# The materials–energy symbiosis

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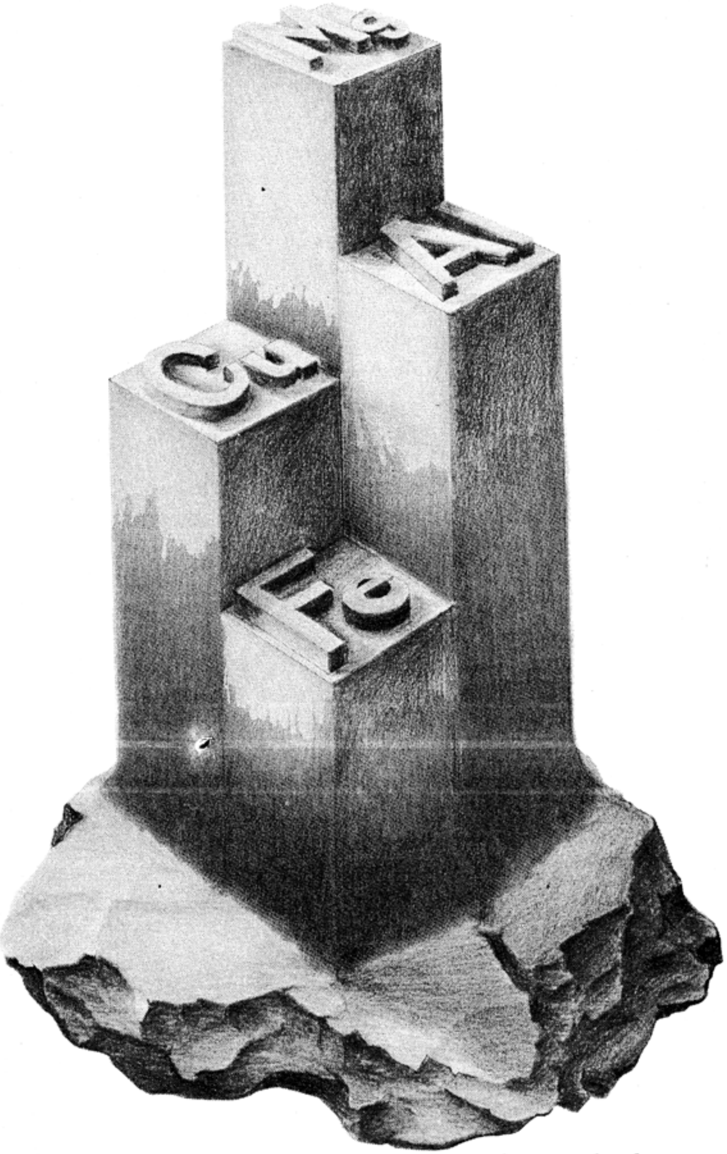

The metals industry is an area in which problems and research opportunities abound. It is estimated that 8% of the nation's total energy consumption is in metals production (*1*, *2*), with the steel industry alone accounting for 5% (*3*). The aluminum industry consumes 4% of total generated electrical energy and at the same time that ores are becoming less accessible, demands on materials are growing (*4*). How well do metals industries make use of energy, and what is the margin for improvement? Table 1 shows efficiencies estimated for aluminum, copper, and steel production (*5*). In the past, cheap energy and an abundant supply of high-grade ores kept the industry competitive. The future may see dramatic changes in both energy costs and ore grade. Yet process changes will be made only if they decrease product cost. It makes no economic sense to design a new copper recovery process that uses half the energy of current methods but requires twice the capital investment, or discharges effluents harmful to health or the environment. Conservation is realized only by a process that saves energy, the environment, *and* capital (*6*). Indeed, energy prices will have to double again before the metals industry can justify changing to new technologies on energy costs alone (*7*). Energy conservation in the metals industry has been studied through energy use patterns (*8–12*), estimates of potential fuel savings (*13*), and identification of R&D areas (*14*). Here I will comment on various aspects of the problem.

The metals industry has taken steps to control and make optimal use of its plant operations. In steel, for example, while there is still room for improvement in primary processing (Table 1), the greatest potential savings are at the finishing end, where reheat furnaces and long-line annealing furnaces consume vast quantities of energy. Energy conversion efficiency has been improved in these furnaces through stack temperature measurement and stack gas analysis (*15*). Furnace redesign to permit monitoring and control of individual burners is desirable.

Control and optimization of primary processing in aluminum and copper is more difficult. In pyrometallurgical processes, the endpoint of the operation is rarely indicated by a temperature or the total pressure inside the reactor. Instead, one must determine the chemical potential or partial pressure of a critical species to identify the endpoint. Exotic transducers don't help in such cases.

One breakthrough has been the development of an electrochemical cell based on a solid electrolyte, which conducts oxygen ions and thus can measure oxygen concentration (*16*). The emf response is rapid and continuous so that the device is useful in feedback control. For example, the sensor can be used to determine the stoichiometric combustion point due to the sharp change in $\mu_{O_2}$ and, hence, the output voltage as the atmosphere shifts from oxidizing to reducing (*17*). Automobile emission control technology relies totally on the ability to measure continuously the exhaust composition by such a solid-electrolyte device (*18*). Among its metallurgical applications are the determination and coulometric control of oxygen in liquid metals, including molten steel (*19*). More recently, solid-electrolyte oxygen sensing has been extended to steelmaking slags (*20*).

The concentration of other dissolved solutes may be calculated from oxygen sensor data provided that these other solutes are in equilibrium with the dissolved oxygen in the molten phase. Rapid progress in minicomputers offers new opportunities to perform on-line analysis of molten metals and thus the use of the sensor in process control. But oxygen is only one of many chemical species of critical importance in endpoint identification.

Many metals, such as copper and nickel, occur as sulfide ores. Unfortunately, no analogous solid sulfide electrolyte exists. Similarly, a solid chloride electrolyte would be useful for monitoring the electrodeposition of metals from molten chloride solutions and the chemical vapor deposition by hydrogen reduction of metal chlorides. Thus the problem of energy conservation through control and optimization of metallurgical processes is often a problem of materials development in the field of sensors. Given a suitable sulfur or chlorine probe, new avenues of dynamic control would open in metals processing. Note that materials occupy a central position in energy research.

**Table 1. Energy efficiencies for selected metals industries**

| Industry/unit operation | Efficiency (%)[a] Direct equivalent (3413 Btu/kWh) | Fuel equivalent (10 400 Btu/kWh) |
|---|---|---|
| Aluminum ingot production | 29.6 | 14.2 |
| Bayer process (including calciner) | 12.3 | 12.3 |
| Hall process | 44.0 | 16.8 |
| Copper ingot production | 3.5 | 2.7 |
| Reverberatory furnace | 43.0 | 43.0 |
| Copper converter | 45.0 | 45.0 |
| Copper refining | 46.0 | 35.0 |
| Steel ingot production | 42.0 | 41.0 |
| By-product coke making | 95.6 | 95.6 |
| Blast furnace | 70.9 | 67.3 |
| Basic oxygen furnace | 89.4 | 87.3 |
| Electric arc furnace | 95.2 | 83.0 |

[a] In comparison to the minimum energy required to produce various materials, efficiency is defined in terms of a First Law analysis as 100 × useful energy output/total energy input.

Greater use of microprocessors and minicomputers offers tremendous opportunities for dynamic control through the combination of spectroscopic instrumentation with digital signal analysis. For example, in oxygen furnace control, gas analysis by means of infrared analysers and mass spectrometers has been attempted. Further control is possible by photometric monitoring of flame characteristics (*21*). In the electrometallurgical sector, there is potential for monitoring such processes as welding, electroslag remelting, and electrodeposition by digital signal analysis of cell voltage with advanced microprocessing equipment capable of performing fast Fourier transformation on-line.

Energy-efficient coppermaking technologies (*9*, *22*, *23*) enter the production chain following the concentration stage. The earlier mining, crushing, grinding, and concentrating operations consume nearly one-half the total energy required to produce copper (*9*). Consider that in the U.S. about 600 tons of rock are moved per ton of metal product. In the course of concentration, for every ton of metal several hundred tons of hard rock are ground to a particle size of less than 100 mesh. As we move to lower and lower domestic ore grades we will have to process even greater amounts of rock per ton of metal and to grind to even finer particle sizes. One potential solution is in situ mining. The process would consist of five basic steps:

- Drilling of injection and production wells in the ore body
- Injection of a liquid or a gas–liquid mixture to dissolve the metals
- Recovery of the pregnant solution
- Purification and recovery of metals from this solution
- Recycling of the barren solvent (*24*).

Because there is no movement of earth, in situ solution mining can decrease capital and operating costs by as much as 50%. There'd be no environmental costs from scarring the landscape through open-pit mining and from tailings ponds. Indeed, mining could be possible in areas normally prohibited. The technology is being used currently for shallow uranium deposits and for copper oxide ores. Kennecott Copper did much to develop the technology for porphyry copper sulfides, which constitute most domestic copper deposits (*9*). At the moment there is no significant research effort in this area. Capital costs for an in situ mining plant are estimated to be two-thirds that of conventional mining and smelting (*24*). Low-grade domestic copper deposits cannot remain competitive with high-grade foreign deposits. Successful development of in situ solution mining would be the technological breakthrough the U.S. copper industry needs at this time.

## Magnesium for cars

At an average $325 \times 10^6$ Btu/ton metal, magnesium is one of the most energy-intensive materials to produce. Yet due to its low density, the use of magnesium in the construction of automobiles would result in net energy savings over the life of the vehicle. If 50 lb of magnesium were used per vehicle, the weight reduction would save gasoline equivalent to 325 milliquads per year (*25*). The critical parameter is net life-cycle energy efficiency, i.e., the difference between the energy conserved in vehicle use and the energy required to produce the component. By this definition, magnesium is by far the most energy efficient of the lightweight materials available for automotive use. Over the 100 000-mile service life of the automobile, one can expect that gasoline savings over iron-based materials will be 50% greater with the substitution of Mg than with the use of Al or plastics. To a first approximation, the use of 2 lb of magnesium in an automobile conserves 1 gal gasoline per year.

The principal barrier to more widespread use of magnesium is its price, when compared to aluminum (1.6 to 1 by weight and 1.1 to 1 by volume). A magnesium price reduction of only 10% would be sufficient for conversion of aluminum die and permanent mold castings to magnesium. Furthermore, the energy required to produce a cubic inch of primary aluminum in today's facilities is 20% more than that to produce the same volume of magnesium. Thus, as energy costs rise, a long-term decline in the Mg–Al price ratio is favored. Even at today's prices, much greater use of magnesium in automobiles is cost-effective in terms of total life-cycle cost to the consumer. It is clearly in our national interest to use more Mg.

We must intensify research efforts in magnesium processing technology (*25*). While energy conservation is important in the primary production of the metal, the main concern is to increase production rates.

## MHD energy generation

The only current advanced technique to directly use coal for electricity production is open-cycle magnetohydrodynamics (MHD). Despite proven scientific principles, long-term high performance has not been demonstrated. The major obstacle in the development of a commercial MHD generator that can efficiently run for thousands of hours is the degradation of the electrode and insulator materials. Conditions inside the MHD channel are severe: temperatures exceeding 1200 °C, corrosive slag-seed melts in contact with the electrode, high thermal fluxes (50–200 W/cm$^2$), Mach 1 gas velocities, and high voltages that can produce localized arcing. In addition, under coal-fired conditions sulfur and ash will be present.

The specific materials requirements for the MHD channel have been described (*26*). Candidate materials fall into two categories: metals and highly conducting ceramics such as perovskite-type oxides. The problem is one of designing a material that can withstand electrochemical attack when covered with molten electrolyte (coal slag containing seed) while conducting electric currents exceeding 1 A/cm$^2$.

One new materials opportunity is rapidly solidified metal, known by the acronyms RS or RSR. Alloys with known corrosion resistance are processed by solidification at cooling rates of $10^5$–$10^6$ K/s. The result is an extremely fine-grained material (2–3 $\mu$m) in which segregation has been greatly reduced. This class of materials is not to be confused with amorphous metals or metallic glasses: RS material is microcrystalline. Significant improvements in corrosion resistance (*27*) and mechanical properties such as specific modulus and specific strength (*28*) are reported. The exciting feature from the point of view of MHD is that at high temperatures grain growth is greatly retarded, and the alloys continue to show extremely high oxidation resistance (*27*). Because the electrode stability problem occupies a critical position in the entire MHD energy program, the potential of rapidly solidified metal in this application should be aggressively pursued.

We must keep in mind that the

- Relationship between materials and energy is very complex.
- Production of materials consumes vast quantities of energy.
- Exploitation of new energy sources and conservation of energy in existing processes rely on advances in materials development.

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**JOHN STUART MILL (1806–1873)**

**The habit of analysis has a tendency to wear away the feelings.**

**MARSHALL McLUHAN**

**When this circuit learns your job, what are you going to do?**