Steel Research — Then, Now and Tomorrow: The 2012 Brimacombe Memorial Lecture

In this paper, the link between research that is focused on process improvement (know how) and research that is fundamental in nature (know why) will be discussed. The role and importance of both types of research in the steel industry will be discussed (know why and how).

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Professor J. Keith Brimacombe was an innovator. He believed that knowledge transmittal, from universities to industry and from industry to universities, was the key to work that had impact. Keith, his colleagues and students did fundamental work, but always for a reason that had practical implication. His group's work in the laboratory or on the computer ended up solving a problem in a plant or giving direction to a process. In this paper, the link between research that is focused on process improvement (know how) and research that is fundamental in nature (know why) will be discussed. The role and importance of both types of research in the steel industry will be discussed (know why and how). Potential future directions in research will be driven locally and globally, and future partnerships among universities, governments and industry will be necessary, as only radical process innovation can solve the challenge of mitigating the environment's effect of steel processing. Future drivers of large-scale steel research and development may require the solution to a number of imposed external constraints and, based on these external constraints, we must determine what must be done next.

Introduction

Professor James Keith Brimacombe's life and achievements have been well documented in the book written by Professors Henein and Samarasekera.[1] Professor Brimacombe was not only a distinguished professor at the University of British Columbia, but was president of the Canadian Institute of Mining and Metallurgy (CIM), the Minerals, Metals & Materials Society (TMS) and the Iron & Steel Society (now AIST). He won 31 major national and international awards.[2] Most of all, Keith is remembered by his friends for his caring nature, his understanding that one should enjoy the time spent with others, his wish to improve everything and, of course, his sense of humor.

I first met Keith when I was a graduate student at the University of Pennsylvania, when he presented his latest research on the continuous casting of steel. Later when I joined Inland Steel in 1979, I met Keith again as he was working on a concept called "cooling with time" — the view that secondary cooling should react to the thermal history of a slab and that spray patterns in a continuous slab caster should be controlled to allow each slab segment to receive the same cooling history regardless of variation in casting operation — for example, during ladle changes. I was very interested in this work and was given the job of overseeing the success of the plant trials, run by Keith's student, Steven Hibbins.[3] This project led to a professional and personal relationship with Keith that lasted until Keith's early demise. In 1987, Keith asked me to join the Brimacombe Continuous Casting Course, and for the last 25 years I have gone to Vancouver and taught this course, which is now given in his memory. It was in this course that Keith's belief that knowledge transmittal, from universities to industry and from industry to universities, as the key to work that had impact, was implemented.

Keith always had many great quotes, such as: "If you wish to hide your work, publish it in a peer-reviewed journal." This was Keith, tongue in cheek as always, pointing out that the professor's job was not over once the work was published, but, in fact, to have impact, the next step was to teach others about the meaning of the work. For Keith, the others were the people in the plant who were responsible for operation of the machines and responsible for product quality. It was due to this belief that Keith not only conducted world-class research, but also spent a significant portion of his time traveling to steel plants and giving classes to those who have the responsibility for technology implementation. Keith understood that, in a world where technology is available, the key to differentiation is the ability to operate the technology using the state-of-the-art knowledge that is available. Keith believed that education was the key to any world-class operation, and while "know how" could be purchased, it allowed one only to repeat, in a very prescriptive manner, past practices. Keith believed in "know why" — the ability to understand the fundamental reasons for an occurrence — and spent his time teaching the art and science of "know why and how." As a researcher, Keith always wished to "know what" must be accomplished and to "know when" it is possible to accomplish a goal, given realistic constraints. This led him to large projects that required three entities working together: government, industry and the university. Keith believed in "informed decision making," to allow one to move forward and take technology into areas that had not been previously thought possible and to avoid practices that were deleterious to operation. This view allows one to have the ability to "know why, how, what and when."

In this paper, I will explore the concept of "know why, how, what and when," and its meaning and application in the steel industry of today and tomorrow.

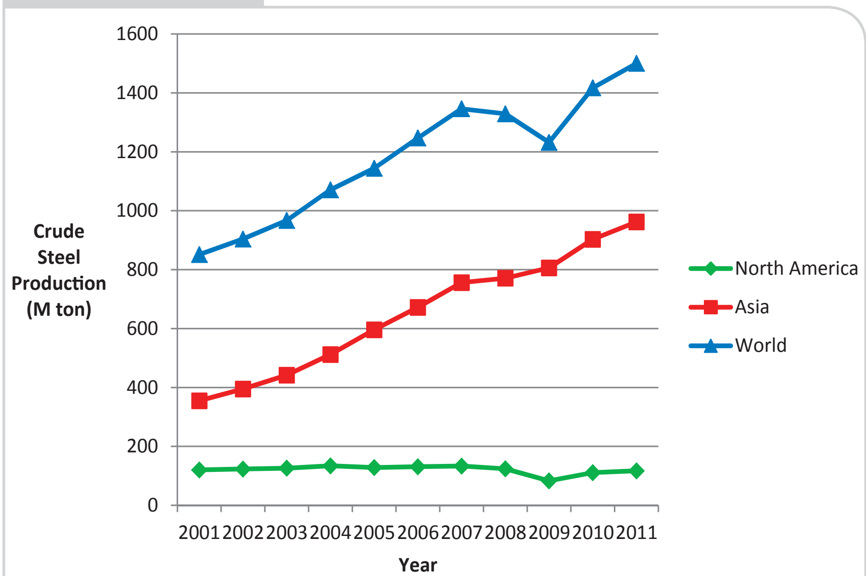
Steel Production and Its Place in the World

To understand steel production, one must also understand the fundamental forces that drive the industry. One makes a product that is remarkably cheap (by weight) and with a full range of properties that allows its application to continuously grow, as humanity's numbers increase. Steel is a fundamental part of civilization — it is a major part of our urban infrastructure, our ability to build industry and our transportation dynamic and, as such, its use and need grows with our population and, most recently, the need for infrastructure development in Asia.

In 1979, I attended a lecture by Father William T. Hogan of Fordam University, where he predicted an enormous increase in world steel consumption based on the potential growth of both China and India as world economic powers. While he was not immediately correct, over time his view was validated and steel production and consumption have grown significantly in the last 10 years. In 2010, crude steel production, according to the World Steel Association,[4] was greater than 1.4 billion tons (Figure 1). As can be seen in Figure 1, the amazing growth in steel production and consumption is due to growth in Asia, in particular in China and India. From 2001 to 2010, China's crude steel production has increased from 152 million tons to 626 million tons. This is an increase of 52 million tons a year, or the equivalent of adding the integrated production capacity of the United States, each year, for nine years! The effect of the financial recession on steel production can also be clearly seen in Figure 1, where decreased production outside of Asia led to a decrease in world steel production, but only a lower rate of increase in Asia.

There were roughly 6 billion people in 1999 and 7 billion people in 2011. In 2001, we produced approximately 0.14 tons of steel per person and, in 2010, approximately 0.2 tons of steel per person across our planet. However, steel consumption is not even across the globe; in the United States, for example, in 2010 we produced approximately 0.36 tons per person. Father Hogan argued that as Asia developed infrastructure and industrialized, their steel production would tend toward that of the United States. In this he was certainly prescient, as China's production per

Figure 1



Total crude steel production (from the *Steel Statistical Year Book,* 2011, World Steel Association[5]).

person has grown from 0.11 tons per person in 2000 to 0.46 tons per person in 2010. We have also seen a massive infrastructure growth in China, driven by the largest migration of people from the countryside to cities in the history of mankind. India, within the same period, has doubled its crude steel capacity per person to 0.06 tons per person and, if a similar infrastructure expansion were initiated in India and India's consumption were to grow to that of China, another 600 million tons of crude steel production would be necessary. However, as Father Hogan's predictions of 1979 took 30 years to come to fruition, perhaps it will take another 30 years for this to happen.

Thus, the steel industry is of a very large scale, where units of millions of tons are reasonable. There are few other industries that are comparable from a raw material standpoint. The cement/concrete, coal/oil and glass industries are other examples of industries that use or produce raw materials in such volumes or weights. Again, these are industries that supply infrastructure or infrastructure-related concerns, and they are directly related to certain basic needs of mankind — heat, shelter and transportation.

Of course, once one wishes to "know why," one is on a path to enlightenment. While one could follow the Dalai Lama and consider the general meaning of enlightenment,[4] here we must consider only a rather more focused view of enlightenment, that of the physical world, explained by physics and chemistry and described in the language of mathematics.

The reduction of the various forms of solid iron oxide by carbon to solid iron can be represented by fairly simple chemical reactions and at temperatures above 570°C, according to the classic work of Darken and Gurry.[6] The reduction reaction sequences follow:

$$3\,Fe_2O_3(s) + CO = 2\,Fe_3O_4(s) + CO_2$$

(Eq. 1)

$$Fe_3O_4(s) + CO = 3\,FeO(s) + CO_2$$

(Eq. 2)

$$Fe_3O_4(s) + 4CO = 3\,Fe(s)$$

(Eq. 3)

$$FeO(s) + CO = Fe(s) + CO_2$$

(Eq. 4)

$$FeO(s) + C = Fe(s) + CO$$

(Eq. 5)

In the above reaction paths, either carbon or carbon monoxide is the reductant. The following reactions account for the production of carbon monoxide:

$$C(s) + \frac{1}{2}O_2 = CO$$

(Eq. 6)

$$CO + \frac{1}{2}O_2 = CO_2$$

(Eq. 7)

$$C(s) + CO_2 = 2CO$$

(Eq. 8)

Both direct and indirect reduction are possible and, in the blast furnace, both reactions can occur; however, in order to understand this process, one must understand both rate kinetics and transport processes. One must also take into account that carbon has solubility in iron. Thus, the following reactions must also be taken into account, and the iron carbon phase diagram also becomes important:

$$Fe(s) + C(s) = \left(Fe - C\right)_{sat,T}$$

(Eq. 9)

$$\left(Fe - C\right)_{alloy} + CO_2 = 2CO$$

(Eq. 10)

$$a_c\left(alloy\right) = \frac{P_{CO}^2}{K_{eq,T}P_{CO_2}}$$

(Eq. 11)

At 1,153°C the solubility of carbon in equilibrium with graphite is 4.3 wt. % and this is the eutectic temperature in the Fe-C phase diagram.[7] At temperatures above 1,153°C, instead of solid iron, a liquid iron-carbon alloy will form. This is very important, as the reduction process is now also a separation process, where the liquid iron-carbon alloy will separate from the ore spontaneously under the action of gravity, and a process for the continuous production of liquid hot metal (the liquid from a shaft or blast furnace which is saturated in carbon) is possible. In addition to producing liquid hot metal, to allow a continuous process, all gangue material must be transformed into a liquid by the addition of fluxing agents. As silica and alumina are the major gangue components from the ore, the addition of lime to the process allows another low-melting-point liquid — a calcium alumino-silicate with varying amounts of FeO — to form and also spontaneously drain. Fortunately, liquid slag has a significantly lower density than liquid hot metal and the liquid slag floats on top of it.

The process of iron production from an ore results in either a mixture of solid iron (with varying carbon content, depending on temperature and gas composition) and a solid gangue material at processing temperatures below 1,150°C, which then must be physically separated, or a liquid iron-carbon alloy which self-agglomerates, separates and can be directly cast or transported into a refining vessel at temperatures above 1,150°C. Thus, the blast furnace became the most important process for producing an alloy containing more than 95% liquid iron.

Table 1

2006 Energy and Carbon Footprint[8]

	Primary energy use (trillion Btu)	Total combustion emissions (million tonnes carbon dioxide equivalent)	Energy percentage	Emissions percentage
All manufacturing	21,972	1,260	100	100
Steel industry*	2,468	119	11	9
Chemicals	4,519	275	21	22
Forest products	3,553	138	16	11
Petroleum refining	3,546	244	16	19
Transportation	904	53	4	4
Aluminum	603	36	3	3
Food and beverage	1,935	117	9	10
Glass	466	26	2	2

*Includes iron and steel, fabricated metals and foundry.

Although there are significant markets and uses of cast iron, the properties of cast iron make it impractical for many utilitarian needs of society. There is a need to reduce the carbon content and add more alloying elements in a steel refining process, usually in a ladle before casting. In addition, like aluminum, the properties of steel alloys are determined not only by chemistry, but also by deformation processing after casting. Manipulation of the amount of deformation and the processing temperature is used to control product structure and the distribution and size of non-metallic particles within the steel. Therefore, deformation processing leads to the ability to have varying product properties from the same grade chemistry. In the days before the invention of the term *nano-engineering*, metallurgists were already manipulating product properties by control of structure at the nanoscale. Aluminum and steel alloys were the first true bulk nano-materials.

Direct reduced iron (processing at temperatures below the eutectic temperature) must be further processed to produce steel in a usable form and is often used as a feed material in the steel recycling route. Of course, steel is probably the world's most recycled material (by weight). For example, according to the Steel Recycling Institute, in 2011 in the United States approximately 73 million tons of steel was recycled, versus 50 million tons of paper and 4 million tons of aluminum. Recycled steel, whether in an electric furnace or in traditional steelmaking, is a major source of the steel produced in North America. In North America in 2011, approximately 62% of the steel produced was recycled steel.

Of course, no general discussion of steel production would be complete without a discussion of energy. The energy bandwidth survey[8] commissioned by the U.S. Department of Energy (DOE) uses data from the studies of R.J. Fruehan and J.R. Stubbles to determine the current and minimum energy usage of the steel processing route. The DOE also commissioned Energetics Inc. to develop energy and carbon footprints for all sectors of manufacturing.[9] Data from this study are shown in Table 1.

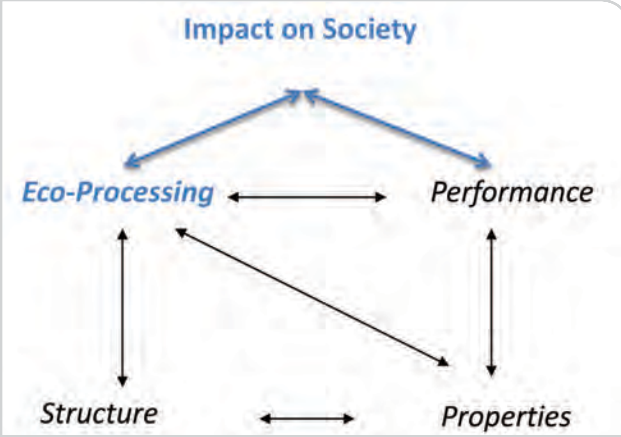
As can be seen, according to Energetics Inc., the steel industry accounts for 11% of the energy utilization and 9% of the carbon emissions of all manufacturing in North America. If energy use is scalable, using North America (this will lead to a conservative estimate, as North America is a stronger recycler than any other area) and assuming that the world energy consumption in 2010 was approximately 510 Quad Btu,[5] then the steel sector is responsible for approximately 6–7% of the world's energy use. According to the U.S. Energy Information Administration, in 2008, 52% of the world energy consumption was industrial, 27% was in transportation and 14% was residential; however, 41% of energy used in the U.S. was used in buildings.[6]

If we look at the steel industry globally, it is a major part of the advancement of our civilization in that steel is one of the most-used materials in utilitarian products — transportation, home goods, buildings and roadways. However, it is also a major part of our growing concern over two of the major issues of today: energy consumption and our impact on the environment through industry (Figure 2).

Steel's Future

There are many views of the future of the steel industry. But it is clear that the future we must consider is one in which the industry is not only a producer of a material broadly used across the world, but also part of the solution to our man-made problems. Already in Japan and Australia, we are seeing the steel plant become a recycling center, not only for steel but also for plastics and other materials. This must, of course, be part of our future, where our ability to work at high temperatures and capture and control hot gases can be used for common good to solve issues of pollution and landfills. This is the view of the steel industry as

Figure 2



The new paradigm for steel research must include the impact of processing and materials on society.

a partner in a community that can solve significant local issues.

Obviously, the steel industry can focus on the efficiency of production and minimize the energy needed per ton of production. It can also minimize the amount of carbon- and sulfur-bearing gases that are emitted into the atmosphere, as well as adequately controlling and transforming all of the varying waste materials of the steelmaking process into useful products. Slag recycling from blast furnaces is already common and used in the process that results in new or refurbished roads — for example, in the state of Indiana. However, if steel utilization is a direct function of the numbers of people on the planet, another view would be to develop steel products that are lighter, stronger and more ductile to allow less steel to be necessary for every application and to think of a world where steel utilization was not a function of population. Of course, the need for infrastructure — homes, roads and transportation — is a major driver of steel's relationship to population; thus, such goals will be very difficult to achieve when economics are considered.

There have been many efforts to make steel production more energy efficient and to decrease the impact of steel production on the environment. For example ULCOS, which stands for "Ultra Low CO_2 Steelmaking," is a very large project supported by the European Union and has as its aim "to reduce carbon dioxide emissions of today's best routes by 50%."[12] ULCOS is aimed at efficiency in process selection, with a view to reduction in carbon dioxide emissions; thus, total emissions will still increase with increased production.

It is instructive to review the process routes chosen in the ULCOS project, not to study each process but to define the potential of each process. The ULCOS project has defined four processes for steel production and three necessary breakthrough technologies in order for these technologies to make their ambitious goal:

1. CO_2 capture and storage at the site of steel production.
2. The use of electricity that is produced by an alternative energy source, other than carbon.
3. The conversion of CO_2 to a biomass and then use of that biomass either as a feedstock to another process or directly back into the steelmaking process as a fuel (note that process #1 is a necessary precursor to process #3).

Breakthrough technology #1, when combined with #3, suggests that a carbon cycle should be developed for an operating steel plant. The natural carbon cycle, the obvious model, is not effective at the production capacities necessary for a modern steel plant. A new technology for rapid production of biomass of some kind is necessary. Sequestration by reaction will just exacerbate the landfill issue, which is probably not a long-term solution, while injection of CO_2 into deep wells assumes that leakage can be avoided. Breakthrough technology #2 needs an alternative energy source at a price point where it is competitive with current carbon-based sources and in sufficient supply so that it is available to the steel plant to allow comparable production rates as today.

Increased recycling of steel can minimize the issue of both energy and environmental impact compared to the integrated route; however, this electricity-based route would be significantly more beneficial if breakthrough technology were widely available.

Thus, we *know how* to make steel, we *know why* the process works, and we *know what* we would like to accomplish, but to *know when* this will be possible lies in our ability to understand realistic constraints.

The world of realistic constraints includes such issues as:

1. Is a new technology necessary to be developed for the process to work (rapid production of biomass from a mixture of CO and CO_2, for example)?
2. Is the marketplace willing to accept the price of a new process as part of a product price increase?
3. Is there government policy or taxation that affects the viability of a process — either through environmental (Clean Air Act?) or economic legislation (carbon tax?)?
4. Are there local regulations or conditions that affect economics (state subsidy for energy or lax environmental regulation?)?
5. Are there prevailing political or emotional issues in the geographic area?

One could continue with realistic constraints; however, it is clear that any solution in the future is not necessarily related to simple technical concerns. For example, let's look at the issue of energy, its price and the effect on the environment. Exelon, one of the major energy companies in the U.S., with a focus on alternate sources of energy to carbon, has a large nuclear fleet within its energy production capability.

As an energy company, it probably produces low greenhouse gas emissions among energy companies in the U.S. Exelon 2020,[13] their plan for the future, includes a very interesting discussion, in the 2011 update of the plan,[14] regarding the effects of various clean air regulations on the price of energy. As clean air regulations have the potential to radically change the competitive nature of not only energy producers but also steel production facilities, it is instructive to look at the view from the energy sector:

1. Natural gas prices and supply will dominate energy pricing in the near future, as it is a cleaner fuel (less SO_2, NOx and Hg than coal-based production units) and produces less CO_2 than coal.
2. The economic upsets of the past five years will slow the growth rate of energy consumption in North America.
3. Federal and state policy and regulation with respect to clean air standards will significantly affect which technologies can and will be implemented.

Exelon presents a number of scenarios in which, depending on one's assumptions of the effect of environmental regulation, the cost of energy and the technologies that must be implemented will change dramatically. Of course, the future from Exelon's view includes increased energy production from natural gas to allow retirement of coal-based facilities, improved efficiency of nuclear power generation and increased use of wind power. There is also a significant increase in the cost of delivered energy in any future strategy, as increased wind energy, retrofitting of coal plants to enable clean standards to be achieved, increased investment to increase efficiency of energy production and increased solar energy use all include significant increases in the price of delivered energy.

As every politician states, energy efficiency is important in the future, as more efficient use of energy will slow the growth of energy production. However, this is a cultural as well as technical issue. Although technology can affect production efficiency, patterns of use will be determined by personal choice. Will North Americans decide to live in a home that is significantly warmer in the summer than it is in the winter? Currently, many choose to set a home temperature that is close to constant throughout the year. Great energy savings are possible by setting thermostats to approximately 65°F in the winter and approximately 75°F in the summer both at home and in the workplace. Can we turn off the lights, drive less in smaller cars, walk more and take public transportation? Again, these are realistic constraints not easily controlled, as they are both cultural and technical.

Even in a general discussion of the future of steel, the big questions are not primarily metallurgical but also societal. One must view the steel plant of the future as an integral part of the community — one that contributes positively to both the local and global environment, one that is viewed positively by its surrounding community, and one that is a partner with local and national governments in solving issues related to the growth of the world's population. As a civilization, we need to solve the basic issues of transportation, provide healthy habitats, control energy consumption, ensure a sustainable environment and provide health care at a reasonable cost. As a major material producer that has an impact on all phases of our civilization, the steel industry has and will have a major impact on our future.

Given this background and accepting the importance of steel, it is important to think about steel research over time and to predict the future directions for steel developments. One could begin by recounting the history of steel; its beginnings in Africa, India, Japan and China; its growth to industrial prominence and mass production in Europe and the U.S. in the early to mid-20th century; the metallurgical developments of the great laboratories of the '60s in the U.S. — the Bain Laboratory of U. S. Steel and the Homer Laboratory at Bethlehem Steel, for example; the subsequent dominance of Japan in technological process development in the '80s and '90s; and the amazing growth of Chinese production in the last 20 years. Yet here I will focus on the potential drivers of technological development.

The major driver of technology development in the steel industry was and will be economic. It should be remembered that the first executive of a major company to be paid US$1 million per year (E.G. Grace) in the United States was a steel executive and that Andrew Carnegie developed his massive wealth by building United States Steel Corporation. When Ken Iverson was asked, "What is it your company makes?" his answer was, "Money!" The future of steelmaking must always include competitive product pricing. We see those companies that control raw materials and their costs becoming very strong, as most companies now have very similar technological prowess.

Current steel research includes the ULCOS project and the Future Steel Vehicle project,[15] which is to "demonstrate safe, structurally efficient steel bodies that reduce GHC emissions." Both are aimed at the issue of CO_2 and are global projects, indicating the power of external stimulus on current steel research and development.

Let's assume that world events in energy and the environment will be a major driver of steel process research in the coming years and anticipate potential trends and the technology necessary for such developments.

Carbon Dioxide Minimization — There are two opportunities for carbon dioxide minimization during steel processing: reduction of CO_2 emissions into the atmosphere during integrated processing, and reducing the amount of integrated production by recycling. In the steel product world, one could develop stronger and more ductile steels and include these new alloys in the product design phase to minimize the impact of steel products on CO_2 emissions. This second view is that one should decrease the volume and thus the weight of steel used in a given application. Another approach would be to develop composites containing steel that would have the same volume but a smaller composite density.

From an ecological point of view, the ultimate goal would be zero emissions, which suggests complete capture of all gases from both ironmaking and steelmaking. The captured gas would be cleaned, cooled and then the carbon in the gases transformed either into an externally sold product or a fuel to be used within the process. Of course, it would be best to develop a process that does not lead to landfilling, as landfill costs continually increase, and sequestration by forming carbonates certainly solves the issue of carbon capture but does not solve the problem of disposal.

Use of the offgas also has its challenges: solid particulates must be removed, sulfur must be captured and removed, temperature must be reduced, and the correct CO/CO_2 ratio must be developed in the offgas. There is a potential for hydrogen production via the water gas shift reaction:[16]

$$CO + H_2O = CO_2 + H_2 \quad \text{(Eq. 12)}$$

This could lead to the potential for energy production using fuel cells; however, this low-temperature and low-rate process does not solve the problem of CO_2.

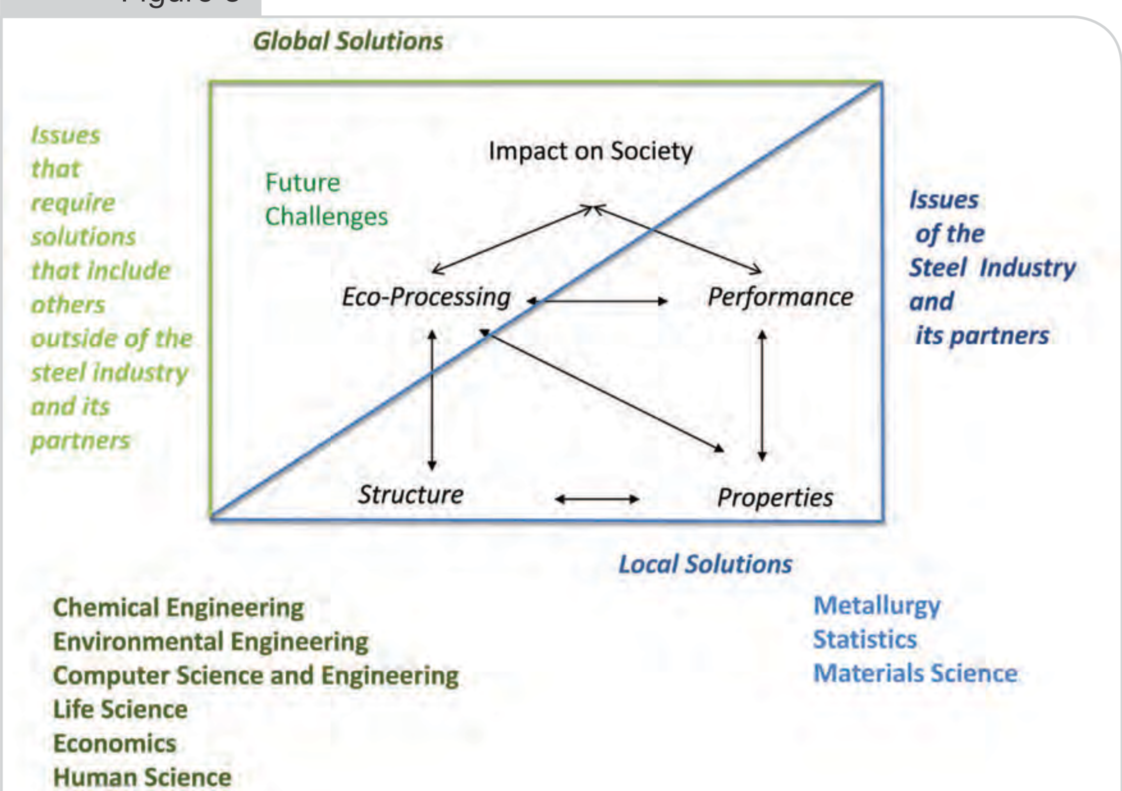
The Carbon Cycle for a Steel Plant — Input carbon in the steel plant is from coal, coke, natural gas and fuel oils. The burning of these fuels allows the energy input necessary to increase the temperatures to the range necessary for high-speed reduction reactions and the formation of a liquid product. Some carbon remains in the steel as part of the alloy; the rest is released as various forms of carbon that is unreacted during the process or as CO, CO_2 and COS. Thus, completion of the carbon cycle requires that gaseous carbon is returned to either a liquid or a solid form.

There are a number of opportunities:

- Production of solid CO_2.
- Production of solid carbon.
- Decomposition of CO gas via the Boudouard reaction: $2CO = C\ (s) + CO_2$.
- Precipitation from a liquid metal by thermal fluctuation close to carbon saturation.
- Formation of algae or plant products.
- Formation of hydrocarbons from CO and H_2 (isosynthesis).
- Formation of carbonates.
- Dissolution in water or other solutes.

The appropriate method will be determined by both technical and economic feasibility; however, direct production of hydrocarbons is interesting, as they can be used directly in the process as a fuel, and formation of algae allows for vertical integration and the potential for fish farming (tilapia, for example).

Figure 3



Global solutions require global thinking.

If we look at what must be accomplished, we can see that we need to develop some fundamental knowledge (know why), develop some technologies and operate them at the industrial scale (know how), and only then will we be able to determine when this will be possible.

In the past, our research was focused on knowing what was possible with steel as a material — the determination of economic processing routes for steels of defined properties (know why and how). However, our future will be defined externally by the necessity to control our impact on society — the world of realistic constraints imposed by regulation. While regulation has always been a part of the industry, it is clear that regulation could dominate the industry in the future and completely change the economics of the industry. The solutions to steel industry issues lie not within the steel industry, but outside of the industry. If we look at the opportunities listed above, all require research and development in areas that are not traditionally associated with the steel industry. For example, the skill set that can lead to potential solutions sits in the life and physical sciences, in chemical engineering rather than materials engineering, and requires thinking that is global rather than local (Figure 3).

Steel Research Trends

As discussed above, one future for steel research is based on an external influence — the issues of energy, the environment and government regulation. There are other external factors that can drive steel research and developments:

- The cost of manpower.
- The cost of transportation.
- Variability in raw material supply.
- Local influences related to geography.
- The development of new processing technology.
- Availability of a cost-competitive alternative material.
- The development of new steel alloys and products.

Many of these drivers lead to local solutions rather than global solutions to issues.

There are also internal factors that can drive research and development:

- Plant efficiency improvement through increased yield and decreased energy utilization.
- Improved product quality aimed at improved customer satisfaction or increased market share.
- New grade development to increase either profitability or market share.
- Customer partnership to develop new product opportunities.

These drivers tend to also be local and of a smaller scale.

We can also look at these research issues in two other ways: product development or process development. One could argue that these two issues are inextricably linked — there are no new products without the development of the process that allows them to be fabricated. But often, a new process leads to the potential for a different product than previously developed. Strip casting would be an obvious example.

It is clear that while in-company research and development can solve many problems, especially where the drivers are internal, many of the issues of today are very large and difficult problems that require significant investment and large multi-disciplinary teams.

If we look at the history of steel research, we can see a general development in the complexity of the problems and a significant change in the methodology that must be used to solve such problems.

In the 1960s — the heyday of the large fundamental and applied research laboratories — a significant amount of fundamental work concerning the nature of steels and their potential application, was conducted by the equivalent of university research faculty members employed directly by steel companies. The partnership with universities existed mainly to ensure that a significant number of students educated in both physical and chemical metallurgy were available to join such research laboratories — the Bain and Homer labs, for instance. Similar large laboratories could be found in Japan, Germany and France, for example. The relationship between the steel industry and universities was very positive, and a significant amount of fundamental research was supported at universities by both steel companies and governments, due to the influence of the steel companies on government policy.

In the 1980s and '90s, depending on location and national policy toward research funding, faculty interest moved toward new materials and away from traditional materials and funding, and interest in steels began to decrease. A great number of metallurgical engineering departments followed MIT's lead and became materials science and engineering departments, with a curricular change that diminished metallurgy, almost eliminating chemical metallurgy and de-emphasizing physical metallurgy, to allow all materials classes to have equal focus in the undergraduate curriculum. This led to a decrease in research related to steels in all major universities.

Eventually this trend was recognized, and Centers of Excellence in Steel Research were initiated and supported by industry — the centers at Carnegie Mellon University and Colorado School of Mines being good examples of the industry's ability to garner government interest, as both centers were initiated as NSF Industry University Cooperative Research Centers (IUCRCs). Other centers in Vancouver and Hamilton were also formed in Canada. In Japan, national projects funded by the government were initiated. In Korea, a large research center was initiated in Pohang in partnership with a new university. More recently, European efforts were funded through a European Commission, and this program eventually led to the large European research program ULCOS. In addition, global steel organizations have developed the beginnings of global projects. Thus, with time, large partnerships have been developed that include industry, government and universities. The American Iron and Steel Institute (AISI) has also acted as a partner with the U.S. Department of Energy to fund research aimed energy minimization in a similar partnership with the U.S. government.

It is clear that all of the work sponsored by these industry/government/university partnerships is focused on "know why," with the desired outcome being "know how." But the most interesting development is that the driver of the research is now fully external, with a focus on determining "what and when" a solution will be developed.

Steel Research and Its Future

It is clear that, due to the scale of problems that must be faced, the future of steel research will be driven by both external and local influences. Issues of energy, environment and the location of a steel plant in the community can be addressed only by large projects with very large budgets where fundamental research leads to process development, which leads to the ability to operate a test facility at commercial scale. The cost of such projects becomes daunting for any company or country and can realistically be taken on only by the world steel community. The future for these projects must be based on a world partnership of companies, governments and universities that develops a very long-range plan aimed at solving the impact of the steel industry on the world. It must also be accepted that many problems are not solely the issue of the steel companies, but are common issues of everyone who uses carbon-based fuels.

In each country, we need qualified personnel to work in the industry. The industry must be involved in the education of its workforce. While there is always a need for metallurgical engineers, the industry needs all types of engineers, including those knowledgeable about software. This means that partnering with universities will continue to be important. However, it is clear that the full range of metallurgical knowledge will not be taught in universities as it was in the past, and metallurgical training after graduation may be necessary for many steel plant personnel. The materials student will have the ability to quickly understand all the concepts of metallurgical practice, even though he/she may not know the details. However, engineers outside of materials engineering will have to learn about liquid metals and their reactions, the formation of non-metallic particles by precipitation, the stability of oxides and their use in refractory materials, basic issues of binary and ternary phase diagrams, phase transformations in the solid state, and other such common metallurgical areas of knowledge.

As to areas of common interest worldwide, topics already discussed related to energy and the environment will continue to be interesting. However, the industry would be radically changed by the development of any of the following breakthrough technologies related to steel production:

- A method to produce liquid iron at volumes of less than 500,000 tons per year that would be economically competitive with a blast furnace.
- A carbonless, low-temperature method of reducing iron oxide to form a controlled size distribution iron powder.
- The development of a composite steel material that would have traditional properties but a significantly lower density.
- A combined reduction/rolling process to produce steel strip directly from powdered oxides.
- The ability to eliminate gravity feeding of liquid steel by the development of an electromagnetic pump.
- The ability to cast liquid steels at temperatures significantly below their liquidus.
- The ability to do in-situ alloying to previously rolled steel strip and produce any product from a generic steel sheet.

The following developments would also radically change the steel industry:

- A process that allowed alumina reduction by carbon to form liquid aluminum.
- The development of a composite material with comparable properties to steel at a similar price but a significantly lower density.
- Regulation that all cars must achieve 100 miles per gallon.
- Significant penalties on the use of carbon or the release of CO_2 into the atmosphere.
- Low-cost electrical power.

Thus, while one develops the next generation of steel processes and products, one must continually be aware of developments in other materials and in the ability of regulation to negatively or positively affect one's industry.

The issues, problems and potentials outlined above will require that large global consortia be created which include industry, government and the universities to work together with a common purpose. The scale of the industry and its impact on the world are such that there can be only large projects if one is to make a significant difference. While small, local projects will lead to local solutions and progress that is incremental, in order to truly solve the issues of the industry and its impact on the local and global environment, only a large vision will suffice, and one where the steel industry must partner with other industries with similar environmental issues. Thus, future projects will not only be global but will cross industry lines.

Conclusion

This paper is dedicated to the memory of James Keith Brimacombe. Keith was a visionary who enjoyed talking about the future. He was a great servant of our societies, our universities and our industry, but most of all he was a great friend to all. He believed in partnership between industry, government and universities, but also believed that educated individuals make the difference. Keith, if he were with us today, would be leading a world team to solve the challenges facing the future of the steel industry. His vision would have been large, and his solution would be in the partnership of people drawn together by common bonds through a wish to improve and solve today's problems. We certainly could not fail by following his lead.

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