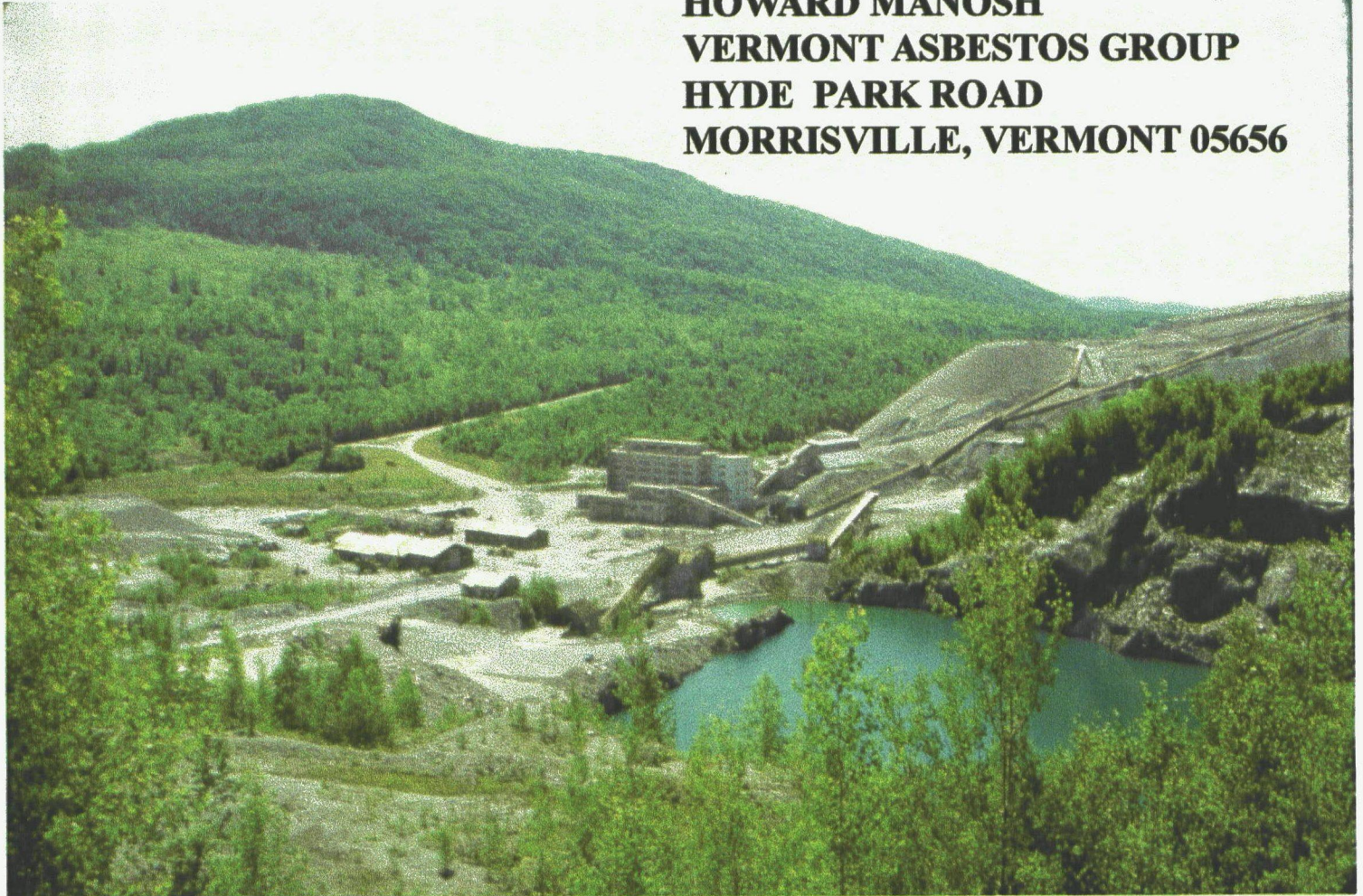# MAGNESIUM EXTRACTION FROM ASBESTOS MINE TAILINGS: A REPORT

SUBMITTED TO:
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DEPARTMENT OF ENVIRONMENTAL
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Executive Summary

The global market for magnesium metal is expected to increase dramatically in the next decade as a result of the use of magnesium as an alloy with other metals such as aluminum; the automotive industry, beverage can, aircraft/aerospace, and machinery industries will be the primary users. Currently, magnesium is extracted from seawater, dolomite, magnesite, and brucite, however, recent research and development efforts have been focussed on finding ways to economically extract magnesium from asbestos mine tailings. Because of their large weight percentage of magnesium (25-30%) and global abundance, asbestos mine tailings are an attractive "ore" of magnesium.

There are two methods of extracting magnesium from asbestos mine tailings that have been successfully tested in subsidized pilot projects; these methods are electrolytically (Magnola) and pyrometallurgically (MAGRAM) -based. The Magnola Electrolytic Process will be implemented at a plant that is under construction in Asbestos, Quebec and will go on-line in the year 2000; this plant will produce 58,000 tons per year of magnesium metal. The MAGRAM method, although tested in a small-scale pilot project in Europe, is still in the final stages of "fine tuning" (6-12 more months estimated).

The Magnola Electrolytic Process involves leaching of asbestos mine tailings with hot concentrated hydrochloric acid (HCl), subsequent formation of a magnesium chloride ($MgCl_2$) brine, and separation of the magnesium metal from $MgCl_2$ in an electrolytic cell (Alcan-MPC) (Brown, 1998). Electrolytic plants such as Magnola must operate at large production scales (>30,000 tons of magnesium metal/ year) to be economically viable and must have access to large amounts of inexpensive electric power. Plant construction costs are quite high, but relative to this, operating costs are low. There were specific environmental concerns associated with the Magnola Process that were outlined by the Quebec Ministry of the Environment in their environmental impact study which were: 1) use of SF_6 (sulfur hexafluoride) as a "cover gas" 2) CO_2, CHC (Chlorinated HydroCarbon), dioxin, and furan emissions, and 4) silica-iron waste products.

The MAGRAM Process involves 1) the mixing of calcined dolomite or magnesite, asbestos mine tailings (up to 35%), and alumina, 2) the introduction of this mixture along with ferro-silicon reductant to a DC Arc furnace at ~1700 C temperatures, and 3) the collection of magnesium vapor in a condensor connected to a port in the top of the furnace. Pyrometallurgical (thermal) plants such as MAGRAM may operate economically at production scales as low as 5000 tons of magnesium metal/ year. Construction costs for thermal plants are relatively low compared to electrolytic plants, however, operating costs are quite high; raw materials and power costs compose 50% and 25% of operating costs, respectively. MAGRAM plants would also require large amounts of inexpensive electrical power.

The advantage of the Magnola Process are: 1) Magnola is the only proven technology for extracting magnesium from asbestos tailings at an industrial scale.

The disadvantages of the Magnola Process are: 1) electrolytic plants must operate at very large scales to be profitable and hence plant construction requires a very large capital investment, 2) Magnola Process is proprietary (Noranda Inc.) and would be difficult to obtain, 3) large amounts of electrical power required, and 4) environmental concerns: use of hot concentrated HCl, use of global warming gases as "cover" gases to prevent Mg oxidation, generation of CO_2 and CHCs (chlorinated hydrocarbons), and Silica-iron rejects have to be placed in a double membrane landfill.

The advantages of the MAGRAM Process are: 1) MAGRAM plants could operate economically at much lower production rates than electrolytic processes, 2) lower initial capital outlay to construct a thermal plant as opposed to an electrolytic plant, 3) more environmentally "friendly" than electrolytic processes as it: a) does not use concentrated HCl, b) waste products should not have to be landfilled, c) dioxins and CHCs are not generated by MAGRAM Process, 4) Slag may be saleable to road aggregate and cement industries.

The disadvantages of the MAGRAM Process are: 1) MAGRAM is not a proven technology at industrial production scales, 2) Operating costs of MAGRAM would be high; supplementary raw materials such as dolomite or magnesite (furnace feed is only 35% asbestos mine tailings), alumina, and ferro-silicon must be obtained, 3) large amounts of electrical power required, 4) environmental concerns: a) A substitute for the anti-oxidation "cover" gas, SF_6, must be found and b) CO_2 emissions may have to be regulated.

The reserve of asbestos mine tailings available without further quarrying at the VAG Asbestos Mine on the east side of Belvidere Mountain is estimated to range from approximately 50-75 million tons. Based on previous geochemical analyses, the VAG mine tailings contain approximately 30% by weight of magnesium; this is comparable to the 25-26% Mg in Asbestos, Quebec mine tailings. Estimated magnesium metal extraction efficiencies for the Magnola and MAGRAM processes are approximately 27.84% and 33.99%, respectively (percentage of magnesium metal recoverable from total magnesium metal in mine tailings). The estimated weight percentage of magnesium metal extractable per ton of asbestos mine tailings processed are 8.5% for the Magnola Process and 10.39% for the MAGRAM Process. The asbestos tailings reserve at the VAG Mine would last at least 89 years using maximum yearly magnesium extraction rates with either the Magnola or MAGRAM process.

Further action can be taken by: 1) identifying possible locations in northern Vermont for an asbestos extraction facility, 2) evaluating the environmental feasibility of the electrolytic and thermal magnesium extraction methods in Vermont, 3) pursue possible alliances with inventors of the extraction technologies, 4) pursue alliances with other mining or raw materials companies, 5) invest in a Pre-Feasibility study with a light-metals consulting company.

Introduction

The worldwide demand for magnesium is expected to double in the next decade largely as a result of the requirements of the automotive industry. The total number of cars in the world is projected to grow from approximately 350 million at the present to one billion by the year 2030. In order to reduce vehicle weights to satisfy fuel efficiency and environmental regulations, magnesium will be used along with (alloyed with) aluminum as a substitute for steel. The use of magnesium in automobiles will make them more impact resistant and consequently safer. In addition to the automotive uses other major users of magnesium are the beverage can, aircraft\aerospace, and machinery industries (Thundersword Resources Inc., 1998; The Magnesium Home Page, 1998).

Currently, the primary sources of magnesium are seawater and brines, dolomite, magnesite, and, recently, in Quebec, **asbestos mine tailings**. Efforts are underway by international car manufacturing companies such as Volkswagon, General Motors, and Ford to build additional magnesium extraction facilities in Israel, Australia, and China. The current total annual world production of magnesium is approximately 325,000 tons and this production will double to 650,000 tons in the next ten years (Thundersword Resources Inc., 1998).

Vermont Asbestos Group (VAG) Mine

Background The VAG Asbestos Mine is located on the east side of Belvidere Mountain in southeast corner of the Hazens Notch 7.5' Quadrangle in northern Vermont. The main entrance to this mine is on the Mines Road which runs from the Town of Eden Mills (south) to the Town of Lowell (north). The VAG mine site straddles the Orleans/Lamoille county line with approximately half of the site in each county and in the townships of Eden Mills (Lamoille County) and Lowell (Orleans County). Figures 1 and 2 show digital aerial orthophotos of the mine site with various features labeled including mined areas and tailings piles.

The VAG Mines, which extracted chrysotile asbestos from ultramafic ore bodies, are currently owned by the Vermont Asbestos Group (VAG) and were operational from the 1930s to the early 1990s. The Eden Mine was active approximately from 1935-50 whereas the Lowell Mine was active from 1950-93 (Figures 1 and 2) (E.A. Jones, personal communication, 1998). Although small compared to asbestos mines in Quebec, the VAG mine was the largest in the eastern United States. The VAG mines were shut down because of a precipitous decline in the market for asbestos associated with the identification of asbestos-related health risks.

Earlier Efforts to Find Alternative Uses for Mine Tailings   Although the extraction of asbestos for industrial uses was always the primary business of the VAG, there was correspondence between VAG geologists and the Vermont Geological Survey as early as 1978 regarding alternative economic uses of asbestos mine tailings. In early 1978 Charles Ratte', the Vermont State Geologist, contacted the U.S. Bureau of Mines Tuscaloosa Research Center via letter about the possibility of including asbestos waste in

Figure 1 - VAG Mine Area from digital orthophoto showing roads in red and ponds in blue; mines and tailings piles are labeled.

Figure 2 - VAG Mine Area from digital orthophoto showing roads in red and ponds in blue; mined areas are outlined in yellow, tailings piles shaded in green.

an Industrial Mineral Waste aggregate project. Other uses for asbestos waste discussed in the letter included ***extraction of magnesium***, *production of refractory bricks, and lightweight concrete aggregate*.

In June of 1978 Jim Gilmore, a VAG Geologist, sent then Vermont State Geologist, Charles Ratte' a memo that cited a <u>Northern Miner</u> article summarizing a Quebec Department of Natural Resources funded pilot project that successfully extracted magnesium from asbestos tailings; Gilmore also indicated the desire of VAG to submit asbestos tailings samples for research into alternative uses. In March of 1979 Martin H. Stanczyk who was the Research Director for the Tuscaloosa Metallurgy Research Center of the U.S. Bureau of Mines (USBM) requested through Charles Ratte' that a 50 pound sample of asbestos tailings from the VAG mine be sent to him to evaluate for suitability for road aggregate. The focus of the research was to "fire" the asbestos tailings in a calcining furnace to reduce health hazards and produce a usable aggregate. An additional 50 pounds of coarse asbestos tailings were requested by and later sent to the Tuscaloosa facility and sample road aggregate was produced.

In August of 1981 a report summarizing the highway aggregate research with industrial mineral waste was published by the U.S. Dept. of Transportation entitled "Ceramic Roadway Aggregates With Improved Polish- and Wear-Resistance" (Petty, 1981). Some important results summarized in the report were: 1) calcining the asbestos mine tailings at 1350 C destroyed any asbestos fibers remaining in the mine tailings and formed forsterite and fayalite (two non-fibrous minerals), 2) the wear resistance of the aggregate produced from asbestos mine tailings was excellent, and 3) the production cost of this aggregate was the lowest of any synthetic aggregates evaluated at $10.62 /ton (1981 U.S. dollars).

<u>Recent Efforts Toward Alternative Uses for Asbestos Mine Tailings</u> Inspired by a Canadian newspaper article touting the extraction of magnesium from asbestos mine tailings in Quebec, Lowell, Vermont resident and Vermont Asbestos Group (VAG) Board of Directors member, AlvinWarner, contacted the Vermont Department of Economic Development about the possibility of extracting magnesium from mine tailings at the closed VAG quarry. George Robson, the Industrial Expansion Coordinator of the Vermont Department of Economic Development, subsequently asked current Vermont State Geologist Laurence R. Becker to investigate the magnesium content of the VAG mine tailings and currently available magnesium extraction technologies. Dr. Jonathan Kim is under contract to the Vermont Geological Survey to conduct this study with a grant from the Vermont Asbestos Group. A possible outcome of this investigation would be a preliminary evaluation of the feasibility of a magnesium extraction and asbestos waste destruction facility in northern Vermont; a magnesium extraction facility would create badly needed jobs in a low income area.

Components of this Report

This report will include the following:

1) A summary of existing information on the physical and chemical properties of the VAG Eden Mills mine tailings.

2) A calculation of existing reserves of mine tailings available at the VAG Eden Mills Mine.

3) A summary of existing techniques for the extraction of magnesium from asbestos mine tailings:

    A. Electrolytic Processes
        1. non-proprietary information about the Magnola Metallurgy Process that will be used in the Asbestos, Quebec plant.
        2. other electrolytic processes.

    B. Thermal Processes
        1. MAGRAM

4) An estimate of the efficiency of each magnesium extraction technique in terms of the percentage of magnesium recoverable from the total magnesium contained in the tailings.

5) Application of the percentage of magnesium recoverable to the reserves present at the Eden Mills Mine.

    A) total amount of magnesium recoverable via various extraction techniques.
    B) estimated life of magnesium reserves as a function of extraction technique and production rate.

6) Recommendations for further action.

Physical and Chemical Properties of the Eden Mills Mine Tailings

The ultramafic bodies at the Eden Mills Mine are part of the Vermont Ultramafic Belt which trends northward into Quebec. The Eden Mills Mine marks the southernmost extent of major asbestos-bearing ultramafic bodies in the northeastern Appalachians. On a large scale, the Vermont Ultramafic Belt is part of a major Appalachian ultramafic belt that extends from Newfoundland, Canada to Alabama, U.S.A. (Chidester et al., 1978).

The general zonation of the larger ultramafic bodies at the Eden Mills Mine is a central core of massive dunite (>90% olivine) and peridotite that grades outward into massive serpentinite, to sheared schistose serpentinite, to a thin outermost shell that consists of any or all of the following: talc-carbonate, carbonate-quartz rock, blackwall chlorite rock, and, rarely, rodingite. Chrysotile asbestos occurred at low concentrations in the dunite and peridotite core and at commercial concentrations in the sheared serpentinite. The mine tailings will consist of varying amounts of all of the above lithologies, however, will be dominated by the sheared serpentinite since lithologies which contained the highest concentrations of chrysotile were preferentially harvested. A photo of the main tailings pile is shown in Figure 3. All of the different lithologies in the ultramafic bodies with the possible exception of the thin margins contain similar amounts of magnesium.

Some representative bulk rock geochemical analyses from Chidester et al. (1978) are shown in Table 1. All values are expressed as weight percent of the oxide of the element. The two samples of typical asbestos ore are probably the most representative of the composition of the Eden Mills mine tailings.

Table 1

	Dunite	Serpentine from typical asbestos ore	Massive Serpentinite	Serpentine Typical Ore
SiO_2 (silica)	39.1%	42.47	38.6	38.76
Al_2O_3 (aluminum)	1.1	1.21	1.8	1.04
Fe_2O_3 (iron +3)	2.9	1.23	5.4	6.1
FeO (iron +2)	3.0	0.48	1.6	1.96
MgO (magnesium)	**47.5**	**41.21**	**40.6**	**39.25**
CaO (calcium)	0.04	0.00	0.07	0.00
Na_2O (sodium)	0.00	0.00	0.00	0.01
K_2O (potassium)	0.00	0.00	0.00	0.03
TiO_2 (titanium)	0.01	0.00	0.02	0.00
P_2O_5 (phosphorous)	0.00	0.00	0.04	0.00
MnO (manganese)	0.22	0.06	0.10	0.11

These representative samples show that the MgO content ranges from 39.25% (serpentinites) to 47.5% (dunites). Since dunites are usually located in the core of the

ultramafic bodies and do not typically contain economic amounts of asbestos, the "Typical Asbestos Ore" samples are more representative of the composition of the mine tailings; it will, thus, be assumed that the mine tailings range from 39.25 to 41.21% MgO. Since it is desired to know how much elemental magnesium is contained in a sample rather than the amount of magnesium with an associated oxygen, one must convert the MgO to Mg by multiplying by a factor or 0.76 (ratio of: atomic weight of magnesium/ atomic weight of magnesium + oxygen). In this case, if we average the two "Typical Asbestos Ore" samples to get 40.23% MgO and convert this value to elemental Mg by multiplying by 0.76 we get 30.57% Mg.

Initially, when the first inquiry was made by Alvin Warner of the VAG Board of Directors into the possibility of using the Eden Mills Mine tailings to extract magnesium from, a direct comparison was attempted between the magnesium values of tailings at the Eden Mills, Vermont mine and the tailings at the Asbestos, Quebec mine. A Canadian newspaper article cited magnesium abundances of 26% from tailings at the Asbestos, Quebec mine and this value was directly compared with MgO values shown in the Chidester et al. (1978) report on the Eden Mills Mine; this comparison resulted in the idea that the Eden Mills mine tailings were 150% richer in magnesium than the Quebec mine. Presumably, the discrepancy results from the fact that elemental magnesium weight percentages from Quebec were compared with MgO weight percentages from Eden Mills. If the 26% Mg from Quebec is converted to MgO then the numbers are close with Quebec tailings = 34.21% MgO and Eden Mills tailings = 40.23%. Mine tailings from different asbestos mines in the same ultramafic belt probably do not have substantial differences in magnesium content.

Existing Reserves of Mine Tailings

Figures 1 and 2 show digital aerial orthophotos of the VAG mine area with the tailings piles and mining areas labeled. There are three separate mine tailings piles with one associated with the Eden Mine on the westernmost part of Figures 1 and 2 and two associated with the larger Lowell mining areas to the east. A photo of the main tailings pile is shown in Figure 3; this pile is over 500' in elevation. The existing reserves of mine tailings at the Eden Mills Mine that would be available for magnesium extraction **without any further quarrying** will be calculated using four different methods. These estimates **do not** include the chrysotile asbestos that was removed as it constituted only 2-3% by weight of the rock and the error in these calculations of tailings reserves likely exceeds this:

1) Calculation of volume and weight of mine tailings from digital elevation models using Arcview 3D-Analyst (Figures 4 and 5):

   Tailings Pile #1 (Eden Mine Pile): 14,796,752.743 meters^3
   Tailings Pile #2 (Main Pile): 23,751,979.503 meters^3
   Tailings Pile #3 (North Pile): 7,203,318.906 meters^3

   Total   45,752,051.152 meters^3

45,752,051.152 meters^3 X 2500 Kg/meter^3 (density of serpentine) = $1.143801279 \times 10^{11}$ Kg

$1.143801279 \times 10^{11}$ Kg X 2.2 lbs/ Kg = $2.516362814 \times 10^{11}$ pounds

$2.516362814 \times 10^{11}$ pounds X 1 English ton/2000 lbs. = 125,818,140.7 tons

125,818,140.7 tons X 0.60 tons solid/1 ton solid + *air (porosity) = **75,490,884.4** English tons of tailings (English ton = 2000 lbs).

*upper limit for the porosity of sand and gravel (Driscoll, 1986)

2) E.A. Jones who is on the Board of Directors for the Vermont Asbestos Group and was a former Plant Manager gave the Vermont Geological Survey estimated production rates for the Eden and Lowell mines in October 1998.

   Eden Mine operational from 1935-1950 (approximately 16 years)

   16 hours of plant operation X 100 tons ore/hour X 365 days/year X 16 years

   = 9,344,000 English tons of tailings

   Lowell Mine operational from 1950-1993 (approximately 44 years)

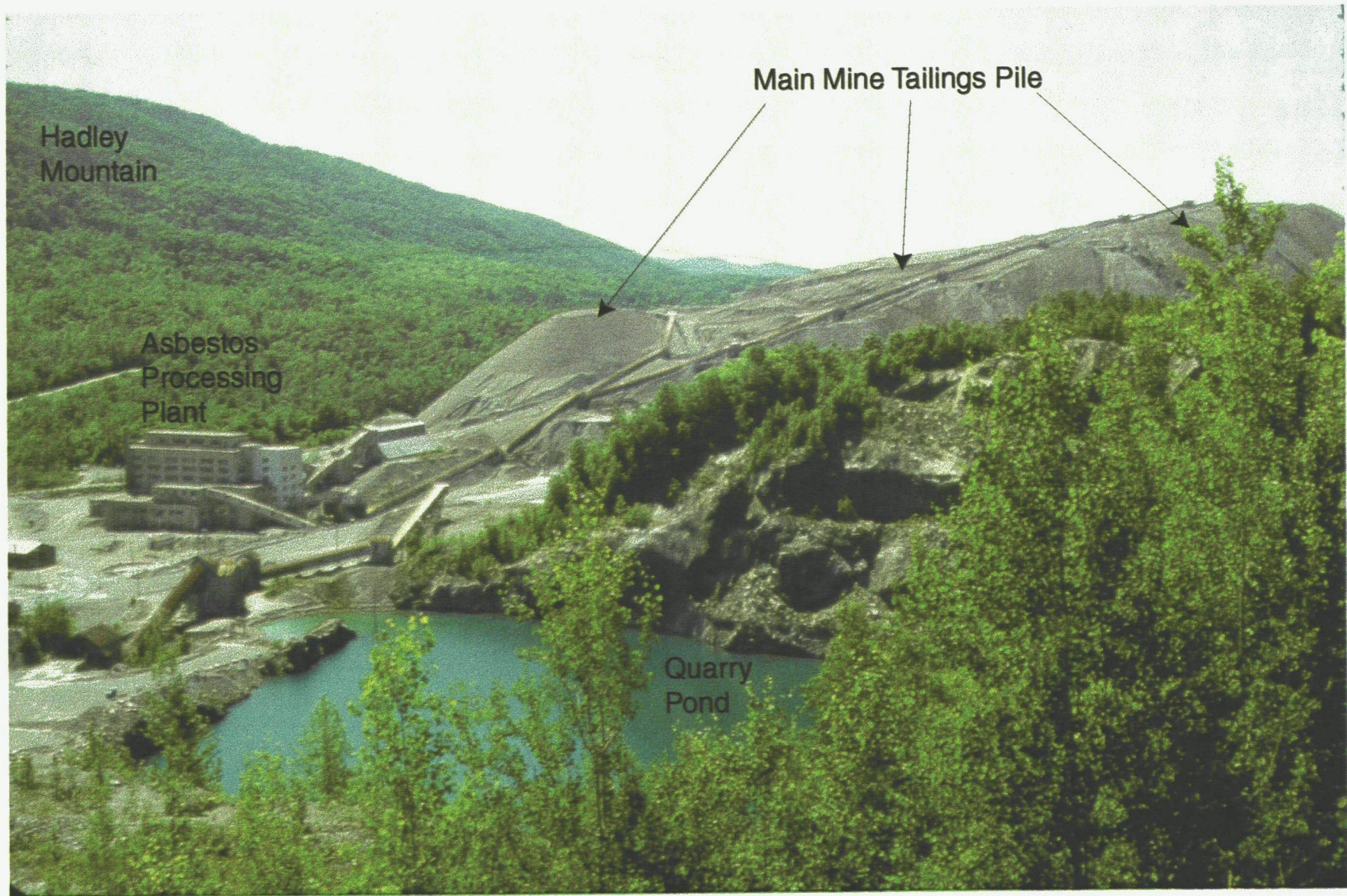Figure 3- Photo of flooded mine (quarry pond), asbestos processing plant, and main tailings pile with conveyor from top of Lowell Pit.

Vermont Asbestos Group Mine Area
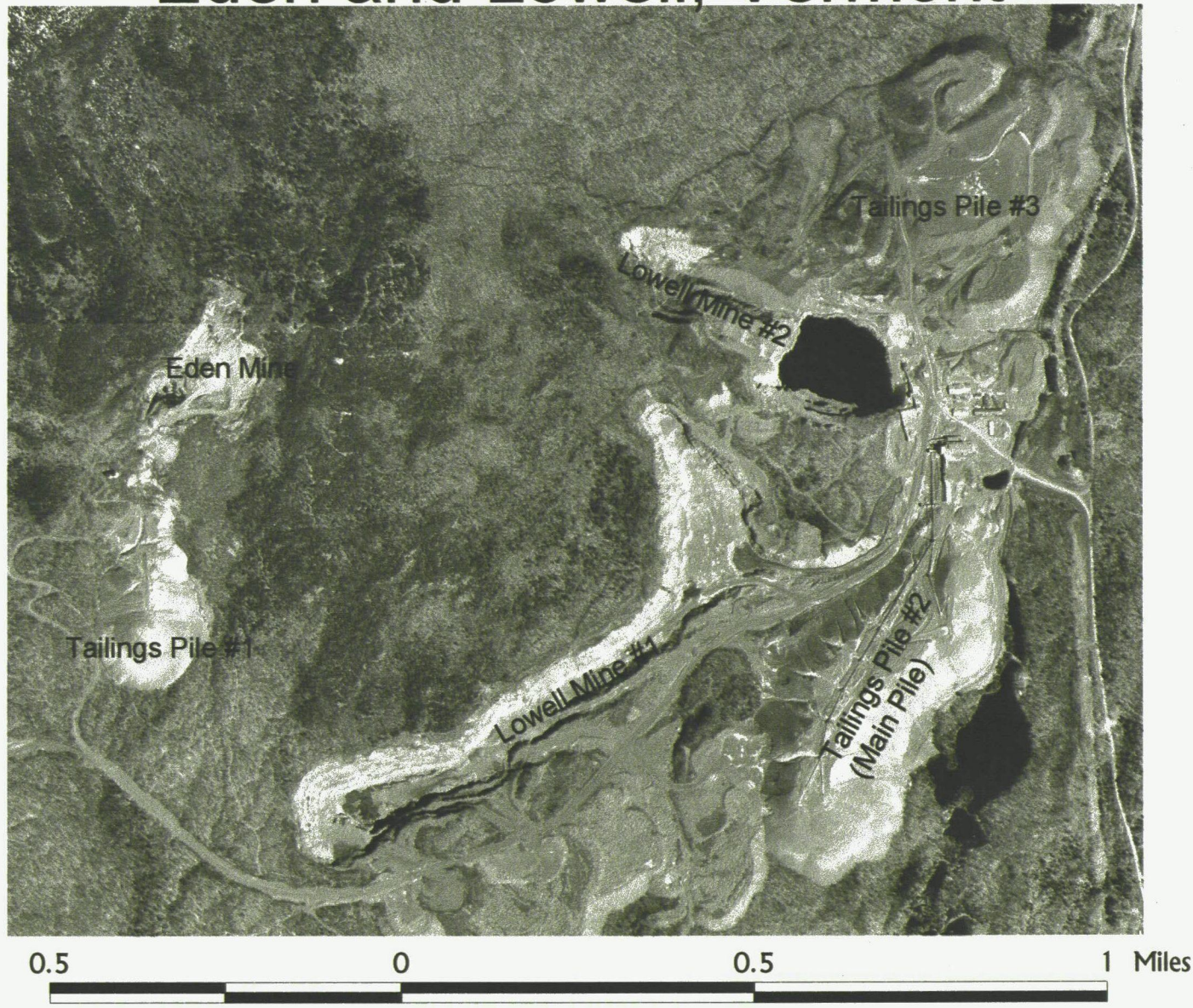# Eden and Lowell, Vermont

Tailings Pile #3

Lowell Mine #2

Eden Mine

Tailings Pile #1

Lowell Mine #1

Tailings Pile #2
(Main Pile)

N
W   E
S

0.5   0   0.5   1 Miles

Figure 4 Digital Orthophoto of VAG Mine area with three tailings piles labeled.

Vermont Asbestos Group Mine Area
Eden and Lowell, Vermont

Mainpile2
Breaklines
- Hard
- Soft

Elevation Range
- 492.163 - 508.35
- 475.977 - 492.163
- 459.79 - 475.977
- 443.603 - 459.79
- 427.417 - 443.603
- 411.23 - 427.417
- 395.043 - 411.23
- 378.857 - 395.043
- 362.67 - 378.857

Tailings pile #3
Breaklines
- Hard
- Soft

Elevation Range
- 437.393 - 444.73
- 430.057 - 437.393
- 422.72 - 430.057
- 415.383 - 422.72
- 408.047 - 415.383
- 400.71 - 408.047
- 393.373 - 400.71
- 386.037 - 393.373
- 378.7 - 386.037

Tailings pile #1
Breaklines
- Hard
- Soft

Elevation Range
- 675.242 - 689.94
- 660.544 - 675.242
- 645.847 - 660.544
- 631.149 - 645.847
- 616.451 - 631.149
- 601.753 - 616.451
- 587.056 - 601.753
- 572.358 - 587.056
- 557.66 - 572.358

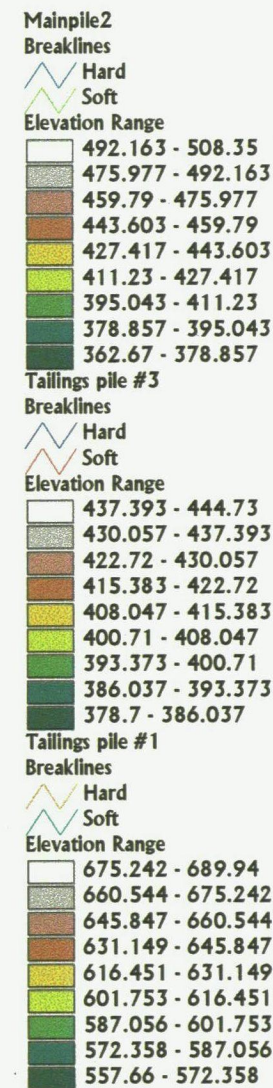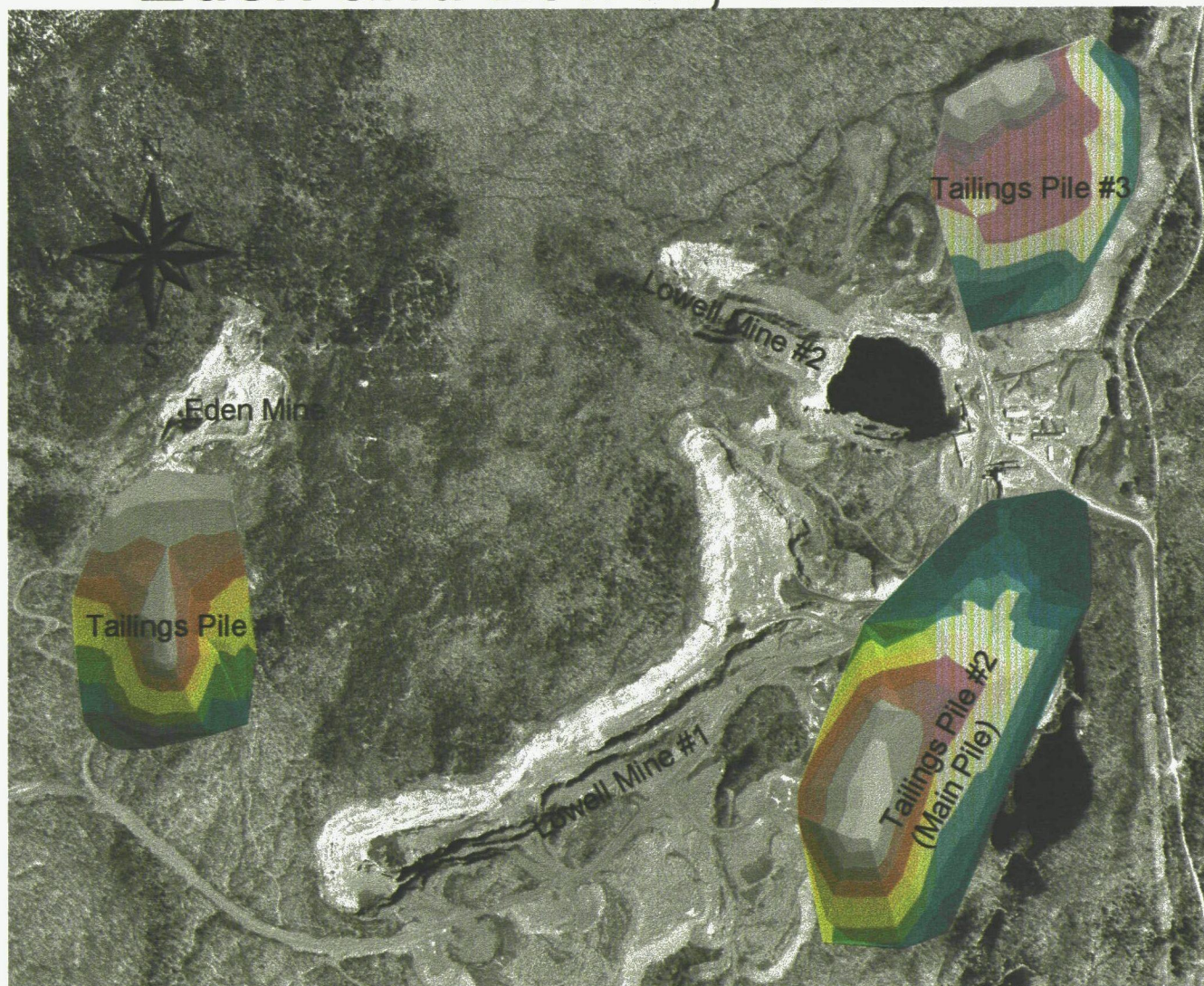1000   0   1000   2000 Meters

Figure 5- Contoured tailings piles from which volumes were calculated

24 hours of plant operation X 125 tons ore/ hour X 365 days/year X 44 years

= 48,180,000 English tons of tailings

Total = 57,524,000 English tons

3) A February 9, 1978 memo from VAG Geologist Jim Gilmore to Vermont State Geologist Charles Ratte' estimated that there were 25 million tons of tailings at the Lowell Mine and 6 million tons of tailings at the Eden Mine. Using these figures as a starting point and using the production rates estimated by E.A. Jones in #2 the following figures were calculated.

Eden Mine 6 million English tons of tailings on February 10, 1978

Lowell Mine 25 million English tons of tailings on February 10, 1978

Calculation of Additional Tailings:

1978 (Lowell Mine Only)

324 days X 24 hours/day X 125 tons ore/hour = 972,000 English tons of tailings

1979-1993 (approximately 15 years of operation of Lowell Mine)

24 hours/day X 365 days/year X 125 tons ore/hour X 15 years = 16,425,000 English tons of tailings

Total = 48,397,000 English tons of tailings

4) John Lupien, who was a manager at the Eden Mills Mine when the employees bought the mine and formed the Vermont Asbestos Group, estimated in a phone conversation to Vermont State Geologist, Larry Becker during early 1998 that there are **70 million English tons** of tailings at the Eden Mills Mine.

Average of the four tailings reserves estimates = **62,852,971 English tons**

Existing Techniques for the Extraction of Magnesium from Asbestos Mine Tailings

Most magnesium metal is derived from seawater and brines, dolomite, magnesite, and brucite (Cameron, 1997; Thundersword Resources Inc., 1998). Seawater contains 0.13% magnesium by weight whereas dolomite ($Ca,Mg(CO_3)_2$), magnesite ($MgCO_3$), brucite ($Mg(OH)_2$) contain 18%, 40%, and 40% Mg, by weight respectively. Thermal, electrolytic, and combination thermal and electrolytic techniques are used to extract magnesium metal from the aforementioned sources. Most of the world's magnesium is produced from the electrolysis of fused magnesium chloride that has been extracted from seawater and brines; thermal processes produce the fused magnesium chloride and electrolytic processes separate the magnesium metal (The Magnesium Home Page, 1998) Pyrometallurgical (thermally-based) techniques are commonly used to extract magnesium from dolomite, magnesite, and brucite at high temperatures (~1700 C) in the presence of chemical catalysts; carbonate (CO_3) and hydroxide (OH) are driven off as vapors (carbon dioxide, hydroxyls) and magnesium-bearing vapor is trapped and condensed. Recent research and development efforts have focussed on using ultramafic rocks and mine tailings as a source of magnesium (Thundersword Resources Inc., 1998; The Magnesium Home Page, 1998; Noranda Home Page, 1998; Brite-Euram II Home Page, 1998; Brown, 1998).

Ultramafic rocks and the tailings from asbestos mines have long been known to contain large amounts of magnesium (~25-30%), however, economically viable extraction technologies have only recently become available. The formation of silica gels during processing of ultramafic silicates makes magnesium extraction considerably more difficult than with carbonates or seawater and brines (Brown, 1998). Although prototype electrolytic (Magnola Process) and thermal (MAGRAM) techniques for deriving magnesium from asbestos mine tailings have been tested in pilot projects, industrial scale magnesium extraction plants will not go on-line before the year 2000 (The Magnesium Home Page, 1998; Noranda Home Page, 1998; Brite-Euram II Home Page, 1998; Brown, 1998).

Electrolytic Techniques- Magnola Process

After more than 10 years of research and development, Noranda Inc. began construction of a $720 million (Canadian dollars) magnesium extraction plant in Asbestos, Quebec that is directly adjacent to 250 million tons of asbestos mine tailings. This plant will produce 58,000 metric tons of magnesium per year which is projected to be approximately 18% of the world's total magnesium production. The plant will be run by Magnola Metallurgy under the ownership of Noranda (60%), Toyota (20%), and Societe Generale de Financement du Quebec (20%). Commercial production of magnesium metal is projected to occur at the Magnola Plant in early 2000. 375 people will be employed at this plant (Noranda Home Page, 1998). A 200 metric tons per year magnesium pilot plant in Valleyfield, Quebec constructed in 1996 successfully poured a magnesium ingot in February 1997 and confirmed the viability of the Magnola Process. Briefly, the Magnola Process involves leaching of asbestos mine tailings with hot concentrated hydrochloric acid (HCl), subsequent formation of a magnesium chloride

($MgCl_2$) brine, and separation of magnesium metal from $MgCl_2$ in an electrolytic cell (Brown, 1998). A detailed discussion of the Magnola Process is shown below.

Magnola Process Flow Chart (modified from Brown, 1998)

1) Transport of asbestos tailings to the screening site (since the tailings contain small amounts of asbestos fiber, transportation protocols are probably established to minimize the amount of airborne asbestos dust).

2) Passing of asbestos tailings through a screen to separate particles that are too large.

3) Asbestos tailings that pass through the screen are slurried with water and passed through a magnetic separator to remove iron bearing particles. Magnetic minerals are stored for later disposal.

4) Leaching of tailings from step #3 with concentrated hydrochloric acid (33%) and HCl gas.

5) Neutralization of excess HCl with added MgO.

6) Filtering of solid residue from the impure brine produced in steps #4 and #5. Disposal of residue in a residue disposal pond.

7) Purification of impure brine solution by addition of chlorine gas under agitation to oxidize and precipitate Ferrous Chloride, Manganous Chloride, and Nickelous Chloride.

8) Final neutralization of solution with MgO and 50% caustic.

9) Filtration of precipitated residue from brine solution and pumping of filtered brine to a storage tank.

10) Final filtrate is passed through ion exchange columns to remove the remaining boron, nickel, and manganese.

11) Dehydration of the concentrated brine on a Fluidized Bed Drier to make granules of hydrated magnesium chloride (prills).

12) Spraying of concentrated brine solution through nozzles onto the prills on the Fluidized Bed Dryer.

13) Prills grow by successive addition of dried $MgCl_2$ layers as sprayed solution dries by accelerated evaporation.

14) Removal of prills from Fluidized Bed Dryer and transfer to "Super Chlorinator" (electrically-heated solid-liquid-gas phase reactor) where they are melted and reacted with HCl gas to remove MgO.

15) Transfer of feed from #14 to electrolytic cells (Alcan-Multi-Polar Cell (MPC) cell. The improvement of the Alcan mono-polar cell to the Alcan Multi-Polar Cell increased

the yearly output of the cell by a factor of 10. Other than the $MgCl_2$ feed from the "Super Chlorinator" the Alcan-MPC cell electrolyte contains sodium chloride (NaCl), Calcium Chloride ($CaCl_2$) and Magnesium Fluoride (MgF_2) (Brown, 1998).

16) Magnesium droplets float to the surface and are siphoned off in an inert atmosphere (SF_6) to prevent oxidation. Chlorine that is recovered from electrolyte is recycled and converted to HCl for leaching process (step #4).

17) Transfer of magnesium to continuous refining furnaces.

18) Casting of magnesium ingots or transfer to alloying section of plant for alloying with other metals.

Magnola Process Environmental Concerns

There were a number of specific environmental issues that had to be addressed by Magnola Metallurgy in order to gain final approval for the construction of the Asbestos, Quebec magnesium extraction facility. Some of the concerns arose during Environmental Impact Statement Review were:

1) SF_6 (sulfure hexafluoride) – This compound is used in the final stages of magnesium extraction when the floating magnesium is siphoned from the Alcan-MPC cell (Step #16 in above flow chart). SF_6 is used as a "cover" gas to prevent oxidation of the molten magnesium. SF_6 was determined by the Norwegian Institute for Air Research to have a large Global Warming Potential (GWP factor = 23,900) (Norsk Hydro, 1996).

The following recommendations were made by the Quebec Government Public hearing Agency after an initial rejection of the Magnola Project regarding the use of SF_6:

    A) limit SF_6 use to 0.6 kg /metric ton of magnesium produced at plant start-up as opposed to the 1.5 kg of SF_6 /ton of magnesium produced that was planned.

    B) eliminate use of SF_6 by the year 2005.

2) Chlorinated Hydrocarbons, dioxins, furans, carbon dioxide (CO_2), and silica-iron rejects are produced during the magnesium extraction process. Since all of these byproducts can be considered as environmental toxins, the following recommendations were made by the Quebec Government Public Hearing Agency after an initial rejection of the Magnola Project regarding Chlorinated Hydrocarbons (CHCs), carbon dioxide (CO_2), and silica-iron rejects:

    A) limit CO_2 emissions to 24,400 metric tons/ year at plant start-up and reduce these emissions according to the objectives established for Canada in the Kyoto, Japan Global Environmental Accords.

    B) Reduce CO_2 emissions for other Noranda plants by the amount that will be emitted by the Magnola Plant.

    C) Elimination of CHCs emissions from the magnesium extraction process through the use of CHC destruction technology. This recommendation was imperative to gaining approval.

    D) Silica-iron rejects should be considered as industrial waste and not as tailings. Double membrane waste basins with leachate collection need to be designed to accept this waste. Silica-iron rejects are generated during three of the earlier stages of the magnesium extraction process. Iron rejects are produced in step #3 when asbestos tailings that pass through the screen are slurried with water and passed through a magnetic separator to remove iron bearing particles. Oversize tailings particles from the size screening in step #1 are also a component of this

waste. Silica rejects are produced in step #6 after solid residue is filtered from the impure brine. Silica-iron rejects are a combination of oversize particles, separated magnetic particles, and solid residue filtrate from the brine.

Pyrometallurgical Techniques- MAGRAM Process

Pyrometallurgical techniques such as the Pidgeon, Carbothermic, and Magnetherm processes are currently used to extract magnesium from dolomite, magnesite, and brucite (Cameron, 1997). These processes are generally 10-15% more expensive than electrolytic techniques. At the present time, none of these processes are directly suitable for extracting magnesium from asbestos tailings. However, under the funding of a European industrial consortium (Brite-Euram II) the Magnetherm process was modified to produce magnesium vapor at atmospheric pressure using DC Arc Furnace technology by changing the slag chemistry to accept up to 35% asbestos mine tailings (MAGRAM Method). By allowing modified Magnetherm (MAGRAM) to operate at atmospheric pressure it was estimated that operating costs could be reduced by up to 30% thus making this process competitive with electrolytic methods. MAGRAM is an acronym for Magnesium Recovery from Asbestos and related waste Materials. Although magnesium was successfully extracted from a combination of dolomite and asbestos mine tailings using the MAGRAM method at a pilot plant location in the early 1990s, this method has not been tested at an industrial scale (Anton et al., 1996; Cameron, 1997). A detailed description of the MAGRAM process is shown below.

MAGRAM Process Flow Chart (modified from Anton et al., 1996 and Cameron, 1997))

1. Calcining of asbestos mine tailings, crushed dolomite/magnesia, and alumina in a calcining furnace to remove water and other volatile phases. These components are blended in specific proportions so that magnesium can be produced at atmospheric pressure in the next step (slag may contain up to 35% asbestos tailings). Off-gassing products from the calcination furnace are cooled and filtered to remove any possible airborne asbestos fibers.

2. Aluminum-ferro-silicon reductant added to blended calcined feed.

3. Injection of argon gas to the heated DC Arc furnace (~1700 C).

4. Introduction of pre-blended calcined dolomite, asbestos tailings, and alumina with added aluminum-ferrosilicon reductant to DC Arc Furnace through a screw feeder. Sampling monitors are installed around screw feeder to detect accidental release of asbestos fibers.

5. Reaction of magnesium bearing phases with reductant yields magnesium in the gas phase which leaves the top of the DC Arc Furnace through an off gas port to a magnesium condensor. Slag residue and spent ferro-silicon reductant are tapped from the bottom of the furnace when the slag reaches a certain height.

6. Addition of SF_6 and CO_2 to condensed magnesium to prevent oxidation. Pouring of molten magnesium into casts.

7. Combustion of residual magnesium in a combustion chamber followed by cooling and filtering of combusted products from air and release of air.

Relative Costs of MAGRAM

Raw materials account for roughly 50% of total operating cost of MAGRAM whereas power consumption accounts for 20-25% of the total operating cost. Atmospheric pressure operation of the MAGRAM Process may save up to 30% of the operating costs of Magnetherm. If electrolytic methods are generally 10-15% cheaper than pyrometallurgical methods (excluding MAGRAM) and the operating costs of MAGRAM will be ~30% less than Magnetherm (a pyrometallurgical method), then MAGRAM could be competitive economically with electrolytic methods.

Potential Environmental Concerns with the MAGRAM Process

The MAGRAM Process has only been tested in a small scale pilot project that was funded by the Brite-Euram II European Consortium; there have been no known formal Environmental Impact Statement–type studies done for the MAGRAM Process. The following environmental concerns are inferred:

1) SF_6- The potential oxidation of magnesium metal after it has been extracted is an important problem for electrolytic and pyrometallurgical processes. In order to prevent the oxidation of magnesium, the transfer of the magnesium metal from the condensor (MAGRAM) must be done in an oxygen-free medium otherwise the magnesium metal will oxidize to magnesium oxide. SF_6 (sulfur hexafluoride) is a compound that is used as a "cover" gas to prevent oxidation. Unfortunately, SF_6 has a very high Global Warming Potential (GWP). A substitute for SF_6 would have to be found if the MAGRAM process were to be used anywhere in the U.S..

2) CO_2– In the MAGRAM Process up to 35% asbestos mine tailings are mixed with either dolomite or magnesite and subjected to ~1700 C in a DC Arc Furnace. As the carbonate (CO_3) in dolomite or magnesite was ignited in the furnace, CO_2 would be liberated in significant quantities. Conceivably, annual emissions of CO_2 would have to be regulated. The amount of CO_2 could be calculated if the production rate of the MAGRAM plant was known. The size and number of DC Arc furnaces, composition of the furnace feed, (%dolomite/magnesite: %asbestos tailings) and feed rate to the furnace(s) would be important variables in calculating CO_2 emissions.

3) Asbestos Fibers- Since asbestos has already been extracted from the mine tailings, the tailings contain very low levels of asbestos, however, protocols will have to be established to minimize or eliminate human exposure to the minimal amounts of asbestos fibers in dust from the tailings. Human exposure to asbestos-bearing tailings dust could occur during the following stages: 1) the initial transfer of tailings to the calcining furnace for drying 2) the calcining furnace stage if the furnace is not adequately sealed (note: if calcining takes place at temperatures above 600 C all asbestos fibers are destroyed as serpentine minerals are converted to olivine (Deer, W.A. et al., 1992)), 3) removal of calcined products from the furnace and 4) transfer from the calcining furnace to the DC Arc furnace. Appropriate filtration and dust minimization technologies would have to be implemented.

4) Waste Slag- The major waste products generated by MAGRAM would be a low Si Fe silicate, and an inert slag composed of $MgO-CaO-Al2O_3-SiO_2$. No Fe (iron) should be found in the slag since FeO (Fe-+2) would be reduced to Fe (Fe-0). The waste components of the MAGRAM Process theoretically should not require a double membrane landfilling procedure, however, this is uncertain. Dr. Andrew Cameron suggested that the Fe silicate could be sold to the steel or electronics industries. Depending on the slag chemistry Cameron speculates that the slag could be made into road aggregate or used in cement production.

Efficiency Estimates of Magnesium Extraction Techniques

In order to estimate the lifespan of the mine tailings reserves in a magnesium extraction operation, it is important to know the approximate percentage of magnesium metal that can be recovered from the total magnesium in the tailings.

Magnola Electrolytic Process

Based on the non-proprietary information that was disseminated by Noranda in press releases the following approximate calculations regarding process efficiency can be made:

Basic Information
Production Rate 58,000 metric tons of magnesium metal/year
Estimated Longevity of Asbestos Tailings Reserves >300 years
Estimated Weight Percent Magnesium in Tailings 25%
Estimated Reserve of Tailings 250 million metric tons

250 million tons tailings X 0.25 metric tons Mg/ton tailings = 62,500,000 total metric tons Mg in all tailings

300 years X 58,000 metric tons Mg produced/year = 17,400,000 metric tons Mg recovered after 300 years

Efficiency = $\dfrac{\text{metric tons of Mg recovered}}{\text{metric tons of Mg available}} = \dfrac{17,400,000}{62,500,000} \times 100 = \mathbf{27.84\%}$

MAGRAM Pyrometallurgical Process

The exact efficiency of the MAGRAM process is dependent on many variables such as furnace size, composition of furnace feed, and condensor efficiency. One of the inventors of the MAGRAM process suggested that the overall extraction efficiency of the MAGRAM Process "will be comparable with or better than the conventional (Magnetherm) process (A. Cameron, personal communication, 1998)". Since the extraction efficiency of MAGRAM and Magnetherm are comparable, this report will use statistics from an operating Magnetherm plant (Northwest Alloys, State of Washington) to calculate an extraction efficiency that will be applied to MAGRAM.

Basic Information
Production Rate 24,000 English tons of magnesium metal/year
Tons of Dolomite Processed 400,000 English tons/year
Weight Percent Magnesium in Dolomite 17.65%

400,000 tons of dolomite processed/year X 0.1765 English tons Mg/ ton dolomite = 70,600 English tons Mg processed

Efficiency = $\dfrac{\text{English tons of Mg metal produced}}{\text{total English tons of Mg processed}}$ = $\dfrac{24,000}{70,600}$ X 100 = **33.99%**

Percentage of Magnesium Recoverable in the Eden Mills, Vermont Mine Reserves

Magnola Electrolytic Process

Estimated Reserves of Tailings
High Estimate of Tailing Reserve: 75,490,884 English tons
Low Estimate of Tailings Reserve: 48,397,000 English tons
Average Estimate of Tailings Reserve: 62,852,971 English tons

Recoverable Mg Formula: tons of tailings X weight proportion of Mg per ton of tailings X recovery percentage

High: 75,490,884 tons tailings X 0.3057 ton Mg/ ton tailings X 0.2784 ton Mg recovered/ ton Mg processed = **6,424,794** English tons Mg

Low: 48,397,000 tons tailings X 0.3057 ton Mg/ ton tailings X 0.2784 ton Mg recovered/ ton Mg processed = **4,118,918** English tons Mg

Average: 62,852,971 tons tailings X 0.3057 ton Mg/ ton tailings X 0.2784 ton Mg recovered/ ton
Mg processed = **5,349,220** English tons Mg

Using the approximate efficiency of the Magnola Electrolytic Process we can predict total Mg metal that could be extracted from the existing Eden Mills Mine tailings to range from **4,118,918 to 6,424,794** English tons Mg

MAGRAM Pyrometallurgical Process

High: 75,490,884 tons tailings X 0.3057 ton Mg/ ton tailings X 0.3399 ton Mg recovered/total ton Mg processed = **7,844,064** English tons Mg

Low: 48,397,000 tons tailings X 0.3057 ton Mg/ ton tailings X 0.3399 ton Mg recovered/total ton Mg processed = **5,028,808** English tons Mg

Average: 62,852,971 tons tailings X 0.3057 ton Mg/ ton tailings X 0.3399 ton Mg recovered/total ton Mg processed = **6,530,891** English tons Mg

Using the approximate efficiency of the MAGRAM Process we can predict total weight of Mg metal that could be extracted from the existing Eden Mills Mine tailings to range from **5,028,808 to 7,844,064** English tons Mg

Estimated Life of Magnesium Reserves as a Function of Extraction Technique and Production Rate

Magnola Process

<u>5,349,220 English tons Mg</u> Total recoverable Mg calculated from the average tailings reserve.

<u>Mg Metal Production Rates</u>
60,000 tons/year = 89.2 years
50,000 tons/year = 107.0 years
40,000 tons/year = 133.7 years
30,000 tons/year = 178.3 years*
20,000 tons/year = 267.5 years

*production rates < 30,000 tons/year are currently not viable

MAGRAM Process

6,530,891 English tons total recoverable Mg calculated from the average tailings reserve, however, since MAGRAM can process a maximum of 35% asbestos mine tailings in the furnace feed the MAGRAM data will be presented differently than Magnola data.

Annual Tons Mg Metal Produced	Total Feed Wt. (tons)	Dolomite Required (tons) (@65% of feed)	Mine Tailings Required (tons) (@35% of feed = maximum)	Tailings Reserve (years)
60,000	577,478.4	375,361.0	202,117.4	311
50,000	481,232.0	312,800.8	168,431.2	373
40,000	384,985.6	250,240.6	134,745.0	466
30,000	288,739.2	187,680.5	101,058.7	621
20,000	192,492.8	125,120.3	67,372.5	933
10,000	96,246.4	62,560.2	33,686.2	1866
5000	48,123.2	31,280.1	16,843.1	3732

Advantages and Disadvantages of Electolytic and Pyrometallurgic Techniques

Magnola Electrolytic Process

Advantages:
-only proven technology for extracting magnesium from asbestos tailings at an industrial scale.
-once plant is constructed operating costs are relatively low.
-does not require addition of supplementary raw materials to asbestos mine tailings.

Disadvantages:
-electrolytic plants **must operate at very large scales** to be profitable. Hatch and Associates Light Metals Consultants suggest that electrolytic plants with production output of less than 30,000 tons of magnesium per year may not have sufficient specific investment cost justification.

-**very large capital investment** is needed to build a plant. The 58,000 metric ton Magnola facility $720 million Canadian translates at current exchange rates (0.67 USD/Canadian $) to $482 million USD. Investors in the plant include Noranda Inc., Toyota, and the Quebec Government.

-accessibility of **large amounts of relatively inexpensive power** is important. Magnola will obtain their electric power from the nearby Hydro Quebec grid.

-**Magnola Process is proprietary** (Noranda Inc.) and would be expensive to obtain.

-**environmental concerns:** use of hot concentrated HCl, use of global warming gases as "cover" gases to prevent Mg oxidation (SF_6), generation of CO_2, CHCs (chlorinated hydrocarbons), dioxins, and furans during Magnola Process, Silica-iron rejects (waste) have to be placed in a double membrane landfill.

MAGRAM Pyrometallurgical Process

Advantages:

-thermal processes such as MAGRAM can operate at **lower production rates** than electrolytic processes. Whereas electrolytic plants can only economically operate at production rates in excess of 30,000 tons Mg/year, thermal plants could operate at 5000 tons Mg/year.

-**lower initial capital outlay** for a thermal plant as opposed to an electrolytic plant.

-more **environmentally "friendly"** than electrolytic processes.
> 1) does not use concentrated HCl.
> 2) waste products <u>should not</u> have to be landfilled. **Slag may be saleable to road aggregate and cement industries.**
> 3) dioxins and CHCs are not generated by MAGRAM Process.

Disadvantages:

-**MAGRAM is not a proven technology** at industrial production scales. One of the co-developers of the MAGRAM Process estimates 6-12 months of condensor technology testing before industrial scale production could begin.

-**Large amounts of raw materials** must be added to the asbestos mine tailings. The MAGRAM Process can accept a maximum of **35% asbestos mine tailings** that would have to be mixed with **65% dolomite and/or magnesite**. A major source of dolomite or magnesite would have to be located and one would have to transport either the asbestos mine tailings or the dolomite or magnesite.

-**Operating costs of MAGRAM would be high.** Raw materials and power costs are estimated to represent 50 and 25% of total operating costs. Alumina and Ferro-silicon reductants are expensive.

-**Large amount of inexpensive power must be available.**

-A substitute for the anti-oxidation "cover" gas, **SF$_6$**, must be found.

-**CO$_2$ emissions** may have to be regulated.

Recommendations for Further Action

1) Evaluate possible locations for a magnesium extraction plant. Discuss concerns that may arise at each potential site.

2) Evaluate whether an electrolytic or thermal magnesium extraction process is preferable. Because of the environmental concerns it is felt that a large-scale electrolytic plant would not be environmentally viable in Vermont. Pre-consultation with appropriate departments in the Vermont Agency of Natural Resources may be advisable.

3) If it is decided by VAG to further pursue a magnesium extraction facility at a particular site then George Robson of the Vermont Economic Development Bureau should be consulted about the potential for an on-site cogeneration facility.

4) If the MAGRAM Process is to be pursued Dr. Andrew Cameron should be contacted in the United Kingdom about the status of his Research and Development efforts.

5) Possible alliances could be made with companies that would utilize the waste products of the MAGRAM Process for road aggregate and cement.

6) If the MAGRAM Process is to be pursued then nearby sources of dolomite and magnesite need to be found. Perhaps these suppliers would want to make an economic commitment to a magnesium extraction facility.

7) Consult with mining companies about partnerships in the magnesium extraction facility.

8) Invest in a pre-feasibility study with a Light Metals Consultant such as Hatch and Associates of Mississauga, Ontario or Fluor-Daniel of Greenville, South Carolina. Hatch and Associates estimates the cost of a pre-feasibility study at $100,000 USD. These studies would provide detailed information about the economic viability of a magnesium extraction plant in northern Vermont.

Discussions with Light Metals Experts

During the course of investigation for this report a Light Metals expert from Hatch and Associates of Mississauga, Ontario, Canada, a consulting company to the Magnola Plant in Asbestos, Quebec was consulted for some basic information. In addition, one of the inventors of the MAGRAM Process from the United Kingdom was also consulted about specifics of the MAGRAM Process. Annotated (in italics) highlights of these conversations are shown below. These conversations provided **very important insight into the magnesium extraction technology and business**.

Hatch and Associates

Question: What would be the "ballpark" costs of a pre-feasibility study for a magnesium extraction plant at the Eden Mills, Vermont mine?

Answer: $100,000 U.S. dollars

Question: Byron Clow of the International Magnesium Association mentioned that to be economically competitive an electrolytic magnesium extraction plant would have to produce at $10,000 U.S. dollars/ annual ton. Could smaller plants also be economically viable?

Answer: $10,000 USD/ annual ton is the typical capital investment cost to establish an electrolytic magnesium plant of 50,000 tons per year or more. *Electrolytic plants work best economically at very large scales and consequently they demand very large initial investments. The Magnola Plant in Asbestos, Quebec will produce 58,000 tons Mg per year and will cost 720 million Canadian dollars to construct (construction is underway).*

The approximate specific cost of a thermal plant is less, but production costs are significantly greater. MAGRAM is not a proven technology.

Question: Are there other electrolytic processes?

Answer: The Russians have an electrolytic cell that is much cheaper than the Alcan-MPC used in the Magnola Process and this Russian cell can also accept a less pure magnesium chloride brine solution. Hatch and Associates have good contact with the Russians and understand their technology in detail, but none of this information is freely available.

Question: You mentioned that there are a fair number of companies that have a magnesium-bearing ore body such as Eden Mills, Vermont and are interested in magnesium extraction. What are some of the key elements that you believe are necessary before one would even consider a pre-feasibility or feasibility study?

Answer: Power cost is crucial, power prices of 20 mils or better are feasible. Access to natural gas, process water, rail or water transport. The resource characteristics such as cost of mining, leach feed preparation requirements, impurity levels also.

Question: If we could cut the cost of our power significantly with the construction of a nearby cogeneration facility, would that be enough of an advantage to make us competitive at a smaller electrolytic plant size?

Answer: Plants of less than 30,000 tons per year might have a tough time in terms of specific investment cost justification. This would require detailed analysis to make any worthwhile conclusion.

Question: What kind of "ballpark" power needs to be available to even consider such a project in northern Vermont?

Answer: 70-120 Megawatts for a 50,000 tons/year plant.

Dr. Andrew Cameron-MAGRAM Process Developer

BOC Gases Ltd., European Development Centre, Rother Valley Way, Holbrook, Sheffield, United Kingdom.

Question: From my reading it seems that we would need at least 75% of the arc furnace feed to be calcined dolomite that is mixed with asbestos tailings (<25%) along with ferrosilicon and/or aluminum reductants that are added later. We have no nearby sources of dolomite and I am wondering if this would be a major problem. Could the cost of raw materials be prohibitive? The MAGRAM Synthesis Report suggested that raw materials would account for ~50% of total operating costs.

Answer: You are correct in assuming that a supplementary source of MgO is required. The reason for this relates to the fact that MAGRAM is intended to operate at atmospheric pressure rather than the reduced pressures used in the conventional thermal process (Magnetherm). You will be able to deduce from my papers that this is an important improvement brining substantial commercial and technical benefit. To reach atmospheric pressure using a ferro-silicon reductant thermodynamics dictates that you must keep the SiO_2 content of the slag below about 25 wt%. Since serpentine tailings contain large quantities of SiO_2, you are therefore limited as to the quantities of tailings which can be used.

One way around this is to use aluminium as the reductant or to use a combination of Al +FeSi. We have investigated these options in greater detail than you can deduce from the literature (unless you read one of my Ph.D. students thesis). The larger Gibbs Energy change associated with the aluminothermic reduction, combined with the fact that you generate less SiO_2 as a reaction product, means that larger quantities of tailings can be used.

The supplementary feed can be dolomite or magnesite. The quantity required and therefore the amount of tailings incorporated in the process depend upon overall mass balance and composition of the raw materials and slag. The slag composition is rather flexible and can be tailored to suit the available raw materials.

To summarize I would suggest that, at this stage, you assume a maximum tailings loading which would constitute about 25-35% of the mass balance and that you would need either Dolime (dolomite) or Magnesite as a supplementary feed.

Regarding cost, raw materials are a significant cost factor for the process. Nevertheless, we have shown that the flexibility of the MAGRAM process allows raw material costs to be lowered below those of the Magnetherm process. We have licensed the process to a major US producer. They have plentiful supplies of dolime and it is not inconceivable that they would be willing to work with you should a project progress. In other words I would not rule the process out simply because you do not have a local supply of dolime (dolomite). Dolime is in any case the cheapest of the raw materials. The real cost lies with the reductants (FeSi or Al).

Question: What size plant could be viable using the MAGRAM process? We know that a 58,000 tpa plant like Magnola is likely to be out of the question. Could we be competitive at 20,000 or 30,000 TPA or less?

Answer: Absolutely. This is a major advantage of the thermal route. You can operate economically at scales above 5000 tpa. This is largely a reflection of the fact that capital costs for the competing electrolytic technologies are an order of magnitude higher. Going up in scale, we don't really know the answer but the use of D.C. arc technology means that a single furnace could be capable of something in excess of 50,000 tpa. (Magnetherm use submerged resistance heating and are limited to about 5000 tpa from a single furnace). We have MINTEK of S.Africa as willing technology partners. MINTEK are well known in the field of DC arc technology and have used the technology in commercial plants at power ratings well in excess of that needed for a 50,000 tpa plant.

Question: Is the MAGRAM Process ready to use at a larger scale or is anybody using it now?

Answer: No. We need to complete another 6-12 months development before we would be ready for commercial implementation.

The process chemistry is well demonstrated and I have no concerns on this aspect of the process. However, towards the end of the EEC funded project, we ran out of time and funds to complete a key objective of the pilot plant development. This relates to condensation of the magnesium vapor. Operation at atmospheric pressure offers the potential to condense direct to the liquid state (Magnetherm have to condense to solid and then remelt). We have built and demonstrated a condenser at bench scale (a few kg/hr). We have also scaled this up and connected a demonstration unit to the 0.4 MW pilot plant furnace but were not able to run with the fully integrated facility due to the aforementioned timing/funding issues.

The pilot plant and condenser still exist and could be used to complete this final stage of development if we had funding to do it. We are currently in discussion with other interested parties and obviously I would be interested to know if, in principle, your clients might be interested in collaboration/cost sharing to complete the exercise? If we do not progress soon then I suspect we will have to dismantle the demonstration plant and future developments would be costly and therefore unlikely.

The contingency against the new condenser technology failing would be to resort to conventional condensation methods. MINTEK already have some commercial experience of this upon which we could draw. We could also access their larger DC arc pilot plant (4MW or equivalent to a single commercial Magnetherm furnace) to address any scaling concerns.

If you can give me an indication as to your clients thoughts re cost-sharing/ collaboration, then I can provide indicative costs and put them in direct contact with the other parties considering participation.

Question: What is the approximate efficiency of the MAGRAM Process (What is the recovery percentage of the total Mg processed?)

Answer: I can't give a direct answer since this will strongly depend upon condenser yield and the precise chemistry employed (e.g. relative proportions of Al Vs FeSi as well as operating temperature). However to give you some feel for this we could take a case with 32% Asbestos in the feed. This would generate a slag to metal product ratio of about 4.3 (mass for mass) which is the same as the Magnetherm process. The MAGRAM process operates with slags in the periclase phase field, hence the MgO content of the slag is of the order 10-12% compared with 5-6% for Magnetherm. At face value MAGRAM loses out but these numbers are based upon evolved Mg not condensed Mg. Condensation at atmospheric pressure should give yields of about 95% whereas Magnetherm (sub-atmospheric condensation) only yields 80-85% due to air ingress. Overall extraction efficiency will be comparable with or better than the conventional process. The actual figure is in fact relatively unimportant in the context of the process economics. I'll try to dig you out some actual figures when I can find time.

Question: Potentially, we could have an on-site cogeneration facility that would reduce the cost of power (available from the northern Vermont grid) by 35%; this would reduce our power costs below the estimated 20-25% that is estimated in the MAGRAM Synthesis Report. Roughly, how much power would we need to run a MAGRAM processing plant?

Answer: This of course depends on the intended scale of operation. The reduction furnace would be the main power consumer. As a rule of thumb 1 MW of furnace power converts to 1000 tpa of magnesium. (Magnetherm furnaces are typically 4.4 MW and produce ~4000 tpa).

Question: What are the specific waste products of the MAGRAM Process? I assume there would be Fe and Al silicates? Could the waste products possibly be used for road aggregate? The waste products would be a key issue for the Dept. of Environmental Conservation.

Answer: Relative to the alternatives, MAGRAM is very environment friendly. The major co-products would be a low Si content FeSi (saleable to the steel industry or electronics industries), and an inert slag comprising MgO-CaO-Al_2O_3 and SiO_2. No iron would be found in the slag since FeO will be reduced to iron. NOTE THE FeO CONTENT OF THE TAILINGS IS AN IMPORTANT ISSUE AND WOULD PREFERABLY BE LOW.

Dependent on chemistry, you could produce either a slag suited to aggregate or a decrepitating slag which I believe would be suited to cement production. Part of the European Consortium for the original project was a Multi-National Building Products company.

Question: If we would have to calcine the asbestos mine tailings beforehand, is there a way to do this so there are no airborne asbestos fibers?

Answer: I believe this could be done though we only have direct experience at the small scales needed for the pilot trials. Another of our partners was the R&D group for the UK electricity utilities. We were considering a combination of electrical calcination with appropriate filtration technologies as a potential solution for large scale operations. In the final analysis this is a simple engineering issue that would be resolvable.

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Considerations for MAGRAM

1. Location

    A. Proximity to Raw Materials
        1. dolomite or magnesite
        2. asbestos mine tailings
        3. ferro-silicon
        4. alumina

    B. Proximity to Electric Power (Cogen?)

    C. Proximity to Transportation Systems

2. Multi-Market Approach

    A. magnesium

    B. ferrosilicates to steel or electronics industry

    C. slag to cement or aggregates industry

3. Environmental Considerations

    A. Carbon Dioxide

    B. substitutes for "cover" gases needed

    C. Waste Slag – does it have to be landfilled?

4. Access to Technology

    A. Contact Dr. Cameron directly.

5. Basic Equipment

    A. trucks and loaders

    B. screens and crushers(?)

    C. calcining furnaces

    D. DC Arc Furnaces and Condensor Apparatus

    E. Mg Casting Equipment

MAGRAM Method

Annual Tons Mg Metal Produced	Potential Gross Profits (@$1.65/lb Mg)	Raw Materials (RM) Costs (~50%)	Power (PC) Costs (~25%)	Gross Profits – RM+PC	Approximate Power Requirements (Megawatts)
60,000	$210,000,000	$105,000,000	$52,500,000	$52,500,000	60
50,000	$175,000,000	$87,500,000	$43,750,000	$43,750,000	50
40,000	$140,000,000	$70,000,000	$35,000,000	$35,000,000	40
30,000	$105,000,000	$52,500,000	$26,250,000	$26,250,000	30
20,000	$70,000,000	$35,000,000	$17,500,000	$17,500,000	20
10,000	$35,000,000	$17,500,000	$8,750,000	$8,750,000	10
5000	$17,500,000	$8,750,000	$4,375,000	$4,375,000	5

*end of 2nd quarter in 1998 Mg price/pound = $1.65 = $3300/ton (Kramer, 1998)

Potential Gross Profit Per Ton of Tailings Processed

Magnola Process 170.21 lbs Mg extractable/ **ton of tailings** X $1.65/lb Mg = $280.85 USD

MAGRAM Process 207.81 lbs Mg extractable/ **ton of dolomite + tailings** X $1.65/lb Mg = $342.87 USD X 0.4730 (ratio of weight of Mg in asbestos tailings/weight of Mg in tailings and dolomite) = $162.18 USD (Mg from asbestos tailings alone)