Steelmaking and Industrial Ecology—Is Steel a Green Material?

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After a brief review of the evolution of the steel industry during the past 25 years, some basic definitions are presented, including that of industrial ecology, advanced materials, and “green” materials. Then, we discuss the environmental problems that are inherently associated with both conventional and novel steel processing technologies, touching on pollution control, waste minimization and recycling. The important conclusion is reached that when modern technologies are employed, steel is both an advanced material and a green material. Particularly noteworthy in the finding is that steel is one of the most recycled materials in current use. The paper concludes with the enumeration of the tasks ahead and with the definition of the steelplant of the future, which will have to be clean, environmentally benign, located close to the customer and will produce no waste. Indeed, it may derive significant revenue streams from the treatment of wastes produced by other industrial activities. By its very nature, the future steelplant will have to use some mixture of scrap and virgin iron units. It will be frugal on energy, highly flexible in operation, and will exploit synergies with other industrial systems.

KEY WORDS: industrial ecology; new steelmaking technologies; green materials; recycling; waste minimization.

1. Introduction

It is a great honor and privilege to be asked to deliver the Yukawa Memorial Lecture, both in view of the great contributions of the late Mr. Yukawa to steelmaking technology and the very impressive list of the famous metallurgists and engineers who have given this lecture before. The very high standards that have been set for this lecture by my predecessors are truly daunting and I hope that at least the topic selected will be of some interest.

Some 25 years ago, steelmaking was at its zenith. Steelmaking was a highly profitable and vital component of national economies; indeed, both white and blue collar jobs in the steel sector were well paid, secure and highly desirable. At that time, environmental and energy issues were secondary; the US, Western Europe and the then USSR were the industry leaders, with Japan making major strides. Integrated steel production was the norm, while scrap-based production using electric arc furnaces was confined to the lowest building grades of steel and played only a marginal role. The world's steel production stood at about 600 M tons, major expansions were planned everywhere and confident expectations were that the world's steel output would reach over a billion tons per annum by the turn of the century.

In the mid 1990s the situation is rather different. Steelmaking has reached a plateau or declined in most developed countries, with most of the growth taking place in the newly industrialized parts of the world, as shown in **Table 1**. With major cutbacks, job losses and bank-

ruptcies in the Western World, being engaged in steelmaking is no longer among the most desirable occupations. In Japan, the steel industry is numbered among

Table 1. IISI world steel consumption forecast. (million metric tons of steel products)

	1993	1994	1995	2000	% Change (1994–2000)
Europe					
EU	93.7	99.5	103.9	110.0	10.6
Other W. Europe	19.3	20.4	21.7	23.0	12.7
Eastern Europe	13.0	13.8	15.4	19.0	37.7
Former USSR	59.0	54.0	53.0	60.0	11.1
America					
Canada	11.0	12.4	12.6	13.0	4.8
United States	90.4	98.7	98.0	93.0	–5.7
Latin America	27.0	28.7	30.2	38.0	32.4
Asia					
China, PR	103.5	95.0	101.0	140.0	47.4
Japan	75.0	73.2	74.6	80.0	9.3
Other Asia	95.2	104.2	110.3	140.0	34.4
Other region					
Australia & New Zealand	5.7	6.0	6.0	6.0	0.0
Africa	13.4	13.7	14.0	15.0	9.5
Middle East	9.1	9.7	10.1	11.0	13.4
World total	615.3	629.3	650.8	748.0	18.9

Source: International Iron and Steel Institute Secretarial Report for 1994.

the 3 K activities, a less than flattering term that is used to characterize the manufacture of most commodity materials.

In many developed countries, notably in the US and Western Europe, in the materials field, research and development, steel-related activities have been almost totally eclipsed by work in the area of advanced materials, which have received generous support from the defense and the space agencies; in contrast, in Japan, major steady advances are being made in the development of new steel grades (*e.g.*, ultra low carbon interstitial-free steels for the automobile industry) and new thermomechanical processing arrangements (accelerated cooling, *etc.*)

Since the mid 1970s (the first energy crisis), energy considerations have become quite important and environmental issues have also been brought into focus, and steel processing technology has undergone substantial changes in order to adopt to these new requirements. As an example, there have been major improvements in energy utilization efficiency, labor productivity and pollution control, over the last two decades. Taking the US as an example, for a typical mill:

- CO₂ emissions appear to have been reduced, on an annual basis, by nearly 1.5 million tons, a drop of more than 28 %;
- SO_x emissions have fallen by more than 198 000 t, a decrease of nearly 95 %;
- Solid waste has been reduced by approximately 2.9 million tons, a drop of about 84 %.

In general,

- Labor requirements have decreased from 6–12 man hours per ton of steel in integrated production in the 70's to about 3–4 man hours per ton; the current values for the mini-mill operations are in the 0.5–1.5 man hour per ton range.
- Energy requirements to produce a ton of steel decreased by more than 40 % since 1975.

The middle 1990s has brought in additional changes and challenges for virtually all industrial activities. With the rationalization of production methods in the West, the continued “kaizen”[‡] in Japan, and the emergence of new important players on the Pacific Rim, international competition has become much sharper.

In the US, the cutbacks in defense expenditures and the recovery of the automobile industry have altered the balance between steel and “advanced materials”; steel production has again become profitable and certain segments of the industry have become technology leaders in the adaptation of new technologies, such as thin slab casting and the new electric furnace melting operations. Furthermore, even in integrated steel production, the US has become one of the lowest cost producers in the world. We should remark that in absolute terms, steel productions has always been a vital component of the US economy; as illustrated in **Table 2**,¹⁾ in spite of the much greater publicity accorded to the new materials. Viewed in the context of the US economy, the annual production value of the steel companies may be com-

pared with some other significant forms of economic activity, as shown in **Table 3**.¹⁾

It is perhaps paradoxical that while the integrated Japanese steel industry is clearly the technology leader in the world, by any technical measure one would care to apply, the economic future of steel production in Japan is rather less certain and most observers agree that major organizational readjustments may be necessary. The point is that the large integrated steelplants are not very flexible and that many of the grades they produce could perhaps be made much more cheaply, *e.g.*, using production methods employed by the mini-mills. In steelmaking, as in any other production facility, there have to be trade-offs between product performance and price.

It is clear that the steel industry is facing a challenging time, although the precise nature of these challenges will be different in different parts of the world. In addition to the obvious questions of profitability, the need to innovate and adapt new technologies to better meet the customer's needs, the industry must also respond to the question, **how well it meets its overall responsibilities to society in terms of its overall environmental performance.** It is this latter question that will be addressed in this presentation. Most of my remarks will be confined to steel technology as practiced in the developed world, although, for the sake of completeness, some comments will be made on the issues facing newly industrialized countries, China and the former Soviet Union.

Regarding the organization of this paper, in the subsequent section we shall present some basic definitions of industrial ecology, advanced materials and green materials and will pose the ecological issues in concrete terms. In Sec. 3, we shall present a brief description of the current steel processing technologies and their environmental impact. Current developmental programs will be briefly discussed in Sec. 4, while the actual longer

Table 2. Estimated world market for “advanced materials” in the year 2000.

	Market volume (\$ – Billion)	Estimated annual growth
Fine ceramics	5	20 %
Composites	15	10 %
Semiconductors	100	5 %
Steel	500	2 %

Table 3. Comparison of expected US expenditures between 1991 and 2000. (\$ – Billion)

A new TV and VCR*	60
• A new car*	2 000
• Rebuild the infrastructure— highways, waterworks, <i>etc.</i>	3 000–10 000
Savings and loans bailout	500
• Defense budget	3 000–5 000
HHS budget	5 000–10 000

* for every US Householder.

• metals intensive.

[‡] Continuous improvement.

term tasks ahead are treated in Sec. 5, and finally, the concluding remarks are contained in Sec. 6.

2. Some Basic Concepts and Definitions

2.1. The Definition of Industrial Ecology

What is industrial ecology and what does it mean to the materials cycle? Industrial ecology means the study of material and energy flows within an industrial ecosystem, with the ultimate objective of finding ways to better mimic nature so that waste streams are eliminated or at least minimized. Here, we should recall that in natural eco-systems there is no waste, there is a dynamic balance between predator and prey, the leaves falling off the trees get composted, used as fertilizer, and the like.

Viewing industrial systems from the standpoint of industrial ecology, it is instructive to recall the classical materials cycle, shown in Fig. 1, which was first proposed in the famous COSMAT report,²⁾ which reflects on

conditions as they were in the early 1970s. Then mining-extraction-refining-fabrication-utilization-waste (with less emphasis on recycling) were the accepted practice. At present, according to a recent article,³⁾ a re-thought materials cycle reflective of current day thinking would take the form shown in Fig. 2. It is seen that here recycling occupies a central position; indeed, not only do we need to consider recycling, but also the re-utilization of existing waste dumps stockpiles. Many of the dumps or landfills may be much richer sources of certain metals (e.g., copper, silver or gold) than their original ore deposits!

Another key point that has to be made here is that it is insufficient to track only the material streams, but we also need to account for the associated cost and the energy flows involved. After an initial stimulus by legislation or tax incentives, recycling and energy conservation should be able to pay for themselves. Indeed, the majority of recycling and energy conservation schemes

Fig. 1. Schematic representation of the global materials cycle.

Fig. 2. The new materials cycle.

have found to be profitable in addition to benefiting society in a general way.

2.2. The Definition of Advanced Materials—Is Steel an Advanced Material?

While most scientists or engineers would pride themselves on working with advanced materials, many would be hard put to define an advanced material. Surely metal matrix composites would qualify as would laser windows, gallium arsenide wafers, and ceramic turbochargers; so would titanium aluminide, but how about structural steels or ultra low carbon interstitial-free steels used in the manufacture of automobile bodies?

One may classify materials by price. As shown in Fig. 3, the price of materials may vary a great deal from much less than a dollar per kg for cement or steel, about a dollar per kg for aluminum, and up to much higher values for titanium, silicon wafers and diamond films. Thus, one could say that anything that costs more than about \$5–10/kg is an advanced material by definition (under these conditions mink coats would certainly qualify!). We may also classify materials by performance, with materials having ultra-high tensile properties, superconductors or exceptional stiffness-to-weight ratios being admitted to this selective class.

A perhaps more appropriate definition would be that a material which acquires superior performance characteristics due to sophisticated processing would qualify. Perhaps keeping with the times, we could **define an advanced material as one which is in commercial use, has superior performance acquired due to sophisticated processing, which has been carried out in a cost effective and environmentally benign manner, and one which can be readily recycled.**

Using this modified definition, most sophisticated steel products would definitely qualify as an advanced material, but perhaps it may be harder to fit some of the metal matrix composites into this category. We should remark here that issues of energy conservation, recyclability or being environmentally benign are not yet key considerations in the production of most advanced materials, in contrast to performance in service which is

the dominant factor.

2.3. The Definition of Green Materials

We can define a “green material” as one which is being produced in an environmentally benign manner (during its extraction, refining and manufacturing), which is environmentally benign during its use, and one which may be readily and economically recycled. In subsequent sections, we shall discuss the extent to which steel meets these criteria.

3. The Current Steel Technologies and the Associated Environmental Problems

In recent years, a great deal has been written on both the assessment of current and future steel technologies; limitation in space prevent us from presenting a detailed survey. Excellent summaries of the current and the projected steel technologies are summarized in the following **Tables 4 and 5**; for a more detailed description of these, the reader is referred to another article by the author,⁴⁾ or to the excellent articles by McAlloon,^{5,6)} Pollock,^{7,8)} Fruehan^{9,10)} and Nilles.^{11,12)}

3.1. Conventional Technologies

As seen in Fig. 4,¹³⁾ there are essentially three con-

Fig. 3. Approximate cost spectrum for the production of different materials.

Table 4. Emerging ironmaking technologies.

	Coke + sinter + BF	Nitrogen free BF	Corex	DIOS	Hlmelt	AISI	Jupiter	CCF (Hoogovens & Ilva)
Present status	Reference	Hot models	Industrial	500 mt/day pilot	300 mt/day pilot	Hot model	Hot model	Hot model
Annual capacity, actual or aimed (mmt/y*)	4	1.5 × BF size	0.7	N.P.**	1	N.P.	N.P.	0.3
Investment cost (\$/T.a.c.)	320	225	370	N.P.	N.P.	160	N.P.	170
Main energy inputs:								
Coal (mt/mthm)	0.620	0.530	1.1	0.8	0.7	0.75	0.57	0.64
Oxygen (Nm ³ /mthm)	50 + hot blast	240	540	500	Hot blast	510	435	550
Energy output (GJ/mthm***)	4	1.6	15	7.8	3	7.4	2.6	4
Variable cost before gas credit (\$/mthm)	133.1	112.3	139.9	N.P.	102.8	N.P.	N.P.	N.P.
Gas credit (IF 1 GJ=3\$)	−12.0	−4.8	−45	−23.3	−9	−22.2	−7.8	−12
Stop and go ability	Poor	Poor	Fair	Poor	Poor	Fair	Poor	Good
Environmental evaluation	Poor	Improved	Good	Good	Fair	Good	Good	Good

* mmt/y—million metric tons per year; ** N.P.=Not Published; *** mthm—metric tons of hot metal.

Table 5. Direct reduction processes existing and under development.

	MIDREX	HYL III	FIOR	AREX	FIOR II	IRON CARBIDE	FASTMENT
Status	Industrial	Industrial	Industrial	'94 startup	Plant design	'94 startup	'95 startup
Iron source	Lumps/pellets	Lumps/pellets	Fines	Lumps/pellets	Fines	Fines	Fines
Type of reactor	Shaft	Shaft	Fluid bed	Shaft	Fluid bed	Fluid bed	Rotar heart
Gas preparation	Reforming	Reforming	Reforming	Self-reforming	Reforming	Reforming	No gas/coal
Pressure	Atmospheric	5 bars	10 bars	Atmospheric	10 bars	—	Atmospheric
Typical plant capacity (mmt/y*)	1	1	0.4	0.5	1	0.32	0.45
Investment cost (\$/T.a.c.)	250	250	300	200	300	200	150
Energy input (Gcal/Mt)	2.5	2.7	4.0	—	—	3.0	3.0
Natural gas [GJ/mt]	10	10.9	18	8.7	13	13	2.5
Coal [kg/mt]	—	—	—	—	—	—	380
Elect. [kWh/mt]	125	85	200	70	150	230	60
Product metallization	>92 %	>92 %	93 %	93 %	93 %	Fe ₃ C > 90 %	95 %
Product carbon content	1–2 %	1–4 %	0.5 %	2 %	1.5 %	< 6 % (Fe ₃ C)	< 2 %

* mmt/y – million metric tons per year.

Fig. 4. Routes and combinations of various iron and steelmaking processes.

ventional routes to produce steel:

- Integrated steel production, which relies principally on virgin ore as the iron source (with some recycled scrap). This ore is sintered or pelletized and is then reacted with coke, preheated air and auxiliary fuels in the iron blast furnace to yield molten pig iron or hot metal. This hot metal is transformed into steel in the Basic Oxygen Furnace; the steel is then treated in ladle furnaces before being continuously cast into slabs, billets and blooms, which are further deformation processed to obtain the finished products, that may include hot or cold rolled sheet or galvanized sheet (e.g., plates, bars, rod, tubes, wires, rails and the like). Integrated steelmaking has been the mainstay of steel production until the last decade; since that time, scrap-based electric furnace steelmaking has been taking a progressively larger share of the market as seen in Fig. 5.
- The alternative technology, which has also been sketched in Fig. 4, involves scrap melting in electric arc furnaces (i.e., scrap recycling rather than using virgin ore!) optionally ladle furnace treatment, followed by continuous casting and deformation processing.

Fig. 5. World crude steel production from all processes and the electric arc furnace.

Until about five years ago, these scrap based operations termed “mini-mills” in the US and Bresciani in Italy had a rather limited product line, producing mainly bars for the building industry with a smaller quantity of higher value-added products, e.g., for automobile use.

A major breakthrough has been achieved by NUCOR, Chaparral and others in the US, through the introduc-

Table 6. Recent mini-mills investment projects in the US.*

Company/Plant	Technology	Place	Commissioned/ Start-up	Capacity (mill tpy)	Investment (mill \$)
Neucor	EFA	Arkansas, Indiana	1994 1995	2.0	
Steel Dynamics, Inc.	Thin slab-rolling/SMS AC-EAF (165 t)/Fuchs Thin slab-rolling/SMS	Butler, IN	1996	1.4#	300+
Acme Steel, Co.**	BOF	Riverdale, IL	1996	0.25#	372+
North Star BHP Steel LLC	Thin slab-hot strip mill/SMS EAF	Ohio	Late 1996	1.5	400+
Gallatin Steel	Thin slab-hot rolling DC-EAF	Gallatin, KY	Early 1996	1.2#	360
Ipsco	CSP-hot rolling/SMS DC-EAF (150 t)/Mann. Demag Slab-Steckel mill	Montpelier, IA	1996	1.2	360
World Class Steel	TSP slab-Steckel mill	Ambridge, PA	1996	1.0	340
Mansfield Steel	Thin slab-Con-Roll/Voest-Alpine	Mansfield, OH	1996	n.a.	76.5

* About 10 million tons of new annual capacity of flat rolled steel, raising US capacity by as much as 40%.

** Integrated/mini-mill venture.

Capacity to be increased in 2nd phase.

tion of near net-shape casting (*e.g.*, thin slab casting or H-beam or beam blank casting), which enabled an entry into a much broader market segment. Many such plants are now being built in the US, as shown in **Table 6**,^{14,15)} and also in the world.

- The third technology, which is also shown in Fig. 4, involves a variation on the theme presented above, by blending scrap with sponge iron or other forms of scrap substitutes as a feed to the electric arc furnace. This mode of operation is attractive in countries where natural gas is cheap facilitating sponge iron production (Direct Reduction), or when scrap prices are very high and when the production of high quality finished products mandates the use of scrap substitutes which do not contain tramp elements, such as copper. Indeed, virtually all the mini-mills that produce flat-rolled products or other higher quality items do use a certain fraction of “virgin” scrap substitutes in their charge mix.

Without going into details of the relative merits of these technologies, it should be stressed that **a key production paradigm in the mid 1990s is that there is no standard solution to steelmaking problems**. Just the contrary, there may exist one or more ideal solutions in terms of a technology that is appropriate to a given set of circumstances. Thus, a large number of new mini-mills has been established in the United States, as seen in the previously given Table 6, while the concept of a truly independent scrap-based mini-mill is still very new in Japan.

3.2. Environmental Issues in Modern Steelmaking Technology

Here, we shall confine most of our remarks to the developed countries, that is the US, Western Europe and Japan, with a few comments on the remainder of the world. We seek to address the following three issues:

- (1) The control of pollutants in the steel manufacturing process.

Table 7. Principal unresolved pollution problems in the steel industry.

- Particulate NO_x and SO_x emissions by sinterplants
- VOC emissions by coke ovens
- Treatment of blast furnace sludges
- Treatment of BOF sludges (Zn)
- Treatment of rolling mill waste
- Treatment of electric furnace dust (Zn)
- Treatment of pickle liquor waste
- Ironmaking and steel making slags
- Waste oils and greases

- (2) The control and utilization of wastes in the steel production.

- (3) How green is steel in its use?

Pollution Control

Through the enactment and enforcement of the clean air and the clean water act in the US, there has been a drastic reduction in the emission of airborne and waterborne pollutants. The net particulate emission has been significantly reduced per ton of steel produced; and at present, over 95% of the water is recycled. Indeed, it is suggested that in the US some 15% of all new capital investment goes toward the installation of environmental control devices. Similar success has been recorded in Western Europe. Since the majority of steelplants in Japan were built during the past 20–25 years, here, “doing things right the first time” enabled construction of very clean plants from the outset. (I do recall visiting the NSC Nagoya Works in 1970 and was most surprised when offered a pair of white gloves that remained fairly clean throughout the trip.)

The principal unresolved pollution problems are listed in **Table 7**, which are seen to occur primarily with integrated steelplants and are associated with sinterplant operation and with coke making. While in principle both these processes can be brought into compliance with current regulations, the cost would be very high, perhaps

comparable to the construction of a new mini-mill of comparable capacity, \$200–300 per annual ton capacity. In addition to these problems, operators of older steelplants have to consider another major issue, namely the remediation of wastes that have been dumped, stored or lagooned on their production site at times when there were no regulations prohibiting such practice.

The electric furnace-based operators have no comparable environmental problems to contend with, although the question of dioxine formation is being raised with increasing frequency. Indeed, the long term growth of the scrap-based mini-mill production facilities is at least in part ascribed to the absence of critical environmental problems posed by the coke ovens and the sinterplants.

Up to this point the discussion has been concerned exclusively with the situation concerning developed countries, *i.e.*, the US, Western Europe and Japan. On commenting briefly on the rest of the world which is responsible for more than half of the total steel produced, the following may be noted. In Korea, Taiwan and Mexico, among others, the new plants built have in general state of the art pollution control arrangements. The implementation of pollution control is very poor in the former Soviet Union and there are many serious problems in China also. The operation of many of these plants represent a serious health hazard to their workers, the local communities and also to the general public. Although there has been very marked reduction in steel-making capacity in Eastern Europe and in the former Soviet Union during the past few years, many of the remaining plants still represent a major environmental hazard. Providing technical aid for the remediation and upgrading of obsolete facilities in the former USSR (and other East European Countries) is a major task for the international iron and steel community, but many of the rate-limiting steps may be political and economic, rather than purely technological. In the installation of new facilities and in the upgrading of old ones in China, environmental considerations should be given greater weighting than is the case at present.

Waste Production in Steelmaking

Until recent times, it was acceptable to term slag and sludge streams produced in steel mills as waste; this is now “politically incorrect” and we should refer to these streams as “by-products”. Indeed, the majority of steel producers are making a concentrated effort to both minimize the production of these “by-product” streams and to find profitable uses for the remainder.

Simply put, on doing a material balance on a typical integrated steelplant, the production of one ton of finished steel products will generate about 420 kg of “by-product” streams, mainly slags, dust and sludges. For the mini-mills, this figure is substantially less. At present, integrated producers spend about \$20/ton of steel produced for the disposal/re-utilization of these materials, while for the mini-mills this figure is rather less—in the \$5–10/ton range.

An excellent survey has been reported by the IISI on Ferruginous wastes,¹⁶⁾ the highlights of which are reproduced in **Table 8**. It is seen that one of the principal

waste streams, *viz*, blast furnace slag, finds ready application in cement manufacture and the only potential impediment is that blast furnace slag has a low intrinsic value so it cannot be transported economically for long distances. In the US this critical distance is only about 50 miles (or 80 kilometers). With the much higher population density in Western Europe and in Japan, the connections between waste producers and possible treatment or user facilities are more readily made.

By the same token, use may also be found for steel-making slags, as roadfill or as an addition to the charge of cement kilns, but these slags have even less intrinsic value than those from the blast furnace. At present, critical problems remain regarding the treatment of sludges from the blast furnace and the steelmaking operations as well as from the various rolling and pickling systems.

While technical solutions do exist for the treatment of these streams, at present many of these are not always economic.¹⁷⁾

Some interesting novel ideas include the use of pickle liquor wastes for the production of magnetic materials (actually practiced by Inland Steel on a commercial scale), use of kish for the production of industrial graphite (also produced by Inland Steel), while some other concepts not fully realized include the use of slags for the production of glasses or ceramics.

Perhaps the most logical use of many of these “waste streams” is to recover the iron units from them. Such a technology has been recently demonstrated through the adaptation of the AISI Direct Ironmaking Process, where such streams would be reacted with carbon and oxygen in a reactor. At present, plans are being drawn for the construction of a demonstration plant and this may provide an opportunity for US-Japanese collaboration. Indeed, such a collaborative agreement has been recently signed.

Table 8. Recycling or reutilization of various steelplant wastes.

Mini-mill:

By-product & waste	Production (kg/t)	Weight %*	Reused %
EHF slag	116	5.5–21	77
EHF dust	18	0.4–3.2	30
Metallic wastes	11	5.4	100
Refractory wastes	10	4.9	20
Other	5	0.2–0.7	0
Total	160		

Integrated:

By-product & waste	Production (kg/t)	Weight %*	Reused %
BF slag	250	15–35	>95
BF dust & sludge	25	1–4	>75
BOF slag	135	5–22	<50
Metallic wastes	7	0.4–0.9	100
Refractory wastes	5.5	0.5–0.65	22
Total	423		

* per ton of hot metal produced.

In listing the amount of waste streams produced by steelmaking technology, we should pause for a moment and establish a sense of perspective. **Table 9**, adapted from different sources,¹⁸⁻²¹⁾ shows the waste streams produced in the production of a range of metals and other tonnage materials. It is seen that with a ratio of 0.6 t of waste per ton of product, steel would appear to be one of the most environmentally benign as far as extraction and refining are concerned. Some qualifying comments should be made here, however.

First, these are average figures, which reflect the trend that much of the iron ore being used today (with sources from Venezuela, Brazil and Australia) contains little gangue and is readily accessible without the need to remove much overburden. A great deal more waste would be generated in the processing of taconite ores from Minnesota (2-3 t of waste per ton of steel produced) or other ore bodies of comparable quality.

In discussing tonnage materials, it may be worth noting that relatively little waste is being produced in cement manufacture and even less in the production of plastics.

How Green is Steel in Its Use?

Table 10 lists principal uses of steel products in the US. It is seen that the main uses are transportation, heavy machinery, construction and consumer durables.

In heavy machinery and in construction, there appear to be no immediate alternatives to steel, which has been and is likely to be the cost effective solution to these problems for a considerable time period.

Transportation is an issue that has been very extensively studied, with several competing life cycle analyses, which have reached divergent conclusions. It is well known that the results of life cycle analyses depend critically on the assumptions made at the outset; rather than entering this controversy, let us examine what has actually happened in the ferrous metals content of automobiles over the period 1984-1993. As depicted in **Table 11**,²²⁾ it is seen that while the actual percentage of steel has been somewhat reduced, steel still remains the key component of most automobiles produced. Indeed, perhaps the most important change that may be seen on

examining **Table 11** is the replacement of ordinary steel with high-strength low-alloy steels.

One argument is that by using aluminum one may produce much lighter vehicles. Using the alloys that are available at present, this argument is debatable, because in order to obtain the desired stiffness, one will need almost comparable weights of aluminum to steel. Furthermore, while admittedly the cost of gasoline is quite low in the US, it has been calculated that by reducing the weight of a car by 1 kg, the net cost saving in reduced gasoline consumption over the lifetime of the

Table 9. Estimated solid waste generated in the production of some metals.

Metal	ton waste/ton metal
Aluminum	5.5
Steel	0.6
Copper	139
Zinc	0.8
Magnesium	5.3
Titanium	3.5

Table 10. Distribution of steel shipments and products in the US in 1993.

Sectors:	
- Warehouses and steel service centers	26 %
- Transportation (predominantly for automotive production)	16 %
- Construction	15 %
- Cans and containers	5 %
- Other	38 %
Products:	
Semi-finished	8 %
Shapes and plates	15 %
Rails	1 %
Bars	16 %
Pipe & tubing	5 %
Wire	1 %
Tin mill products	5 %
Sheet & strip	50 %

Table 11. Estimated average material consumption (kg) in US-built cars.

Material	1980	Weight %	1993	Weight %	% Change
Conventional steel (inc cold-rolled & precoated)	788.60	53.2 %	624.70	43.7 %	-17.9 %
High Strength Steel	34.05	2.3 %	117.59	8.2 %	258.0 %
Stainless Steel	12.49	0.8 %	19.75	1.4 %	64.0 %
Other Steels	24.52	1.7 %	21.79	1.5 %	-7.8 %
Iron	219.74	14.8 %	186.82	13.1 %	-11.9 %
Aluminum	59.02	4.0 %	80.36	5.6 %	41.2 %
Rubber	59.47	4.0 %	61.06	4.3 %	6.4 %
Plastics/Composites	88.53	6.0 %	110.32	7.7 %	29.2 %
Glass	37.91	2.6 %	40.18	2.8 %	9.9 %
Copper	15.89	1.1 %	19.75	1.4 %	28.8 %
Zinc die castings	9.08	0.6 %	7.26	0.5 %	-17.1 %
Powder Metal Parts	7.72	0.5 %	11.80	0.8 %	58.6 %
Fluid and lubricants	80.81	5.5 %	85.58	6.0 %	9.8 %
Magnesium castings	0.68	0.0 %	2.95	0.2 %	349.2 %
Other materials	42.90	2.9 %	39.04	2.7 %	-5.7 %
Total	1481.40		1428.97		-3.5 %

Fig. 6. Evolution of the US scrap price: actual vs. deflated.

car would be of the order of \$4.00 or perhaps ¥360 or less. This impact would be quite small even for substantially higher gasoline prices if one were to consider all the other costs involved in operating an automobile.

The beverage can market is an interesting case study, because aluminum has made major inroads in the US, while for a variety of reasons steel has been able to hold quite firm in Japan. As far as consumer durables are concerned, steel is sturdy, should have a long product life and it would not be easy to make a strong case against steel not being "green" in its service use.

Finally, a comment should be made on a very interesting potentially large use of steel for the construction of individual family dwellings. As discussed at a recent International Iron and Steel Meetings,^{13,23)} the use of steel, replacing wood offers a potential market for up to 7 million tons of steel per annum in the US. Such an application could be regarded as environmentally benign for several reasons. The excessive cutting of forests and the associated destruction of wildlife would be prevented; furthermore, steel houses would be more durable and could be more readily insulated, saving energy. (Of course, there may be the counter argument that using properly tended forest products, we would be utilizing a renewable resource.) I will leave this to the life cycle analysts; nonetheless, the use of steel products in single family dwellings appears to be yet another important, environmentally benign, green application for steel. Such products could be readily made from recycled steel; indeed, it has been suggested that about seven car bodies could be used to provide enough steel for a single family house. It should be remarked that this is a typically US application, both in terms of the size of a single family dwelling and the average size of the automobile concerned. In Germany, the strict building codes specify the use of reinforced concrete so that a single family dwelling may already have some 3–5 t of steel in it as part of the construction material.

Recycling

When it comes to recycling, steel appears to score very strongly, with an overall recycling rate of between 50–67%, depending on the type of account used—this

Fig. 7. Recycled content in the production of US automobiles.

is much higher than all other materials combined (steel is the most recycled material).

According to the Institute of Scrap Recycling Industries, over 90% of the automobile bodies are recycled in the US and the overall recycling rate of steel now approaches 44% of the consumption. The high scrap prices, the evolution of which is shown in Fig. 6,²⁴⁾ are not only likely to accelerate this trend, but should also lead to an increased scrap recovery from the obsolete scrap pool. Figure 7, supplied by the Steel Recycling Institute, shows the extent to which recycled steel is being used in the production of US automobiles.

According to the Steel Recycling Institute (SRI),²⁵⁾ in 1993 36 million appliances were recycled in the US (refrigerators, washers, dryers, water heaters, and other so called "white goods"), making this sector the fastest growing in recycling rate—from 4% in 1985 to 61.8 in 1993.

It is of importance to note that most of the steel used today is low carbon or low alloy material, the properties of which are often obtained by careful thermomechanical processing. This is a critical point, because such steels are readily re-melted in electric furnaces or BOF-s, without any significant loss in value. For other metals, e.g., aluminum alloys recycling can be a serious problem; here, aluminum beverage cans represent a notable exception, because they are designed for recyclability in the

first instance.

We should note here that the recycling of plastics is a largely unresolved problem, especially in view of the very large variety of materials that fall under this category; these materials will have to be segregated before any rational processing strategy may be applied that would recover a substantial part of their original value. While research has been initiated in this area, the recycling of composite materials, including fiberglass and metal matrix composites, is a very long way from realization. We should remark here that the recycling of high alloy steel and superalloy manufacturing wastes is being accomplished to a significant extent, due to their high intrinsic value; but this requires a very complex infrastructure for their prompt collection and segregation.

4. New Technologies and Their Promise

Traditionally, development in steelmaking has been an evolutionary, rather than revolutionary process, with a gap of about 20 years between the invention and widespread application of a technology. This has been typical of tonnage materials. Notable exceptions are emerging, however. Thin-slab casting was first demonstrated on a commercial scale some 4–5 years ago and now we have some 10–14 million tons per annum of capacity, either installed or in the process of being installed. By the same token, the COREX technology for ironmaking is about to “take off” with over 5 million tons of capacity being installed at present.

Other new technologies that are waiting in the wings include the great variety of direct ironmaking* processes (see Table 4) and the great variety of near net-shape casting operations. Important, but perhaps of smaller overall impact, is the whole range of scrap preheating systems, such as CO-Steel and the Fuchs System and post combustion, both in the BOF and the EAF.

All these new technologies appear to be environmentally benign; the new ironmaking technologies would replace coke ovens and sinterplants, but their actual record of emissions or more precisely the waste streams that they are likely to generate (the equivalent of BOF sludge, *etc.*) is not quite obvious. Near net-shape casting will certainly save on rolling mill and pickle liquor wastes.

So, all the new technologies appear to be heading in the right direction, not only economically, but environmentally. As far as new ironmaking processes are concerned, we may be approaching a “shake out” period; it is quite likely that only a few of the entries in Table 4, if any, will actually survive the very hard test of commercialization.

5. What Are the Tasks Ahead?

Being a college professor whose job description does not include the design and operation of economically viable plants, one tends to be perhaps less encumbered by reality than those whose everyday tasks rest on meeting a bottom line and satisfying not only customers

but a host of other constituents.

During the past few years, there have been a number of very interesting projections for the future, but I wonder whether these have been adventurous enough. Simply put, the rapid evolution of the mini-mill industry in the US had drastically changed the way in which one segment of the industry functions, benefiting the environment, the stockholders, the employees involved and the whole community. Whether this trend can continue unchecked or will be slowed down or even reversed by the non-availability of iron units, we need to seek comparable changes in what is currently termed integrated steel manufacture. Within this framework, may I suggest a number of possible guidelines in the development of a vision for the future?

The modern production paradigms are:

The customer's needs represent the main driving force, but one has to answer to many other constituents, including shareholders, employees and the local community. The actual tools to be employed include:

- Flexible manufacturing
- Lean production
- Worker empowerment
- Energy conservation
- Waste minimization (every stream leaving the system should be a useful product!)
- Sustainable development
- Design for the environment in an economically defensive manner.

We must realize that steelmaking as we practice it today has its roots in the 19-th, if not in the 18-th century. The first rudimentary blast furnace was built some 400–500 years ago, the basic shape of the steelmaking vessel has not really changed from the Bessemer converter to the modern BOF, and twin roll strip casting was first proposed by Bessemer in the last century. At the time the industry evolved, the principles listed above were not a consideration in the development of these technologies. Indeed, sustainable development in energy conservation, environmental control and waste minimization were not issues even 30 years ago, let alone in the 1980s.

For our industry to be really successful, we must shake of the 18-th and 19-th century heritage and completely re-think how the industry should operate in the 21st century. In a sense, one segment of the industry, the mini-mills, has responded to this challenge by establishing an operation which is fundamentally recycling-based, is lean and mean, highly profitable, and at the same time has a much less adverse environmental impact than integrated steel production. Clearly, the mini-mill model cannot be the total answer; many of our current products cannot be made purely from scrap and because of the usage pattern the iron units in scrap cannot sustain the demand for steel.

The steelplant of the future will be clean, environmentally benign, located close to the customer and will produce no waste. Indeed, it may derive significant revenue streams from the treatment of wastes produced by other industrial activities. By its very nature, the future steelplant will have

* Here, special mention should be made of the AISI Direct Ironmaking Process, which is now being adopted to waste oxide recycling.

Fig. 8. Potential synergies among various materials production plants.

to use some mixture of scrap and virgin iron units. It will be frugal on energy, highly flexible in operation, and will exploit synergies with other industrial systems.

One possible arrangement is sketched in Fig. 8, where a steelmaking operation is carried out in close collaboration with cement manufacture, with glass production, with recycling, and perhaps the treatment of household garbage and maybe hazardous wastes. Until recent times, steelmakers strongly resisted the suggestion that steel plants may be effectively utilized for the treatment of wastes produced by other industries. Some of these objections were based on potential legal impediments, others on the difficulties with logistics; however, the main difficulty is associated with the perception that steelmakers see their mission to make high quality steel efficiently, thus waste treatment would be an unwelcome diversion. In contrast, cement manufacturers have been using waste fuels and, in fact, steelplant wastes for many years—to good advantage. The reduced cost of waste fuels or the revenues that may be derived from waste treatment could provide a major positive impact on the bottom line. Steel technologists have a unique knowledge of materials processing at elevated temperatures and have access to broad range of processing equipment. This knowledge-base could and should be the source of profitable enterprises. One possible example is the company Molten Metals in the US, concerned with waste treatment, using a technology which has been developed from steelmaking experience. Other variations should be possible on this general theme.

To close with the famous American Question—How do we get there from here? I believe that thinking about new possibilities should begin now and it should engage teams of perhaps “wild” original thinkers combined with progressive people who have their feet firmly on the ground.

The end goal is ambitious but certainly not unattainable. We must look at the outstanding environmental record of our industry and the very major accomplishments both in the field of established technologies and technological and organizational innovation. When Gordon Forward of Chaparral Steel suggested, at a recent meeting at MIT, that one should envision a steel-making technology which entails zero waste and good thermal energy and iron unit recovery from steelmaking slags, we all took him quite seriously. After all, this was not an academic, but a practical steelmaker talking.

The steel industry has technical personnel with outstanding qualifications, a good research record, and excellent technical capabilities. We must be given the opportunity to rise to the challenge of the 21-st century to make steelmaking a really green enterprise, but at the same time, a really profitable one to the benefit of our whole community.

6. Concluding Remarks

In this presentation we sought to develop the argument that when steel technology is being practiced at its best, steel is both an advanced material and green in its production and end use.

While steelmaking has its origins in the industrial revolution, major advances have been made in steel production during the past decade, which has resulted in substantial energy conservation, waste minimization and major reduction in the emission of pollutants.

Most important, steelmakers have developed an outstanding technology base, with very capable personnel that make full use of the state-of-the-art technological tools, such as computers, process control and process optimization.

The major challenge facing us all is to make another

quantum jump in technological and economic efficiency by eliminating waste streams and fully exploiting synergies with other related industrial operations.

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