PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Recycling Effects on the Composition of Non-Ferrous Metals

J. A. Charles

Phil. Trans. R. Soc. Lond. A 1980 **295**, 57-68
doi: 10.1098/rsta.1980.0075

Phil. Trans. R. Soc. Lond. A **295**, 57–68 (1980)
Printed in Great Britain

Recycling effects on the composition of non-ferrous metals

By J. A. Charles

Department of Metallurgy and Materials Science, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, U.K.

As in steel, the basic problem in the recycling of non-ferrous metals is the dispersion of individual metals or alloys in composite artefacts and in mixed scrap loads. A general view of the non-ferrous situation is not easily achieved, and recycling effects tend, in the natural thermodynamic order of things, to be specific to particular metals. There are, however, some overall differences from iron and steel which arise in relation to the intrinsic value of the materials themselves, their use both as high purity metals as well as in alloys (which has led to long-established refining techniques), and the potential for scrap use in the production of chemicals.

The statistics of reuse are considered for Al, Cu, Zn, Pb and Ni, and the ways in which some specific impurities are dealt with are considered. Aspects of 'design for recycling' are introduced.

General considerations

There is little that can be said generally about problems in non-ferrous metal recycling, since cost and basic thermodynamics dictate the extent of difficulty, and each material has to be considered on its own; but in some respects, initial distinction between ferrous and non-ferrous materials is a reasonable one. First, there is the obvious point that with ferrous materials one specific matrix material is being considered where the range of 'difficult' impurities in terms of removal during refining can be identified on thermodynamic grounds, and where the effect of these impurities is likely to apply widely in the one general class of material. Secondly, and this is of significance in the present discussion, steel constitutes the great bulk of metal in service, and many of the non-ferrous metals are widely disseminated within that ferrous bulk. While some non-ferrous metals do recirculate through closely controlled specific items, the first stage in scrap recovery is usually an attempt to separate the higher value non-ferrous components from iron and steel, and to sort out one class of non-ferrous material from another. Where the various metals are not thinly applied as coatings or finely dispersed and mixed in a fabricated form, physical separation may be achieved. In its crudest form, this is reflected in the activities of the car breaker where batteries, carburettors, alternators, wiring, etc., are ripped out for separate recovery. At a more advanced level, shredding, freezing, crushing and sorting methods have been developed for more extensive separation of intimately mixed metals in components. The extent to which such separation can be taken economically does, of course, reflect the content of non-ferrous residuals in steel, because any price margin between low-residual and high-residual steel scrap is not likely to enable significant extension of physical sorting or recovery on its own; this is where we would wish to be able to operate a bulk chemical process for residual element removal during steelmaking.

A consideration of scrap recycling and its effect on composition should distinguish between in-production scrap and returned scrap after service, although frequently the available statistics do not make such a distinction. In-house scrap should be of known unadulterated composition, but it is clear that, from an economic view, recycled production scrap costs more than primary material. It has already borne primary conversion costs without market income, and at best such internal scrap can only be valued at the price of graded external scrap. It is thus misleading to evaluate the success of an overall metal recovery circuit where in-house scrap is not separately accounted. However, it has been estimated that on average, 33 % of non-ferrous metal output derives from scrap and that, in the longer term, 60–70 % of non-ferrous metals produced are eventually recycled; see table 1 (Whalley & Broadie 1977).

TABLE 1. U.K. CONSUMPTION OF NON-FERROUS METALS

	consumption/kt		amount from scrap/kt		amount from scrap (% of consumption)	
metal	1973	1974	1973	1974	1973	1974
Copper	718*	660*	271	253	38	38
Aluminium	691†	694†	249	251	36	35
Zinc	392	353	86	85	22	24
Lead	364	325	204‡	161‡	56	50
Manganese	300	—	—	—	65§	—
Chromium	99	—	—	—	40§	—
Nickel‖	32	27	2	4	—	—
Tin¶	18	17	2	2	—	—

* Estimated copper consumption at fabricating stage.

† These figures include a contribution from the aluminium content of exported alloys which is not easily quantifiable.

‡ Includes remelted lead alloy, but this is not included in secondary refined lead production.

§ These figures are the percentages used in steel and are assumed to be recycled as scrap steel.

‖ These figures exclude nickel contained and recycled in stainless steel.

¶ These figures refer to consumption of primary and secondary refined tin only. They exclude about 3–4 kt of tin recycled directly in alloy and recovered from fume for solder making.

Source: Data are derived from World Metal Statistics.

As stated above, the distinction between internal and external scrap supplies is not clear and it is thus difficult to identify specific areas for improvement.

One of the most significant developments in recent years has been from advances in the field of fabrication by forming, where method and design have resulted in minimized waste material. In terms of economics this is a key factor, reducing the amount of in-house scrap. At the same time, lower specific consumption of materials for a given service requirement through improved design (for example, mass of copper per megawatt in power generating equipment) can mean greater proportions of scrap available from historic output for the overall mix, particularly when coupled with lowered production caused by economic recession. Where there exist problems of accumulation of residuals in the secondary refining circuits, these will be exacerbated.

PROCESS METALLURGY CONSIDERATIONS

From the thermodynamic point of view, treating the non-ferrous metals as a group makes no sense at all. Clearly, while in the actual processes the selective removal of elements in refining will be modified by the control of activity in reactants and products by temperature, pressure, the composition of slag systems and by aspects of reaction kinetics, the general picture remains that where the value metal is a reactive one (exemplified by a high negative free energy of compound formation), it will be more difficult to remove associated impurities without heavy loss of metal values and high cost. Metals of high stability, with low negative free energies of compound formation compared with associated impurities, are, first, easier to produce in a primary smelting stage at high purity by selective reduction and, secondly, most easily refined of such impurities as are reduced from their ores (figure 1). This latter consideration is, of course, equally applicable when refining in secondary circuits.

As a group, however, the non-ferrous metals have one important distinction from ferrous materials. This is their wide requirement as pure metals, often at greater than 99 % purity and at substantial price, starting from primary raw materials in which their initial concentration was low. This has led over the years to the development of sophisticated refining techniques, where recycling or separate treatment of value-rich dross and slag has become an accepted part

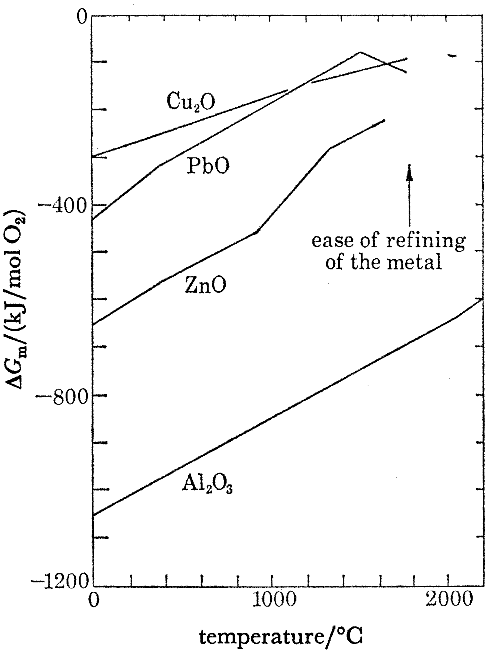

FIGURE 1. Free energy of oxide formation in relation to ease of refining.

of pyrometallurgical systems. Figure 2, for example, shows a primary lead extraction and refining flow sheet, largely derived from information given by Dennis (1961). Many of the techniques used there are similarly incorporated in secondary metal treatment (figure 3). As a further example, the conversion of 'black copper', a copper alloy derived from the secondary blast furnace and containing iron, nickel, tin, lead, zinc, antimony, etc., uses similar equipment to that used for primary matte treatment in the form of air-blown Pierce–Smith converters. Similarly, again, the copper product is further refined in anode furnaces and finally by electrolysis, as indicated in figure 4 (Nelmes *et al.* 1961). In non-ferrous practice in general, there is a major emphasis on hydrometallurgical extraction of values and electrolysis, by which the selectivity of refining can be maximized, and this approach again has its place in secondary treatment.

In contrast, the bulk of steel production has been by the use of high value content ores, often almost pure iron oxides. Although iron may often have been contaminated by copper in the Iron Age through its development from and association with copper smelting, the separate iron

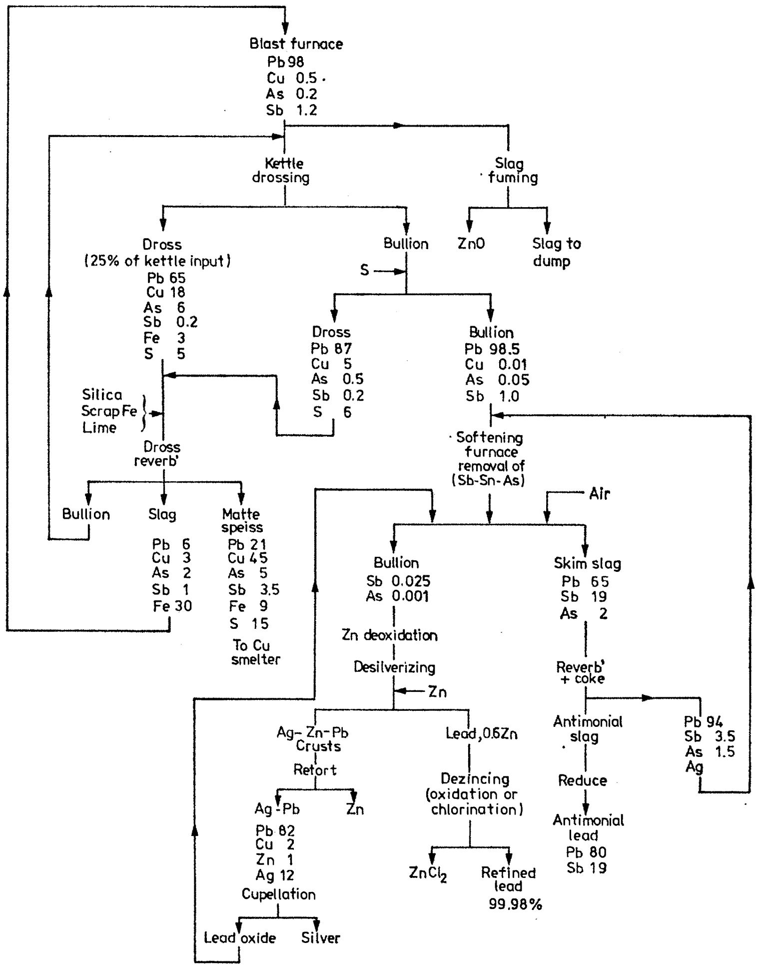

FIGURE 2. Flow sheet of extraction and refining processes for primary lead.

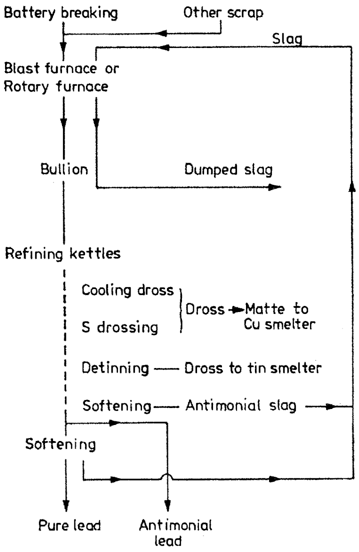

FIGURE 3. Flow sheet for refining secondary lead.

oxide deposits from which have come the great bulk of ferrous production give a low non-ferrous content, apart from silicon, manganese and phosphorus. The process of steelmaking then develops as one of over-reduction to give an iron–carbon–silicon–manganese–phosphorus alloy, which is then oxidized for removal of these impurities to the required levels, with the necessary slag composition control. No techniques have been derived from long primary practice that enable the control of such impurities as copper, nickel and tin admitted through scrap, although clearly the task is thermodynamically daunting.

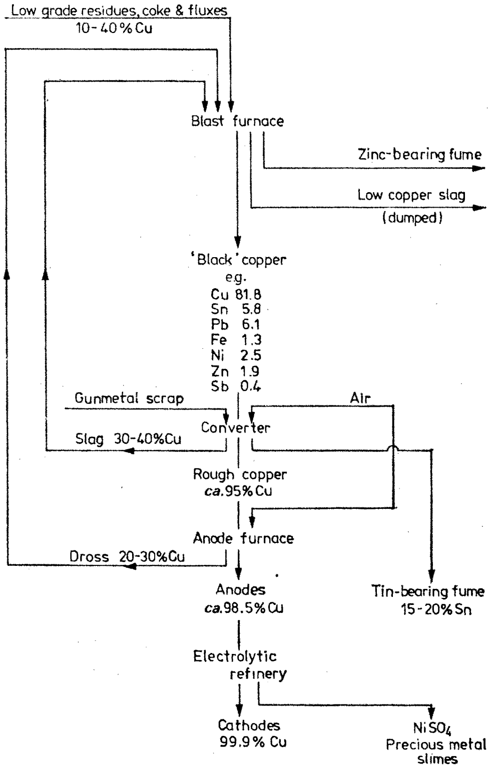

Figure 4. Flow sheet for refining secondary copper.

The production of chemicals

A further general difference between the ferrous and non-ferrous metals industries is in the demand for chemicals, where the existence of almost pure natural iron oxide is an obvious starting point, whereas with non-ferrous metals, scrap may often be suitable as an alternative to pure metal as the raw material. Galvanizer's ash, for example, is a major source for zinc chemicals.

Alloy production

The production of alloys from scrap by remelting is clearly the most desirable and economic method of recycling metal. In this technique, the scrap is carefully classified and after a minimum of refining, if any at all, depending on the system, the metal is cast into ingots to standard specifications. In making up alloys by remelting, it is necessary to plan a production sequence to build up the purity of the product progressively to the desired level with regard to specific impurities in order to meet the most rigorous specifications. Similarly, because of pick-up in the furnace, the more highly alloyed compositions will be programmed as far as is practicable to minimize the production of non-standard material during change-over from one alloy to another.

In spite of the advantages in control and back-up analysis facilities that the use of larger integrated units should bring to this sort of work, the increasing number and complexity of alloys in use has prevented growth in this area for some metals. Here we see a desirable objective in rationalizing, reducing the number of and, where possible, simplifying, alloy specifications.

Design for recycling

In the recovery of non-ferrous values from genuine service scrap we meet the particular problem that in materials selection, the best solution to a given service requirement is often a composite one. Thus to achieve a desired surface stability against corrosion or wear, surface coatings are applied, with the bulk requirements of cost per unit strength or cost per unit volume being met by a different main material. Sometimes the overall service requirement can only be met by one or two specific technical solutions, and the recycling problem thus created has to be accepted. Frequently, however, a range of possible solutions may exist but other market pressures do not allow the rational choice from a conservation and recycling point of view.

One could hardly imagine a more difficult mixture to recycle than a thinly tinned steel can having soldered seams and an aluminium top. Some brave attempts have been made to recover the tin by chlorination, or by incorporation of cans in the charge to cast iron, where the tin has a beneficial effect, but so far this is a small effort and much development is needed if we are to continue using this form of packaging and to conserve tin supplies. In steelmaking, not only is there a potential residuals problem from tin and lead, but the aluminium content creates difficulties in slag system control, unless this class of can can be separately employed as part of a deoxidation addition.

Cans may consist of deep drawn steel and non-metallic coatings may be applied in certain types of service. Wholly aluminium cans, with organized recovery, or recycled glass, would offer more acceptable solutions from the recycling point of view.

It is in the context of the motor car and design for recycling that a most interesting development has occurred in the use of aluminium alloys. It is clear that the use of widely differing alloys of the same base in the same mass-produced equipment will give rise, both in-house and in due course in historic scrapping, to a recovery problem. Unless the components are separated before melting, which, since they are of the same base, will be difficult and expensive, the recovered alloy will be comparatively useless owing to its composition. The Aluminium Company of America (Alcoa) have therefore deliberately moved away from some use of Al–Cu–Mg alloys for vehicle body sheet, in favour of Al–Mg–Si alloys, to avoid in-house scrap recovery problems. Either wrought material is compatible with the casting alloys occurring elsewhere in a vehicle, when it reaches the stage of historic scrap, since mixed Al–Cu–Mg–Si casting alloys do exist, but even here there may be some advantage in reducing the copper rather than the silicon content of the mix.

The theme of design for recycling was an important feature of Professor Nutting's address as President of the Metals Society in 1977.

SPECIFIC METALS

The Spring Meeting of the Metals Society in 1973 was given over to a full discussion on non-ferrous scrap recovery, and for full and detailed consideration of the industry and the handling and refining processes employed, the many papers then presented should be consulted. Without wishing to repeat much of what was said then, or in a subsequent review by Fletcher (1976), five of the most important metals are now considered individually in relation to some of the specific effects of recycling.

Copper

The widespread use of copper for its physical or electrical properties and chemical stability often requires a high degree of purity. Small quantities of impurity can greatly affect electrical conductivity (Copper Development Association 1964) as shown simplified in figure 5. In very small amounts impurities impair the ability to produce fine wire by continuous casting and drawing processes, where grain boundary properties are affected by solutes or by the formation of compounds.

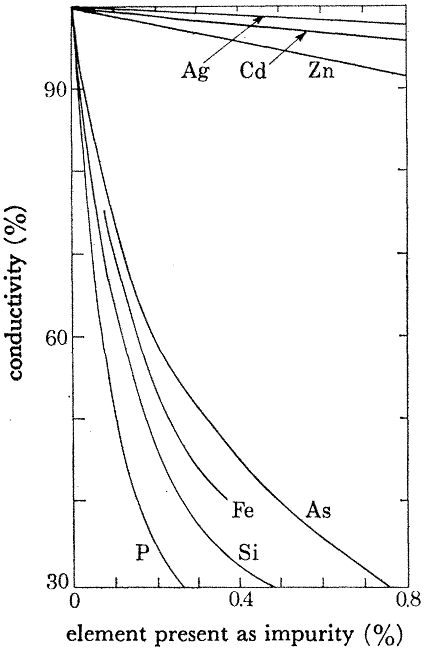

FIGURE 5. Effect of impurities upon the electrical conductivity of copper.

Theoretically, in primary extraction, it is possible to produce primary cathode copper with very low levels of the bismuth, tellurium, arsenic, antimony and nickel, etc., which occur with the copper variously from mine to mine. However, industrial conditions are far from ideal, and owing to the incorporation of anode slime or build-up of impurities in electrolytes, these impurities are found in cathode copper in small concentrations, perhaps most notably in the case of selenium in copper electrowon from ores containing this element.

It has been stated (Whalley 1977) that in 1974 the U.K. copper refining industry produced about 160 kt of refined copper, of which 57 % originated from scrap, and the remainder from imported blister copper. Copper has a long history of use and old copper scrap is relatively important as a source compared with industrial scrap. At the present time there is a shortage of copper scrap and the market is very competitive, a situation which is partly derived from scrap stocks being held back while the price is low in the hope of market recovery.

An important aspect of copper recycling has been its re-use in alloying; for example, 40 % of zinc in the brass produced in the U.S.A. is derived from the incorporation of brass scrap (Bever 1976). Unfortunately, this section of the industry has been in decline for some years, for reasons associated with the increasing complexity of alloys. Only a limited amount of refining is possible in such copper alloy systems without the loss of other alloying elements. For example, in refining brass it is not possible to remove iron without considerable loss of zinc. The composition of copper–tin alloys can be adjusted by dilution or addition, but refining by oxidation will inevitably result in the loss of tin. Classified scrap, after melting, is rapidly analysed by modern techniques; if a predicted alloy composition cannot be obtained, for example because of high nickel, then the bath is either diluted with low nickel material, or the alloy adjusted to meet another specification of higher nickel content.

Unclassified and contaminated scrap, process scrap and residues are passed to the secondary smelters and refiners. Under certain commercial conditions relating to copper and alloy demand, the scrap normally used by the alloy makers, for example car radiators and gunmetal scrap, may be treated in secondary smelters. At present, smelting and electrorefining is the only economic method of treatment for low grade and highly contaminated scrap (figure 4). The process recovers the copper and eliminates impurities, mostly as valuable by-products. Secondary copper cathodes do not contain selenium, tellurium or bismuth (which are sometimes troublesome in primary metal), because of the second electrolysis, but lead and nickel are found to a greater extent than in primary cathodes because of their initial concentration in the black copper. These different trace impurities do not, however, constitute a difference in marketing quality.

In both the primary and secondary copper industries, there is always pressure to increase output from electrolytic cells, thus reducing the capital costs of new plant or the running costs of existing plant. The consequent operation at higher current density brings with it the risk of increased impurity incorporation in the cathode, and considerable attention is being given to this aspect of the technology.

Thus, in copper, refining methods exist for obtaining any desired purity in secondary circuits and no particular accumulation problems can be foreseen in the future that cannot be dealt with.

Aluminium

Taken overall, the aluminium situation is largely that the waste from wrought aluminium and aluminium alloy production provides most of the feedstock for the castings industry. Total consumption of secondary aluminium in the U.K. in 1974 was 251 kt (Whalley 1977), about one-third from old scrap. Drossing losses during remelting are appreciable, with considerable entrapped aluminium metal in the surface oxide formed, and dross reclamation is important.

From earlier comment on the thermodynamic basis of refining, illustrated by the free energy diagrams for oxides, chlorides and fluorides, it is clear that the opportunity for simple impurity removal from secondary aluminium by pyrometallurgical means is very limited. Magnesium, sodium and lithium are removable by chlorine; magnesium is also removed by treatment with NaF–KF fused salt and sodium with $MgCl_2$. Titanium and vanadium can be separated from molten aluminium by precipitation with excess boron and settlement of the borides, as employed in the production of electrical grade aluminium, where, as with copper, small quantities of impurity can markedly affect conductivity.

For the removal of iron, silicon, manganese, zinc and copper the three layer electrolytic refining process (Al–Cu alloy, fused salt electrolyte and refined aluminium floating on top), normally applied to up-grading molten aluminium from the primary cells, is equally capable of refining remelted secondary metal, though at a price. In the context of the purification of commerically pure aluminium from the reduction cells, which is normally achieved by the electrolytic refining process, demand for the super-purity metal thus achieved has been decreasing owing to the development of finishing processes (e.g. anodizing) that are less sensitive to impurity levels and that can use material of 99.86 % base, a purity obtained by selective tapping from normal primary reduction cells operated with tight control of feed materials.

Over the last two decades there have been renewed attempts to utilize the old techniques of fractional crystallization or remelting in several areas of non-ferrous metal refining, taking advantage of the better understanding of the fundamentals of solute redistribution as used also so effectively in zone refining. It is interesting that at least one commercial plant for upgrading standard aluminium to 99.9 % or better is based on this approach, and of course, zone refining itself can be employed to produce the highest grades. Any manganese present in pure aluminium complicates the grain size control in final sheet; lithium has to be low in dry-annealed foilstock to avoid the formation of 'blue-foil' on subsequent exposure to humid conditions; sodium in alloys with a high magnesium content will give cracking problems in rolling; boron has to be low in alloys for nuclear energy purposes because of neutron absorption.

Some years ago, zinc was probably the most awkward element in aluminium scrap, originating from contamination with zinc-based alloys, brass and the casting alloys containing 12 % Zn, which used to be popular. The higher growth in aluminium use relative to other metals and the reduced use of individual alloys, containing such high zinc levels, together with an increasing average content in the casting alloy mix, has seen the problem disappear.

In both primary and secondary treatment circuits, the main problem at present is iron, because of its effect on the production of bright anodic finishes and other alloy qualities.

In making up aluminium alloys, contamination may occur through the 'master alloy' additions. For example, in adjusting the silicon content of LM6 (a pressure die-casting alloy of normally wide specification tolerance), contaminants such as calcium may be introduced and special ferrosilicon grades have to be employed if the calcium is specified at a low level. Should accumulation of calcium ever arise in scrap circuits it would be removable in the same way as magnesium, with chlorine.

There appears to be little sign that levels of impurity in the aluminium industry are on the increase, although with so little secondary refining at present carried out, one might have expected that this would be the case. This must be mainly due to the relatively small contribution of historic scrap to current supplies in a material which has undergone rapid growth at relatively high purity levels, which has not yet accumulated greatly as historic scrap, and where a wide range of alloy specifications exist, enabling recovery by remelting.

Zinc

The total zinc consumption in the U.K. in 1974 was 353 kt, of which 24 % was secondary zinc (Whalley 1977). This forms a considerably lower proportion of output than in the other major non-ferrous metals, principally because many uses of zinc are intrinsically dispersive in the form of sacrificially protective coatings or anodes. Almost half of the recycled zinc quoted was in recycled brass, and does not, therefore, enter the true zinc account.

Zinc for galvanizing must contain less than 0.25% aluminium and no copper, and there are stringent limits on the impurity levels in alloys for die casting. Since zinc has very limited solid solubility for most other metals, there can be problems associated with corrosion at grain boundaries, where a high local corrosion potential can exist between the rejected solutes and the adjoining matrix structure. This applies particularly to iron, tin, lead and cadmium impurities, the last two elements being usually found in zinc ores. The resultant intercrystalline corrosion leads to dimensional instability and loss of strength. The basic zinc for the manufacture of the die casting alloys must therefore be such that these impurities are strictly limited.

In the 1955 revision of BS 1004 covering zinc and its die casting alloys, other impurities previously specified as 'trace' were given definite limits. Indium was one of these, as investigation had shown that it might be particularly detrimental. In the 1972 revision a maximum limit has been included for nickel in the ingot alloys. Nickel may enter from the melting equipment, and the limit also allows the use of a limited amount of in-house plated scrap material.

Table 2. BS 1004:1972 ZINC ALLOYS FOR DIE CASTING (percentages)

	A	B
Al	3.8–4.3	3.8–4.3
Cu	0.01 max.	0.75–1.25
Mg	0.03–0.06	0.03–0.06
Fe	0.10 max.	0.10 max.
Ni	0.006 max.	0.006 max.
Pb	0.005 max.	0.005 max.
Cd	0.005 max.	0.005 max.
Sn	0.002 max.	0.002 max.
Tl	0.001 max.	0.001 max.
In	0.0005 max.	0.0005 max.

The specification does allow for the re-use of reclaimed metal from the manufacturer's own die casting operations, provided the compositional limits in the product are maintained. The incorporation of zinc scrap or secondary zinc alloy is forbidden, however, in the production of alloy ingot for resale.

Secondary zinc scrap is used for the production of zinc oxide, zinc dusts and other zinc chemicals; considerable attention is being paid, however, to routes by which the scrap could be refined.

Galvanized steel is recycled for its steel value, and such zinc as is not lost sacrificially by oxidation during its life will appear in the furnace flue dusts. The increasing use of electric arc steelmaking furnaces working on light, low-grade, scrap has seen the recovery of large quantities of such zinc-containing dusts. Their zinc content makes them unsuitable for recycling through the iron blast furnace and they are also unsuitable for direct incorporation in the charge to a zinc process. There is a need for a new process here. One entirely different approach is that developed at Duisberger Kupferhütte, where, it is understood, galvanized scrap is employed in a cementation process for the recovery of copper from solutions. The zinc can then be recovered as hydroxide or carbonate from the leaching solutions.

Lead

The consumption of lead in the U.K. was 325 kt in 1974 (Whalley 1977), of which 55–60 % was supplied by the secondary lead industry. While use in lead–acid storage batteries has been growing, most other uses have declined, for example in cable sheathing. In the battery, recycling is very efficient (*ca.* 90 %), attributable to the short working life at high tonnage, good collection facilities sometimes involving a small credit to the user. Battery recovery has, in fact, become the most important activity of the secondary lead industry (figure 3).

The battery plates are most widely based on antimony-hardened lead. The alloy is not ideal, however, and the antimony content is responsible for much of the gassing and break-down problems that occur. In Europe this has led to a reduction in the level of antimony and generally to a search for alternative means of stiffening the lead-based grids. In the U.S.A. there has been a change toward Pb–Ca–Sn and Pb–Cd alloys, in what are known as 'maintenance-free' batteries.

As predictable from thermodynamic considerations, processes can be set up to remove impurities from lead to very high levels of purity. The primary pyrometallurgical refining circuit for lead has already been referred to, and similar stages may be incorporated in a system for the treatment of secondary lead. For example, normal sulphur drossing is employed to remove copper as sulphide, and tin can be separated to high tin drosses which on re-reduction will be acceptable as feed to solder compositions.

The introduction of the new alloys for battery plates should not create technical difficulties in refining other than those due to complexity, and clearly a single type of material for batteries is a distinct commercial and conservation advantage. The immediate problem that is created in Europe, however, is the increasing amounts of high-antimony lead available on the market, reflecting both the change to new alloys in the U.S.A. and the lower antimony contents employed elsewhere. Bearing in mind the cost of the initial prime antimony content, loss of value in stocks and scrap available could create commerical difficulty, for there are few other outlets for the antimony thus made available.

Lead chemicals have been conventionally prepared from prime high purity lead. Secondary lead is now becoming more widely accepted for this purpose.

Nickel

In its substantial use as an alloying element in steel and dispersed as a coating on carbon steels, nickel presents its own recycling and accumulation problems in the ferrous industry. In elemental nickel and nickel alloys, many uses exist for critical physical, mechanical and/or chemical applications where closely defined compositional limits are required, both in terms of impurities and of alloying elements. The overall trend in alloys is therefore to use high-purity virgin nickel and sophisticated melting techniques for the most stringent requirements (e.g. superalloys and magnetic alloys) and to pass contaminated scrap from these materials to less critical alloys (e.g. electrical resistance, oxidation resistant materials), and in turn on to austenitic steels and finally into low-alloy steels, although it is understood that some identification of specific alloy components and remelting is practised.

The A.S.T.M. specification for refined nickel (B39) is: Ni, 99.80 % min.; Co, 0.15 % max.; Cu, 0.02 % max.; C, 0.03 % max.; Te, 0.02 % max.; S, 0.01 % max.; P, As, Bi, Mn, Pb, Sn, Si, Sb, Zn, each less than 0.005 %. This specification underlines the need for high purity in nickel with regard to certain elements in order to maintain ductility. Sulphur is the main culprit in the loss of ductility by the formation of grain boundary films of eutectic of low melting point ($Ni–Ni_3S_2$, m.p. 643 °C). Malleable nickels are produced by treatment with Mn, Mg or Ca to form stable, separable sulphides. Carbonyl-refined nickel is especially low in cobalt content, in comparison with other forms, and hence may be preferred as the primary source for in-pile nuclear components to avoid the formation of ^{60}Co.

While suitable refining processes might be set up for secondary nickel if it were available in sufficient quantity, existing outlets into non-critical alloys and into steel make this unattractive.

The critical aspect of composition in many nickel alloys has been referred to, where almost any other additional elements upsets the properties, mitigating against scrap incorporation. For this reason, such alloys are increasingly produced by powder metallurgical techniques from high purity powder, avoiding contamination in melting.

Many impurity elements, e.g. Pb, Bi, Te and As, impair the fabrication and service properties of the creep resisting nickel-based alloys. Vacuum melting and the provision of special slags is normally practised to remove and control the level of such impurities.

Conclusions

While it is not wholly legitimate to consider non-ferrous metals as a complete class from which general conclusions can be drawn, it is clear that, in the main, the refining problems that have always existed in primary production have generated techniques capable of producing the high levels of purity often required from complex mixtures of raw material. Similarly, techniques are usually available for the solution of refining problems in secondary circuits, if cost allows. Clearly the more reactive the metal, the less easily it may be refined, and future difficulties may arise with aluminium, where downgrading through alloy systems is currently the main practice.

The situation would be greatly improved by reducing the degree of dispersion of elements in components and introducing a conservation factor into the initial materials selection situation, where a complex or composite solution is often technically unnecessary but at present the most economic. This would simplify not only refining circuits, giving a higher value content feed to each, but also the remelting circuits, where less downgrading would be required. In an ideal world, perhaps, a recycling charge could be attached to each component, with a cost advantage where care had been taken to facilitate recovery of constituent materials. It is difficult, however, to see how such an incentive to manufacturers could be put into practice, but it is certainly a basic philosophy which should be explored and emphasized.

I am deeply grateful to friends in industry for a great deal of help with detailed information on the specific metals, particularly to Dr W. Betteridge, Mr A. Cooper, Dr E. F. Emley, Mr W. S. Nelmes and Dr A. W. Richards. They cannot, however, be held responsible for any of the more generalized comment.

References (Charles)

Betteridge, W. & Heslop, J. 1974 *The nimonic alloys*. London: Arnold.
Bever, M. B. 1976 *Conserv. Recycl.* **1**, 137–147.
Copper Development Association 1964 *Publ. no.* 56 (*Copper cables*). London.
Dennis, W. H. 1961 *Metallurgy of the non-ferrous metals*. London: Pitman.
Fletcher, A. W. 1976 *Proc. R. Soc. Lond.* A **351**, 151–178.
Nelmes, W. S., Charles, J. A. & Cowen, A. G. 1961 *J. Metals, N.Y.* **13**, 216–220.
Whalley, L. & Broadie, V. E. 1977 *Resour. Policy* **3**, 243–260.