INDCOR LIMITED

TECHNICAL OVERVIEW OF THE PRODUCTION OF MAGNESIUM METAL BY THE CARBOTHERMERIC ROUTE AND A PRELIMINARY ASSESSMENT OF THE MTL TECHNOLOGY

<u>CONFIDENTIAL</u>

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EXECUTIVE SUMMARY

1 INTRODUCTION

The future word-wide production of magnesium metal is projected to increase substantially over the next decade and beyond, principally as a response to the perceived requirement to reduce the on-road weight of a range of vehicles as a major way in which fuel consumption can be improved with a concurrent reduction in the generation of greenhouse gases.

The production of magnesium is technically challenging, as well as having relatively high capital and operating costs. In their simplest form, the two principal methods of producing magnesium metal involve (a) high-temperature reduction of magnesium oxide and (b) electrolysis of molten magnesium chloride. Both options are characterised by having high energy requirements.

Over the past decade most technology developments have been concerned with the electrowinning technology, since this was perceived to have the lower operating costs as a consequence of being a continuous process. More than 20 magnesium metal projects have been proposed over the past five or so years, and with only one or two exceptions, were to be based on the electrowinning technology.

For a number of reasons, including ill-conceived and/or executed development strategies, increased production from existing operations, especially those in China and a slower than expected actual consumption by the vehicle industry, virtually all of the proposed projects have failed to materialise. Those that have progressed the furthest, including Noranda's Magnola, SAMAG's Port Pirie and AMC's Stanwell projects, have either been mothballed or face very significant financial and technical hurdles.

Despite the failure of the proposed projects, there appears to be an opportunity to meet the expected increase in magnesium metal demand. The essential processing factors that will dictate success in meeting this opportunity include

- Ability to sustain continuous operation,
- Minimisation of energy input, and
- Minimisation of environmentally deleterious byproducts.

From a project point-of-view, essential factors include

- Ability to meet realistic market requirements,
- Resource quality and quality, and
- Adequate/reliable sources of process consumables, together with minimal capital expenditure on infrastructure requirements, and access to a suitable pool of technical expertise for all operating and maintenance requirements.

Analysis of the technical and commercial attributes of the majority of the projects that have recently failed to come to fruition suggests that for the current to mid-term future, the "ideal" magnesium metal project would be one that has the following characteristics.

- Is continuous and can be operated on a modular basis, of say 5-10,000 t/a units, with minimal cost or technical penalties associated with changes in actual production rates.

- Is cost competitive in comparison to current producers, especially those based in China that currently use the so-called Pidgeon process. In this context, it should be noted that the Chinese themselves have increased the productivity of the original horizontal Pidgeon process furnaces by a factor of about five, while at the same time reducing the labour requirement.

Indcor Limited (Indcor) currently retains certain rights to the very significant magnesite resources located in the Arthur/Lyons Rivers region of northern Tasmania. Previously these resources have been evaluated by others in terms of the production of magnesium metal at a rate of up to 90,000 t/a using either the electrowinning flowsheet based upon Alcan's high performance cell design or that developed by VAMI-Solikamsk.

In an attempt to develop the Arthur/Lyons Rivers resource via a more conservative route, Indcor is currently investigating the potential of the so-called carbothermic method of magnesium metal production, an advanced version of which is being marketed by Magnesium Technologies Limited (MTI). As discussed later in this report, the MTI technology has yet to attain commercial status, although it has been subjected to continuous operation at the pilot plant scale. These tests outlined a number of modifications that would be required for the technology to be competitive in capital and operating cost terms with current commercially available technologies. Indcor has also held preliminary discussions with the Light Metals Flagship Group at CSIRO regarding possible collaboration to ascertain the applicability to the Arthur/Lyons Rivers magnesite and undertake any further development of the carbothermic reactor design and operating principles. Discussions between Indcor and the Tasmanian Government have also been held, with Indcor advising the Government of their current and proposed development strategies for the Arthur/Lyons Rivers magnesite and their interaction with MTL.

Following preliminary discussions between the management of Indcor and PTA, PTA was subsequently retained by Indcor to prepare a technical overview of the carbothermic method of magnesium metal production and provide a preliminary assessment of MTL's technology.

2 SCOPE OF WORK

The following scope of work was agreed between Indcor and PTA.

- Prepare an overview of the metallurgical principles of the carbothermic process.
- Outline previous work carried out at the laboratory, pilot and commercial scales.
- Provide a compilation of relevant technical papers and patents covering the process.
- Initiate discussions with Jens Frederiksen and carry out a preliminary assessment of the documents to be provided by Frederiksen. This assessment will involve:
  - Comment on the effectiveness of the adiabatic nozzle work to date with an opinion on what is required to commercialise.
  - Outline a possible test program going forward and identify ball park costs.
  - Overview of the competitors position to this technology with possible cash operating comparison.
  - Comment on the fatal flaw going forward.
- Initiate discussions with CSIRO (Tony Filmer and Raj Rajakumar in particular) with the object of assessing the potential for Indcor and CSIRO to undertake any joint development of the condensation technology developed by Frederiksen. This will include a request for CSIRO to submit a provisional R and D testwork program, together with provisional comments on intellectual property rights, etc.

The agreed scope of work was to be undertaken by Dr J H Canterford, Principal of PTA. He trained as an Inorganic Chemist with BSc and PhD degrees from the University of Melbourne. He joined the CSIRO Division of Mineral Chemistry in 1970. Over the next 17 years he was progressively promoted to Senior Principal Research Scientist and Manager of the Metallic Minerals Section of CSIRO. As such, he was directly involved in the initiation, conduct and review of a wide range of R and D programs, including direct collaboration with a wide range of industrial sponsors, commercial negotiations with clients, management of the relevant patent portfolios, etc. He was responsible for the initiation of the wide-ranging CSIRO project of magnesite, magnesia and magnesium metal. In 1987 he was appointed Director and General Manager of the Technology Division of the Minproc Group of Companies. In this role he played a major part in the evaluation of emerging technologies for a wide range of clients and was responsible for the execution of R and D activities for and on behalf of Minproc and its clients. He now acts as Group Consultant to the GRD Minproc Group of companies as a contractor through PTA, and periodically acts as Study Manager and has an on-going input into business development activities. Through PTA he also provides consulting services to a wide range of clients, including financial institutions, R and D groups, operating companies and government and statutory authorities. He is also Technical Director of DevMin Consultants Pty Ltd.

3 INFORMATION SOURCES

PTA has developed a very substantial database of technical papers, reports, patents and patent applications on a wide range of mineral and metallurgical processing technologies, projects, etc. A compilation of references on the carbothermic reduction of magnesium oxide-containing feeds (derived from magnesite, dolomite and/or magnesium silicate feeds) is provided in Appendix I. While this compilation is not claimed to be complete, it does demonstrate the range of information on the carbothermic process that is in the public domain.

At the present time, public domain information relating to MTL's carbothermic technology is limited to the following:

- The MTL Process: A Carbothermic Route to the Production of Magnesium Metal – Three page MTL brochure (undated but probably 2001 or 2002).

- J. Engell, J.S. Frederiksen and K.A. Nielsen (Mineral Development International A/S), Manufacture of magnesium, magnesium oxide, or a refractory materials by carbothermic smelting with a condensation zone, **International Patent Application** 94/11 539 (1994).

- J. Engell, J.S. Frederiksen and K.A. Nielsen (Mineral Development International A/S), Method of producing metallic magnesium, magnesium oxide or a refractory materials, **US Patent** 5 803 947 (1998).

Information in the above MTL brochure indicates that intellectual property rights to the above patents have been reassigned to MTL, which is a JV company between Mineral Development International A/S and the BoMc Group.

In order for PTA to undertake the agreed scope of work for Indcor, the following confidential documents relating to MTL's development activities and proprietary know-how were provided to PTA.

- Production of Mg metal, ceramic powders (SiC, MgO) and recovery of rare metals by carbothermal processing of low cost materials, by Mineral Development International A/S (1996) – REFERENCE MTL/1.

- Technical evaluation of the MTL Magnesium Project (Volumes 1 and 2, together with preliminary financial modeling data), by R.R. Odle of Metallurgical Viability Inc. (1999) – REFERENCE MTL/2.

- Presenting an opportunity in the carbothermal production of magnesium, by R.R. Odle of Metallurgical Viability Inc., and B. Brown of Magnesium Assistance Group Inc. (undated but probably late1999 or early 2000) – REFERENCE MTL/3.

- General layout of 1 kg/h demonstration plant constructed by Vacua-Therm Sales Ltd of Hamilton, Scotland (1999) – REFERENCE MTL/4.

The confidential nature of these documents is protected by the Confidentiality Agreement executed between PTA and Indcor dated 23 July 2003.

4 THERMAL REDUCTION OF MAGNESIUM OXIDE

For the purposes of this report, the past and current status of the carbothermic reduction of magnesium oxide are briefly reviewed. It is beyond the scope of this report to provide a detailed analysis of the reduction of magnesium oxide to magnesium metal by the carbothermic and other high temperature reduction processes. Many aspects of these processes are outlined in one or more of the references noted in Appendix I. The basic principles and early development work on the carbothermic route are described in the report entitled “An economic and technical evaluation of magnesium production methods. 2. Carbothermic”, by D.A. Elkins, P.L. Placek and K.C. Dean and published as **US Bureau Mines RI 6946** (1967). A recent excellent overview is provided in the article “Advances in Thermal Reduction Technology for Magnesium” by A.M. Cameron and published in **Light Metals 1997**, ed. C.M. Bickert and R.I.L. Guthrie, Canadian Institute Mining Metallurgy, Montreal, 1997, 579-602. A copy of this review paper is included in this report as Appendix II.

As noted previously, all methods of magnesium metal production are characterised by having high energy requirements. It was also noted that one of the perceived advantages of the electrowinning technology over the thermal reduction approach is that the former is a continuous operation, whereas the latter is generally operated on a relatively small, batch-scale basis. The significance of energy costs in overall operating profitability is clearly demonstrated by the fact that the two largest thermal reduction operations (North-West Alloys at Addy and Pechiney at Marignac) have now been shut down.

4.1 Basic Principles

Reduction of magnesium oxide, obtained by calcination of magnesite, dolomite or “magnesium silicate”, to magnesium metal is a relatively simple reaction in chemical terms.

$$MgO + \text{“R”} = Mg + \text{“RO”}$$

In order for the reaction to proceed from left to right, high operating temperatures [in excess of 1550^{o}C (Al) and up to 2300^{o}C (Si)] are required. In addition, thermodynamic calculations indicate that there is a very limited number of potential reductants. For the above reaction to proceed, the oxide of the corresponding reductant must be chemically more table than the reductant itself at the operating temperature. Thus suitable reductants are essentially restricted to aluminium, silicon and carbon – the corresponding oxides, Al_2O_3, SiO_2 and CO, respectively, are chemically stable at the appropriate operating temperatures. While "pure" metallic aluminium and silicon can be used, such reductants are high cost raw materials and secondary aluminium alloys/aluminium scrap and ferrosilicon (FeSi) are used in various combinations in current commercial operations.

From a raw material point of view, the carbothermic reduction route has great merit in the sense that the reductant (coal or coke) is both cheap and widely available. Neither the raw material (calcined magnesite, dolomite, or "magnesium silicate") or the reductant (coal or coke) is pure MgO and C, respectively. The impurities in both raw materials, which include CaO, Al_2O_3, SiO_2, etc., combine at the operating temperature to form an inert, molten slag. This molten slag facilitates operation of the high temperature furnace.

With respect to the carbothermic reduction of magnesium oxide

$$MgO + C = Mg + CO$$

reaction regime involves the reaction between two solid components at temperatures of about 1800°C (at atmospheric pressure) to generate two gaseous products. Unless the two gaseous products are rapidly separated there is a tendency for the two products to recombine so that the right to left reaction proceeds. It is this separation step, involving the condensation of the magnesium metal vapour and the prevention of the back reaction occurring that represents the most significant technical-engineering challenge with respect to the commercialisation of the carbothermic production route for magnesium metal.

The problems associated with separation of magnesium metal vapour from the carbon monoxide-containing off gases was recognised during the very early stages of the development of the carbothermic route and a number of patents were granted during the 1940's and 1950's covering various means of achieving this objective. Some of the more significant US patents are noted below.

- T.H. McConica (The Dow Chemical Co.), Method of condensing magnesium vapour, **US Patent** 2 238 908 (1941).

- J.D. Hanawalt and J.S. Peake (The Dow Chemical Co.), Production of light metals, **US Patent** 2 256 161 (1941).

- R.C. Kirk (The Dow Chemical Co.), Process of condensing magnesium vapours, **US Patent** 2 257 910 (1941).

- W.C. Seifert (Electric Heating Equipment Co.), Method for the recovery of metallic magnesium from mixtures of elemental magnesium and carbon monoxide, produced by the carboniferous reduction, at high temperatures, of magnesium oxide, **US Patent** 2 268 779 (1942).

- R.C. Kirk (The Dow Chemical Co.), Production of magnesium, **US Patent** 2 286 209 (1942).

- J.D. Hanawalt and J.S. Peake (The Dow Chemical Co.), Production of metallic magnesium, **US Patent** 2 308 418 (1943).

- R.H. McCarroll, F.G. Shaub and J.S. Laird (Ford Motor Co.), Method of magnesium production, **US Patent** 2 330 724 (1943).

- E.C.R. Spooner (Anglo California National Bank San Francisco), Manufacture of metallic magnesium, **US Patent** 2 334 451 (1943).

- E.S. Merriam (Marietta Manufacturing Co.), Reduction of metal oxides, **US Patent** 2 364 742 (1944).

- R.C. Kirk, C.E. Nelson and T.H. McConica (The Dow Chemical Co.), Recovery of magnesium from vapour mixtures, **US Patent** 2 391 713 (1945).

- T.H. McConica (The Dow Chemical Co.), Method of producing magnesium, **US Patent** 2 391 727 (1945).

- J.C. Munday (Standard Oil Development Co.), Production of metals, **US Patent** 2 398 443 (1946).

- A.C. Byrns (The Permanente Metals Corp.), Production of magnesium-containing mixtures, **US Patent** 2 399 096 (1946).

- D.S. Chisholm (The Dow Chemical Co.), Recovery of magnesium from vapour mixtures, **US Patent** 2 381 403 (1945).

- T. Griswold (The Dow Chemical Co.), Recovery of magnesium, **US Patent** 2 381 405 (1945).

- H. Ford, E.E. Ensign and A.C. Quinn (Ford Motor Co.), Magnesium, **US Patent** 2 382 047 (1945).

- H. Curch (The Permanente Metals Corp.), Distillation of volatilisable metals, **US Patent** 2 456 918 (1948).

- H.F. Fisher (The Permanente Metals Corp.), Refining of volatilisable metals, **US Patent** 2 456 935 (1948).

- F.J. Hansgirg (North Carolina Magnesium Development Co.), Production of magnesium, **US Patent** 2 582 119 (1952).

- F.J. Hansgirg (North Carolina Magnesium Development Co.), Production of magnesium, **US Patent** 2 582 120 (1952).

In passing, it is interesting to note that The Dow Chemical Company expended a considerable amount of R and D on the carbothermic and related metallothermic methods of magnesium production before apparently abandoning this approach and developing their proprietary electrowinning technology, ultimately becoming a major magnesium metal producer in their own right using this technology. It would seen not unreasonable to conclude that despite the considerable R and D programs undertaken, The Dow Chemical Company took the view that the continuous electrowinning technology was superior in technical and capital/operating cost terms.

4.2 Current Status of the Carbothermic Route

Although a discussion of the potential of producing magnesium metal by the carbothermic reduction of magnesium oxide-containing feeds was recorded over 100 years ago, it was not until the early 1940’s that the first commercial plant became operational at Permanente (USA). Similar plants were also built at Swansea (UK) and at Konan (Korea), but few details of these two plants are now available. These three operations were largely the result of the pioneering work Hansgirg and others who clearly recognised the necessity to separate the magnesium vapour from the carbon monoxide-containing furnace off-gases. The carbothermic reduction studies carried out by Hansgirg and others formed part of an extensive magnesium metal production development strategy than also involved the investigation of a wide range of potential reducing agents.

The Permanente plant, with a nominal plant capacity of 12,000 t/a, used a total of five DC arc furnaces, with four units in operation and one on standby at any time. The furnace off gases were subjected to shock cooling by injection of natural gas into the cooling cone attached to the sidewall of the furnace. The recovered solid product typically contained 50% Mg, 20% MgO and 30% C and was then subjected to a further sublimation step to recover "pure" magnesium metal. This step on its own was quite challenging, given the highly pyrophoric nature of the solid product. The relatively high "impurity" content of the solid product recovered after shock cooling was largely a result of the entrained transport of reagent fines by the high volume of gas. This was despite the fact that the MgO and C feed had been pelletised prior to introduction into the furnace. This entrainment of unreacted feed materials in the solid product recovered from the furnace is a feature of other continuous/semi-continuous reduction processes such as the aluminothermeric technologies developed by Mintek and by Heggie and coworkers, both of which are based upon the use of plasma arc furnaces (see below).

Apart from a number of operational problems associated with the off-gas cooling circuit and the need to recover magnesium metal by a subsequent sublimation step, the furnace itself was difficult to control and the total energy consumption was approximately 150% of the theoretical amount. Co-reduction of impurities in the magnesium oxide feed also resulted in a higher than theoretical energy consumption.

Overall the carbothermic reduction route as practiced at Permanente was not a commercial success and operations were finally shut down.

During the 1960's and for the next two decades most effort relating to the thermal reduction of magnesium oxide was concerned with the use of ferrosilicon and aluminium, separately and in combination, as the reductant. A major achievement was the development of the Magnatherm version of the original Pidgeon process and the construction of two major operations (North-West Alloys at Addy and Pechiney at Marignac) with a combined total capacity of about 60,000 t/a. However, as noted previously, both of these operations have recently been shutdown as being non-competitive in operating cost terms.

The potential of the carbothermic route has not been totally ignored over the part 20-30 years. Billiton, in particular, played a major role in these development activities and is reported to have spent in excess of US$10 million on the laboratory and pilot-scale development activities. Unfortunately only a limited amount of information about Billiton's development activities, including extensive studies on condenser design, is available for review.

As would be expected, much of the development work undertaken by various parties other than Billiton focussed on the design and operation of an efficient condenser system to rapidly remove the magnesium from the carbon monoxide-containing off-gases. Some of the more significant developments are noted below.

- The use of liquid magnesium to induce shock cooling [J.M. Avery, Method for producing magnesium, **US Patent** 4 290 804 (1981)].

- Condensation under reduced pressure [R. Winand, M. Van Gysel, A. Fontana, L. Segers and J.C. Carlier, Production of magnesium by vacuum carbothermic reduction of calcined dolomite, **Transactions Institution Mining Metallurgy**, 99, C105-C111 (1990)].

- Various types of nozzle design with/without injection of coolant gas to induce adiabatic cooling – See for example, F. Hori, Apparatus for obtaining Mg and Ca through carbon reduction, **US Patent** 4 200 264 (1980), and N. Kawakami, T. Goto, I. Hirano and Y. Itakura (Toyo Soda Manufacturing Co. Ltd), Apparatus for preparing metallic magnesium, **US Patent** 4 139 181 (1979). As discussed in Section 5, the MTL condenser technology incorporates the use of the so-called Lavalle nozzle.

Condensation of magnesium vapour is also a critical component of the aluminothermic and silicothermic methods of reducing magnesium oxide-containing feeds, although in these cases the problems are somewhat simpler than those of the carbothermic route since there is no (or at least very limited) potential for a back reaction to occur. Both the current version of the Mintek and Heggie DC plasma arc processes incorporate the use of a condenser held at 50-150°C above the melting point of magnesium (650°C) so that liquid, rather than solid magnesium metal can be continuously recovered. The so-called MAGRAM process (magnesium recovery from asbestos and related waste materials), a modification of the atmospheric Magnatherm process and developed to the pilot scale, also incorporated a novel condenser technology, consisting of a primary condensation section, precipitation region, and liquid metal collection. No further details of this condenser design are currently available.

At the present time, none of the above condenser technologies has been developed beyond either the conceptual stage or subjected to extensive operation at the pilot or demonstration scale. The lack of a viable condenser technology, proven at the commercial scale, is a major impediment to the commercialisation of the carbothermic route for magnesium metal production from magnesium oxide-containing feeds.

5 THE MTL TECHNOLOGY

5.1 Background

The origin of the current MTL technology can be traced back to development work carried out by Jens Frederiksen, a principal of Mineral Developments International A/S, in the late 1980's/early 1990's on the production of mineral fibres by the carbothermal processing of olivine and other low cost materials. Included in this work was a reasonably detailed thermodynamic analysis of the MgO-C and related systems.

Evaluation of this testwork program led to the initiation of a series of laboratory-scale batch tests on the carbothermic reduction of various magnesium-containing feeds, including magnesia and magnesium silicate, to produce magnesium metal. The end result of this work was the filing and ultimate granting of the US and EEC patents noted in Section 3.

Magnesium Technologies Limited was formed in 1999 as a joint venture between Mineral Development International A/S and BoMc Holdings Ltd with the express objective of commercialising the carbothermic reduction of magnesium oxide-containing feeds to produce high quality magnesium metal.

5.2 Process Proving at the Laboratory Scale

Reference MTL/1 describes in detail a substantial range of test results on the carbothermic reduction of magnesium-containing feeds using a novel laboratory scale reactor system that incorporated a Lavalle nozzle and capable of yielding 12.5 g/h product. Various reaction parameters, including temperature, feed type and amount, reductant type and amount, nozzle dimensions, etc., were examined in detail, as was the composition of the final product. The basic principles of the furnace as well as some of the results obtained are outlined in the patents issued to Mineral Development International A/S. A copy of the US patent is attached to this report at Appendix II.

It is beyond the scope of this report to review the data generated. As noted in Section 5.4, thus author of this report is of the view that the results have an acceptable and appropriate level of scientific integrity.

5.3 Process Proving at the Demonstration Scale

Prior to discussing the design and testwork program of the so-called demonstration scale facility outlined in Reference MTL/2, it is the opinion of the author of this report that the scale of operation of this facility (up to 5 kg/h) should not be classified as being of the demonstration scale. It is the opinion of this author that demonstration scale specifically means of a scale that can be directly used for detailed design, engineering and cost studies at a level consistent with a bankable feasibility study, that is, with a confidence level at a minimal level of +/- 10-15%. Direct scale up from the proposed 5 kg/h throughput level to a full scale commercial operation at say 10,000 t/a (equivalent to approximately 1250 kg/t) would be untenable in terms of technical risk. As noted in Section 6.2, a more realistic demonstration scale facility for the yet to be proven MTL carbothermic technology would have a throughput of 50-100 kg/h. It is relevant to note that Odle (Reference MTL/2, Section 5.3.1 in Volume 1) indirectly concedes that the so-called demonstration facility should in fact be classified as a pilot scale facility. He notes that with respect to the Lavalle nozzle technology, "either a larger scale demonstration plant will have to be considered, or possibly, just the Lavalle nozzle can be scaled up using vapourised magnesium vapour and carbon monoxide (or an inert gas) in a 'wind tunnel lab' or similar".

Having successfully completed the batch laboratory-scale testwork program, it was quickly appreciated that larger scale testwork, preferably on a continuous basis, was the next absolutely essential step required to ultimately achieve commercial reality for the carbothermic reduction technology.

Reference MTL/2 provides details of the so-called demonstration scale vacuum furnace designed and constructed by Vacua-Therm Sales Ltd (Hamilton, Scotland) together with an outline of the proposed testwork program. The objectives of the development program were listed as follows.

- Demonstrate that magnesium metal can be produced on a continuous basis by the MTL process using magnesia or olivine as a feed source.
- Quantify the efficiency of magnesium recovery as a function of process variables including the power input, the reaction temperature, the temperature of condensers, the Lavalle nozzle design, the pressure drop across the Lavalle nozzle, absolute pressure in the system, and gas flow rates.
- Qualitatively define the conditions under which the magnesium metal produced is not pyrophoric.
- Define the distribution of minor impurity elements in the system.
- Define the quality of metal produced by the process.

- Define and verify any subsequent refining of the metal required.

- Carry our material and energy balance for the demo plant.

- Determine where the bottlenecks are in the demo plant, and explore operating the front of the plant near atmospheric pressure.

Odle noted that there is a proprietary issue with using magnesia as the feed material. The author of this report is not aware of this issue but agrees with Odle that it must be confirmed by meaningful testwork.

Reference MTL/2 outlines a suggested program of test variable to examined, concluding with three continuous runs, each of 7 days duration. The author of the present report is of the opinion that the proposed testwork program is both necessary and realistic. It would, almost certainly, lead to a requirement for additional confirmatory testwork ahead of any reliable, independent engineering/cost feasibility study.

For a number of reasons the proposed testwork program was never completed. All parties concerned are in agreement that the completion of such a testwork program is an essential step in the overall transition towards commercial reality where the technical and economic criteria and associated risk factors have been independently quantified.

5.4 Independent Review of Testwork Data and Proposed Development Strategy

Robert R Odle of Metallurgical Viability Inc. was retained by the Varshney Chowdhry Group to carry out an independent technical review of the MTL carbothermic magnesium metal project. Odle's report was made available to the author of the present report as Reference MTL/2, and is based upon Reference MTL/1, also available to the present author. Odle and Bob Brown of Magnesium Assistance Group Inc. prepared a separate report (Reference MTL/3), also based upon Reference MTL/1.

As a general comment, the present author is in agreement with Odle’s view that Reference MTL/1 is “somewhat lacking in focus. However, the technical content of the report is excellent and no violation of fundamental scientific principals was found in this report.”

Because the proposed process proving at the so-called demonstration scale was not completed, **some** of the assumptions, models and final conclusions provided in Odle’s report are considered in appropriate under present circumstances. For example, comparison with the Heggie technology is inappropriate as it has now been effectively abandoned, while a long term (stable) magnesium metal price of US$1.20/lb and projected cashflows from the first commercial MTL operation in 2003 to five MTL operations by 2008 are clearly inappropriate.

On the other hand, some of the comments/general conclusions made by Odle still remain relevant. These include the discussion of non-financial risks outlined in Section 5.3.1 in Volume 1 of Reference MTL/2. The technical risk discussion relating to the performance of the Lavalle nozzle and the requirement for a high conversion of magnesium in the feed to a marketable magnesium metal product for the process to be economically viable is particularly pertinent.

Odle concludes that “an engineering feasibility study needs to be done to improve the accuracy of the capital and operating costs done by MTL”. The author if this report is in total agreement with this conclusion and, as noted in Section 6.2, such a study is recommended following completion of a pilot scale development program and prior to the initiation and completion of a larger, demonstration scale development program. Such a feasibility study will provide MTL, in particular, with a very useful “go/no go” indicator.

5.5 MTL Proprietary Technology

As clear from the preceding sections, a critical factor in the technical viability of the carbothermic magnesium metal production route is the continuous concurrent condensation of magnesium metal vapour and its separation from carbon monoxide. In the MTL process this is achieved by rapid adiabatic cooling of the vapour via a Lavalle nozzle. While it is beyond the scope of this report to provide a detailed review of the thermodynamic basis of the operation of the MTL Lavalle nozzle/condensation system, the information provided in the MTL documents (reports and patents) appears to be well founded.

The use of a Lavalle nozzle cannot be regarded as novel or proprietary in its own right with respect to MTL, as it is specifically covered in the two US patents granted to Hori (see Appendix I for details). It is not clear if Hori ever successfully carried out test programs using the Lavalle nozzle. However, the patents granted to MTL, which specifically relate to a batch mode of operation, clearly indicate how and why they were able to demonstrate the effectiveness of their use of the Lavalle nozzle, at least on the laboratory (bench) scale, with several operating criteria such as temperature and pressure regimes being described in the body of the patents as well as being included in the claims. As noted in reference MTL/3, it would appear that MTL’s proprietary know-how is directly related to the stabilisation of pressures through the Lavalle nozzle so that any oscillation between sonic and supersonic gas flow through the nozzle is eliminated. A further level of proprietary know-how also relates to how the entire furnace/condenser unit can be operated on a continuous basis.

There is a further aspect of the MTL technology that distinguishes it from previous approaches, such as that disclosed in the Hori patents, and this relates to the incorporation of a first condensation zone ahead of the Lavalle nozzle for the removal of “SiO/SiC” from the furnace off-gases. This is considered to be very important, both in terms of the impurity level of the final magnesium metal product and a reduction of the wear of the Lavalle nozzle. SiC, in particular, is known to be highly abrasive, especially considering the velocity of the gas flowing through the nozzle.

Overall, it has been concluded that MTL owns and controls significant proprietary know-how that appears to be more technically advanced than previously developed condensation technologies applicable to the carbothermic process for magnesium metal production. It must be noted, however, that the MTL know-how has yet to be technically or commercially proven at an industrially viable rate of magnesium metal production.

5.6 Comparison with Alternative Pyrometallurgical Magnesium Metal Processes

It was previously noted that a major breakthrough in magnesium metal production centred on the development of a continuous production route that could be operated at a relatively low rate on a continuous modular basis. Several flowsheets involving the pyrometallurgical reduction of magnesium oxide-containing feeds undergoing development appeared to meet these requirements. The most significant of these involve the use of plasma arc furnaces with aluminium and/or ferrosilicon as the reductant, together with proprietary condenser technologies.

The so-called Heggie process, which uses calcined dolomite and aluminium as the “ideal” reaction feed, was initially proposed for the Batchelor magnesium project in Northern Territory (Australia). Argon is used as a carrier gas, with a condenser operating at just above the melting point of magnesium metal to allow the continuous recovery of liquid magnesium. Details of the pilot scale furnace and its operation are provided in the article "Magnesium metal by the Heggie-Iolaire process" by M.W. Wadsley and published in **Magnesium Technology 2000**, ed. H.I. Kaplan, J. Hyrn and B. Clow, TMS-AIME, Warrendale, 2000, 65-70. While the results obtained were promising, further development of the Heggie process, and in particular is application for the Batchelor project, has now been abandoned. One of the reasons for abandonment was the high cost of a suitable aluminium reductant.

Mintek (South Africa) has played a significant role in the development of plasma arc furnaces for a wide range of high temperature applications, including the production of magnesium metal using ferrosilicon and other reductants – see the article "A plasma-arc process for the production of magnesium" by A.F.S. Schoukens and published in **Extraction Metallurgy 89**, Institution Mining Metallurgy, London, 1989, 209-223. Details of the current design and operation of the Mintek plasma arc furnace/condenser for magnesium metal production are disclosed in the **International Patent Application** 03/048 398 (2003) by A.F.S. Schoukens and assigned to Mintek.

Following the abandonment of the Heggie technology, the owners of the Batchelor project opted to examine the application of the Mintek approach using ferrosilicon rather than aluminium as the reductant. Test work ranged from laboratory batch through to continuous operation of the 100 KVA furnace at a feed rate of up to 10 kg/h. Despite a number of operating difficulties, the test programs were considered to be positive and the owners of the Batchelor commissioned the execution of an independent Prefeasibility Study at the +/- 30% confidence level for a 12,500 t/a magnesium metal plant located at the Batchelor resource site.

Due to a number of corporate matters and anticipated delays in obtaining low-cost energy (electric power and gas) at the Batchelor site, the owners of the project abandoned the proposed development strategy using the Mintek technology and examined alternative means of exploiting the Batchelor magnesite resource.

It is understood that Mintek is still active in developing their plasma arc furnace technology for magnesium metal production, but no details of current projects/clients are presently available in the public domain.

With respect to the actual physical scale of development, both the Heggie and the Mintek approaches could be regarded as more advanced than the MTL process, since the latter has not been subjected to continuous testwork at feed rates of 1 kg/h or greater. As noted in Section 5.3, the 1 kg/h MTL furnace was never operated satisfactorily.

Despite this limitation, the carbothermic route developed by MTL has a number of inherent potential capital and operating cost advantages over alternative pyrometallurgical routes that use ferrosilicon and/or aluminium as the reductant. These include a lower energy input since the operating temperature is much lower and a cheaper reductant. There are a number of potential disadvantages, including the occupational health and safety issues relating to the handling of the carbon monoxide off-gas stream. At present there is insufficient information available to make a realistic comparison of the relative technical and economic merits of each of the MTL, Heggie and Mintek technologies. In reality, this comparison should be limited to MTL and Mintek since it is understood that it is highly unlikely that any further development of the Heggie technology will be undertaken.

5.7 Projected Capital and Operating Cost Estimates

Although very limited in-house and external estimates of the capital and operating costs for the MTL, Mintek and Heggie flowsheets have been made, these estimates must be treated with a great deal of caution. They are based upon conceptual design criteria and factored estimates rather than on reliable data generated from extended continuous operation at the demonstration scale, say 100 kg/h of magnesium metal. There are substantial differences in the capital and operating cost items included in the estimates presently available with widely differing battery limits, as well as different base dates. For example, the prefeasibility study on the application of the Mintek technology for the Batchelor project includes the capital and operating costs of mining and calcining magnesite, whereas the financial model of the MTL process developed by Odle (REFERENCE MTL/2) uses a price of US$100/t (FOB) for magnesite (presumably deadburnt). For the Batchelor project, operating labour was costed at A$90,000/a whereas in the Odle model the equivalent cost was approximately A$40,000/a.

Several major consulting and broking companies, including Charles River Associates, Roskill and Salmon Smith Barney, have prepared cost comparison studies for both existing and proposed magnesium metal production facilities. As a general rule, the installed capital cost for the processing plant (excluding any mining/beneficiation/calcination but including foundry) is typically US$3.0-4.5/lb for electrolytic plants. For pyrometallurgical routes, the installed capital cost is about 50% of the electrolytic flowsheet. Total direct operating costs are typically US$0.70-1.00/lb for electrolytic plants and US$1.00-1.50/lb for pyrometallurgical plants. The higher operating cost of the pyrometallurgical operations is, in part, a reflection of the smaller scale of operation and the generally batch operating mode.

Odle estimated the capital cost of a 50,000 t/a MTL plant at approximately US$200 million (approximately A$310 million at current exchange rates) with an operating cost of US$0.55/lb (approximately A$0.85/lb). Both estimates included a considerable contingency and had a confidence level of +/- 30%. Considering the lack of “hard” data and the number of assumptions made, it is considered that the capital cost is probably reasonably realistic with the cash operating cost on the low side.

With respect to the cash operating cost, this should be compared with the current selling price for 99.8% Mg of approximately US$1.00/lb for European producers/suppliers, with Chinese product typically US$0.80-90/lb.

The world magnesium price has been, and continues to be, under significant downwards pressure, especially by Chinese producers. As noted in Section 1 of this report, the Chinese producers have recently made significant improvements with their modifications to the original Pidgeon process, particularly with respect to operating costs. The recent closure of Noranda’s Magnola plant has been blamed, to a large extent, on the reduction of the world magnesium price as Chinese productivity and cash operating costs have respectively increased and decreased.

Commercialisation of the MTL technology will only proceed if, amongst other things, the total capital and cash operating costs can be kept to an absolute minimum without increasing the technical risk to an unsustainable level. It is considered that this must be based on a very thorough development strategy with a substantial budget. Further comments on this matter are included in Section 6.2.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 General Comments

Given the time and information made available, the author of this report is of the opinion that the MTL carbothermic technology has the potential to be a cost-competitive route to magnesium metal production. At this stage it has not been possible to identify any obvious technical fatal flaw. The technology is not commercially proven and not without potential technical risk, although the latter is generally considered not insurmountable. The author of this report is of the opinion that Indcor should undertake negotiations with MTL re further development of the basic technology with particular emphasis on its application to the production of magnesium metal from the Arthur/Lyons River magnesite resource. It is also recommended that the necessary development strategy should be undertaken in collaboration with CSIRO Light Metals Flagship Group.

6.2 Conceptual Development Strategy

Neither Indcor nor MTL has the facilities or the expertise to commercialise the MTL technology in their own right or even collectively. That is, both parties require very substantial technical input, initially from a Research and Development Institute of international standing with the appropriate expertise and facilities, and secondly by a world class design/construction engineering company to carry out an independent technical audit followed by a feasibility study, ultimately at the bankable level of confidence.

With respect to the technical developments required, the possibility of a joint effort with the CSIRO Light Metals Flagship Group, principally involving the CSIRO Division of Minerals, is one that has significant appeal and should be fleshed out without delay. The joint effort would, of necessity, incorporate appropriate commercial matters such as ownership of intellectual property, third/fourth party license/royalty agreements/rights, etc. It is beyond the scope of this report to address these matters here. However, it is appropriate to note that involvement by the Flagship Group with Indcor in the development of the MTL technology is consistent with the objectives of the Flagship Group and provisional agreement has already been reached to jointly undertake further development of the MTL technology, subject to certain commercial/corporate matters being resolved.

With respect to purely technical development matters, the attributes of direct involvement with the CSIRO Light Metals Flagship Group include the following:

- World class chemical and mineralogical characterisation/assaying facilities for all inputs and outputs.
- World class process modelling capabilities backed up by very substantial thermodynamic data banks.
- Very significant experience in the design, construction and operation of high temperature furnace operations, particularly at the pilot scale (say 1 kg/h feed), together with an experienced pool of scientific and technical staff.
- Current magnesium metal production know-how.

Based upon general experience relating to the development of innovative processing technologies, it is recommended that development of the MTL technology be undertaken in two distinct inter-related stages separated by an independent engineering/cost audit. In effect, this audit would act as a “go/no go” indicator. One objective of the audit would be to highlight those areas that should be targeted to reduce capital and/or operating costs and/or reduce technical risk factors.

The first stage would involve the design, construction and operation of a continuous pilot scale facility with nominal capacity of say 1-5 kg/h product, the second stage would be a demonstration scale facility with a nominal capacity of say 50-100 kg/h product. Between the two stages a feasibility study at the +/- 20% level would be completed. If the second stage were successfully completed, this would be followed by a bankable feasibility study. If appropriate, this would lead to the first commercial project initiation.

Provided that agreement between all parties was attained, it would be logical for the first (pilot) stage development activities to be undertaken at CSIRO's facilities at Clayton, Victoria. The second (demonstration) stage involves a significant amount of materials handling, including beneficiation and calcination of the magnesite raw material as well as of the carbonaceous reductant, and this would probably be more efficiently located in Tasmania.

With respect to the first (pilot) stage of development, it is recommended that a furnace and development program similar to the "demonstration" scale furnace and development program outlined in REFERENCE MTL/2 be constructed and undertaken. As noted in Section 5.3, the objectives and methodology of the proposed testwork program outlined in the above reference are regarded as both realistic and essential. The principal technical aspect of the furnace design to be agreed upon would be the mode of heating used. It is probable that the necessary energy would by provided by an arc furnace, rather than by induction heating as in the rig designed and constructed by Vacua-Therm Sales Ltd (see Section 5.3). The input of MTL in the design, construction and operation of the pilot furnace would be of paramount importance.

Subject to agreement by all parties concerned, it is recommended that CSIRO be requested to prepare a draft development program similar to that outlined in REFERENCE MTL/2. It is considered that a minimum budget of A$5 million would be required to complete the work required together with the proposed feasibility study prior to commitment to the second (demonstration) phase of overall technology development. An additional budget of at least A$20 million would be required for this purpose. While this may seem a substantial financial commitment to R and D, it is consistent with the expenditure involved in the development of similar technologies such as Mintek's plasma technology, and other innovative technologies such as bacterial leaching of non-ferrous and precious metal sulphide ores and concentrates, pressure leaching of nickel laterites, advanced electrowinning technologies such as the EMEW cell, etc. Indcor would also incur additional costs associated with resource development to the stage such that mining and beneficiation activities could be undertaken.

While execution of the proposed development strategy cannot be guaranteed to be 100% successful, now matter how success is measured, what can be clearly stated is that a less detailed strategy would almost certainly lead to failure.

APPENDIX 1

Technical reference database on the production of magnesium metal by the carbothermic technology. These references have been abstracted from PTA's main reference database. Copies of the references can be made available upon request.

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APPENDIX II