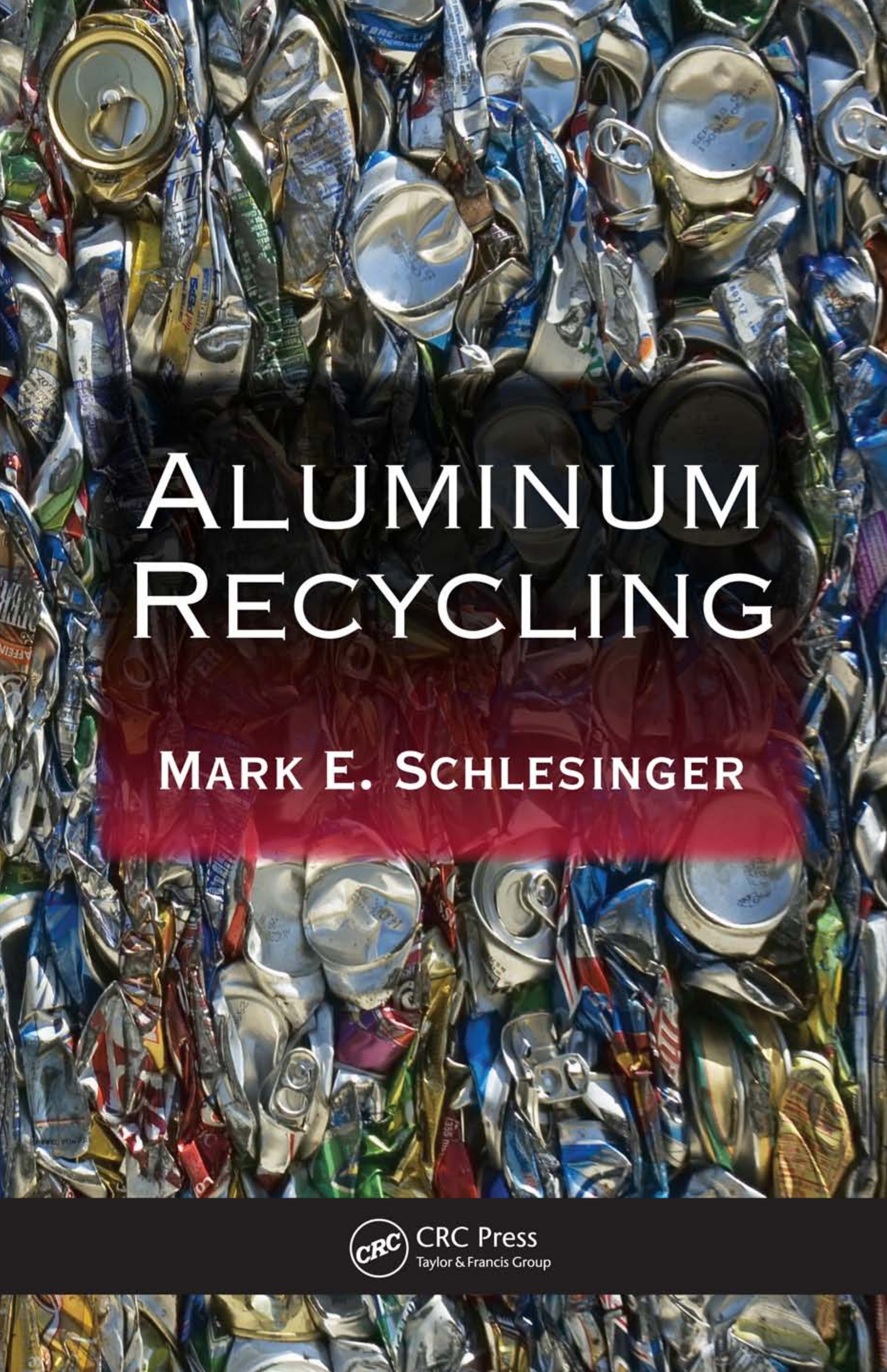

ALUMINUM RECYCLING

MARK E. SCHLESINGER

CRC Press
Taylor & Francis Group

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an informa business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

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Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8493-9662-X (Hardcover)
International Standard Book Number-13: 978-0-8493-9662-5 (Hardcover)

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Library of Congress Cataloging-in-Publication Data

Schlesinger, Mark.
Aluminum recycling / Mark Schlesinger.
p. cm.
Includes bibliographical references and index.
ISBN 0-8493-9662-X (alk. paper)
1. Aluminum--Recycling. 2. Scrap metals--Recycling. 3. Extraction (Chemistry) 4. Aluminum--Metallurgy. I. Title.

TD812.5.A48S35 2006
673’.7220286--dc22 2006043686

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Preface

I wrote this book because I could not find one like it.

I am one of a vanishing breed in North America — professors who teach extractive metallurgy. Extractive metallurgy used to be defined as the winning of metals or alloys from naturally occurring ores, but over the past half-century this has changed. Increasingly, the ore body is now found *on* the ground, rather than in it. The majority of iron and steel produced in North America is now obtained from recycled material, as are 40% of the copper, 80% of the lead — and more than 50% of the aluminum. As a result, extractive metallurgy instruction now includes significant exposure to recycling technology and the unique processes used to recover metal from this strange type of "ore."

Since most extractive metallurgy textbooks do not include recycling technology in their discussion of "minerals processing," and discuss molten-metal refining in a way that excludes the refining of recycled metal, I went searching for a text that focused on metals recycling. Although several conference proceedings on the subject have been published, and some books (in particular Nijkerk and Dalmijn's *Handbook of Recycling Techniques*) have dealt with one or more parts of the recycling process, there is no treatment of the overall process. This matters, because decisions made during the collection and upgrading of scrap metals often have an impact on the melting and refining strategies employed later. As a result, an integrated treatment of the recycling process is needed.

This turned out to be particularly true for aluminum. Monographs dealing with aluminum extractive metallurgy in general are uncommon and usually include no more than a few pages on recycling. The last (and possibly the only) English-language book to specifically address aluminum recycling was Anderson's *Secondary Aluminum,* published in 1931. More than one-third of the aluminum produced worldwide comes from recycled material, but the operations of the recycling industry are not well known to the general public or to the metallurgical community in general.

This is not to say that information is lacking on aluminum recycling technology. There are literally thousands of documents and Web pages pertaining to every aspect of the industry from sources around the globe. Unfortunately, this information is as scattered as its sources. Much of it has appeared in the annual *Light Metals* symposia proceedings published each year by the American Minerals, Metals & Materials Society of the American Institute of Mining, Metallurgical, and Petroleum Engineers (TMS-AIME) and more in the proceedings of Australian and Canadian symposia. Other sources include aluminum industry journals such as *Aluminium* and *Light Metal Age* and recycling industry magazines such as *Recycling Today* and *Scrap.* The burgeoning presence of industry associations, recycling firms, and equipment suppliers on the Web is also an increasingly good source of information. However, this information has not been gathered in one place or synthesized to show the entire picture. This book is an attempt to produce that picture.

Since the recycling of aluminum is a type of extractive metallurgy, the structure of this book follows the traditional extractive metallurgy sequence. This begins with a description of the ore body and the type of minerals (aluminum alloys) it contains, the mining technology and infrastructure used to obtain it, the mineral-processing equipment used to beneficiate it, initial thermal processing to remove coatings and other metals, melting furnaces and practice, and refining technology. Additional chapters introduce other important elements of the story: the economics of scrap recycling, the structure of the recycling industry, and the ongoing effort to make aluminum recycling safer and more environmentally benign. For those interested in more in-depth information about the material in a particular chapter, a short list of recommended additional sources is provided.

I owe a tremendous debt to two individuals who shared my vision and were willing to share their knowledge and expertise to help me get it right. Don Stewart of Alcoa and Ray Peterson of Aleris International spent much of their time straightening me out on the differences between what I had read and what I should know, and the book reflects their efforts. David Roth and the staff at Altek/MDY subsequently added their expertise to the editing enterprise and found several more "whoppers" to eliminate. Greg Gelles of the economics department at the University of Missouri–Rolla graciously agreed to contribute the chapter on recycling economics. Others who lent their time to looking over parts of the material include Mike Skillingberg of the Aluminum Association, Adam Gesing of HVSC, and John Green. Their assistance has helped turn my sow's ear of a manuscript into Naugahyde, if not a silk purse.

There are others who helped make this book a reality as well. The staffs of the University of Missouri–Rolla and Linda Hall Libraries were invaluable in obtaining information for me from obscure and distant sources. Jason Harris redrew many of the figures, reducing my dependence on the scanner. Finally, my appreciation goes out to all the organizations that allowed me to reproduce their illustrations, either on-line or in print. If a picture is worth a thousand words, their permission is worth much of this book.

Aluminum recycling is a dynamic industry, with constantly changing technology and business strategies. As a result, judgments about the advantages and disadvantages of various equipment and operating methods written months ago may be invalid by the time you see this. In some cases, I may have made a judgment that was wrong under any circumstances. In any case, any errors you may see are my responsibility. The number of such errors is undoubtedly greater than I would desire; my hope is that it is fewer than it might have been.

About the Author

Mark E. Schlesinger is professor of metallurgical engineering at the University of Missouri–Rolla, where he has been since 1990. His teaching and research interests are centered around the production of metals and their alloys, in particular their extraction from ores and secondary materials. His previous books include *Mass and Energy Balances in Materials Engineering* and the coauthored *Extractive Metallurgy of Copper* (4th ed.).

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1 Introduction

The industrial-scale production and use of aluminum metal are barely a century old, yet in that time, the industry has grown until it is second only to the iron and steel industry among metals producers (Mahi et al., 1990). The growth in aluminum usage was particularly rapid in the years following World War II, and every sector of the industry can point to products that were never produced from aluminum a generation ago but are now primarily manufactured from an aluminum alloy. Beverage cans, sports equipment, electrical bus work, window frames — all are now produced from aluminum, along with thousands of other products.

Books on the production of aluminum metal have previously focused on its recovery from naturally occurring raw materials. The primary natural ore for aluminum is bauxite, a mineral consisting primarily of hydrated aluminum oxides. Aluminum is recovered from bauxite by a selective leaching sequence known as the *Bayer process* (Wolf and Hoberg, 1997), which dissolves most of the aluminum while leaving impurities behind. The aluminum is recovered from the leach solution by precipitating it as aluminum hydroxide. The hydroxide is then dried and calcined to generate purified alumina. The calcined alumina is fed to electrolytic cells containing a molten salt electrolyte based on cryolite (Na_3AlF_6). The alumina dissolves in the cryolite and is electrolyzed to generate molten aluminum metal and carbon dioxide gas. This process has been the sole approach for producing *primary* aluminum metal since the late 1800s and will likely continue in this role for decades to come.

However, in recent decades an increasingly large fraction of the world's aluminum supply has come from a different "ore" source. This ore is the aluminum scrap recovered from industrial waste and discarded postconsumer items. The treatment of this scrap to produce new aluminum metal and alloys is known as *recycling,* and metal produced this way is frequently termed *secondary.* About one-third of the aluminum produced in the world is now obtained from secondary sources, and in some countries the percentage is much higher. As a result, the extraction of aluminum by recycling is now a topic worth describing.

The processes used for recycling aluminum scrap are very different from that used to produce primary metal but in many ways follow the same general sequence. This sequence begins with "mining" the ore, followed by mineral processing and thermal pretreatment, and then a melting step. The metal is then refined, cast into ingots or rolled into sheet, and sent to customers. Aluminum recyclers also face similar challenges to the producers of primary aluminum: the need to produce a consistent alloy with the required chemistry, minimize energy usage, reduce the amount of waste generated, and manufacture the highest-quality product at the lowest possible cost from raw materials of uncertain chemistry and condition.

This book will lead readers through the sequence used for recycling scrap aluminum. It will start with a description of the “minerals” (aluminum alloys) that are contained in the ore body and describe the various “mines” where aluminum scrap is found. It will then describe the practices used to separate scrap aluminum from the other materials with which it is mixed and the means for purifying it of coatings and other impurities. Subsequent chapters will describe the furnaces used for remelting the recovered scrap and the refining techniques used for improving its purity and quality. A final chapter will consider the unique environmental and safety challenges that recycling operations face and how these challenges are addressed.

A BRIEF HISTORY OF ALUMINUM RECYCLING

The successful recycling of aluminum depends on several factors:

- A plentiful and recurring supply of the metal, concentrated sufficiently in one area to justify the cost of collecting it
- A mining infrastructure for collecting the scrap metal, removing impurities, and delivering it to a recycling facility
- A method for recycling the metal that is economically competitive with production of the metal from primary ores
- A market for the recycled metal, should its composition or quality differ from that of primary metal

Large-scale production of aluminum metal did not begin until the 1890s, with the advent of the Hall–Heroult electrolytic process for recovery of aluminum metal from a molten salt bath. Because of this, the beginnings of aluminum recycling did not occur until the early 1900s (Hollowell, 1939; Aluminum Association, 1998).

Figure 1.1 shows the fraction of aluminum consumption in the United States (the source of the most complete statistics) obtained from recycled material from 1913 through 2000. The changing percentages show the impact of several factors on the incentive to process scrap instead of producing primary metal:

- *Sudden increases in demand.* The importance of scrap as an aluminum supply jumped during both world wars (Anderson, 1931; Smith, 1946; Martchek, 1997; Morrison, 2005) as demand for aluminum increased faster than new primary smelters could be built. As primary smelting capacity caught up with demand, the fraction of aluminum supply obtained from secondary sources declined. Curve B in Figure 1.2 shows the ratio of “old” (postconsumer) to “new” (prompt industrial) scrap used in the United States over time (van Linden, 1990). The ratio is higher in the 1940s than the 1950s owing to war-time scrap drives.
- *The cost of producing primary aluminum.* Scrap became a less important source of aluminum metal in the United States during the late 1930s and 1950s. The reason was the construction of dams in the Columbia and Tennessee River valleys, which generated large amounts of low-cost hydroelectric power. This in turn encouraged the construction of new

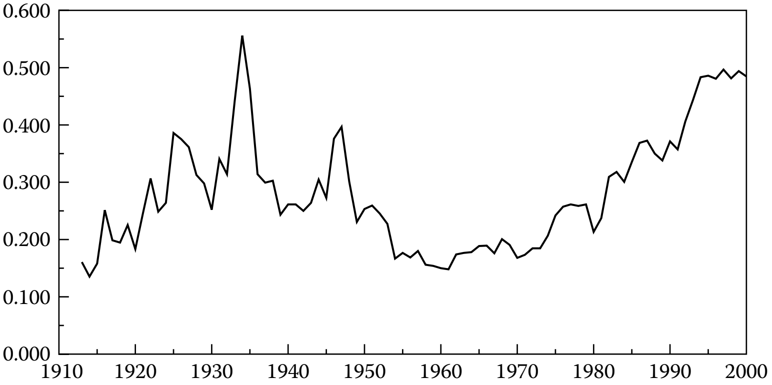

FIGURE 1.1 Fraction of aluminum consumption in the United States obtained from recycled material from 1913 through 2000.

primary smelting capacity, which reduced the demand for scrap (van Linden, 1985). In recent years, increases in the cost of power have led to the closing of primary smelters in the United States and Europe, making secondary aluminum production more significant. Curve A in Figure 1.2 shows the ratio of scrap used by primary aluminum producers in the United States to that processed by secondary smelters over time (van Linden, 1990). The ratio reached a minimum in the 1950s and 1960s, as cheap primary aluminum made scrap acquisition uneconomic. As primary metal production costs rose in the 1970s and 1980s, scrap began to look more attractive to primary producers, and the fraction of used scrap recycled in the primary industry rose as well. The ratio currently exceeds 1.0.

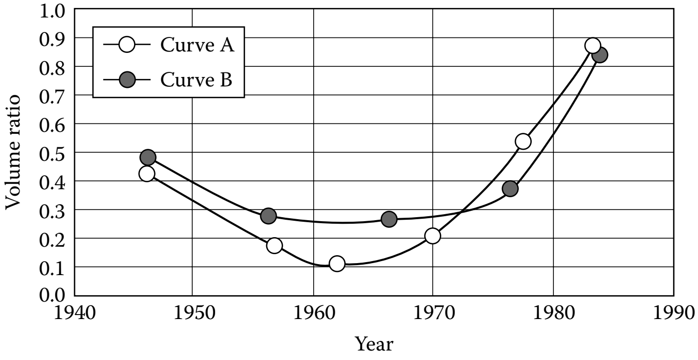

FIGURE 1.2 U.S. aluminum recycling by producer type (curve A) and scrap type (curve B), 1946–1989. (From van Linden, J.H.L., in *Light Metals 1990,* Bickert, C.M., Ed., TMS-AIME, Warrendale, PA, 1990. With permission.)

- *The influence of the government.* Starting in the late 1960s, governments at all levels became increasingly concerned about the amount of waste discarded by industrial societies. The response was a series of laws and regulatory initiatives designed to minimize waste disposal and encourage recycling. The increase in the old-to-new scrap ratio from the 1970s seen in curve B in Figure 1.2 resulted largely from efforts to collect and recycle aluminum used beverage containers (UBCs). These efforts were spurred by the aluminum industry, which was attempting to avoid restrictions and mandatory deposits on the cans.
- *Improved quality.* In the early years of the industry, the secondary aluminum produced by recycling facilities was considered inferior to primary metal (Anderson, 1931; Smith, 1946). This was due in part to poor chemistry control, which resulted in uncertain composition. It was also due to poor removal of dross and slags, which led to metal with too many inclusions. As tighter composition control was enforced and improved refining technology eliminated more impurities and inclusions, this stigma began to disappear.

Aluminum recycling was at first conducted *directly,* with purchased scrap being consumed by foundries without prior treatment (Aluminum Association, 1998). However, as scrap began to travel over greater distances and the reliability of its composition improved, it became desirable to produce a scrap product of greater consistency. As a result, secondary smelters began to appear after 1910 (Hollowell, 1939). These smelters produce a secondary ingot from mixed loads of scrap, with a composition matching one of several standardized grades. Table 1.1 lists the compositions of secondary alloys specified in the United Kingdom in 1946 (Smith, 1946). The alloys correspond to the primary alloys popular at the time and were used mostly in foundries.

ADVANTAGES (AND CHALLENGES) OF RECYCLING

There are several advantages to society when aluminum is produced by recycling rather than by primary production from bauxite ores:

- *Energy savings.* Production of aluminum from ores requires considerable inputs of energy, as Figure 1.3 shows (Rombach, 1998). Most of the energy use is due to the molten-salt electrolysis of alumina. Fossil fuel is required to produce the carbon electrodes and remelt the ingots produced by electrolysis, and large inputs of electrical energy are required to overcome the resistance of the electrolyte and break down the dissolved alumina in the bath. The 113 GJ per metric ton (tonne) described in Figure 1.3 is that used in the production of aluminum metal itself; when inefficiencies in the production of electricity are factored in, total energy consumption rises to 174 GJ/tonne. Direct energy usage in the production of secondary (recycled) aluminum is much smaller (Rombach, 1998), as Figure 1.4 shows. The largest energy

TABLE 1.1
Chemical Compositions of Secondary Aluminum Alloys

	Chemical Composition (%)[a]										
Alloy Designation	**Cu**	**Mg**	**Si**	**Fe**	**Mn**	**Ni**	**Zn**	**Pb**	**Sn**	**Ti**	**Other**
LAC 113B	2.5–4.5	0.1	1.3	1.0	0.5	0.5	9.0–13.0	—	—	—	Pb + Ni + Sn + Mn < 1.0
ALAR 505·Z6	4.0–6.0	0.15	2.5	1.0	—	—	5.0–7.0	Pb + Sn < 0.5		—	Pb + Ni + Sn + Mn < 1.0
L33	0.1	—	10.0–13.0	0.6	0.5	0.1	0.1	0.1	0.04	0.2	Modifying agents < 0.3
ALAR 00·12	0.4	0.15	10.0–13.0	0.7	0.5	0.1	0.2	0.1	0.05	0.2	Cu + Zn < 0.5 Pb + Sn < 0.1
ALAR 00·5	0.1	0.1	4.5–6.0	0.8	0.3	0.1	0.1	0.1	0.05	0.2	Pb + Sn < 0.1
LAC 112A	0.75–2.5	0.3	9.0–11.5	1.0	0.5	1.5	1.2	—	—	—	Cu + Ni < 3.0 Others < 0.5
DTD 428	6.0–8.0	0.1	2.0–4.0	1.0	—	—	2.0–4.0	—	—	—	Pb + Ni + Sn + Mn < 1.0
DTD 424	2.0–4.0	0.15	3.0–6.0	0.8	0.3–0.7	0.35	0.2	0.05	—	0.2	Fe + Mn < 1.3
LAC 10	9.0–10.5	0.15–0.35	0.6	0.3–1.0	0.6	0.5	0.1	0.1	0.1	—	Fe + Mn < 1.4 Pb + Sn + Zn < 0.2
L24 “Y”	3.5–4.5	1.2–1.7	0.6	0.6	—	1.8–2.3	0.1	0.05	0.04	0.2	Si + Fe < 1.0 Sn + Zn < 0.1

[a] Maximum unless otherwise indicated

Source: Smith, F.H., *Metallurgia,* 33, 1946.

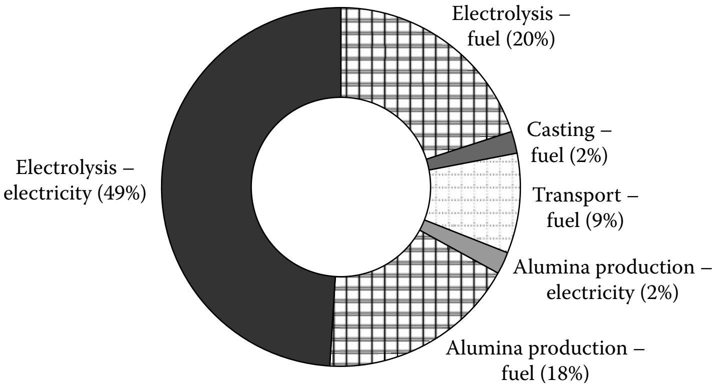

FIGURE 1.3 Energy requirements (113 GJ total per metric tonne) for the production of primary aluminum. (From Rombach, G., in *Material for the Future: Aluminium Products and Processes,* DMG Business Media, Ltd., Surrey, UK, 1998. With permission.)

user is the melting step, which can be done using either fossil fuel or electricity. In either case, the direct energy use is reduced by 88% from that required to produce primary aluminum. If electrical generation inefficiencies are figured in, total energy consumption per tonne of secondary aluminum increases to 20 GJ; this too is 88% lower than that needed for primary aluminum.

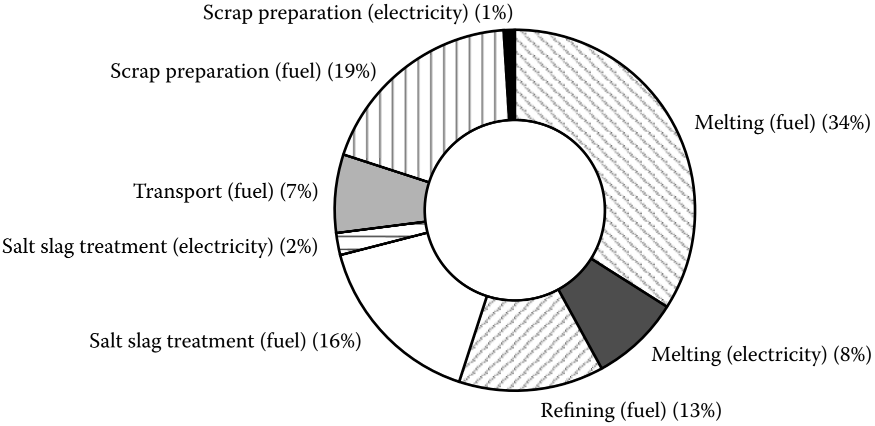

FIGURE 1.4 Energy requirements for production of aluminum from scrap (13.6 GJ/tonne total). (From Rombach, G., in *Material for the Future: Aluminium Products and Processes,* DMG Business Media, Ltd., Surrey, UK, 1998. With permission.)

- *Reduced waste disposal.* Primary aluminum production generates solid waste at every step in the process. The most significant of these are mine wastes, the red mud residue created during alumina purification, and spent pot liner from the electrolytic cells (Wolf and Hoberg, 1997). While aluminum recycling generates solid wastes as well (primarily the dross and salt slag created during remelting), the volumes are much smaller. European estimates suggest that the mass of solid waste generated per tonne of recycled aluminum is 90% lower than that for primary metal (Martchek, 1997). Lave et al. (1999) estimate that recycling aluminum reduces hazardous waste generation by over 100 kg per tonne of metal produced.
- *Reduced emissions.* Primary aluminum production generates both hazardous (fluorides, sulfur dioxide) and nonhazardous (carbon dioxide) emissions. While aluminum recycling presents its own air-quality challenges, the numbers are again much reduced. The amount of CO_2 and total air emissions are both reduced by over 90% per tonne when aluminum is produced by recycling rather than primary processes (Martchek, 1997).
- *Reduced capital cost.* Primary aluminum production requires a mining operation, a Bayer-process plant to produce purified alumina, and an electrolytic pot line to extract aluminum metal from the alumina. The capital equipment used for recycling is less complex and thus less expensive. A 1976 estimate suggests that producing aluminum by recycling rather than by primary methods reduces capital costs per tonne by 80 to 85% (Mahi et al., 1990).

Challenges to the industry include:

- *Ensuring adequate supply.* Scrap is a difficult sort of ore body to utilize, since it tends to be spread out over the landscape rather than concentrated in a single location. As a result, its collection can be a problem. This is particularly true for old scrap, as will be seen in Chapter 3. The cost of collecting and processing old scrap can make this type of recycling uneconomic.
- *Emission control.* While gaseous emissions from scrap aluminum remelting are much lower than for primary production, secondary aluminum smelters and remelters are more likely to be located in urban areas (Anderson, 1931), making them subject to tighter emissions standards (Martchek, 1997). Furthermore, the potential emissions from secondary producers are much different than those of primary producers. The processing of greasy and oily scrap, along with scrap coated with organic resins or lacquers, generates off-gases with organic compounds that must be eliminated.
- *Treatment and disposal of byproducts.* Aluminum recycling generates solid waste products not produced in primary smelting. The most significant of these is *saltcake,* the residue of smelting under a salt flux (Aluminum Association, 1998). Another is the *shredder fluff* produced when junk automobiles are shredded to separate the recyclable metals they contain from each other. Recyclers are working on new ways to treat these solid wastes and to eliminate them if possible.

RECOMMENDED READING

Aluminum Association, *Aluminum Recycling Casebook,* Aluminum Association Washington, DC, 1998.

Martchek, K.J., Life cycle benefits, challenges, and the potential of recycled aluminum, in *Proc. Air & Waste Manage. Assoc. 90th Ann. Meet. Exhib.,* Paper 97-RP124B.01, 1997.

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2 The Ore Body

In traditional extractive metallurgy, the raw material used to produce a metal is an ore mined from the earth. The ore contains *minerals,* chemical compounds that include the desired metallic element. It also contains other chemical compounds that do not include the metallic element; these are known as *gangue* minerals. The ore mineral contains *impurity* elements in addition to the metallic element. These must be chemically separated from the metal during the extraction process.

In aluminum recycling, the ore body consists of scrap metal found on the ground, rather than in it. However, the similarities are greater than might appear at first. Aluminum scrap comes with gangue minerals of its own, in the form of attached items and coatings. It also includes impurities that can have a significant influence on the recycling process. As a result, a description of the ore body for aluminum recycling will explain why some processes and strategies have been adopted.

This chapter will introduce the families of aluminum alloys and the products made from them. It is not meant to be an extensive discussion. Other sources provide a much more complete description of aluminum metallurgy and products (Bray, 1990; Kearney, 1900; Altenpohl, 1998), and the reader is encouraged to consult these for more information. The purpose of this chapter is to describe the raw material the recycler obtains and how it impacts the available process options.

THE WROUGHT ALUMINUM ALLOY SYSTEM

As the name suggests, wrought aluminum alloys are those that are turned into consumer products by a solid-state process: extrusion, forging, or rolling. There are over 200 of such alloys. Nearly all consist of at least 90% aluminum, and most over 95%. Wrought aluminum alloys are divided into eight classes based on the choice of alloying element, according to a system developed in the United States in the 1950s. Table 2.1 lists the composition of several common aluminum alloys from the different classes (Bray, 1990).

1xxx alloys are the purest aluminum alloys, containing 99% or more aluminum. The high aluminum content ensures high electrical conductivity and corrosion resistance but results in lower strength than other alloys. 1xxx alloys are used in electrical applications, as well as for packaging foil and for chemical equipment. Because the minimum required aluminum percentage is so high, it is difficult to use scrap for producing these alloys. As a result, only primary aluminum and carefully selected 1xxx alloy scrap are used. However, 1xxx scrap can be readily used for producing alloys from any other series.

2xxx alloys contain 1.0 to 6.0% copper, depending on the alloy. Other alloying elements in 2xxx alloys include iron, magnesium, manganese, and silicon. These are

TABLE 2.1
Composition of Common Wrought Aluminum Alloys

Alloy	% Si	% Fe	% Cu	% Mn	% Mg	% Cr	Other	% Zn	% Ti	Others Each	Others Total
1050	0.25	0.40	0.05	0.05	0.05	—	0.05 V	0.05	0.03	0.03	>99.5 Al
1100	0.95 Fe + Si		0.050–0.20	0.05	—	—	—	0.10	—	0.05	>99.0 Al
1175	0.15 Fe + Si		0.10	0.02	0.02	—	0.03 Ga, 0.05 V	0.04	0.02	0.02	>99.75 Al
1350	0.10	0.40	0.05	0.01	—	0.01	—	0.05	—	0.03	0.10
2007	0.80	0.80	3.3–4.6	0.50–1.0	0.40–1.8	0.10	0.20 Ni, 0.20 Bi, 0.80–1.5 Pb, 0.20 Sn	0.80	0.20	0.10	0.30
2011	0.40	0.70	5.0–6.0	—	—	—	0.20–0.60 Bi, 0.20–0.60 Pb	0.30	—	0.05	0.15
2017	0.20–0.80	0.70	3.5–4.5	0.40–1.0	0.40–0.80	0.10	—	0.25	0.15	0.05	0.15
2024	0.50	0.50	3.8–4.9	0.30–0.90	1.2–1.8	0.10	—	0.25	0.15	0.05	0.15
2038	0.50–1.3	0.60	0.80–1.8	0.10–0.40	0.40–1.0	0.20	—	0.50	0.15	0.05	0.15
2048	0.15	0.20	2.8–3.8	0.20–0.60	1.2–1.8	—	—	0.25	0.10	0.05	0.15
2090	0.10	0.12	2.4–3.0	0.05	0.25	0.05	1.9–2.6 Li	0.10	0.08–0.15 Zr	0.05	0.15
2091	0.20	0.30	1.8–2.5	0.10	1.1–1.9	0.10	1.7–2.3 Li	0.25	0.04–0.16 Zr	0.05	0.15
2117	0.20–0.80	0.7	3.5–4.5	0.40–1.0	0.40–1.0	0.10	—	0.25	0.25 Zr + Ti	0.05	0.15
2124	020	0.30	3.8–4.9	0.30–0.90	1.2–1.8	0.10	—	0.25	0.15	0.05	0.15
2219	0.20	0.30	5.8–6.8	0.20–0.40	0.02	—	0.05–0.15 V, 0.10–0.25 Zr	0.10	0.02–0.10	0.05	0.15
2224	0.12	0.15	3.8–4.4	0.30–0.90	1.2–1.8	0.10	—	0.25	0.15	0.05	0.15
2324	0.10	0.12	3.8–4.4	0.30–0.90	1.2–1.8	0.10	—	0.25	0.15	0.05	0.15
2618	0.10–0.25	0.90–1.3	1.9–2.7	—	1.3–1.8	—	0.90–1.2 Ni	0.10	0.04–0.10	0.05	0.15
3003	0.60	0.7	0.05–0.20	1.0–1.5	—	—	—	0.10	—	0.05	0.15
3004	0.30	0.70	0.25	1.0–1.15	0.80–1.3	—	—	0.25	—	0.05	0.15

3005	0.60	0.70	0.30	1.0–1.5	0.20–0.60	0.10	—	0.25	0.10	0.05	0.15
3103	0.50	0.70	0.10	0.90–1.5	0.30	0.10	—	0.20	0.10 Ti + Zr	0.05	0.15
3104	0.60	0.80	0.05–0.25	0.80–1.4	0.80–1.3	—	0.05 Ga, 0.05 V	0.25	0.10	0.05	0.15
4032	11.0–13.5	1.0	0.50–1.3	—	0.80–1.3	0.10	0.50–1.3 Ni	0.25	—	0.05	0.15
4043	4.5–6.0	0.8	0.30	0.05	0.05	—	—	0.10	0.20	0.05	0.15
5005	0.30	0.70	0.20	0.20	0.50–1.1	0.10	—	0.25	—	0.05	0.15
5017	0.40	0.70	0.18–0.28	0.60–0.80	1.9–2.2	—	—	—	0.09	0.05	0.15
5042	0.20	0.35	0.15	0.20–0.50	3.0–4.0	0.10	—	0.25	0.10	0.05	0.15
5052	0.25	0.40	0.10	0.10	2.2–2.8	0.15–0.35	—	0.10	—	0.05	0.15
5082	0.20	0.35	0.15	0.15	4.0–5.0	0.15	—	0.25	0.15	0.05	0.15
5083	0.40	0.40	0.10	0.40–1.0	4.0–4.9	0.05–0.25	—	0.25	0.15	0.05	0.15
5182	0.20	0.35	0.15	0.20–0.50	4.0–5.0	0.10	—	0.25	0.10	0.05	0.15
5252	0.08	0.10	0.10	0.10	2.2–2.8	—	0.05 V	0.05	—	0.03	0.10
5356	0.25	0.40	0.10	0.05–0.20	4.5–5.5	0.05–0.20	—	0.10	0.06–0.20	0.05	0.15
5454	0.25	0.40	0.10	0.50–1.0	2.4–3.0	0.05–0.20	—	0.25	0.20	0.05	0.15
5457	0.08	0.10	0.20	0.15–0.45	0.80–1.2	—	0.05 V	0.05	—	0.03	0.10
5657	0.80	0.10	0.10	0.03	0.60–1.0	—	0.03 Ga, 0.05 V	0.05	—	0.02	0.05
5754	0.40	0.40	0.10	0.50	2.6–3.6	0.30	—	0.20	0.15	0.05	0.15
6005	0.60–0.90	0.35	0.10	0.10	0.40–0.60	0.10	—	0.10	0.10	0.05	0.15
6016	1.0–1.5	0.50	0.20	0.20	0.25–0.60	0.10	—	0.20	0.15	0.05	0.15
6060	0.30–0.60	0.10–0.30	0.10	0.10	0.35–0.60	0.50	—	0.15	0.10	0.05	0.15
6061	0.40–0.80	0.70	0.15–0.40	0.15	0.80–1.2	0.04–0.35	—	0.25	0.15	0.05	0.15
6063	0.20–0.60	0.35	0.10	0.10	0.45–0.90	0.10	—	0.10	0.10	0.05	0.15
6082	0.70–1.3	0.50	0.10	0.40–1.0	0.60–1.2	0.25	—	0.20	0.10	0.05	0.15
6111	0.70–1.1	0.40	0.50–0.90	0.15–0.45	0.50–1.0	0.10	—	0.15	0.10	0.05	0.15
7005	0.35	0.40	0.10	0.20–0.70	1.0–1.8	0.60–1.2	0.08–0.2 Zr	4.0–5.0	0.01–0.06	0.05	0.15
7020	0.35	0.40	0.20	0.05–0.50	1.0–1.4	0.10–0.35	0.08–0.20 Zr	4.0–5.0	—	0.05	0.15
7075	0.40	0.50	1.2–2.0	0.30	2.1–2.9	0.18–0.28	—	5.1–6.1	0.20	0.05	0.15

(continued)

TABLE 2.1 (CONTINUED)
Composition of Common Wrought Aluminum Alloys

Alloy	% Si	% Fe	% Cu	% Mn	% Mg	% Cr	Other	% Zn	% Ti	Others Each	Others Total
7150	0.12	0.15	1.9–2.5	0.10	2.0–2.7	0.04	0.08–0.15 Zr	5.9–6.9	0.06	0.05	0.15
7175	0.15	0.20	1.2–2.0	0.10	2.1–2.9	0.18–0.28	—	5.1–6.1	0.10	0.05	0.15
7178	0.40	0.50	1.6–2.4	0.30	2.4–3.1	0.18–0.28	—	6.3–7.3	0.20	0.05	0.15
7475	0.10	0.12	1.2–1.9	0.06	1.9–2.6	0.18–0.25	—	5.2–6.2	0.06	0.05	0.15
8011	0.50–0.90	0.60–1.0	0.10	0.20	0.05	0.05	—	0.10	0.08	0.05	0.15
8017	0.10	0.55–0.80	0.10–0.20	—	0.01–0.05	—	0.04 B, 0.0003 Li	0.05	0.10	0.05	0.15
8090	0.20	0.30	1.0–1.6	0.10	0.60–1.3	0.10	2.2–2.7 Li	0.25	0.04–0.16 Zr	0.05	0.15

Source: Cayless, R.B.C., in *Metals Handbook,* Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* 10th Ed., ASM International, Materials Park, OH, 1990. With permission.

among the highest-strength aluminum alloys and are noted for their toughness. They are widely used in aircraft and for fasteners. 2xxx alloys are not very corrosion resistant, and thus are typically painted or clad before being put in service. Many aluminum alloys outside the 2xxx series are limited to 0.30% copper or less (Tribendis, 1984), so 2xxx scrap cannot be used to produce wrought alloys from most other classes.

The number of *3xxx* series alloys is limited, but their use is widespread. These alloys feature up to 1.5% manganese and usually contain 0.7 to 0.8% iron. They can be strain-hardened and have excellent corrosion resistance. These alloys are best known for their use in the bodies of aluminum beverage cans (Sanders et al., 1990). They are also widely used in cooking utensils, automobile radiators, roofing and siding, and heat exchangers. Restrictions on the use of 3xxx scrap center around the manganese and iron content, which are often unwanted in other aluminum alloys.

The number of *4xxx* alloys is also limited, and these alloys are not as widely used as other classes. 4xxx alloys contain up to 13% silicon, which improves their wear resistance. Their primary use is in forgings such as aircraft pistons. They are also used for welding other aluminum alloys. The high silicon content makes them largely unusable for recycling into anything but casting alloys or 4xxx wrought alloys.

5xxx alloys feature up to 5.5% magnesium. They are especially noted for their corrosion resistance and toughness and are easily welded. As a result, the use of 5xxx alloys is widespread. They are used in items as large as bridges and storage tanks and items as small as the lids of beverage cans (Sanders et al., 1990). They are also increasingly popular in automotive structural applications, notably body panels. Magnesium is the only alloying element that can be easily refined from molten aluminum. As a result, 5xxx alloys are more recyclable for wrought-alloy production than most other alloys. However, the cost of magnesium recommends that these alloys be recycled back into 5xxx compositions if possible.

The *6xxx* alloys also feature up to 1.5% magnesium, along with silicon levels up to 1.8%. The presence of these two elements makes them heat-treatable, and the low overall alloy content gives them extrudability. Their best-known uses are in architecture, but they are also used in automotive applications, welded structural applications, and as high-strength conductor wire. As with 4xxx alloys, the primary limitation on their recyclability is the silicon content.

7xxx series alloys are the most heavily alloyed of the wrought aluminum alloys. They feature 1.5 to 10% zinc, depending on the alloy. 7xxx alloys also have up to 3% magnesium, and some feature up to 2.6% copper. Heat-treated 7xxx alloys have the highest strengths of the common wrought aluminum alloys, and impressive toughness levels. As with the 2xxx alloys, their lower corrosion resistance usually results in their being painted or coated when put in service. Historically, their greatest use has been in the aircraft industry, but they have also found use in transport applications. Their zinc and copper content make 7xxx alloys difficult to recycle into anything except 7xxx alloy or some casting alloys.

8xxx alloys feature alloying elements not used in the other series. Boron, iron, lithium, nickel, tin, and vanadium are some of the elements used in 8xxx alloys. Because this is a catch-all category, 8xxx alloys cannot be characterized in terms of property or use. One notable trend in aluminum-alloy development reflected in this series is the increasing number of lithium-containing aluminum alloys. These alloys have an especially high modulus of elasticity and are increasingly used in aircraft construction to save weight without sacrificing stiffness. Lithium is also added to some 2xxx alloys. The recycling of lithium-containing alloys is a particular challenge, since the value of the lithium contained in these parts recommends closed-loop recycling into the same alloy if at all possible.

As previously suggested, the difficulty in recycling wrought aluminum alloys is the problem of *tolerance,* the ability of an alloy to absorb elements not normally present in its composition (D'Astolfo et al., 1993). To provide an example, the wrought-aluminum fraction of an automobile will be considered as a potential charge to a recycling furnace. A simplified breakdown for the wrought aluminum might consist of (Zapp et al., 2002):

- 35% alloy 6060 (0.45% Si, 0.2% Fe, 0.5% Mg)
- 11% alloy 6082 (1.0% Si, 0.3% Fe, 0.7% Mn, 0.9% Mg)
- 10% alloy 3003 (0.5% Si, 0.5% Fe, 1.3% Mn)
- 9% alloy 5182 (0.1% Si, 0.2% Fe, 0.4% Mn, 4.5% Mg)
- 14% alloy 5754 (0.3% Si, 0.2% Fe, 0.4% Mn, 3.2% Mg)
- 15% alloy 6016 (1.25% Si, 0.3% Fe, 0.5% Mg)
- 6% alloy 7020 (0.2% Si, 0.3% Fe, 0.3% Mn, 1.2% Mg, 4.5% Zn)

Melted down, this mixture would produce an alloy analyzing 0.57% Si, 0.26% Fe, 0.32% Mn, 1.27% Mg, and 0.27% Zn. The zinc content is higher than the allowed maximum for many common alloys outside the 7xxx series. However, the silicon content is higher than allowed in 7xxx compositions. As a result, the wrought scrap cannot be used to produce new wrought alloy unless one or more of the impurities are diluted by the addition of primary metal. If cast scrap is included in the mix, the problem becomes even worse.

THE CAST ALUMINUM ALLOY SYSTEM

There are now over 200 cast aluminum alloys in addition to the wrought compositions. Cast alloys tend to have higher alloy content than wrought alloys. This makes them difficult to recycle into anything other than cast alloy, since the removal of most alloying elements from molten aluminum is impractical. As is the case for wrought alloys, cast alloys are divided into classes based on the alloying elements used, using a system devised in the 1950s. The numbering of these alloys is meant to correspond roughly to similar classes of wrought alloys. Table 2.2 lists the compositions of the most commonly used cast alloys (Kearney, 1996).

1xx.x cast alloys are quite rare in service, but have aluminum contents of 99% or higher, similar to 1xxx wrought alloys. Generally they are produced only as ingot, for remelting and alloying to a different composition. Their use as consumer products is limited to applications requiring high electrical conductivity, such as pressure-cast integral conductor bars.

2xx.x alloys all contain 3.5 to 10.7% copper, just as 2xxx wrought alloys feature copper as the primary alloying agent. 2xx.x alloys can also have significant

TABLE 2.2
Composition of Common Cast Aluminum Alloys

Designation	% Si	% Fe	% Cu	% Mn	% Mg	% Cr	Other	% Zn	% Ti	Others Each	Others Total
201.0	0.10	0.15	4.0–5.2	0.20–0.50	0.15–0.55	—	0.24–1.0 Ag	—	0.15–0.35	0.05	0.10
203.0	0.30	0.50	4.5–5.5	0.20–0.30	0.10	—	1.3–1.7 Ni, 0.20–0.30 Sb, 0.20– 0.30 Co, 0.10–0.30 Zr	—	0.15–0.25	0.05	0.15
295.0	0.7–1.5	1.0	4.0–5.0	0.35	0.03	—	—	0.35	0.25	0.05	0.15
308.0	5.0–6.0	1.0	4.0–5.0	0.50	0.10	—	—	1.0	0.25	—	0.50
319.0	5.5–6.5	1.0	3.0–4.0	0.50	0.10	—	0.35 Ni	1.0	0.25	—	0.50
332.0	8.5–10.5	1.2	2.0–4.0	0.50	0.5–1.5	—	0.50 Ni	1.0	0.25	—	0.50
347.0	6.5–7.5	0.15	0.05	0.03	0.45–0.60	—	—	0.05	0.20	0.05	0.15
355.0	4.5–5.5	0.60	1.0–1.5	0.50	0.40–0.60	0.25	—	0.35	0.25	0.05	0.15
356.0	6.5–7.5	0.60	0.25	0.35	0.20–0.45	—	—	0.35	0.25	0.05	0.15
357.0	6.5–7.5	0.20	0.20	0.10	0.40–0.70	—	0.04–0.07 Be	0.10	0.04–0.20	0.03	0.15
A356.0	6.5–7.5	0.20	0.20	0.10	0.25–0.45	—	—	0.10	0.20	0.05	0.15
359.0	8.5–9.5	0.20	0.20	0.10	0.50–0.70	—	—	0.10	0.20	0.05	0.15
A360.0	9.0–10.0	1.3	0.60	0.35	0.40–0.60	—	0.5 Ni	0.50	—	—	0.25
361.0	9.5–10.5	1.1	0.50	0.25	0.40–0.60	0.20–0.30	0.2–0.3 Ni, 0.1 Sn	0.50	0.20	0.05	0.15
364.0	7.5–9.5	1.5	0.20	0.10	0.20–0.40	0.25–0.50	0.02–0.04 Be, 0.15 Sn, 0.15 Ni	2.15	—	0.05	0.15
380.0	7.5–9.5	2.0	3.0–4.0	0.50	0.10	—	0.5 Ni, 0.15 Sn	3.0	—	—	—
A390.0	16.0–18.0	0.50	4.0–5.0	0.10	0.45–0.65	—	—	0.10	0.20	0.10	0.20

(*Continued*)

TABLE 2.2 (CONTINUED)
Composition of Common Cast Aluminum Alloys

Designation	% Si	% Fe	% Cu	% Mn	% Mg	% Cr	Other	% Zn	% Ti	Others Each	Others Total
A413.0	11.0–13.0	1.3	1.0	0.35	0.10	—	0.15 Sn	3.0	—	—	0.25
B413.0	11.0–13.0	0.50	0.10	0.35	0.05	—	—	0.50	—	—	0.20
443.0	4.5–6.0	0.80	0.60	0.50	0.05	0.25	—	0.15	0.25	—	0.35
512.0	1.4–2.2	0.60	0.35	0.80	3.5–4.5	0.25	—	0.50	0.25	0.05	0.35
514.0	0.30	0.30	0.10	0.10	3.6–4.5	—	—	1.4–2.2	0.20	0.05	0.15
520.0	0.25	0.30	0.25	0.15	9.5–10.6	—	—	0.15	0.25	0.05	0.15
535.0	0.15	0.15	0.05	0.10–0.25	6.2–7.5	0.25	0.003–0.007 Be, 0.005 B	0.35	0.25	0.05	0.15
705.0	0.20	0.80	0.20	0.40–0.60	1.4–1.8	0.20–0.40	—	2.7–3.3	0.25	0.05	0.15
850.0	0.70	0.70	0.70–1.3	0.10	0.10	—	0.7–1.3 Ni, 5.5–7.0 Sn	—	0.20	—	0.30

Source: Cayless, R.B.C., in *Metals Handbook*, Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, 10th ed., ASM International, Materials Park, OH, 1990. With permission.

levels of iron, magnesium, nickel, or silicon. These alloys have the highest high-temperature strength and hardness of the cast alloys and require heat-treatment to prevent stress-corrosion cracking. As with the 2xxx wrought alloys, coating or painting is usually required because of the lower corrosion resistance of these alloys.

The *3xx.x* alloys are the most widely used of all cast aluminum alloys. They have silicon levels ranging from 4.5 to over 20% and copper levels ranging from 0.5 to 5.0%. Some 3xx.x alloys also include magnesium (0.2 to 1.5%), and a few have nickel (0.5 to 3.0%). The high silicon increases fluidity, reduces cracking, and minimizes shrinkage porosity in castings. The copper and magnesium provide solid-solution hardening. The nickel reduces the coefficient of thermal expansion (as does higher silicon content), useful in pistons and cylinders.

4xx.x alloys also feature 3.3 to 13% silicon but much smaller levels of other elements. Copper, iron, or nickel are sometimes added. Their ductility and impact resistance make them useful in applications such as food-handling equipment and marine fittings.

As is the case with 5xxx wrought alloys, the specifications for *5xx.x* cast alloys include 3.5 to 10.5% magnesium. Lower levels of iron, silicon, and zinc are sometimes used. Along with 2xx.x, 7xx.x, and 8xx.x alloys, 5xx.x alloys are not as castable as high-silicon compositions, requiring some care in mold design.

The *7xx.x* cast alloys specifications require 2.7 to 8.0% zinc, similar to their 7xxx wrought counterparts. Magnesium (0.5 to 2.0%) is present in many of these alloys, and chromium (0.2 to 0.6%) is sometimes added as well. They have better corrosion resistance than other cast alloys and develop high strength through natural aging, eliminating the need for heat treatment.

The *8xx.x* series of cast alloys employs 5.5 to 7.0% tin and 0.7 to 4.0% copper, which provides strength and lubricity. These alloys are used for bearing applications, such as connecting rods and crankcase bearings. 8xx.x alloys are much less used than alloys from other series.

As with the wrought alloys, the difficulty in recycling cast alloys is one of tolerance. Most alloys outside the 7xx.x series have a strict upper limit on the allowable level of zinc, while some 3xx.x alloys have low maximum allowable levels of iron. An exception to this is alloy 380.0, which has reasonably high levels of all the major alloying elements. As a result, alloy 380.0 is often the main product of secondary smelters trying to make use of all the available cast scrap. This alloy can be diluted by customers with 1xxx or 1xx.x scrap, or with primary metal, to produce more desirable alloys.

For example, if 100 kg of 380.0 scrap (8.5% Si, 2.0% Fe, 3.5% Cu, 0.5% Mn, 0.5% Ni, 0.1% Sn, 3.0% Zn) is diluted with 200 kg of primary metal (0.05% Si, 0.06% Fe), the result will be 300 kg of metal analyzing 2.87% Si, 0.71% Fe, 1.17% Cu, 0.17% Mn, 0.17% Ni, 0.03% Sn, and 1.00% Zn. By adding additional amounts of some elements, the melter can create casting alloy 332.0 (9.5% Si, 1.2% Fe, 3.0% Cu, 0.5 Mn, 1.0% Mg, 0.5% Ni, 1.0% Zn, 0.25% Ti), a popular alloy for automotive castings. The required level of dilution with primary aluminum is substantial, but this tactic allows the recycling of all the cast aluminum scrap, without the need to separate one alloy from another.

THE PRODUCT MIX

The market for aluminum products is generally separated into seven segments: building and construction, transportation, consumer durables, electrical, machinery and equipment, packaging, and other. Figure 2.1 illustrates the fraction of aluminum products falling into these applications using recent data from several countries. As can be seen, the product mix varies substantially from one country to another, which ultimately affects the nature of the scrap supply.

The properties of aluminum that make it most valuable in the building and construction sector are its low density, its high corrosion resistance, and the design flexibility resulting from the ease with which aluminum can be extruded.

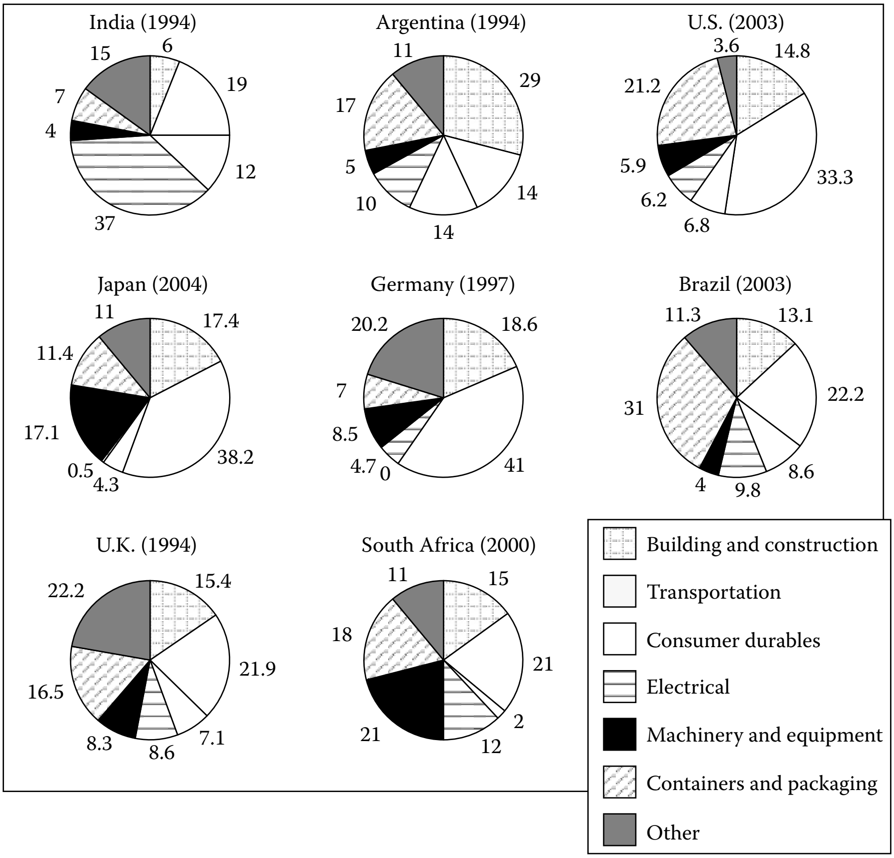

FIGURE 2.1 Aluminum use by sector in various countries. (Sources include Aluminum Association; Associação Brasileira do Alumíno; Japan Aluminium Association; Lahiri, A., *Aluminium Today,* 8(1), 22, 1995; Rombach, G., in *Light Metals 2002,* Schneider, W., Ed., TMS–AIME, Warrendale, PA, 2002.)

Examples of applications benefiting from these advantages include (Altenpohl, 1998):

- Mobile military bridges
- Flag poles
- Window frames
- Mobile and bridge cranes
- Highway guard rails
- Ladders
- Loading ramps
- Automatic doors
- Greenhouses
- Road sign supports
- Building cladding and facades
- Cable support towers

Most of the alloys used in this sector are wrought alloys, particularly from the 5xxx and 6xxx series. The more commonly used alloys are 3103, 3105, 5005, 5083, 5085, 5754, 6005, 6060, 6061, 6063, and 6082. Much of the use of aluminum in this sector is relatively new, and the lifetime of the products in which aluminum is used are fairly lengthy; 20 years is common, and some items may be in service as long as 50 years. As a result, the share of old scrap derived from building and construction debris should increase over the next 20 years. Rombach (2002) predicts that 40 to 45% of all German scrap will come from this sector by 2010.

Gangue materials that are potential contaminants in aluminum scrap recovered from building and construction debris include:

- Ceramic materials, including brick, concrete, glass, etc.
- Dirt and paint
- Polymers, including plastic and rubber
- Steel pieces, including those attached to the aluminum

As Figure 2.1 points out, the fraction of aluminum used for electrical engineering applications in developing countries such as India is much higher than in developed countries (Lahiri, 1995). This is the result of continuing construction of the energy grid in developing countries, which uses large amounts of aluminum cable. In developed countries growth rates of zero are forecast in this sector (Bruggink, 2000; Rombach, 2002). Alloys 1350 and 6201 are used for wire and rod, and alloy 6101 for bus bars and other large conductors. 6xxx alloys have much greater strength than the 1xxx alloys, with relatively small losses in conductivity. However, their use complicates recycling efforts, since 6xxx scrap cannot be used to produce new 1xxx alloy. A small amount of 1xx.x cast alloy is also used. For smaller cable and wire, builders increasingly favor copper over aluminum. As a result, wire and cable will be a smaller fraction of the aluminum scrap supply in the future.

Potential gangue impurities in aluminum scrap recovered from electrical products include:

- Steel supports from steel-reinforced cable
- Copper wire mixed with aluminum wire
- Plastics used to coat wire and cable

The use of aluminum in packaging can be divided into two subcategories: rigid containers (cans) and foil products (Altenpohl, 1998). Aluminum beverage cans were introduced in the United States in 1959, and over the next two decades came to dominate the market for small soft-drink and beer containers, driving the competing steel can out of this market. While some competition from plastic and glass remains, the average American now uses 350 aluminum cans per year. Several factors have contributed to this, including the recyclability of the can. Aluminum is the only packaging material that has significant value as a recyclable material. This generates an incentive to recover the cans, resulting in a higher recycling rate than for plastic or glass.

In Europe and Japan, the popularity of aluminum cans has not spread as quickly as in North America. Per capita use of aluminum cans in Europe is about one-seventh of that in the United States (Flaa, 1992) In Japan the aluminum can has become predominant over the steel can for soft-drink and beer containers but still faces significant competition from glass bottles and paper cartons (Itou, 1995). Aluminum is also used in food cans and aerosol containers but is not as popular in these applications.

The typical aluminum beverage can is produced from three alloys (Sanders, et al., 1990). The can body (75% of the total weight) is produced from alloy 3004. The lid (22% of the total weight) is made of alloy 5182, and the tab (3% of the weight) is alloy 5017, 5042, or 5082. Alloy 3104 is occasionally used for the body, and alloys 5050 and 5352 are sometimes used in the lid. One producer has used alloy 5017 to produce the entire can, but this is uncommon. This mixture presents a challenge in recycling the can, since the alloy produced simply by remelting the can as-is has too much magnesium to be used as 3004 and too much manganese to be used as 5182. As a result, used beverage containers (UBCs) must be diluted after melting with primary metal or low-alloy scrap to produce more cans.

Aluminum strip and foil is also used to produce a variety of pouches, food trays, and single-serve beverage containers. These containers are often produced from rolled 1xxx alloys or 8011 (Gesing, 2001), and thus ought to be easily recycled. However, packages of this sort are often composite structures, with large quantities of paper and plastic that must be separated from the thin aluminum foil before the metal can be remelted. Because of this, the cost of recycling per unit weight of metal recovered is high. This reduces the incentive to recovery foil- and strip-based packaging from the waste stream and results in much lower recycling rates for this type of aluminum.

Contaminants in aluminum recovered from packaging applications include:

- Paper and plastic, especially from pouches and composite boxes
- Steel cans in recovered UBCs
- Lead pieces added to UBCs by unscrupulous collectors
- Organic coatings and paint on can surfaces

A wide variety of cast and wrought aluminum alloys are used to produce consumer durables. Examples include (Bray, 1990; Kearney, 1990):

- 3003 (cookware)
- 360.0 (cookware, instrument cases, cover plates)
- 3004 (lamp bases)
- 380.0 (lawnmowers, dental equipment)
- 5005 (utensils, appliances)
- B443.0 (waffle irons)
- 5052, 6463 (appliances)
- 513.0 (ornamental)
- 5056 (insect screens)
- 5457, 5657 (appliance trim)
- 6005 (TV antennas)
- 6061 (furniture, canoes)
- 6063 (furniture)

Generalizing about this category is not possible, given the diversity. However, scrap from this class of items is more likely to come with attached contaminants than other types of aluminum scrap and thus requires more processing. This kind of scrap is also less likely to be deliberately collected than others, meaning its collection rate is usually lower.

The use of aluminum in transport applications has long affected recycling patterns. The first major surge in recycling rates resulted from the scrapping of aluminum parts from surplus aircraft following World War I (Morrison, 1995). More recently, the transport sector has become the largest user of aluminum, meaning that used vehicles will be a substantial fraction of the available scrap supply. As a result, the patterns of aluminum alloy use in transportation are especially significant.

Aluminum continues to be the primary material for aircraft construction (Altenpohl, 1998), as Figure 2.2 shows, despite inroads made by composites. 2xxx alloys have long been heavily used in aircraft construction, in particular 2024, 2124, 2224, and 2324. Some 7xxx alloys (7055, 7075, 7150) are also used. In recent years, lithium-containing alloys (2090, 2091, 8090) have become part of the mix. Aluminum is also extensively used in passenger ships, particularly 5xxx and 6xxx alloys. However, as Figure 2.3 shows (Melo and Krüger, 1999), these sectors are a very small fraction of aluminum transport use. Aluminum use in trains is more significant, particularly for freight cars but increasingly for passenger cars as well.

However, most of the aluminum used in transport applications goes into automobiles, SUVs, light trucks, and motorcycles. This use began after World War II and has increased steadily since. The average use of aluminum was 124 kg per vehicle in the United States in 2002 and was projected to rise to 181 kg per vehicle by 2005. Longer-term projections suggest that usage will reach 200 or even 250 kg per vehicle (Rombach, 2002; Zapp, et al., 2002). Automotive and other vehicles have a much longer life span than cans, so the effect of this increased usage on the scrap supply will not be noticed immediately. Nevertheless, it is projected that over 30% of all aluminum scrap will come from transport uses by 2040.

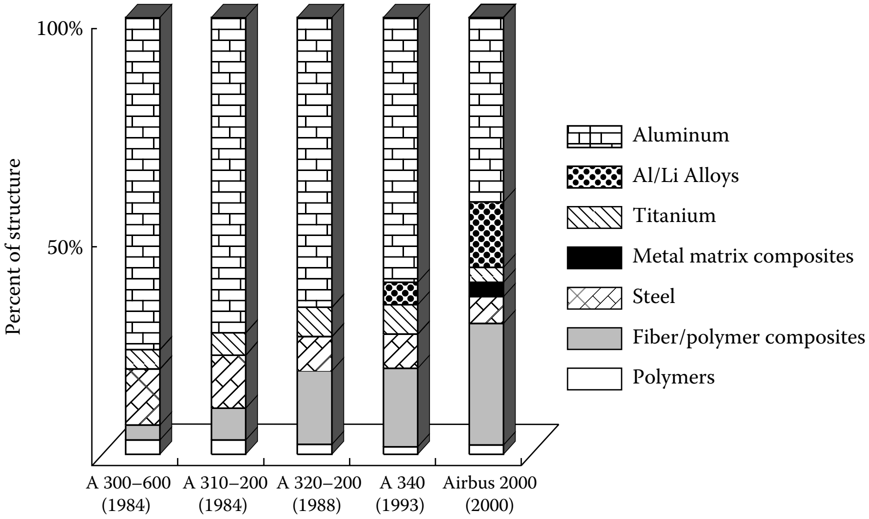

FIGURE 2.2 Usage of different materials in Airbus aircraft. (Modified from Altenpohl, D.G., *Aluminum: Technology, Applications, and Environment,* 6th ed., TMS–AIME, Warrendale, PA, 1998. With permission.)

As the amount of aluminum has increased, the mix of alloys has changed (Tribendis, 1984). Nearly all of the early aluminum usage in automobiles was in the form of cast alloys, and cast alloys still comprised two-thirds of all automotive aluminum in 2000 (Tessieri and Ng, 1995). 3xx.x alloys are widely used in powertrain components, particularly alloys 319.0, 356.0, and 380.0. A356.0 and 357.0 are used for wheels. Because of this, 60% of all cast-alloy aluminum production in Germany is used in automotive applications (Rombach, 2002), a figure that may

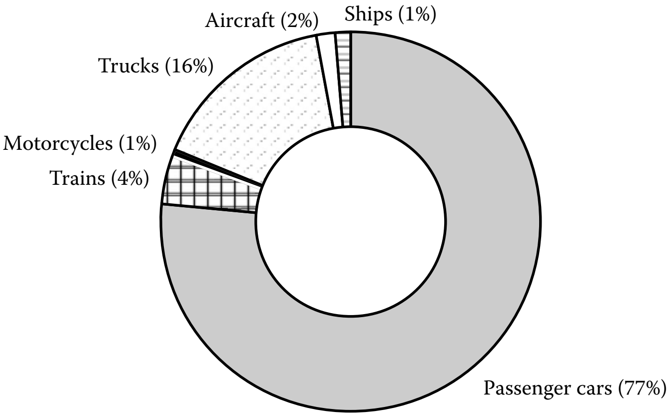

FIGURE 2.3 Aluminum use in transportation, by industry sector. (Adapted from Melo, M.T., and Krüger, B., *Aluminium,* 75(1/2), 27, 1999.)

eventually rise to over 80%. However, the advantages of aluminum use in cars and trucks, particularly for weight reduction, create incentive for the use of wrought aluminum as well as cast alloys. A variety of applications use wrought alloys (Zapp, et al., 2002), including bumpers (6061, 7003, 7129), seat frames (6061, 6063), "hang-on" parts such as fenders, hoods, and deck lids (2022, 5182, 6016, 6111), radiators and condensers (1100, 3003, 4043), and structural parts such as control arms and subframes (5754, 6016, 6061, 7005).

Common contaminants in transport-sector aluminum scrap include:

- Ferrous scrap, both attached (rivets) and separate pieces
- Magnesium and zinc diecastings in automotive scrap
- Plastic and fabric in shredded automotive scrap

The influence of automotive aluminum use on recycling patterns is significant, since most recycled aluminum is used in this sector. The current predominance of cast alloys makes this easier, since cast alloys have a higher tolerance for impurities and can absorb a wider variety of scrap. This is particularly true of alloys 319.0 and 380.0 (Tessieri and Ng, 1995), making their employment in automotive applications even more attractive. However, the increasing use of wrought alloys may change this picture (Rombach, 2002), since the lower alloying-element content of wrought alloys makes them much less tolerant of mixed scrap loads. Because of this, the need exists for a means of separating aluminum scrap by alloy or alloy group. This has resulted in a series of technical advances in scrap processing with significant potential. These will be discussed in Chapter 5.

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3 Scrap Collection

THE MATERIALS LIFE CYCLE

Figure 3.1 illustrates the life cycle in which raw materials are processed to generate consumer products and then disposed of after the life of those products ends (Henstock 1996). In the case of aluminum, the raw materials are the bauxite ore from which the metal is generated, the petroleum coke used to produce anodes and cathodes, and the other chemicals used in the Bayer process and the electrolytic cells. Primary production is the process by which aluminum is extracted from the bauxite, electrowon from a molten-salt electrolyte, refined and cast into ingot or billet, and shipped to customers. The Engineering materials generated by this process include pure aluminum and the alloys described in Chapter 2. Manufacturing is the process by which the ingot or billet is transformed into consumer products; as mentioned in Chapter 2, most aluminum placed in service is classified either as cast or wrought product. The types of products made from aluminum, and their usage patterns, have significant impacts on recycling technology and will be discussed in greater detail.

The scrap streams shown in Figure 3.1 are numbered according to their classification. Stream 1 is better known as *in-house, home,* or *run-around* scrap (Ness, 1984). In-house scrap consists of pure aluminum metal or alloy with a known composition, without any coatings or attachments. Ingot and billet croppings are the most common sources of in-house scrap, along with edge trimmings from sheet and plate. Because it is unadulterated, in-house scrap can be directly recycled simply by putting it back into the melting furnace. As a result, it is usually not included in recycling statistics. It is generated in both primary and secondary production plants. In addition, directly recycled manufacturing scrap (stream 2a) can be considered in-house scrap as well. Examples include casting gates and runners, skeletons from stamping operations, and croppings from extrusions. In-house scrap can usually be recycled directly back into the same alloy composition in which it was produced. This is a good example of *closed-loop* recycling.

Streams 2, 2, and (in some cases) 2a are known as *new, prompt industrial,* or *internal arising* scrap. Every manufacturing operation generates at least some new scrap, and some generate considerable amounts. Primary production, secondary production, and some manufacturing facilities also generate dross, which can be considered a form of new scrap as well. Table 3.1 lists the average percent of the input aluminum turned into scrap by manufacturing operations in different industrial sectors (Bruggink, 2000). The values range from as little as 10% in foil production to 60% in airplane production. If the metal or alloy has not been adulterated, it can sometimes be recycled directly within the generating facility (stream 2a). Otherwise, it must be

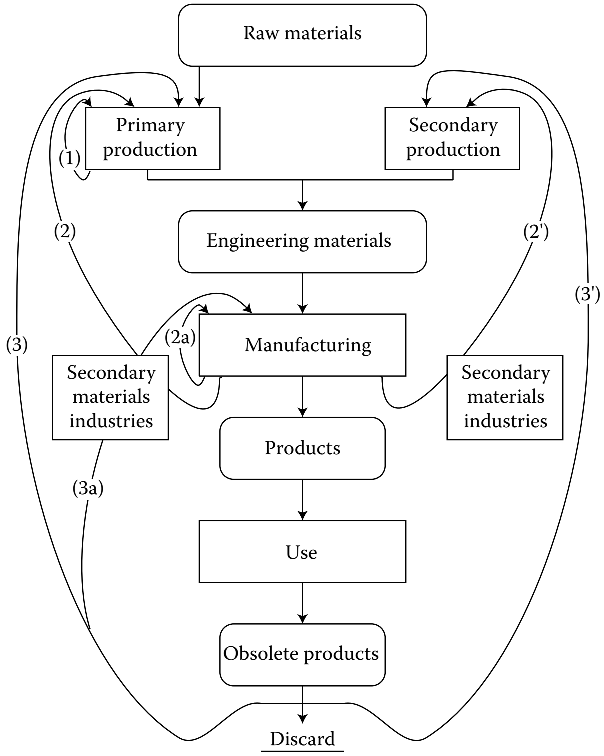

FIGURE 3.1 The materials life cycle.

processed to a purity and form suitable for recycling and returned to a metal production facility. *Open-loop* recycling of this sort is the role of the secondary materials industries in Figure 3.1 (Henstock, 1996). The upgraded scrap produced by the secondary materials industries is purchased by both primary (stream 2) and secondary (stream 2) production facilities. In recent years, primary producers in industrialized countries have become more active in scrap purchasing. The amount of indirectly recycled metal used by processors to alloy with primary metal in the United States is now greater than that processed in secondary smelters, as Figure 3.2 shows (van Linden, 1999).

Finally, streams 3, 3, and 3a are collectively known as *old, obsolete, post-consumer,* or *external arising* scrap. As the name suggests, old scrap consists of consumer products that have been discarded or taken out of service. The amount of old scrap available depends on several variables:

- **Urbanization.** In order for old scrap to be economically collected, it must be present in large enough amounts to justify the effort. As a result, the presence of abandoned cars, appliances, cans and bottles, and so on is much more apparent in rural areas.
- **Ease of recycling.** Large bulky items such as castings and extrusions are much more easily recycled than thin, heavily adulterated items such as

TABLE 3.1
Fabricator Recovery from Scrap by Market Sector

Market	Recovery (%)
Building and construction	80
Transportation: aerospace	40
Transportation: auto and light truck	75
Transportation: trucks, buses and trailers	75
Transportation: rail	75
Transportation: other	75
Consumer durables	80
Electrical	90
Machinery and equipment	85
Containers and packaging: foil	90
Containers and packaging: other	75
Other	75

(*Source:* Bruggink, P.R., in *4th Int. Symp. Recycl. Met. Eng. Mater.,* Stewart, D.L., Stephens, R., and Daley, J.C., Eds., TMS-AIME, Warrendale, PA, 2000. With permission.)

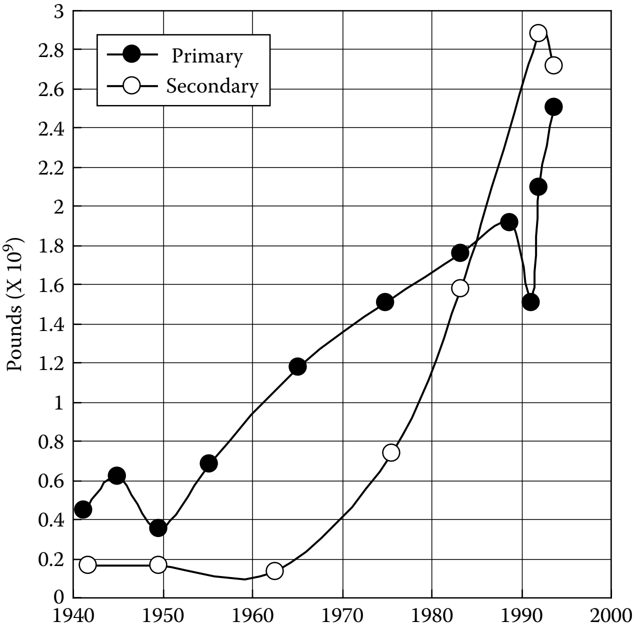

FIGURE 3.2 Mass of aluminum recycled in the United States by primary and secondary producers. (From van Linden, J.H.L., in *5th Aust. Asian Pac. Conf. Alum. Cast House Technol.,* Nilmani, M., Whiteley, P., and Grandfield, J., Eds., TMS–AIME, Warrendale, PA, 1999. With permission.)

TABLE 3.2
Product Life and Recycling Effectiveness for Market Types of Aluminum Scrap

Market	Average Product Life (years)	Estimated Recycle Rate (%)	Estimated Metal Recovery (%)
Building and construction	40	15	85
Transportation: aerospace	30	30	90
Transportation: auto and light truck	13	80	90
Transportation: trucks, buses, and trailers	20	70	90
Transportation: rail	30	70	90
Transportation: other	20	70	90
Consumer durables	15	20	90
Electrical	35	10	90
Machinery and equipment	25	15	90
Containers and packaging: foil	1	2	80
Containers and packaging: other	1	25–60	90
Other	15	20	90

Source: Bruggink, P.R., in *4th Int. Symp. Recycl. Met. Eng. Mater.,* Stewart, D.L., Stephens, R., and Daley, J.C., Eds., TMS-AIME, Warrendale, PA, 2000. With permission.

aluminum foil and wiring. As a result, the former are more likely to be recycled. Table 3.2 shows the product life and recycling rate in the United States for aluminum products in various sectors (Bruggink, 2000). The higher recycling rates are associated with transportation products, for which a well-developed recycling infrastructure exists.

- **Concentration.** Aluminum cans require more processing to recycle, but the percentage of aluminum in them is above 90%. The extrusions and aluminum conduit in building debris are easier to remelt, but the concentration of aluminum in the debris is about 0.01%. As a result, the recycling rate for aluminum cans is much higher than for aluminum from construction debris.
- **Legislation.** European Union regulations require the recycling of construction debris. As a result, the recycling rate for aluminum from buildings in Europe is 80% or higher (Melo, 1999), rather than the 15% U.S. rate cited in Table 3.2 (Bruggink, 2000). Providing a subsidy or other economic incentive increases recycling rates, as demonstrated in Taiwan and the Netherlands (Lee, 1997; van Schaik et al., 2001).
- **Industrial involvement.** When industry deliberately acquires obsolete items of its own manufacture, the recycling rate goes up. Power and telecommunications firms have long collected scrap cable as they lay replacements. Can producers have constructed several facilities specifically for recycling used beverage containers (UBCs) (Taylor, 2003) and

now deliberately seek supplies of discarded cans (Broughton, 1994; Goodrich, 2001). Other types of industries (car dealers, computer makers) are now required to take back their obsolete products (Zhang and Forssberg, 1998; Kirchner, 2002). (This is another reason why transportation-sector recycling rates are high.) Lack of industry involvement in recovering obsolete items (e.g., "white goods," the consumer durables in Table 3.2) results in a lower recycling rate.

Obsolete aluminum products that are not recycled are either landfilled, lost, or *dissipated.* A dissipative use of aluminum is one that destroys its value as a potentially recyclable material. The best example is the use of aluminum as a deoxidant in molten steel. Low-grade aluminum scrap added to the steel reacts with dissolved oxygen, resulting in deoxidized steel and aluminum oxide dissolved in the slag. The value of the steel is increased, but the value of the aluminum is destroyed. Other dissipative uses include the use of aluminum as an alloying agent in bronzes and zinc die-casting alloys and the use of aluminum as a reducing agent in the metallothermic production of refractory metals and ferroalloys. The fraction of aluminum used in dissipative purposes is very small, however.

SCRAP COLLECTION PRACTICE

NEW SCRAP

The traditional approach to collecting new scrap involves three parties: the *dealer,* the *broker,* and the *processor* (Aluminum Association, 1998).

The scrap dealer is the primary acquirer of metal scrap from industrial sources. This involves entering into a contract to purchase the scrap, physically taking it to a central collection facility (better known as a *salvage yard, scrap yard,* or *junkyard*), and then reselling it to a broker or processor. The contract can be arranged either by direct negotiation with the generator or it can be the result of competitive bidding. Several means of transport can be used, but the relatively small amounts of scrap generated by most sources mean that trucking is the most common method.

The broker purchases scrap from several traders and sells it in large lots to processors (Broughton, 1995). By purchasing from several traders, the broker can act as a supermarket, offering customers different grades of scrap at different prices. This allows the broker to sell to each processor the type of scrap that best suits the processor's operation.

The processor converts scrap to a form that can be sold to a smelting or remelting facility (NARI, 1982). Tasks that a processor may perform include:

- Sorting the scrap to separate one metal from another or to separate different grades of scrap from each other
- Shearing or shredding the scrap to "liberate" the aluminum from attachments and reduce it to a size convenient for transportation and further processing

- Cleaning the scrap to remove dirt and other extraneous material
- Baling or briquetting the scrap to make subsequent transport easier
- Simple melting (e.g., sweat melting) to separate aluminum in the scrap from attached iron and convert the scrap to ingot for shipping

In practice, these three roles are often not distinct from one another. Dealers frequently perform some processing and often sell their scrap directly to processors or smelters, bypassing the broker. Processors often negotiate directly with large scrap generators for scrap, eliminating the need for a dealer or a broker. This process of *vertical integration* has accelerated in the past 20 years.

A second change in new scrap collection and disposition involves the relationship between generator and processor. Increasingly, large generators of scrap deal directly with processors (Kiser, 1996), signing long-term contracts to supply all their scrap to the processors. The processors then sort and remelt the scrap, returning the secondary metal to the original generator. This eliminates the trader and broker and in some cases the scrap yard as well. In several cases scrap processors have set up operations adjacent to or on the generator's property, resulting in a dedicated recycling facility. This reduces costs and improves the potential for closed-loop recycling, since the alloy content of the scrap sent to the dedicated recycling facility is known and can be easily segregated.

Some large scrap generators have taken this concept one step further by processing their scrap in house. This eliminates the need for external scrap handling altogether. In-house processing is particularly attractive (Watkins, 1998; Anonymous, 2001), since it allows the dross to be processed hot (see Chapter 13) and eliminates regulatory concerns associated with shipping what is sometimes considered a waste material.

A third major change in scrap dealing and processing concerns the structure of the industry (Novelli, 1992; Kiser, 1993). Scrap dealers have traditionally been small family-owned businesses, acquiring most of their scrap from the immediate region. However, better communications (in particular, the Internet) have made it possible in recent years for dealers and processors to seek out scrap supplies from a much broader region (Reid, 2000), resulting in increased competition and decreased profit margins for smaller operations. In addition, small operations face increasing regulatory and environmental costs. Scrap yards located in urban areas are often targeted for closure under zoning laws (Meyer, 2005), and the noise and dust that scrap processing generates are increasingly unacceptable. As a result, consolidation in the scrap trading and processing industry has been a noticeable trend. Family-owned scrap businesses have been sold to or merged with large public corporations that operate on a national or even global scale. Such large corporations can effectively fill the roles of trader, broker, and processor by themselves.

OLD SCRAP

The sources of old scrap can be divided into the main use sectors of aluminum: transportation, buildings, packaging, wire and cable, and other.

Transportation

The collection of automotive scrap varies in different parts of the world. In general, end-of-life vehicles are obtained by one of four agents (Lee, 1997; Woodyard, 1999):

- Automobile dealers, who obtain the old vehicles when customers trade them in for newer ones
- Repair shops, who receive the remains of vehicles that have been irreparably damaged by accident (Ness, 1984)
- Highway authorities, who recover cars that have been abandoned by the roadside
- Salvage yard operators, who occasionally purchase vehicles directly from their owners

The relative importance of these four agents in collecting depends on location, the perceived value of the car as scrap, and the regulatory environment. In rural environments salvage yards are not as convenient to car owners, and the distance of the salvage yards from markets for the car or its parts make it less valuable. As a result, abandonment of obsolete vehicles is a more attractive option to owners, and highway departments play a larger role in collection. In urban environments salvage yards are more accessible, and the parts of the car are more valuable (Swamikannu, 1994). This results in fewer abandonments, and more recovery of obsolete vehicles by dealers and salvage yards.

The composition of automobiles has also affected the pattern of obsolete automobile collection. As the amount of aluminum and magnesium in cars has increased (see Chapter 2), their value to the recycling industry has increased as well. (The inclusion of catalytic converters with small but valuable amounts of platinum-group metals has also encouraged collection.) This makes it more likely that obsolete automobiles will be returned for recycling through proper channels, rather than simply being abandoned. As Table 3.2 points out (Bruggink, 2002), 80% of all passenger vehicles sold in the United States are now recovered for recycling. The percentages recovered in Europe and Japan are similar and will likely increase in the future.

Once collected, most obsolete vehicles are ultimately sold or given to salvage yards. About 10,000 of these exist in the United States, usually run as small family operations (Swamikannu, 1994). The salvage yards perform the first steps in the recycling process. These include removing hazardous or environmentally difficult materials from the car, including fluids and glass. This is followed by dismantling those parts of the car that need to be recycled separately (Ness, 1984; Lee, 1997); these typically include the battery, copper radiators, the catalytic converter, the tires and wheels, and the gasoline tank. Salvage yards also remove parts that can be reused as replacement parts for other vehicles being repaired. This type of dismantling is done automatically in urban salvage yards and on a more haphazard basis in rural yards.

As Table 3.2 shows (Bruggink, 2002), recycling rates for buses and trucks are similar to those for personal vehicles. The lower rate for aerospace is misleading, since obsolete aircraft are more likely to be used as sources of parts than other vehicles, and as a result are not listed as "recycled."

Building

This type of scrap is often known as C & D (construction and demolition) debris. It comes from residential as well as commercial buildings (Franklin Associates, 1998), and also includes debris from construction and demolition of other infrastructure (e.g., roads and bridges). Some definitions also include debris from land clearance, such as rocks, stumps, and dirt. Although the fraction of aluminum in it is 1% or less (Hargreaves, 2004), the amount of debris is so vast that the aluminum recovered from it is over 25% of the total old scrap supply in Germany (Rombach, 2002).

The fraction of the aluminum recovered from C & D debris has been historically much higher in Germany (> 85%) than in the U.S. (15%). The most important reason for this is the influence of government. European Union regulations encourage the processing of C & D debris to recover construction materials (Hargreaves, 2004), with the prospect of fines and increased disposal fees when this is not done. On the other hand, regulations in the U.S. vary from location to location (Clark et al., 2006), and until recently have not provided much incentive for debris recycling beyond the value of the materials themselves. Because of this, Bruggink (2000) suggests that the aluminum content of C & D debris will soon be the largest source of unrecovered scrap in the U.S.

As the incentives for recycling of C & D debris increase, the technology used for demolition has begun to change to make recycling more feasible. Deconstruction of buildings is increasingly seen as an alternative to demolition (Dantata et al., 2005). Deconstruction, which is done by taking a building apart piece by piece rather than attacking it with an excavator, is currently more expensive than demolition in the U.S., even taking into account the increased value of the recyclables recovered. However, this is highly dependent on place–specific variables (labor costs, tipping fees, value of recyclables), and the results may be different elsewhere. The design of beneficiation equipment specifically for processing of C & D debris has also increased the recycling rate (Curro, 2001; Hargreaves, 2004; Gubeno, 2005).

Packaging

Until recently the most common source of old aluminum scrap has been packaging, in particular the UBC. As Chapter 2 points out, the beverage can has risen to prominence only since the mid-1960s. As a result, for some time concerted efforts to recover the cans were not considered important. Descriptions of aluminum recycling technology from the 1960s and early 1970s treat UBCs as a minor source of metal, and an undesirable one at that (Fine et al., 1973). However, this changed in the early 1970s for several reasons (van Linden, 1985):

- Governments, noticing the increasing prevalence of aluminum cans in roadside litter, began enacting legislation banning or restricting the use of aluminum beverage containers. A common legislative initiative was to require payment of a deposit for each beverage container purchased, refundable when the empty container was returned (Knutsson and Sjöberg, 1991; Wirtz, 1992; Aluminum Association, 1998; Reid, 2002). To protect its market and forestall legislation of this type, the aluminum industry began developing infrastructure and technology specifically for collecting and recycling UBCs (Broughton, 1994).

- The energy crisis of the early 1970s had a significant impact on the cost of producing primary aluminum. The greatly reduced energy requirement for recycling metal made this alternative look increasingly attractive.
- Since an increasing percentage of the aluminum industry's output consisted of beverage cans, an increasing percentage of the available scrap consisted of this material, too. If the industry was to obtain sufficient supplies of scrap, recycling UBCs was necessary.

As a result, several pathways have been developed for the collection of UBCs. The higher rate of aluminum can usage in North America has meant greater development of collection infrastructure there. However, many of the same approaches are used elsewhere in the world as well. Collection methods include:

- *Part-time* and *subsistence collectors,* who gather aluminum cans from trash bins and other disposal areas.
- *Buy-back centers* sponsored by aluminum producers or recycling facilities (Borsecnik, 1996).
- *Municipal Recycling Facilities (MRFs),* which sort through garbage to recover UBCs and other recyclables.
- C*urbside separation and collection*, which feeds a separated stream of recyclables into the MRF (Jenkins et al., 2003). Curbside serves nearly half of the U.S. population.

Individual collectors have a variety of economic and social backgrounds and various motivations (Gerson, 1993; Medina, 1998; Janser et al., 2002). Some collect cans for the income, some for the exercise, some out of a sense of obligation toward the environment. Part-time collecting is seasonal (Ambrosia, 1992; Harler, 1999), with far more cans being collected during the warmer months.

Buy-back centers differ considerably in their degree of sophistication and size. The simplest are first-tier facilities, which purchase cans and perform some rudimentary sorting (Aluminum Association, 1998). Figure 3.3 illustrates a typical reverse vending machine, which returns a small amount of cash for cans fed into it. Machines like this are typically employed in states or countries where mandatory deposits are required. Because of this, they can often accept several types of UBC in addition to aluminum and can perform sorting and flattening as well as collecting operations. Where mandatory deposits are not required, a first-tier facility may consist of nothing more than a drop-off trailer. Cans are left at the trailer and periodically retrieved by the site owner or manager.

When the number of cans being returned is sufficient to justify it, a second-tier facility will be constructed to process cans collected from first-tier facilities (Broughton, 1994; Phillips, 1995; Harler, 1998; Goodrich, 2001). Second-tier facilities have a magnetic sorter to remove steel cans and other ferrous scrap from the aluminum cans. They also have a baler or flattener to increase their bulk density and make the cans easier to ship. If the can collection operation is large enough, third-tier centers may be built (Aluminum Association, 1998). These are primarily processing rather

FIGURE 3.3 A reverse vending machine. (From Can and Bottle Systems, Inc., http://www.canandbottle.com/pages/onestop.html. With permission.)

than collecting centers and perform shredding and cleaning of the collected cans in addition to magnetic separation.

In many cities a large fraction of the UBCs returned for recycling are collected by sorting through municipal trash. Because UBCs are easily recognizable and a common item in the trash, it is common for municipalities to ask (or require) homeowners and other trash generators to presort their garbage for curbside pickup (Aluminum Association, 1998; Jenkins et al., 2003). In addition to aluminum and steel cans, the types of garbage presorted may include glass, paper, and cardboard. This presorted material is then placed in a distinct container (a "blue bag," bin, or

FIGURE 3.4 Sorting truck for unseparated recyclables. (From Kann Manufacturing Corp., http://www.kannmfg.com/curbsorter.htm. With permission.)

tub) and set aside at the curb for separate collection. Once collected, the blue-bag contents will be sorted by sanitation personnel into the separate categories of recyclable materials (Malloy, 1998) and sold to dealers or reprocessors. Figure 3.4 illustrates a truck specifically designed for such sorting.

Alternatively, the municipality may choose to collect its garbage in one container and then separate out the recyclables at an MRF. The reasons for recovering recyclables are twofold (Steverson, 1995; Malloy, 1998; Lave et al., 1999):

- Recovering recyclables reduces the amount of garbage to be landfilled, reducing land usage and the cost of acquiring and operating landfills (Rooy and van Linden, 1990). In regions where available land is scarce (e.g., Japan), this is particularly important (Itou, 1995).
- The recovered recyclables have value as scrap. Many MRFs were constructed on the assumption that the proceeds from selling these recyclables (along with the savings from reduced landfill usage) would more than pay the cost of operating the MRF, becoming a net money earner for the operator. The aluminum cans in the garbage are particularly important in this regard, since they represent more than one-fourth of the total value of the recyclables, despite being only 2% of the garbage (Aluminum Association, 1998; Mahoney, 1999).

In practice, MRFs have not always been as successful as originally envisioned (Reid, 2002). Low prices for recyclables and lower-than-anticipated landfilling costs have made many MRFs in North America unprofitable, and some have been closed or curtailed. Elsewhere, conditions have been more favorable.

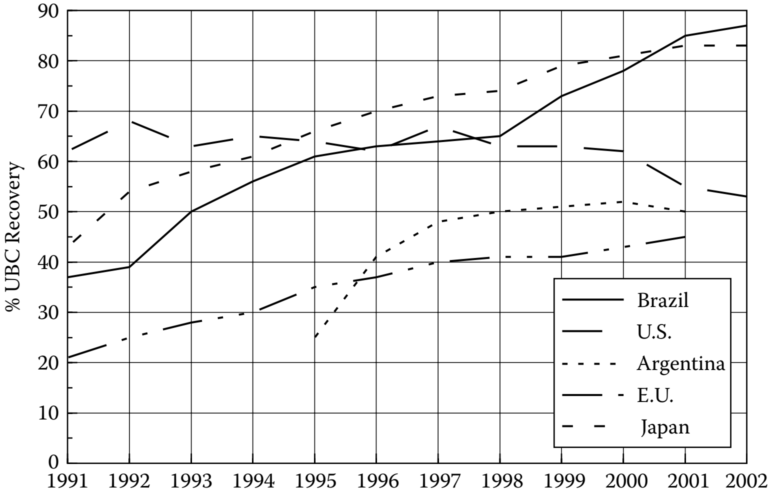

FIGURE 3.5 UBC recycling rates around the world from 1991 to 2002.

As a result of these collection efforts, UBC recycling rates have risen steadily wherever concerted collection efforts have been made. Figure 3.5 shows the current percentages in various areas of the world. Collection rates are currently highest in Brazil and Japan, at well over 80% (Filleti et al., 1997). The European rate masks considerable differences between countries. In Germany and Sweden, mandatory deposit legislation has pushed recycling rates to levels above 70% (Knutsson and Sjöberg, 1991).

A note of concern can be found in the UBC recycling statistics for the United States shown in Figure 3.5. From a high of 67% in the late 1990s, the percentage has shrunk to just over 50% in 2002 (Fialka, 2002). Reasons for this include (Reid, 2002):

- The low price of aluminum (Taylor, 2003). This is reflected in a lower price for aluminum scrap, which means reduced incentive for collectors to recover cans.
- Reduced levels of public interest. Recycling has in some ways become yesterday's news.
- The reduced cost of alternatives. With landfilling costs less than anticipated and MRF operating costs greater than forecast, some municipalities no longer operate MRFs. The result is reduced UBC collection.
- The reduced mass of the can, which weighs one-third less than in 1970. This means that 33 cans are now required for a pound of metal instead of the 21 needed 30 years ago. This further reduces the incentive for collecting cans.

Many of these causes may have a long-term impact on can collection rates. As a result, increasing these rates may require legislative initiatives, such as the mandatory-deposit legislation described earlier.

Aluminum foil is also used in food and beverage packaging, especially aseptic juice boxes. These boxes are popular packages for single-serving products. However, separating the thin layer of aluminum foil from the layers of paper and plastic comprising the package is a complex and expensive operation (Mutz and Meier-Kortwig, 2001), difficult to justify given the negligible amount of metal recovered. As a result, the recycle rate for this material is only 2% in the United States and somewhat higher elsewhere.

Wire and Cable

The fraction of recycled aluminum obtained from scrap wire and cable is likely no more than 5%. Reasons for this include the relatively small amount of aluminum used in this application and the low recovery rate (see Table 3.2). Most aluminum-containing wire is collected from industrial sources: wire manufacturers, telephone companies, power and utility companies, and scrap dealers sorting building debris (Sullivan, 1985). The decreasing popularity of aluminum power cable suggests that the importance of wire scrap as a source of recycled aluminum will continue to decline.

The growing amount of electronic scrap generated by economically advanced societies points to another potential source of recycled aluminum. Printed circuit boards (PCBs) consist of 2% or more metallic aluminum (Sum, 1991), and processes have been developed for recovering an aluminum "concentrate" as one of the products of circuit-board recycling. However, the relative value of the aluminum in a PCB is minimal compared with that of several other materials in the PCB, and as a result aluminum recovery is negligible.

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4 Aluminum Recycling Economics

Gregory M. Gelles

Recycling in aluminum markets is often advocated on economic grounds. Aluminum recycling saves substantial amounts of energy and in general eliminates the environmental damage associated with aluminum mining and increased energy use. Yet despite the seemingly obvious social advantages of recycling, primary ore prices have fallen in the past 10 to 15 years in inflation-adjusted terms and recycling rates for scrap material such as aluminum beverage cans have fallen to under 50%. Some analysts say that aluminum prices are too low because the markets for primary and recycled aluminum are flawed and the prices do not accurately reflect the full social costs of aluminum mining. Others say market failures in aluminum markets are relatively minor and aluminum prices are low because aluminum ore is abundant and the technology to extract it is quite powerful.

This chapter looks at the markets for aluminum, both primary and recycled, from an economics perspective. We examine the history of aluminum, the technologies used in its production, its economic uses, and various economic aspects of aluminum recycling.

HISTORY OF ALUMINUM PRODUCTION

Aluminum is the most abundant metallic element in the earth's crust and, after oxygen and silicon, by mass the third most abundant of all elements in the earth's crust. It constitutes approximately 8% of the earth's crust by mass (King, 1987). It is found in some portion in nearly all rocks and mineral deposits. However, because it has atomic number 13 with three electrons in its outer shell, it has a strong affinity to bond with other elements, particularly oxygen to form very stable oxides (e.g., Al_2O_3) and silicates. For this reason it is not found in its pure metallic form in nature.

Because of the stability of aluminum compounds, it was not until 1808 that the existence of aluminum was established (International Aluminium Institute, History). Thirteen years later in 1821 a claylike material, rich in aluminum oxide, was found in southern France. It was named bauxite. Bauxite deposits are found worldwide and today are the primary source of aluminum metal.

In 1825 Hans Christian Oersted produced for the first time minute quantities of aluminum (International Aluminium Institute, History). In 1854 Henry Deville created the first commercial process for making aluminum metal. In 1886 two young scientists, Charles Martin Hall of the United States and Paul Louis Heroult of France, simultaneously and independently patented an identical process in which processed aluminum ore is dissolved in molten crylite and the aluminum is precipitated out using large amounts of electricity. This reduction process is now known as the Hall–Heroult process. Despite many efforts to find alternative processes, the Hall–Heroult process remains today the most efficient method to produce aluminum in commercial quantities.

The introduction of the Hall–Heroult process ushered in the modern era of aluminum production. In the mid-1800s aluminum metal existed in such small quantities that it was regarded as a precious metal; in 1852 aluminum sold for almost $550 per pound (over $3000 per pound in 2006 dollars). After Deville's process was introduced in 1854 the price fell precipitously to nearly $25 in 1857. By the time the Hall–Heroult process was perfected in 1890, aluminum was selling for $2 a pound.

The drop in aluminum prices coincided with explosive growth in production of aluminum worldwide (International Aluminium Institute, History). In 1900 annual output of primary aluminum was 8,000 metric tons. By 1920 this had increased by a factor of 16 to 128,000 metric tons. In another 18 years, shortly before the start of World War II, it had further increased fourfold to 537,000 metric tons. In 2004 world production of primary aluminum totaled 30 million metric tons, with another 9 million metric tons produced from new and old recycled aluminum scrap. Between 1910 and 2004 primary worldwide aluminum production grew at an average annual rate of nearly 8.5%.

PRODUCTION OF PRIMARY ALUMINUM

Primary aluminum is aluminum metal produced from virgin ore. The production of primary aluminum can be broken down into five basically independent stages: mining the raw material (primarily bauxite), production of alumina (Al_2O_3), production of primary aluminum, fabrication of aluminum, and production of finished aluminum product. Bauxite that is economically suitable for making aluminum generally contains at least 50% aluminum. In the United States the largest bauxite deposits with this aluminum density are found in Arkansas (Plunkert, 2000).

Bauxite is generally found in deposits close to the surface, so most bauxite is mined in open pits. Treatment at the mining site is minimal, usually confined to crushing and drying. The crushed bauxite is then treated using a process developed by Karl Josef Bayer in 1989. The Bayer process transforms the aluminum in the bauxite into alumina.

The converted alumina is then shipped to a reduction plant, where primary smelting occurs using the electrolytic Hall–Heroult process. Two pounds of alumina, small amounts of carbon and cryolite, and approximately 10,000 watt-hours of electricity are required to produce one pound of pure aluminum metal. The smelting of alumina to make primary aluminum is supplemented by secondary smelting of new and old recycled aluminum. The secondary smelting process uses significantly less energy compared to primary smelting.

Aluminum in its pure state is very weak. However, small amounts of alloying metals such as zinc, iron, nickel, lead, copper, and cadmium can be added to enhance its strength and hardness. Once the aluminum alloy is made, the metal is transported to plants that produce semifabricated aluminum products such as metal sheets, plates, and forged parts. The semifabricated products are then shipped to fabrication plants, where finished products are made for consumers.

USES

Aluminum applications can be found in many areas of the U.S. economy. Aluminum's most attractive characteristics are its strength (if properly alloyed) and its light weight (having approximately one-third the density of iron). It is resistant to corrosion and is an excellent conductor of electricity and heat. The three largest markets for aluminum use in the United Stares are transportation (33.9% in 2004), containers and packaging (20.3%), and building and construction (14.8%) (Plunkert, 2000).

Transportation sector uses for aluminum include airplanes and aerospace, trucks, buses, railroad cars, and tractor trailers. Significant inroads have been made in the past 15 years into the automobile industry. Much of this increased aluminum substitution has been in transmissions and wheels. However, recently engineers have begun working on new and radical car designs that utilize aluminum as the primary component in automobile bodies (Kelkar et al., 2001).

Container and packaging uses include aluminum beverage cans, food containers, and household and industrial aluminum foils. Aluminum beverage cans are the single largest use of aluminum in this sector. In 2004, 100.5 billion aluminum cans were sold. Aluminum beverage cans are mobile homes and also one of the largest sources of recycled aluminum in the United States (CRI, Aluminum). The principal uses of aluminum in the construction industry are interior and exterior building applications, including window frames, roofing, siding, and heating and air conditioning (Plunkert, 2000).

In addition to the three main applications, aluminum usage is also important in the electrical sector, where aluminum has partially replaced copper for electric transmission wiring, in the construction of machinery, and in consumer durables such as cookware. It also has important specialty applications such as coatings on telescope mirrors.

ALUMINUM RECYCLING

Metals are important, reusable resources. Although metals, in contrast to resources such as lumber, are not renewable and therefore exist in finite supply, advancements in mining and recycling technology have made it possible to acquire large amounts of resources from the earth while simultaneously increasing the amount that is recycled from the manufacturing and consumption of metal goods.

When we refer to *primary* metal production, we mean metal that is produced from ore found in deposits in the earth's crust. *Secondary* production indicates material acquired through recycling. Potential recyclable metal waste can be divided into two types of scrap: new scrap and old scrap (Tietenberg, 2006). New scrap is composed of the leftover materials generated during production. For instance, as circular tops and bottoms from aluminum beverage cans are punched out from an aluminum sheet, there will be leftover material that qualifies as new scrap. Old scrap is metal recovered from recycled consumer products, including the finished beverage cans themselves.

TABLE 4.1
Recycling Statistics for U.S. Aluminum Production from 2000 to 2004 (thousands of metric tons)

	1 Recycled from New Scrap	2 Recycled from Old Scrap	3 Total Recycled (1+2)	4 Domestic Primary Production	5 Total Domestic (3+4)	6% Domestic Recycled (3/5)	7 Net Exports	8 Supply (5+7)	9% of Supply That is Recycled (3/8)
2004	1870	1160	3030	2516	5546	55	2900	8446	36
2003	1750	1070	2820	2703	5523	51	2590	8113	35
2002	1750	1170	2930	2707	5637	52	2470	8107	36
2001	1760	1210	2970	2637	5607	53	2150	7757	38
2000	2080	1370	3450	3668	7118	48	2150	9268	37

From: Recycling-Metals, *U.S. Geological Survey Minerals Yearbook-2004*

Aluminum has physical characteristics that make its recycling economically attractive. A primary incentive for recycling metals is that the process used to produce a given mass from recycled scrap consumes less energy than producing the same mass from virgin ore. This advantage is particularly magnified with aluminum, where the energy cost of producing metal from virgin ore is very high (owing to the chemical difficulty of extracting the pure metal from its oxide form), while the energy cost of producing metal from scrap is relatively low (given the low melting temperature). It is estimated that to produce a given mass of aluminum from recycled scrap requires only 5% of the energy necessary to produce the same mass from virgin ore (see Chapter 1).

Table 4.1 provides an overview of domestic primary and recycling output of aluminum from 2000 to 2004. In 2004 primary aluminum production in the United States equaled 2.52 million metric tons. Secondary recovery of aluminum equaled 3.03 million metric tons, with 1.16 million metric tons from old scrap (38%) and 1.87 million metric tons (62%) from new scrap. As a result, approximately 55% of total domestic production of aluminum in 2004 came from recovery of scrap, while 45% came from primary production of new ore.

Table 4.1 shows additional trends in the domestic aluminum industry. During the period 2000 to 2004 the domestic aluminum industry saw a drop in aluminum production from 7.12 million metric tons to 5.55 million metric tons, a decrease of approximately 22%. Domestic primary production fell over the 2000 to 2004 period by 1.15 million metric tons, a decrease of over 31%. Aluminum production from recycled scrap (old and new) fell during this period by 0.42 metric tons, a decrease of approximately 12%. The percentage of total domestic aluminum production produced from recycled scrap increased from 48% in 2000 to a historic high of 55% in 2004.

Another interesting trend seen in Table 4.1 is the explosive growth in net imports (imports minus exports) over the period 2000 to 2004. Net imports of aluminum metal from this period increased by 0.750 million metric tons, approximately 35%.

There appears to be a developing trend in domestic aluminum production that will bear watching in future years. Define aluminum supply to equal domestic

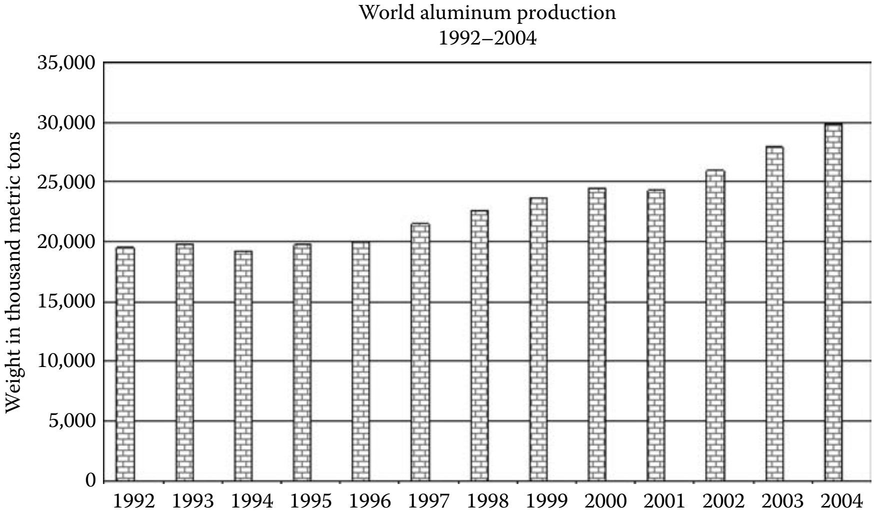

FIGURE 4.1 World aluminum production from 1992 to 2004 (Plunkert, 2004).

primary production + total recycled + imports – exports. In 2000 the percentages of aluminum supplied by primary domestic production, total recycled scrap and net imports were, respectively, 40, 37, and 23%. The same numbers in 2004 were 30, 36, and 34%. The trend is a shift in the composition of overall supply as domestic primary production significantly decreases and is replaced by a significant increase in net imports. The percentage of supply coming from recycled scrap has remained relatively stable over the period 2000 to 2004.

At the same time that primary aluminum production has decreased in the United States, primary production of aluminum has grown steadily worldwide. Figure 4.1 shows that primary production of aluminum worldwide has grown 19.3 million metric tons in 1993 to 30.0 million metric tons in 2004, an average annual rate of increase of over 3.5%. Figure 4.2 shows the increase in world primary aluminum production and the simultaneous decrease in domestic primary aluminum production. From 1993 to 2004 worldwide aluminum production from scrap averaged about 30% of primary aluminum production. For instance, in 2004 worldwide aluminum production from scrap was approximately one million metric tons (Plunkert, 2004).

RECYCLING OF USED ALUMINUM BEVERAGE CANS

The backbone of the old scrap recycling market is the aluminum used beverage can (UBC). The aluminum can was introduced in the early 1970s, and initially the public treated aluminum cans as a discardable product. However, by the late 1970s recycling of aluminum cans began to take off as the industry and public saw the environmental and economic advantage of recycling. Recycling centers and material recovery facilities provided a new importance to the public for collecting and processing

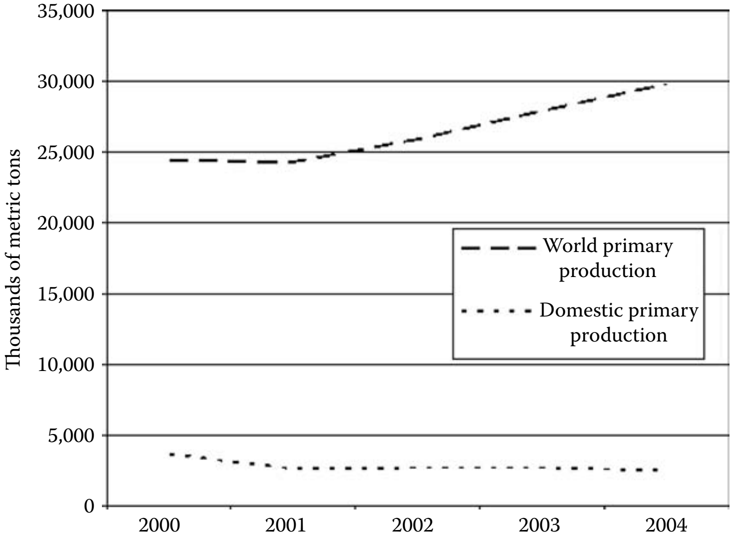

FIGURE 4.2 World and U.S. production of primary aluminum from 2000 to 2004 (Plunkert, 2004).

waste materials. By the late 1980s millions of American households began participating in curbside recycling programs. Most prominent among the curbside recyclables is aluminum UBCs (Gitlitz, 2002).

Today approximately 40% of all scrap aluminum is old scrap, and approximately 50% of old scrap comes from aluminum UBCs (Plunkert, 2004). Figure 4.3 shows

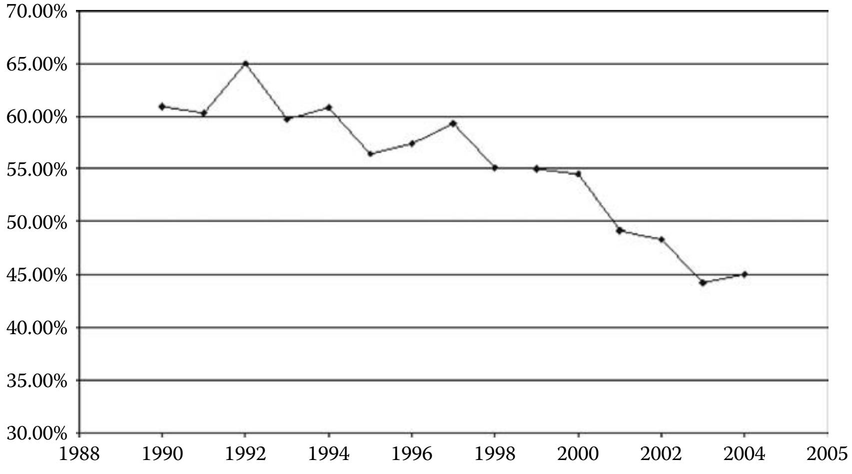

FIGURE 4.3 U.S. aluminum can recycling rates from 1990 to 2004 (Container Recycling Institute, n.d.).

a graph of the recycling rate for aluminum UBCs from 1990 to 2004, using the Environmental Protection Agency's recycling rate methodology. It should be noted that the recycling rate in the United States for UBCs peaked at 65% in 1992 and since then has trended downward to a rate of 45.1% in 2004. The Container Recycling Institute (CRI) reports a slight improvement in the recycling rate in 2005 over 2004, but the rate remains significantly below 50% (CRI, Aluminum).

It is worth asking why the recycling rate for aluminum UBCs has been decreasing and has remained stubbornly below 50% since 2000. Industry and environmental groups are quite correct when they note the numerous social benefits to aluminum recycling. For instance, given the high energy cost of separating aluminum from its oxide and silicate compounds and the relatively low melting point of aluminum metal, there are considerable energy savings to producing aluminum metal from scrap rather than from bauxite ore. Remelting aluminum scrap saves 95% of the energy required to convert bauxite ore into virgin aluminum; that is, 20 cans can be made from recycled cans with the same energy needed to produce one can from virgin ore. The CRI estimates that the 46 billion aluminum cans recycled in 2005 saved the equivalent of 14 million barrels of crude oil, nearly one day of U.S. gas consumption, or enough energy to generate electricity for 22.7 million U.S. homes for a year. The CRI estimates that 1.1 trillion aluminum cans have been trashed since 1972. If these cans were recycled, it would have saved the equivalent of 520 million barrels of oil (Gitlitz, 2002).

Environmental groups also point to the environmental damage caused by aluminum can production through the mining of virgin ore. Mining of bauxite ore results in damage to the land and water and the production of toxic waste products through the mining of bauxite and coal. Some social and environmental groups point to the damage done to wildlife and indigenous cultures from bauxite mining in third world countries. These groups point out that many of these environmental and social problems can be alleviated to the extent that UBC recycling can be increased (Gitlitz, 2002).

Given this information on the social benefits associated with aluminum recycling, there are two questions to consider: First, despite the obvious benefits to recycling, why is the UBC recycling rate decreasing? Second, should we care that it is decreasing? Several reasons might explain the declining aluminum UBC recycling rate in the United States over the past decade. First, and likely the foremost cause of the decreasing recycling rate, is the fall in the price of primary aluminum. It is certainly not a coincidence that the decline in the can recycling rate shown in Figure 4.3 mirrors closely the drop in the inflation-adjusted raw aluminum prices shown in Figure 4.4. The CRI estimates that the average price of recycled scrap aluminum cans from 2000 to 2004 was $0.54/pound. Multiplied by 33 cans/pound, this translates into an average selling price of 1.5 cents per recycled can, certainly not an exorbitantly large return for someone recycling a UBC (Gitlitz, 2002).

In addition to the drop in real aluminum prices, there are several other explanations for why recycling rates for aluminum UBCs might be declining (Gitlitz, 2002). Lifestyle changes, including more mobility and traveling by U.S. citizens, may result in more consumption of aluminum cans away from the home and correspondingly away from curbside recycling bins. A number of states instituted deposits on aluminum cans in the 1970s and 1980s, but inflation has eroded the value of these

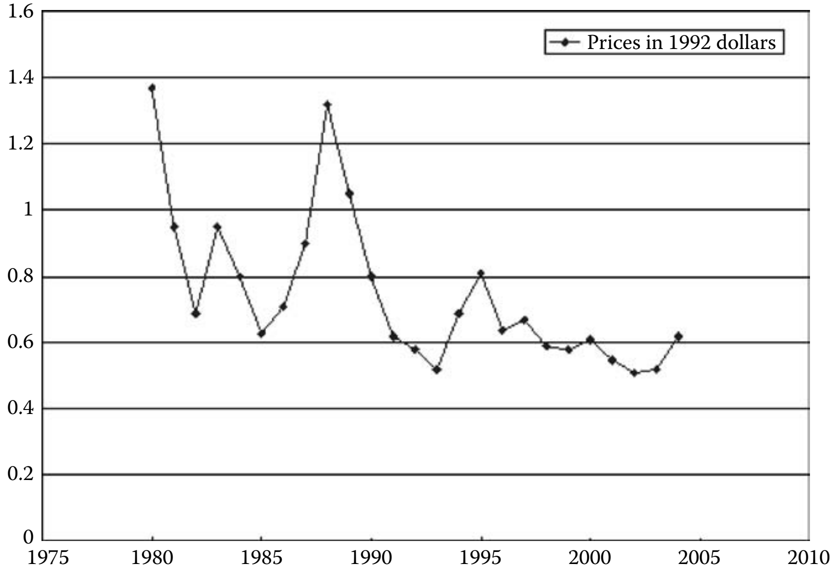

FIGURE 4.4 Inflation-adjusted aluminum prices (1992 U.S. dollars per pound) from 1980 to 2005.

five-cent deposits. The strong U.S. economy during the 1990s and into 2000 has resulted in a low unemployment rate and a corresponding disincentive to use valuable time to locate aluminum cans. The realization that as a country we are not running out of available space for landfills has reduced focus on the immediacy of recycling.

The second question mentioned above is whether we should be alarmed that the recycling rate for UBC is decreasing in the United States. Is the declining recycling rate a bad thing for society or is the decreasing recycling rate an expected, appropriate, and efficient adjustment owing to changes in lifestyle and raw material prices? These are difficult questions for economists to answer. Any economic analysis would require a balancing of the increased cost to society of an enhanced recycling rate with the benefits detailed above of producing greater amounts of raw aluminum through the melting of recycled scrap aluminum. As the CRI correctly notes, the recycling rate could certainly be increased through use of, for example, a sufficiently large nationally imposed deposit tax on aluminum cans (Gitlitz, 2002), but is this a correct policy for us to pursue? In the next section we will present a framework for evaluating the efficiency of aluminum recycling and efforts to increase recycling rates in the United States.

ALUMINUM RECYCLING: AN ECONOMIC PERSPECTIVE

When economists determine a market condition to be efficient they mean that the allocation of scarce resources meets the condition that the benefit to society of the last unit of the activity provided (social marginal benefit) is equal to the cost to society of the last unit of the activity provided (social marginal cost). This condition that social marginal benefit and social marginal cost are equal is at the bedrock of the theory for allocating resources to the maximum net benefit of society. Adam Smith noted that free markets with flexible and unfettered prices would ideally result in just such an efficient allocation by ensuring that benefits and costs to individual economic agents matched those as seen by society as a whole. Individuals in this scenario would be free to pursue their own economic self-interest while markets themselves, the clearing houses for the activities of countless economic individuals, ensured that the interests of society were met. Central to all this economic activity is the existence of transparent market prices that contain within their values all the available market information on the social benefits and costs of the given economic product. It is the market prices that provide the signals for individuals to buy and sell goods and services. Of course, economists have long been aware that market prices may be distorted by market failures that create a divergence between the interest of economic agents searching to maximize their own self-satisfaction and the interest of society to ensure the existence of economic efficiency.

Many of the sources of market failures have been studied extensively by economists (Nicholson, 2004). They include:

- **The problem of monopoly and monopsony.** Excessive market power by either sellers or buyers can force market prices away from the efficient price. The problem is that monopoly and monopsony market prices may not be efficient.
- **The problem of externalities.** Some market participants may perceive costs or benefits of a transaction as different than the full costs or benefits to society. A firm able to costlessly dump pollution that imposes costs to a third party is one example of this.
- **The problem of public goods.** Some good may have characteristics, the benefits of which cannot be excluded from nonpaying consumers. In extreme cases public goods will not be produced in any quantities by private markets.
- **The problem of inefficient information.** Both buyers and sellers may be ignorant of important information concerning a good or service. Or one party, for example, the seller in the case of a used car, may have better information than the other party. In both cases the price will not contain all available information and will therefore not be efficient.

Information concerning market failures is key to a discussion of recycling policy because ideally, as described by Adam Smith, free competitive markets will establish an efficient allocation of recycling activities. Baumol (1977) described how such an efficient level of recycling would occur in a competitive market devoid of externalities.

Tietenberg (2006) also describes how a competitive market devoid of market failures and imperfection would determine the efficient level of recycling. Initially virgin ore is plentiful and the extraction cost is so low that there is little economic incentive to recycle. However, as the economy grows, two things may happen: First, the richest ore deposits become exhausted. As mining moves to less gainful fields, it is possible that, at least for a while, prices will not increase as improved technology extracts comparable ore from the secondary fields. However, eventually we would expect prices for virgin ore to rise, resulting in higher prices for primary aluminum.

Second, as the economy grows, landfill sites should become scarcer so that disposal costs for waste will increase. Both higher costs for virgin ore and higher disposal costs for waste will increase the economic value of recycling. Recycling provides an alternative to mining virgin ores and reduces the waste disposal load on landfills.

This analysis describes how a market for recycled metals such as aluminum might arise and how prices would be determined. However, economists want to do more than describe how markets for recycled metal might arise. They also want to determine whether such markets are efficient and whether in equilibrium they result in an efficient amount of recycling. Can recycling markets, without government intervention, provide an efficient allocation of recycled metals, or are the markets characterized by inefficiencies and market failures, requiring a role for government pricing policy?

Certainly market mechanisms as shown above create incentives for recycling that move in the right direction but not necessarily with the correct strength. There are arguments that prices for recycled aluminum and correspondingly aluminum recycling rates are too low. Since environmental damage possesses aspects of non-excludability, it is unlikely that prices for either aluminum ore or recycled aluminum scrap fully incorporate the environmental social damage associated with aluminum mining. Recycling advocates such as the CRI advocate that beverage consumers pay hefty refundable deposits on aluminum cans to encourage recycling. They correctly point out that states such as California with refundable deposit schemes on aluminum cans have higher recycling rates then the United States as a whole (Gitlitz, 2002).

Another possible source of market failure in recycling stems from the prevalence of flat-fee waste disposal across the United States (Tietenberg, 2006). Because in many places consumers pay a fixed monthly fee for trash disposal, a waste disposer faces (within limits) a zero marginal cost of disposing of an addition unit of waste. Thus, a consumer with a scrap aluminum beverage can and a choice of either transporting the can to a recycling center or disposing it in the trash will find the marginal cost of disposal to be zero. However, the social cost of disposal is not zero. This leads to a divergence between private and social interests and an inadequate level of recycling.

One solution to the inefficiency of fixed-fee trash collection is to move to a system of volume pricing. Under such a plan disposers would pay by the bag to dispose of their trash. Such a system would theoretically force trash disposers to internalize the cost of disposing of an additional unit of trash and thus encourage more recycling. In practice, volume pricing has not been successful. Studies by Fullerton and Kinnaman (1996) and by Reschovsky and Stone (1994) have examined volume pricing schemes for trash collections in several communities. Both found that volume pricing did not significantly increase recycling and had the unintended consequence of increasing illegal dumping, most likely among low-income consumers. Fullerton and Kinnaman concluded that given the higher administrative costs, such variable cost schemes were ill-advised.

Tietenberg (2006) discusses other market failures that would artificially reduce the price of virgin ore and reduce recycling. These include favorable tax treatment for mining, through depletion allowances and other subsidies. Tientenberg notes that low prices for virgin ore and therefore low recycling rates may also increase our reliance on foreign sources for aluminum. This could negatively impact national security. It is unlikely that market prices fully incorporate national security concerns.

This discussion has likely not exhausted all sources of potential inefficiency in the recycling markets. However, there are no indications that the recycling markets for aluminum are substantially off balance as a result of these potential inefficiencies. Instead it appears that the decrease in the recycling rate over the past decade is mostly a result of the fall in the inflation-adjusted price of primary aluminum. Recycling advocates may bemoan that in the United States less than 50% of aluminum beverage cans have been recycled in recent years, but given the vast size and large rural areas of the United States, the increasing mobility of the citizens resulting in aluminum can consumption away from home, and the overall low price of primary aluminum, a 45% recycling rate may be close to efficient. There clearly seems to be no indication that the situation requires a vast new taxing structure designed to provide new recycling incentives.

CONCLUSION

While materials such as coal and oil that are used to produce energy are dissipated in use and cannot be reused, the same is not true for metals. In general, metals maintain their elemental structure and can be recaptured and reused countless times. Aluminum, while expensive to retrieve from the compounds in which it is bundled, is relatively easy and inexpensive to acquire from recycled scrap. In this paper we have examined various aspects of aluminum metals. A historical review of aluminum production noted that in contrast to metals such as iron or copper, its discovery was quite recent. The next section described the full production process required to produce primary aluminum from virgin ore. This was followed by a short summary of the many applications for aluminum.

The next section discussed the recycling of aluminum in greater detail. Substantial energy savings are associated with producing aluminum from recycled aluminum scrap instead of virgin ore. The percentage of domestic aluminum production from recycled aluminum scrap exceeds 50%, and that an increasing fraction of overall aluminum supply in the United States comes from imports.

Following this we looked at recycling of UBCs in the United States. From a peak UBC recycling rate of 62% in 1992, the rate has decreased to 45% in 2004. This decrease coincided with the steady decrease of the inflation-adjusted aluminum price, and environmental groups point to the many benefits of producing aluminum from recycled cans including energy savings and environmental and social preservation. However, substantive costs are associated with increased recycling that are often ignored when the benefits of recycling are discussed.

Subsequently we discussed aluminum recycling in the context of economic theory. We demonstrated that markets for recycled metals will arise naturally and we discussed whether the prices determined in such markets will be efficient.

Several market failures exist in the production of aluminum ore, each of which could create a less than efficient recycling rate for aluminum. Our conclusion is that market failures do exist in the markets for primary aluminum production and the corresponding recycling markets but that overall, the inefficiencies are small. Given the low prices paid for primary aluminum and for recycled aluminum scrap, a recycling rate of 45% for UBCs may be close to the efficient level. A small deposit scheme for cans might be appropriate, but further government intervention in the aluminum recycling market does not appear justified.

What does the future hold for aluminum markets? Metals of all kinds are fixed in quantity. Demand for metal will certainly continue to grow, and although technological advancements will enable enhanced metal recovery from lower-grade deposits, we would expect that recycling will play a larger role in the metals market. Ayres (1997) outlines a vision that elevates recycling to a far more prominent role than exists today. Ayres sees a future where all production will be tied to the concept of recycling and reuse. Companies will no longer sell products but instead will sell only the services associated with the product. Thus, General Motors will not sell cars but instead will sell "driving services." The car itself will remain "owned" by GM and ultimately will be reclaimed by the company. The theory is that this model will provide incentives for GM and other manufacturers to design products that will be easy to dismantle and recycle.

Ayres advocates instituting policies that will gradually increase recycling rates and set the stage for a more holistic use of resources. He notes that one reason that recycling has had difficulties paying for itself and competing with primary mining is that primary mining has definite economic advantages over recycling. In particular he notes the economies of scale that favor primary mining and smelting over much smaller and more decentralized recycling operations. Ayres also observes that mining is a very capital- and resource-intensive operation, while recycling is more labor-intensive. In a sense recycling substitutes labor inputs for energy, virgin ores, and landfill space. The problem is that the present tax code relies more heavily on taxes placed on labor while undertaxing resources and energy. Ayres suggests gradually shifting the tax burden away from labor and onto resource consumption to encourage producers to rely more heavily on recycling markets.

In a similar light, other researchers have investigated the possibilities of optimizing recycling through changed economic and engineering policies. Reuter et al. (2004) present an enhanced model to optimize the resource cycle of production. Zheng et al. (2004) have looked at methods for optimizing the entire recycling system for aluminum cans, including collection, transportation, and processing. Shinkuma (2003) analyzes various public and tax policies to enhance waste recycling including disposal fees coupled with recycling subsidies.

There exist today huge deposits of bauxite sufficiently large to provide hundreds of years of primary aluminum production at present consumption levels. Set against this high-energy mining production is a low-energy substitute, recycled aluminum. Presently, in the United States recycled aluminum makes up about one-third of the total aluminum supply, and similar fractions apply worldwide. Given the availability of rich primary ores, it is likely that this level is presently efficient. However, considerable research is being conducted to examine policy changes that would increase the use recycled aluminum scrap and other recycled metal. U.S. policy makers should keep their minds open to possibly increasing the role of government in the market when necessary.

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5 Beneficiation Technology

After mining, the next step in traditional metal extraction is mineral processing, in which the valuable minerals are liberated from the gangue material in the ore. Following this, the minerals are separated into a separate stream, using differences between their physical properties and those of the gangue. In some cases, chemical or thermal processes may be used to remove impurities from the concentrated minerals. As a final step, the concentrated minerals may be agglomerated to make them easier to ship and easier to handle in subsequent smelting processes.

Chapter 3 described the "mining" (collecting) of scrap aluminum. The next two chapters will introduce the equivalent mineral processing (*beneficiation* or *upgrading*) of this ore. This chapter will introduce the techniques and equipment used to separate scrap aluminum from contaminants. This will be followed by a description in Chapter 6 of how this technology is put into practice. As with the processing of traditional minerals, the beneficiation of scrap can be divided into four types of unit process: comminution, separation, thermal processing, and agglomeration.

The following discussion relies heavily on the *Handbook of Recycling Techniques* by Nijkerk and Dalmijn (1998, and other versions). Readers seeking more information are strongly encouraged to consult this work.

COMMINUTION

Aluminum scrap comes in a wide variety of sizes and conditions. Pieces can be as small as the aluminum wires used in electronic equipment or as large as a jet airliner. Scrap is sometimes *liberated,* that is free of any attached pieces of other materials. More often, it is found bolted, welded, or otherwise attached to other parts. In order to be remelted, the scrap has to be separated from these other materials. The *hand dismantling* of automobiles and other large assemblies accomplishes this to some degree. However, in many cases, the value of the scrap recovered by hand dismantling is insufficient to justify the expense of this labor-intensive process.

Many sorting processes require scrap pieces of a given size to be effective. In addition, furnaces have maximum sizes of scrap that can be successfully fed. Consistent particle size is also essential to the proper functioning of some sorting devices. Some scrap already has the proper size for automated sorting, but most of it does not. *Comminution* is the process by which oversized material is reduced to the proper size for further processing. The comminution of naturally occurring minerals is usually done by crushing it into smaller rocks. However, metal scrap cannot be turned into smaller separate pieces in this fashion. Instead, it must be torn apart. Hundreds of devices have been invented for tearing apart metal scrap. Here, they will be separated into three categories: *shears, impact shredders,* and *rotary shredders.*

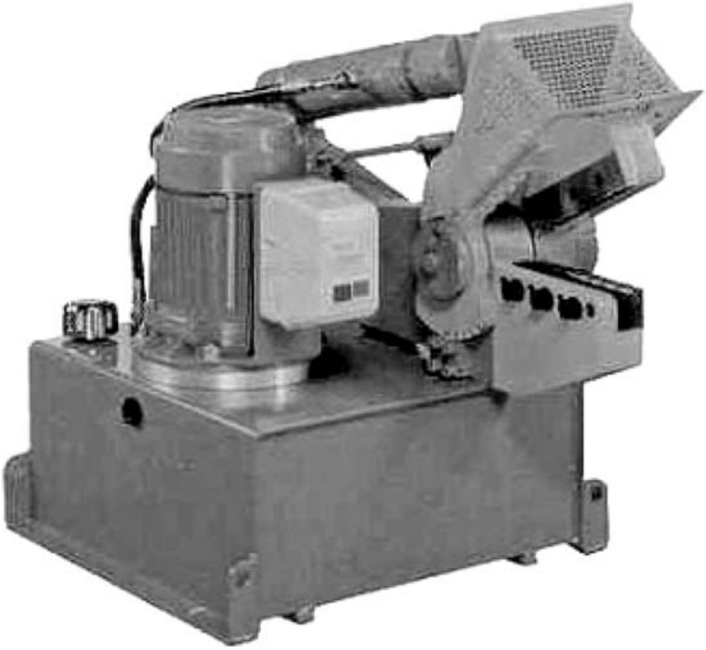


FIGURE 5.1 Alligator shears. (From Ohio Baler Co., http://www.ohiobaler.com/alligator-shear.htm. With permission.)

Most of the shears in operation are either *alligator* or *guillotine* shears. Figure 5.1 shows a typical alligator shears (Fowler, 2003), so named because the hinged cutting motion is similar to that of an alligator's mouth. Only the top portion of the jaw moves during operation. The cutting blade is made of hardened tool steel and can be resharpened when it gets dull. Sizes and power ratings vary according to the size and type of material to be cut.

Alligator shears have been available since the early 1900s. Major changes in the basic design include:

- The use of hydraulic rather than mechanical flywheel drives. Hydraulic drives allow the machine to be stopped immediately to prevent damage to the machine or injury to the operator, a feature not available in flywheel-driven shears.
- The addition of a hold-down clamp to keep scrap pieces still while being cut.
- The addition of guards around the machine to prevent injury to the operators. Alligator shears were notorious safety hazards before the introduction of these guards, which are now mandatory in most countries.

One of the advantages of the alligator shear is its versatility. This is particularly important in the processing of aluminum scrap, which takes a variety of forms. Figure 5.2 shows a crane-mounted shear, used for recovering scrap that cannot be brought to a processing plant. Crane-mounted shears remove aluminum and other

FIGURE 5.2 A crane-mounted shear. (From Harding Metals, Inc., http://hardingmetals.com/company.htm. With permission.)

scrap metals from aircraft, ships, rail cars, and other large objects. Another special type of alligator shear is the nibbling, or metal cleaning, shear, used for detaching small metal attachments such as bolts and collars. Metal-cleaning shears are especially popular for separating steel parts from cable scrap.

Figure 5.3 shows a *guillotine* shear, which operates the same way as the well-known device used for executing people. Scrap is placed underneath a cutting blade,

FIGURE 5.3 A guillotine shear. (From Gershow Recycling, http://www.gershowrecycling.com. With permission.)

which drops down onto the scrap with the help of vertical guide rails. Since scrap is more difficult to chop than human heads, hydraulic power is used to accelerate the blade rather than relying on gravity alone. Guillotine shears have higher productivity than alligator shears and can be built with higher power ratings. As a result, they have replaced alligator shears in many applications, particularly for cutting steel scrap. However, they are less important in the processing of scrap aluminum.

There are literally hundreds of different designs of shredders, and describing all of them would fill a book by itself. The discussion provided here summarizes the more important types. For a more complete description, the reader is encouraged to see other sources, in particular Nijkerk and Dalmijn (1998).

Figure 5.4 shows a cutaway view of an older model *hammer mill,* the most popular type of impact shredder. These were first used for shredding automobiles in the late 1950s (Ness, 1984) and have since become the predominant means for processing auto hulks. They are also used for processing white goods such as refrigerators and ovens and have been adapted to process smaller items as well. The model shown here is used for shredding auto hulks but is similar in function to those used for other purposes.

The description of a hammer mill starts with the rotor assembly. The rotor is several feet long and has a series of "spider" assemblies attached to it. The assemblies

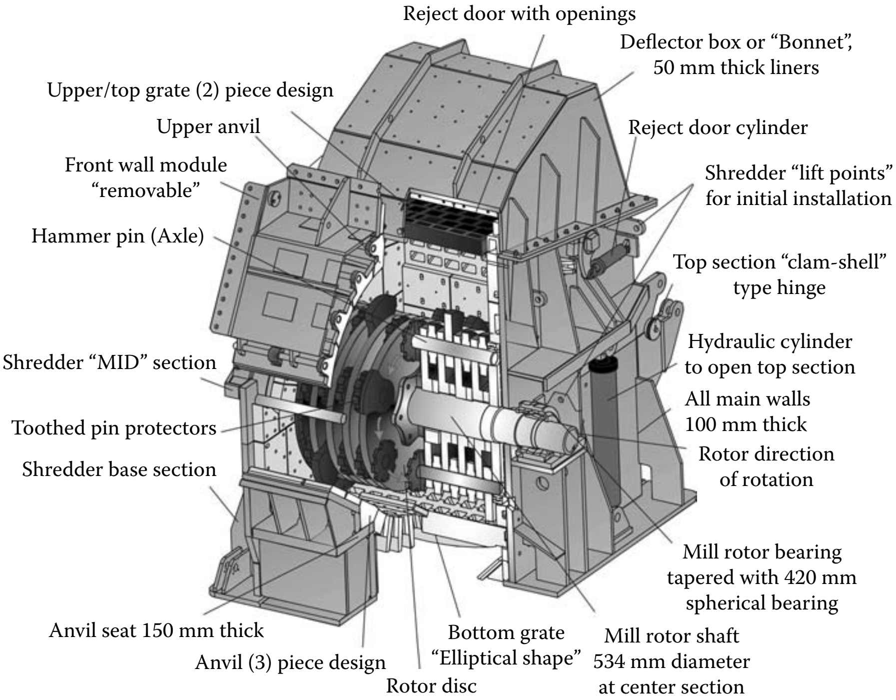


FIGURE 5.4 Exploded view of hammer-mill shredder. (From Metso Texas Shredder. With permission.)

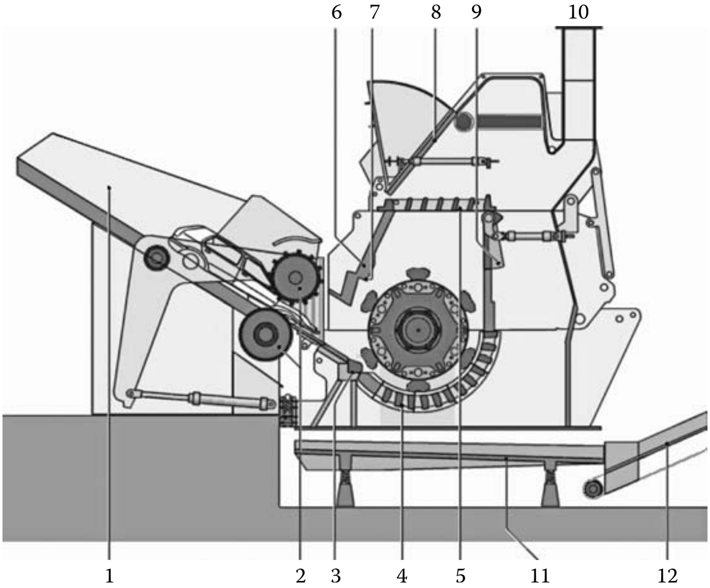


FIGURE 5.5 Cross section of a top-and-bottom discharge shredder. (From Metso Texas Shredder. With permission.)

have wear-resistant steel caps; attached to each cap is a “hammer” made of ductile iron or manganese steel. The hammers weigh 50 to 300 kg depending on the capacity of the hammer mill and are allowed to swing freely as the rotor turns. The rotor turns at 500 to 600 rpm, requiring several thousand horsepower.

Figure 5.5 shows a cross section of a hammer mill. Scrap fed to a hammer mill is first passed through a flattener or compressor (part 2 in the figure). This device (a) increases the density of the feed, which improves the operation of the shredder (Kiser, 2002), and (b) controls the rate at which the scrap is fed to the machine, ensuring steady-state operation. When the scrap enters the main chamber, a breaker bar absorbs the shock. The swinging hammers then engage the scrap, pounding it repeatedly against the anvil or cutter bar (part 3). (Remember the mass of the hammers and the rotor speed.) This action tears the scrap apart, turning it into fist-size chunks that go through the holes in the manganese steel grate (part 4).

Although shredders are extremely powerful machines, occasionally a scrap piece will come through that is too thick or massive to be shredded. The reject door (part 9 in Figure 5.5) allows these pieces to be removed from the shredder before they can damage the machine. Other oversize pieces simply go around and are eventually caught against a baffle plate (part 7). These have a similar function as the anvil and give the hammers another chance to finish the job. A second grate is provided at the top (part 5) to allow shredded material and fluff a second chance to leave the shredding chamber. This reduces the load of returned material and improves shredder capacity.

All shredders generate dust and fine particles during operation. These would be an environmental and workplace hygiene hazard if released. Furthermore, the shredder operation generates heat. If the dust contains organic vapors from vaporizing grease or oil in the scrap, this can result in a significant explosion hazard. Because of this, all shredders have a dust collection system (part 10 in Figure 5.5), operating under negative pressure to draw the dust off. Spraying water into the shredder during operation also helps keep the dust down (Kiser, 2002).

Figure 5.6 shows the cross section of an *impact crusher,* also used to shred large and heavy scrap. The impact crusher is similar to a hammer mill but uses hammers fixed to the spider assembly rather than being allowed to swing freely. A series of breaking surfaces replaces the single anvil in the hammer mill. The impact crusher is used more frequently to crush minerals than metallic scrap and is rarely used for auto shredding.

Hammer mills and impact crushers were designed to shred large pieces of ferrous scrap, such as those in automobiles. As a result, they use tremendous amounts of energy, generate large quantities of fines (particles smaller than 20 mesh, or 0.76 mm) from more easily shredded materials, and are very noisy. For shredding lighter and weaker materials, more cost-effective machines are available. Figure 5.7 shows a double-rotor *rotary shredder* (also known as a *rotary shear*). These shredders are more widely used for processing paper and plastic (Kiser, 2003), but process light metal scrap as well, particularly foil and used beverage containers (UBCs).

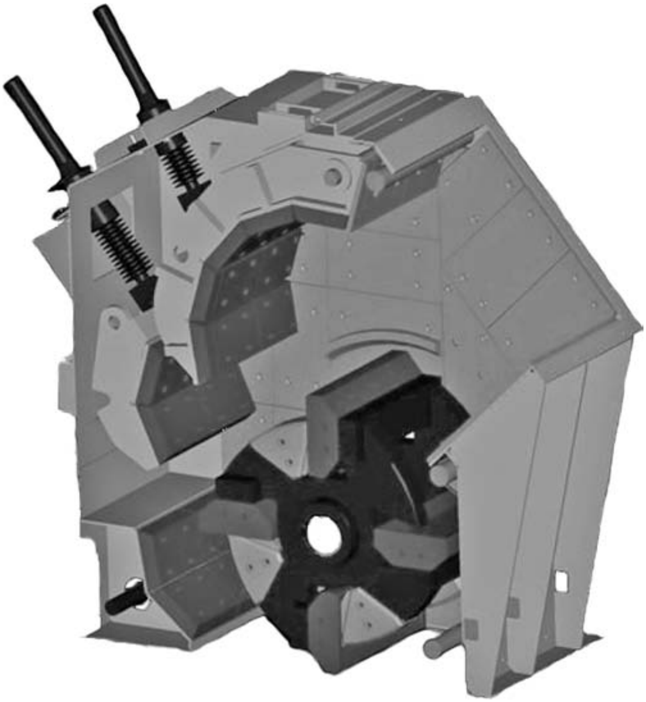


FIGURE 5.6 View of an impact crusher. (From Roc-Impact s.a.r.l., http://www.concasseur.com/crusher01.htm. With permission.)

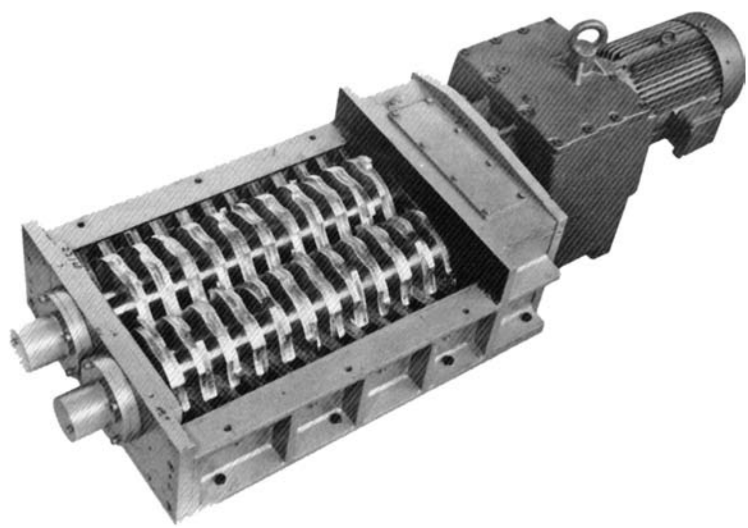


FIGURE 5.7 Double-rotor rotary shear. (From Metso Minerals, http://www.metsominerals.com/inetMinerals/MaTobox7.nsf/DocsByID/F9790232BD1B5BF442256B440047DC5B/$File/1243_RO_EN.pdf. With permission.)

They are also the primary device used for wire chopping to recover metal from cable scrap (Sullivan, 1985). As with impact shredders, many designs are available.

The rotors in a rotary shredder turn in opposite directions. Each has several knife blades attached, such as those shown in Figure 5.8. Each knife blade includes one or more hooks, which grab pieces of scrap and pull them down into the space between

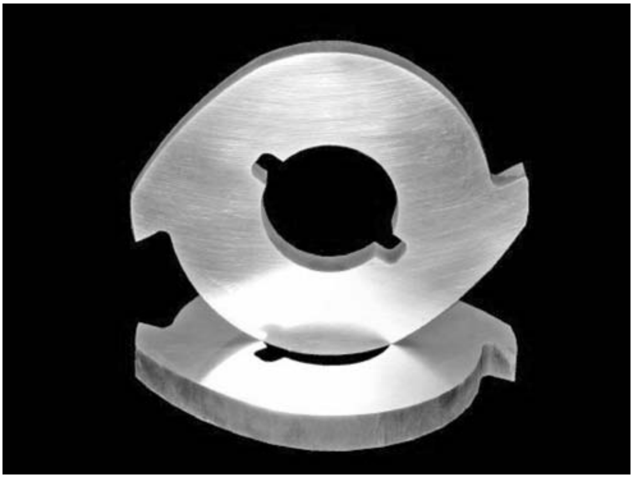


FIGURE 5.8 Knives for a rotary shredder. (From Komar Industries, Inc., http://www.komarindustries.com/pdf/tiger-electro.pdf. With permission.)

TABLE 5.1
Comparison of Shredder Technologies

Measurement	Hammer Mill	Impact Crusher	Contrashear	Monoshear
Shredding action	Impact	Impact	Shear	Shear
Compaction of shredded product	Medium	Medium	High	Low
Size uniformity of shredded product	Poor	Poor	Poor	Good
Generation of fines	High	High	Low	Low
kWh/1000 kg for shredding loose UBC bales to 5-mm pieces	42.0	N/A	88.0	27.0
Cost of electricity (USD/1000 kg @ $0.06/kWh)	$2.78	N/A	$5.82	$1.79
Cost of replacement cutters (USD/1000 kg)	$3.32	N/A	$1.61	$2.82
Total running cost (USD/1000 kg)	$6.10	N/A	$7.43	$4.61
Noise	Poor	Poor	Good	Good

Source: Evans, R.J., in *7th Aust. Asian Pac. Conf. Alum. Cast House Technol.,* Whiteley, P.R., Ed., TMS–AIME, Warrendale, PA, 2001, p. 331. With permission.

the rotors, where the knives slice them into smaller shreds. The shreds fall either directly onto a conveyor that takes them away or onto a screen that makes the return of oversized pieces to the shredder possible. The size of the shreds is determined by the shredder design; increasing the number of rotors decreases the size, as does reducing the rotor diameter. Rotary shredders use either electric or hydraulic drive and can be powered either directly or indirectly.

Rotary shredders substitute high torque and low speed (5 to 50 rpm) for the low torque and high speed of hammer mills. As a result, the power use of double-rotor shredders such as that shown in Figure 5.7 is similar to that of hammer mills. However, the lower speed produces a more uniform product, reduces the generation of dust and fines, and makes shredding much less noisy. The shreds generated by these devices tend to be less wadded up than those coming from a hammer mill; this makes decoating and paint removal more effective. Rotary shredders can also be operated under an inert environment, reducing the risk of explosion. One approach to reducing the high power cost is the use of a single-rotor shredder, in which the metal is held against a stationary plate while being shredded. Table 5.1, taken from the assessment by Evans (2001), compares the use of different shredding devices for UBCs.

SEPARATION

HAND SORTING

As the name suggests, this is the process of going through a feed stream, removing desirable items by hand, and putting them into separate bins for later processing. It was the first method used for sorting garbage or scrap and continues to be popular.

The most widespread use of hand sorting is the initial processing of household waste. The collection of aluminum scrap from this source was described in Chapter 3.

The “blue bag” used to separate recyclables from other garbage is a form of hand sorting. Many cities with municipal recycling facilities (MRFs) perform their own hand sorting once garbage reaches the main processing facility (Glenn, 1991; Sandoval, 2005; Palmer and Nixon, 1999). The material removed from the garbage varies among facilities but almost always includes metal scrap, in particular, copper, brass, and aluminum.

Another common location for hand sorting is the product streams from shredders (Mutz et al., 2003). The magnetic fraction can contain items such as motors and other items with attached contaminants. Removing these items helps reduce impurity levels in the ferrous scrap. The nonmagnetic fraction is also frequently hand sorted, even if other sorting devices are used. This helps remove items of similar density but different composition. An example of this is the pieces of copper wire in aluminum scrap. The plastic or rubber coating of these wires gives them a density similar to that of aluminum, and the conductivity of the copper makes it responsive to eddy-current separation. Hand sorting to remove the wire accomplishes a separation not readily achievable by machine. Separating aluminum from copper wire in cable scrap is also typically a hand-sorting process (Reid, 2001).

Hand sorting is obviously labor-intensive, in addition to being unpleasant and possibly unhealthy work. However, in parts of the world where labor costs are low, it is still a preferred method for scrap sorting. Much of the nonferrous scrap generated by automotive shredding in North America and Europe is sent to China (Schaffer, 2002; Minter, 2003), where hand sorting is less expensive than the automatic processes used in more developed nations. It is still a preferred method for garbage sorting as well (Sandoval, 2005).

Hand sorters use several visual recognition tools to distinguish desirable items in a feed stream (Mutz et al., 2003). Color is the most important, allowing separation of metallic from nonmetallic items and allowing the removal of copper, brass, and lead from other metals. Shape is also important in the sorting of garbage, since tableware is usually made of stainless steel, cans are made of aluminum or steel, plastic milk cartons are produced from high-density polyethylene, and so on. A significant challenge in aluminum recycling is the recovery of aluminum from composite aseptic packaging such as juice boxes. Juice boxes consist mostly of paper and plastic and are not separated from other garbage by methods that depend on density difference or metallic properties. Visual recognition and removal can create a supply of this type of packaging large enough for a separate treatment process.

Hand sorting has limitations. Metal parts that are painted or plated with another metal can be misidentified. Some parts are produced using a choice of alloys, so shape recognition may not be sufficient to segregate by type of metal. Lastly, if labor costs are too high (Sandoval, 2005), the value of recovered materials may not justify the cost of sorting (particularly in MRF operations). As a result, efforts have been made to develop visual-recognition technology that can replace hand sorting (Mutz et al., 2003; Gubeno, 2005). This field is in its infancy.

AIR CLASSIFICATION

Metal scrap often contains high levels of low-density impurities. Municipal waste consists mostly of waste paper and plastic. The shredder fluff from auto shredding contains small amounts of metal and large amounts of organic material from the carpets, dashboard, and so on. A more recent source of scrap metal is electronic scrap (Sum, 1991), in particular, circuit boards. These consist mostly of plastic, which must be separated from the metal.

When the fraction of low-density material in the raw material is much higher than that of the metal to be recovered, air classification devices become useful. These devices use an upward flow of air to lift the paper and plastic away from the metal. A large number of air classifiers have been developed; the reader is encouraged to see Nijkerk and Dalmijn (1998) for a complete listing. Two of the more important will be described here.

Figure 5.9 illustrates a *zig-zag* vertical air classifier, widely used for processing municipal solid waste. Air blown in through the bottom pushes low-density material up and out, while allowing higher-density metal scrap to fall to the bottom. The zig-zag design improves efficiency by agitating the contents. This keeps paper and metal

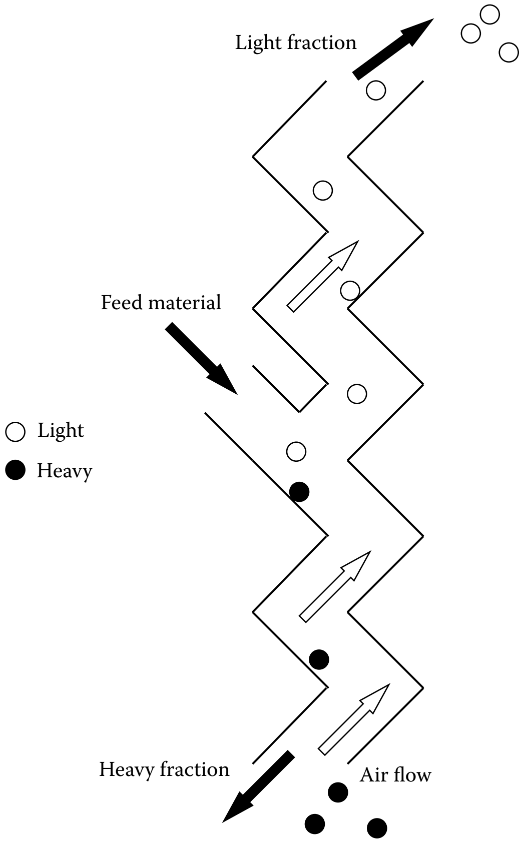


FIGURE 5.9 A zig-zag air classifier. (From Nijkerk, A.A. and Dalmijn, W.L., *Handbook of Recycling Techniques,* Nijkerk Consultancy, The Hague, The Netherlands, 1998. With permission.)

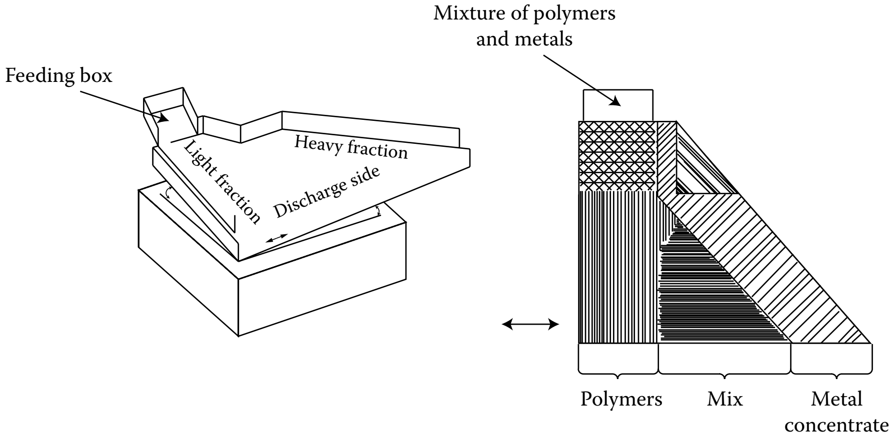


FIGURE 5.10 An air table. (From Nijkerk, A.A. and Dalmijn, W.L., *Handbook of Recycling Techniques,* Nijkerk Consultancy, The Hague, The Netherlands, 1998. With permission.)

pieces from sticking together or blocking each other's path. Zig-zag classifiers have also been used for metal recovery from auto shredder fluff (Phillips, 1996).

Figure 5.10 depicts an *air table,* widely used for metal recovery from shredded wire and cable (Sullivan, 1985; Phillips, 1996). This material has a small particle size and thus needs to be processed more gently than the large pieces fed to vertical air classifiers. Unseparated material fed in the box at the top left is gently shaken as it moves along the sloping table toward the discharge at the far end. At the same time, air blown through small holes in the table lifts the lighter plastic and rubber in the feed, moving it toward the near side of the table. Metal scrap is less affected by the air and continues toward the far end. Collecting separate fractions from opposite sides of the discharge end produces two concentrates. A third *middlings* fraction, with too much plastic and metal to use as either fraction, is recycled to the feed box for another try. Shredded electronic scrap is also separated using air tables (Sum, 1991).

MAGNETIC SEPARATION

This is one of the simplest steps in the upgrading of aluminum scrap. Its purpose is to remove the iron and steel and nickel-based alloys if any are present. A wide variety of separators are available for performing this task (Steinert, Inc., n.d.); the most common are *drum magnets* and *overhead belt magnets* (Figure 5.11). A drum magnet features a stationary magnet around which a drum rotates. Nonmagnetic material falls off the drum and is collected on a conveyor running below; magnetic material sticks to the drum and continues to do so until the drum rotates past the field generated by the magnet. Then it too falls off and is removed by a separate conveyor. In a belt magnet the drum is replaced by a conveyor belt running over the stationary magnet. Magnetic particles are pulled off a conveyor running below this assembly by the magnetic field and stick to the upper belt. When this

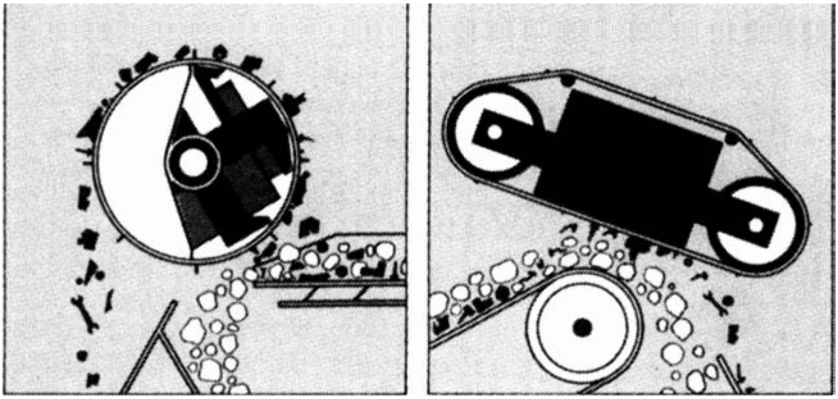


FIGURE 5.11 Drum and overhead-belt magnetic separators. (From Nijkerk, A.A. and Dalmijn, W.L., *Handbook of Recycling Techniques,* Nijkerk Consultancy, The Hague, The Netherlands, 1998. With permission.)

belt moves away from the magnetic field, the magnetic particles drop off and are collected on a separate conveyor. Nonmagnetic particles are unaffected by the magnet and remain on their original conveyor belt.

Figure 5.12 shows a typical strategy for magnetic separation of auto shred (Ness, 1984). In this case the magnetic fraction from a drum separator drops onto a conveyor belt that carries it under a second drum separator. The purpose is to clean the magnetic material of any paper or other nonmagnetic material that might have

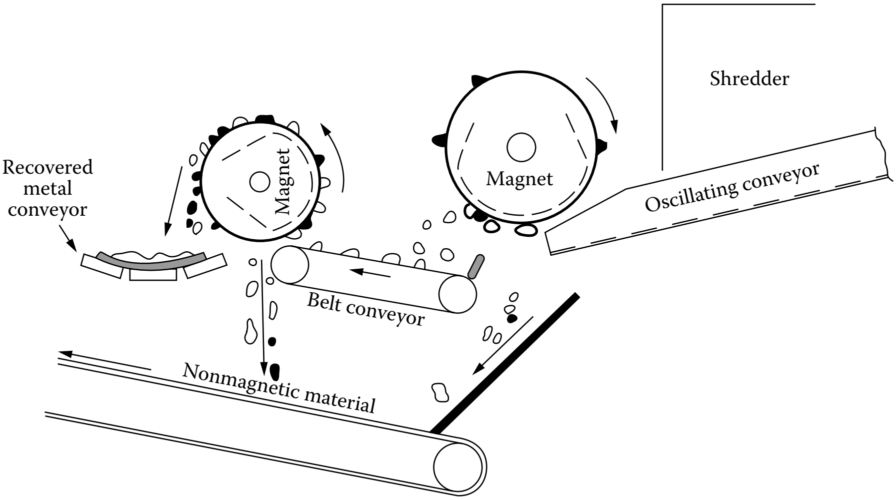


FIGURE 5.12 Magnetic separation of auto shred. (From Ness, H., in *Impact of Materials Substitution on the Recyclability of Automobiles,* ASME, New York, 1984, p. 39. With permission.)

inadvertently stuck to it when it was pulled onto the first drum. In plants trying to remove the ferrous impurity from the nonferrous fraction (such as UBC recyclers) it is the nonferrous fraction instead that is passed under a second magnet for cleaning. Iron contamination of scrap aluminum is increasingly unacceptable, so aluminum scrap may wind up being passed under magnetic separators both during upgrading and before charging to a furnace for remelting.

EDDY-CURRENT SORTING

Figure 5.13 illustrates a conductive particle (such as a piece of scrap) entering the magnetic field generated by a permanent magnet. The magnetic field causes an electric current to flow in the conductive particle (Dalmijn, 1990). This current is known as an *eddy current.* The magnitude of the current is determined by the strength of the magnetic field, the electrical conductivity of the particle, and the size and shape of the particle. The eddy current in turn generates a secondary magnetic field around the particle, aligned with the primary magnetic field generated by the permanent magnet.

When this particle passes into the magnetic field generated by a magnet of reverse polarity, the secondary magnetic field is now opposed to the primary magnetic field. This creates a repulsive *Lorentz force* that flips the particle and realigns it with the new primary magnetic field (Meier-Staude et al., 1991). As the particle flips, it deflects from its original direction (Ness, 1984; Phillips, 1995). The degree

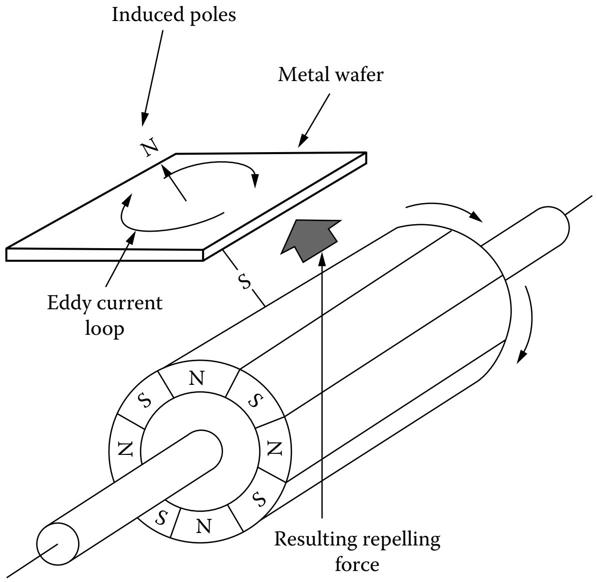


FIGURE 5.13 Formation of eddy currents by alternating magnetic fields. (From Walker National, Inc., http://www.walkermagnet.com/mag/separation/recovery/eddysep.htm. With permission.)

TABLE 5.2
σ/ρ for Various Materials

Material	σ/ρ (M^2/Ω-kg · 10^3)
Aluminum	14.0
Magnesium	12.9
Copper	6.7
Silver	6.0
Zinc	2.4
Gold	2.1
Brass	1.8
Tin	1.2
Lead	0.45
Stainless steel	0.18
Glass	0.0
Plastics	0.0

to which it deflects is determined by several factors, but the most significant is the material itself. Table 5.2 lists several materials according to their value of σ/ρ, where σ is the electrical conductivity and ρ is the density. Aluminum and magnesium have high conductivity and low density. This means they can be easily deflected from a given path by passing them through a series of magnets of alternating polarity. Copper is also very conductive, but its density is much higher. As a result, a piece of copper scrap is less affected by alternating fields. Stainless steel is less affected still. This is important, since stainless steel is not easily distinguished by aluminum by hand sorters and is also not removed by magnetic separators. Finally, plastic and paper are nonconductors, and thus are unaffected by magnetic fields. Changing magnet polarities will have no effect on them at all.

Figure 5.14 shows the design of an early linear-motor type of eddy-current separator (ECS) Ness, 1984; Dalmijn, 1990). The separator consists of a series of permanent magnets of alternating polarity placed on top of each other at an incline. The stack of magnets is then inclined, and raw material (mixed scrap, municipal garbage) is allowed to fall down the incline. High-σ/ρ pieces deflect the most from a vertical path and are collected as group III. Low-σ/ρ metallic pieces are deflected less and are collected as group II. Nonconductors fall straight down the incline, and are collected as group I. Separators like these were among the first to be used for treatment of scrap and garbage in the early 1980s. However, they have several disadvantages (Dalmijn, 1990). The large number of magnets required makes them expensive to construct. More importantly, any ferromagnetic particle that might have escaped the magnetic separator will immediately stick to the first magnet when it enters the ECS. This will eventually clog the separator, requiring operations to be suspended while the ferrous pieces are removed.

Figure 5.15 illustrates a better approach for eddy-current separation. Feed is placed on a conveyor, which passes over a rotating drum containing permanent magnets arranged in alternating polarity. As the particles on the conveyor belt pass over the

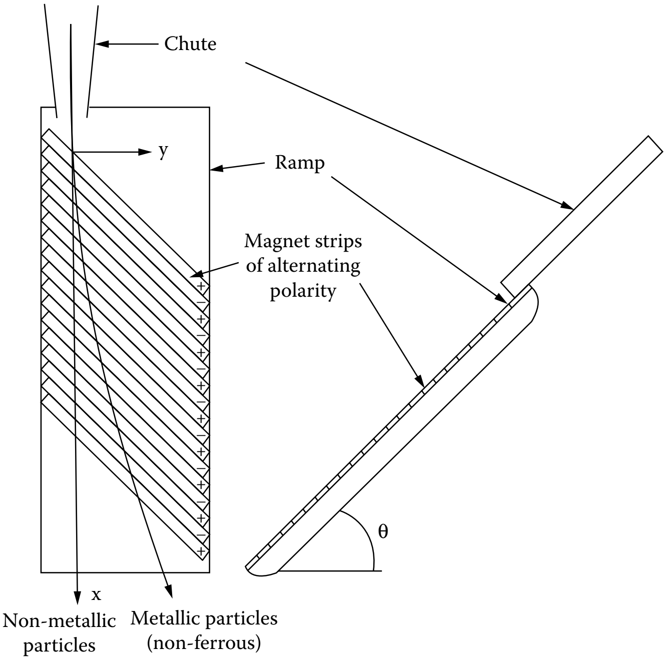


FIGURE 5.14 A linear-motor ECS. (From Ness, H., in *Impact of Materials Substitution on the Recyclability of Automobiles,* ASME, New York, 1984, p. 39. With permission.)

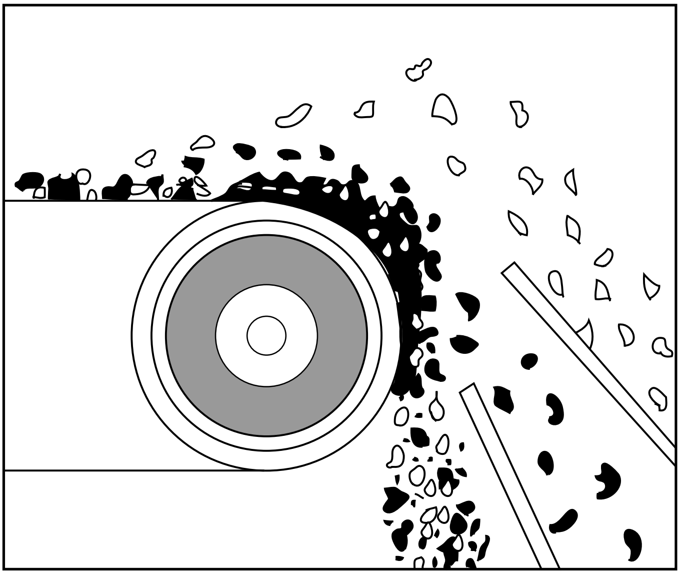


FIGURE 5.15 Conveyor-type eddy-current separator. (From Global Equipment Marketing, Inc., Magnetics Division, http://www.globalmagnetics.com/link7.html. With permission.)

magnets, the same sort of deflection occurs as on the linear-motor separator. However, in this case the deflection causes conductive particles to fly off the end of the conveyor; the higher the value of σ/ρ, the farther the particle goes. Nonconducting particles, or those with a low value of σ/ρ, simply fall off the end of the conveyor. Ferrous particles stick to the magnet as before, but as the conveyor moves them away from the drum these particles fall off, eliminating the need to clean them off the belt.

In addition to the material, other factors influence how far particles fly off the end of a conveyor-type ECS (Reid, 2002):

- *Field strength of the magnets.* Larger magnets improve the separation efficiency of an eddy-current unit but add to the cost.
- *Mass of the particles.* Larger particles generate larger eddy currents, which generate larger secondary magnetic fields, which results in larger Lorentz forces. As a result, larger pieces of aluminum will fly farther than smaller ones. ECS works best when handling uniform-sized feed.
- *Particle shape.* The more nonspherical the particle, the more eddy current is generated. As a result, a piece of foil will fly farther than a ball bearing of equivalent mass.
- *Particle bulk density.* Hollow pieces have a larger equivalent "size" than bulkier particles. As a result, using an ECS to separate UBCs requires weaker magnets than needed for separating aluminum castings.

The conveyor-type separator shown in Figure 5.15 is sometimes known as a *Lindemann* ECS, after the company that first introduced it (Dalmijn, 1990). It is the most widely used type of ECS, but it has one significant disadvantage. Ferrous pieces that happen to drop to the inside of the belt will stick to the drum as it rotates. Squeezed between the belt and drum, these pieces will eventually penetrate the drum and wedge between the drum and the rotating magnets, causing considerable damage. Figure 5.16 compares the Lindemann design with the more recent Steinert ECS (Phillips, 1995; Steinert, Inc., n.d.). In units of this type the rotating magnets are mounted nonconcentrically to the conveyor pulley. This leaves a gap at the bottom between the pulley head and the support drum for the magnets. Ferrous pieces landing on the inside of the belt are pulled away by the conveyor, improving the likelihood that they will eventually fall off before causing any damage.

Figure 5.16 also illustrates an alternative way of arranging the magnets in an ECS. Most units use the arrangement shown in the bottom left, in which magnets of reverse polarity are alternated. However, a more recent design by Huron Valley Steel Corp. (bottom right) rotates the polarity by 90° in each adjacent magnet, rather than 180°. This produces a stronger magnetic field at the surface and a sinusoidal field pattern that improves the performance of the separator.

The biggest limitation of ECS has been particle size. For the most part, scrap pieces smaller than 10 mm cannot be sorted using conventional devices. This makes their use difficult in treating shredded electronic scrap. A series of possible solutions have been tested. These include operating the ECS under a water flow, rotating the magnets in a direction opposite to that of the pulley, running the conveyor underneath the rotating magnet drum (Meier-Staude et al., 1991), and new High-Force® ECS units

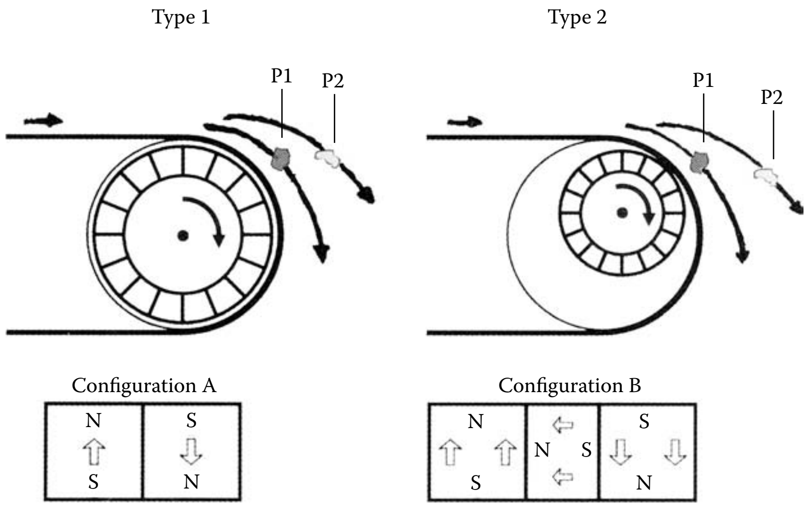


FIGURE 5.16 Conventional and HVSC magnet arrangements for ECS. (From Nijkerk, A.A. and Dalmijn, W.L., *Handbook of Recycling Techniques,* Nijkerk Consultancy, The Hague, The Netherlands, 1998. With permission.)

(Zhang et al., 1998). Another possible improvement in ECS would be the development of units using electromagnets, rather than the rare-earth permanent magnets currently used (Dalmijn, 1990; Phillips, 1995). Electromagnets would be lighter and less expensive, and easily adjusted to change the strength of the field as conditions warrant.

Over the past 10 years the conductivity of metals has led to a second separation technology for separating metals from nonmetals in a scrap stream. *Induction separation* uses the same principle as the metal detector used for finding small metal objects on the ground. A copper transmission coil surrounds smaller receiving coils as scrap passes over (or under) it. When metal passes the coils, the receiver coils generate a signal proportional to the size and conductivity of the particle. Figure 5.17 illustrates how this is used to upgrade scrap streams (Steinert, Inc., n.d.). By using the signal from the receiver coils to actuate air jets, metallic scrap can be blown off of the conveyor and separated from nonconducting paper and plastic. Induction separation is not used to separate aluminum from other metals, but by separating metals from nonmetals, it improves the operation of ECS and heavy-media separation units. Its sensitivity also allows the recovery of small (>2 mm) particles that might otherwise be lost and cannot be detected by hand pickers. This helps in the cleaning of metal from shredder fluff and waste plastic streams, in addition to recovering additional metal.

HEAVY-MEDIA SEPARATION (HMS)

Table 5.3 lists the densities of aluminum and common contaminants in aluminum scrap. A simple way of separating these materials from the aluminum is to put the mixed scrap in a fluid with a density between that of aluminum and the contaminant

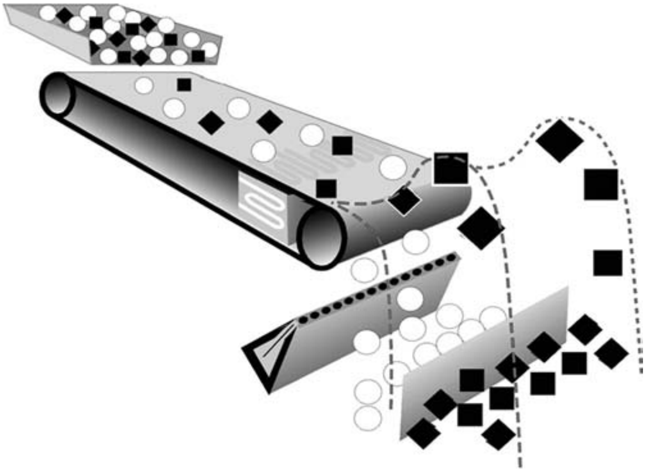


FIGURE 5.17 Induction sorting system for metal separation from nonmetallic feed. (From Steinert Elektromagnetbau GmbH on-line brochure, http://www.steinert.de/uploads/media/Induktions-sortiersystem.pdf. With permission.)

(Ness, 1984). Materials with a density less than that of the fluid will float, while those denser than the fluid will sink. HMS involves the creation of "designer fluids" to allow such separations. There are three types of fluid.

The first type is water (specific gravity = 1.0). All metals and some plastics have densities higher than 1.0, but wood, paper, shredder fluff, and most plastics are lighter than water and will float. Municipal recovery facilities often use water-based separation devices to separate a metal-rich fraction from other garbage. Figure 5.18 shows a *rising current separator,* or *water classifier,* in which water pumped up through a column floats a low-density fraction that overflows at the top (Ness, 1984;

TABLE 5.3
Densities of Aluminum and Contaminant Metals

Material	Density (g/cm^3)
Aluminum	2.7
Copper	8.97
Silver	10.5
Zinc	7.14
Lead	11.3
Tin	7.28
Brass	8.4
Stainless steel	7.9
Magnesium	1.87

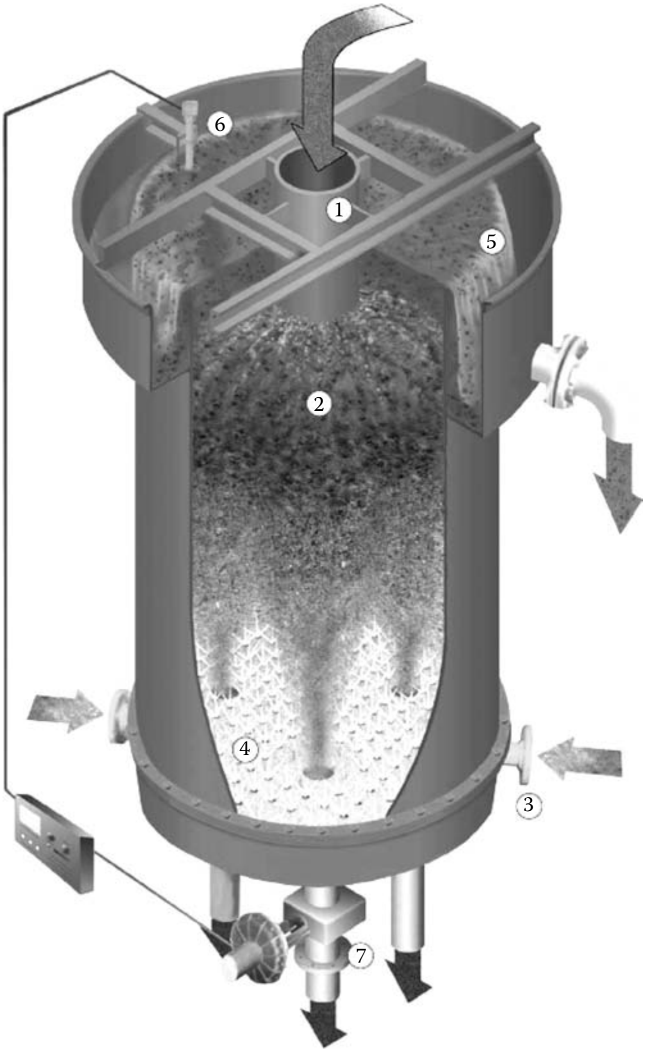


FIGURE 5.18 A rising-current hydraulic separator. (From LPT Group, Inc., http://www.lptgroupinc.com/ pdf/lpt_litesoutclassifier.pdf. With permission.)

Phillips, 1996) and recovers a high-density fraction from the bottom. Water-only HMS is rare for scrap with a high metal content.

The addition of a dissolved salt can create fluids with specific gravities higher than 1.0 (Phillips, 1996). Calcium chloride, calcium nitrate, and potassium carbonate are frequently used for this purpose. The resulting solution has a specific gravity higher than that of polyvinyl chloride (PVC), the plastic most commonly used to coat wires. As a result, dissolved-salt solutions are most commonly used in wire-chopping operations. Dissolved-salt solutions with a specific gravity higher than that of magnesium are difficult to prepare. Because of this, these solutions are limited to separating nonmetallics from metals in the feed material.

The most common type of fluid is a suspended-solid slurry (Wills, 1997; Novelli, 2000), in which small particles of a dense solid are suspended in water. The solid is usually either ferrosilicon (84% Fe, 16% Si) or magnetite (Fe_3O_4). These materials are ferromagnetic, which allows them to be easily removed from the solution. They are also inexpensive, corrosion resistant, and nonhazardous to the environment if lost or disposed of. By adding different levels of ferrosilicon or magnetite, the specific gravity of the suspension can be varied to values greater than 3.0. This allows the industrial use of two heavy-media suspensions (Yamamoto, 1991). The first, with a specific gravity of about 2.0, separates aluminum and heavier materials from the magnesium, plastic, and other light materials in the feed stream. The second, with a specific gravity higher than 2.4, recovers aluminum in the floats while other metals remain in the sink fraction.

Figure 5.19 shows a typical drum separator used for HMS. HMS is widely used for recovering aluminum from mixed scrap (Schaffer, 2002), but it has disadvantages (Yamamoto, 1991):

- Sludge and dirt in the feed can affect the specific gravity of the suspension, making it difficult to control.
- Composite materials with intermediate specific gravities may report to the wrong fraction. An example is plastic-coated copper wire, which has an overall specific gravity low enough to be confused with aluminum.
- As a wet process, HMS requires drying of the products following separation. It also requires washing the media off the product and recovering it, an additional capital expense.
- The loss of suspension media with the product may be a source of contamination. This is a particular problem if minimizing the iron content in aluminum scrap is important. Media lost in the product also has to be replaced, which increases operating costs.

Because of this, efforts have been made to develop a dry heavy-media system to replace the suspensions (Phillips, 1996; Novelli, 2000). The dry system uses a fluidized bed of sand, kept in motion by electric vibrators. By varying the type of

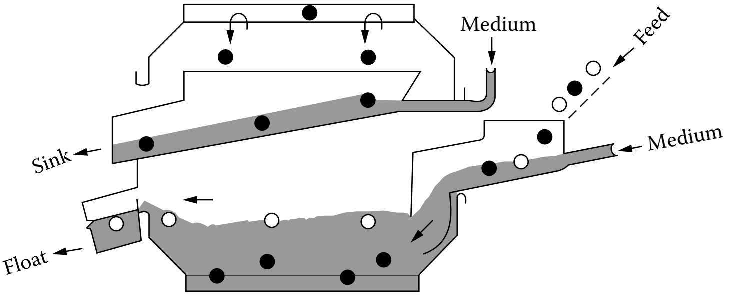


FIGURE 5.19 A drum-type heavy-media separator. (From Sepor, Inc., http://www.sepor.com/new/HeavyMed.pdf. With permission.)

sand used, the specific gravity of the bed can be varied between 2.3 and 4.6. Scrap fed to the fluidized bed sinks or floats according to its specific gravity. Dry HMS is not useful for separating aluminum from lighter materials but can be used to separate it from heavier metals. Whether this approach is cost-effective is still uncertain.

THE ALLOY SEPARATION PROBLEM

In Chapter 2 the concept of alloy tolerance was introduced. Tolerance is the ability of an alloy to absorb different grades of scrap during its manufacture, rather than requiring the use of primary metal. The tolerance of most wrought aluminum alloys is low. Most alloys have too much copper, iron, silicon, or zinc to be used to any extent as scrap for preparing wrought alloys outside their original class. The higher alloy content and higher impurity limits of cast alloys, in particular 380, give them much greater tolerance than wrought alloys. As a result, the vast majority of scrap processed by secondary smelters is used to produce cast alloys.

However, the changing nature of the aluminum marketplace makes this pattern of recycling difficult to sustain. Several estimates claim that the rate at which wrought alloys are used in automotive and other transport applications will grow at a much faster rate than that of cast alloys (Rosenfeld et al., 1995; Le Guern et al., 1999; Gesing et al., 2003). Furthermore, the other areas in which aluminum use will increase are all sectors where wrought alloys are used. As a result, there is a need to make scrap more usable for producing wrought alloys than is currently possible. Since the tolerance of wrought alloys will decrease in the future as maximum allowable contents of iron and other impurities are reduced, the only two ways of making scrap more usable are (a) developing cost-effective technologies for removing excess alloying elements from molten aluminum and (b) finding a way to separate aluminum alloys from each other during the upgrading process. Attempts to achieve the first goal are described in Chapter 12. Efforts to achieve the second goal are described here.

The first research efforts aimed at sorting aluminum scrap by alloy centered around efforts to separate cast scrap from wrought in shredded mixed alloy scrap. While this does not help make the production of wrought alloys from scrap more viable (since the wrought alloy portion of the scrap is still mixed), it does help make production of casting alloy from scrap easier. The reason is that wrought-alloy scrap often has more magnesium than most casting alloys allow (Gesing et al., 2003). While excess magnesium can be removed from molten aluminum, the process is time-consuming and expensive. Removing 5xxx and 6xxx wrought scrap from the cast-alloy material in mixed scrap could be a less expensive approach. There are several possible ways to distinguish pieces of shredded cast scrap from pieces of wrought alloy (Gesing et al., 2002):

- Cast aluminum alloys tend to have lower solidus (initial melting) temperatures than wrought alloys, causing them to weaken earlier when heated. U.S. Bureau of Mines researchers developed a *hot-crush* technique based on this to crush cast scrap into smaller pieces (Ambrose et al., 1983), which could then be screened away from the larger wrought scrap. The process (and its ultimate lack of success) is described more completely later in this chapter.

- To the trained eye, shredded cast aluminum scrap looks different than wrought-alloy shred (de Jong et al., 2000, 2001). The cast scrap is less shiny than the wrought, and the pieces are more angular. Hand-sorting can be used to separate cast scrap pieces from wrought with reasonable efficiency (Gesing et al., 2001). Attempts have been made to develop automated image-analysis systems to perform this task in place of the trained eyes.
- X-ray scanning of mixed scrap discriminates between particles based on composition. Heavy metals (copper, lead) block X-rays more effectively than low–atomic number elements such as aluminum and magnesium. There has been some success in discriminating between cast-aluminum-alloy scrap pieces and wrought-alloy pieces as well (de Jong et al., 2001). Cast-alloy pieces have more silicon and copper, and thus appear slightly darker in X-ray transmission images.
- It has long been known that the application of various acids and bases to the surface of aluminum alloys changes the color of the surface, depending on the particular alloy. In particular, treating the surface of cast alloys with sodium hydroxide turns them black, while most wrought-alloy surfaces turn light grey (de Jong et al., 2000). A more recent discovery is that even those wrought-alloy surfaces that do turn black when exposed to sodium hydroxide will lighten when subsequently treated with nitric acid (Le Guern et al., 1999). Cast-alloy surfaces remain black.

Based on these findings, a few commercial separation facilities have tried to produce separate cast- and wrought-alloy streams from mixed aluminum scrap (Gesing et al., 2001). Details are difficult to come by, but it is likely that more such processes will operate in the future.

Separating wrought alloys in scrap from each other is even more difficult, since the distinctions that make separation of cast material from wrought possible are of no further use. One of the remaining possibilities is color etching. Exposure to strong sodium hydroxide solutions has no effect on 5xxx and some 6xxx alloys (Wyss and Schultz, 1999; Gesing et al., 2002), but colors 2xxx/6xxx (dark gray), 3xxx (light gray), and 7xxx (black) alloys. When heat-dried, 2xxx alloys take on a gold hue and 3xxx alloys become brown, making them even more distinct. The hope has been that the color distinctions are sufficient to allow separation using a commercial color sorter, similar to those used to separate different colors of waste glass. Table 5.4 shows the results of color separation experiments from sodium hydroxide–etched pieces of aluminum scrap. These experiments demonstrate that some separation is possible, but not at sufficient levels to generate clean product streams. Color separation presents other concerns. Painted or coated scrap does not respond well to the technique, and the need for a sodium hydroxide solution generates a potential plant safety hazard.

In the past decade a new approach to alloy separation has been developed that has better potential. Laser-induced breakdown spectroscopy (LIBS) involves illuminating a spot on a piece of scrap with a focused laser beam (Gesing et al., 2003).

TABLE 5.4
Recovery of Different Alloys to Color-Separated Product Streams after Sodium Hydroxide Etching

	% Recovery			
Alloy	**Product 1 (Bright)**	**Product 2 (Light Gray)**	**Product 3 (Gray)**	**Product 4 (Dark)**
5182	100			
4147		100		
6061		70	30	
3003		28	72	
6111	10	20	70	
7129	10	20	70	
7016		30	70	
2036			20	80
7003				100

Source: Gesing, A. et al., in *Aluminum 2002,* Das, S.K. and Skillingberg, M.H., Eds., TMS–AIME, Warrendale, 2002, p. 3. With permission.

This causes the scrap surface to fluoresce. Optical emission spectroscopy (OES) of the fluorescence photons is used to produce a quantitative analysis of the alloy composition, which is then compared with alloy specifications. Once identified by alloy, the scrap piece can then be diverted to the proper scrap bin, separating it from scrap of differing compositions.

LIBS analysis of various aluminum alloys (Gesing, 2003) compared the measured percentages of zinc, copper, silicon, manganese, and magnesium with the specific range of the particular element in the alloy. The results showed that this approach works reasonably well in determining the composition of the alloys. However, the analysis also demonstrated the need for considerable care in surface preparation of the scrap to get the right result. Surfaces need to be free of paint to avoid analyzing the paint instead of the alloy. They also need to be decoated, since some coatings (such as zinc phosphate) contain alloying elements. Calibration of the detector is also vital to getting accurate results.

In practice, LIBS analysis of the scrap surface involves hitting it twice with a laser (Gesing et al., 2003). The first shot vaporizes away paint and coatings, generating a clean surface for the second shot. Particles are presented to the laser one at a time, at an average rate of 40 per second. LIBS processing is performed on shredded scrap with a fairly uniform particle size and mass (20 to 50 g). This allows processing of 3 to 6 tonnes per hour. Figure 5.20 shows the layout of a proposed scrap sorting facility using cast–wrought separation followed by LIBS analysis and separation of the wrought fraction (Rosenfeld et al., 1995). The first industrial facility of this type was recently commissioned by Huron Valley Steel Corp. in the United States.

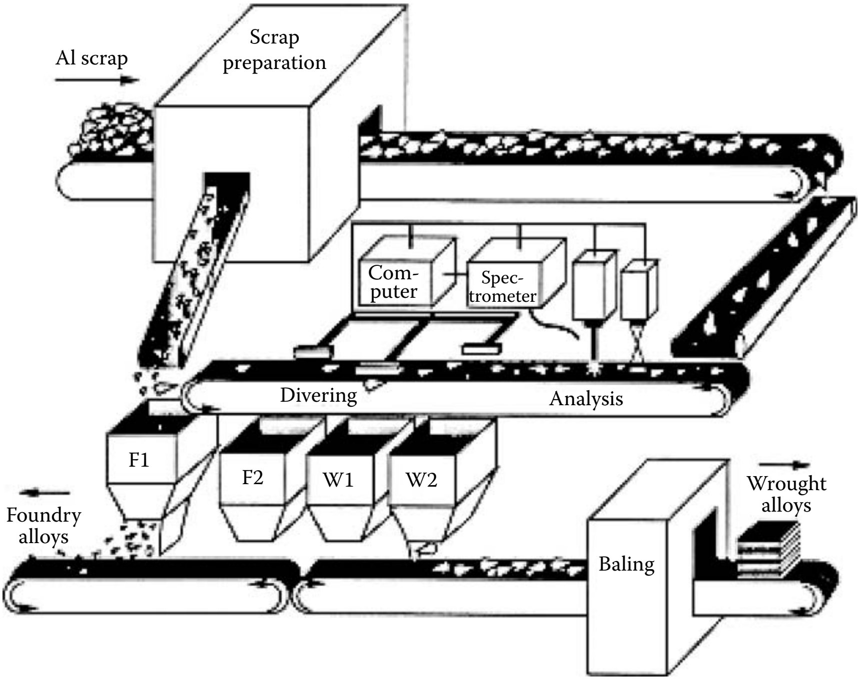


FIGURE 5.20 Scrap sorting facility for separating aluminum scrap by type (cast or wrought) and wrought-alloy family. (From Rosenfeld, A., Gesing, A., and Farahbakhsh, B., in *3rd Int. Symp. Recycl. Met. Eng. Mater.,* Queneau, P.B. and Peterson, R.D., Eds., TMS–AIME, Warrendale, PA, 1995, p. 751. With permission.)

THERMAL PROCESSING

DECOATING

Aluminum and its alloys often come coated with an organic material of some sort. A variety of lacquers and polymers are used to coat extruded material, most notably can stock and foil. 2xxx and 7xxx alloys are often painted, and turnings and borings from machining operations bring with them substantial levels of grease and oil. Table 5.5 lists the coatings of different aluminum products (Evans, 2001) and the weight fractions of the products consisting of organic material.

Typical practice until the 1980s was to charge coated or oily material directly into the melting furnace along with the rest of the scrap. This had several harmful effects (McAvoy et al., 1990):

- The organic material would burn upon being charged to the furnace. The resulting smoke and soot was a workplace health hazard and difficult to remove from the plant off-gas.

TABLE 5.5
Scrap Types and Their Coatings

Scrap Type	Coating/Structure	Coating Wt. (%)
Aerosols	Lacquers, paints	2–3
Capstock	Polymers, lacquers	30
Converted foil	Inks, lacquers	7
DSD (flexible packaging)	Various	<85
Epoxy strip	Epoxy, paint	6
Frag	Oil, paint, polymers	<4
Lid stock	Vinyls	8
New lithographic plate	Phenolic resin, paper	<4
Mill foil	Rolling oils	<10
Paper laminate	Paper, inks	50–60
Plastic laminate	Polymers, inks, wax	40–90
Painted sidings	Paints	3
Tube laminate	Polymers, lacquers	70
Turnings	Cutting oils	<20
UBC/new can stock	Lacquers, paints	2–3
Used lithographic plate	Phenolic resin, inks	2
Window frames	Thermolacquers, resins	21

Source: Evans, R.J., in *7th Austr. Asian Conf. Alum. Cast House, Technol.,* Whiteley, P.R., Ed., TMS–AIME, Warrendale, PA, 2001, p. 331. With permission.

- The burning coating heated the metal underneath, causing it to oxidize as well (Rossel et al., 1997). Figure 5.21 shows the melt loss from various types of coated and uncoated scrap charged directly to a furnace (McAvoy et al., 1990). It can be seen that painted or lacquered scrap oxidizes more than bare scrap regardless of alloy. Melting under a salt flux helps somewhat, but melt losses from laminated material are still over 5%.
- In addition to soot and smoke, other troubling emissions from the burning coating included dioxins and furans. Dioxins and furans were more likely to form as the temperature rose and are considered especially dangerous in even minute quantities (Wei, 1996).

Because of this, coated or oily scrap became unwanted material in some secondary smelters and foundries. UBCs were especially unpopular (van Linden, 1994), since they were difficult to submerge in the melt and even more likely to be a high melt-loss material. However, the growing popularity of aluminum beverage cans and the development of specialized facilities to recycle them encouraged research into finding better ways of removing oil and lacquer from scrap surfaces.

A decoating process has several goals:

- Complete removal of the organic material from the scrap surface
- Minimized oxidation of the scrap surface

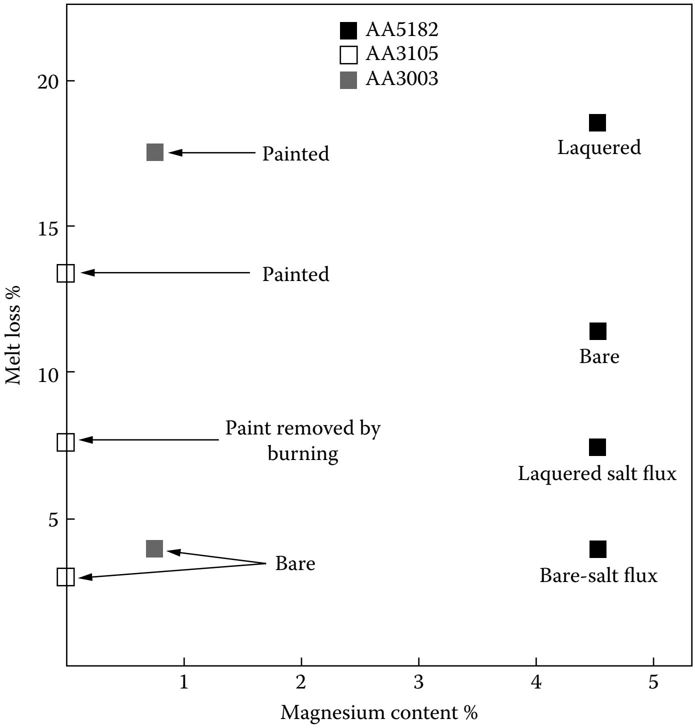


FIGURE 5.21 Effect of alloy type and coating on melt loss in fluxed and flux-free remelting. (From McAvoy, B., McNeish, J., and Stevens, W., in *2nd Int. Symp. Recycl. Met. Eng. Mater.,* van Linden, J.H.L., Stewart, D.L. Jr., and Sahai, Y., Eds., TMS–AIME, Warrendale, PA, 1990, p. 203. With permission.)

- Low emissions of harmful byproducts, such as VOCs (volatile organic compounds), dioxins/furans, and NO_x (nitrous oxides)
- Use of the fuel value of the organic material to make the process *auto-thermal,* capable of supplying its own energy needs
- Minimal capital and operating cost

Figure 5.22 (Kvithyld et al., 2002) illustrates the results of thermogravimetric analysis (TGA) of lacquered aluminum scrap as it is heated in a low-reactivity environment (Ar + 1% O_2). The bottom curve shows the weight decrease of the sample as the lacquer is decomposed to form gaseous species; the top curve shows three peaks representing the thermal effects of chemical reactions. The first of these peaks is thought to represent the breaking of the polymer chains from which the coating is formed. The second peak is the formation of VOCs. Mass spectrometric analysis of the off-gas from inert-atmosphere decoating of scrap reveals a large number of organic compounds; the most significant are benzene, toluene, phenol, styrene, benzaldehyde, dioctylphthalate, and bisphenol-A (Roussel and Gaboury, 1987). The formation of VOCs leaves a residue on the surface known as *char.*

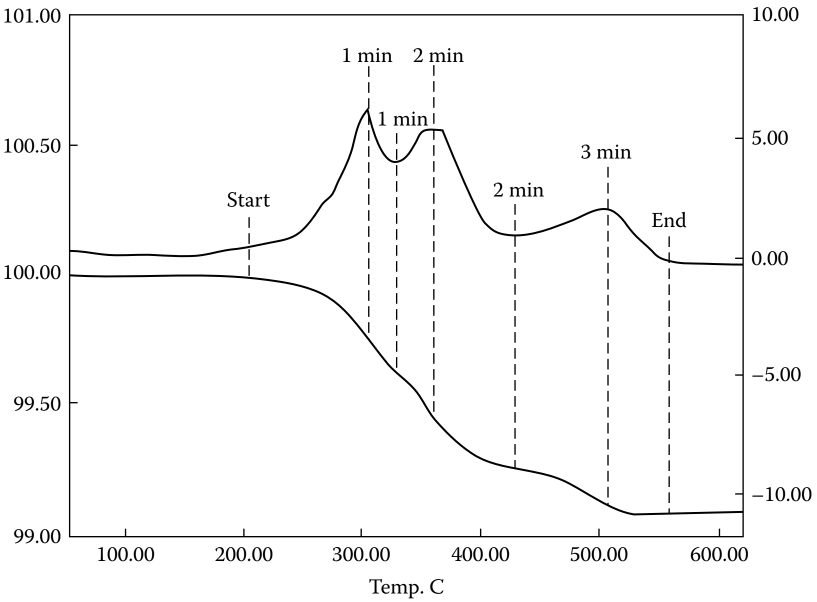


FIGURE 5.22 Thermogravimetric analysis of the thermal decomposition of the lacquer coating on UBCs. (From Kvithyld, A., Engh, T.A., and Illés, R., in *Light Metals 2002*, Schneider, W., Ed., TMS–AIME, Warrendale, PA, 2002, p. 1055. With permission.)

The third peak of the top curve in Figure 5.22 represents the oxidation of this char. When scrap is decoated in an oxygen-free environment, this third peak does not appear.

The rate at which these reactions happen varies with temperature and atmosphere. Table 5.6, adopted from the results of Kvithyld et al. (2002), predicts the lifetime of coatings at different temperatures under Ar and Ar + 1% O_2 atmospheres. Higher temperatures have an obvious impact, particularly on the second step of the process.

TABLE 5.6
Lifetime of Lacquer Coating during Thermal Decoating under Varying Conditions

	Atmosphere		
Decoating Temperature	**Ar**	**Ar + 1% O_2**	**Air**
400°C	21 s	13 s	7 s
500°C	0.4 s	0.2 s	0.2 s
600°C	0.02 s	0.01 s	0.01 s

Source: Kvithyld, A. et al., in *Light Metals 2002,* Schneider, W., Ed., TMS–AIME, Warrendale, PA, 2002, p. 1055. With permission.

However, decoating at higher temperatures increases energy use, making it more difficult to operate the process autothermally. It also increases surface oxidation of the metal during the process of burning off the char, which results in higher melt loss.

As a result, two basic strategies have emerged for thermal decoating of aluminum scrap (van Linden, 1990). The first is prolonged exposure at a lower temperature (480 to 520°C), which minimizes metal oxidation. However, this can also result in incomplete decoating, leaving behind unoxidized char (Stevens and Tremblay, 1997). The second is rapidly heating the scrap to a temperature just below the melting point (590 to 620C), with very short exposure. The limitation of this approach is the potential for excess metal oxidation if the exposure at the top temperature is too long.

Three types of furnace have been developed for decoating (Stevens and Tremblay, 1997). Figure 5.23 depicts the first of these, a rotary kiln. The kiln utilizes the second of the basic strategies for heating scrap, mixing the incoming scrap with hot *process gas*. This gas consists of VOCs from the delacquering process (Wojciechowski and Fundine, 1990; Newberry and Jenkins, 1995), burned with excess air to produce a gas generally containing 6 to 8% O_2. (Oxygen levels above 10% encourage excess oxidation; levels under 4% make it difficult to oxidize the char.) The kiln is equipped with internal flights that help "throw" the scrap through the gas, improving heat transfer and helping the scrap heat faster.

Three types of rotary kiln are used. In the first, process gas is added at the same location as the incoming scrap and flows *co-current*ly with the charge (Newberry and Jenkins, 1995). The large temperature difference between the two incoming streams ensures higher heat-transfer rates and quicker heating of the scrap. This in turn reduces the amount of char generated. However, much of the oxygen in the process gas reacts with the VOCs during heating, so less is available to react with the char. In a *counter-current* rotary kiln, the process gas and scrap are added at opposite ends and flow opposite to each other. This allows more heat to be removed from the gas, improving thermal efficiency. It also means more oxygen is available in the gas to react with the char. However, the smaller temperature differences between gas and scrap mean that heat-transfer rates are lower and the scrap heats

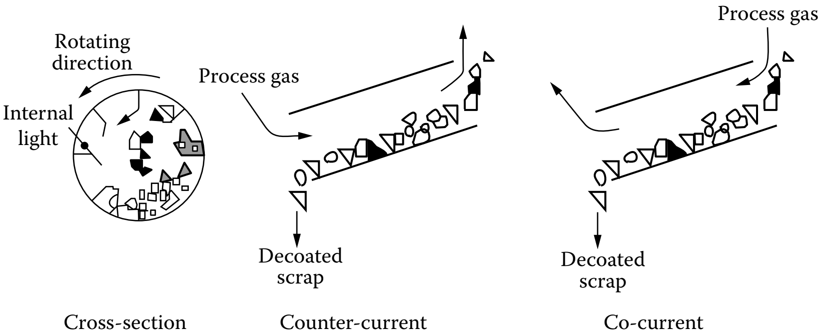


FIGURE 5.23 Rotary-kiln decoating furnace. (From Stevens, W. and Tremblay, F., in *Light Metals 1997,* Huglen, R., TMS–AIME, Warrendale, PA, 1990, p. 709. With permission.)

at a slower rate. As a result, there is more char to be oxidized than co-current rotary kilns generate. The IDEX furnace attempts to achieve the advantages of both types by introducing the gas through a central coaxial tube in a co-current direction (Perry and DeSaro, 1997). The temperature difference between the gas and scrap is sufficient to encourage heat transfer by radiation. When the gas exits the tube at the discharge end of the kiln, it retains sufficient oxygen content to burn off the char. It then flows back through the scrap, transferring more heat to the charge and improving thermal efficiency. The extra complexity increases capital costs, however.

The second class of decoating furnace is a *packed-bed reactor* or *belt decoater.* Figure 5.24 shows the basic design of this furnace, which heats coated scrap to a lower temperature for an extended period. Scrap is packed in a bed on a moving wire-mesh belt (McAvoy et al., 1990). As it moves through the furnace, hot process gas is blown or drawn through the bed. As with the rotary kiln, the gas consists of combusted VOCs generated by the decoating scrap, burned with excess air to generate a gas with 6 to 8% O_2. The scrap is heated to lower temperatures than the rotary kiln (480 to 520°C) and stays in the furnace for a longer time (5 min).

Proper operation of a belt decoater is tricky (McAvoy et al., 1990), because several variables must be controlled properly to get optimal results. These include the gas flow rate through the bed, the inlet gas temperature, belt speed, bed thickness, and particle size of the shredded scrap. Typical practice is for a bed thickness of 75 mm and inlet gas temperatures of 500 to 600°C. The use of a traveling bed guarantees equal residence time for all the feed particles and contact with the gas for all the scrap. The thin bed depth reduces temperature gradients, encouraging consistent results.

The newest type of decoating furnace is the *fluidized bed decoater*, developed by Alcan in the early 1990s (McAvoy et al., 1990). Figure 5.25 is a schematic of this type of furnace, which like the belt decoater uses longer exposures at lower temperatures for decoating. The key to this technology is the bed of inert particles that is fluidized by heated process gas fed through the bottom of the unit. The hot particles transfer heat to the solid pieces of scrap more efficiently than the hot gas

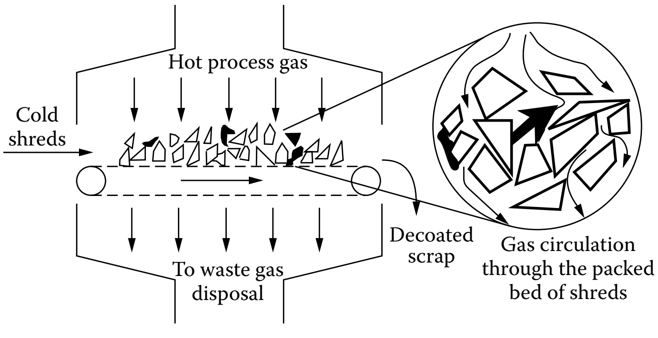


FIGURE 5.24 Belt decoating furnace. (From Stevens, W. and Tremblay, F., in *Light Metals 1997,* Huglen, R., TMS–AIME, Warrendale, PA, 1990, p. 709. With permission.)

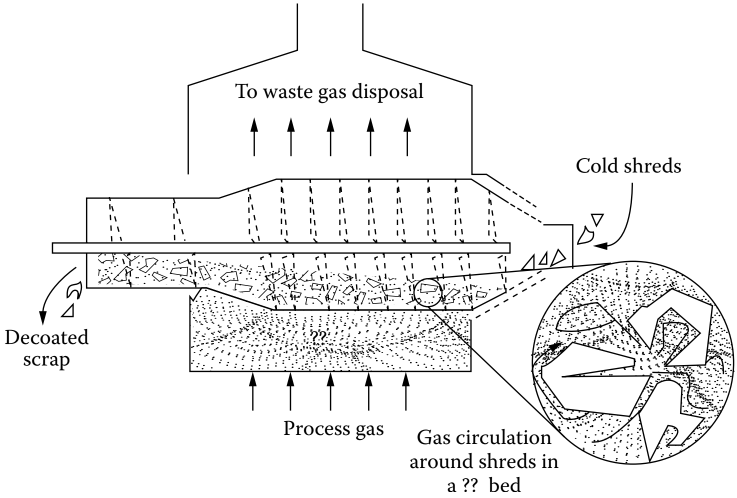


FIGURE 5.25 Fluidized-bed decoating furnace. (From Stevens, W. and Tremblay, F., in *Light Metals 1997,* Huglen, R., TMS–AIME, Warrendale, PA, 1990, p. 709. With permission.)

alone (Tremblay et al., 1995), resulting in shorter required residence times than needed in a belt decoater. The operating temperature and rotation speed of the rotating decoater drum through which the scrap is fed allow decoating of a variety of feed types.

In operation, scrap is fed through the airlocks at the left and enters the drum, which has been perforated to allow fluidizing medium in and out. The fluidizing gas fed through the bottom is a mixture of compressed air and natural gas. The combustion of the natural gas and the VOCs generated by the decomposing coating generates heat to operate the process. In the first portion of the drum, the gas mixture is kept oxygen-poor, to encourage volatilization of the coating without excessive oxidation of the scrap. As the scrap moves through the drum, the mixture becomes progressively oxygen-rich to encourage burning off the char. The rotation of the drum keeps the scrap from settling to the bottom. As the decoated scrap leaves the furnace, it goes through a desanding zone and then a hot media screen designed to recover the fluidizing medium. This reduces both losses of the medium and impurities in the decoated scrap.

A common element to all three types of decoater is the need to combust the VOCs in the off-gas. This provides process heat and ensures an environmentally acceptable discharge from the facility. In the fluidized bed decoater, VOCs are burnt off in a thermal decoating zone inside the unit (Tremblay et al., 1995). In rotary kilns and belt decoaters, a separate afterburner is provided. Temperature control of the combustion is important. If the temperature is too low, the VOCs will not be completely oxidized; if the temperature is too high, unacceptable levels of NO_x and dioxins and furans may result. In practice, afterburners often operate at around 800 to 850°C (Trosch, 1990; Newberry and Jenkins, 1995; Perry and DeSaro, 1997; Bateman et al., 1999).

PYROLYSIS OF COMPOSITE PACKAGING

As mentioned in Chapters 2 and 3, some of the aluminum used in packaging is in foil form, rather than the extruded can stock most commonly encountered. Aluminum foil is used in a variety of packages, most often laminated or attached to paper or plastic. The percentage of aluminum in these packages is low, and the thin aluminum foil is easily oxidized, so recycling this material with minimal melt loss is particularly difficult (Bateman et al., 1999).

The furnaces used for pyrolysis of composite packaging are similar to those used for decoating. Rotary kilns, belt decoaters, and fluidized-bed furnaces have all been tried (van Craen et al., 1999; Takahashi et al., 2001; Escherle, 2002). However, there are differences in operating practice. The organic content of composite packaging is much higher than in ordinary coated material, so the volume of VOCs generated is higher per unit of aluminum recovered. Furthermore, the plastics encountered (in particular, polyethylene terephthalate, better known as PET) leave behind much more char when pyrolyzed than does the lacquer on aluminum cans (Rossel et al., 1997). Because the aluminum alloys used for foil have much lower alloy contents than those used in other applications, pyrolyzing furnaces can be run at higher temperatures without the concern of incipient melting. However, the foils are thin (7 to 9 μm), so a layer of oxide on the surface is a much larger weight fraction of the scrap than for other aluminum products. As a result, a compromise is in order. Lower-temperature pyrolysis is more common. This results in greater amounts of char. However, the plastic and paper in composite packaging is often not tightly bonded to the metal underneath. As a result, the char is easily knocked loose from the surface and can be recovered by screening.

PAINT REMOVAL

Decoating and pyrolysis is effective at separating scrap aluminum from organic coatings and contaminants. However, much aluminum scrap is painted, and paint removal is more difficult. The organic component of paint can be volatilized, but paint often contains inorganic compounds (in particular TiO_2) that do not respond to thermal processing (Bateman et al., 1999). The inorganic compounds remain with the scrap and wind up in the dross when the scrap is remelted. This increases melt loss and increases the amount of dross that must be handled. Furthermore, some of the TiO_2 may be reduced by the molten aluminum:

$$3\ TiO_2 + 4\ Al\ (l) = 3\ \underline{Ti}\ \text{(dissolved in metal)} + 2\ Al_2O_3\ \text{(dross)} \tag{5.1}$$

To some degree, paint can be removed by abrasion during the decoating process. The tumbling action during rotary-kiln operation removes some of the paint (Bateman et al., 1999). The abrasion caused by the fluidizing medium during fluidized-bed decoating is even more effective. Research has shown that a formic acid–halogenated acetic acid solution causes the paint to swell and loosen itself from the can, making it easier to remove (Fujisawa et al., 2000). However, the practicality of this approach is doubtful, except for large quantities of heavily painted scrap.

PARTIAL MELTING

A previous section discusses the value of separating aluminum scrap on the basis of alloy content. One of the early attempts to partially accomplish this goal used differences between the solidus temperatures of various alloys. The solidus is the temperature at which melting of the alloy begins to occur. Depending on the appropriate phase diagram, alloys with high amounts of added elements (such as casting alloys) can have a lower solidus than lightly alloyed wrought compositions (Maurice et al., 2000). This is particularly true of alloys with a high copper content. Research conducted in the 1980s by the U.S. Bureau of Mines sought to take advantage of this by heating a mixture of wrought and cast scrap to temperatures ranging between 540 and 590°C (Ambrose et al., 1983). The heated scrap was then processed in a laboratory jaw crusher. Cast scrap pieces heated to a temperature higher than the solidus of the alloy were easily crushed, while pieces of wrought alloy were merely flattened by the crusher. As a result, screening the crusher product effectively separated cast scrap from wrought.

This research was never used to develop a commercial process for separating cast scrap from wrought. Subsequent research at the same laboratory cast doubt on the accuracy of the early results (Maurice et al., 2000). However, the concept of using differences in solidus temperature to accomplish alloy separation was eventually used in a different process. As mentioned in Chapter 2, aluminum beverage cans are typically made of three wrought alloys: a low-alloy body (3003 or 3004) and high-magnesium alloys such as 5182 for the top and tab. The solidus temperature of 3004 is 629°C, while that of 5182 is 581°C, some 48°C lower. Using this information, Alcoa designed a rotary delacquering kiln for UBCs to operate at an intermediate temperature (Bowman, 1985). The tumbling action of the kiln is sufficient to decompose the lids into small flakes, while the can bodies remain unaffected. Screening the product separates the two alloys. This allows closed-loop remelting of the can bodies to produce 3004 and similar closed-loop melting of the 5182 flakes to produce separate lid stock. However, the use of partial melting to separate mixed-alloy scrap ultimately proved uneconomic.

SWEAT MELTING

While most aluminum scrap can be liberated from other metals to which it is attached by shredding, there are exceptions. Some aluminum parts are so intricately attached to iron parts that they will not be separated by ordinary shredding. Examples include transmissions, cylinder heads, and manifolds. These items are known as *high-irony* scrap because of the extremely high levels of iron (50% or more at times). Scrap of this type has too much aluminum to be classified as ferrous scrap but too much iron to be remelted by secondary smelters.

Figure 5.26 shows a traditional solution to this problem (Nijkerk and Dalmijn, 1998), a *sweat furnace*. Sweat furnaces can be either the rotary type shown here or a less sophisticated stationary dry-hearth design. In either case, the principle is simple. High-irony scrap fed to the furnace is heated to a temperature just above the melting point of aluminum (660°C). At this temperature, the aluminum slowly melts away (hence the term *sweating*), leaving the higher-melting-point iron behind.

FIGURE 5.26 A large-scale rotary sweat furnace. (From EnviroAir, Inc., http://www.enviroair.net/ Rotary SweatFurnacePage.htm. With permission.)

The liquid aluminum drains from the bottom of the furnace and is cast in the form of sows or pigs. (The product is often known as *sweated pig*.) The furnaces can be operated with a variety of fuels and are also used for melting zinc away from solid aluminum in scrap radiators at lower temperatures. (This recovers aluminum as well as zinc.) Rotary furnaces do a better job of separating the melted aluminum from the iron pieces, and thus tend a produce pig with lower iron content.

Sweated pig is commonly sold in one of three grades, 1-1-1, 1-1-2, and 1-1-3 (Tribendis et al., 1984). The numbers refer to the maximum allowable percentages of magnesium, iron, and zinc in the product. There are no limits on the percentages of other alloying elements. The aluminum scrap melted in sweat furnaces is normally cast alloy, so typical copper contents might be 2.5 to 3.0%, the normal silicon range is 6.0 to 9.0%, and manganese might range from 0.2 to 2.0%. Sweated pig is usually sold to secondary smelters, where it is remelted and mixed with other scrap.

AGGLOMERATION

BALERS

The aluminum scrap recovered using the technology previously described consists of loose pieces with a very low bulk density. This makes it difficult to handle and ship and makes it more likely that it will pick up moisture during shipment. As a result, some method of densification is desirable before shipping. Figure 5.27 illustrates the operation of a baler, which compresses scrap using hydraulic rams. The baler shown here is a three-stroke unit (Zöllner, 2003). This process starts by compressing from the side perpendicular to the door; it then compresses from the top down, and lastly in the direction of the door. As the final compression is

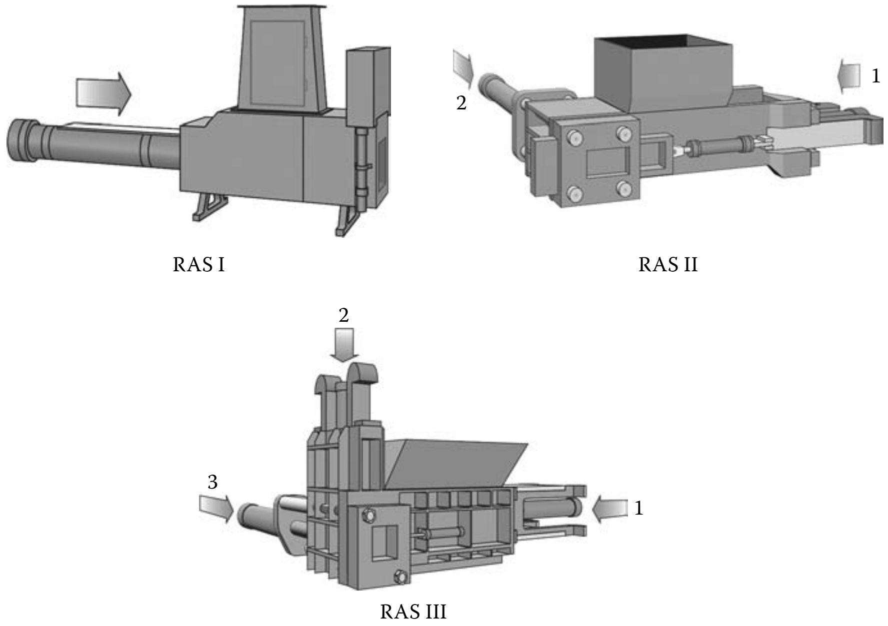


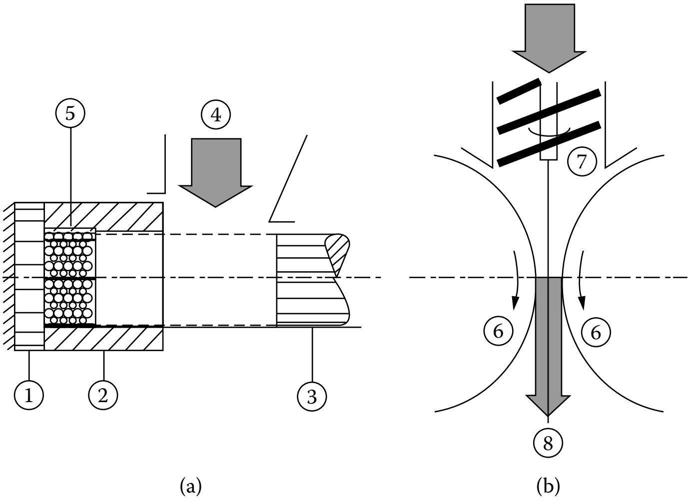
FIGURE 5.27 Operation of a three-stroke baler. (From Metso Minerals, http://www.metsominerals.com/inetMineals/MaTobox7.nsf/DocsByID/277BAEB1DECCC2FD42256B4100451C96/$File/1229_RAS_EN.pdf. With permission.)

completed, the door opens and the finished bale is pushed out. Because baling deforms the metal during compression, metal bales are more cohesive than those made from plastic or paper and usually do not require tying with wire.

While consolidation of some sort is essential prior to shipping scrap, bales are not always popular with scrap consumers. The bales are often too big to charge directly to a furnace, and bales often contain surprises: moisture, contaminants, grease, and oil. Because of this, bales are often shredded and reprocessed by the consumer upon arrival. This has made *logging* more popular (Taylor, 2003). Logging is similar to baling but produces a lower-density product. Logs are easier to shred and thus more desirable to consumers.

BRIQUETTING

One of the more difficult types of new scrap to recycle is turnings and borings generated by machining operations (Pietsch, 1993). This type of scrap has a very large surface area to volume ratio, making it more prone to oxidation during melting. Furthermore, turnings and borings are frequently covered with grease or oil, which is highly undesirable in remelting. In response, turnings and borings are often *briquetted.* This too is a process of compaction under pressure (30 MPa is typical), using much higher pressure and producing much smaller compacts.



(a) (b)

FIGURE 5.28 Punch-and-die (a) and roller press (b) briquetting machines. (From Pietsch, W., in *Light Metals 1993,* Das, S.K., Ed., TMS–AIME, Warrendale, PA, 1993, p. 1045. With permission.)

Briquetting reduces the effective surface area to volume ratio of the turnings, helping to reduce melt loss. It also squeezes much of the grease and oil out of the feed, which makes subsequent processing easier.

Figure 5.28 illustrates the two types of briquetting technology (Pietsch, 1993). A traditional punch-and-die machine produces cylindrical briquettes, or *pucks,* with diameters of 12 to 15 cm and heights of roughly 10 cm. A newer approach involves feeding the material to a roller press, which operates continuously and produces a strip of compacted material with a density near theoretical. Roller presses are more productive than punch-and-die briquetting machines, particularly for handling aluminum swarf. However, punch-and-die machines are more cost-effective for small operations and handle more elastic turnings and borings better. The practice of shredding turnings prior to briquetting helps improve the results.

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6 Beneficiation Practice

The previous chapter introduced the technology used to beneficiate aluminum scrap. The processor of scrap material has several ways to turn collected scrap into a material that can be sold to customers. The choice of options depends on the cost of different processing technologies, the added value the scrap will have when improved to a particular grade, the demand for particular grades of scrap, and the impact of government regulations. This chapter will examine the paths for processing different sources of scrap aluminum and the reason for choosing a particular technology. This will be done using the same categories of ore described in Chapter 3: new scrap, UBCs, automotive and transportation scrap, electrical and electronic scrap, and municipal solid waste (MSW).

NEW SCRAP

The variety of types of new scrap, and the variety of ways in which it is collected and distributed, make it impossible to generalize about how it is processed. However, compared with old scrap, new scrap has several advantages that make it easier to upgrade:

- *New scrap is a known.* The purchaser of new scrap knows how much material is being purchased and which alloys it consists of. The impurities in the scrap — iron, plastic, other metals — are also known. This makes it easier to design processing schemes.
- *New scrap is usually cleaner.* Because it has never been put in service, new scrap has less dirt and moisture on it and is usually in better condition. This makes it easier to generate a clean product for sale to remelting facilities.
- *New scrap does not require disassembly.* New scrap is usually obtained as pieces of alloy and is less likely to include attachments, paint, and other materials that will require physical separation. This reduces processing costs.

Because of this, a scrap dealer or broker can often *grade* new scrap and sort it into products meeting specifications for chemistry and condition. Figure 6.1 lists 35 classes of aluminum scrap (ISRI, 2005), defined by the U.S. Institute of Scrap Recycling Industries (ISRI). Many of these classes describe aluminum recovered from old scrap, but several are classes of new scrap. ISRI descriptions are used primarily by brokers and dealers rather than by processors or remelters, but the descriptions of these grades help explain what characteristics determine the value of aluminum scrap. The purpose of scrap upgrading is to meet standards such as those listed in Figure 6.1.

Tablet – Clean Aluminum Lithographic Sheets

To consist of alloys 1100 and/or 3003, to be free of paper, plastic, excessively inked sheets and any other contaminants. Minimum of three inches (8 cm) in any direction.

Tabloid – New, Clean Aluminum Lithographic Sheets

To consist of 1000 and/or 3000 series alloys, to be free of paper, plastic, ink, and any other contaminants. Minimum size of three inches (8 cm) in any direction.

Taboo – Mixed Low Copper Aluminum Clippings and Solids

Shall consist of new, clean, uncoated and unpainted low copper aluminum scrap of two or more alloys with a minimum thickness of 0.015 inches (0.38 mm) and to be free of 2000 and 7000 series, foil, hair wire, wire screen, punchings less than $^1/_2$ inch (1.25 cm) diameter, dirt, and other non-metallic items. Grease and oil not to total more than 1%. Variations to this specification should be agreed on prior to shipment between the buyer and seller.

Taint/Tabor – Clean Mixed Old Alloy Sheet Aluminum

Shall consist of clean old alloy aluminum sheet of two or more alloys, free of foil, Venetian blinds, castings, hair wire, screen wire, food or beverage containers, radiator shells, airplane sheet, bottle caps, plastic, dirt, and other non-metallic items. Oil and grease not to total more than 1%. Up to 10% Talc permitted.

Take – New Aluminum Can Stock

Shall consist of new low copper aluminum can stock and clippings, clean, lithographed or not lithographed, and coated with clear lacquer but free of lids with sealers, iron, dirt and other foreign contamination. Oil not to exceed 1%.

Talc – Post-Consumer Aluminum Can Scrap

Shall consist of old aluminum food and/or beverage cans. The material is to be free of other scrap metals, foil, tin cans, plastic bottles, paper, glass, and other non-metallic items. Variations to this specification should be agreed upon prior to shipment between the buyer and seller.

Talcred – Shredded Aluminum Used Beverage Can (UBC) Scrap

Shall have a density of 12 to 17 pounds per cubic foot (193 to 273 kg/m^3). Material should contain maximum 5% fines less than 4 mesh (U.S. standard screen size) (6.35 mm). Must be magnetically separated material and free of steel, lead, bottle caps, plastic cans and other plastics, glass, wood, dirt, grease, trash, and other foreign substances. Any free lead is basis for rejection. Any and all aluminum items, other than used beverage cans, are not acceptable. Variations to this specification should be agreed upon prior to shipment between the buyer and seller.

Taldack – Densified Aluminum Used Beverage Can (UBC) Scrap

Shall have a biscuit density of 35 to 50 pounds per cubic foot (562 to 802 kg/m^3). Each biscuit not to exceed 60 pounds (27.2 kg). Nominal biscuit size range from 10″ to 13″ × 10T_+' (25.4 × 33 × 26 cm) to 20″ × 6T_+' to 9″ (50.8 × 15.9 × 22.9 cm). Shall have banding slots in both directions to facilitate bundle banding. All biscuits comprising a bundle must be of uniform size. Size: Bundle range dimensions acceptable are 41″ to 44″ × 51″ (104 to 112 cm) to 54″ × 54″ (137 × 137 cm) to 56″ (142 cm) high. The only acceptable tying method shall be as follows: Using minimum 5/8″ (1.6 cm) wide by .020″ (0.05 cm) thick steel straps the bundles are to be banded with one vertical band per row and a minimum of two girth (horizontal) bands per bundle. Use of skids and/or support sheets of any material is not acceptable. Must be magnetically separated material and free of steel, lead, bottle caps, plastic cans and other plastic, glass, wood, dirt, grease, trash, and other foreign substances.

FIGURE 6.1 Description of classes of aluminum scrap. (From *Scrap Specifications Circular 2002,* ISRI, Washington, 2002. With permission.)

Any free lead is basis for rejection. Any and all aluminum items, other than used beverage cans, are not acceptable. Items not covered in the specifications, including moisture, and any variations in the specification should be agreed upon prior to shipment between the buyer and seller.

Taldon – Baled Aluminum Used Beverage Can (UBC) Scrap

Shall have a minimum density of 14 lbs per cubic foot (225 kg/m^3), and a maximum density of 17 lbs per cubic foot (273 kg/m^3) for unflattened UBC and 22 lbs per cubic foot (353 kg/m^3) for flattened UBC. Size: minimum 30 cubic feet (0.85 m^3), with bale range dimensions of 24″ to 40″ (61 to 132 cm) × 30″ to 52″ (76 to 132 cm) × 40″ to 84″ (102 to 213 cm). The only acceptable tying method shall be as follows: four to six 5/8″ (1.6 cm) × 0.20″ (5 mm) steel bands, or six to ten #13 gauge steel wires (aluminum bands or wires are acceptable in equivalent strength and number). Use of skids and/or support sheets of any material is not acceptable. Must be magnetically separated material and free of steel, lead, bottle caps, plastic cans and other plastics, glass, wood, dirt, grease, trash and other foreign substances. Any free lead is basis for rejection. Any and all aluminum items, other than used beverage cans, are not acceptable. Variations to this specification should be agreed upon prior to shipment between the buyer and seller.

Taldork – Briquetted Aluminum Used Beverage Can (UBC) Scrap

Shall have a briquette density of 50 pounds per cubic foot (800 kg/m^3) minimum. Nominal briquette size shall range from 12″ to 24″ (30.5 to 61 cm) × 12″ to 24″ (30.5 to 61 cm) in uniform profile with a variable length of 8″ (20.3 cm) minimum and 48″ (122 cm) maximum. Briquettes shall be bundled or stacked on skids and secured with a minimum of one vertical band per row and a minimum of one girth band per horizontal layer. Briquettes not to overhang pallet. Total package height shall be 48″ (122 cm) maximum. Banding shall be at least 5/8″ (1.6 cm) wide by .020″ (5 mm) thick steel strapping or equivalent strength. The weight of any bundle shall not exceed 4000 pounds (1.814 mt). Material must be magnetically separated and free of steel, plastic, glass, dirt and all other foreign substances. Any and all aluminum items, other than UBC are unacceptable. Any free lead is a basis for rejection. Items not covered in the specification, including moisture, and any variations to this specification should be agreed upon prior to shipment between the buyer and seller.

Tale – Painted Siding

Shall consist of clean, low copper aluminum siding scrap, painted one or two sides, free of iron, dirt, corrosion, fiber, foam, or fiberglass backing or other non-metallic items.

Talk – Aluminum Copper Radiators

Shall consist of clean aluminum and copper radiators, and/or aluminum fins or copper tubing, free of brass tubing, iron and other foreign contamination.

Tall – E.C. Aluminum Nodules

Shall consist of clean E.C. aluminum, chopped or shredded, free of screening, hair-wire, iron, copper, insulation, and other non-metallic items. Must be free of minus 20 mesh materials. Must contain 99.45% aluminum content.

Talon – New Pure Aluminum Wire and Cable

Shall consist of new, clean, unalloyed aluminum wire or cable free from hair wire, ACSR, wire screen, iron, insulation and other non-metallic items.

Tann – New Mixed Aluminum Wire and Cable

Shall consist of new, clean unalloyed aluminum wire or cable which may contain up to 10% 6000 series wire and cable free from hair wire, wire screen, iron, insulation and other non-metallic items.

FIGURE 6.1 (Continued).

Tarry A – Clean Aluminum Pistons

Shall consist of clean aluminum pistons to be free from struts, bushings, shafts, iron rings and other non-metallic items. Oil and grease not to exceed 2%.

Tarry B – Clean Aluminum Pistons with Struts

Shall consist of clean whole aluminum pistons with struts. Material is to be free from bushings, shafts, iron and other non-metallic items. Oil and grease not to exceed 2%.

Tarry C – Irony Aluminum Pistons

Shall consist of aluminum pistons with non-aluminum attachments to be sold on a recovery basis or by special arrangement between buyer and seller.

Tassel – Old Mixed Aluminum Wire and Cable

Shall consist of old, unalloyed aluminum wire and cable which may contain up to 10% 6000 series wire and cable with not over 1% free oxide or dirt and free from hair wire, wire screen, iron, insulation and other non-metallic items.

Taste – Old Pure Aluminum Wire and Cable

Shall consist of old, unalloyed aluminum wire and cable containing not over 1% free oxide or dirt and free from hair wire, wire screen, iron, insulation and other non-metallic items.

Teens – Segregated Aluminum Borings and Turnings

Shall consist of aluminum borings and turnings of one specified alloy. Material should be free of oxidation, dirt, free iron, stainless steel, magnesium, oil, flammable liquids, moisture and other non-metallic items. Fines should not exceed 3% through a 20 mesh (U.S. standard screen).

Telic – Mixed Aluminum Borings and Turnings

Shall consist of clean, uncorroded aluminum borings and turnings of two or more alloys and subject to deductions for fines in excess of 3% through a 20 mesh screen and dirt, free iron, oil, moisture and all other non-metallic items. Material containing iron in excess of 10% and/or free magnesium or stainless steel or containing highly flammable cutting compounds will not constitute good delivery. To avoid dispute, material should be sold on basis of definite maximum zinc, tin and magnesium content.

Tense – Mixed Aluminum Castings

Shall consist of all clean aluminum castings which may contain auto and airplane castings but no ingots, and to be free of iron, brass, dirt, and other non-metallic items. Oil and grease not to total more than 2%.

Tepid – Airplane Sheet Aluminum

Should be sold on recovery basis or by special arrangements with purchaser.

Terse – New Aluminum Foil

Shall consist of clean, new, pure, uncoated, 1000 and/or 3000 and/or 8000 series alloy aluminum foil, free from anodized foil, radar foil and chaff, paper, plastics, or other non-metallic items. Hydraulically briquetted material and other alloys by agreement between buyer and seller.

Tesla – Post Consumer Aluminum Foil

Shall consist of baled old household aluminum foil and formed foil containers of uncoated 1000, 3000, and 8000 series aluminum alloy. Material may be anodized and contain a maximum of 5% organic residue. Material must be free from radar chaff foil, chemically etched foil, laminated foils, iron, paper, plastic and other non-metallic contaminants.

FIGURE 6.1 (Continued).

Tetra – New Coated Aluminum Foil

Shall consist of new aluminum foil coated or laminated with ink, lacquers, paper, or plastic. Material shall be clean, dry, free of loose plastic, PVC and other non-metallic items. This foil is sold on a metal content basis or by sample as agreed between buyer and seller.

Thigh – Aluminum Grindings

Should be sold on recovery basis or by special arrangements with purchaser.

Thirl – Aluminum Drosses, Spatters, Spillings, Skimmings and Sweepings

Should be sold on recovery basis or by special arrangements with purchaser.

Throb – Sweated Aluminum

Shall consist of aluminum scrap which has been sweated or melted into a form or shape such as an ingot, sow or slab for convenience in shipping; to be free from corrosion, dross or any non-aluminum inclusions. Should be sold subject to sample or analysis.

Tooth – Segregated New Aluminum Alloy Clippings and Solids

Shall consist of new, clean, uncoated and unpainted aluminum scrap of one specified aluminum alloy only with a minimum thickness of 0.015″ (0.38 mm) and to be free of hair wire, wire screen, dirt, and other non-metallic items. Oil and grease not to total more than 1%. Also free from punchings less than $^1/_2$″ (1.27 cm) in size.

Tough – Mixed New Aluminum Alloy Clippings and Solids

Shall consist of new, clean, uncoated and unpainted aluminum scrap of two or more alloys with a minimum thickness of 0.015″ (0.38 mm) and to be free of hair wire, wire screen, dirt, and other non-metallic items. Oil and grease not to total more than 1%. Also free from punchings less than $^1/_2$″ (1.27 cm) in size.

Tread – Segregated New Aluminum Castings, Forgings and Extrusions

Shall consist of new, clean, uncoated aluminum castings, forgings, and extrusions of one specified alloy only and to be free from sawings, stainless steel, zinc, iron, dirt, oil, grease and other non-metallic items.

Troma – Aluminum Auto or Truck Wheels

Shall consist of clean, single-piece unplated aluminum wheels of a single specified alloy, free of all inserts, steel, wheel weights, valve stems, tires, grease and oil and other non-metallic items. Variations to this specification should be agreed upon prior to shipment between the buyer and seller.

Trump – Aluminum Auto Castings

Shall consist of all clean automobile aluminum castings of sufficient size to be readily identified and to be free from iron, dirt, brass, bushings, and non-metallic items. Oil and grease not to total more than 2%.

Twang – Insulated Aluminum Wire Scrap

Shall consist of aluminum wire scrap with various types of insulation. To be sold on a sample or recovery basis, subject to agreement between buyer and seller.

Tweak – Fragmentizer Aluminum Scrap (from Automobile Shredders)

Derived from either mechanical or hand separation, the material must be dry and not contain more than 4% maximum free zinc, 1% maximum free magnesium, and 1.5% maximum of analytical iron. Not to contain more than a total 5% maximum of non-metallics, of which no more than 1% shall be rubber and plastics. To be free of excessively oxidized material, air bag canisters, or any sealed or pressurized items. Any variation to be sold by special arrangement between buyer and seller.

FIGURE 6.1 (Continued).

Twire – Burnt Fragmentizer Aluminum Scrap (from Automobile Shredders)

Incinerated or burned material must be dry and not contain more than X% (% to be agreed upon by buyer and seller) ash from incineration, 4% maximum free zinc, 1% maximum free magnesium, and 1.5% maximum of analytical iron. Not to contain more than a total 5% maximum of non-metallics, of which no more than 1% shall be rubber and plastics. To be free of excessively oxidized material, air bag canisters, or any sealed or pressurized items. Any variation to be sold by special arrangement between buyer and seller.

Twist – Aluminum Airplane Castings

Shall consist of clean aluminum castings from airplanes and to be free from iron, dirt, brass, bushings, and non-metallic items. Oil and grease not to total more than 2%.

Twitch – Floated Fragmentizer Aluminum Scrap (from Automobile Shredders)

Derived from wet or dry media separation device, the material must be dry and not contain more than 1% maximum free zinc, 1% maximum free magnesium, and 1% maximum of analytical iron. Not to contain more than a total 2% maximum of non-metallics, of which no more than 1% shall be rubber and plastics. To be free of excessively oxidized material, air bag canisters, or any sealed or pressurized items. Any variations to be sold by special arrangement between buyer and seller.

Zorba – Recyclable Concentrates of Shredded Mixed Nonferrous Scrap Metal in Pieces—Derived from Fragmentizers for Further Separation of Contained Materials

Shall be made up of a combination of the nonferrous metals: aluminum, copper, lead, magnesium, stainless steel, nickel, tin, and zinc, in elemental or alloyed (solid) form. The percentage of each of these metals within the nonferrous concentrate shall be subject to agreement between buyer and seller, may vary from shredder to shredder and may, in some cases, be zero for a particular metal. Shall be obtained by air separation, flotation, screening, eddy current, other segregation technique(s) or a combination of the same. Shall have passed one or more magnets to reduce or eliminate free iron and/or iron attachments. Shall be free of radioactive material, dross or ash. May be screened to permit description by specific size ranges. May contain high density non-metallics such as rock, glass, rubber, plastic and wood. Items of exclusion, inclusion or limitation not set out in the above specifications, such as moisture and free iron and/or attachments or the presence or absence of other metals, are subject to agreement between buyer and seller. Material to be traded under this guideline shall be identified as ZORBA with a number to follow indicating the estimated percentage nonferrous metal content of the material (e.g. ZORBA 63 – means the material contains approximately 63% nonferrous metal content).

FIGURE 6.1 (Continued).

The classes Tablet and Tabloid in Figure 6.1 both concern scrap lithographic sheet. Tabloid is uncoated and unpainted and thus is more valuable than tablet. Scrap with excessive levels of coatings or paint have to be decoated, which increases processing costs. Both grades should be free of paper, plastic, and other contaminants. Such contaminants require air classification to remove them if they are present. Both classes have a minimum three-inch (7.62-cm) size requirement. Smaller pieces are more difficult to feed to a furnace and oxidize more readily during melting. As a result, the melt loss that occurs during the remelting of smaller pieces is higher, reducing their value. This is also true for other scrap grades.

The class Taboo consists of mixed low-copper (MLC) scrap. While scrap of this type still contains too many impurities to be used in producing most wrought alloys, the low-copper specification allows it to be used in the production of some casting alloys (A356.1, 360.1) that otherwise could not be produced from scrap. MLC can be used to produce at least one common wrought alloy (3105) as well. That increases the value of this type of scrap. The specification contains several conditions that are already familiar: MLC should be clean, uncoated and unpainted, and larger than 0.5 inches (1.27 cm) in size. The limitation on oil and grease content ensures that this material will not have to be decoated before charging to a furnace and is common to many grades of aluminum scrap. The exclusion of 7000 series scrap keeps out zinc, which is unacceptable in sheet alloy and several casting alloys (see Tables 2.1 and 2.2). The other unacceptable impurities contribute to melt loss and thus are undesirable. Limitations like these are impossible to enforce for old scrap, so the class "Taint/Tabor" is much less restrictive. Taint is also less valuable.

Talon and tann are grades of new aluminum wire and cable scrap. The difference between the two is the allowance in Tann of up to 10% 6000 series alloy. Talon scrap is pure 1xxx series and can be remelted directly to produce 1xxx series alloy. Limitation of new scrap to a single alloy or series allows closed-loop recycling such as this and increases the value substantially. The classes Teens, Tooth, and Tread also specify single-alloy scrap.

The classes Teens and Telic are for borings and turnings, a special class of new scrap. Borings and turnings are small pieces of aluminum, which turn easily into dust if they get too small. To minimize this, both specifications include a maximum of 3% fines (particles smaller than 20 mesh, or 0.76 mm). The small particle size eliminates the use of most sorting technology, so magnesium and stainless steel impurities are strictly forbidden. Borings and turnings are usually oily, and thus are degreased prior to remelting. Even so, highly flammable cutting oil is a safety hazard in this material and is also forbidden.

New scrap comes in many conditions and purities, and most of the beneficiation techniques described in the previous chapter are applied to one or more grades. However, some are more commonly used than others. These include:

- *Hand sorting.* Because a load of mixed new scrap often includes a limited number of alloys, hand sorting often makes it possible to produce single-alloy scrap products. Even if this is not possible, hand sorting can help meet specifications for other scrap grades by removing impurities. Often, a dealer's experience and knowledge of his suppliers is useful in hand sorting, because the appearance of a piece of new scrap — the shape of a punching, the type of scrapped casting or part — will be sufficient to identify the alloy.
- *Screening.* This is used both to remove undersize pieces of aluminum and to separate out dirt and other extraneous matter.
- *Shredding.* This is done primarily to reduce large pieces of scrap (such as stamping skeletons and cable) to a size suitable for charging to a furnace. However, it is often done to turnings as well, because smaller turnings are easier to briquette (Nijkerk and Dalmijn, 1998).
- *Briquetting.* This is used primarily for turnings and borings and is usually performed before degreasing. It helps squeeze out some of the oil and grease, in addition to turning small particles into an equivalent larger piece of scrap (Nijkerk and Dalmijn, 1998).

- *Thermal decoating.* If the amount of grease and oil in a scrap load is less than 1%, the scrap can be charged directly to a remelting furnace without concern over excessive smoke or melt loss. However, higher levels will require degreasing, using one of the thermal decoating technologies described in the previous chapter. Degreasing is usually required for borings and turnings.

MUNICIPAL SOLID WASTE

Of all the sorting technologies introduced in the previous chapter, hand sorting remains the most common method of recovering aluminum and other recyclables from MSW. Hand sorting is performed at one of several locations:

- *By the waste generator.* Municipalities often encourage or require households and businesses to presort their trash before disposal. A common approach is the provision of a "blue bag" into which recyclables are placed. The list of accepted recyclables varies but always includes metal scrap. Cardboard, glass, paper, and plastics may also be directed to the blue bag. In most schemes, a common container is used to hold all recyclables. However, some locations provide different containers for each type of recyclable (Nijkerk and Dalmijn, 1998; Reid, 2002). The containers are placed at curbside along with the container of nonrecyclable trash. As a result, this type of recycling is known as *curbside* collection.
- *By the primary collector.* Figure 3.4 shows a truck specifically designed for collecting curbside recyclables. The truck contains separate compartments for each type of recyclable. As the driver retrieves blue bags, he sorts the contents into the separate compartments. It is claimed that such sorting at the initial point of collection has lower operating costs than hand sorting at a municipal recycling facility (MRF). This is offset by the higher capital cost of the truck.
- *At centralized MRFs.* In industrialized countries this is still the most popular location for hand sorting municipal refuse. However, the labor costs associated with hand sorting have provided incentive for new technology (Glenn, 1991; Arimoto et al., 1998). Screening incoming garbage eliminates small items such as bottle caps and glass shards that can contaminate product streams. Use of an air separator to separate heavy materials such as glass and steel from lighter materials such as plastic and aluminum again makes the job of hand sorting easier. The key is to foster *negative sorting,* in which sorters remove impurities from a stream consisting primarily of the desired material. This is more productive than positive sorting, in which the desired material is removed from a stream consisting primarily of impurities. If a blue-bag system is in use, the metal content of the bag may be high enough to permit hand sorting without such pretreatment.
- *At the dump.* MRFs are expensive to construct and operate, and their economic viability is uncertain at best. In many cases the value of recyclables in refuse is less than the cost of recovering them. Aluminum scrap is the only consistent exception to this shortcoming. As a result, municipalities

> in less-developed countries dump or landfill their trash without attempting to sort it. This creates an opportunity for dumpsite scavengers (Filleti et al., 1997), who make the recovery of aluminum and other metal scrap from city dumps their vocation. Medina (1998) has described the activities of these occupational scavengers in Nuevo Laredo, Mexico. Although the work is not the most desirable from a health or safety standard, it does yield income levels higher than that of the average Mexican wage earner. Whether this is so elsewhere is not known.

MRFs use several flowsheets for processing municipal refuse (Glenn, 1991; Steverson, 1995). Screening is an important element of most of these (Harler, 1998). Screening can be used to either (a) separate oversize material such as paper and cardboard from the rest of the garbage or (b) separate undersize material such as glass shards and bottle caps from the bulk of the material (Palmer and Nixon, 1999). Trommels are the most common type of screen. Most MRFs also feature magnetic separation in their process. Magnetic separators recover a ferrous product that can be sold to steel recyclers and they purify the nonferrous fraction of iron that would otherwise be a contaminant. The use of eddy-current separators (ECSs) is newer but increasingly popular for generating an aluminum fraction with fewer impurities (van Linden, 1990).

The importance of product purity in the aluminum recovered by MRF facilities is highlighted by Table 6.1. This is a set of specifications for grades of MRF-recovered aluminum, listing the maximum of various impurity elements allowed in each grade. (The specifications, produced by the American Society for Testing

TABLE 6.1
Chemical Specification for Grades of Aluminum Scrap Produced by MRFs

	Composition (max. % allowable)					
Element	**Grade 1**	**Grade 2**	**Grade 3**	**Grade 4**	**Grade 5**	**Grade 6**
Silicon	0.30	0.30	0.50	1.00	9.00	9.00
Iron	0.60	0.70	1.00	1.00	0.80	1.00
Copper	0.25	0.40	1.00	2.00	3.00	4.00
Manganese	1.25	1.50	1.50	1.50	0.60	0.80
Magnesium	2.00	2.00	2.00	2.00	2.00	2.00
Chromium	0.05	0.10	0.30	0.30	0.30	0.30
Nickel	0.04	0.04	0.30	0.30	0.30	0.30
Zinc	0.25	0.25	1.00	2.00	1.00	3.00
Lead	0.02	0.04	0.30	0.50	0.10	0.25
Tin	0.02	0.04	0.30	0.30	0.10	0.25
Bismuth	0.02	0.04	0.30	0.30	0.10	0.25
Titanium	0.05	0.05	0.05	0.05	0.10	0.25
Others (each)	0.04	0.05	0.05	0.08	0.10	0.10
Others (total)	0.12	0.15	0.15	0.20	0.30	0.30
Aluminum	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.

Source: Specification E753-80, ASTM, West Conshohocken, PA, 1999. With permission.)

and Materials, have since been abandoned.) Grades 5 and 6 are suitable for reuse in the production of casting alloys; grades 1 to 4 are potentially useful for producing various types of wrought alloy. The high limits for magnesium content reflect the predominance of used beverage containers (UBCs) in the aluminum recovered by MRFs. The iron, chromium, and nickel limits reflect the challenge of removing stainless steel from aluminum. In addition to the chemical elements listed in Table 6.1, aluminum recovered by MRFs should have no more than 1 wt.-percent fines for class A product, or 3% for the lower-value class B. A maximum of 2% loose combustible material is specified, as is a maximum of 0.5% moisture.

UBCs AND OTHER PACKAGING

UBCs are among the few types of old aluminum scrap recycled primarily into wrought alloy rather than cast. As a result, the quality requirements for UBC scrap are tighter than for other grades of old scrap. This means more upgrading is performed on UBCs than on other scrap types.

Scrap UBCs come primarily from two sources: cans recovered by blue-bag recycling programs, MRFs, and municipal garbage scavenging and cans specifically collected by buy-back centers and similar operations. In either case the collector usually performs some upgrading of the collected cans before selling them to the remelting facility (Broughton, 1994; Steverson, 1995; Harler, 1998). Beneficiation of the cans by the collector often includes (a) flattening the collected cans, (b) magnetic separation of iron and steel, and (c) baling or logging prior to shipping. A significant concern during flattening and baling is the presence of aluminum aerosol cans, which contain fluids under pressure. These cans are not common, but the contents sometimes include flammable liquids and are potential explosion hazards (Smith et al., 2001). The level of hazard that aerosol cans pose is a matter of debate. Another problem in UBC scrap can be the presence of used hypodermic needles (Goodrich, 2001). The steel in these needles is nonmagnetic stainless, so they are difficult to remove.

The scrap grade specifications in Table 6.1 include several for UBCs. Taldon is the most important of these, since most UBCs are baled prior to shipping. The specification excludes any material other than UBCs. Other container materials such as plastic and steel are specifically unwelcome. One of the more surprising impurities that UBC processors deal with is lead (Steverson, 1998). This appears to come mostly from the dirt attached to the cans, as well as from deliberate contamination (Taylor, 2001b). Since even small levels of lead can injure the properties of 3xxx series alloys, processors and remelters go to considerable lengths to eliminate the dirt. Even so, remelted UBCs often contain 50 tp 100 parts per million of lead, which is an ongoing concern.

Once the baled UBCs are received by a remelt facility, a series of additional upgrading processes are performed (Wilson, 1994; Taylor, 2001b). The first is shredding of the bales, using a low-speed shredder. This (a) reduces the cans to a uniform particle size, (b) exposes the lacquered inside surface of the cans, making them easier to decoat, (c) allows trapped moisture or liquids to be drained away, and (d) releases trapped contaminants in the cans, allowing them to be removed. The shredded cans are then screened and conveyed under another magnetic separator.

Once the impurities are removed, the final step before remelting is decoating. The environmental and hygienic advantages of decoating were described in the previous chapter. Decoating is also useful because it preheats the scrap (McAvoy et al., 1990). This reduces the time needed to melt the UBCs in the melting furnace. Because of this, more metal can be melted per hour in a furnace. In addition, utilizing the fuel value of the volatile organic compounds (VOCs) reduces total required energy costs.

Separate processing of foil and low-aluminum packaging is rare in North America, since separation of this material is rarely required or encouraged (Municipality of Brockton, n.d.; Printers' National Environmental Assistance Center, n.d.). In Europe recovery of foil packaging is often required. As a result, a sufficient supply of this type of packaging exists to justify specific recycling facilities. Two general processing schemes have been developed.

Figure 6.2 illustrates the first (Tetra Pak, n.d.; Charlier and Sjöberg, 1995), which begins by treating laminated beverage cartons in a *hydropulping* tank. The tank contains hot water, which dissolves the glue holding the laminate together. The paper then separates from the polyethylene and aluminum in the laminate. The mixing action of the hydropulping tank shreds the paper, which is then sorted from the other material by wet screening. The polyethylene–aluminum fraction is shredded, followed by ECS to recover the aluminum. Some polyethylene continues to stick to the aluminum, however, and must be removed. This is done by a decoating-type process known as *pyrolysis*. Pyrolysis is similar to decoating in the choice of temperature (about 480°C) and the choice of furnace. A rotary kiln is most common (Escherle, 2002), but moving-bed pyrolysis ovens similar to the moving-bed decoater are also available.

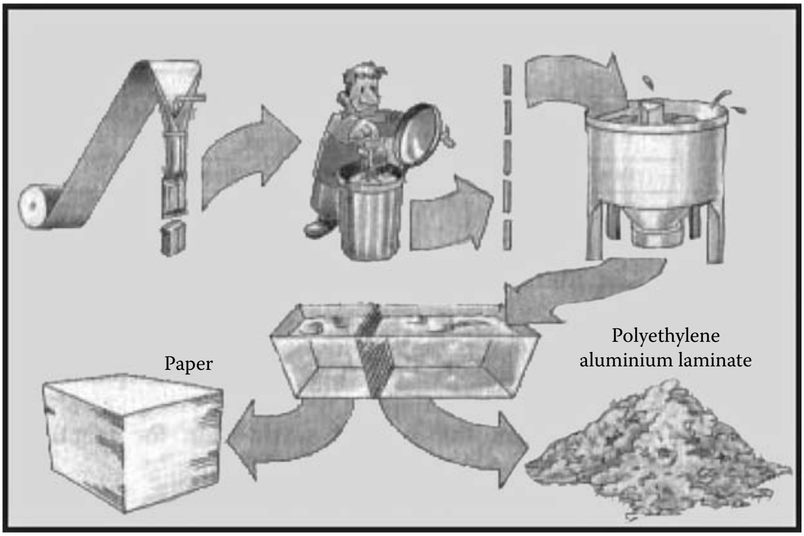

FIGURE 6.2 Flowsheet for recovery of aluminum from laminated beverage cartons by hydropulping. (From Charlier, P. and Sjöberg, G., in *3rd Int. Symp. Recycl. Met. Eng. Mater.,* Queneau, P.B. and Peterson, R.D., Ed., TMS–AIME, Warrendale, PA, 1995, p. 676. With permission.)

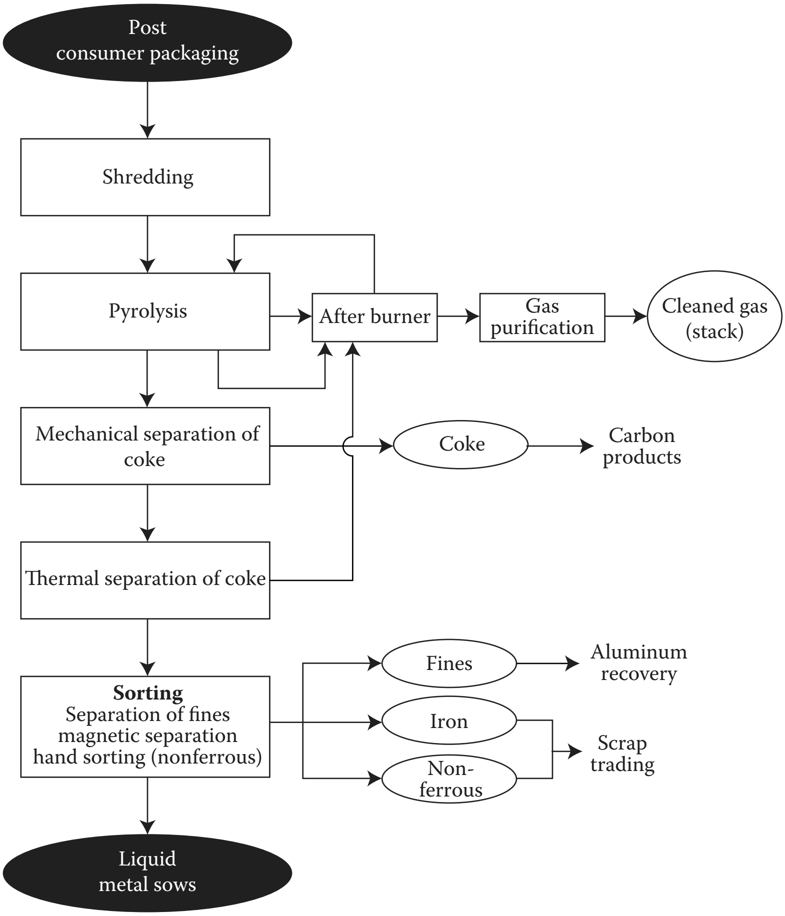

FIGURE 6.3 Flowsheet for recovery of aluminum from laminated beverage cartons by direct pyrolysis. (From Pawlek, R.P., *Light Metal Age,* 63(2), 62, 2001. With permission.)

Figure 6.3 shows the second process for recovering aluminum from foil-type packaging (Pawlek, 2001). This process leaves out the hydropulping step and puts the shredded material directly into a pyrolysis oven. This eliminates a unit process and allows the process to be done dry. However, the feed to the pyrolysis oven (usually a rotary kiln) in this flowsheet has a much higher fraction of organic material. Because of this, the amount of char (here called coke) left behind after pyrolysis is too high to charge to a furnace (Escherle, 2002). The char must be removed, first by sieving and then by controlled oxidation. If the feed is mixed, removal of iron and other nonferrous metals is also required. The low aluminum content of the feed makes it difficult to operate a plant such as this profitably. As a result, burning the foil in a power plant to recover the fuel value might make more sense.

AUTOMOTIVE SCRAP

Figure 6.4 shows a typical flowsheet for the recovery of aluminum from scrapped automobiles (van Linden, 1990). This process was initially developed to recover the iron and steel, which was by far the most valuable part of the hulk. However, the increasing use of aluminum in automobiles means the value of the aluminum in a scrapped car is now roughly equal to that of the iron and steel. As a result, recovery of the aluminum is now just as important and will be more so in the future.

The first step in recycling an automobile is the dismantling process. Initially, the list of parts removed before shredding was brief: the battery, radiator, tires, gas tank, and muffler. However, as the potential value of car parts has grown, the list of items removed by dismantlers has also increased (Creel, 1992). Catalytic converters contain platinum-group metals worth recovering; carburetors can be reconditioned and sold (Swamikannu, 1994). Dismantling also improves the safety of shredding operations. In addition to the gas tank, the removal of air bag canisters is desirable.

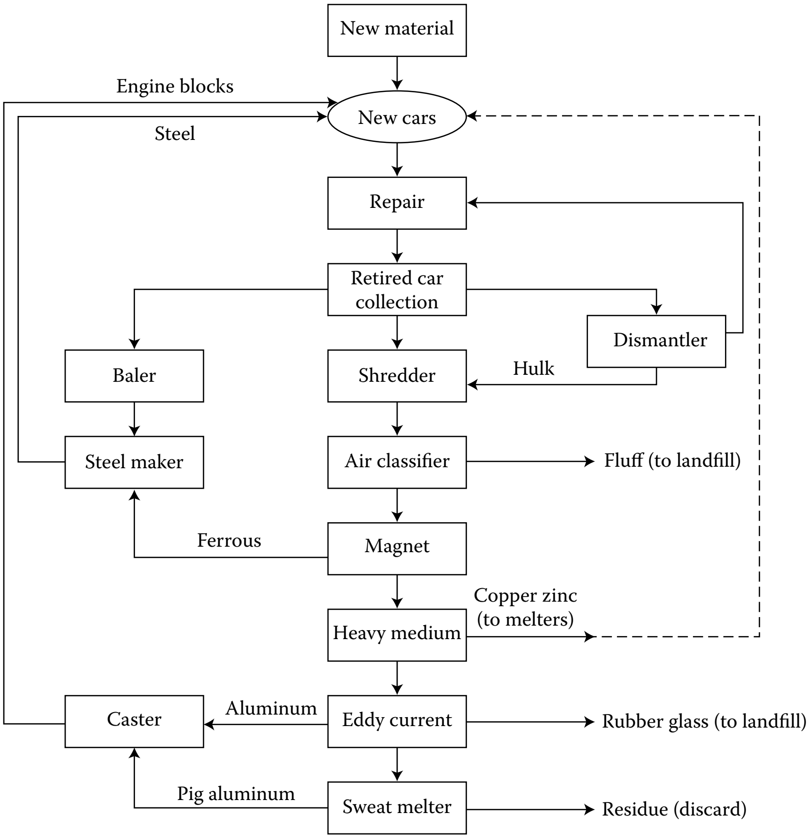

FIGURE 6.4 Typical flowsheet for recovery of scrap metal from automobile hulks. (From van Linden, J.H.L., in *Light Metals 1990,* Bickert, C.M., Ed., TMS–AIME, Warrendale, PA, 1990, p. 675. With permission.)

These can explode when charged to a furnace, and some smelters will no longer accept scrap shipments that contain them (Anonymous, 2003). All remaining fluids in the car are drained prior to dismantling.

Aluminum parts with enough potential value to be deliberately removed from a vehicle before shredding include wheels, compressors, alternators, water pumps, transmissions, and possibly engine blocks and heads (Gariépy et al., 1993; D'Astolfo and Bruggink, 1994). Dismantling is increasingly important as a recycling process. Swamikannu (1994) notes that the value of dismantled parts from a typical junked automobile is more than 15 times that of the scrap metal left behind. Even so, the parts recovered from a typical dismantled auto contain only about 20% of the aluminum used in the vehicle.

A second type of dismantling that affects aluminum recovery from auto hulks is assembly dismantling (Zapp et al., 2002). Figure 6.5 shows a German auto recycling flowsheet in which parts of the body are separated from the engine and drive train before shredding. The advantage of this is that shredding different parts of the car separately makes it possible to choose shredder conditions that work best for the particular type of material. Car bodies feature more wrought material, along with plastic parts. The transmission and drive train consist mostly of cast alloy, which is more difficult to shred but generates less dust.

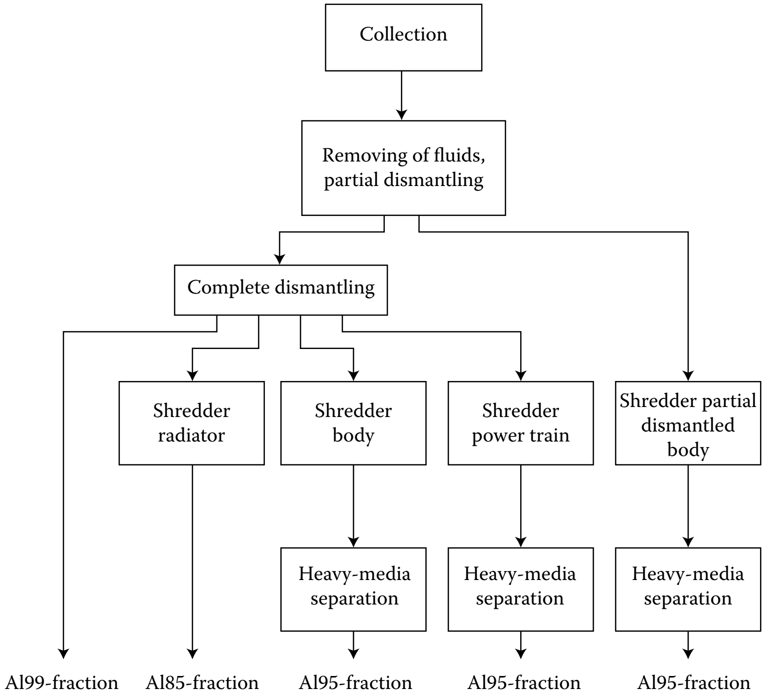

FIGURE 6.5 Flowsheet for auto hulk processing using assembly dismantling. (From Zapp, P., Rombach, G., and Kuckshinrichs, W., in *Light Metals 2002,* Schneider, W., Ed., TMS–AIME, Warrendale, PA, 2002, p. 1003. With permission.)

Once the desired dismantling has been done, the remaining auto hulk is shredded (Ness, 1984). Nearly all automobiles are shredded using the hammer mill described in the previous chapter. As is the case with most processing equipment in the industry, the trend is toward larger and more powerful shredders, which can process more hulks per hour. Once the car is shredded, a magnetic separator removes most of the iron and steel. The remaining residue is then sent through an air separator, which removes most of the light material (plastic, paper, fabric). This light material is then mixed with the dust recovered from the shredder to form a product stream known as *automobile shredder residue (ASR)* or *shredder fluff.* The remaining material is called the *nonmagnetic shredder fraction (NMSF)* and contains most of the nonferrous metals in the auto hulk, along with rubber, glass and some unrecovered plastic. About 15% of the aluminum in a scrap auto winds up in the shredder fluff, and 60% end up in the NMSF (D'Astolfo and Bruggink, 1994). (The remainder was recovered in dismantling.)

Depending on the mix of cars being shredded, NMSF (grade Zorba in Figure 6.1) analyzes between 20% and 40% aluminum (Rousseau and Melin, 1989). Several strategies are used to process it. The previous chapter discussed the use of hand sorting in less-developed countries, and this is a common approach (Minter, 2003). Even given the cost of shipping, hand sorting has significant financial advantages (Schaffer, 2002). A less labor-intensive approach uses heavy media separation to remove the heavier metals and eddy-current separation to separate the aluminum and magnesium from nonmetallics (Novelli, 2000). ECS typically generates three products (Gariépy et al., 1993): a nonconductor stream containing most of the rubber and plastic, a mixed-metal stream containing high-density metals and pieces of aluminum attached to other metals, and a "pure" aluminum product. Figure 6.1 includes the ISRI scrap grade specification for Twitch, which includes maximum allowable percentages for free zinc (3%), free magnesium (1%), ferrous alloys (1.5%), and nonmetallics (5%). (Free metals are those present as pieces of zinc, magnesium, etc., rather than as part of an aluminum alloy.) ECS units must be adjusted to generate a product meeting this specification. Aluminum can be recovered from the mixed-metal fraction by sweat melting (van Linden, 1990).

The aluminum content of shredder fluff is only 1.5 to 2%, and the percentage of other metals is even smaller. As a result, shredder fluff has traditionally been landfilled. However, this is increasingly unacceptable from an environmental standpoint. Regulations such as the European Union recycling targets discussed in Chapter 3 have made it increasingly necessary to process shredder fluff. The processing scheme for shredder fluff parallels that for shredded MSW — initial screening using a trommel, followed by ECS. Without the disincentives of increased landfilling costs or regulatory demands, metal recovery from shredder fluff is not economically justifiable (Johnson and Wang, 2002). However, both of these are having an impact, and it is likely that aluminum recovery from junked automobiles will increase from its current 80 to 85% to a value approaching 100% in the future.

ELECTRICAL AND ELECTRONIC SCRAP

Upgrading schemes for wire and cable scrap vary according to the type of scrap being processed. As a result, there is no typical flowsheet for the process. However, several unit operations are common to most cable scrap processing sequences (Sullivan, 1985).

The first step in cable processing is often hand sorting, which separates cable scrap by metal (aluminum or copper) and by size (Reid, 2001). This is typically followed by a shearing step, which reduces the cable to 25- to 50-cm lengths. Portable alligator or guillotine shears are commonly used for this. Some operations now use high-speed shredders, and prechop the scrap to lengths as small as 2 cm (Taylor, 2001a).

Figure 6.6 shows the construction of a typical underground cable (Nijkerk and Dalmijn, 1998). Recycling this cable is more difficult than recycling the typical plastic-coated above-ground cable. In addition to the materials shown here, underground cables can also have lead sheathing, mastic, oil, grease, and tar-impregnated paper. Because of this, wire-chopping scrap underground cable can present a serious safety and environmental hazard. To mitigate this hazard, sheared underground cable is often stripped to separate the coating layers (Sullivan, 1985). The stripping opens up the layers, and the metal content is pulled out by hand. The process is slow and justifiable only for large-diameter cables.

For other cables, chopping (also known as granulation) follows shearing (Reid, 2001; Sullivan, 1985). Chopping is a specialized form of low-speed shredding,

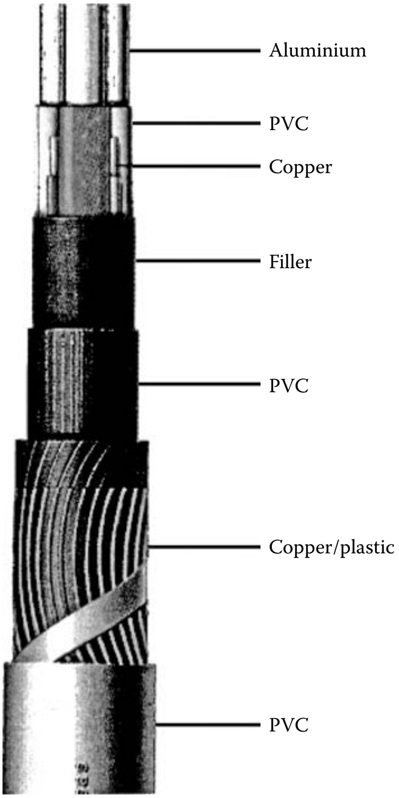

FIGURE 6.6 Construction of an underground cable. (From Nijkerk, A.A. and Dalmijn, W.L., *Handbook of Recycling Techniques,* Nijkerk Consultancy, The Hague, The Netherlands, 1998. With permission.)

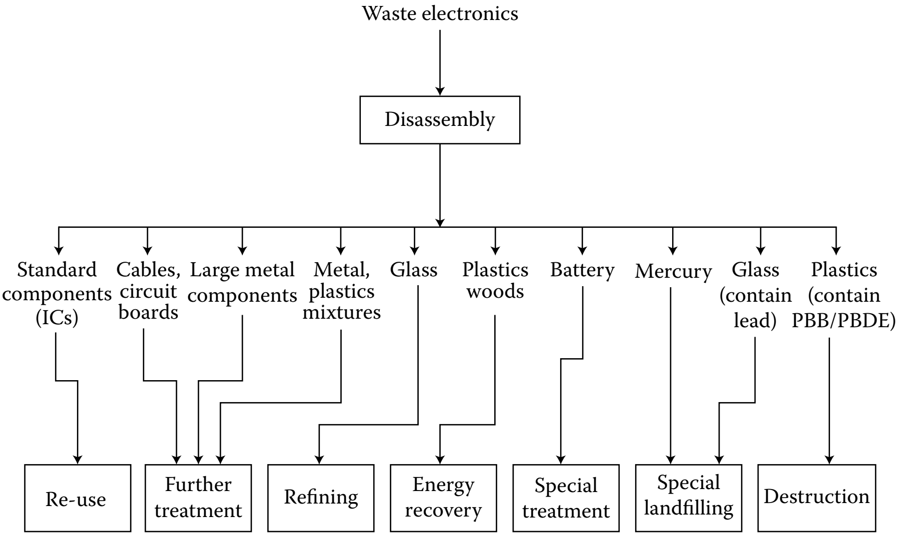

FIGURE 6.7 Flowsheet for materials recovery from obsolete computers. (Reprinted from *Journal of Hazardous Materials,* Vol. 99, J. Cui and E. Forssberg, E., Mechanical recycling of waste electric and electronic equipment: a review, pp. 243–263, copyright 2003, with permission from Elsevier.)

intended to separate the metal in the cable from the plastic or rubber coating. The smaller the size of chop produced by this step, the greater the liberation of the metal from the insulation. However, chopping to a smaller size increases costs and reduces the productivity of the granulator. Some operations have a two-stage chopping sequence to minimize this bottleneck. The final chop size is usually less than 1 cm.

The next step is often magnetic separation to remove any steel pieces from the chop. Larger pieces of steel are usually removed by hand shearing prior to chopping, but small pieces may remain, and must be removed. This is followed by separation of the metal from the insulation, using the difference between the specific gravity of the two. This is most commonly done using air tables (Sullivan, 1985), but air knives are also used, as are water-based rising current separators. If the cable has not been well separated before chopping, a second classification step is needed to separate copper from aluminum.

The recovery of aluminum from electronic scrap is different than from other types because the average aluminum content of discarded electronic equipment is small, perhaps about 2% (Sum, 1991). The value of other materials in the scrap, in particular copper and precious metals, is greater than that of the aluminum. As a result, recovery of the aluminum is not a high-priority concern. However, the recycling of scrap computers and associated equipment is increasingly mandated by law (Zhang and Forssberg, 1998). The development of recycling schemes that minimize the amount of waste to dispose of means that recovery of aluminum is important, in spite of its low value.

Figure 6.7 shows one of many schemes for processing obsolete computers (Cui and Forssberg, 2003). This scheme focuses on dismantling rather than mechanical processing. The "metals" products include metal cases, rails, and structural parts.

Dismantling improves recovery of these parts while minimizing contamination. It also increases the possibility of closed-loop recycling. However, dismantling is also labor-intensive, and the parts it recovers cannot be resold as in auto recycling. As a result, more automated processes are also used. Figure 6.8 is the process flowsheet for nonmanual electronics recycling (Kozlowski et al., 2000). In some ways, this flowsheet simulates an auto recycling plant, with shredding steps followed by classification (screening), magnetic separation, ECS, and air classification. The plant generates several product streams, which are further processed to separate the aluminum, copper, and other metals. Without the push provided by mandatory recycling legislation, it is doubtful whether a facility like this would be economically justified.

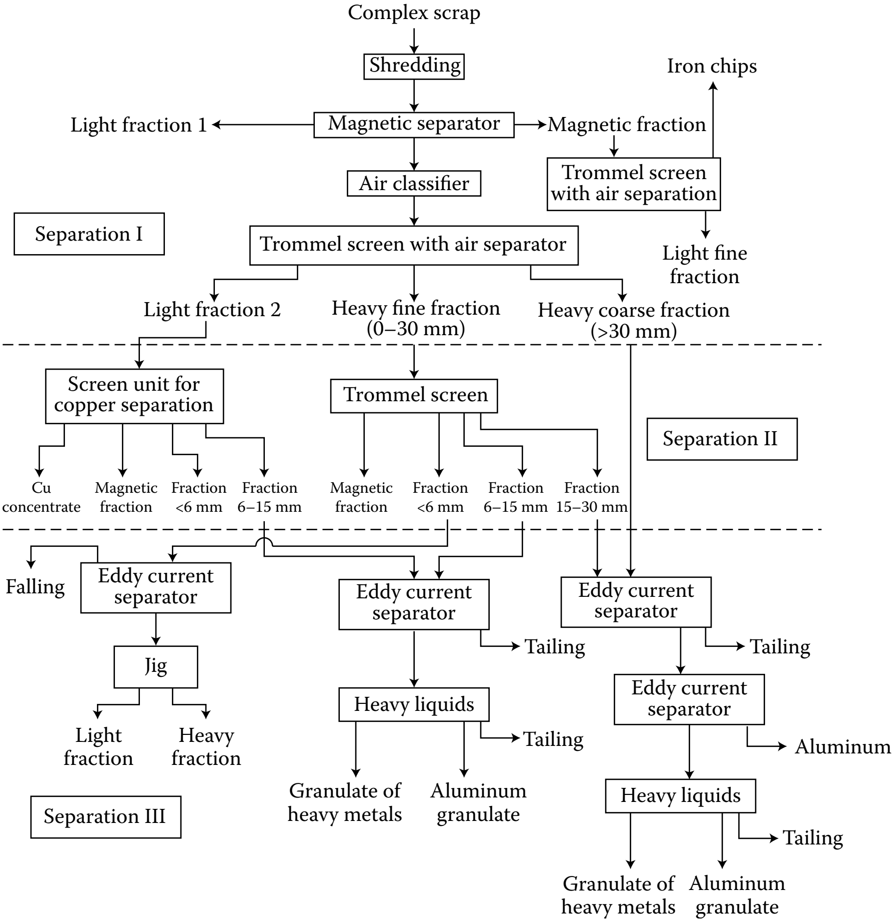

FIGURE 6.8 Nonmanual processing of electronic scrap. (From Kozlowski, J. et al., *Metallurgy*, 54, 645, 2000. With permission.)

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7 Melting Furnace Fundamentals

Most of the scrap aluminum recycled today is remelted in a furnace fired with fossil fuels, most commonly natural gas. Furnaces of this type have been used since the recycling of aluminum began, and while the number of designs has proliferated, the fundamentals behind the melting of aluminum have not. Appreciation of these fundamentals is important to understanding the reasons for the numerous furnace designs and equipment innovations that have taken place over the past 20 years.

HEAT-TRANSFER KINETICS

Figure 7.1 presents a simple view of a typical *reverberatory* (reverb) furnace for melting solid aluminum. The furnace is typically fired with natural gas, causing heat to be transferred from the burner to the mixture of solid and/or molten aluminum in the hearth (furnace bottom) below. While much of the heat is transferred directly from the flame to the metal, some is transferred to the metal by indirect transfer from the flame to the refractory walls. The heat reverberates (bounces) off the walls and impinges on the aluminum in the hearth. Heat may bounce back and forth between the metal and the walls several times before it is absorbed by the metal, since aluminum reflects heat better than most other metals. As a result, reverb furnaces feature shallow baths, maximizing the surface area per ton of contained metal.

Heat is transferred from the flame to the metal by one of two means: *radiation* and *convection*, the direct contact of hot gas on the surface of the bath itself. The heat transfer by radiation is governed by the expression (Wu et al., 1993; Jenkins, 2000):

$$q_s = \varepsilon\sigma A\left(T_g^4 - T_s^4\right) \tag{7.1}$$

where q_s is the rate of heat transfer in watts per square meter of bath surface, A is the amount of the metal surface exposed per square meter of bath surface (1 if the metal is molten, less if not), σ is Planck's constant ($5.67 \cdot 10^{-8}$ W/m^{2}K^4), ε is the emissivity of the aluminum in the hearth, and T_g and T_s are the temperatures of the flame and the solid aluminum, respectively. ε is extremely low for polished aluminum (~0.05); as the metal heats up and acquires a thicker oxide surface, ε increases to about 0.35 (Alchalabi et al., 2002). A is increased by a thicker layer of solid scrap in the hearth

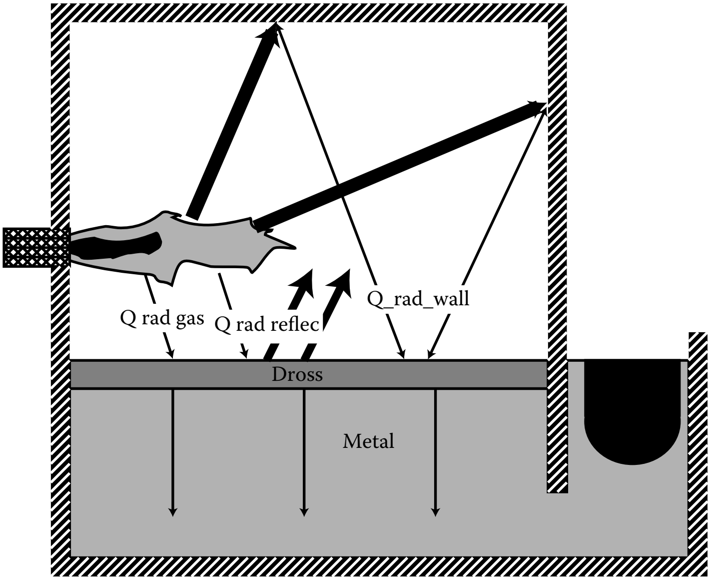

FIGURE 7.1 Cross section of reverberatory melting furnace, illustrating radiation heat transfer. (From Alchalabi, R., Meng, F., and Peel, A., in *Light Metals 2002,* Schneider, W., Ed., TMS–AIME, Warrendale, PA, 2002, p. 739. With permission.)

and decreased by greater porosity (open space) in the scrap layer and by larger pieces of scrap in the charge. Equation 7.1 calculates only direct radiation heat transfer rates, not radiative heat transfer by reverberation. Equation 7.1 is also accurate only for surfaces directly facing the radiation source. For the surface not directly facing the radiation source, a "view factor" is used to calculate a reduced value of q_s.

Because q_s is a function of T_g^4, raising the flame temperature is especially important in increasing heat-transfer rates by radiation. However, this has its drawbacks. Because surfaces directly facing the radiation source receive the most radiation, the metal nearest the flame heats much more rapidly than metal farther away from the flame. This causes overheating, which leads to excessive oxidation of the overheated metal. As a result, melt loss and dross formation are increased (Yap, 1995).

The rate of heat transfer by convection is also calculated by a simple expression:

$$q_s = h\,(T_g - T_s) \tag{7.2}$$

where q_s is again the rate of heat transfer per unit area of bath surface, and T_g and T_s are the temperatures of the gas above the surface and of the solid (or liquid) metal. h is a convection heat transfer coefficient, determined by the composition, pressure, temperature, and flow characteristics of the gas; typical values for melting conditions are 10 to 30 W/m^2-°C (Jenkins, 2000). Higher pressures increase h, as does directing gas flow at the metal rather than parallel to it (Goetz, 1983). Convection heat-transfer depends less on flame temperature than radiation but is still promoted by higher temperatures. Because no single point source is involved, it is less likely to cause overheating than radiation. However, it is also less effective at heat transfer. Radiation accounts for 80% of the heat transfer in the typical reverb furnace (Kiss et al., 2002). In addition, the surface turbulence caused by the gas can break through dross layers, exposing fresh metal and increasing melt loss (Yap, 1995).

Once heat is transferred to the surface of the metal, it is transferred away from the surface to the bulk of the aluminum. In molten metal this is done partly by convection; in solid and molten metal conduction plays a large role as well. The expression governing heat transfer by conduction per unit area of melt surface is

$$q_c = (k/L)\,(T_{sur} - T_{bulk}) \tag{7.3}$$

where k is the thermal conductivity of the metal, L is the depth of the melt, T_{sur} is the temperature at the surface, and T_{bulk} is the temperature of the bulk of the melt (or solid charge). The thermal conductivity of solid aluminum is higher than that of liquid (Goetz, 1983), but this is reduced in scrap loads by the gaps between the charged pieces. Aluminum has a high thermal conductivity, but that of dross is lower, and heat transfer through the dross layer can be a limiting factor in melting rates (Alchalabi et al., 2002).

Because heat is constantly being transferred to the metal surface in a melting furnace, the surface temperature will always be higher than the bulk temperature. If conduction is the primary heat-transfer mechanism, the *stratification* in the molten metal that results can be severe (Riverin et al., 1997; Alchalabi et al., 2002), with temperature differences between the top and bottom of the melt of 100°C or higher. As a result, increasing the convective heat transfer coefficient h is important. Since the temperature and composition of the metal are fixed, stirring is the most effective method of increasing h. Several stirring devices are described in the next chapter with this in mind.

COMBUSTION

Most reverb furnaces burn natural gas to provide energy for melting. Natural gas consists mostly of *methane* (CH_4), usually with some *ethane* (C_2H_6). Several other hydrocarbons and other gases are present in smaller concentrations; the composition varies from place to place. The overall combustion of natural gas reacts the hydrocarbons with oxygen to generate carbon dioxide and water vapor:

$$CH_4 + 2\,O_2 = CO_2 + 2\,H_2O\,(g) \tag{7.4}$$

The energy produced by this reaction heats the product gases to a characteristic flame temperature. The radiation from this flame and the heat transfer from the product gases to the metal by convection heat up and then melt the scrap charge in the furnace.

Several characteristics of the flame are adjustable. The most important is the flame temperature. Normal air contains roughly 21% oxygen and 79% nitrogen. Nitrogen does not participate in the combustion reaction, but it does absorb much of the heat that combustion generates. As a result, with more gas to absorb the same amount of energy, flame temperatures are relatively low (<2000°C). When pure oxygen is mixed with air to create an enriched air, the amount of nitrogen brought into the furnace decreases. With less nitrogen to adsorb heat, the flame temperature can increase by several hundred degrees (Becker and Heffron, 1994). The flame temperature can also be increased by preheating the incoming air. If further cooling is needed, recycling some of the off-gas back into the furnace absorbs additional heat and reduces the flame temperature (Anonymous, 2005).

High flame temperatures have the advantage of increasing heat transfer rates and improving furnace productivity. However, there are also disadvantages. The *hot spot* problem caused by excessive radiation heating is a problem at higher flame temperatures (Yap, 1995). The higher temperature of the refractory furnace lining resulting from higher flame temperatures also shortens its life. A bigger problem is unwelcome side reactions that are more likely to occur at flame temperatures above 2000°C. The most troublesome are reactions between nitrogen and unreacted oxygen to form nitrogen oxides:

$$N_2 + O_2 = 2\ NO \tag{7.5}$$

$$N_2 + 2\ O_2 = 2\ NO_2 \tag{7.6}$$

NO and NO_2 are the main constituents of NO_x, a significant pollution concern. Reactions 7.5 and 7.6 become more feasible as the flame temperature increases (Becker and Heffron, 1994). However, lower partial pressures of N_2 in the exhaust gas caused by the use of oxygen-rich air reduce NO_x generation. As the gas temperature decreases, NO and NO_2 will decompose to N_2 and O_2 if given enough time.

If the amount of oxygen mixed with the fuel in the burner is not sufficient to immediately burn the fuel, Reaction 7.4 will happen by stages. The first stage is *pyrolysis* of the fuel to generate hydrogen and small particles of soot (Wechsler and Gitman, 1990):

$$CH_4 = C + 2\ H_2 \tag{7.7}$$

The soot and hydrogen then react with more oxygen to produce carbon monoxide and water vapor:

$$C + 2\ H_2 + {}^3/_2\ O_2 = CO + 2\ H_2O \tag{7.8}$$

The carbon monoxide then reacts with more O_2 to combust completely to CO_2. This reaction sequence is significant because the soot increases the *luminosity* of the flame (Yap, 1995) — its ability to radiate. Sootier flames tend to be more spread out and radiate from a larger area. However, the slower reaction sequence tends to generate a lower flame temperature.

THE CHEMISTRY OF FLUXING

All aluminum scrap fed to a furnace has a very thin skin of aluminum oxide on the surface, caused by the spontaneous oxidation of aluminum in air:

$$2\ \mathrm{Al} + {}^{3}\!/_{2}\ \mathrm{O_2} = \mathrm{Al_2O_3} \qquad (7.9)$$

The skin grows very slowly at normal temperatures and thus is usually not apparent on the surface. When the scrap is heated in a furnace, the higher temperatures cause the skin to grow more rapidly, especially if the scrap is heated in air or an oxidizing environment.

When the aluminum melts, the Al_2O_3 floats to the surface, forming a second phase known as *dross*. Because of the surface tension of the skin, metallic aluminum is also trapped in the dross. The metal content of the dross can be anywhere from 15 to 80%, depending on melting conditions. As a result, reducing metal loss rates to the dross is an important consideration in scrap remelting.

One of the options available to remelters trying to reduce metal loss is to use a *drossing flux* designed to break the oxide skin and release the entrapped metal. Peterson (1990) lists the following requirements for such a flux:

- Should cover the molten metal and limit further oxidation
- Should dissolve or suspend dirt, oxides, and other nonmetallic substances
- Should promote coalescence of the metal droplets in the dross by stripping away the Al_2O_3 layer
- Should have a melting point lower than that of aluminum (660°C)
- Should have a density less than that of molten aluminum (2.3 g/cm^3)
- Should not react with or contaminate molten aluminum
- Should not attack furnace refractories
- Should be nontoxic
- Should have a low vapor pressure
- Should not be hygroscopic (avoid adsorbing water)
- Should be inexpensive or easily recycled
- Should have a low viscosity
- Should separate cleanly from the metal

These requirements quickly reduce the list of available materials to a short list of chloride and fluoride salts. Over time, a standard base flux composition of 50 wt.-% NaCl, 50% KCl has become commonplace (Peterson, 1990). (An *equimolar* flux analyzing 56% KCl and 44% NaCl is also used.) However, while this flux is effective at covering the metal and dissolves oxides to some degree, it is less effective at causing coalescence. Furnace operators have learned that adding small levels of fluoride salt to the base drossing flux promotes coalescence and generates a dross with much less metal in it. The most popular fluoride addition is *cryolite* (Na_3AlF_6), but NaF and KF are also effective (Crepeau et al., 1992).

The reason that fluoride additions are effective remains a matter of some dispute. Initially, it was held that added fluoride increased the solubility of oxides in the

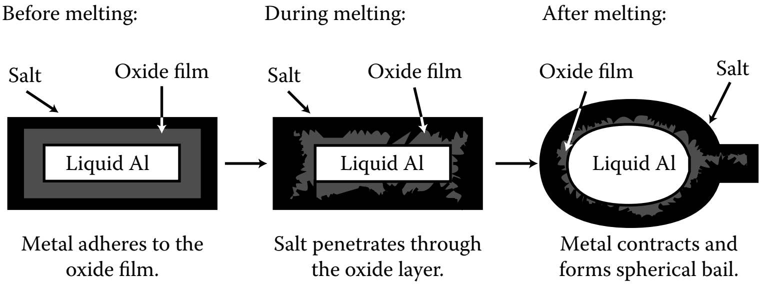

FIGURE 7.2 Impact of fluoride-containing fluxes on aluminum droplet coalescence in molten dross. (From Friesen, K.J. et al., in *Light Metals 1997,* Huglen, R., Ed., TMS–AIME, Warrendale, PA, 1997, p. 857. With permission.)

drossing flux (van Linden and Stewart, 1988), including Al_2O_3, and that the oxide skins simply dissolved. Most recent evidence, illustrated in Figure 7.2, suggests a different scenario (Friesen et al., 1997). In this view, the changing shape of the aluminum in a droplet as it melts causes the oxide skin to crack. Molten flux penetrating the cracks makes contact with the molten droplet. It has been repeatedly shown that fluoride additions (particularly Na_3AlF_6, NaF, and KF) greatly reduce the surface tension of molten flux on molten aluminum (Ho and Sahai, 1990), which causes the flux to spread out along the droplet surface. As this happens, the remnants of the oxide skin separate from the metal, freeing it to combine with other droplets as they come into contact.

REFRACTORY INTERACTIONS

Although the demands on refractories in aluminum melting and holding furnaces are not as severe as those in other molten-metal processes, there are still some requirements:

- Lack of reactivity with the molten aluminum
- Low solubility in molten flux
- Lack of reactivity with the Al_2O_3 in the dross
- Low thermal conductivity
- Hydration resistance (important since the atmosphere above the melt has a high water-vapor content from the combustion of the fuel)
- Oxidation resistance
- Stability at temperatures up to 1200°C (or higher if oxygen-enriched air is used in the burners)
- Good mechanical strength (important given the repeated loading of the furnace with solid scrap)

Of course, the most significant requirement is low cost.

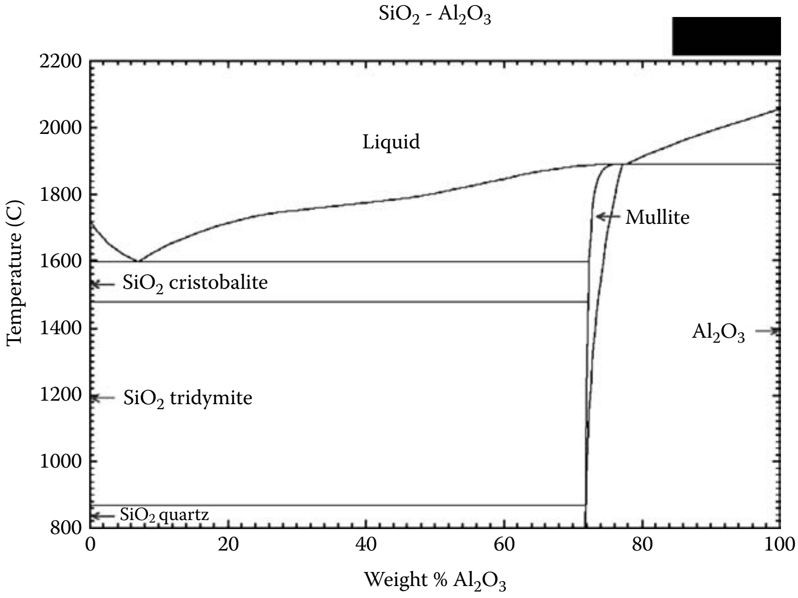
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FIGURE 7.3 The alumina–silica phase diagram.

The combination of these requirements eliminates most of the available refractory compositions. Of the remaining choices, those that have by far become the most popular for melting and holding furnaces are refractories based on the alumina-silica system. Figure 7.3 illustrates the system, which features the ternary compound *mullite* ($Al_6Si_2O_{13}$) in addition to pure *corundum* (Al_2O_3) and *silica* (SiO_2). The refractories used in contact with molten metal and dross in aluminum melting and holding furnaces have a high alumina content (60 to 85% Al_2O_3) and typically consist mostly of a mixture of corundum and mullite. However, there are variations in composition (CaO is often added to these refractories) and mineralogy (aluminosilicate refractories often contain significant levels of free silica). Recent developments in refractory composition and selection will be described in the next chapter.

The biggest concern in refractory use in molten aluminum has been corrosion, especially at the melt line, or *bellyband.* Corrosion results from the reaction between the molten aluminum and the refractory to generate corundum and elemental silicon (McCollum, 1989; Afshar and Allaire, 1996):

$$4\ Al + 3\ SiO_2 = 2\ Al_2O_3 + 3\ Si \tag{7.10}$$

$$4\ Al + {}^{3}/_{2}\ Al_6Si_2O_{13} = {}^{13}/_{2}\ Al_2O_3 + 3\ Si \tag{7.11}$$

Both reactions are thermodynamically favored at furnace temperatures. However, below the melt line the reaction is limited by the formation of a surface layer of corundum, which prevents further access of the metal to the refractory underneath and stops the reaction. The surface layer is less adherent when the molten alloy contains higher levels of zinc or magnesium, and refractory corrosion is a greater concern in these conditions (Drouzy and Richard, 1974).

At the bellyband conditions are different, owing to presence of oxygen in the adjacent furnace environment. As molten metal penetrates into the pores of the refractory, the oxygen reacts directly with the aluminum to form corundum (Quesnel et al., 1996). The higher temperatures at the bellyband cause the reaction to occur even more quickly, and the porosity of the refractory allows the metal to migrate upward through the brick, forming corundum at locations above the melt line. The result is a corundum deposit large enough to reduce furnace capacity and adherent enough to take some of the original refractory with it when mechanically removed during cleaning (Raju, 2003).

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8 Melting Furnace Parts and Accessories

As Chapter 9 will show, there are numerous types of gas-fired melting furnaces for scrap aluminum. These furnaces have many parts in common. Advances in the design of these parts affect all types of furnaces. These advances include the creation of accessories — equipment that is attached to the main body of the furnace, either for occasional or semicontinuous use. The purpose of these parts and accessories is to meet a common goal — melting aluminum scrap in the shortest possible time, with the highest possible efficiency and the lowest possible melt loss.

BURNERS

The developers of improved burners try to meet several goals, some of which are at odds with each other:

- Improving thermal efficiency, which is lower than 30% for many furnaces
- Decreasing fuel costs
- Increasing the rate of heat transfer to the charge, which increases furnace productivity
- Decreasing melt loss
- Increasing refractory life, particularly at or above the melt line
- Decreasing emissions of pollutants, particularly NO_x

Many new designs have been proposed. Some of the more important trends in burner design and operation are described below:

USE OF ENRICHED AIR

The difficulties caused by the 79% nitrogen in air were described in the previous chapter. The biggest of these difficulties is the heat lost in the nitrogen when it is put out the stack, which represents wasted energy and money. High nitrogen content in the furnace atmosphere also increases the size of the ductwork needed to contain it and reduces flame temperatures, which can be undesirable in some furnaces. As a result, some furnace operators now enrich their combustion air by adding oxygen. Figure 8.1 illustrates the impact on flame temperature of oxygen enrichment (Becker et al., 1997). As the previous chapter pointed out, hotter flames transfer heat more quickly to the metal underneath, improving productivity. The reduced nitrogen throughput of oxygen-enriched combustion means less heat lost in the nitrogen and thus higher efficiency. Figure 8.2 illustrates another consequence of oxygen

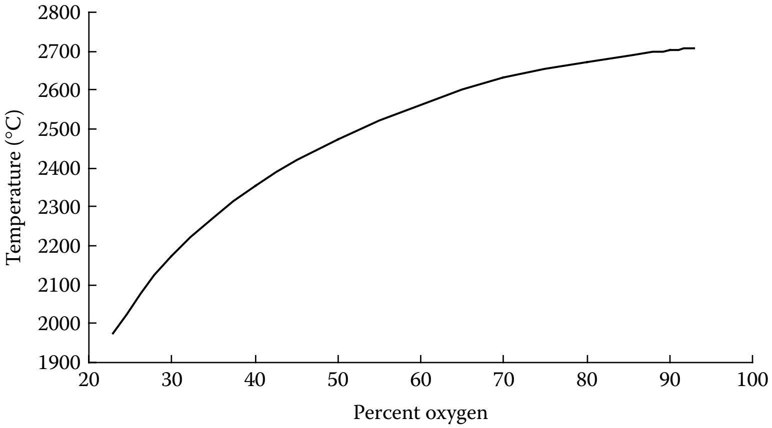

FIGURE 8.1 Impact of oxygen enrichment on natural-gas flame temperature. (Adapted from Becker, J.S. et al., in *EPD Congress 1997,* Mishra, B., Ed., TMS–AIME, Warrendale, PA, 1997, p. 673. With permission.)

enrichment: higher flame velocity (Abernathy et al., 1996). As the previous chapter pointed out, heat transfer by convection is increased by higher gas turbulence. This is especially useful when heating solid aluminum.

However, oxygen enrichment presents challenges as well (Abernathy et al., 1996; Becker et al., 1997). Higher flame temperatures improve heating rates but can also lead to localized overheating and increased melt loss (Wechsler and Gitman, 1990).

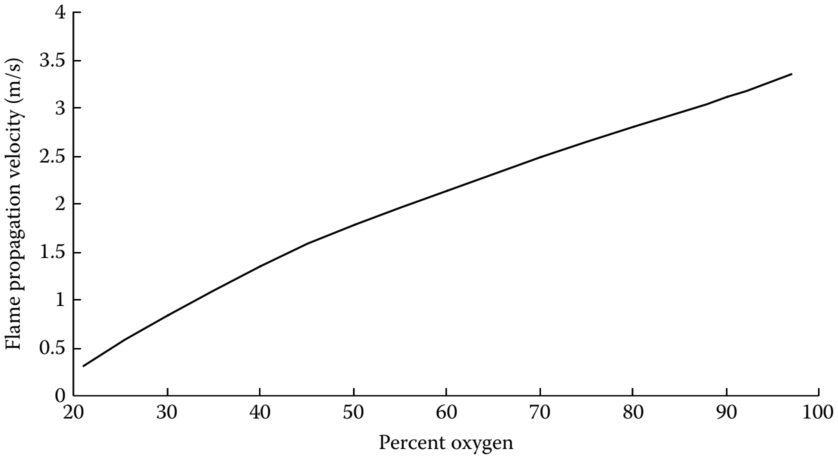

FIGURE 8.2 Impact of oxygen enrichment on natural-gas flame velocity. (Adapted from Abernathy, R., McElroy, J., and Yap, L.T., in *Light Metals 1996,* Hale, W., Ed., TMS–AIME, Warrendale, PA, p. 1233, 1996. With permission.)

Higher flame temperatures also mean more refractory degradation above the melt line. Finally, higher flame temperatures encourage the formation of NO_x (Beichner, 2002). As a result, burner designs for enriched air usage often include special features to reduce the flame temperature and encourage NO_x decomposition. Because most of the improvement from oxygen enrichment occurs in the initial stages (Hewertson, 2000), oxygen-enriched combustion is usually limited in practice to levels below 30% O_2.

REGENERATION

Regeneration is a technique for heat recovery from the combustion of off-gases, introduced to the secondary aluminum industry in the 1980s. Figure 8.3 illustrates the principle behind regenerative burners (Bowers, 1988, 1991). In this case burners are mounted at opposite ends of the furnace. Each burner features a regeneration bed, comprised of a nonreactive ceramic (Lied, 1990). When the burner at the left is in operation, exhaust gas is drawn through the regeneration bed at the right. The bed absorbs heat from the exhaust gas, heating up in the process. Eventually, the burner at the left is shut down and the one at the right is fired up. When this happens, combustion air is drawn through the heated regeneration bed. The air is preheated by the bed, which loses its energy in the process. At the same time, the regeneration bed at the left is opened to receive exhaust gas, and is heated up in turn. When the regeneration bed at right has given up most of its stored heat, the left burner becomes operational again and the process is repeated.

By preheating the air, regeneration increases flame temperatures, improving furnace productivity. Furthermore, the recovery of heat from the off-gas means that less heat is lost from the furnace; this decreases fuel costs. Because the impact of regeneration is similar to that of oxygen enrichment, the two techniques are rarely used at the same time. Regeneration also presents the same potential disadvantages as oxygen enrichment: higher melt loss, greater refractory wear, high NO_x generation (de Groot, 1993; Schalles, 1998).

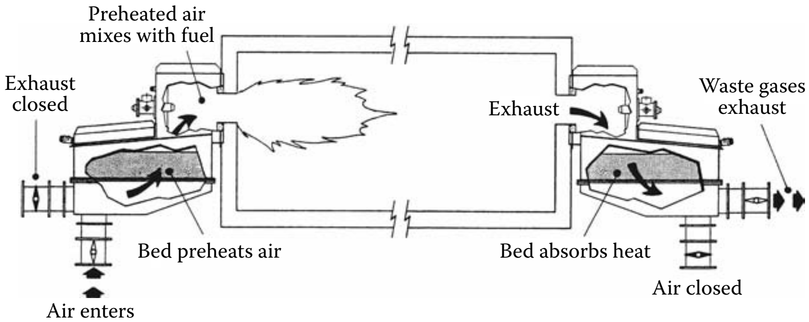

FIGURE 8.3 Schematic of regenerative burner arrangement for reverberatory melting furnace. (From Bowers, J.D., *Die Casting Engineer,* 35(3), 45, 1991. With permission.)

FLAME MANIPULATION

Furnace operators have learned that different types of flame are desired at different points during the melting process. For example, during the early stages of melting, the low emissivity of metallic aluminum makes heat transfer by radiation difficult. A flame that transfers more energy by convection is desirable. After the metal is molten, the dross layer on top absorbs more radiation; in addition, the disturbance of the dross layer by turbulent exhaust gas increases melt loss. Because of this, a flame with better radiation characteristics is preferred (Beichner, 1999). In addition, a flame that radiates from an area rather than a single point reduces the overheating of both metal and refractory.

In response to this, burner manufacturers have developed designs that manipulate flames in several ways (Abernathy et al., 1996; Becker et al., 1997; Krichten et al., 1997; Beichner, 1999). A popular manipulation is the so-called *flat flame,* in which the flame is spread out over some width, rather than an axisymmetrical cone. The *staged* introduction of air or fuel helps spread out the flame over an area, rather than a single location (Lied, 1990; Wechsler and Gitman, 1990; Schalles, 1998). The staged introduction of air also encourages incomplete initial combustion of the fuel. This results in pyrolysis, as described in the previous chapter. The soot created by the pyrolysis makes the flame more luminous, encouraging heat transfer by radiation. When oxygen enrichment is used, the flame is often shrouded in recycled exhaust gas; this lowers the flame temperature without generating more exhaust gas. Increasing the fuel and air velocity helps generate a *long* flame, which reduces overheating.

BAFFLES

Minimizing NO_x generation has increasingly become the overriding factor in burner design for melting furnaces (Lied, 1990). This generally requires keeping flame

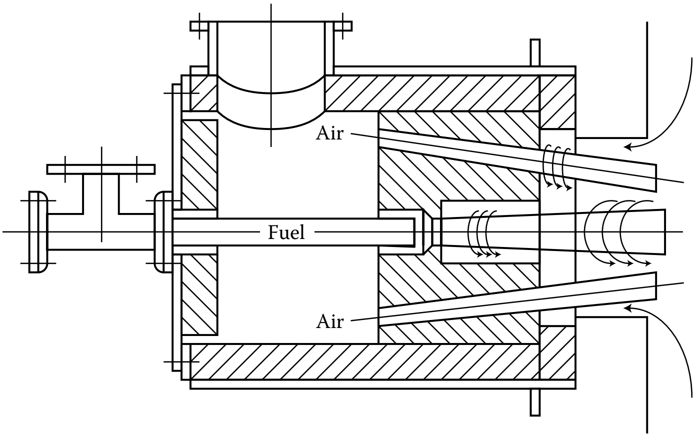

FIGURE 8.4 Use of baffles in burner design. (From Lied, C.R., in *Energy Conservation Workshop XI: Energy and the Environment in the 1990s,* Aluminum Association, Washington, 1990, p. 227. With permission.)

temperatures down. It is also recommended to use a *reducing* flame, in which the fuel is incompletely combusted. A reducing flame generates an exhaust with a very low partial pressure of oxygen. This retards the formation of NO and NO_2. Another approach to reducing NO_x formation is the use of baffles in burner design, as shown in Figure 8.4. The baffles cause product gases to be entrained around the air and fuel jets, lowering flame temperatures and discouraging NO_x formation.

RECUPERATORS

Recuperators perform a similar function to regenerators in that they recover heat from the furnace exhaust gas and use it to preheat the combustion air. The main differences between the two are that (a) recuperators are a separate piece of equipment, rather than the integral part of the burner shown in Figure 8.3 and (b) recuperators operate on a steady-state basis, instead of the semicontinuous operation of regenerators.

Figure 8.5 illustrates a typical convection-type recuperator from the 1980s (Ottie, 1990). As the name suggests, the primary method of heat transfer in these devices is by convection from the hot exhaust to the surface of the metal tubes through which cold combustion air is input. Further convection heat transfer from the inside surface of the tubes heats the combustion air. Metal tubes (nickel-based) have been used because of their high thermal conductivity. However, the use of salt fluxes in melting

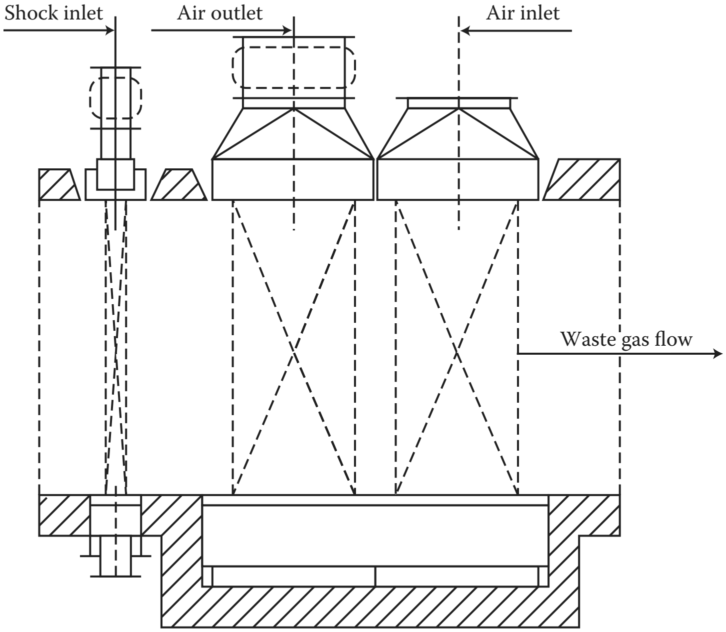

FIGURE 8.5 Schematic of a recuperator with shock-tube bundles. (From Ottie, T.W., in *Energy Conservation Workshop XI: Energy and the Environment in the 1990s,* Aluminum Association, Washington, DC, 1990, p. 551. With permission.)

furnaces creates problems in recuperators (Ward et al., 1988; Sikirica, 1990), since halide vapors given off by the molten salt corrode the tubes at temperatures above 540°C. As a result, the combustion air cannot be preheated above 350 to 400°C.

Two solutions to this problem have been proposed (Ottie, 1990). The first, shown in Figure 8.5, is the addition of a small section of *shock tube* bundles at the front end of the recuperator. These shock tubes operate at higher temperatures, and so wear out quickly but have been designed to be easily replaced. The second is the replacement of the metal tubes with a thermally conductive ceramic such as silicon carbide (Ward et al., 1988). These ceramics are more expensive and less conductive than metal tubes, but they potentially allow the air to be preheated to above 800°C.

REFRACTORIES

The challenges to refractory performance in aluminum melting and holding furnaces were described in the previous chapter. Responses vary from operator to operator, but some trends are apparent:

- A shift away from bricks toward monolithic linings (Allaire, 1992; Pauline and Turner, 1999). These are cheaper to install and have no joints to penetrate. However, monolithic linings do not have the same mechanical strength as bricks, and thus are more easily damaged when the charge is dumped into the furnace. The development of low-cement castables and gunning mix has been especially significant.
- The use of nonwetting agents in linings to limit metal penetration (Pauline and Turner, 1999; Afshar and Allaire, 2001). Barium sulfate is the most common of these; aluminum fluoride and calcium fluoride are sometimes used as well.
- Higher-quality refractory. Eliminating free silica is especially important for reducing corundum formation (Afshar and Allaire, 2001).

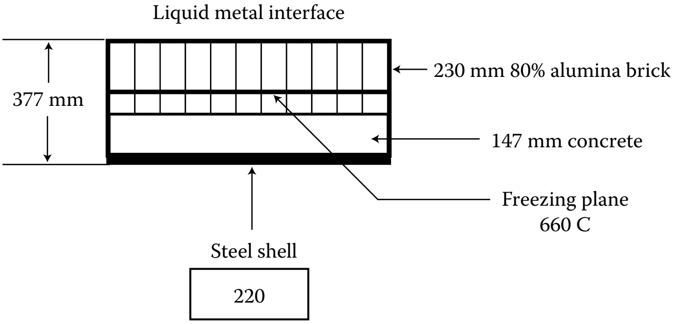

FIGURE 8.6 Composite monolithic refractory structure for reverberatory melting furnace. (From Morrow, R., in *Alum. Cast House Technol.: Eighth Australas. Conf.,* Whiteley, P.R., Ed., TMS–AIME, Warrendale, PA, 2003, p. 101. With permission.)

- Composite refractory walls such as that in Figure 8.6 (Morrow, 2003), with a corrosion-resistant refractory at the hot face and a low-density insulating material underneath to reduce heat losses. It is important to make sure that the high-temperature refractory is thick enough that the "freeze plane" below which penetrating metal solidifies remains within it (Dunsing, 2002). Insulating brick is less resistant to molten metal and should not be exposed to it. Furthermore, if molten metal penetrates beyond the thickness of the facing refractory, the lining can heave up from the wall or bottom as the metal freezes between the facing refractory and insulating material.

STIRRING

The term *stirring* encompasses a wide range of technologies, often designed for specific furnace architectures. Stirring is meant to accomplish one or more of several goals (Henderson et al., 1996):

- *Elimination of thermal gradients.* Because heat is transferred entirely from the top to the charge in a melting furnace, the temperature of the melt at the top can be up to 100°C higher than that at the bottom. Thermal gradients lead to excessive dross formation and melt loss (the metal is too hot at the top), variable chemistry, and problems with casting when metal of varying temperatures is tapped. Stirring evens out the metal temperature, improving product quality and reducing melt loss. It also reduces the temperature at the metal surface, which in turn lowers refractory temperatures above the melt.
- *Submergence of light scrap.* Light scrap such as used beverage containers (UBCs) tends to float on top of molten metal when charged. Leaving it there leads to excessive melt loss, so submerging it under the melt as quickly as possible is important.
- *Elimination of inclusions.* While good quality control in most cast shops now requires filtration, the larger inclusions in molten aluminum can be eliminated either by flotation on bubbles of introduced argon or by attachment to the furnace walls. Stirring makes this easier to accomplish.
- *Higher melt rate.* Stirring increases the convective heat transfer coefficient h, improving heat transfer from the top of the melt to the metal or scrap below. This increases melt rates.

The numerous devices used for stirring molten metal can be separated into five basic types of device: *bubble injection, mechanical pumps, pneumatic stirrers, electromagnetic pumps,* and *electromagnetic stirrers.*

Bubble injection is accomplished in one of two ways: through a porous plug in the furnace bottom or through a lance or fluxing wand inserted through the top. The bubbles are argon or an argon–chlorine mixture and are injected primarily for degassing or fluxing rather than for stirring. Recently introduced rotary flux injectors are more effective for stirring but again are primarily meant for other purposes.

FIGURE 8.7 Photograph of an improved mechanical pump for molten aluminum stirring. (From Tensor™ Series Pumps Website, http://www.metaullics.com/tensor.html. With permission.)

Most of the mechanical pumps in use for molten aluminum service are centrifugal (see Figure 8.7) rather than positive displacement, owing to the higher discharge volumes and velocities of centrifugal designs. These pumps cost less per unit capacity than other stirring devices and cost less to operate as well (Henderson et al., 1996); maintenance costs are higher, but development work has focused on improving their reliability (Vild et al., 2002). Mechanical pumps are often portable and can be used on more than one furnace. They are usually used only on open-well furnaces, however (Henderson et al., 1996); closed-system furnaces require a different type of stirrer. They also have difficulty in furnaces where metal drains away from the pump as the furnace is emptied and thus are less desirable for round and dry-hearth furnaces. Nevertheless, their low cost and simplicity of operation make them the most widely used type of metal circulation device.

Figure 8.8 illustrates the principle behind the jet stirrer introduced by Alcan in the early 1990s (Thibault et al., 1991). The jet stirrer is a pneumatic stirrer, relying on a constant cycle of vacuum and pressure to raise and lower the level of the metal

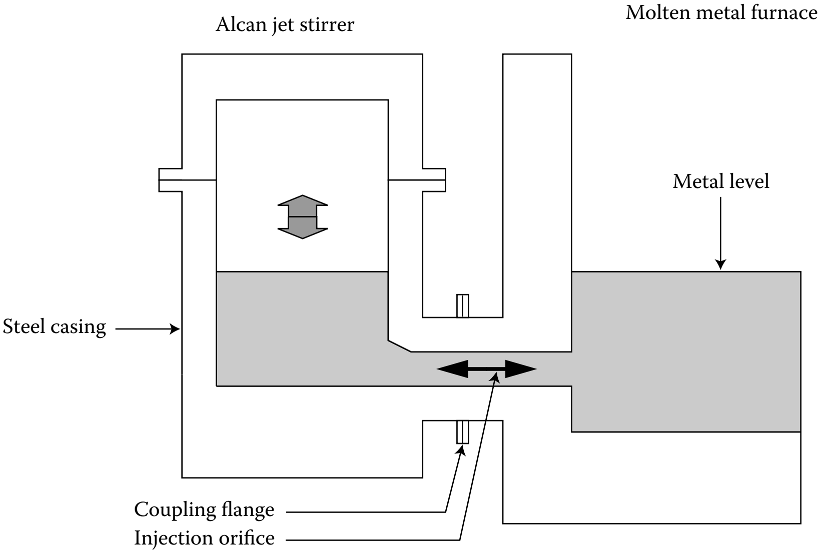

FIGURE 8.8 Schematic of a jet melter. (From Henderson, R.S., Chandler, R.C., and Brown, W., in *Light Metals 1996,* Hale, W., Ed., TMS–AIME, Warrendale, PA, 1996, p. 869. With permission.)

in the main chamber shown here. As the metal level rises and falls, metal is continually sucked in and forced out through the injection orifice at the bottom. The small size of the orifice ensures sufficient velocity to do a reasonable job of stirring, and jet stirrers can be installed on any furnace. However, jet stirrers are more expensive to install than mechanical pumps and more expensive to operate (Henderson et al., 1996), so their use is not widespread.

Figure 8.9 illustrates the operating principle behind the most recent version of the electromagnetic pump, introduced to the aluminum industry about 15 years ago (Jones, 1995; Henderson et al., 1996; Peel, 2003). The equipment consists of a well, lined with the same high-alumina refractories used for the furnace, and the pump itself, wrapped around a silicon carbide inlet tube. The pump consists of a coil wrapped around the tube, through which mains-frequency alternating current flows; the forces exerted on the metal in the tube are the same as those described for the eddy-current separator in Chapter 6. In this case exerting this type of force on molten metal causes it to flow through the tube. (The same principle is behind the operation of induction furnaces, described in Chapter 10.) Electromagnetic pumps are more effective than mechanical pumps in round and dry-hearth melters and offer some reduction in energy and maintenance costs; however, they are much more expensive to install. As a result, their use is spreading primarily in new installations.

Electromagnetic stirrers use a similar principle to the induction furnaces used for melting (see Chapter 10). Mounted externally to the furnace, they consist of an iron core adjacent to a set of water-cooled stirrer coils (Eidem et al., 1996; Peel, 2003). AC electric current passed through the stirrer coils generates a magnetic field,

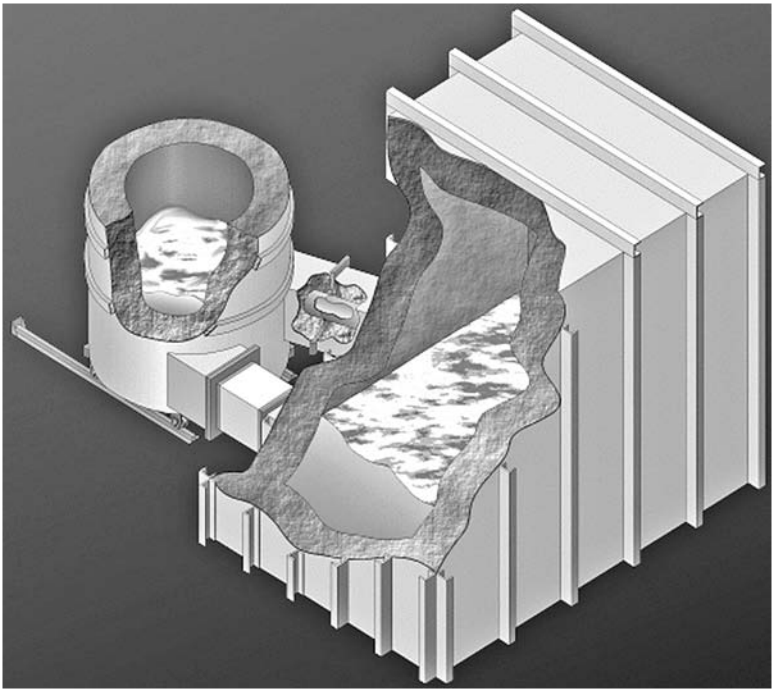

FIGURE 8.9 Illustration of an electromagnetic pump attached to a melting furnace. (From EMP System > How it Works website, http://www.emptechnologies.com/emp/dom93/index.htm. With permission.)

which in turn generates a secondary electric current in the molten metal in the furnace. As the current oscillates, the changing magnetic field in the metal generates eddy currents, which stir the metal. As with induction furnaces, low frequencies generate better depth of penetration of the magnetic field, allowing use of refractories of normal thickness (Sjöden and Sävenäs, 2001). Electromagnetic stirrers can be

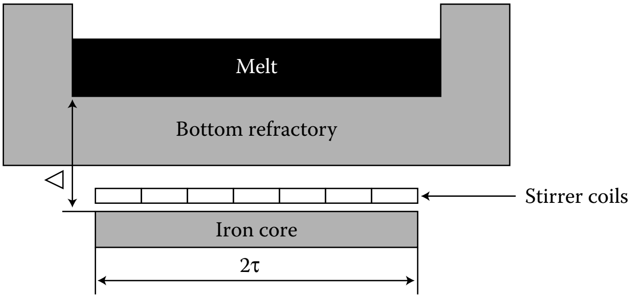

FIGURE 8.10 Schematic of a bottom-mounted electromagnetic stirrer. (From Eidem, M., Tallbäck, G., and Hanley, P.J., in *Light Metals 1996,* Hale, W., Ed., TMS–AIME, Warrendale, PA, 1996, p. 861. With permission.)

mounted either under the furnace, as shown in Figure 8.10, or to the side. A bath height of 0.4 to 0.8 m is recommended.

Electromagnetic stirrers are more effective than any other stirring device, which maximizes the gains in productivity and product quality that can be achieved. However, they are also more expensive to install than any other stirring device and their operating costs are much higher as well (Henderson et al., 1996). Furthermore, the increase in fluid motion can increase refractory wear under the melt line. As a result, the spread of this type of stirring device has been slow.

ENVIRONMENTAL EQUIPMENT

Reverberatory furnaces can emit a variety of interesting substances when melting aluminum scrap. The most significant of these are chloride gases and vapors. Scrap that has not been decoated often contains chlorinated polymer coatings, such as polyvinyl chloride (PVC). Furthermore, the salt used for fluxing is a KCl–NaCl mixture and gives off vapors of its own when molten. Improperly combusted fuel is a potential source of volatile organic compounds (VOCs) and may react with chloride vapors to generate chlorinated organic vapor compounds such as furans or dioxins. Along with this, scrap charging often generates dust that must be dealt with.

Figure 8.11 shows a schematic dry scrubber system used to control plant emissions (Bundy Environmental Technology, n.d.). Dry scrubbing has largely replaced wet scrubbing for secondary aluminum production because of the chlorides in the off-gas, which would generate a hazardous effluent if allowed to contact water. Instead, the off-gases are air-cooled, and send on to the baghouse. Those facilities adding reagents to the cooled off-gas often use lime or calcium carbonate, which reacts with chlorides in the off-gas to generate calcium chloride. This reduces

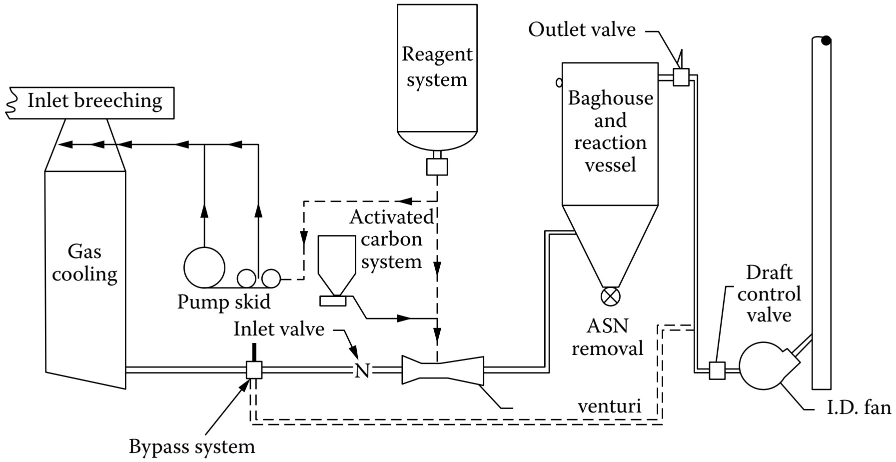

FIGURE 8.11 Schematic of a dry scrubbing facility. (From Bundy Environmental Technology, http://www.bundyenvironmental.com/syscomp.html#baghouse. With permission.)

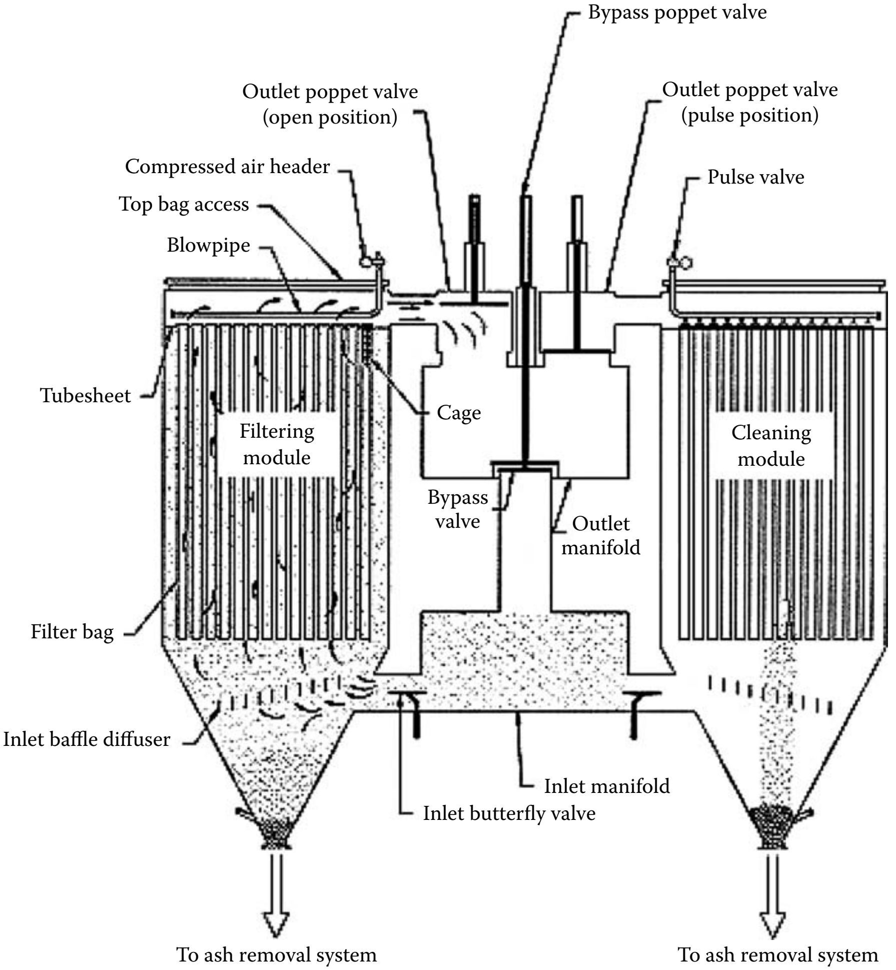

FIGURE 8.12 Schematic of a baghouse. (From Bundy Environmental Technology, http://www.bundyenvironmental.com/syscomp.html#baghouse. With permission.)

gaseous chloride emissions and, more importantly, reduces dioxin concentrations in the gas (see Chapter 14).

Figure 8.12 shows a typical baghouse used to filter the cooled off-gas (Bundy Environmental Technology, n.d.). The bags in a baghouse are large fabric filters, capable of removing micron-size dust particles from furnace exhaust gas. Polyesters are typically used for the fabric in aluminum remelting plants, owing to their resistance to the HCl in the exhaust gas. However, their relatively low limiting operation temperature requires that gases be diluted with air to cool them below this temperature before being filtered.

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9 Fossil-Fuel Furnaces

The reverb furnace used to melt aluminum scrap has a variety of designs and sizes, and new designs appear on a regular basis. The goal of furnace design is consistent, however: to generate the highest melting capacity per unit volume while maximizing thermal efficiency to reduce fuel costs. Other considerations include the ability of the furnace to handle finely divided scrap without excessive melt loss; the ability to process coated scrap if prior decoating is unavailable, minimizing maintenance costs; and ease of charging and tapping.

There are a number of ways to classify furnace designs. This chapter will separate them into *single-chamber* and *multiple-chamber* types. Additional sections will describe two specialized types of gas-fired furnace, the *rotary* and *crucible* furnace.

SINGLE-CHAMBER DESIGNS

Figure 9.1 shows the earliest and simplest type of reverberatory furnace design, the *wet-hearth* single-chamber furnace (Anderson, 1931; Brooks, 1970; McKenna and Wisdom, 1997; Kearney, 1988). Scrap is simply dumped or loaded into this type of furnace, the furnace opening is closed, and melting begins. When the molten metal reaches the desired temperature, it is either pumped out or tapped from a hole in the bottom. Burners are mounted at the opposite end of the furnace from the charge well; mounting the flue near the charge well gives hot combustion gases more chance to transfer energy to the melt as they head toward the flue. Burners can be roof- or side-mounted; for larger-capacity furnaces, regenerative burners or the use of preheated air is advantageous. Common practice in single-chamber furnaces is to leave a heel of molten metal in the furnace bottom after tapping (Kendzora, 2000) to make melting easier for the next charge and to reduce damage to the bottom refractories from the shock of the scrap being dumped in.

Metal removal from wet-hearth and other furnaces is accomplished one of three ways. Use of a hydraulic pump is the oldest (Brooks, 1970) and is used mostly for furnaces that are not integrated into a melting, holding, and casting line. However, the pumps require maintenance and periodic replacement, and safety is a concern. A more common approach requires a hole drilled through the furnace bottom and filled with a quick-setting mortar plug. When the molten metal is ready to tap, the plug is removed and replaced by a tap that allows metal to drain into a launder or transfer ladle. When the furnace is mostly empty, fresh mortar is pumped into the hole, replacing the plug. Tapping can be slow, especially toward the end of the tap when molten metal levels in the furnace are low. Furthermore, the mortar can be a source of inclusions in the metal. The newest tapping approach involves tipping the entire furnace up, causing metal to drain through a pouring spout located at the front.

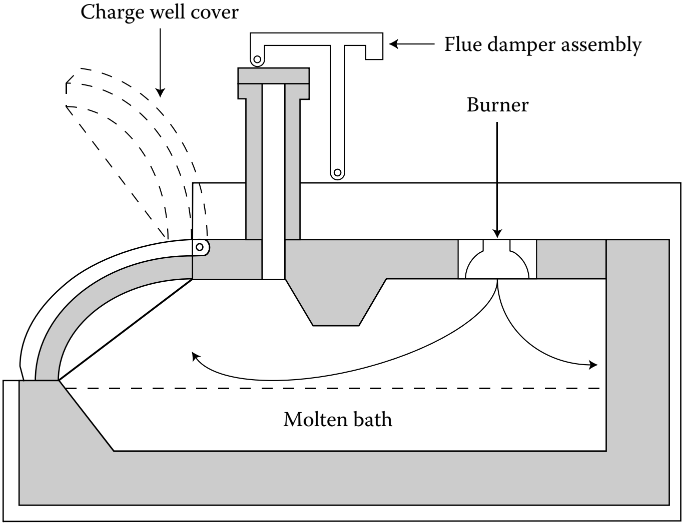

FIGURE 9.1 Generic wet-hearth melting furnace. (From McKenna, J.P. and Wisdom, A., *Die Casting Engineer,* 41(6), 64, 1997. With permission.)

Tipping has a significant power requirement and costs more than tapping arrangements. At the same time, it offers greater control of drainage rate than tapping and reduced inclusion content in the metal. Because of this, furnaces that tip are increasingly chosen for new installations.

The wet-hearth furnace has several limitations, the most severe of which is the problem of charging through a relatively small opening. An early improvement in furnace design was the development of designs with wide charging doors, allowing much larger loads to be placed in the furnace than before. However, charging furnaces this way is slow. The next step was the design of a round melting furnace (Seco-Warwick, Inc., n.d.), which features side burners and a removable top. Removing the entire top allows the furnace to be charged with a single bucket load of scrap, reducing charging time and worker exposure to the furnace environment. However, other limitations of wet-hearth furnaces remain, including:

- Poor thermal efficiency and high fuel bills as a result
- Poor heat transfer to the charge, resulting in low melting rates
- High melt loss rates, especially for smaller scrap such as used beverage container (UBCs)
- Difficulty in sealing the furnace, which can result in pollution concerns when melting coated or contaminated scrap
- Contamination from metallic impurities in the scrap, in particular iron inserts or attachments

As a result, wet-hearth furnaces are best suited for melting good-quality scrap, such as sows from sweat furnaces, large castings, and other bulky uncontaminated scrap.

Good clean junk like this is in limited supply, so the need for better furnace designs is apparent.

Figure 9.2 shows the next step in the evolution of melting furnaces, the *dry-hearth* furnace (McKenna and Wisdom, 1997; Kearney, 1988). This furnace features a sloping hearth at the right, onto which solid scrap is placed for initial heating. As the metal melts, it drains down the hearth into the bath at the left, leaving other metallic materials behind. The scrap also dries during the heating process, reducing the possibility of explosions and reducing the potential for melt loss from interaction between the metal and water vapor.

Dry-hearth furnaces solve some of the problems associated with wet-hearth melting (Kendzora, 2000). A particular advantage is the reduction in melt loss caused by the use of different types of flame over the solid scrap and the metal bath. Convective flames are used in the dry hearth area to maximize heat transfer to the solid scrap; flat luminous flames work better to heat the molten metal. Top-loading dry-hearth furnaces are widely used to maximize capacity. As a result, dry-hearth furnaces are the most popular approach for melting large or bulky scrap.

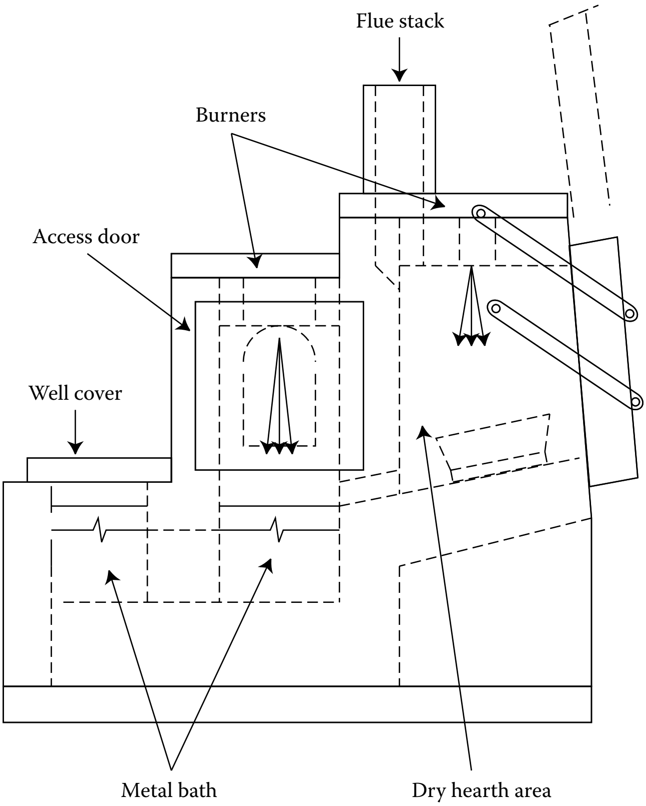

FIGURE 9.2 Dry-hearth melting furnace. (From McKenna, J.P. and Wisdom, A., *Die Casting Engineer,* 41(6), 64, 1997. With permission.)

However, dry-hearth furnaces also have limitations. Refractories in the elevated portion of the hearth are more prone to breakage by the solid scrap being dumped on them without a cushion. The lack of direct contact between combustion gases and the charge means that thermal efficiencies are still low (30 to 35%). Scrap size is still a limitation as well, since smaller scrap piled on the hearth is less likely to stay there.

The next step in the progression is the *stack* melter shown in Figure 9.3 (McKenna and Wisdom, 1997). Here scrap is input directly into the exhaust stack, forcing the exhaust gas to go through the scrap as it leaves the furnace. As the heated scrap descends to the sloping hearth, additional burners melt it, causing it to flow into the molten bath. This in turn allows more scrap to descend to the hearth, creating a semicontinuous melting operation.

Stack melting has several advantages over traditional wet- or dry-hearth melting (Kear et al., 2000; Kendzora, 2000). The most significant is improved efficiency. With most of the heat removed from the exhaust gas (exit temperatures are reduced to 500°C or less), energy savings of over 50% are common (Groteke and Fieber, 1999). The preheating of the scrap by the exhaust gas also reduces melting time on the hearth, improving furnace productivity. The elimination of the open charging well reduces melt loss by 80% or more and minimizes emissions. Stack melting is not suitable for very large scrap, but a stack can be combined with a dry hearth to accommodate a range of charge materials. These advantages often justify the additional investment required for a stack melter.

Although a considerable improvement over simpler single-chamber furnaces, stack melting has a few disadvantages. The foremost is controllability; scrap descends as quickly as it melts, which makes slowing down the melting rate difficult. The pressure of the scrap on the stack limits the depth to which it can be stacked, and this in turn limits the length of time that it can be preheated. Uneven heating is also a concern if the charged scrap has a range of sizes. Figure 9.4 illustrates the

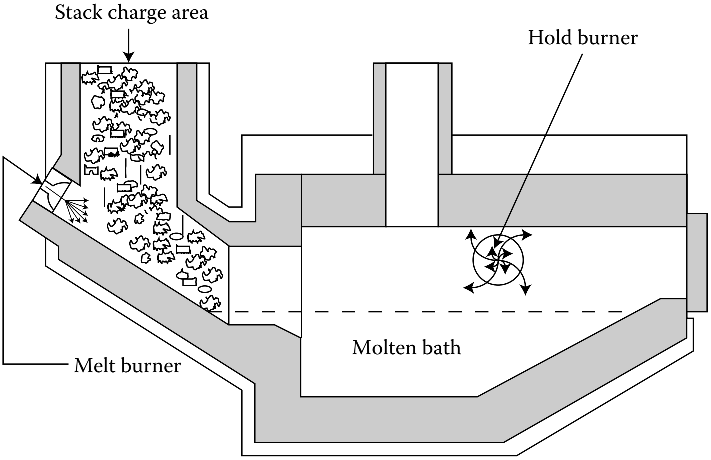

FIGURE 9.3 Stack melter. (From McKenna, J.P. and Wisdom, A., *Die Casting Engineer,* 41(6), 64, 1997. With permission.)

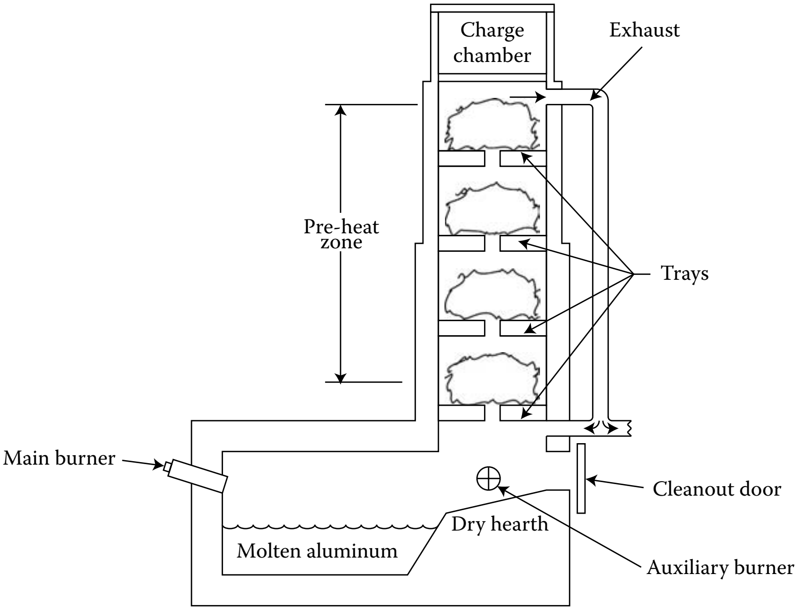

FIGURE 9.4 A vertical tower melter. (From Frank, C.A. and Boeckenhauer, K.A., *Die Casting Engineer,* 30 (4), 61, 1986. With permission.)

next step up, the *tower* melter introduced in Japan in the early 1970s (Frank and Bockenhauer, 1986). The tower through which exhaust gas flows consists of several chambers separated by cast iron bars. Scrap is introduced into the top chamber while melting is completed in the furnace hearth below. When metal is tapped from the furnace, the bars on each chamber are sequentially released, and the scrap falls into the next chamber. Very large scrap can again be charged directly onto the dry hearth in the main furnace chamber as needed. The design allows a greater amount of scrap to be held in the column, improving heat recovery and ultimately furnace efficiency (values of 60 to 77% are claimed). The lack of direct contact between the flame and the scrap also helps reduce melt loss. However, tower melters have higher capital costs than other furnaces, and the number of moving parts is a potential maintenance headache. As a result, the use of tower melting furnaces is uncommon.

MULTIPLE-CHAMBER FURNACES

Figure 9.5 illustrates the *sidewell* melting furnace, which has been used for several decades for the melting of light scrap (Butterwick and Smith, 1986; DeGroot and Migchielsen, 2003). The sidewell furnace was designed to eliminate direct interaction between combustion gases and solid scrap, which increased melt loss and dross generation. Instead, only the molten metal in the clean chamber at the left is heated, using high-luminosity flames (see previous chapter). The superheated molten metal flows underneath a baffle and contacts solid scrap charged to the side

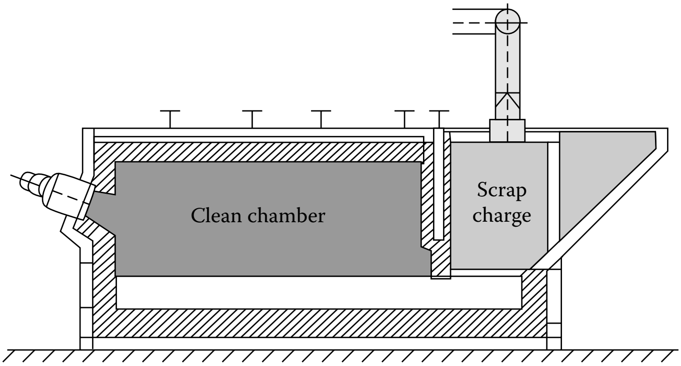

FIGURE 9.5 Cross-section of a simple sidewell furnace. (From de Groot, J. and Migchielsen, J., in *Aluminium Cast House Technology: Eighth Australasian Conference,* Whiteley, P.R., Ed., TMS–AIME, Warrendale, PA, 2003, p. 57. With permission.)

well (Gershtein et al., 2000), heating and ultimately melting it. When the charge is melted, the molten metal is then reheated to pouring temperature and tapped, and the process is repeated.

Sidewell furnaces are an effective way to melt light scrap such as UBCs with minimal melt loss (DeGroot and Migchielsen, 2003). However, improvements have been desired ever since their introduction. Because no preheating of scrap is provided, fuel efficiencies are poor. The use of tactics such as regeneration or air enrichment to improve efficiency has been a common response (Stewart, 2002). A bigger problem has been the slow kinetics of melting (Gershtein et al., 2000), limited by the rate at which metal can flow under the baffle to contact the scrap in the well. The metal-pumping devices described in the previous chapter were designed largely to improve metal flow rates around the baffle and increase melting rates. Both mechanical and electromagnetic pumps are widely used.

Even though the sidewell furnace prevents direct exposure of the scrap to combustion flames, the finely divided material oxidizes sufficiently during heating to generate a significant amount of dross. Until the 1990s, the only response to this was to use salt as a flux (Butterwick and Smith, 1986), which minimized metal loss to the dross but generated an environmentally undesirable waste product. As a result, a means was sought to submerge the pieces of scrap in the molten metal in the sidewell while they melted, which would minimize oxidization of the scrap and eliminate the need for fluxing. Two methods have been developed to accomplish this (Stewart, 2002). Figure 9.6 illustrates the first, marketed by Premelt Systems (Areaux and Corio, 1999). This technology uses a separate charge well, with a graphite gas-lift pump to input molten metal from the main furnace chamber. The high velocity of the input molten metal and the design of the charge well creates a vortex that submerges scrap before it can oxidize. A ceramic cover over the charge well allows charging in an inert environment, further reducing oxidation. The use of a gas-lift pump means that no moving parts are required, which reduces maintenance costs. Figure 9.7 shows the second scrap submergence technology, LOTUSS

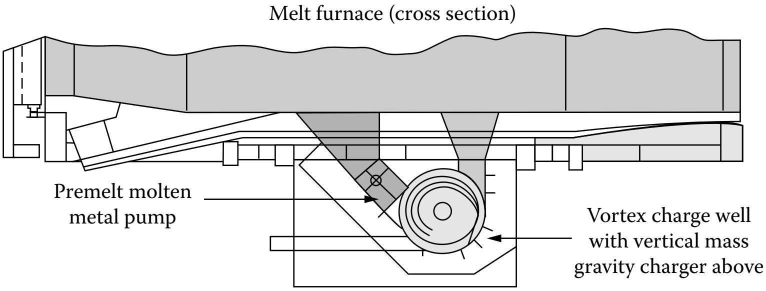

FIGURE 9.6 Premelt Systems vortex melter. (From Areaux, L.D. and Corio, P., *Ind. Heat.,* 66(8), 39, 1999. With permission.)

(van Linden et al., 1998; Metaullics, Inc., n.d.). Here a mechanical pump is used to pump superheated molten metal into a vortex chamber. In addition to a pumping chamber and the charge well, LOTUSS furnaces have a separate well between the vortex and main chamber, where dross generated during melting (or sheared loose from the charged scrap) is allowed to float. This makes dross removal easier.

The problem of melting small scrap becomes greater if coating material and other organics are still present when the material is charged. For scrap of a consistent type (such as UBCs), a preliminary decoating step (see Chapter 5) is justified, but mixed scrap loads are often charged directly to the melting furnace without prior decoating.

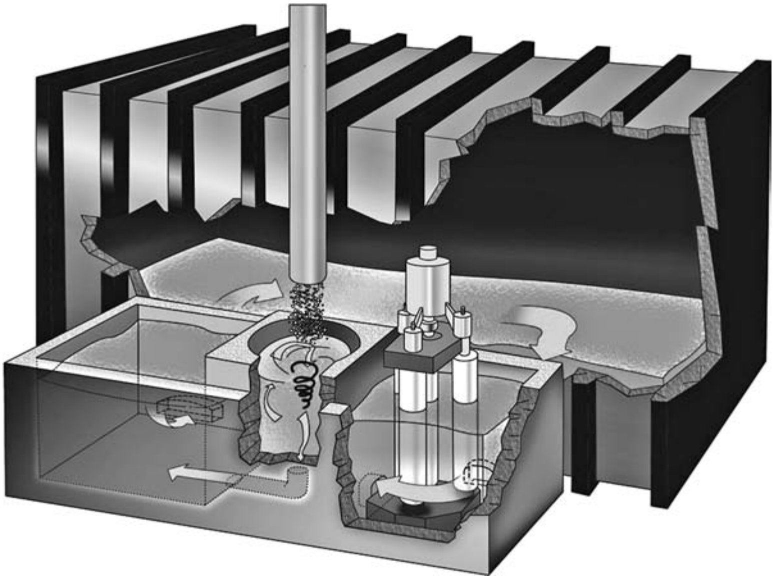

FIGURE 9.7 The LOTUSS scrap submergence system. (From Metaullics, Inc., www.metaullics.com/lotuss.html. With permission.)

This leads to higher melt losses, as carbon in the coatings reacts with the aluminum to generate aluminum carbide. The gases given off by decomposing coatings are also an environmental concern. Figure 9.8 presents a solution to this, the twin-chamber furnace developed in Germany (Schröder and Martosko, 2000; Meyer, 2003). The furnace features a scrap chamber that is effectively an enlarged sidewell, and a heating chamber where molten metal is superheated. An electromagnetic pump circulates metal between the two chambers; regenerating burners improve thermal efficiency. The most significant advance in the furnace is a recirculating flue gas circuit, in which gases given off by decomposing coatings are burned to recover additional energy and minimize emissions. Temperatures at the top of the scrap chamber are controlled at 550°C to maximize pyrolysis rates. The nonoxidizing atmosphere in the furnace helps minimize melt loss, and this in turn allows operation

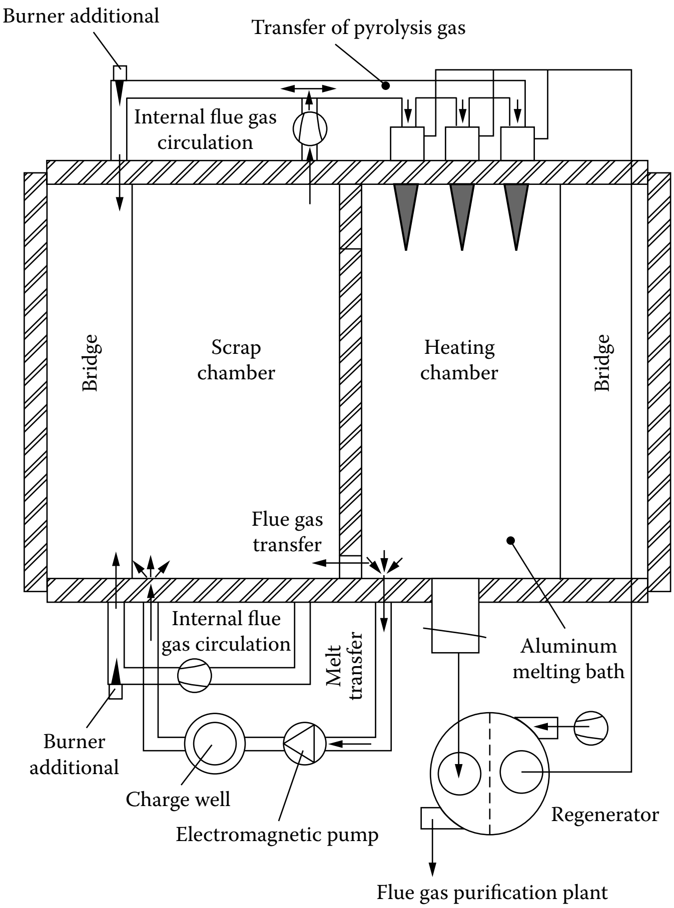

FIGURE 9.8 Top view of a twin-chamber melting furnace for contaminated scrap. (From Meyer, H.J., *Ind. Heating,* 70(2), 30, 2003. With permission.)

without salt. De Groot and Migchielsen (2003) have described similar furnaces built elsewhere. If the quality of the scrap supply is inconsistent enough, these furnaces are a good choice for environmentally viable melting. For a steady supply of coated scrap, separate decoaters are a more competitive choice.

SMALL-VOLUME MELTERS

The furnaces described in the previous sections are used primarily for large-volume applications (>1000 kg/hour melt rate). For smaller-volume melting operations, minimizing capital outlay becomes increasingly important, even at the expense of energy efficiency (Ramsell, 1999). Smaller-volume melters must also be easily operated on an on–off basis, rather than the steady-state operations used by larger melting operations. This means a furnace with a smaller thermal mass is desirable, such as one that can be completely emptied and started up cold. Electric furnaces (see Chapter 10) are often used for applications of this type, but gas-fired furnaces are also used where electricity is too expensive.

Crucible furnaces are available in stationary or tilting models (Anderson, 1931; Kearney, 1988; MPH, n.d.); stationary furnaces can have either removable or fixed (bale-out) crucibles. A recent Japanese innovation is the development of crucibles with spiral guides around the outside (Tanaka et al., 2001); these increase the length of time that combustion gases remain in contact with the crucible, reducing fuel consumption by about 20%. A small dry-hearth melter has also been developed, useful for melting wet or oily scrap.

ROTARY FURNACES

For highly oxidized scrap, the use of flux during melting is a requirement. Separating the resulting salt slag from the metal is difficult without sufficient agitation. To deal with this problem, the rotary furnace shown in Figure 9.9 was developed. The rotary furnace is a long sloping tube, tilted back for charging and firing and tilted forward for slag and molten metal discharge (Artola and Roth, 1990). Firing occurs at the bottom (Bamji, 1984), using natural gas or occasionally fuel oil. As the hot exhaust gas travels upward through the furnace, it passes through the charge, preheating it as in a stack melter. The gas also heats the refractory walls of the furnace; this allows heating of the charge by conduction from the walls (Peterson, 1995; Schmitz, 1998), as well as by radiation and convection. When the contents have reached the desired temperature, the furnace is tilted and the metal and salt slag are poured off. Rotation of the furnace is slow during the early stages of the melting process, to prevent damage to the refractories from large pieces of scrap or dross; as a molten pool begins to form, the speed is increased to roughly 7 to 8 m per second at the inside surface. Melting times vary with furnace size and loading but are usually shorter than in a comparable wet-hearth furnace (MDY Engineering, n.d.).

Rotary furnaces are faster and more efficient than ordinary reverberatory furnaces (Paitoni and Benedini, 2004). However, they are also more expensive to install and more difficult to maintain. As a result, they are generally best suited for melting dross and other oxidized scrap (Hall, 2004). Small-sized scrap such as clean

FIGURE 9.9 View of a rotary melting furnace. (From MDY Engineering, http://www. mdy-engineering.com/images/VCM_14_MT_2.jpg. With permission.)

punchings and turnings are now better suited to a vortexing furnace, where they can be melted in a salt-free environment.

HOLDING AND DOSING FURNACES

In smaller melting facilities, molten metal tapped from a melting furnace is usually transferred to a ladle prior to casting. Larger facilities often employ a holding furnace (Emes, 2002), where the temperature and composition of the metal can be adjusted. This allows the melting furnace to be used mostly for its intended purpose, increasing productivity. The use of a holding furnace also makes it possible to operate the melting furnace under conditions that most favor heating of solid scrap (reducing condition, convective heat transfer), improving the efficiency and melting rate.

Many different holding furnaces are available, and both gas-fired and electric furnaces are widely used. Figure 9.10 illustrates a well-known concept in gas-fired

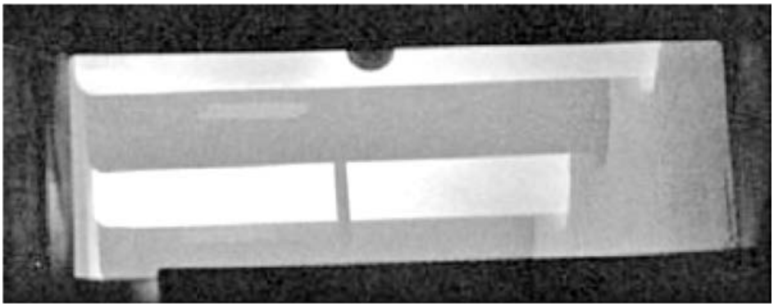

FIGURE 9.10 Inside of a radiant-tube furnace. (From Sandvik Materials Technology, Gas Heated Furnaces, http://www.sandvik.com/sandvik/0971/internet/SE19042.nsf/ fd8745f326323f31ca2567c8001284ee/c8bb5bf54dfa62d7c1256b97003635e0/$FILE/6-B-4%20Gas%20heated%20furn.pdf. With permission.)

holding furnaces, a *radiant-tube* furnace (Faulkner, 1988; Sandvik Materials Technology, n.d.; Wunning, n.d.). In this furnace products of combustion are passed through ceramic tubes mounted in the furnace; as the tubes heat up, they radiate energy to the molten metal below. The use of a tube separates the combustion gases from the metal, limiting oxidation and disturbance and reducing melt loss. Electrical resistance elements mounted in the roof have the same effect (Gilstrap, 1988). Reverberatory furnaces operating under luminous flame conditions are less expensive and are also common (Thermtronix, n.d.).

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10 Electric Furnace Melting

As illustrated in previous chapters, most aluminum scrap is melted in furnaces heated by the combustion of a fossil fuel — natural gas, oil, or perhaps coal. However, the use of fossil fuels as an energy source has disadvantages, which have also been discussed. These include the interaction of combustion products with the molten aluminum, toxic or hazardous compounds in the off-gas, poor efficiency in some furnaces, high capital equipment requirements for others, and low availability of fossil fuels in some areas.

Electricity has been used as an alternate energy source for melting aluminum scrap for some time. The first electric furnace for melting scrap was installed in the United States in 1918 (Anderson, 1987) and appeared in Europe soon afterward. These furnaces have been in use ever since and have evolved over time. The most important innovation was the introduction of induction furnaces for melting in the 1930s. These have largely displaced the resistance and arc furnaces originally used.

Electric furnaces have important advantages over fossil-fuel furnaces for melting aluminum scrap. The most important of these is cleaner metal. Because there are no combustion products in an electric furnace environment, dross generation is much less (Lessiter, 1997), as is gas pickup. As a result, melt losses are lower (Hentschel and Feldmann, 1982; MacIntosh, 1983; Kreysa, 1991; Groteke, 1997) and metal purity is improved. The stirring motion of an induction furnace minimizes temperature gradients within the melt (Heine and Gorss, 1991), improving consistency. Electric furnaces are generally more efficient than gas- or oil-fired furnaces (Fishman, 2002), especially in smaller sizes. The lack of fuel combustion means there is little or no off-gas, which greatly reduces environmental concerns. In addition, electric furnaces are less noisy.

However, there are also disadvantages. The stirring motion that improves homogeneity can also prevent dross from separating, increasing the risk of inclusions. While electric furnaces are more efficient, electricity is often a more expensive form of energy than fossil fuels, eliminating the cost advantage (Fishman, 2002). Electric furnaces tend to have higher capital costs than fossil-fuel furnaces of equivalent capacity (Hellsing and Tallbäck, 1982; MacIntosh, 1983). Most importantly, electric furnaces have difficulty matching the melting capacity of large-scale reverberatory furnaces (Groteke, 1997).

As a result, electric furnaces are most often found in small-volume operations such as foundries. Owing to the need to minimize dross generation, they are more likely to be used for melting ingot than scrap; when scrap is melted in these furnaces, it is usually home scrap rather than purchased material. As a result, while no statistics are available, the amount of aluminum scrap melted in these furnaces is a small fraction of the total. However, changing environmental restrictions and the need to produce cleaner metal in a melting furnace may encourage greater use of electric furnaces in the future.

The electric furnaces used in aluminum melting can be classified in several ways. The most important is the type of electrical heat generation, which is by *induction* or *resistance.* Induction furnaces can be further divided into *channel* and *coreless* units. A second means of classification is the function of the furnace. Some electric furnaces operate as *melting* units, others as *holding* furnaces, and some as both. The choice of frequency is another means of classifying electric furnaces, as is the means by which molten metal is removed (in a separate crucible, by hand-dipping, or by being tapped to a ladle). In this chapter electric furnaces will be sorted first into induction and resistance furnaces and then by the other classification methods.

INDUCTION FURNACES

Chapter 5 introduced the concept of an eddy current as a technology for separating aluminum from other nonmagnetic metals in a scrap stream. An eddy current is the electric current induced in a conductor by the magnetic field associated with an adjacent magnet or electric current. In an eddy-current separator, powerful permanent magnets are typically used to generate this field. Passing a piece of scrap over a series of magnets with alternating polarities generates Lorentz forces that repeatedly flip the piece of scrap and cause it to veer from its original path.

If the scrap piece (or any other conductor) remains in the magnetic field generated by alternating current for a period of time, its resistance to the reversing eddy current generated by the field will cause it to heat up. This is called *induction heating* and is used for several metallurgical applications. The industrial use of induction heating for melting purposes dates from the 1930s, and today it is used for most nonferrous metals, as well as irons and steels. Two general approaches have been taken in the design of induction-based melting furnaces. In the first, solid metal is directly heated and melted by eddy currents in a *coreless* furnace. In the second, molten metal is heated to a high temperature in the bottom of a *channel* induction furnace; the superheated molten metal then melts added scrap or ingot charged to the top of the furnace.

CORELESS FURNACES

Figure 10.1 shows the construction of a typical coreless induction furnace (Perkul, 1988). The induction coil surrounding the outside of the lining containing the metal charge consists of water-cooled copper tubing embedded in a ceramic grout to reduce corrosion and provide additional support. In furnaces with removable crucibles, the coil reaches nearly to the top of the furnace. In tiltable furnaces like that shown here, room is left for a pouring spout. The magnetic field generated by the coil is equally strong on both sides; to prevent the stray flux from heating the outer furnace shell, a series of vertical laminations of transformer iron known collectively as the yoke is located outside the coil. In addition to tiltable furnaces like this, coreless induction furnaces are available that can be tapped from the bottom, along with removable crucible furnaces (Lessiter, 1997).

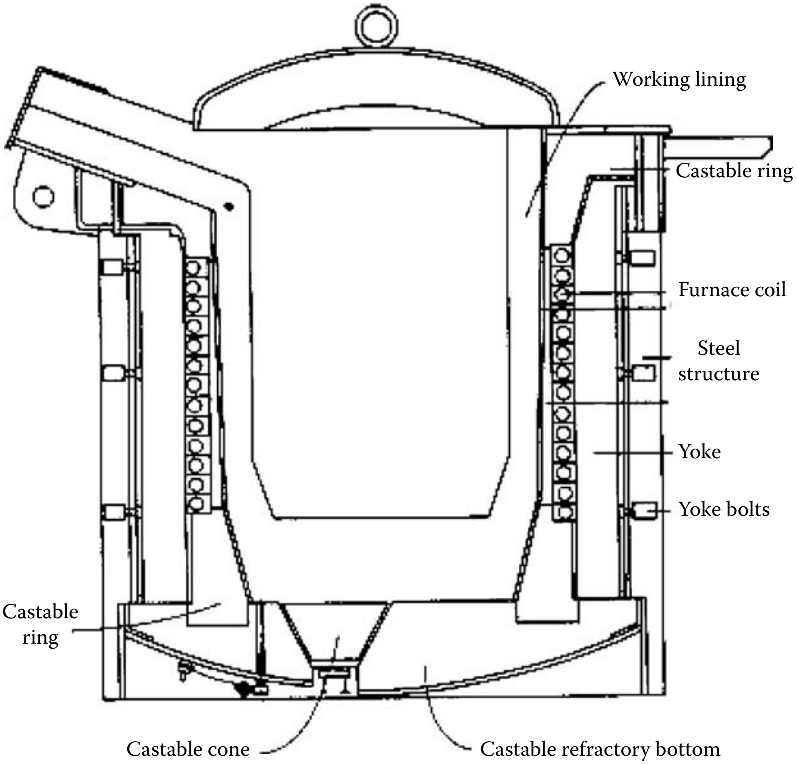

FIGURE 10.1 Construction of a coreless induction furnace. (From Perkul, R.Y., in *Metals Handbook,* Vol. 15, *Casting,* 9th ed., ASM International, Materials Park, OH, 1988, p. 368. With permission.)

The biggest decision in specifying a coreless induction furnace is the choice of operating frequency. Until the 1970s, there was no such choice; virtually all coreless units operated at *mains frequency,* 50 to 60 Hz. This had several consequences. The first stems from the impact of furnace frequency on the penetration depth of the magnetic field. Robiette (1972) describes penetration depth using the expression

$$p = \frac{1}{2\pi}\sqrt{\frac{\rho}{\mu f}} \qquad (10.1)$$

where p is the penetration depth in centimeters, ρ is the resistance of the conductor affected by the field (i.e., the furnace charge), μ is the magnetic permeability of the conductor, and f is the frequency. For a given material, p is proportional to $1/f^{0.5}$. The high penetration of mains frequency means a large-diameter furnace is required to eliminate bucking or canceling of the field (Hipple, 1982). However, practical considerations limit the coil diameter to a maximum of 3.65 m outer diameter

(Knödler, 1986; Heine and Gorss, 1991). As a result, mains frequency induction furnaces often have lower efficiencies, especially during melting when the resistance of the charge is greater (and p is higher as a result). Furthermore, Knödler suggests that the minimum size of aluminum scrap (or ingot) that can be efficiently melted in a coreless furnace is 3.5 p. This means the use of mains-frequency induction furnaces for melting is best reserved to ingot and large-diameter scrap such as casting runners and gating.

A second consequence of mains-frequency furnace operation is the impact of frequency on stirring in the melt. Shuichi (1988) calculates stirring action with the expression

$$F = \alpha \frac{P}{\sqrt{f D H}} \tag{10.2}$$

where α is a constant determined by the metal being melted, P is the power input to the furnace, D is the inside crucible diameter, and H is the coil height. Lower frequencies mean increased stirring. This stirring theoretically makes it easier to melt thin-gauge scrap, by rapidly drawing the scrap under the melt surface. However, stirring is also more likely to hurt metal quality, by increasing melt contact with the atmosphere and increasing hydrogen absorption. The increased stirring also raises the height of the *meniscus,* or dome of molten metal that forms above the melt. A meniscus that gets too high can result in metal spillage. Preventing this requires (a) turning down the power (and reducing furnace melt capacity) or (b) increasing the distance by which the crucible wall extends above the coil, which creates thermal gradients with the melt. As a result, the use of mains-frequency coreless induction furnaces for melting scrap is not widespread. When used for this purpose, they are generally operated with a *hot heel* of molten metal (Smith and Hayes, 1992), to which scrap is added. This reduces the resistance of the charge and allows the stirring action to transfer heat to the solid scrap more effectively.

In the 1970s the development of solid-state frequency converters (thyristorized or oscillating-circuit) made possible *medium frequency* (150 to 600 Hz) furnace operation (Knödler, 1986). Medium frequency operation reduces the penetration depth generated by the coil compared with mains-frequency operation. Higher-frequency operation also decreases the stirring and thus the meniscus height. This in turn increases the power density that can be used for a furnace of a given size (Goyal, 1985), as Figure 10.2 illustrates. This power increase means reduced melting times for a given charge, and the reduction in furnace size made possible by medium frequency operation reduces capital costs and improves efficiency (Hipple, 1982). The reduced stirring and shorter melting times translate into lower melt losses than mains-frequency melting, and the reduced penetration depth means that smaller pieces of scrap can be melted (Kreysa, 1991). Another advantage of medium-frequency melting is that a cold charge can be melted more easily, while mains frequency furnaces generally use a molten heel (Heine and Gorss, 1991).

The optimal frequency of a coreless induction furnace to use for melting scrap depends on the capacity, the size of material to be melted, and equipment and

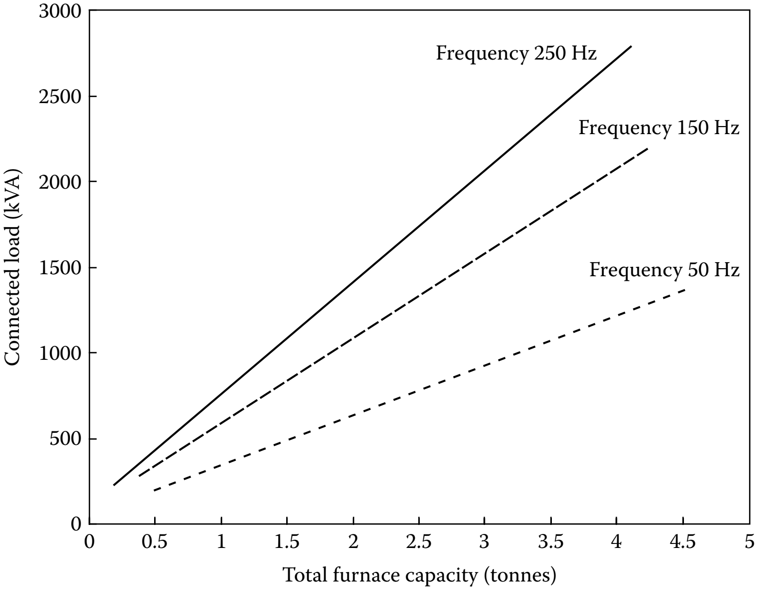

FIGURE 10.2 Coreless induction furnace load versus capacity for different frequencies. (From Knödler, G., *Casting Plant Technol.,* 1, 22, 1986. With permission.)

electricity costs. Figure 10.3 shows an approach suggested by Hipple (1982); the greater the capacity (and the larger the furnace), the lower the frequency. A second approach can be obtained from the work of Rowan (1987), who published a "frequency selection chart" based on experience with a variety of foundries. The published chart recommends an optimum frequency for a given furnace capacity, with a margin of uncertainty called the "green zone." The published chart is primarily for ferrous melting furnaces but can be adapted for frequency recommendations for aluminum melting as well. From Rowan's results, the following expression can be obtained:

$$\log y = (-0.6056 \log x + 4.409) \pm 0.3 \tag{10.3}$$

where y is the optimal frequency and x is the capacity of the furnace in kilograms. For a furnace with a capacity of 3000 lb (1361 kg), the recommended frequency from the expression would be 324 Hz, at the low end of what Figure 10.3 suggests. A furnace with a capacity of 8000 lb (3629 kg) would have a recommended frequency of 111 Hz, well below that suggested by Hipple (1982).

Figure 10.4 shows the solid-state frequency-conversion equipment used for medium-frequency furnaces (Hipple, 1982). The isolation transformer can be replaced with an ordinary power distribution-type isolator for medium-frequency operation. The lack of tap changes and capacitor contactors means supply line surges do not occur, which pleases power companies; it also means reduced maintenance costs.

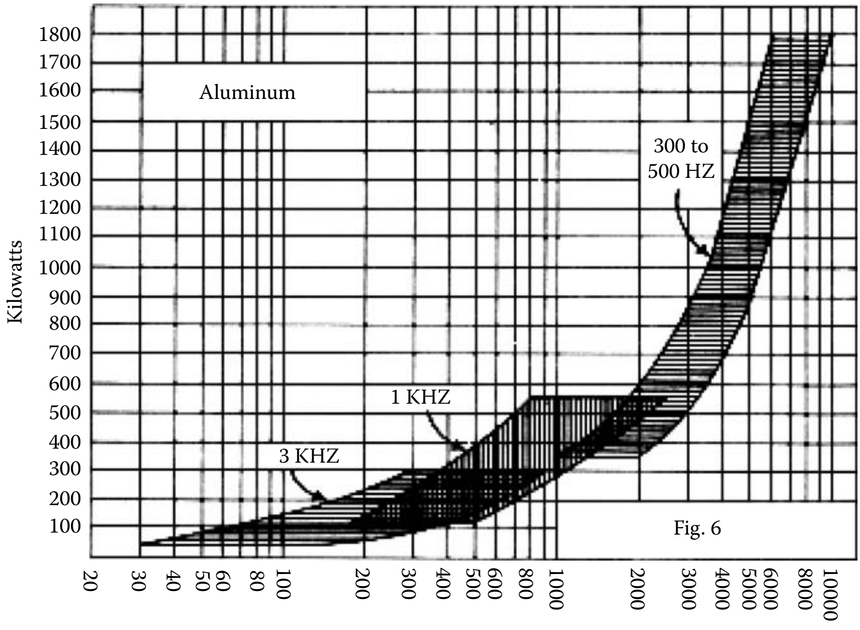

FIGURE 10.3 Coreless induction furnace load versus capacity, showing optimal frequency ranges. (From Hipple, W.F., *Modern Casting,* 72(8), 39, 1982. With permission.)

The equipment shown here is a parallel inverter (Perkul, 1988), in which the capacitor bank is connected in parallel with the induction coil. This eliminates the need for a matching transformer and operates at efficiencies of 95% or higher, an improvement over series inverters. As a result, this design of electrical circuit is favored (Goyal, 1985).

Coreless induction furnaces are operated in one of two basic methods (Perkul, 1988). The first is a batch operation, in which the furnace is completely emptied after every heat. The second is a tap-and-charge operation, in which the furnace is operated semicontinuously, with about 50% of its contents removed after each heat. The more consistent temperature of a tap-and-charge operation ensures longer refractory life; however, batch operation has a higher electrical efficiency (Kreysa, 1991). While tap-to-tap times are longer in batch melting, the frequency of tapping is reduced, ultimately maximizing furnace utilization. In addition, the ability to operate medium-frequency coreless furnaces with a completely solid charge means some oily or wet scrap can be used in a batch operation, as long as no liquid heel is left after tapping (the oil and water are vaporized during heat-up). It is recommended that the fraction of wet scrap in a charge be limited to one-fifth or less of the total (Groteke, 1997).

Charging frequency depends on the type of operation (batch or tap-and-charge) and the furnace size and frequency. The lower melt capacity of mains-frequency

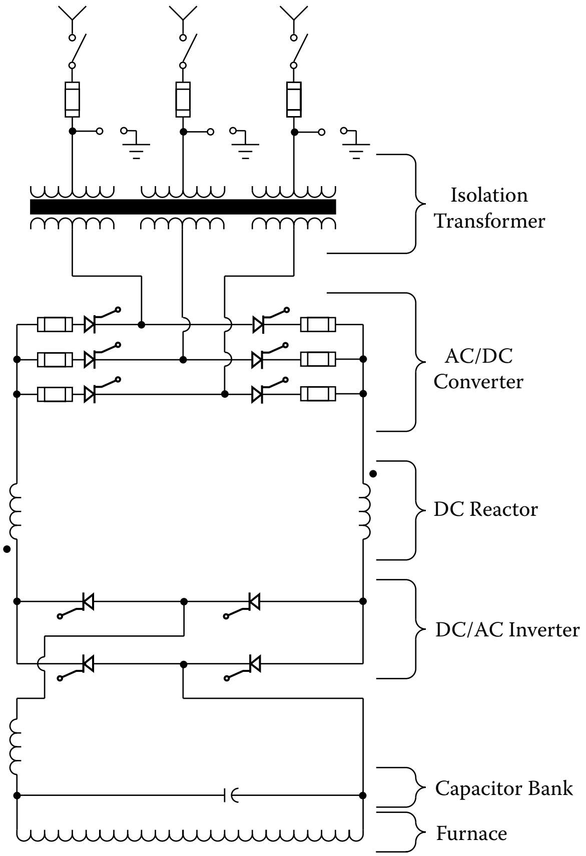

FIGURE 10.4 Solid-state frequency conversion schematic for medium-frequency induction furnaces. (From Hipple, W.F., *Modern Casting,* 72(8), 39, 1982. With permission.)

coreless furnaces means they need to be charged less often; the appetite of medium-frequency furnaces is such that a continuous charging device may be appropriate (Groteke, 1997; Kreysa, 1991). The size of solid pieces charged to a coreless unit should be less than two-thirds of the furnace diameter to prevent bridging (Perkul, 1988).

A peculiar concern in the operation of coreless furnaces is the disposition of dross. Ordinarily, dross from aluminum melting furnaces rises to the top, where it is skimmed off. However, the stirring in coreless units draws dross down instead into the melt (Smith and Hayes, 1992). As the metal circulates, the dross agglomerates on the furnace walls (Goyal, 1985). This poses several concerns. The first is refractory penetration (Shuichi, 1988). The dross contains small amounts of entrapped metal, which will become superheated when trapped near the crucible wall (where the magnetic field from the coil is strongest). The superheated metal penetrates refractories easily, shortening lining life. A second problem is the increase of lining thickness resulting from dross adsorption. This reduces power input to the melt. A third possible concern is dross being eroded from these side deposits by circulating metal and ultimately winding up in the metal. Special mechanical scrapers have been designed to periodically remove the deposited dross without disturbing the molten metal surface (Perkul, 1988).

CHANNEL FURNACES

Figure 10.5 illustrates the basic construction of a channel induction furnace (Perkul, 1988). As before, a water-cooled copper-tubing coil is used to generate a magnetic field, which heats the metal in the channel surrounding the coil. However, there are several differences. The most significant is that the channel is placed outside the coil, whereas the metal in a coreless induction furnace is placed inside the coil. To redirect the magnetic field generated by the coil to act entirely on the metal in the channel, an iron core is placed inside the coil. This serves the same function as the iron yoke placed outside the coil in a coreless unit.

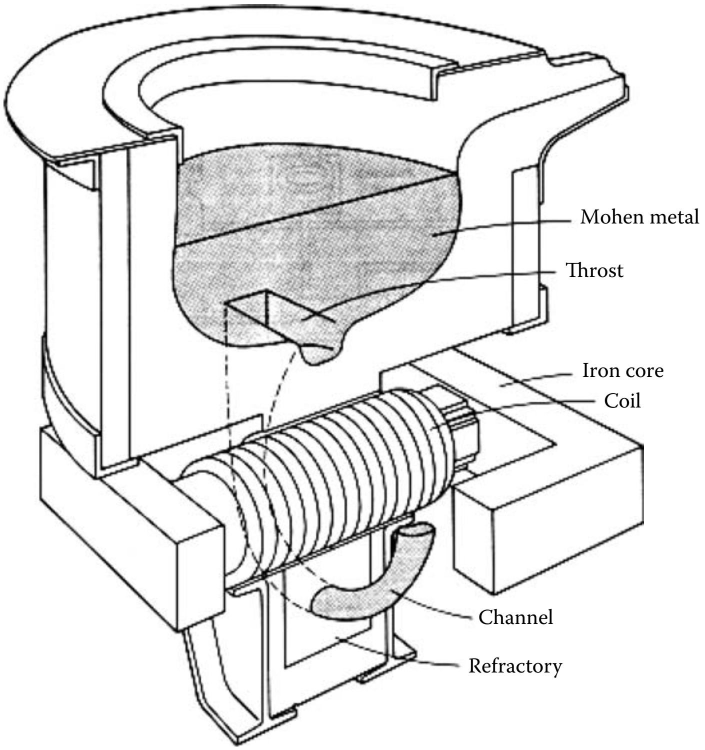

FIGURE 10.5 Construction of a channel induction furnace. (From Perkul, R.Y., in *Metals Handbook,* Vol. 15, *Casting,* 9th ed., ASM International, Materials Park, OH, 1988, p. 368. With permission.)

A bigger difference between the channel and coreless induction furnaces is that the amount of metal in the channel surrounding the coil is much smaller than the amount of metal being acted on by the field in a coreless unit. As a result, channel furnaces heat metal by an indirect method. Metal flowing through the channel is superheated by the field and moved along by the same forces that cause bath circulation in coreless units. As the superheated metal exits the channel into the main body of the furnace, it transfers heat to the rest of the melt. (This can be seen as an electric-furnace analog to sidewell melting furnaces heated by fossil fuel combustion.) Scrap or ingot fed to the furnace is melted by this indirect approach, rather than going through the channel.

Nearly all channel furnaces operate on mains frequency. Because of this, the power density is limited, making the direct melting of scrap impossible. This in turn means that a heel of molten metal must be maintained in the furnace (Perkul, 1988). This reduces furnace flexibility and makes alloy changes difficult. As a result, channel furnaces are used more often as holding furnaces, rather than as melting units, and typically for larger operations. However, for these applications, channel furnaces have advantages. Their efficiency is typically 70 to 75%, compared with the 50 to 55% efficiencies of coreless furnaces (Knödler, 1986). A second advantage is the reduced agitation in channel furnaces. This minimizes dross formation compared with coreless units and reduces gas pickup. However, the reduced turbulence also makes it more difficult to charge low-bulk scrap, such as cans, shredded material, and trimmings (Kreysa, 1991). These materials must be baled or otherwise densified before charging to reduce melt loss.

Until the early 1980s, a second limitation on channel furnace capacity was the induction coil itself, which was air-cooled (Hellsing and Tällback, 1982; Knödler, 1986). This limited inductors to power ratings of 250 kW and less. The development of water-cooled inductors allowed power ratings to increase to 1000 kW or higher. Using multiple induction loops on a furnace also increases furnace capability. However, this comes at a price; channel furnaces are more expensive per unit melting capacity than coreless units (and much more expensive than fossil-fuel furnaces).

The biggest operating concern in the use of channel furnaces is the rapid metal flow through the channel, which can lead to two opposing difficulties (Nacke, 1993). The first is rapid wear of the refractory lining of the channel (Hellsing and Tallbäck, 1982; Hentschel and Feldmann, 1982; MacIntosh, 1983), which causes the need for replacement at a more frequent rate than coreless units. The second concern is the deposition of dross on the refractory surface, similar to the deposition of dross on the crucible walls of coreless furnaces. This dross can over time build up and clog the channel, forcing the furnace to be taken out of service while the clog is removed. Solutions to the clogging problem include increasing the metal flow rate through the channel, which reduces dross deposition, and injecting an inert gas (argon or nitrogen) into the channel. Both of these tactics increase the refractory wear rate, however. The problem is less severe in larger furnaces, which have wider channels and thus are less prone to clogging.

RESISTANCE FURNACES

Electric resistance furnaces feature a wire element looped throughout the sides of the furnace. When current is passed through the wire, its resistance generates heat, raising its temperature. Eventually the element temperature rises to the point where it glows. The glowing element radiates heat to the surroundings, including the crucible placed inside the furnace. This heats the metal inside or keeps it warm if it is already molten. Changing the current to the element changes the power generated, allowing temperature control.

The element in most resistance furnaces is made of the nickel–chromium alloy Nichrome. The chromium in this alloy forms an impervious oxide layer when the element is used. The oxide layer prevents further oxidation and allows the element to be used for an extended period of time before replacement is required. The element is often installed as an open-coil element supported on high-purity ceramic tubes; elements can also be obtained semiembedded in refractory panels (Atkins, 1992), which are simply swapped out when the element fails. Open-coil elements are preferred for aluminum melting because of the higher power loading (and increased melt rate) possible with this type; however, improved semiembedded elements are available that may eliminate this advantage.

Resistance furnaces generally belong to one of two categories: small crucible *bale-out* furnaces, and radiant-heat-holding *electric reverberatory* furnaces and tundishes (Davies, 1987; Atkins, 1989; Smith, 1993). The capacity of the bale-out furnaces can be as high at 1500 kg but is usually much smaller. They can be operated with a molten heel but are usually charged cold. Efficiencies are high (80%), but the low power input means melting capacity is poor compared to other furnaces. Because no stirring is provided by these furnaces, only bulky scrap can be used (along with primary ingot). However, the use of electricity provides the same advantages of cleaner metal and reduced dross generation that other electric furnaces have. Crucibles are usually made from silicon carbide, which is preferred over clay–graphite because of its higher thermal conductivity.

Electric reverberatory furnaces (see Figure 10.6) are used as holding furnaces (Davies, 1987; Atkins, 1989; Smith, 1993). They typically feature silicon carbide elements embedded in the furnace roof and can hold up to 6000 kg of molten metal, although they are usually much smaller. The high reflectivity of molten aluminum means a large bath surface is required for effective heating, and this in turn increases the potential for dross formation and hydrogen pick-up during holding. As a result, use of these furnaces is limited.

Attempts have been made to overcome the disadvantages of resistance-heated furnaces. One of the more promising is a hybrid furnace that uses fossil-fuel heating for charge heating and melting and resistance heating for heating and holding the molten metal. This improves melting capacity while preserving the electric heating advantages of cleaner metal and reduced gas pick-up. A second attempt is the *direct-heat* concept offered by Inductotherm, which uses an induction coil to heat a silicon carbide crucible. The high resistivity of the crucible causes it to heat rapidly, heating the metal inside. Because the induction field is applied to the crucible rather than the metal, the stirring action of other coreless induction furnaces is avoided, reducing

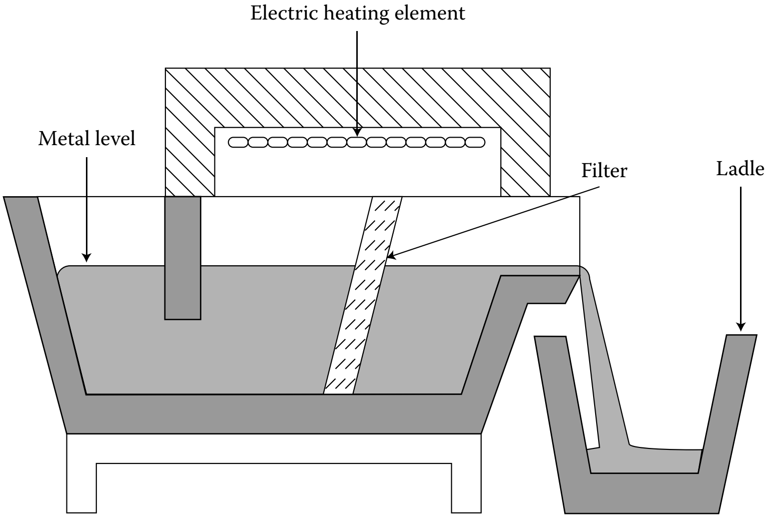

FIGURE 10.6 Cross-section of a resistance holding furnace. (From Atkins, R., *Foundry Int.,* 15(4), 166, 1992. With permission.)

drossing and gas pick-up. However, the use of electric furnaces for large-scale melting of scrap is likely to remain the less preferred option for some time to come.

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11 The Recycling Industry

Some of this chapter will be out of date before you read it. The recycling industry is constantly changing, and the number of facilities processing aluminum scrap or dross grows or shrinks with time in different locations owing to several factors. As a result, some recyclers counted in this chapter are now defunct, and new ones have begun operations since this was written. In addition, the definitions used to describe the recycling industry are no longer as precise as when they were first used.

Secondary aluminum is a commodity material, and the driving forces that influence other commodity processors also influence the aluminum recycling industry. Most of these forces are rationalizing the industry, resulting in fewer but larger processing facilities. The changing nature of the scrap supply also affects which recycling facilities will thrive, as does the shifting geography of the demand for aluminum.

WHO RECYCLES ALUMINUM?

In recent years the majority of aluminum scrap recycled in the United States has actually been consumed by *primary aluminum smelters* rather than by scrap processors. Primary smelters use scrap because:

- It is a cheap source of aluminum. In countries with high power costs and distant bauxite resources, the cost of purchasing and remelting scrap may be less than that of producing aluminum from ore (Wilkinson, 2003; Toto, 2004). As a result, a primary smelter can lower its costs by remelting as much scrap as possible. (Of course, the entry of primary smelters into the market can drive scrap prices up, reducing this advantage.) In countries with lower power costs or nearby bauxite resources, this factor becomes less important.
- It is a cheap source of alloying elements. Most aluminum alloys contain one or more of five alloying elements: copper, magnesium, manganese, silicon, and zinc. As the prices of these metals increase (silicon has been particularly expensive at times), the alloy content of scrap is increasingly valuable.
- It reduces power usage and emissions associated with primary smelting. Primary aluminum smelters consume substantial amounts of electrical energy and are often the biggest electricity consumers in a region. As other consumers in the region increase the demand for power, reducing power use in smelters is a net contribution to the available supply. In addition, many industrial societies have committed themselves to reducing carbon dioxide emissions to the atmosphere. The CO_2 emitted during the recycling of aluminum is 90% less than that created during primary production (Morrison, 2005).

However, because primary smelters produce primarily wrought alloys and are not equipped to do substantial amounts magnesium removal, they are selective about the scrap they buy. New scrap with a known composition is vital; uncoated material is also needed, since primary smelters have different environmental equipment than secondary smelters and may not be able to adequately handle the organic vapors generated by decomposing coatings. As a result, primary smelters in developed areas with large scrap markets are more likely to use scrap than smelters in less-developed regions.

Some primary smelters in North America and Europe have also begun to produce casting alloys such as A319.0 (Anonymous, 1999). The low iron content of primary aluminum makes it easier for these smelters to produce low-iron casting alloys, and the presence of nearby customers such as auto producers provides a further economic advantage. The production of cast rather than wrought alloys also means greater consumption of scrap, since these compositions can absorb more in the charge.

The second category of recycling operation is the *remelter.* Like primary smelters, remelters also produce primarily wrought alloys (Bijlhouwer, 1994; Kirchner, 2002a), meaning that careful selection of scrap grades and chemistries is essential. Again, remelters use primarily new scrap, with some added primary metal to dilute impurity content to the needed level (Kevorkijan, 2003). Remelting operations fall into three categories (Kirchner, 1998):

- *Integrated* operations generate a consumer product, often extrusions, rather than merely producing billets. Scrap generated during extruding is recycled along with purchased scrap.
- *Non-integrated* operations produce alloy billet for sale to other processors.
- *Toll* operators accept scrap from a single source and melt it down for return to the originator without ever owning the material. This type of operation has become more popular in recent years, as large manufacturers arrange with secondary aluminum producers to operate dedicated recycling facilities designed to process only the manufacturer's scrap (Anonymous, 1999; Pinkham, 1999; Kevokijan, 2003).

Initially, remelters were distinguished from secondary smelters by a lack of refining capability. However, the demand for higher product quality now means that many remelters refine and filter their molten metal, regardless of its initial source.

A special type of remelter is the *used beverage container (UBC) recycler,* which uses a feedstock consisting primarily of recovered beverage cans (Sanders et al., 1990). These first began to appear in the 1980s, when the number of discarded cans became sufficient to justify a specialized facility. UBC recyclers are similar to remelters in that they produce a wrought alloy, typically 3004. However, because their feedstock is a mixture of can bodies (3004) and lids (5175 and others), additions of primary aluminum and alloying elements must be made to produce the correct alloy composition. In addition, refining and filtration are required to produce a quality product. UBC recyclers are numerous in industrialized countries, but the recent decline in can recycling rates has forced occasional shutdowns (Worden, 1995).

Secondary smelters, known as *refiners* in Europe, are the most common type of aluminum recycling facility. Secondary smelters produce casting alloys (Kirchner, 2002a), in particular A380.0, and as a result use types of obsolete or low-grade scrap that other recycling facilities cannot use. As the demand for better-quality scrap from other recyclers increases its price, secondary smelters increasingly rely on old scrap to meet their needs (Borsecnik, 1994; Buchanan, 2002). However, the use of old scrap makes quality control more challenging, so refining and filtration are increasingly necessary. The use of old scrap also makes operating in an environmentally acceptable manner more difficult, since old scrap has more painted and coated material and is also more likely to contain plastics and salts.

INFLUENCES ON THE ALUMINUM RECYCLING INDUSTRY

THE IMPACT OF GOVERNMENT

Government decisions have a significant impact on where aluminum recycling facilities are located and how they do business. Three examples are listed below:

- Russia imposed a 50% export duty on nonferrous scrap exports in 1999, increasing it from 30% (Buchanan, 2002). This raised scrap prices to recyclers in Western Europe, which had relied on the availability of low-cost scrap from Russia and Eastern Europe (Buchanan, 2001). The result of this has been to encourage recycling in Russia (Wilkinson, 2001) and to make remelting and refining less feasible in Western Europe. This is one of the reasons why some European secondary smelters have closed (Anonymous, 2004a).
- Other nations use import duties to impact flows of aluminum scrap. India has an import duty of 15% on imported aluminum scrap (Lobo, 2001) to protect domestic primary aluminum producers. However, this hurts the domestic recycling industry and drives scrap to other Southeast Asian countries. The 6% European Union import duty on primary aluminum also hurts secondary smelters and refiners (Conserva and Spa, 2003), since primary metal is used to dilute excess levels of alloying elements in remelted scrap.
- In 2000 the European Union enacted directive 2000/53/EC, better known as the End-of-Life Vehicles (ELV) directive. This directive requires automotive manufacturers to take ELV vehicles back when their working life is finished and to ensure appropriate disposal (Kirchner, 2002a,b). The directive requires recovery or reuse of 85% (eventually 95%) of the material in the vehicle, with emphasis on reuse rather than reprocessing of materials. Since automakers will bear the cost of processing or disposal, recovering costs will be important, and this encourages the development of closed-loop recycling, using a few favored scrap processors. This will further reduce the number of small recycling operations in Western Europe. Another possible response by automakers is to sell ELVs to countries outside the European Union (Stanford, 2005), ultimately encouraging recycling of their aluminum content elsewhere.
- Other government mandates that impact the aluminum recycling industry include initiatives to increase recovery of UBCs, discussed in Chapter 3;

required recycling of computers and other electronic devices; and initiatives to increase materials recovery from construction and demolition debris. These tend to support recycling facilities in industrialized countries, where these materials streams are generated.
- In 2000 the U.S. Environmental Protection Agency enacted new MACT (maximum achievable control technology) rules for several industries, including secondary aluminum smelters (Strieter, 2003; Toto, 2004). These rules were designed to reduce emission of several air toxins, including dioxins and furans, NO_x, and SO_2. Several U.S. secondary smelters have since been found in violation of these standards (McCann, 2004), resulting in financial penalties and the required installation of new pollution control equipment. Environmental restrictions have affected secondary smelters and remelters in other industrialized countries as well.

The impact of environmental restrictions is threefold. The first is the disappearance of smaller smelters and remelters, unable to afford the equipment necessary to achieve required emissions limits. Schwalbe (1998) claims that this equipment now represents 25% of the processing cost for aluminum recycling in Germany. The second impact is the flow of scrap to facilities that are not required to meet the emission limits. In the United States, this means increasing direct purchase of scrap by foundries, replacing recycled secondary ingot (RSI) produced by secondary smelters (Toto, 2004). The third is the movement of aluminum recycling to countries where environmental restrictions are less severe. Secondary smelting in Mexico and China has benefited from this in particular (Wilkinson, 2001).

THE IMPACT OF DEMAND

Secondary aluminum smelters exist primarily to serve the needs of the transportation industry, in particular auto producers; 70 to 80% of their production is sold to this sector (Bontempi, 2002). As a result, secondary smelters tend to be located near foundries serving the auto industry, and when the auto industry moves, the secondary smelting industry moves with it. This is especially apparent in Eastern Europe and Mexico (Lenhart, 1998; Wilkinson, 2001; Buchanan, 2002).

For remelters, the development of closed-loop recycling arrangements with scrap generators has meant more stability. This has meant less movement of this industry than secondary smelters (Bijlhouwer, 1994; Kevorkijan, 2001). UBC recyclers in particular have remained primarily in North America, since that is where both the scrap cans and the can producers are located. However, broader changes in metal demand affect this branch of the industry as well. The rapid and sustained growth of the Chinese economy in recent years has increased demand for all metals, and this has contributed to the sustained increase in scrap flow to China (Schaffer, 2004; Stanford, 2005; Morrison, 2005).

Figure 11.1 shows the location of major (>20,000 tonnes/year) aluminum recyclers in the United States in 2004 (Toto, 2005). The × symbols mark the location of two primary smelters that use more scrap than the others; both are located in the

FIGURE 11.1 Location of U.S. secondary aluminum producers, by type of facility.

Ohio River valley, a relatively high-cost region for primary producers. Seven facilities (▲) exist primarily to recycle UBCs. All are located in the eastern United States, where higher population densities mean larger concentrations of UBCs to collect. Secondary smelters (o) and remelters (★) are more geographically dispersed, but are still concentrated in areas where customers (auto producers, aircraft manufacturers) are likely to be found.

THE IMPACT OF COST

For aluminum recyclers, the cost of operation can be separated into two categories: the cost of obtaining scrap and the cost of processing it. As might be suspected, recyclers tend to be located in areas where these costs are less.

Some of the factors affecting the price of scrap have already been mentioned, including export or import fees, and competition for scrap from primary smelters. Scrap prices are also affected by the price of primary aluminum and by quality. (New scrap sells for more than old scrap, and scrap separated into alloy types sells for more than mixed scrap.) Sudden increases in scrap availability without an increase in nearby smelting or remelting capacity lowers prices, encouraging recycling operations to set up shop. The increase in smelting capacity in Eastern Europe has been credited with this (Lenhart, 1998). As demand for scrap increases, the price eventually increases too, erasing this cost advantage.

The cost of operation is affected by the costs of energy, capital equipment, labor, and waste disposal. Since most secondary aluminum remelters and smelters fire their furnaces with natural gas, increases in natural gas price are important. Areas with lower energy prices become attractive, even if other costs are higher there (Millbank, 2001). As pointed out in Chapter 6, lower labor costs in China have made hand sorting

TABLE 11.1
Secondary Smelter Numbers in Western Europe from 1995 to 2000

Year	Smelters with Capacity <1,000 Tonnes/yr	Smelters with Capacity >50,000 Tonnes/yr
1995	102	4
1997	59	10
2000	37	13

more profitable than automated sorting in Europe and North America (Tu, 1996; Minter, 2003); this is another reason scrap supplies have been moving to China. Waste disposal costs are also higher in Western Europe and North America, particularly for salt slags (Schwalbe, 1998), and this too encourages the industry to move elsewhere.

THE IMPACT OF TECHNOLOGY

The story of aluminum recycling has been largely the story of facilities attempting to manufacture a quality product suitable for customers. The most important technological development has been the installation of refining and filtration equipment, which has made the quality of secondary aluminum close to that of primary. Another important technological development has been the construction of crucibles in which smelting and remelting facilities can send molten metal directly to customers (Peterson and Blagg, 2000; Anonymous, 2004b), without the need to cast it into ingots or billets. Shipping molten metal eliminates the expense of casting it and saves the customer money by eliminating the energy cost otherwise required to remelt it. However, a recycler shipping molten metal needs to be physically close to his customer, and this has provided further encouragement to recyclers to relocate as needed. Closed-loop recyclers are particularly subject to this restriction.

The most noticeable impact of improved technology can be seen in Table 11.1 (Bontempi, 2002). Small "garage" secondary smelters used to be quite common in Europe, collecting scrap over a small area and producing RSI for sale to foundries (Nappa, 1994; Lenhart, 1998). However, these small operations cannot afford to install the refining and environmental equipment increasingly needed to produce a quality product and meet government regulations. As a result, these operations have been falling by the wayside (Novelli, 1997; Schwalbe, 1998; Wilkinson, 2001), while the number of large smelting facilities has been increasing.

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12 Metal Refining and Purification

For many years aluminum produced by remelting scrap was less valuable than primary metal produced from bauxite. The reason for this was concern over the purity of the recycled metal, which was often inferior to that of primary. The development of refining technology for molten aluminum is the main reason this stigma no longer exists and is why recycled metal now competes with primary in almost every application. Much of the technology used for refining molten aluminum has been introduced only in the past 20 years, and what was once a minor footnote in an aluminum production flowsheet is a now a major consideration.

The choice of refining strategy and technology used by scrap remelters depends on several factors: the type of scrap being remelted, the type of furnace used, the type of product being generated, and most importantly the needs of customers. As a result, there is no universal refining technology. A complicating factor is the blending of scrap with primary metal in melting furnaces, which also combines the refining concerns of the two types of metal. Because of this, much of the technology used for refining remelted aluminum scrap is also used to purify molten primary metal. Since the basic principles are the same, a discussion of refining technology for secondary aluminum is essentially a discussion of molten aluminum refining in general.

The following discussion is a brief introduction to the theory and equipment used for molten aluminum refining. Enough in-depth information exists on this technology alone to write an entire book about it. Those wishing to learn more about aluminum refining are encouraged to consult the references at the end of this chapter.

COMMON IMPURITIES IN MOLTEN ALUMINUM

Table 12.1 lists the most common impurities in molten aluminum (Waite, 2002) and compares their concentration in primary and secondary metal. The impurities can be divided into three classes: hydrogen, reactive metals (including magnesium), and inclusions.

HYDROGEN

Hydrogen in molten aluminum is obtained from a reaction between water vapor and the molten aluminum (Altenpohl, 1998):

$$3\ H_2O + 2\ Al = Al_2O_3 + 6\ \underline{H} \tag{12.1}$$

The magnesium in remelted alloy scrap also reacts with water vapor:

$$H_2O + \underline{Mg} = MgO + 2\ \underline{H} \tag{12.2}$$

TABLE 12.1
Common Impurities in Primary and Secondary Molten Aluminum

Impurity	Concentration in Primary Metal	Concentration in Secondary Metal
Hydrogen	0.1–0.3 wppm	0.4–0.6 wppm
Inclusions	>1 mm^2/kg	$0.5 < mm^2/kg < 5.0$
(PoDFA scale)	(Al_4C_3)	(Al_2O_3, MgO, $MgAl_2O_4$, Al_4C_3, TiB_2)
Alkali:		
Sodium	30–150 ppm	<10 ppm
Calcium	2–5 ppm	5–40 ppm
Lithium	0–20 ppm	<1 ppm

Source: Waite, P., in *Light Metals 2002,* Schneider, W., Ed., TMS–AIME, Warrendale, PA, 2002, p. 841. With permission.

Both reactions are highly favored thermodynamically and limited only by the formation of an oxide skin on the melt surface, which prevents contact between the water vapor and the molten metal. Factors that encourage these reactions and increase the dissolved hydrogen content of the metal include:

- A higher vapor pressure of water vapor in the atmosphere (i.e., higher humidity), which drives the reactions to the right (Waite, 1998; Le Brun, 2002)
- Metal turbulence, which destroys the oxide skin and allows the reactions to continue (Eckert, 1992; Fielding, 1996)
- Wet or damp charge materials, which make water vapor directly available to the melt

In addition to natural humidity, water vapor in the products of combustion (POC) from fossil-fuel fired furnaces is a source of hydrogen (Eckert and Cochran, 2000; Le Brun, 2002). As a result, extended exposure to POC in transfer ladles can raise dissolved hydrogen content still further. Some alloying elements (Cu, Fe, Si, Zn) raise the activity coefficient of dissolved hydrogen in molten aluminum, decreasing its solubility (Sigworth, 1999; Djurdjevic et al., 2002); others (Li, Mg, Zr) lower the activity coefficient and raise the solubility. As Table 12.1 shows, the hydrogen content of remelted scrap is usually higher than that of primary metal. This is caused mostly by water in the scrap and by the use of fossil fuels for remelting it.

The unit for hydrogen analysis in molten aluminum is unusual. Hydrogen contents are often expressed as standard cubic centimeter of H_2 gas contained per 100 g of molten Al (Altenpohl, 1998). The reason is that hydrogen is virtually insoluble in solid aluminum. Because of this, any hydrogen dissolved in the molten metal will exsolve during solidification, resulting in porosity in the cast product. Since 100 g of solid aluminum has a theoretical volume of 37.04 cm^3, a dissolved hydrogen content of 0.5 $cm^3/100$ g would result in a porosity level of 1.33% in the solid product, unacceptable for nearly all applications. Customer specifications often call for $\underline{H}$ levels in purchased aluminum of 0.18 $cm^3/100$ g (0.16 wppm) or less for wrought-alloy applications (Fielding, 1996), and this specification continues to decrease as rolled sections get thinner and less tolerant of porosity. Allowable hydrogen levels for casting alloys are higher (0.4 cm^3/100 g) but still lower than the level initially present in most molten scrap. Dissolved hydrogen levels in scrap melts can often exceed 0.50 cm^3/100 g (0.45 wppm).

The analysis of hydrogen has been revolutionized over the past 15 years by the development of on-line analytical tools that can almost instantaneously measure hydrogen levels in molten aluminum. The number of devices used to measure the hydrogen content of molten aluminum is too large to review here, but they can be organized into four classes (Chen et al., 1994; Stucky and Richard, 1998; Neff, 2004):

- *Indication* methods measure the apparent density of a sample of metal when it solidifies in a closed chamber. The more hydrogen contained in the molten metal, the greater the porosity when it solidifies and the lower the apparent density. This method is slow, and its accuracy is limited.
- *Direct-determination* methods measure the partial pressure of H_2 generated by the dissolved hydrogen in a molten sample. Extensive improvement in the equipment used for direct determination has made these devices increasingly useful for both large-scale remelters and foundries. Two complications impact the reliability of direct-determination hydrogen analysis. The first is that the relationship between p_{H2} and dissolved hydrogen content is a function of alloy content and metal temperature, so these must be known when measurements are made. The second is that correct analytical technique is required to achieve accuracy, and this is still evolving.
- *Analytical* methods determine the amount of H_2 exsolved from a sample into a vacuum or carrier gas during solidification. This method is more accurate but too slow for use where quick turnaround is required.
- *Electrochemical* analysis is the newest category of hydrogen analysis method (Martins et al., 1998). This uses a solid electrolyte capable of conducting protons (H^+ ions) generated by the dissolved hydrogen in the molten metal; the higher the hydrogen content, the greater the ionic current generated in the electrolyte.

REACTIVE METALS

Although this group of impurities in theory includes all the alkali and alkaline earth metals, in practice three elements matter most: sodium, calcium, and magnesium. The sodium (and lithium) content of primary metal results from interaction between the aluminum generated in molten-salt electrolytic cells and the sodium and lithium salts dissolved in the bath. Since this bath is not used to remelt scrap, secondary metal has little or no sodium or lithium. Some calcium is found in remelted scrap, however. The most significance source of calcium in scrap is the calcium-containing salts used for deicing roads and bridges, which can wind up attached to aluminum car and truck parts. Because primary metal is often added to molten scrap, the presence of sodium is often a concern as well.

The amount of magnesium in molten scrap depends on the alloys being remelted and can range to 5% or higher. Whether this magnesium is treated as an impurity to be removed depends on the alloy being created; because magnesium is more expensive than aluminum, alloy practice that produces alloys with higher magnesium content than that of the melt is encouraged. However, in some cases this is not feasible, and demagging is a part of the refining process. While published specifications usually do not set a specific limit on reactive-metal impurities, customers often require sodium and lithium levels of less than 10 ppm.

As is the case with hydrogen, analysis of the reactive-metal content of molten aluminum is increasingly conducted on the shop floor, and quick turnaround time is important. The most popular technique is optical emission spectrometry (OES), which can also measure the concentration of other trace metals (Weaver, 1997). Automation of the analytical process has been a significant improvement.

INCLUSIONS

Inclusions are mostly solid particles suspended in molten aluminum. The number and size of these particles depends on a variety of things, in particular the initial quality of the scrap being melted and the impurities contained in that scrap. Inclusions are nonmetallic particles, usually less than 100 μm in size. They consist mostly of oxides, although several other types of compound are represented. There are two basic classes of inclusion, *exogenous* and *indigenous.*

Exogenous inclusions are particles already existing as a separate phase before melting (Eckert, 1992; Wang et al., 1996). Small pieces of furnace refractory that break off into the melt are the best known example (Weaver, 1997); bits of oxide or dirt attached to scrap are another. Exogenous inclusions consist almost entirely of oxide and are much larger than most indigenous inclusions. Because of this, their presence in aluminum is more harmful than that of indigenous inclusions; however, their larger size makes them easier to remove.

Indigenous or *in-situ* inclusions are formed by chemical reactions taking place in the melt (Eckert, 1992; de la Sablonierre and Samuel, 1996). An example is the reaction of dissolved oxygen with the molten aluminum to generate alumina:

$$2\ \mathrm{Al} + 3\ \underline{\mathrm{O}} = \mathrm{Al_2O_3} \tag{12.3}$$

The thermodynamic stability of alumina increases as the temperature decreases, and the solubility of oxygen in molten aluminum decreases with temperature as well, so Reaction 12.3 automatically occurs in aluminum as it cools. In magnesium-containing alloys, magnesia and spinel are also created (Fielding, 1996):

$$\underline{\mathrm{Mg}} + \underline{\mathrm{O}} = \mathrm{MgO} \tag{12.4}$$

$$\underline{\mathrm{Mg}} + 2\ \mathrm{Al} + 4\ \underline{\mathrm{O}} = \mathrm{MgAl_2O_4} \tag{12.5}$$

If nitrogen is used during degassing, AlN can form; if $MgCl_2$ is used as a flux, chloride inclusions can form as well. These inclusions are much smaller than exogenous inclusions and much harder to remove.

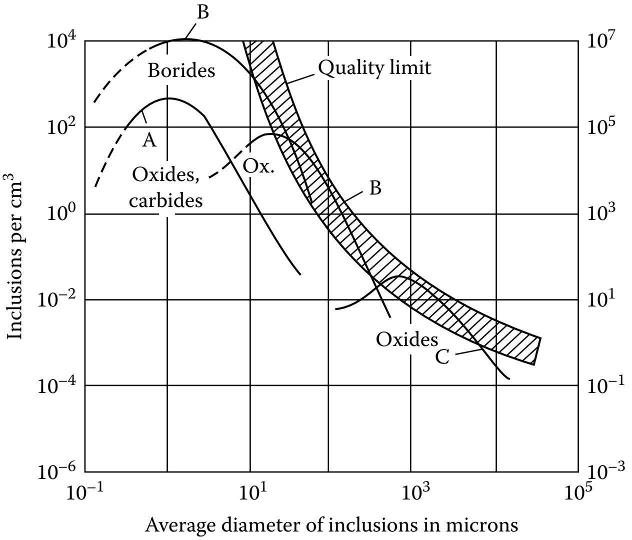

FIGURE 12.1 Concentrations of different types of inclusion in molten aluminum, by particle size. (From Altenpohl, D. G., *Aluminum: Technology, Applications, and Environment,* 6th Ed., TMS–AIME, Warrendale, PA, 1998. With permission.)

The inclusions in remelted aluminum scrap are different than those in primary metal, as Table 12.1 shows. Scrap inherently has more dirt and oxide in it than primary metal, and the oxide skins generated during melting increase the inclusion count even more (Altenpohl, 1998). As a result, inclusion removal is a much more significant element of secondary aluminum production. Remelting of bulky scrap generates metal with fewer inclusions than remelted used beverage containers (UBCs) or light scrap; the price of bulky scrap is higher as a result. Remelting of high-magnesium alloys generates a higher inclusion count, owing to the greater tendency of magnesium to react during melting.

Figure 12.1 describes in greater detail the significance of different types of inclusion in molten aluminum (Altenpohl, 1998). The hatched area is an unofficial quality limit for the concentration of inclusions of different size in cast aluminum. (The limits are lower in wrought aluminum.) The y-axes are inclusion concentration per unit area of as-cast microstructure; the x-axis is the average diameter of the inclusion. Curve C is for inclusions generated during casting, that is, oxide skins and slag inclusions; exogenous inclusions would also fall along this curve. Curve B is for indigenous inclusions generated during melting and melt treatment. In general, oxide inclusions tend to be larger than those composed of carbide or boride particles (Simensen and Berg, 1980) and the ones most in need of removal for quality standards.

The unit of inclusion analysis (mm^2/kg) in Table 12.1 is unusual. The reason has to do with the choice of analytical method. Before the 1980s inclusions were counted by analyzing the microstructure of cast metal and counting by hand.

However, the small number of inclusions made this a difficult and time-consuming process. In the 1980s the introduction of *PoDFA* and *LAIS* made inclusion analysis easier (Sampath et al., 1996; Neff, 2004). PoDFA and LAIS use the filtration of a known amount of molten metal through a porous filter to collect the inclusions (de la Sablonierre and Samuel, 1996; Waite, 2002), which are then counted and measured. The total area of inclusion per kilogram of metal filtered is the variable measured and used in Table 12.1.

A more recent development has revolutionized inclusion measurement in molten aluminum. *LiMCA* is based on a Coulter counter, which detects inclusions by their impact on the electrical conductivity of aluminum flowing through a small tube (Engh, 1992; Waite, 2002). Each inclusion is registered separately, allowing them to be counted per unit mass of metal. Recent improvements in the new LiMCA II device have improved its accuracy and reliability still further (Dupuis et al., 1999), and this device will be a mainstay of the aluminum industry over the near future.

THE FOURTH CLASS OF IMPURITIES

Although not listed in Table 12.1, there is a fourth class of impurities that remelters would like to remove if possible. These are the alloying elements present in aluminum scrap: copper, iron, manganese, silicon, and zinc. Percentages of these elements vary, depending on the scrap charge and the amount of primary metal added. However, concentrations of these elements that are too high limit the number of alloys that can be produced from a melt, as discussed in Chapter 2.

The development of technology for segregating scrap by alloy type was discussed in Chapter 6; the commercial use of this technology is in its infancy. In the meantime, the only current response to high concentrations of alloying elements is either the production of an alloy with even higher concentrations of these elements, such as 364.0 or 380.0, or dilution of the alloying elements to a lower level with added primary metal. Attempts to develop an economically acceptable chemically based refining process to remove these elements have so far proved unsuccessful (van der Donk, 1995). A process for removing iron would be especially welcome, since many commercial alloy specifications specifically call for low iron content.

FUNDAMENTALS OF IMPURITY REMOVAL

HYDROGEN

The only successful technique for removing hydrogen from molten aluminum is to transfer it to a gas phase, by the reaction:

$$2\ \underline{\mathrm{H}} = \mathrm{H}_2\ (g) \tag{12.6}$$

The equilibrium constant for this reaction can be rearranged to a form of *Sievert's Law*:

$$[\underline{\mathrm{H}}] = S\ (p_{\mathrm{H2}})^{1/2} \tag{12.7}$$

where [H] is the dissolved hydrogen concentration in $\mathrm{cm}^3/100$ g of Al, p_{H2} is the partial pressure of hydrogen in atmospheres, and S is the equilibrium constant at a given temperature. Sigworth (1999) suggests that the most accurate expression of S in pure aluminum as a function of temperature is

$$\log S = -2692/T + 2.726 \tag{12.8}$$

where T is expressed in K. At 700°C (973 K), $S = 0.911$, and molten aluminum with a dissolved hydrogen concentration of 0.4 cm^3/100 g (0.36 wppm) will generate p_{H2} equal to 0.156 atm. As long as the partial pressure of hydrogen is less than that, degassing will proceed; when the equilibrium level is reached, the overall reaction will stop. Producing a hydrogen level of 0.2 cm^3/100 g (0.18 wppm) requires a partial pressure of H_2 less than 0.048 atm.

The rate at which Reaction 12.6 proceeds is a function of driving force (the difference between the equilibrium p_{H2} and the actual p_{H2} in the vapor phase), the temperature, and the relative surface area of interface between melt and vapor phase per unit volume of melt. Removal rates can be increased by:

- Reducing the partial pressure of H_2 in the gas, either by using a vacuum or bubbling gas into the melt
- Raising the temperature (although this increases energy costs and raises $\underline{\text{H}}$ solubility)
- Generating a higher relative surface area by adding lots of very tiny bubbles to the melt (Engh, 1992; Waite et al., 1997)

Although molten aluminum will degas to some extent as it waits in the ladle for pouring, the degree of natural degassing is not sufficient for an acceptable-quality product. As a result, deliberate degassing of some sort is required (Fielding, 1996).

It was thought that the use of chlorine in degassing atmospheres might further enhance hydrogen removal (Peterson et al., 1995), through the reaction

$$2\ \underline{\text{H}} + \text{Cl}_2 = \text{HCl}\ (g) \tag{12.9}$$

However, HCl is thermodynamically less stable than AlCl_3, so the likelihood of chlorine being effective for hydrogen removal is doubtful. Several experiments conducted during the 1990s reached the conclusion that chlorine use in degassing, while essential for alkali removal, is no more effective at hydrogen removal than any other gas (Williams et al., 2000).

REACTIVE METALS

Figure 12.2 shows the logarithm of the equilibrium constant at 727°C for the reaction (Utigard, 1991),

$$\text{Al} + (3/n)\ MX_n = \text{Al}X_3 + (3/n)\ M \tag{12.10}$$

where M is another metal and X is either chlorine or fluorine. The graph shows that aluminum is less reactive with chlorine and fluorine than the reactive metals contained in it (as evidenced by the negative "log K_{eq}" values of the y-axis), and as

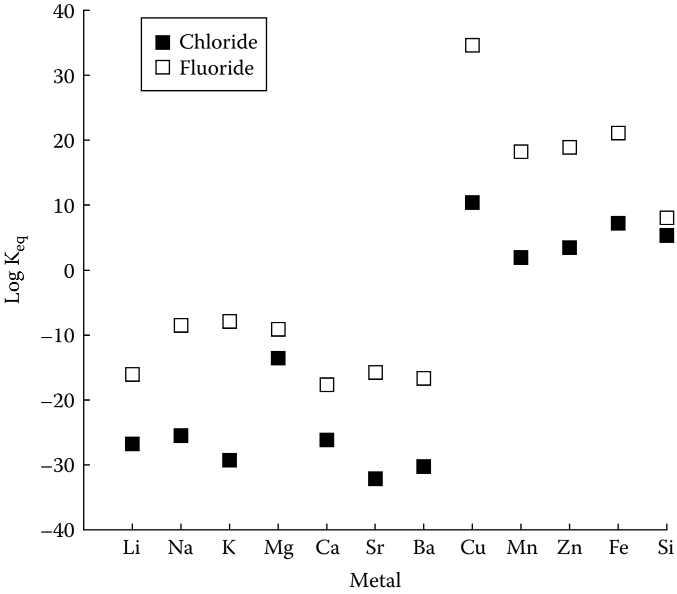

FIGURE 12.2 Logarithm of the equilibrium constant at 727°C for the reaction of molten aluminum with impurity-metal fluorides. (From Utigard, T., in *Extraction, Refining, and Fabrication of Light Metals,* Sahoo, M., and Pinfold, P., Eds., CIM, Montreal, 1991, p. 353. With permission.)

a result added chloride or fluoride is more likely to react with calcium, lithium, and sodium. This is why a molten sodium–aluminum fluoride salt bath is used for the electrowinning of primary aluminum and why lithium salts can be added to that bath. It also forms the basis for the removal of impurity calcium and sodium from molten aluminum scrap. Chlorine gas is added and reacts with the impurities to form sodium or calcium chloride, which floats to the salt slag on top:

$$\underline{\mathrm{Ca}} + \mathrm{Cl_2} = \mathrm{CaCl_2}\ (\textit{slag}) \tag{12.11}$$

$$\underline{\mathrm{Na}} + {}^{1}/_{2}\ \mathrm{Cl_2} = \mathrm{NaCl}\ (\textit{slag}) \tag{12.12}$$

Chlorine also reacts preferentially with magnesium and is the key to demagging of molten aluminum scrap as well:

$$\underline{\mathrm{Mg}} + \mathrm{Cl_2} = \mathrm{MgCl_2}\ (\textit{slag}) \tag{12.13}$$

However, the use of chlorine gas presents environmental concerns, since it also reacts with the aluminum to generate aluminum chloride vapor:

$$2\ \mathrm{Al} + 3\ \mathrm{Cl_2} = 2\ \mathrm{AlCl_3}\ (g) \tag{12.14}$$

This reaction occurs when the concentration of other impurities is low, and thus occurs in low-magnesium molten scrap or primary metal. The aluminum chloride reacts with water vapor above the melt to generate hydrochloric acid vapor (Eckert, 1992):

$$2\ AlCl_3\ (g) + 3\ H_2O\ (g) = Al_2O_3\ (s) + 6\ HCl\ (g) \tag{12.15}$$

In addition, unreacted chlorine also winds up in the atmosphere above the melt. The workplace hygiene and environmental concerns resulting from this have led to an increasing need to replace chlorine gas as a refining agent (Béland et al., 1995; Peterson et al., 1995; DeYoung, 2001; Taylor, 2002).

Fluorine gas is not used for refining, but solid fluxes containing aluminum fluoride have been developed that can react with the impurities (Béland et al., 1995; DeYoung, 2001; Taylor, 2002):

$$2\ AlF_3 + 3\ \underline{Ca} = 2\ Al + 3\ CaF_2\ (\mathit{slag}) \tag{12.16}$$

$$AlF_3 + 3\ \underline{Na} = Al + 3\ NaF\ (\mathit{slag}) \tag{12.17}$$

$$2\ AlF_3 + 3\ \underline{Mg} = 2\ Al + 3\ MgF_2\ (\mathit{slag}) \tag{12.18}$$

Because of this, AlF_3 fluxes cannot be used to remove calcium and sodium from magnesium-containing alloys; the AlF_3 would remove the magnesium as well. For these alloys, fluxes containing $MgCl_2$ have been developed:

$$MgCl_2 + 2\ \underline{Na} = \underline{Mg} + 2\ NaCl\ (\mathit{slag}) \tag{12.19}$$

$$MgCl_2 + \underline{Ca} = \underline{Mg} + CaCl_2\ (\mathit{slag}) \tag{12.20}$$

Many of the same methods for improving degassing kinetics also improve the kinetics of reactive-metal removal. The effectiveness of chlorine injection is improved by decreasing the bubble size (increasing relative surface area), stirring the melt (to eliminate transport to the bubble surface as a limiting factor), and to a limited extent increasing the concentration of chlorine in the gas. The effective use of flux for calcium and sodium removal requires small particle size and some agitation as well (DeYoung, 2001).

INCLUSIONS

Inclusions can be removed from aluminum in three ways. The first is *sedimentation,* the natural settling of inclusions to the bottom of a furnace (Engh, 1992; Altenpohl, 1998). The rate at which small particles settle in a fluid is governed by a version of Stokes' Law:

$$u_r = \frac{2\Delta\rho g a^2}{\rho v 9} \tag{12.21}$$

where u_r is the settling rate of the inclusion, in m/s; $\Delta\rho$ is the difference between the density of the inclusion and the fluid (in this case molten aluminum); g is the gravitational constant (9.81 m/s^2); a is the inclusion diameter, in meters; and ρ and ν are the density and kinematic viscosity of molten aluminum. For a 100 μm (10^{-4} m) alumina inclusion in molten aluminum, Engh (1992) has calculated a typical settling rate of $1.36 \cdot 10^{-3}$ m/s (8.16 cm/min). The settling rate for inclusions smaller than 100 μm is even slower; a 10-μm inclusion would settle at a rate of 0.082 cm/min. As a result, sedimentation is not a significant factor in inclusion removal in most furnaces.

A more effective means of inclusion removal is *flotation* (Altenpohl 1998), which is caused by the attachment of inclusions to bubbles rising to the melt (such as those used for degassing and reactive-metal removal). Complex models have been developed for estimating the rate at which inclusions are removed by flotation in both continuous and batch reactors (Engh, 1992). The removal rate is a function of:

- *Inclusion size:* Smaller inclusions are less likely to be floated out.
- *Gas flow rate per unit volume of furnace:* More gas equals more bubbles for inclusions to attach to.
- *Furnace height:* The greater the distance bubbles have to rise, the more likely they are to run into inclusions.
- *Collision efficiency:* This is equal to the square of the ratio of the inclusion diameter to the bubble diameter.
- *Bubble size:* Smaller bubbles provide more relative surface area.
- *Gas inside the bubble:* Inclusions attach more readily to bubbles containing some chlorine (Neff and Cochran, 1993; Roy et al., 1998; Williams et al., 2000; Le Brun, 2002).

It has been suggested that flotation alone is sufficient to remove enough inclusions to meet quality specifications for some applications. However, in most cases additional purification is required, especially for smaller inclusions.

The most significant tool for inclusion removal is *filtration,* which has been used for several decades. The two main types of industrial filtration are (Engh, 1992; Altenpohl, 1998) *cake* and *deep bed.* A cake filter relies on pore openings smaller than the solid inclusions to stop inclusions at the surface, eventually piling them up into a cake of increasing thickness. Cake filters are highly effective, but the metallostatic pressure required to force metal through the cake makes their use impracticable and too expensive. As a result, cake filters are rarely used for filtering molten aluminum, except in very small-volume applications (Brochu et al., 1996).

Figure 12.3 illustrates deep-bed filtration (Engh, 1992; Aubrey and Smith, 1999). Deep-bed filtration relies on the attachment of solid particles to the inside walls of the filter, rather than blocking them at the surface. This prevents a cake from forming at the filter surface, minimizing the pressure-drop problem of cake filters. However, this happens only if the solid particles are much smaller than the pores of the filter. As a result, deep-bed filtration depends upon prior removal of the largest inclusions, usually by flotation. A dual-filter arrangement is often used, in which a large-pore filter is backed by a smaller-pore filter.

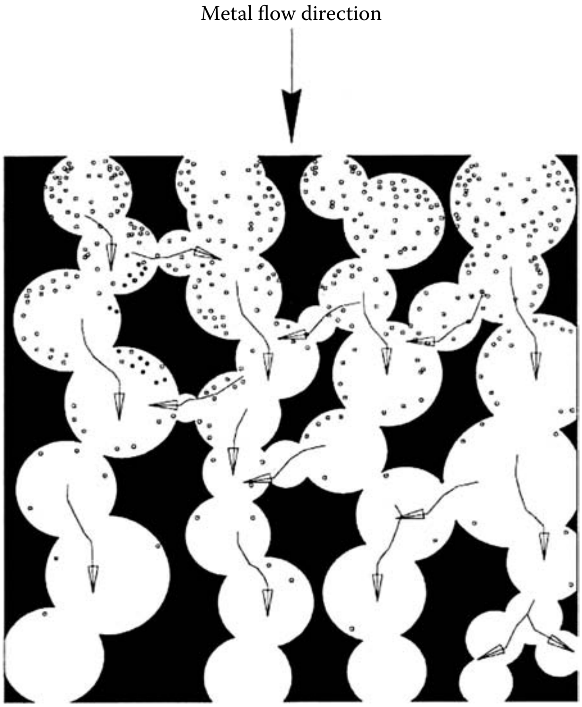

FIGURE 12.3 Mechanism for deep-bed filtration. (From Aubrey, L.S. and Smith, D.D., in *6th Aust. Asian Pac. Conf. Alum. Cast House Technol.,* Whiteley, P.R. and Grandfield, J.F, Eds., TMS–AIME, Warrendale, PA, 1999, p. 133. With permission.)

Deep-bed filtration is designed primarily to remove inclusions of 5 to 20 μm diameter. The efficiency of these filters depends primarily on (Engh, 1992):

- Inclusion size (larger inclusions are easier to capture)
- Relative filter surface area per unit volume of melt
- Tortuosity (the fraction of filter surface facing the direction of metal flow)
- Filter height
- Metal flow velocity (lower is preferred, in part because higher flow rates cause reentrainment of deposited particles)

The difficulty with maximizing filtration efficiency is designing a more effective filter without also increasing the required metallostatic head beyond an acceptable limit. Several solutions have been devised and will be described later in this chapter.

REFINING STRATEGY

Figure 12.4, from the work of Waite (2002), illustrates a general flowsheet for molten aluminum processing. While not every recycling facility uses all five of the steps shown here (in some facilities, the melting furnace and the casting furnace are

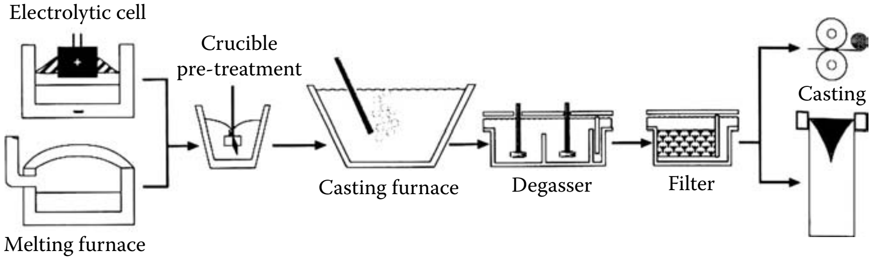

FIGURE 12.4 Flowsheet for aluminum melting and refining. (From Waite, P., in *Light Metals 2002,* Schneider, W., Ed., TMS–AIME, Warrendale, PA, 2002, p. 841. With permission.)

the same), the refining functions described above are carried out in one or more of the vessels shown here. The figure points out that the refining sequence for primary metal from electrolytic cells is similar to that for secondary metal from remelting furnaces. As previously mentioned, the refining principles and technology are similar as well.

The development of refining technology over the past 20 years has focused on achieving several goals:

- Reducing alkali metal content to three parts per million or less
- Reducing inclusion levels (particularly 5 to 20 μm) to part-per-trillion levels
- Reducing hydrogen levels to 0.20 $cm^3/100$ g or less
- Decreasing processing times
- Encouraging continuous instead of batch processing
- Decreasing or eliminating the use of chlorine gas

MELTING FURNACE

The primary refining step performed in melting furnaces is demagging. This requires the use of chlorine gas, as the special demagging fluxes described previously are different in composition from the fluxes used for absorbing oxide impurities (Neff and Cochran, 1993). Previous chlorine-based demagging techniques were inefficient and generated excessive levels of fugitive chlorine gas and chloride fumes. The gas injection pump described in Chapter 9 is more efficient and is now extensively used for demagging (Henderson et al., 2001). It may also be useful for inclusion flotation and alkali removal, although not to the levels required for product-quality purposes. The fluoride-based fluxes used for dross removal during melting also help with magnesium and other alkali removal, as per Reactions 12.16 to 12.18.

CRUCIBLE PRETREATMENT

The use of crucible pretreatment is not universal, since improvements in other refining technologies appear to have made it less necessary. However, it may still have advantages, especially for alkali removal. One advantage of crucible treatment is that it allows the use of solid fluxes as a replacement for chlorine gas (Waite, 2002). These fluxes contain $MgCl_2$ to carry out Reactions 12.19 and 12.20; the $MgCl_2$ is contained in a premelted mixture with KCl and NaCl (DeYoung, 2001; Taylor, 2002). The mixture has a lower melting point than pure $MgCl_2$, improving the reaction rate. It also solves the problem created by the tendency of pure $MgCl_2$ to pick up water. Because dross removal has been previously performed in the melting furnace, this flux can be specifically designed for alkali removal and does not need added fluoride. The development of a rotary flux injector has improved the efficiency of solid flux injection over the previous lancing technique (Béland et al., 1998).

CASTING FURNACE

In many facilities the melting and casting furnace are the same, so the discussion of refining practice in melting furnaces from Chapter 9 applies here. If there is no crucible treatment facility, the casting furnace is where alkali removal and primary degassing take place. As Waite (2002) points out, this presents a problem. Reverberatory melting and casting furnaces are designed with heat transfer in mind and do not function well as chemical reactors.

Refining in casting furnaces has traditionally been performed using stationary lances injecting a mixture of nitrogen and chlorine gas. The large bubble size and poor mixing of these lances lead to low effectiveness, wasted chlorine, and workplace hazards caused by the unreacted chlorine (Waite, 2002). As a result, the development of better mixing technology has been a primary focus for casting-furnace refining (Béland et al., 1995). Chapters 8 and 9 described the three types of advanced stirring devices used in melting furnaces: pneumatic jet, electromagnetic, and rotary stirrers. Porous plugs have also been used as gas delivery devices, using permeable cones to reduce plugging (Richter and Nelson, 1999).

Figures 12.5 to 12.7, from the results of Hopkins et al. (1995), show the results achievable in a casting furnace using a rotary gas injection pump. Figure 12.5 shows the hydrogen content of molten aluminum (~2.5% Mg) under different refining conditions; the use of chlorine in the purge gas makes no difference in the reduction of hydrogen content. Figure 12.6 shows the inclusion content of the melt as a function of time; here, the impact of adding 5% Cl_2 to the gas is obvious. Figure 12.7 shows the reduction of alkali content achievable when using an Ar–5% Cl_2 mixture. As a result of Reactions 12.19 and 12.20, most of the calcium and sodium are removed without removing the magnesium as well. As the figures show, casting-furnace refining is effective, especially at alkali and inclusion removal, but very slow and inefficient. Because of this, the trend over the past generation has been to minimize degassing in the casting furnace and replace it with *in-line* degassing and filtration (Fielding, 1996; Pouly and Wuilloud, 1997). In-line processes are designed specifically for hydrogen and inclusion removal. Their increased efficiency and kinetics justify the capital and operating costs of the additional processing (Williams et al., 2000).

IN-LINE DEGASSING

Figure 12.8 shows a cross section of the SNIF process, one of several in-line degassing devices introduced in the early 1980s. The device features a spinning (300

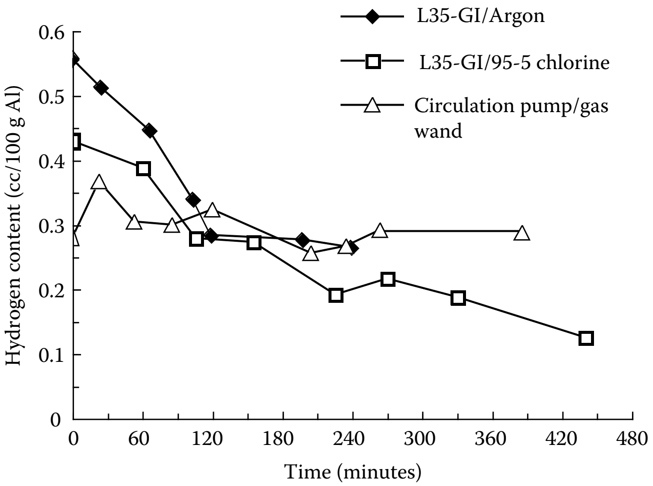

FIGURE 12.5 Hydrogen content of molten aluminum versus refining time using Ar and Ar–5% Cl_2 mixture. (From Hopkins, L. et al., in *3rd Int. Symp. Recycl. Met. Eng. Mater.*, Queneau, P.B. and Peterson, R.D., Eds., TMS–AIME, Warrendale, PA, 1995, p. 31. With permission.)

to 400 rpm) rotor inserted in the molten aluminum, through which a gas mixture (often Ar–5% Cl_2) is fed. The spinning rotor breaks up the gas into very fine bubbles, which increase the relative amount of surface area between the metal and the gas. This improves degassing kinetics and efficiency. The smaller bubbles also encourage removal of smaller inclusions. In-line devices like this are designed to operate

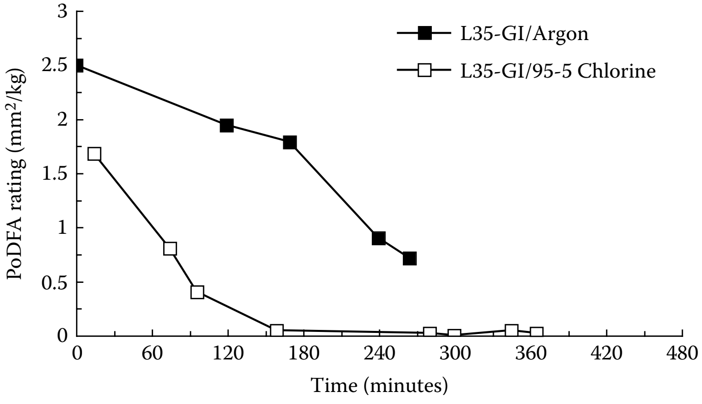

FIGURE 12.6 Inclusion content in molten aluminum versus refining time using Ar and Ar–5% Cl_2 mixture. (From Hopkins, L. et al., in *3rd Int. Symp. Recycl. Met. Eng. Mater.*, Queneau, P.B. and Peterson, R.D., Eds., TMS–AIME, Warrendale, PA, 1995, p. 31. With permission.)

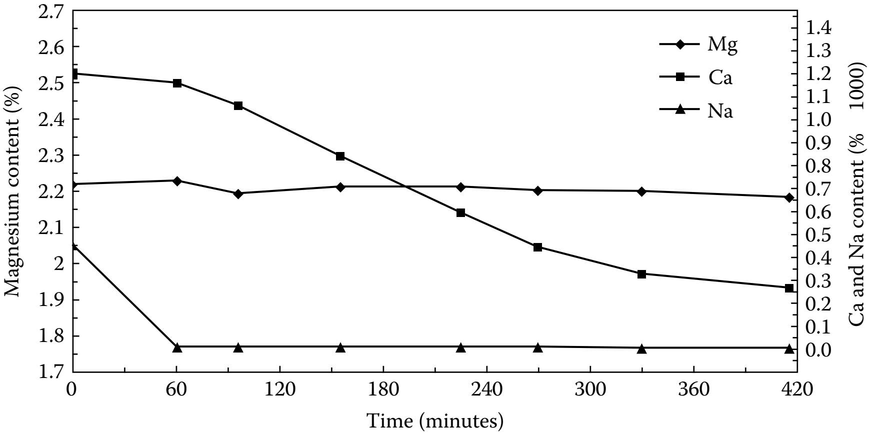

FIGURE 12.7 Magnesium and molten-alkali content of molten aluminum versus refining time using Ar–5% Cl_2 mixture. (From Hopkins, L. et al., in *3rd Int. Symp. Recycl. Met. Eng. Mater.,* Queneau, P.B. and Peterson, R.D., Eds., TMS–AIME, Warrendale, PA, 1995, p. 31. With permission.)

continuously, with molten aluminum constantly being fed at the top and removed through a plug in the bottom. The vessel size is determined by the metal flow-through rate and the time required to lower the hydrogen level to a desired value.

Since their introduction, a number of improvements have been made to in-line degassing units like this (Waite, 2002). The use of multiple stages generates lower hydrogen levels than a single unit of comparable size. The degassers are now sealed to prevent contact with air (Waite, 1998) and flushed with argon to reduce dross generation. Faster rotor speed (900 rpm in new Hycast units) results in even smaller bubble size and better kinetics (Mæland et al., 2002). The most recent Alpur and Hycast devices include equipment for heating the metal (DeRidder and Terrier, 1999), which is important if molten metal is to be held in the unit between casts.

The newest trend in in-line degassing eliminates the degassing vessel altogether. Figure 12.9 illustrates the operating principle behind the Alcan Compact Degasser (Lavoie et al., 1996; Waite et al., 1997), which substitutes the casting trough for the degassing vessel. Baffles located in the trough create the equivalent of a multistage degassing vessel, with a rotary gas injector for each compartment. Degassing and inclusion removal efficiencies in this device are similar to those of a degassing vessel; however, the use of the trough reduces the space requirement considerably. In addition, use of a trough degasser eliminates metal retention between casts (Fielding, 1996). This is important in plants casting a variety of alloys, since metal retained in a degassing vessel between casts must usually be drained and remelted.

FILTRATION

Filtration of molten secondary aluminum has been practiced for several decades but has in recent years become increasingly important as product quality standards have

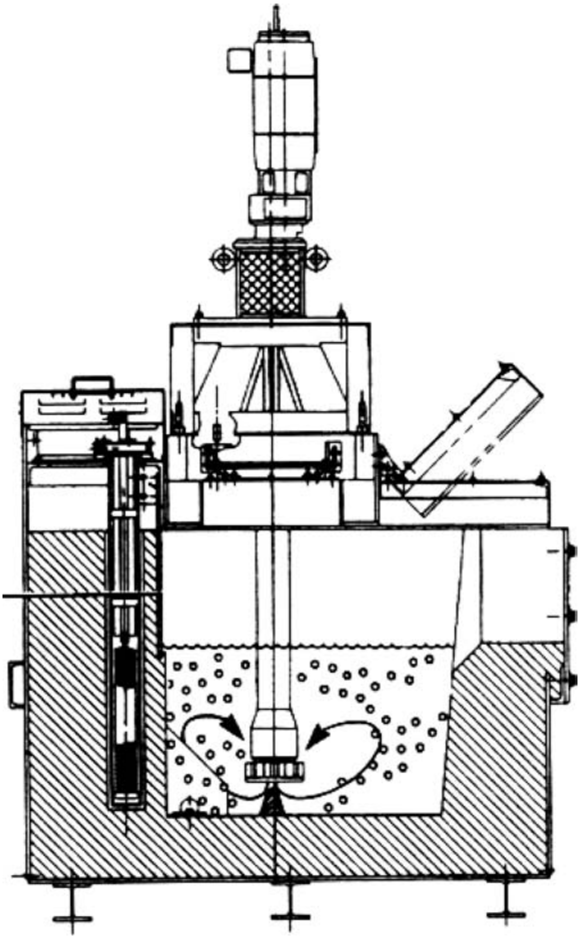

FIGURE 12.8 Schematic of the SNIF degassing vessel. (From Altenpohl, D. G., *Aluminum: Technology, Applications, and Environment,* 6th Ed., TMS–AIME, Warrendale, PA, 1998. With permission.)

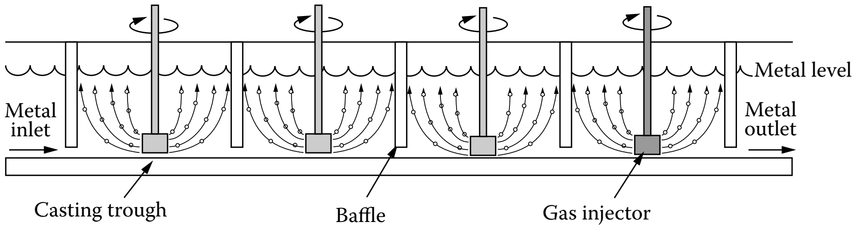

FIGURE 12.9 Schematic of the Alcan Compact Degasser. (From Waite, P., Lavoie, S., and Pilote, E., in *5th Australas. Asian Pac. Conf. Alum. Cast House Technol.,* Nilmani, M., Whiteley, P., and Grandfield, J., Eds., TMS–AIME, Warrendale, PA, 1997, p. 143. With permission.)

tightened (Waite, 2002). Almost all filtration of molten aluminum uses the deep-bed principle. However, numerous filter materials and filtration devices exist within that category (DeYoung, 1999). The choice of filtration technology depends on a number of factors, including:

- *Type of product:* Castings have a higher tolerance for inclusions than wrought product and may not require the same degree of filtration.
- *Plant production rate:* Melting facilities with higher capacity can justify investing in more expensive types of filtration equipment.
- *Number of alloys produced:* A facility that frequently changes alloy will avoid filters that retain large volumes of metal between casts.
- *Available floor space:* Some filtration equipment has a much larger footprint than others.
- *Type of inclusion:* Most of the inclusions present in remelted scrap consist of oxides, which interact better with some filter materials than others. However, the use of $MgCl_2$-based fluxes for alkali removal creates concern over the presence of small $MgCl_2$ inclusions in the metal (DeYoung, 1999). Removing these requires different filter materials.

Weaver (1997) divides the filters used for molten aluminum into two groups, those meant for a single use and those that can be used for several times before replacement. Multiple-use filters have a higher capital cost and a larger footprint. They also have higher capacities and lower operating costs, since they are replaced less often. As a result, they are more likely to be used in large-volume shops casting a limited number of alloys. Figure 12.10 illustrates the *granular* type of deep-bed filter (Clement, 1995), which has been in use since the 1940s (Fielding, 1996; DeYoung, 1999; Chesonis et al., 2002). Metal is fed through the bottom of the filter to reduce turbulence and flows upward through a composite structure consisting of alumina balls (13 to 19 mm diameter) and gravel (3 to 6 mesh). A typical flow rate up through the filter is 0.1 to 0.4 cm/sec; the low velocity improves filtration efficiency. The supporting grid at the bottom distributes the metal evenly and reduces channeling. The addition of heaters to maintain metal temperature in the filter is a recent innovation.

Figure 12.11 shows a more recent type of multiple-use filter (Mabry et al., 1997; Schneider et al., 1999), the *rigid-media tube filter* (*RMTF*). The cartridge in the figure is a bundle of tubes made up of bonded ceramic (usually silicon carbide) particles with variable-size pores. Metal fed into the filter flows through the pores into the inside of the tubes and from there to the outlet. The RMTF is the most efficient filter available, but breakage of the tubes is a concern (DeYoung, 1999), and as a result its use in this form is not widespread.

Introduced in the 1970s, the single-use foam filter has become the most widely used in the industry (Wang et al., 1996). Figure 12.12 shows several shapes of foam filter (Parker et al., 1999), which is produced by impregnating a porous foam with a ceramic slurry, allowing the slurry to dry, and firing the foam (Chesonis et al., 2002). When the organic foam decomposes and vaporizes, the sintered ceramic structure left behind forms a framework capable of filtering molten metal.

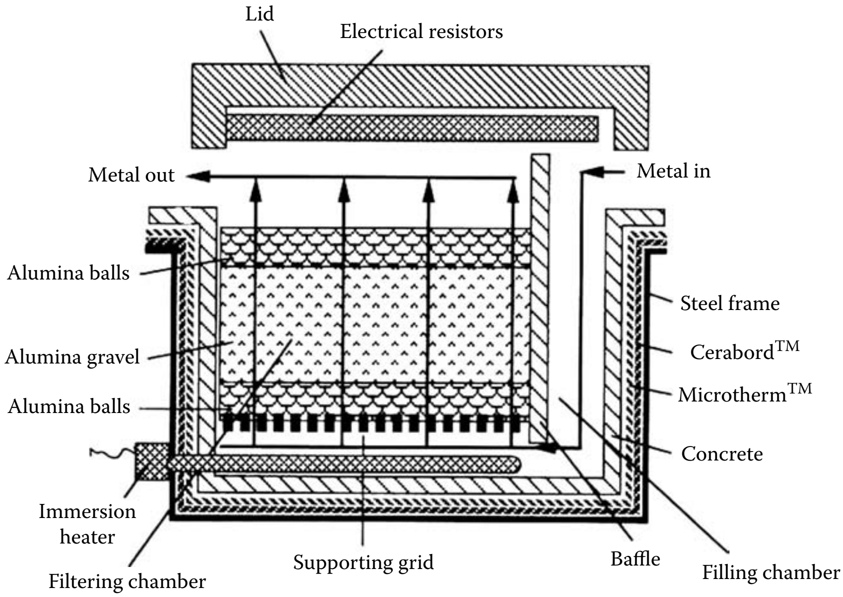

FIGURE 12.10 Construction of a granular deep-bed filter. (From Clement, G., in *Light Metals 1995,* Evans, J., Ed., TMS–AIME, Warrendale, PA, 1995, p. 1253. With permission.)

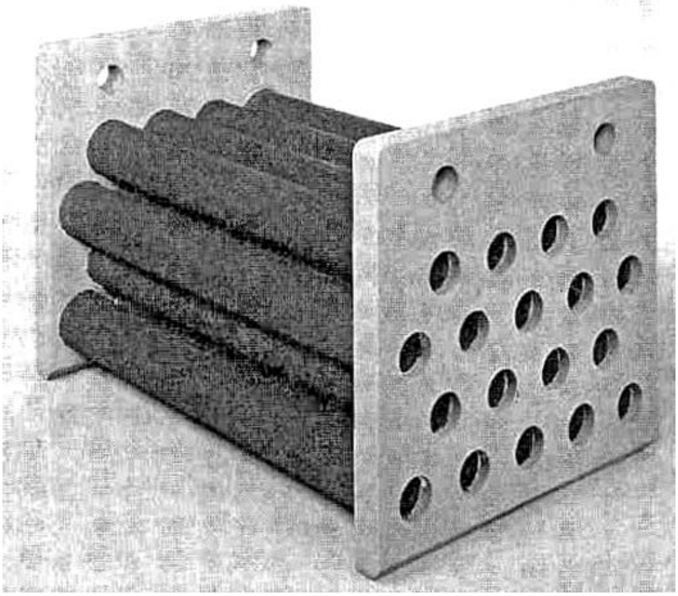

FIGURE 12.11 A rigid-media tube filter. (From Eichenmiller, D.J., Henderson, R.S., and Neff, D.V., in *Light Metals 1994,* Mannweiler, U., Ed., TMS–AIME, Warrendale, PA, 1994, p. 1007. With permission.)

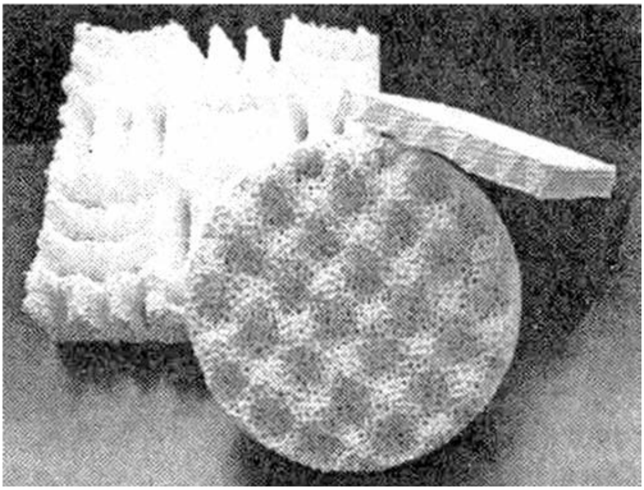

FIGURE 12.12 Different shapes of foam filter. (From Parker, G., Williams, T., and Black, J., in *Light Metals 1999,* Eckert, C.E., Ed., TMS–AIME, Warrendale, PA, 1999, p. 1057. With permission.)

Ceramic foam filters can be produced with a range of pore sizes and cost less than other filters (DeYoung, 1999). However, they are less efficient than other filter materials (Fielding, 1996), which limits their usefulness. Figure 12.13 shows a recent innovation, a staged ceramic foam filter (Barbis et al., 1998; Aubrey and Smith,

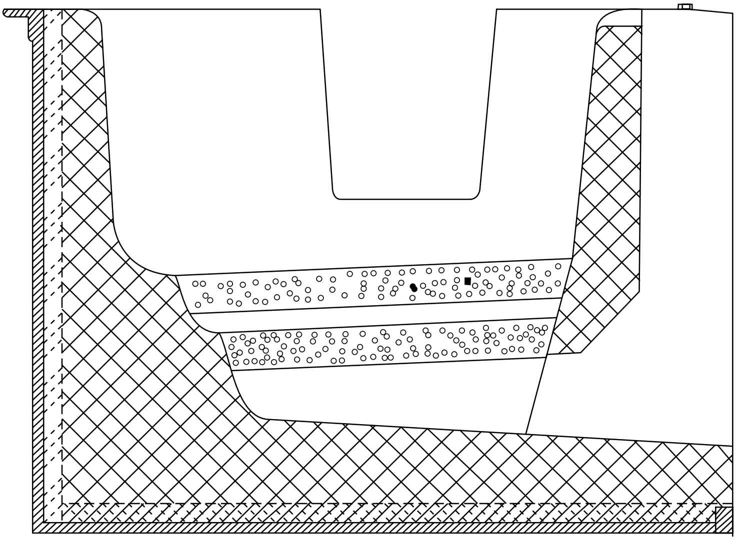

FIGURE 12.13 Cross section of a staged ceramic foam filter. (From Aubrey, L.S. and Smith, D.D., in *6th Aust. Asian Pac. Conf. Alum. Cast House Technol.,* Whiteley, P.R. and Grandfield, J.F, Eds., TMS–AIME, Warrendale, PA, 1999, p. 133. With permission.)

1999). In this arrangement, a coarse filter occupies the top slot in the filter frame, and a finer-pore filter occupies the lower position. This improves capacity and improves capture efficiency for smaller inclusions.

The bonded-particle filter material described earlier can be manufactured in disposable elements as well as tube cartridges. The elements are reusable, resulting in cost savings over single-use ceramic foam, and their higher efficiencies make them useful for applications requiring better removal of finer inclusions (Keegan et al., 1996). Other innovations include the development of multistage filters designed to remove liquid $MgCl_2$ as well as solid inclusions, and the production of filter materials for improved removal of nonoxide inclusions.

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13 Dross Processing

The furnaces used for melting recycled aluminum generate three products. The first is the molten aluminum, which is cast or transferred to customers. The second is the off-gas, which will be discussed in the next chapter. The third is a semisolid skim removed from the melt surface. This skim, better known as dross, is a mixture of molten aluminum metal and various oxide and chloride compounds. Its composition depends on the choice of melting practice and the amount and composition of fluxes used. Regardless of composition, the processing of dross has always been important. Dross processing can (a) recover the valuable metal and salt content of the dross and (b) minimize the amount of waste material to be disposed of after treatment. The state of the art in dross treatment is much different than 20 years ago and is changing rapidly. This chapter will describe the choices available in dross treatment technology, and the factors determining whether one technology is favored over another.

TYPES OF DROSS

In general, drosses fall into two categories: *nonsalt dross* and *salt dross* (Kulik and Daley, 1990; Peterson and Newton, 2002).

Nonsalt dross (called white or gray dross in the United States and black dross in Europe) is produced by melting facilities that melt without using flux. These include all electric furnaces, reverberatory furnaces melting bulky scrap or ingot, and the holding furnaces used for primary aluminum. It can be generated in four ways (van Linden, 1997):

- During molten metal transfer, when the oxide skin on the metal surface ruptures, exposing new surface and generating more oxide.
- During melting and holding, when the oxide skin forms on the melt surface. High-melt-loss types of scrap often have surface oxide present before melting starts, and as a result generate more dross at this stage of the recycling process.
- During molten metal processing and refining, when stirring and surface disruption create a fresh surface for oxidation.
- As a result of metal spills or *skulls*. These are not drosses themselves but are often added to the dross recovered from the melt surface for remelting.

The first key to dross treatment is reducing the amount generated in the first place. This can best be accomplished by minimizing the amount of surface disruption that takes place during melting. The use of level transfer rather than cascading during metal transfer is helpful. A practice of even greater value is the submergence of scrap during melting to prevent surface disruption. Keeping flame temperatures down during melting in stationary furnaces (i.e., reverbs) reduces oxidation, as does reducing temperature stratification.

Nonsalt dross typically has a light gray color (Manfredi et al., 1997). It consists almost entirely of Al_2O_3 and aluminum metal trapped by the surface tension of the oxide skin. (Because of the amount of molten aluminum they contain, these drosses are sometimes called "wet.") The metal content can vary from 15 to 80%, depending on the amount of melt loss and the sampling technique. Small amounts of aluminum carbide (Al_4C_3) and aluminum nitride (AlN) are also frequently present, caused by reactions that occur mostly after the dross has been removed from the furnace. Dross from primary smelting furnaces may also contain small levels of cryolite (Na_3AlF_6). This is the result of electrolytic cell bath accidentally being removed from the cells along with the molten aluminum. If the alloy being remelted contains magnesium, the dross will also contain some periclase (MgO) and spinel ($MgAl_2O_4$). Magnesium is preferentially oxidized to aluminum during remelting and thus is present in higher fractions in the dross than in the original alloy.

Salt dross is the skim produced by furnaces remelting scrap with the use of flux (Pickens, 2000). This usually occurs during the remelting of finely divided or high-magnesium scrap and is most likely to be produced in reverberatory furnaces. Fluxing practice in reverbs has been previously described. Its purpose is to reduce metal losses by breaking up the oxide skin, thereby releasing the metal trapped inside. As a result, salt dross usually contains less than 20% aluminum metal and 30 to 50% aluminum oxide; the rest is the fluxing salt (mostly sodium chloride and potassium chloride). *Saltcake* is a related product that will be described later.

PROCESSING OPTIONS FOR DROSS

HOT PROCESSING

Figure 13.1 presents a hierarchy of options for processing and treatment of dross. The first option is whether to allow the skimmed dross to cool and solidify or to process it immediately after skimming while the entrapped aluminum is still molten. Hot processing has two advantages:

- It allows the operation to retain the heat energy present in the dross when it was first skimmed. If the dross is allowed to solidify, additional energy will be required to reheat it for further processing.
- It offers greater potential recovery of the metal in the dross, since reprocessing occurs before the metal has a chance to oxidize.

However, there are also disadvantages:

- Equipment used for processing semimolten dross at 750 to 800°C is expensive to build and maintain.

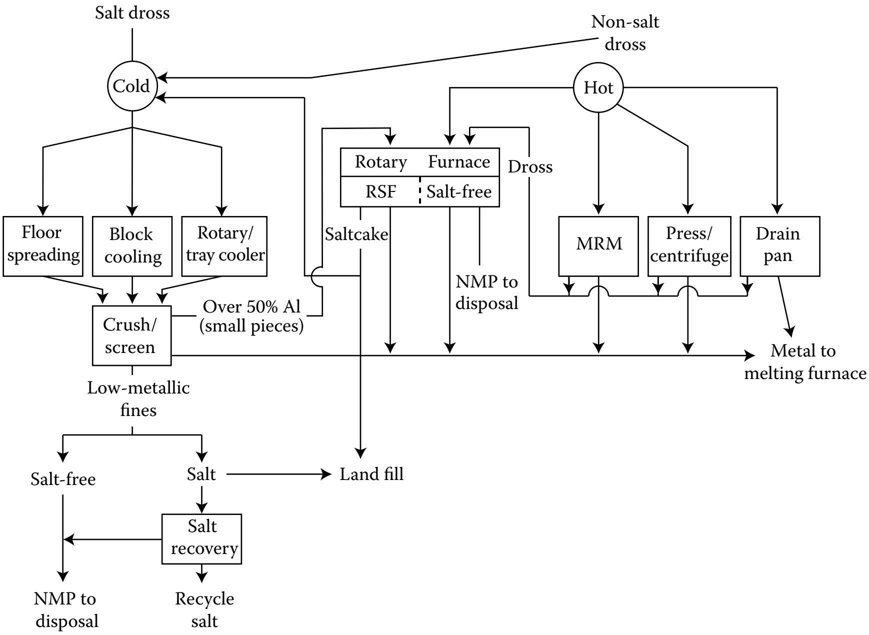

FIGURE 13.1 Process options for treatment of aluminum melting furnace dross.

- Hot dross processing must be synchronized with production schedules in the melting furnaces.
- Hot dross is subject to *thermiting,* which is the oxidation of the metal in the dross to form aluminum oxide or nitride:

$$2\,Al + 1.5\,O_2 = Al_2O_3 \tag{13.1}$$

$$Al + 0.5\,N_2 = AlN \tag{13.2}$$

As the name suggests, thermiting is an exothermic (heat-generating) process. Uncontrolled, it can heat the dross to temperatures that can damage equipment. Furthermore, thermiting turns much of the metal in the dross into relatively worthless oxide. As a result, hot dross processing requires special techniques to minimize or eliminate thermiting.

Many traditional dross-treatment processes involve heating the dross in a rotary salt furnace. As a result, the simplest way to retain the energy in hot dross is to simply charge it directly to the rotary salt furnace without solidifying it first. The difficulty in doing this is synchronizing the skimming of the dross from the melting furnace and the operating cycle of the dross processing furnace. This can be solved either by treating the two as a single process under the control of one operator or by using special holders as a buffer, supplying an argon gas "blanket" to prevent thermiting (Spoel and Zebedee, 1996).

A second approach to hot dross treatment involves agitation of the dross to break the oxide skin surrounding the molten metal, allowing the metal to coalesce and ultimately be recovered. The metal reclaim machine (used extensively in East Asia) does this with an agitating impeller, recovering 55 to 60% of the metal in the dross (Simonian, 2001; Whiteley, 1993; Okazaki et al., 1999). The more recent Drosrite process does this in a rotary furnace rotating at three revolutions per minute (Drouet et al., 2000). The AROS dross-cooling unit performs a similar function, as will be described later.

Two other hot dross processing technologies use pressure to squeeze the molten aluminum loose from the oxide skin. The first is the dross press, which was first used in 1895. Figure 13.2 illustrates the basic principle behind dross pressing. Dross poured into the space between the press head and steel shell is squeezed by a hydraulic ram. Molten metal pours through the metallic drain in the center and into a sow mold. At the same time, the remaining dross is solidified. With proper head design, up to half of the metal in the dross can be recovered (Ruff, 1998; Zeng and Campbell, 2000). The solidified shell, a mixture of metal and oxide/salt, is removed for further processing. The amount of metal recovered is a function of press head design and

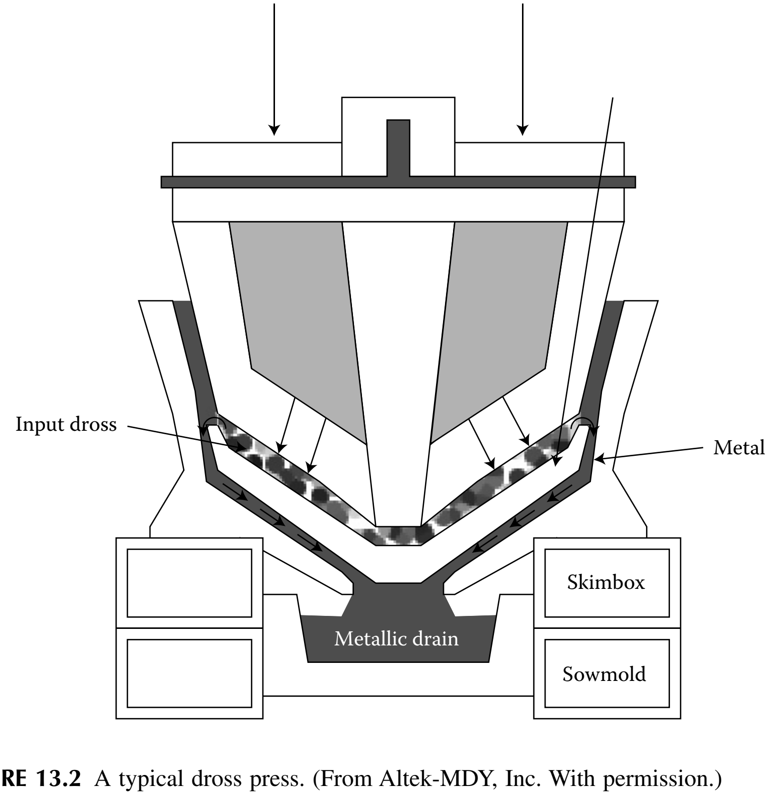

FIGURE 13.2 A typical dross press. (From Altek-MDY, Inc. With permission.)

the metal content of the dross. Optimal head design is controversial, and extensive testing of new designs has been conducted in recent years (Perry, 2000). Water- or air-cooling of the head has recently been added to some units to improve cooling rates and further decrease metal losses. Because of this, dross presses are currently the most popular choice for new dross-cooling equipment.

The other use of pressure to squeeze molten aluminum loose from hot dross is centrifuging. In the Ecocent process (Kos, 2000) hot dross is put in a converter and heated to 750°C (cold dross can also be charged) and stirred to homogenize it. The heated dross is then poured into a centrifuge, which forces the liquid metal through a screen against the side of the centrifuge. The centrifuge can generate either a ring of solidified metal for recharging to a furnace or molten metal that can be tapped from the bottom of the unit. Recovery of up to 90% of the input metal is claimed.

DROSS-COOLING OPTIONS

If the dross is not processed hot, it must be cooled. Dross cooling converts the material to a solid form suitable for storage or shipment and prevents the loss of metal content by thermiting. Several technologies have been developed for dross cooling. Selecting the best means judging the alternatives against these criteria:

- Minimizes thermiting and loss of metal value
- Minimizes capital and operating costs
- Minimizes environmental impact
- Minimizes hazards to operating personnel

The oldest (and perhaps still the most common) approach to dross cooling is to simply spread the material on the floor and let it cool naturally (Roberts, 1990). While this has the lowest capital and operating cost of any option, it also results in the loss of much of the metal value through thermiting. It also generates large quantities of oxide fume, which is hazardous both to plant personnel and to local air quality. In addition, the burning aluminum is a safety hazard. Some shops have tried spreading the dross on steel plates to encourage heat transfer and accelerate cooling. Pouring the dross into a water-cooled vibrating chute has also been tried, which offers some improvement. However, none of these open-air approaches eliminates the problems of floor-spreading. As a result, they are gradually being abandoned.

Some use has been made of specially designed skimming boxes in which the dross is left to cool in a solid block. Thermiting can be limited by adding a salt blanket to cover the material and limit access to air. This process is slow and levies a financial penalty in the form of (a) the cost of the salt blanket or (b) metal losses from thermiting. Originally developed by Alcan, the Inert Gas Dross Cooler provides an argon cover to exclude air (Taylor and Gagnon, 1995), improving metal recovery by 20%. However, dross cooled this way solidifies into a massive block, requiring crushing to recover the metal. Dust generation is eliminated, but subsequent processing costs are higher.

Introduced in the late-1970s, the rotary dross cooler was widely adopted in the 1980s for cooling and solidifying both salt and nonsalt drosses (McMahon, 1990;

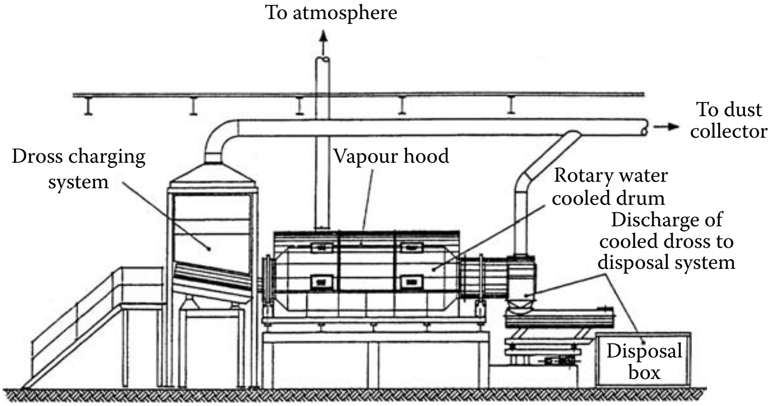

FIGURE 13.3 A rotary dross cooler. (From McMahon, J.P., in *Energy Conservation Workshop XI: Energy and the Environment in the 1990s,* Aluminum Association, Washington, DC, 1990, p. 165. With permission.)

Ferrell and McMahon, 1991; Mitchell, 1995). Figure 13.3 illustrates the layout of a typical rotary dross cooler. The centerpiece of the device is a rotating drum fabricated from structural steel plate, with welded internal flights to help raise the dross as the drum rotates. Water is sprayed onto the outside of the top of the drum, flowing around the outside and collecting in a pool at the bottom. As it does, it extracts heat from the dross inside. Some of the water vaporizes and leaves through the vapor hood at the top. Replacement water is added through a nozzle at the side. Although thermiting is reduced by the more rapid cooling in this unit, some does occur, and the tumbling action crumbles the dross, generating more dust. As a result, dust collection hoods are located at both ends of the unit. Even so, the safety hazard presented by the dust has decreased the popularity of rotary dross cooling in recent years.

Dross added to the cooler spends 5 to 15 minutes in the unit, during which its temperature is reduced below 50°C. The tumbling action reduces its size, making it easier to subsequently crush and screen. A trommel screen at the discharge end removes oversize material (+50 mm is typical). The oversize has a much higher metal content than the undersize, so it can be directly returned to the melting furnaces or further processed to remove more of the nonmetallic content. Screen undersize is sent on for rotary-salt furnace melting or further solid processing.

Use of rotary dross cooling can improve metal recoveries by up to 50% over floor spreading, but the lack of an inert environment means thermiting is still a concern, limiting overall recoveries to 40 to 45% of the contained metal. Two approaches have been taken to solve the problem. Figure 13.4 illustrates the AROS dross cooler, introduced in the early 1980s (Roberts, 1989, 1990, 1991). The unit is sealed to minimize air intrusion and thus reduce thermiting. The water spray is replaced by a jacket placed around the central cooling drum. Cooled dross is discharged into the outside grinding drum, which turns with the cooling drum.

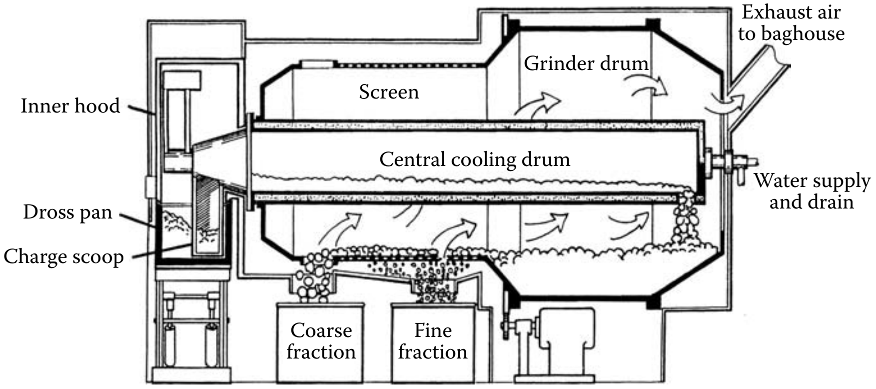

FIGURE 13.4 The AROS dross-cooling system. (From Roberts, R.P., in *Energy Conservation Workshop XI: Energy and the Environment in the 1990s,* Aluminum Association, Washington, 1990, p. 143. With permission.)

Large lumps of metal in the discharge act as the "grinding balls" in this drum, knocking pieces of oxide and salt loose from the larger metal particles. A screen built into the grinding drum separates a coarse fraction (>8 mm), analyzing more than 90% metal. This material can be directly remelted. Undersize from this screen is fed through a second screen built into the unit shell; the oversize from this fine screen (>0.2 mm) also analyzes 75 to 80% metal. This product is sent for further upgrading. The undersize from the second screen, along with dust collected in the baghouse, is combined into a dust fraction. The metal content of the dust is less than 25% and can either be further processed for salt recovery or landfilled.

The second solution is to provide an inert environment (argon or nitrogen) to the rotary gas cooler. This improves metal recoveries by 15% over rotary dross cooling in air. Whether this improvement justifies the cost of the argon is uncertain.

COMMINUTION

With the exception of AROS units, dross coolers generate a product with a wide size range, from dust to chunks of several centimeters. As previously mentioned, the largest chunks have high enough metal content to remelt, while smaller pieces require upgrading to separate the metal from the oxide/salt content. Again, the dross processor has an option. Crushing the cooled dross will better "liberate" the metal from the attached oxides and salt, generating a product that is easier to directly remelt. However, both the capital and operating costs of crushing can be high. As a result, cooled nonsalt dross with over 50% metallic aluminum content is often fed directly to rotary-salt furnaces, while salt and lower-grade nonsalt drosses are crushed and upgraded to produce a concentrate with sufficient aluminum content.

Dross comminution is a multistage process, beginning with reduction of the largest chunks (>20 cm). This is typically performed using an impactor or jaw crusher. The crusher product is screened, and oversize (>2.5 cm) material is returned to the melting furnace. The undersize from the screen is subsequently milled. Hammer mills have typically been used for this purpose, but cage mills may be more effective at crushing the nonmetallic particles without destroying the metal particles as well (Roth and Beevis, 1995). The mill product is again screened (300 to 500 μm); undersize is disposed of or processed to recover the salt, while oversize is used in rotary-salt furnaces to recover the metal. The Tumbler (Roth, 1996; Roth and Schirk, 2000) is a recently developed comminution unit that combines primary and secondary crushing.

MELTING OPTIONS: THE ROTARY SALT FURNACE

Developed in the mid-1960s, the rotary salt furnace (RSF) is the primary method for recovering aluminum from dross. It is primarily used to treat high-grade nonsalt drosses and the concentrates produced by milling and screening salt and low-grade nonsalt drosses. There are several varieties of RSF, but the operating principle is similar in them all.

Figure 13.5 illustrates a typical RSF. The furnace operates on a batch basis, with a total charge of 5 to 10 tonnes per batch (Gripenberg et al., 1995). The charge is a mixture of dross and/or dross concentrate, along with fluxing salt. The fluxing salt composition is a eutectic mixture of sodium chloride and potassium chloride, similar to that used in fluxed melting operations. As before, a flux with a few percent of an added fluoride salt (typically cryolite) helps break the oxide skin around the molten aluminum as the contents are heated (Shell et al., 1995; also see Chapter 7). This allows the molten aluminum to coalesce, increasing recovery. The added salt also protects the metal underneath from oxidation by forming a molten blanket on top.

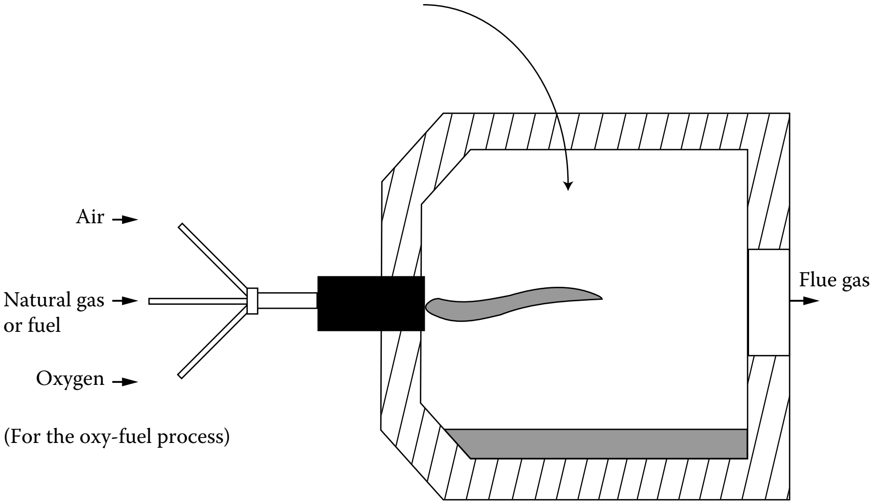

FIGURE 13.5 Cross section of a rotary salt furnace. (From Drouet, M.G. et al., in *3rd International Symposium on Recycling of Metals and Engineered Materials*, Queneau, P.B. and Peterson, R.D., Ed., TMS-AIME, Warrendale, PA, 1995, p. 803. With permission.)

The amount of salt added varies with the composition of the added dross, ranging from 50 to 500 kg of added salt per tonne of charged dross. In older RSFs, the goal is for the mass of salt to equal the mass of nonmetallic oxides in the dross. In newer furnaces, a lower ratio (0.2:1 to 0.4:1) is used. In either case, a higher-grade charge will use less salt than a low-grade charge.

In its typical configuration, energy is provided to the RSF by an air/fuel burner input through the side. Heat transfer from the flame to the charge is hindered by the molten salt layer on top, which has poor thermal conductivity. This problem is solved in the RSF by rotating the furnace. The refractories above the bath are heated by the flame. As the furnace rotates, the heated refractories move below the bath line and transfer heat to the charge.

RSFs can be fired with natural gas (more common) or fuel oil. The use of oxyfuel burners has spread from scrap melting operations to RSFs for the same reasons (Phillips et al., 1993; Paget et al., 1997). The reduced nitrogen output from the furnace improves thermal efficiency, and the higher flame temperature increases the heat-transfer rate to the refractory. The use of regenerative burners has also spread from melting furnaces to RSFs. Fuel usage in an air/natural gas furnace is 3500 to 4000 kJ/kg of dross melted. When oxyfuel burners and double-pass regenerators are installed, this figure can be reduced by as much as two-thirds.

Heat times are a function of the mass of charge and the heat transfer rate. In older RSFs tap-to-tap time can be four hours or longer; in newer units, as little as one hour. Nontilting RSFs generate two products. The first is molten aluminum, which is cast and sold as recycled secondary ingot (RSI). The second is a liquid nonmetallic product, which is cast into blocks known as *saltcake.* The saltcake has a composition similar to that of salt dross and still contains 2 to 10% metallic aluminum. Recoveries vary, but extracting 75% of the charged aluminum is not unusual.

The standard-model RSF has several drawbacks, the first of which is the production of liquid saltcake. Tapping two liquid products from the furnace inevitably results in contamination, which can hurt metal purity or reduce recoveries. As a result, several dross processors now use a tiltable rotating barrel furnace (Geus et al., 1995; Zeng and Campbell, 2000). Furnaces like this allow the molten aluminum to be decanted from the vessel first, so that a second liquid product is no longer needed. As a result, a dry dross smelting process can be used, in which the salt usage is reduced by half and a solid saltcake is produced. This reduces materials and energy costs and makes product removal easier.

However, even the dry process requires salt additions. This results in salt vapor emissions from the furnace, along with the production of saltcake. The saltcake is expensive to process, as will be discussed later, and cannot be landfilled in many countries. As a result, considerable efforts have been made over the past 20 years to develop salt-free methods for recovering aluminum from nonsalt dross.

SALT-FREE PROCESSES

Initial attempts to operate rotary barrel furnaces without flux were unsuccessful, largely because the lack of a salt cover allowed thermiting to occur. The exothermic reaction caused rapid heating of the charge, which increased the thermiting still further.

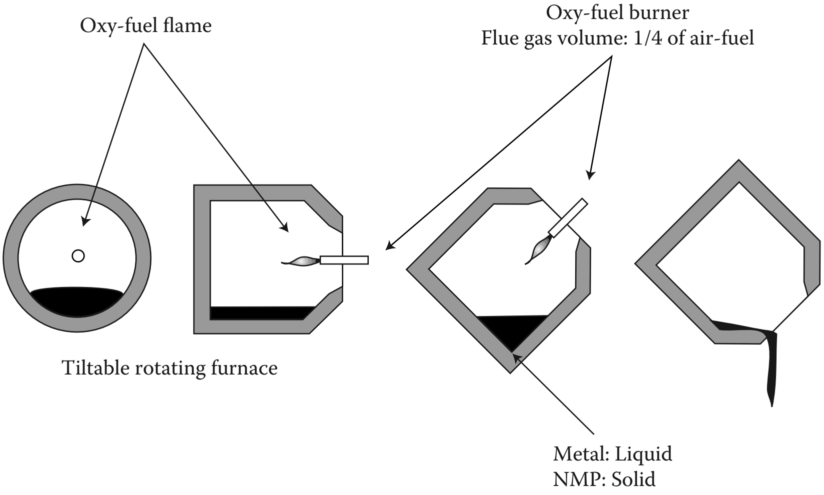

FIGURE 13.6 Schematic of ALUREC dross processing technology. (From Gripenberg, H. et al., in *3rd International Symposium on Recycling of Metals and Engineered Materials*, Queneau, P.B., and Peterson, R.D., Ed., TMS-AIME, Warrendale, PA, 1995, p. 819. With permission.)

As a result, metal recoveries were poor and frequent relining was required. In response to this, development efforts produced four new salt-free melting technologies (Simonian, 2001).

The simplest of the four is ALUREC (Figure 13.6), developed by AGA in partnership with Hoogovens Aluminium and MAN GHH (Gripenberg et al. 1995, 1997). ALUREC uses an oxyfuel burner as an energy source, with a sealed furnace door to keep air out. Replacing air with pure oxygen eliminates nitrogen from the furnace environment. This reduces the flame size, meaning less direct heating of the dross. It also increases flame temperature, improving heat transfer to the walls and increasing the heating rate of the charge. As with other salt-free processes, ALUREC relies on the mixing generated by furnace rotation to break the oxide skin on the metal in the dross, allowing it to coalesce. Operation of a pilot plant at Hoogovens yielded recovery of up to 90% of the metal in the dross, with fuel usage of less than 1300 kJ/kg of dross processed. The solid saltcake recovered from the furnace is half of that resulting from RSF processing. Reducing the amount of flux to purchase and the amount of saltcake to process gives ALUREC a 45% cost advantage over standard RSF processing. However, ALUREC technology has not become widespread, owing to high capital costs and lower recoveries.

The most widely publicized of the four processes is the plasma dross treatment technology introduced in the early 1990s by Alcan (Lavoie et al., 1991; Lavoie and Lachance, 1995). Figure 13.7 shows a simplified view of a non-transferred-arc plasma torch. A gas (air or nitrogen) is passed through the gap between the two copper-alloy electrodes. Applying high-voltage power to the torch generates an electric arc between the electrodes that heats the gas to plasma temperatures (>5000°C).

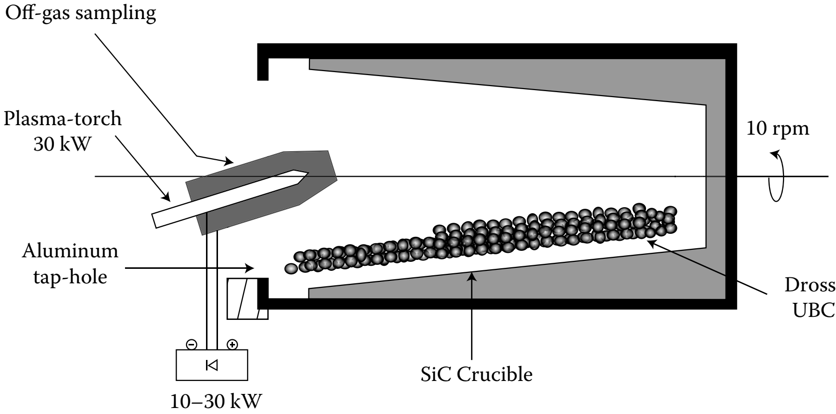

FIGURE 13.7 Non-transferred-arc plasma dross treatment furnace. (From Kassabji, F. and Weber, J.C., in *Extraction and Processing for the Treatment and Minimization of Wastes,* Hager, J., et al., Eds., TMS-AIME, Warrendale, PA, 1993, p. 687. With permission.)

Gases this hot give off nearly all of their available heat by radiation, resulting in much higher thermal efficiency than that of an RSF. As a result, gas usage is minimal, resulting in much lower off-gas volumes than RSF. This reduces oxidation and results in metal recoveries of over 95%. Again, salt-free processing yields the same advantages as previously described. However, plasma dross processing has also not succeeded commercially. High electricity prices and high capital costs are the likely causes.

Figure 13.8 shows a DROSCAR transferred-arc plasma furnace using graphite electrodes (Drouet et al., 1994, 1995; Meunier et al., 1999). Again, the application

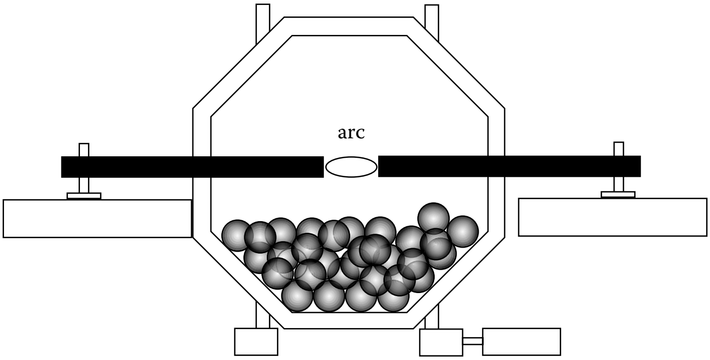

FIGURE 13.8 Droscar transferred-arc plasma furnace. (From Kassabji, F. and Weber, J.C., in *Extraction and Processing for the Treatment and Minimization of Wastes,* Hager, J., et al., Eds., TMS-AIME, Warrendale, PA, 1993, p. 687. With permission.)

of high voltage causes an arc to be struck between the electrodes, generating high temperatures and heat transfer by radiation to the walls and directly to the charge. As with the other salt-free processes, the DROSCAR process seals the furnace to keep air out. As a result, gas volumes are even lower than for the non-transferred-arc plasma (3 m^3/tonne of processed dross versus 30 for the Alcan furnace; RSF processing generates 300 m^3/tonne). An argon environment is provided to reduce thermiting and prevent the formation of aluminum nitride. This results in metal recoveries similar to the other salt-free processes. Again, high electricity costs can be a concern, and lumpy dross pieces can break the electrodes as they tumble during furnace rotation.

SALTCAKE AND SALT DROSS PROCESSING

It is common practice to recover much of the aluminum from salt dross by crushing and concentration. However, this still leaves a saltcake residue, consisting mostly of flux salts (25 to 45%), aluminum nitride, and various oxides (Pickens, 2000). Land-based disposal of this material is still economically feasible in the United States but is either banned or too expensive elsewhere. Because of this, further treatment is required. The goals of this further processing include:

- Minimizing or eliminating the residue to be discarded
- Generating a nonhazardous residue that can be discarded if necessary
- Recovering the salt content in the feed
- Recovering the metallic aluminum in the feed
- Reducing the cost and complexity for the process
- Minimizing the environmental impact of the process

Figure 13.9 illustrates the basic process used for most saltcake treatment (Unger and Beckmann, 1991; Sheth et al., 1996; Russell and Sweeney, 2000). The feed has been

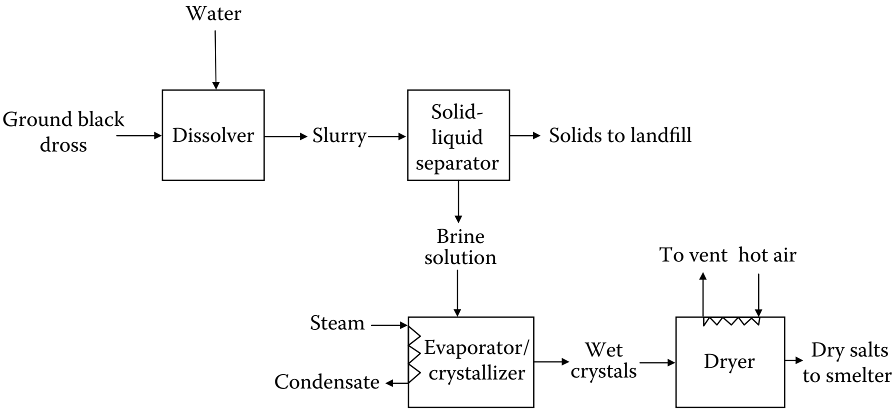

FIGURE 13.9 Standard processing flowsheet for saltcake. (From Sheth, A.C., Parks, K.D., and Parthasarathy, S., *JOM*, 48(8), 1996. With permission.)

crushed and screened as previously described to remove most of the aluminum metal. Since the water will have to be removed later, only enough is added to produce a brine with about 22 to 25% dissolved salt content. The salts (primarily NaCl and KCl) generate heat when they dissolve, raising brine temperatures as high as 60°C. The solid–liquid separator is usually a two-stage process, beginning with a centrifuge, which separates out most of the non-metallic product (NMP, i.e., the oxide content). The liquid leaving the centrifuge is then passed into a clarifier, which generates a sludge containing the rest of the NMP. This is washed and filtered, resulting in a low-salt NMP that can be landfilled or possibly used for other purposes. This purifies the brine and removes solids such as calcium sulfate and magnesium hydroxide. These can cause scaling in the crystallizer if not removed.

The brine generated by dissolution is then processed to remove the water. This is usually done with an evaporator crystallizer. These crystallizers have traditionally been multieffect forced circulation units, but mechanical vapor recompression systems have higher efficiencies and have become a preferred option. A more recent development by Engitec has promoted the use of flash evaporation crystallization (Reynolds and Olper, 1990; Sheth et al., 1996). This reduces energy requirements, at the cost of additional process complexity. The result of crystallization is wet salt crystals that are subsequently air-dried and reused as flux. The potassium chloride in melting flux is preferentially vaporized during melting, so the salt recovered from the brine has a higher NaCl/KCl ratio than the salt used as flux. Purchased KCl is added to bring the ratio back to the desired level.

The NMP recovered from the process consists of alumina and other oxides, with some aluminum nitride and possibly some aluminum carbide (Pickens, 2000). It can be landfilled as a nonhazardous material, and this is the normal end result. It can also be sold to cement producers or used in the production of calcium aluminate. Efforts have been made to find a more commercially viable use for NMP, but none has so far been particularly successful.

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14 Safety and Environmental Considerations

In addition to its economic advantages, aluminum recycling has desirable environmental benefits. Chapter 1 pointed out that production of aluminum from recycled sources reduces CO_2 emissions to the atmosphere by 90% compared with primary metal, in addition to reducing fluoride and SO_2 emissions. Production of secondary metal reduces energy usage by 88% compared with primary metal and reduces the amount of waste generated by 90%.

However, the technology of aluminum recycling presents potential hazards of its own to both the work force and the general public. As the public's tolerance of these hazards decreases, the need to improve the performance of recycling operations grows. This last chapter will explore the unique hazards of aluminum recycling and describe the measures taken in response. The result of these measures will be an industry that moves into the future with confidence in its value to society.

COLLECTION AND BENEFICIATION

Chapter 3 described the two basic types of metal scrap, *new* and *old.* New scrap is obtained directly from manufacturing operations, while old scrap is obtained from discarded manufactured items. The fraction of new scrap that is recycled is higher than that of old scrap; however, the fraction of old scrap being recycled is increasing, owing to the limited amount of new scrap available and the cost of producing primary aluminum in some parts of the world (Europe in particular).

In general, the collection of new scrap presents fewer hazards and environmental concerns than that of old scrap. Because new scrap is produced in a limited number of locations, it is easier to collect and rarely requires separation from other materials. New scrap is purer and thus requires less processing; impurities that might pose workplace or environmental hazards are less likely to be present. Finally, new scrap is a known, and contains fewer surprises. The increasing number of captive recycling operations that accept scrap from one industrial facility and return secondary ingot directly to that facility makes processing new scrap even less hazardous.

Old scrap is more difficult to process safely and presents several hazards. These include:

- *Hazardous chemicals:* All sorts of chemicals are put in aluminum containers, and recovering these chemicals without exposure of the workforce or the general public can be difficult. Larger items such as discarded automobiles and appliances are especially likely to contain fluids (PCB-containing oils, refrigerants) requiring special handling (Pierce and Hubbard, 1992; Ludwig, 1996).

- *Labor usage:* Because old aluminum scrap has to be separated from other materials, recycling is often labor-intensive. The use of hand sorting was discussed in Chapter 6; disassembly of large items such as ships and aircraft is also done largely by hand. This exposes workers to the hazards (heat, noise, dust) normally associated with this type of work, in addition to the unique hazards of demolition work (falling objects, asbestos in shipbreaking). Cutting equipment such as shears or saws can be especially hazardous.
- *Explosive material:* Mention was briefly made in Chapter 6 of the problems posed by aerosol cans in scrap. Shredded under pressure, these cans can explode (Glenn, 1998), and the contents can make the explosion worse if they are flammable. Military scrap can also contain explosive material if not properly decommissioned (Jacoby, 2000). Items as small as a butane lighter can become an explosion hazard if not spotted (Pierce and Hubbard, 1992).
- *Radioactive material:* Although no radioactive aluminum alloys are commercially produced, mixed scrap can contain other radioactive sources that have not been properly disposed of. These radiation sources can contaminate an entire recycling facility if not caught and isolated quickly (Pierce and Hubbard, 1992).
- *Location issues:* Many scrap yards were located on the edge of town when they first began operating several decades ago. These yards now find themselves in the middle of an expanded urban area. The residents of adjacent neighborhoods find scrap collectors and processors undesirable neighbors, and the heavy equipment and hazardous chemicals represent a threat to those living near as well as working at the yard.

The response to these hazards varies considerably with location and the type of scrap upgrading technology used. Several common strategies are available. These include:

- *Automation:* Although hand picking is still widely practiced in third world countries, the hazards that it poses to the workforce are increasingly unacceptable in more advanced societies. As a result, minerals-processing technology (optical sorting, specific-gravity separation, eddy-current devices) is replacing hand-pickers in many locations.
- *Improved equipment:* The equipment used by scrap processors is much safer to operate than it was a generation ago. Shears have guards to protect operators; hammer mills have exhaust filters to remove dust; explosion-proof shredders are designed to withstand the impact of an exploding aerosol can or flammable gas mixture. In addition, shredders are sometimes installed underground to reduce the noise. A current focus is improving baler safety, using devices that sense when an operator is in the main chamber and prevent the ram from activating (Toto, 2003).

- *Collection by type:* The hazards of processing old scrap differ according to the product being recycled. Used beverage containers (UBCs) have lacquer coatings not found on automotive scrap; discarded automobiles contain motor oil and fluids not found in UBCs. Separating old scrap by product type makes it easier to deal with these hazards. Automobiles and UBCs are already processed separately in dedicated facilities in many locations, as are aircraft and old electrical cable. Efforts are being made to separate white goods into a distinct processing stream as well (Ludwig, 1996).
- *Regulation of scrap and sorting facilities:* Increasingly, governments have become involved in directing the movement of scrap and the operation of facilities for processing. The goals of the regulatory process include eliminating the uncontrolled dumping of hazardous chemicals recovered from scrap, protection of the general public from noise and discharges from the facility, and ensuring worker safety (Spoel, 1992). In some cases scrap yards in populated areas have been forced to close or curtail operations. The regulatory process often goes hand-in-hand with the writing of standards (see below).
- *Development of standard operating practices:* The development of safe work practice in scrap yards and municipal recycling facilities (MRFs) until recently followed standards used at construction sites (Glenn, 1998). These are of limited value, since the equipment used for tearing items apart is different from that used for putting things together. However, two U.S. initiatives have recently been announced to develop more industry-specific standards. The first is the publication of ANSI (American National Standards Institute) Z245.41, which applies to MRF operations. More recently, the industry group ISRI has developed RIOS (Recycling Industries Operating Standard), which will also standardize responses to environmental issues (Schaffer, 2004).

THERMAL PROCESSING AND MELTING

Facilities that remelt aluminum scrap receive raw material both from scrap processors that upgrade old scrap and directly from producers of new scrap. As a result, the environmental and safety hazards faced by processors are also present at remelting facilities. Additional hazards include (Pierce and Hubbard, 1992; Jacoby, 2000):

- *Water:* Moisture comes with scrap either as trapped liquid, as snow and ice accumulated during storage, or as rainwater collected during transportation. It is a significant safety hazard. If water is charged to a melting furnace along with the scrap, the resulting steam explosion can injure or kill plant personnel and damage equipment (Epstein, 2003). The problem is serious enough that separate statistics are kept for steam explosions.
- *Rust:* Rust is hydrated iron oxide (Fe_2O_3). It represents a safety hazard because of its reactivity with molten aluminum:

$$Fe_2O_3 + 2\ Al\ (l) = 2\ Fe\ (l) + Al_2O_3 \qquad (14.1)$$

TABLE 14.1
Estimated Dioxin Emissions from Various Countries, by Source

	Emissions/Year (g-TEQ)[a]				
Source Category	**USA (1995)**	**Japan (1999)**	**U.K. (1997/1998)**	**Germany (1994/1995)**	**38 European Countries (1990s)**
Waste incineration (total)				32	2660
Municipal waste incineration	1100	1350	710–2600		
Industrial/hazardous waste incineration	5.7	690			
Ferrous metal industry (total)				181	1960
Sintering plants	25.8	101.3	25–30	158	1650
Electric arc furnace		141.5	59	5	287
Nonferrous metal industry (total)					1610
Primary copper	0.5	0.46	24	26.8	1500
Secondary copper	541	0.05			
Primary lead		0.04			18.0
Secondary lead	1.63	0.45	95–220		
Primary zinc		0.14			30.0
Secondary zinc		18.4		41.8	
Aluminum industry (total)		14.0		49.7	37.3
Primary aluminum			0.082		
Secondary aluminum	0.23		29–320	22.9	

[a] A g-TEQ is the equivalent mass of toxic dioxin emitted per year; 1 g-TEQ is roughly equal to 61 g of total dioxin.

Source: Nakamura. T. et al., *Metall. Rev. MMIJ,* 17, 93, 2001. With permission.

This *thermite* reaction is highly exothermic, to the point of being explosive. The excess heat caused by the reaction can also lead to more oxidation of the molten metal, further increasing melt loss.

- *High-temperature toxics:* These are chemicals that pose no hazard during ambient-temperature processing and handling but give off toxic fumes when heated. The organic coatings on UBCs are a good example of this; the selenium and arsenic coating of photo receptor tubes is another.
- *High-temperature explosives:* The reaction of nitrate chemicals with molten aluminum when charged with a scrap load is a notorious safety problem in remelting operations. The most common source is ammonium nitrate from discarded fertilizer (Epstein, 2003). The ammonium phosphate in discarded fire extinguishers also reacts violently with molten aluminum. Oxidized material has on occasion been mistaken for flux, with deadly results (Caniglia, 2004).
- *Flux:* The salt flux used in rotary and some reverberatory furnaces vaporizes to a small extent during melting, generating chloride fumes. Dust given off by salt slag also presents a workplace hazard. More recently,

the hygroscopic nature of salt accumulated on workplace tools has been identified as a path by which water can be introduced to melting furnaces (Williams, et al., 2005) and thus a cause of steam explosions.

Perhaps the most significant concern resulting from the use of chlorides is their reaction with organic vapors given off by decomposing coatings and plastics. The reaction generates several chlorinated hydrocarbon vapor species, most notably dioxin. Even present in minute quantities, this compound is a significant concern for most aluminum recycling operations. Table 14.1, from the 2001 review by Nakamura et al., compares dioxin emissions from various industries in Europe and the United States. The numbers are subject to considerable uncertainty, but the much larger values for the European secondary aluminum industry reflect in part the wider use of rotary furnaces, which require fluxing (Sweetman et al., 2004). Dioxin generation is more feasible in the remelting of aluminum scrap than other metals because of (a) the melt temperature of 700 to 800°C, which is below the temperature at which optimal decomposition of dioxins occurs, and (b) the input raw material, which often includes chlorine- and bromine-containing plastics. Electronic scrap is a particular concern (Sinkkonen et al., 2004).

RESPONSES TO HAZARDS

The responses to these hazards fall into two classes. The first has to do with scrap acquisition and storage, and the second is changes in charging and melting practice.

Scrap Acquisition and Storage

Preventing steam explosions is the most important task in the receiving and handling of scrap aluminum (or any metal scrap, for that matter). Visual inspection of incoming scrap can determine if a load is especially wet, but measures taken after receiving are more important. Storing scrap in a covered location is recommended, as is a FIFO (first in, first out) policy for charging. Although baled scrap is more convenient to charge, shredding the bales is increasingly required to uncover surprises and give undesired fluids a chance to drain away (Inductotherm, n.d.; Jacoby, 2000).

Inspection of incoming scrap is vital for removing other hazards, and training personnel to recognize hazards is an important part of a safety program (Pierce and Kenney, 1997). Many facilities now supplement visual inspection with a radiation detection station (Pierce et al., 1993), since radioactive material is the hardest to spot and the most damaging if not caught. Magnetic separators can remove most of the ferrous material (and the rust) from incoming scrap, and this is commonly practiced as well. A good relationship with brokers and other scrap suppliers will often prevent problems from reaching the recycling facility in the first place.

Chapter 5 introduced the types of decoater used for decomposing the organic coatings on aluminum scrap, in particular UBCs. It was pointed out that decoating reduces melt loss of treated scrap and reduces fluxing requirements. It also reduces soot and organic vapor generation in the melting furnace, reducing the amount of environmental equipment required for the furnace. By collecting the organic vapor

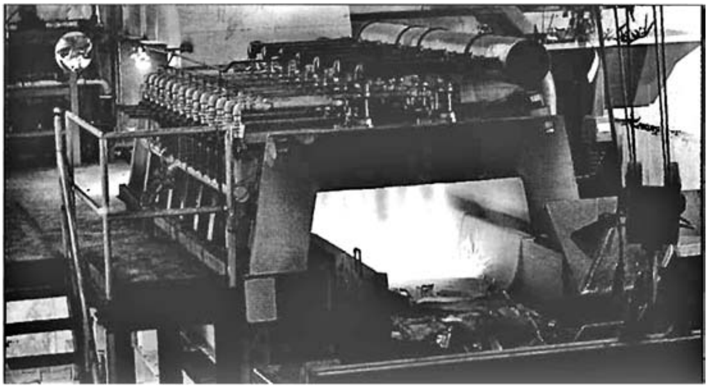

FIGURE 14.1 A drying furnace for aluminum scrap. (From Inductotherm, Inc., Safety Manual, http://www.inductotherm.com/safety/safety.htm, n.d. With permission.)

in one process stream, postcombustion of the vapor to generate CO_2 and H_2O is easier, and the lack of flux in a decoater reduces the possibility of dioxin generation as well. Because of this, thermal pretreatment of scrap to decompose organic material is increasingly recommended for all old scrap, not just UBCs.

Decoating furnaces obviously remove water as well as organic coatings; even if decoating is not performed, a drying furnace such as that shown in Figure 14.1 is still recommended for water removal (Emes, 2004). (The heat input to the scrap in a drying furnace shortens melting times and increases productivity as well.) In addition to scrap, other inputs to a melting furnace should be kept dry: alloying elements, skimming tools, and primary or secondary ingot charged with the scrap. Water trapped in the shrinkage cavity of aluminum sows is recognized as one of the major causes of steam explosions (Epstein, 2003; Niedling and Scherbak, 2003), and as a result preheating of any input to a melting furnace is now recommended (Jacoby, 2000). Any melting furnace with a built-in preheating system, such as a shaft or tower furnace, is useful for water removal as well.

CHARGING AND MELTING

Improving safety in the charging of aluminum scrap to a melting furnace has three elements: separation of personnel from the process, placing barriers between workers and the furnace, and personal protection of workers. Separation of personnel is the most effective of the three, and the development of remotely operated charging devices is of interest in all scrap metal remelting operations (Anonymous, 2004; Emes, 2004; Inductotherm, n.d.). Continuous feeding of scrap to steel remelting furnaces has been available for some time, and equipment of this type is now being installed by aluminum remelters as well. In addition to reducing the risk of explosions and maintaining steadier furnace conditions, continuous charging seems to reduce the amount of dioxin and other organic emissions from the furnace, most likely by keeping furnace temperatures above the range in which dioxins are most

FIGURE 14.2 An operator-shielded melt control station for furnace charging. (From Inductotherm, Inc., Safety Manual, http://www.inductotherm.com/safety/safety.htm, n.d. With permission.)

likely to form (Kaune et al., 1999; Ollenschläger and Rossel, 1999). Using conveyors or vibrating feeders rather than charge buckets also helps separate personnel from the furnace during charging (Gillespie + Powers, n.d.).

Figure 14.2 illustrates a melt control station with a barrier to separate the operator from the furnace. This reduces the chance of injury from splashing of molten metal or small steam eruptions (Anon., 2004; Emes, 2004). The introduction of video monitoring of charging operations now makes it possible to move the operator even farther away, and this will be more popular in the future. The aluminum industry has also made significant efforts in recent years to improve personal protection for plant personnel (Inductotherm, n.d.). These efforts include research on fire-retardant fabrics (Johnson, 2003).

Significant effort has been made in recent years to develop salt-free melting practices. This includes the introduction of vortexing and twin-chamber reverberatory furnaces, decoating equipment, and efforts to develop a salt-free dross processing technique (see Chapter 13). Eliminating salt eliminates the production of salt dross. It also minimizes chloride fumes in the plant environment and the generation of chlorinated hydrocarbons in furnace exhaust gas. For the same reasons, eliminating chlorine gas from refining operations is also a goal of many casting facilities.

Table 14.2 lists dioxin concentrations in the exhaust gas from secondary aluminum processing, again from the review of Nakamura et al. (2001). The treatment of most exhaust gas includes (a) contacting it with slaked lime or sodium bicarbonate,

TABLE 14.2
Dioxin Concentration in Untreated and Purified Exhaust Gases from Aluminum Melting Facilities

Aluminum Melting Facility	Untreated Exhaust Gas (ng-TEQ/m^3)	Treated Exhaust Gas (ng-TEQ/m^3)	Treatment Method
Reverberatory furnace			Slaked lime; fabric filter
Before optimization	0.18; 1.05	0.13; 0.68	
After optimization	0.015–0.066	0.007–0.016	
Two rotary furnaces and four holding furnaces			Two-stage absorption process, followed by fabric filter
Combustion with air	42.2	9.1	
Oxy-fuel combustion	82.1	11.6	
Two rotary drying furnaces and one holding furnace (oxy-fuel combustion	18.47	0.014	Two-stage absorption process, followed by fabric filter; slaked lime added to process

Source: Nakamura. T. et al., *Metall. Rev. MMIJ,* 17, 93, 2001. With permission.

which reacts with chlorinated hydrocarbons (such as dioxin) to generate calcium or sodium chloride and nonhazardous hydrocarbons (Ollenschäger and Rossel, 1999), and (b) the use of a fabric-filter baghouse to recover small particles and mists from the exhaust gas (Blau and Powers, 1987). The input of small particles of soot or coke to the gas-treatment train helps collect dioxins and furans, further reducing gaseous emissions. A newer approach is to quickly quench the off-gas, minimizing the time during which it is in the optimum temperature range (300 to 400°C) for dioxin formation.

Furnace operating characteristics also play a role in dioxin formation. Firing with oxygen-enriched air tends to increase dioxin concentrations, in part by reducing the volume of exhaust gas generated. However, using dilution of off-gas with air to decrease dioxin concentration is not acceptable in many locations. Optimization of reverberatory furnace practice to preheat scrap and minimize flux usage helps even more.

RECOMMENDED READING

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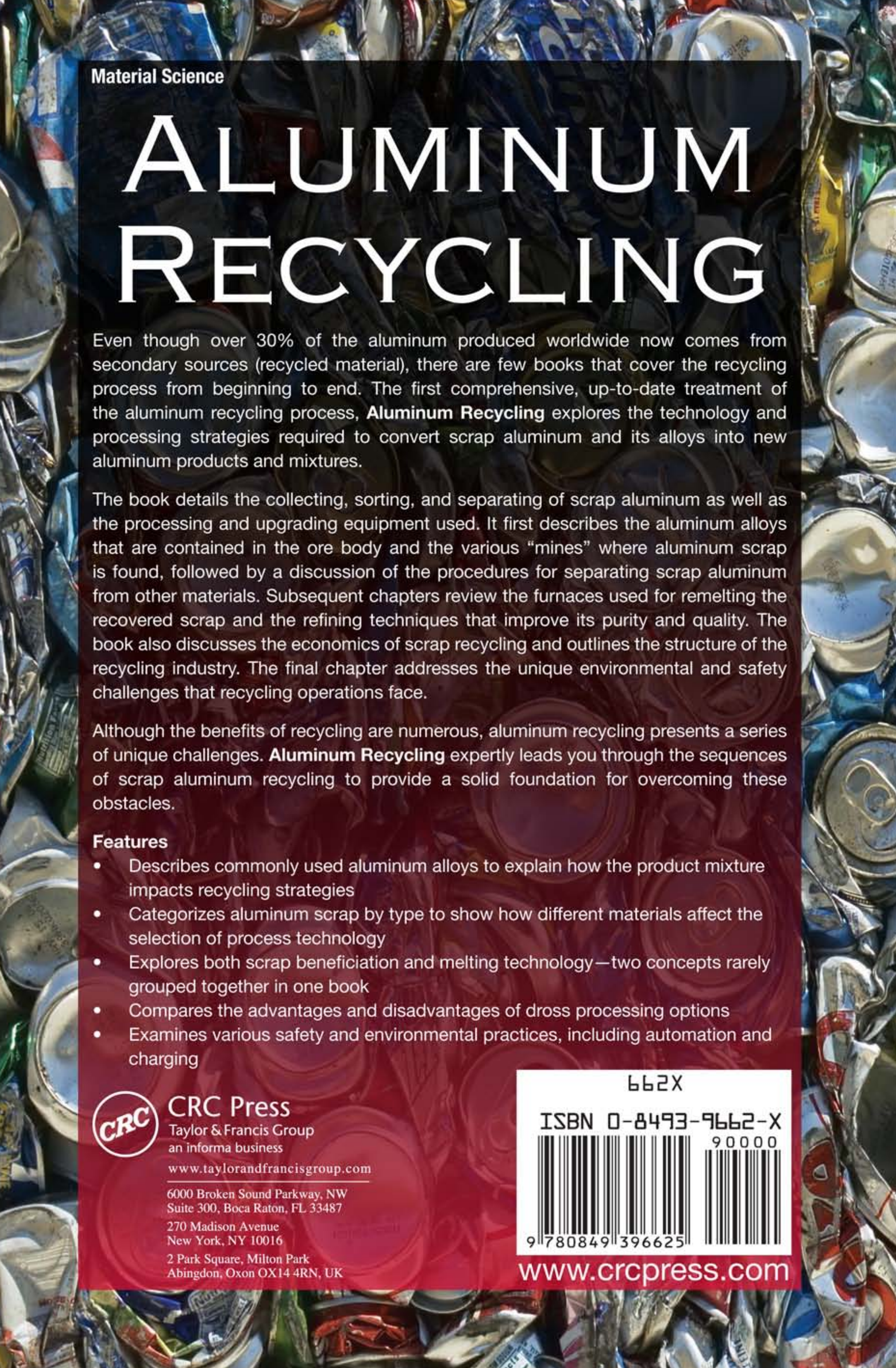

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