THE ECONOMIC BENEFITS OF RESEARCH AND DEVELOPMENT IN THE CANADIAN MINING AND METALLURGY SECTOR

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In the 1930s, gold mining in Canada
surpassed manufacturing in the total
value of output.

He still needed a lot of money, to allow him
to drill ever deeper through the dense layers
of rock and build a mill so that he
would no longer have to ship his ore
south for refining into bullion.

– Charlotte Gray,
Murdered Midas *(2019)*

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Executive Summary

Mining makes the modern world possible. Even though many people will never see an operating mine in their lifetime, we rely on natural resources to enjoy the products and services we take for granted in the 21st century. In other words, if you can't grow it, then it has to be mined. Indeed, the pathway to a sustainable net-zero emissions economy needs more metals than have been unearthed in the entire history of humanity. Electric vehicles, renewable energy, electricity storage and energy-efficient infrastructure for cities will require steel, copper, nickel, lithium and a range of materials classified as 'critical metals.'

The prospect of extracting these materials against the backdrop of increasing orebody complexity and low public trust towards the industry is daunting. Mining in the future will need to be very different from today if global needs for mined materials are to be met. However, we have been here before. If the mining industry had not embraced a series of innovations through the 20th century, then copper extraction costs would be four times higher than what they are today, with consequences for the affordability of electrical technology. Innovation in the mining industry has enabled global economic development in the past, and it will do so in the future as well.

The critical message for executives and policymakers from *The Economic Benefits of Research and Development in the Canadian Mining and Metallurgy Sector* is that the golden age of Canadian Mining was underpinned by public and private innovation programs that made Canada a world leader in industrial materials. After the Second World War, the advent of centralized corporate R&D labs was vital for creating internationally competitive Canadian metallurgy and metal products.

Inco was created in 1905 to commercialize a new copper-nickel process by merging the US owner of the technology with the Canadian owner of the Sudbury nickel deposits. The dominant pattern of Inco's growth until the 1970s was developing new technologies to bring resources and value-added products to market. Internal "research stations" developed many of these innovations, including one designed for pilot-scale testing of metallurgical processes. The construction of a laboratory at Mississauga, Ontario, enabled university-trained researchers to enjoy an urban lifestyle while working on Inco's technical challenges.

Sommaire

L'exploitation minière rend le monde moderne possible. Même si de nombreuses personnes ne verront jamais une mine en activité de leur vie, nous dépendons des ressources naturelles pour tous les produits et services que nous tenons pour acquis au XXI^{e} siècle. En ce qui concerne les ressources terrestres, si on ne peut pas les faire pousser, alors il faut les extraire du sol. En effet, la voie vers une économie durable à zéro émission nette nécessite plus de métaux que ceux qui ont été déterrés dans toute l'histoire de l'humanité. Les véhicules électriques, les énergies renouvelables, le stockage d'électricité et les infrastructures urbaines à haut rendement énergétique nécessiteront de l'acier, du cuivre, du nickel, du lithium et toute une variété de matières classées comme « critiques ».

La perspective d'extraire ces matériaux dans un contexte de complexité croissante en ce qui concerne les gisements et le faible niveau de confiance du public envers l'industrie suscite de l'angoisse. L'extraction minière de demain devra être très différente de celle d'aujourd'hui si l'on veut répondre aux besoins mondiaux en minerais. Mais nous sommes déjà passés par là. Si l'industrie minière n'avait pas adopté une série d'innovations au cours du XX^{e} siècle, les coûts d'extraction du cuivre seraient quatre fois plus élevés qu'aujourd'hui, ce qui aurait des conséquences importantes sur les coûts de la technologie électrique. L'innovation dans l'industrie minière a permis le développement économique mondial dans le passé, et elle continuera de le faire dans l'avenir.

Le message crucial à l'intention des dirigeants d'entreprises et des décideurs politiques dans l'ouvrage *The Economic Benefits of Research and Development in the Canadian Mining and Metallurgy Sector* de Peter Warrian est que l'âge d'or de l'industrie minière canadienne a été soutenu par des programmes d'innovation publics et privés qui ont fait du Canada un leader mondial dans le domaine des matériaux industriels. Après la Deuxième Guerre mondiale, l'avènement de laboratoires de R-D privés et centralisés a été vital à la création de produits métallurgiques et métalliques canadiens concurrentiels pour le marché international.

La société Inco a été créée en 1905 pour commercialiser un nouveau procédé pour le cuivre-nickel suivant la fusion du propriétaire américain de la technologie et du propriétaire canadien de gisements de nickel à Sudbury. Jusqu'aux années 1970, le principal modèle de croissance d'Inco était de mettre au point de nouvelles technologies afin de commercialiser

The case of Stelco has many similarities to Inco with the formalization of a metallurgical laboratory on the grounds of the Hilton Works in Hamilton, Ontario. This lab grew into a separate research department in 1967 called the Stelco Research Center. At its peak of 132 employees, it was one of the largest centers of metallurgy in Canada. One of the most significant steel production innovations supported by the center was the Coilbox, supported by Canadian R&D tax rebates and grant funds for a full-scale mill test in 1973. Patents were filed around the world, which alerted competitors like BHP to the existence of the technology. The performance of the Coilbox was such a breakthrough that major steel producers were eager customers. In addition to the productivity improvements in Stelco's operations, each sale contributed three million dollars to Stelco's earnings. By the early 2000s, 70 units were in steel mills around the world.

The successes achieved through the model of large corporate laboratories were mirrored in other industries worldwide from the mid-twentieth century. Well known examples include the Bell Laboratories in the USA and Bosch's R&D center in Germany. Until 1999, Australia's mining giant, BHP, had research facilities that were among the largest in the country.

A combination of natural resource endowments, demand fueled by military conflicts and post-industrialization, and the emergence of management practices for large industrial corporations created the perfect environment for Canadian metallurgical innovation. While the takeovers of the iconic Canadian metallurgical innovators in the twenty-first century ensured the industrial R&D lab's demise, the big central laboratory was an artifact of the twentieth-century innovation process. In the early twenty-first century, the internalized innovation model was changing into a distributed innovation system, where innovation inputs come from a network of different actors, often from other industries. These have been called innovation ecosystems that support the new model of distributed innovation networks or "open innovation."

The reasons for the opening up of innovation to include multiple organizations include the increasing complexity of technology and the shortening product lifecycle. Relying on an internal laboratory to develop and deploy the best solutions to mineral processing and metal production is slower and limited by the available expertise. In the twenty-first century, innovation is a team sport where the winners have the best network of organizations, rather than the best R&D lab.

des ressources et des produits à valeur ajoutée. Des « postes de recherche » internes ont mis au point nombre de ces innovations, dont une visant à tester des procédés métallurgiques au moyen d'essais pilotes. La construction d'un laboratoire à Mississauga, en Ontario, a permis à des chercheurs formés à l'université de profiter d'un mode de vie urbain tout en travaillant à relever les défis techniques d'Inco.

Le cas de la société Stelco présente de nombreuses similitudes avec celui d'Inco, avec la formalisation d'un laboratoire métallurgique sur le terrain de l'usine Hilton Works à Hamilton, en Ontario. Ce laboratoire est devenu le Stelco Research Center en 1967, soit une division de recherche distincte. Pendant ses meilleures années, le centre comptait 132 employés et était l'un des plus grands centres de métallurgie au Canada. Une des innovations les plus importantes en matière de production d'acier au centre a été le Coilbox, soutenu par des rabais fiscaux pour la R-D et des fonds de subvention pour un essai en usine à pleine échelle, en 1973. Des brevets ont été déposés dans le monde entier, ce qui a alerté des concurrents comme BHP de l'avènement de cette nouvelle technologie. Le rendement du Coilbox a été tel que les plus importants producteurs d'acier ont tous voulu se le procurer. La productivité augmentait à Stelco, et chaque vente venait ajouter la somme de trois millions de dollars aux coffres de Stelco. Au début des années 2000, on trouvait déjà 70 unités dans des aciéries partout dans le monde.

Les réussites découlant du modèle des grands laboratoires d'entreprises se sont reflétées dans d'autres industries sur la scène internationale à partir du milieu du XX^{e} siècle. Parmi les exemples les mieux connus figurent les laboratoires Bell aux États-Unis et le centre de R-D de Bosch, en Allemagne. Jusqu'en 1999, le géant minier australien BHP disposait d'installations de recherche parmi les plus importantes au pays.

La combinaison de la richesse en ressources naturelles, de la demande alimentée par les conflits militaires et la postindustrialisation et de l'émergence de pratiques de gestion dans les grandes entreprises industrielles a donné lieu à un environnement parfait pour l'innovation canadienne en métallurgie. Alors que la mainmise sur les emblématiques innovateurs métallurgiques canadiens du XXI^{e} siècle a entraîné la fin des installations de R-D, le grand laboratoire central est devenu un artefact de l'innovation du XX^{e} siècle. Au début du XXI^{e} siècle, le modèle d'innovation internalisé s'est transformé peu à peu en un système d'« innovation distribuée » où les apports d'innovation provenaient d'un réseau de différents acteurs, souvent d'industries variées.

There were early signs of this transition to innovation ecosystems in Canadian metallurgy. The case study of Hatch shows that the decline of the corporate laboratory enabled opportunities for different business models. As an engineering solutions provider with expertise in metallurgy, Hatch was able to work closely with clients to develop solutions that could be used in other projects. Through acquisitions, Hatch acquired IP and skilled staff but also licenced out IP when the opportunity arose. Hatch's open innovation strategy can be seen in their membership in the Digital Technology Supercluster program launched in 2018. Teck is also a member of the Digital supercluster. Their engagement with research consortia and new-ventures is an example of how the Canadian mining sector embraces the development of innovation ecosystems.

Will Canada regain its global leadership position in metallurgy and mining? Resource endowment and global demand are two of the factors that enabled the golden years of Canadian mining. They are present today. Canada is endowed with essential metals and materials for the twenty-first century, including copper, nickel, zinc, cobalt, uranium, graphite, helium and rare-earths. The demand for these materials is projected to increase through the next decade rapidly. However, the blueprint for the future of innovation in Canadian metallurgy and mining is different from the blueprint of the past. The barriers between industry sectors are disappearing, and mining companies are significant users of telecommunications, biotechnology, renewable energy, robotics, artificial intelligence, and cloud computing.

Like the beginning of the twentieth century, new entrants into the modern Canadian mining sector innovate to create new metallurgical processes to bring resources to market. Frequently they are collaborating with research institutions, engineering consultants and mining technology suppliers to achieve this. Examples include Euro Manganese reprocessing old tailings in Czechoslovakia and FPX Nickel developing a metallurgical circuit to commercialize unconventional nickel alloy deposits in British Columbia. Nouveu Monde Graphite has licensed battery material technology from Hydro Quebec to add value to their graphite deposit which is planned to be the first electricity-powered open pit mine in the world. There are many examples of smaller Canadian mining companies taking new approaches to bring known deposits to market. Perhaps the Canadian policy of flow-through shares could extend beyond exploration costs to R&D to facilitate this form of innovation.

Larger Canadian companies and policymakers need to consider strategies to build productive innovation

On parlait d'écosystèmes d'innovation qui soutenaient le nouveau modèle de réseaux d'innovation distribuée ou « ouverte ».

L'ouverture de l'innovation à des organisations multiples s'explique notamment par la complexité croissante de la technologie et le raccourcissement du cycle de vie des produits. Mais se fier à un laboratoire interne pour mettre au point et déployer les meilleures solutions en matière de traitement des minéraux et de production de métaux ralentit les choses, et se limite à l'expertise disponible. Au XXI^{e} siècle, l'innovation est devenue un sport d'équipe où les gagnants sont ceux qui disposent du meilleur réseau d'entreprises, et non du meilleur laboratoire de R-D.

Des signes avant-coureurs ont annoncé cette transition vers les écosystèmes d'innovation dans le secteur de la métallurgie canadienne. Le cas de la société Hatch illustre que le déclin des laboratoires internes a ouvert la voie à de nouveaux modèles d'affaires. En tant que fournisseur de solutions d'ingénierie ayant une expertise en métallurgie, Hatch a pu travailler en étroite collaboration avec ses clients pour mettre au point des solutions qui pouvaient aussi être utilisées dans d'autres projets. Par le biais d'acquisitions, la société s'est procuré de la propriété intellectuelle et du personnel qualifié, mais a également concédé des licences lorsque l'occasion s'est présentée. La stratégie d'innovation ouverte de Hatch est manifeste lorsqu'on pense à l'adhésion de l'entreprise au programme de la Supergrappe des technologies numériques lancée en 2018. La société Teck est également membre de la Supergrappe. Cet engagement envers les consortiums de recherche et les nouvelles entreprises illustre bien comment le secteur minier canadien ouvre grand les bras à la mise sur pied d'écosystèmes d'innovation.

Le Canada retrouvera-t-il sa position de leader mondial en matière de métallurgie et d'exploitation minière? La richesse de nos ressources naturelles et la demande mondiale sont deux des facteurs qui ont mené à l'âge d'or de l'exploitation minière au Canada. Et les deux y sont toujours. On trouve au Canada les métaux et matières qui sont essentiels au XXI^{e} siècle, notamment du cuivre, du nickel, du zinc, du cobalt, de l'uranium, du graphite, de l'hélium et des métaux des terres rares. La demande pour ces matières devrait augmenter rapidement au cours de la prochaine décennie. Toutefois, le plan d'action pour l'avenir de l'innovation dans le secteur canadien de la métallurgie et de l'exploitation minière est différent de celui du passé. Les barrières entre les secteurs industriels disparaissent, et les sociétés minières sont d'importants utilisateurs de télécommunications, de biotechnologie, d'énergie renouvelable, de robotique, d'intelligence artificielle et d'informatique en nuage.

ecosystems. The Federal supercluster program is one such example of an approach to building such ecosystems through providing incentives to bring diverse companies together around significant industrial challenges. A lesson from the twentieth century's metallurgical successes is that changing the industry to support a new style of innovation takes time. Consistency and ongoing commitment from the government and the corporate sector to innovation will be needed to bring Canadian mining into a new golden age.

Dr. John Steen,
EY Distinguished Scholar in Global Mining Futures,
and Director of the Bradshaw Initiative in Minerals and Mining (BRIMM), The University of British Columbia

Comme au début du XX^{e} siècle, les nouveaux arrivants dans le secteur minier canadien moderne innovent pour créer de nouveaux procédés métallurgiques afin d'acheminer les ressources vers les marchés. Et ils collaborent souvent avec des instituts de recherche, des génies-conseils et des fournisseurs de technologies minières pour y parvenir. Il suffit de penser à Euro Manganese qui retransforme des résidus en Tchécoslovaquie et à FPX Nickel qui travaille sur un circuit métallurgique pour commercialiser des gisements d'alliages de nickel non conventionnels en Colombie-Britannique. Nouveau Monde Graphite, de son côté, a obtenu d'Hydro-Québec une licence d'exploitation pour le développement de matériaux utilisés dans les batteries afin d'ajouter de la valeur à son gisement de graphite, et sa mine à ciel ouvert devrait devenir la première au monde à être alimentée par électricité. Il existe de nombreux exemples de petites sociétés minières canadiennes qui adoptent de nouvelles approches pour commercialiser des matières connues. Il serait à souhaiter que le programme canadien d'actions accréditives s'étende au-delà des coûts d'exploration et vise également la R-D afin de favoriser ce type d'innovation.

Les grandes entreprises canadiennes et les décideurs du gouvernement doivent réfléchir à des stratégies aptes à créer des écosystèmes d'innovation productifs. Le programme fédéral de la supergrappe est un bon exemple de l'approche nécessaire pour en venir à de tels écosystèmes, en offrant notamment des stimulants pour inciter le regroupement d'entreprises variées autour d'importants défis industriels. Une leçon à tirer des réussites métallurgiques du XX^{e} siècle est celle-ci : changer l'industrie pour soutenir un nouveau style d'innovation prend du temps. De la cohérence et un engagement continu envers l'innovation au gouvernement et dans le secteur des affaires seront nécessaires si l'on veut faire entrer l'industrie minière canadienne dans un nouvel âge d'or.

John Steen, Ph.D.,
distingué érudit en avenirs miniers mondiaux
et directeur de la Bradshaw Initiative in Minerals and Mining (BRIMM) de l'Université de la Colombie-Britannique

Foreword

The Economic Benefits of Research and Development in the Canadian Mining and Metallurgy Sector

Mining and metallurgy have contributed much to the development of the Canadian economy. However, the last 40 years have seen downgrading and elimination of industrial, governmental and academic research into mining and metallurgy in Canada. As Asia became the center of gravity for primary metals consumption and production, Canada's share of world production of ferrous and base metals dropped precipitously. A century of production has lowered reserves, and high operating costs and capital costs, frequently associated with environmental concerns, have resulted in closure of operating facilities. Today, only two Canadian copper smelters are in operation down from five in 1985. After repeated foreign takeovers, major Canadian steel mills are now "branch plants" of foreign entities.

At the same time, Canada remains a resource-rich country and the efficient mining and processing of natural resources is vital to the digital economy. So, in this atmosphere what is the role of innovation in mining and metallurgy? Valuable innovations of the past came from industrial and governmental organizations. In a globalized world, where do these come from? How does Canada participate?

These questions were pondered at the Metallurgy and Materials Society's board of directors meeting in 2017, and the Historical Metallurgy Section, in our fourth collaboration with the Ingenium: Canada's Museums of Science and Innovation, took on the challenge of providing answers. After deliberation and discussion it was decided that a backward-looking, forward-looking approach should be taken. By looking back we would document and describe the impact that innovation played in creating the modern world of mining and metallurgy. In turn, this material would provide the basis for looking forward, and project what a viable, valuable innovation model might look like and would provide guidance for policy-makers and those involved in future planning. Understanding the economics of the innovation process seemed most important and therefore Peter Warrian, a Canadian economist at the University of Toronto's Munk School of Global Affairs and Public Policy, with broad experience in the steel industry, was contracted for the study.

Dr. Warrian, working with research assistants, interviewing individuals and groups, and referencing published literature, has created an extensive narrative about the role that technology development has played in creating the current mining/metallurgy enterprise including environmental improvement. He compares the old technology development process with the current "innovation ecosystem" in Canadian mining/metallurgy, identifies what areas of innovation are most likely to generate maximum value, and elaborates about technical and social changes implied. Specifically, the case study on Inco illustrates the crucial role that technology development played in creating the modern mining industry; the case study on Hatch shows how innovation is producing value and jobs today, and the discussion of digitalization of mining projects how innovation, properly supported and organized, shall produce riches in the future.

While this document does not provide definitive answers, it is a beginning point, and we know of no other comparable study of this difficult, complex problem. Without the financial support of the organizations below, it would not have been possible. We owe them tremendous thanks.

Canadian Institute of Mining, Metallurgy and Petroleum (CIM)

Metallurgy & Materials Society (MetSoc of CIM)

Canadian Mineral Processors (CMP)

The Management & Economics Society of CIM. The Toronto Chapter

Arithmetek Inc.

Hatch Limited

Teck Resources Limited

Woodgrove Technologies

Sam Marcuson,
Past Chairman, Historical Metallurgy Section of the Metallurgy & Materials Society of CIM

Introduction

AIMS AND GOALS OF THE STUDY

The objective of this Study is to enhance Canadians' appreciation of the historic contribution of mining and metallurgy to the Canadian economy, as well as to illustrate its potential for continuing positive contributions to our future. Canada has long been regarded as having a major industrial competitive advantage through the availability of vast natural resources, particularly in metal mining, and in downstream industrial manufacturing capacity. However, the specific mechanisms to link these complementary capabilities, research and technology transfer have been, until now, relatively unexamined. Finally, though this may seem counterintuitive to many people, the digital economy needs mining—and more of it. For reasons pertaining to the quality of ore grades and those required for digital applications, the next generation of mine designs may pertain predominantly to underground mines. This is the sort of mining at which Canada has traditionally excelled.

Metallurgy in the Canadian economy during the twentieth century was primarily conducted within vertically integrated mining and metals companies. The leading example was the International Nickel Company Limited (Inco). In its heyday, Inco was one of the world's largest operating companies in the mining industry and was a global leader in metallurgy. Most of that technical capacity is now lost. Across the industry, the relative marginalization and decline of metallurgy has been most associated with widespread downsizing related to the global consolidation of mining companies in the first decade of the new century. Given the continued importance of industrial production to the economy, it is curious that there have been virtually no systematic studies in the business history literature of R&D throughout the life of the corporation. The objective of this study is to delineate the value chain of research and innovation activity from mines research to materials processing to product development.

The transformation in mining and metallurgy can be summarized in two narrative threads. In the first, the "downside" Inco Story, we encounter a golden age followed by corporate decline and marginalization of metallurgy. In the second, the "upside" Hatch Story, we see the dramatic growth of a small engineering consulting firm from, in the period of Inco's decline, a 600-person to a 6,000-person operation, and eventually to what we have today: a global mining and metallurgy consultancy encompassing the expertise of 9,000 staff. For this reason, case studies of these two companies are the major original research contributions of this study.

The profile of Inco as a mining giant is known to many Canadians. On the other side, Hatch Limited,[1] starting in the 1970s, developed a strong technical specialization around new furnace technology, with the associated gas handling and cleaning. This remains a core competency of the company to this day. As computer processing power grew, the company developed further numerical methods to analyze such issues as off-gas flow through tools like Fluent and others. As a result, Hatch has accumulated technical expertise beyond both the company's internal resources and that which is present in universities. The sophistication and efficiency of these tools were, at least in the furnace area, a competitive advantage over its competitors. In addition to Hatch's cumulative talent and resources, the company supplemented its inherited or purchased talent with new recruits. At one point in the 1970s, Hatch was the largest recipient of NSERC post-doctoral industrial fellowships in Canada. In the late 1980s, the company boasted about 300 PhDs on staff. This made possible a focus on the fundamentals needed to solve complex real life problems. It proved a key differentiator in the marketplace.

The reader of this study may reasonably ask: Can the Canadian mining industry of today contribute what the world-leading mining and metallurgy companies of the past did in the golden age? The answer is "No". But that may not be the right question. The accomplishments of vertically integrated industrial corporations produced a certain kind of industrial production knowledge and products. For this, the research-and-development functions within the companies were critical. Even before the foreign takeovers and consolidations of the 2000–2010 period, the system of innovation in mining was changing from an individual corporate function to a networked system of innovation. In this respect, the industry in future may be able to make a broader contribution to the economy and society than in the past, when the economic benefits of innovations flowed mainly to individual firms.

It is also possible that the mining and metallurgy industry in Canada will proceed at two different speeds into the future, driven by technology and economic factors. Digital technologies will be led by precious metals exploration and development. By contrast, base metals technology progress will be more characterized by incrementalism dominated by the original equipment manufacturers (OEMs). Meanwhile, entrepreneurial technology firms that fit into the category

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[1] Over its long history, Hatch underwent several name changes. It is referred to as Hatch in this document.

of small and medium enterprises (SMEs) will remained positioned at the margin with a limited ability to scale. Precious metals producers will be driven by the crisis in reserves. Base metals will continually struggle with the discovery rate and the crisis of productivity.

On the economics side, two key recent studies differ in their analysis and predictions. In the David Humphreys economic scenario, the industry as a whole will never be able to overcome the productivity lag of the early 2000s.[2] It will take a fundamental shift in typical mining business models, to a circular economy rental model, to add value to the underlying resource. In the Barclays[3] scenario, technical innovation can overcome market surplus and a reduced hurdle rate (the minimum rate of return required). Some producers will make it and some won't. Multi-site operators with the ability to scale will succeed, providing that they have the resources to make the investments and have near-term implementable technologies. It is of course possible that both of these economic scenarios can be reconciled.

The Key Arguments of this Study

Four arguments are put forward in this book.

1. Metallurgy has made significant contributions to the Canadian economy and society.

The classic form of corporate industrial organization, modelled on the German industrial firm in the late nineteenth century, saw technical and laboratory capacities form part of the standard architecture of the modern industrial corporation. This key development drove the expansion of modern mass production and pushed the frontiers of productivity. In the past, these major metallurgy centres provided the underlying physical and technological substructure for Industrial Canada, its manufacturing, transportation and infrastructure base for our modern mass production and mass consumption society. To understand the contribution of metallurgy, it is important to document the pathways and networks of transmission of metallurgical knowledge and technology across the economy. The marginalization of these capabilities has been a major contributor to the decline of mining innovation and productivity in the Canadian industry.

2. R&D is the fundamental value creator of the corporation.

In primary metals companies in particular, R&D is the function that creates the fundamental value of the corporation. Without it, mining companies face the perpetual struggle of the "commodities trap," i.e., base metal prices are inherently subject to downward pressure by lowest-cost producers, to a level where profits become insufficient to sustain operations. R&D is a way out of this trap.

3. The downward "tipping point" for Canadian mining and metallurgy happened earlier than is widely believed.

Innovation in process-based industries is uniquely risky, costly and complex, because it involves both technical and organizational complexity. The book framing this research theme is *R&D for Industry: A Century of Technical Innovation at Alco*a, by Margret Graham and Bettye Pruitt (Cambridge University Press 1990). The implication is that the tipping point for Canadian metallurgy turning downwards was not the consolidation of the mining industry in the early 2000s, but instead the withdrawal from fundamental research that took place over the decade spanning 1985 to 1995. It was during this period that mining and metals companies such as Inco and Stelco, which had enjoyed market oligopolies during most of the post-war period, were facing new competitors from low-cost producers in developing countries. This led them, individually, to conclude that they could no longer afford to carry the costs of basic research for the whole industry. Mining and metals companies were not alone in this. North American corporations as a whole, in the period from the 1970s and 1980s, became disillusioned by the unfulfilled promise that large investments in basic research necessarily lead to clear and near-term impacts on the bottom line. Within the corporation, metallurgy became more narrowly focused on technical support services. This trend was further amplified by the commodities boom associated with the growth of China in the first decade of the 2000s.

4. Canadian expertise and potential for innovation in metallurgy still exist, but in a different form.

In future, the important contribution of metallurgy will be made through an innovation eco-system, not the traditionally vertically integrated mining Corporation. Our underlying expert metallurgy talent was not entirely lost to Canada. Much of it was re-located to academe, government and private industry in the form of consultancies, engineering firms and suppliers of technical goods and services to operating companies. For instance, recent research suggests that as many people are now employed in the Sudbury mining services cluster as are employed in the mines themselves.

While the corporate research centres and labs went away, the need for and existence of modern metallurgy was still vital to the modern economy and its progress. New networks and agents emerged. Many individuals migrated from private industry to universities and government labs. Expanded roles

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[2] Humphreys, D. "Mining Productivity and the Fourth Industrial Revolution," *Mineral Economics* (January 2019).

[3] Barclays Research. *Mining innovation breaking through*. Barclays 11 December 2019.

emerged for engineering consulting companies like Hatch. Public research infrastructure and universities came to play a proportionally larger role. Mining sites and regional economies like Sudbury saw service clusters took over much of the innovation role that the classic corporate centres once played.

STRUCTURE OF THE BOOK

The book is organized into six parts.

Part One, "Historical Contexts," offers an overview of Canadian mining and metallurgy. It explores the rise and composition of the twentieth-century mining industry in Canada. Great mines arose upon the locations of great ore bodies. Technical development was very much a localized affair. Key technical developments, in mineral processing in particular, produced the modern mine-mill industrial complex that was the core production configuration of the industry across the world in the twentieth century. This became the platform for worldwide metallurgical innovations in the so-called golden age of Canadian Metallurgy, which lasted from about 1950 until 1990.

In Part Two, "The Rise and Fall of Corporate R&D," research and development's role in Canadian mining and metallurgy is outlined and anlayzed, making the case that R&D within individual vertically integrated mining companies was ground zero for such developments Discussion here focuses on the cases of Inco, Stelco, Alcan and, at the public policy level, Sheridan Park in Ontario, as well as the cluster of metallurgical expertise represented by Falconbridge, Noranda and Cominco.

Part Three, "The Changing Narrative of Mining and Metallurgy," addresses the corporate downsizing of R&D and its impacts, as well as the contrary narrative of Hatch which, within a single decade, became a global metallurgical player. This section also considers the rise of environmental concerns and related public policy, and how this began to affect the mining and metallurgy sector and the way it operates.

In Part Four, "The Resilience of Metallurgy and Mining Innovation," we consider a new era of innovation related to Industry 4.0, a term coined in 2011 to label what is considered the Fourth Industrial Revolution, the integration of smart (or computerized) technology into manufacturing processes. Mining 4.0, as some conceive, it refers to a mine that is automatically operated by smart intelligent systems with very few operators, many of whom would be off site. Others envision it as the merging of technology and the person to promote more productive labour. What is key is that this new industrial era seeks to balance production with environment concerns and the use of disruptive technologies such as AI and robotics. Supply chains, technologies and environmental externalities are changing the boundaries of the firm in mining as they are in all other modern industries.

Part Five, "Estimating and Realizing the Benefits," turns to the ways in which new approaches to extraction and processing raise questions about how we measure value and returns on investment. Past practice in the industry was based, primarily on one metric: ore grade.[4] New metrics and methodologies are emerging to challenge this single metric, including the value of information and how external partnerships such as agreements with Indigenous peoples can increase the enterprise value of the mining company.

Part Six, the "Conclusion" suggests how the future of mining and metallurgy may be different. The boundaries of the Firm will change from the classic vertically-integrated mining corporation. It suggests that metallurgy by itself may not be enough to sustain the economic viability of the mining company. The dynamics of innovation in the industry are now dispered along the supply chain, from equipment to service providers. Environmental issues will shift the operating boundaries further to incorporate the watersheds of their associated Indigenous communities.

As stated, there is also the risk of a two-speed mining future. Precious metals will lead the implementation of cutting-edge digital technologies, driven by the critical need to establish proven reserves. Base metals mining will struggle with incremental technological improvements to recover lagged productivity. Some will succeed at bending back the efficiency curve and others will not. Those companies that find ways to add value to the underlying resource and thus become major players in the circular economy may prove to be most likely to succeed.

GLOSSARY OF KEY TERMS:

Mining and Metallurgy: The mining engineering discipline makes the distinction between "metallurgy," which refers to minerals processing at the mining level, and most often to the milling and smelting of ores and their refining into final products; and "structural metallurgy," which refers to product development and metal manufacturing.

Innovation: The Organization for Economic Cooperation and Development (OECD) definition: "An innovation is the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations."[5]

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[4] Other metrics included ground conditions, overburden, depth, and stripping ratio.

[5] OECD Statistics, "Glossary of Statistical Terms," OECD Glossary of Statistical Terms - Innovation Definition (OECD, September 2005).

R&D: The Organization for Economic Cooperation and Development (OECD) definition:

> Research and development (R&D) comprise creative work undertaken on a systematic basis in order to increase the stock of knowledge (including knowledge of man, culture and society) and the use of this knowledge to devise new applications. R&D covers three activities: basic research, applied research, and experimental development. Basic research is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular application or use in view. Applied research is also original investigation undertaken in order to acquire new knowledge; it is, however, directed primarily towards a specific practical aim or objective. Experimental development is systematic work, drawing on existing knowledge gained from research and/or practical experience, which is directed to producing new materials, products or devices, to installing new processes, systems and services, or to improving substantially those already produced or installed.[6]

BRIEF LITERATURE REVIEW

The narrative accounts in the following chapters draw from the following books, studies and documents: *The Canadian Metallurgical & Materials Landscape 1960 to 2011, by Joel Kapusta, Phillip Mackey and Nathan Stubina (2011,* The Canadian Institute of Mining, Metallurgy and Petroleum); *Stelco R&D History: From the Beginning*, by former Stelco director Jock McKay (2013); *All that Glitters: Readings in Historical Metallurgy*, by Michael Wayman, (1989, Metallurgical Society of the Canadian Institute of Mining and Metallurgy) and *The Development of Metallurgy in Canada since 1900: Historical Assessment Update*, by Erich Weidenhammer (2017: The Canadian Institute of Mining, Metallurgy and Petroleum and The Canada Science and Technology Museum).

Given the importance of industrial production in the economy, it is curious that there have been virtually no systematic studies of the historic role of R&D within the corporation. The one great exception is *R&D for Industry: A Century of Technical Innovation at Alco*a, by Margret Graham and Bettye Pruitt (Cambridge University Press, 1990). This has been a critically important reference point in the organization of this book.

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[6] OECD. “Expenditure on R&D.” (OECD, 2012).

PART I: Historical Contexts

1.1 INTRODUCTION

The emergence and scale-up of the modern mining industry was largely a function of the military economy, through such necessities as shell production during the First World War. Two key mining metallurgy innovations, led by Canadians in the first decade of the twentieth century, made this possible. First came the introduction of cyanide as a means to leach, and therefore extract, gold from rock. The second was the development of flotation as the process to further separate minerals from the ore and concentrate it into commercially viable product. This led to a practical economic outcome: Canada no longer had to export raw minerals to the USA and Europe for processing.

Combined, these two technological developments generated the mining and smelting complex that became the economic engine of the modern mining corporation, and the mining industrial cluster that dominated the past century and made Canada a world leader. After the Second World War, this formed the foundation of the great metallurgy centres of the post-war economy, with the rise of legendary locations in the industry, such as Sudbury, Noranda, Trail, and Arvida. These became the great centres of excellence that, in the 2000s, Canada would lose. They remain centres of metallurgy, but things have changed. Noranda's Horne Smelter in Rouyon-Noranda, for instance, no longer has mines because their ore ran out. It operates on the basis of the Noranda Reactor, developed in Canada, which recycles copper that is mainly sourced from the USA, as well as copper concentrates from other locations.

A Timeline of Mining Innovation Cycles

1920-1990: The system was driven by internal operations management and a local network of specialized suppliers.

1990-2015: Operating companies stepped back from major innovation, while equipment OEMs became the major drivers of innovation and key gatekeepers for access to the mining innovation networks.

2015 to Present: Efforts to share R&D costs more broadly, access to government funding, and improving ability to leverage new technologies and talent pools are, in combination, leading to the emergence of a more open and collaborative practice of innovation in the industry. Service and consulting companies such as Deloitte, Hatch and Stantec have arisen to partner with equipment OEMs and operating companies in supporting industry-wide mining innovation.

1.2 A BRIEF HISTORY OF CANADIAN MINING AND METALLURGY

NARRATIVE HISTORY

As illustrated in the concluding remarks from Michael Wayman's *All that Glitters: Readings in Historical Metallurgy*, by the early decades of the twentieth century, Canada was blessed with a successful metallurgy industry that was quick to develop new technologies and to maximize its yield. These characteristics remained prevalent during the Second World War and in the decades that followed.

The early history of Canada's metal extraction industry was also characterized by a high degree of technology transfer. The metallurgists of the time became skilled at adopting and adapting processes developed elsewhere. Some of these processes were old and proven, whereas others were new and untried. There was a propensity toward experimentation on a large scale with plants that were often built in advance of their actual technical or economic viability, or even that the guarantee of an adequate supply of ore, had been ascertained. As a result, there were many failures for every success.

There were several reasons for all of this metallurgical activity. First, a strong incentive developed to reduce the cost of shipping ore to distant smelters in the United States and elsewhere, as well as to increase the return to the mine owner. Secondly, new processes had to be devised to separate the valuable metals or to increase recoveries. Thirdly, many of the early smelters stopped short of producing refined metal and shipped matte or crude metal to refineries outside Canada. This practice eventually gave way to domestic refineries, often through the adoption of new technology. The relatively small scale of mining and metallurgy facilities, combined with loose to non-existent regulations in the 1920s and 1930s, contributed to the pace of innovation. At Copper Cliff, near Sudbury, for instance, two smelters were built in a rather short period of time, which would not be possible today.

Within a few decades of 1900, a strong metallurgical industry had arisen in Canada that included iron and steel, copper, nickel, cobalt, lead, zinc, silver, gold, and aluminum. With it, Canada's strength in metals extraction was firmly established. What is most visible today however, is the lack of Canadian-driven metallurgy and mining innovation. Much of what once were Canadian-based capabilities are now managed by foreign companies. In contrast, during the rapid rise of the industry a century ago, most innovation and decisions took place locally.

In the past, the major metallurgy centres provided the underlying physical and technological substructure for Canada's industrial heartland: the manufacturing, transportation and infrastructure base of our modern mass production and mass consumption society. In order to understand the contribution of metallurgy, it is important to document the pathways and networks of the transmission of metallurgical knowledge and technology in its diffusion across the economy. Much of this knowledge and diffusion of technology was led by the great personalities of Canadian metallurgy, including Robert Crooks Stanley, RGK Morrison and Keith Brimacombe, a fact reflected in their Mining Hall of Fame recognition.

That was then and this is now.

The great centres of metallurgy associated with Canada's leading mining and materials—Inco, Noranda, Alcan, Cominco and Stelco— from the mid-1990s to the late 2000s were all marginalized from their important status in senior corporate management and mostly reduced to a service function for operating departments. These companies fell victim to corporate and financial changes, including the movement of investments to developing countries, changes in shareholder value ideology, and the decline of the classical corporate R&D laboratory in the industrial landscape. These sorts of changes were not limited to mining and they occurred across industry sectors. Well-known examples include the decline of the legendary laboratories at AT&T, IBM, DuPont, General Motors and US Steel.

Nevertheless, this is also a story about intellectual and industrial resilience. While the corporate centres and labs went away, the need for and existence of modern metallurgy was still vital to the modern economy and its progress. New networks and agents emerged. Many key individuals migrated from private industries to universities and government labs, and roles for engineering consulting companies, such as Hatch, expanded. Public research infrastructure and universities came to play a proportionally larger role in R&D. The regional economies in mining areas, such as Sudbury, saw the emergence of a new cohort of mining engineering and technology supply companies. These grew to a combined size that equalled or exceeded the size of the direct production work forces of the industry's heyday. These service clusters took over the innovation role previously played by the classic corporate centres.

Mining and the Canadian Economy

Mining has contributed many benefits to Canadian society and its economy over the years. This includes the material backbone of the industrial economy and its infrastructure, the building of mining communities, their employment and income bases, the support of national defense and security requirements, the manufacturing sector and the general economy and well-being of Canadians.

There are three general categories of benefits that flow to our economy and society from mining and metallurgy.

1. Benefits to the Firm: Operating companies seek improvements in efficiency, yield, and estimated reserves.
2. Social Benefits: Employment, safety, health, and environment.
3. Benefits to the Economy: Technology innovation and movement to Industry 4.0.

Going forward, the path of transformation is far from linear. Recent decades have witnessed an unprecedented metals price supercycle, along with a 28 percent decline in mining productivity. (The Bank of Canada defines commodities "supercycles" as extended periods of boom and bust, which can have significant effect on trade, exchange rates, employment, income and inflation.) It has also seen the marginalization and elimination of the classic centres of Canadian metallurgy.

Are these things connected? Do they matter?

The industry is at a technological inflection point. The development and application of emerging digital technologies, known as "digitization," is of increasing interest to the mining industry. Digitization of ore bodies and digital technologies, such as robotics and machine learning, offer the prospect of a greater number of employees working on the surface, and even the development and operation of zero-emissions mines. At the same time, if the mining industry is to survive in Canada, it must deal with its productivity challenges.

While the nineteenth century in Canada was dominated by precious metal mining of gold and silver, the twentieth century was the era of base metal mining of iron ore, nickel, copper, lead, and zinc. This distinction between precious metal mining and base metal mining reappears today in important ways in the discussion of current mining technologies.

Mining Innovation: Barriers and Opportunities

Mining has a long history and reputation of having a very conservative managerial culture in terms of investing in new technologies. Occasionally, however, changes do happen in terms of the extraction and production model for the industry. For example, a significant change occurred with the movement to "bulk mining" led by Inco in the late 1980s and early 1990s. While the bulk mining model was then locked in for the next 30 years, it is a paradigm that is now under pressure for many reasons, which include opportunities to apply new digital technologies and problems of heat and energy consumption as the next generation of operations enter the 3–5 thousand metre depth levels.

A significant challenge to innovation for the mining industry is the volatility of metal markets. When prices are high, industry is too busy to innovate. And, when prices are low, it doesn't have the money to invest in innovation. There appears to never be a "good" time. Another challenge to innovation is that mine designs are exceptionally complex and not easily changed. Once mines are designed and development has commenced, it is difficult to implement disruptive technology, and most times only incremental change is practical. It is more complicated to implement a disruptive technology in a mine than it is in an auto factory. This is a challenge of change in all legacy industries.

Nonetheless, new categories of possible benefits emerge as mining and metallurgy interact with and, at certain junctures, become part of the digital economy. A particularly interesting example of this arises from intangible assets such as Intellectual Property (IP) and data sets. Who owns, controls, and exploits the data that is generated in Canada will determine who gains from this wave of transformative innovations. Data will become the "raw resource" that drives investment, jobs, income and growth. However, unlike earlier staples that provided the impetus for economic development, data is not restricted to Canadian applications and locations. As numerous research studies suggest, the fundamental issue surrounding the adoption and diffusion of digital technology will have to do with data. Who owns it? Where is it stored? How is it valued? Who can or should have access to it? Data ownership has become a monumental issue that governance experts around the world are only just starting to tackle.

At every mining gathering these days, digitization is, overwhelmingly, the theme of conversation. The objectives of increased and pervasive automation of operations have emerged as a key management objective. For an economist, all of these efforts converge around a fundamental for mining productivity: the utilization rate of equipment in mining as compared to other industries.

EQUIPMENT UTILIZATION RATES

Underground Mining	Open Pit Mining	Mining Crushing & Grinding	Oil & Gas	Steel	Oil Refining
29%	38%	70%	88%	90%	92%

Source: Barclays 2019

However, the long-range impact of digitization may not prove to be found in efficiency gains in the extraction and processing of physical resources alone. Instead, it may be found in the leveraging of the intangible resources that are key to all modern industries. In this, the mining industry lags its comparators.

Economists have historically spent considerable efforts analyzing firms' abilities, particularly in heavy manufacturing industries, to successfully exploit their tangible assets such as plant, equipment and workforces. More recently, the focus of economic analysis has shifted towards intangible assets such as intellectual property, employee know-how and, increasingly, data. This line of query has now gone further, to consider a broader set of assets that includes big data, knowledge (explicit and tacit), and business intelligence.[1]

In *Advances in Manufacturing II*,[2] this important new study, the authors point out in the heavy industry comparables are:

Mining extraction

Mining beneficiation

Chemicals

Petrochemicals

Refining

Pulp & paper

Steel

According to the authors, an industry can be scaled for its "digital maturity" regarding four variables: programmable digital logic control, digital control systems, advanced process control, and artificial intelligence. For Erickson and Rothberg, the first three industries (Mining extraction, beneficiation and Chemicals) belong in the second stage, meaning they have transitioned to from electro-mechanical to digital control systems. On the other hand, the final four have reached the third stage (advanced process control), with refining coming closest to fully incorporating artificial intelligence into its set of competencies. Industries were also scored in relation to digital opportunities. In this case, enhanced asset performance (just about all "high"), digital workforce (all "low," except for steel), asset network coordination (all "low"-to-"medium"), and robotics (all "low" save steel and mining extraction, which rated "medium" and "high" respectively).

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[1] Erickson G.S., Rothberg H.N. "Digitization and Intangible Assets in Manufacturing Industries." In: Trojanowska J., Ciszak O., Machado J., Pavlenko I. (eds) "Advances in Manufacturing II." Lecture.

[2] Trojanowska J., Ciszak O., et al. "Advances in Manufacturing II."

For Erickson and Rothberg, the majority of companies in the sector "are at or below average in terms of the perceived knowledge assets." On the other hand, they do have an abundance of knowledge, obtained through learning how to improve repetitive processes. In summary, the authors state that: "The median industry score is somewhere in the 10-25 range, and huge outliers exist in especially highly competitive, active industries. In the case of these industries, almost all at below the median for intelligence activity. Mining is a little higher than the others but much of that may be due to the prospecting function (identifying and securing high-potential sites) more than operations."[3]

Finally, the authors describe how "various metrics on intangibles (data, explicit knowledge, tacit knowledge, intelligence) support these conclusions. But they also suggest that improvements in performance will be incremental. Big data will be monitored, with adjustments made, perhaps through algorithms, as indicated. Similarly, workers will learn how to improve performance by referring to the data but most adjustments will be incremental and explicit, easy to understand and share. Alternatively, predictive analytics leading to deeper insights through study of the data is less likely in these industries."[4]

We're only in the early innings with regard to this kind of research, but such analyses give us a framework and some initial metrics for how the mining industry can be assessed as it moves more deeply into the digital economy. The initial take away is that digitization in mining will be important and contribute to identifiable improvements in mining company performance, but, as David Humphreys, as cited earlier asserts, the industry as a whole will still fall short of climbing all the way out of the performance slump it suffered in the 2000s.

A Canadian Theory of Mine Organization

Commensurate with the leading position of Canadian mining companies' status in the post-war economy, Canadians were also thought leaders in mine management. The canonical text was *Mine Managemen*t by D. A. Sloan[5] first published in 1983. Legendary Canadian mine managers such as Jon Gill of Inco had it constantly on their shelves and even use it as a consulting reference up to today.[6] The book sets out, for the mining industry, a new theory of organization, knowledge and incentives to bring mining industry practices into line with other modern industrial corporations. In today's management rhetoric, it sought to introduce management by objectives and measurement to the traditional mine management system.

Interestingly, Sloan begins by challenging the traditional management culture of underground mining:

> Happily, a fast-disappearing breed is the manager who uses the honour system for achieving high productivity by placing his subordinates on their honour to turn in good performance and their best effort. This may be effective with a few employees, but low performance by some, coupled with peer pressure on the others, usually brings the overall performance down to the lowest common denominator unless there are management systems to objectively monitor each manager's performance. These systems are analogous to the financial accounting systems that monitor the financial performance of the company. And just as with the financial systems, the management systems also should be periodically audited to ensure that the systems are accurately reflecting the performance.[7]

The 'honour system' Sloan challenges was the tacit norms of the 'blacksmith' culture of mining and metals companies referenced elsewhere in this study.

Sloan's inspiration in organizational theory was the leading British theorist of management, Col. Lyndall Urwick, who combined the classical Scientific Management principles of Fredrick Taylor with the Human Resources theory emanating from the legendary Hawthorne Studies.[8] Urwick established a Canadian affiliate Urwick, Currie who were well known management consultants in Canadian mining and industrial manufacturing, and for whom Sloan worked.[9]

Moving to Formal Mine Organization

The fundamental change in organization at mid-century was from traditional hierarchies, titles and rules based on the inherited tacit knowledge of 'how things were done" in a mine to a system of formal organization, duties, responsibilities and evaluation.

> The formal organization is a system of well-defined jobs, each bearing a definite measure of authority, responsibility and accountability, the whole consciously designed to enable the people of the enterprise to work most effectively together in accomplishing their

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[3] Ibid.

[4] Ibid.

[5] Sloan, D. *Mine Management* (Toronto: Methuen Publications, 1983).

[6] Jon Gill. Personal communication June 11, 2020

[7] Sloan, p.5

[8] Parker, L. and Ritson, P. "Rage, rage against the dying of the light: Lyndall Urwick's scientific management". Journal of Management History Vol. 17 No. 4, (2011) pp. 379-398.

[9] Urwick, Lyndall, "Why Do We Need Formal Organization?" Address to the Empire Club, Toronto, Nov. 2, 1967.

> objectives. The formal organization is characterized by being well defined, bound by delegation and relatively stable.[10]

This redesign of skills and knowledge from the ground-up, enabled the change in Executive philosophy to Management by Objectives (MBO).

> A MBO plan is a statement of the results which are of immediate importance in the job in a stated period, together with the supporting action required at a higher level. Job descriptions and the MBO plan are not alternatives. At any time a manager should have both if he is really to understand what is expected of him.
>
> Hence, job descriptions and MBO plans developed in this manner meet the first of the manager's needs: understanding and acceptance of the results expected in this job. In the sense that such involvement also leads to clarifying the organization structure, including the authority of the job holder, it also meets another need of the manager that of creating the job conditions necessary to effective performance: providing the maximum opportunity to perform.[11]

Mine Management Culture and Change

From the perspective of today, there are three critical challenges that were not in view for Douglas Sloan' framing of modern mine management. First, the system of accounting metrics and incentives he defined were intended for the systematic management of the vertically integrated mining corporation. As argued throughout this study, that form of industrial organization is now going away. Second, the financial accounting system he put in place in the 1980s was overtaken in the 2000's by a new management ideology of 'shareholder value". Among other things it meant that important mine engineering and metallurgy innovations that could boost overall mine productivity by 2-3%, which in huge operations such as Inco would be the equivalent of a new small mine without the capital expense, would be rejected because the payback period would be 3 years and not 3 months. Third, the Sloan system, as it applied underground at the practical level, meant that there was a culture and incentives for underground foremen or shift bosses that would be inimical to radical technological change that would threaten their bonuses, interests, position and livelihoods. This persists as a major challenge of mining change management to today.

1.3 The Golden Age of Canadian Metallurgy

The so-called golden age of Canadian metallurgy spanned four decades, from approximately the late 1950s to 1990. Large R&D capacities were built within the mining companies. Mining schools and programs were established at universities and colleges. There was also active government support programmes for exploration and development led by the federal government through Natural Resources Canada.

The Canadian Mines Branch/Canmet has been active in support of the industry for over 100 years[12]. Early on, the Dominion Assay Office in Vancouver was important for development of the precious metals sector. By the mid-1930s, most gold mills were using processes developed in the Ore Dressing and Metallurgical Laboratories of the Mines Branch.

However, it was in the post-war economy of the 1950s that the Branch took on an explicitly 'research' role where base metals production overtook precious metals as the dominant mining sector. Prior to that the work of the Mines branch was mostly of a practical nature: industry statistics, mineral and resources economics and technical reports. The research efforts included both long term and applied projects. Expertise was developed in such things as rock mechanics. But in the post-war period, R&D came to be viewed as be critical to the future of the whole economy. The Department of Mines and Resources began directing resources at development of new mineral sources and extractive metallurgical processes. By the 1960's the Mineral Sciences Division came to focus on the fundamental properties of ore minerals. The view was that much of Canada's natural wealth was contained in complex and low-grade sulphide ore bodies and the key to improved processing involved more fundamental knowledge of the structure and properties of the minerals.[13]

During this period, in the private sector, the industry was extremely active in patenting and transferring technology around the world. Among the classic locations of Canadian mining and metallurgy, Inco, Stelco and Alcan stand out. From the outset, their metallurgical efforts were explicitly linked to downstream structural metallurgy and manufacturing. To give an example, Stelco was a steel company that originally owned its own iron ore mines. In fact, the largest single expansion of metal mining in the post-war era resulted from the development of iron ore mines in Ontario, Quebec and Newfoundland to support steelmaking.

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[10] Sloan, p.101.

[11] Ibid p. 134

[12] Udd, J. (2010) *A Century of Service: The Hundred Year History of the Canadian Mines Branch/CANMET 1907-2007.* Ottawa: Tri-Corp Group (2010)

[13] Ibid, p. 10

Along with the Avro Arrow and the CANDU Reactor, the Stelco Coilbox was one of the leading industrial innovations of 20th century Canada. It combined metallurgy, structural metallurgy and manufacturing processing to address a fundamental challenge in the Japanese auto steel quality revolution, through better control of the cooling cycle for steel coils. It remains the industry standard around the world to this day.

Alcan, as described below (in Chapter 2.4), was a parallel example. Similar to Canadian base metals during the First World War, the modern aluminum industry was also a product of the war economy, namely aircraft production during the Second World War. Because bauxite ore is imported, related metallurgy developments were always oriented downstream to final products. Alcan had R&D centres at Arvida, Quebec; Kingston, Ontario; and Banbury in the UK. A search for consumer product applications was undertaken to desperately try to absorb the excess capacity built up after the war.

From a public policy perspective, the leading initiative to stimulate expansion of the linkages between upstream mining metallurgy and downstream manufacturing structural metallurgy was the Ontario government's Sheridan Park initiative in Mississauga, just north of Oakville, Ontario in the 1960s and 1970s. There has been no dedicated study to date of Sheridan Park. An overview follows below (in Chapter 2.6).

Inco made a major investment in Sheridan Park in establishing the J. Roy Gordon Centre, a research facility with a focus on mineral processing. It is ironic that Inco used the Gordon Centre largely to develop new hydrometallurgy and pyrometallurgy processing for laterite nickel ore bodies in Central America and Asia as an addition to production to Canada and Sudbury, which had sulphide ore bodies. This technology development facilitated a major corporate strategy shift within Inco, away from its Ontario division as its chief production location and towards sites in Guatemala—which proved a fiasco—and Indonesia.

For students of innovation, Sheridan Park offers examples of other policy failures. Political competition emerged between the municipal politicians and Queen's Park. Land use and zoning incentives for locating in Sheridan Park were later undermined by the introduction of new incentives for firms to locate in Brampton. Eventually, the political will for the concentration of R&D at Sheridan Park and its hoped-for synergies faded away, and the remaining activities were folded into the Ontario Development Corporation.

PART II: The Rise and Fall of Corporate R&D

2.1 INTRODUCTION

The story of Canadian metallurgical R&D is well illustrated by the story of Stelco, which was originally called The Steel Company of Canada. Its name and contribution to the economy are highly correlated.

Historically, Canadian iron ore has been leaner and less abundant than the rich hematite ore of the Lake Superior region that drove Pittsburgh steel production in the United States. Canada was initially dependent on imports of American ore, with the exception of Nova Scotia, which had access to ore from Bell Island, Newfoundland. This situation began to change following the end of the Second World War. In 1948, foreign ore supplied 93 percent of Canadian consumption. By 1970, this had declined to 18 percent, with Canada becoming the world's fourth-largest producer of iron ore. Over this same period, Canadian ore consumption climbed from 3.6 million tonnes (4 million tons) 10.4 million tonnes (11.5 million tons). As of 2014, Canada was the tenth-largest steel producer in the world.

As Erich Weidenhammer summarizes the Canadian steel/Stelco story in his 2017 *The Development of Metallurgy in Canada Since 1900*:[1]

> The first steel producer in Ontario was Algoma Steel of Sault Ste. Marie, Ontario. The company was established by Francis Hector Clergue (1856-1939), a Philadelphia promoter who had become interested in the Sault region because of its potential for hydroelectric power. Following the discovery of hematite ore by gold prospectors in 1897, Clergue sought to develop the area for iron production. Located in the Wawa township (formerly the Michipicoten), this became the Helen mine, named after Clergue's sister. Production began here in 1900. (…)
>
> Stelco, the Steel Company of Canada, was a conglomerate founded in 1910 out of five existing companies across Ontario and Quebec.[2] This arrangement was encouraged by the Canadian government. Despite early management difficulties arising from the merger of former competitors, the new company expanded quickly, establishing the world's second electrically powered blooming mill, as well as the first electrically powered rod and bar mill to be installed in North America. Stelco acquired a controlling interest in American iron ore fields and, by 1918, had installed new open hearth furnaces, a new sheet mill, and modern coke ovens. By 1921, Stelco equalled the combined size of Algoma and Dominion Iron and Steel (DOSCO).
>
> Like other steel producers, Stelco throve under the supply management scheme of the Second World War. It acquired, for instance, a 63.5-tonne electric arc furnace and a 2.8m (110-inch) plate mill, which became operational in 1941. Along with smaller plate mills at Dofasco and DOSCO, they provided material for the Allied ship building effort. A metallurgical laboratory, first established in 1931, was tasked with developing new alloys and materials for building British military equipment. Adapting these British designs to local materials and engineering standards proved a significant challenge.
>
> During the 1950s and 60s major advances took place at the Stelco Hamilton plant in iron smelting and steel making. In 1967, a new research centre was founded in neighbouring Burlington, Ontario. A series of research-based improvements led to the development of a low-slag smelting practice that became standard among steelmakers globally. Where its rival Dofasco renovated its steelmaking operations by adopting the Linz-Donawitz converter technology (the LD Process later to be known as the basic oxygen furnace or BOF process), Stelco initially sought efficiency through a novel method for producing direct reduced iron (DRI) in a rotary kiln. Experimentation with the "SLRN Process," named after the joint developers, Stelco, the Lurgi engineering firm of Frankfurt, as well as the Republic Steel and National Steel companies in the U.S., began in the late 1950s.
>
> Traditional ironmaking requires the use of blast furnaces and coke ovens to produce hot metal, a

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[1] Weidenhammer, E. *The Development of Metallurgy in Canada Since 1900*: Historical Assessment Update. Ottawa (2018) Historical assessment / Canada Science and Technology Museum Corporation Volume 20 of Transformation series.

[2] Stelco was formed by a young stockbroker named William Maxwell Aitken who later became Lord Beaverbrook.

process that removes impurities through slag after iron is reduced to a liquid state. The direct reduced iron (DRI) method uses a gas or coal-fired kiln or shaft furnace to remove oxygen from iron ore, producing a heavily reduced solid product known as "sponge iron." The method is much less energy-intensive than the blast furnace, less polluting, and works in conjunction with electric arc furnace (EAF) steelmaking. This proposed technology was abandoned by Stelco by the early 1970s, when the company shuttered its open hearth furnaces and moved over to BOF steel production. The DRI/EAF approach to steelmaking has been successfully applied around the world, including at the Montreal-based steelmaker, Sidbec-Dosco.

2.2 LINKING MINING AND MANUFACTURING THROUGH STEEL

INTRODUCTION

If we equate mining as breaking rocks and extracting minerals, mining for steel production (iron ore and metallurgical coal) accounts for 90 percent of the mining activity in the world today, and has greatly expanded with the emergence of China in the world economy. That is why technical innovation in steel is a critical part of the mining and metallurgy story.

The Stelco Coilbox story is important not only because it is the source of a major post-war Canadian innovation with global impact, but also because metallurgical research was a core competency at the heart of the success of a large integrated steel company, a classic industrial champion of the post-war Canadian economy.

While the academic discipline of "business history" has produced many volumes of corporate histories that have made critical contributions to our understanding of the economy and the linkages between business, technological development and public policy, there are relatively few histories of private industrial research departments. An exemplary exception is Margaret Graham and Bettye Pruitt's *R&D for Industry: A Century of Technical Innovation at Alcoa* (New York, 1990). The approach Graham and Pruitt take creates an important reference point for telling the Stelco technology story in context, particularly so because little has previously been written about the role of R&D in process innovation industries.

While the steel industry suffered a precipitous decline in the 1980s, the aluminum industry did not. Graham argues that the difference was Alcoa's R&D strategy. During the 1970s, Alcoa Labs increased its contacts with the outside world and learned to see itself as others saw it. What it saw was a company with a long history of innovation that had defined itself as technologically mature, but that was now hampered by a laboratory that had lost its sense of direction.

The corporate laboratories emerging in the late nineteenth century were mostly "works laboratories" designed for testing and control at production sites. As they evolved through the twentieth century, corporate labs began integrating activities from different parts of the organization, pursuing generic technologies known as "general research," and transferring technology across the corporation. This became the basis for exploitation of technical information for the new generation of "science-based" enterprises. According to Graham, metals companies participated in this industrial transformation in some ways, but not in others. Through the adoption of new reduction processes for metal production, firms became large, integrated and scientifically managed. Metalworking and metallurgy, however, continued to be dominated by a strong craft tradition that resisted the infusion of scientific techniques. Graham argues that in the transition from craft-based to science-based metallurgy, nonferrous metals led the way, the most progressive among them being aluminum. The traditionalists within Alcoa would have preferred to continue producing intermediate products—primary metals and chemical by-products. But an altered marketplace required the company to create demand for its metal by developing new aluminum products, and, along with those, developing the metal working processes by which customer companies could fabricate them. However, for the most part, traditional company R&D units gradually became less effective as a source of competitive advantage and regressed into a limited technical-support function. This is basically the path that Stelco took. Alcoa focused on innovation in processes as much as in product development. The latter direction also responded to the broader critique of economic policy in North American manufacturing R&D in the 1980s: that it was relatively strong on product development but lagged its international competitors in process innovation.

The story of metallurgy and metals companies is not just about materials science and technology. It is also critically related to a company's capacity to manage technological innovation. Stelco hit a key turning point in the 1980s, when the company established a separate R&D entity called Steltech in a prestigious, but isolated, location north of the city of Hamilton, thus separating its research and production activities. The move reinforced a cultural divide in the organization between the process-improvement needs of operations and the expanding horizon of new product development.

THE HISTORY OF THE STELCO RESEARCH CENTRE

The following historical account relies heavily on and quotes from a self-published history, *Stelco R&D History: From the Beginning*,[3] written by Jock McKay, a forty-year employee at Stelco and ultimately the director of the Stelco Research Centre.

THE STELCO "WORKS LAB"

The original metallurgical laboratory at Stelco was located on the grounds of the gigantic Hilton Works in Hamilton. Within the lab, the core unit regarding innovation was the development and special duties division. By the early 1950s, it had assembled a team of university graduates specializing in metallurgy and was situated close to the open-hearth steelmaking and ingot departments. The technical employees worked on mill problems, such as trying to see whether the blast furnace hearth size affected pig-iron carbon content. The problem-solving process began with consulting the relevant technical engineering literature in the library at McMaster University for clues. Knowledge interaction was also important. Previously, if there had been technical advice to communicate to mill superintendents, it was communicated verbally, in person to the production superintendent. It was with the creation of this metallurgical team in the early 50s that formal written research reports began to be produced and collected. This body of work resembles the beginnings of the transition Graham described in her study on Alcoa, away from the research department being a "works lab" to becoming more of a general knowledge centre for spreading innovative and problem-solving knowledge across the company.

However, the whole system still functioned within an overall culture and organizational hierarchy of steelmaking as a craft, as described by Graham. Internally, this was referred to as a "blacksmith" culture. Within each production unit, such as the blast furnace, open hearth, or hot and cold rolling mills, the mill superintendents functioned as "kings" of their domains, and much of the impact of metallurgical research was dependent on the researcher having a personal relationship with the individual superintendents. Decisions based strictly upon scientific knowledge and careful deliberation, in the minds of the production supervisors, were equated to "ineptitude". There was an ingrained divide within the company, where the metallurgists were regarded as alchemists and the operations line superintendents were quick-fix blacksmiths. The metallurgical department itself reported to the vice-president of operations. For research investigators, yesterday's "know-how" solution would become tomorrow's puzzling problem, because the quick fixes often solved a technical issue in an "upstream" mill, only to cause a more serious problem in a "downstream" mill. As McKay describes it "the plant was divided into two areas of operation: primary and secondary mills. Primary included the coking ovens, sintering plant, blast furnaces and steelmaking furnaces. Secondary included all the forming mills: slabbing, blooming, hot strip, pickling, cold rolling and coating (galvanizing and tinning)."[4]

From an innovation perspective this provided a terribly difficult environment for communication and diffusion of knowledge. In the day, Stelco had a uniquely complex multi-layered hierarchy to manage its 5,000 products, more than any other major steel company. Its staff complement comprised more than 1,300 job titles.

In the early 1950s, senior metallurgical staff had great depth in a certain kind of knowledge, but were lacking in others. They were well-versed in the products produced and their properties, but knew relatively little about the modern scientific metallurgy of the materials underlying them. Their canonical text was the industry bible: *The Making, Shaping and Treating of Steel: Steelmaking and Refining*, published by the United States Steel Corporation. Metallurgists at the mill level regularly encountered the attitude that their expertise was of little value or interest at the shop floor level. As McKay recounts, they'd be told, "Just tell us what to do to get rid of the problem. What you have done to find the answer to a problem is of no interest to us." Their issues mostly constituted "firefighting" related to customer complaints. Consistent with this focus on the production floor, while the research department did add some PhDs, the largest expansion of new hires in the 1950s were community college graduates who fought "operating" fires.

In general, McKay recalls, the word "research" had a negative connotation in the steel plant. That is why, until the 1960s, research activities were referred to as "development and special duties." An important turning point came in the mid-1950s, when steel faced its first major challenge from aluminum as a competing material for railway car construction. The steel handbook did not provide any useful response. It took research at McMaster University's scientific library to find the key: a direct comparison between the steels used, D-grade and Stelcoloy steels (copper-containing steel that would not show uneven rust) versus the proposed type B54 SF aluminum, which affected the manufacturability of the downstream product.

The evolving mill processing technologies themselves were starting to tip the scales towards more scientific metallurgy. In the mid-1950s, Stelco took a major gamble to get ahead of the market by purchasing a new continuous annealing

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[3] McKay, J. *Stelco R&D History: From the Beginning* (2013). [Online]. Available at: https://docplayer.net/21800081-Stelco-r-d-history-from-the-beginning-jock-mckay-director-retired.html. Unless identified by a footnote, all quotes in this section come from McKay's online publication.

[4] Ibid

machine. Despite its multimillion-dollar cost, there was actually no understanding of the heat cycle of the process within the company, a critical bit of scientific know-how if the company was to put this expensive new equipment to efficient and beneficial use.

As a result, cold rolling, the final step in the lengthy process of turning ingots into a thin strip steel, could create finished steel unsuitable for forming in downstream manufacturing. Annealing and reheating, made the steel softer and therefore regained its ability to be formed into a shape such as an auto part.

Only a couple of continuous annealing lines existed in the world at the time, and they ran without any assurance as to whether or not the time-temperature cycle was correct. These lines worked, but the question was: were they being used to their maximum efficiency? If not, the cost was far from negligible. At that time, all cold-rolled steel was batch annealed, through a time-temperature cycle that took days to complete, versus the seconds required for continuous annealing. However, each foot of the continuous annealing line cost more than $100,000. As McKay bluntly explains, "no one had the foggiest idea how long it took to anneal the deformed cold-rolled steel grains. (. . .) It was a blank in the book of metallurgical process knowledge." A deep dive by Stelco's research group into the scientific metallurgical literature and many experiments led to development a complete modelling of the continuous annealing heat cycle. From there, the goal was to develop an appropriate automated control system to monitor the annealing line.

A critical connection between steelmaking metallurgy and innovation addressing downstream issues in the manufacturing process was demonstrated in developments related to deep-drawn steel, a method for sheet metal processing. McKay recalls that Stelco's customers making parts such as automobile roofs, fenders, hoods, and oil pans experienced cracking and stretcher strains during forming. "Deep-drawing steel needs a special microstructure. The grains are large and elongated like pancakes. This grain structure gives the maximum degree of formability. I had to learn how and why the grains formed into this shape. Without such knowledge, I could not see how one could begin to dream about the solution."[5] The solution, again after consulting the scientific literature and many regression analyses, came from the precise fine tuning of the aluminum and copper additions to the molten steel.

The General Metallurgical Knowledge Hub

The position of the Research Department evolved over time. At one point, Stelco's tinplate was its most profitable product, and the American Can Company its most important client. To make tinplate, a steel strip was immersed in a hydrochloric acid solution. The chemical reaction time during the immersion determined the quality of the product. No one knew the reasons for the variance. It could have come from a dozen operational processes. There was no central coordination in the metallurgical approach to a solution. Eventually, the problem went away, but no specific conclusion could be made as to why. Stelco operations management simply moved on. But the researchers didn't. Their answer emerged later: moisture entering at the annealing stage affected the outcome. This was an example of the position of the research department starting to change within the corporation. Slowly, it was becoming the central hub for metallurgical knowledge and the channel for diffusing technological change across the company.

Another example of the research department evolving into a corporate, industry-wide scanner for new technology developments can be found in Stelco R&D's engagement with continuous casting (CC), one of the transformative technologies in the post-war steel industry. Continuous casting was a European-led innovation, though by 1959, Atlas Steel in nearby Welland, Ontario, had a caster producing stainless steel products. For Stelco to shift its fundamental steelmaking process from rolling ingots to continuous casting was, however, a multimillion-dollar prospect. The decision was made to proceed with the new technology, despite the opposition of those in charge of traditional operations departments. Operations remained the cradle of the traditional "craft" mentality and relied heavily on those exact processing steps that would be most displaced by the technology change. Successful implementation of the continuous casting method critically depended on key new scientific metallurgy principles including the solidification rate of the liquid steel and thermal stresses in the billet, along with the strict and continuous control of steel prior to casting. Because of these complexities, there were many disputes about plant layout and machine design within the company, reflecting differing philosophies and interests. The initial pilot failed. By the 1980s, however, the technology had become the anchor of the Lake Erie Works, the crown jewel of Stelco's steelmaking sites.

Centre of Product and Process Innovation

Stelco's traditional blacksmith managerial culture, as mentioned previously, was based on pride in its "know-how" as opposed to its "know-why." As discussed, this disconnect between scientific metallurgical enquiry and the kind of knowledge applied on the shop floor was why R&D was called the "development and special duties" division. From the 1950s, the aspiration of the lead metallurgists in that department was to someday form a separate research department. Their hopes were realized in 1962, with the corporate decision to establish a separate research

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[5] Ibid.

department. Around that time, steel companies all across North America were establishing research centres. The Stelco Research Centre was finally officially established in 1967.

In the new regime of research project administration at Stelco, each project began life with a formal R&D project description. On this form, the author had to succinctly describe a measurable objective for the proposed project, as well as an expected completion date before it would be "signed off" on and allowed to formally proceed. In addition, a policy was introduced that no project could begin without a production or sales manager signing a project approval form, expressing full agreement that the project outcome, if achieved, would benefit the relevant mill or product line.

Management took a "portfolio investment" approach to research. McKay says: "I viewed the multitude of projects like one would view and manage an investment portfolio. It was balanced: Trouble shooting, 40 – 50%; Protective research, 25 – 35%; Aggressive research, 10 – 20%; and Future-assurance research, 5 – 15%. Trouble shooting is aimed at solving chronic and acute problems affecting adversely current profitability. Protective research is aimed at improving Stelco's products and processes to keep them competitive. Aggressive research is aimed at increasing market share beyond traditional market penetration, and at manufacturing facilities to modernize them. Finally, Future-assurance research is aimed at creating wholly new products and developing new processing facilities, leading edge stuff."[6] Eventually, the department grew to 132 employees and a budget of $12 million[7], making it one of the largest and most important centres of metallurgy in the country.

At the same time, proximity to actual production sites became a problem. The new facility was built in north Burlington, miles from the Hilton Works site in Hamilton East, as well as other Stelco operations across the country. The experience of applied research at the Hilton Works had established that the knowledge produced in the lab needed to be closely connected with those working in the mill, or it would be deemed irrelevant. Research knowledge and technical expertise were not enough. Research results had to pass the commercial test before being recognized in mill operations. McKay tells us that mill managers did not accept strangers easily. "One had to gain their trust and confidence, and this meant frequent meetings and keeping in touch, being seen on the factory floor often, and giving quick response to their requests for assistance." He added "The new R&D centre was too far removed from the action, from its customers." This was partly offset by locating some personnel at the plants. In the mid-1970s, one R&D "resident" (as engineering employees were called while on-site) was assigned to work in Edmonton, two in Montreal, two in Welland Tubes, one in Canada Works, and (initially) five in Hilton Works. The residents engaged in finding practical solutions and in development work. In the 1980s, the resident numbers at Hilton Works to rose to about 20. By then, Lake Erie Works began operations and four residents were placed there. The number of staff in Edmonton was also increased to three. However, the central research hub remained in Burlington.

The movement of the research department to Burlington was part of a larger strategy, under the presidency of Peter Gordon and with the approval of the board of directors, to decentralize Stelco. All of the company's major centres would move away from the old central steel mill, Hilton Works. The executive offices and many of the corporate executive functions—finance, legal, and so on—would move to Toronto, closer to Bay Street bankers and government officials. Gordon, McKay wrote, "also felt an obligation to have other marketing, sales, accounting, purchasing and personnel executives occupy space in a newly constructed tower in downtown Hamilton, supposedly for them to be in closer communication with other local business and politicians."

Some former Stelco employees, looking back, consider this the point when Stelco began its twenty-year journey to bankruptcy. Management of the older hierarchical but unified and consistent company, lost touch with its production operations and its people. Stelco's processes became fragmented. Sales managers became estranged from production managers, as well as service people in finance, and purchasing. Marketing lost sight of the core business.

Interestingly, from the point of view of this book, there had been a proposal that the Stelco research centre be built in Sheridan Research Park. But, as McKay explains, management within the research department composed a counterargument that, if situated in the "Park along with the Ontario Research Foundation, Cominco's Product Research Centre, IBM and others, Stelco's centre would be one among many, instead of a stand-alone home showcasing Stelco's progressive face to the public."

STELCO RESEARCH AND THE COILBOX

As stated above, among the 'hall of fame' members of Canadian metallurgy, Stelco stands out since its technical efforts were directly linked to downstream structural metallurgy and manufacturing.

The practical realities of applied research in a steel mill described earlier gain further insight in McKay's account of the development of the transfer coiling unit in the hot strip mill in the 1960s. In this case, McKay and Les McLean had

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[6] Ibid.

[7] Throughout this study, dollar figures are in Canadian dollars unless otherwise noted.

to convince the mill superintendent that the new technology would not jeopardize production capacity and the smooth functioning of the mill by minimizing downtime and maximizing throughput. As we will see below in the case of Inco's efforts to implement robotic technology years later, new technologies often conflict with the incentive compensation programmes that apply to middle management. At Stelco, the middle-management salary and bonuses were based on mill performance. As a "horse trade," McKay made an offer of a new transfer table for the mill as a concession that would otherwise require a major capital expenditure from the mill budget.

For such a breakthrough invention in the history of Canadian metallurgy, with its transformative contribution to the Japanese-led quality revolution in automotive manufacturing, the Stelco Coilbox story had a rather mundane beginning.

McKay writes that at the beginning of the 1970s, he learned (to his dismay) that management had decided to construct a new steel mill at Lake Erie that would ultimately produce 9.1 million tonnes (10 million tons) of steel per year. For him, the implied customer demand to support this additional capacity was beyond reality and belief. He questioned "[w]here did the company get its rosy forecast of future domestic demand? There had been a rapid rise in demand over the last 20 years, but this was due to the paradigm shift from an agrarian to an industrial economy, and from one-car families to two or more cars. This growth had to attenuate soon." To McKay, the signs were clear. "Steel had lost, and was continuing to lose, market share to other materials, especially plastics; and third-world countries were rapidly building new plants and would, with their lower labour costs, crimp our ability to export steel abroad and could eat into our domestic markets, too. The USA had already set quotas for foreign steel and it repeatedly accused Canada of dumping, sometimes justifiably (Sidbec-Dosco) but most often not."

McKay voiced deep concerns to Stelco's vice-president of engineering, research and corporate planning. However, the vice-president of marketing dismissed his concerns and deferred instead to the well-known but overly optimistic, in McKay's opinion, economic studies of Jesuit Father William T. Hogan, an economist from Fordham University. Hogan extrapolated future steel demand as a straight line extrapolation of the previous trend. Cynically, he may have been just telling the industry what it wanted to hear. In the end, Canada's domestic consumption for the next twenty years remained flat, at about 15 million tonnes (16.5 million tons), roughly where it was in 1972.

Nonetheless, McKay assembled a team to design an innovative hot strip mill for the new location. As he describes, "[i]n a Hot Strip Mill, the processing units, from start to finish, includes a slab reheating furnace, roughing mill, transfer table, shear, finishing mill, run-out table and down coiler and are configured in a straight line. The whole Hot Strip Mill from slab-heating furnace to coiler is a massive array of heavy machinery." His instructions to his development team were to come up with two or more designs, but not necessarily in a straight line configuration.

Hot strip steel processing is done in two stages: an initial "roughing" stage, followed by a "finishing" stage. In a straight line configuration, however, this expanded the space requirements significantly and added to the capital costs of the mill within a budget framework that was already oversubscribed. Confronted with the innovation team saying that they couldn't see how to get the transfer bar from the roughing stage to the finishing stage without taking up more mill space, MacKay writes that he blurted out, "Oh hell, just roll up the transfer bar and move it across."[8]

From that Eureka moment, automotive steel would never be the same again! This is how McKay remembers these events:

> Two weeks later, an exited Innovation Team asked to meet with me. They had come up with a potential breakthrough. Again in Conference Room No. 2 at the R&D Centre, they laid out the plan. They had gone back to the traditional straight-line configuration except now the transfer bar exiting from the roughing mill would be coiled up and then peeled off into the finishing mill. My flippant comment to Bill Smith turned into a sensible suggestion. This simple notion of coiling the transfer bar would decreased the length of the Hot Mill building substantially, a huge capital saving. Now that the team had a direction, they had to prove it. No one knew if a thick transfer bar, 0.75 to 1.75 inches, could be wrapped into a coil like a toilet-paper roll. It was a tall order and it had to be proved before practical full-scale pilot tests could be attempted. We needed a model upon which the concept could be proved or disproven. Fortuitously, lead at room temperature, has a bending behaviour similar to steel at 1900F. This similitude gave us the opportunity to remove some uncertainty. The lead-strip, coiling trials took place at the R&D pilot plant. Harold Cipywnyk, Research Investigator had Ray LaPointe, Research Technician (Machinist) in our machine shop, constructed a model unit that would coil lead strip. The model test indicated that we could expect no problems in hot coiling of the transfer bar. Lucky break!
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> While the innovation team was doing its thing, I paid a visit to Crosson Clarke, the Hot Strip Mill

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[8] Ibid.

(HSM) Superintendent and asked Crosie if he would let Les McLean (PhD in Mechanical Engineering), a Senior Research Investigator and one of those in the Innovation Team, set up shop in his mill. I wanted Les to become familiar with the HSM process, the equipment and the operators. Crosie agreed. He knew me from my early research days in the Cold Mill, when he was a foreman on the Tinning Line. Besides, over the years I made a habit of dropping in on superintendents as part of my wanderings through Stelco's many mills and had often stopped in to chat with Crosie.

Les McLean soon made himself useful. I chose him to be my principal pitch man for persuading whomever that R&D should proceed with building a full-size pilot transfer-bar coiling unit and test it on the Hot Strip Mill. I knew from experience that I had to sweeten the deal before we could hope to proceed on a full-scale mill test. Fortunately at that time the Canadian Government offered generous tax incentives for research and development: PAIT (Programme for Advancement of Industrial Technology) and IRDIA (Industrial Research and Development Incentives Act). With incentives from these two sources of government cash, the cost to Stelco would be somewhere between 12 and 25 cents on the dollar. Les convinced all parties—company and government—that this development deserved to receive funding. Also, Les in the foreground and me in the background convinced Stelco Hilton Work's managers to go ahead with the expenditure. However, Crosson Clarke did not want to jeopardize his mill's production capacity and smooth functioning—minimum downtime and maximum throughput. His salary and bonus were based primarily on mill performance. Knowing this, I made Crosson an offer of a new transfer table, an offer he couldn't refuse as it was a major capital expenditure. The approval process for capital spending in Stelco was daunting: every Tom, Dick and Harry had to approve it. With luck and 72 signatures (This no exaggeration.), assuming the Board of Directors approved, capital funding might be made available. The transfer table consists of water-cooled rollers upon which the long, hot transfer bar rests as it slowly feeds into the Hot Strip Mill's finishing stands. Since I could easily hide a $100,000 plus for a transfer table in the segment within the Research Project budget allotted for discretionary spending, Crosson would have a new table in a matter of weeks rather than a dozen months, and best still from his viewpoint, no administrative effort expended and no questions asked.

In 1973, the prototype "Coilbox" was designed to allow the transfer bar to be or not to be coiled (that phrase has a ring to it, n'est-ce pas?). This precaution of having an escape route, i.e., return to the status quo at will, is a must in introducing change into a massive production unit. Downtime translates into production loss, a totally unacceptable cost. Just as the lab model had forecasted, we were able to coil the one inch+ bar with relative ease except the wrapped bar surfaces stuck together and would not uncoil freely into the finishing mill, an embarrassing oversight. The team, however, came up with a solution: they designed and installed a peeler, a long hydraulic-actuated steel arm that resembled a scorpion's stinger to separate the bar from the hot coil. The plant trials were carried out over a period of two years removing mechanical bugs and making refinements to the design, and during this development period, more than 2000 bars were coiled. The research team managing and observing the tests included: Keith Wilson, Hank Averink and Blair Otterman under the initial direction of Les McLean and later, for most of the trial duration, Nick Daneliak. (…)

During the later stages of the mill trials, I had two surprise visitors appear at my door from BHP's Port Kembla Steelworks located NSW, Australia. They requested permission to see our Coilbox in operation. I immediately asked them, "How in hell did you find out about our secret development". We had filed patent applications in every country that had a large steel industry, but these applications should not have become public so soon. BHP had wisely subscribed to South Africa's patent office, which published applications upon filing. So two weeks after the filing, they had the patent application in hand and, more importantly, they had a burning need for our budding development. From my own experience and from that of others, I knew that the steel industry had an unwritten rule of openness and courtesy to fellow steelmakers. So, I took the two, Plant Manager and Mill Superintendent, to see first-hand the prototype Coilbox wrap the transfer bar in a mandrel-less coiler and then peel off into the finishing mills. We stood on an elevated walkway where one had an excellent view of the Coilbox in operation. Bar after bar coiled and uncoiled without a hitch, and after an hour of this flawless repetitive performance, they said they wanted to be the first to install the unit in their proposed new hot strip mill. A mutually beneficial deal was worked out subsequently with BHP management: They were to welcome any visitors Stelco sent to observe the Port Kembla Coilbox in operation, and BHP would pay Stelco a flat license fee of $3 million. However, every time one of the visiting groups to Port Kembla Hot Strip Mill purchased a Coilbox, BHP would receive a $300,000 credit toward the flat fee. I don't remember who came up with this ingenious scheme, maybe Les McLean. And happily, as a result, Port Kembla didn't have to pay Stelco a penny because they hosted many Coilbox customers. The Coilbox had become a must-have unit and many were sold in plants around the world and each sale put $3 million directly to Stelco's bottom line. The R&D department was well on its way to becoming self-financing. (…)

We shipped off the first production Coilbox in 1977. The ship carrying the Coilbox ran into a wild storm in the Tasmania Sea south of Melbourne and the Coilbox, strapped on deck, broke loose, slipped off and sank. Another was soon built and it reached its destination, and the Coilbox was installed successfully. In 1978, Port Kembla commissioned its Hot Strip Mill years ahead of Stelco's Lake Erie Hot Strip Mill. The success at Port Kembla ensured that Stelco management would follow suit. In 1980 a Coilbox was retrofitted into Stelco's 56in-Mill —the same Mill in which the pilot tests were performed— and another was incorporated into the 80in-Mill at the Stelco's new Lake Erie Works. Les McLean transferred to a group that had the responsibility for promoting and selling Coilboxes. His team soon signed up nine heavy equipment builders. As of 2012, more than 70 units have been sold worldwide. The patent has long expired, so that USS doesn't receive royalties from Coilbox sales. The chief promoter and owner of several improvement patents is Hatch & Associates Ltd., a Canadian engineering and consulting company.

The Coilbox offered more than the expected decrease in capital cost; it substantially improved steelstrip quality and lowered electrical-power costs, two major benefits we had not anticipated. The coiled configuration of the transfer bar reduced the radiating surface by as much as 97 percent. This heat conservation before the bar is progressively uncoiled feeding into the finishing stands was so effective that much larger coils could be processed, using less power and fewer stands than would be required in a traditional mill without a Coilbox. Additionally, because the head and tail of the bar are reversed, the bar remains at a nearly constant temperature, which gives rise to more uniformity in hot-rolled, strip-steel.

Looking back on the invention, McKay said in his memoir that he learned important lessons about the nature and management of metallurgical innovations, including lessons related to relationship networks within the firm, the social side of innovation and what is now called "change management," He learned how to be a facilitator who can deal with political and financial, and he learned how to create a corporate culture that ensures a successful commercial outcome. From a micromanager, "who gave too much help" he transformed into a "communicator and defender of R&D activities," who brought together management and research.

Stelco & Direct Reduced Iron

While Stelco is most renowned for its innovation with the Coilbox, its early efforts in direct reduced iron (DRI) also led to a key development. Ironically, Stelco pioneered many technologies in the steel industry, and the concept of charging DRI in the electric air furnace (EAF) was an innovation that now enables EAF shops to compete with integrated plants, such as Stelco, in the flat-rolled automotive business. They were a leader in this with their SLRN DRI process and continuous feeding into the EAF. Stelco worked on this in mid-1970s, and today it is seen in modern flat-rolled mini mills.

In his memoir, McKay was quite open in his views about Stelco management and its interest in DRI. The chapter relating to DRI was entitled "I Don't Care." The aim of, what he viewed as an ill-advised process "was to avoid the need for expensive coke ovens and blast furnaces. Direct reduction removes the oxygen from the iron-ore pellets in the solid state (temperatures below the melting point) and turns them into porous, sponge-like material, suitable for charging into electric-arc steelmaking furnaces."

The thermodynamic calculation suggested that it was possible to save considerable amount of energy through direct reduction. The DRI product was a "sponge iron" that could be fed into a blast furnace. In McKay's view, direct reduction would only prove commercially viable in a niche market where either government subsidies or a unique local context, or a combination of the two, made it possible. He says he did more work on modelling the financial benefits of DRI than on any other innovation in Stelco Research. The most likely estimate he hit on was that it would take twenty-one years to recoup the initial costs. However, Stelco had a strict policy and would not approve of capital expenditures with a payback periods of more than three years. The first tests were conducted in October and November of 1959 at a pilot-plant in Frankfurt am Main, Germany. The test results showed a major technical problem. In his words: "[w]all accretions, much like blood vessel plaque, continue to grow, slowing the process and choking the kiln and eventually bringing the operation to a halt. Here was the handwriting on the wall, yet no one at Stelco heeded the warning."

In 1960, a large pilot kiln was built on the Hilton Works property. It was plagued with operational problems, including a risk of explosions from methane gas. In 1962, Hilton shipped DRI samples to Atlas Steel in Welland, Ontario, which had an EAF in operation. Tests in Welland revealed another unanticipated operating problem: sponge iron doesn't behave like scrap steel in an EAF. The team hired outside engineering consultants to re-design this feeding system for them. In due course, the Hatch-designed feed unit found itself attached to the Edmonton, Alberta based Premier Works EAF, which Stelco would later purchase.

Problems with the input iron pellets remained a barrier to profitability. Notwithstanding the identified problems, Stelco senior management approved the building of a commercial unit at Stelco's Griffith Mine, an iron ore mine in Red Lake, Ontario, in 1972. Management actually stated that they did not care about concerns regarding the technology's prospects. When the system came online, the underlying issue regarding the iron pellets, unsurprisingly, surfaced again. Masses of fused pellets formed in the kiln, and some had fallen off thereby obstructing the transfer chute. The Red Lake kiln was eventually shut down. It never operated again, and Stelco wrote off $40 million in development costs.[9]

EVALUATING THE STELCO RESEARCH STORY

Business history is replete with examples of alternative technology innovations and the "road not taken." The Stelco research story is perhaps an unacknowledged addition to this tradition where a major development or even breakthrough took place, but its long-term benefits flowed to others. It echoes, in a way, the famous case of Xerox in Stanford Research Park, developing the technology that became the Macintosh computer. As history tells it, Xerox developed all of the key underlying technologies, while Apple eventually acquired them and assembled its ground-breaking commercial product.

In the 1990s, 100 Stelco research engineers left the company to join Hatch. They took the intellectual property rights of the Coilbox with them. The transfer of talent and IP rights meant that the major economic benefits of the Coilbox innovation ultimately flowed to Hatch and not to Stelco.

In the case of DRI, early developments at Stelco that were regarded as an error and failure ultimately flowed to new start-up companies such as Nucor in the EAF sctor of the industry. The technology enabled them to break into auto steel markets in ways that undermined the position of integrated producers such as Stelco.

At the end of his account, McKay summarizes his time in Stelco Research. "I arrived at Stelco when making improvements in steelmaking processes and products were relatively simple because the industry had up to then survive largely on know-how (the slow process of trial and error). Know-why (science) makes process and product improvements easier to do."

However, there was no guarantee that subsequent management priorities and decision-making processes would lead to sustainable success for the corporation.

THE BLACKSMITH CULTURE OF STELCO

As we have seen, Jock McKay writes about the traditional 'blacksmith' culture of Stelco and how this affected operations management's attitude towards innovation and the entrance of university-trained employees into the company and onto the shop floor. This was one example of an industry-wide issue of how craft traditions persisted in steel, well beyond their eclipse in modern manufacturing in the early twentieth century, as mass production became the norm across virtually all industrial sectors. This phenomenon has been named and documented as the impact of Sheffield Steel in America.[10]

Sheffield had once been the technical heart of the international steel industry. In the nineteenth century, a method known as crucible steelmaking was the leading process for toolmaking: files, axes, saws, etc. By the mid-twentieth century, crucible steel had become a relatively minor share of production related to specialty steels. However, its traditions and culture maintained a strong hold on the culture of the industry. The technical and commercial success of Sheffield steel in the nineteenth century was achieved without a true understanding of its underlying science of metallurgy. The chemist was an unfamiliar figure in the steelworks. The idea of analyzing steel in a laboratory with a view to improving its commercial application was virtually unknown. One of the most crucial tests, the calculation of the carbon content of the steel, was performed by simply breaking the bar and gazing at its crystalline structure. A skilled worker could give a reading that was accurate within a fraction of one percent. Thus, even as laboratory methods emerged, "rule of thumb" practices predominated. For some traditionalists in the industry, science was considered an occupation of the leisured classes. Until the early twentieth century, employees with little education or formal training made most of the metallurgical discoveries.

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[9] In the mid-1970s, Sidbec in Countrecoeur, Quebec built the first fully-integrated DRI based plant using natural gas as reductant.

[10] Tweedale, G. *Sheffield Steel and America* (Cambridge University Press, 1987).

In the absence of a scientific base of understanding of steelmaking processes, the skill and experience of individual workers were the only reliable yardstick for the production of steel. These were the "true metallurgists of Yorkshire." The local, highly skilled labour pool was a critical factor in Sheffield's continuing success, and its absence was a prime reason why other countries made slow progress in acquiring the necessary underlying metallurgical knowledge. How might this cultural factor have affected the history of Stelco and its culture of steelmaking?

In his 1960 history, William Kilbourn chooses the Stelco blooming mill, the most modern in the industry and most fully automated in the company, as his metaphor for science-based steelmaking at mid-century. The first qualitative leap occurred with Stelco's founding, with its delicately manoeuvred merger of five previously distinct (and competing) steel companies. The second came with the firm's tripling of capacity between 1950 and 1960, to meet the dramatic growth of demand for steel in the post-war boom. As Kilbourn notes, the impressive (and necessary) pace of progress in technical knowledge and technology was not matched by a change in organizational culture within the company. His stylized phrase to characterize the traditional shop floor culture of the Stelco organization was to call it "Neo-Technic Man." The sometimes-maligned "Organizational Man" of the 1950s had fully emerged within Stelco at the senior executive level. The last of the old guard of works superintendents with links to the Victorian iron age of Sheffield had retired. The new face of Stelco was embodied in the appointment of Bert McCoy as general sales manager for the critical early post-war period. However, McCoy had to contend with the inherited culture of Stelco, where his predecessor had indulged a tradition of ongoing warfare with and among plant superintendents. Among the latter had been the legendary Frank McKune, who served as superintendent of the Open Hearth steelmaking department for forty years. McKune was a showboat martinet, but he had something of the native technical genius about him. He had an inherent curiosity about ways to improve the open-hearth furnace and an uncanny ability to convey difficult engineering concepts simply and clearly. He held several patents in open-hearth methods and was eventually recognized by the American Iron and Steel Institute for his contributions.

The end of the 1950s saw the most dramatic shift in Stelco management. For the first time, the company hired a president, Vincent Scully, who had not risen through operations. Scully was an accountant. In fact, he had a background as a civil servant and head of a crown corporation, Victory Aircraft, before joining Stelco as comptroller in 1951. It was on his watch that the company made the shift to a more professionally qualified administrative staff and organization. This is the organizational and cultural background within which McKay's career and account of the evolution of Stelco research needs to be situated.

Sources of Innovation at the Industry Level

The metallurgy innovations developed and implemented by Canadian steel companies such as Stelco, Dofasco and Algoma put them on a competitive trajectory ahead of their American cousins. It also put them on a growth path that brought with it a huge expansion in iron ore mining. The laggardly performance of the American steel industry in the 1950s and 1960s with regards to innovation, when they tragically invested backwards into the older open hearth technology, was matched by a similar reluctance by Stelco. The two transformative technologies of the modern steel industry—the basic oxygen furnace and the continuous caster—were already available in Canada. The failure was related to a relative absence of forward-thinking among the major steel producers themselves.[11]

It wasn't just Canadians who made progress with regards to innovation in the industry. In the early 20th century German producers, for example, became the leaders in "Thomas" or carbon steel, a low-phosphorus, mass-produced steel. As Janet Knoedler describes, "[b]y contrast, U.S. steel producers, operating in a moderately protected domestic market, lagged in developing, and even in adopting, new technologies. The standard explanation for this sluggishness and its continuation for most of the twentieth century has been that the U.S. steel industry was a highly concentrated, dominant-firm oligopoly that, under U.S. Steel's stewardship, was more concerned with maintenance of stability in prices and products than with innovation."

As cited below, in "Market Structure, Industrial Research, and Consumers of Innovation", Knoedler gives a different perspective. Metallurgy innovation can equally be driven by knowledge and cultural factors:

> U.S. Steel, pursued a strategy that, for both corporate and cooperative reasons, was aimed chiefly at ending the destructive price competition that had characterized the industry toward the end of the nineteenth century. The firm instituted a durable and manageable system of price leadership and followership for most steel products that substantially thwarted price and nonprice competition. Thus, when two significant innovations came along in the 1950s and the 1960s—the basic oxy- gen furnace and the continuous casting process—most major steel producers in the United States, ill attuned to the rigors of competition, were slow to adopt these new techniques; the industry has suffered since, seeing its shares of both the international and national markets for steel eroded.

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[11] Knoedler, J. "Market Structure, Industrial Research, and Consumers of Innovation: Forging Backward Linkages to Research in the Turn-of-the-Century U.S. Steel Industry." *Business History Review*, 67: 1 (Spring 1993): 98-139.

> (…) [E]emphasis on the high concentration of the steel industry as an explanation for the lack of innovation by steel producers has obscured the innovation that did take place—in particular, the important contributions made to innovation in steel products and processes by early steel consumers.
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> Although the U.S. steel industry’s concentrated market structure and well-established production technology curbed active research by most steel firms, between 1880 and 1910 vertical research arrangements between steel producers and steel consumers, notably the Pennsylvania Railroad, became a key factor in promoting both increased innovation in basic steel products and increased innovative effort by steel producers, albeit slowly and gradually. (…) Even by 1930, only fourteen of the top thirty-three steel-producing firms in the United States had established industrial research laboratories. (…) [A]ctive research into steel was initiated, not by steel producers but by steel consumers, who established in-house industrial research laboratories and interfirm cooperative research arrangements as a means of solving their technical problems with steel products. This kind of interaction between steel-consuming and steel-producing firms eventually led to backward-linked research efforts, in which producing and consuming firms worked together to conduct research to improve steel quality. They also began to work toward creating an institution—the American Society for Testing Materials—that would allow for effective interaction with other consuming firms and, eventually, with producing firms to exchange information and build consensus. (…)
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> The ASTM established two primary goals at its creation: first, to develop tests and specifications for materials of importance to American industry, and second, to design specifications on which producers and consumers could agree. Realization of these goals required scientific investigation of many industrial products, as well as a means of obtaining consensus between producers and consumers regarding the results—or, in other words, backward-linked industrial research. The ASTM created an institutional framework to induce effective backward-linked industrial research. It placed producers and consumers of commercial engineering materials together on working committees and succeeded in giving both groups approximately equal representation to elicit input from both sides and eventually to achieve consensus on specifications. (…)
>
> Such increased cooperation signaled that the ASTM had moved steel producers and steel consumers away from wrangling over the causes of defects and toward cooperating to develop and implement more scientific testing techniques and better manufacturing processes. Steel producers were becoming more interested in conducting their own research into steel metallurgy and fundamental science. (…) Such increased cooperation signaled that the ASTM had moved steel producers and steel consumers away from wrangling over the causes of defects and toward cooperating to develop and implement more scientific testing techniques and better manufacturing processes. Steel producers were becoming more interested in conducting their own research into steel metallurgy and fundamental science.

From the perspective of this study, Knoedler points to the critical role of standards and standard setting in the ultimate determination of technology direction and adoption at the industry level. Her account of ASTM as an early indicator of a process of inter-firm collaboration but also an example of a collaboration between producers and consumers identifies these critical variables and insights about the dynamics of industrial change. She further states that “[t]he story of industrial research in steel has obvious implications for current efforts to spur more research and development by U.S. industry. The ASTM was one of several interfirm research organizations that were successful during the early decades of this century. Yet these kinds of institutional structures for cooperative industrial research did not become the norm in the United States.”

2.3 Inco Research 1960-1990

Introduction

As recounted in *The Development of Metallurgy in Canada since 1900*, by Erich Weidenhammer[12], for most of the twentieth century, the International Nickel Company (Inco Ltd., after 1976) was the largest producer of nickel in the world. Inco was created through a succession of mergers of companies based in the Sudbury basin, and its present incarnation as Vale Canada represents the majority of nickel production within Vale’s multinational operations, currently the second-largest nickel producer in the world. As the largest of the three major Canadian nickel producers in Canada over the twentieth century, Inco played a significant role in developing Canada’s metallurgical industry.

As described by Weidenhammer, in 1888 the Canadian Copper Company—a member of the consortium that joined

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[12] Weidenhammer, E. *The Development of Metallurgy in Canada Since 1900* (Ottawa: Canada Science and Technology Museums Corporation, 2017).

forces fourteen years later, in 1902, to become Inco—built a blast furnace for copper smelting Sudbury, Ontario ore. This marked the beginning of the long and storied history of metallurgy in Sudbury. An upgrade and expansion in 1930 transformed the Copper Cliff smelter into a massive facility, ultimately the most iconic such operation in Canada, incorporating modern technologies such as reverberatory furnace smelting. Copper Cliff also supplied the nearby refinery with blister copper for manufacture of various products. Infamous for what Weidenhammer calls its "incandescent slag pours," Copper Cliff polluted its surroundings with a combination of sulphur dioxide emissions and metal particulate waste, contributing to the creation of what became known as Sudbury's "lunar landscape."

In the 1970s, the Inco "Superstack," which stood 380 metres and remains the second-tallest freestanding chimney in the world, was built to disperse sulphur gases in the air. Its days are now numbered: Vale Canada's current plan for emission-reductions will see the superstack decommissioned and replaced by two smaller stacks. Vale will eventually dismantle the stack. Until it comes down, however, the superstack will remain a local landmark and potent reminder of an earlier era of substandard environmental policy.

In 1937, Inco opened a process research laboratory in Copper Cliff, becoming the first major metals company in Canada to ambitiously pursue its own internal research and development program. The approach paid off, with researchers building on earlier developments at the Orford Smelter in Bayonne, New Jersey, and quickly establishing Inco's R&D system as a major centre for Canadian innovation in metallurgy. In his history, Weidenhammer describes the advent in this centre of what would fast become a major Canadian contribution to the worldwide method of smelting of nickel-copper sulphide ore: "Between 1943 and 1948, a physical matte separation process was developed and implemented at Copper Cliff to more efficiently separate copper sulphide from nickel sulphides. Once the physical process was implemented, the cumbersome, high-temperature chemical Orford process was discontinued."

In 2006, Inco was purchased by the Brazilian mining giant CVRD, later renamed Vale. The agreement has Inco (now Vale Canada Ltd) run as a distinct nickel mining division that also manages Vale's existing nickel and copper operations in Brazil. The copper refinery in Sudbury had been closed before the CVRD purchase. When a major nickel-copper-cobalt ore deposit was found near the Atlantic coast in Labrador in eastern Canada, Inco purchased the rights to the deposit in 1996 and Voisey's Bay mine began operations which were late incorporated into Vale Canada.

INNOVATION AT INCO[13]

From the beginning of nickel mining in Sudbury in 1888 to the takeover of Inco in 2006 by Vale, and beyond, research and technology development have played key roles in major aspects of the company's business, from its foundation to its stability and growth to, in more recent years, the development of cleaner and more environmentally friendly operations. Within the corporation, Inco nurtured deep technical knowledge of all aspects of the enterprise including exploration, mining, extraction, alloy and product development. It became the dominant force in the world's nickel and nickel alloy markets, contributing major innovations and reaping huge profits. Changes in the world's economy and the supply of nickel, the energy crisis of the 1970s, and missteps by management contributed to decline of this former titan.

THE FOUNDING OF INCO AND ITS PREDECESSOR COMPANIES, 1888-1915

The simultaneous discovery of nickel deposits near Sudbury, Ontario, in 1886 followed by the 1889 development of superior nickel-containing naval armour plating ensured the supply of and demand for large amounts of refined nickel. There was a hitch, however. The Sudbury nickel deposits contained significant amounts of copper, while a commercially viable method of separating copper and nickel was yet to be discovered. Colonel Robert M. Thompson and his employees at the Orford Copper Company in Constable Hook, New Jersey, developed the first large-scale, copper-nickel separation process, the Orford Process, in 1893. With this technology, Orford was able to secure long term contracts with the U.S. Navy. In 1902, with financial backing from J. P. Morgan, the Orford Company (the U.S.-based owner of the technology and controller of the supply chain) merged with the Canadian Copper Company, owner of the nickel deposits, to form Inco under the control of the U.S. Steel Corporation.

Improvements to copper-nickel separation and the development of a revolutionary electrolytic process for refining nickel, innovations led by Noak Victor Hybinette, Inco's (and formerly Orford's) chief metallurgist, enabled Inco's further growth, which included the establishment of a nickel electro-refinery in Port Colborne, Ontario, in 1918. Ambrose Monell, Inco's first president and himself an accomplished metallurgical engineer, obtained U.S. patent 811239 for the manufacture of a nickel-copper alloy that, though developed by company metallurgist Robert Crooks Stanley, was named Monel alloy 400 in Monell's honour (the

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[13] The following account has benefited enormously from many conversations and access to private notes and texts by Sam Marcuson, former Director of Inco Research.

slightly altered spelling was because trademarks could not be issued in a person's name). Stanley later became president himself, and is credited with building Inco into a global powerhouse. Developed in an attempt to transform a high-copper containing nickel ore into useful product, Monel was widely adopted and used for everything from countertops to roof flashing well into the 1940s. Though its popularity waned when stainless steel emerged in the 1950s, it has a long history as a corrosion-resistant material that remains very much in demand, particularly in crude oil processing.

Technological innovations in conjunction with natural assets, unavailable elsewhere, provided the basis on which Inco was built and its legacy created.

Development of an alternative nickel-copper separation process, the Mond process (also called the Langer-Mond process), which yielded pure nickel, and led a second nickel-producing entity to link its operations to the Sudbury basin: the UK's Mond Nickel Company. Discovered and developed in 1888 in the UK by chemists Ludwig Mond and his colleague Carl Langer, the refining process, based on a combination of brilliant research and engineering, employed nickel carbonyl, a volatile, poisonous and highly inflammable compound as the active agent. On the basis of the method's success, a refinery was constructed in Clydach, Wales and opened in 1902 to treat Sudbury sulfide matte.

From the First World War to the Second World War

The outbreak of war dramatically increased demand for nickel and the years during the First World War were prosperous for Inco. Before the entry of the United States into the war, the company was accused of supplying Canadian nickel to Germany and its allies. The most provocative accusation alleged that a German submarine clandestinely transported the war metal. Due to public pressure for "home refining" and the 1917 Report of the Royal Ontario Nickel Commission, Inco agreed to construct a refinery in Port Colborne, Ontario. The Port Colborne refinery operated for much of the twentieth century and was the world's major source of refined nickel until the 1980s.

After the end of the First World War, the industry suddenly found itself dealing with an oversupply of nickel and a dramatic decline in demand. Inco faced an existential need for new markets. Profits dropped from US$2 million in 1921 to US$1.2 million the following year, and the company shuttered its Sudbury mines for more than six months. Robert Crooks Stanley, Inco's president at the time, was adamant about the need to explore new markets, rather than continuing to rely on military demand.

The company's response to this crisis resulted in the creation of one of the world's powerhouses in alloy development, characterization, and manufacturing. The effect of aluminium and titanium on the hardening of nickel alloy was investigated by N. B. Pilling, E. Merica, and P. D. Merica, leading to the development of Monel alloy K-500, a high-strength, corrosion-resistant product with many applications to this day. Work by O. B. J. Fraser allowed for the production of the Inconel alloy at Inco's Huntington plant, which became the first chromium-containing alloy on the market.

Based on these developments, which were supported by astute and effective marketing, Stanley, who would serve a thirty-year term as president, returned Inco's sales to their wartime peak by the late 1920s. Much of the new revenue came from the growing automobile industry. Inco's first major investment after the First World War was a US$3 million rolling mill in Huntington, West Virginia, designed for the production of the Monel copper-nickel alloy with automotive applications.

Competition from Mond Nickel Company, however, was fierce in the mid-1920s. Both companies owned an equal share of one of the best nickel deposits in Sudbury, and each produced high-grade nickel. In 1928, the two firms opted to merge. Headquarters remained in New York City, but the combined entity was incorporated in Canada to avoid Sherman anti-trust legislation. Mond remained a UK subsidiary of Inco, giving the company better access to European and Asian markets, further establishing its global monopoly.

One of the merged corporation's first actions was construction of the 1930 Copper Cliff smelter. Built in just two years on a cost-plus basis, the new facility expanded production capacity and replaced heap roasting with multiple-hearth roasters, emitting its SO2-containing gases from 130-metre stacks. Simultaneously, the company built the first copper refinery in Canada. The smelter, coupled with continued mine development, served as a sustained growth engine for Inco over the next thirty years. By the outbreak of the Second World War, Inco was the sixth-largest producer of copper and the largest supplier of platinum in the world. During the war, the company produced 1.5 billion pounds of nickel, equivalent to its entire production during its prior 54 years of existence. Technical prowess in carbonyl technology enabled Inco to produce iron powder that was important in the development of radar and nickel powders, which were employed in the separation of uranium isotopes by gaseous diffusion.

The War generated new weaponry, particularly with the advent of gas turbines and the race to produce the first fighter jet. This required new materials such as superalloy 718, which was put to use making jet turbine blades that were stronger, more durable, and capable of high-temperature service under extreme conditions. Meanwhile, work in the

United Kingdom by L. B. Pfeil resulted in the development of Nimonic alloy 80. In Huntington, the first age-hardenable variety of Inconel alloys was developed, known as Inconel alloy X. The Germans produced the first jet fighter the Messerschmidt 262 but it had chronic wear and maintenance problems with its nickel alloy engine blades. Its RAF competitor, the Meteor, had better performance in large part because of the Inco alloys.

By avoiding overproduction and the creation of large stockpiles, Inco found itself with overwhelming market dominance at the end of the war, with all the opportunities of an expanding peacetime economy in view.

The Growth Years: 1945–1970

The post-war boom, the Korean conflict and the Vietnam War were powerful factors increasing nickel demand and creating huge profits. Inco's virtual control of the market, combined with its leadership's solidly optimistic view of the future and steadfast belief in the ability of science and technology to improve peoples' lives, generated an atmosphere conducive to technological innovation. The company's researchers did not disappoint.

A vastly improved and cleaner method of copper-nickel separation, the matte separation process, was commercialized in the late 1940s and quickly supplanted the fifty-year-old Orford process. In 1952, aiming to cut costs and provide liquid sulphur dioxide for northern Ontario's paper industry, the company pioneered, under the technical direction of Paul E. Queneau, the application of tonnage oxygen in non-ferrous metallurgy, commercializing the first oxygen-based flash smelting furnace. Today, oxygen-flash smelting is ubiquitous. Further, the technology provided the basis of Inco's massive SO2-abatement project during the 1990s. Other applications of tonnage oxygen followed: oxygen was added to the Peirce-Smith converter air blast to increase productivity and melt additional scrap; oxygen-enriched fluid-bed roasting of nickel sulfide increased productivity and allowed shutdown of dirty, cancer-causing sintering machines; and oxygen use enabled pneumatic converting of nickel sulfide directly to nickel metal in 1973.

Another pioneering project of the 1950s was the iron ore recovery plant at Copper Cliff, which recovered all of the commercially important products contained in pyrrhotite, a high-sulphur, high-iron, low-nickel mineral. Processing this challenging material had reduced the ability to efficiently smelt high-grade pentlandite concentrate, limiting production. The new operation lifted this bottleneck. Completed in 1955 and incorporating the largest fluid-bed roasters in the world, the plant recovered all of the values present in low-grade, one-percent nickel pyrrhotite concentrates. Iron was recovered as an oxide ore for further treatment in steelmaking; sulphur and nickel were recovered as commercial grade sulphuric acid and nickel oxide respectively; and the excess energy created by the roasting process was recovered as steam. A technical success, with significant environmental and health improvements, but with questionable economics, the plant operated until the 1980s.

Nickel demand in the early 1950s was growing at 10 percent per annum, challenging the overall capacity of the Copper Cliff mines. To increase production from new sources, the company began to develop technology for treating offshore nickel laterites and initiated exploration projects both within Canada and beyond its borders. Aided by newly developed aeromagnetic techniques, the latter initiative hit pay dirt with the 1956 discovery of nickel deposits in northern Manitoba. Negotiations with the Manitoba government proceeded rapidly, and in January 1957, tractor trains reached the site to begin construction. The company agreed to build a town near the mine site, naming it Thompson in honor of Inco's chief executive officer at the time, John Fairfield Thompson. To facilitate the development, the company loaned the province CAN$20 million at below-market rates to finance a hydroelectric plant. Completed by 1961, the project comprised mines, a mill, a smelter employing electric furnaces, and a nickel refinery incorporating cost-saving technology developed at the Port Colborne nickel refinery. At a cost of CAN$170 million and financed with internal resources, the Thompson site was the first completely integrated mine-mill-smelter-refinery complex in the world.

Perhaps the most ambitious process development of the period was the research and engineering that led to commercialization of the Inco pressure carbonyl process at the Copper Cliff Nickel Refinery in 1973. Primarily aimed at improving the processing and recovery of platinum group metals, the new refinery incorporated two new technologies. Nickel sulfides were converted to crude nickel metal via oxygen converting, and this intermediate product was then refined to metallic nickel at 99.99 percent purity, the purest commercial grade nickel available, employing nickel carbonyl at elevated pressures. Due both to its toxicity and its flammability, this process required major engineering and operating innovations. Copper-containing residues from the plant were further treated by a pressure-leaching electrowinning process that had also been developed in-house.

To support these and other initiatives, the company constructed new R&D facilities. The first of these, Research Station #1, was built at Port Colborne to develop the pressure carbonyl technology. Research Station #2, also at Port Colborne, was used to investigate pyrometallurgy processes, especially treatment of nickel laterite ores. Research Station #3 was built for pilot-scale testing of hydrometallurgical processes. These pilot plants commonly operated 24/7. Their capabilities rivalled or exceeded those in existence anywhere in the world.

In order to investigate processes and extractive metallurgy on a smaller, more fundamental scale, the company established the J. Roy Gordon Research Laboratory in Mississauga, Ontario, in 1966. The laboratory was populated primarily by researchers and engineers, many of whom held PhDs, who had been stationed in the process research laboratories in Copper Cliff. One driving force behind the creation of this lab was the previous challenge of attracting talented candidates north to Sudbury, and retaining them there. With establishment of this facility, Canada's position as the leading centre for research in nickel process metallurgy was solidified.

Around this same time, a new research facility was also built in Clydach, Wales, to investigate extraction and refining processes associated with nickel carbonyl and to create new nickel powders with proprietary technology controlled by Inco. The carbonyl process enables production of high purity nickel powders and that can be easily manipulated to control particle size and morphology to meet customer specifications. Production rates of nickel powder were relatively small compared with "commodity" nickel. However, due to the nature of applications, prices were high and margins good. Begining in the 1940s, the Clydach refinery had produced both iron and nickel powders by carbonyl technology. Eventually, production of iron powder was halted in the early 1970s due to the availability of cheaper methods of production. However until then, the nickel powder business was booming. The Clydach refinery produced two major types of nickel powders, known as Type A and Type B. Type A nickel powder, later known as Type 123 nickel powder (or T123™ nickel powder), was a dense powder that had a uniform shape, usually cubic or spheric, with a spiky surface. Type A nickel powder was a revolutionary development. The product was widely used in the production of diffusion barriers for uranium enrichment for both nuclear weapons and energy. Type B nickel powder had a filamentary structure and was widely used in battery production, especially in nickel-cadmium batteries prevalent before the mid-1980s. In 1961, an annual production of 141 tonnes (155 tons) of type B powder was recorded, most of the sales going to nickel-cadmium battery customers such as Saft, Varta and Sanyo. By the early 1970s, the nickel-cadium battery business was thriving and just under 1,600 tonnes (1,764 tons) of battery-grade nickel powder were bring produced per annum. With completion of the Copper Cliff Nickel Refinery in 1973, battery-grade powder production increased even further, reaching 4,500 tonnes (4,960 tons) in 1985, which represented 45 percent of Inco's total powder sales that year.

Alloy research by Inco to create broader applications and grow new markets continued. Alloy development laboratories operated in the UK and in the manufacturing facility at Huntington, West Virginia. To expand efforts further, Inco joined the elite group of mining companies that boasted corporate research laboratories. Named in honor of a prized Inco metallurgist, the Paul D. Merica Research Laboratory in Sterling Forest, NY, opened in 1964, comprising 30,000 square metres of floor space and staffed by 300 scientists, engineers and support workers.

Over the years, the demand for more advanced nickel superalloys dramatically increased. At Inco's research laboratories, metallurgist Clarence Bieber led this effort to meet that demand. From the mid-1940s to the early 1970s, Bieber developed more than ten different nickel superalloys. He invented maraging steels, which have good ductility, superior strength and toughness, while maintaining ductility. At the same time, at Inco's Huntington Alloys Corporation, Herbert Eiselstein was responsible for the development of numerous wrought steels, which are to this day the backbone of the nickel industry. The company modified the well-known Shaeffler diagram by including nitrogen in its calculations, thus improving the welding properties of stainless steel. On a more pedestrian note, it developed both nodular iron, a nickel-containing casting alloy, which has superior ductility, and the sandwich alloy employed in American coinage since 1964.

Expansion, Contraction and the Environment: 1970–2006

Driven by the war demand, Inco began to expand its business. Existing sulfide-based mines were recapitalized. Capital projects to extract nickel from overseas laterite ores were initiated, and the company concluded a hostile takeover of a battery producer, its first lateral acquisition.

During the 1970s, Inco developed laterite deposits in Guatemala and Indonesia, each based on in-house research and development, which called for production of a matte intermediate by processing in rotary kilns, electric furnaces and pneumatic converters. Like all pyrometallurgy treatments of laterite ores, this process consumes large amounts of fossil fuel and electric energy. Construction on the Guatemala project started in July 1974, and the first matte was tapped in June 1977. However, the explosion in the price of oil, driven by the 1973 energy crisis, made the project uneconomic and the operation was shut down in 1981—a technical success, but an abject economic failure.

A similar fate would have befallen the Indonesia project, run by the multinational partnership PT Inco, were it not for the presence of a large resource of untapped hydroelectric power. To cope with ballooning energy prices, the scope of the Indonesian project was enlarged partway through construction to triple its original size and to include a hydroelectric power plant. Capital costs escalated from a 1972 estimated range of $135–$247 million to an actual cost of $900 million. The plant was dedicated in April 1977, and the first production achieved in April 1978. However, the operation was plagued with significant operating difficulties and fully commercial product was not achieved until 1990, after expenditure of an additional capital outlay of $87 million and many years of marginal or negative operating profits. Ultimately, despite its costly and lengthy ramp-up, PT Inco's Soroako project became the world's largest integrated producer of nickel from laterites. But its ultimate success was fully dependent on low-cost hydroelectric power.

In 1974, Inco initiated a hostile takeover of ESB, a battery manufacturer based in the United States. The first hostile takeover on the New York stock exchange, Inco initially bid USD$28 per share, when the pre-bid market price was $19.50, as reported in the *New York Times* in July 1974. Initially, ESB resisted the offer, asserting that an Inco takeover would violate anti-trust laws because it would reduce competition in nickel salts, other electroplating products and the battery market. After the bid was increased to $41 per share, ESB accepted, and the USD$225-million purchase was consummated. This acquisition was another abject failure. The US government agreed that the merger violated anti-trust regulations and the company was initially enjoined from making capital improvements or altering the operation. The business suffered massive losses, and, by the mid-1980s, it divested these assets.

The 1970s brought increasing environmental pressure on Inco's flagship operations in Sudbury. After years of continued expansion, its Copper Cliff and Coniston smelters were annually emitting a combined two million tonnes of SO2. These emissions, coupled with damage created by heap roasting in the early part of the century, had destroyed vegetation and acidified creeks and lakes in the Sudbury region, creating a "moonscape" that Sudbury was noted for. The beginning of local environmental activism began in the 1960s. On Earth Day in 1971, Inco announced that it would build a 350m superstack in Copper Cliff to disperse the noxious gas. During this time, it agreed to close the obsolete Coniston smelter and to begin implementation of measures to reduce local ground-level emissions, which included production shutdowns. Almost immediately, annual SO2 emission rates were reduced to one million tonnes. This began an incremental series of new regulatory rulings that, over the next fifty years, would require ongoing R&D efforts and major capital investments.

Economic pressures on the company were further exacerbated by a drop in nickel demand and resultant product surpluses, emergence of other nickel producers, and creation of the London Metals Exchange, which offered an alternative marketplace to the company's internal price setting. The company no longer maintained complete control over the marketplace. Moreover, production costs had skyrocketed due to increasing costs of energy and labour (including debilitating strikes in 1966, 1969, 1979); operation of inefficient old capital assets such as the Port Colborne Nickel Refinery; and unproductive operating practices. The "hammer fell" in 1982 when the nickel price collapsed, a strike was called, and the Copper Cliff operations were shuttered for nine months while inventory reductions re-balanced to reduced market demand.

This emergency had wide-ranging impacts on technology development. During the next few years, the corporate engineering group in Toronto was drastically downsized. With loss of market share, the development of new alloys lost urgency and importance. The corporate research laboratory in Sterling Forest, NY, was, accordingly, shut down. Vestiges of alloy development remained in the UK and the US, and targeted efforts were initiated in Canada. The Clydach research laboratory was also closed, and responsibility for development of new products based on the company's proprietary carbonyl technology shifted to the Mississauga laboratory, which worked hand-in-glove with a new business unit: Inco Special Products.

The transfer of these technologies to Sheridan Park, and the movement of engineering staff from downtown Toronto, breathed new life into the facility. Research was divided into two groups: product and process. New laboratories and offices were built to house transferees and accommodate research into nickel carbonyl. These initiatives allowed the purchase and development of technologies for making novel nickel-carbonyl-based products, including ultra-fine nickel powders, nickel-coated carbon fibre and nickel foam. Scale-up of production of these products, especially nickel foam, was difficult, and market response lukewarm. Vale eventually discontinued these efforts soon after its acquisition of Inco.

On the process-research front, new cobalt and precious metal refineries were constructed at Port Colborne based on in-house research and development. To reduce SO2 emissions in Copper Cliff with minimal capital expenditures, novel methods of rejecting pyrrhotite during the milling process were developed in Mississauga and at Copper Cliff's mineral dressing test centre, a mineral processing pilot plant. These efforts reduced SO2 emissions from a million tonnes per year to 685 kilotonnes. Longer-term technologies and strategies for SO2 abatement were developed and tested at laboratory, pilot-plant and commercial scales. Sheridan Park, Port Colborne Research Station #2, the Thompson Smelter, and the Copper

Cliff smelter and nickel refinery were all involved in this expensive, comprehensive work. While costs of these projects are not available, expenditures on metals recovery smelting tests in Thompson in 1981–1982 were pegged at $30 million. Technologies tested and developed in this work provided the basis for the $600-million SO2 air-pollution capital project at Copper Cliff, which reduced annual SO2 emissions to 265 kilotonnes, dramatically reduced ground-level concentrations (GLCs) of SO2, significantly reduced the energy consumed in smelting, and improved workroom environment.

In the 1990s, the Sheridan Park mineral processing group, working collaboratively with operations-based engineers and technologists, developed inexpensive methods that allowed continued exploitation of the Birchtree deposit in Thompson and increased recovery of nickel from Copper Cliff mines by some four percent, equivalent to the production of a new small mine.

Based on increasing demand, Inco continued its long term quest to develop new properties. In 1992, it secured rights to the nickel deposits in southeastern New Caledonia, including the deposit at Goro. It also obtained rights for the pressure-leach technology developed and pilot tested by U.S.-based AMAX Inc. and BRGM, the French geological survey, during the 1970s and 1980s. In-house laboratory and mini-pilot-plant testing to further develop the technology began. Pilot plant tests were conducted at Port Colborne and New Caledonia. Engineering companies were engaged in process evaluations and feasibility studies. The technologies were tweaked to improve efficiencies. After a number of starts and stops, generated by variations in the marketplace, technical uncertainties, environmental and societal concerns, construction of the Goro processing plant began in 2004. A massive undertaking, its path from commissioning and startup to commercial operation was extremely slow. The project remains economically challenged through to today.

The 1996 purchase of nickel deposits at Voisey's Bay in Newfoundland and Labrador, was followed by a 2002 development agreement in which Inco promised to build a hydrometallurgy-based extraction and refining facility at Argentia, Newfoundland, presented another new technology development challenge. A novel process was created at the laboratory scale. Then, to accelerate pilot-testing, an additional laboratory facility was acquired, and a continuous mini-pilot plant constructed and operated. In 2009, ground was broken for the new refinery.

Overall, the period from 1982–2006 saw establishment and operation of an aggressive and ground breaking programme in Inco mines research, largely driven by Walter Curlook, who retired as vice-chair in 1994. For example, under his guidance, new bulk mining methods such as vertical crater retreat mining were developed, which doubled productivity as soon as they were implemented.

The Copper Cliff North Mine was re-opened in 1984 as a research mine and functioned in this capacity until 1994. In 1989, the *Inco Triangle*, a monthly corporate publication published from 1936 to 1998, touted safety and productivity improvements created by development of a remotely operated, PLC-controlled rock-bolting and screening machine. Developed during a two-year collaboration with Spar Aerospace of Toronto, Ontario, it allowed the operator to screen and bolt the back (roof of the mine) from a distance, thereby reducing operators' exposure to potentially hazardous situations.

In May 1987, refurbished as an all-electric mine, the Crean Hill Mine made its first ore shipment since its closure in 1978. It was billed as one of the most "technologically sophisticated in Canada." Every piece of underground equipment was designed to be electrically powered, computerized, self-monitoring and capable of adjusting itself or shutting itself down when there was variance in established settings. It was designed to produce 2,722 tonnes (3,000 tons) of ore per day at a productivity of 22.9 tonnes (25.2 tons) per worker-shift, equivalent to triple the productivity of the mine when it had closed nearly a decade earlier. Complete electrification was not achieved, however. The mine reincorporated diesel power a few years later.

Other Inco innovations included the first automatic skip, the first automatic cage and the first mine with a broadband video system enabling it to run equipment from the surface via tele-robotics. As manager of mines research, Greg Baiden was a leading proponent of tele-mining, which, by eliminating the need of workers to travel to and work at the face, promised enhanced safety, increased productivity and lowered costs. In 1991, Inco introduced an automated load-haul-dump machine (LHD) that employed an on-board computer and cameras and specialized software allowed the driver to remain at the surface and operate the machine. With time, the machine was able to haul 1.4 million tonnes (1.5 million tons) of ore. In 1994, Prime Minister Jean Chrétien operated a scoop tram remotely from the arena in Garson, Ontario.

Applying automated mining required many auxiliary developments. For example, an article from the March 1996 issue of *Inco Triangle*, describes how methods and equipment to create smooth underground roads were developed to facilitate the most efficient use of automated equipment. The automation agenda was pursued before emergence of modern Wi-Fi systems. Great effort was expended on communication technology. All of these innovations were on the "bleeding edge" of technology development and required massive investment. Many went beyond the imagined needs of managers actually managing the operating mines. However, established mining equipment manufacturers failed to embrace the developments. In the early 2000s, Inco discontinued these efforts.

Another mining-research effort of the day, the Diesel Emission Evaluation Project (DEEP), a university-industry-government consortium headed by Inco vice-president Bruce Conard, was reported in *Inco Triangle* in November 1997. The article outlines how DEEP, with the aim of reducing hazards to human health and reducing the need for mine ventilation, investigated the effectiveness of biodiesel as a fuel and conducted testing of diesel particulate filters, which were then in an early stage of development, in the Copper Cliff mines.

The Vale Takeover

Based on the corporate goals of remaining competitive in existing operations, improving environmental performance, growing the roster of proprietary products based on nickel carbonyl technology, and especially by the need to develop new greenfield mines and appropriate metallurgical processes for treating their extracted ores, these focused R&D activities have continued under new ownership. As part of the agreement to purchase Inco, Vale had signed covenants with the Canadian government to keep R&D at the same level in Canada for a given time period. Vale was legitimately enthusiastic about Inco's expertise and facilities. Meetings and technical reviews between Brazilian and Canadian groups were organized and employee exchanges implemented. Researchers in Canada and Brazil were encouraged to pursue new opportunities. Funding was made available for new projects. Feasibility studies on emerging and competitive processes provided stimulation for the process engineering group. Vale Canada became the leading sponsor of industrial consortia to develop two new technologies, The Rail-Veyor™ ore transport system and the staged flotation reactor of Woodgrove Technologies, a Toronto-based start-up. The Port Colborne Research Station #2, mothballed in 1995, was reopened to study methods of reducing SO2 emissions from the Indonesian operations and redesigning gas-cleaning equipment in the Copper Cliff smelter.

These were halcyon, but short-lived, times. With the financial crisis and collapse in commodity prices of 2012, Vale scaled back its R&D activities in both Canada and Brazil, implementing personnel and budgetary cuts of almost 70%. The scope of the process research and process engineering groups was reined in to focus on technical support of existing operations. Thus, the facility originally known as the J. Roy Gordon Research Laboratory joined a parade of similar Canadian facilities, all of which were likewise either shuttered or dedicated solely to short-term activities.

The Value Chain of Inco Research

Two distinct circuits ran within the overall Inco R&D "value chain." The primary nickel circuit consisted of mines and processing research in Sudbury and Sheridan Park, which was aimed at producing the purest, most cost-efficient, basic commodity nickel product possible (as well as by-products such as copper) at the extraction, smelter and refinery stages. Global commodity markets, cycles, and prices were the primary economic drivers of this circuit.

Meanwhile, the special products circuit, with activities centred at research facilities in Sterling Forest, NY, Huntington, WV, and Wiggin, UK, consisted of product-development research and development of alloys, powders, foams and secondary product market. The economic drivers of this circuit were chiefly industrial markets for turbines, jet engines, and petrochemicals. On their best days, these facilities and their capacities also helped support the commodity business, offsetting, to some degree, the volatility of commodity markets. While the second circuit was an attempt to broaden the nickel market, ultimately, its R&D costs could not be supported by the extended downturn in commodities alongside the cost pressures of the 1970s and the erosion of Inco's position as the leader in the global nickel industry. By the 1980s, Inco had decided that it could no longer carry such a large portion of the R&D load for the industry, and the company began shutting down and consolidating its research centres. In retrospect, the pathway to further R&D consolidation during the Chinese-commodity boom and bust of the 2000s seems inevitable.

Finally, a close look at Inco-Hatch's joint activities in SO2-abatement (see Chapter 3.3) provides an important insight into the changing dynamics of innovation in mining and metallurgy: the nature of their knowledge and technology transfer. Hatch's knowledge concentrated on the design of specific pieces of equipment and circuits. Inco expertise was mainly concerned with process flow, the fundamental chemistry of necessary processes, and operating expertise. Today, Hatch's expertise remains intact and, indeed, has undoubtedly grown. Vale, meanwhile, continues to accumulate and improve on its operating expertise. However, whether Vale Canada (formerly Vale Inco) retains the knowledge and the personnel to perform and understand the chemistry, the ability to conceptualize a new flowsheet and approach, and the capability of pushing back against inappropriate ideas from suppliers, including engineering companies, is debateable. It may well have dissipated.

2.4 ALCAN

METALLURGICAL RESEARCH AND CORPORATE RESTRUCTURING: THE ALCAN EXAMPLE[14]

Alcan Aluminum Ltd. serves as a good example of the trend to reconceive the place of metallurgical research within the existing corporate structure. Staff of the Banbury Laboratories in the UK, preserved their accounts of the work at Alcan in unpublished *Recollections, 1938-2003*'

> A change in Alcan policy in 1979 resulted in a re-grouping of the R&D resources into one unit, to be known as Alcan International Ltd (Alcanint). Ihor Suchoversky was appointed Vice President for research and operations technology — the first time that the term 'operations' had been included in the chief technical officers brief. Jeff Edington joined the company as director for Banbury after a career in university R&D in both UK and USA. Jeff came with a reputation in electron optics. Under his leadership the divisional organisation of the Banbury Lab was removed and replaced by a matrix structure that placed the scientists and engineers into 'silos', led by Principal Scientists. Programme Managers led each area of business related projects. The function of the Programme Manager was to deliver R&D results on time and on budget to the businesses or, in the case of corporate R&D, to the satisfaction of senior Alcan management. The Principal Scientists took responsibility for guiding the scientific performance of the programmes and maintaining the quality of the Lab's scientific capability, including maintaining relationships with appropriate universities and other external centres of excellence.
>
> Charged with the responsibility of providing research and development group-wide, Alcanint was required to consult with the operating companies in order to establish both its annual budget and its priorities. As the operating companies met the cost of R&D, either directly or through a Group-wide levy, both the R&D budget and the programme priorities were to prove 'hot potatoes' at Alcanint's annual planning event, when the programme for the year ahead was thrashed out between the three main laboratories and the businesses. Programmes comprised three types of projects. Work undertaken to address specific needs of an operating company was described as a 'Joint Development Project' and was funded directly by the company concerned. Where the whole of a business stream — such as extrusion — was considered to be the beneficiary of the work, or where the research was aimed at providing fundamental understanding to support a number of Joint Development Projects, the term 'General Project' was used. The business stream, on the basis of individual company rated capacity, funded these projects collectively. Thirdly, project work of a long term nature, considered to be in the overall interest of Alcan's future — either for the existing businesses or for potentially new businesses — was funded at a corporate level, with a levy placed upon the whole company. These were described as 'Corporate Projects' and were to assume greater importance in the 1980s as Alcan sought to widen the scope of its business interests — the New Opportunities programme. Finally, a small proportion of the capacity of the laboratories was earmarked for 'Technical Assistance', to be provided at short notice, and to be charged by the hour, in response to immediate problems being experienced by the operating companies in their plants or in their markets. It was understood that the call for Technical Assistance (T.A.) took priority over other work and it was well appreciated by Labs staff that successful T.A. worked wonders for relationships with those otherwise reluctant to pay for R&D!
>
> In 1982 Alcan merged its UK interests with those of the British Aluminium Company, creating a new wholly owned British Alcan. In addition to its portfolio of operating companies, British Aluminium brought into the Group a further well-established research centre at Chalfont Park. An immediate task for Alcan's research management, and, in particular for Jeff Edington, was the rationalisation of the activities of the two laboratories. Over time, this process resulted in a progressive closure of the Chalfont Park research operation and a transfer of some of its key personnel and unique programmes to Banbury. In particular, British Aluminium's research programme into aluminium lithium aerospace alloys had begun earlier than the work at Banbury and was further advanced. As a result, the two projects were merged under the leadership of Roger Grimes, Project Leader for the Chalfont work. His paper 'The Aluminium Lithium Development' recounts the extensive and complex programme of work undertaken, not only to develop high performance light weight alloys but also the herculean efforts to solve the problems of their manufacture. In particular, the difficulties and hazards of casting these reactive alloys led to new casting technologies and equipment, production versions of which were

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[14] This account depends heavily on an unpublished manuscript Alcan Labs Banbury Recollections 1938-2003. http://banburyrecollections.co.uk/ Unless otherwise identified in a footnote, all quotations in this section are from this manuscript.

> subsequently installed at Kitts Green. The research programme was discontinued in 1992 when Alcan sold its aerospace manufacturing businesses. Despite this disappointing end to a high profile programme, much of the knowledge gained from the Banbury work continues to be employed at Kitts Green and other companies that supply a growing demand for aluminium lithium alloys.

This period also saw Alcan investing in R&D for new applications of aluminium in the automotive industry, as part of a diversification portfolio the company named, simply, "New Opportunities," which resulted in an expansion of manufacturing, development of some successful products and new sales. Yet, in overall, the business opportunities created by this program could not justify its high budget. In the early 1990s, Alcan reverted to its primary operations, and by the end of the decade looked at some potential mergers that would economise on the research resources. Peter Brant reminisces in the *Recollections*:

> In 1999 Alcan startled the metals industry by attempting a three-way merger with its major European rivals — Pechiney of France and the Swiss company Algroup. Whilst each of the three companies had complementary strengths, there existed considerable areas of overlap, which offered the potential for substantial cost savings by surgery. The merger was blocked by the European Commission on the grounds of reduced commercial competition. However, in 2000, Alcan did acquire Algroup and a process of 'rationalising' the resources of the two companies began. The Banbury Lab was now joined with the Algroup R&D centre at Neuhausen in Switzerland to act as a pair under the management of Harald Jenny. Along with the lab at Kingston, the joint fabrication R&D resources were seen to be oversized and in need of reduction. It was clear that one of the R&D centres would be closed. Despite its strong connections to the Alcan global fabrication system and its depth in skills — demonstrated at a joint meeting of project leaders of the three Labs in Kingston in 2001 — Banbury was selected as the candidate for closure. The absence of dependent U.K. manufacturing operations and the relative ease of closing businesses in the U.K. no doubt had their influences. In 2002 Alcan announced its plan to close the Banbury Laboratory the following year.
>
> (…)
>
> [I]n 2005 Alcan's entire Rolled Products Division — previously the Banbury Laboratory's principle customer and sponsor — was spun off as a new company, to be named Novelis. The Kingston Lab was part of the deal. In 2007, Novelis was purchased by Hindalco, a division of the Indian Aditya Birla Group. In the same year, Alcan was taken over by the Anglo-Australian mining giant Rio Tinto, whose main interest in Alcan was its upstream operations from mining through smelting. Over the next two or three years, Rio disposed of Alcan downstream packaging and engineering divisions, closing its Neuhausen Lab. In 2011, the Novelis Kingston Lab was broken up with some resources being moved to Atlanta, Georgia and a few kept in Kingston pro tem. What remained of Alcan — now Rio Tinto Alcan — was a major mining and mineral processing company with a research centre continuing to thrive in Arvida, Quebec. The company had returned to its 1927 origins and strengths. The cycle was complete.

2.5 ADDITIONAL CASE STUDIES

In addition to those discussed above, several other important Canadian technical expertise and innovation centres operated across the country.

FALCONBRIDGE

Falconbridge Ltd. (now Glencore Sudbury Integrated Nickel Operations) was historically the second major mining company in the Sudbury area. American investor and prospector Thayer Lindsley (1882–1976) founded the company in 1928 in the town of Falconbridge, Ontario. Lindsley owned a large mineral exploration company called Ventures Ltd., which included Falconbridge. This vast and complicated company accumulated numerous mining properties, while initially exploiting only a few of them. The Falconbridge property was its most important asset.[15]

Erich Weidenhammer describes this as follow[16]:

> Overseas expansion began in the late 1960s when the company's subsidiary in the Dominican Republic, Falcondo Dominicana, began working on a facility in Norway for producing ferro-nickel from lateritic ore for processing. Beginning in the late 1970s, and through the 1980s, a number of

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[15] Eventually the Falconbridge facility was turned into a technology assistance organization and part was sold off to become Lakefield Research and later sold to SGS.

[16] Weidenhammer, E. *The Development of Metallurgy in Canada Since 1900* (2017). Unless otherwise identified in a footnote, all quotations in this section are from Weidenhammer's publication.

efficiencies and environmental improvements were implemented at Falconbridge's Sudbury smelter. Several new technologies, including methods for processing laterite ore from the Dominican Republic and improvements to the Norwegian refinery, were developed, adapted, or tested at Falconbridge's research facilities near Toronto.

In the 1980s, Falconbridge expanded into other commodities, notably acquiring the Kidd Creek copper mine and smelter in Timmins, Ontario. New mines were opened in the Sudbury area through the early 1990s. Between 1996 and 1998, a new mine and mill were established at the Raglan deposit on the Ungava peninsula on the northern tip of Quebec, a project carried out in consultation and partnership with local Inuit communities. In the 1990s, Falconbridge successfully expanded into South American copper through mines acquisition and development.

Like Inco, Falconbridge produces a great deal of cobalt, which has been processed at its Norway refinery since 1952. Beginning in the 1980s, the Falconbridge Smelter became an increasingly important processor of secondary materials. This includes both nickel scrap and cobalt scrap recycled from alloys. A significant proportion of both materials produced by Falconbridge now comes from recycled materials.

In 2003, Falconbridge merged with Noranda Inc., a major Quebec-based copper company, and in 2006, the combined company was acquired by Xstrata, a Swiss multinational headquartered in London, UK. In 2013, Xstrata merged with Glencore, another Swiss-based multinational, forming Glencore plc. Falconbridge's former mines and smelter in Sudbury are currently run under the company name Sudbury Integrated Nickel Operations.

NORANDA

Although copper has been smelted since prehistoric times, in the last decades of the nineteenth century it became one of the crucial resources in the process of urban and rural electrification and in telecommunication infrastructure. New processing methods, which would continue to be used until the 1980s, were developed during this time. Weidenhammer writes:

> Copper ore would be concentrated before being smelted in a reverberatory furnace to produce a furnace matte of iron and copper sulphides. The matte would be purified in a Peirce-Smith horizontal converter. Air would be blown through the molten metal and silicate flux added to further remove iron and sulphur impurities in the form of sulphur dioxide gas and iron-rich slag. The resulting blister copper, over 98-percent pure, would be further refined in an anode furnace before being cast into anode plates. Shipped to a refinery, these anode plates would be electrolytically refined to a final level of purity. (…)
>
> The mining and smelting of copper were relatively widespread in Canada's early industrial development. One count finds nearly 50 smelters put into production between 1849 and 1960. Most early smelters were small and built near mine sites in order to reduce the cost of shipping concentrate to the refinery. This system was superseded by the improvement of transport networks and the emergence of large, sophisticated smelters, able to process a range of concentrates from different mines.
>
> A notable aspect of Canadian copper production is its link to nickel production through the copper-nickel ores of Sudbury. Two of the six smelters operating in 1960 belonged to Inco and Falconbridge respectively. In Inco's case, copper concentrates were converted to blister copper at the Copper Cliff smelter before being transferred to the Copper Cliff refinery for casting into copper anodes and electrolytic refining. Inco's copper refinery was closed in 2005. Anodes are now cast in the smelter and transferred to the Noranda refinery in Montreal East. In the case of Falconbridge, nickel-copper Bessemer matte is sent to the Kristiansand refinery in Norway.
>
> Since the 1960s, copper smelting has advanced substantially towards improved energy efficiency, automation, and the capture and conversion of sulphur dioxide emissions to sulphuric acid. Three notable Canadian contributions to this area are discussed in the third chapter: Inco's flash furnace provides much greater efficiency than the older reverberatory furnace. The Noranda process reactor, developed starting in the 1970s, greatly simplified the smelting of copper concentrates, increasing productivity and permitting the capture of sulphur dioxide gas. The Gaspé tuyere puncher, developed at the Gaspé smelter, has also improved the efficiency of copper smelting operations.
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> The Noranda story is especially significant because of the company's scale, its longevity, its engagement with large-scale, sophisticated refining operations, and its research contribution to metallurgy. The efficiency of the Noranda process has ensured that the Horne

smelter remains the only major copper smelter still operating in Canada.

In 1921, Edmund Horne (1865-1953), an experienced gold prospector from Nova Scotia, staked his claim to a gold deposit that he had discovered several years earlier while prospecting by canoe in eastern Quebec. In 1922, this claim was purchased by the newly-formed Noranda Mines Ltd., led by James Y. Murdoch (1890–1962), a 32-year-old Toronto attorney specializing in mining law. Murdoch was to lead Noranda until 1956, overseeing its expansion into a major Canadian mining company. He would remain the company's chairman until his death in 1962.

In 1923, diamond drill exploration of the Horne claim revealed that the gold deposit discovered by Horne covered rich and extensive deposits of copper sulphides. This unexpected find proved sufficient to convince the Canadian government to provide road and railway connections to the remote site. By 1924, Rouyn was the site of a booming mining camp. By 1927, the town was incorporated and the railway arrived.

The impact of Noranda on Quebec's metallurgical output was enormous. In 1926, before Noranda's Horne mine began operation, Quebec's mineral output was worth just under $1.9 million. Ten years later the figure had exceeded $30.6 million. By the end of the Second World War, the figure had risen to $150 million. Unlike previous mining and smelting operations, Noranda had ambitions to become an integrated company.

By 1939, Canadian Copper Refiners was the country's second largest copper refinery with a capacity of 102,000 tonnes per year. By 1960, this had risen to 194,000 tonnes. Noranda acquired full ownership of the plant in 1953. Two decades later, after further expansion, it was considered among the most advanced copper refineries in the world. Canadian Copper Refiners (now named CCR) remains the only copper refinery in Canada. Over the years it has undergone numerous upgrades to improve its capacity, most recently in 2000.

In 1930, Noranda extended its operations into finished copper products with the purchase of a mill, located near the Montreal smelter, for producing copper rod and wire. It also purchased part of the Canada Wire & Cable Company based in Leaside, Ontario. As the company grew through repeated acquisitions, copper production would become only a part of a business empire built on mining and smelting several metals.

A second major copper operation was developed on the York River in Quebec's Gaspé Peninsula. As with the development of the town of Rouyn-Noranda, this involved the development of a new community, Murdochville, named after the company's president, James Murdoch. In 1955, a concentrator and smelter was opened by Gaspé Copper Mines Ltd., a subsidiary of Noranda. The addition of a sulphur dioxide capture for acid production was a novel feature for that period, now standard on all smelters. The Gaspé smelter is notable for the invention of the Gaspé tuyere puncher, an automated system that was widely adopted at copper smelters throughout the world. The facility was modernized and expanded beginning in 1991 in an effort to focus on smelting operations in the face of declining local ore reserves. It closed in 2002 with the company citing low commodity prices and increasing environmental requirements. (…)

Like other major Canadian metal companies, Noranda established research-and-development facilities around the middle of the century. The Noranda Technology Centre, located in Pointe Claire, a suburb of Montreal, opened in 1961. It was here that, in the mid-1960s, development of the Noranda process reactor began. First implemented at the Horne smelter in 1973, this was the first commercial-scale copper furnace to both smelt and convert copper in a continuous process. It was joined in 1989 by a large plant for converting SO2 gas to commercial sulphuric acid, and in 1997 by the Noranda continuous converter. Both were part of Noranda's successful SO2 abatement plan. The technology centre also developed a series of sensor technologies for measuring and quantifying metallurgical operations.

One new research-based technology in particular, the Magnola project to produce magnesium from asbestos mine tailings, proved an expensive failure that contributed to Noranda's debt problems and eventual takeover. The project began as a joint venture initiated with Lavalin Industries (now SNC-Lavalin) in 1988. The following years saw the construction of a test plant and, in 1995, a demonstration plant financed as a joint venture between SNC Lavalin, Société Générale de Financement du Québec (SGF), and Aisin Seiki Co. Ltd., a Japanese manufacturer of auto parts. Aisin Seiki and SNC Lavalin eventually dropped out of this arrangement. SGF and Noranda together invested $1.3 billion in constructing and starting up a full-scale plant in Danville, Quebec. The plant came online in 2000 and was beset by technical problems. Meanwhile, Chinese producers had begun to flood the magnesium market. In 2002, Noranda took a write-down of $630 million of the value of the plant. The plant was put on standby in 2003 pending an improvement in the market. It was closed and dismantled in 2006.

Noranda suffered from labour troubles and low commodity prices throughout the late 1980s and early 1990s. In the late 1990s, it sold a number of its holdings to focus on metals and mining, further concentrating on its core copper and nickel operations amid rising debt in the early 2000s. In 2005, Noranda merged with Falconbridge. In 2006, it was acquired by Xstrata (now merged with Glencore), a global mining and trading firm based in Switzerland.

Notwithstanding its record of technical achievement, the technology centre was eventually closed and the people dispersed to other private and public organizations.

COMINCO

The development of a major metallurgical complex in Trail, British Columbia is another important part of the history of Canadian metallurgy. Established just 22.5 kilometres (14 miles) north of the United States border, the Trail Smelter was adapted to treat the abundant zinc-lead-iron sulphide ore of the Sullivan mine near Kimberly, British Columbia. Over the course of its evolution, the company that began as the Consolidated Mining and Smelting Company of Canada Ltd. (known, over much of its history, as "Cominco") emerged as a dynamic Canadian metallurgical giant, opening new mines, establishing partnerships overseas, and constantly modernizing its metallurgical facility in Trail.

The development of onsite research facilities, as we have seen with other large Canadian metallurgical companies, has been critical to resolving extraction and processing challenges. The makeup of the ore from the Sullivan mine was very complex and that made efficiently extracting both lead and zinc concentrates tricky. But that challenge provided an impetus for innovation. Lead and zinc are often found together and the need to process these two metals simultaneously led to the historical and ongoing importance of Cominco's Trail complex.

The Trail smelter was constructed on the Columbia River during 1895–1896, along with a railway to transport ore from the Rossland Mines. In 1896, with the incorporation of British Columbia Smelting and Refining Ltd., the mine and smelter transferred to government ownership In 1898, a main blast furnace was constructed to process the local lead-silver ores, and by 1901, two more furnaces were added. At first, the crude lead bullion was refined in San Francisco. In 1902, the Betts electrolytic process was introduced at Trail, and the lead bullion was processed locally. The process facilities at Trail, were the world's first commercial application of the Betts lead electrorefining process.

The Consolidated Mining and Smelting Company of Canada (CM&S) was created in 1906, by a merger of the plant at Trail; the War Eagle and Centre Star mines 10 kilometres away at Rossland, British Columbia; and the St. Eugene Mine at Moyie, British Columbia, further east. In 1909, CM&S secured a lease on the Sullivan lead-zinc mine in Kimberly, which was unexploited since 1892 because of its highly complex zinc-lead-iron sulphide ore. In the first decades of the twentieth century, the Sullivan mine was among the most abundant sources of zinc in the world.

Weidenhammer writes that "initially, the zinc content of this ore was considered too expensive to process using the pyrometallurgical processes of the time. However, experiments on the electrolytic production of zinc began at Trail in 1912, and an experimental electrolytic zinc plant was constructed in 1913, which operated until 1915. The outbreak of the First World War created significant demand for zinc-copper alloys used in making brass cartridges and shell casings. CM&S was initially granted a contract from the Imperial Munitions Board for 31.8 tonnes (35 tons) of zinc per day. This figure increased throughout the war, and a new electrolytic zinc plant began operation in 1916."

During the war, CM&S also opened Canada's first copper refinery, bringing a new flotation process online that represented the first time metal separation had been achieved by flotation. Within a decade, due to its successful implementation of this new process, Cominco had become one of the world's largest lead and zinc producers. This increased capacity, however, produced a corresponding increase in sulphur dioxide emissions, which nearly doubled from approximately 4,250 tonnes (4,685 tons) per month in 1924 to more than 8,150 tonnes (8,984 tons) per month in 1929. The result was a cross-border dispute with the United States, leading to major efforts to reduce smelter emissions.

One consequence of those efforts was the development of facilities to produce sulphuric acid and, by reacting it with phosphate rock, to produce phosphate fertilizer. Cominco's diversification into new chemical markets continued after the war. By 1960, in addition to being the largest producer of fertilizer in the world, Cominco also produced sulphuric acid, sulphur dioxide, anhydrous ammonia, aqua ammonia, ammonium nitrate, chlorine and caustic soda.

During the Second World War, ammonia produced in the ammonium phosphate fertilizer plant in Trail was used to make explosives for the war effort. The production of ammonia was expanded under government contract, and new plants were built in Trail and in Calgary, Alberta. The company also opened new mines in British Columbia to produce tungsten for armour-piercing projectiles and mercury for use in bomb detonators. As the company had done pioneering research in the production of heavy water, an electrolytic hydrogen plant was built at Trail in 1943, financed by the Americans. It was used as a source of heavy water for The Manhattan Project, and later for the Canadian nuclear program. Other innovations born at the Trail refinery include the introduction of a slag fuming furnace to recover the significant amount of zinc contained in the slag from the lead-smelting circuit.

During this period Cominco also expanded its surveying and exploration activities to find and develop new mines, including the aerial survey of Canada's north. The resources at the future Con gold mine south of Yellowknife, Northwest Territories, which was purchased in 1938, and the Pine Point lead-zinc mine on the south shore of Great Slave Lake, which produced from 1964–1987, were discovered during this time. According to Weidenhammer, "[i]n 1989, the Red Dog lead-zinc open pit mine began operations above the Arctic Circle in northwestern Alaska. Among other things, this development involved an innovative profit-sharing agreement with the local Iñupiat people. By 1991, concentrates from the isolated mine were being processed at the Trail smelter. The Red Dog mine is currently one of the three largest zinc deposits in the world and is a significant source of revenue for the company. Within Canada, ore from the Red Dog mine was essential for replacing concentrates from the Sullivan mine, which was exhausted in 2001. However, significant portions of Red Dog ores are also sent to Asia for processing."

In 1986, Teck, a Vancouver-based mining company, took control of Cominco and in 2001, the two companies merged when Teck purchased the remaining Cominco shares. Teck is currently the world's third-largest producer of mined zinc. The former technical services unit of Cominco became part of CESL Limited (CESL), a wholly owned subsidiary of Teck Resources based in Richmond, British Columbia, that oversees the development of proprietary hydrometallurgical technology.

2.6 Public Policies to Link Mining and Manufacturing: The Case of Sheridan Park

Introduction

The potential to leverage Canada's manufacturing base with its vast mineral resources has long been a public policy objective. The economic and technological benefits seem obvious, but the actual pathway has been much more complex and difficult than policy ideas by themselves might suggest or assume.

From a public policy perspective, the most direct initiative to stimulate development of the linkages between upstream mining metallurgy and downstream manufacturing structural metallurgy was the Sheridan Park Research Community, established in 1956 in Mississauga, Ontario, an initiative of the Ontario government. The project, central to the province's effort to raise the technological level of manufacturing in Ontario at that time, was launched to provide facilities for private companies engaged in industrial research, and to bring these efforts in proximity with the publicly funded Ontario Research Foundation, the centrepiece of the campus-like development.[17]

Major funding and incentives were put in place for companies to locate their R&D facilities in Sheridan Park. By the early 1970s, ten privately owned firms with, collectively, more than 1,500 employees, were operating at the centre.[18] Among these were Inco and Cominco, lured in part by Ford's Oakville assembly plant, which was literally down the street. A dominant Ontario policy target was to link mining and automotive manufacturing. Sheridan Park seemed a natural site for such synergies to take place. Ford at that time was pursuing a major initiative involving batteries, and actively joined forces with the mining companies, such as Cominco, which operated a facility manufacturing battery components. However, the Inco lab at Sheridan primarily researched the processes by which metals are extracted and refined.

Whatever the final judgment determines regarding the fate and impact of the government's policy experiment at Sheridan Park, there is little doubt that two of the key players that rose to prominence at the park were Inco Research and Hatch.

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[17] To date there has been no dedicated study of Sheridan Park.

[18] Rea, K.J. *The Prosperous Years: The Economic History of Ontario 1939-1975* (Toronto: University of Toronto Press, 1985).

INCO RESEARCH AND THE GORDON CENTRE

Here is how Jane Werniuk described Inco's J. Roy Gordon Lab in 2002 article for the Canadian Mining Journal.[19]

> The J. Roy Gordon Research Laboratory (JRGRL), located in Sheridan Park, Mississauga, some 20 minutes from Inco Limited's corporate office in downtown Toronto, was home to Inco's research and development activities. As can be seen from the many patents on display in the reception area, JRGRL is a focal point for the innovation that has been a key Inco strength throughout the company's one-hundred-year history. (…) The research centre, which started operation in 1967, was mandated to develop processing methods for these laterite ores. The laboratory and pilot plant efforts lead to the design of the PT Inco plant in Indonesia, where nickel matte is produced from laterite ore. Today, the research centre carries out 90 % of the research for Inco's worldwide operations, providing process research, metallurgical research, and nickel product research. The head of the Sheridan Park R&D activities is Dr. W. Gordon Bacon, Inco's vice-president of technology and engineering. Reporting to Bacon are the Process Research and Product Research teams, as well as Inco Tech, a commercial unit that markets Inco's proprietary cyanide destruction process. (…) The activities of the Product Research team are closely linked to the strategies of Inco's Special Products. The director of Product Research at the J. Roy Gordon laboratory was Dr. Sam Marcuson, whose accent reveals his southern Virginia origins. He emphasizes that, while his group is a research group, it only works on products that can be used and sold at a high margin. The group does laboratory research at all scales — lab-size, pilot plants and commercial development and research work.

As mentioned previously, Inco activities relating to new product development based on nickel carbonyl technology were transferred to Sheridan Park. The facility was significantly expanded to meet these demands. In the mid-1980s, the #3 research station at Port Colborne was converted to a precious metals refinery. The #1 research facility closed in 1971 when the new nickel refinery in Copper Cliff was completed. The #2 research station remained in operation. But most efforts were devoted to researching new smelting processes to enable the cleanup of SO2 in Copper Cliff. A number of grants were obtained from the federal government to support these activities. Processes such as roast-reduction smelting, continuous-flash converting, continuous converting by lance injection of oxygen and solids, and a modified method of producing copper were piloted at Copper Cliff. The latter was commercialized in the early 1990s and played a significant role in emissions reduction. In 1995, at the conclusion of the Copper Cliff SO2 abatement program, the #2 research station was mothballed. In 2009, it was reopened as a site that could accommodate some large-scale testing, but closed again in 2012.

The research station worked in conjunction with other R&D personnel. While not glamorous to the public eye, this operation proved critical for improving industrial processes. It also represented significant expenditures. When Sam Marcuson joined Inco in 1980, the #2 research station at Port Colborne operated on a 24 hour basis and frequently up to seven days a week. Later, as economics dictated, methods of operating on day shift only were developed. In the 2009–2012 period, the station operated with only a few personnel on site during preparatory periods, and would bring in contractors and staff from Sheridan Park for intensive test periods. When operating with a full crew, the cost of the research programme was between $500,000 and $1 million per month.

From 1981–1983, the company conducted commercial scale tests on roast-reduction smelting at Thompson. This technology was intended for commercialization at Copper Cliff, but was discarded in favor of another approach. The costs of these tests were in the tens of millions of dollars. The tests were based on calculations and experiments at Sheridan Park and piloting at Port Colborne. Additionally, commercial testing of different approaches was pursued at Copper Cliff during the 1980s.

In the same environmental improvement effort, Sheridan Park—in conjunction with the mineral processing pilot plant located at Copper Cliff—developed the pyrrhotite-rejection process, which enabled significant reductions in SO2 emissions without major losses in metal production. This research was largely completed between 1980 and 1986. It is hard to overstate the importance of the contribution of pyrrhotite rejection to the cost-efficient reduction of SO2 emissions during this period.

Major efforts aimed at developing a suitable process to treat the laterites in New Caledonia commenced about 1990, when Inco secured the rights to exploit this resource. Novel approaches were developed. Some of these were piloted in New Caledonia. Others were tested at a larger scale in suppliers' facilities. Activities supporting the New Caledonia operation continued at Sheridan Park.

The Sheridan Park facility also developed the process metallurgy implemented at the Argentia facility in Newfoundland. This was a major effort, starting with

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[19] Werniuk, J. "INCO R&D: Process Development, Product Development and Cyanide Destruction. The Three R's of Inco Research,' *Canadian Mining Journal* (April/May 2002).

conceptualization of approaches followed by laboratory testing of processes and continuous testing in a pilot plant. The latter necessitated purchase and retrofitting of an additional facility, the Hadwen building in Sheridan Park, which was sold in 2014 after outliving its usefulness to the company. The Newfoundland refinery is now operating approximately as planned. However, the capital costs extended far beyond projections made at the time of conceptualization and piloting.

Meanwhile, work at Sheridan Park played a major role in recovery improvement projects at Copper Cliff during the 1990s and 2000s. In each case, nickel recoveries were increased by 2 to 4 percent relative to the baseline of the time. Since Copper Cliff was producing about 90 million kilograms (200 million pounds) of nickel per annum, this amounted to increased production of 1.8 to 3.6 million kilograms (4 to 9 million pounds) increased production for essentially no increase in operating costs. Capital costs were repaid within a year or two.

Product research commenced in Sheridan Park during the mid-1980s. The nickel powders produced at the Clydach and Copper Cliff refineries found ready and profitable markets in the production of nickel-cadmium batteries and powder metallurgy. Many of the early innovations behind these products had taken place previously at Clydach. Sheridan Park pursued the development of new products, including nickel hydroxide, nickel foam, nickel-coated graphite, and ultra-fine nickel powders. However, commercialization of these was more difficult and time-consuming than originally expected. In the case of nickel foam, the process developed at Sheridan Park, based on concepts created by an entrepreneur in the United States, ultimately proved technically viable. However, during the years of development, a low-tech process had been developed in China that, given the lower costs and higher availabilty of labour in that country, undermined the economics of Inco's high-tech approach. Also, the decline of nickel-cadmium batteries decreased demand for the existing nickel powders.

As such, various Inco innovations of the time, including nickel foam, did not find markets or significant applications. In 2009, three years after purchasing Inco, Vale abandoned this line of work. Today, all nickel producers anticipate major increases in the use of nickel in electric vehicles. This market requires materials of high purity that dissolve in acid rapidly without generating solid residues. Vale currently remains in a good position in this market, but this position is based on technology developed by Inco researchers during the last century.

Hatch and Sheridan Park

The account of the Stelco Coilbox development has been described above, concluding with its ultimate transfer to Hatch. It is interesting to hear the side of the story as told by people who were actually part of the process.

Hatch was founded in 1955 and established an office in Hamilton in 1956, primarily to service Stelco. In the mid-1990s, the firm bought Steltech, the former Stelco Research Centre. This steel technology group, combined with the team that specialized in training for steel operations, still forms the core of current activities in the Hamilton office.

The coilbox, comprising approximately $10 million worth of physical equipment designed to be placed in the middle of a steel hot strip mill, has been installed—by virtue of Hatch's continued development and marketing of the innovation—in about half of the hot strip mills in the world. A parallel product that continues to be a going concern at Hatch is the electric furnace used for the production of ferro-nickel. Hatch holds 100% of the global market share for these high-powered furnaces. These technologies represent but two examples from the remarkable Hatch engineering success story.

The Hatch Business Model

Three key components make up the Hatch business model. The first of these is consulting, which encompasses both strategy consulting and management consulting for industrial clients, a service that earns a much higher profit margin than billable engineering hours by themselves. The second component is the sale of proprietary technologies. Thirdly, at the core of the Hatch business model lies the leveraging of equipment sales, such as the coilbox or ferro-nickel furnaces, to sell consulting and EPCM (Engineering, Procurement, Construction Management) services. Essentially in the technology sales group, Hatch uses the physical machinery as a way to sell an engineered package, and use the unique engineering skills the company has developed to support the package.

The success of this model is based in part on the global reputation Hatch has built for high-quality engineering. The key to Hatch's success over the past fifty years is its emphasis on effective project design, and the implementation of appropriate technology that Hatch, in turn, can service, and on which it does ongoing consulting. Engineering is often regarded within industry as a commodity—the cheaper the better. Hatch, by contrast, operates on the principle that it hires top talent, pays them well, and expects them to deliver the best quality work.

Rather than relying on the standard bidding process for procuring work, Hatch's business development prioritizes repeat business and negotiated contracts. The Hatch model is founded on a belief that in the long term, value comes from the offering of quality design and service. That quality is achieved in part by sourcing and converting new ideas into intellectual property. Typically, these ideas come from Hatch customers and clients themselves, who come to Hatch looking to solve specific problems. In response, Hatch conducts in-house R&D, but that is step two. The first step is onsite consultation: new ideas come from the local project situation itself. Internal R&D is then conducted to see if the approach is valid. When the customer comes to Hatch, they typically have a detailed plan that they would like Hatch to follow, or they are looking to achieve certain goals, such as an increase in throughput. In such cases, before they build anything, Hatch engineers will work through a series of conceptual designs, pilots, and test work in order to reach the specification that's been agreed upon, so that they and the client would both be part of a continuum. Sometimes Hatch will get involved even earlier on the consulting side, starting with the markets, and work back toward the specifications put forward by the plant, only then delving into the equipment and design in more detail.

Some of the ideas developed in-house by Hatch originate in universities. However, most innovation is directed to specific problems that customers need to solve. Typically, Hatch will do the internal R&D to prove the concept, and then work clients to build a demonstration plant, because these involve significant capital costs. In such arrangements, Hatch and its client would share the IP for the new technology, with the client then obtaining a license for its use. Hatch is then able to sell licenses for the new technology to new clients, to the benefit of its own bottom line and also but not necessarily that of its original client.

The IP comes in different forms, including patents and copyright. Since a significant portion of IP is based on drawings, Hatch makes sure to claim copyright to its internally produced drawings. Clients don't particularly like this practice. For this reason, project agreements often entail confidentiality provisions, which may or may not be effective in the end.

Most of Hatch's patents are defensive patents. These allow the company to continue doing what it wants, though others may come along and sue them down the road. This is simply considered a normal part of doing business.

Hatch is also engaged in many joint ventures around the world in order to gain exposure and access to new kinds of expertise, as well as different strengths and styles of approach. These ventures also arise from the fact that Hatch's involvement is preferred by some clients to alternative partners.

Hatch and the Innovation Ecosystem

Hatch actively engages with the broader innovation ecosystem, particularly that stemming from universities. The company derives two main benefits from university involvement. First, it fosters connections with professors, leading to awareness of their research activities, concerns and emerging technologies. Second, good relationships with universities lead to referrals of top students, giving Hatch first pick of rising new talent in the industry.

Hatch's competitors are generally attracted less by where the universities are and more on where they can find a good pool of existing engineering talent. Denver, Colorado, for example, is a prized location because it's home to a host of local mining talent. Oil and gas players prefer Houston, Texas. Aluminum players are drawn to Montreal, where tremendous strength exists in that field. In Hatch's view, the advantage of locating in major Canadian centers, Toronto, Montreal and Vancouver, comes down to having a pool of skilled workers within reach, with different companies clustered together drawn by the presence of these skilled professionals. For example, compared to Hatch, other engineering groups in Hamilton tend to be at the lower end of engineering services, including plant support groups focused primarily on plant engineering. But in nearby Mississauga, by contrast, there is a strong and broad pool of talent from which the company may draw. This talent pool supported the move of the head office from Toronto to Mississauga, due in large part to high real estate costs in the downtown. This broader talent pool and the global footprint enables Hatch to innovate and lead in production methods.

Hatch's experiences with university technology transfer offices, however, have generally not been good. In its view, the university commercialization model tends to be unrealistic. In their exprience, the transfer office staff are often not from industry. They fail to account for the fact that the person who takes the biggest risk is not the inventor, but the person putting up the money to run a the commercial demonstration of a new technology. Some universities, meanwhile, would hold out for 80 percent or so of the royalties. In Hatch's view, in the real world, inventors earn 5 percent return if they're lucky.

Hatch does not physically produce anything. If the company is selling a coilbox, for example, the physical product comes from a supplier. Hatch provides the design and may hire consultants for all kinds of specialized and local projects. Typically these consultants are selected for a particular expertise that is not available locally. Location really is no longer an issue for the expertise-based subcontractors. With videoconferencing and electronic communications, experts can connect and contribute from anywhere in the world.

From the engineering side, as a project evolves, it goes through various reviews. Quite often, in particular circumstances, Hatch will bring in external reviewers. These might come from a small specialist consulting firm, from the university, or from any number of other places—other companies, even competitors. What's wanted is tough critique. Competitors, unsurprisingly, tend to be pretty critical, but there are limits to how much of what you're doing you can tell them. Experts from within universities are more suited to these situations and may be used for reviews of evolving or new technologies.

Hatch networks mostly at technical conferences, as opposed to trade shows. There are many technical societies that Hatch supports that are active in the area including consulting engineering associations in many countries and provinces, the CIM (Canadian Institute of Mining, Metallurgy and Petroleum), Association for Iron & Steel Technology (AIST), SME (formerly the Society of Manufacturing Engineers), The Southern African Institute of Mining and Metallurgy (SAIMM), and the Australasian Institute of Mining and Metallurgy (AusIMM) to name a few. Place matters in innovation and this brief summary presents a sketch of how, where and why locating in Sheridan Park eventually led to the firm becoming the major tenant and highly successful entity in what otherwise was only a marginallly succesful policy initiative by the tax payers.

2.7 CONCLUSION: MARGINALIZATION AND CLOSURE OF CORPORATE R&D CENTRES

Built originally on the model of the late nineteenth-century German industrial corporation, technical and laboratory capacities became part of the standard architecture of the 20th century industrial corporation.

Between 1960 and 2010, the place of metallurgy within corporations was impacted by external forces, which, among other things, framed the debate about the social benefits expected from metallurgy development. These external economic, market and political pressures of the period included the environmental movement, which from the 1960s onwards drove legislation that changed attitudes toward extractive industries, emissions and effluent discharges. Meanwhile, major increases in energy costs occurred in the 1970s and 1980s, at the same time that workplace health and safety awareness and enforcement also gained momentum. Competitive pressures were increased by the North American Free Trade Agreement (NAFTA), which came into effect in the 1980s, and more recently by agreements signed under the World Trade Organization. Since 2000, amid such fast and broad evolution in industrial practices and in the conditions for business globally, more than 80% of Canada's metallurgical capacity has been sold to foreign interests.

The basic organization and responsibilities of metallurgical research has likewise undergone significant change. During the formative period of the Canadian mining and metallurgical sector, and up until the 1970s, the approach to projects was fairly standard. Owners conducted R&D in their own research facilities and carried out the required metallurgical engineering and overall management of the projects. The civil and structural design was done either by specialized consulting engineering firms, or by in-house resources of the contractors, fabricators or owners. Major contractors or fabricators did most of the detailed design, along with the construction and construction management.

Two things are immediately apparent from this. First, until the 1970s, is the overwhelming presence of major foreign groups at that time, and second is the relatively small number, historically, of Canadian engineering firms with a metallurgical process capability. Primarily these included: Hatch Associates, Wright Engineers, Kilborn Engineering, Simon Carves with Ferrco and MacByrne Engineering in the steel sector. Most of the latter have now been acquired or merged in domestic or international consolidations.

The twenty years from the early 1970s to early 1990s, included four recessions and the stagnation of metal prices. In order to contain costs during this period, major metallurgical production companies steadily shed their in-house research, project development and delivery capabilities. They relied increasingly on contract research laboratories, consulting engineers and project management groups to provide services as required. A few companies retained strong core groups to manage the "outside" groups, and a few maintained a strong research and development capability.

As the owners increased their reliance on external consultants, new engineering firms were created in response to this opportunity. Following the 1990s recession, major Canadian fabricators, such as Dominion Engineering and Dominion Bridge, shed their engineering groups or shut down completely. Again, this presented an opportunity for engineering consulting companies to further expand their scope.

During this same period, many Canadian mining companies ventured further overseas. As they went, they often took their engineering and project management providers with them, introducing them to international work and sowing the seeds for the current Canadian global prominence in several sectors. Early examples of this include the projects of Inco discussed earlier, as well as projects by Falconbridge, Quebec Iron and Titanium (QIT, now QIT-Fer et Titane, a subsidiary of Rio Tinto) and Barrick Gold Corporation. QIT built RBM/RBIT to mine titanium in South Africa, while Barrick built Goldstrike in Nevada.

By 2010, the active engineering companies in Canada had undergone a sea change, with many of the leading engineering firms of the 1960s transforming or disappearing through a dizzying succession of mergers, acquisitions, and bankruptcies. Wright Engineers was acquired by Texas-based Fluor (its Canadian operations are headquartered in Calgary), while H. A. Simons was bought by UK-based AMEC. Kilborn Holdings, Simon Carves Engineering, Geco, Fenco, Shawinigan Engineering and Lavalin had all been absorbed by SNC, now SNC-Lavalin Inc. Acres International and Kaiser Engineers had been bought by Hatch, while H. G. Engineering, founded in the early 1970s, was bought by WorleyParsons. Stone & Webster was bought out of bankruptcy in 2000 by the Shaw Group, while Davy Corporation was acquired by UK conglomerate Trafalgar House and subsequently by Norway's Kvaerner. It was later transferred to Aker Solutions, along with parts of Chemetics. Aker's process and construction business was subsequently purchased by Jacobs Engineering Group.

In summary, the 1980s saw changes in corporate structures in Canada's leading mining companies that began to shift the role of metallurgical research. Across the board, internal company R&D programs were slimmed down and relegated to providing technical assistance to operating divisions rather than performing independent primary research activities. The changes in Canadian metallurgical engineering companies has been well summarized by Chris Twigge-Molecey.[20]

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[20] Twigge-Molecey, C. "The Dynamic Evolution of the Metallurgical Engineering Companies in Canada 1961-2011" in Kapusta, Joël, Philip Mackey, and Nathan Stubina. *The Canadian Metallurgical & Materials Landscape 1960 to 2011*. (Montreal: The Canadian Institute of Mining, Metallurgy and Petroleum, 2011).

PART III: The Changing Narrative of Mining and Metallurgy

3.1 SUMMARY

THEN AND NOW: STRATEGIC MANAGEMENT DECISIONS

The loss of the great centres of metallurgy associated with Canada's leading mining and materials manufacturers was primarily the result of larger corporate and financial movements, including the shifting of investment to developing countries, the rising prominence of shareholder-value ideology, stock market short-term focus versus long term focus and the decline of the classical corporate R&D laboratory in the industrial landscape. It was less a story of "paradise lost", as some Canadian metallurgists mourn in private gatherings, than one of fundamental changes affecting industrial organization and corporate strategy across the global economy.

While the forms and norms of the modern industrial corporation underwent a seismic shift that led to the downgrading of metallurgical knowledge and expertise, and the suspension of many research efforts within the corporate milieu, advances in metallurgy remained vital to the modern economy and its progress. Metallurgy didn't, couldn't, go away. New networks and agents emerged. Many individuals involved in these technologies migrated from private industry to universities and government labs. Public research infrastructure and universities came to play a proportionally larger role, and there were expanded roles for engineering consulting companies such as Hatch.

THE DIGITAL FRONTIER IN MINING

When today's mine operators look at new technologies, they are primarily concerned with productivity improvements and reduction of both business and human risk. As stated earlier, mining is an inherently risky business and much attention in the development and application of technologies focuses on risk-reduction through changes in processes and procedures. In addition, much of the ongoing cost of mining is associated with risk mitigation. Mining is an inherently high uncertainty industry.

For instance, during the course of development and production, a mine will have thousands of bore holes drilled, many of these with uncertain prospects. The costs associated with these bore holes include activities such as drilling, core logging, face inspection and plan assays. New digital technology applications within these activities include automated surveying, rock characterization, blast optimization, and automated face inspection, among many others.

Much of the robotic technology adopted for mine operations draws on the most advanced automotive industrial robotics, such as those used at Nissan. However, while a car plant offers a static environment, in which a robot is deployed in fixed operations, mine development and production occurs in a dynamic physical environment that changes every day with each operation or activity.

3.2 THE HATCH STORY

TALENT FLOWS: THE HATCH STORY

For researchers of innovation studies, whenever a lead firm or industry undergoes a major restructuring, what happens to the talent pool is invariably of great interest, for its fate is critical to charting and evaluating the outcome. With regards to the implosion of Canada's mining companies over the past decade under the impact of the global consolidation of the mining industry, most attention has been focused on job losses such as downsizing and the elimination of the traditional centres of metallurgy. However, there is another side to the story, as represented by Hatch, which has grown, since 1995, from a respectable firm of 600 employees to the global mining and metallurgy powerhouse it is today, employing a staff of 9,000. But the future does not just repeat the past. It is always different.

The manner in which Hatch conducts its business leads to additional questions. Does it matter if Hatch's "Hall of Fame" technologies are developed for operations outside of Canada? Yes, but it also reflects the evolution of the industry. In the past, the benefits of R&D were transmitted, for the most part, through and within the international operations of a client's individual company. There was minor knowledge exchange through industry conferences and academic channels. If Hatch is primarily developing innovative technologies to be used outside of the country, are there negative or positive effects for Canada from this? The key metric here would be at what point Hatch began to derive a majority of its revenues from international sources. However, when software companies do this, we celebrate their success. The key immediate benefit to Canada probably becomes net employment growth, or the lack of it. We may get a smaller share of a larger pie. Even though Hatch may be one of the few companies still creating innovation in Canada, if that cutting-edge technology is not being used locally, are we left at a disadvantage as a country? It is hard to answer this question without going very deep, and considering the situation on a case-by-case basis. The following is the Hatch Case.

Overview of Hatch

To understand how technological and scientific knowledge is transferred during a major disruption in industries, it is critical to examine what happens to the workers who hold (and developed) that knowledge. Researchers try to study how the skilled workforce chooses to redirect its talent. Such is the case with Inco's innovators, who were crucial to the emergence of the mining services and the supply chain in Sudbury after the sale of Inco to Vale in 2006. In other cases, we may observe a dispersion and regrouping of talent, which is applied to new business models.

The following case study of Hatch is important to the history of the economic impact of Canadian metallurgical innovations in two respects. First, it offers an illuminating opportunity to witness the dispersion and regrouping of significant engineering and metallurgical talent in Canada. Second, it contributes to the story of Sheridan Park, where, perhaps not immediately consistent with the original economic policy rationale for the park, a parallel story emerges, of the technological upgrading of the Ontario mining and metals sector. In this context, Hatch became both the largest entity in Sheridan Park and an important player in both the Canadian and global economies.[1]

Hatch describes itself as an engineering and business knowledge company operating in 150 countries. The company has a flat corporate sturcture, which allows for collaboration and creativity. It is also fully employee-owned, however, the option to buy shares is only offered to "mid- and senior-level employees."[2] Hatch uses share ownership as a strategy to keep valuable employees, and to ensure that the interests of its highly skilled workforce remain inline with the interest of the company.

In *Hatch: The Art of Innovation*, a corporate history published in 2005 to commemmorate the firm's fiftieth anniversary, the company's origin is dated back to the establishment, by British civil engineering firm W. S. Atkins & Partners, of its first Canadian office. Bill Atkins, who founded the Canadian branch, predicted that post-war Canada would offer good opportunities for expansion. Atkins' instincts paid off, and the company was awarded a contract for conducting the tunneling study for an expansion of the subway system in Toronto. In 1957, Atkins approached Gerald G. Hatch, then plant manager at Quebec Iron and Titanium (QIT) in Sorel, Quebec, and offered him the position of president of the company. Gerald agreed, and went on to develop "a truly comprehensive engineering firm for the metallurgical process industry [which entailed]: consulting to management for appraisals of technologies, markets and companies; developing client technologies; process engineering; multidisciplined design groups; and strong capabilities in project and construction management of projects through to sucessful start-ups."[3] Hatch's tenure at the company began in January 1958. He led a team of but six employees, among them Ted Noskiewicz. The main focus of the business was civil engineering. Archie Lamont, a process engineer, joined the company in the summer 1958. In 1965, Hatch, Noskiewicz and Lamont purchased the company from W. S. Atkins. They quickly established a structure in which fulltime employees could become shareholders. In 2005, forty years later, Hatch credited this decision for the company's continued success. With his R&D background in metallurgy, and having previously worked for QIT, he was commited to growing the company, then known as Atkins, Hatch & Associates, in the metallurgy sector. Hatch began building its reputation in metals by working with primary metals and mining companies. Under his leadership, the company experienced steady, organic growth through the formation of meaningful partnerships with clients. In 1988, when Hatch stepped aside from the position of president to assume the role of chair, the company counted 600 employees, valued for their technical knowledge and research and development experience, and for thorough understanding of corporate operations and markets.[4]

Hatch's steady, longterm growth is representative of the shift in the approach to R&D that was occurring in the mining and metals sector at the time. As discussed previously in this study, from the 1970s onward, a multitude of pressures led to the closure of many in-house research centres. This created the need for operating companies to depend more heavily on external research laboratories, consulting engineers and project management groups. Hatch, being one of the few Canadian engineering firms with a specialty in metallurgical processes, was well positioned to fill the gap. Moreover, a new trend arose with the subcontracting and parcelling out of large industrial construction projects. Hatch recognized through its engineering, procurement and construction management or EPCM approach that this created a need

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[1] Hatch, "About the Company." [Online]. Available at: https://www.hatch.com/en/About-Us/About-the-Company [Accessed: Dec. 2, 2019].

[2] Hatch, "About the Company." [Online]. Available at: https://www.hatch.com/en/About-Us/About-the-Company [Accessed: Dec. 2, 2019]; C. McIntyre, "How Thinking Long-term made Hatch one of Canada's Best Managed Companies," *Canadian Business* (Jan. 3, 2017). [Online]. Available at: https://www.canadianbusiness.com/lists-and-rankings/best-managed-companies/hatch/ [Accessed: Dec. 2, 2019].

[3] Hatch, Gerald G. *Hatch: The Art of Innovation, Celebrating 50 Years of Excellence* (Toronto: Hatch, 2005), 16.

[4] Ibid, 16-35.

for skilled engineers who could act as project managers. New graduates with technical degrees increasingly began to seek employment with engineering consultancies; they knew there was a need for talent, but were also lured by the prospect of being involved in exciting R&D projects. Hatch focused on human capital and a hands-on approach: to ensure the success of large and often extremely complex engineering projects, the company would appoint senior, experienced staff to manage logistics and relationships. For example, Ted Noskiewicz and Ron Nolan (Nolan would later become CEO), were both part of the team that developed a new implementation methodology as part of a complex international project for Iron & Steel Company of Trinidad and Tobago (ISCOTT).[5]

David Rudge, the global director of engineering equipment at Hatch, describes the growth of the company under Hatch's leadership as organic. Nolan, who took the helm as CEO in 1988 transitioned to a more strategic approach, through acquisitions and mergers, that gave Hatch access to innovative researchers and technologies.[6] By acquiring companies and their research divisions—their "talents" as well as assets—Hatch was able to further stake its claim as an R&D and innovation leader in the industry. One of the company's first acquisitions, negotiated in 1993, was Steltech, an arm of Stelco, a deal that added sixty-five employees to the Hatch payroll, including the coil box team, all bringing with them unique expertise in hot-strip mill installations and flat rolling operations, including a firm grip on the requisite simulations and impact assessments of technological upgrades in these areas. Hatch's acquisitions went on to include, among others, Rescan Mining (1998), Australia's BHP Engineering (1999), the metallurgy division of Kaiser Engineers (2000), and Corus Consulting (2001). Each acqusition was timed to provide Hatch with the needed expertise to expand beyond purely technical mining and metallurgical expertise to more strategic investment and business practices and could evolve into on going partnerships with operating companies such as the Hatch-Glencore Technology Centre in Sudbury. As such, the executive leadership's priorities were broadened to include high performance, maintenance, energy management, training, system consulting and senior management and financial advice.[7] It was during this period of negotiating numerous successful acquitisions, between 1988 and 2003, that the company grew tenfold, to 6,000 employees.[8] Hatch's expansion continued throughout the 2000s, with several further acquisitions, including: Acres International in 2004, MEK Engenharia in 2012, and Upside in 2019.[9] Access to the intellectual property owned by the acquired firms, plus the experienced talent they brought with them, proved the two most significant advantages of Hatch's bold expansion. Key to its success was insuring a cultural fit with the rest of the organization.

Creating and licensing intellectual properties was an essential part of Hatch's business model. Typically, IP was a product of the projects that Hatch took on for its clients. Through the design and execution of engineering projects, Hatch would develop solutions that could be transferable to projects with other clients who had similar needs. These transferable solutions were often technologies that Hatch could patent and then license, such as, for example, furnace cooling elements. When Hatch acquired companies, it inherited the IP that the companies had previously developed internally, which in turn would allow Hatch to grow in areas where it may not have had in-house expertise. Hatch could also use this IP to attract business by differentiating themselves from the competition. However, without the necessary engineering talent that came with the acquisitions, the IP would only go so far, until the patents expired. As such, the recruitment and retention of talent became critical to Hatch's success. Specialized employees from acquired firms brought with them intimate understanding of the patented technologies they'd developed; they were able to leverage that knowledge to further develop those technologies and to create related products for licensing. From Hatch's perspective, maintaining an extensive team of talented employees ensured that its clients would receive high-quality service.[10]

Hatch's motivation to innovate derives from the basis of its technology group's business model, which breaks

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[5] Ibid, 39-40.

[6] David Rudge, Private Communications (Nov. 1, 2019).

[7] Ibid, 82.

[8] Ibid.

[9] "Great Panther Silver Adds Mining/Metallurgical Expertise to Board," (*Mexico Mining Center*, Mar. 17, 2011). [Online]. Available: https://www.mexicominingcenter.com/great-panther-silver-adds-mining-metallurgical-expertise-to-board/ [Accessed: Dec. 3, 2019]; M. Gibb-Clark, "Hatch Engineers Global Business," (*The Globe and Mail*, Mar. 23, 2018). [Online]. Available: https://www.theglobeandmail.com/report-on-business/hatch-engineers-global-business/article1036163/ [Accessed: Dec. 3, 2019]; "Hatch Buys Mining Group," (*The Globe and Mail*, Apr. 6, 2018). [Online]. Available: https://www.theglobeandmail.com/report-on-business/hatch-buys-mining-group/article25472580/ [Accessed: Dec. 3, 2019]; J. Saunders, "Venerable Acres International bought by larger Ontario rival," (*The Globe and Mail*, Apr. 20, 2018). [Online]. Available: https://www.theglobeandmail.com/report-on-business/venerable-acres-international-bought-by-larger-ontario-rival/article1000706/ [Accessed: Dec. 3, 2019]; P. Williams, "Hatch Group acquires Brazilian engineering firm MEK Engenharia," (*Daily Commercial News*, May 9, 2012). [Online]. Available: https://canada.constructconnect.com/dcn/news/projects/2012/05/hatch-group-acquires-brazilian-engineering-firm-mek-engenharia-dcn050051w [Accessed: Dec. 3, 2019]; "Hatch rounds out oil and gas portfolio with acquisition of Upside Engineering Ltd.," (*Hatch*, Sep. 11, 2019). [Online] Available: https://www.hatch.com/en/About-Us/News-And-Media/2019/09/Hatch-rounds-out-oil-and-gas-portfolio-with-acquisition-of-Upside-Engineering-Ltd [Accessed: Dec 3, 2019].

[10] Twigge-Molecey, Chris. Private Communications (2007).

down into two fundamental parts. First, Hatch sells specific technologies. Second, Hatch offers consulting engineering services that support the use of these proprietary technologies. These technologies may be developed in partnership with clients, where the client supports the expenses of piloting the technology, or they may be used in their existing form. In either case, the IP is licensed to the client. By this point, the client has entered into a longstanding partnership with Hatch, as the technology generally requires upkeep, which compels the client to go back to Hatch for upgrades and further engineering services.

Hatch's ability to innovate is fueled by the needs of the clients, who do not run their own internal R&D. The shift from in-house research centres to outsourced consulting is not without its challenges for a company like Hatch. Its clients may be conservative and risk-averse, especialy on longterm or unique projects, on which they may, for example, be reluctant to underwrite the trial of a new technology, for such trials are often conducted, by necessity, on a massive scale, and are therefore attended by huge costs. Part of this aversion to new technological solutions may also be a result of a general change in management structures. Before the 1990s, it was far more common for an engineer to lead a mining and metals company than it is today. As banks entered this market, the senior management gradually became more likely to boast a finance background. Therefore, the technologically-minded leadership of an engineering consulting company, and its finance-minded clients, may have different understandings of where and how to invest in innovation.[11]

An additional challenge that arises when technology research is conducted outside of the user or client context is the risk that the consulting engineers receive a limited view of how the technology fits into a larger framework for the client. A client has a better gauge of how a new technology will affect its company overall, and of the constraints posed by the interrelated lines of business by which it functions. For example, Hatch may be able to make an innovative new furnace technology that is 20 percent more energy efficient, however, it is not clear whether investing in this new technology would improve the big picture for a client. There may be other factors that need to be considered, such as whether the operator has only an operating-expense budget, as opposed to a capital expense budget. Hatch does not just create new innovations based on what it knows is possible; it validates that operators are willing and able to invest in such technologies. It is for this reason that Hatch's business model is client-centric and relies so heavily on developing and maintaining good relations with clients in order to understand their real market needs. Hatch depends on its clients' trust. In comparison with the original equipment manufacturers (OEMs), Hatch has the advantage of these meaningful relationships with clients to make products, services or systems catered directly to their needs.[12]

'HALL OF FAME' TECHNOLOGIES

In its first sixty-five years of operation, Hatch developed numerous proprietary technologies. As had already been discussed, developing and licensing IPs has been a central objective of their business model. The following overview of four of Hatch's "Hall of Fame" technologies demonstrates how these innovations were instrumental to the company's success and help us understand how Hatch conducted research, development and innovation.

Furnace Cooling[13]

The story of Hatch's furnace-cooling technology is one of organic and gradual growth. The specific cooling technology sprouted out of a milestone project, which Hatch developed with Falconbridge Dominicana. As Hatch continued to obtain contracts for similar work on ferro-nickel smelters, the company refined its cooling technology further, to become the leading technology in use today.

The furnace-cooling technology was first developed in 1973 for an electric furnace for ferro-nickel smelting that was engineered by Hatch, with Falconbridge Dominicana, for its Falcondo smelter in the Dominican Republic. Hatch provided a solution that retrofit the original furnace after it experienced severe refractory wear within a few months of starting operations. The damage was due to the composition of the ore, which produced a more corrosive slag than the furnace was designed to sustain. Hatch's solution was to install solid members of partially water-cooled, high-conductivity copper. This design successfully remediated the problem by preventing further erosion and allowing a layer of frozen slag to build, which would further stabilize the lining of the machinery wall.

A second major application of the cooling technology followed shortly after, in 1978, for the repair of three furnaces at PT Inco's operation in Indonesia. At the time, Elkem, a major OEM for furnaces, was leading the developer of this facility. Within a few months of operation, the furnaces began to face similar challenges as those seen at the Falcondo smelter. The use of a highly acidic lateritic ore contributed to the rapid decline of the refractory lining. The

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[11] Beckermann, Stephen. Private Communications (Nov. 1, 2019).

[12] Beckermann, Stephen. Private Communications (Nov. 1, 2019).

[13] Walker, Chris. Private Communications (Nov. 1, 2019); B. O. Wasmund, N. Voermann, A. MacRae, R. Veenstra, "Hatch Associates Solid Copper Cooling Systems for Furnace Refractory Protection," (1998); A. Daenuwy, A.D. Dalvi, M.Y. Solar, and B. O. Wasmund, "Development of electric furnace design and operation at PT INCO (Indonesia)." *Proceedings of the 31st Conference of Metallurgists, Canadian Institute of Mining and Metallurgy (CIM)* (1992).

original magnesia brick lining had only lasted for twenty months. The same lining was re-installed, only to suffer the same fate, eroding to one-sixth its original thickness within eight months. In efforts to limit the damage, furnaces were operating at a decreased power level, reducing efficiency.

At this point, Hatch was brought in based on its already well-established reputation for remediating these types of issues. Applying a similar copper cooling system as that used at Falcondo, Bert Wasmund and John Coop, who worked closely with Inco's experts, came up with several designs to retrofit the furnaces. They first tried two differing designs on Furnace No. 1 and No. 2, and then, after analysing the results achieved by each of those systems, determined a final design for Furnace No. 3. This solution, when combined with improved mining and blending practices to lower the acidity of the ore, considerably improved the operations of the furnaces. Most of the design and fabrication was done in a shop on-site. After several months of successful operation, the refined design was applied to other furnaces. Hatch was not only able to drastically extend the service life of the refractory, its cooling technology allowed for the site's operating power capacity to nearly double.

In the early days of Hatch, the company was less focused on proprietary technology than on building a reputation for its team, as the people who fixed other people's designs. In the case of PT Inco, Hatch demonstrated both the creativity and forensic problem-solving ability that set it apart from the OEM. Hatch was not selling off-the-shelf technologies. The company was developing customized and client-based solutions that drew on its experience in prior projects.

As Hatch continued to amass experience with furnace-cooling technology, its engineers began to see challenges with the ways in which furnaces processed platinum group metals and, as a result, Hatch widened its service clientele. As Hatch's reputation grew, the company became involved in more early-stage projects, where its cooling technology would be integrated into the initial furnace design. By using a combination of fingers, plates and blocks, this technology was able to limit wear of furnace lining for smelters that produce highly corrosive slags, support an increase in operating power capacity, and ultimately increase productivity and capital cost gains. Eventually, Hatch started licensing the cooling elements themselves, typically through an engineering assignment with a licensing agreement attached. Selling the hardware became part of the service, in part because the cooling elements need to be custom-designed for application. Within the twenty-five years of its initial development, Hatch had installed its cooling technology in more than forty furnaces.

Coilbox[14]

The story of Stelco's development of the coilbox technology has been described previously (see Chapter 2.2: Linking Mining and Manufacturing Through Steel). However, the coilbox technology has come a long way since its first prototype in 1973 and first installation in 1978. The technology was easily accepted at the time, since it offered many advantages, including product optimization, yield and quality improvements.

The acquisition of Steltech was a strategic move for Hatch, as it allowed the company to build an iron-and-steel consulting team and, by extension, its reputation in ferrous metals. The addition of Stelco's specialized engineers facilitated significant growth in the company, and their knowledge was key to the success of the iron-and-steel team going forward. These new employees came armed with the background and expertise to both commercialize the technology and to provide the necessary technical support.

By around 2000, the patents that Hatch had obtained for the coilbox were beginning to expire. This prompted Hatch to change its commercial model and move from technology licensing and high-level support to a firm that provided support on a design-and-supply basis. The goal here was to keep the coilbox technology evolving beyond the limits of the original patents, in order to prevent competitors from simply copying it. And, the talent that came with the acquisition of the coilbox meant Hatch had the expertise to effectively apply this strategy. The coilbox was a piece of equipment that, where installed, would require maintenance and upgrades, through which Hatch would ensure repeat business. The more the technology could advance, the more Hatch would maintain its niche.

Beyond the coilbox IP itself, the talent recruited by Hatch and transferred to Hatch through its various acquisitions and mergers proved key to its success. Without the talent, Hatch could not have further developed the technology and retained its hold on the market. Had Hatch not acquired the coilbox from Stelco, the coilbox would not have gained the popularity it has attained, nor would it have undergone upgrades and improvements, because Stelco had drastically scaled back its R&D division. Might the technology still have been commercialized under Stelco? Perhaps, but the investment that Hatch made in the coilbox and in R&D personnel ultimately benefited the innovation, the company and its clients. Where Stelco focused on using the innovation in its own operations, Hatch put greater emphasis on further developing and distributing the coilbox technology for the broader market.

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[14] Rudge, David. Private Communications (Nov. 1, 2019).

The acquisition of Steltech and the coilbox was at the beginnning of Hatch's era of major growth, a growth that was both opportunistic and necessary. In order to respond to the increased demand for consulting, Hatch needed to hire more engineers; naturally, the engineers were acquired from clients who had let their talented specialists go. Where Hatch gained in talent through this dispersion and regrouping of the labour force, its clients lost the ability to innovate in-house and were now highly reliant on consulting engineering firms and on OEMs. However, consulting engineering firms, such as Hatch, and OEMs, in turn, may have more challenges in identifying opportunities to innovate, or in the finding opportunities to carry costly innovations from concept-to-market without strong commitments from clients. Good channels of communications and trust between clients and consultants are now as essential to secure capital for innovations as is the need for technological solutions. Successful innovations involve many components: originating challenge, ideas, investment, research, prototyping and testing, social networks, implementation and improvements. If one element falls through, so does the innovation. The client-consultant relationship makes this process event more complex.

Within the current climate of R&D, large mining and metals companies struggle to embody the innovative spirit they once possessed. Big players in the industry, such as Glencore and Rio Tinto, have become highly risk-averse, largely due to their relationships with the banks. Securing a modest loan of a few million dollars to conduct preliminary research can be more difficult than securing hundreds of millions of dollars to build a tried-and-true technology for a greenfield mine. The problem is only exacerbated when smaller companies, traditionally more open to high-risk and innovative solutions, are regularly acquired by larger operators. However talented and creative its workforce may be, this pervasive mindset impacts Hatch's abilities to innovate. If the coilbox were to be invented by today, it might have proved difficult to bring to market at all.

Still, its deep and versatile pool of acquired talent gives Hatch the capacity to seek fresh opportunities for mature technologies. The coilbox is one of these mature technologies that is constantly applied to solve new problems, a reality that makes it still very relevant today.

Tube Digestion[15]

The Bayer process is the primary method used to refine and produce alumina from bauxite. The process involves four main steps, which are (i) digestion, involving the use of caustic soda to dissolve the bauxite at elevated temperature and pressure, (ii) clarification, separating the residue solids from the enriched liquid, (iii) precipitation of the alumina out of the caustic solution in the form of alumina tri-hydrate, and (iv) calcination to produce a pure alumina. Since the 1960s, industry standard practice involved preheating the caustic liquor through shell and tube heaters via a dual-stream circuit that was then mixed with the bauxite stream at the digester vessel. This type of system is traditionally used for processing boehmitic or diasporic bauxites that require operation at elevated temperatures between 250°C to 270°C.

Kaiser Engineers later developed a more efficient technology for the digestion stage of the Bayer process. Known as tube digestion, it combined the bauxite and caustic for single-stream digestion. In 1973, tube digestion technology was used in a greenfield alumina refinery commissioned by Aluminium Oxid Stade, an alumina refinery in Germany. Production was initially projected to be 0.6 million tons per annum of alumina but the results exceeded expectations: from the point of commissioning to 2006, production increased to 0.925 million tons per annum. The tube digestion technology offered several benefits, including maximized digestion temperature, which reduced caustic soda consumption, and improved energy efficiency. Other benefits that were observed in this facility

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[15] Haneman, Brady. Private Communications, (Nov. 1, 2019); B. Haneman, "Evolution of Tube Digestion Technology for Alumina Refining," (2017); K. Robert, M. Edwards. D. Deboer, P. McIntosh, "New technology for digestion of bauxites." *Essential Readings in Light Metals* (2006), 371-376; "Alumina Tube Digestion." [Online]. Available at: https://www.hatch.com/en/Expertise/Services-and-Technologies/Alumina-Tube-Digestion [Accessed: Dec. 8, 2019].; "Al Taweelah Alumina Refinery." [Online]. Available at: https://www.hatch.com/en/Projects/Metals-And-Minerals/Al-Taweelah-alumina-refinery [Accessed: Dec. 8, 2019]; "Maadan Alumina Refinery." [Online]. Available at: https://www.hatch.com/en/Projects/Metals-And-Minerals/Maaden-Alumina-Refinery [Accessed: Dec. 8, 2019]. "Yarwun Alumina Refinery." [Online]. Available at: https://www.hatch.com/en/Projects/Metals-And-Minerals/Yarwun-Alumina-Refinery [Accessed: Dec. 8, 2019]; "ICF Kaiser International, Inc. History." [Online]. Available at: http://www.fundinguniverse.com/company-histories/icf-kaiser-international-inc-history/ [Accessed: Dec. 8, 2019].

as a result of the new technology included reduced capital costs and energy requirements, improved liquor productivity, and a reduction in heater-cleaning frequency from every three days to every three weeks.

In 1994, Kaiser patented its multi-cell heating technology, which modified tube digestion technology. This innovation was first implemented in a facility of the Korean General Chemical Company in the early 1990s. Though the facility was small, with a capacity of only 0.22 million tons per annum, the application of the technology represented a milestone for Kaiser. The technology facilitated an increase in production capacity by three-to-four times, coupling multiple heater trains into a single slurry-circuit evaporator. The success of the KGCC plant paved the way for the world's largest tube-digestion facility, the Comalco Alumina Refinery in Australia, which operated at a capacity of 1.4 million tons per annum. The plant used two tube-digester units that incorporated the multi-cell heating technology, each able to process 0.7 million tons per annum. The time and investment required to build a plant of this size and install the requisite technology is significant. In 1995, a project to design the refinery using this modified tube-digestion method was initiated under a partnership between Kaiser Engineers, Lurgi Chemie, and VAW Aluminum. After the feasibility study was completed in 2001, the project execution was initiated in November of that year. Exactly thirty-six months later, the project entered its commissioning stage. During a scheduled maintenance eight months later, in 2005, the flash vessels and jacketed pipe heaters used had minimal scaling to be removed. The lack of scale validated the quality of the product and the success of the new technology. Overall, the plant realized a reduction in operating costs of 20 to 30 percent.

Kaiser Industries had a long history. It was formed by Henry Kaiser in the United States in 1914. Around the time of the Second World War, the engineering department in the company branched off to form Kaiser Engineers. Kaiser Engineers began seeking more international projects, and, in the mid-1980s, the company split in two: the Australian and Asian operations were sold to Elders Group IXL; the rest went to American Capital and Research Corporation, which, by the end of the decade, had become ICF Kaiser Engineers.

Hatch acquired Kaiser Engineers in 2000, towards the end of the Comalco project, and with, it the patents for multi-cell heating tube digestion. As the Comalco plant was a joint project with Lurgi and VAW, Hatch entered into a partnership with both companies. In 2001, Lurgi (with its patents) was acquired by Outotec. As a result, Hatch and Outotec came together as an unincorporated joint venture under the name of Hatch-Outotec to deliver the tube-digestion technology. This partnership carried forward into a 2012 expansion of the Comalco plant (now the Rio Tinto Yarwun plant), incorporating technological advances that brought the plant up to a capacity of 3.4 million tons per annum.

The next greenfield alumina refineries in which Hatch employed tube digestion were located in the Middle East. In addition to the IP that Hatch could provide to these projects, the company also had the talent and expertise obtained from Kaiser Engineers, which helped them tackle difficulties particular to building a refinery in Middle East locations. The Ma'aden Alumina Refinery presented unique challenges, such that making alumina products on its own would not be profitable. The plant needed to be fully integrated in order to make it economically viable, meaning that it would perform all operations: first, mining the bauxite; then, refining it to alumina; and finally, smelting and rolling. The ore type required high-temperature refining, making tube digestion the best option. Employing Hatch's patented multi-cell jacketed pipe heater technology allowed the plant to be designed with minimum maintenance commitments. The plant, completed in 2014, began producing 1.8 million tons per annum. It would become the world's second-largest single-stream, high-pressure alumina refinery.

Hatch was also involved in the Al Taweelah alumina plant in the United Arab Emirates, commissioned by Emirates Global Aluminum (EGA) in 2013. Prior to the development of this plant, the UAE imported all of its alumina, so this development offered a novel opportunity for the country to become more independent and manufacture an alumina product at a more competitive rate. As part of the project, Hatch leveraged its multidisciplinary skillset to do more than technical design. Hatch facilitated the development of strategies to address both environmental and economic considerations. The feasibility study for the project was again a joint venture with Outotec. Together, the two companies integrated the multi-cell jacketed heater technology into the design for a tube-digestion refinery. This technology, offering the ability to maximize alumina product out of the bauxite ore, provided both cost and energy benefits. Though Hatch's involvement was primarily centered on implementing the patented tube-digestion technology, the company also applied the skills and expertise to produce an operational readiness planning-and-execution solution, using its in-house operational readiness management system (ORMS). Additionally, Hatch was involved in advancing the power plant associated with the refinery, which would provide power and steam. This project, which reached its commissioning phase by March 2019, involved partnerships across the UAE, South Africa, India, and Australia, and is a prime illustration of the global reach and context of Hatch innovation.

By and large, the multi-cell, jacketed pipe heaters tube-digestion technology is another story of opportunistic strategic growth. This technology came into Hatch's possession through the acquisition of Kaiser Engineers. The patents combined with the new talent absorbed from Kaiser helped Hatch obtain new greenfield contracts, specifically the two located in the Middle East. It is a good example of the effectiveness of Hatch's strategy: as the company continued acquisitions, it expanded its areas of expertise and its repository of knowledge, and with that secured more contracts globally. Though the technological innovation was largely developed under the Kaiser name, Hatch contributed to the somewhat more challenging side of the innovation process: the implementation phase. As seen with the Al Taweelah refinery, Hatch initially secured the client's support because of the IP, but was able to add to the success of the project by offering an all-encapsulated solution for the client, which included cost and sustainability assessments, as well as project management support. This project is an excellent example of the Hatch business model at work: the client is attracted to Hatch because of the benefits of the IP; the client then seeks Hatch's related consulting services, as these offer a more seamless integration of the IP into the project as a whole.

IAS Industrial Automation

The growth and evolution of Hatch happened in many stages. The company's first two decades, from about 1955 to 1975, can be considered its "early years," or, to borrow an expression from Gerald Hatch, its "solid foundation" years.[16] During the second phase, from approximately 1975 to 1990, the company added project and construction management to its engineering capacities. One could argue that the third phase began in the 1990s, when Hatch set its sights on globalizing and consolidating its operations. Up to that point, at its core, Hatch was still fundamentally an applied science and engineering company, and built its trust relationships with clients—and through that its growth—based chiefly on its scientific, technological and engineering expertise. From the 1990s to the 2000s, Hatch accelerated this growth, expanding its competencies and its reputation as a global company. In 2008, through a merger with Industrial Automation Services, known as IAS, it added industrial automation to its already formidable repertoire of expertise, as it had the coilbox and tube digestion in previous decades. However, the merger with IAS provides a further insight into Hatch's evolution.

IAS was an engineering consultant firm with offices in Newcastle, New South Wales, Australia; and Pittsburgh, Pennsylvania. The company specialized in computer controls for metal processing. Industrial automation had been born at a time when there was little use of computer controls in the rolling of flat metal products. Although flat rolling technology had been around since the 1940s and most of the theory was well-established, there was no computing capacity to do real-time calculations in the mill. Originally, the computing technology that would go into the design of industrial automation was produced for the aerospace industry. The implementation of any new technology in the aerospace sector is generally slow, as it requires rigorous testing. As more information on computing started to become available, British Steel Corporation and others with interest in the tandem-mill rolling of flat metals, invested in research conducted by the department of computing at Imperial College London. This led to the formation of the Industrial Automation Group in 1970, whose members, working closely with experts at British Steel, embarked on a three-year study on the automation of tandem-rolling mills. The group was led by Greyham Frank Bryant, under whose guidance it developed new sensor and controller technology, new industrial processes, computer methods, and philosophies for the field of control engineering. The knowledge gained from this study was consolidated in 1973 in the textbook *Automation of Tandem Mills*. Over time, the theories found in this text would be adopted in nearly all rolling mills worldwide. [17] Some of the research produced by the Industrial Automation Group was also employed by Australia's BHP. When IAS was formed in the early 1980s, the company approached BHP to request licensing of the rolling technology; it then focussed solely on rolling automation and took the technology global. Progressively, IAS expanded on the theories and application capacities for the technology. As the company grew, computer technologies were also advancing, allowing for improved performance of the IAS system. As the popularity of computer science grew in the 1980s, IAS was able to attract an impressive roster of new talent. One aspect of the work that was particularly attractive to new graduates was the potential for projects to rapidly advance from inception to implementation. For the next two decades, the company continued to use enhanced computing capabilities to expand on the original tandem mill technology that came out of Industrial Automation Group. However, in the 2000s, most concomitant innovations for rolling automation had largely been realized. There were no new sensors to develop; there was little new information to obtain. The technology had peaked, and the company became more focused on simply selling its products. This plateau in the field of innovation affected the company's ability to attract and retain talent in areas such as the aluminum industry.

In 2008, Hatch acquired IAS and its remaining researchers and engineers. Unlike the coilbox or the tube digestion, the technology obtained in the IAS acquisition was already at its peak. However, Hatch recognized that the new IP could

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[16] Hatch, Gerald G. "Chapter 1" in *Hatch: The Art of Innovation*.

[17] Brant, G. F. *Automation of Tandem Mills* (London: Iron and Steel Institute, 1973).

be used to expand the coilbox packages, offering clients the chance to produce a better rolled product with more accurate predictions on rolling behaviour and superior control when it came to achieving the desired material properties. Other than in the context of a new generation of high-strength steels, the IAS technology is quite adaptable for integration with most flat-metal mills. As with IAS, for Hatch, the IP offered a simple revenue-generating stream. The IAS talent, however, could be shifted into other projects in order to facilitate more sophisticated contributions to the company. The former IAS engineers' knowledge of automation and controls could be applied to other areas of the company, where there was a need to convert theory into computer modelling.

HATCH IN THE TWENTY-FIRST CENTURY

From Hatch's founding in the 1950s to the end of the 1980s, the company, under the guidance of its first CEO, Gerald Hatch, established its foundations as an engineering-based consultancy firm. Through the work of talented employees and strong partnerships, the company cultivated its reputation for excellent engineering solutions. During this time, the company was involved in global projects, but it was primarily a Toronto-based firm serving Canadian clients internationally. Moving into the 1990s, the company's new CEO, Ron Nolan, changed course. Expanding on its core competencies, Hatch began acquiring smaller companies that had their own reputations as leaders in their respective areas of expertise. From this point on, into the 2000s, Hatch firmly established itself as a renowned global consulting engineering firm.

Though fundamentally the same core company, Hatch in the twenty-first century continues to expand into new areas, and to face the challenges that go along with this expansion. Overall, the company still operates on the basis of developing IP and licensing that IP to its clients. It uses the information gained from a client's experience, as well as from discussions about the technologies in action exchanged by clients in user forums, to improve the IP and the product before it is offered to another client. The company then offers supporting consulting services, ensuring it is therefore paid not just for its product but also for its expertise and knowledge. Clients, meanwhile, cover the costs of the installation and in-situ testing of the IP and technologies. It may well be this hub-and-spoke approach to technological development that has enabled Hatch to achieve and maintain its success: that is, it is actually being paid for much of the development process, in direct contrast to an operating company that must pay for development.

In recent years, Hatch has shifted its vision to focus on values of environmental sustainability and social responsibility. In the area of consulting services, Hatch has expanded its core services to include digital solutions, operational performance, and capital advisory. The company's recent activities also suggest that its approach to partnerships is adapting, veering toward a more collaborative approach to IP development and ownership.

Hatch in the twenty-first century is characterized by its approach to sustainability and innovation, and the success of this shift is seen in the company's growing size and profitability. The company attributes its achievements to a focus on environmentally sustainable projects and more industry partnerships. Global partnerships have radically changed the company's operations. Where, prior to the mid-2000s, Hatch would typically only have a handful of billion-dollar projects on the go, the company now handles twenty to thirty large projects simultaneously. As in the past, talented human capital supports Hatch's growth. The company encourages its employees to adopt a global mindset; this is also the key quality that Hatch seeks in its employee-shareholders. As a key element of its strategy to build an innovative, creative, and loyal workforce, Hatch attracts new graduates with scholarships and early-career support programs.[18]

John Bianchini, Hatch's current CEO (and a board member since 2003), acknowledges 2008 as a turning point for the company. At a time when others were struggling to stay afloat in the midst of a global recession, Hatch created opportunities to restructure its values and goals. The company recognized that the financial crisis was not the sole challenge it faced, but that its future clients would look for more environmentally sustainable solutions. "Our clients were demanding new skills, new ideas, new products, new services. We've had to rethink our entire business in what we're calling the new era of Hatch," says Bianchini.[19] As part of this shift, the new Hatch advisory services group focuses the company on better community engagement protocols and places greater emphasis on environmental sustainability as part of technological solutions as well as capital-generation for their clients. Under this umbrella, Hatch is expanding its data-science capabilities.

This shift has had no negative effect on the flow of talent, nor has it resulted in major staff turnover. Hatch engages its current employees by rotating them into new leadership roles, while challenging them to adapt to the modernized business framework and remain informed of Hatch's overarching plan. In Hatch's business model, the quality of work that the company provides to clients is firmly based in the quality and engagement of its employees. Attracting the best talent, a practice that has always been part of Hatch's story, has been reinforced by the launch of Hatch advisory

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[18] C. McIntyre, "How Thinking Long-term made Hatch one of Canada's Best Managed Companies," *Canadian Business* (Jan. 3, 2017). [Online]. Available: https://www.canadianbusiness.com/lists-and-rankings/best-managed-companies/hatch/. [Accessed: Dec. 2, 2019].

[19] Ibid.

services. By actively participating in universities through scholarships and project collaborations, Hatch has been able to continuously hire hundreds of new graduates every year. The company also developed a young professionals program that provides career development support to its staff.[20]

As discussed earlier in this chapter, part of the company's shift in the new millennium is to expand its consulting services. For Hatch, this means going beyond purely engineering services and shifting towards a full-service consultancy firm, including into the area of management consulting. This has also signalled a shift in the kind of talent attracted to the firm. While Hatch's core areas of expertise remain mining, metals, energy and infrastructure, the services it provides to these industries stretch beyond purely technical engineering solutions. Hatch's website advertises their "expertise" in sustainable business; urban solutions and smart cities; responsible energy; digital transformations; innovation in mining; water development; and analytics and optimization. As part of the Hatch advisory services, consultants support businesses in areas of mergers and acquisitions, business-case analysis and strategy, market studies, organization design, risk management, capital productivity, and business transformation.[21]

Part of the shift in the company's vision is most certainly due to Hatch's desire to maintain a competitive edge in a market filled with larger professional services firms angling to move into what was Hatch's traditional sector. For example, Deloitte, a company that has generally been known as an accounting services firm, now offers advisory services for mining and metals, energy, and infrastructure. Deloitte's "operational excellence" services for the energy and resource industry overlap significantly with many of Hatch's service offerings, including asset management, risk management, sustainability, operational readiness, and operations technology.[22] Deloitte offers services such as market analysis and price projections in support of business decisions, and technical and economic assessments for mining projects. In the area of mining and metals, Deloitte publishes annual trend reports that provide advice on the top issues affecting the industry.

Hatch and Deloitte's overlap goes beyond their services. Both companies are members of the Canada Mining Innovation Council (CMIC). The involvement of both firms in this council illustrates two realities. First, it confirms that the mining and metals space is no longer what it was in its golden age, from the 1950s to 1980s. Leaders of innovation are no longer the owners of the mines, but rather third-party players: it's these who are shaping the future of the industry. Second, it shows that despite the inherent competition between Hatch and Deloitte in the advisory services sector, there is also a degree of cooperation between the two companies that is directly linked to the demands of the industry. Mining is a global industry; very little innovation can occur in isolation, due in part to the high cost and risk of implementing new technologies or methodologies.

Hatch's story in the twenty-first century is marked by the company's willingness to form partnerships and to collaborate on IP development. This is not necessarily a choice so much as a requirement for a firm to maintain its presence in the industry. Previously, Hatch had been averse to sharing IPs, as it interfered with its client relationships and the sale of consulting services. Today, as a member of CMIC, Hatch serves its clients in complex and extended partnerships. For example, on the Conjugate Anvil-Hammer Mill project a new, energy-efficient technology under development that may replace conventional crushers and semi-autogenous grinding mills, Hatch works with seven other companies. Here, Hatch had to settle on keeping only a share of the IP in the context of the partnership.[23]

There are other cases of Hatch actively participating in programs that require partnerships. Hatch is a member of Canada's Digital Technology Supercluster, a cross-industry collaboration geared towards developing technological innovations aimed at strengthening Canada's competitiveness and resilience in the global economy. The Digital Technology Supercluster is one of five designated by the Federal government as priorities for Canada going forward. The program is relatively new: it was officially launched in 2018. The program is designed to support the development of IP with the expectation that there should be frictionless access to the technology. The program allows for the commercialization and sale of IP, though its intent is to allow for IP partnerships and sharing among all members. Hatch's participation in this specific supercluster demonstrates how the company is modernizing its business. The overhead associated with intangible technologies, such as software, is substantially lower than that of a tangible technology associated with a material asset (such as a furnace or a coilbox). By moving into the digital technology space, Hatch will be able to better accommodate its clients' needs, which will ultimately improve profitability.

Increasing globalization is another challenge Hatch must address in its business model and its strategies for future growth. The broad acquisitions of the 1990s and the early 2000s throughout the industry largely fueled this global movement. Around the same time, Hatch also made strides

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[20] Ibid.

[21] Hatch. "Expertise." [Online]. Available at: https://www.hatch.com/en/Expertise. [Accessed: Dec. 13, 2019].

[22] Deloitte. "Operations Excellence." [Online]. Available at: https://www2.deloitte.com/ca/en/pages/energy-and-resources/articles/operations-excellence.html. [Accessed: Dec. 13, 2019].

[23] CMIC. "CAHM: A Disruptive Grinding Platform Technology." [Online]. Available at: https://cmic-ccim.org/project-list/conjugate-anvil-hammer-mill-cahm/. [Accessed: Dec. 13, 2019]; Stephen Beckermann, Private Communications (Sep. 10, 2019).

to build a stronger presence in China. One of Hatch's early projects in the region was to install the coilbox into Chinese mills and this continues to be a draw for work in China. In the two decades that have elapsed since the initial installation, Hatch has formed a strong relationship with several Chinese state-owned enterprises and holds a national Class A design license, which allows the company to operate on the same level as Chinese-based firms, meaning it may directly provide engineering services to local metallurgical industries. Hatch has engaged in four strategic partnerships with Chinese companies, focusing on resource and infrastructure projects. Most recently, Hatch has formed a joint venture with Zhongshe Baiqi Joint Investment Development Company to address environmental challenges facing China. It currently has offices in Beijing, Shanghai, and Shenyang.[24]

Summary and Conclusions

Through more than sixty years of operation, Hatch has managed to steadily grow and strengthen its presence in an industry that has seen many ups and downs. Evolving under the leadership of Gerry Hatch, from a small infrastructure-based firm of few employees in the late 1950s, the company's core competencies expanded to include mining and metals. Hatch quickly developed a strong reputation for furnace design and organically began gaining more international projects. Following the downturn of the mining industry after the 1980s, Hatch took this opportunity to acquire diminishing research centres that operators had deemed they could no longer afford to maintain. Mergers and acquisitions became the thrust behind the strategy Ron Nolan, Hatch's successor as CEO, adopted to diversify areas of competency and accelerate Hatch's global reach. As the company navigates the twenty-first century, it continues to prioritize building a global enterprise with a new emphasis on environmental sustainability and socially responsible projects.

For the author, there is another, system level lesson suggested by the Hatch experience. In looking at the four Hall of Fame technology cases referenced here, the furnace technology was and continues to be internally developed. The other three cases were technologies acquired from other primary metals companies. The implication is that if Canada does not remain active in primary metallurgy research and development at the producer level, then a purely IP market strategy by itself will be self-limited.

3.3. Mining, Metallurgy and the Environment

Mining and metallurgy, as an industry, has been addressing its environmental impact and footprint for more than fifty years. This chapter presents two windows on those efforts. The first considers the early case of Inco's and Hatch's efforts to deal with SO2-abatement. The second offers an overview of where the industry is situated amid the current discussions and debates regarding ecological health and the circular economy.

SO2-Abatement: An Example of Inco-Hatch Collaboration

A major cause of the high levels of sulphur dioxide emissions in Sudbury were the significant levels of pyrrhotite present in local nickel-copper ore.[25] A high-iron, high-sulphur, low-nickel mineral, pyrrhotite releases large amounts of sulphur dioxide gas when it is smelted. At the start of the various environmental improvement programs, Inco was in a poor position to capture and fix these amounts of sulphur. The existing reverberatory furnaces generated large amounts of SO2, but at low concentrations, unsuited to capture. The Peirce-Smith converters were also large emitters, and the hooding and gas-handling system was unsuited to produce the 10 percent SO2 stream that would have allowed recapture through acid manufacture. These challenges were further exacerbated by the very large amounts of SO2 generated, and the necessity to find a market for the sulphuric acid after capture and fixation.

The following is an account of Inco's sulphur dioxide abatement program of the 1980s and 1990s, and the relationship between Hatch and Inco during this time. The two companies collaborated in their areas of expertise: Inco brought process and operational knowledge, while Hatch contributed the engineering knowledge connected with furnace design and gas handling systems. At times turbulent, the Hatch-Inco relationship nonetheless provided much-needed technological innovation that helped protect the environment and improved the efficiency of operations.

Sudbury and the Origins of the SO2 Programme

Over nearly a century, Sudbury mining and smelting released a total of more than 100 million tonnes of sulphur dioxide into the atmosphere, as well as thousands of tonnes of copper, nickel, and iron particles.[26] This was mostly caused by the massive expansion of the domestic nickel market that

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[24] Rudge, David. Private Communications, (Nov. 1, 2019); "Hatch-Zhongshe joint venture to target environmental challenges in China," *Cision* (Sep 1, 2016). [Online]. Available at: https://www.newswire.ca/news-releases/hatch-zhongshe-joint-venture-to-target-environmental-challenges-in-china-592018311.html [Accessed: Dec. 13, 2019]; "Hatch-Zhongshe joint venture to target environmental challenges in China," *Hatch* (Sep. 1, 2016). [Online]. Available at: https://www.hatch.com/es-CL/About-Us/News-And-Media/2016/09/Hatch-Zhongshe-joint-venture-to-target-environmental-challenges-in-China [Accessed: Dec. 13, 2019].

[25] Bouillon, Dan F. "Developments in Emission Control Technologies/Strategies: A Case Study," in *Restoration and Recovery of an Industrial Region: Progress in Restoring the Smelter-Damaged Landscape near Sudbury, Canada,* edited by John M. Gunn, (Springer-Verlag New York, 1995), 277.

[26] Ibid, 51.

occurred from the 1920s until the 1970s.[27] In 1970, when the work on SO2 abatement started, Inco's Sudbury operations were emitting 2 million tonnes of the gas annually. Sulphur dioxide emissions create the phenomena commonly known as acid rain, which can heavily damage the environment by acidifying lakes to the point that they become unviable for wild life; acidifying soil, thereby destroying or damaging crops and forests; and even causing buildings to deteriorate.[28]

As described previously, following the First World War, the nickel industry took a significant downturn because of the lack of demand, but this dip only lasted for a few years.[29] As world economies boomed in the 1920s, so too did sales of automobiles, and with them the need for the infrastructure required to support them. This, combined with new developments in how to use nickel, such as stainless steel, superalloys, and nickel-iron alloys, gave rise to an extremely lucrative industry. Nickel experienced an almost unbroken boom that lasted roughly from the 1930s to the early 1970s.[30] The market for nickel was so insatiable that by the 1960s, Sudbury's smelting and mining complexes were contributing 4 percent of the world's global emissions.[31] Environmental and political protests demanded actions be taken to curb the pollution.[32]

These calls to action were heightened in the 1960s, 1970s and the 1980s by the growth of the environmental movement, as there was a visible deterioration of the environment and growing public support for environmentalism. Greenpeace, founded in 1971, placed great emphasis on the environmental sciences in education and heightened media attention to environmental issues.[33] In 1972, Sweden brought evidence of the global effects of transnational pollution forward to the United Nations.[34] North American scientists began to collect data on acid rain and emissions from cars, and factories.[35] In 1979, Canada and the United States, along with thirty-two European nations, signed the Convention on Long Range Transboundary Air Pollution (Acid Rain Control), though no standards or penalties were set for not meeting the goals of the convention.[36] Research studies of the time were showing that pollution in North America was mostly regional, with a majority of acid rain and snow impacting southern Ontario and nearby parts of the United States, with pollution from Sudbury being traced, however, as far as Nova Scotia.[37] The issue of transnational pollution was seen as a threat to the Canadian economy as Canadian lakes were being acidified, and along with neighbouring jurisdictions.[38] With tourism at the time making up roughly 8 percent of the Canadian gross domestic product, it became a priority to prevent further damage, mitigate the damage that was already done, and begin recovery, whenever possible.[39]

The Ontario government responded to the increasing awareness of environmental damage by introducing the *Environmental Protection Act* in 1967, which provided a conceptual framework for later legislation dealing with the environment.[40] The province would then go on to impose annual limits on sulphur dioxide emissions, with the first orders detailing those limits issued against Sudbury mining companies in 1969 and 1970.[41] These orders marked the beginning of the provincial sulphur dioxide emissions abatement program. However, Inco's sulphur dioxide program would not be significantly implemented in its Ontario division until the mid-1980s, and at a cost of at least $600 million[42]

These collective actions brought emissions down to 650,000 tonnes annually. However, during this period, it was demonstrated that gas from the superstack was damaging vegetation as far away as Nova Scotia, and acid containing gas from the Midwestern United States was impacting the eastern U.S. and parts of Canada. A growing chorus for change arose about the problems associated with acid rain including cross-border agreements between Canada and the United States. Subsequently, Ontario's Countdown Acid Rain program was legislated, mandating significantly higher rates of sulphur capture, rates unattainable with the existing equipment and processes. Simultaneously, concerns arose about particulate and SO2 levels in both the workplace and the external environment at ground level. Comprehensive studies identified the copper-smelting circuit as a major contributor. On the economic front, in the face of ever-increasing oil prices, energy efficiency was important, and the existing reverberatory furnaces used for smelting nickel were also major consumers of fuel.

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[27] Marcuson, S.W. and C.M. Diaz, "The Changing Canadian Nickel Smelting Landscape," *Canadian Metallurgical Quarterly: The Canadian Journal of of Metallurgy and Materials Science* vol. 46, no. 1, (2007), 38.

[28] Potvin, Raymond, and John Negunsanti, "Declining Industrial Emissions," in in *Restoration and Recovery of an Industrial Region: Progress in Restoring the Smelter-Damaged Landscape near Sudbury, Canada,* edited by John M. Gunn, (Springer-Verlag New York, 1995), 55.

[29] Marcuson and Diaz, "The Changing Canadian Nickel Smelting Landscape," 10.

[30] Ibid, 10.

[31] Potvin and Negunsanti, "Declining Industrial Emissions," 51.

[32] Ibid, 52.

[33] Bouillon, Dan F. "Developments in Emission Control Technologies/ Strategies: A Case Study," 275.

[34] Potvin and Negunsanti, "Declining Industrial Emissions," 54.

[35] Ibid, 55.

[36] Rosencranz, Armin. "The Acid Rain Controversy in Europe and North America: A Political Analysis." *Ambio* 15, No. 1 (1986): 42.

[37] Potvin and Negunsanti, "Declining Industrial Emissions," 55.

[38] Ibid, 55.

[39] Rosencranz. "The Acid Rain Controversy," 47.

[40] Bouillon. "Developments in Emission Control Technologies," 276.

[41] Potvin and Negunsanti, "Declining Industrial Emissions," 52.

[42] Bouillon. "Developments in Emission Control Technologies," 279.

Clearly, a major reworking of the smelting process and equipment was necessary. Inco initiated a multi-year program to identify and study options, and then chose the preferred approach on the basis of environmental outcomes, production, and economic performance. Internal resources in Copper Cliff, Thompson, Sheridan Park and Port Colborne were marshalled for this purpose, as were professors and engineering consulting firms, including Hatch, with whom Inco had an especially close association.

THE INCO-HATCH RELATIONSHIP

In the late 1960s and early 1970s, Inco furnaces at the Thompson operation were showing signs of dangerous wear, stemming from improper planning, design and construction.[43] Hatch was had technical experience in the engineering and design of smelting and furnace technologies. It was a rapidly expanding company and was contracted by Inco to help solve its problems in the Thompson smelter. As the project emerged, not only were the Thompson furnaces appropriately modified, improved ventilation systems were designed and installed on the basis of Hatch's input and expertise.

Shortly after Inco's Indonesia smelter opened in 1977, major problems arose with furnace refractory life. Hatch's expertise, having been enhanced by work on the Falcondo furnaces in the Dominican Republic, was contracted to contribute to an improvement study. By this time (as described more fully in Chapter 3.2: The Hatch Engineering Story), Hatch had developed an early generation of copper coolers that were inserted into the furnace wall to reduce wear caused by slag attack on the brickwork. Once this crisis was dealt with, Hatch and Inco continued to work together on electric furnace operations. This work evolved into a multi-year collaboration on topics as diverse as high-voltage smelting trials (1989), digital power control, faster variable-speed electrodes, covered-arc feeding, new furnace transformers for high-voltage operation, arc stabilization, programmable logic control, and furnace roof design.

It was natural, then, for Hatch to become involved in Inco's efforts toward SO2-abatement for Sudbury in the early 1980s. Inco had originated the concept of a process called roast reduction smelting (RRS), which, in theory, would allow the Copper Cliff operation to meet the proposed standards without the necessity of capturing exhaust gas from the nickel converters, a significant capital cost savings. As well, it offered additional recovery of both nickel and cobalt. Commercial success demanded a high-productivity, high-throughput electric furnace operation, something that did not exist within the company's expertise. Hatch provided the design and consulting advice. Over a two-year period, Inco conducted two major plant tests at a cost of $30 million, employing an existing furnace in Thompson, Manitoba, that was modified on the basis of Hatch's input. Personnel from both organizations worked hand-in-glove. Hatch personnel, most often Bert Wasmund, commuted weekly to Thompson aboard the Inco jet, shared Inco office space, and reviewed operating data on a daily basis in order to make recommendations.

In the main, these commercial tests were successful. However, commercialization at the scale required would necessitate construction and operation of the largest electric furnaces in the world. Capital cost would be significant, and power costs high. Cobalt recoveries would increase, but perhaps not enough to justify the added electricity consumption. Additionally, the roast reduction process did not deal with the workplace and ground-level emissions created by the copper smelting operations. Moreover, operators in Sudbury were unfamiliar with electric furnace operation. Taken together, these factors presented unacceptable risk. The search for alternative approaches continued. Finally, after much study and internal and external reviews, Inco decided to redesign the process flow-sheet around a bulk-smelting process. That is, the nickel and copper minerals would be smelted as one stream, to be separated later in the refining process. While the specific method by which copper would be smelted was unclear, there were enough ideas in development to believe that this was feasible. Since this approach allowed the use of oxygen flash furnaces, a technology developed by Inco in the 1950s and operated for more than thirty years, operators' concerns about new technology were largely allayed. As well, the proposition presented operating cost savings. Again, plant tests confirmed the efficacy of the approach and the decision was made to proceed, with the objective of having new facilities operational by November 1993.

This was a major undertaking. Not only were a number of technology issues to be solved, the project work involved huge amounts of demolition; construction of new steelwork within an operating smelter; plus the supply, delivery and installation of new equipment designed and built to required specifications, all according to a strict timeline. To the surprise of many in both Inco and Hatch—which, on the basis of the two companies' long and close association, had expected to receive the engineering, procurement and construction management (EPCM) contract—Inco instead awarded the EPCM contract to Davy McKee. However, Hatch was not cut out of the project. It would concentrate on elements related to its engineering expertise: the specifics of flash furnace design, including the gas cleaning and handling system; and the design of the copper smelting vessel, also known as the MK reactor. Thus, the Inco-Hatch association was stressed but not broken.

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[43] This section is heavily based on an interview with a group of eight former Hatch and Inco managers that took place on December 2, 2019, at the Galbraith Building at the University of Toronto.

Again, Hatch and Inco personnel worked closely together. John Schofield and others from Hatch worked with the smelter development group on the design of the copper smelting equipment. Hatch and Inco collaborated on pilot-plant tests on gas cleaning options: Hatch and Inco provided design ideas; engineering support came from whichever party was better suited for each particular application; and, with input from Hatch, Inco tested concepts at either the Port Colborne research station or in the Copper Cliff smelter. Information was readily shared between the teams.

While the construction, commissioning and start-up of the first flash furnace was considered a success, during start-up and early operations in 1991 and 1992, many challenges arose both from the novelty of the process design and from glitches in the smelting equipment. For example, these included:

- The refractory in the gas uptake overheated and failed rapidly.
- The quench chamber, designed to rapidly cool furnace exhaust gas, had significant operability problems and had to be reconfigured.
- Heat transfer to the bottom of the furnace was low, and a thick layer of magnetite rapidly formed, limiting furnace capacity. This was unexpected, for the furnace had been designed to cope with excess heat loss through the hearth.
- The furnace water cooling systems in the sidewalls, tap holes and skimming holes required a number of modifications.
- The furnace roof failed prematurely and had to be redesigned.

These issues disrupted operations, limited output, and in some cases presented safety problems, again stressing the Inco-Hatch relationship. However, in the main, it was recognized that the difficulties were largely a product of the unknown aspects of the new equipment and process. Both parties worked together to resolve the problems without excessive discord.

This changed in about 1994, when another engineering company identified what it claimed were significant design deficiencies that threatened the mechanical integrity of the Hatch-designed MK reactor. A three-party meeting was convened, and Inco, accepting the findings of the competing firm's report, elected to take Hatch to court seeking damages. This obviously cast a pall on the longstanding Inco-Hatch practice of cooperation. Copper Cliff personnel were not allowed to consult with Hatch. Sheridan Park personnel were instructed to shun Hatch personnel. This standoff lasted for some months and was eventually settled over lunch by the two CEOs, Mike Sopko of Inco and Ron Nolan of Hatch. Clearly, doing business together gave better results than fighting. Today, Vale Canada and Hatch still work together on many projects, including the nickel refinery in Argentia, Newfoundland and developments at the Voisey's Bay site.

The Outcomes of the SO2 Program

The original program aimed at reducing and stabilizing Sudbury's sulphur dioxide emissions at no more than 265,000 tonnes by 1994. This meant bringing down SO2 emissions to 14 percent of Inco's peak year of 1960, when emissions clocked in at 2.5 million tonnes. Inco's program of using new technologies (such as its new furnaces), reductions in use, and extended shutdowns, proved so successful that 1994 emissions of sulphur dioxide were down to 216,000 tonnes, well below the required limit of 365,000 tonnes. The effect of these reductions was tangible, with evidence since the early 1990s showing that the Sudbury environment has been slowly recovering. Lichens, which are highly susceptible to air pollution and thus serve as a useful monitor of ecological health, began returning in large numbers to the Sudbury area and continued to do so beyond the 1990s. Despite this, some regional soils remain toxic to sensitive plant species and it is difficult to determine what exactly is causing the issues for regrowth. Meanwhile, improvements continued apace: by the completion of the abatement program in 2017, SO2 emissions did not exceed 30,000 tonnes.[44]

In summary, Inco's "Ontario Division Sulphur Dioxide Abatement Program" was immensely successful. Aside from its ten-fold decrease in emissions and studies since the 1990s showing continued improvements in local environmental conditions, the program provided social, environmental and economic innovations that worked for the environment, the people, the communities, and the companies involved. The relationship between Hatch and Inco, while at times turbulent because of competing ideas and interests, was ultimately a source of the program's success, because of the sharing of relevant expertise between the two parties. The relationship provided substantial innovation in energy efficiency, environmental health, and production in the mining and metallurgy industry.

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[44] Potvin and Negunsanti, "Declining Industrial Emissions," 56-57.

PART IV: The Resilience of Mining and Metallurgy

4.1 INTRODUCTION

There are competing views in the Sudbury, Ontario, mining innovation ecosystem regarding the future technological paradigm for mining. These competing views are based, to some degree, on conflicting ideas about the role of physics in the future of mining. The view put forward by Canada's Centre of Excellence in Mining Innovation (CEMI) holds that future exploitation of difficult ore bodies requires deep mining technology, and processes that address two fundamental physical challenges: heat and energy. The competing view is expressed by Penguin Automated Systems Inc. (Penguin ASI) of Sudbury. According to CEO Greg Baiden, "web enabling and battery power won't do it."[1] In Penguin's view, digitized ore bodies, drilling plans and locational technology will be required to enable a new era of precision mining.

The mental model for mining executives seeking to reverse the 2000s' productivity challenge is to use the new digital infrastructures to lift the roof off the mine and run underground operations, like an Industry 4.0 automotive factory. There are, however, serious problems with this model. The production function in Manufacturing 4.0 is to take standardized inputs and convert them into complex and heterogeneous outputs. In mining, Industry 4.0 is inverted—you take complex and heterogeneous inputs (the ore body) and convert them into standardized outputs.

Further, modern extractive industries tend to be dominated by huge global firms. The last commodities boom escalated mergers and acquisitions among already highly concentrated companies. Many of these deals were over-leveraged and based on unrealistic expectations for future commodity markets. Individual units and properties from these ventures are now being dismantled and sold off. However, some small- and medium-sized mining companies in Canada are succeeding while pushing the technology curve forward. These include Dundee Precious Metals (DPM), with its headquarters in Toronto and regional offices and operations (including two gold mines) in Bulgaria; and Anaconda Mining, another gold-mining firm, this one based on Newfoundland.

EXAMPLES OF SMALL- AND MEDIUM-SIZED MINING COMPANIES

Dundee Precious Metals, though a new and relatively small mining company with annual revenues in the order of $400 million, has emerged in recent years as the potential disruptive technology leader in the Canadian mining industry. Ironically, the technical core and management leadership at Dundee came from the Inco robotics group that was abandoned in the mid-2000s. Its mine at Chelopech, Bulgaria is widely viewed as the underground mining robotics leader among currently operating mines around the world. Among the operating companies, it is DPM that leads the story of taking the lid off the mine and running it like an Industry 4.0 auto factory. They bought the mine out of bankruptcy in 2003 and concluded that they had to change the mine design in order to effectively implement robotics.

Anaconda Mining is a small, 165-person, gold-mining firm in Newfoundland, with a further development underway in Nova Scotia. In 2018, it won a Prospectors and Developers Association of Canada award for innovation for its introduction of a new drilling and extraction technology, which was deemed a new mining method offering efficiency gains, and improvements in sustainable mining practices.

4.2 THE SHIFT IN MINING TECHNOLOGY DEVELOPMENT

The early years of the golden age of metallurgy were largely driven by the application of thermodynamic principles to understand and improve metallurgical processes and products. In the latter years, principles of kinetics, heat and mass transfer were employed to increase productivity and yield. In later years, these same principles were applied to address environmental problems associated with the mass production of commodity materials. Driven by environmental and economic forces, engineering expertise was devoted to creating larger equipment, larger mills and larger smelters.

However, going forward, the world of mining may not see a similar transformation. Realistically, the industry will not be able to increase productivity on the basis of scale to

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[1] Personal communication April 26, 2019.

the extent that it did in the past. From the 1960's to 2005 drilling rates increased by thirteen-fold reaching 450 metres per hour. The jack-leg drills of the 1930-1960's and narrow-gauge rail cars gave way to diesel-powered, rubber tired, mobile equipment. To improve productivity equipment size was gradually increased. An early 1960s mining truck could carry 27 tonnes (30 tons); today, the largest truck can carry more than 450 tonnes (nearly 500 tons). But clearly, the opportunity to improve productivity by simply increasing scale faces diminishing and possibly negative returns—larger equipment requires larger ore passes and drifts which means mining more valueless rock.

TELE-OPERATIONS

The work to operate mining equipment remotely, pioneered by Inco, proposed productivity increases with a different paradigm—tele-operation would reduce or eliminate the production downtime associated with shift-change and the necessity to move operators to the mine face; tele-operation would enable one operator to control multiple pieces of equipment and tele-operation would remove workers from hazardous locations improving safety. Driverless trucks would perform the routine task of ore haulage while people-directed equipment would conduct the high-value drill-blast cycles. Initial pilot testing of a tele-operated LHD (load haul dump) system at Inco demonstrated that from a remote operations center, a single operator could tele-operate three LHDs, allowing for twenty-three hours of continuous operation within a twenty-four-hour period. This compared favourably against the norm under manual operation, of fifteen hours of productive activity. While the effort at Inco was ultimately abandoned, the productivity model it created has continued, matured, and outlines the future pathway for major productivity improvements in the mining operations.

These pioneering, leading-edge technology efforts also received government support through the Precarn program (see the box describing Precarn). Combined with technology maturation and twenty-first-century globalization trends, the long-term result has been revolutionary shift in the prospects for underground mining and value creation. Yet today, there is no federally-sponsored mining supercluster. The mining application was turned down for reasons that have not been disclosed.

CASE STUDY: PUBLIC SUPPORT FOR MINING INNOVATION — THE STORY OF PRECARN

In late 1990s and early 2000s, Canadian industry and academia were leaders in R&D related to tele-operated mining with the support of Precarn, an industry consortium designed to translate advanced research in robotics and intelligent systems into practical use. In 1998, Inco articulated a vision for automated mining whereby from any location in the world, a teleoperator can instruct intelligent, automated mining equipment to execute their missions.[2] If the equipment encounters an unexpected situation beyond its ability to manage, it will ask for help. The teleoperator will respond immediately to these requests for help from a wide range of intelligent, automated mining equipment. With the support of Precarn, Inco—along with technology providers and academic partners—pursued a series of technology development projects to automate various types of mining vehicles and operations in order to improve productivity.

Precarn supported industry-university collaboration related to human-machine interaction for heavy equipment, leading to the spin-off of Motion Metrics International from the University of British Columbia in 2000. Today, Motion Metrics continues to develop machine vision and sensor systems directed toward improving safety, efficiency, and productivity in mining.

During this period, there were also research chairs at Canadian universities focused on mining automation, including the NSERC/Noranda chair in mining automation at École Polytechnique de Montréal and a Canada Research Chair (CRC) in robotics and mine automation at Laurentian University. Penguin ASI, a technology company based near Sudbury, Ontario, that develops automation technologies, is a spin-off from the work of the CRC at Laurentian.

Despite a strong start, the mining industry generally shied away from long term participation in Precarn. This lack of robust participation was related to three factors. First, market pressure on the companies from the fall in commodity prices was such that they were not able to commit to future rounds of funding. Secondly, there was a loss of Canadian ownership in several of the operating companies, such that the Precarn model was not as applicable. Finally, a slow culture of adoption in the mining industry made financial commitments for pre-commercial technology elusive.[3]

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[2] Canadian Mining Journal Dec 2001

[3] The following account is based on personal communications with two Precarn former Board members.

Precarn did achieve one significant success. It brought together people and companies, ultimately forming a network of knowledge-sharing and R&D across the country. For example, an active computer division was formed at the University of British Columbia, built around work by Institute for Robotics and Intelligence Systems (IRIS) researcher Alan Mackworth, which led to the development of 3-D camera systems and the formation of Point Grey Research, a company subsequently acquired by Oregon-based FLIR Systems. Another group formed around IRIS researcher Peter Lawrence, who worked on developing computer vision technology for shovels used in oil sands production in Alberta. With the support of Precarn, members of Lawrence's group involved in the Syncrude project formed Motion Metrics. Another IRIS researcher, Greg Dudek at McGill University, was active in marine robotics and is, at the time of writing, director for the Canadian Field Robotics Network.

Through IRIS, Precarn was active in keeping talent within Canada. For example, Geoff Hinton, a professor at the University of Toronto, also involved with the Canadian Institute for Advanced Research (CIFAR), a global charitable organization, was active in the IRIS Network Centre of Excellence. He was ultimately central to the creation of the Vector Institute for Artificial Intelligence at the Toronto General Hospital, and was instrumental in Google's decision to locate a research presence in Toronto.

Precarn established a research management committee to conduct project-proposal evaluation and make recommendations for project funding to its board of directors. While Precarn was not in the technology transfer business, it had close contact with university technology transfer offices through its academic member institutions within the extensive IRIS NCE network, which included virtually all Canadian universities that had research ongoing in robotics and intelligent systems.

During this time, Precarn regularly employed the "valley of death" motif—this alludes to the period of negative cash flow a company must weather between creating a product and reaping the monetary rewards through sales—to characterize the innovation challenges for SMEs trying to bring new technologies to the marketplace. The organization saw its role in helping to bridge this gap.

4.3 DIGITIZATION OF MINING OPERATIONS

In its prediction of the top trends for 2017 for the mining industry, Deloitte rated the digital revolution among the top catalysts with the potential to transform the industry.[4] Thus, the mental model for mining executives seeking to reverse the productivity challenge of the last decade is to use the new digital infrastructures to lift the roof off the mine and run underground operations, like a Manufacturing 4.0 automotive factory, i.e. Mining 4.0. While there are many social and economic factors associated with Mining 4.0, operationally the goal, is the digitalization of mining, implementing the Internet of Things (IoT) creating fully automated mines and connecting these with technologically sophisticated ore processing facilities. The fundamental challenge is to build integrated process-control systems across the mine-mill value chain capable of improving plant-wide efficiency and productivity. To be successful it must cope with variable inputs and ever-changing operating conditions, in-exact understanding of fundamentals, and different requirements of the component processes. Moreover, the digitalization of mining needs to be implemented all the way from the mine to the final product, through smelters and refinery. The process is complicated and manifold.

Up to the present, the leading mining robotics applications have been based on the automotive industry, and hinged on a traditional industrial robot approach. However, in auto plants robots function in relatively static physical environments operating from fixed positions buttressed by massive digital infrastructures. By contrast, a mine is a constantly changing production environment; robots must be able to move and operate within this dynamic environment. While today most mining automation systems control systems control fixed plant equipment such as pumps, fans and other individual pieces of equipment, the key challenge going forward is to create the mobile equivalent of the manufacturing assembly line for mining with the goals of speeding up production, improving worker safety, and reducing capital and operating costs

Advanced, high-capacity, mobile computing and communications networks are a foundation of tele-mining, enabling the future underground mine to be run remotely from operation centres on the surface and enabling the IoT. Since neither conventional GPS nor Wi-Fi work in underground mines alternative communication methods solutions which provide the communication bandwidth needed to support activities as mobile personal

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[4] Gosine, R. and P. Warrian. "Digitalizing Extractive Industries: The State-of-the-Art to the Art-of-the-Possible. Assessing Opportunities and Challenges for Canada." (Innovation Policy Lab, University of Toronto, November 2017).

computing and communication, equipment-to-equipment communication, and video feeds to surface operations centres are necessary. Some of these approaches have been and are being developed.

MINING 4.0

Mining 4.0 goes beyond automation and communication. Scenarios put forward by Lööw, Abrahamsson, and Johansson[5] envision miners employing exoskeletons for increased strength, augmented reality glasses to receive and send data, including video, virtual reality training for workers to prepare them for realistic emergency situations; and sensors that monitor the health and location of miners, especially in case of a collapse. Mining 4.0 envisions the use of personal AI systems to manage work efficiently; the use of robots to perform repetitive tasks, and the use of big data to assist in all the aspects of mining, from excavation to ore processing. In principle, this technology could also place the entire control and production rooms for a mine operation in virtual space. It could also enable a decentralization of the many workings of a mining corporation, by having an AI assistant help fix equipment, with its control operator on a different continent. In these scenarios, only a relatively small group of miners may need to be in place physically at the mine site.

The challenges facing Mining 4.0 in mineral processing plants are different from other industries. In these other industries, automation aims to improve process control, metals recovery and accounting and production management. While mineral processing is not subject to the same sort of difficult operating environment as is found in mining, and there are greater similarities with other types of production lines, there are also significant challenges in terms of adoption of advanced process-control technologies. The chemistry and physics of the sub-processes at the heart of mineral processing are, to this day, not fully understood, making it challenging to develop accurate process models. Furthermore, variability in ore composition—that is, the lack of standardized input—does not fully align with the production function in Industry 4.0.

In mineral-processing operations, the objective of the grinding and flotation processes is to prepare a concentrate of the target minerals at the requisite grade and recovery, both of which may be dependent on transient economics. In the grinding process, the objective is to achieve an ore size that optimizes the mineral extraction from flotation or leaching processes. Too fine a grind is associated with excessive energy consumption, reduced throughput, premature wear of equipment and added costs; insufficient grinding reduces the recovery. Grinding is an energy-inefficient process that can account for 25 percent of production costs. Direct (such as mass and volume flow rates, power consumption, rotation speed) and indirect (such as acoustic, computer-vision, power frequency analysis) measurements are used to tune the process. The flotation process aerates and agitates an ore slurry of ore to contact the valuable minerals with bubbles recovering these at the slurry surface of the slurry for recovery in a smelting facility. The flotation process is tuned in response to ore properties, feed rate, energy consumption, reagent costs and metal market price, to achieve a trade-off between the concentrate and tonnage, the impurity contents of the produced metal and the production cost. While conventional control approaches, including proportional-integral, feedforward, and multi-variable, have been used for flotation process, as grades of ore decrease and the complexity of ores increase, there is a need for more sophisticated process-control approaches. These could be founded on advanced digital technologies, such as automated computer-vision systems and more modern, data-driven control techniques.

However, the potential implementation of such technology may give rise to conflict and criticism: would Mining 4.0 technologies be developed to be used by humans, or would they be used to reduce the number of employees needed, so as to increase profitability? The tension around such questions could leave Mining 4.0 at risk of creating more social problems than it attempts to solve. If the technical knowledge required is not transferred to the existing workforce because of cost, or due to difficulty encountered by training users on new digital systems, many workers will themselves become obsolete and will be need replacing. In spatial justice terms, a control room located in a large urban setting could generate hardship or even socio-economic collapse in distant, vulnerable rural towns. The interface between the mine, mill and smelter will remain critical, along with geo-metallurgy in determining the value of the material at a particular part of the mine. For local employment impacts, the critical factor will be where the concentrate will be processed.

As noted by multiple authors, Kaasinen et al, Lööw et al, and Roldan et al,[6] a prominent impact of Mining 4.0 will be the issue of knowledge transformation. Kaasinen et al. argues for the need of easy knowledge sharing, as this will be critical for a fair and equitable transition to a new economic paradigm. There needs to be understanding of the different technical skills workers may have or be able to learn. Currently, working environments are relatively static,

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[5] Kaasinen, E. et al. "Empowering and Engaging Industrial Workers with Operator 4.0 Solutions." *Computers and Industrial Engineering* (January 30, 2019): 1-13; Roldán, J. et al. "A Training System for Industry 4.0 Operators in Complex Assemblies based on Virtual Reality and Process Mining." *Robotics and Computer-Integrated Manufacturing* 59 (October 2019): 305-316.

[6] Kaasinen, E. et al. "Empowering and Engaging Industrial Workers with Operator 4.0 Solutions." *Computers and Industrial Engineering* (January 30, 2019): 1-13; Roldán, J. et al. "A Training System for Industry 4.0 Operators in Complex Assemblies based on Virtual Reality and Process Mining." *Robotics and Computer-Integrated Manufacturing* 59 (October 2019): 305-316.

physically orientated and have changed little over time, whereas in the future, with its focus on data analytics, the work environment will be uncertain and require flexible problem solving skills. Roldan et al[7] present an excellent example of the type of product that could contribute to a smoother economic transition; that is, through the development of a virtual software training system for Operator 4.0.[8] The risk here is that the workforce would be partitioned between the very highly skilled and others, those left with legacy skillsets, or even those who are deskilled as the technology rapidly advances and requires more and more specialized knowledge. The shift from craft or trade skills to technical and digital skills is fraught. New demands for teamwork and understandings of production flow accompany a transition from process-dependent to process-independent systems.

These issues could open up new economic opportunities for external companies, such as consulting firms, or for the mining company itself, in the creation of training software that can consistently be updated to reflect the new skills required. The focus for new employees will be their ability to engage with data analytics, coding and programming. A useful comparison can be found in a different transition already experienced in the industry: when processes in the past were automated, it was usually the former manual operator who became the operator of the new system. While this shift was possible because the manual operator had a fundamental understanding of the technology and the industrial processes and environment surrounding it, this might not be the case with the rapid system changes proposed.

4.4 Digital Technology Trajectories

The mining industry currently has three different digital technology trajectories. Within the operating companies, there is relatively little internal innovation directly dedicated to digitization. Most operating companies depend on equipment vendors and other supply chain providers for this. Digitalization among operating companies, to the extent that it exists, is led by precious metal producers. For the purposes of this study however, gold mining is generally considered part of the financial economy, not the industrial economy with no significant linkages between mining, materials science and advanced manufacturing. As the decline of Canadian metallurgy continues, an important gap in realizing the full potential of new technologies in advanced manufacturing will remain.

Mining equipment providers, like car manufacturers, remain captive to their existing product design platforms. There is no great advance to be made by simply web-enabling existing electro-mechanical robotics equipment used in conventional bulk mining operations. The next generation of deep mining, with precision drilling linked to digitalization of ore bodies, will require different kinds of innovative mining technologies. Regional supply chain clusters, as in Sudbury, are experimenting with these developments, but these are mostly small- and mid-sized enterprises (SMEs) with constrained technical and financial resources.

The most advanced digitalization technologies are being developed and applied in the exploration and development for the precious metals segment of the mining industry, as evidenced by recent presentations at the 2019 PDAC (Prospectors and Developers Association of Canada) conference. While in this part of the mining sector Canada remains a global leader, beyond exploration, there is relatively little downstream digital innovation impact on mine operations and manufacturing. Linking the digital technologies in mining to the broader economic linkages of advanced manufacturing remains a challenging gap in the Canadian economy.

Case Study: Digital Technology and Big Data in Exploration — Geophysics and Geodata

The forces of globalization and de-verticalization have been highlighted by Timothy Sturgeon and Richard Florida with regards to their effect on the auto industry in their 2004 paper Globalization, Deverticalization, and Employment in the Motor Vehicle Industry.[9] The mining industry has similarly been impacted by these forces, and, in response, has been re-organizing itself towards a lean production model, which itself clearly distinguishes between senior producers and junior exploration companies. While large senior producers focus on enhancing internal efficiencies and reducing risk in production, their efforts in exploration are predominantly focused on brownfield exploration and, increasingly, on indicated and inferred resources. There is an old adage in the gold-mining industry that the best place to find a new gold mine is beside an old gold mine. Exploration in the shadow of a headframe currently commands the majority of the exploration budget of senior producers. By comparison, junior exploration companies engage in the high-risk activity of greenfield exploration. It is these exploration companies, which fundamentally lack the capacity to remove the risk from exploration, that stand to benefit the most from the provision of geophysical data and that are most likely to drive innovation in the research and development of new mining projects. Such exploration companies stand to benefit from our evolving understanding of how and where mineralization occurs, and by what means ore bodies come to be deposited within these bands of mineralization.

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[7] Ibid.

[8] Ibid.

[9] Sturgeon, T. and R. Florida. "Globalization, Deverticalization, and Employment in the Motor Vehicle Industry," in *Locating Global Advantage: Industry Dynamics in the International Economy*, edited by Martin Kenney (California: Stanford University Press, 2004).

Geoscience conducted independently of industry competition, often by government-led scientific bodies, is a key component to de-risking exploration, and increasing informed decision making in greenfield exploration. It has been reported that precompetitive geoscience programs typically achieve a twenty-to-one leverage on investment. Australia's support for precompetitive geoscience is among the primary explanations for its outperformance globally on the value-to-spend ratio with regards to mining exploration, as well as its relative outperformance on both the number of discoveries and a value of those discoveries in relation to the cost of finding them. Consider the following excerpt from Dr. J.M. Duke in his presentation to the PDAC geosciences committee in 2010.[10]

If exploration were merely a lottery, the only way to ensure success would be to investigate a very large number of prospects. The number of targets that must be tested to be reasonably assured of at least one economic discovery. Mackenzie (1989), using a similar formulation, concluded that in order to have a 90 percent probability of discovering at least one economic deposit, a company would have to have to spend 2.3 times the average discovery cost. This has important implications for the economics of exploration. With discovery costs on the order of $100 million, a company requires very deep pockets to be assured of success.

Contrary to Adam Smith's analogy though, mineral exploration is not merely a lottery. Australia's investment in precompetitive public geoscience is designed to shift the odds more in favour of exploration firms. Through the publication of publicly available geoscience, including heat mapping of information like total magnetic intensity, gravity anomaly and radio metrics, Australia's geophysics database provides exploration companies with salient insight about where to target their exploration programs. The probability of successful mineral exploration is ultimately the result of three unique probabilities multiplied together. For exploration to be successful, a mineral deposit must actually be present in the area being explored, the exploration company must actually strike the deposit, and the deposit must be valuable enough to be worth extracting. The comparative advantage of public precompetitive geophysics data is that it inherently improves an exploration firm's ability to de-risk these probabilities. Exploration firms can not only target exploration in areas with high potential for containing a deposit, but also have the ability to be selective about locations more likely to contain economically viable deposits. With more confidence in the presence of mineralization indicators, exploration firms can drill more intensively in a concentrated area, increasing the likelihood of striking an ore body.

Writing a 2010 article for *Geoscience Canada*, the quarterly technical journal published by the Geological Association of Canada, Blyth Robertson summarized a number of findings about the value of geoscience data and attempts to quantify the impact government support. For every dollar the government invested in geoscience, five dollars would be stimulated in private-sector exploration expenditure. What's more, as a result of the enhanced exploration activity, $125 million of in-situ value would be discovered for every $1 million invested in public geoscience. In fact, just increasing the geoscience map resolution in the already mature mining district of Baffin Island Nunavut had an eight-to-one impact on private expenditure, versus the cost of the mapping program.

In Chile, calculations on the direct economic return to the government from the provision of public geoscience information showed a net present value of $11.50 for every dollar spent, and an internal rate of return of 21 percent. All of these quantifiable impacts are evidence that public geoscientific research often plays a critical role in attracting exploration to relatively unexplored regions, as well as increasing activity in mature jurisdictions.

Production and provision of publicly available geoscience data de-risks exploration projects by highlighting areas of high mineralization potential. In combination with incentives for new exploration techniques and the use of models and theories that can be applied in new areas, more activity can be stimulated with regards to both process and product innovation based on the production, dissemination and interpretation of the geoscience data itself. The adoption and adaptation of satellite imagery, developed for other industry sectors, can be used to provide exploration heat maps. The development of aerial geophysics instrumentation, as well as software to interpret and model the data, are examples of innovations that directly support the provision of public geoscience. New types of exploration drilling rigs that are designed to drill deeper, faster, and at a lower cost will allow both mineral exploration companies, as well as government geoscience programs, to perform better geoscience below the surface, and detect potential mineralization at depths that are currently too expensive to map with traditional drilling methods, and too deep to assess using conventional aerial surveys.

While some consider asteroid mining as the final frontier for the mining industry, it's actually through the provision of public geoscience for exploration target identification and subsurface geochemistry that industry is poised to make its greatest innovations to date, and push the boundaries of both physical- and knowledge-capabilities. The provision of public geoscience offers the exploration industry opportunities to make new discoveries in areas that may have previously been overlooked, discounted or deemed too risky. The application

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[10] Duke, J. "Government Geoscience to Support Mineral Exploration: Public Policy Rationale and Impact" (prepared for The Prospectors and Developers Association of Canada, March 2010).

of existing technology to the mapping of new mining areas is an example of a process innovation that, when applied at scale, can significantly increase exploration activity

The National Research Council of Canada (NRC), along with NSERC, want to implement and integrate quantum technology into the mining industry, as they argue it will boost Canada's global position in science and technology. Mining companies want to use quantum technology to improve the efficiency and effectiveness of exploration and development, optimize their operations, reduce their environmental footprint and reduce the long-term liabilities of mining and closure costs. They want to use quantum sensors to efficiently find and characterize ore deposits, which requires improved measurements at greater depths, fewer boreholes and more accurate, real-time data analysis. Quantum magnetic sensors can be used for driverless vehicles to improve navigation and enable continuous operations, while geophotonics can be used for real-time feedback in mineralogy processes. Lastly, these sensors could also be used for monitoring excavation sites, and to advance rock mechanics. They can detect underground gravity differences, identification of which can provide composition data during exploration. This data can then be used to help reduce the use of water, energy and land through effective management. The data collected would then be analyzed by either quantum computers or, at the least, upgraded computers to handle the amount of data and provide holistic data structures around planning, operating and closing a mine, providing multiple perspectives on factors such as energy production, waste removal, water use, employee health and safety, and environmental impacts.

As noted in the 2017 Mining Industry Engagement Workshop Summary, by NRC and NSERC, quantum (or upgraded) computers could collect and use data to optimize mine planning, and efficiently monitor remote operations and automation. This is in addition to improved analysis of chemical and mineral-metal composition, continuous core scanning, and the monitoring of resources such as water, to support a circular economic model. Holistic data structures, where as much data as possible is gathered, interpreted and calculated, would help the mining industry meet the twin goals of a reduced carbon footprint and more efficient operations. Access to enhanced characterization of existing tailings, continuous monitoring of waste water effluents and slope and structure stability, and the improved accuracy of predictive modeling for rehabilitation and reclamation scenarios, would also reduce long-term liabilities and closure costs for mining corporations.

4.5 DIGITIZATION AND LABOUR MANAGEMENT RELATIONS

Questions of technology and change must always be understood within their social context. The realization of social benefits such as health-and-safety improvements in mining technology, through such things as the early developments in robotics and automation, were both encouraged and limited by the socio-technical systems at Inco. This included forms of industrial relations as well as the incentive systems for workers and supervisors. Indeed, the technology changes in underground mining operations often threatened the economic rewards ("bonuses") for both miners and supervisors, and were therefore resisted, even though they would have improved safety and environmental conditions if they were fully implemented.[11]

INDUSTRIAL ORGANIZATION

According to Chaykowski, from the standpoint of industrial organization, the mining technology advances through three stages.

Stage 1: Industrial Engineering

Chaykowski argues that this stage:

> corresponding to that of "industrial engineering," has been associated with the period from the early-1900s through the early 1980s. [T]his stage was characterized by advances that yielded process time and quality improvements. Organizational structures were hierarchical and technology defined jobs narrowly, limiting employee discretion. The labor relations system was adversarial with clear lines of demarcation between the roles of management and the union and employees. Of course, new organizational structures and forms of work organization emerged as the technological development proceeded. The movement from the industrial engineering stage on to more advanced stages is along a continuum and, in fact, overlaps later stages of technological development.

Stage 2: Remote-Controlled Mining

The period of industrial engineering was followed by the advent of computer-controlled systems, and led to the second major stage by the early 1980s, with the rise of two breakthrough technologies: remote-controlled mining

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[11] Chaykowski, R. "Re-Inventing Production Systems and Industrial Relations: Technology-Driven Transformation in the Canadian Metal-Mining Industry." *Journal of Labor Research*, XXIII: 4 (Fall 2002). Unless identified in a footnote, all quotes in this section are from Chaykowski's paper.

and multiple teleoperation. This second stage remains in something of a transitional period, and will continue to until R&D and engineering advance to a point that supports a "take-off" into the third stage, expected in the coming decades of the twenty-first century.

According to Chaykowski, the second stage of technological advancement in which, he argued, the mining sector was at the time he wrote the article, brought important changes in work organization and industrial relations. Potentially the vast majority of workers could be displaced by the new technologies. The core skilled operators would run the equipment for drilling, loading, hauling, and dumping from a control centre at the surface of the mine, eliminating the underground work force and their supervisors. These operators would work together cooperatively to solve problems and to achieve continuous improvement. This cooperation is facilitated by interaction with engineers who are engaged in R&D and in the implementation, with mine-site employees, of new technologies into the mine. For employees, pay remains a central concern. Health-and-safety of employees are greatly improved, but pay is still a central concern. New issues, such as ergonomics have emerged. In this environment, as well, concerns over who and how contributes to decision making takes priority. The above-mentioned changes are a significant departure from the more traditional work organization and industrial relations in the mining sector.

Stage 3: Automated and Self-Deploying Systems

Here is how Chaykowski describes the next stage:

> The period of development of technologies that have enabled remote-controlled mining and teleoperation may be viewed as establishing the foundation for the eventual third stage of technological advancement, which is the development of fully automated and self-deploying mining systems. According to industry leaders, autonomous mine-operating equipment such as surface haulage trucks, load-haul dump trucks, surface drills, and shovels are all anticipated developments by 2005.

Much of the technology in this stage relates primarily to mine operations, its diffusion reaches "up to the surface" to create a fully automated mining "factory," that is, one encompassing the whole process, from start to finish: extraction, milling, smelting, and refining. To quote Chaykowski:

> This stage represents a quantum leap in technology, engineering, organizational structures, the concept of work, and the nature of labor relations. These emergent communications, computer, and robotic technologies, applied widely, have the potential to fundamentally transform production systems as well as the accompanying work organization and industrial relations systems in the industry. Highly skilled engineers would work alongside relatively few very highly skilled and educated operators, who would be supported in the work sites by maintenance teams. Just as the production functions between production segments become more seamless, so too would employee functions become increasingly integrated, requiring very few job types, broader teamwork, the elimination of any conventional line supervision requirements, and complete information sharing throughout the operations. The number of employees in the "mine factory" could be no greater than in a small manufacturing plant, with employees hired from the external labor market. The self- management required to operate this mode of production is the antithesis of traditional job-control unionism.

INCO STRIKE (1982-1983)

As discussed earlier, awareness of these factors led Inco in the late 1980s to adopt a strategy of developing advanced production technologies throughout all three stages of the mining, smelting and refining segments. The objectives were to lower labour costs, increase productivity and safety, improve product quality, and create new high-value-added applications for its products in the manufacturing and consumer markets. However, this business strategy also became the central issue in the Inco strike of 1982–83.

The strike nearly resulted in the collapse of both the firm and the union. It created the impetus for a change in the tenor of labour relations and the adoption of more cooperative approaches. Even so, the basic characteristics of labour-management relations and collective bargaining have remained "traditional." Work organization and rules, organizational structures and job content all continued to develop along traditional management philosophy and norms associated with the prevailing mass-production technologies; the union-management relationship was adversarial and arms-length, with the "spheres" of management and the union each clearly defined; and collective bargaining focused on wage increases, job security, health and safety, and regulating the workplace.

As Chaykowski summarized the prolonged period of labour-management confrontation:

> The employment and organizational impacts of Inco's technology strategy were particularly relevant to the state of unionism and to the company's conduct relating to labour relations. Total employment at lnco declined from a peak of just under 40,000 in the late 1970s to around 10,000 in 2000. Aside from fluctuations in output attributable to changes in demand during business cycles, output has remained in the range of 15 million short tonnes. The change in organizational structure is illustrated by the

substantial reduction in job types and the shift in employment away from lower-skilled (and lower-paid) employment toward high-skill employment. Union responses to this evolution were entirely within the "traditional framework:" an emphasis on easing the impact of ongoing employment reductions, obtaining increases in wages as productivity increased, and attempting to develop more cooperative approaches to managing the workplace change process, such as by establishing a broader range of joint committees). Union attempts to mitigate the impacts of technological change through collective bargaining illustrate the traditional approach to these issues. Each bargaining unit includes employees across all of the facilities at Sudbury and Thompson, respectively, including multiple mines, milling, smelting and refining operations. Both of these contracts include provision for advanced layoff notice (60 days) and for the formation of a joint union-management technological change committee that is mandated to consider the impacts of proposed technological changes and to make nonbinding recommendations. Both contracts also include provision for severance pay in the event of a layoff, and pay protection and opportunities for retraining when employees are dislocated from their current jobs.

Management therefore retains full decision-making authority regarding matters relating to technological change. The contract clauses are designed to alleviate the detrimental effects of technological changes as they are imposed on employees, but they neither limit managerial authority nor provide for substantive union or employee input into technological change at either the workplace or at strategic levels of the organization. Taken together, though, these types of technology-driven organizational outcomes and union responses have been observed in many firms that underwent significant restructuring during the 1980s and 1990s. What is different in this case was Inco's strategic choice to not just emphasize technology throughout its operating segments, but to extend this capability to include the development and application of breakthrough technologies in the mining segment—arguably the most challenging. Inco's mining technology strategy has centered on the development of remote-controlled and, subsequently, fully automated mining systems as steps toward the development and creation of a "mine factory."

The magnitude of the potential operational efficiency gains from remote-controlled mining and multiple teleoperation have been apparent at Inco's Stobie mine facility in Sudbury. This mine became the centerpiece of the company's mining robotics program. Automated mining methods dramatically decrease the usage of all inputs, especially labour, while substantially increasing output. However, Stobie Mine is now closed, after functioning on "life support: for at least 10 years.

Prior to World War II, mining productivity at Inco averaged roughly 907 tonnes (1,000 tons) per person-year. With the advent of industrial engineering on a broader scale, productivity increased in the decades between 1940 and 1980 to around 1,814 tonnes (2,000 tons) per person-year. With the movement to the remote-controlled and multiple-teleoperation stage of technological advancement, Inco was able to take a leap in productivity: by the 1990s, it had achieved around 3,175 tonnes (3,500 tons) per person-year, with the expectation of doubling that level to around 6,350 tonnes (7,000 tons) per person-year by 2020.

The realized benefits from early digitalization efforts in mining include increased productivity due to improved capital utilization (e.g., the ability for mine operators to operate several systems simultaneously); longer equipment operating cycles; reduced equipment downtime associated with employee rest periods or workplace accidents; improved efficiency of maintenance schedules; lower maintenance costs because of the consistency of operating methods; improved monitoring and response; lower energy costs; reduced labour costs through significantly lower staffing requirements; increased employee health and safety, resulting in lower workers' compensation costs; and increased employee training, productivity, and pay levels.

Early digitalization initiatives at Inco also substantially altered work organization and methods including increasing skill requirements; altering work methods through job enlargement; altering work schedules; and creating pressures to alter compensation methods and to address new health concerns. For example, the increase in productivity arising from automated mining methods has occurred alongside the enlargement of operator job responsibilities; but operators' pay was not raised under the normal "bonus" incentive system available to manual drillers. This anomalous situation established a risk of low morale among operators, and led to a suggestion from operators to establish a productivity gainsharing plan known as "drillshare."

In contrast, the overall union response did not represent a significant departure from its traditional and ongoing approach. This is most likely because, up to the end of the 1990s, the application of remote-controlled mining methods had been somewhat limited—even across mining operations. In fact, the broader application of such technologies has still not reached the point where an integrated "mining factory" (or "complex factory" that includes the smelting and refining) has been established. Therefore, the potential pressures arising from the achievement of "breakthrough technologies" have not yet fully impacted the organization. Inco's technology program may be best characterized as firmly situated within the second stage of development and poised for a "take-off" to the next level. When substantial components of the "mine factory" concept are implemented in the future, production employment levels will plummet.

Given current levels of digitalization in underground mines, the main requirement for underground employees is in the repair and maintenance functions. Even there, staffing requirements have been very significantly reduced from the levels needed in the 1980s. Employee skills are higher, and the operating and maintenance functions require exercising much greater discretion. The conventional concept of employee supervision no longer applies, and the organizational hierarchy, already flattened as a result of the application of advances in industrial engineering, merges into a single layer of employees performing a mix of functions. The result is a blurring of managerial and employee roles. While management remains an organizational feature, employee and management interests are increasingly aligned.

With the prospective qualitative change in technology and productivity pending, we do not want to repeat the mistakes of the past.

PART V: Estimating and Realizing the Benefits

5.1 ESTIMATING AND REALIZING THE BENEFITS

Since mining is an industry with an extraordinary high level of uncertainty, the social, economic and business benefits of mining can only be realized by taking risks. It is critical therefore to consider the risk models that mining companies employ to assess project viability.

RISK MODELS, MINING AND INNOVATION

The most popular approach to model mining projects is discounted cash flow (DCF) analysis, which calculates the net current value of the future revenues and expenditures in a project, taking the time value of money and other risks into consideration.

Recent research has begun to examine alternatives to this widely used DCF approach, particularly in the era of digitization.[1] The distinction between product and process innovation is widely discussed and understood across many industries. The unique situation in mining and other extractive industries is that end products, and the methods of producing those end products, are inextricably bound together in unique ways. This means that the mining industry is not able to produce a 'new' product innovation in any way that the term is understood in electronics or automotive manufacturing. Consequently, for miners or mine equipment suppliers, the objective is usually to make incremental improvements in task-oriented processes at the mine complex, as contrasted to broader process innovations that may affect the context in which mining companies operate.

A fundamental reference point in natural resource economics is the "Hoteling Rule," which was defined in 1931. It states that all else being equal, a mining company will schedule production from the most profitable lots in a given operational site to the least profitable. Even if the *in-situ* value were constant across all blocks, the marginal cost will increase such that two blocks of equal grade and similar geophysical and geochemical properties will have different cost structures at different depths. This inherent decline in resource quality input and efficiency of extraction implies that within extractive industries, the natural state of multifactor productivity is in a continuous decline. There can also be an external impact due to a rise in commodity prices such that a previously "unprofitable" block suddenly becomes commercially viable. One part of a mine resource that was previously classified as "waste" while at another price point is now classified as "ore." However, the costs of inputs, labour and capital have not changed. Measured productivity will fall, while profitability of the mine will rise. In the long run, productivity and profitability are closely correlated, but in the short run they may not be.

WHITTLE OPTIMIZATION MODEL

The strategic planning methodology and software package developed in 2004 by Whittle Consulting, an international mining consulting firm with its head office in Australia and operations in several countries, including Canada, changes this whole approach by seeking to change decision-making across the entire life of the mine.[2]

The first step is to establish the viability of the base-case scenario. This requires establishing marginal cut-off grade to maximize net cash. Having established that the project is capable of generating positive net cash, the question becomes whether the project has a positive net present value. The base-case scenario then allows for the optimization of processes and operations external to stope design or pit geometry.

The Whittle Enterprise Optimization software was first used to construct the optimized base-case scenario. Subsequently, specific variables are adjusted either independently or as a contingent outcome of another process. The same approach can be used in underground mining where the variation occurs in the marginal cut-off grade.

Dynamic modelling is inherently an iterative process. Underground, each stope can be modelled with its own grade and tonnage graph, and with variations of cut-off grade. Depending on the geotechnical properties of the ore body, the method of mining selected depends on the relative position of stopes to each other. After modelling the ore body in each zone and creating a series of nested stope shells corresponding to variations in cut-off grades, average grades and cumulative tonnes, calculations for net present value can be derived for each stope separately.

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[1] Cooper, L. "Innovation and Digitization in Mining." Research paper. Innovation Policy Lab, University of Toronto, Mimeo. (2019).

[2] Whittle, Gerald. "Global Asset Optimisation." *Orebody Modelling and Strategic Mine Planning* (November 2004). [Online]. Available at: https://pdfs.semanticscholar.org/2b31/6aa5ee3cbc6e8b70ba43930ee223018c8db2.pdf.

Modeling the Value of Information

Managing the variety and complexity of risks and uncertainties in mining operations is an incredibly complex task. The disaggregated nature of the mining industry across the value chain, in addition to the "silo" management structures within the mine–mill complex, has exacerbated this inherent difficulty. Exploration geologists seek to maximize resources, mine engineers seek to maximize equipment utilization. Metallurgists are incentivized to seek to maximize recovery, while many mine managers, as well as corporate executives, focus on production targets and quarterly results. Not only can each mining manager be viewed as a feudal lord exercising dominion over their operation, but the silo framework, and disaggregated responsibilities within each phase of the production process, lead professionals in each subfield or subsector to compete for resources in order to realize their segmented goals, often to the detriment of the efficient allocation of scarce resources across the operation as a whole. An efficient and effective mine plan should be greater as a whole than the sum of its parts, but too often mining plans suffer from compounded systemic failures to achieve operational efficiency.

Mike Samis, a mining engineer and the head of Toronto-based Strategic Capital Management (SCM) Decisions, has developed an additional approach by illustrating the value of information as it applies to decisions along the multiple points of project development.[3] He argues that traditional risk models have led to a zero-sum game, where a company requires close to a billion dollars in capital to bet on a new mine. For many metallurgists, this has come to mean that the future looks like an absolute loss of metallurgy because there are no more big mines. Samis' approach seeks to descale these long-established risks to enable more effective innovation to take place and open the door to new management strategies such as real options on new investments in mining which area based on real assets instead of financial instruments.

He uses the example of the design and construction of a mill, and the adoption of new metallurgical processes. Reliance on pilot projects can serve to pursue both higher return on investment, and lower risk. Rigorous calculation of net present value at each stage of the pilot highlights the importance of information, and incremental information gains, to the overall economic viability of a project. It's a methodology that can reduce malinvestment and unnecessary capital expenditure that would occur when large, aggregate capital expenditures are undertaken with significant levels of uncertainty due to unacknowledged technical risks. Reliance on pilots entails a cost for obtaining this information, but this is dwarfed by the costs of making a poor decision.

A proper accounting of the risks posed along each segment of the value chain is crucial to correcting these sources of inefficiency. Disaggregating sources of risk to account for the unique challenges faced by each of the integral components of mining project development necessitates moving away from a simple DCF model for assessing financing risk. As a single measure of project value, the application of a uniform discount rate across the entirety of a mine-mill complex is insufficient. So inherently flawed is its application as the predominant, if not exclusive, method of risk accounting, that financial firms routinely demand higher fees in order to conduct deeper research by specialized analysts.[4]

For Samis, in place of a linear discount rate as a universal risk metric, quantification of unique project risks should include quantifying resource risk inherent in the estimation of ore reserves; sampling risk in the methodological approach to generating ore reserve estimations; geo-metallurgical variation in the mineralization exclusive of grade concentration; as well as the standard sensitivity estimations across commodity prices and input prices. The recent commercialization of related technologies and methodologies such as these are becoming increasingly viable for adoption and adaptation in the mining sector.

Modelling Risk for Digital Mining

The above examples illustrate the dramatic impact that digitalization can have on improving the performance of the mining industry through better decision-making processes at the management level. Integrated strategic planning and enterprise optimization software can be used not only to improve the performance and net present value of mining projects themselves, but can also be used to model the impact of adopting innovative products or processes such as autonomous haul systems and ultra high-intensity blasting.

Specific to underground mining, mine scheduling and enterprise optimization software each add significant value independent of solving for an optimal pit or stope design, though the use of heuristics and genetic algorithms to approximate optimal stope solutions further enhances the value available through dynamic integrated optimization. The adoption of genetic algorithms to find high-quality optimization solutions combined with integrated dynamic modeling has the potential to transform marginal projects into economically viable developments. This may be especially true for underground mining where enterprise optimization can significantly improve operational performance constrained by complex, networked, contingent events.

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[3] Samis, M. "Using Pilot Programs to Create Value and Reduce Capital Risk Exposure in the Mining Industry." White paper, SCME Decisions Corp. (Nov. 8, 2018).

[4] Botin,J., R. Guzman, and M. Smith. "A Methodological Model to Assist in the Optimization and Risk Management of Mining Investment Decisions." *Dyna* (December 2011).

5.2 INNOVATION IN THE SUPPLY CHAIN

Modern extractive industries tend to be dominated by huge global firms. Such massive entities aren't well situated for leading radical change though there are exceptions such as BHP in Australia automating the complete logistics chain from the shovel in the pit to transportation to the port. There are structural features which limit the large mining and supply companies from creating and implementing truly disruptive technologies. Disruptive technologies tend to be driven from the bottom up, by smaller and less traditional firms. As we have seen, the digitalization movement has been driven by the smaller, more nimble operations and currently fewer than 10 percent of mining companies are believed to have developed a digital strategy.

Recent research argues that extractive industries are converging around the general advanced manufacturing supply chain model. The argument centres on the emergence of a collaborative innovation model that is being applied to production across economic sectors, including resource-based industries and their service and supply chains. In this innovation model, it is not possible for sole companies or individuals to independently master the skills required to be at the forefront of development, due to the speed and uncertainty of change in technology and in markets. As a consequence, the leading firms will depend on a dynamic set of partners within their supply chain to develop and apply technologies. The key to success will be the ability to collaboratively adapt general technologies to specific applications, and to raise the level of general understanding based on the results of those adaptations. A natural outcome of this collaborative work will be a new form of contract that facilitates joint innovation domestically and over international borders.

The automotive industry provides an example of a vertically integrated manufacturing industry that has evolved into an enterprise driven by an extensive, diverse, dispersed supply chain. A new standardized framework for analyzing and modelling the relevant processes in the supply chain operations reference (SCOR) has been developed and implemented. Explicit comparative analyses of the mining and automotive industries have been made. However, the early part of the supply chain remains insufficiently accounted for in these discussions. Deep integration of the mineral raw materials industry has yet to happen, and the processes at play in the mining industry differ greatly from those of manufacturing. Within the supply chain, the role of the mining company is to "find, delineate and develop mineral deposits and then to extract, process and sell (supply) the raw materials derived from these deposits."[5]

Applying the SCOR model to extraction processes in the mining industry would provide practical benefits to both mining and manufacturing companies. Working with the SCOR model and validating key performance indicators (KPI) across the supply chain may allow for greater transparency of mining industry processes. Differentiating between the products that result from mining processes and the raw materials that go into them is important in adapting the SCOR There is a need for more research in order to model the exploration and development processes. As well, the particular raw materials and product developed by each process must be identified. Such research would support the development of "an integrated, overarching model" of the sourcing process and lead to better understanding of key concepts such as "product definition, product classification, product life, mineral commodity life, product life cycle, mine life cycle, new-product development, and new mine project development." Based on such research, the most appropriate existing frameworks, KPIs and best practices could be identified and adapted for use in modeling the sourcing processes for the mining industry

5.3 METALLURGY, MINING AND THE CIRCULAR ECONOMY

While the circular economy is defined differently by various organizations and states, it is generally agreed upon that it is a system in which products are built for high performance and durability instead of planned obsolescence. This system relies on the use of raw materials, which will be optimized efficiently through the intelligent recycling and re-use of waste products to support a sustainable economy. This definition is championed by the International Council on Mining and Metals (ICMM), as well as the Ellen MacArthur Foundation, a foundation that advocates for the establishment of a circular economy, and that outlined a prominent policy paper on the economic incentives of the circular economy at the 2017 World Economic Forum.[6] The circular model answers a compelling need in the industrial economy: to transform traditional manufacturing, in which goods are made (at great cost and with significant impact on the environment), then discarded after their initial life cycle is over. The objective now is to gain acceptance and traction within industry is to create and maintain environmentally friendly and sustainable manufacturing practices that ensure a proper management of resources. Following these principles, at the end of a product or a good's life cycle, the materials used in its manufacturing would be disposed of responsibility, if at all possible, either through re-use or recycling of the materials. This creates a cyclical system that enables a more efficient waste reduction system. The term "re-manufacturing" is coming into vogue.

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[5] Raul Zuñiga, Thorsten Wuest & Klaus-Dieter Thoben. "Comparing Mining and Manufacturing Supply Chain Processes: Challenges and Requirements," *Production Planning & Control* 26: 2 (2015), 81-96.

[6] See "Circular Economy and Materials Value Chain." World Economic Forum. https://www.weforum.org/projects/circular-economy.

The concept of a circular economy is not new. Its implications, and issues of sustainability, have existed as long as humans have. But its contemporary concept began to emerge in the 1960s and 1970s, with work by U.S economist Kenneth Boulding, who argued for open economies.[7] Open economies are economic systems in which the input resources are the recycled materials from the output resources, a model that ensures sustainability.

The ICMM argues that mining is a leading candidate for inclusion in the circular economy.[8] Metals have an almost unlimited ability to be re-used or recycled, as they have properties of strength and durability. Some are anti-corrosive, which enhances the longevity of the products in which they are used.

The ICMM provides, on its website,[9] three examples of businesses in Japan where steps have been taken to embed a circular economy within the operations' financial models. Mitsubishi Materials Corporation has adopted a group-wide recycling business model, through recycling materials across a different range of products, from home appliances to aluminum drinking cans. Smelting technology is being used to recycle metals at Mitsubishi's smelters and refineries, where they also recycle scrap for materials, thermal energy or the recovery of valuable metals. The company also takes in clinker dust as a by-product from its cement plants and uses components such as calcium for additional raw materials for smelting. After use, clinker dust becomes copper slag, which can then be recycled back into a raw material at a Mitsubishi cement plant. Another example is JX Nippon Mining and Metals, which recycles a wide variety of materials, including mobile phones, industrial waste and oil, through its own environmental companies, with 83 percent of waste materials reused internally and 26 percent of its total scrap production recovered in the company's copper recycling system. Finally, Sumitomo Metal Mining has similarly taken steps to improve its recycling endeavours. This is exemplified by Sumitomo's having doubled, from 2010 to 2015, the recovery rates of its copper scrap. Good quality copper scrap is processed in its Toyo smelter and refinery, while e-scrap such as circuit boards—which contain low-grade precious metals and copper—are pre-processed by a subsidiary company before being delivered back to Sumitomo's Toyo smelter.

THE CONCEPT, PRINCIPAL AND APPLICATION OF RENTING IN THE MINING INDUSTRY

The idea of a rental economy has recently become a popular concept within sustainability, and has become a key element in discussions of Industry 4.0 and the circular economy. With the histories and definitions of the various concepts and terms in mind, the basis of an alternative economic model of renting for Mining 4.0 was introduced by David Humphreys in 2019. In his article cited previously, Humphreys argues that the basic value proposition of mining was delivery cheap raw materials through a focus on efficient management of inputs. He further argues that while the scope for doing this has not yet been fully exhausted, the ability to achieve new gains in mining may be diminishing because of the lack of substantial development of new technologies. Currently, any improvements are incremental and rather small. As a result, Humphreys argues that it would be beneficial for mining companies to seek out alternative methods by which to extract value. This might involve placing a premium on their products based on the branding of sustainable and responsible activities. Humphreys further argues that this could include companies renting out their products for life of the goods in which they are incorporated rather than selling them. By doing so they would increase the value of the inputs rather than trying to make the current inputs more efficient.

The mining industry is already engaged with a specific version of the natural resource rental model, specifically the rental of ore bodies and the different contracted services required to operate a mine. Natural resource policy involves companies paying to rent for use of an ore deposit or mine property in a sovereign country and pay usually through royalty payments. These mines are run collectively by multiple firms that bring different specialties to the operation. In Canada, for example, multiple national and international firms offer a variety of services to mines, ranging from legal services to product development. For example, DSI Underground specializes in underground mining and tunneling projects; Fasken offers legal services to many sectors that include mining; Sudbury, Ontario's Hard-Line offers remote-controlled equipment for mines; Major Drilling Group offers a professional drilling company; RPA offers services in data analysis and advice; Sandvik supplies heavy equipment; the Saskatchewan Research Council offers research and development of products to mines; and Shell Lubricants offers speciality oils for mining equipment.[10]

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[7] Worrel, Ernst and Markus Reuter. *Handbook of Recycling: State of the Art for Practitioners, Analysts and Scientists*. Amsterdam: Elsevier, 2014.

[8] Brady, Kevin and Richard Earthy. "Mining and Metals and the Circular Economy" (paper presented at International Council on Mining and Metals, London, UK, 2015). [Online]. Available at: https://www.icmm.com/website/publications/pdfs/responsible-sourcing/icmm-circular-economy-1-.pdf.

[9] International Council on Mining and Metals. "Mining with Principles: The 'Circular Economy' in Mining and Metals" (Last Modified, 2019). [Online]. Available at: https://miningwithprinciples.com/the-circular-economy-in-mining-and-metals.

[10] *Northern Miner* staff. "Ten Firms that Keep Canada's Mineral Industry Moving." *Mining* (July 19, 2019). https://www.mining.com/ten-firms-that-keep-canadas-mineral-industry-moving/.

The alternative model of renting, as described by Humphreys, also exists in other industries. Currently, this rental system is not uniform. The Circular Economy Toolkit, as referenced by Arnold Tukker,[11] notes that product services could be available on a pay-per-service model, where the customer pays each time they use the product. Such a fee-based system could be optimized for usage, maintenance, reuse of parts, remanufacture and recycling, and product renting or sharing. In one scenario, the customer pays to access the product for a certain period of time, after which other customers sequentially use the product. In another, product leasing, ownership is retained by the provider but the customer has continuous access to the product. In this case the provider would typically control, maintain, and collect the product at the end of the agreement. Product pooling, yet another alternative, would allow a product to be used simultaneously by many customers.[12]

Depending on the type of good, product or service, the rental economy will probably result in a loss of profit for corporations that depend solely on exporting as much product as possible. How companies react to this possibility remains to be seen. For more environmentally and socially conscious businesses and their supporters, the idea of a rental system presents a unique opportunity to elaborate different economic models. For other businesses, and individuals who place high priority on the private ownership of assets, the concept is a tough sell.[13]

For a rental economy to work, priority would need to be placed on designing for longevity through the use of materials that are durable and can be repaired, otherwise it may prove not so different from the system we have now, in which goods are used for their life spans and then disposed of inefficiently.

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[11] Tukker, Arnold. “Eight Types of Product-Service System: Eight Ways to Sustainability? Experiences from Suspronet.” *Business Strategy and the Environment*, vol. 13 no. 4 (July 13, 2004): 246-260.

[12] Bocken, Nancy, Jamie Evans. “Circular Economy Toolkit.” [Online]. Available at: http://circulareconomytoolkit.org/about.html.

[13] Khoso, Mikal. “The Rental Economy.” *Medium* (February 6, 2019).

PART VI: Conclusion of the Study

6.1 The Shifting Boundaries of the Enterprise

Recent discussion in innovation literature points to the impact of digital technologies on established forms of industrial organization. Specifically, it changes the boundaries of the firm. This is a big deal in economics. A mine, in modern Canada, will often negotiate community benefits agreements (CBAs) with numerous local Indigenous communities. The importance and growth of such agreements has become part of the ambient operating environment in the industry.

Econometric analysis suggests that, contrary to historical views that such agreements are perhaps unavoidable but ultimately just draw resources away from the operating mining company, CBAs actually boost the enterprise value of mining companies.[1] Further, crucial to note across the breadth of extractive industries, virtually all the mineral deposits needed for future development are found on Indigenous lands. In addition, because water is the number one environmental issue for mining operations, the watersheds of these Indigenous communities naturally become the boundaries for future governance of the industry.[2]

Finally, for economic analysis and discussion, the future of mineral economics will not simply be driven by the hegemonic determination of yield, but will have to scope contracting with non-market actors.[3]

6.2 This Time It Will be Different

The reader of this study can reasonably ask: Can the Canadian mining industry of today contribute what the world-leading mining and metallurgy corporations of the past did in what we refer to as the golden age of mining and metallurgy in this country?

The answer is No. However, the question may be flawed. The accomplishments of vertically-integrated industrial corporations produced a certain kind of knowledge and products. For this, the R&D functions within the companies were critical. Even before the foreign takeovers and consolidations of the period from 2000 to 2010, innovation practices in mining were changing from an individual corporate function to a networked system. In this respect, the industry in future may be able to make a broader contribution to the economy and even to society, compared to the traditionally narrower benefits sought and achieved in the past for the individual firm.

The direction of future developments in metallurgy will now, as previously stated, be a function of foreign direct investment (FDI) decisions made by global mining companies. They will not, as in the past, be domestically determined. Any broader beneficial outcomes that emerge will be a function of the complex interactions between multinational enterprises and the absorptive capacities of the locally based firms in the supply chains, alongside their public research infrastructure partners.

6.3 Mining, Metalllurgy and the Future

How will mining and metallurgy contribute to the emerging digital economy? What role will it play? The sector will continue to be a critical contributor, but the path forward may not be a linear extrapolation forward of the kind of contribution that was made to the industrial economy during Canadian metallurgy's golden age. The 2017 report on mining and metals by the World Economic Forum provides a reasonable outline of the digital transformation that lies ahead for the industry. It is challenging, complex and outlines different scenarios, all with importantly different trajectories for the positioning of metallurgy. As the report points out, some five years after the "commodity boom peaked in 2011, the global mining and metals industry is still adjusting to a set of strong headwinds. These include: anaemic global demand growth, as China's economy shifts away from resource-intensive manufacturing; massive excess capacity in some metals, weak pricing and increasing volatility; workforce skill gaps; increasing pressure from customer requirements; growing resource nationalism and regulation; declining resource access and quality; and mounting trade friction along all steps in the value chain. There is no evidence to suggest that these trends will reverse any time soon. On the contrary, they are likely to persist indefinitely, defining the industry's "new normal."

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[1] Dorobantu S., W. J. Henisz, and L. J. Nartey. "Not all sparks light a fire: Stakeholder and shareholder reactions to critical events in contested markets." Administrative Science Quarterly 62(3) (2017): 561–597.

[2] Dorobantu S., K. Odziemkowska. "Valuing Stakeholder Governance: Property Rights, Community Mobilization, and Firm Value." *Strategic Management Journal* 38(13) (2017): 2682–2703.

[3] Dorobantu, S. and K. Odziemkowska. "Contracting Beyond the Market." Columbia University. Mimeo. (November 2019).

Within the mining and metals industry, digitalization will be a force that changes the nature of companies and their interaction with employees, communities, governments, and the environment at every step of the value chain. From mineral exploration and valuation, through mining, ore processing and metals production, to downstream sales and distribution, digitalization is blurring traditional industry lines and challenging the business models of the past."

WHAT IF METALLURGY WILL NOT BE ENOUGH?

The most immediate impact and economic imperative of metallurgy is to improve productivity, defined as the physical efficiency of input costs to output, as well as, at a basic scientific level, confronting the perpetual problem of declining ore grade. David Humphreys, formerly chief economist of Rio Tinto and author of the 2015 book *The Remaking of the Mining Industry*, is the leading expert on productivity and mineral economics in the world. He has recently published an article in which he makes the case that metallurgy and physical efficiency gains, while important, will not lift the mining industry back onto a sustainable economic curve.[4] Instead, Humphreys proposes that improved productivity, and exploration, are the primary ways in which mining can address resource depletion. Over the past 150 years, the mining industry has been remarkably successful with regards to productivity growth. However, since 2000, gains have slowed. Some aspects can be explained by cyclicality, but there is growing apprehension that some of the underlying, longer-term factors that kept productivity on an upward curve for so long are losing their potency. According to Humphreys:

> Key amongst these factors are the physical contributions that the second industrial revolution, beginning in the late nineteenth century, brought to mining, most notably in the form of larger equipment operating in larger mines. There is much discussion in the industry around the arrival of a fourth industrial revolution and how this might 'disrupt' the sector and deliver a new boost to productivity through the promotion of intelligent mining but thus far there is little the evidence of such a boost. In its absence, the mining industry faces the prospect of rising costs as grades fall and waste volumes grow.[5]

Many of the recent developments in mining technology were not the products of the mining industry itself but of the mining equipment and technology services (METS) sector. This makes mining companies increasingly dependent of the efforts of others for their success, forcing a reassessment of what, for a vertically-integrated mining company, constitutes its core skills set and competitive advantage.

Regarding metallurgy and productivity, the focus on internal operational dynamics, however, has tended to ignore the larger external issues of ecology and the circular economy. As Humphreys argues,

> the value proposition of miners has typically been found in the delivery of cheaper raw materials achieved through a relentless focus on the efficient management of inputs. It would be wrong to suppose that we have exhausted the scope for doing this. However, if, as seems possible, the ability to achieve substantial new gains in this area is diminishing, then the industry may have to explore other avenues to extract value. It might, for example point to mining companies seeking, and being able, to secure premiums for their products by branding based on the responsible and sustainable manner of their production. Or it might involve companies 'renting out' their products for the life of the goods into which they are incorporated rather than selling them, thereby positioning themselves as pivotal players in the circular economy. In other words, it may lie not in increasing the efficiency of use of inputs but discovering ways to promote the value of outputs.

6.4 GLOBAL IMPACTS

A global overview of the industry and the digital future has been given by the World Economic Forum.[6] The WEF does not paint a bleak picture ahead for the industry. Its value-at-stake analysis is a quantitative model that aims to assess the cumulative value impact over the next ten years of digital transformation initiatives on the mining and metals industry, its customers, society, and the environment. Key findings from this analysis show that digitalization could generate:

- More than US$425 billion of value for the industry, customers, society, and environment over the coming decade (at the time of writing, the next five years, to 2025). This is the equivalent of 3 percent to 4 percent of industry revenue during the same period.
- More than US$320 billion of industry value over the next decade, with a potential benefit of approximately US$190 billion for the mining sector and US$130 billion for the metals sector. The total for mining and metals is equivalent to 2.7 percent of industry revenue and 9 percent of industry profit.

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[4] Humphreys, D., "Mining Productivity and the Fourth Industrial Revolution." *Mineral Economics* (2020): 33. The arguments in this section are heavily based on Humphreys' work. Unless identified in a footnote all quotations in this section are from Humphrey's article.

[5] Ibid.

[6] World Economic Forum. *Digital Transformation Initiative: Mining and Metals Industry* (Davos, January 2017).

- A reduction of 610 million tonnes of CO2 emissions, with an estimated value to society and the environment of US$30 billion.
- An improvement in safety, with around 1,000 lives saved and 44,000 injuries avoided. This equates approximately to a 10 percent decrease in lives lost and a 20 percent decrease in injuries in the industry.

However, the potential loss over the same period of about 330,000 jobs, or nearly 5 percent of the industry's workforce, as a consequence of increased digitalization, must also be considered and, where possible, mitigated.

The pace of progress will be uneven. For those organizations that can move from being digital laggards to digital first movers, the promise of reward is real: a pro-forma projection of value at stake at the enterprise level for an average mining and metals company showed a substantial increase in 2025 EBITDA of a digital first mover versus a digital laggard. Companies—in collaboration with the larger community—must take steps to enhance their digital capabilities, which will enable them to improve their bottom lines, become more responsive and resilient to industry challenges, and develop into more sustainable, transparent organizations.

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APPENDIX: List of Selected Canadian Innovations in Mining and Metallurgy

Exploration and Development

Name of Invention • Function	Inventor/Company/Research Centre	Year
Airborne magnetic surveying. • Geographical physical survey, shows minerals with magnetic properties.	Hans Lunberg.	circa 1930.
Analytical geochemistry. • Established concept of "Structural Provinces" in Canadian Shield for basis of geology and geochemistry in mineral exploration.	James Edward Gill/McGill University.	1930.
Biogeochemistry. • Dispersion pattern of trace elements in water, soil, and vegetation provide vectors to mineralization potential.	Harry Warren/Robert Devault.	1959.
Digital seismic signal processing. • Helps understand the geometry and physical properties of the subsurface when prospecting for oil and gas.	Roy Oliver Lindseth/Teknica Resource Development.	1972–1992.
Electromagnetic unit for airborne EM systems. • Aerial geophysics.	Stanley Davidson/Sherritt.	n.d.
E-Phase. • Airborne conductivity mapping system.	Anthony Barringer/Selco Exploration.	n.d.
Fluoroscan. • Laser-induced fluorescence-based system that allowed for improved exploration of oil and gas.	Anthony Barringer/Selco Exploration.	n.d.
Geostatistics for resource and reserve estimations. • First English-language book on geostatistics for resource evaluation leading to global application in the industry.	Michel David/Polytechnique Montréal/Geostat Systems International.	1977.
Induced polarization. • Determines the voltage decay of minerals.	Harold O. Seigel/University of Toronto.	1949.
Induced pulse transient. • Airborne Electromagnetic System.	Anthony Barringer/Selco Exploration.	n.d.
Magmatic sulphide systems Ni-Cu-PGE. • Fundamental research in petrology and sulphide-silicate relationships in ore genesis for Ni-Cu-PGE exploration.	Anthony James Naldrett/University of Toronto.	1972–1998.
Mobile electromagnetic unit. • Mobile exploration.	Stanley Davidson/Sherritt.	n.d.
Plate tectonics advanced research. • Provided a more advanced theory of plate tectonics for exploration. Applying geophysics and other remote sensing for exploration.	J. Tuzo Wilson/University of Toronto.	1960s.

NAME OF INVENTION • FUNCTION	INVENTOR/COMPANY/RESEARCH CENTRE	YEAR
Porphyry copper systems. • Researched/authored/developed models associating plate tectonic subduction, hydrothermal systems and volcanism, and porphyry copper deposits globally.	R.H. Sillitoe/University of London (England).	1970.
Radiophase. • Airborne conductivity mapping system.	Anthony Barringer/Selco Exploration.	n.d.
Stochastic mine planning innovations. • Advanced research and graduate education with particular emphasis on modelling ore bodies and strategic mine planning.	Roussos Dimitrakopoulos/Cosmo Stochastic Mine Planning Laboratory at McGill University.	2006.
Time-resolved photoluminescence. • Helps detect deposits such as zinc, tungsten, tin, gold, and molybdenum.	Harold O. Seigel/Scintrex.	2002.
Towards sustainable mining program. • Program based on improving the economic and environmental sustainability of mining in Canada.	James E.C. Carter/Syncrude.	n.d.
Ultra-high frequency 3-D borehole seismic imaging. • Allows imaging of subsurface geological structures while reducing 3-D survey costs.	Acoustic Zoom Inc.	n.d.
VMS deposits and exploration (development and refinement). • Developed a model for identifying volcanogenic massive sulphide deposits and how to explore them.	James Franklin/Geological Survey of Canada.	n.d.

Product Development

Family of software and databases that can assist in performing thermodynamic calculations.		1984.
Air Curtain. • Used when underwater structures needed protection from a blast.	Adolpe La Prairie /CIL Explosives Inc.	n.d.
Airtrace. • Particulate analyzer.	Anthony Barringer/Selco Exploration.	n.d.
BeltGenius. • Creates a digital twin of belt conveyors that can provide real-time insight into the behaviour of the operation, identifying risks and inefficiencies.	Voith Turbo.	n.d.
Bilmat. • Statistical data reconciliation and mass balancing methodology and software.	Department of Mineral, Metallurgical and Materials Engineering at Laval University.	1981.
Continuous mini pilot plant. • Reduced time to steady state and better ability to perform variability analysis.	Falconbridge.	2006.
Continuous mining systems. • Advances in automation, and the adaptation of computer and laser technology.	Walter Curlook/Inco.	1982.
Cospec. • Correlation spectrometer used to measure atmospheric dispersions of various gases.	Anthony Barringer/Selco Exploration.	n.d.

Name of Invention • Function	Inventor/Company/Research Centre	Year
Cotran. • Particulate analyzer.	Anthony Barringer/Selco Exploration.	n.d.
Electric furnace smelting. • Smelting technology.	Frederick Archibald and Gerald Hatch.	n.d.
Electric smelting furnace for Impala Platinum in South Africa. • New design for electric smelting furnace that tripled daily production and reduced energy requirements by 25 percent.	Bert Wasmund/Hatch.	1989.
F*A*C*T system.	Christopher Bale and Arthur Pelton of Polytechnique Montreal/ Vincent Thompson of McGill University/with support from Natural Sciences and Engineering Research Council of Canada (NSERC) and later the Centre for Research in Computational Thermochemistry at Polytechnique Montréal.	n.d.
Gaspe puncher. • Improves the efficiency of copper converters.	Gaspe Copper/A. D. Fowler and B. Heino at Noranda.	1962.
Gaspec. • Infrared remote sensor for atmospheric gases which has been used by NASA to measure the worldwide atmospheric distribution of carbon dioxide.	Anthony Barringer/Selco Exploration.	n.d.
Hatch copper coolers. • Actively cooled refractory walls.	Hatch.	1973.
Ion beam applications (TOF-SIMS and TOF-SIMS). • "Analysis of mineral surfaces from flotation stream products and laboratory tests."	Chrissoulis et al.	1992.
KORE. • Uses instruments on drill rig to provide automated data collection for machine learning and artificial intelligence (AI).	KORE Geosystems Inc.	n.d.
Lasertrace. • Particulate analyzer.	Anthony Barringer/Selco Exploration.	n.d.
LIBS analyser. (Laser-induced breakdown spectroscopy). • Online and in the field analysis.	Mohamad Sabsabi/National Research Council (NRC).	2012.
MineLife VR. • Creates an interactive, one-to-one scale of a mine plan using virtual reality.	LlamaZoo Interactive Inc.	n.d.
Noranda process reactor. • First commercially viable continuous copper smelting and converting process.	Nick Themelis, Noranda.	1973.
Noranda pyrometer. • More effective instrument to measure temperature by comparing the radiation from the incandescent surface of a substance to be measured with radiation produced at a known temperature.	J. Lucas and A. Pelletier, Noranda.	1983.
Ore transport. • Ore transport.	Rail-Veyor™.	1991.

Name of Invention • Function	Inventor/Company/Research Centre	Year
Porous ceramic plugs. • Molten steel could be stirred by bubbling argon gas, instead of using a steel ingot.	Robert Lee.	Mid 1960s.
Savard-Lee shrouded tuyere. • Prevented tuyeres from overheating.	R. Lee and G. Savard/Air Liquide Canada.	1967.
Seismic trace inversion. • The process of transforming seismic reflection data into a quantitative rock-property description of a reservoir.	Roy Oliver Lindseth/Teknica Resources Development.	1972–1992.
Shovel sensors. • Sensors allow for more accurate ore and waste classification.	Minesense.	2017.
Solid copper cooling elements for cooling smelting furnaces for Falconbridge. • Helped ensure cooling inside smelting furnace, enhances productivity, lifespan and energy efficiency.	Bert Wasmund/Hatch.	1973.
Solid-state welding developments to recycle zinc electrowinning cathodes. • Pioneered an automated solid-state welding solution that recovers spent cathodes. The double-cathode life span offers both economic and environmental benefits.	NCR/Groupe Tremblay/CEZinc.	2014.
Stelco coilbox. • Improvement of hot strip mill coilbox.	Stelco/Hatch.	1973.
Surtrace. • Particulate analyzer. Unsure.	Anthony Barringer/Selco Exploration.	n.d.
Synthetic well logs. • Can help analyze reservoir properties when the set of logs in are incomplete.	Roy Oliver Lindseth/Teknica Resources Development.	1972–1992.
Thiosulphate. • Gold leaching (non-cyanide).	Barrick.	2014.
Trucks and shovels (development of largest). • Improved extraction capacity.	James E.C. Carter/Syncrude.	n.d.

Extraction

Name of Invention • Function	Inventor/Company/Research Centre	Year
Bio-Mine. • Targeted metal recovery.	Bio-Mine Ltd.	n.d.
Cementation. • Proof of concept: Would allow ore to be transported to the surface with a pump-driven pipeline loop. (Only in concept.)	Cementation Canada Inc.	n.d.
Gravity-recoverable gold test. • Assess amenability of ores to gravity recovery.	McGill University/Knelson.	1990s.
Ground freezing for potash mining. • Allowed shaft sinking through water.	Unknown Developer.	n.d.

Name of Invention • Function	Inventor/Company/Research Centre	Year
Hydro-transport of oil. • First patent of hydro-transport of oil sand.	James E.C. Carter/Syncrude.	n.d.
Knelson centrifugal gravity separator. • Used gravity to separate and recover minerals.	Bryon Knelson.	1976.
Mechanized cut-and-fill systems. • Increased production.	William Guy Brissenden/Noranda.	n.d.
Muckahi mining system. • Underground mining system.	Torex.	2018.
Noranda tuyere silencer. • Noise reduction and improves converter operation.	A. Pelletier/Noranda.	1974.
Polar forcite 60 percent. • Improved explosive. Unsure. *Most likely not as most explosives are now ammonium nitrate.	Adolpe La Prairie /CIL Explosives.	n.d.
Rock mechanics. • Concepts of rock stress/strain, “doming,” and “sequential mining” to reduce ground failures associated with open-stope mining.	R. G. K. Morrison/McGill University.	1942.
Sustainable mining by drilling. • Two-stage drilling method for narrow vein deposits.	Anaconda Mining/Memorial University of Newfoundland and Labrador.	n.d.
Trackless room-and-pillar mining method. • Increased production.	William Guy Brissenden/Noranda.	n.d.
Vertical crater retreat mining. • Doubled productivity in bulk mining.	Walter Curlook/Inco.	n.d.

Mineral Processing

Acid pressure leaching (developments in). • Created optimum conditions for leaching nickel-cobalt-sulphide concentrates.	Vladimir Mackiw/Sherritt.	1962.
Ammonia pressure leach process. • Dissolution of metal into a solvent medium within a pressure vessel. Once dissolved, materials can be selectively removed through further processes.	Sherritt.	1940s–1950s.
Arsenical ore treatment. • A new process for treating arsenical ores.	Frederick Archibald/Ventures.	n.d.
Biosulphide process. • Remove metals selectively from metal contaminated water.	BioteQ.	1993.
Bitumen upgrading. • Removes need for diluent.	Sherritt.	1970s.

Name of Invention • Function	Inventor/Company/Research Centre	Year
Bubble size analyzer. • Estimation of bubble size.	McGill University.	2001.
Caste nickel matte into sulphide anodes for direct electrolysis. • Avoided the need to grind, roast, and smelt ore to produce nickel metal anodes. Unsure.	Louis Renzoni/Copper Cliff.	1948.
Clarabelle circuit. • No magnetic separation before rougher flotation, additional of a rougher cleaner with diethylenetriamine/sodium sulphite (DETA/NA2SO3) for depression of polonium (Po).	Clarabelle Mill.	n.d.
Conventional Flotation Column. • Helps clean flotation concentrates.	Pierre Boutin and Remi Tremblay.	1961.
Copper-arsenic processing. • Copper concentrates with high arsenic, recovery of copper from arsenic-containing process feed.	Sherritt.	1970s.
DETA/NA2SO3. • Decreases the rate of flotation of Po, rock recovery was increased.	Vale.	1999.
Differential froth flotation. • Ore separation.	Randolp W. Diamond/Cominco.	1917–1920.
Eco-Tec acid purification unit. • Pioneered a method for purifying acid.	Eco-Tec.	1977.
EnviroLeach. • Economic and environmental alternative to cyanide.	EnviroLeach Technologies.	n.d.
Fluid-ded roasting. • Smelting technology.	Frederick Archibald/Falconbridge.	n.d.
Gas-holdup sensor. • Analyze the gas mixture of liquid and gas in gas hold up.	McGill University.	1996.
Gas superficial-velocity sensor. • Measure gas velocity.	McGill University.	1996.
Hydride process. • Produce uranium metal; key component of Manhattan Project.	Frederick Archibald.	1941–1945.
Hydro zinc process. • Low-cost zinc processing.	Cominco.	2001.
Kidd process. • Copper electrorefining and electrowinning technology.	Kidd Creek Mines.	1992.
Mini-mill steelmaking. • Produces steel from recycled scrap.	Gerry Heffernan.	1963.
Oxygen flash furnace. • Allowed smelters to stay below regulated S02 levels, improved cost-efficiency and energy costs.	Inco/Copper Cliff.	1954.

Name of Invention • Function	Inventor/Company/Research Centre	Year
Pidgeon process. • Magnesium metal production method.	Lloyd Montgomery Pidgeon/NRC.	1941.
Powder-rolling processes. • Helped production of coins and specialty composite powders for seals on jet engines.	Vladimir Mackiw/Sherritt.	n.d.
Pressure ammonia leaching. • Better extraction for copper, nickel, cobalt, sulphur and high-grade nickel.	Frank Forward/Sherritt.	1955.
Pressure carbonyl process. • Recovers 90 percent of the nickel from crude nickel feed.	Inco.	1973.
Pressure hydrometallurgical process technology. • Listed as massive influence and leader in the technology. Massive improvements to hydrometallurgy. Many technological improvements over time.	Vladimir Mackiw/Sherritt.	n.d.
Pelletized nickel sulphide roasting process. • Roasts pelletized nickel sulphide to granular oxide sinter less than .5 percent sulphur. Pilot plant.	Walter Curlook/Inco.	n.d.
Pyrrhotite depression technology. • More pure ore extraction.	Inco/Falconbridge.	Post-Second World War.
Pyrrhotite rejection. • Flotation.	Falconbridge.	1950s.
SART Process. • Helps manage cyanide in mining operations. Acronym SART stands for: sulfidization, acidification, recycling, thickening.	SGS Lakefield.	1998.
SO2/AIR process. • Improve milling process by using cyanide to selectively remove pyrrhotite from the smelter concentrate.	Inco.	1984.
Soda-sinter process. • Recover aluminum from clay.	Frederick Archibald.	n.d.
Staged flotation reactor. • Result is a machine that optimizes the three stages of flotation within three separate zones, such that each zone is mutually exclusive from the requirements of the other zones. Froth drop back is minimal and tightly controlled. The constrained froth-recovery zone allows for much better level-control in a scavenger SFR, resulting in better recovery and upgrading.	Woodgrove (Glenn Dobby).	2016.
Sublimation of arsenic trioxide. • Processing. Used in 50 percent global arsenic trioxide (As2O3) production in 1980s.	Chris Twigge-Molecey/Hatch.	1974.
UGS Process. • Upgrade titanium slag to produce synthetic rutile.	QIT-Fer and Titane.	2003.
Voisey's Bay circuit. • Treat rougher-cleaner tails and scavenger concentrate.	Voisey's Bay.	1997.
Zinc-sulphide pressure leaching. • Better zinc extraction.	Sherritt Gordon.	1980.

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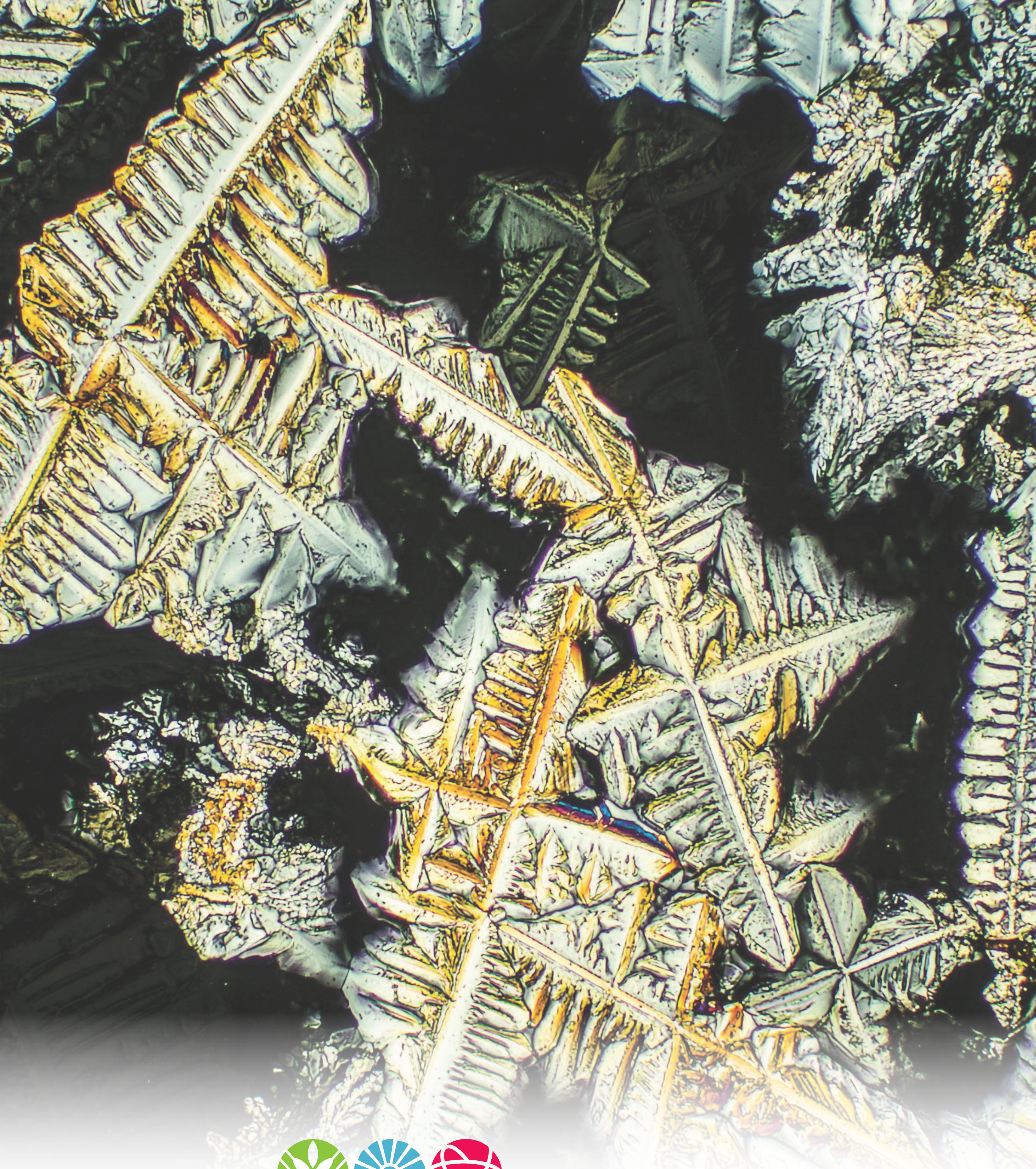

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