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Steel production in an age of 'universal machines'

Part II of a series by Robert Gallagher on plasma technologies just over the horizon.

The first article in this two-part series, "Plasma reactors will end reliance on foreign minerals," discussed how plasma metals processing promises to produce a way to increase steel production over five-fold in the decade ahead, and enable the United States to process domestic ores of aluminum, titanium and chromium. This second part discusses the individual technologies that are within our grasp.

For the industrial revolution that we must build, we can no longer be pinned down to machines that are intrinsically useful for one and only one function. We need machines that can be adapted to produce everything from cement to specialty steel or aluminum. Today, this dream is becoming reality. We stand on the threshold of an age of universal machines.

Below we present in summary form, the plasma technologies that are within our grasp, or just over the horizon. See **Figure 1** for a comparison of these new technologies with existing ones. We begin however, with a description of the Jordan blast furnace iron-making process, by which we can nearly double the output of existing steelmaking capital equipment within a few years.

The Jordan process

Under the process invented by Robert Jordan, Sr., small blast furnaces with a pig iron output-capacity on the order of 3,000 tons per day (one million tons per year), can be converted to double their output, using a pure oxygen blast. The process operates at 2,200°C, 600° higher than conventional blast furnaces, and permits the use of coal in the blast furnaces, obviating the need to construct additional coke ovens. The process produces considerable carbon monoxide, which can be used as a feedstock in other industries.

Converted blast furnaces would have to be relined with higher-grade refractories to withstand the higher temperature (for example, silicon carbide brick). The capital cost is $55 per ton of new capacity, considerably cheaper than building new blast furnaces and coke ovens (about $650 per ton of new capacity).

It is estimated that very few additional basic oxygen steel refining furnaces (BOFs) will have to be built to accommodate the increased load, for the following reasons:

1) BOFs are today run considerably below their capacity. In 1984, for example, only 66% of capacity was utilized.

2) The main limitation on BOF throughput is a materials problem. If the furnace is run as fast as possible, the explosive combustion of the impurities in the molten metal, will destroy the furnace lining. However, these furnaces can probably be relined with new materials, such as carbon-carbon composites used on the surface of the Space Shuttle that must withstand the highest re-entry temperatures. Laboratory furnaces have been built with such linings, capable of withstanding 3,000°C for indefinite periods, and have endured repeated thermal shocks in cooling down to room temperature over a period as short as an hour, with no impairment to future high temperature operation.

By using existing BOFs at full capacity with more advanced ceramic linings, their throughput could probably be doubled relative to 1984 utilization.

An investment of $65 million to convert one 3,000-ton per day furnace to the Jordan process, is immediately required to confirm its feasibility for other furnaces. Because of the limitation of the process to smaller blast furnaces, Jordan reports, it would not be of use in Japan, which committed itself to large, 6,000-ton-per-day furnaces in the 1960s. However, it would be applicable in West Germany, Italy, the United States, India, and elsewhere.

Plasma processes using a reducing agent

Mesabi Metals Project: Pickands Mather & Co., Westinghouse, and Minnesota Power have collaborated in a pilot project at Hibbing, Minnesota for a plasma furnace, with a nominal capacity of one-half ton per hour. The plasma source for the furnace is a Westinghouse plasma arc gun that has a total power of 1.5 megawatts. The plasma is confined by a magnetic field that rotates at 1,000 cycles per second. The system passes a recyclable process gas through the plasma for superheating; the gas serves as the reducing agent. The average energy consumption is about 4,200 kwh per ton.

A Pickands Mather spokesman stated that they are presently orienting toward the market for manganese alloys, but that if the economic climate improves, investment in larger machines will produce low-carbon steel cheaper and more efficiently than the blast furnace and BOF. Future objectives include:

> Design, construction, and operation of a semi-commercial sized demonstration plant to produce 100,000 metric tons per year of hot metal using Minnesota iron concentrates taconite and low cost reductants coal, charcoal, or peat. . . .

FIGURE 1
Efficiency of existing and future technologies

	Energy flux density (watts/m²)	Output per unit energy (tons/GWh)
Enriched uranium		
Gaseous diffusion*	10^7	0.424 kg/MWhe
Atomic laser process	10^{15}	18.5 kg/MWhe
Aluminum from bauxite		
Bayer plus Hall Processes	6×10^4	14.5
Magnetic separation	10^8	185-250
Cement production		
Calcining	10^6	2,300
Tylko SSP	10^8	23,000
Iron and steel		
Blast furnace plus BOP	10^7	200
with Jordan Process	2×10^7	3,400
Mesabi Metals	10^7	235
Eketorp	NA	300
Ashmont Metals	10^8	500
Tylko SSP	10^8	600
Magnetic Separation	10^8	730-1000

*Shaded lines indicate existing technologies.

FIGURE 2
Plasma magnetic separation
output per unit energy (tons/GWh)

Pure iron	
from Magnetite	760-1,000
from Hematite	713-1,000
Aluminum (from alumina)	185-250
Titanium (from TiO_2)	290-400
Hydrogen	40-54
Oxygen	FREE as by-product
	0.88 tons/ton Al
	0.4 tons/ton Fe
	0.66 tons/ton Ti
	8 tons/ton H
Product from 1 ton Wahkiakum Laterite	
Iron	310 lbs.
Aluminum	338 lbs.
Titanium	42 lbs.
Silicon	47 lbs.
Hydrogen	83 lbs.
Oxygen	1,181 lbs.

The Phase I development program currently under way in the pilot plant operation, will lead to the development of a semi-commercial 100,000-ton demonstration plant in the 1987-88 time frame. This plant would be designed in a modular fashion so it could be expanded to a larger, commercial size plant in the 1988-90 period.

Pig irons and shotted iron are the products expected to be initially produced.

Eketorp Hydrogen Reactor: Sven Eketorp of the Royal Institute of Technology, Stockholm, has produced a conceptual design for a direct steelmaking process using hydrogen heated in an arc discharge plasma. Molecular hydrogen is dissociated to atomic hydrogen, producing a faster rate of reduction, through bypassing the slow reduction sequence that occurs in blast furnaces. As a result, hematite ore becomes more economical than in existing blast furnace processes.

Reportedly, his design can compress the throughput of a blast furnace the size of 10,000 cubic meters, into a vessel the size of 1 or 2 cubic meters. The technique would reduce the Greenfield steel plant to the size of a few truckloads of assembly-line-produced equipment. Only the development of available hydrogen sources holds the project back.

In the Eketorp design, the injection of such a low-temperature hydrogen plasma into a 1,600°C molten bath of iron and iron ore, reduces the ore by explosive combustion

FIGURE 3

Capital investment in plasma metals processing versus conventional processes

(Indicated units)

Technology	Capacity (1,000 tons)	Operatives required	Tons output per worker	Capital investment per ton capacity (1985 $)	Construction time (years)
Steelmaking (300 MW)					
Greenfield plant	460	270	1,700	3,000	3
Mesabi metals	600	36	16,000	n/a	2
Eketorp furnace	788	18	40,000	n/a	n/a
Ashmont fetals	1,314	18	70,000	1,000	2
Tylko SSP	1,560	18	87,000	1,000	1.5-2
Magnetic separation	1,920	18	105,000	n/a	n/a
Aluminum (30 MW)					
Hall Process	4.5	30	125	1,000*	n/a
Magnetic separation	48	18	2700	1/2	n/a
Ferrochrome (30 MW)					
Conventional	13	10	1300	750	2
Tylko SSP	130	100	1300	450	1.5-2
Cement (30 MW)					
Conventional Portland cement	604	45	2,860	200	3.5-4
Tylko SSP	6,040	48	26,000	67	1.5-2

* 1986 ** shaded lines indicate existing technology

Sources: Capital investment data for conventional steel and iron making, from U.S. Office of Technology Assessment study, 1980. Ashmost suggests cost of one of their plants to be approximately that of an electric arc furnace plant. Capital costs for cement manufacture from Tylko; for ferrochrome from Rand Daily Mail, inflated to 1985 dollars.

with oxygen. The transformation power (output per unit energy consumption) given in **Figure 2** is simply computed from the heat of formation of H_2O from the reaction:

$$Fe_2O_3 + 6H \rightarrow 2Fe + 3H_2O$$

Energy requirements per ton of pure iron output are estimated to be about 3,268 kwh. However, the capital cost per ton, is low. We at present, have inadequate data on the Eketorp process. Given that its compression ratio is in the range of 5,000 to 1, it may hold more promise than appears at first glance.

Ashmont Metal Plasma Furnace: Ashmont Metals in New York City, headed by Hsin Liu, has developed a laboratory plasma furnace for reduction of ore to any steel alloy desired. Iron ore is fed into the furnace with carbon powder. In the Ashmont design a conical direct-current plasma arc discharge is pulsated with alternating current, producing a non-equilibrium plasma, as described by Jozef Tylko (see box on Sustained Shockwave Plasma). Ashmont applies magnets to confine the plasma. According to the inventor, the process requires only 500 kwh (electric) per ton of product, plus 120% stoichiometric carbon for the reduction to take place (0.18 tons of carbon per ton of steel). It is unclear in what ratio the furnace produces carbon monoxide and carbon dioxide, or how recoverable the carbon monoxide may be. Energy consumption per ton of steel product is in the range of 2,000 kwh (electric and thermal).

Universal machines

An excellent example of the machines of the future is the free electron laser, under development around the world. This is a laser, whose radiation emission wavelength is even more tunable than is your radio, to perform specific industrial-chemical tasks, for separation of any isotope, for catalysis of any chemical reaction. The plasma machines now conceived, are approximating this "tunable" characteristic. Perhaps the most advanced one is the Tylko Sustained Shockwave Plasma (SSP).

The Sustained Shockwave Plasma reactor is the second-generation industrial plasma technology developed by Jozef Tylko of Plasma Holdings and of the Mineral Resources Research Center at the University of Minnesota. In order to explain better its operation, it is best we begin with discussion of the Expanded Precessive Plasma (EPP), Tylko's first-generation technology.

Expanded Precessive Plasma (EPP): Unlike other early plasma torch applications, the EPP is based on rotation of the plasma arc discharge to produce a conical reaction volume, which entrains mineral feedstock fed in from above (see **Figure 4**). The feedstock descends the cone swept out by the plasma, in a logarithmic spiral, maximizing the time of residence in the plasma, and thereby increasing the time for the plasma to act on the material. An EPP plasma rotates at about 1,000 rpm. Since the principle of arc rotation fundamental to the EPP has been adopted by several other plasma torch researchers discussed below, we report on it in some detail.

A research and development report of Foster-Wheeler Development Corp. states:

- the use of conical rotation increases the effective volume of the plasma;
- the rotation creates "*a plasma arc front,*" which entrains the feedstock particles as they descend;
- the entrained solids then follow a spiral path downward, maximizing their time of residence in the plasma;
- the descending curtain of solid particles protects the refractories lining the reactor shell; and
- the process permits continuous processing feedstock and tapping of products.

Sven Eketorp reviewed the EPP technology in 1978 for the Swedish government, which at that time was considering investment in it. Eketorp wrote about the EPP design:

> The EPP process . . . subjects the charge to the special electric and magnetoelectric plasma effects which are expected when material is treated inside a volume of plasma. No other existing so-called plasma processes have these special properties. The EPP process . . . allows for process kinetics to dominate over thermodynamic equilibrium. . . . The radiation emitted by the plasma has catalytic effects.

The process, he writes, enables the use of "minerals and energy bearing raw materials, some of which are today considered useless." Eketorp contrasted the EPP with the University of Toronto Extended Arc Process, and the Bethelehem Steel Falling Film Plasma Reactor, which, he wrote, "merely use the thermal properties of the plasma."

Tylko once explained the plasma action of the EPP in terms of what he calls "a two-plasma model": in one definable portion of the EPP plasma, the energies of the electrons and ions are in equilibrium, but in another definable portion, they are not in equilibrium. This produces more rapid reduction and reaction of the feedstocks. Tylko wrote:

> On close examination of the EPP action, it is convenient to use a two-plasma model. There is present in the "expanded" truncated cone, the background diffused plasma, the so-called thermally equilibrated plasma (because the temperature of the heavy particles of the gas and the electrons are almost the same), and there is also a much smaller volume of the plasma, rapidly spinning and channeling between the solids, and derived from the core of the arc itself. The latter type of plasma is at its periphery thermally non-equilibrated, and is in many respects similar to the plasma formed in shock waves. It is the combined effect of both of these plasmas on the falling particles that is of great importance. As the experimental evidence shows, the solid particles introduced into the EPP in such a manner undergo extremely fast physical and chemical changes. Although the exact mechanism of such changes is not yet fully understood, it appears that not only thermal phenomena are involved.

In the development of his Sustained Shockwave Plasma, Tylko further developed the two-plasma mode of action as follows:

1) he increased the speed of rotation of the plasma, to 1,000 cycles per second; and

2) more important, he pulsates the plasma arc, so that alternating compression and rarefaction waves sweep through the plasma and the entrained solids (see **Figure 5**), producing a plasma oscillation between equilibrium and non-equilibrium states, within that already established by the arc rotation.

With these features, the SSP achieves a high energy efficiency for an arc discharge plasma, requiring only about 1,680 kwh (electric and thermal) per ton of finished steel. Tylko explains the action of the pulsation as follows:

> The following chain of events may be postulated. . . .
>
> 1) The power supply to the plasma is rapidly increased, causing a widening of the arc channel and a rapid increase in the gas temperature of the surrounding atmosphere. This expands or rarefies the gas in the immediate vicinity and drives ahead of it a compression front.
>
> 2) The power supply to plasma is then rapidly decreased, causing a narrowing of the arc channel and decreasing the temperature of the surrounding atmosphere. This action stops the expansion and attenuates somewhat the acoustic wave created at (1), above.
>
> 3) The orbiting plasma arc enters the region through which acoustic waves are being propagated and is

How the 'Sustained Shockwave Plasma' reactor works

The *Sustained Shockwave Plasma* reactor is the second-generation industrial plasma technology developed by Jozef Tylko of Plasma Holdings and of the Mineral Resources Research Center at the University of Minnesota. It is based on the following operating principles:

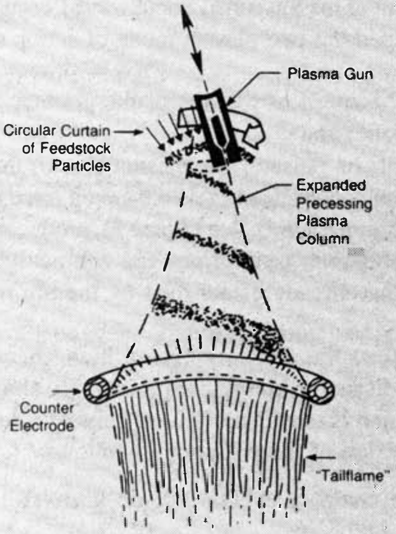
1) Rotation of the plasma arc discharge at 1,000 cps, produces a conical reaction volume, which creates "*a plasma arc front*," which entrains ore particles as they descend; and

2) Pulsation of the plasma arc, so that alternating compression and rarefaction waves sweep through the plasma and the entrained solids.

With these features, the SSP achieves a high energy efficiency for an arc discharge plasma, requiring only about 1,680 kwh (electric and thermal) per ton of finished steel. The pulsations within the plasma increase the reduction reaction rates. Tylko reports that the rate of pulsation can be "tuned" to "resonate" with the material being worked on.

The machine can be used to produce various types of cement, carbon steel, specialty steel, chromium, aluminum, alumina from alumina silicates, etc., and even simultaneously, produce net energy and cement precusor material from colliery spoil waste. The SSP represents a first-generation "universal infrastructure machine."

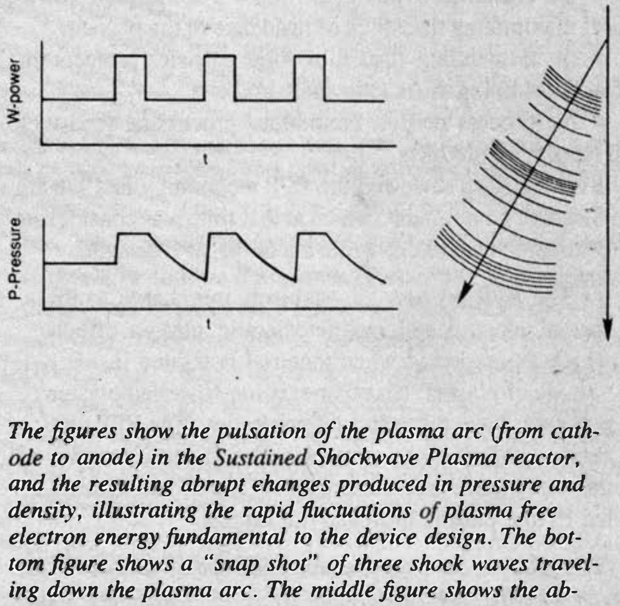
FIGURE 4
Rotation of plasma arc discharge



The diagram shows the principle of operation of the Expanded Precessive Plasma (EPP) furnace invented by Jozef K. Tylko. The EPP is based on rotation of the plasma arc discharge to produce a conical reaction volume, which entrains mineral feedstock fed in from above, longer than were the plasma not rotated. The feedstock descends the cone swept out by the plasma, in a logarithmic spiral. An EPP plasma rotates at about 1000 rpm. The principle of arc rotation fundamental to the EPP, has been adopted by several other plasma torch researchers. The using of the conical rotation increases the effective volume of the plasma, and creates a plasma arc front, which entrains the feedstock particles as they descend. The entrained solids follow a spiral path downward, maximizing their time of residence in the plasma.

Source: Foster-Wheeler Corp., *Heat Engineering*, October 1978.

FIGURE 5
Pulsation of the plasma arc



The figures show the pulsation of the plasma arc (from cathode to anode) in the Sustained Shockwave Plasma reactor, and the resulting abrupt changes produced in pressure and density, illustrating the rapid fluctuations of plasma free electron energy fundamental to the device design. The bottom figure shows a "snap shot" of three shock waves traveling down the plasma arc. The middle figure shows the abrupt changes, or discontinuities in plasma pressure (and density) that occur, and the top figure shows how these phenomena are produced by imposing an alternating plasma current upon the direct current plasma arc.

Source: J. Tylko et al., "Reduction of Lean Chromite Ore Using a New Type Plasma Reactor," in: H.Y. Sohn et al. (eds.), *Extractive Metallurgy of Refractory Metals*, The Metallurgical Society of AIME, 1981.

> substantially affected by such waves. Thus, plasma travels through a compression region, it rapidly approaches equilibrium between its ion and its electron temperatures (T_i is approximately equal to T_e) but where it enters a rarefaction region, a non-equilibrated plasma results (T_e is greater than T_i). The presence of the entrained particles considerably modifies this picture, by introducing new, and intensifying the already present strong discontinuities, that is to say, shockwaves.

The SSP seems to induce resonance-like phenomena among the ore particles being reduced by the rotating, pulsating plasma arc.

> The third characteristic feature of an SSP system lies in its ability to entrain and process large quantities of solid particles. Under normal conditions, arc plasma devices will tolerate only very small amounts of fine powders, and any further additions lead to arc instability and extinguish the discharge. It may be recalled that lifetimes of plasmas are considerably smaller than 1 millisecond, indicating a rough measure of the length of interruption in supplies which could be tolerated. Yet, the spinning and pulsating low-temperature plasma discharge departs markedly from the above; not only are such discharges very stable in the presence of dense particle populations, but also they tend to increase the channeling of the primary arc discharge and provide strong local departures from equilibrium. The reason for this striking behavior, lies in the collective behavior of the particles which act as a "porous plug," that is, a plug permeable to discharge. At the same time, the particles themselves have a dynamically constricting effect on the discharge by reducing the effective cross-section of the discharge channels. In this respect, the moving porous plug of particles behaves as a large number of minute arc-constricting plasmatrons.

The pulsations within the plasma increase the reduction reaction rates, according to Tylko; this may be partly due to the removal of the reaction products. The pulsation also increases the length of time the solids are entrained in the plasma, transforming the path of descent from a simple logarithmic spiral, into a spiral whose fine structure is composed of smaller-scale vortices.

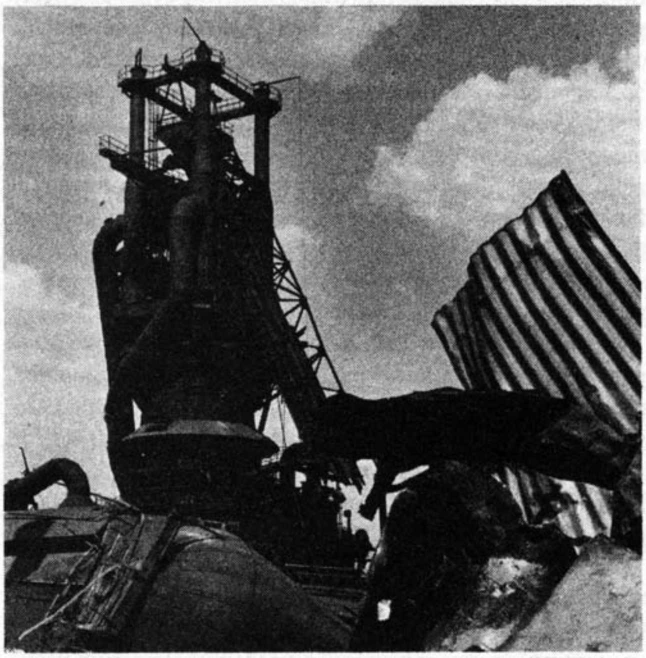
Tylko reports that the rate of pulsation (determining the plasma oscillation characteristics, the divergence between T_e and T_i) can be "tuned" to "resonate" with the material being worked on.

The machine can be used to produce various types of cement, carbon steel, specialty steel, chromium, aluminum, alumina from alumina silicates, etc., and even simultaneously, produce net energy and cement precursor material from colliery spoil waste. The SSP represents a first-generation "universal infrastructure machine."

Low-temperature magnetic separation

In 1969, Bernard Eastlund and William Gough, then at the Atomic Energy Commission, announced the concept of using magnetic separation technology and a fusion plasma source from a controlled nuclear fusion reactor, to dissociate and separate low-grade ore, and even municipal waste, into their constituent elements, for metals and other materials production. The concept, known as the "Fusion Torch," was based originally on merely thermal properties of the plasma, and required, of course, fusion power sources for operation, at a temperature that Eastlund and Gough estimated to be 50 million degrees Celsius. From the standpoint of energy efficiency, for aluminum production at least, it did not appear to offer any significant advantage over the current mainstay aluminum production processes for concentration of alumina from bauxite (the Bayer Process) and the electrolysis of alumina into aluminum and oxygen (the Hall Process). However, Eastlund pointed out that it would make low-grade alumina deposits economical to reduce, enable us to recycle industrial and municipal waste, and for a vast array of materials, free the United States from dependence on foreign sources of supply.

Then in 1972, James E. Drummond, while at Boeing in Seattle, invented a process for magnetic separation of ores at


NSIPS/Chris Lewis

U.S. Steel's National Tube Plant in McKeesport, Pennsylvania, dynamited in April 1985 by its owners, who decided that steel is not profitable in the "post-industrial society." But the technologies are close at hand for a revolution in steel production, which could make America competitive again.

approximately half the energy consumption of the original fusion torch concept, one that could operate at 4,700°C! The result was a magnetic separation process that uses ordinary arc discharge plasmas, or coal burnt at high temperatures, as energy sources to dissociate the compound of the ore feedstock and lightly ionize desired product materials. This development put magnetic separation of low-grade ore into the category of next-generation technology. The process would no longer require fusion power for development, although, like many other industrial processes, would benefit from it.

Drummond showed that for separation of the aluminum and other metals from the process stream (which may include free oxygen or other elements, or molecules), it is only necessary to ionize 1% or 2% of the metal, if its ionization potential (the amount of energy required to strip one electron off an atom in the gaseous state) is about half that of the other element in the process stream from which it has been dissociated, because "a factor of 2 difference in ionization potential can result in a factor of one hundred difference in percentage ionization" of the metal over the oxygen. This proves to be the case for the principal metallic ores, such as hematite, magnetite, alumina, titanium dioxide, titanium tetrachloride, zirconia, aluminum silicate, nickelous oxide, chromium, copper ores, cassiterite (tin ore), and a host of other materials.

It is possible to magnetically separate these metals when ionized to only 1% or 2% for the following reason: in Drummond's words, because of "the very rapid (resonant) exchange of charge between atoms and ions of a single species." In a partially ionized metallic gas, charge continually flows from one atom to another, in a magnetohydrodynamic effect, so that the metals behave as if each atom had, for example, one-hundredth of a charge, and, as Drummond states, "can be regarded as 'partial aluminum ions.'" As Drummond wrote, "Fluid flow, rather than molecular flow exists," and the metal can be drawn from the process stream using magnetic forces. This charge density requires a high magnetic flux to perform the separation, but Drummond has shown that supercooled (cryogenic) magnets can provide the required field with almost no power consumption per ton of product, because their conductivity is so high.

Contrary to the widely held assumption, that high temperatures would optimize magnetic separation, Drummond proved that the opposite is the case. As explained in his 1976 patent, "the lowest temperature, 4,500°K to 5,000°K, for which these ionization conditions hold will be the best." Drummond proposed to confine the plasma with magnets to protect the ceramic lining of the vessel.

Most of the energy required to perform the reduction, is that of dissociation of the molecules of interest (their heat of formation), plus the light ionization. On the basis of this accounting, energy consumption per ton of aluminum product (from alumina) is about 5,420 kwh, or less than one-third the energy consumption of the Hall Process for the electrolytic separation of alumina (16,000 to 20,000 kwh per ton).

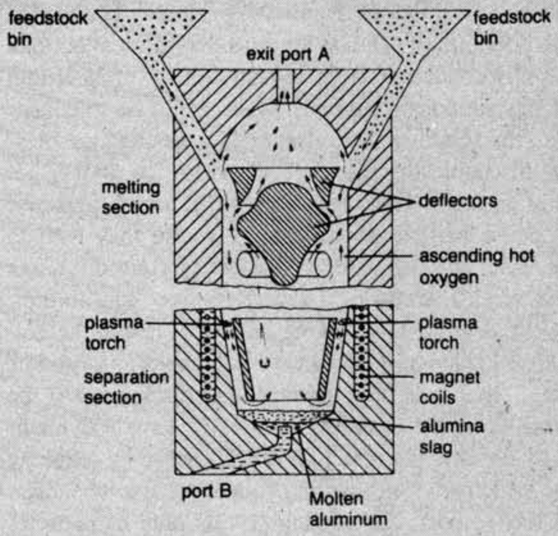
Significantly, in his major patent on the invention, Drum-

What is plasma magnetic separation?

Plasma magnetic separation is a process for breaking ore compounds up into their constituent elements, and separating desired metals and other products with the use of super-cooled magnets. A plasma torch would dissociate a compound, such as alumina (Al_2O_3), into aluminum and oxygen, and ionize about 1% of the aluminum atoms. The lightly ionized aluminum metal behaves as a magnetic fluid, which can be drawn out by magnets. This process can be applied to separation of several metal species from a low-grade ore.

FIGURE 6

Drummond aluminum separation device



This figure shows the engineering design for a plasma torch magnetic separation aluminum reduction machine, designed by J. Drummond, D. Chang, and D. Mahaffey. Alumina is fed in through the feedstock bins, descends through the machine. It is deflected by deflectors into the melting section, where it is liquified by ascending heat. Plasma torches then vaporize the ore and lightly ionize the aluminum atoms in the separation section. Superconductive magnet coils separate the aluminum from the oxygen, which is then permitted to flow upwards through the furnace, transfering its heat to the descending feedstock, and then exiting at port A. Molten aluminum is tapped from port B; an alumina slag floats above molten aluminum.

Source: J. Drummond, D. Chang, D. Mahaffey, "Method and Apparatus for Reducing and Separating One of the Elements from other Elements," U.S. Patent No. 3,942,975, March 9, 1976.

mond proposed the use of an arc plasma rotating at 6,000 to 12,000 rpm, as a means to pump energy into the ore to be dissociated and separated, for the same reasons given by Tylko in his EPP patents, to maximize entrainment of the particles in the plasma. In addition, Drummond argues:

"The conical rotating arc provides a sufficiently long residence time to vaporize solid particles because the vaporization of the leading edge of the particles supplies a force that pushes the particles [still in a solid state—RLG] away from the arc. Thus, the particle will not pass through the arc until it is completely vaporized."

Drummond estimated that his design for "such a machine is capable of producing aluminum at rates to tens of tons per day in an apparatus whose dimensions are measured in meters and using moderate flow rates" (see **Figure 6**). This would be an apparatus in the range of 6-10 megawatts power, a considerable scale-up from the electrolysis pots of the existing Hall Process for the separation of aluminum from alumina.

Boeing was going to develop the process for aluminum production for aircraft, until the company learned that alumina supplies were monopolized by their would-be competition in the aluminum industry. Like the high-temperature gas reactor, the concept was not further developed.

The Eastlund-Gough-Drummond process is not limited to separation of a single molecule species. With rather straightforward engineering, a commercial plant could be built within a decade that could accept low grade ores and dissociate it even into its constituent elements, based on differences in the heats of formation of the molecules, the atomic weights of the elementary constituents and their ionization potentials, as the ore-gas flows through the separation device.

In either application, the hot, ionized products (e.g., molten iron) are cooled via a heat exchanger for co-generation of electricity, further reducing the net energy requirements of the process. Metals could be directed into a continuous casting process, or quenched into powder form for use in powder metallurgy or ceramics manufacture.

The energy efficiencies are the best of all known processes, and are shown in Figure 2, but it must be understood that these are "ideal" figures. For example, they do not take into account the energy required to operate other equipment at the plant, an amount, however, that is a tiny fraction of the energy consumption per ton. In addition, in his patents, Drummond assumed that only 75% of the metal could be effectively separated based on 1972 technology horizons. We have assumed in our figures that 100% could be separated.

Creating new resources

As a concept, magnetic separation has the following advantages over processes using a reducing agent:

1) In ore separation, oxygen is produced as a free by-product, for use in rocket propulsion and in supporting life on the Moon and Mars.

2) There are no restrictions on the quality of the feedstock. The process permits use of low grade ores, and permits elimination of all ore concentration processes, such as the Bayer Process for concentrating alumina from bauxite. Distinct chemical species may be separated out magnetically.

Today, we import most of the bauxite and alumina that we use. In 1973, 91% of U.S. aluminum metal was imported in the form of alumina or bauxite. However, in Washington and Oregon, there exists over 40 million tons of laterite ore that can provide a plentiful source of alumina, but cannot be processed economically by the Bayer Process because its concentration of alumina is too low. In addition, this ore contains large amounts of hematite iron ore, titanium oxide, and hydrogen in the form of water. The table shows how much of these materials can be extracted using a magnetic separation process. For one of these deposits, in just two counties in Washington State (Cowlitz and Wahkiakum, just north of the Columbia River), there exists 25 million tons of ore with the following composition:

Cowlitz and Wahkiakum ore composition

(millions of tons)

	Percent weight	Additional metal reserves
Alumina	32	4.3
Hematite	22	3.9
Titania	3.5	0.5
Silica	5	
Water	37	

Regarding the figures for magnetic separation processes in the Figure 2, note that there is always a range given. The low figure represents the energy transformation power, or productivity, achievable with 32% energy recovery; the high figure, that with 50% recovery. In other words, it is reasonable to assume that at least 32% of the energy can be recovered, and perhaps as great as 50%.

For titanium and aluminum, it was assumed that only 1% ionization (of the first ionization potential) was required; these are two metals for which Drummond had calculated that this was sufficient ionization to separate the materials. For other metals, approximately 5% was used. For hydrogen, only the dissociation energy was assumed to be required, plus a light electrolysis to separate the hydrogen metal from oxygen at these high temperatures.

The technologies discussed above, define the next species of reducing power in intermediate goods production. At the point of application of the plasma torch, they each have roughly an order of magnitude greater energy flux density than existing processes. The future will entail integrating ore separation plants with a fusion plasma source. Beyond that, our task is to mine the Moon, the asteroids and the stars.