"Materials-Cycle Optimisation in the Production of Major Finished Materials"
CHAPTER 4: CHROMIUM SOURCES, USES & LOSSES

by

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This chapter is part of a report made for the EC DGXII on a project entitled ***"Materials-Cycle Optimisation in the Production of Major Finished Materials".*** This project aims at facilitating the identification of longer-term R&D needs for materials-cycle optimisation, especially by using wastes, co-products, or by-products from one process as inputs to other processes. Book publication is envisaged. Following is the list of chapters:

All chapters are individually available as INSEAD Working Papers.

CHAPTER 4. CHROMIUM SOURCES, USES AND LOSSES[1]

4.1. Summary

Chromium (along with cobalt) is the archetypical "strategic metal". Because of its importance in corrosion and heat resistant alloys, especially "stainless" steel and so-called "superalloys". Stainless steel is needed for chemicals processing and storage, nuclear power plants, pollution control equipment — such as catalytic convertors for automobiles — and a host of consumer products. Superalloys are used for jet engines and other applications in aerospace technology. "It is by no means an exaggeration to assert that modern technology is largely built on chromium in general, and stainless steel in particular" [Bennett & Williams 1981 p. 28].

Because production and known reserves are concentrated in a few countries, there is at least some theoretical possibility of a supply interruption. In the 1970's, when the two major sources of world supply were the Soviet Union and South Africa, this was a serious concern for the industrial countries. The UN Security Council instituted mandatory sanctions against Rhodesian exports in 1966. (Rhodesia is now Zimbabwe). The U.S. complied until the end of 1971; the embargo against Rhodesia was reinstituted in 1977. In the same year an embargo against South Africa was imposed and continued in place until 1994, although chromite and ferrochromium exports were excluded from the embargo and continued. This concern led to a number of studies of the economic impact of a possible supply disruption. These, in turn, resulted in a significant increases in the U.S. strategic stockpile of chromium. Today these geo-political concerns are much reduced, although they could be rekindled by untoward political developments in the world.

However a newer concern has arisen, namely the public health and ecological impacts of dissipative losses (and uses) of chromium compounds to the environment. Hexavalent chromium (Cr VI) is particularly toxic. This fact provides a further incentive to minimize losses of chromic acid (chromium trioxide) and its compounds. Yet, while some historical uses of chromium chemicals (e.g. as pigments and for electroplating) have declined, others have grown. In particular, chromium sulfate is still the major leather tanning chemical, while copper-chromium-arsenic chemicals have become the most important wood preservative (replacing pentachlorophenol in most countries). Virtually all chemical uses are inherently dissipative.

A more subtle danger has also appeared on the horizon. While the more common trivalent form of chromium (Cr III) is non-toxic and immobile in soils and sediments, it has been demonstrated that under some (i.e. oxidizing) conditions Cr (III) can convert to toxic Cr (VI) [Bartlett & James 1979]. Different forms of manganese (Mn) may serve as oxidizing agents. In soils with high organic matter content, this is unlikely to occur because oxygen is rapidly consumed. However, in soils with little organic matter the turnover of Cr (III) to Cr (VI) is a distinct possibility. Hence, it may be necessary to worry about accumulations of Cr (III) in soils and sediments due to past industrial activities, as well as current ones [Bergback *et al* 1989].

For all these reasons, there are strong arguments for increasing the rate of recycling of chromium alloys, while reducing dissipative uses of chromium chemicals:

Public Policy Goals: Reduce dependence on imports of raw materials; reduce dissipative uses, especially of chromic acid and its derivatives (Cr VI); increase recycling of chromium-containing products, especially stainless steel.

4.2. Sources of Chromium

Table 4.1. Chromium materials production 1991 (kMT)

	Chromite Ore	*Ferro chromium*	*Chromium Metal, 92*	*Sodium Di-chromate*	*Chromic Acid*
Finland	458	190			
France		23	1.2		
Germany		50	0.5		
Greece	22	11			
Italy		47			
Norway		90			
Spain		6			
Sweden		122			
United Kingdom			3,0		
W. Europe	**480**	**539**	**4.7**	**23.5**	**0**
Albania	587	25			
Czechoslovakia		37			
Poland		12		19.2	2
Romania		20			
Yugoslavia	9	60			
W. Europe	**596**	**154**	**0**	**19.2**	**2**
Turkey	870	85			
USSR	3800	925			
USA		68	3	146.9 (UN)	
World Total	**13245**				

Source: [Roskill 1993, "Chromium"] & [UNIS 1988]

Chromium constitutes 185 ppm (0.0185%) of the earth's crust [Taylor & McLennan 1985, pp 15-16]. It is obtained, in practice, entirely from so-called chromite ore, which consists of variable chromium oxide (Cr_2O_3), ferrous and ferric iron oxides (FeO and Fe_2O_3), and alumina (Al_2O_3), plus traces of TiO_2, MnO and V_2O_5. This ore is found in commercially viable grades in relatively few locations. The two largest producers, by far, are Kazakhstan (2.9 MMT in 1993) and South Africa (2.84 MMT) [Papp annual for 1993, Table 22]. Other significant producers are India (1.07 MMT), Turkey (490 kMT), Zimbabwe (400 kMT), Finland (500 kMT), and Brazil (430 kMT). Total world production of ore was 9.3 MMT in 1993 (10.99 MMT in 1992), of which only 500 kMT (from Finland) came from Western Europe. (See *Table 4.1*).

The ore currently being mined averages about 44% Cr_2O_3 or 30% chromium (Cr) content. Chromium content of U.S. imports was 29.5% [Papp 1994, Table 9]. Apparent chromium content of the chromite ore produced globally in 1992 was therefore 3.309 MMT [Papp annual for 1993].

4.3. Production and Major Uses of Chromium

Chromite ore is classified by the U.S. Bureau of Mines as refractory, metallurgical or chemical, depending on its intended use. Chromite is used in its raw (oxide) form in the manufacture of refractory bricks for high temperature furnace liners, such as electric steel-making furnaces, reverberatory copper refining furnaces, and heat-exchanger sections of glass-making furnaces. It is also used as an abrasive. This "route" involves physical processing (grinding, compaction and sintering) only. It accounts for 8% of total global chromite consumption (3% in the U.S.), or 265 kMT of contained chromium [ibid]. We have no data on refractory chromite usage in Europe.

The metallurgical route involves smelting with coke and fluxes in an electric furnace to yield ferrochromium, an alloy of iron and chromium used mainly as an alloying component in the production of stainless steel, other chromium wrought or cast alloy steels. Ferrochromium is classified by carbon and silicon content. In general, chromite is smelted with coke and a silica (quartz), limestone, dolomite or alumino-silicate flux. The iron in the ore (and some silicon) remains with the ferrochromium product, while the slag consists mostly of alumina and the other impurities. Ferrochromium slag could potentially be used as a source of aluminum, though residual iron and silica constitute a disadvantage as compared to bauxite.

Ferrochromium accounts for 87% of total U.S. chromite consumption [Papp annual for 1993]. The percentage of world chromite production used for ferrochromium has been variously estimated at 77% to 80% [Papp 1994]. However, if refractories account for 8% and chemicals for 8% or 9% (discussed later), it would seem to follow that ferrochromium accounts for as much as 83% or 84% of world chromite output. Total world output of ferrochromium in 1992 was 3.579 MMT, of which 619 kMT was produced in Western Europe [Roskill 1993, "Chromium" p. 37]. Assuming ferrochromium accounted for 79% of the chromite ore, with a recovery of 78% [Papp 1994], it would have contained 2.036 MMT Cr in 3.425 MMT ferrochromium. That is to say, ferrochromium would, on the average, consist of 60% Cr, the remainder being iron, carbon, silicon and/or trace quantities of other metals. Losses in the production of ferrochromium are obviously significant, amounting to 583 kMT (Cr) in 1992. If ferrochromium accounts for 84% of chromite, the imputed loss of chromium would be closer to 610 kMT (Cr).

Both refractory production and ferrochromium production generate fairly large quantities of chromium emissions. In fact, on a gross tonnage basis, these are by far the dominant sources of environmentally mobile chromium. In 1970, in the U.S. more than 50% of all uncontrolled chromium emissions (and 68% of post-control emissions) were due to ferrochromium production in electric furnaces [GCA, 1973]. Another 20% arose from the production of chromite-based refractory bricks and chromium alloy steels. It is important to point out, however, that emissions from these metallurgical operations are of the non-hazardous trivalent (Cr III) form.[2]

Major producers of ferrochromium and other chromium ferroalloys in 1991 were the former USSR (CIS) and South Africa, which accounted for 52% of the total output (down to 44% in 1992, due to a temporary cutback in South African output to reduce stocks). The other major producers of ferrochromium in 1992/1993 were China (400/190 kMT), Japan (266/215 kMT), India (220/244 kMT), Finland (187/218 kMT), Zimbabwe (186/140 kMT), Sweden (135/128 kMT) and Norway (114/80 kMT) [Roskill 1993, "Chromium" p. 38]. It is noteworthy that ferrochromium production is increasingly co-located with mining. Significant capacity cutbacks have occurred in countries lacking chromite ore resources. Nevertheless, capacity in Western Europe still stood at 521 kMT (contained Cr) as of year-end, 1992 [Roskill 1993, "Chromium" p. 48]

Ferrochromium is used predominantly (70%) in the manufacture of stainless steel. On the average, chromium constituted 17% of the mass of stainless and heat resisting steels produced in the U.S. between 1962-1983. Recently the unit requirement for chromium in steel has declined slightly due to increased use of Type 409, a ferritic low chromium steel used for automotive exhaust systems with catalytic convertors [Papp 1991]. Nevertheless, demand for stainless steel drives the market for chromite.

Chromium metal is produced in relatively small quantities. Total world capacity is estimated at 25 kMT/y of which 9.5 kMT/y (from three producers) is in Western Europe [Roskill 1993, "Chromium"]. Recent production has been well below capacity. It is made by two routes, electrolytic (1/3 of world production capacity) and aluminothermic (2/3 of production capacity). The first of these routes starts from ferrochromium. The second starts from chromic oxide, using metallic aluminum as a reducing agent. All European producers of chromium metal use the aluminothermic process. Output is used in so-called superalloys (with nickel and cobalt), mainly for jet engines and gas turbines.

Metallic uses of chromium and chromium alloys *per se* do not cause significant environmental risks. Metallic chromium that cannot be recycled is ultimately embodied as a tramp contaminant in iron or steel foundry products, or is discharged to slag heaps and landfills in insoluble form; very little gets into air or water [GCA, 1973]. The main concern is that, under some conditions, dispersed chromium as Cr (III) may be oxidized to the toxic Cr (VI) form. Thus, both criticality and potential toxicity argue for increased emphasis on recycling metallurgical chromium to the maximum feasible extent.

4.4. Major Uses of Chromium Chemicals

According to the US Bureau of Mines, "Minerals Yearbook" [USBuMines 1991 "Chromium" p. 370] chemical uses account for 13% of worldwide chromite consumption. However this figure has been corrected in a more recent study. Apparently, chemical uses currently account for 8% (or 9%) of total global chromite consumption, or about 280 kMT of contained chromium [Papp 1994].

Chromium chemicals ("the chemical route") begin with the manufacture of sodium dichromate (or bichromate), $Na_2Cr_2O_7$. This is done by a hydro-metallurgical process involving roasting of chromite ore with sodium carbonate and lime to yield sodium chromate, followed by leaching with sulfuric acid, then evaporation and crystallization of the sodium dichromate (with sodium sulfate as a by-product). Identified world production capacity for sodium dichromate was estimated at 329 kMT (Cr equivalent) in 1992 [USBuMines 1991; Roskill 1993, "Chromium" p. 55]. Gross world sodium dichromate capacity (329 kMT) corresponds to just under 10% of gross output of contained chromium in 1992 and a little less for 1991. The largest producer is Russia (62 kMT) followed by the USA (55 kMT), the UK (51 kMT) and Kazakhstan (42 kMT). Total capacity located in Western Europe was 82 kMT. Production has seemingly been very close to capacity in recent years, due to very strong demand [ibid]. The ratio of sodium dichromate (dihydrate) weight to its chromium content is 2.87:1. Thus U.S. production capacity of 55 kMT (Cr) translates into 158 kMT sodium dichromate ($Na_2Cr_2O_4.2H_2O$). Capacity in the rest of the world may have been underestimated, since new capacity has been added in the U.K., India, China, Brazil and other developing countries, in recent years.

Actual production of sodium dichromate (equivalent) in the US was 130.8 kMT in 1990 [Roskill 1993 p. 57]. This production rate is 83% of nominal capacity. Domestic U.S. consumption in 1991 appears to have been about 115 kMT (see below). The U.S. was a net exporter of 13 kMT of sodium dichromate in 1989, 15 kMT in 1990 and 12 kMT in 1991 [Papp annual for 1991]. There is no direct data on chromium chemical production or consumption in Europe *per se*. However, assuming the same capacity utilization rate as the U.S., this implies a European production level of 173 kMT (sodium dichromate) for 1991. Gross world production, at the same level of capacity utilization (83%), would have been 273 kMT (Cr-content).

Recovery of chromium by the chemical industry in the U.S. apparently averages about 81% [Papp 1994], implying losses at this stage of 19%, or 8.8 kMT (contained Cr) in the U.S. for 1992. On this basis, downstream chromium chemicals produced and consumed in 1992 (U.S.) can be assumed to have contained roughly 36.8 kMT(Cr), of which some was exported. Assuming the same recovery rate, losses from dichromate production in Europe were presumably about 13.6 kMT. The global loss in production would have been 0.19*273 = 52 kMT(Cr), on the same basis. Downstream chemicals presumably contained the remainder of the chromium, or 221 kMT(Cr). Production and use of these chemicals accounts for a high proportion of environmentally harmful and toxic chromium emissions.

Subsequent chemical conversions (U.S.) were as follows [Papp annual for 1991]: chromic acid (55%), chromic oxide (10%), leather tanning chemicals (8%), pigments (7%), wood preservatives (other than chromic acid) 2%, drilling mud additives, 2%, other uses 3% and export 13%. Chromic acid (more precisely, chromium trioxide, CrO_3), in turn, is used to manufacture wood preservatives (70%), for metal finishing (27%), and to make chromium dioxide (3%; used in magnetic recording tapes).(See *Figure 4.1*).

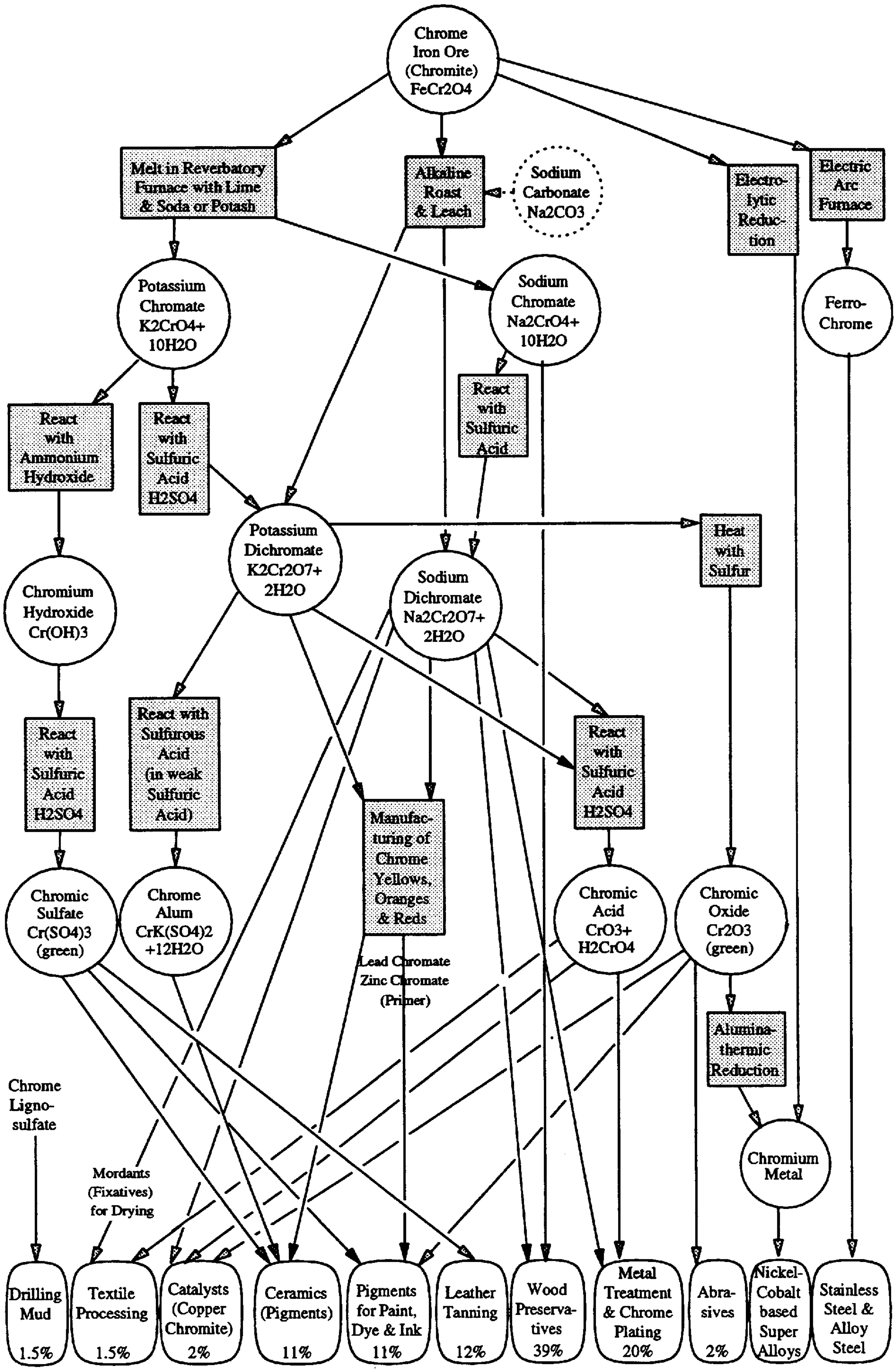

Figure 4.1. Chromium process-product flows (Europe 1992)

There is considerable confusion among various data sources with regard to chromium chemical production and use. This arises from the fact that there are only a few manufacturers, and that they typically sell both sodium dichromate and its derivatives. For instance, the biggest producer in the western world, Harcros Chemicals (U.K.) — which has subsidiaries in many countries — reports sales of sodium dichromate as 28% of output, along with derivatives such as chromic acid (31%), chromium oxide (24%) and chromium sulfate (14%). In terms of end-uses, 40% of its world-wide sales go to leather tanning, 20% to pigments, 17% to metal treatment, 14% to wood preservation and 6% to chromium metal [Roskill 1993, "Chromium"]. This allocation is quite different from that reported above by the US Bureau of Mines for the U.S., for instance. The Harcros allocation is also quite different from the Japanese allocation, discussed below.

One of the largest single uses of chromium chemicals, globally, is for waterborne wood preservatives, primarily copper-chromium-arsenate (CCA). The most common formulation in countries with stringent environmental regulations consists of 47.5% hexavalent chromium (measured as chromic oxide CrO_3 equivalent), plus 18.5% copper (as CuO) and 34% arsenic (as As_2O_3) [Roskill 1993, "Chromium" p. 474]. The actual chemical composition, however, is a mixture of 44.7% sodium dichromate ($Na_2Cr_2O_7.2H_2O$), 33.2% copper sulfate ($CuSO_4.5H_2O$) and 22.1% arsenic pentoxide ($As_2O_5.2H_2O$). Contained chromium in wood preservatives is about 17%. [Roskill 1993, "Chromium" p. 475]. Chromic acid is also used in wood preservatives, which depend largely on the toxicity of hexavalent chromium.

This use accounted for 43% of U.S. chromium chemical consumption in 1991, and the market has been growing at 10% per annum. In that year U.S. consumption of sodium dichromate for wood preservation was 47.230 kMT [Roskill 1993, "Chromium" p. 482]. Global consumption of CCA in 1991 was estimated to be 118 kMT (or 20 kMT contained Cr) assuming the U.S. accounted for 40% of the global CCA market and Europe 33% [ibid]. The European market of 39 kMT (sodium dichromate equivalent) was further broken down as follows: U.K. 28%, Scandinavia 26% and (west) Germany 23% [ibid p. 483]. Apparently there is also a large market for chromium-based wood preservatives in Australasia, where tropical conditions cause rapid deterioration of unprotected wood.

Japan, the world's largest importer of wood, used 96.5 kMT of CCA wood preservatives in 1980, although the dichromate content was not reported [ibid p. 481]. Apparently, however, usage of chromium chemicals for this purpose in Japan has declined sharply. By 1989 it was under 2 kMT, evidently due to substitution by other types of wood treatment. This illustrates the difficulty of extrapolating consumption patterns from one country to another.

The single biggest use of chromium chemicals in Japan (40%) was for metal treatment, especially chromium plating for the automobile industry (which starts with chromic acid). Plating accounted for 15.98 kMT dichromate equivalent in Japan in 1990 [Roskill 1993, "Chromium" p. 505], or 40% of total Japanese consumption of chromium chemicals (40 kMT, sodium dichromate equivalent). The same use accounted for 17.27 kMT in the U.S. in 1991[3], which was only 15% of total consumption [ibid] but 27% of non-CCA consumption. For Europe, these would translate to 21%-31% of total consumption (sodium dichromate equivalent).

A third major use of chromium chemicals has been in pigments, dyes and colorants (e.g. for ceramics and glass). Japanese consumption for this category of uses was 8.378 kMT (about 21% of total) in 1990, while U.S. consumption in this category was 9.16 kMT (8% of the total or 14% of the non-CCA total) in 1991. Lacking any specific data, it seems reasonable to estimate European consumption in this category to be intermediate between the two, as a percentage of non-CCA use, or somewhere between 11% and 16% of total consumption.

A fourth significant use of chromium chemicals, globally, is for leather tanning. As noted above, this use accounts for 40% of the output of Harcros Chemicals Co., the largest western producer. Japanese consumption for this purpose was about 7 kMT (18% of domestic demand) in 1990, while U.S. consumption was about 10.3 kMT (9% of domestic demand, and 15.7% of non-CCA demand) in 1991 — down from 13.4 kMT in 1988 and 30 kMT in the early 1980's. On a proportional basis, it seems reasonable to assume that tanning would account for 16%-17% of non-CCA chromium chemical consumption in Europe, or 12%-13% of total consumption (sodium dichromate equivalent) in 1991. However, leather tanning has been declining in the industrialized world, and moving to the so-called developing countries where environmental regulation is much less stringent. Global consumption for tanning was 180 kMT (sodium dichromate equivalent) in 1988, of which U.S. consumption was only 7%. India, alone, consumed 25 kMT in 1991, up from only 5 kMT just five years earlier.

Chrome tanning requires 22.2 kg of chromium sulfate per tonne of "bovine raw stock" (i.e. cattle hides). This yields 645 kg of "wet blue leather" and 149 kg of solid wastes (scrapings and trimmings) [Roskill 1993, "Chromium" p. 509]. Only 40% of the chromium is embodied in the product (leather); 25% remains with the solid waste, while 35% is left in 5000-10,000 liters of liquid tannery waste [ibid]. The latter also contains 206 kg of organic materials. On a global basis, this waste stream amounted to 108 kMT (sodium dichromate equivalent) in 1988. Tanning activity is increasing at the world level, though declining in the industrial countries. Cattle hides are now imported, and finished leather goods are re-exported in large quantities by Thailand, China, India, Brazil, South Korea and Turkey [Roskill 1993, "Chromium" p. 512].

Glass and ceramics constitute another significant use of chromium chemicals. Chromium compounds are used mainly as colorants. In Japan, this use accounted for 4.2 kMT in 1990, or 11% of domestic demand. In the U.S. the glass and ceramic category is lumped together with abrasives and chromium metal production from chemicals. The total of all these amounted to 13.08 kMT in 1991. (Of the latter, 3.3 kMT is estimated, below, to have been for abrasives, leaving 9.8 kMT or 15% of non-CCA demand for use in glass, ceramics and chromium metal). The glass and ceramics industry in Europe could have taken 9%-11.5% of all chromium chemicals.

Oil well drilling muds are another (highly variable) use of chromium chemicals, namely chromium lignosulfonates. They act as thinning and anti-corrosion agents. Consumption depends on the number of wells drilled, and on a variety of other factors. U.S. consumption in 1984 (when 72,138 wells were drilled) was 5 kMT; in 1992 only 23,813 wells were drilled in the U.S., and chromium chemicals for drilling muds probably dropped to 2.3 kMT (sodium dichromate equivalent). Most petroleum exploration around the world is carried out by U.S. or Western European firms, so it would not be unreasonable to assume that specialized chemicals like chromium-lignosulfonates would also be produced in the U.S. or Western

Europe. However, we have no further information on this point. Other miscellaneous small uses of chromium chemicals include catalysts (2.2% Japan; 1.9% U.S.); abrasives (2.3% Japan, 3% U.S.); mordants for textile dyeing (1.3% Japan & U.S.).

As noted, there are no direct data for chromium chemical consumption or trade in Western Europe, but capacity was previously estimated to be 82 kMT (Cr-content) or 235 kMT (sodium dichromate equivalent), with actual production of 173 kMT in 1991. On this basis, we estimate that wood preservatives (CCA) accounted for 22.6% (39 kMT), metal plating and finishing 21%-31%, leather tanning 12%-13%, pigments 11%-16%, glass and ceramics 9%-11.5%, with miscellaneous uses taking up the difference. Since the "misc" category should probably not exceed 10%, it would seem that the actual numbers are likely to be near the upper ends of their ranges. It must be emphasized that the ranges given are little better than guesses, with a considerable margin of error.

It is interesting to note that Western Europe, the U.S. and Japan among them appear to have consumed about 338 kMT (sodium dichromate equivalent) or 118 kMT (Cr-content). The rest of the OECD countries and Asian "Tigers" might conceivably account for a further 20-25 kMT (Cr). If Papp's lower estimate of 8% of chromite consumption is accurate, this leaves 130 kMT (Cr) that is presumably consumed — and mostly produced — elsewhere. Unquestionably, significant quantities of chromium are used for leather tanning outside the OECD (roughly, 80% of the total used for this purpose, or 52 kMT, chromium content).

This would still leave 78 kMT (Cr-content) for other uses in the rest of the world, which seems somewhat excessive. True, the CIS (former USSR) has the largest nominal production capacity for these chemicals (104 kMT, Cr-content), which admittedly does suggest a comparably large domestic demand. But the allocation of domestic uses and exports is very unclear. We would speculate that metal plating and finishing, pigments, wood preservatives and tanning may be the largest uses in the CIS. The large market for wood preservatives in Australasia has been mentioned. Oil well drilling may also be a significant use. China is also probably a significant user of chromium chemicals, today. Nevertheless, we suspect that chemicals account for slightly less than 8% of total chromite production.

4.5. Recovery of Chromium Chemicals

From a strategic point of view (perhaps not important at present) the problem has been seen as how to increase the recovery and recycling of stainless steel and other chromium-bearing alloys. Recycling of industrial scrap is already very efficient. However annual losses of chromium from scrappage of manufactured products is quite large. For instance, the use of stainless steel (Type 409) in automotive exhaust systems has been mentioned. However few, if any, scrap dealers are prepared to remove and recycle the stainless steel components of automobiles. (This situation may improve, however, as automobile companies pay more attention to the potential for remanufacturing and resource recovery in future years).

Chromium plating and other uses of chromium chemicals are essentially dissipative. Metal plating operations are notorious polluters, and have been among the earliest targets of environmental controls. There has been a substantial reduction in pollution from this source in the more advanced industrial countries (but not all). Decorative chrome plating for automobiles and other products has also been sharply reduced in recent years, as other materials have increasingly been used. However, "hard" chromium plating is still used for many purposes and the chromium that is used in this way is essentially unrecoverable by present methods.

Use of chromium pigments has fallen sharply in the U.S., but much less so in Europe (due to lack of effective environmental regulation in this field. Use of chromium for tanning has also fallen, though not nearly as rapidly as it might. Chrome-tanned leather is eventually worn to powder and washed into rivers and streams, or it becomes a household waste and is disposed of in landfills or incinerators where it would largely end up in the ash. On the other hand, chromium-based wood preservatives now dominate the market in both Europe and the U.S. (though not in Japan). This use has no immediate harmful consequences, but the chromium compounds bound to cellulose (in wood) are not permanently immobilized. Eventually the wood will still decay, at least if it is exposed to water and weather. The accumulation of chromium and other toxic metals in wood structures will eventually result in metals being incorporated in demolition waste, if not burned. Either way, there is a potential for re-mobilization. Alternatives to the use of toxic heavy metals for wood preservation would seem to be a particularly appropriate objective for research. In this context, we call attention to the possibilities of developing synthetic wood from recycled plastics. (See *Chapter 11, Packaging Wastes*).

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Endnotes(4)

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2. Chromium takes both trivalent and hexavalent forms. Chromic oxide Cr_2O_3 and trivalent chromic salts are not classified as toxic. According to the American Conference of Government Hygienists Chromates and dichromates (e.g. CrO_4,Cr_2O_7), on the other hand, are toxic and a confirmed human carcinogen. Also [Windom & Duce, 1977, Chapter 12].

3. Consumption for this purpose in the U.S. had dropped by 50% between 1976 and 1988, due to reduced use of decorative chromium plating and environmental concerns with regard to the electroplating industry. Consumption is still declining at about 1% per annum.