Applying Ausmelt Technology to Recover Cu, Ni, and Co from Slags

Stephen Hughes

The technical feasibility of recovering copper, nickel, and cobalt from smelting and converting slags using Ausmelt's top-submerged lancing process has been demonstrated at the pilot-plant scale and in several commercial applications. Process conditions may be tailored to achieve the maximum economic recovery of valuable metals and to yield a product composition that is suitable for downstream processing requirements. Strong economic justification for a slag-cleaning process exists where the contained value of metals recovered exceeds $50 per tonne of slag treated. The top-submerged lance system offers a relatively low-cost solution where this value is predominantly associated with the recovery of cobalt.

INTRODUCTION

Maximizing the recovery of copper, nickel, and cobalt is critical for the economic operation of smelters treating copper/nickel/cobalt feed materials. With the current trend toward the production of higher matte grades and the adoption of continuous converting processes, effective slag cleaning is of increasing importance. To address this need, Ausmelt has developed and commercialized processes for treating smelting and converting slags using top-submerged lancing technology. A description of this technology and its development has been presented previously by Floyd.[1] A brief overview of the process development is given in the sidebar.

Ausmelt's top-submerged lancing technology is established in a number of commercial plants treating a wide range of feed materials. The versatility of the technology has been demonstrated for a range of processes, ranging from copper converting under highly oxidizing conditions to ironmaking under highly reducing conditions. The most recent development is the construction of a demonstration furnace (2 t/h feed rate) at Whyalla in South Australia to produce pig iron. This is a key stage in the implementation of the South Australian Steel and Energy project, with the production of 2.5 million t/y of pig iron as the ultimate goal. Other recent commercial applications are listed in Table I; most of these applications include either a purpose-designed, slag-cleaning furnace or a slag-cleaning process stage.

TESTWORK RESULTS

Much of the testwork was conducted in Dandenong, Australia, at Ausmelt's pilot plant, which has been designed to operate over a range of operating conditions. The results of slag-cleaning tests at this scale are shown in Table II.

Metal Reduction Rates

Copper and nickel reduced from slag at higher rates than cobalt (Figure 1). In the testwork on Peirce-Smith converter slags, dissolved sulfidic copper in slag served as a limiting factor in recovering a matte product, as shown by the low levels of copper present in oxide form.

Considerable iron reduction occurs in conjunction with cobalt reduction, particularly as the cobalt level in the slag drops below 0.2%.[5] This can result in high levels of metallic iron in the metal/matte product.

Metal Recovery

Overall metal recoveries were affected by the feed grade, the extent of metal oxides reduction, product composition, and the separation of metal/matte from the slag. Due to the high degree of turbulence within the furnace promoting mixing of the slag and reductants, the reduction reactions could essentially proceed to equilibrium under suitable process conditions. Consequently, the level of copper, nickel, and cobalt in discard slag was a function of the equilibrium between the metal/matte phase and slag and the degree of separation achieved. A 5–10 minute settling period with the lance raised above the bath prior to slag tapping was conducted to facilitate the settling of the metal/matte product.

The smaller differential between the density of matte and slag and the lower

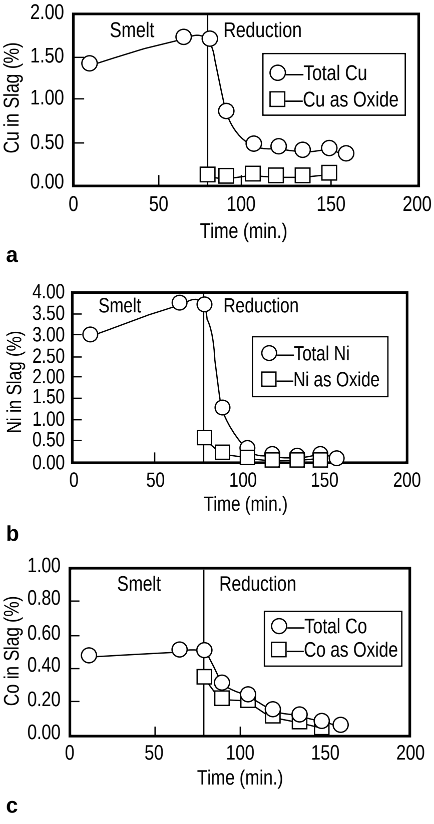

Figure 1. The reduction of (a) copper, (b) nickel, and (c) cobalt from slag.

Table I. Recent Ausmelt Commercial Plants

Client	Location	Design Feed Rate (t/y)	Feed Type
Rio Tinto Zimbabwe	Eiffel Flats, Zimbabwe	7,500	Cu/Ni residue
Korea Zinc Co. Ltd.	Onsan, Korea	90,000	Pb/Zn slag
Mitsui Mining and Smelting Co.	Hachinohe, Japan	100,000	Zn/Pb slag
Anglo American Corporation	Bindura, Zimbabwe	12,000	Cu residue
Korea Zinc Co. Ltd.	Onsan, Korea	120,000	Zn residue
Metaleurop	Nordenham, Germany	122,000	Pb materials
Funsur/Minsur SA	Pisco, Peru	40,000	Sn concentrates
Gold Fields of South Africa	Tsumeb, Namibia	120,000	Pb materials
Portland Aluminium*	Portland, Australia	12,000	Spent pot lining
CNIEC	Zhong Tiao Shan, China	200,000	Cu concentrates
Korea Zinc Co. Ltd.†	Onsan, Korea	100,000	Pb secondaries
Yunnan Tin Corporation†	Gejiu City, China	50,000	Sn concentrates
Korea Zinc Co. Ltd.†	Onsan, Korea	100,000	Pb/Zn slag
Korea Zinc Co. Ltd.†	Onsan, Korea	100,000	Pb tailings

* Development plant.
† Design/construction in progress.

Table II. Pilot-Plant Test Conditions and Results

Test Conditions*	Metal/Matte (%) Cu	Metal/Matte (%) Ni	Metal/Matte (%) Co	Slag (%) Cu	Slag (%) Ni	Slag (%) Co	Recoveries (%) Cu	Recoveries (%) Ni	Recoveries (%) Co
Feed One									
29% O_2, 1,300–1,400°C, 15% pyrite addition	11.6–26.8	—	2.4–10.5	0.01–0.28	—	0.01–0.35	86–96	—	91–98
Feed Two									
33–35% O_2, 1,380–1,420°C, 5–20% pyrite addition	0.7–4.6	1.2–8.3	0.8–3.1	0.01–0.04	0.04–0.05	0.04–0.08	59–64	66–75	41–65
Feed Three†									
33% O_2, 1,300–1,350°C, 8.5–10% Cu conc. addition	27–74	0.5–0.62	0.3–6.8	0.5–1.0	0.01–0.03	0.03–0.11	70–85	90–97	77–94
Feed Four									
28% O_2, 1,280–1,330°C, no sulfidizing agent	35–67	13–22	0.8–6.3	0.4–0.5	0.03	0.08–0.14	85–88	97–99	70–84
Feed Five									
33–35% O_2, 1,250–1,300°C, 10% pyrite addition	8.0–15.5	14.5–35.5	1.0–2.0	0.2–0.4	0.03–0.08	0.02–0.05	81–91	98–99	90–97

* Feeds are specified in Table 1.
† Separate metallic and matte phases recovered.

interfacial tension when compared with metal/alloy and slag can still result in the loss of very fine matte prills (<1 mm) as a result of entrainment. This mechanism is a major potential cause of unduly high metal losses and must be carefully addressed during the process and plant design stage.

Slag Composition

Slag composition was observed to play a significant role in affecting overall metal recoveries, as viscous slags inhibited both the rate of reduction and the subsequent settling of the reduction products. Fayalite slags containing high levels of silica are highly viscous, and foaming can occur as iron is reduced from the slag, particularly in cobalt-reduction processes.

While effective control of the reduction process endpoint will minimize the extent of iron reduction from slag, the addition of a lime-bearing flux may be used to achieve the required slag properties. This was found to be necessary in the case of cobalt recovery from smelting slags, which typically contain lower levels of iron than converting slags.[5] The addition of small amounts of lime (5%) to converter slag can also facilitate the separation of matte and slag, thereby improving metal recoveries.

The Selective Reduction of Copper/Nickel and Cobalt

Due to the differences in the process conditions and reduction rates, it is theoretically possible to recover separate products in a multiple-stage operation. A copper/nickel product can be recovered initially after completing a partial reduction followed by a cobalt-rich metal alloy.

Several pilot-plant trials treating Peirce-Smith converter slag containing significant levels of all three metals were conducted to evaluate the feasibility of such a process. While a degree of product separation was achieved (Table III), problems were encountered in tapping the second-stage metal product from the furnace. This problem highlighted the need to operate at varying temperatures to maintain fluidity of the two different types of product. A variation of this process has been applied commercially at the Bindura smelter to meet the nickel-in-blister specification while maximizing the direct yield of copper in the blister-copper product.

COMMERCIAL IMPLEMENTATION

Cleaning copper/nickel/cobalt slags has been implemented commercially by Rio Tinto Zimbabwe at the Empress nickel refinery and by Anglo American Corporation at the Bindura smelter and refinery. Both of these plants are located in Zimbabwe. In both plants, a single Ausmelt furnace is used to treat a residue via a multistage process.

At the Empress nickel refinery plant, described previously by Markham et al.,[6] a residue typically containing 50% copper, 12% nickel, and 0.2% cobalt is smelted at 1,300°C under neutral conditions. This yields a matte product containing 4–6% sulfur, which is tapped from the furnace when the maximum bath level is reached. A 25 minute slag-reduction step is then conducted, followed by a ten-minute settling period prior to tapping slag, which represents the only significant source of metal losses from the system. The metal/matte product is retained in the furnace for the resumption of the smelting stage. During the reduction stage the lance is operated at 90% stoichiometry with 400 kg/h of lump-reductant coal added. The furnace temperature is steadily raised to 1,350°C. The combined Cu/Ni assay of the discard slag is typically 0.5–2.0%, with higher levels attributed to losses resulting from entrainment.

The operation of the Bindura smelter and refinery plant, which is currently on cold standby due to unfavorable economic circumstances, has been described in detail by Mounsey et al.[7] A process including smelting, converting, and slag-reduction stages was employed. The residue, predominantly comprising copper sulfide, was smelted under slightly oxidizing conditions to produce a high grade matte (~77% copper, 1% nickel) suitable for the subsequent converting stage. The slag at the conclusion of the converting process may contain high levels of copper if a low-sulfur blister copper product was targeted. An initial 45 minute reduction stage was conducted to maximize copper recovery to the blister product, which was then tapped from the furnace. The reduction stage was completed to produce a discard slag and a Cu/Ni metallic product. During the reduction stage the lance was operated at 80% stoichiometry with the 400 kg/h of lump-reductant coal added, while the temperature was steadily raised from 1,250°C to 1,300°C. Copper levels of 0.5–1.0% in slag were achieved.

PROCESS ECONOMICS

The commercial viability of installing a slag-cleaning furnace is determined by the margin between the value of the metals recovered and the operating and capital recovery costs that are associated with the slag-cleaning furnace. In cases where the installation of a slag-cleaning furnace replaces recycling slag via the smelting furnace, the processing of additional new feed materials may also be possible.

Slags associated with the production of low-grade Cu/Ni mattes from reverberatory and electric furnaces typically contain low levels of copper and nickel and generally do not warrant further treatment. An exception is where the level of cobalt in slag is greater than 0.2%. Slag stockpiles also represent a source of slag that may be retreated in conjunction with current hot-slag production.

Table III. Selective Reduction Test Results

	Cu (%)	Ni (%)	Co (%)	Fe (%)	S (%)
Feed	2.8–4.5	0.7–1.0	0.6–0.7	52.0–54.5	0.7–1.2
Metal Product					
Tap 1	62.0–70.0	16.6–22.0	1.3–2.0	5.5–10.0	1.6–6.0
Tap 2	17.9–41.0	6.0–22.3	7.1–11.5	27.9–67.6	0.2–2.1
Discard Slag	0.4–0.8	<0.1	0.1–0.3	47.9–54.3	—

Table IV. Contained Metal Value in Converting Slags

		Peirce-Smith Copper Converter		Peirce-Smith Cu/Ni Converter		Continuous Copper Converter	
Element	**Value ($/t)***	**(%)**	**Value† ($/t)**	**(%)**	**Value† ($/t)**	**(%)**	**Value† ($/t)**
Cu	1,750	3.3	49	0.6	2	15.0	254
Ni	9,000	0.1	—	1.0	81	0.1	—
Co	35,250	0.3	88	0.5	159	0.1	—
Total			137		242		254

* June 2000

† Metal value recovered based on 0.5% Cu, 0.1% Ni, 0.05% Co in discard slag.

Slags generated from Peirce-Smith converter operations have traditionally been retreated by recycling to the smelting furnace, by milling and flotation, or via a dedicated slag-cleaning furnace. As high-grade matte smelting and continuous converting processes are increasingly adopted, the requirement for a separate slag-cleaning process is becoming more prevalent. The economic incentive to recover copper, nickel, and cobalt from these slags is illustrated in the values shown in Table IV.

Operating Costs

Operating costs depend on local unit costs for labor, energy, and consumables, as well as process considerations, such as throughput, feed and fuel composition, and the use of oxygen enrichment. Typical operating costs for an Ausmelt furnace system treating 100,000–300,000 t/y of slag will range from $20–40/t slag treated. Furnace worker requirements may be kept to a minimum by automating the process-control and lance-changing operations. Tapping operations form the major portion of time where attendance is required.

Coal requirements (as fuel and reductant) will be approximately 15% of the weight of slag treated for copper/nickel slag reduction and for larger-scale plants targeting cobalt recovery. The coal requirement will increase to approximately 20% of the weight of slag that is treated for smaller-scale cobalt recovery processes.

Electric-power requirements may range from 100–400 kWh/t slag treated. Electric power consumption may be minimized through the use of oxygen enrichment to reduce the lance air and off-gas volumes that are handled.

Refractory maintenance is another major cost item and may account for up to 30% of the annual furnace-operating costs. The use of copper cooling elements can deliver major improvements in refractory performance, with consequent operating cost benefits. Other significant operating costs may include process-specific fluxes and water for gas cooling where installation of a waste heat recovery plant is not economically justifiable.

Capital Costs

The Ausmelt furnace system is a relatively low capital cost system compared with competing technologies. Installed capital costs will be highly dependent on the slag throughput and the plant location and configuration. As a slag-cleaning furnace would normally be installed either as an addition to an existing smelter or as an integral part of a new facility, considerable savings can be realized by maximizing the use of existing or common personnel and infrastructure to minimize operating and capital costs.

The capital costs for a stand alone slag-cleaning plant treating 100,000–300,000 t/y of slag will typically range from $100–250 per t/y slag treated, with lower costs generally associated with relatively simple, larger-scale plants. These costs are inclusive of the Ausmelt furnace, a purpose-designed building, liquid and solid feed handling systems, a gas handling plant, product granulation facilities, services, EPCM, and installation costs. The Ausmelt furnace itself typically comprises less than 20% of the total installed plant costs.

Optimization of the use of oxygen is an important consideration, as operating costs and capital cost savings may be delivered as a result of the reduced lance-fuel and air-supply requirements and lower off-gas volumes treated with increasing oxygen enrichment of the lance air. These savings must be balanced against the operating costs and

PROCESS DEVELOPMENT

The use of top-submerged lancing was pioneered in the early 1970s for the reduction of tin-bearing slags. At an early stage in the development of the technology, the possibility of recovering other metals from slags was recognized. Initial pilot-scale testwork proved the technical feasibility of recovering lead, zinc, copper, and nickel from slags. Extensive testwork programs aimed at recovering copper from slag were conducted at ER&S (Port Kembla, Australia), Copper Refineries (Townsville, Australia), and MIM (Mount Isa, Australia) using furnaces with one-tonne slag-holding capacity. Ausmelt has subsequently conducted further pilot-scale testwork on a range of copper/nickel/cobalt materials, including reverberatory furnace slags, electric furnace slags, Peirce-Smith converter slags, and Ausmelt converter slags. The analyses of typical slags from these sources are given in Table 1.

The selection of process-operating conditions is influenced by the targeted product composition, which may be either sulfide or metallic in nature, and the required recoveries. The addition of a sulfide-bearing material to produce a matte phase will facilitate operation at lower temperatures, while decreasing the oxygen potential will promote increased recoveries, albeit with accompanied product dilution by iron reduction. In the top-submerged lancing system, the oxygen potential is controlled by varying the combustion stoichiometry of the lance and adding lump reductant coal.

Metal losses in slags result from two mechanisms—chemically dissolved metal in either oxide or sulfide form, which may be recovered by reduction, or entrained metal or matte, which may be recovered by modifying the slag viscosity and providing sufficient time for settling. The overall chemical reactions taking place during reduction with the addition of pyrite as a sulfidizing agent are summarized as follows:

$$FeS_{2(solid)} \rightarrow FeS_{(matte)} + 1/2S_{2(gas)}$$

$$FeO_{1.5(slag)} + 1/2C_{(solid)} \rightarrow FeO_{(slag)} + 1/2CO_{(gas)}$$

$$Cu_2O_{(slag)} + FeS_{(matte)} \rightarrow Cu_2S_{(matte/alloy)} + FeO_{(slag)}$$

$$NiO_{(slag)} + C_{(solid)} \rightarrow Ni_{(matte/alloy)} + CO_{(gas)}$$

$$CoO_{(slag)} + C_{(solid)} \rightarrow Co_{(matte/alloy)} + CO_{(gas)}$$

$$FeO_{(slag)} + C_{(solid)} \rightarrow Fe_{(alloy)} + CO_{(gas)}$$

$$CO_{(gas)} + 1/2O_{2(gas)} = CO_{2(gas)}$$

The actual metal-reduction mechanism in the presence of carbon may occur through intermediary steps such as

$$MO_{(slag)} + CO_{(gas)} \rightarrow M_{(alloy)} + CO_{2(gas)}$$

where M is a metallic element (Cu, Ni, Co, or Fe).[2]

Ferric, copper, and nickel oxide can be readily reduced from slag under mildly reducing conditions, while cobalt requires more strongly reducing conditions. Subsequent processing requirements for the recovered matte/metal product will largely determine the required composition and properties. Production of a sulfide- or copper-rich product will typically enable operation at temperatures of 1,250–1,300°C, while metallic iron/nickel/cobalt products may require operating temperatures up to 1,400°C. Where a sulfur-deficient matte is produced, a review of phase diagrams[3,4] shows that metallic phase separation is promoted at lower operating temperatures, which may not be desirable.

The slag properties will also affect the required system operating temperature. Sufficient superheat above the liquidus temperature is required to produce a slag of suitable viscosity, without excessively compromising refractory performance. In some cases, the addition of a fluxing agent may be needed to reduce the slag liquidus temperature and enhance the settling properties. The incorporation of copper cooling elements into furnaces operating with elevated temperatures and low viscosity slags enables process conditions to be optimized while achieving extended vessel campaign life.

Table 1. Pilot-Plant Feed Materials

Source	Cu	Ni	Co	Fe	S	SiO_2	Al_2O_3	CaO	MgO
Reverberatory	1.1	0.0	0.8	25.3	0.7	43.1	6.7	7.1	2.3
Electric Furnace	0.1	0.2	0.2	24.2	0.5	46.3	1.8	1.1	18.9
Peirce-Smith Converter (1)	3.3	0.3	0.5	52.5	1.2	25.1	0.6	0.7	0.3
Peirce-Smith Converter (2)	3.3	0.9	0.6	53.7	1.0	19.3	1.1	0.3	—
Ausmelt Converter	1.5	3.7	0.5	47.1	0.6	27.0	0.9	0.3	1.4

Table V. Leach Test Results

Sample	Cu	Ni	Co	Fe	Cd	Zn	Pb	As
Peirce-Smith Converter Slag—Reduced (%)	0.42	0.01	0.08	38.6	—	—	—	—
Elutriate (mg/l)	0.1	<0.1	<0.1	1.2	<0.01	0.03	<0.1	<0.01

the capital costs that are associated with oxygen supply.

ENVIRONMENTAL CONSIDERATIONS

The top-submerged lancing system represents a significant improvement over many competing smelting technologies by virtue of the intense turbulence generated, which promotes high reaction rates and allows the slag and gas to equilibrate. These combined effects allow a discard slag containing minimum levels of heavy metals to be produced, with consequent low levels of heavy metals leached from slags. Results from leaching tests conducted in accordance with the Victorian Environmental Protection Agency guide for the disposal of waste are shown in Table V.

The Ausmelt furnace is a tightly sealed system, which presents a number of environmental advantages. Gas emissions are minimized, and negative pressure can be maintained via direct measurement and control of furnace draft. Also, there are reduced gas volumes to be treated due to low air infiltration.

A relatively simple gas handling system, including an evaporative cooler or waste heat boiler to cool the gases and a baghouse to capture fume, is typically employed to treat the off-gases from a slag-cleaning furnace. If significant levels of sulfur dioxide are present, a wet scrubbing process may be utilized.

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News *(Continued from page 10.)*

Recent Literature

Metals and the Royal Society. *By D.R.F. West and J.E. Harris.*

ISBN 1 86125 028 2. London, IOM Communications Ltd. 1999. Hardcover. 787 pages. $80.

When Walter Rosenhain, on the eve of the First World War, published his revolutionary book, *An Introduction to Physical Metallurgy*, he defined his new field of metallurgy as "a branch which concerns itself with the nature, properties and behavior of metals and of alloys as such, as distinct from the far older branch of metallurgy which deals with the reduction of metals from their ores." He went on to claim that "thus defined and understood the scope of physical metallurgy is an exceedingly wide one, and one which brings it well over the border-land of several sister sciences."

These words, quoted on page 168 of the book *Metals and the Royal Society* might serve as a general apologia for the whole ambitious enterprise. In its 19 chapters, this book by D.R.F. West (of Imperial College in London) and J.E. Harris (lately of Berkeley Nuclear Laboratories in England) seeks to map the history of scientific metallurgy in the broadest imaginable sense through an account of, and a tribute to, the labors of more than 500 fellows of the Royal Society of London, selected from some 8,000 fellows elected since the Society was founded in 1660.

The Royal Society of London for Improving Natural Knowledge, to give its full title, is the United Kingdom's science academy and elects an extremely wide range of scientists and engineers to its fellowship. A major benefit of the book is the range of chemists, physicists, engineers, and natural philosophers (such as Michael Faraday, who cannot be classified at all) who are treated in its pages. There is a strong emphasis on both domestic fellows and international members; inevitably, however, there is a special emphasis on British scientists. Many early fellows, such as the microscopists Hooke (1635–1703), van Leeuwenhoek (1632–1723) and Réaumur (1683–1757), receive copious attention. Isaac Newton himself features prominently, in part for his genuine interest in applications of metals.

In addition to the 19 thematic chapters, specialized themes are treated, such as platinum-group metals (which incorporates a fascinating account of the rise of Johnson and Matthey); coinage; ferrous and nonferrous extractive metallurgy; modern themes, such as materials in relation to the early days of electricity; and physical metallurgy itself, such as the dawning of modern solid-state physics in relation to metals, characterization methods, plastic deformation, and the Hume-Rothery revolution. The authors devote a short chapter to nonmetallic materials, with special attention to plastics in their early days, followed by a major chapter on metals and the atomic age, which constitutes an invaluable potted history of atomic metallurgy, including radiation damage. The main part of the book concludes with a survey of the Royal Society and the Industrial Revolution, covering three centuries.

Chapter 19 is followed by more than 250 pages of short biographies of fellows and members of the Royal Society whose researches were deemed relevant to the theme of the book. People still living receive, quite properly, only the most cursory of treatments, while hundreds of deceased scientists and engineers receive up to a full page each.

The last 90 pages of the book are appendices, mostly devoted to such matters as lists of Royal Society Awards. Nobel Prize winners, various honors specific to metallurgy and materials science, a complete chronological list of those covered in the alphabetically arranged section of biographies, and a select bibliography of sources arranged chapter by chapter conclude the book.

This work is one of the most ambitious and comprehensive surveys of the antecedents of modern science. The book is not expensive in view of its size, it is beautifully produced, and it should soon be found in a wide range of university libraries, as well as on personal shelves.

Robert Cahn
Sussex University and University of Cambridge

Technology Forces at Work: Profiles of Environmental Research and Development at DuPont, Intel, Monsanto, and Xerox. *By S.A. Resetar, B.E. Lachman, R.J. Lempert and M.M. Pinto.*

ISBN: 083302728X. Rand, Santa Monica, CA. 1999. Softcover. 144 pages. $15.

This book provides information about the profile of environmental-technology-related research in private industries to increase the understanding of government decisionmakers about private sector R&D activities related to environmental research and technology. Environmental technologies are defined as those that allow sustainable development by reducing the risk to human health and the environment, enhancing cost effectiveness by improving process efficiency, and creating environmentally beneficial or benign products and processes. The information is gathered through literature reviews on innovation in environmental R&D and collaborated research, as well as via case studies of four industries (DuPont, Intel, Monsanto, and Xerox), leaders in the chemical, electronics, biotechnology, and document management sectors.

As explained in the book, industry has previously viewed environmental research as an expense. In recent years, however, it has begun to change. Industry leaders now see cost advantages in optimizing their processes to maximize product yields, converting by-products into saleable products, recycling waste solutions, and reducing overall process-waste discharge. This movement now goes beyond mere compliance with environmental regulations, as had been the norm for most companies in the past.

The book clearly defines product and process innovation processes and how these terms are related to environmental technology policies. It also highlights industrial R&D trends and how these are linked to corporate business goals. The timeline of bringing a product to the market as well as the global nature of markets and technologies are also emphasized. Information on environmental-technology investments, public-private research partnerships, and the need for collaborated research, as well as an overview of selected research partnerships, is also provided.

The book contains five chapters. A detailed summary of the book and appendices describing environmental-technology definitions, data on environmental R&D activities, and detailed profiles of environmental research at DuPont, Intel, Monsanto, and Xerox are also provided.

This book will be very useful to environmental scientists, process engineers, and research scientists involved in R&D activities in private companies. The book is written in a technical report format and would serve as a good manual for people who have not had extensive training in writing technical reports; all of the chapters present their information in a clear and very readable format and provide a comprehensive and current overview of environmental technology research.

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