Sustainable steelmaking paradigms for growth and development in the early 21st Century*

J.P. Birat (Irsid-Usinor)

The drivers for steelmaking development, since the end of World War II, have been mass production, the search for quality, cost cutting and product and customer engineering. The next innovation driver will be the environment.

■ INTRODUCTION

Nils Bohr once suggested that "technological forecasting is a difficult task, especially when it tackles the future". The vanity and the challenge inherent in future studies have fortunately never prevented experts from engaging in the exercise, probably because, being aware of the difficulty, they believe that it is a useful prerequisite to any kind of long term planning. The purpose of this paper is to project a vision of steelmaking process technology for the early part of next century, beyond the horizon when decision on new investments have already been made and before projections loose any credibility. Because we are convinced that global environmental issues will become essential, the projection will focus on the internalization of the concept of sustainable development into steelmaking technology, which we call the "sustainability of steelmaking".

As Future Studies are just as interested in the past and the present as in the future, a historical perspective will be drawn initially. The present situation of steelmaking will serve then as a springboard to introduce a discussion on trends for incremental and for radical changes.

■ A BRIEF HISTORY OF STEELMAKING (1772-1989)

The historical evolution of a technology is driven by a variety of unrelated forces and follows a path that is not deterministic. Historians would call it rhizomic rather than monolithic (1 to 3). The keywords of these drivers have been development, supply and demand, market forces and competition, logic of firms, technological innovation and ecological balance, with emphasis on one or the other depending on time and local culture. We shall illustrate that by concentrating on a historical retrospective on carbon steels, as special steels would deserve more space than is available here *(table I)*.

Early developments

The history of steelmaking begins in the 19th century, when Réaumur of France in 1772, Kelly of the United States in 1850 and Bessemer of Britain in 1856 discover how to improve on pig iron by controlling the carbon content of iron alloys, which thus truly become steels. The first one, a chemist, is driven by scientific curiosity, but the others, as engineers, are responding to the need for larger quantities and better qualities of metal, that the industrial revolution,

** Keynote lecture presented to the 1999 Annual Meeting of the Chinese Society for Metals, in Beijing (October 19-21, 1999).*

Sidérurgie durable. Paradigmes de croissance et de progrès pour le début du XXI^{e} siècle

J.P. Birat (Irsid-Usinor)

La sidérurgie s'est développée depuis la dernière guerre jusqu'à un haut niveau d'excellence technique, tirée par des moteurs de progrès divers qui se sont succédés dans le temps :

• Elle a développé d'abord des outils permettant une production de masse : le train à larges bandes, le convertisseur à l'oxygène, les hauts-fourneaux géants, la coulée continue sont les principaux réacteurs métallurgiques qui sont apparus pour répondre à ce besoin.

• Elle s'est ensuite préoccupée de répondre à des exigences sévères de qualité, soit en termes de niveau et de régularité de propriétés d'emploi, soit en termes de qualité de surface. Les outils déjà cités ont démontré leur capacité à prendre aussi en compte cette exigence et des ateliers nouveaux ont été créés pour atteindre de meilleurs résultats (métallurgie en poche, métallurgie sous vide, nouveaux procédés d'élaboration d'aciers inoxydables).

• La fin de la période de croissance a conduit à rechercher à tout prix des réductions de coût de revient, ce qui a été facilité par la mise en continu des procédés (laminage continu, coulée continue, recuit continu, galvanisation en continu) et des ateliers (ligne de coulée continue de brames minces couplée à un laminage compact, enfournement chaud, décapage et laminage couplés) et par la recherche d'économie de ressources, énergie ou matière première.

• Puis est venue la période de redécouverte des besoins du client, avec la mise au point de solutions-aciers, qu'on appelle aussi avec bonheur en anglais product engineering *ou* customer engineering.

En parallèle avec ces injonctions de l'économie et du marché, de nouvelles technologies à fort potentiel de progrès sont apparues, capables de répondre successivement aux différents besoins qu'on vient de citer. On peut qualifier de telles technologies de robustes, pour exprimer leur capacité à évoluer pour répondre à ces demandes aussi bien en termes de forte production, de haute qualité, de bas prix de revient et de nouveaux produits. Le four électrique moderne, la coulée continue de brames minces, la coulée continue de bandes, le laminage tandem à froid font partie de cette catégorie de procédés qu'on nomme aussi des technologies agitatrices (disruptive technologies)*, pour exprimer qu'elles apportent un renouveau qui remet en cause de façon profonde les habitudes de fabrication.*

Ces nouvelles technologies se sont d'abord imposées dans le contexte unidimensionnel de la production d'aciers-commodités. La coulée de brames minces, par exemple, s'est développé initialement sur les marches bas de gamme des marchés des produits plats au carbone. Le four électrique à forte productivité a été réinventé par les minimills fabriquant du rond à béton, avant d'investir la totalité des marchés de produits longs, puis, petit à petit, celui des produits plats en aciers au carbone. Puis, ces procédés ayant mûri et dépassé leurs difficultés de jeunesse, ils se sont tournés avec succès vers des niches de plus en plus exigeantes en termes de qualité, jusqu'à inventer de nouveaux produits. La coulée de brames minces se met aujourd'hui en place dans les aciéries intégrées ciblées sur les aciers au carbone haut de gamme, pour y remplacer des coulées continues vieillissantes et laisse présager la mise sur le marché d'aciers à très haute résistance, obtenus par laminage ferritique. Il est probable que la coulée continue de bande suivra à terme la même trajectoire de développement.

Comment aller plus loin et pérenniser cette dynamique de progrès technique, seule capable d'assurer que notre civilisation continuera de bénéficier de ce matériau exceptionnel et bon marché qu'est l'acier, au niveau où elle le mérite et où elle en a besoin ?

La réponse nous paraît se situer dans la logique du développement durable, déjà largement à l'œuvre dans les usines sidérurgiques, mais qui devrait rapidement et encore plus que par le passé devenir le moteur principal du changement et du progrès continu.

Les ressorts en sont multiples :

– des procédés encore plus sobres, c'est-à-dire plus économes en ressources, minerai et énergie bien sûr, mais aussi eau et air ;

– des procédés plus propres, c'est-à-dire se rapprochant du zéro déchet, en conjuguant des politiques d'évitement audacieuses avec une réutilisation, une valorisation et un recyclage des déchets, qu'on n'appelle déjà plus des coproduits, mais des produits non sidérurgiques.

Les challenges sont nombreux, depuis la nécessité d'éviter la formation de composés organiques volatils, y compris des micropolluants comme les dioxines et les furanes, celle d'oxydes d'azote, surtout en milieux urbains ou péri-urbains, ou celle de gaz à effet de serre.

Ils portent en eux le développement attendu des filières ultra-courtes, basées par exemple sur la coulée continue directe de bande, mais aussi peut-être de méthodes de fabrication radicalement nouvelles ne faisant plus appel au carbone pour réduire les oxydes de fer des minerais.

Cela est d'autant plus probable que la dématérialisation de l'économie, à l'œuvre déjà dans les pays les plus développés, peut, à terme, laisser imaginer un fonctionnement basé plus largement qu'aujourd'hui sur l'utilisation de fer recyclé.

Table I : Historical evolution of steelmaking

Tableau I : Évolution historique de la sidérurgie

4000 BC	"Accidental iron" / Meteorites? By-product of bronze smelting
2500 BC	Direct reduction
– 500	Small furnaces, production of blooms requiring repeated heating and forging
– 400	Partially decarburized blooms : Noricum steel
100	Discovery of cast iron in China
1100	Iron appears in Gaul Invention of the tilt hammer
1300	Cast iron
1300	Largest furnaces, production of pigs, remelted and refined in an air blast
1550	Invention of water-powered bellows
1760	Printing influences dissemination of knowledge (e.g. *De Re Metallica*)
1784	Replacement of charcoal by coal Invention of the puddling process
1850	Modern metallurgy
1856	Bessemer converter
1865	Siemens Martin (open hearth) furnace
1877	Thomas (basic Bessemer) process
1900	Production of converter steel overtakes wrought and puddled iron
1950	Oxygen-blown converter
1930	Electric steelmaking

with its looms, steam engines, machines and railroads, has created. A dialectical relationship between science and technology has already started.

The basic concepts of refining pig iron by oxidizing carbon in a liquid bath are invented at that time. This is a radical change from the gas-solid reaction in the shaft furnaces, the ancestors of blast furnaces, which reduce iron ore with charcoal, or from the puddling of iron, a forging and refining technology carried out in the solid state, that has no modern equivalent*.

The reactivity of innovation at the end of the 19th Century is impressive, as the open hearth furnace, which can melt scrap in addition to refining hot metal, is discovered 9 years only after the Bessemer converter in 1865, and the basic Thomas converter, that can refine the phosphorous rich iron ore of Lorraine and Luxemburg, 12 years later in 1877.

The next major innovation in steelmaking, which follows closely the invention of electricity, is the electric arc furnace (EAF) introduced by Héroult in La Praz around 1900. It develops in the Alps valleys close to the source of this new energy that cannot yet be transported over long distances. The innovation lies in tapping an energy that is a substitute to coal and also in melting scrap in even larger quantity than did the open hearth, thus starting an economy of recycling, that will eventually give to steel the status of being the most recycled material in the world.

** Unless one considers that spray forming or thixoforming belong to the same intellectual tradition.*

The integrated steel mill

The end of WWII starts the explosive economic expansion of the **30 glorious years** *(fig. 1)*. Reconstruction of the economies destroyed by the war, but more importantly, the popular success of the car industry and the consumer culture that it launches in the Triad, induce the true transformation of the steel industry into its modern impersonation. The hot strip mill, invented in the USA in the 1930s, initiates a race towards gigantism that will create the integrated steel mill (ISM), where each process step in the steel manufacturing route is brought up to a capacity of 3 to 4 Mt/year. Steelmaking invents the oxygen converter, known in Europe as the LD and in America as the BOF *(fig. 2)* : size, up to several hundreds of tons and process time, down to half an hour, make it possible to convey the stream of iron and steel from the blast furnace to the hot strip mill. The continuous caster (CC), another postwar development, becomes the last ring of the chain, putting a final touch to the fluidity and the continuity of route *(fig. 3)*. This introduction also eliminates the slabbing and blooming mills and the ingot pit furnaces: the route is simplified by erasing a complete process step. The simplification is the initial justification for investing in the complex caster technology, along with the increase in yield, which is a first foray into materials conservation and makes the steel industry more ecology conscious.

Steel production increases sevenfold after WWII and steelmaking process technology develops and thrives because of the progress driven by the large R&D centers of the steel industry. Lively technical forums organize the exchange of information in numerous conferences and journals. This productive age is busy taming the new processes and scaling them up, in order to collect the full benefits of the economies of scale brought about by the giant integrated mill. But steelmill operators also learn to ripe the full potential of the new reactors and thus to renew the offer of steel products, especially in the field of carbon steels.

It appears, though, that the demand for better steels, in terms of purity, cleanliness in non-metallic inclusions, chemical homogeneity and tight specifications, cannot be satisfied with the existing reactors, if productivity has to remain high. A new section is therefore added to the steelshop, to act as a buffer between meltshop and caster. This secondary metallurgy section is equipped with reactors for high precision trimming of temperature, composition and inclusions, which include vacuum treatment and strong stirring *(fig. 4)*. These new reactors initially add to invest-

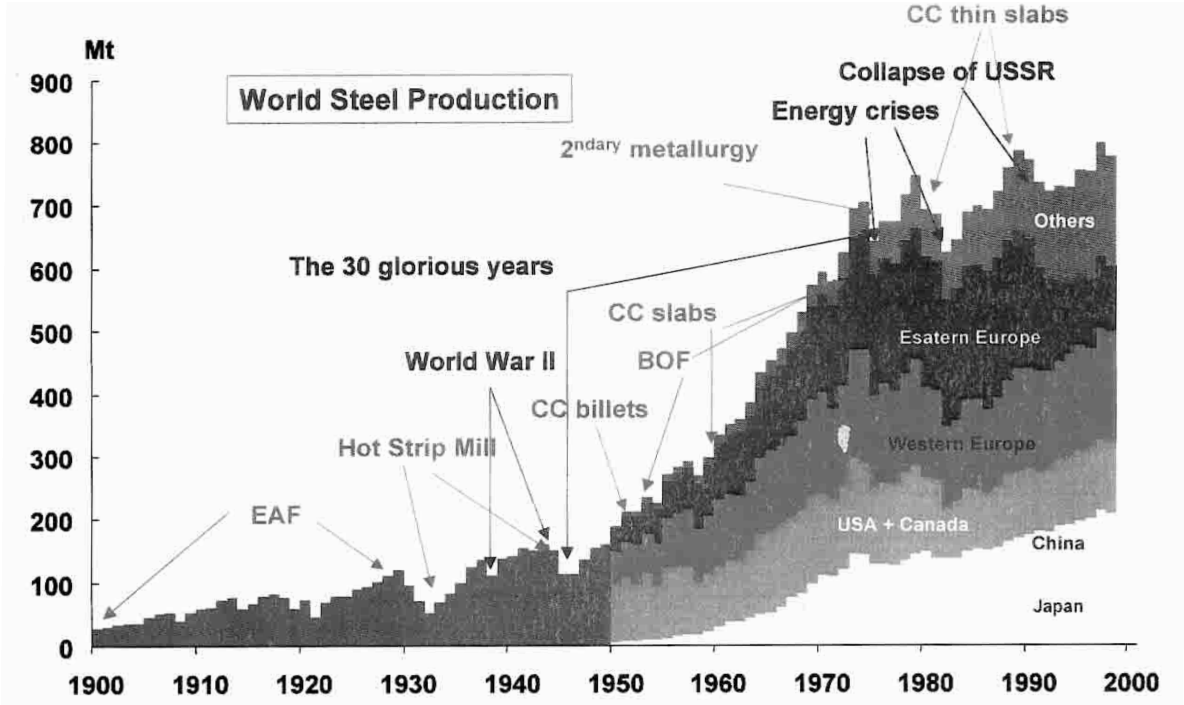


Fig. 1 – The increase in steel production in the 20th Century in the perspective of world history and technology changes in the steel industry.

Fig. 1 – Évolution de la production d'acier au XX^{e} siècle en relation avec l'histoire du monde et les changements technologiques dans la sidérurgie.

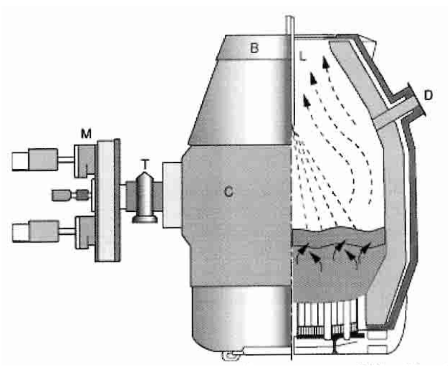


Fig. 2 – The oxygen converter (BOF or LD type).

Fig. 2 – Le convertisseur à l'oxygène (BOF ou LD).

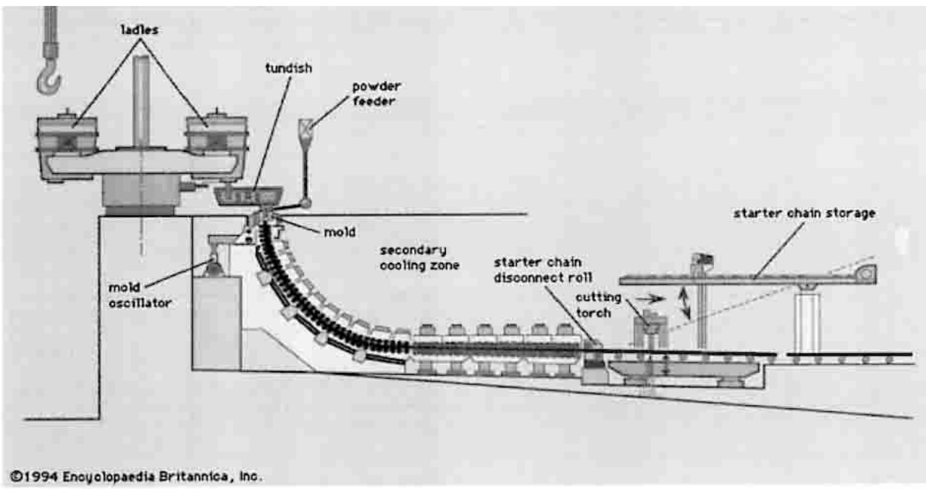


Fig. 3 – A modern continuous caster for slabs.

Fig. 3 – Une machine moderne de coulée continue de brames.

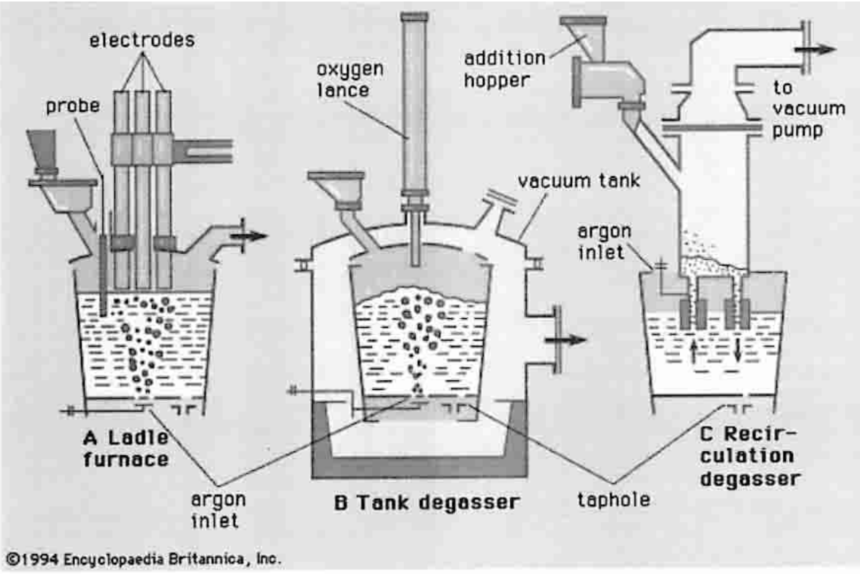


Fig. 4 – Secondary metallurgy (ladle furnace, tank degasser and RH degasser).

Fig. 4 – Équipements de métallurgie secondaire (four poche, vide en poche, RH).

ment and operating costs, but this is rapidly overcome by gains in productivity and by the added value of the new products.

The first minimills

Prosperous Northern Italy and W. Korf, a German visionary in steel technology, invent a new type of steel mill in the late 60s for producing long products, the minimill. They have understood faster than anyone else that the compounding of technological progress that is funneled into the steel industry will lead to a stabilized technology and to steadily decreasing steel prices. The consumer will benefit from the commodification of large segments of the steel market, but steel operators will have a strong problem running their business unless they switch to new management concepts. The minimill is small (less than 1 Mt/year, initially) compared to the integrated mill, which provides the opportunity to stay close to the market, to shorten delivery times and to ride the waves of steel price and demand by inventing the concept of lean manufacturing, 20 years before it becomes a buzzword in *Business Week*.

New challenges for the steel industry

The two energy crises stop the love affair of Western countries with the steel industry for a while. The growth transition that marks the end of the **30 glorious years** is poorly understood at the time : a spiral of heavy losses mares the industry in Europe and a lack of profit steers investors away from it in the US. Only the Far East continues to grow healthily, in Japan, Korea, Taiwan and Mainland China. In Europe, governments step in through nationalization or subsidies, not as much to salvage the steel industry as to assuage its transition towards a much leaner workforce. However, technology development continues unabated in Europe and Japan, although it starts slackening down in North America, where corporate research is trimmed or simply shut down and the function outsourced to the academic world.

Energy conservation is a strong paradigm for progress at the time. The industry launches an exhaustive battle plan, based on the tightening of process procedures, the reduction of operating times and the increase in the continuous features of individual processes and of process interfaces : hot charging of CC slabs in the reheating furnace of the hot strip mill is invented at the time, prompting the suppression of the steel inventory stockpiled in the slab yard and significant progress in the control of slab quality (4). The effort is quite successful, as energy consumption is reduced by 40 to 50 % over a period of 35 years, as the example of France shown in *figure 5* makes clear. Once more, the steel industry demonstrates its concern for ecological issues.

In Japan, which may be the most strongly minded **energy warrior** because of its lack of national energy resource, steelplants erected in the 60s or the 70s are partly rebuilt in the 80s in a radical revamping effort aimed at cutting energy consumption and cost. Elsewhere, the same result is reached at a more moderate investment level.

The restructuring of the steel industry in Europe and the return to profitability that follows quickly bears testimony to the renaissance of this activity. The steel industry has

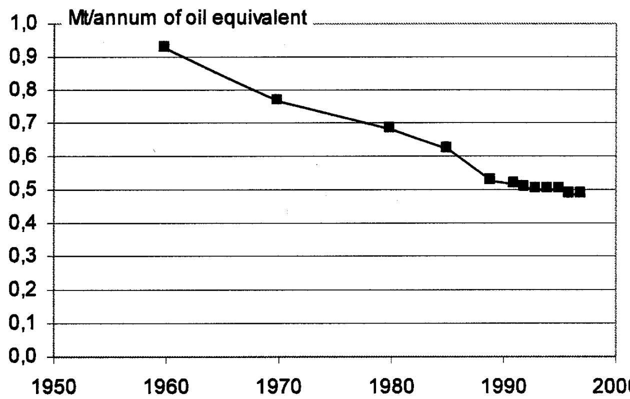


Fig. 5 – Energy savings in France over the last 35 years in the steel industry.

Fig. 5 – Économies d'énergie dans la sidérurgie française au cours des 35 dernières années.

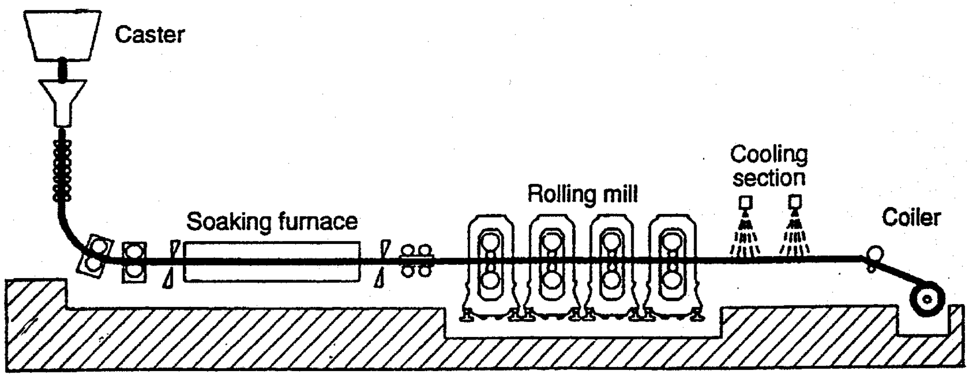


Fig. 6 – The initial thin slab and compact rolling line of NUCOR.

Fig. 6 – La configuration initiale de la ligne de coulée continue de brames minces et de laminage de NUCOR.

jumped again on the hightech bandwagon and adopted up-to-date information technologies, including an essential subset of it, sensor technology. Privatization is widespread and gives birth to large and successful steel companies. The steel industry is “born again” !

In the meanwhile, the US reach the conclusion that their steel production capacity is too low for their national needs. Investors are indeed again willing to bet on the future of steel industry, all the more so since European equipment manufacturers have invented new technologies that make it possible to extend the concept of the minimill to flat products (5). Based on EAF technology and thin slab casting (TSC), the first minimill of Nucor in Crawfordsville pioneers another paradigm shift in steel manufacturing *(fig. 6)*. It also acknowledges the commodification of part of the flat product market.

In the rest of the world, where growth continues and holds still more promises, the steel industry keeps thriving relentlessly. In Japan, the Chairman of Nippon Steel is still the Head of Keidanren and steel companies build brand new R&D centers filled with light, equipment and eager researchers. Equipment manufacturers sell new plants with up-to-date technology to China, Korea and Brazil. The world is still hungry for steel, although the collapse of the USSR and of its steel production balances out and hides the emergence of Asia and South America in overall world production.

In the late 80s, where we shall arbitrarily stop this historical survey, oxygen steelmaking and conventional continuous casting have reached high levels of perfection, with seemingly little room left for progress outside of radical innovation. The ISM steel plant as a whole is efficient, cost effective and has reached some form of perfection.

■ STEELMAKING TODAY (1990-1999)

The last decade of the 20th century, which might have seen the “end of history” according to Fukuyama (6) and become ossified and boring, turns out to be intensely alive and interesting because the World is looking actively for an alternative geopolitical strategy to the cold war (7). Business and the steel industry are participating fully to these busy and exciting times.

The post-oil crises blues have definitively left the US and, more recently, Europe. South America seems to be back on the growth track. China is booming, grasping on the way the rank of premier steel producing nation in the World. Japan is stagnating, while the rest of Asia is going from growth to crisis and probably to growth again.

Steelmaking capacities grow, which makes it easier to adopt new technologies, at least moderately radical ones such as thin slab casting, not only in mini-mills, but also in new or expanding integrated mills. Steel Corporations grow stronger and start looking at the world as their natural **Lebensraum**.

Environmental issues also become more pregnant in this decade, as the world gets richer and more aware of its power on nature, including at a global scale : sustainable development becomes a rallying motto of the governments and the economy.

The BOF is the keystone of IM steelmaking

As the BOF field encountered perfection in the 80s (8), it has simply consolidated its position in the 90s.

A BOF vessel typically taps 220 t of liquid steel every 30 to 45 min at 1635 °C, containing 0.100 % carbon and 500-1000 ppm oxygen. The metal feed is hot metal with 10 to 35 % of scrap. Top blown converters have been gradually transformed to combination blowing technology and the bottom blown converters are an exception. Dynamic control based on offgas carbometry, sublance sampling and drop-in-thermocouples, makes quick-tapping, i.e. tapping on the fly without stopping to wait for a chemical analysis, a common practice. The slag stopper is also a standard piece of equipment that keeps oxidized slag out the ladle. The present strength of BOF steelmaking is its reliability and clock-like operation, the control of refractory wear by gunning, slag coating and slag splashing, which allows blowing campaigns of 1,500 to 5,000 heats with records at 15,000, and the purity of the steel that it produces, in terms of oxygen, carbon and nitrogen, but also tramp elements.

The BOF generates 15 kg of dust per ton of steel, which are collected in a wet scrubbing system and transformed into sludge. Slag is generated at the level of 120 kg/t of steel. At the end of the period, no universal solution for handling these by-products has been found and the fraction that is not recycled on the sinterplant is usually landfilled.

Variants of the BOF have been designed to melt larger quantities of scrap, up to 100 % of the charge (9). Energy is provided by coal and oxygen and these converters are competing with the electric arc furnace. Yield is lower than in the BOF due to iron losses to the slag and sulfur is high due to the coal. Only local conditions like the lack or high price of electricity may justify the process, but it still has to compete with solutions like a cupola, that provide a hot metal intermediary phase where desulfurization can be carried out more easily.

Secondary metallurgy has matured

The 90s have seen no major change either in the secondary metallurgy scene, except for a generalization of the practice with the objective of smoothing out the metal stream in the steelshop, and an increasing use of vacuum, especially to produce the extra-low carbon steels, which exhibit that high cold-formability that the automotive industry has come to like for its rounded-looking car bodies.

The state-of-the-art in secondary metallurgy may be outlined as follows :

• Metal stream control and coordination between furnace and continuous caster, to allow for long sequence operation, determines the number of secondary metallurgy stations, which act as buffers for liquid steel and trim its temperature. This has in turn saved time and reduced operating cost at the furnace by tapping at lower temperatures (e.g. 1635 °C in a carbon steel EAF shop, as compared to 1660 °C, 10 years earlier).

• Decarburization to the low carbon levels of IFS or extra-low carbon steels is carried out either in a RH or in a tank-degasser.

• Deoxidation, alloying, cleanliness control and inclusion modification are carried out either in simple argon-stirred ladles, under a canopy (CAS systems), or under full vacuum, with a preferred technology of wire injection for introducing deoxidation or alloying elements.

• Desulfurization and dephosphorization are carried out in a ladle with strong pneumatic (or, rarely, electromagnetic) stirring, with particular care being paid to preventing oxygen or nitrogen pick-up by using a tight ladle cover.

• Dehydrogenation is carried out under vacuum, in a tank degasser, for special steels and pipe grades to the level of 0.5 ppm.

• Denitrogenation in a tank degasser may be the only new addition to secondary metallurgy technology (10). 25 to 35 ppm of nitrogen can thus be obtained from an initial 50 ppm level, depending on sulfur content in liquid steel, with a strong argon stirring under a 1 mbar vacuum at a rate of 40 Nm^3 for a 185-t ladle.

The electric arc furnace enters the flat product steelshop

The electric arc furnace, focused earlier in the century on niche applications, became the preferred steelmaking furnace for special steels, engineering as well as stainless steels. What was of the essence then was not time but rather the “simmering” of a very sophisticated alloyed steel.

The minimill revolution of the late 60’s turned the EAF into the basic reactor for “rebar” production, i.e. for the commodity segment of the steel market that historically appeared first. Time became a primary factor and the EAF discovered its ability to play in the high productivity league, first by increasing the size of the vessel and then by relentlessly reducing operating times.

This transformation of the EAF has turned it into one of the key technologies that lie at the root of the wide family of minimills that blossom in the late 80’s and early 90’s. Most long product mills switch over to the EAF route, for example ARBED in Luxembourg closing off its blast furnace route and replacing it with 3 EAFs for its structural beam market, or Unimétal in France erecting a twin-shell 160-t DC-furnace for its wire-rod market. The higher-end carbon steel market in long product manufacturing thus turns to the EAF route. This raises novel technical issues especially concerning scrap quality and purity and nitrogen level in steel. The commodification of part of the flat product market starts also at that time, with NUCOR as the pioneer in the USA and Arvedi in Europe. The driving force for developing EAF technology thus gains even more momentum.

The technologies that have been coordinated in order to boost the efficiency of the EAF are the following (11 to 13) :

• Increased furnace size (typically 130 t for longs and 150 t for flats).

• Increased electrical power input (0.75 MVA per ton of tapped steel), with secondary voltage of 950 V and current of 54 kA.

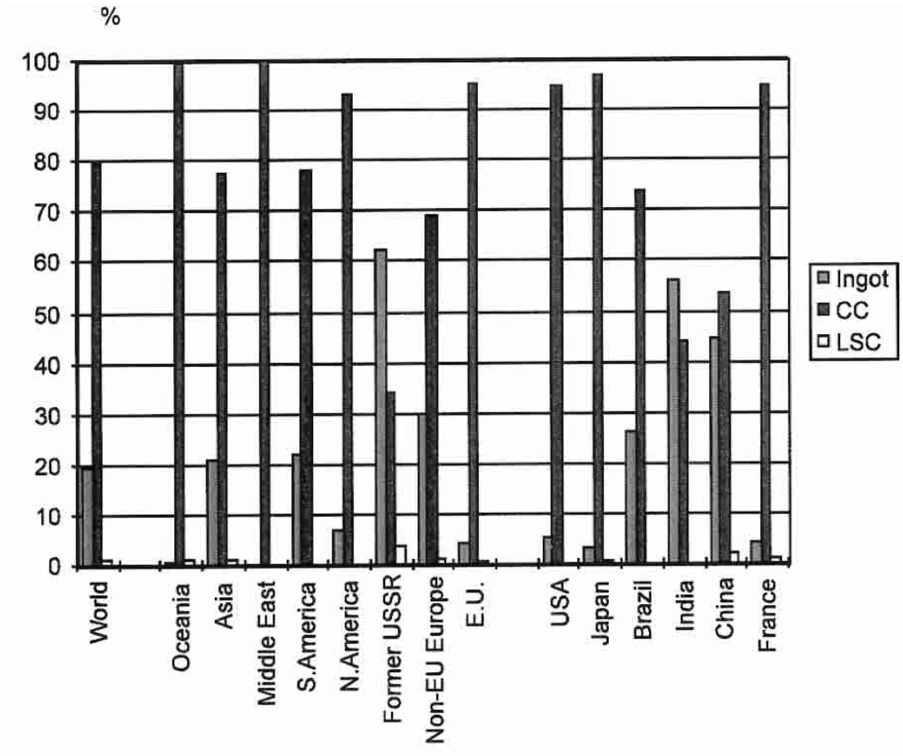


Fig. 7 – Ingot, continuous casting (CC) and steel for foundry (LSC : liquid steel for foundries) ratios in the major geopolitical regions of the World in 1997 and in selected countries.

Fig. 7 – Proportion d'acier coulé en lingots, coulé en continu (CC) et moulé (LSC : acier liquide pour fonderies) dans les principales zones géopolitiques du monde en 1997 et dans quelques pays sélectionnés.

• Increased use of fossil energy to complement electric energy (up to 30 % of the total energy input of the furnace) and to provide localized energy input to accelerate melting (C : 20-40 kg/t ; O_2 : 30-60 Nm^3/t).

• Systematic use of slag foaming for carbon and stainless steels to improve the yield of energy from the electric arc to liquid steel during flat bath operation.

• Implementation of post-combustion technology in the furnace to recover more energy from fossil fuel by oxidizing CO into CO_2. Typical post-combustion ratio (PCR) is 40-80 % and heat transfer efficiency (HTE) 50-80 %.

• Reduction of air entries, by developing tight-furnace technologies.

• Bottom stirring through porous plugs and tuyeres, to reach the equilibrium between slag and steel faster.

• Water-cooled panels on the walls and roof to sustain the operation at higher power.

• Operation with a heel and eccentric tapping from bottom hole in order to save time and to avoid slag carry over into the steel ladle.

• Preheating of scrap either in a shaft adjacent to the furnace, which also saves on operating time, or through a long tunnel (Consteel technology).

• Use of twin shells in order to separate power-on-time from logistical times for charging and tapping.

The modern EAF has typical operating ratios of 392 kWh/t, down from 450, 10 years ago, 1.9 kg/t of electrode graphite from 2.9, 3.1 kg/t of refractory from 6.9 and a median furnace productivity of 94 t/h from 61. Best operation is at 320 kWh/t.

Continuous casting has matured and near net shape casting technology is taking over on the innovation front

The continuous casting ratio has plateaued in the 90's to values close to 100 %. *Figure 7* shows that Japan and the European Union are the major operators of CC, with ratios of 96.6 and 95.2 %, closely followed by the USA (14). In these countries, non-CC production is confined to forging ingots and special steels, such as tool steels or high-end low-alloy grades (e.g. bearing steels). World regions that have a lower CC ratio, such as Eastern Europe, the former USSR countries, India or China, do not propose a challenging model, but lag behind in economic development and constitute potential markets for equipment manufacturers. Conventional CC technology has become universal for at least a decade.

The state-of-art of continuous casting is summarized in *figure 8*. The complexity of this technology tree and the numerous alternative solutions that are available attest of the maturity that conventional continuous casting has reached.

The 90's see the strong emergence of Thin Slab Casting technology in North America, Europe and Asia (5). The announced capacity, in use or under erection is presently of

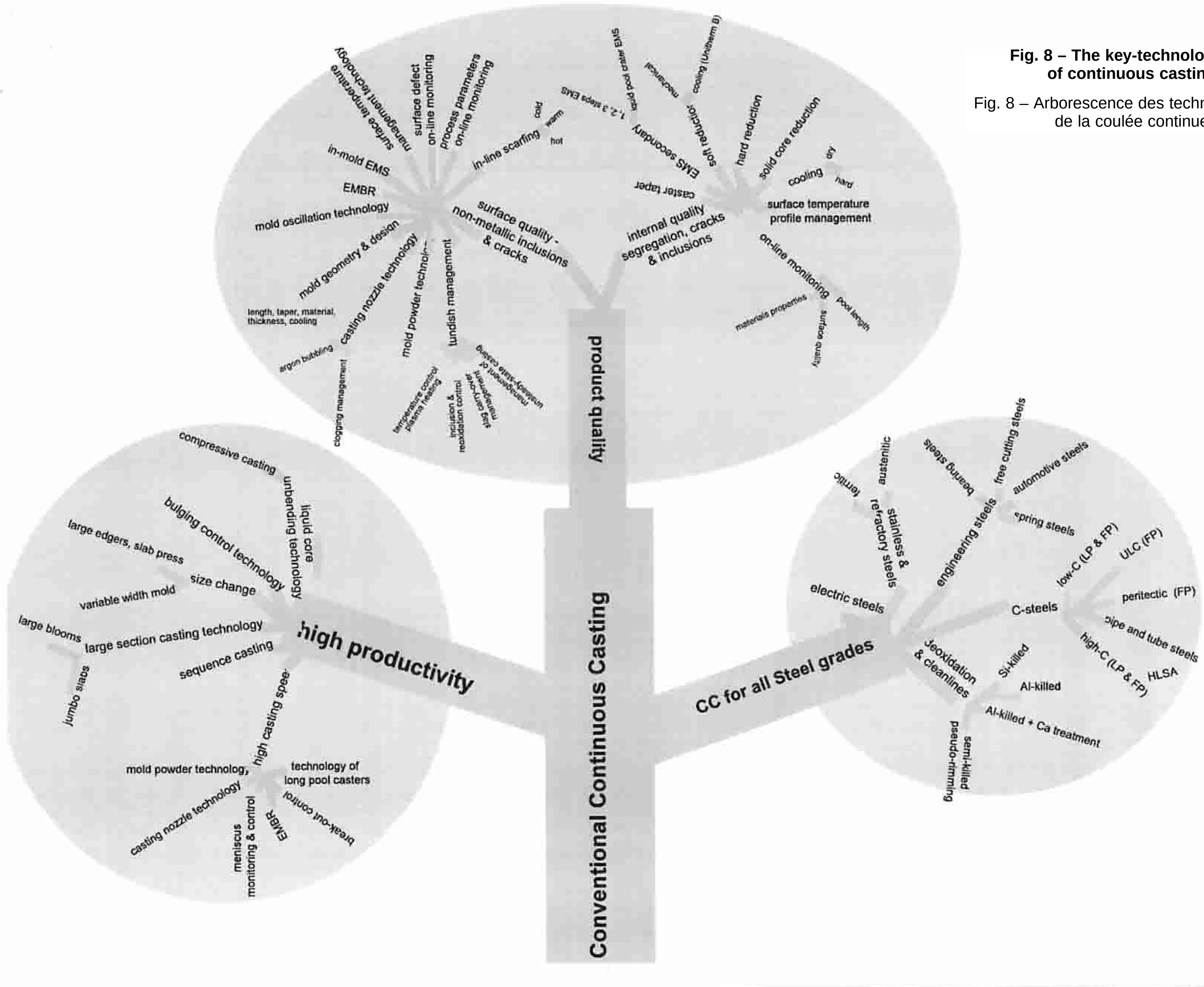


Fig. 8 – The key-technology tree of continuous casting.

Fig. 8 – Arborescence des technologies-clés de la coulée continue.

43 Mt/year. TSC are built, not only in flat product minimills, but also in BOF shops, either new or revamped ones. TSC is no longer confined to commodity flat products, but is penetrating into the higher end of the flat product market.

Strip casting, i.e. the direct production by solidification of a steel strip equivalent to the product of a hot strip mill, has been pre-emergent in the 90s, with the crystallization of the proliferation of R&D projects of the 80's into just a few industrial pilots: Myosotis at Isbergues, in France, Nippon Steel at Hikari in Japan, Project M at Port Kembla in Australia and CSM-Terni Special Steels at Terni in Italy. Most of the pilots are producing stainless steel, mainly 304 austenitic grade, but carbon steels have also been produced in Australia on a routine basis and on the other casters experimentally. Technical success has been clearly met, with material sold confidentially but in large quantities to the market, as heats were teemed on the casters several times a week from 100-t ladles, but commercial production is still being eluded, except for the NSC project which announced commercial operation in October 1998. The audacity of the technology and the size of the innovative step that it involves is making it difficult to adopt the technology as fast as it deserves. The time necessary for developing a radically new process in the steel industry is at least of 20 to 30 years and, if the initial laboratory work on the strip casting processes started in the late 70's, and the hot models were experimented on only in the mid-80's, another 5 or 10 years might still be necessary before the transition actually takes place.

The environment

The environment has brought to the forth novel issues for steelmaking in the 90's. Air pollution is the major keyword, both inside (occupational health issues) and outside of the steelshop. In the EAF shop, fume-collecting systems have been upgraded, both to meet more stringent environmental regulations and to absorb the extra volume generated by high fossil fuel operation. Secondary collecting systems have become the norm, while enclosed meltshops are not uncommon Wet combustionless collection is typical of the BOF, with subsequent use of the steelshop gas in reheating furnaces and the collection of dust as a sludge, while the EAF prefers to burn its gas in a post-combustion chamber and to collect the dust in a baghouse.

Emissions of COVs, dioxins and furans have attracted attention in the late 90's. Some mills had to install abatement technologies very rapidly and probably before the technology had time to mature. The issue remains a task for the future and will be discussed again later in the paper.

The concept of steel solutions

In the higher-end segments of carbon steels as in most of the special steels, the steel industry sells a service to its customers along with the product, i.e. a function rather than a mere material. This product-service package is usually called a “steel solution” (15). This differentiation marks the divide between specialty and commodity steels.

■ STEELMAKING FOR TOMORROW (2000-2030)

Beyond the first few years of the next century, the evolution of the steel industry partakes of all the uncertainties of the future. Technological forecasting traditionally makes use of scenarios to represent this branching out of the future into various possibilities. It is not necessary for our purpose, however, to go through the long and tedious process of scenario building, as we only wish to present future trends in the light of one strong assumption, i.e. that environmental issues will become a structuring driving force in the long term evolution of the steel industry. One might see this as one of several possible scenarios, in which the leading role is given to the environment. Other scenarios could have been organized around the likely drivers of the future : globalization and market economy, emergence of Asia, technological breakthroughs, etc.

Trends

We shall assume that some general trends will model the context in which process technology in steelmaking will develop :

– globalization,
– ubiquity of information and intelligence technology,
– innovation as a moral and business value,
– tertiarization of industry,
– and, of course, pregnancy of environmental issues.

We shall also assume a dialectical tension with seemingly opposite trends that will coexist with them and breed change :

– regionalism and promotion of cultural differences,
– traditional communication and team work,
– culture of urgency, recurrent campaigns for cost savings and short term improvisation,
– permanence of a strong traditional industrial base,
– strong opposition to an angelic view of ecology and to the uneconomic and unsustainable costs it may entail.

Among the most interesting examples of this tension will be the split of the steel industry into commodity steel and specialty steel producers, that will take place not only in the business of carbon steels for flat products, but also of special steels, engineering steels as well as stainless steels. But a strong interaction will remain between both poles, not only through competition in the market on border products,

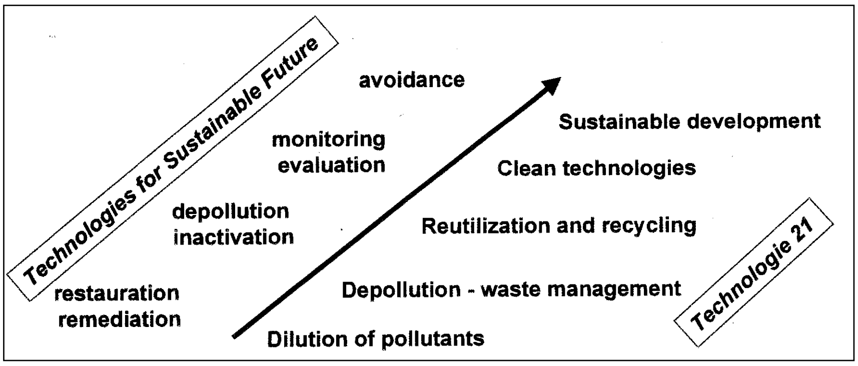


Fig. 9 – Methodological scale of values of ecological behaviour.

Fig. 9 – Échelle méthodologique de valeurs pour caractériser la performance écologique.

but also through technological interaction – as minimills will test-run new technologies, and across the material recycling loop – as minimills will recycle mainly steel from specialty producers.

A program for an environmentally friendly steelmaking

Ecology, being a young discipline with ideological overtones, likes to order its options along a scale of values that is really a scale of ecological correctness *(fig. 9)*.

In the olden times, when pollution was the daily fare of industry, the dilution of pollutants was the first environmentally conscious attitude. Then came the time of repentance and atonement for sins past led to depollution, restoration and to the thriving business of waste management. The present talk is about monitoring, recycling and clean technologies. Given the size of the task, particularly in terms of process technology, this will endure for many years to come. And in the future ecology will aim at avoidance, the most virtuous approach and the most ambitious one, as it requires a level of ecological consciousness and a coordination among economic operators and governments, that will need time to develop at the necessary scale.

The clean technologies of steelmaking

Clean technologies are technologies that do not generate waste, or pollution.

The matter of waste is interesting at the level of management theory, as it is related to the concept of core business : the steel industry's core business, for example, is to produce steel and anything else coming out of the steel mill is waste or, at best, a by-product. Dust generated in the EAF steelshop, for example, used clearly to be a waste that added to the operating cost, when it had to be landfilled. Under regulatory pressure, dust has become a low-grade zinc concentrate, which is sent to specialized operators for upgrading to a concentrate that has value for zinc smelters. The situation is still under tension as steel mills have to pay a fee for treating their dust and zinc smelters are still wary of a source of zinc units that is ill-defined and perturbs their process and habits. Recycling zinc is not yet commonly perceived as a core business of the steel industry and recycling waste from the steel industry not as one of the zinc smelters either.

To continue on the dust example, what is needed to reach the full awareness of clean technologies is to reach some kind of integration between zinc and steel issues. The steel industry can picture itself as a recycling business for both iron and zinc units for example. This in turn means that process scientists have to provide a description of the dual nature of the electric arc furnace as a metallurgical reactor for generating zinc concentrate in addition to its traditional role as a steel producing reactor (16). The same is true of slag, another important by-product of the steelshop.

These scientific prerequisites are being worked out and will be integrated into steelmaking prac-

Table II : Solutions for re-use of steelmaking waste and by-products

Tableau II : Solutions pour la réutilisation de déchets et de co-produits de la sidérurgie

Type of waste	Solutions	Robustness
EAF dust	Recycling of Zn and Pb at zinc smelting facilities Recycling of Fe and CaO in steelshop	Driven by regulation and cost of landfill Market economy solutions likely to emerge
BOF sludge	Recycling at the sinterplant	Common practice today
BOF slag	Civil engineering use Incorporation into special concrete	Acceptability to be developed
EAF slag		
Used steelshop refractories	Reuse in downgraded application today	Emergent technology Better separation and less downgrading?
Secondary metallurgy slags	?	Solutions urgently needed

tice soon, provided that a rationale for doing it at the business level is established. An arbitration between a market mechanism and a regulatory one based on an ecological fee or tax will be necessary. This is an important society issue that goes beyond the problems faced by the steel industry as it raises the question of whether recycling is about waste and should therefore be paid for by the polluter, or about using renewable raw materials, in which case the user should pay for them according to their value-in-use, provided that a positive value-in-use would have been developed through technology.

Whatever the solution path that will be chosen, steelmaking waste is likely to disappear in the early 21st century as all of it will be recycled one way or another. *Table II* shows some of the likely solutions that will be privileged and the remaining problem areas that still need answers.

Pollution, mainly air pollution from the fumes of steelmaking furnaces, is another issue that is not completely solved today. Heavy metals and organic compounds, including dioxins and furans are particularly focused here. One may safely project that these issues will find satisfactory solutions soon, not only based on the technology already developed for incinerators, but also on developments original to the steel industry that are pre-emergent in R&D activity (17 to 21). In this area, the concept of environmental cleanliness of raw materials (22) will help reduce emissions by promoting avoidance: for example, what is required in the case of steel scrap is to limit the amount of non-scrap materials, especially organic materials before charging this recycled steel into the EAF.

Recycling provides a renewable raw material to the steel industry

Recycling is a complex issue *(fig. 10)*. At its simplest level, it means only reuse, such as the second-hand second life of automobiles. The recycling of parts, a thriving business in the automobile world, comes next. Dismantling is a prerequisite. Recycling of materials is more complicated, as a more sophisticated dismantling is necessary, that may include a separation at a chemical or a metallurgical level, if one wants to recover basic materials, for example when coating or alloying is involved *(fig. 11)*.

The steel industry is mainly interested in the recycling of metals, starting obviously with iron but including other metals that are associated with iron in coating and alloying. Zinc as a coating material has already been discussed. Chromium and nickel, because of their price, have also been recovered from steelmaking slag and dust on a routine basis and will continue to be in the future. The matter of tin remains open, as its recovery is difficult and presently uneconomic (22).

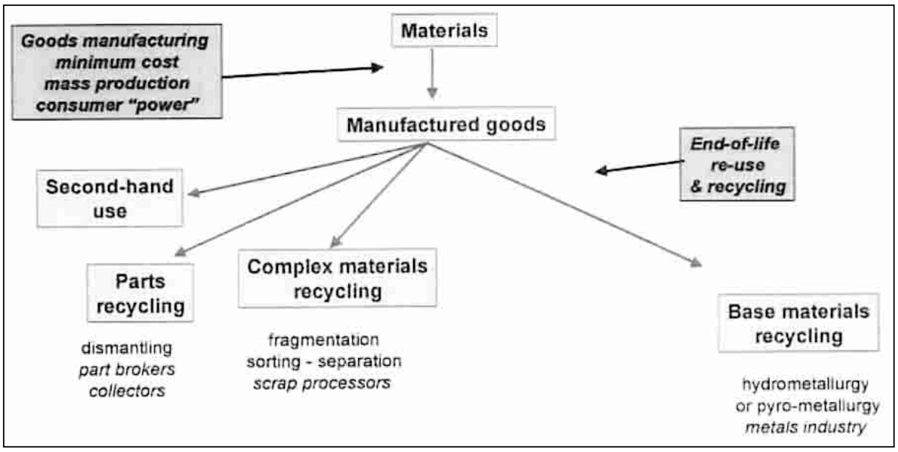


Fig. 10 – Principles of recycling.

Fig. 10 – Principes du recyclage.

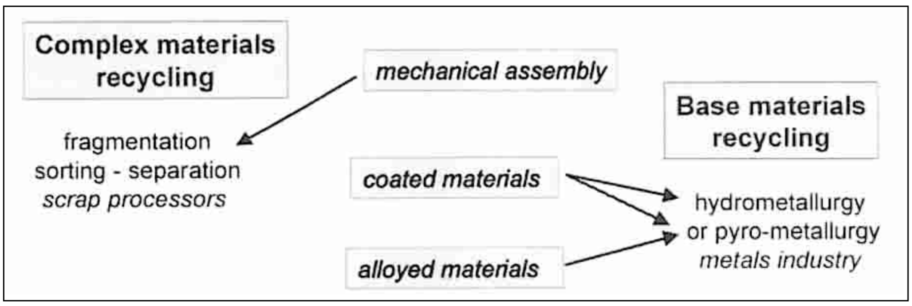
Recycling of steel has a long historical track and the age of words used to designate scrap in different languages attests of it*. The scrap business today is a profitable economic activity in countries with a long industrial tradition.

Figure 12 shows past records and future projections for the recycling of steel in the European Union. The scrap potential is the amount of obsolete scrap that is generated each year by the "death" of investment or consumption goods, when they reach the end of

** The French word for steel scrap,* ***ferraille****, was reportedly used for the first time in the 14th century.*

Fig. 11 – Principles of materials recycling.

Fig. 11 – Principe du recyclage des matériaux.



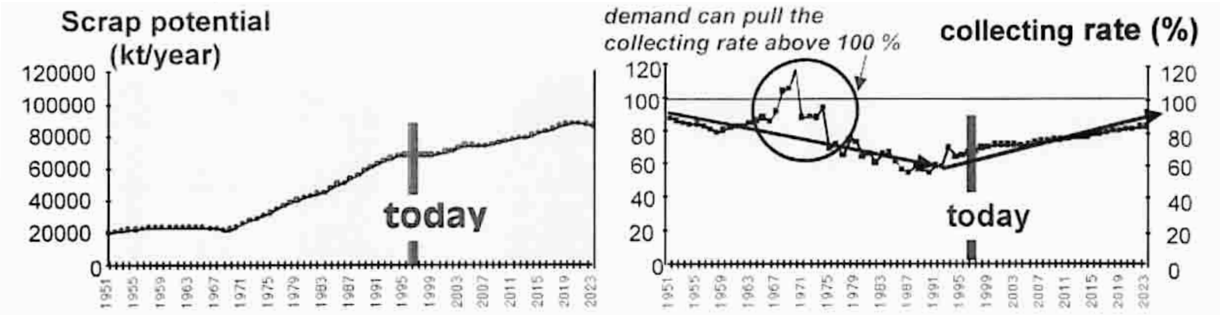


Fig. 12 – Evolution of obsolete scrap potential and collecting rate over 70 years (12-countries EU).

Fig. 12 – Évolution du gisement de ferrailles usagées et du taux de collecte sur une période de 70 ans (Europe à 12 pays).

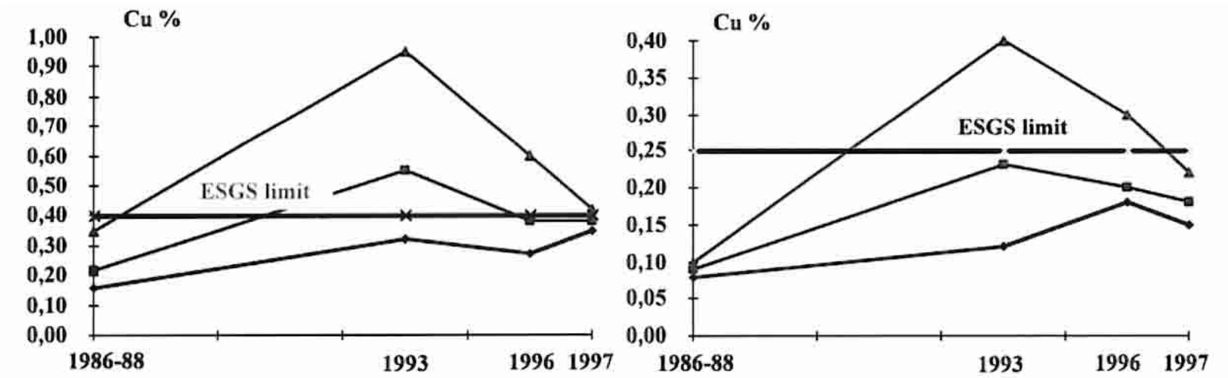


Fig. 13 – SPC-like evolution of copper content in E1 and E3 scrap (maximum, average and minimum values).

Fig. 13 – Présentation de type SPC de l'évolution de la teneur en cuivre des ferrailles de catégories E1 et E3 (maximum, minimum, moyenne).

their life. The collecting rate is the fraction of this scrap potential that is actually collected. The collecting rate of steel scrap in Europe today is at around 75 %, which properly qualifies steel as the most recycled material, both in terms of rate and volume. Indeed, the amount of scrap used in the world in 1997 was 356 Mt/year, to be compared to the 1998 steel production of 774 Mt, i.e. a scrap ratio of 46 %. Another interesting ratio for documenting this issue is the EAF ratio, which amounted to 34 % in 1998.

The projections for Europe are based on projections of steel consumption and of scrap collecting rate, which in turn reflects the expectation on steel recycling. In Europe, it is believed that recycling will increase, pulled both by government will and by the need for scrap as a raw material. The European trend is likely to extend to the whole world as the same drivers will be at play everywhere. Indeed, a recent Delphi survey projected a supply of 407 Mt/year of scrap and a collecting rate of 55 % in 2010, up from an estimate of 45 % for the world today (23). This seems to dispose of the **scarcity theory**, which has been predicting a rarefaction of scrap and an increase in its price, especially in the low residual scrap category, and has encouraged the erection of prereduction capacities to prepare for this situation.

An important issue about scrap is the matter of its purity, or the risk of pollution of the scrap resource by tramp element metals such as copper, tin, chromium, nickel or molybdenum, which might accumulate in the recycling loop as they are difficult to eliminate in the steelshop – where refining is mainly based on selective oxidation of impurities. Investigations carried out in Europe (24) (28) have demonstrated that, although the risk is real, a number of solutions are available to limit the pick-up in residuals to a level that is acceptable for the steel industry and its customers. This involves :

• A strict quality control on scrap at the entry of steelworks, based on a standard that fosters the proper segregation of scrap in narrow categories defined according to their composition. The new European Scrap Grading System (ESGS) (22) has been pioneering this approach in Europe and shown, since its introduction in 1996, that the scrap market is indeed able to adapt to the ESGS requirements and that the level in tramp elements has been brought back on the Western European market to satisfactory levels *(fig. 13)*.

• Encouraging process R&D on the preparation of scrap in order to summon up the whole power of applied research on the issue of separating materials. *Figure 14* gives an

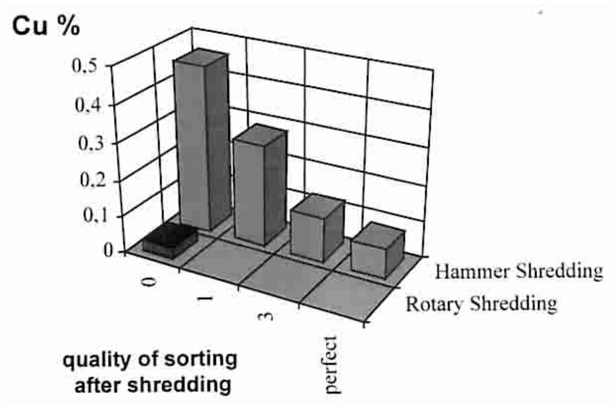


Fig. 14 – Improvement of shredded scrap quality according to shredding technology and quality of materials separation after shredding (0-3 hand-sorting operations; perfect sorting: all Cu bearing material is hand removed).

Fig. 14 – Amélioration de la qualité de la ferraille broyée en fonction de la technologie de broyage et de l'efficacité du tri des matériaux après broyage (niveau 0 à 3 : tri manuel ; tri parfait : tous les fragments contenant du cuivre sont séparés à la main).

example of what improvement in copper level can be achieved by careful handpicking of impurities at the exit of a traditional hammer shredder that produces shredded scrap. More elaborated programs have been launched, for example on the pilot shredder *(fig. 15)* of the Centre Technique pour le Recyclage de l'Acier (CTRA), with the target of reducing the level in tramp elements by a factor of 2 with respect to what is presently required in the ESGS, e.g. a copper level at 0.125 % instead of 0.250 %.

• The redefinition of the needs in the level of purity for most steels, both in terms of the requirements of the steel industry itself on issues such as hot shortness and fire-cracking – on the continuous caster or in reheating furnaces, and of steel users. This search for useless quality overspecifications has been going on with success, especially by former IM operators who have switched to the EAF route (25 to 27).

• Compounding this scrap resource management with a far-looking policy on recycling, that insists on the early separation of materials which are poisonous to each other in the integrated recycling loop and, in the longer term, on

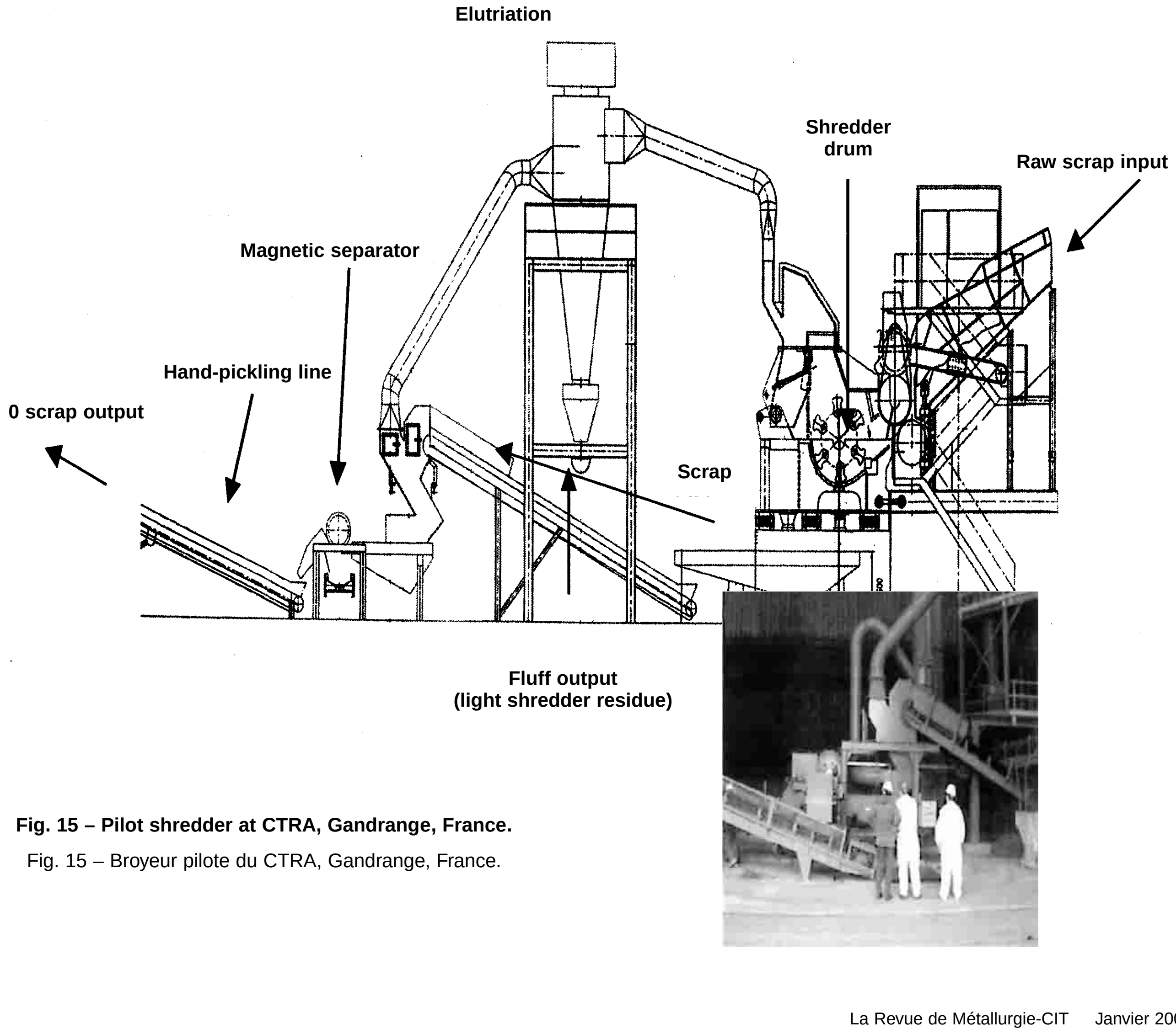


Fig. 15 – Pilot shredder at CTRA, Gandrange, France.

Fig. 15 – Broyeur pilote du CTRA, Gandrange, France.

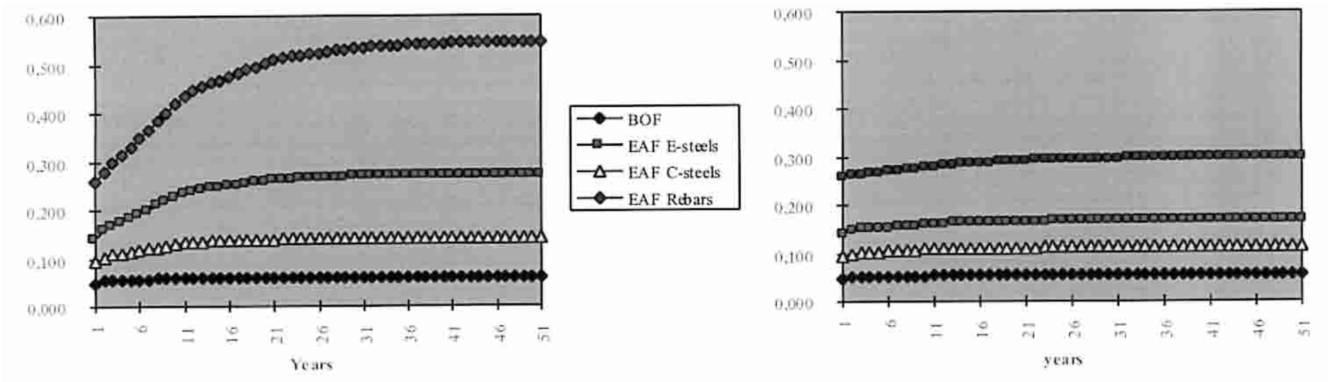


Fig. 16 – Evolution of copper in steel over the next 50 years with 2 contrasted scenarios: a laissez-faire scenario on the left, without any management of the quality and purity of the scrap resource, and a scrap management scenario on the right. The right-hand side scenario demonstrates sustainable recycling.

Fig. 16 – Évolution de la teneur en cuivre de l'acier pendant les 50 années à venir, suivant deux scénarios contrastés : à gauche, scénario du laissez-faire sans souci de la qualité et de la pureté de la ressource de ferrailles ; à droite, scénario de véritable gestion des ferrailles.

those that foster design for recycling. This issue will be further discussed under the heading of avoidance.

Recycling has a number of other virtues that are worth emphasizing (28). It taps a resource of Iron Units that is renewable, a concept for raw materials that is akin to that of renewable energies. Moreover, if the scrap resource is properly managed to avoid an irreversible build up of tramp elements according to the principles outlined above, simulations show that recycling can take place an indefinite number of times *(fig. 16)*, thus avoiding the curse of a downgraded use of recycled materials; recycling of steel is therefore sustainable, in the true sense of the term. Recycling is also the best and most reasonable way to answer the challenge of reducing greenhouse gas emissions of the steel industry (cf. last section). Last, it is a strong driving force for innovation. One may also add that the virtues of recycling are not unique to steel but apply just as well, mutatis mutandis, to other materials.

The EAF comes of age

Increased recycling means increased use of the electric arc furnace. This will induce a strong evolution of its technology, which is already obvious today. In contrast with the BOF, which has fully matured in the 1980's, the EAF still has a strong potential for progress. According to the Delphi study already mentioned, the expected development should bring the EAF ratio to 40 %* of total steel production in 2010, i.e. up to 330 Mt/year from 260 Mt in 1998. This means building between 50 and 70 new furnaces over the next 12 years. Most furnaces ought to be built in Asia (37 %), in North America (22 %) and in Europe (11 %), as shown in *figure 17*. Longer-term estimates of 50 to 60 % EAF ratio can be made, but they depend on a large number of arbitrary assumptions.

The EAF is the recycling tool of the whole steel industry: it also recycles steel from the EAF and the BOF route – mainly that, as a matter of fact today – and, as such, creates a loop that links together integrated producers and minimills.

The image of the EAF by 2010 is also given in the same Delphi study, the conclusions of which are shown in *tables III to VIII* for a trend scenario, which projects an average image. The EAF will stay resolutely based on scrap

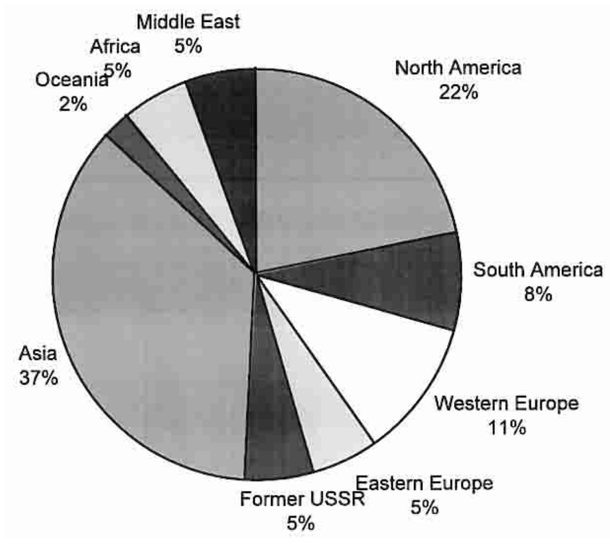


Fig. 17 – Geographical location of new EAF facilities until 2010.

Fig. 17 – Situation géographique des aciéries électriques qui seront construites d'ici à 2010.

* *The projections were in the bracket of 40 % + 5 %, – 0 %.*

World production	EAF steelmaking	EAF for flats	EAF for longs
760 -> 830 Mtpy 1% growth per year	33 -> 40 %	8 -> 20 % 20 -> 66 Mtpy	92 -> 80 % 230 -> 264 Mtpy

Table III : Production structure in 2010

Tableau III : Structure de la production sidérurgique en 2010

Table IV : Raw materials data : trend scenario (1997-2010)

Tableau IV : Situation des matières premières : scénario général (1997-2010)

Scrap	Pig iron	DRI/HBI	Hot metal	Others
Index of utilization 100 -> 112	6 -> 9 Mtpy	30 -> 50 Mtpy	2 -> 5 Mtpy	Iron Carbide 0 -> 1 Mtpy
Recycling rate 45 -> 55 %		Merchant DRI 2 -> 10 Mtpy		Need-expectation for Fe_3C 10 %
Purity (Cu in E40) 0.25 %		80% use for flats 20 % for longs		
New technologie s none		50 % continuous charging hot charging 3 -> 10 %		
Price index 100 -> 102		Price index (vs. Scrap) 110 -> 110		

Size	Electrical power	Carbon/coke	Oxygen	Cycle times
150 -> 160 t for flats 130 t for longs hot heel 12 t 1.5 to 1.65 Mtpy	Rated 1 MVA/t max 1.2 MVA/t 390 -> 360 kWh/t min 300 kWh/t	Average 23 kg/t max 40 kg/t Price no change	30 -> 40 Nm^3/t max 60 -> 70 Nm^3/t price no change	TTT: 68 -> 58 POT: 50 -> 45 min
	Price 100 -> 102	Natural gas 6 -> 6 Nm^3/t max 11 -> 12 Nm^3/t price - 8 %		

Table V : Operations data : trend scenario (1997-2010)

Tableau V : Prévisions relatives au fonctionnement du FEA : scénario général (1997-2010)

Table VI : Operations data : trend scenario (1997-2010)

Tableau VI : Évolution de la technologie du FEA : scénario général (1997-2010)

Continuous charging	*Scrap Preheating*	*DC/AC*	*Consumptions*
0 -> 10 %	*10 -> 30 %*	*45/55 -> 50/50*	*Hearth life 2500 heats bottom electrode DC 1500 heats*
	Twin shell 37 % Shaft 50 % Consteel 5 % Others 0 %	***Air Tight furnace***	***Manpower***
	Average 300 °C max 800 °C	*10 -> 20%*	*0.3 ->0.25 man hr/t 6-> 5 person per shift*

Major issues by 2010	Fume collection	Slag	Dust
CO_2 dioxin	Primary and secondary collection Post-combustion chamber water quench 15 % bagfilter	120 kg/t stable valorization 40 -> 60 %	17 -> 15 kg/t landfill/ valorization 60/40 -> 30/70 Zn recycling

Table VII : Environment : trend scenario (1997-2010)

Tableau VII : Environnement : scénario général (1997-2010)

Table VIII : Products : trend scenario (1997-2010)

Tableau VIII : Produits : scénario général (1997-2010)

High-end production by EAF	Low C	Low N	2ndary metallurgy
Auto body exposed by 2005 Tinplate by 2005	0.035 %	40 ppm at tap	Bubbling 100 % LAF 60 % degassing 15 %

and electricity, thus deserving to retain the name of EAF. It will have left the ghetto of special steels and of low-end long product commodity steel, to enter the lucrative markets of specialty carbon steels for long and flat products. In this case, new iron units, in the form of DRI / HBI, hot metal and pig iron (but very little Fe_3C), will supplement scrap but not overwhelmingly. EAF in flat products will not longer be found only in minimills, but will come to be associated in integrated mills to BOF steelmaking and minimill originating technologies, such as near-net shape casting.

The operating ratios will be an extrapolation of what they are today, without any strong discontinuity, maybe because process R&D will have yielded to pragmatic progress, driven by equipment manufacturers rather than steel companies. No strong changes are expected in the environment of the EAF : scrap will neither become unavailable, nor polluted by tramp elements. Prices of utilities and raw materials will remain stable or fall a little. Fume treatment will be based on existing technologies, but nevertheless eliminate the dioxin problem.

Some optional technologies will start to play an important role, although they will not be used for the majority of furnaces. Thus, the use of virgin iron units will be more sophisticated, for example hot charging of DRI in a shaft or use of pig iron from new processes (Redsmelt, Ausmelt, Hismelt, Tecnored, fluidized bed prereduction or smelting reduction and cupola). The furnace technology will incorporate preheating of scrap to a rather high temperature and a design that facilitates a tight-furnace operation. Sophisticated fume collection system will have abatement technologies against dioxin that comprise both a post-combustion chamber and a water quench.

Finally, to enter the high-end market of carbon steel flats, steelshops that do target this segment will be equipped with degassing.

Some images of the evolution of the arc furnace are shown in *figures 18 to 22*, as imagined mostly by furnace manufacturers. They propose various solutions for :

• scrap preheating :

– either in a shaft mounted as a tower in the EOF style *(fig. 19)*, electricity being brought by slanted electrodes,

– or in a doughnut-shaped shaft arranged around a single electrode *(fig. 20)*,

– or in a shaft equipped with a scrap-lock shut off by fingers *(fig. 21)*,

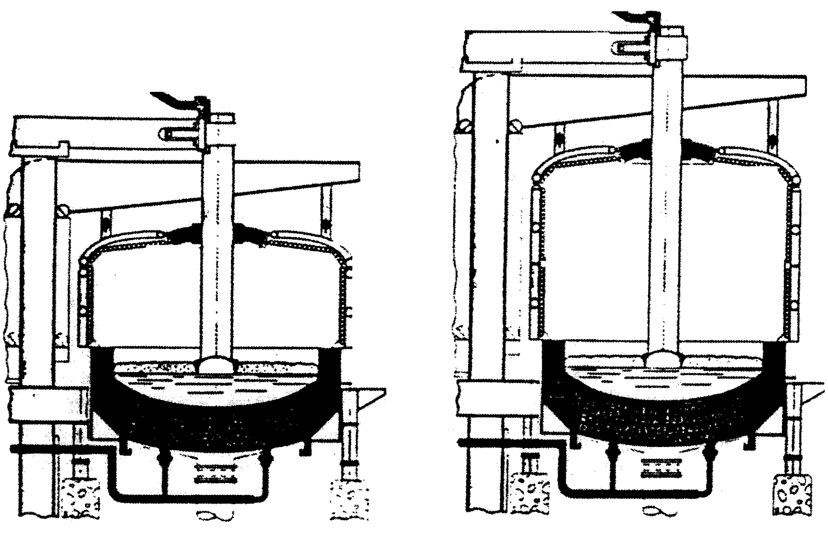


Fig. 18 – ABB EAF design with high vessel for single basket charging.

Fig. 18 – FEA de conception ABB avec une cuve rehaussée pour l'enfournement en un seul panier.

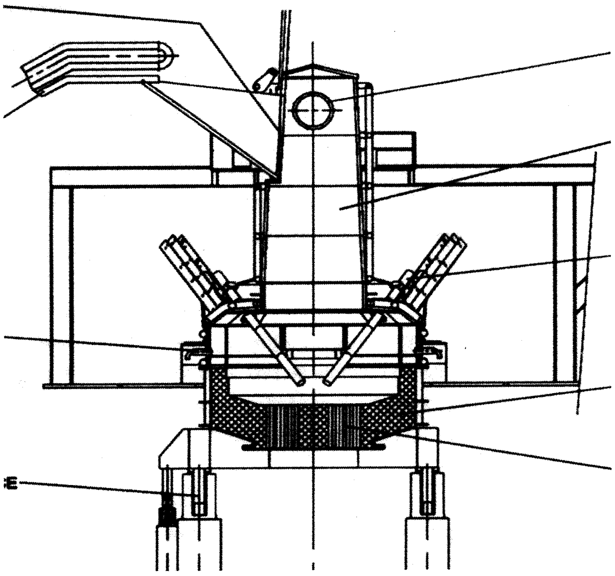


Fig. 19 – The Comelt furnace of VAI.

Fig. 19 – Le four Comelt de VAI.

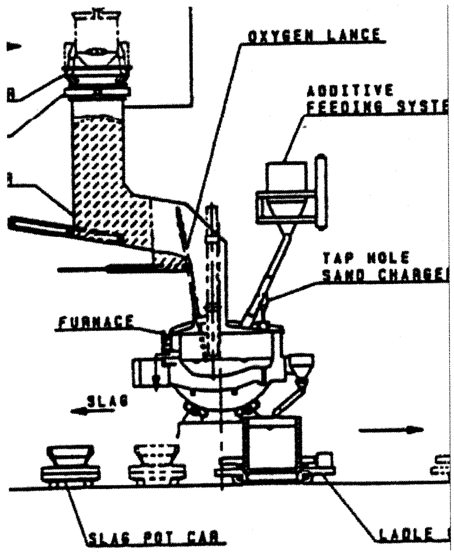


Fig. 21 – The IHI shaft furnace with a lock for scrap charging.

Fig. 21 – Le four shaft d’IHI avec un sas pour l’enfournement des ferrailles.

– or in a system of two consecutive preheating furnaces, a kiln and a shaft *(fig. 22)* ;

• making the furnace air-tight *(fig. 22)* ;

• charging scrap into the furnace with minimum logistical time, i.e. with a single basket *(fig. 18)*, continuously *(fig. 22)* or through a very large preheater *(fig. 21)*.

Beyond the technology of the design of the furnace, some subtle metallurgical issues will need to be tackled, in order to make credible the prediction made in the Delphi study that the high-end flat product market for the automotive or the packaging industry will be accessible to the electric arc furnace.

The matter of purity in tramp elements has already been discussed, but there remains the questions of whether low levels of carbon and nitrogen can be reached in the EAF.

Low carbon will be reached by a combination of tapping at 0.035 % carbon and further decarburization under vacuum, in RH or tank degassers that will become as popular and common in EAF shops as they are today in BOF shops.

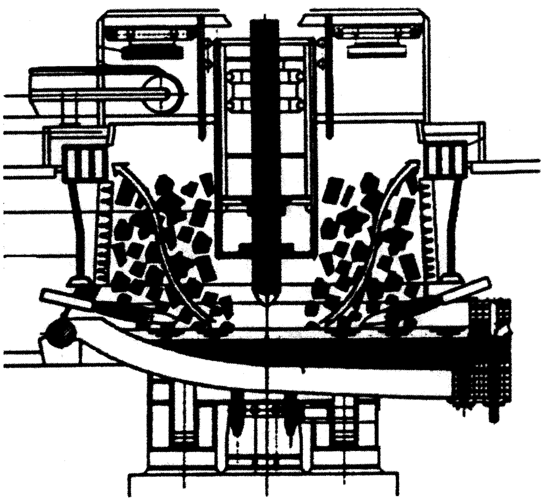


Fig. 20 – The Contiarc furnace.

Fig. 20 – Le four Contiarc.

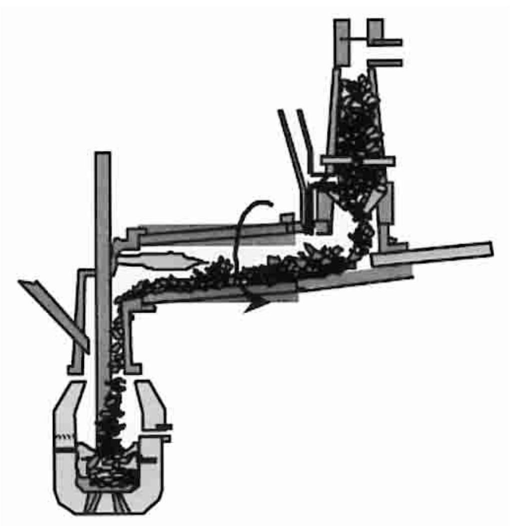


Fig. 22 – The Japanese Shinseiko concept : double preheating of scrap in shaft and rotary kiln.

Fig. 22 – Le système japonais Shinseiko : double préchauffage des ferrailles dans une cuve shaft et un four tournant.

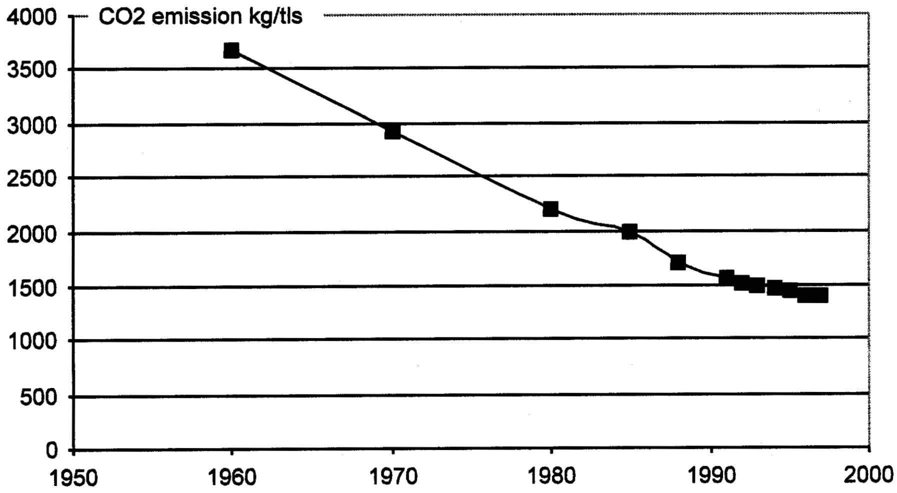


Fig. 23 – Emissions of CO_2 per ton of steel over the last 35 years.

Fig. 23 – Évolution de la quantité de CO_2 émise par tonne d'acier au cours des 35 dernières années.

Reaching low nitrogen levels is a more complex issue, as the EAF, in its capacity of producing mainly special steels or low-end carbon steels, had been producing steels with a typical level of 100 to 120 ppm nitrogen. The only published solutions for obtaining lower levels involved using either prereduced pellets or hot metal as a high proportion of input iron units. The regular production of 40 ppm nitrogen steels has been demonstrated, for example at Unimétal (29) and the Delphi study projects this value as the standard for EAF shops in 2010. Lower levels are also projected in the Delphi study. Moreover, vacuum denitrogenation, by washing the metal with large quantities of argon (10), has also the potential of eliminating nitrogen, so that the nitrogen levels necessary to the high-end carbon steel for the automotive industry will be produced by a combination of furnace and secondary metallurgy methods.

This ought to bring the EAF furnace to the level of sophistication that the BOF has reached for many years.

Avoidance and design for recycling

Avoidance is an idealistic concept, which states that society should organize in order to make human activities sustainable and friendly to the environment, while ensuring a high enough standard of living and a quality of life to all mankind. All countries will probably embrace avoidance in the distant future when poverty will have vanished from the face of the Earth, just to preserve natural resources.

From the narrower viewpoint of the industry today, avoidance means encouraging sustainable recycling practices. For example, this means that recycling should be carried out an indefinite number of times, i.e. that questions of materials mutual pollution should be solved at the early stage of designing new products.

In the case of an automobile, for instance, what is at stakes is the mixing of copper from electrical motors and wires with steel scrap, when the end-of-life vehicle is shredded. Improving shredding and separation technologies will help solve part of the problem. But using less copper in the design of a new car, or incorporating copper in such a way that it could be separated more easily from steel during shredding would be a more powerful and long reaching answer : aluminum wiring in the car, optical fibers to transport light rather than electricity to the front and to the back of the car, motors where the core on which the copper wires are wound would be brittle, would bring useful solutions towards solving the matter of designing a truly recyclable car, in the sense of sustainable recycling.

The search for lighter weight vehicles, which as a matter of fact does not simply mean using lighter materials as the ULSAB project has demonstrated (30), would also raise the issue to a higher level. Going even further, a deeper rethinking of the social function of transportation would cut a wider swath in the global issue : more public transportation or an increasing use of bicycles beyond China and Northern Europe would certainly bring society even closer to true avoidance.

Greenhouse gas emissions (31) (32)

The steel industry, being very energy intensive, has been using large quantities of carbon and emitting it back to the atmosphere as CO_2. As shown in *figure 23*, the emissions have decreased by more than a factor of 2 over the last 35 years, an evolution that strictly parallels the energy conservation steps taken during the same period *(fig. 5)*. The question remains, however, of whether more can be gained and how.

Figure 24 shows the level of CO_2 emissions of model steel mills, that take into account the various steel production processes that are available today to the steel industry.

Two factors control the amount of emissions :

– the major one relates to the source of iron units, virgin iron leading to emissions 4 times larger than scrap ;

– the carbon intensity of electricity is also a factor, whether it is used in the EAF or as a substitute to carbon in the blast furnace.

This clearly shows that recycling is the most powerful answer to the matter of greenhouse gas emissions that the

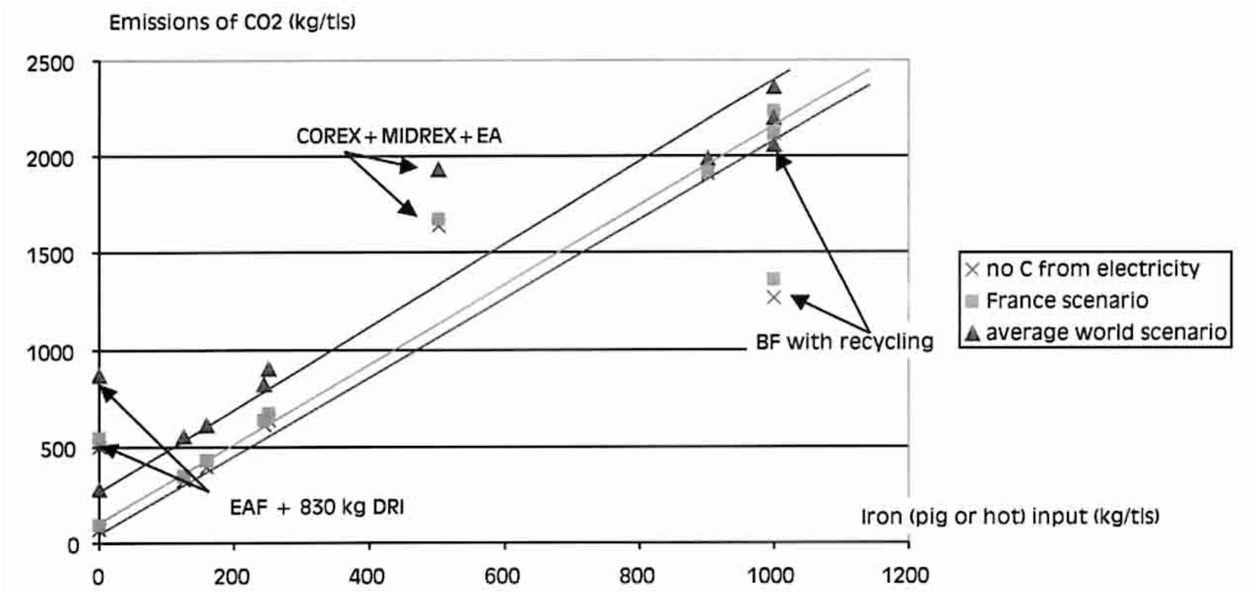


Fig. 24 – Emissions of CO_2 by model steel mills according to virgin iron input (horizontal axis) and carbon intensity of electricity (as a parameter).

Fig. 24 – Émissions de CO_2 calculées pour différentes usines types en fonction du taux d'utilisation de fer neuf (axe horizontal) et du contenu « carbone » de l'électricité (utilisé comme paramètre).

steel industry can propose in a reasonably short term. Reducing emissions means increasing scrap collection and scrap utilization in steel mills, mainly in EAF mills but also to a significant extend in integrated mills. It was demonstrated earlier that there is indeed a strong potential for doing this.

In the longer term, other paths may have to be trodden. Sequestration of CO_2 is one tentative solution, although the concept is not yet supported by a technology that could carry out the task at the level required in the steel industry* ; furthermore, the cost would be enormous. Using more carbon-free electricity or replacing carbon as a reducing agent by hydrogen (hydrogen prereduction) or electrons (electrolytic production of steel) would only be possible if or when renewable energies become more widely available. These issues, however open they are today, will probably be the focus of a lively debate in the early decades of next century.

Energy and material conservation remain a strategic target

Energy and material conservation will remain a strong paradigm of progress and innovation in the next decades, mainly as strip casting still awaits becoming commercial. The debugged technology of twin-roll casting *(fig. 25)* will be in the foreground, but later in time, more daring and risky solutions, such as the single roll caster of *figure 26*, might make it possible to produce net shape, rather than near-net-shape semi-products. The real open question is how fast these technologies will be adopted and whether they will penetrate the carbon steel market.

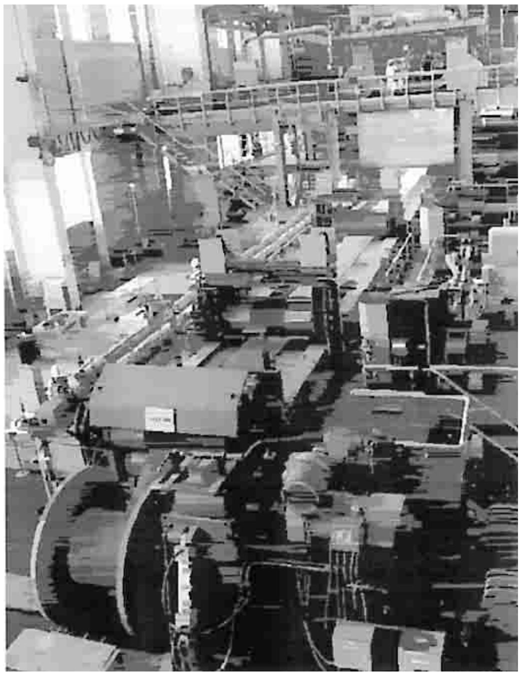


Fig. 25 – The pilot Myosotis twin-roll continuous caster.

Fig. 25 – L'installation pilote Myosotis de coulée de bandes minces entre cylindres.

** A 4-Mt/y blast furnace generates 9.6 Mt/y of CO_2.*

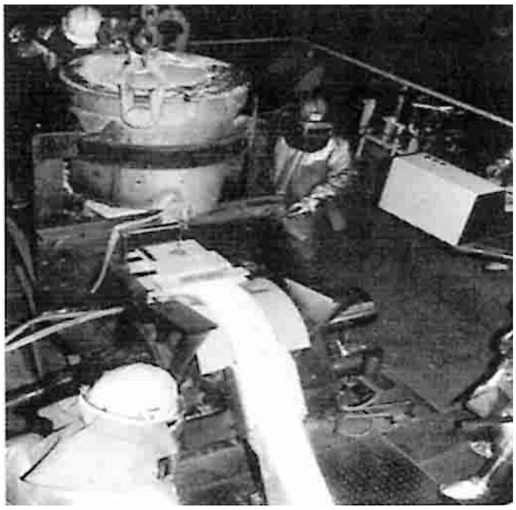


Fig. 26 – The Irsid single roll pilot continuous caster in operation.

Fig. 26 – L'installation pilote de l'Irsid de coulée continue à un seul cylindre.

Another open and exciting issue is that of direct steelmaking, i.e. of producing steel rather than carburized hot metal directly from iron ore in a single step (33). This is still a dream of steelmakers, as it would shortcut the separate ironmaking and steelmaking steps and do away completely with ore and coal preparation in sinterplants and coke-ovens. Just as appealing would be its environmental performance, as it would rely on steelmaking abatement technologies that are robust. Unfortunately for today, no impersonation of direct steelmaking is described in the literature. The only candidate process is the IFCON process of ISCOR (34), in South Africa, which has been reportedly running at a pilot scale, using a channel type induction furnace, and feeding it with ore and coal plus oxygen to activate post-combustion. A 0.02-0.10 % carbon steel is produced.

A direct steelmaking process might deliver the promises that smelting reduction never did, i.e. lower energy consumption, lower investment and lower operating costs than the integrated route. The stakes are worth some more exploratory work, as many other solutions than the IFCON process are possible on paper.

■ CONCLUSIONS

The Bible may help conclude this technological forecasting essay by putting the educated guesses that we have made into their true perspective : "*for now we see through a glass darkly ; but then face to face ; for now I know in part ; but then I shall know even as I am known*" (35).

In terms of process technology of steelmaking, we have mainly acknowledged the maturity reached by such key processes as oxygen steelmaking, secondary metallurgy and conventional continuous casting. We have predicted a strong development of the electric arc furnace and of near-net-shape casting, especially strip casting. All these technologies were imagined and developed in the 20th Century, although some of them still need to be perfected to reach full commercial use. In essence, we have been arguing that metallurgical process technology has been perfected in the 20th Century, just as mechanical technology was perfected in the 19th Century. This will leave biology, life sciences and biotechnology as the challenge for next century until some new frontier can be discovered for the mind.

Among the issues important for the steel industry that did not belong in this discussion centered on steelmaking, let us mention the future of cokemaking and that of smelting reduction, either in its blast furnace avatar or in some more modern one. More important still is the matter of new steels and new steel solutions, which does not seem to come close to saturation yet : the complexity of the field is akin to that of biology, by the sheer combinational number of solutions that metallurgy keeps available.

From a different perspective, environmental issues and the need for a sustainable future will most probably bring new needs, new ideas and new concepts in the realm of the steel industry. As steel is likely to remain one of the major assets of mankind to master its future, steel technology will adapt to maintain its availability at a low price.

Moreover, as technology will dig its roots into non-European cultures, the emergence of original solutions is to be expected.

■ REFERENCES

(1) CHEZEAU (N.), FLUZIN (P.). Historique des aciers spéciaux. Les Aciers spéciaux, p. 4-19. Lavoisier TEC&DOC, Paris (1997).

(2) GIAUQUE (G.). The history of carbon steel. The Book of Steel, p. 5-10. Lavoisier TEC&DOC, Paris (1995) and CD-ROM, Sollac (1997).

(3) CASTRO (R.). Historique des aciers inoxydables. Les aciers inoxydables, p. 1-9. Les Éditions de Physique, Les Ulis (1990).

(4) DELHALLE (A.), MARIOTTON (J.F.), BIRAT (J.P.), FOUSSAL (J.), LARRECQ (M.), TOURSCHER (G.). New developments in quality and process monitoring on Solmer's slab caster. *ISS Transactions*, n° 6 (1985), p. 69-80.

(5) BIRAT (J.P.). Metallurgical and operational results of continuous casting : past, present and future. 3rd European Conference on Continuous Casting, Proceedings, book 1, p. 21-32, UNESID, Madrid (1998).

(6) FUKUYAMA (F.). The end of history and the last man. Penguin Books (1992).

(7) HUNTINGTON (S.P.). Le choc des civilisations. Éditions Odile Jacob (1997).

(8) MILLER (T.W.), JIMENEZ (J.), SHARAN (A.), GOLDSTEIN (D.A.). Oxygen Steelmaking Processes, p. 475-524. The Making, Shaping and Treating of Steel, 11th edition, The AISE Steel Foundation, Pittsburgh (1998).

(9) Aspects of steel recycling. IISI, Bruxelles (1995).

(10) BANNENBERG (N.), BERGMANN (B.), GAYE (H.). *Steel Research*, 63 (1992), p. 283.

(11) BERTHET (A.), GROSJEAN (J.C.). The 90's electric arc furnace steelmaking route : the leap forward. 6th International Iron and Steel Congress Proceedings, vol. 4, p. 180-189, ISIJ, Japan (1990).

(12) DOLLÉ (G.). Present situation and prospects in the field of electric steelmaking. 5th European Electric Steel Congress, Paris (June 19-23, 1995). *Revue de Métallurgie-CIT*, 92, n° 10/11 (1995), p. 1177-1186.

(13) Report on EAF Technology, IISI Publication, Brussels (1999).

(14) I&SM, Annual Statistical Review and Membership Directory (July 15, 1998).

(15) SANZ (G.). L'acier, un matériau qui n'a pas fini d'étonner. *Revue de Métallurgie-CIT*, 96, n° 3 (1999), p. 395-410.

(16) HUBER (J.C.), PATISSON (F.), ROCABOIS (P.), BIRAT (J.P.), ABLITZER (D.). Some means to reduce emissions and improve the recovery of electric arc furnace dust by controlling its formation mechanisms. Recycling, San Sebastian (1999).

(17) WERNER (C.). Maîtrise des émissions de micropolluants organiques au four électrique. Paris, 19th International Steelmaking Days, Proceedings, *Revue de Métallurgie*, hors série ATS-JSI 98, p. 134-135.

(18) WERNER (C.). Control of organic micropollutants from the EAF. Encosteel – Steel for Sustainable Development, Stockholm, Conference papers, p. 247-255, IISI, Brussels (1997).

(19) ARION, BARONNET (F.), LARTIGES (S.), BIRAT (J.P.). Characterization of emissions during the heating of tire contaminated by scrap. The 6th International Congress on Toxic Combustion By-products, Karlsruhe (27-30 juin 1999).

(20) ROMELOT (P.), ANTOINE (J.), GROS (B.). Optimization of scrap recycling routes for environmental protection. Encosteel – Steel for Sustainable Development, Stockholm, Conference papers, p. 94-107, IISI, Brussels (1997).

(21) ONAKA (K.), NIWA (Y.), KITABAYASHI (S.), MORI (H.), HOJOE (H.). Development of dioxins removal systems for EAF. *Denki Seiko*, vol. 70-2 (April 1999), p. 127-132.

(22) BIRAT (J.P.), RUSSO (P.), GROS (B.), de GUERRY (C.), DALSHEIMER (J.). Usinor fosters recycling and its long term sustainability. 4th International Conference and Exhibition on the Recycling of Metals, ASM, Vienna (17-18 June, 1999).

(23) BIRAT (J.P.). A Delphi future study on the electric arc furnace at the 2010 horizon. Electric Furnace Conference, Pittsburgh, lSS (1999). *Revue de Métallurgie-CIT*, n° 11 (2000), p. 1347-1363.

(24) BIRAT (J.P.). Residuals and tramp elements in scrap and steel. Process Technology Conference Proceedings, PTD, p. 53-65, ISS, USA (1996).

(25) Effects of tramp elements in flat and long products. European Commission, technical steel research, Report EUR 16672 EN, Brussels (1995).

(26) HOUPERT (C.), LANTÉRI (V.), JOLIVET (J.M.), GUTTMANN (M.), BIRAT (J.P.), JALLON (M.), CONFENTE (M.). Influence of tramp elements in the production of high quality steels using the scrap/electric arc furnace route. *Revue de Métallurgie-CIT*, n° 11 (1997), p. 1369-1384.

(27) HOUPERT (C.), JALLON (M.) LANTÉRI (V.), JOLIVET (J.M.), GUTTMANN (M.), BIRAT (J.P.). Production of high quality steels using the scrap/electric arc furnace route. 1996, 15th PTD Conference Proceedings, p. 67-77.

(28) BIRAT (J.P.), LE COQ (X.), RUSSO (P.), LARAUDOGOITIA (J.J.), GONZALÈS (E.). Scrap quality monitoring on the European steel scrap market. 4th International Conference and Exhibition on the Recycling of Metals, Vienna (17-18 June, 1999).

(29) MAILHAN (J.C.) et al. Carbon and nitrogen control in the EAF. 20th International Steelmaking Days, ATS-JSI 99, Paris (1999).

(30) www.ulsab.com ; www.iisi.be

(31) BIRAT (J.P.), ANTOINE (M.), DUBS (A.), GAYE (H.), de LASSAT de PRESSIGNY (Y.), NICOLLE (R.), ROTH (J.L.). Vers une sidérurgie sans carbone ? *Revue de Métallurgie-CIT*, 90, n° 3 (1993), p. 411-421.

(32) BIRAT (J.P.), VIZIOZ (J.P.), de LASSAT de PRESSIGNY (Y.), SCHNEIDER (M.), JEANNEAU (M.). CO_2 emissions and the steel industry's available responses to the greenhouse effect. Seminar on Abatement of Greenhouse Gas Emissions in the Metallurgical and Materials Process Industry, San Diego, CA (28 February – 3 March, 1999). *Revue de Métallurgie-CIT*, 96, n° 10 (1999), p. 1203-1215.

(33) FRUEHAN (R.J.), NASSARALLA (C.L.). Alternative oxygen steelmaking processes, p. 743-759, The Making, Shaping and Treating of Steel, 11th edition, The AISE Steel Foundation, Pittsburgh (1998).

(34) FOURIE (L.J.). Steelmaking process. US Patent 5,411,570 (May 2, 1995).

(35) The Bible, I Corinthians 13, 12.

Jean-Pierre BIRAT, 51 ans, ingénieur des Mines de Paris (promo 1966), Master of Sciences (UC Berkeley, 1970), Prix Rist 1980. Entré à l'Irsid en 1971 au service « Recherche Coulée continue ». Actuellement chef du projet « Filière ferraille et recyclage » d'Usinor. Membre de la Direction scientifique et technique de l'Irsid où il est chargé de l'animation de l'innovation.