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Testimony
For
United States Senate Committee on Energy and Natural Resources
September 30, 2010
By
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While you will hear a lot of testimony today regarding the Rare Earth Elements (REEs), this testimony focuses on another strategic mineral absolutely essential to the successful deployment of clean energy technologies and other strategic applications like national defense and energy security; this strategic mineral is the essential element, cobalt. This testimony includes a discussion on current and projected uses of cobalt, cobalt supply and demand, and the need to re-energize U.S. strategic mineral policy. Recently, Formation Capital Corporation, U.S., responded to a Request for Information from the U.S. Department of Energy regarding REEs and other materials used in energy technologies. Given the similarity in subject matter, our response to that RFI is enclosed with this testimony for your review.

Current and Projected Uses

The fastest growing use of cobalt is in the production of rechargeable batteries. Virtually all mainstream battery chemistries require significant amounts of cobalt. Both hybrid electric vehicles (HEVs) and all electric vehicles (EVs) rely on electrical storage capacity to function. In addition to HEVs and EVs, electronics such as computers, cell phones, portable tools, and power supply backups also rely on NiMH or Li-Ion technology for their rechargeable batteries. The rechargeable battery demand in the U.S. is growing and has already overtaken other cobalt applications in terms of percentage of use.

Cobalt is also the essential element needed in almost every form of clean energy production technology being developed today. Gas to liquid (GTL), coal to liquid (CTL), clean coal, oil desulfurization, photovoltaic cells (or solar panels), wind turbines, gas turbines, and fuel cell technologies all require cobalt. As a catalyst, cobalt is essential for cleaning traditional carbon-based energy sources as well as reducing dependence on foreign sources of carbon-based energy sources through leveraging domestic sources available in coal, gas-shales, and oil-shales. Cobalt catalysts are responsible for cleaning our current automobile fuel, through removal of sulfur, thereby keeping our air cleaner.

Super-alloy is a general term for alloy metals that are used in elevated temperature and/or elevated pressure environments and are used extensively in the aerospace sector. The U.S. national defense, as well as our robust civil air transportation backbone, relies on cobalt to provide reliable, safe, and efficient jet propulsion. Needed to construct evermore light and powerful jet engines operating at higher and higher temperatures, cobalt is the essential element used in turbine blades to retain their structural integrity while being subjected to torturous corrosion, temperatures and pressures. Typically, a high by-pass, turbofan jet engine of the 40,000 lb. thrust class requires 110 to 132 pounds of cobalt in each finished engine. Major users of high-purity cobalt include General Electric, Boeing, Pratt & Whitney, Rolls Royce, and other aerospace companies. Today, super-alloys account for almost half the U.S. annual consumption of cobalt.

Cobalt is not a competitor or replacement for other strategic minerals like REEs. On the contrary, it is the symbiotic relationship that cobalt and other minerals share that makes so many technologies effective. A great example of this relationship is that of cobalt and certain REEs in the production of permanent magnets. Permanent magnets are needed to make wind turbines and other land based clean energy production technologies. Cobalt's extremely high Curie temperature allows these permanent magnets to maintain their magnetic properties at high temperatures. While some permanent magnets contain cobalt as a primary constituent, other magnets often named for their REE primary constituents also rely on cobalt in their production. While some permanent magnets are finished in the U.S. for end-use, they are largely manufactured overseas in Asian markets.

Research being conducted at MIT shows an exciting projected use of cobalt in synthesizing photosynthesis to produce carbon-free energy by separating hydrogen and oxygen for use in fuel cells. This process, which uses dissolved cobalt and phosphate to split the water molecule, can be coupled with solar and wind power generation technologies to provide power storage during periods of darkness or no wind thereby making clean, carbon-free energy available 24 hours a day.

Supply & Demand

With no current domestic primary production (i.e., mining and refining) of cobalt in the U.S. and stockpiled supplies available in the strategic reserve dwindling, the U.S. is completely dependent on foreign supplies; although, a very small fraction of production does occur as a by-product of other metal production and recycling. As of December, 2009, the strategic reserve contained only 293 tonnes of cobalt. With the U.S annual demand for cobalt accounting for nearly 20% of the world's annual supply of approximately 60,000 tonnes, the remaining strategic reserve is insignificant.

Most cobalt production comes as a by-product of other metal production such as nickel and copper. Many of the largest producers of cobalt as a by-product are located in countries that are either unstable or unfriendly to the U.S. Two of the largest cobalt by-product producers are the Democratic Republic of Congo and Zambia. With on-going political and civil strife in the regions, the mines are sometimes forced to shut down and, once shuttered, these operations can take years to re-open. China has rapidly become the world's largest producer of refined cobalt and is growing into the world's largest consumer. China has the potential to become the virtual OPEC of cobalt refining, potentially controlling major producers both domestically in China as well as Africa. China's latest move to potentially limit REE exports to Japan is further evidence of this monopoly.

According to the Cobalt Development Institute (CDI), the demand for portable electronic device rechargeable batteries has doubled over the past several years. Increasing numbers of HEVs and EVs drives the demand for rechargeable batteries ever higher. The deployment of more and more clean energy production technologies further swell demand. In fact, the growing demand for cobalt in battery and catalyst use has surpassed super-alloys as the primary demand for cobalt. Furthermore, the demand in the battery and catalyst sectors has shifted from the U.S. and Europe to Asia and is evidenced by the battery and catalyst production in Asian countries. This shift, however, may reverse as large-scale battery production operations in the U.S. take hold, such as those starting up in Michigan and Tennessee.

The rapid growth of the Chinese industrial and consumer base, along with increasing competition for cobalt in the emerging clean energy sector, further strains the U.S. already tenuous position of foreign dependency. Moreover, it is estimated that approximately 80% of the high-purity cobalt market, that is the purity of cobalt needed in super-alloys and many high-tech applications, is controlled by a single foreign company. With U.S. demand for high-purity cobalt at 60% of the world's supply and no currently operating domestic sources or refineries, we are completely dependent on other countries for our supply of high-purity cobalt.

There is, however, at least one primary source of high-purity cobalt in the U.S. being developed in Idaho. The Idaho Cobalt Project includes development of an underground mine and refinery. Cobalt was formerly mined in this area from the early 1900's until the 1970's. When in production, the Idaho Cobalt Project mine and refinery will be the only U.S. domestic, primary source of high purity cobalt.

Policy

The importance of re-energizing effective policies regarding the exploration, development, and production of strategic minerals in support of clean energy technology development is underscored by the U.S.' precarious position of dependency. The Western Governors Association (WGA) recently adopted policy resolution 10-16, titled "National Minerals Policy." This policy resolution states, "WGA urges the federal government to fund an effort by the U.S. Geological Survey and state geological surveys to identify potential, domestic REE deposits and other critical minerals for alternative energy technologies." As you now know, the U.S. demand for strategic minerals and REEs for clean energy technologies, as well as other uses, vastly outpaces the limited or non-existent production in the United States today.

The challenge of permitting a new mine in the U.S. must be weighed by companies exploring or trying to develop strategic mineral deposits domestically. Additionally, uncertainties regarding policies towards mining can further hamper efforts to develop domestic sources. A vital component of effective energy policy must include the development of the essential minerals required to effect U.S. energy security.

Cobalt is essential for the future of the U.S.' national defense and energy security. While demand for cobalt increases globally, the supply continues to be controlled by an exclusive group of countries or foreign companies that may not be friendly to the U.S. or are politically unstable. The U.S.' cobalt dependency can only be remedied through effective application of policy that makes the domestic production of cobalt, via environmentally sustainable mining and refining, a priority.

Respectfully Submitted,

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Enclosure

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Response to the Request for Information
Materials Strategy
U.S. Department of Energy
Washington, DC

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On behalf of Formation Capital Corporation (Formation), let me extend our sincere appreciation to the Department of Energy for not only allowing us to respond to your Request for Information (RFI), but more importantly, for recognizing the fact that the United States needs to swiftly update its policies and actions with regards to strategic materials, including cobalt. This is important with regards to our nation's energy security, our national security, and the areas where those two vital interests overlap.

Earlier this year, we began the initial construction phase of the Idaho Cobalt Project (ICP), which, when we commence production in 2011, will be the United States' only primary cobalt mine. Located in east central Idaho, the ICP has estimates of 1,525 tons annually of super-alloy grade high-purity cobalt metal over a minimum ten-year mine life. The project's output will be equivalent to 3.3% of the entire global cobalt supply and it will be able to feed 14.9% of North American demand for cobalt.

Making the ICP more uncommon and strategically important is the fact the mine will produce high-purity cobalt. As your RFI so appropriately noted, cobalt is among the materials that "are important to the development and deployment of a variety of clean energy technologies, such as wind turbines, hybrid vehicles, solar panels and energy efficient light bulbs."

Thus, the Idaho Cobalt Project will be the sole in-country producer of high-purity cobalt which is essential to our country's national and energy security, and is necessary for the advancement of clean energy technologies that the Administration and our nation are working diligently to increase. Importantly, the ICP will be an environmentally sound mine (it was endorsed by the state's leading environmental organization, the Idaho Conservation League) and will provide a rural area of the nation with more than 150 family wage jobs with excellent benefits, plus another 35-40 jobs at the facility where the cobalt will be refined, also in Idaho.

Below you will find the information we submit for the record, and would like considered as you use the information in future reports and policy decisions.

Cobalt: Material of interest

Category 1: Demand

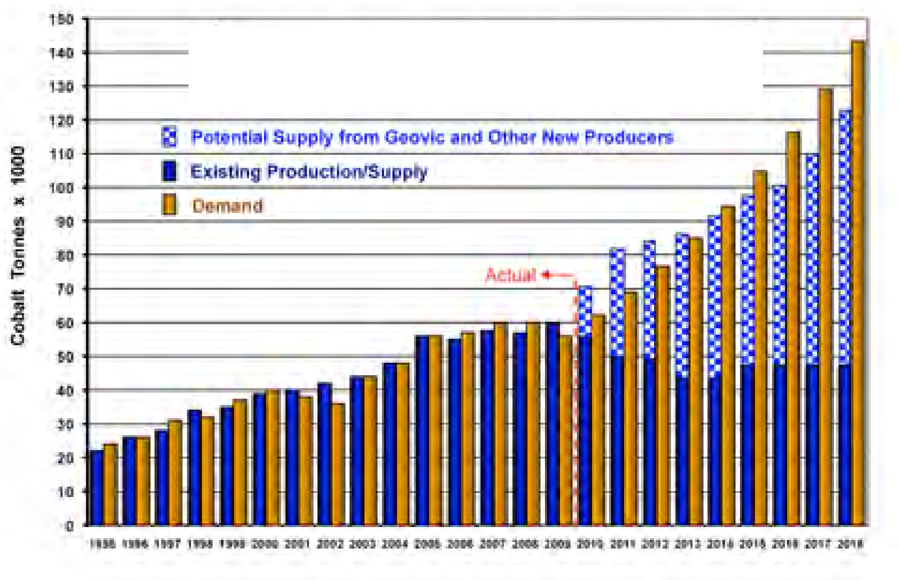
• For which materials of interest used in energy applications will future US and global demand increase most significantly in the short (<5 years) and longer term?

Cobalt is a material that is critical to a broad array of energy applications. The refining process for cobalt produces different purity levels. In general all levels of purity are required for different energy applications. Detailed data on the demand for cobalt can be found in “World Cobalt Statistics,” which was cooperatively produced by the Cobalt Development Institute (CDI) and the World Bureau of Metal Statistics (WBMS). These data are derived from worldwide import/export figures. Global consumption appears to be around 56,000 tonnes for 2009, which is a decrease of 8% from the previous year. The Americas, Europe and Asia (non-China) saw significant declines but China once again recorded a huge increase. The decrease is attributed to the impact of the global economic crisis. From 1995 to 2008, cobalt consumption increased from 24,000 tonnes to 60,800 tonnes, for a compound annual growth rate (CAGR) of 7.4% for the 13-year period.

While the last two years have shown declines due to the world economic troubles, the overall future demand is projected to increase significantly due in large part to the increased use alternative energy technologies. Additionally there is predicted to be a rebound effect from the recession that will push demand even higher.

• What is the forecast demand of each of these materials? Please explain the basis for this forecast, its assumptions, and how it is calculated.

In the chart below, Geovick Mining Company show actual world supply and demand data from external sources (USGS, the CDI, and others) through 2009 with the projections from 2010 through 2018 based on an 11% CAGR (principally due to the "catch-up effect" following the aforementioned significant demand decline in 2009). The combination of production from existing mines and new production is expected to yield an 8% CAGR between 2010 and 2018, which would result in potentially large supply deficits in 2014-18 period.



Source: Actual supply and demand by USGS, The CDI and other independent research groups. Projections after 2008 were developed by Geovic Mining.

Roskill Consulting, an international group that researches mineral industry information, estimates 2011 demand will most likely rise to 72,500 tonnes, 5% above the forecast from Geovic Mining. The forecast accounts for the potentially dramatic growth in batteries for hybrid vehicles and new demand from emerging markets such as China and India.

From the Somika Societe Miniere du Katanga Global cobalt consumption by country and the increase for the four-year period ending 2006 is shown below.

Tonnes Cobalt

Country	2002 (Tonnes)	2006 (Tonnes)	% Change
Europe	11,100	13,730	24

Japan	7,250	12,300	70
China	4,300	11,000	156
USA	9,250	11,450	24
Other	5,200	7,520	45
Total	**37,100**	**56,000**	**51**

From the Somika Societe Miniere du Katanga website: http://www.somika.com/cobalt-properties-ores-minerals-lubumbashi.php

• What portion of the overall demand is for energy applications and how will this change over time?

In 2009, the percentage of cobalt use for rechargeable batteries rose to 25% of total cobalt demand, its highest-ever level, and that percentage is forecast to rise to approximately 45% by 2018.

This shift is most markedly for rechargeable batteries for portable devices and the new generation of Hybrid Electric Vehicles and all Electric Vehicles. There is also a demand for Cobalt for superalloys in both gas turbines and wind turbines. There is additional demand for cobalt as a catalyst in solar panels, oil desulfurization, gas-to-liquids, and coal-to-liquids technologies.

Cobalt in rechargeable batteries is the fastest growing use, while chemical (versus metallurgical) uses continue to surge as a percentage of the total. Nickel metal hydride and lithium-ion batteries both contain cobalt and are used in hybrid electric vehicles (HEVs), computers, cell phones, portable tools, audio/visual units, and numerous electronic devices.

The USGS Mineral Commodity Summaries for cobalt, 2010, states that more than 60 industrial consumers were surveyed on a monthly or annual basis. Data reported by these consumers indicate that 49% of the cobalt consumed in the United States was used in superalloys, mainly in aircraft gas turbine engines; 9% in cemented carbides for cutting and wear-resistant applications; 15% in various other metallic applications; and 27% in a variety of chemical applications. The total estimated value of cobalt consumed in 2009 was $270 million.

These data demonstrate that cobalt for use in the energy market is increasing substantially and is in competition with the cobalt uses in other markets.

Category 2: Supply

• What are the most significant supply risks for the identified materials of interest? Please also describe any risks due to supply chain fragmentation.

The major supply risks to the US include the following:

- With the exception of a minute fraction of cobalt that comes from domestic recycling, the vast majority of the cobalt the US consumes is imported. Thus, the US verges on being totally reliant on other countries for our cobalt. Additionally, even some of the materials that are recycled are imported as well.
- The US strategic reserve of cobalt is less than 293 tonnes as of December 31st 2009.
- Economic recession and deflation of the dollar impacts the ability for companies to obtain financing for all start-up projects in all industries; including mining and refining.
- Rapid growth of Chinese economy creating a large consumer.
- Cobalt for use in the energy sector is in competition with other areas where cobalt is still in high demand.
- Trade restrictions.
- There are very few primary producers of cobalt. Cobalt is usually obtained as a byproduct of nickel and copper mining. Thus, cobalt production is heavily reliant on strong nickel and copper markets.
- Some of the largest producers of cobalt as a byproduct are in unstable political environments, such as the Democratic Republic of Congo (DRC). When countries have political strife – such as is occurring at this time (2010) in the DRC – mining often shuts down and very little cobalt is produced from existing mines. Additionally, once shuttered, mines are difficult to re-open and doing so can take years.
- An estimated 80% of the high-purity cobalt market is currently controlled by the Glencore International AG/Xstrata axis, a privately held entity headquartered in Switzerland.
    - Xstrata was formerly known as "Falconbridge, Ltd." In 2006, the European Union Commission reviewed the proposed, but ultimately withdrawn, Inco/Falconbridge

merger. The European Union Commission stated at the time that “. . . Inco, Falconbridge [i.e., now Xstrata] and Eramet/Glencore are the only three suppliers of high purity cobalt for the most critical applications” and estimated that at the time Falconbridge [now Xstrata] was to hold “70% – 80% and Eramet/Glencore to hold 5% of “worldwide high purity cobalt production capacity.” Today, the Falconbridge and Eramet/Glencore interests are now collectively held by Xstrata, Plc, and Glencore, respectively, while in turn Glencore controls Xstrata.

- The permitting environment in US is extremely onerous, deterring most mining companies from attempting to permit a new mine. Permitting in United States can take well in excess of 10 years and tens of millions of dollars with no guarantees that the project sponsor will be able to go into production at the end of that time. Lawsuits and injunctions can push this time line out and the cost up even further. Additionally it is extremely difficult to predict pricing or demand for their product for these extended periods of time.

The USGS Mineral Commodity Summaries for cobalt, 2010, states that the United States did not mine or refine cobalt in 2009; however, negligible amounts of byproduct cobalt were produced as intermediate products from some mining operations. U.S. supply comprised imports, stock releases, and secondary materials, such as cemented carbide scrap, spent catalysts, and superalloy scrap. The sole U.S. producer of extra-fine cobalt powder, in Pennsylvania, used cemented carbide scrap as feed. Seven companies were known to produce cobalt compounds. In 2009, a cobalt plant in North Carolina ceased operations, and one plant in Ohio was placed on care-and-maintenance status.

According to the Somika Societe Miniere du Katanga, today cobalt’s market is very dynamic but rather small in comparison with other base metals. Approximately 48% of the world’s 2007 cobalt mined was byproduct of nickel from sulfide and laterite deposits. An additional 37% was produced as a byproduct of copper operations, mainly in the Democratic Republic of the Congo (DRC) and Zambia. The remaining 15% of cobalt mining came from primary producers.

The following table was obtained from the CDI. It shows the sources (mining and refining) for cobalt around the world. Of predominant importance is the fact that at this time (2010) none of those sources are in the US.

Country	Mined	Refined	Approx. Refined Qty
Australia	×	×	4,050
Botswana	×		
Brazil	×	×	1,000
Belgium		×	2,150*
Canada	×	×	4,900
China	×	×	23,000
Cuba	×		
France		×	350
Finland		×	8,900
India		×	1,000
Japan		×	1,300
Morocco	×	×	1,600
New Caledonia	×		
Norway		×	3,500
Russia	×	×	2,400
South Africa	×	×	250
Uganda	×	×	650
D.R.C.	×	×	3,000
Zambia	×	×	1,500
TOTAL			**59,550 (Tonnes)**

* Including cobalt produced by facilities in China

The second set of tables from the CDI shows the refining production for 2003-2009. Of importance is also the fact that over these years shown, none of the refined cobalt was refined in the US. This demonstrates how the US is virtually totally reliant on outside sources of cobalt for all purity levels.

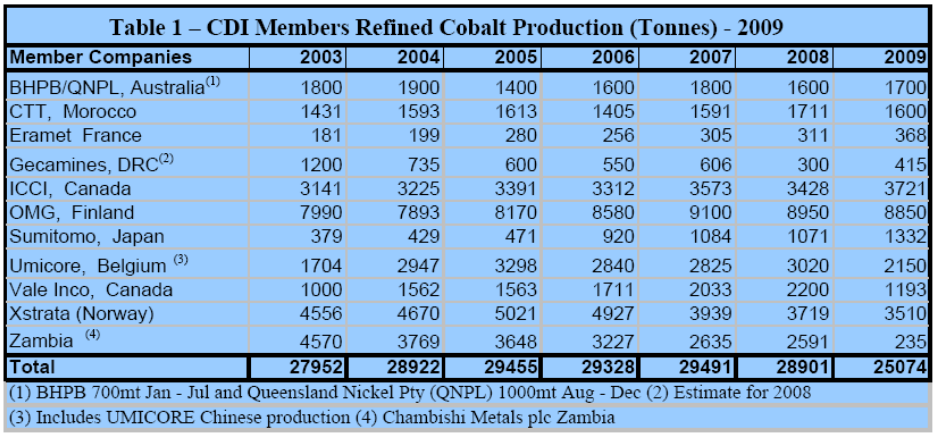


Table 1 – CDI Members Refined Cobalt Production (Tonnes) - 2009

Member Companies	2003	2004	2005	2006	2007	2008	2009
BHPB/QNPL, Australia(1)	1800	1900	1400	1600	1800	1600	1700
CTT, Morocco	1431	1593	1613	1405	1591	1711	1600
Eramet France	181	199	280	256	305	311	368
Gecamines, DRC(2)	1200	735	600	550	606	300	415
ICCI, Canada	3141	3225	3391	3312	3573	3428	3721
OMG, Finland	7990	7893	8170	8580	9100	8950	8850
Sumitomo, Japan	379	429	471	920	1084	1071	1332
Umicore, Belgium (3)	1704	2947	3298	2840	2825	3020	2150
Vale Inco, Canada	1000	1562	1563	1711	2033	2200	1193
Xstrata (Norway)	4556	4670	5021	4927	3939	3719	3510
Zambia (4)	4570	3769	3648	3227	2635	2591	235
Total	**27952**	**28922**	**29455**	**29328**	**29491**	**28901**	**25074**

(1) BHPB 700mt Jan - Jul and Queensland Nickel Pty (QNPL) 1000mt Aug - Dec (2) Estimate for 2008
(3) Includes UMICORE Chinese production (4) Chambishi Metals plc Zambia

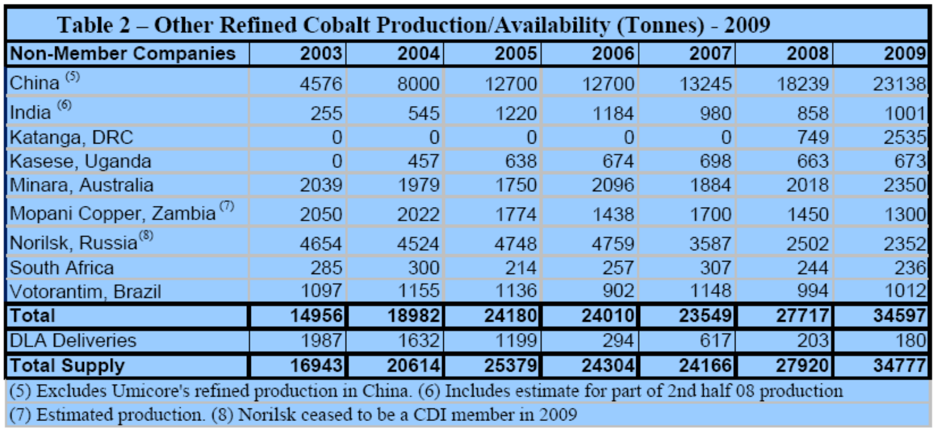


Table 2 – Other Refined Cobalt Production/Availability (Tonnes) - 2009

Non-Member Companies	2003	2004	2005	2006	2007	2008	2009
China (5)	4576	8000	12700	12700	13245	18239	23138
India (6)	255	545	1220	1184	980	858	1001
Katanga, DRC	0	0	0	0	0	749	2535
Kasese, Uganda	0	457	638	674	698	663	673
Minara, Australia	2039	1979	1750	2096	1884	2018	2350
Mopani Copper, Zambia (7)	2050	2022	1774	1438	1700	1450	1300
Norilsk, Russia(8)	4654	4524	4748	4759	3587	2502	2352
South Africa	285	300	214	257	307	244	236
Votorantim, Brazil	1097	1155	1136	902	1148	994	1012
Total	**14956**	**18982**	**24180**	**24010**	**23549**	**27717**	**34597**
DLA Deliveries	1987	1632	1199	294	617	203	180
Total Supply	**16943**	**20614**	**25379**	**24304**	**24166**	**27920**	**34777**

(5) Excludes Umicore's refined production in China. (6) Includes estimate for part of 2nd half 08 production
(7) Estimated production. (8) Norilsk ceased to be a CDI member in 2009

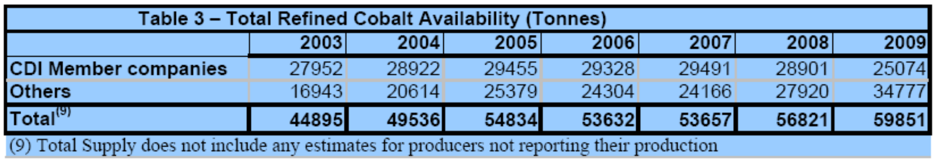


Table 3 – Total Refined Cobalt Availability (Tonnes)

	2003	2004	2005	2006	2007	2008	2009
CDI Member companies	27952	28922	29455	29328	29491	28901	25074
Others	16943	20614	25379	24304	24166	27920	34777
Total(9)	**44895**	**49536**	**54834**	**53632**	**53657**	**56821**	**59851**

(9) Total Supply does not include any estimates for producers not reporting their production

The global economic downturn that began in late 2008 resulted in reduced demand for and supply of cobalt. During the first half of 2009, the world availability of refined cobalt (as measured by production and U.S. Government shipments) was 13% lower than that of the first half of 2008. The decrease was primarily because of a decline in 2009 production from China and the closure of a Zambian refinery in late 2008. During the second half of 2009, a labor strike at a company in Canada resulted in reduced production of refined cobalt from that country. Beginning in late 2008, production of cobalt-bearing concentrates and intermediates was impacted by cutbacks at numerous nickel operations and at some copper-cobalt operations in Congo (Kinshasa). Financing, construction, and startup of some proposed brownfield and greenfield projects that would add to future world cobalt supply were delayed by various factors, including global economic conditions and low cobalt, copper, and nickel prices.

• What are the current investment trends in global sources (including locations) of the materials of interest? Include investment plans and trends at each point in the supply chain (i.e., exploration, mining, separation, refining, alloying, and manufacturing).

From the Somika Societe Miniere du Katanga website (www.somika.com/cobalt-properties-ores-minerals-lubumbashi.php): Since 1920, D. R. of Congo has been the dominant producer of Cobalt in the World. The Copper belt in the Democratic Republic of the Congo and Zambia yields most of the worldwide-mined Cobalt. Other major producers are Russia, Zambia, Australia, Canada, Finland, Cuba, and Germany.

Domestically in the U.S. there is the Idaho Cobalt Project (ICP). It is located in east central Idaho and is a unique primary cobalt deposit with production estimates of 1,525 tons annually of super-alloy grade high purity cobalt metal over a minimum ten year mine life. The project's output will be equivalent to 3.3% of the entire global cobalt supply and it will be able to feed 14.9% of North American demand for cobalt. The ICP is 100% owned by Formation Capital Corporation U.S. (a subsidiary of Formation Metals Inc.).

The Idaho Cobalt Project includes development of an underground mine and a refinery. The permitting process is complete for an underground mine in the historic Blackbird Mining district near Salmon, Idaho. Cobalt was produced from this area during World Wars I and II and the Korean War. In addition Essential Metals Corporation, another subsidiary of Formation Metals Inc., owns the refinery in Kellogg, Idaho when the concentrate from the mine will be refined. Making this the only mine and refinery in the United Sates producing high purity cobalt. Once financing is secured construction will begin on the support facilities and the underground mine, estimated in the 3^{rd} quarter of 2010.

Other potential sources include the Madison Mine in Fredericktown, Missouri which is primarily a lead and copper mine. Grades obtained from exploration work in the 1980's showed a resources of 6Mtgrading 0.306% cobalt, 0.470% nickel, and 0.743% copper using a cobalt equivalent cutoff grade of 0.20% (U.S. Cobalt Inc., 2002a-c). This mine is currently designated a CERCLA site and no mining has occurred in many years. Exploration was completed in the 1980's but due to environmental reasons the resources have not been pursued. It would take several years to attempt to get it producing again. It may never pass environmental hurdles to get it open.

In 2002 minor amounts of cobalt present in the ores mined for platinum-group metals at the Stillwater Complex of southern Montana were recovered from converter matte at Stillwater Mining Co.'s refinery and sold as a byproduct. In November of 2002, Russia's Open Joint Stock Company Mining and Metallurgical Company Norilsk Nickel entered into definitive agreements to acquire 51% of Stillwater Mining Co. (OJSC MMC Norilsk Nickel, 2003a, p. 11; Stillwater Mining Co., 2003, p. 14-15).

• What current or anticipated research and development (R&D) related to mining and extractive processing will benefit supply by contributing to more efficient and environmentally sound extraction of the materials of interest?

The current work performed in developing the refining process at Essential Metals is a major step forward on the efficiency and environmentally sound extraction and purifying cobalt. The facility was designed to have zero liquid discharge. The process utilizes hydrometallurgical processes so there are no air emissions of $S0_2$ as is the case with smelters and related processes. The facility makes a number of bi-products that are sold improving the project efficiency by better utilizing the resource. The products, in addition to cobalt, include gold, copper, nickel, magnesium sulfate, and Zinc. The process is also capable of processing some forms of scrap so that it can be re-used as a source.

Category 3: Technology Applications and Processes

For this category, we recommend you refer to and incorporate Attachment 1: USGS report material Use in the United States_2008-5141)

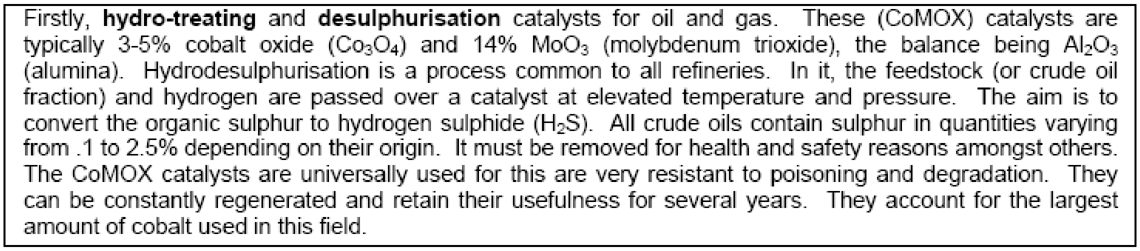
• What are the specific energy technology applications of the materials of interest? Please consider component technologies (such as permanent magnets or batteries), finished products (such as vehicles, wind turbines or PV cells) and other energy related processes (such as oil refining).

- Gas-to- liquids technology
- Coal-to-liquids technology
- Oil desulfurization
- Solar panels
- Wind turbines
- Lithium Ion batteries
- Fuel Cell technologies

Cobalt in rechargeable batteries is the fastest growing use. In CY 2007 the percentage of Cobalt use in rechargeable batteries rose to 25% of the total cobalt demand from 22% in 2006. From Somika Societe Miniere du Katanga's website ***Cobalt: History, Properties, Minerals, Extraction, Applications** (http://www.somika.com/cobalt-properties-ores-minerals-lubumbashi.php).*

• What is the material requirement of these energy technology applications? What is the level of purity required? Please express material requirements in terms of weight percentage per magnet of a given size, content per unit of generation or storage capacity, content per vehicle, weight requirement per industrial process output, or other appropriate metric. Please also provide information on processing losses.

- Gas to liquid technology ~ 160 emu/g cobalt (Seoul University). Data from: ***Crystallographic and Magnetic Properties of Cobalt Particles Dispersed on Spherocarb Support, Kwan Kim, May 14, 1987***
- Coal to liquid technology-20-30 wt% cobalt (Energy Intl Corp) Table 4 Co.005 20%, Co.011 20%, Co.018 20%. Data from: ***Technology Development for Cobalt Fischer-Tropsch Catalyst, Alan H. Singleton, Energy International Corporation***
- Oil desulfurization. Data below from: ***Cobalt Facts, Cobalt in Chemicals, Section 6.4 Cobalt in Catalysts, CDI, 2006.*** *http://www.thecdi.com/cdi/images/documents/facts/COBALT_FACTS-Chemicals.pdf*



Firstly, **hydro-treating** and **desulphurisation** catalysts for oil and gas. These (CoMOX) catalysts are typically 3-5% cobalt oxide (Co_3O_4) and 14% MoO_3 (molybdenum trioxide), the balance being Al_2O_3 (alumina). Hydrodesulphurisation is a process common to all refineries. In it, the feedstock (or crude oil fraction) and hydrogen are passed over a catalyst at elevated temperature and pressure. The aim is to convert the organic sulphur to hydrogen sulphide (H_2S). All crude oils contain sulphur in quantities varying from .1 to 2.5% depending on their origin. It must be removed for health and safety reasons amongst others. The CoMOX catalysts are universally used for this are very resistant to poisoning and degradation. They can be constantly regenerated and retain their usefulness for several years. They account for the largest amount of cobalt used in this field.

- Solar panels
- Wind turbines
- Lithium Ion batteries (See Attachment 1)
- Fuel Cell technologies-cobalt nanoparticles (MIT), 0.5-40.0 wt% metallic cobalt (CDI). Data from: ***Patents-Fuel Cells, CDI, WO 2006/090207 A2 (08/31/2006) More Energy Ltd., Meiklyar, V., Finkelshtain, G., Katsman, Y., Anode for Liquid Fuel Cell Team Takes first atomic-scale compositional images of fuel-cell nanoparticles, Elizabeth Thomson, 10/2/08 MIT News***

Super alloys using cobalt account for almost half of the United States' annual consumption, with much of the super alloys containing Cobalt used in the production of jet engines and gas turbine engines for energy generation. Typically a high by-pass, turbofan jet engine (40,000 lb. thrust class) requires 110 to 132 pounds of cobalt in the finished engine.

• Describe any areas of innovation, research and development, or alternative techniques or processes that are likely to reduce the material requirements per unit (i.e. per weight, volume, power rating, etc.).

One of the most recent areas of innovation and research is related to the potential for unlimited solar and/or wind energy. This research, by MIT Professor Daniel G. Nocera and postdoctoral fellow Matthew Kanan, is based upon the use of dissolved cobalt and phosphate as a water-splitting part of photosynthesis to separate hydrogen and oxygen to power a fuel cell whenever energy is needed. This process would generate clean, carbon-free energy, 24/7, on a massive scale. This process would change solar power into an unlimited, mainstream energy source. This information was obtained from: ***Solar Energy, All Night Long. Jonathan Fahey. 7/31/08.*** *www.forbes.com/2008/07/30/nocera-solar-power-biz-energy-cz_jf_0731solar.html*

• Based on knowledge of the technologies and potential innovations, what is a feasible range for material requirements per unit (i.e. per weight, volume, power rating, etc.) in 5 years? In 20 years? How do these future material requirements compare to present requirements?

The demand for cobalt in portable electrochemical devices (batteries) has more than doubled in the last few years (***Cobalt Facts, 2006 CDI***). Of the three battery technologies, Nickel-Cadmium, Nickel-Metal Hydride and Lithium-Ion, the Li-ion battery is the most advanced. This system also utilizes the greatest amount of cobalt per cell. ***(Cobalt News 10/2, CDI).***

• What is the anticipated US and global market scale up of these energy technology applications in the short (< 5 years) and longer term?

See Attachment 1, ***USGS Scientific Investigations Report 2008-5141. Material Use in the United States-Selected Case Studies for Cadmium, Cobalt, Lithium, and Nickel in Rechargeable Batteries for studies on the consumption of cobalt***. We request the DOE include this report in its entirety or by reference.

Category 4: Costs and Availability

• What are the price projections of materials of interest and what factors drive the projections?

Cobalt is primarily traded on the London Metals Exchange (LME). Considerable information about cobalt trading can be found on the LME website at: http://www.lme.com/minormetals/cobalt.asp:

In addition, the U.S. Geological Survey in 2008 produced an Open-File Report 2008-1356 titled ***"Factors that influence the price of Al, Cd, Co, Cu, Fe, Ni, Pb, Rare Earth Elements, and Zn"*** that we recommend the DOE include in its entirety or by reference (Attachment 2). In Attachment 3 the US Geological Survey compiled statistics for cobalt pricing from 1900 through November 2009 that we request the DOE include in its entirety or by reference.

The projections of cobalt prices are driven by multiple factors, including supply, demand, substantial market concentration, and the growth of economies in other countries, particularly China. Historically, cobalt prices have been more volatile than most other metals.

• To what extent does the cost of the materials of interest influence the cost of energy technology applications (components, finished products or energy related processes)? What percent of the total cost of energy technology applications are attributed to the cost of the identified materials of interest?

This is not our field of expertise and therefore we're not qualified to adequately answer this question. However, if DOE needs information, please contact us and we will work to locate the appropriate sources for the information.

• To what extent are uncertainties in materials future prices and/or availability driving technology investment decisions?

This is not our field of expertise and therefore we're not qualified to adequately answer this question. However, if DOE needs information, please contact us and we will work to locate the appropriate sources for the information.

• How are the materials of interest typically procured? Is there substantial use of long-term contracting? If so, how are such contracts typically characterized?

This is not our field of expertise and therefore we're not qualified to adequately answer this question. However, if DOE needs information, please contact us and we will work to locate the appropriate sources for the information.

Category 5: Substitutes

• What research is required to find substitutes that will have the desired functionality for specific energy technology applications? Please consider both substitutes for the materials themselves and also substitutes for energy technology applications.

The cobalt price dictates the rate at which new substitutes for cobalt are explored. In many cases alternatives do not provide a suitable substitute for cobalt because alternatives typically produce an inferior product. The following paragraphs were taken from the sources and links noted.

From: **The Encyclopedia of the Earth** (link provided below)

"At times, cobalt prices rise significantly and there is concern about the amount of cobalt easily available around the world. As a result, industries have tried to conserve cobalt consumption. There are some replacements for cobalt but they do not work as well as cobalt. For example, nickel-iron or neodymium-iron-boron alloys can be used to make strong magnets. Nickel and special ceramics can be used to make cutting and wear-resistant materials. Nickel base alloys containing little or no cobalt can be used in jet engines. Manganese, iron, cerium, or zirconium can be used in paint driers."

http://www.eoearth.org/article/Cobalt#Substitutes_and_Alternative_Sources

From: **Minerals and Commodities Survey 2010 (U.S. Dept of Interior) (USGS)**

"**Substitutes:** In some applications, substitution of cobalt would result in a loss in product performance. Potential substitutes include barium or strontium ferrites, neodymium-iron-boron, or nickel-iron alloys in magnets; cerium, iron, lead, manganese, or vanadium in paints; cobalt-iron-copper or iron-copper in diamond tools; iron-cobalt-nickel, nickel, cermets, or ceramics in cutting and wear-resistant materials; iron-phosphorous, manganese, nickel-cobalt-aluminum, or nickel-cobalt-manganese in lithium-ion batteries; nickel-based alloys or ceramics in jet engines; nickel in petroleum catalysts; and rhodium in hydroformylation catalysts."

The substitution for $LiCoO_2$ by manganese and nickel based systems is expected to increase only if triggered by higher cobalt prices. However $LiCoO_2$ systems will likely require smaller energy packs for the same energy requirements, thus reducing overall cost competition. **(Cobalt News 10/2, CDI)**

- **What are the current and potential R&D efforts with respect to substitutes for these materials?**

This is not our field of expertise and therefore we're not qualified to adequately answer this question. However, if DOE needs information, please contact us and we will work to locate the appropriate sources for the information.

Category 6: Recycling

- **What are the best recycling opportunities for the materials of interest? Consider technical, logistical and economic feasibility.**

This is not our field of expertise and therefore we're not qualified to adequately answer this question. However, if DOE needs information, please contact us and we will work to locate the appropriate sources for the information.

- **What are the current and projected levels of recycling?**

In 2009, cobalt contained in purchased scrap represented an estimated 24% of cobalt reported consumption.

Historic information is contained in open file report: ***Cobalt Recycling in the United States by Kim Shedd USGS open file report 02-299***. We recommend the DOE include in its entirety or by reference (Attachment 4).

- **What areas of research and development will improve the efficiency and effectiveness of recycling processes?**

This is not our field of expertise and therefore we're not qualified to adequately answer this question. However, if DOE needs information, please contact us and we will work to locate the appropriate sources for the information.

- **What innovations will promote design for recyclability of energy technology applications?**

This is not our field of expertise and therefore we're not qualified to adequately answer this question. However, if DOE needs information, please contact us and we will work to locate the appropriate sources for the information.

Category 7: Intellectual Property

- **To what extent does intellectual property protection constrain firms from entering or expanding into markets related to the identified materials of interest? To what extent do these constraints impact cost or affect innovation?**

This is not our field of expertise and therefore we're not qualified to adequately answer this question. However, if DOE needs information, please contact us and we will work to locate the appropriate sources for the information.

Category 8: Additional Information

- **Is there additional information, not requested above, that you believe DOE should consider in developing a strategic plan? If so, please provide here.**

Cobalt is both integral and irreplaceable for future of America's national security and energy security. Today, the United States produces a miniscule amount of the cobalt we use, and that limited production comes as a byproduct and from recycling. At the same time, the need for cobalt is increasing, and that increase is coming in highly strategic areas, particularly the tools we need for conservation (hybrid vehicles) and clean energy (gas turbines, wind turbines), as well as our national defense (jet engines).

Meanwhile, the cobalt market is substantially controlled by an extremely small number of countries and foreign companies, some of which are not friendly to the United States or are politically unstable. Thus the U.S. cobalt supply is in a precarious state that can best be remedied by policies that make the domestic production of cobalt – via environmentally sound mining and refining – a priority.

As you know, a strategic material is a commodity whose lack of availability during a national emergency would seriously affect the economic, industrial, and defensive capability of the US. That unquestionably includes our energy supply – particularly our green energy supply. Yet, the United States is almost completely import- dependent for its supplies of cobalt, and imports about 20% of world production.

Again, we commend the DOE for issuing this RFI, and sincerely appreciate the opportunity to respond. Please do not hesitate to contact us if we can answer any questions or provide additional information.

Sincerely,

Annette McFarland, Project Engineer
Formation Capital Corporation U.S.

Material Use in the United States—Selected Case Studies for Cadmium, Cobalt, Lithium, and Nickel in Rechargeable Batteries

Scientific Investigations Report 2008–5141

U.S. Department of the Interior
U.S. Geological Survey

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By David R. Wilburn

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U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

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Conversion Table

Multiply	By	To obtain
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)

Material Use in the United States—Selected Case Studies for Cadmium, Cobalt, Lithium, and Nickel in Rechargeable Batteries

By David R. Wilburn

Abstract

Consumer preferences, environmental regulations, new end-use markets, reduced production costs, and technological advances have contributed to the consumption and substitution patterns of rechargeable batteries, particularly in automotive and consumer electronic product applications; therefore, a thorough understanding of the use and disposal of the metals used in such batteries is warranted. Four case studies assessing the material use patterns for cadmium, cobalt, lithium, and nickel contained in cell phone, camera and camcorder, portable computer, and hybrid vehicle batteries were conducted for 1996 through 2005 based on an analysis of U.S. International Trade Commission trade data.

The cadmium content of camcorder, camera, and cell phone batteries used annually in the United States declined to about 7 metric tons (t) in 2005 from about 100 t in 1995, as a result of the implementation of regulations affecting nickel-cadmium battery recycling and disposal and the introduction of technological advancements in lithium-ion and nickel-metal-hydride (NiMH) batteries that are increasingly used as alternatives. An analysis of cell phone recycling data suggests that up to 91 t of cadmium contained in cell phone batteries was available for recovery between 1996 and 2005. Some of this material resides in storage.

The cobalt content of rechargeable batteries used annually in camcorders and cameras, cell phones, and portable computers in the United States increased to about 2,300 t in 2005 from 55 t in 1996 because of increased demand and technological improvements that have reduced the cost of these products while making them more efficient. Analysis of cell phone data suggests that 410 t of cobalt may have been recovered from recycled cell phone batteries, and about 4,700 t of cobalt contained in cell phone batteries was available for recovery during the 10-year study period.

The lithium content of rechargeable batteries used annually in consumer electronic products in the United States increased to about 290 t in 2005 from about 87 t in 1996. Estimates of U.S. lithium apparent consumption, which exclude products such as batteries that are contained in imported manufactured products, decreased during much of this period. Lithium used in cell phone batteries in the United States increased between 1996 and 2005 to about 170 t in 2005 from 1.8 t in 1996. Lithium used in portable computer batteries increased for this same period to about 99 t in 2005 from 3.3 t in 1996. Technological developments in camcorder and camera technology for the period had the net effect of reducing the lithium content per battery for these applications, but the increasing popularity of the digital camera led to an increase to 19 t of lithium in camera batteries in 2005 from 100 kilograms in 1996. Less than 10 t of lithium contained in cell phone batteries was recycled during the 1996–2005 period, suggesting that up to 580 t of lithium in cell phone batteries was available for recovery, primarily after 2001.

Nickel content in batteries used annually in camcorders and cameras, cell phones, and portable computers in the United States increased to about 3,000 t in 2005 from 280 t in 1996, mostly a result of increased use of the NiMH battery in these applications. Estimates of nickel use in batteries for hybrid vehicles increased to 2,700 t in 2005 from a negligible amount in 1996. By the year 2010, it is estimated that the amount of nickel used in hybrid vehicle batteries could exceed 7,300 t. Cobalt content of hybrid vehicle batteries used in the United States is expected to reach about 210 t in 2010. An analysis of cell phone recycling data suggests that about 410 t of nickel in batteries was recycled between 1996 and 2005; about 3,100 t was likely available for recovery, although some of this material resides in storage.

Introduction

This report examines the changes that have taken place in the consumer electronic product sector as they relate to the use of cadmium, cobalt, lithium, and nickel contained in batteries that power camcorders, cameras, cell phones, portable (laptop) computers and the use of nickel in vehicle batteries for the period 1996 through 2005 and discusses forecasted changes in their use patterns through 2010. Market penetration, material substitution, and technological improvements among nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), and lithium-ion (Li-ion) rechargeable batteries are assessed. Consequences of these changes in light of material consumption factors related to disposal, environmental effects, retail price, and serviceability are analyzed in a series of short case studies.

This study supplements U.S. Geological Survey (USGS) mineral commodity production and consumption statistics by providing estimates of the amount of materials consumed by important market sectors. It provides information that allows government, nongovernmental organizations, and the public to gain a better understanding of how much and where these materials are used and to draw inferences on how the substitution of different battery chemistries may affect the amount of these materials available for disposal or recycling. The study is part of a series of USGS materials flow assessments on cell phones (Sullivan, 2006), lead-acid batteries (Wilburn and Buckingham, 2006), and NiCd batteries (Wilburn, 2007) and draws in part on data collected for and estimates derived from these previous studies.

Environmental regulations, new end-use markets, and technological advances all have played a role in the changing consumption and substitution patterns of rechargeable batteries, particularly in automotive and consumer electronic product applications. Figure 1 illustrates how the nonautomotive rechargeable battery sector has changed since 1994. In 1994, NiCd batteries accounted for about 88 percent of the world market for rechargeable batteries in terms of the number of batteries sold. By 1999, the market share for NiCd batteries had dropped to below 50 percent, and the NiMH battery market share had grown to about 40 percent. By 2005, the market share of NiCd battery sales had declined to about 34 percent, the NiMH market share had decreased to about 23 percent, and a new battery technology—the Li-ion battery—had developed a market share of almost 40 percent.

In 2002, it was estimated that 350 million rechargeable batteries were purchased annually in the United States (U.S. Environmental Protection Agency, 2002a). The number of batteries has since increased to provide power for the increasing number of cell phones, portable (laptop) computers, and other electronic consumer products used in the United States. The large quantity of batteries in use makes a quantitative assessment of the use and flow of the mineral constituents contained in these batteries essential to understanding the level of risk to human health and the ecosystem associated with these materials.

Some materials contained in batteries can potentially cause harm to the environment and humans if they are manufactured, used, or discarded improperly. In 1992, the U.S. Environmental Protection Agency classified cadmium as a Group B1 probable human carcinogen (U.S. Environmental Protection Agency, 2000). In that same year, about 146,000 t of consumer batteries of all types, some of which contained cadmium, was discarded in the United States (Klimasauskas and others, 2006). NiCd batteries accounted for an estimated 75 percent of the cadmium found in U.S. municipal solid waste (MSW) landfills in 1995 (U.S. Environmental Protection Agency, 2002b); however, the leaching of cadmium into the soil over time from NiCd batteries that are deposited in properly designed landfills is mitigated by lining the landfills with impenetrable materials. In recognition of the potential environmental hazards associated with cadmium metal exposure, some States have limited cadmium use in some consumer

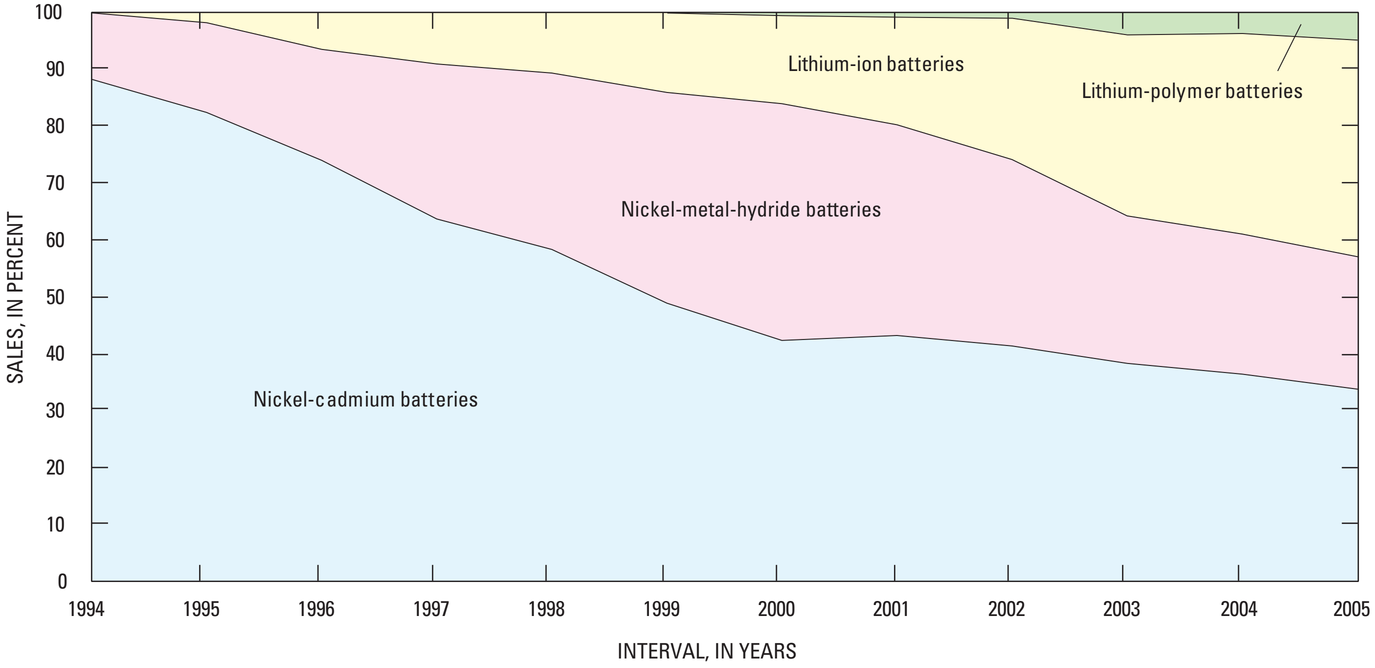

Figure 1. Graph showing percentage of global rechargeable battery sales for the principle battery types from 1994 through 2005. (Data from Pillot, 2005b, p. 19.)

products and are regulating cadmium battery disposal (Klimasauskas and others, 2006). The U.S. Congress passed the Mercury Containing and Rechargeable Battery Act (referred to as the Battery Act) in 1996 to facilitate the recycling of NiCd and other rechargeable batteries by standardizing the collection, disposal, and labeling requirements previously enforced by State agencies (U.S. Environmental Protection Agency, 2002a). The battery industry is expected to be further affected by European Union directives issued in 2000 (2000/52/EC) and 2006 (2006/66/EC) that are designed to limit the use of batteries containing cadmium and mercury and to regulate the disposal and recycling of batteries.

The development and subsequent growth in the number and use of new products that require batteries have provided (and likely will continue to provide) opportunities for technological development within the battery sector. The use of cell phones in the United States, which grew to about 180 million units in 2004 from 340,000 units in 1985, is just one example where the growth of an industry has led to technological improvements in batteries designed to supply that end use (Most, 2003; Charny, 2005). Similarly, statistics reported by the U.S. International Trade Commission (ITC) show that significant expansion has transpired in the number of U.S. imports of portable computers (1,200 percent growth from 1996 to 2005), digital cameras (5,600 percent growth from 1996 to 2005), and other electronic games, toys, and music devices (data not reported separately). In the automotive sector, the development of advanced battery technology is expanding and is supported by industry and the U.S. Government. The Advanced Energy Initiative, announced in 2006 by President Bush, proposed to provide $31 million toward advanced battery research (National Economic Council, 2006). Studies suggest that U.S. sales of hybrid vehicles powered by rechargeable NiMH and Li-ion batteries are likely to achieve 550,000 units by 2010, which is up from the 2005 level of about 190,000 units (U.S. Department of Energy, 2006). Consumer acceptance, cost considerations, energy requirements, supply issues, and size considerations of such products often determine which batteries will best meet the needs of such new applications. Technological changes by product manufacturers can lead to battery substitution from one type to another. Battery substitutions result in material use changes associated with these batteries; therefore, understanding the material requirements of available options is essential in order to assess present and future changes in material use, environmental consequences, and source of supply.

Environmental regulation and product end-use research and development have led to changes in battery composition, efficiency, and size. To date, however, no single battery technology has the cost, power, and efficiency requirements to meet the needs of the consumer for all applications. Consequently, battery manufacturers develop batteries that fit the requirements of a broad spectrum of products, thereby maximizing the power and efficiency profiles of the batteries to fit the requirements of those products. Technological advances further change the materials used in consumer batteries. As a result, batteries with a broad range of chemistries, shapes, and sizes are produced. Industry competition, rapid technological change, and the wide variety of batteries available all create challenges to gathering data about batteries used in the United States.

Because U.S. production of rechargeable batteries is limited to small-scale, high-profit-margin niche markets, such as medical, military, or space applications, most of the rechargeable batteries used in applications considered in this analysis are imported, primarily from China, Japan, and the Republic of Korea (Brodd, 2005). Comprehensive information on U.S. battery consumption, composition, recycling, and trade by end-use application often is not compiled or not made available to the public. The ITC reports data on the number of individual batteries imported into and exported from the United States annually and separately reports data on the number of manufactured products that use batteries. The ITC does not report the material content of these batteries. Battery recycling data have been reported since 1994 by the Rechargeable Battery Recycling Corporation (RBRC), but RBRC data are reported in terms of pounds of batteries recycled, and statistics on specific batteries collected and their material content are not reported over the range of years studied in this report. Although the RBRC is the largest U.S. rechargeable battery recovery organization, some municipalities, armed services, and government agencies also have conducted battery collection programs; and some larger battery manufacturers collect batteries and send them either to the International Metals Reclamation Company (INMETCO), the principal U.S. battery recycler, or to Asian or European recyclers (Boehme and Panero, 2003, p. 41).

Because comprehensive data on rechargeable battery use by type are not uniformly available, selected case studies were performed to provide the reader with several sets of data pertaining to material consumption issues related to the rechargeable battery industry. Each case study of selected battery end uses provides complementary assessments of the rechargeable battery industry. A more comprehensive picture of the industry can be developed by looking at a composite of these case studies.

Study Methodology

To gain a more complete understanding of the amount of material derived from mineral commodities that is used in the United States over time, it is useful to assess the amount of the material used both in its raw forms (ore, concentrate, or refined metal) and in manufactured products. The USGS reports annual production and consumption statistics for many mineral commodities in such annual publications as the Mineral Commodity Summaries and the Minerals Yearbook. The USGS does not, however, include in its annual assessments materials contained in manufactured products that are imported into or exported from the United States. Collection or estimation of these data is often impractical because of the number and variety of products involved and the amount of time required to collect and publish the data. Estimating the amount of a specific mineral commodity used in a product is difficult if that product comes in a variety of sizes and is produced using a variety of chemistries (as in the case of rechargeable batteries). Estimates can be made, however, if the industry uses a high percentage or large tonnage of the targeted mineral constituent in the end-use product, the product has a well-defined market structure, and data useful for estimating material usage of that mineral commodity are available.

Most of the rechargeable batteries used for consumer electronics and hybrid vehicles in the United States are imported, so a thorough study of the rechargeable battery sector requires data on the quantity of batteries, by type, which are imported and exported by the United States. The author selected data collected by the U.S. Bureau of the Census and reported by the ITC (U.S. International Trade Commission, 2006); these data are based on Harmonized Tariff Schedule of the United States (HTS) product classifications. The reported trade data are for batteries of different chemistries and are expressed in terms of the number of batteries or the number of products that contain batteries. The author used annual import and export data for 8 types of nonrechargeable (primary) batteries as indicated by the HTS code and 15 types of rechargeable (storage) batteries, as well as trade data for selected manufactured products that typically contain a battery as part of the prepackaged product. Products considered in this report include battery-powered automobiles and other vehicles, camcorders, cameras, cell phones, clocks and watches of different types, portable computers, power tools, and other small consumer devices.

Because ITC data are most often expressed in terms of the quantity of batteries, an estimate for the average amount of cadmium, cobalt, lithium, or nickel contained within each HTS battery classification or product code (which depends on the end use) was developed. Generalized material content specifications for each major battery chemistry or end-use application were developed from data reported in published material safety data sheets by selected manufacturers that produce the specified battery. Representative mineral content values were assigned by averaging the generalized material content data reported by these manufacturers. Based on the reported description for each HTS classification, a specific battery or group of batteries was selected to depict the “representative” battery for that classification. Cadmium, cobalt, lithium, and nickel content were estimated for each HTS classification on the basis of average weight of all batteries included in that classification as reported by the manufacturers and estimates of the typical material content for that battery type (Vangheluwe and others, 2005, p. 11). The HTS classifications for each battery chemistry and end-use application used in this study are included in the appendix. In cases where an HTS classification was thought to contain multiple battery chemistries or shapes, a determination was made as to what percentage of the classification was attributable to each battery chemistry or shape based on the reported worldwide distribution of batteries by application (Pillot, 2004, p. 29–31; 2005b, p. 14). Annual worldwide rechargeable battery sales data were used as an approximation for the types of batteries included in each of the major U.S. end-use applications (Pillot, 2004, p. 29–31).

Details on the estimation methods and the estimates of the average amount of cadmium, cobalt, lithium, and nickel contained in representative battery chemistries by end-use application for this report are summarized in the appendix. Not all battery constituents were assessed for this study; only the content of cadmium, cobalt, lithium, or nickel as metals or selected compounds was considered. Of the principal battery chemistries, NiCd batteries of a type used in selected end-use applications were evaluated for cadmium, cobalt, and nickel content; NiMH batteries were evaluated for their cobalt and nickel content; and primary lithium and Li-ion batteries types were evaluated for their cobalt and lithium content.

Although a variety of battery chemistries exist and other battery chemistries are being developed, only a select number of battery chemistries was analyzed for their cadmium, cobalt, lithium, and nickel content in this study. It should be noted that there is no lithium metal in the Li-ion batteries analyzed in this study; lithium occurs primarily in the form of lithium cobalt oxide ($LiCoO_2$) or lithium hexafluorophosphate ($LiPF_6$) compounds. Cobalt and nickel most commonly occur as cobalt hydroxide ($Co(OH)_2$) or nickel hydroxide ($Ni(OH)_2$) in positive electrodes of NiCd or NiMH batteries or as material components mixed with other metals contained in negative electrodes of NiMH batteries. Cadmium occurs as cadmium hydroxide ($Cd(OH)_2$) in positive electrodes of NiCd batteries.

Case Study 1—Cell Phones

The goals of the cell phone case study are as follows: illustrate the material changes that have taken place in the cell phone battery industry since 1995, estimate the growth in U.S. consumption of batteries used to power cell phones during the past 10 years, and discuss the effects of that growth on disposal alternatives (household storage, incinerating, landfilling, or recycling). Estimates were developed for the amount of material contained in cell phone batteries in the United States, the amount available for disposal at municipal solid waste (MSW) facilities, and the amount that was recycled.

The types of batteries used in cell phones worldwide have changed significantly since the early 1990s, when NiCd batteries dominated the world market. In 1996, the first year analyzed in this study, NiMH batteries represented an estimated 40 percent of the cell phone market, NiCd batteries represented an estimated 37 percent, and Li-ion batteries represented an estimated 23 percent (Pillot, 2005b, p. 19). Since 1996, the use of NiCd batteries in the world market has decreased while Li-ion battery use has significantly increased, first at the expense of NiCd batteries and then at the expense of NiMH batteries. Estimates suggest that, by 2005, NiCd batteries had been completely replaced by Li-ion batteries for use in cell phones and that the NiMH battery market share had decreased to about 4 percent (Pillot, 2005b, p. 19). Since 2004, the Li-ion battery market share has fallen in favor of lithium-polymer batteries, which represented about 17 percent of cell phone batteries in use in 2005 (Pillot, 2005b, p. 19).

Figure 2 summarizes estimated U.S. cell phone battery use and disposal data for the period from 1996 through 2005. U.S. cell phone subscription data were derived from Most (2003) and Charny (2005). Estimates of the number of imported batteries (by type) were derived from ITC data (U.S. International Trade Commission, 2006) that are based on the number of cell phones imported into and exported from the United States annually; because data on the number of individual batteries traded annually could not be differentiated by chemical type, they were excluded from this assessment. Estimates of the number of batteries available for disposal during the 10-year period were developed based on an average cell phone life of 2 years (Environmental Literacy Council, 2004; Ramamoorthy, 2006), the assumption that cell phones may be available for recycling or disposal at the time of service contract termination, and that the average cell phone requires only one rechargeable battery during its short life. For this analysis, it was assumed that 20 percent of batteries used in cell phones entering service in any given year would be retired in that year; 70 percent of these batteries would be retired in the second year, and the remaining 10 percent would be retired in the third year. Data suggest that about 90 percent of all cell phone batteries that are considered obsolete are either placed in temporary household storage or are discarded as MSW, and about 10 percent are recycled, according to estimates derived from data reported by the Rechargeable Battery Recycling Corporation (2005).

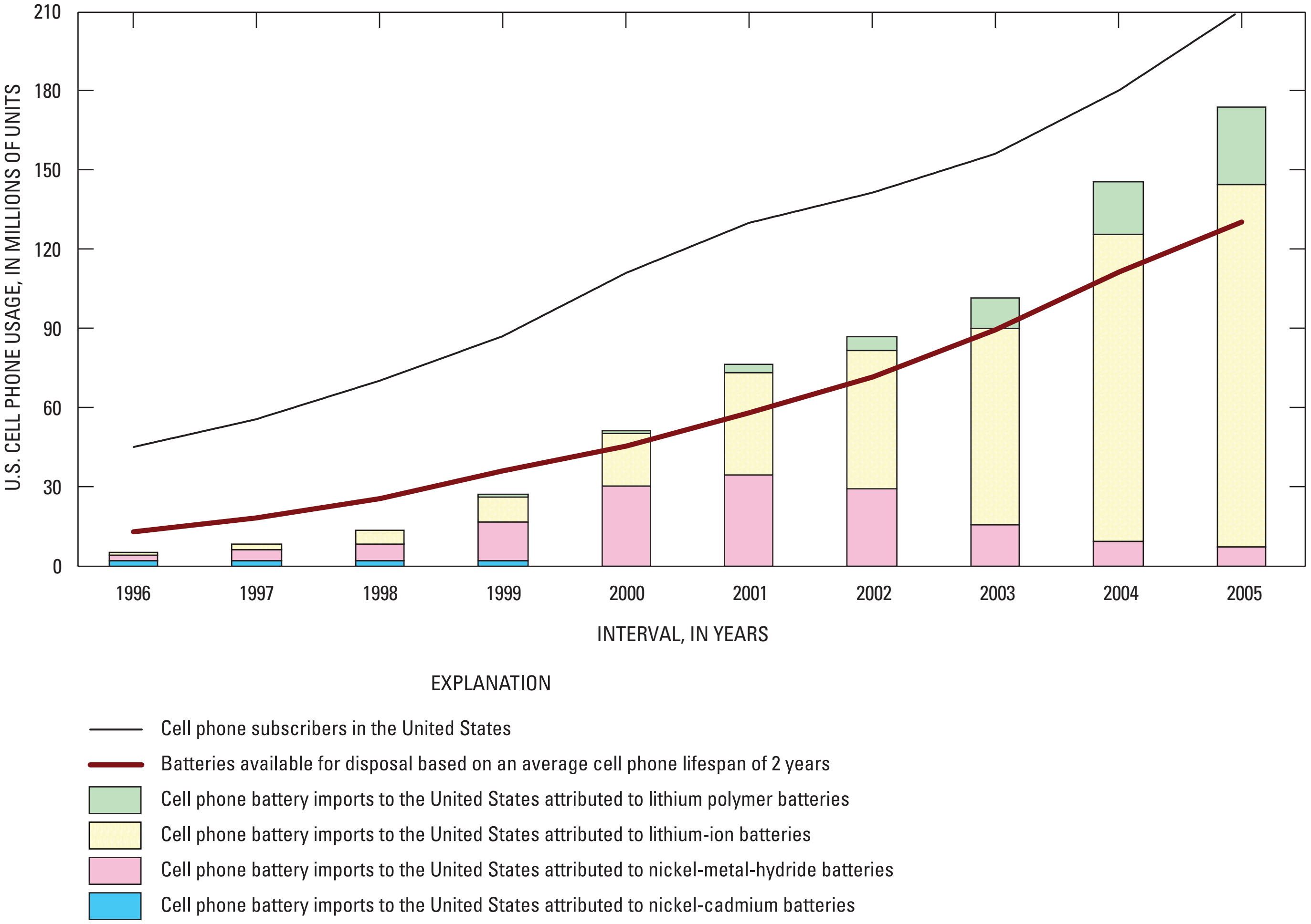

Figure 2. Graph showing U.S. cell phone subscription and import data compared with estimates for the number of cell phones available for disposal at the end of life. U.S. cell phone battery production data are not available but are to be assumed negligible when compared to the number of imported batteries. Subscriber data from Most (2003) and Charny (2005); import data from U.S. International Trade Commission (2006). Estimates for cell phone end-of-life data are based on an assumed contract life of 2 years (Fishbein, 2002), the assumption that each cell phone requires only 1 battery during its life, and the assumption that cell phones are available for disposal at the time of contract termination.

The results of this study suggest that about 12 million cell phone batteries were available for disposal in 1996, which increased to about 130 million batteries in 2005. This increase is consistent with an estimate of 130 million cell phones anticipated to be retired by 2005, as reported by the U.S. Environmental Protection Agency (2005).

For this study, an assumption was made that the worldwide cell-phone-battery chemistry distribution, as reported by Pillot (2005b), is equivalent to the United States cell-phone-battery chemistry distribution. The material requirements reported in the appendix for the selected battery chemistries were used to develop estimates for the amount of cadmium, cobalt, lithium, and nickel contained in these batteries. The relative proportions of these materials in cell phone batteries are highly dependent on battery technology. Environmental regulations, changing cell phone technologies, and shifting consumer preferences during the 10-year study period led to substitution for NiCd batteries in cell phones, first by NiMH batteries, and then by Li-ion batteries. By 2005, lithium-polymer batteries began to erode the market share of the Li-ion batteries in cell phones. The estimates for battery distribution on an annual basis are necessary because of the rapid changes taking place in the types of batteries that were used in cell phones during the study period.

Technological innovation not only stimulated changes in cell phone battery technology, but also led to a noticeable reduction in cell phone size and weight because lithium-based batteries are lighter than NiCd batteries and electronic circuitry refinements lead to increased miniaturization. The Environmental Literacy Council (2004) reported that the weight of a typical cell phone in the early 1990s was about 11 ounces and in 2000 was 7.7 ounces. In 2006, a typical cell phone weighed about 4.1 ounces (Nokia Corporation, 2006). The newest and most widely used lithium-based battery chemistries (Li-ion and lithium-polymer) weigh much less than older NiMH and NiCd batteries.

The study results suggest that about 4,700 metric tons (t) of cobalt, 3,100 t of nickel, 580 t of lithium, and 91 t of cadmium were contained in cell phones that were estimated to be available for disposal from 1996 to 2005 in the United States. Estimates based on recycling data provided by the Rechargeable Battery Recycling Corporation (2005) suggest that about 410 t of cobalt, 170 t of nickel, and less than 10 t each of cadmium and lithium contained in cell phone batteries may have been recovered from batteries recycled between 1999 and 2005. Thus, it is likely that about 4,300 t of cobalt, 2,900 t of nickel, 570 t of lithium, and 83 t of cadmium were contained in cell phone batteries discarded during the same period. Discarded material includes batteries retained in household storage for a time before entering the MSW landfills. Most of the cadmium, which is attributable to NiCd batteries, was discarded prior to 2001; most of the lithium was discarded after 2001. A significant quantity of nickel is contained in NiCd and NiMH batteries which were discarded during the entire 10-year period. A small amount of the discarded cell phone batteries was likely incinerated at MSW facilities.

The United States used about 28 percent of the 734 million cell phones that were sold worldwide in 2005 (Charny, 2005; Gartner, Inc., 2005). Growth in cell phone sales is taking place most rapidly in China and India; by 2008, it is estimated that these two countries may possibly account for about 45 percent of world cell phone use (Pillot, 2004, p. 26). By 2010, cell phone use in the United States may require about 250 million batteries, mostly of the Li-ion and lithium-polymer type. If current trends in battery use continue, the tonnage of cadmium from cell phone batteries that may potentially enter landfills in 2010 will be very small, the amount of lithium and nickel that may potentially enter landfills will likely be similar to what was entered in 2005, and the amount of cobalt destined for landfills or household storage is likely to increase. These estimates assume that the recycling rate for cell phone batteries will increase at a rate similar to that forecasted for total battery recycling in the United States; the estimates do not account for an increased rate of substitution of cobalt by nickel and other metals. It is assumed that State regulations will continue to govern the types of batteries that will be allowed in MSW landfills in the States.

Case Study 2—Cameras and Camcorders

The focus of the camera and camcorder (video recording camera) case study is to show how the growth in the use of batteries that power these popular business and consumer products during the past 10 years in the United States has changed and to discuss the effects of this change on materials use and disposal. Estimates were developed for the amount of cadmium, cobalt, lithium, and nickel contained in camera and camcorder batteries that are used in the United States for each of the principal battery chemistries associated with these products, as summarized in the study methodology section and shown in the appendix.

The quantity and composition of materials used in nonrechargeable (primary) and rechargeable camera batteries and in analog and digital camcorder batteries have changed during the past 10 years because of technological developments associated with the products. Imports of still-image cameras (digital and film-based types) into the United States have grown to about 38 million in 2005 from about 680,000 in 1996 (U.S. International Trade Commission, 2006) because more cameras are manufactured outside the United States. Imports of video cameras and camcorders (both digital and analog types) into the United States also have increased, but at a slower rate—to about 5.9 million units in 2005 from about 3.7 million units in 1996. Figure 3 shows the quantity of U.S. net imports (imports minus exports) of cameras (fig. 3*A*) and camcorders (fig. 3*B*) for the period from 1996 through 2005. In 1996, about 90 percent of cameras used various types of primary (nonrechargeable) batteries, and about 10 percent used rechargeable NiCd batteries; by 2005, however, worldwide sales data suggest that

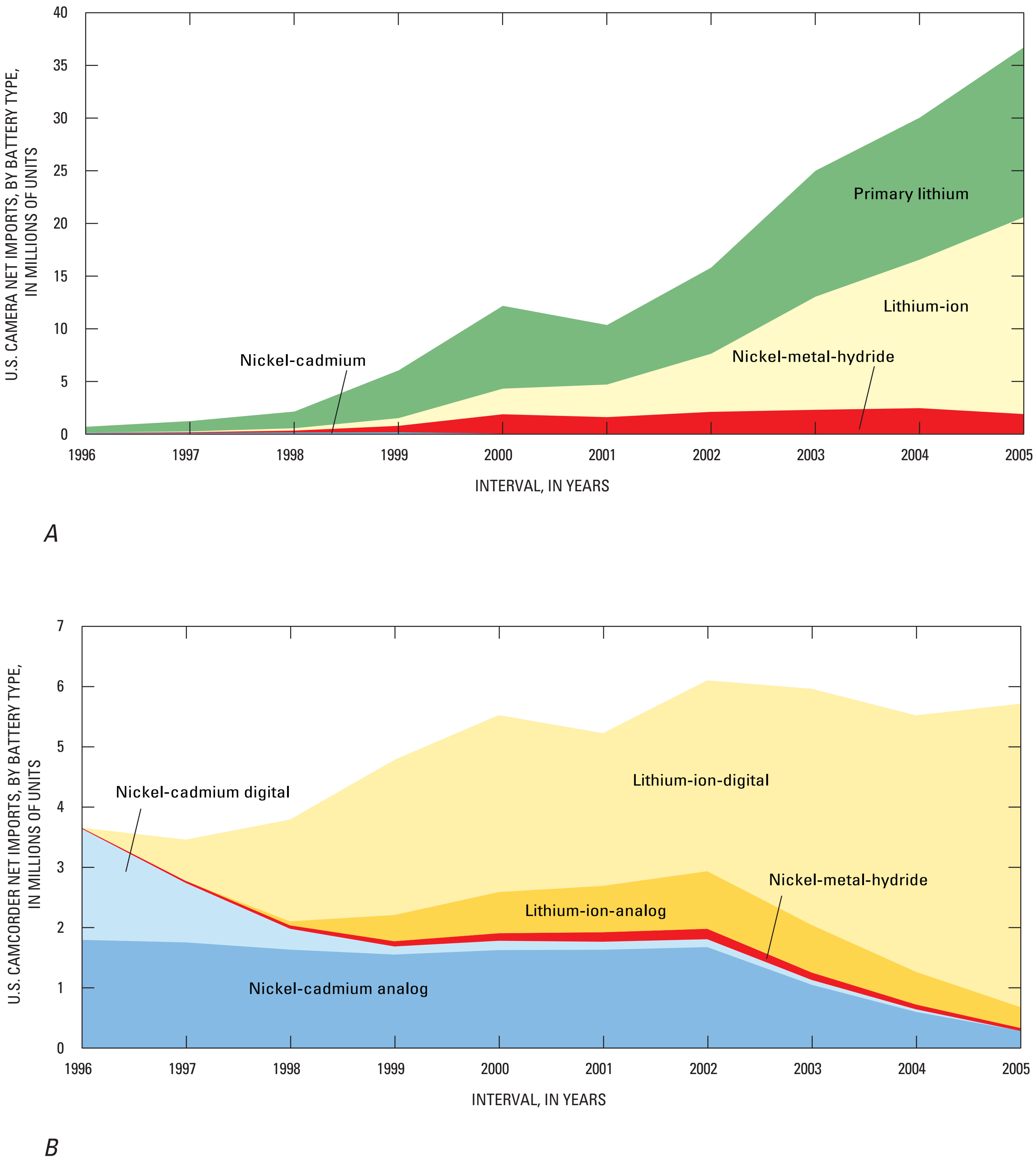

Figure 3. Graphs showing estimated U.S. net imports of *A*, cameras, and *B*, camcorders by battery type, in millions of units. Estimates were developed based on trade data from U.S. International Trade Commission (2006), net import data (imported products minus exported products) for each year, and percentage allocations by product type for each given year. World estimates for the camera and camcorder markets (Pillot, 2005a, p. 7) were assumed to apply to the United States.

about 51 percent of camera batteries were Li-ion rechargeable batteries, 44 percent were primary batteries, and about 5 percent were NiMH rechargeable batteries (Pillot, 2004, p. 27). In 1996, about one-half of all U.S. camcorders were analog (8-millimeter) types; by 2005, about 88 percent of all camcorders imported into the United States were digital types (U.S. International Trade Commission, 2006). Modern cameras and camcorders have become much more compact than those produced in the 1990s, primarily because of circuitry miniaturization; additionally, batteries contained in newer products have become more energy efficient, although most batteries used in these applications are similar in size to those used in 1996.

Significant material consumption patterns have changed within the camera sector as a result of cheaper prices, shifts in consumer preferences, and technological improvements. The changes are based on the assumption that observed variations in the quantity of selected U.S. imported products over time indicate trends. The increase in the use of camera batteries containing lithium (fig. 3*A*) represents the most significant change for the camera sector during the 10-year study period. The estimate for the aggregated total lithium content of batteries contained in digital and film-based cameras sold in the United States has increased to more than 19 t of lithium in 2005 from 100 kilograms of lithium in 1996. The NiCd batteries used in this application were phased out by 2000. The total cobalt content of camera batteries used in the United States increased to almost 50 t in 2005 from a negligible amount in 1996. The total nickel content of batteries used in this sector increased slightly to about 10 t in 2005 (attributed primarily to NiMH batteries) from about 2 t in 1996 (attributed to both NiCd and NiMH battery chemistries).

Although figure 3 shows a more modest growth pattern overall for the U.S. camcorder sector, the pattern of change in battery chemistry used during the 1996–2005 period is quite significant. Within this modest growth, some rather dramatic changes can be seen. Figure 3*A* shows that growth within the camera battery sector happened mainly with primary lithium and rechargeable Li-ion batteries. Figure 3*B* suggests that most of the growth in imports within the camcorder sector occurred during a transition from camcorders with NiCd batteries to camcorders with lithium-based batteries. In 1996, the number of camcorders using rechargeable Li-ion batteries was negligible; by 2005, about 50 percent of analog camcorders and almost 100 percent of digital camcorders used Li-ion batteries (Pillot, 2005a, p. 7). NiCd battery use correspondingly decreased during the period to about 5 percent of camcorders (mostly analog) in 2005 from approximately 100 percent of all camcorders because of changes in consumer preference, battery availability, and technological factors. Figure 3*B* shows the following three distinct periods of change for camcorder battery consumption:

1. From 1996 to 1998—Characterized by a rapid decrease in NiCd battery imports for digital camcorders and a corresponding increase in Li-ion battery imports for this application.
2. From 1998 to 2002—Characterized by an increase in Li-ion battery imports in analog and digital camcorders.
3. From 2002 to 2005—Characterized by a decrease in imports of analog camcorders coupled with a decrease in imports of all principle battery chemistries except Li-ion batteries.

Since 1996, some States have placed limitations on the use of consumer batteries containing mercury, enacted guidelines for battery disposal, and encouraged increased recycling for all battery chemistries. During this same period, more efficient and powerful battery technologies have been developed that have increased the use of rechargeable batteries in a large number of end-use applications. In general, the material content of electronic consumer-product batteries used and disposed of in the United States has changed significantly in the past 10 years. Figure 4 illustrates some of the changes that have taken place since 1996 for camera and camcorder batteries. In the case of cameras and camcorders, the amount of cadmium contained in camera and camcorder batteries has decreased to about 7 t in 2005 from about 83 t in 1996. The amount of nickel contained in camera and camcorder batteries has similarly decreased to about 22 t in 2005 from about 130 t in 1996, primarily as a result of decreasing use of NiCd batteries within the sector. With the increase in use of lithium-based batteries in the sector, the amount of lithium contained in camera and camcorder batteries has increased to about 26 t in 2005 from about 82 t in 1996, and the amount of contained cobalt has increased to 96 t in 2005 from about 5 t in 1996. Recycling of used batteries in this sector has also increased. The net effect is that consumer preferences, government regulations, and technological advancements have combined to effectively reduce the amount of cadmium and nickel from batteries disposed of in MSW landfills because of an increase in the use of Li-ion batteries in end-use applications, such as cameras and camcorders.

Case Study 3—Portable Computers

As the price of the average portable (laptop) computer has decreased to the average price of a desktop computer 5 years ago, and as wireless Internet connections have become more available, the number of portable computers in use in the United States has grown. Net imports of portable computers into the United States have grown to about 20.6 million in 2005 from about 1.4 million in 1996 (U.S. International Trade Commission, 2006). In 2005, for the first time in U.S. history, portable computers outsold desktop computers and accounted for 51 percent of all U.S. personal computer sales (Kanellos, 2006). The focus of this case study is to show how technological advances in computers and the batteries used to power them led to the growth in portable computer use during the past 10 years, to discuss the changes in battery chemistry used in these products and the changing material

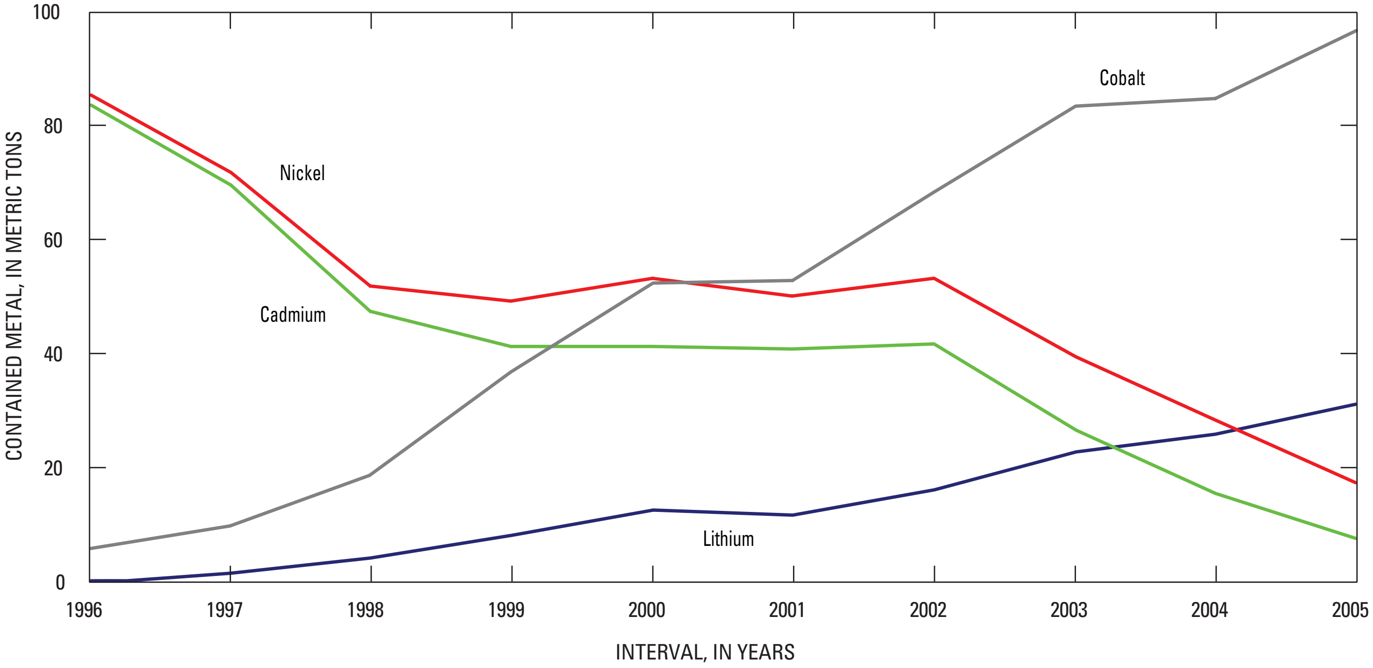

Figure 4. Graph showing estimated amounts of cadmium, cobalt, lithium, and nickel contained in rechargeable camera and camcorder batteries used in the United States from 1996 through 2005. Estimates were developed based on trade data from the U.S. International Trade Commission (2006), net import data (imported batteries minus exported batteries) for each year from the U.S. International Trade Commission (2006), assumed average metal content of batteries, and percentage allocations by battery chemistry for each given year. The worldwide rechargeable battery distribution by chemical type as reported by Pillot (2004, p. 27–31) is assumed to be equivalent to the United States rechargeable battery market distribution for cameras and camcorders.

needs of these batteries, and to discuss the ramifications of these changing growth patterns on material consumption and disposal. Estimates were developed for the amount of cobalt, lithium, and nickel contained in the Li-ion and NiMH batteries used in these computers. The estimates are based on ITC trade statistics and the average material requirements for specified battery classifications as determined by averaging the battery specifications reported by selected manufacturers.

Data for Li-ion and NiMH batteries used in portable computers show different trends. The shaded areas in figure 5 show that the use of Li-ion batteries in portable computers increased at a much faster rate than the use of NiMH batteries, primarily because of technological improvements in the Li-ion batteries that resulted in a lower unit price and increased energy efficiency. In 1996, NiMH batteries represented 55 percent of all net battery imports used in U.S. portable computers, as reported by the ITC; by 2005, the market share of NiMH batteries used in portable computers had dropped to about 8 percent (Pillot, 2005a, p. 6). Conversely, Li-ion batteries represented about 92 percent of the market share in 2005 and about 45 percent in 1996 (U.S. International Trade Commission, 2006).

Li-ion batteries have grown in popularity as a function of both price and efficiency relative to other principle battery chemistries. The Li-ion batteries are priced higher than other comparable battery types, but the average price of a Li-ion battery dropped from about $5 per cell in 2000 to about $2.50 per cell in 2005, compared with a 2005 price estimate of about $0.75 per cell for NiCd and $1.00 per cell for NiMH batteries (Pillot, 2005b, p. 18; Pillot, 2006b, p. 17). The Li-ion battery, however, has a higher energy density (greater energy storage capacity per weight) and is lighter (less dense) than NiCd or NiMH products, which makes it preferable as a power source for portable items such as cell phones, camcorders, and portable computers. Technological advances have improved the performance characteristics of Li-ion batteries. In 1992, when they were first introduced, the Li-ion battery had only a 10 percent higher energy density than a comparable NiMH battery; by 2005, the Li-ion battery had an average energy density about 80 percent greater than the NiMH battery (Pillot, 2005b, p. 16). As the price difference between these two types of batteries decreases, consumers and manufacturers may be more willing to use batteries with the higher energy density and lower weight.

Estimates of the quantity of cobalt, lithium, and nickel contained in batteries consumed by the portable computer sector from 1996 to 2005 are illustrated on figure 5. Assumptions used in developing these estimates are reported in the appendix (table A–6). ITC trade data for the United States were used to estimate the amount of net imports by battery chemistry, and battery data reported by selected manufacturer's material safety data sheets were used to assign average composition values for each of the principal rechargeable battery chemistries. HTS classifications for each battery chemistry and end

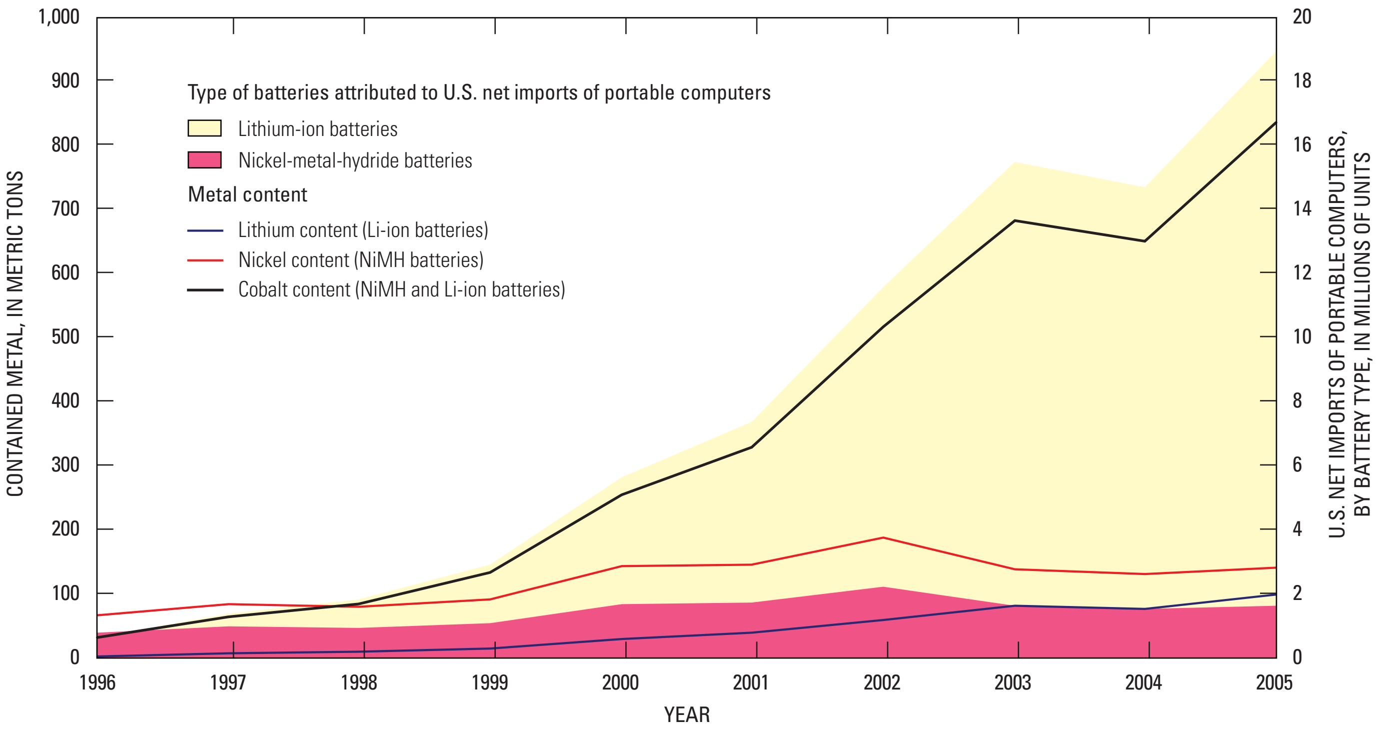

Figure 5. Graph showing estimated imports of portable computers by battery type and amounts of cobalt, lithium, and nickel contained in rechargeable portable computer batteries used in the United States from 1996 through 2005. Estimates are based on trade data from the U.S. International Trade Commission (2006), net import data (imported batteries minus exported batteries) for each year from the U.S. International Trade Commission (2006), assumed average metal contents of these batteries, and percentage allocations by battery chemistry for each given year. The worldwide personal computer rechargeable battery market distribution as reported by Pillot (2005a, p. 6) is assumed to be equivalent to the United States rechargeable battery market distribution for portable computers.

use analyzed in this study are listed in the appendix (table A–11).

The total amount of lithium contained in Li-ion batteries used by portable computers in the United States has increased to nearly 100 t in 2005 from less than 4 t in 1996 owing to the increased use of Li-ion batteries in portable computers. Total nickel content of NiMH batteries used in portable computers increased to about 190 t of nickel by 2002 from about 67 t of nickel in 1996, then dropped to about 140 t of nickel by 2005. Assuming that the predominant Li-ion battery chemistry is $LiCo(OH)_2$, the total cobalt content of Li-ion and NiMH batteries used in portable computers increased to about 840 t (about 8 t in NiMH and 830 t in Li-ion) in 2005 from 32 t (4 t in NiMH and 28 t in Li-ion) in 1996. The number of portable computers sold worldwide is projected to increase by 35 percent from 2005 to 2010, and estimates suggest that Li-ion batteries will hold a near 100 percent market share of rechargeable batteries used in portable computers in 2010 (Pillot, 2005a, p. 6), barring the commercial implementation of new technologies, such as fuel cells, which have different material requirements. Applying these figures to the most recent U.S. trade data suggests that in 2010 the U.S. portable computer sector may use more than 1,100 t of cobalt and 130 t of lithium for the manufacture of portable computer batteries. From 2005 through 2010, nickel consumption is expected to decrease as NiMH batteries are further replaced by Li-ion batteries in portable computers.

These estimates assume that there are no large changes in the overall chemical composition of rechargeable batteries from 2005 through 2010; it is expected, however, that continued technological improvement could result in small variations in battery composition and that some market penetration by lithium-polymer or fuel cells could take place by 2010. Changing commodity prices could also influence substitution. Pillot (2005a, p. 14) suggests that fuel cell use in portable computer applications may well account for as much as 4 percent of the market by 2010; other researchers report that widespread use of fuel cells to power small consumer products is more likely to take place after 2010.

Li-ion batteries used in selected models of portable computers have been recalled by various computer manufacturers since 2005 because of a possible fire hazard posed by the battery overheating. This study does not attempt to assess the effect of such recalls on future battery consumption, but it does assess the effect of these recalls on the amount of lithium that has entered recycling and disposal flows. Based on the data reported by the U.S. Consumer Product Safety Commission, approximately 235,000 Li-ion batteries were recalled in the United States in 2005, and about 4.3 million additional batteries were recalled in the United States as of November

2006 (U.S. Consumer Product Safety Commission, 2007). If it is assumed that each of these recalled battery packs contained nine individual cells, and each cell contains an average of 4.9 grams (g) of cobalt and 0.58 g of lithium per cell, then the cumulative amount of cobalt contained in the recalled batteries is estimated to be about 10 t of cobalt and 1.2 t of lithium in 2005 and about 190 t of cobalt and 22 t of lithium in 2006. However, because these recalls are voluntary, the amount of batteries actually returned by the consumer may be lower. While it is uncertain how much of this material will end up in U.S. landfills, Li-ion batteries are generally considered less toxic than NiCd batteries, and the environmental effect of these sudden recalls is expected to be minimal (Ames, 2006). Many of the computer manufacturers have contracts with the RBRC to recycle discarded batteries, so it is likely that most of those batteries that are returned to the manufacturers will be recycled; the recycled material is then returned to the manufacturers as feed material for new batteries. Metals recovered from battery recycling by INMETCO may be used in steelmaking. The RBRC reported a 6.4 percent increase in batteries recycled during the first 6 months of 2006 compared with the same time period in 2005; some of this increase could be attributable to Li-ion batteries that were recycled as a result of the recalls.

Case Study 4—Hybrid Vehicles

A study of rechargeable batteries would not be complete without considering the effect of the growth in the hybrid electric vehicle (HEV) industry on the rechargeable battery industry. HEVs combine the internal combustion engine of a conventional vehicle with the battery and electric motor of an electric vehicle. The first commercially produced HEV was introduced into the U.S. market in 1999; since that time, more U.S. and foreign automobile manufacturers have included HEVs in their U.S. automotive lineup, and demand for vehicles equipped with hybrid electric technology is increasing. Because this market sector for rechargeable batteries is changing rapidly, this case study evaluates not only 1996–2005 material use levels, as was done in the other case studies, but also assesses anticipated cobalt, lithium, and nickel use in this sector from 2005 to 2010. Material use estimates for this period were derived from U.S. HEV sales estimates reported by the U.S. Department of Transportation and the U.S. Department of Energy, Energy Information Administration, and from estimates of the percentage of vehicles that use various types of HEV batteries, as reported by Madani (2005).

Much research into improving automotive battery technology by the creation of low-cost but energy-efficient battery systems is ongoing. As of 2008, all commercially available HEVs are powered by NiMH battery systems and internal combustion engines. Li-ion battery systems, improved NiMH systems, and hydrogen-powered fuel cells are in development, but NiMH battery systems are expected to remain the predominant source of electric power for HEVs until at least 2010.

The two main hindrances to the establishment of a strong, growing HEV sector in the short term are the time required for battery development and the high price of HEV batteries. Research suggests that the period of battery development to commercial implementation is from 4.5 to 7 years (Madani, 2005, p. 15). Consequently, battery technologies undergoing initial research in 2005 are not likely to be placed in service before 2010. A number of research initiatives conducted jointly by automobile manufacturers and battery producers to develop commercially viable Li-ion batteries for vehicles have been initiated since 2003. Batteries generated from these collaborative efforts, however, are unlikely to reach the market before 2008. Large-scale Li-ion battery production suitable for HEVs is therefore unlikely before 2010.

Although the technology required to produce the small cells used in portable consumer electronics is transferable to the production of battery packs suitable for HEVs, the optimum energy storage characteristics of HEV batteries are different and make these batteries more costly. One first-generation HEV battery weighed about 50 kg and required 228 D-size NiMH cells. Another first-generation HEV battery used 240 to 250 D-size NiMH cells that weigh a combined 144 kg (Madani, 2005, p. 9). The higher cost of such battery packs requires automobile manufacturers to charge a premium for their HEVs over conventionally powered automobiles that use lead-acid batteries to power internal combustion engines.

Battery electrical energy requirements vary by battery chemistry and the intended battery use. The more popular HEVs use batteries primarily designed to provide rapid acceleration rather than as the primary source of motive power. One desirable attribute of this kind of battery is high specific energy [the amount of energy stored in watthours (Wh) per unit mass in kilograms (kg)] or energy density [energy stored in Wh per unit volume in liters (L)]. A main advantage of the Li-ion battery technology is its ability to provide a high energy density that ranges from 175 to 310 Wh/L (144 to 255 Wh/kg). A conventional lead-acid battery designed to be the primary power source for a vehicle typically achieves only 89 Wh/L (73 Wh/kg) (Gaines and Cuenca, 2000, p. 6). The specific energy for a NiMH battery system used in HEVs is about 56 Wh/L (46 Wh/kg) (Panasonic EV Energy Co., Ltd., 2006).

The cost to provide the high level of specific energy necessary for an HEV battery is significant. In 2005, the cost of a typical NiMH battery was $0.50 per watthour, while the cost of a Li-ion battery was about $2.20 per watthour (Madani, 2005, p. 18). At an average energy requirement of 1,300 watts (W), this translates to an average cost of about $650 per NiMH battery and about $2,860 per Li-ion battery. Battery costs are projected to drop to an estimated $0.28 per watthour for a NiMH battery and $0.80 per watthour for a Li-ion battery by 2010 (Madani, 2005, p. 19). If so, the typical cost of an 1,800-W battery in 2010 would be about $500 for a NiMH battery and about $1,400 for a Li-ion battery. Improvements in battery technology could result in further cost reductions.

Given the cost and technology constraints, what effect did the changing vehicle battery market have on the use of cobalt, lithium, and nickel in hybrid vehicle batteries for the period 1996 through 2005 and their projected use for 2006 through 2010? Vehicle production statistics reported by the U.S. Department of Transportation, vehicle sales projections reported by the U.S. Department of Energy, trade statistics reported by the ITC, HEV sales forecasts provided by Pillot, (2006a, p. 17), Paumanok Publications, Inc. (2006), and the National Renewable Energy Laboratory (Pesaran, 2006) were used to estimate the relative amount of these materials consumed in vehicle batteries through 2005 to provide estimates of selected material use based on projections of HEV vehicle sales for the period from 2005 through 2010.

Table 1 provides estimates of the amount of cobalt, nickel, and lithium contained in batteries from domestic and imported HEVs in the United States from 1996 to 2010. The estimates are based on the number of HEVs reported as sold or leased from 1996 to 2003 and projections of U.S. vehicle sales from both domestic and foreign manufacturers to 2010 (U.S. Department of Energy, 2006; U.S. Department of Transportation, 2006). These estimates assume one battery pack per vehicle sold during the period considered for this study and do not take into account defective or replacement batteries. HEVs were first introduced commercially to the U.S. market in 1999. Since that year, HEV vehicle imports to the United States gradually increased until 2004, when some U.S. automobile manufacturers added HEVs to their product lines. Available data suggest that the rate of HEV vehicle sales after 2004 will grow more rapidly, such that the quantity of HEVs sold in the United States may reach 550,000 units in 2010. Projections by Madani (2005), Paumanok Publications (2006), and The Freedonia Group Inc. (2006) suggest a higher level of future HEV sales than do estimates from the U.S. Department of Energy (2006) used in this analysis, because they include sales of replacement HEV batteries in their estimates. Projections, however, can be affected by changes in energy prices, technological breakthroughs, and other unanticipated factors.

Estimates for the amount of nickel contained in NiMH batteries used in HEV passenger vehicles and light trucks is expected to increase by a factor of 10 between 2003 and 2010, reaching about 7,300 t, as demand for HEVs that use this type of battery increases. Estimates for the amount of cobalt used in HEV batteries are likely to increase gradually from 2003 to 2008, at which time commercial production of Li-ion batteries for HEVs is expected to come online. If this takes place, then cobalt use in HEV batteries is projected to increase to about 210 t in 2010 from about 7 t in 2007, including both NiMH and Li-ion HEV batteries. Data suggest that in 2010, NiMH batteries would still be found in about 95 percent of HEVs, or more than 3 percent of the vehicles sold in the United States. The amount of lithium in HEV batteries is expected to remain at low levels until 2010, a function of low HEV battery production levels, the small percentage of HEVs that use Li-ion batteries, and the small amount of lithium contained within a Li-ion battery.

Summary and Conclusions

Consumer preferences, decreasing battery costs, environmental regulation, increasing fuel costs, new end-use markets, and technological advances have all played a role in the changing consumption and substitution patterns of rechargeable batteries, particularly in automotive and consumer electronic product applications. Table 2 summarizes cadmium, cobalt, lithium, and nickel consumption estimates for batteries used in selected consumer products assessed in this report for the period from 1996 through 2005. For each of the four mineral-based commodities evaluated, the amount of material used in selected end-use applications is given along with reference values of total annual U.S. apparent consumption for these metals as reported by the USGS. Although comparison of such data may be used to suggest gross trends in material consumption, direct comparison is not recommended because calculations of total U.S. apparent consumption do not include material contained in manufactured products imported to or exported from the United States, so total material consumption may be underestimated (Wilburn and Buckingham, 2006).

Total U.S. apparent consumption of cadmium appeared to decrease in a manner similar to that of the overall decline for the analyzed end-use sectors. U.S. apparent consumption of cobalt remained generally constant during the 10-year study period. In contrast, cobalt use attributed to rechargeable cell phone and portable computer batteries increased. In 2005, the cobalt content of cell phone batteries in use in the United States was estimated to be 1,400 t, or about 12 percent of the calculated 2005 U.S. apparent consumption value. Similarly, the estimated 2005 cobalt content of portable computer batteries in use in the United States was 840 t, or about 7 percent of the calculated 2005 U.S. apparent consumption value. U.S. apparent consumption of lithium decreased from 2001 through 2004 primarily as a result of decreased U.S. aluminum production (Ober, 2002). Lithium use in the United States that is attributable to the rechargeable battery sector, however, increased since 2002, primarily in such popular consumer products as cell phones and portable computers. The most noticeable trends in nickel use in rechargeable batteries relate to the decrease in the amount of nickel used in cell phone batteries as Li-ion batteries have increasingly replaced NiMH batteries in cell phones, and the increasing amount of nickel used in HEV batteries. As the number of hybrid vehicles in use increases, the use of nickel in NiMH batteries that power such vehicles also will increase, until such time as alternative technology supplants the use of NiMH in batteries.

U.S. cadmium use in consumer electronic batteries has generally declined (table 2) since cadmium was recognized as a possible human carcinogen in 1992. This finding resulted in the implementation of regulations affecting battery recycling and disposal and the introduction of technological advancements in other battery chemistries that are increasingly used as alternatives. For the period 1996 through 2000, camcorder batteries imported into the United States used more cadmium (up to 82 t)

Table 1. Content of key material components contained in hybrid electric vehicle batteries.

[HEV, hybrid electric vehicle. NiMH, nickel-metal hydride. XX, negligible]

Category	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Estimated U.S. car and light truck HEV sales[1]	0	0	0	3,500	18,000	30,000	25,000	49,000	92,000	190,000	310,000	300,000	480,000	490,000	550,000
Percentage of vehicles by battery type:[2]															
NiMH batteries	0	0	0	XX	0.1	0.2	0.2	0.3	0.6	1.3	2.1	2.0	3.1	3.1	3.1
Lithium-ion batteries	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.2	0.5
Metal content of NiMH HEV batteries, in metric tons:[3]															
Cobalt content	0	0	0	XX	XX	0.7	0.6	1.2	2.2	4.6	7.4	7.2	80	120	210
Nickel content	0	0	0	49	250	420	350	690	1,300	2,700	4,300	4,200	6,600	6,700	7,300
Lithium content	0	0	0	0	0	0	0	0	0	0	0	0	8	13	23

[1] Estimates for 1996 through 2002 are based on manufacturer press releases. Estimates for 2003 through 2010 are based on data from the U.S. Department of Energy (2006).

[2] Estimates are reported by Madani, 2005b, p. 20.

[3] Cobalt, lithium, and nickel content estimates are based on representative battery manufacturer data for batteries of D-cell type and HEV battery data provided by Geelan and Kirkpatrick (2006).

Table 2. Reported U.S. apparent consumption for selected metals and the content of these metals in batteries used in popular consumer products for the period 1996 through 2005.

[Units expressed as metric tons. XX, negligible]

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Cadmium										
U.S. apparent consumption[1]	2,250	2,510	2,100	1,850	2,010	1,000	1,460	637	1,170	656
Cadmium content, by battery type:[2]										
Camcorder batteries[3]	82	68	45	38	41	40	41	26	15	6.9
Camera batteries[3]	1.2	1.1	2	2.3	0	0	0	0	0	0
Cell phone batteries[3]	20	22	19	18	12	0	0	0	0	0
Total	100	91	66	58	53	40	41	26	15	7
Cobalt										
U.S. apparent consumption[4]	9,380	11,200	11,500	10,700	11,600	11,800	9,830	10,000	9,920	11,900
Cobalt content, by battery type:[2]										
Camcorder batteries[3]	5.2	9	17	33	43	43	52	52	47	47
Camera batteries[3]	XX	0.4	0.9	3	8.6	9.8	15	31	37	49
Cell phone batteries[3]	18	44	73	160	310	380	510	730	1,100	1,400
Hybrid vehicle batteries[5]	0	0	0	XX	XX	0.7	0.6	1.2	2.2	4.6
Portable computer batteries[3]	32	65	84	130	260	330	520	690	650	840
Total	55	120	170	330	620	760	1,100	1,500	1,800	2,300
Lithium										
U.S. apparent consumption[6]	2,700	2,800	2,800	2,800	2,800	1,400	1,100	1,400	1,900	2,500
Lithium content, by battery type:[2]										
Camcorder batteries[3]	82	68	45	38	40	40	43	26	15	6.9
Camera batteries[3]	0.1	0.3	0.5	1.7	4.1	3.9	6.5	12	15	19
Cell phone batteries[3]	1.8	4.9	8	18	34	45	62	92	140	170
Portable computer batteries[3]	3.3	7.1	10	15	29	38	60	81	77	99
Total	87	80	63	73	110	130	170	210	250	290
Nickel										
U.S. apparent consumption[7]	206,000	222,000	212,000	211,000	233,000	210,000	205,000	200,000	212,000	213,000
Nickel content, by battery type:[2]										
Camcorder batteries[3]	130	100	74	65	71	72	74	48	28	13
Camera batteries[3]	1.8	2.2	3.6	6.5	9.3	7.9	10	11	12	9.4
Cell phone batteries[3]	84	120	210	430	830	540	450	230	140	110
Hybrid vehicle batteries[5]	XX	XX	XX	49	250	420	350	690	1,300	2,700
Portable computer batteries[3]	67	84	79	92	140	150	190	140	130	140
Total	280	310	370	640	1,300	1,200	1,100	1,100	1,600	3,000

[1] Source data for 1996-2003, U.S. Geological Survey (2005); source data for 2004-05, Cooper and Kuck (2007). Apparent consumption is reported here for reference only, as it does not include materials contained in manufactured products imported to or exported from the United States.

[2] Sum of the metal contained in net imports of batteries applicable to each end use evaluated in this study. Values rounded to 2 significant digits and totaled to nearest whole number.

[3] Estimates derived from U.S. International Trade Commission (2006).

[4] Source data for 1996-2003, U.S. Geological Survey (2005); source data for 2004-05, Shedd (2007).

[5] Estimates derived from U.S. Department of Energy (2006), U.S. Department of Transportation (2006), U.S. International Trade Commission (2006).

[6] Source data for 1996-2005, Ober (1997-2007), Ober (2002), Ober (2003), Ober (2004), Ober (2005), Ober (2006), Ober (2007).

[7] Source data for 1996-2003, U.S. Geological Survey (2005); source data for 2004, Kuck (2005); source data for 2005, Kuck (2007).

than any other application examined in this study. Cadmium use in camcorder batteries declined to about 7 t in 2005 from 82 t in 1996. NiCd rechargeable batteries have been replaced by Li-ion and NiMH rechargeable batteries in cameras since about 2000 and in cell phones since about 2001. In contrast to the decline in NiCd battery usage, the number of spent NiCd batteries that end up in landfills has increased in the past 10 years. Study data suggest that about 91 t of cadmium was contained in cell phone batteries available for recovery or disposal from 1996 through 2005, although much of this material was discarded prior to 2001. Efforts to recycle NiCd batteries have increased. The percentage of cadmium metal recovered from the reservoir of available NiCd batteries of all types was estimated by the USGS to range from 10 to 27 percent for the 1996 to 2007 period. The collection rate for large industrial NiCd batteries in the United States was reported to be approximately 80 percent, while the collection rate for small portable rechargeable batteries in the United States was reported to range from 5 to 21 percent (Hawkins and others, 2006).

During the period from 1996 through 2005, cobalt use in rechargeable batteries grew in all the end-use applications assessed in this study (table 2). Cell phones and portable computers consumed the greatest amount of cobalt in 1996, the former because of the large number of battery cells in circulation and the latter because of the larger cobalt content in computer battery packs. Estimates suggest that in 1996, cell phone batteries accounted for about 18 t of cobalt; by 2005, the amount of cobalt contained in cell phone batteries had increased to about 1,400 t. The use of cobalt in portable computer batteries similarly increased to about 840 t in 2005 from about 32 t in 1996 because of increased use of Li-ion batteries in portable computers. Of the estimated 4,700 t of cobalt from cell phones available for recovery or disposal between 1996 and 2005, about 410 t was recycled, and about 4,300 t was exported, stored, or disposed of in MSW landfills.

Lithium use in rechargeable batteries has grown with the increased use of Li-ion and lithium-polymer battery chemistries in consumer electronics. Although U.S. apparent consumption of lithium (excluding materials contained in manufactured imported products) decreased from 2000 through 2004 (table 2) primarily as a result of decreased U.S. aluminum production (Ober, 2002), increased U.S. consumption of lithium as a component of rechargeable batteries contained in consumer electronic products imported to the United States may have helped offset reduced U.S. consumption from other sectors. Cell phones and portable computers consumed the greatest amount of lithium in 2005, the former because of the large number of battery cells in circulation and the latter because of the larger lithium content in computer battery packs. In 1996, cell phone batteries accounted for 1.8 t of lithium; by 2005, the amount of lithium contained in cell phone batteries had increased to 170 t. Similarly, portable computer batteries accounted for 3.3 t of lithium in 1996 and 99 t in 2005. Study data suggest that up to about 580 t of lithium was contained in cell phone batteries available for recovery or disposal from 1996 through 2005. Changes in camcorder and camera technology from 1996 through 2005 had the net effect of reducing the lithium content per battery for these applications; because the number of cameras (primarily digital) used in the United States increased during this period, however, the total quantity of lithium contained in camera batteries used in the United States increased.

The overall pattern of U.S. nickel consumption for the electronic consumer products studied changed significantly during the period from 1996 through 2005. Nickel consumption derived from NiCd batteries that powered cell phones increased to 830 t in 2000 from 84 t in 1996, then decreased to 110 t in 2005 (table 2) as lithium-based batteries increasingly substituted for NiCd batteries and then for NiMH batteries, and as cell phone batteries became smaller and used less nickel per cell. Nickel consumption in portable computer batteries gradually increased to 140 t in 2005 from 67 t in 1996; nickel consumption in camera batteries remained below 13 t for the entire period; and nickel consumption in camcorder batteries decreased to 13 t in 2005 from 130 t in 1996. Technological and consumer preference changes are the primary reasons for these consumption pattern changes. Of the estimated 3,100 t of nickel in cell phones available for recovery or disposal between 1996 and 2005, about 170 t of nickel was recycled and about 2,900 t was exported, stored, or disposed of in MSW landfills.

As the number of HEV vehicles increase, nickel use in HEV NiMH batteries is expected to increase by a factor of 10 by 2010 to about 7,300 t of nickel. Changes in energy prices, technological breakthroughs, and other unanticipated factors may affect the rate and size of this anticipated increase. NiMH batteries will continue to be the most widely used HEV battery in 2010. Based on available data, nickel used in HEV batteries may represent about 1.5 percent of total nickel apparent consumption in the United States in 2010.

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Appendix

The appendix lists the assumptions and estimates used in this study. Table A–1 summarizes material content assumptions and estimates for nickel-cadmium batteries; table A–2 summarizes material content assumptions and estimates for primary lithium-based batteries; table A–3 summarizes material content assumptions and estimates for nickel-metal-hydride batteries; and table A–4 summarizes material content assumptions and estimates for lithium-ion and lithium-polymer batteries. Manufacturers' data were derived from selected Material Safety Data Sheets, which where publicly available from battery manufacturers having a sizeable U.S. presence. Average battery weights and material contents for each HTS classification applicable to each manufactured product under review were developed from these data. Table A–5 summarizes specific material content assumptions for cell phone batteries; table A–6 summarizes specific material content assumptions for portable (laptop) computer batteries; table A–7 summarizes specific material content assumptions for camera batteries; table A–8 summarizes specific material content assumptions for video camera (camcorder) batteries; and table A–9 summarizes material content assumptions for batteries designated for hybrid vehicles considered in this study.

HTS classes applied to each end use are listed for nickel-cadmium batteries in table A–10 and for lithium-ion and nickel-metal-hydride batteries in table A–11. Some classifications apply only to either export or import data; most apply to both export and import data. Tables A–10 and A–11 report the years for which each HTS class was applicable for the study period, and whether the class applies to export data, import data, or both.

Table A–1. Selected material content assumptions and estimates for nickel-cadmium batteries used in this study to determine the flow of cadmium in the United States from 1996 through 2005.

[NA, not available; XX, not applicable; —, zero]

Battery class (based on end use)	Manufacturer and/or battery type	Cell weight range[2], in grams	Average weight of cell[2], in grams	Cadmium content[2], in percent	Cadmium content/cell or pack[3], in grams	Cobalt content[2], percent	Cobalt content/cell or pack[3], in grams	Nickel content[2], percent	Nickel content/cell or pack[3], in grams	Nickel-cadmium, in percentage of total estimate[4]	Years for which data applied
General nickel-cadmium storage battery[5]	NA	NA	NA	14	NA	0	NA	22	NA	NA	1996–2005
Storage batteries, separate:											
Electrically-powered vehicle batteries	Saft STM	12,900–17,000	14,400	16	2,300	1	100	22	3,200	100	1996–2005
Sealed consumer batteries	Saft VRE	19–150	60	10–15	8.4	0.4–1	0.4	20–28	13.2	100	1996–2005
	Sanyo Cadnica	NA	NA	11–26	NA	0	0	13–29	NA	100	1996–2005
Industrial batteries	Saft SLM	1,000–45,000	14,900	8	1,200	0.2	30	9	1,300	100	1996–2005
	Saft SPH	NA	NA	16	NA	1	0	22	NA	100	1996–2005
Batteries enclosed in products:											
Power tools	Saft VRE–C	NA	43	10–15	6	0.4–1	0.3	20–28	9.5	91	1996–2005
Cordless phones	Battery selection[6]	63–113	80	14	11.2	0.9	0.7	22	17.6	40	1996–2005
Camcorders	Battery selection[6]	59–376	160	14	22	0.9	1.4	22	35	30	1996–2003
	XX	XX	XX	XX	XX	XX	XX	XX	XX	18	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	6	2005
Cameras	Battery selection[6]	20–318	130	14	19	0.5	0.5	22	29	30	1996–1999
Portable radios	Saft VRE–AA	14–32	21	10–15	2.9	0.4–1	0.1	20–28	4.6	6	1996–2005
	Sanyo Cadnica-AA	NA	NA	11–26	NA	0	0	13–29	NA	6	1996–2005
Shavers	Saft VRE–AA	14–32	21	10–15	2.9	0.4–1	0.1	20–28	4.6	45	1996–2003
	Sanyo Cadnica-AA	NA	NA	11–26	NA	0	0	13–29	NA	34	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	22	2005
Electric toothbrushes	Saft VRE–AA	14–32	21	10–15	2.9	0.4–1	0.1	20–28	4.6	45	1996–2003
	Sanyo Cadnica-AA	NA	NA	11–26	NA	0	0	13–29	NA	34	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	22	2005
Portable vacuum cleaners	Saft VRE–Cs	43–150	97	10–15	13.6	0.4–1	0.7	20–28	21.3	45	1996–2003
	Saft VRE–D	NA	NA	10–15	NA	0.4–1	NA	20–28	NA	34	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	22	2005
Flashlights	Sanyo Cadnica	19–145	49	11–26	6.9	0	0	13–29	10.8	4	1996–2003
	XX	XX	XX	XX	XX	XX	XX	XX	XX	3	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	2	2005
	Energizer	NA	NA	13–22	NA	0.5–2	NA	20–32	NA	—	1996–2005
	Panasonic	26–51	40	NA	NA	NA	NA	NA	NA	—	1996–2005
Portable electric lamps (bicycle lamps, for example)	Saft VE	18–150	64	10–15	9	0.4–1	0.4	20–28	14	24	1996–2003
	XX	XX	XX	XX	XX	XX	XX	XX	XX	18	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	12	2005
Clock batteries, reported separately	Saft VRE–AA	14–32	21	10–15	2.9	0.4–1	0.1	20–28	4.6	4	1996–2003
	Sanyo Cadnica-AA	NA	NA	11–26	NA	0	0	13–29	NA	3	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	2	2005
Military batteries, reported separately	Saft VRE–AA	14–32	21	10–15	2.9	0.4–1	0.1	20–28	4.6	16	1996–2005
	Sanyo Cadnica-AA	NA	NA	11–26	NA	0	0	13–29	NA	16	1996–2005

[1] Manufacturer was selected based on the volume of production and the availability of data. Battery selection was based on the applicability to the end-use category. Batteries selected are assumed to be representative for the given classification.

[2] Based on reported weights given by the manufacturer for all batteries in that classification. Data were obtained from the specified manufacturer's Web site.

[3] Calculated using (average weight of cell or pack) × (specified commodity content). When a percent range is shown, the average percentage reported by Vangheluwe, Verdonck, and Versonnen (2005) was used for calculations.

[4] Percent allocation of the number of batteries listed as nickel-cadmium batteries, based on end-use distributions reported by Pillot (2004, p. 29–31; 2005a, p. 5–8). In some cases, the 2004 and 2005 percentages were reported to be lower than the percentages of previous years. Where no years are reported, value applies to entire study period.

[5] Vangheluwe, Verdonck, and Versonnen (2005).

[6] Based on a random selection of batteries used for each of these applications (Zbattery.com, written commun., November 22, 2006).

Table A–2. Selected material content assumptions and estimates for primary lithium-based batteries used in this study.

[NA, not available; V, volt]

Battery class (based on chemistry)	Battery type[1]	Manufacturer[1]	Cell weight/range[2], in grams	Average weight of cell[2], in grams	Lithium content[2], in percent	Lithium content per cell[3], in grams
Manganese-dioxide-lithium primary (alkaline type)	CR coin type	Sanyo Electric Co. Ltd.	0.8–6.9	3.2	~3	0.065
	CR coin type	Energizer Battery Manufacturing Inc.	0.7–6.9	2.4	1–6	0.051
	CR coin type	Sony Corporation	0.7–10	3.2	NA	0.096
	CR coin type	Panasonic Corp.	0.7–6.8	2.6	NA	0.078
	Button/coin type	AA Portable Power Corp.	0.7–10.5	2.8	NA	0.084
	BR cylindrical type	Sanyo Electric Co. Ltd.	3.3–38	20.7	~3	0.64
	SE cylindrical type	Sanyo Electric Co. Ltd.	9–42	21	NA	0.69
	CR cylindrical type	Energizer Battery Manufacturing Inc.	3–40	23	NA	0.73
	LM series cylindrical type 3.2 V	Saft Group SA	2.9–6	4.3	~3.3	0.142
	AAA size cylindrical type	Panasonic Corp.	11	11	NA	NA
	AAA size	U.S. average (1996)	NA	12	NA	NA
	AA size	U.S. average (1996)	NA	30	NA	NA
	AA size cylindrical type	Panasonic Corp.	23	23	NA	0.69
	C size	U.S. average (1996)	NA	70	NA	NA
	C size cylindrical type	Panasonic Corp.	70	70	NA	NA
	C size cylindrical type	Ultralife Batteries Inc.	61	61	1–4	1.52
	LM series cylindrical type C-cell	Saft Group SA	55	55	~3.3	1.81
	D size	U.S. average (1996)	NA	140	NA	NA
	D size cylindrical type	Panasonic Corp.	141	141	NA	NA
	D size cylindrical type	Ultralife Batteries Inc.	115	115	3–4	4
	LM series cylindrical type D-cell	Saft Group SA	116	116	~3.3	3.8
	9V type	Ultralife Batteries Inc.	33.8–36.4	35	1–4	0.87
	9V size	U.S. average (1996)	NA	50	NA	NA
	Prismatic type	Ultralife Batteries Inc.	3.5–15	9	5–8	0.59
	Military type	Ultralife Batteries Inc.	10–61	44	1–4	1.1
Lithium iron disulfide primary	Cylindrical type	Energizer Battery Manufacturing Inc.	34–36	35	5–8	1.35
Lithium thionyl chloride primary	LS/LST series cylindrical type	Saft Group SA	8.9–23.5	14.4	3.5–5	0.61
	LSH series cylindrical type	Saft Group SA	24–100	65	3.5–5	2.76
Lithium sulfur dioxide primary	LO/G series cylindrical type	Saft Group SA	8–300	72	<3	2.1

[1] Manufacturer was selected based on the volume of production and the availability of data. Battery selection was based on the applicability to the end-use category. Batteries selected are assumed to be representative for the given classification.

[2] Based on reported weights of cell or pack given by the manufacturer for all batteries in that classification. Data were obtained from the specified manufacturer's Web site.

[3] Calculated from (average weight of cell or pack) × (specified commodity content). When a percent range is shown, the average weight percentage was derived by averaging all batteries of similar type.

Table A–3. Selected material content assumptions and estimates for nickel-metal-hydride batteries used in this study.
[e, estimate; NA, not available]

Battery type[1]	Manufacturer[1]	Cell weight range[2], in grams	Average weight of cell or pack[2], in grams	Cobalt content from Co or LiCo(OH)$_2$[2], in percent	Cobalt content/ cell[3], in grams	Nickel content[2], in percent	Nickel content/cell or pack[3], in grams
AA size cylindrical type	Saft Group SA	25–26	25.5	0.6–3	0.56	30–45	9.4
C size cylindrical type	Saft Group SA	59	59	0.6–3	1.3	30–45	22
D size cylindrical type	Saft Group SA	160	160	0.6–3	3.5	30–45	59
D size hybrid vehicle type	Sanyo/Saft	NA	43,600	0.4–1e	300	40	17,000
D size hybrid vehicle type	Matsushita/Panasonic	NA	39,500	NA	NA	35.5	14,000
Cylindrical type battery pack	Panasonic Corp.	12– 170	51	NA	NA	NA	NA
Cylindrical type	Energizer Battery Manufacturing Inc.	NA	NA	1.5–3.6	NA	30–50	NA
Button type	AA Portable Power Corp.	1.8– 13	6.9	NA	NA	NA	NA
Prismatic type	AA Portable Power Corp.	9– 26	18	NA	NA	NA	NA
Button type	Linden, David, 1995: Handbook of Batteries, 1995, p. 33.28	NA	NA	NA	NA	NA	NA
Cylindrical type	Linden, David, 1995: Handbook of Batteries, 1995, p. 33.28	25– 52	37	NA	NA	NA	NA
Prismatic type	Linden, David, 1995: Handbook of Batteries, 1995, p. 33.28	17– 24	21	NA	NA	NA	NA
Average of all types	Rydh and Svard, 2003, Impact on global metal flows arising from the use of portable rechargeable batteries: table 3, p. 172.	NA	NA	2.5–4.3	NA	25–46	NA

[1] Manufacturer was selected based on the volume of production and the availability of data. Battery selection was based on the applicability to the end-use category. Batteries selected are assumed to be representative for the given classification.

[2] Based on reported weights of cell or pack given by the manufacturer for all batteries in that classification. Data were obtained from the specified manufacturer's Web site.

[3] Calculated from (average weight of cell or pack) × (specified commodity content). When a percent range is shown, the average weight percentage was derived by averaging all batteries of similar type.

Table A–4. Selected material content assumptions and estimates for lithium-ion and lithium-polymer batteries used in this study.
[AH, amp-hours; g, grams; NA, not available]

Battery class (based on chemistry)	Battery type[1]	Manufacturer[1]	Cell or pack weight range[2], in grams	Average weight of cell or pack[2], in grams	Cobalt content from Co or LiCo(OH)$_2$[2], in percent	Cobalt content/cell[3], in grams	Lithium content from Li or LiCoO$_2$[2], in percent	Lithium content/cell or pack[3], in grams
Lithium cobalt dioxide ion rechargeable	Theoretical equivalent lithium content	Source: Linden, 1995, p. 36.48	NA	NA	NA	NA	NA	0.3 × capacity (AH)
	Cylindrical type	Panasonic Corp.	42–46.5	44.8	NA	NA	NA	NA
	Cylindrical type	Sanyo Electric Co. Ltd.	15–21	18.6	15	2.8	1.8	0.34 g/cell
	Cylindrical type	Sanyo Electric Co. Ltd.	15–80	36.7	15	5.5	1.8	0.66 g/cell
	Cylindrical type	Ultralife Batteries Inc.	15–41	22.6	20	4.5	2.4	0.55 g/cell
	Cylindrical type	Source: Linden, 1995, p. 36.48	18–39	30	NA	NA	NA	NA
	LC cylindrical type	AA Portable Power Corp.	5.6–53	26	15–24	5.1	1.8–2.8	0.6 g/cell
	LC cylindrical type	Sanyo Electric Co. Ltd.	11.5–46	22.2	1 5– 24	4.3	1.8–2.8	0.51 g/cell
	Prismatic type	Source: Linden, 1995, p. 36.48	20–65	41.5	NA	NA	NA	NA
	Prismatic type	Panasonic Corp.	15–40	25	NA	NA	NA	NA
	Prismatic type	AA Portable Power Corp.	13.5–39.6	25	NA	NA	NA	NA
	Prismatic type	Energizer Battery Manufacturing Inc.	NA	NA	9–18	NA	1.1–2.1	NA
	MP series prismatic type	Saft Group SA	68–153 per pack	117 per pack	18	21 per pack	~2.1%	2.46 g/cell
	VLE series hybrid vehicle battery pack	Saft Group SA	8,000 per module × 5 modules	40,000 per pack	18	7,200 per pack	~2.1%	860 g/pack
Lithium-ion industrial battery pack	VLM series	Saft Group SA	770–1070 per pack	920 per pack	18	166 per pack	~2.1%	19 g/cell
	VLP series	Saft Group SA	370–1,100 per pack	760 per pack	18	137 per pack	~2.1%	16 g/cell
	Military type	Ultralife Batteries Inc.	925–1440	1146	15–24	223	1.8–2.8	26 g/cell
	Military type	Matsushita Battery Industrial Co. Ltd.	NA	NA	12–19	NA	1.4–2.5	NA
Lithium cobalt dioxide polymer rechargeable	UPF series prismatic type	Sanyo Electric Co. Ltd.	8.3–46	21.7	6–12	0.5–5.5	1.1–2.2	0.36 g/cell
	Prismatic type	Ultralife Batteries Inc.	3–85	17	1.8–2.6	0.37	15–21	3.1 g/cell
	Prismatic type	Ascent Battery Supply Corp.	NA	NA	15–18	NA	1.8–2.1	NA

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[1] Manufacturer was selected based on the volume of production and the availability of data. Battery selection was based on the applicability to the end-use category. Batteries selected are assumed to be representative for the given classification.

[2] Based on reported weights of cell or pack given by the manufacturer for all batteries in that classification. Data were obtained from the specified manufacturer's Web site.

[3] Calculated from (average weight of cell or pack) × (specified commodity content). When a percent range is shown, the average weight percentage was derived by averaging all batteries of similar type.

Table A–5. Material content assumptions for selected metals and materials in batteries designated for cell phones, by year.

[Li, lithium; Li-ion, lithium-ion battery; Li-polymer, lithium-polymer battery; NiCd, nickel-cadmium battery; NiMH, nickel-metal-hydride battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 23; 2005a, p. 5; 2005b, p. 19). Values may not add to totals shown owing to rounding]

Year	Cell chemistry	Number of units	Cell mass, grams per battery	Cadmium fraction, in percent	Cobalt fraction, in percent	Lithium fraction, in percent	Nickel fraction, in percent	Cadmium mass, in kilograms	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
1996	NiCd	1,800,000	80	14	0.9	0	22	20,000	1,300	0	31,000
	NiMH	1,900,000	74	0	2.2	0	37	0	3,100	0	53,000
	Li-ion	1,100,000	72	0	17.6	2.3	0	0	14,000	1,800	0
	Li-polymer	0	47	0	15.9	1.7	0	0	0	0	0
1997	NiCd	2,000,000	80	14	0.9	0	22	22,000	1,400	0	34,000
	NiMH	3,300,000	74	0	2.2	0	37	0	5,300	0	89,000
	Li-ion	2,900,000	72	0	17.6	2.3	0	0	37,000	4,900	0
	Li-polymer	0	47	0	15.9	1.7	0	0	0	0	0
1998	NiCd	1,700,000	80	14	0.9	0	22	19,000	1,200	0	30,000
	NiMH	6,500,000	74	0	2.2	0	37	0	11,000	0	180,000
	Li-ion	4,800,000	72	0	17.6	2.3	0	0	61,000	8,000	0
	Li-polymer	0	47	0	15.9	1.7	0	0	0	0	0
1999	NiCd	1,600,000	80	14	0.9	0	22	18,000	1,200	0	29,000
	NiMH	15,000,000	74	0	2.2	0	37	0	24,000	0	400,000
	Li-ion	10,000,000	72	0	17.6	2.3	0	0	130,000	17,000	0
	Li-polymer	270,000	47	0	15.9	1.7	0	0	2,000	220	0
2000	NiCd	1,000,000	80	14	0.9	0	22	12,000	700	0	18,000
	NiMH	30,000,000	74	0	2.2	0	37	0	48,000	0	810,000
	Li-ion	20,000,000	72	0	17.6	2.3	0	0	260,000	33,000	0
	Li-polymer	1,000,000	47	0	15.9	1.7	0	0	7,700	830	0
2001	NiCd	0	80	14	0.9	0	22	0	0	0	0
	NiMH	35,000,000	42	0	2.2	0	37	0	32,000	0	540,000
	Li-ion	39,000,000	48	0	17.6	2.3	0	0	330,000	43,000	0
	Li-polymer	3,100,000	42	0	15.9	1.7	0	0	21,000	2,200	0
2002	NiCd	0	80	14	0.9	0	22	0	0	0	0
	NiMH	29,000,000	42	0	2.2	0	37	0	27,000	0	450,000
	Li-ion	52,000,000	48	0	17.6	2.3	0	0	440,000	58,000	0
	Li-polymer	6,100,000	42	0	15.9	1.7	0	0	41,000	4,400	0
2003	NiCd	0	80	14	0.9	0	22	0	0	0	0
	NiMH	15,000,000	42	0	2.2	0	37	0	14,000	0	230,000
	Li-ion	75,000,000	48	0	17.6	2.3	0	0	630,000	83,000	0
	Li-polymer	12,000,000	42	0	15.9	1.7	0	0	83,000	8,800	0
2004	NiCd	0	80	14	0.9	0	22	0	0	0	0
	NiMH	8,800,000	42	0	2.2	0	37	0	8,100	0	140,000
	Li-ion	120,000,000	48	0	17.6	2.3	0	0	990,000	130,000	0
	Li-polymer	20,000,000	42	0	15.9	1.7	0	0	140,000	15,000	0
2005	NiCd	0	80	14	0.9	0	22	0	0	0	0
	NiMH	7,000,000	42	0	2.2	0	37	0	6,400	0	110,000
	Li-ion	140,000,000	48	0	17.6	2.3	0	0	1,200,000	150,000	0
	Li-polymer	30,000,000	42	0	15.9	1.7	0	0	200,000	21,000	0

Table A–6. Material content assumptions for selected metals and materials in batteries designated for portable (laptop) computers, by year.

[Li-ion, lithium-ion battery; NiMH, nickel-metal-hydride battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 29; 2005a, p. 6). Values may not add to totals shown owing to rounding]

Year	Cell chemistry	Number of units	Cobalt mass, in grams per battery pack	Lithium mass, in grams per battery pack	Nickel mass, in grams per battery pack	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
			U.S. import data					
1996	NiMH	1,000,000	5	0	85	5,100	0	86,000
	Li-ion	830,000	46	5.2	0	36,000	4,300	0
1997	NiMH	1,200,000	5	0	85	6,300	0	110,000
	Li-ion	1,700,000	46	5.2	0	75,000	8,900	0
1998	NiMH	1,200,000	5	0	85	5,900	0	99,000
	Li-ion	2,300,000	46	5.2	0	99,000	12,000	0
1999	NiMH	1,300,000	5	0	85	6,500	0	110,000
	Li-ion	3,500,000	46	5.2	0	150,000	18,000	0
2000	NiMH	1,900,000	5	0	85	9,700	0	160,000
	Li-ion	6,400,000	46	5.2	0	280,000	33,000	0
2001	NiMH	1,900,000	5	0	85	9,800	0	160,000
	Li-ion	8,300,000	46	5.2	0	360,000	43,000	0
2002	NiMH	2,400,000	5	0	85	12,000	0	200,000
	Li-ion	13,000,000	46	5.2	0	550,000	66,000	0
2003	NiMH	1,800,000	5	0	85	8,900	0	150,000
	Li-ion	17,000,000	46	5.2	0	740,000	88,000	0
2004	NiMH	1,900,000	5	0	85	9,500	0	160,000
	Li-ion	18,000,000	46	5.2	0	790,000	94,000	0
2005	NiMH	1,900,000	5	0	85	9,600	0	160,000
	Li-ion	22,000,000	46	5.2	0	960,000	110,000	0
			U.S. export data					
1996	NiMH	230,000	5	0	85	1,100	0	19,000
	Li-ion	190,000	46	5.2	0	8,100	1,000	0
1997	NiMH	250,000	5	0	85	1,300	0	21,000
	Li-ion	350,000	46	5.2	0	15,000	1,800	0
1998	NiMH	230,000	5	0	85	1,200	0	19,000
	Li-ion	440,000	46	5.2	0	19,000	2,300	0
1999	NiMH	200,000	5	0	85	1,000	0	17,000
	Li-ion	540,000	46	5.2	0	24,000	2,800	0
2000	NiMH	230,000	5	0	85	1,200	0	19,000
	Li-ion	770,000	46	5.2	0	34,000	4,000	0
2001	NiMH	210,000	5	0	85	1,100	0	18,000
	Li-ion	910,000	46	5.2	0	40,000	4,800	0
2002	NiMH	200,000	5	0	85	1,000	0	17,000
	Li-ion	1,000,000	46	5.2	0	46,000	5,500	0
2003	NiMH	150,000	5	0	85	700	0	13,000
	Li-ion	1,400,000	46	5.2	0	61,000	7,300	0
2004	NiMH	350,000	5	0	85	1,700	0	29,000
	Li-ion	3,300,000	46	5.2	0	140,000	17,000	0
2005	NiMH	260,000	5	0	85	1,300	0	22,000
	Li-ion	3,000,000	46	5.2	0	130,000	15,000	0

Table A–6. Material content assumptions for selected metals and materials in batteries designated for portable (laptop) computers, by year.—Continued

[Li-ion, lithium-ion battery; NiMH, nickel-metal-hydride battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 29; 2005a, p. 6). Values may not add to totals shown owing to rounding]

Year	Cell chemistry	Number of units	Cobalt mass, in grams per battery pack	Lithium mass, in grams per battery pack	Nickel mass, in grams per battery pack	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
				Net import data				
1996	NiMH	770,000	5	0	85	4,000	0	67,000
	Li-ion	640,000	46	5.2	0	28,000	3,300	0
1997	NiMH	990,000	5	0	85	5,000	0	84,000
	Li-ion	1,400,000	46	5.2	0	60,000	7,100	0
1998	NiMH	940,000	5	0	85	4,700	0	79,000
	Li-ion	1,800,000	46	5.2	0	79,000	9,500	0
1999	NiMH	1,100,000	5	0	85	5,500	0	92,000
	Li-ion	2,900,000	46	5.2	0	130,000	15,000	0
2000	NiMH	1,700,000	5	0	85	8,500	0	140,000
	Li-ion	5,600,000	46	5.2	0	250,000	29,000	0
2001	NiMH	1,700,000	5	0	85	8,700	0	150,000
	Li-ion	7,400,000	46	5.2	0	320,000	38,000	0
2002	NiMH	2,200,000	5	0	85	11,000	0	190,000
	Li-ion	12,000,000	46	5.2	0	510,000	60,000	0
2003	NiMH	1,600,000	5	0	85	8,200	0	140,000
	Li-ion	15,000,000	46	5.2	0	680,000	81,000	0
2004	NiMH	1,500,000	5	0	85	7,800	0	130,000
	Li-ion	15,000,000	46	5.2	0	640,000	77,000	0
2005	NiMH	1,600,000	5	0	85	8,300	0	140,000
	Li-ion	19,000,000	46	5.2	0	830,000	99,000	0

Table A–7. Material content assumptions for selected metals and materials in batteries designated for cameras, by year.

[Li-ion, lithium-ion battery; NA, not available; XX, not applicable; NiCd, nickel-cadmium battery; NiMH, nickel-metal-hydride battery; Primary Li, primary lithium battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 27, 30; 2005a, p. 7). Number of units reflects the number of net camera imports to the United States. Net export situations are represented by a 0 value. Domestic camera battery production is assumed negligible. Values may not add to totals shown owing to rounding]

Year	Cell chemistry/ product type	Number of units	Cadmium mass, in grams per pack	Cobalt mass, in grams per pack	Lithium mass, in grams per pack	Nickel mass, in grams per pack	Cadmium mass, in kilograms	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
1996	NiCd	61,000	19	0.5	0	29	1,200	31	XX	1,800
	Analog	61,000	19	NA	0	29	1,200	NA	XX	1,800
	Digital	0	0	NA	0	0	0	NA	XX	0
	NiMH	0	0	NA	0	NA	XX	0	XX	0
	Analog	0	0	1.1	0	19	XX	0	XX	0
	Digital	0	0	0.3	0	5.2	XX	0	XX	0
	Li-ion	0	0	NA	NA	0	XX	0	0	XX
	Analog	0	0	9	1.1	0	XX	0	0	XX
	Digital	0	0	2.4	0.72	0	XX	0	0	XX
	Primary Li	550,000	0	0	1.3	0	XX	0	110	XX
	Analog	550,000	0	0	1.3	0	XX	0	110	XX
	Digital	0	0	0	1.3	0	XX	0	0	XX
1997	NiCd	58,000	19	0.5	0	29	1,100	29	XX	1,700
	Analog	32,000	19	NA	0	29	620	NA	XX	950
	Digital	26,000	0	NA	0	0	480	NA	XX	750
	NiMH	58,000	0	NA	0	NA	XX	41	XX	700
	Analog	32,000	0	1.1	0	19	XX	NA	XX	580
	Digital	26,000	0	0.3	0	5.2	XX	NA	XX	120
	Li-ion	58,000	0	NA	NA	0	XX	330	54	XX
	Analog	32,000	0	9	1.1	0	XX	NA	36	XX
	Digital	26,000	0	2.4	0.72	0	XX	NA	18	XX
	Primary Li	990,000	0	0	1.3	0	XX	0	220	XX
	Analog	550,000	0	0	1.3	0	XX	0	120	XX
	Digital	440,000	0	0	1.3	0	XX	0	100	XX
1998	NiCd	100,000	19	0.5	0	29	2,000	52	XX	3,000
	Analog	28,000	19	NA	0	29	530	NA	XX	820
	Digital	75,000	0	NA	0	0	1,400	NA	XX	2,200
	NiMH	160,000	0	NA	0	NA	XX	76	XX	1,300
	Analog	45,000	0	1.1	0	19	XX	NA	XX	740
	Digital	120,000	0	0.3	0	5.2	XX	NA	XX	530
	Li-ion	210,000	0	NA	NA	0	XX	750	170	XX
	Analog	56,000	0	9	1.1	0	XX	NA	50	XX
	Digital	150,000	0	2.4	0.72	0	XX	NA	120	XX
	Primary Li	1,600,000	0	0	1.3	0	XX	0	370	XX
	Analog	430,000	0	0	1.3	0	XX	0	100	XX
	Digital	1,200,000	0	0	1.3	0	XX	0	270	XX
1999	NiCd	120,000	19	0.5	0	29	2,300	61	XX	3,500
	Analog	25,000	19	NA	0	29	480	NA	XX	730
	Digital	95,000	0	NA	0	0	1,800	NA	XX	2,700
	NiMH	600,000	0	NA	0	NA	XX	270	XX	4,600
	Analog	130,000	0	1.1	0	19	XX	NA	XX	1,000
	Digital	470,000	0	0.3	0	5.2	XX	NA	XX	3,600
	Li-ion	720,000	0	NA	NA	0	XX	2,600	580	XX
	Analog	150,000	0	9	1.1	0	XX	NA	120	XX
	Digital	570,000	0	2.4	0.72	0	XX	NA	460	XX
	Primary Li	4,500,000	0	0	1.3	0	XX	0	1,100	XX
	Analog	950,000	0	0	1.3	0	XX	0	230	XX
	Digital	3,600,000	0	0	1.3	0	XX	0	870	XX

Table A–7. Material content assumptions for selected metals and materials in batteries designated for cameras, by year.—Continued

[Li-ion, lithium-ion battery; NA, not available; XX, not applicable; NiCd, nickel-cadmium battery; NiMH, nickel-metal-hydride battery; Primary Li, primary lithium battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 27, 30; 2005a, p. 7). Number of units reflects the number of net camera imports to the United States. Net export situations are represented by a 0 value. Domestic camera battery production is assumed negligible. Values may not add to totals shown owing to rounding]

Year	Cell chemistry/ product type	Number of units	Cadmium mass, in grams per pack	Cobalt mass, in grams per pack	Lithium mass, in grams per pack	Nickel mass, in grams per pack	Cadmium mass, in kilograms	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
2000	NiCd	0	19	0.5	0	29	0	0	XX	0
	Analog	0	19	NA	0	29	0	0	XX	0
	Digital	0	0	NA	0	0	0	0	XX	0
	NiMH	1,800,000	0	NA	0	NA	XX	740	XX	12,000
	Analog	250,000	0	1.1	0	19	XX	NA	XX	4,600
	Digital	1,600,000	0	0.3	0	5.2	XX	NA	XX	7,800
	Li-ion	2,400,000	0	NA	NA	0	XX	7,900	1,800	XX
	Analog	340,000	0	9	1.1	0	XX	NA	250	XX
	Digital	2,100,000	0	2.4	0.72	0	XX	NA	1,500	XX
	Primary Li	7,900,000	0	0	1.3	0	XX	0	2,200	XX
	Analog	1,100,000	0	0	1.3	0	XX	0	310	XX
	Digital	6,800,000	0	0	1.3	0	XX	0	1,900	XX
2001	NiCd	0	19	0.5	0	29	0	0	XX	0
	Analog	0	19	NA	0	29	0	0	XX	0
	Digital	0	0	NA	0	0	0	0	XX	0
	NiMH	1,500,000	0	NA	0	NA	XX	580	XX	9,700
	Analog	150,000	0	1.1	0	19	XX	NA	XX	2,800
	Digital	1,400,000	0	0.3	0	5.2	XX	NA	XX	6,900
	Li-ion	3,100,000	0	NA	NA	0	XX	9,200	2,300	XX
	Analog	310,000	0	9	1.1	0	XX	NA	230	XX
	Digital	2,800,000	0	2.4	0.72	0	XX	NA	2,100	XX
	Primary Li	5,700,000	0	0	1.3	0	XX	0	1,600	XX
	Analog	570,000	0	0	1.3	0	XX	0	160	XX
	Digital	5,100,000	0	0	1.3	0	XX	0	1,500	XX
2002	NiCd	0	19	0.5	0	29	0	0	XX	0
	Analog	0	19	NA	0	29	0	0	XX	0
	Digital	0	0	NA	0	0	0	0	XX	0
	NiMH	2,100,000	0	NA	0	NA	XX	690	XX	12,000
	Analog	100,000	0	1.1	0	19	XX	NA	XX	1,800
	Digital	1,900,000	0	0.3	0	5.2	XX	NA	XX	9,700
	Li-ion	5,500,000	0	NA	NA	0	XX	15,000	4,100	XX
	Analog	280,000	0	9	1.1	0	XX	NA	200	XX
	Digital	5,200,000	0	2.4	0.72	0	XX	NA	3,900	XX
	Primary Li	8,200,000	0	0	1.3	0	XX	0	2,400	XX
	Analog	410,000	0	0	1.3	0	XX	0	120	XX
	Digital	7,800,000	0	0	1.3	0	XX	0	2,300	XX
2003	NiCd	0	19	0.5	0	29	0	0	XX	0
	Analog	0	19	NA	0	29	0	0	XX	0
	Digital	0	0	NA	0	0	0	0	XX	0
	NiMH	2,200,000	0	NA	0	NA	XX	780	XX	13,000
	Analog	130,000	0	1.1	0	19	XX	NA	XX	900
	Digital	2,100,000	0	0.3	0	5.2	XX	NA	XX	12,000
	Li-ion	11,000,000	0	NA	NA	0	XX	30,000	8,000	XX
	Analog	640,000	0	9	1.1	0	XX	NA	480	XX
	Digital	10,000,000	0	2.4	0.72	0	XX	NA	7,500	XX
	Primary Li	12,000,000	0	0	1.3	0	XX	0	3,800	XX
	Analog	720,000	0	0	1.3	0	XX	0	230	XX
	Digital	11,000,000	0	0	1.3	0	XX	0	3,600	XX

Table A–7. Material content assumptions for selected metals and materials in batteries designated for cameras, by year.—Continued

[Li-ion, lithium-ion battery; NA, not available; XX, not applicable; NiCd, nickel-cadmium battery; NiMH, nickel-metal-hydride battery; Primary Li, primary lithium battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 27, 30; 2005a, p. 7). Number of units reflects the number of net camera imports to the United States. Net export situations are represented by a 0 value. Domestic camera battery production is assumed negligible. Values may not add to totals shown owing to rounding]

Year	Cell chemistry/ product type	Number of units	Cadmium mass, in grams per pack	Cobalt mass, in grams per pack	Lithium mass, in grams per pack	Nickel mass, in grams per pack	Cadmium mass, in kilograms	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
2004	NiCd	0	19	0.5	0	29	0	0	XX	0
	Analog	0	19	NA	0	29	0	0	XX	0
	Digital	0	0	NA	0	0	0	0	XX	0
	NiMH	2,400,000	0	NA	0	NA	XX	780	XX	13,000
	Analog	100,000	0	1.1	0	19	XX	NA	XX	1,900
	Digital	2,300,000	0	0.3	0	5.2	XX	NA	XX	11,000
	Li-ion	14,000,000	0	NA	NA	0	XX	36,000	11,000	XX
	Analog	560,000	0	9	1.1	0	XX	NA	720	XX
	Digital	13,000,000	0	2.4	0.72	0	XX	NA	10,000	XX
	Primary Li	14,000,000	0	0	1.3	0	XX	0	3,900	XX
	Analog	540,000	0	0	1.3	0	XX	0	160	XX
	Digital	13,000,000	0	0	1.3	0	XX	0	3,700	XX
2005	NiCd	0	19	0.5	0	29	0	0	XX	0
	Analog	0	19	NA	0	29	0	0	XX	0
	Digital	0	0	NA	0	0	0	0	XX	0
	NiMH	1,800,000	0	NA	0	NA	XX	600	XX	10,000
	Analog	83,000	0	1.1	0	19	XX	NA	XX	1,500
	Digital	1,800,000	0	0.3	0	5.2	XX	NA	XX	9,500
	Li-ion	19,000,000	0	NA	NA	0	XX	49,000	14,000	XX
	Analog	840,000	0	9	1.1	0	XX	NA	570	XX
	Digital	18,000,000	0	2.4	0.72	0	XX	NA	13,000	XX
	Primary Li	16,000,000	0	0	1.3	0	XX	0	5,400	XX
	Analog	730,000	0	0	1.3	0	XX	0	260	XX
	Digital	15,000,000	0	0	1.3	0	XX	0	5,100	XX

Table A–8. Material content assumptions for selected metals and materials in batteries designated for video cameras (camcorders), by year.

[Li-ion, lithium-ion battery; NA, Not available; XX, Not applicable; NiCd, nickel-cadmium battery; NiMH, nickel-metal-hydride battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 27, 30). Values may not add to totals shown owing to rounding]

Year	Cell type	Number of units	Cadmium mass, in grams per pack	Cobalt mass, in grams per pack	Lithium mass, in grams per pack	Nickel mass, in grams per pack	Cadmium mass, in kilograms	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
1996	NiCd	3,700,000	22	1.4	0	35	82,000	5,100	XX	130,000
	Analog	1,800,000	22	1.4	0	35	41,000	2,600	XX	64,000
	Digital	1,900,000	22	1.4	0	35	41,000	2,600	XX	65,000
	NiMH	18,000	0	3.4	0	NA	XX	62	XX	1,000
	Analog	18,000	0	3.4	0	57	XX	62	XX	1,000
	Li-ion	0	0	NA	NA	0	XX	0	0	XX
	Analog	0	0	27	3.3	0	XX	0	0	XX
	Digital	0	0	7.3	2.2	0	XX	0	0	XX
1997	NiCd	2,800,000	22	1.4	0	35	68,000	3,900	XX	98,000
	Analog	1,800,000	22	1.4	0	35	40,000	2,500	XX	63,000
	Digital	990,000	22	1.4	0	35	28,000	1,400	XX	35,000
	NiMH	36,000	0	3.4	0	NA	XX	120	XX	2,100
	Analog	36,000	0	3.4	0	19	XX	120	XX	2,100
	Li-ion	690,000	0	NA	NA	0	XX	5,000	1,500	XX
	Analog	0	0	27	3.3	0	XX	0	0	XX
	Digital	690,000	0	7.3	2.2	0	XX	5,000	1,500	XX
1998	NiCd	2,000,000	22	1.4	0	35	45,000	2,800	XX	71,000
	Analog	1,700,000	22	1.4	0	35	37,000	2,300	XX	58,000
	Digital	350,000	22	1.4	0	35	7,800	500	XX	12,000
	NiMH	54,000	0	3.4	0	NA	XX	180	XX	3,000
	Analog	54,000	0	3.4	0	19	XX	180	XX	3,000
	Li-ion	1,800,000	0	NA	NA	0	XX	14,000	3,900	XX
	Analog	71,000	0	27	3.3	0	XX	1,900	240	XX
	Digital	1,700,000	0	7.3	2.2	0	XX	12,000	3,700	XX
1999	NiCd	1,800,000	22	1.4	0	35	38,000	2,400	XX	60,000
	Analog	1,600,000	22	1.4	0	35	35,000	2,200	XX	56,000
	Digital	140,000	22	1.4	0	35	3,100	190	XX	4,800
	NiMH	80,000	0	3.4	0	NA	XX	280	XX	4,800
	Analog	80,000	0	3.4	0	19	XX	280	XX	4,800
	Li-ion	3,000,000	0	NA	NA	0	XX	31,000	7,100	XX
	Analog	440,000	0	27	3.3	0	XX	12,000	1,500	XX
	Digital	2,600,000	0	7.3	2.2	0	XX	19,000	5,600	XX
2000	NiCd	1,800,000	22	1.4	0	35	41,000	2,500	XX	64,000
	Analog	1,700,000	22	1.4	0	35	37,000	2,300	XX	58,000
	Digital	160,000	22	1.4	0	35	3,500	220	XX	5,500
	NiMH	120,000	0	3.4	0	NA	XX	420	XX	7,000
	Analog	120,000	0	3.4	0	19	XX	420	XX	7,000
	Li-ion	3,700,000	0	NA	NA	0	XX	40,000	8,700	XX
	Analog	690,000	0	27	3.3	0	XX	19,000	2,300	XX
	Digital	3,000,000	0	7.3	2.2	0	XX	22,000	6,400	XX
2001	NiCd	1,800,000	22	1.4	0	35	40,000	2,500	XX	63,000
	Analog	1,700,000	22	1.4	0	35	37,000	2,300	XX	59,000
	Digital	140,000	22	1.4	0	35	3,000	190	XX	4,800
	NiMH	160,000	0	3.4	0	NA	XX	520	XX	8,800
	Analog	160,000	0	3.4	0	19	XX	520	XX	8,800
	Li-ion	3,400,000	0	NA	NA	0	XX	40,000	8,100	XX
	Analog	780,000	0	27	3.3	0	XX	21,000	2,600	XX
	Digital	2,600,000	0	7.3	2.2	0	XX	19,000	5,500	XX
2002	NiCd	1,800,000	22	1.4	0	35	41,000	2,600	XX	65,000
	Analog	1,700,000	22	1.4	0	35	39,000	2,400	XX	60,000
	Digital	130,000	22	1.4	0	35	2,000	190	XX	4,700
	NiMH	170,000	0	3.4	0	NA	XX	570	XX	9,600
	Analog	170,000	0	3.4	0	19	XX	570	XX	9,600
	Li-ion	4,200,000	0	NA	NA	0	XX	49,000	10,000	XX
	Analog	970,000	0	27	3.3	0	XX	26,000	3,200	XX
	Digital	3,200,000	0	7.3	2.2	0	XX	23,000	6,900	XX

Table A–8. Material content assumptions for selected metals and materials in batteries designated for video cameras (camcorders), by year.—Continued

[Li-ion, lithium-ion battery; NA, Not available; XX, Not applicable; NiCd, nickel-cadmium battery; NiMH, nickel-metal-hydride battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 27, 30). Values may not add to totals shown owing to rounding]

Year	Cell type	Number of units	Cadmium mass, in grams per pack	Cobalt mass, in grams per pack	Lithium mass, in grams per pack	Nickel mass, in grams per pack	Cadmium mass, in kilograms	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
2003	NiCd	1,200,000	22	1.4	0	35	26,000	1,600	XX	41,000
	Analog	1,100,000	22	1.4	0	35	25,000	1,500	XX	39,000
	Digital	81,000	22	1.4	0	35	1,800	110	XX	2,000
	NiMH	120,000	0	3.4	0	NA	XX	400	XX	6,800
	Analog	120,000	0	3.4	0	19	XX	400	XX	6,800
	Li-ion	4,800,000	0	NA	NA	0	XX	50,000	11,000	XX
	Analog	810,000	0	27	3.3	0	XX	22,000	2,700	XX
	Digital	4,000,000	0	7.3	2.2	0	XX	28,000	8,600	XX
2004	NiCd	690	22	1.4	0	35	15,000	930	XX	24,000
	Analog	650,000	22	1.4	0	35	14,000	870	XX	23,000
	Digital	44,000	22	1.4	0	35	1,000	61	XX	1,500
	NiMH	78,000	0	3.4	0	NA	XX	250	XX	4,200
	Analog	78,000	0	3.4	0	19	XX	250	XX	4,200
	Li-ion	4,900,000	0	NA	NA	0	XX	46,000	11,000	XX
	Analog	570,000	0	27	3.3	0	XX	15,000	1,900	XX
	Digital	4,300,000	0	7.3	2.2	0	XX	31,000	9,400	XX
2005	NiCd	320,000	22	1.4	0	35	6,900	430	XX	11,000
	Analog	320,000	22	1.4	0	35	6,900	430	XX	11,000
	Digital	0	22	1.4	0	35	0	0	XX	0
	NiMH	44,000	0	3.4	0	NA	XX	140	XX	2,400
	Analog	44,000	0	3.4	0	19	XX	140	XX	2,400
	Li-ion	5,600,000	0	NA	NA	0	XX	46,000	12,000	XX
	Analog	360,000	0	27	3.3	0	XX	9,000	1,200	XX
	Digital	5,200,000	0	7.3	2.2	0	XX	37,000	11,000	XX

Table A–9. Material content assumptions for selected metals and materials in batteries designated for hybrid vehicles, by year.

[Co, cobalt; HEV, hybrid-electric vehicle; kg, kilograms; Li-ion, lithium-ion battery; NA, not available; Ni, nickel; NiMH, nickel-metal-hydride battery; %, percent]

Manufacturer	2005 market share, in percent	Cell mass, in grams per cell	Number of cells	Battery mass, in kilograms	Nickel fraction, in percent
Matsushita/Panasonic	92	173	228	39.5	35.5
Sanyo Electric Co. Ltd.	8	178	245	43.6	40

2. Calculation: 0.92 × [39.5 kg/battery × 35.5% Ni] + 0.08 × [43.6 kg/battery × 40% Ni] = 14 kg Ni
0.92 × [39.5 kg/battery × 0% Co] + 0.08 × [43.6 kg/battery × 0.7% Co] = 24 g Co

Li-ion type battery

Manufacturer	Market share, in percent	Cell mass, in grams per module	Number of modules	Battery mass, in kilograms	Lithium fraction, in percent
Saft/Johnson Controls	0	8,000	5	40	2.15

3. Calculation: 40 kg/battery × 2.15% Li = 0.86 kg Li; 40 kg/battery × 18% Co = 7.2 kg Co

4. Hybrid vehicle sales and sales projections from selected sources

Data source	Units × 1,000	2002	2003	2004	2005	2006	2007	2008	2009	2010
NREL/Avicenne (2006)[1]	World sales	NA	NA	NA	200	300	900	1,200	1,700	2,050
	% Li-ion	NA	NA	NA	0	0	1	2	3	4
Johnson Controls (2006)[2]	World sales	NA	100	150	200	340	510	780	1,100	1,600
TTI. Inc. (2006)[3]	World sales	NA	NA	NA	NA	NA	NA	NA	NA	3,000
Advanced Automotive (2006)[4]	World sales	NA	NA	NA	NA	400	NA	NA	1,000	NA
Avicenne (2005)[5]	World sales	NA	NA	160	320	550	860	1,220	1,650	2,100
	% Li-ion	NA	NA	NA	0	0	0	2	3	5
	U.S. HEV sales	61	81	166	190	240	370	500	650	800
Caltrans/UC Davis (2004)[6]	U.S. HEV sales	NA	NA	NA	200	300	400	500-700	750-1,000	1,200-1,500
U.S. Department of Transportation[7]	U.S. HEV sales	25	49	92	190	310	300	480	490	550

5. Summary estimates used in this study

U.S. HEV sales	25	49	92	190	310	300	480	490	550
NiMH percent of U.S. HEV sales	100	100	100	100	100	100	98	97	95
Li-ion percent of U.S. HEV sales	0	0	0	0	0	0	2	3	5
NiMH units x 1000	25	49	92	190	310	300	470	470	520
Li-ion units x 1000	0	0	0	0	0	0	10	20	30
Metric tons of contained cobalt	1	1	2	5	7	7	80	120	210
Metric tons of contained nickel	350	690	1,300	2,700	4,300	4,200	6,600	6,700	7,300
Metric tons of contained lithium	0	0	0	0	0	0	8	13	24

[1] Pesaran (2006). [2] Fredonia Group Inc. (2006). [3] Paumanok Publications Inc. (2006). [4] Advanced Automotice Batteries (2006). [5] Madani (2005).
[6] Cao and Mokhtarian (2004). [7] U.S. Department of Transportation (2006).

Table A–10. Harmonized Tariff Schedule (HTS) classes applied to selected end uses of nickel-cadmium batteries for this study.

Battery class (based on end use)	HTS numbers applied to this battery classification	Years classification was used	Trade source (import or export)
Storage batteries, separate:			
Electrically-powered vehicle batteries	8507304000	1996-2005	Import
Sealed consumer batteries	8507308010	1996-2005	Import
	8507300050	1996	Export
	8507300000	1997-2005	Export
Industrial batteries	8507308090	1996-2005	Import
Batteries enclosed in products:			
Power tools	8508100010	1996-2001	Import/Export
	8467210010	2002-2005	Import/Export
Cordless phones	8517110000	1996-2005	Import/Export
Camcorders	8525408020	1997-2005	Import/Export
	8525400020	1996-1997	Import
	8525408050	1997-2005	Import/Export
	8525400050	1996-1997	Import
Cameras	8525400000	1996-1998	Export
	8525400090	1996-1997	Import
	8525404000	1997-1999	Import/Export
	8525408085	1997-1999	Import/Export
Portable radios	8527120000	1996-2005	Import/Export
Shavers	8510100000	1996-2005	Import/Export
Electric toothbrushes	8509800045	1996-2005	Import
Portable vacuum cleaners	8509100020	1996-2005	Import/Export
Flashlights	8513102000	1996-2005	Import
Portable electric lamps (bicycle lamps, for example)	8513104000	1996-2005	Import
	8513100000	1996-2005	Export
Watch batteries, reported separately	9101110000	1996-2005	Export
Clock batteries, reported separately	9103100000	1996-2005	Export
	9103102020	1996-2005	Import
	9103102040	1996-2005	Import
	9103104030	1996-2005	Import
	9103104060	1996-2005	Import
	9103108030	1996-2005	Import
	9103108060	1996-2005	Import
	9105114030	1996-2005	Import
	9105114050	1996-2005	Import
	9105108040	1996-2005	Import
	9105118070	1996-2005	Import
	9105214030	1996-2005	Import
	9105218050	1996-2005	Import
	9105914030	1996-2005	Import
	9105918050	1996-2005	Import
	9106905520	1996-2005	Import
	9109111030	1996-2005	Import
	9109112030	1996-2005	Import
	9109114030	1996-2005	Import
	9109116030	1996-2005	Import
	9109191030	1996-2005	Import
	9109192030	1996-2005	Import
	9109194030	1996-2005	Import
	9109196030	1996-2005	Import
Military batteries, reported separately	9104000000	1996-2005	Export
	9104000520	1996-2005	Import
	9104001020	1996-2005	Import
	9104002520	1996-2005	Import
	9104003020	1996-2005	Import
	9104004520	1996-2005	Import
	9104005030	1996-2005	Import

Table A–11. Harmonized Tariff Schedule of the United States (HTS) classes applied to selected end uses of lithium-ion and nickel-metal-hydride batteries for this study.

General battery class[1]	Specific battery class (based on end use)[1]	HTS number applied to this battery class	Years HTS class used	Trade source (import or export)
Lithium batteries, separate	Primary batteries, lithium	8506500000	1996–2005	Import and export
Lithium storage batteries, separate	Rechargeable storage batteries used as the primary source of electrical power for electrically-powered vehicles of subheading 8703.90	8507804000	1996–2005	Import
Lithium storage batteries, separate (rechargeable)	Other storage batteries, not otherwise specified or indicated (NESOI)	8507800000	1996–2005	Export
Do.	Other storage batteries, NESOI	8507808000	1996–2005	Import
Enclosed in electrically-powered vehicles	Passenger motor vehicles, NESOI	8703900000	1996–2005	Import and export
Enclosed in cell phones	Radio telephones designed for the public cellular radio telecommunication service, weighing 1 kilogram (kg) or under	8525209070	1996–2005	Import and export
Enclosed in portable computers	Portable digital ADP machine weighing not more than 10 kg, consisting of at least a CPU, keyboard, and display unit	8471300000	1996–2005	Import and export
Enclosed in video cameras (camcorders)	Camcorders, 8 millimeter (mm), analog	8525408020	1996–2005	Import and export
Do.	Camcorders, color, 8 mm, analog	8525400020	1996–1997	Import
Do.	Camcorders, other than 8 mm, digital	8525408050	1997–2005	Import and export
Do.	Camcorders, color, other than 8 mm, digital	8525400050	1996–1997	Import
Enclosed in digital cameras	Still image video cameras	8525400090	1996–1997	Import
Do.	Still image video cameras and other video camera recorders	8525400000	1996–1998	Export
Do.	Digital still image video cameras	8525404000	1997–2005	Import and export
Do.	Still image video cameras, NESOI	8525408085	1997–2005	Import and export
Clock batteries, reported separately	Batteries for travel clocks, battery powered with opto-electronic display, excluding subheading 9104	9103102020	1996–2005	Import
Do.	Clocks with watch movements, electrically operated, excluding subheading 9104	9103100000	1996–2005	Export
Do.	Batteries for clocks, except travel clocks, battery powered, with opto-electronic display, excluding subheading 9104	9103102040	1996–2005	Import
Do.	Batteries for clocks, battery powered, having no jewels or only one jewel in the movement, excluding subheading 9104	9103104030	1996–2005	Import
Do.	Batteries for clocks, except travel clocks, battery powered, having no jewels or only one jewel in the movement, excluding subheading 9104	9103104060	1996–2005	Import
Do.	Batteries for travel clocks, battery powered, NESOI	9103108030	1996–2005	Import
Do.	Batteries for clocks, except travel clocks, battery powered, NESOI	9103108060	1996–2005	Import
Do.	Batteries for travel alarm clocks, battery powered, with opto-electronic display	9105114030	1996–2005	Import
Do.	Alarm clocks, battery powered	9105100000	1996–2005	Export
Do.	Batteries for alarm clocks, except travel, battery powered with opto-electronic display	9105114050	1996–2005	Import
Do.	Batteries for travel alarm clocks, with opto-electronic display	9105118040	1996–2005	Import
Do.	Batteries for alarm clocks, except travel, battery powered, with opto-electronic display	9105118070	1996–2005	Import
Do.	Batteries for wall clocks, battery powered, with opto-electronic display	9105214030	1996–2005	Import
Do.	Wall clocks, battery powered	9105210000	1996–2005	Export
Do.	Batteries for wall clocks, battery powered, with opto-electronic display	9105218050	1996–2005	Import
Do.	Batteries for other clocks, battery powered, with opto-electronic display only	9105914030	1996–2005	Import

Table A–11. Harmonized Tariff Schedule of the United States (HTS) classes applied to selected end uses of lithium-ion and nickel-metal-hydride batteries for this study.—Continued

General battery class[1]	Specific battery class (based on end use)[1]	HTS number applied to this battery class	Years HTS class used	Trade source (import or export)
Clock batteries, reported separately (continued)	Other clocks, battery powered	9105910000	1996–2005	Export
Do.	Batteries for other clocks, battery powered, except opto-electronic display	9105918050	1996–2005	Import
Do.	Batteries for device with opto-electronic display for measuring, recording time, battery powered	9106905520	1996–2005	Import
Do.	Other time of day device, NESOI	9106900000	1996–2005	Export
Do.	Batteries for clock movements of alarm clocks, complete and assembled, battery powered, with opto-electronic display only	9109111030	1996–2005	Import
Do.	Clock movements of alarm clocks, complete and assembled, battery powered	9109110000	1996–2005	Export
Do.	Batteries for clock movements of alarm clocks, complete and assembled, battery powered, measuring not over 50 mm in width or diameter	9109112030	1996–2005	Import
Do.	Batteries for clock movements of alarm clocks, complete and assembled, battery powered, measuring over 50 mm in width or diameter, value not over $5 each	9109114030	1996–2005	Import
Do.	Batteries for clock movements of alarm clocks, complete and assembled, battery powered, measuring over 50 mm in width or diameter, valued over $5 each	9109116030	1996–2005	Import
Do.	Batteries for clock movements, complete and assembled, except for alarm clocks, battery powered, with opto-electronic display only	9109191030	1996–2005	Import
Do.	Clock movements, complete and assembled, electronically powered, except for alarm clocks, NESOI	9109190000	1996–2005	Export
Do.	Batteries for clock movements, complete and assembled, except for alarm clocks, battery powered, measuring not over 50 mm in width or diameter	9109192030	1996–2005	Import
Do.	Batteries for clock movements, complete and assembled, except for alarm clocks, battery powered, measuring over 50 mm in width or diameter, valued not over $5 each	9109194030	1996–2005	Import
Do.	Batteries for clock movements, complete and assembled, except for alarm clocks, battery powered, measuring over 50 mm in width or diameter, valued over $5 each	9109196030	1996–2005	Import
Batteries for military application, reported separately	Batteries for instrument panel clocks, with clock movements measuring over 50 mm in width or diameter, valued not over $10, with opto-electronic display only	9104000520	1996–2005	Import
Do.	Batteries for military application, reported separately	9104000000	1996–2005	Export
Do.	Batteries for instrument panel clocks and similar for vehicles, aircraft, spacecraft, measuring over 50 mm in width or diameter, valued not over $10, including battery	9104001020	1996–2005	Import
Do.	Batteries for instrument panel clocks and similar for vehicles, aircraft, spacecraft, or vessel, measuring over 50 mm in width or diameter, valued over $10, with opto-electronic display	9104002520	1996	Import
Do.	Batteries for instrument panel clocks and similar for vehicles, aircraft, spacecraft, or vessel, measuring over 50 mm in width or diameter, valued over $10, electric including battery	9104003020	1996–2005	Import

Table A–11. Harmonized Tariff Schedule of the United States (HTS) classes applied to selected end uses of lithium-ion and nickel-metal-hydride batteries for this study.—Continued

General battery class[1]	Specific battery class (based on end use)[1]	HTS number applied to this battery class	Years HTS class used	Trade source (import or export)
Watch batteries, reported separately	Batteries for instrument panel clocks and similar for vehicles, aircraft, spacecraft, or vessel, with opto-electronic display, NESOI	9104004520	1996–2005	Import
Do.	Batteries for instrument panel clocks and similar for vehicles, aircraft, spacecraft, or vessel, measuring over 50 mm in width or diameter, valued over $10, electric including battery, NESOI	9104005030	1996–2005	Export
Do.	Batteries for wrist watches, battery powered, with cases of precious metal, with mechanical display only, having no jewels or only one jewel	9101114040	1996–2005	Import
Do.	Wrist watches, cases of precious metal and mechanical display	9101110000	1996–2005	Export
Do.	Batteries for wrist watches, battery powered, with cases of precious metal, mechanical display only, with more than one jewel	9101118040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with cases of precious metal, having no jewels or only one jewel, NESOI	9101194040	1996–2005	Import
Do.	Wrist watches, with cases of precious metal, NESOI	9101190000	1996–2005	Export
Do.	Batteries for wrist watches, battery powered, with cases of precious metal, having more than one jewel, NESOI	9101198040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having no jewels or one jewel, with band of base metal with gold/silver case	9102111040	1996–2005	Import
Do.	Wrist watches, battery powered, mechanical display only, with cases of base metal	9102110000	1996–2005	Export
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having no jewels or one jewel, with band of textile or with base metal case	9102112540	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having no jewels or one jewel, with gold/silver-plated case	9102113040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having more than one jewel, with base metal case	9102114540	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having more than one jewel, with band of textile or base metal, gold/silver-plated case	9102115040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having more than one jewel, with band of textile or base metal, base metal case	9102116540	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having more than one jewel, with gold/silver-plated case	9102117040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having more than one jewel, with base metal case, NESOI	9102119540	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with other display, having no jewels or one jewel, with band of textile or base metal	9102192040	1996–2005	Import
Do.	Wrist watches, battery powered, other display, cases of base metal	9102190000	1996–2005	Export

Table A–11. Harmonized Tariff Schedule of the United States (HTS) classes applied to selected end uses of lithium-ion and nickel-metal-hydride batteries for this study.—Continued

General battery class[1]	Specific battery class (based on end use)[1]	HTS number applied to this battery class	Years HTS class used	Trade source (import or export)
Watch batteries, reported separately (continued)	Batteries for wrist watches, battery powered, with other display, having no jewels or one jewel, NESOI	9102194040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with other display, having more than one jewel, with band of textile or base metal	9102196040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with other display, having more than one jewel, NESOI	9102198040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with cases of precious metal, having no jewels or one jewel	9101914030	1996–2005	Import
Do.	Other watches, with cases of precious metal, battery powered, except wrist watches	9101910000	1996–2005	Export
Do.	Batteries for other watches, battery powered, with cases of precious metal, NESOI	9101918030	1996–2005	Import
Do.	Batteries for other watches, battery powered, with base metal case, with opto-electronic display only	9102912020	1996–2005	Import
Do.	Other watches, with cases of base metal, battery powered, except wrist watches	9102910000	1996–2005	Export
Do.	Batteries for other watches, battery powered, having no jewels or one jewel	9102914030	1996–2005	Import
Do.	Batteries for other watches, battery powered, with base metal case, NESOI	9102918030	1996–2005	Import

[1] General and specific battery classification descriptions as reported by the U.S. International Trade Commission, modified where necessary for consistency.

Wilburn—**Material Use in the United States—Selected Case Studies for Cd, Co, Li, and Ni in Rechargeable Batteries**—SIR 2008–5141

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ATTACHMENT 2

USGS Open File Report 2008-1356. Factors that influence the price of Al, Cd, Co, Cu, Fe, Ni, Pb, Rare Earth Elements, and Zn.

Factors that influence the price of Al, Cd, Co, Cu, Fe, Ni, Pb, Rare Earth Elements, and Zn

By John F. Papp, E. Lee Bray, Daniel L. Edelstein, Michael D. Fenton, David E. Guberman, James B. Hedrick, John D. Jorgenson, Peter H. Kuck, Kim B. Shedd, and Amy C. Tolcin

Open-File Report 2008–1356

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia 2008

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Conversion Factors

Mass		
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton, long (2,240 lb)	1.016	megagram (Mg)
ton per day (ton/d)	0.9072	metric ton per day
ton per day (ton/d)	0.9072	megagram per day (Mg/d)
ton per day per square mile [(ton/d)/mi^2]	0.3503	megagram per day per square kilometer [(Mg/d)/km^2]
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
ton per year (ton/yr)	0.9072	metric ton per year

Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)
metric ton per day	1.102	ton per day (ton/d)
megagram per day (Mg/d)	1.102	ton per day (ton/d)
megagram per day per square kilometer [(Mg/d)/km^2]	2.8547	ton per day per square mile [(ton/d)/mi^2]
megagram per year (Mg/yr)	1.102	ton per year (ton/yr)
metric ton per year	1.102	ton per year (ton/yr)

Factors that influence the price of Al, Cd, Co, Cu, Fe, Ni, Pb, Rare Earth Elements, and Zn

By John F. Papp, E. Lee Bray, Daniel L. Edelstein, Michael D. Fenton, David E. Guberman, James B. Hedrick, John D. Jorgenson, Peter H. Kuck, Kim B. Shedd, and Amy C. Tolcin

Summary

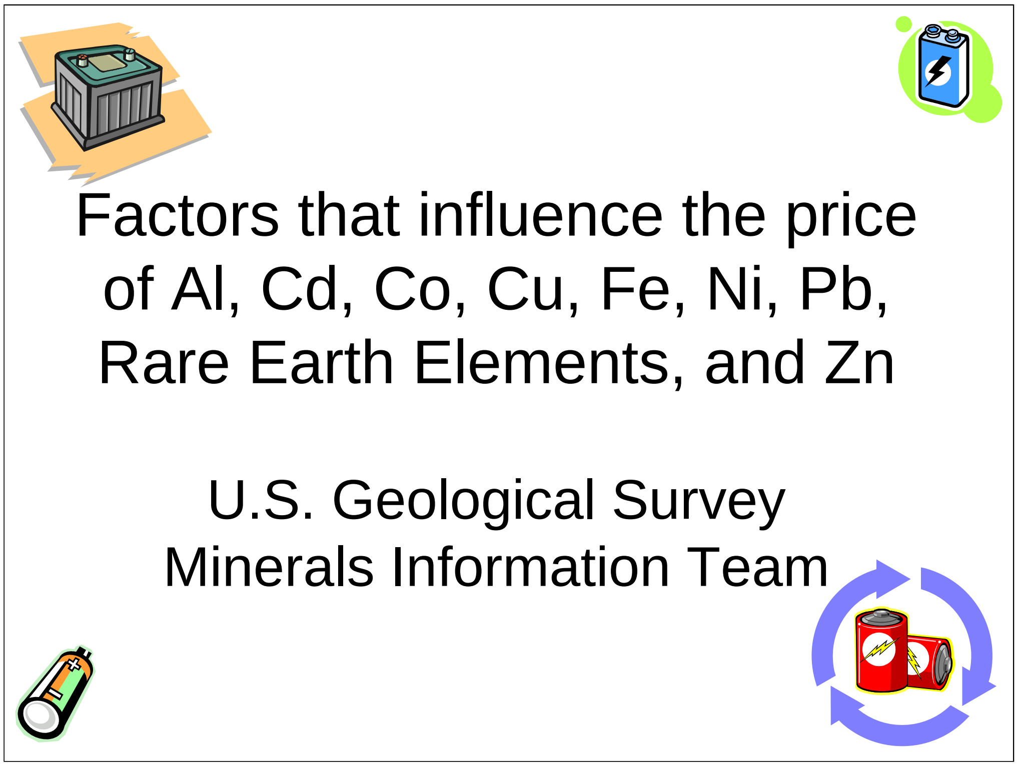
This report is based on a presentation delivered at The 12th International Battery Materials Recycling Seminar, March 17-20, 2008, Fort Lauderdale, Fla., about the factors that influence prices for aluminum, cadmium, cobalt, copper, iron, lead, nickel, rare earth elements, and zinc. These are a diverse group of metals that are of interest to the battery recycling industry. Because the U.S. Geological Survey (USGS) closely monitors, yet neither buys nor sells, metal commodities, it is an unbiased source of metal price information and analysis.

The authors used information about these and other metals collected and published by the USGS (U.S. production, trade, stocks, and prices and world production) and internationally (consumption and stocks by country) from industry organizations, because metal markets are influenced by activities and events over the entire globe. Long-term prices in this report, represented by unit values, were adjusted to 1998 constant dollars to remove the effects of inflation. A previous USGS study in this subject area was “Economic Drivers of Mineral Supply” by Lorie A. Wagner, Daniel E. Sullivan, and John L. Sznopek (USGS Open File Report 02-335).

By seeking a common cause for common behavior of prices among the various metal commodities, the authors found that major factors that influence prices of metal commodities were international events such as wars and recessions, and national events such as the dissolution of the Soviet Union in 1991 and economic growth in China, which started its open door policy in the 1970s

but did not have significant market impact until the 1990s. Metal commodity prices also responded to commodity-specific events such as tariff or usage changes or mine strikes.

It is shown that the prices of aluminum, cadmium, copper, iron, lead, nickel, and zinc are at historic highs, that world stocks are at (or near) historic lows, and that China's consumption of these metals had increased substantially, making it the world's leading consumer of these metals.

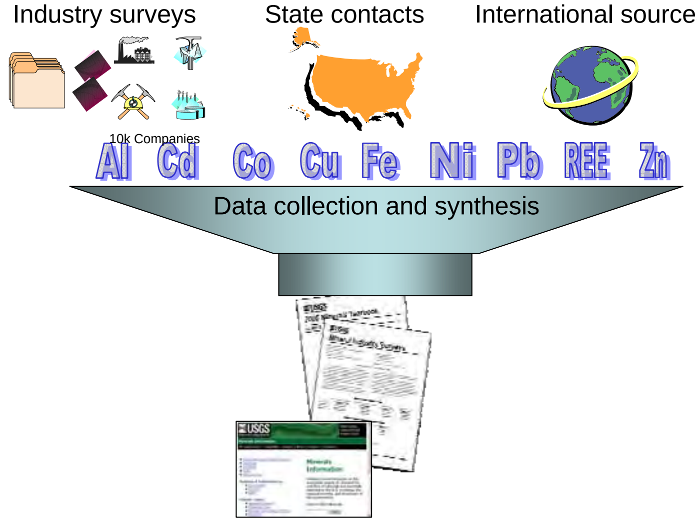


Factors that influence the price of Al, Cd, Co, Cu, Fe, Ni, Pb, Rare Earth Elements, and Zn

U.S. Geological Survey
Minerals Information Team

This presentation is an analysis of factors that influence the price of aluminum (Al), cadmium (Cd), cobalt (Co), copper (Cu), iron (Fe), nickel (Ni), lead (Pb), rare earth elements (REE), and zinc (Zn). The price analysis is based on consumption, production, stocks, and industry events reported by a variety of sources. This is a diverse group of metals significant to the battery recycling industry.

U.S. Geological Survey
Minerals Information Team



Industry surveys State contacts International sources

10k Companies

Al Cd Co Cu Fe Ni Pb REE Zn

Data collection and synthesis

Data Products

http://minerals.usgs.gov/minerals/

The USGS collects domestic minerals information from producers and consumers and international information from a variety of sources. The USGS collects, analyzes, and distributes, primarily on the Internet, the information that it collects.

Information Collected by the USGS

Production
Consumption
Stocks

Trade
Prices
Issues
Developments

Analysis

Apparent consumption
Import reliance

Price trends
Material flow studies

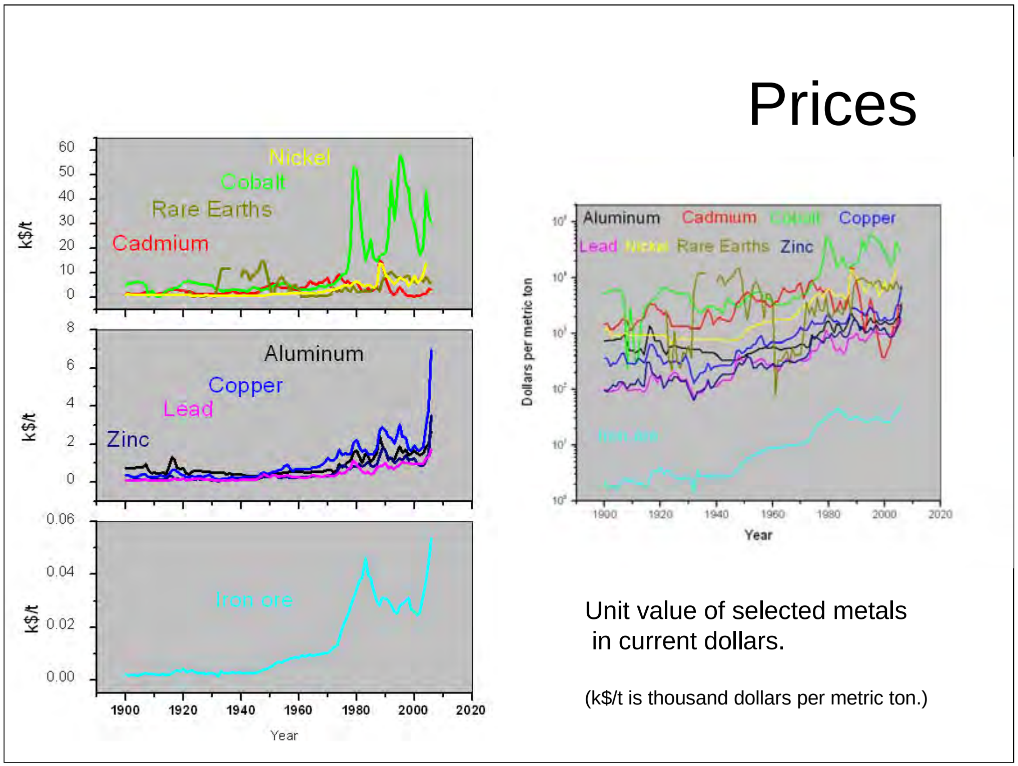
The USGS collects mineral commodity information about production, consumption, stocks, trade, prices, and industry issues such as capacity, cost of production, material use, and environmental issues. The USGS uses the information to quantify U.S. apparent consumption, price trends, material flows, and net import reliance.

[Net import reliance is net imports (imports minus exports) plus adjustments for stock changes. Apparent consumption is mine plus recycle production plus net import reliance. Mine production includes primary product, coproduct, and byproduct materials, including materials recovered during processing or from tailings. Note that apparent consumption and import reliance are material dependent, which means that the quantitative measures depend on which materials are included in the estimation. Because USGS minerals information emphasizes raw materials, the materials included in trade are typically mineral or metal ores and concentrates and intermediate materials, such as ferroalloys or mill products that supply the domestic manufacturing industry. Manufactured products, such as vehicles, electronic equipment, and so forth, typically are excluded.]

Factors that influence the price of Al, Cd, Co, Cu, Fe, Ni, Pb, Rare Earth Elements, and Zn

(1900-2006)

Examples of factors that influence raw materials' prices include mining and material processing industry events, such as changes in consumption, production, or stocks that result from mine or plant openings or closings, strikes, or technology changes; however, the raw materials industry does not operate in isolation. It is subject to external influences such as deflation of the U.S. dollar, the breakup of the Soviet Union, economic recessions, rapid growth of the Chinese economy, and trade restrictions. First, look at the prices of these metals together over a long time period (1900-2004) and then individually over a shorter time period (1991-2006). The long-time-period prices are unit values of apparent consumption, so for some of these metals they represent a composite of forms, as reported in U.S. Geological Survey Data Series 140, Historical Statistics of Minerals and Materials in the United States. The short-time-period prices are those reported in the U.S. Geological Survey, Mineral Commodity Summaries.



Prices

Unit value of selected metals
in current dollars.

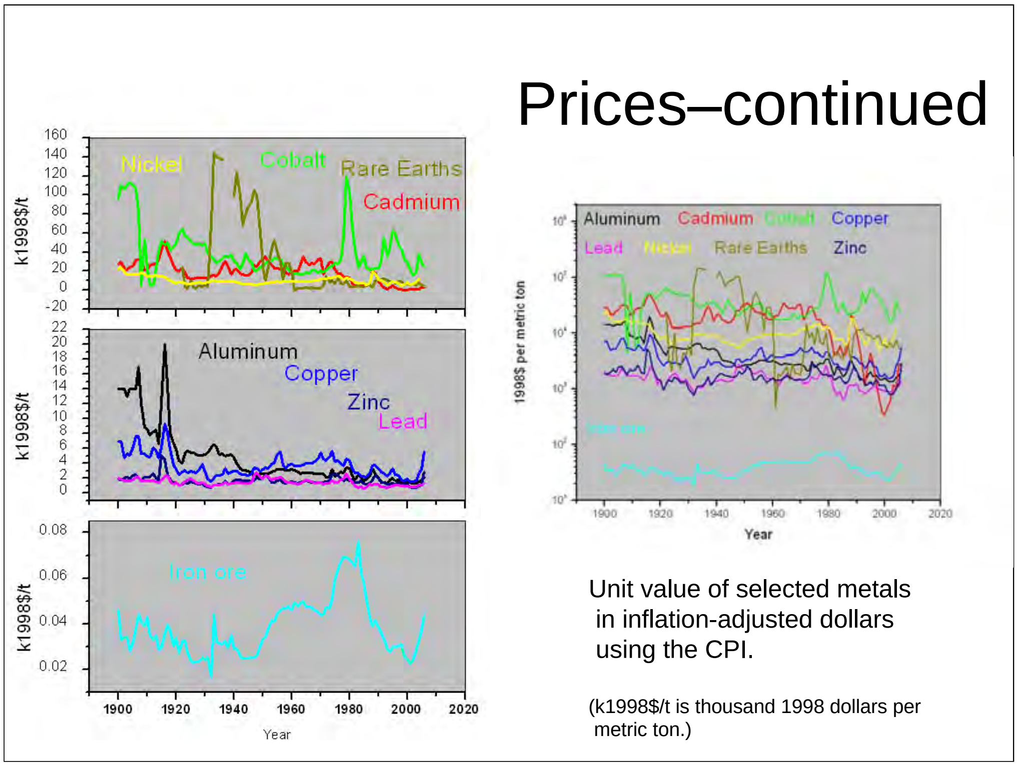
(k$/t is thousand dollars per metric ton.)

These price histories create a jumble of lines that are difficult to untangle and present in a visually appealing way, not to mention that these prices have a wide range (five orders of magnitude). They are shown together here in three panels and on a logarithmic scale to show historical prices of nine metals on a single graph. They show many peaks and troughs of various sizes. Each price fluctuation cannot be explained but some trends common to them can.

There are three common behaviors: (1) Prices (in nominal terms) start out low and end up high; (2) price fluctuations are smaller in the middle of the time period than they are at the beginning or end; and (3) in 2008, prices are at historical highs for most of these metals. Most metals displayed price peaks just before 1920 (World War I), a stable price through the 1940s (when World War II price controls were in effect), and price peaks just before 1980 (post-Vietnam era).

The quantitatively larger price changes apparent in the recent years are no larger, as a percentage of current price, than price changes in the early part of the time period.

It appears that, from the beginning to the end of the time period, prices went up, and that there was greater price stability in the middle of the time period as implied by the smaller price fluctuations; however, …



Prices–continued

Unit value of selected metals in inflation-adjusted dollars using the CPI.

(k1998$/t is thousand 1998 dollars per metric ton.)

… when price is adjusted for inflation, the trends are not the same. Measured in inflation-adjusted (constant) dollars; (1) prices are now quite similar to their historical values, marginally higher, or even lower, and (2) price fluctuations are now quite similar to historical fluctuations, and the upward trend disappears.

There is a pattern of fluctuating prices throughout the time period; however, there was relative price stability in the central portion of the time period (about 1940-60) owing to government price controls and allocations during wartime.

The disappearance of the upward current-dollar price trend when deflated to constant dollars (as indicated by the Consumer Price Index used to deflate current to constant dollars) suggests that these long-term metal prices (measured in current dollars) have changed at about the same pace as inflation.

[This is the only place where deflated values are used. All other values in this report are in current U.S. dollars. Note about price range as reported in the U.S. Geological Survey, Mineral Commodity Summaries and Data Series 140: MCS (1991-2006) range from about $108/t-Mn in 1999 to $71,000/t-Mo in 2005. Data Series 140 (1900-2006) range $19/t-Mn in 1921 to $25,700/t-Mo in 2004.]

Supply and Consumption

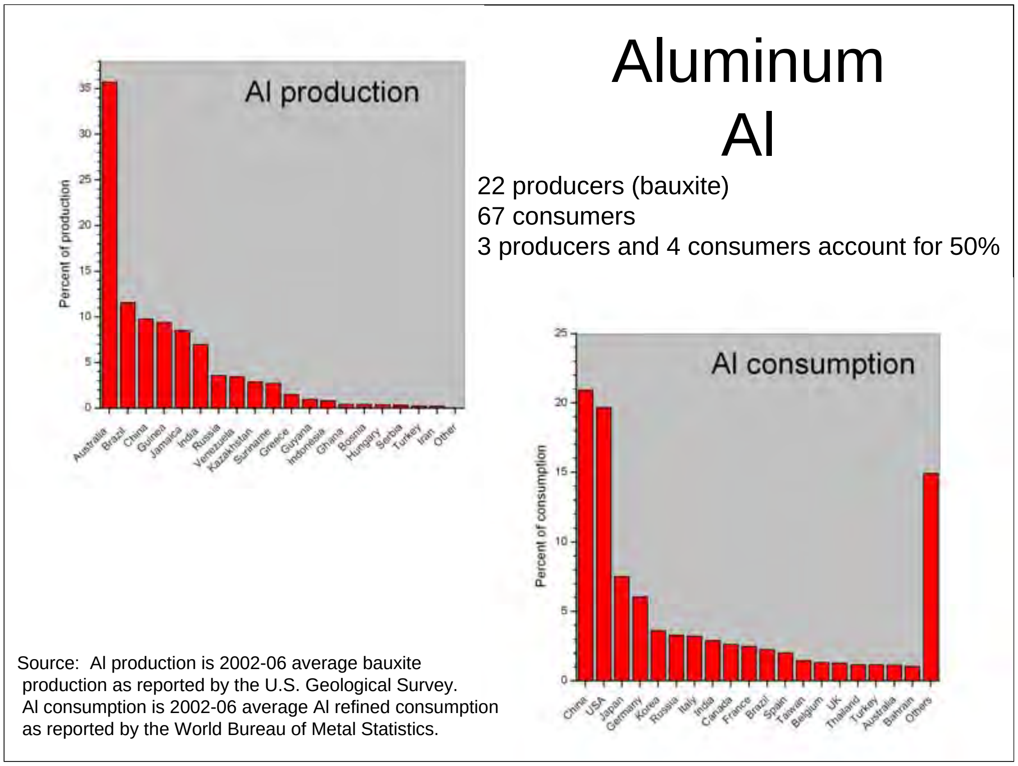
The geographic distribution of world metal mine production and consumption.

In addition to supply of and demand for a mineral commodity, money supply is also an important factor in determining price. The geographic distribution of metal mining is influenced by where the economic deposits are located. Consumption of these metals is distributed among several leading consuming countries and many smaller consuming countries that are geographically distributed around the world.

The following bar charts show percent of production (and consumption) by country in descending order of national share of world production (or consumption). The bar to the right labeled “others” represents collective production (or consumption) for the countries not listed separately.

When one country accounts for a large share of production or consumption, it suggests that the country, or events in that country, could have a significant impact on the commodity price.

[Bar charts are based on a 5-year average of the most recently available production (consumption) data reported by the USGS or industry organizations.]



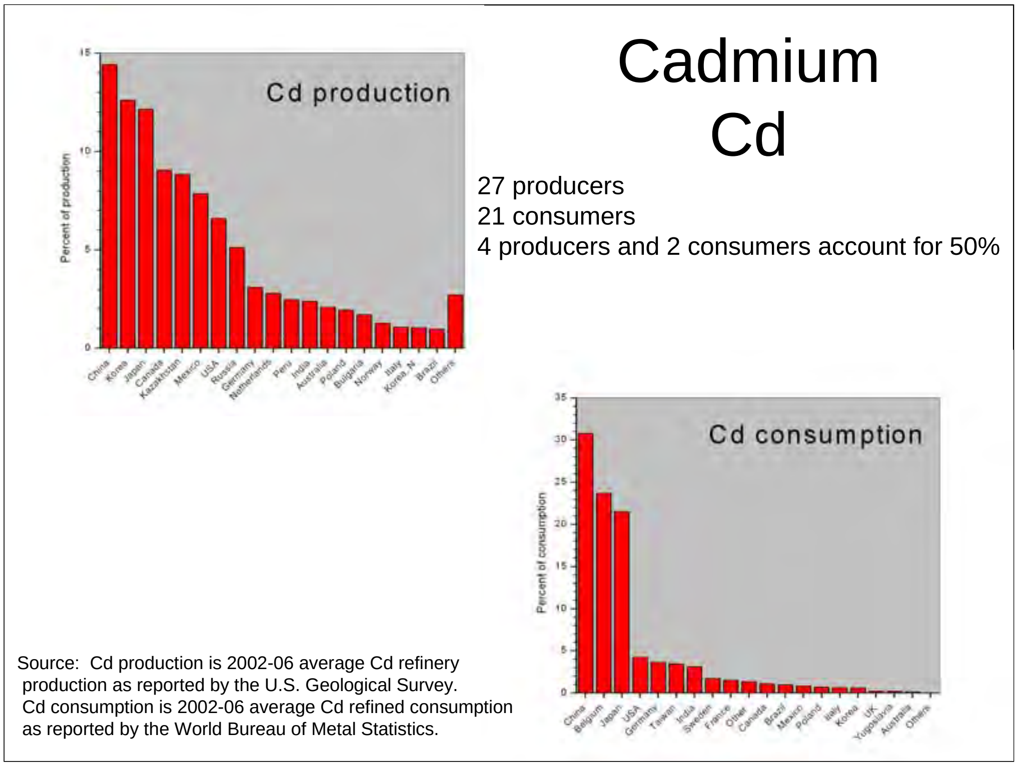
Aluminum
Al

22 producers (bauxite)
67 consumers
3 producers and 4 consumers account for 50%

Source: Al production is 2002-06 average bauxite production as reported by the U.S. Geological Survey.
Al consumption is 2002-06 average Al refined consumption as reported by the World Bureau of Metal Statistics.

Among 22 aluminum (in the form of bauxite)-producing countries, the leading producer (Australia) accounts for about 36% of production; the leading 3 producers (Australia, Brazil, and China) account for more than 50% of worldwide production.

Among 67 aluminum-consuming countries, the leading 2 consumers (China and the United States) each account for about 20% of consumption; the leading 4 consumers (China, the United States, Japan, and Germany) account for more than 50% of world consumption.



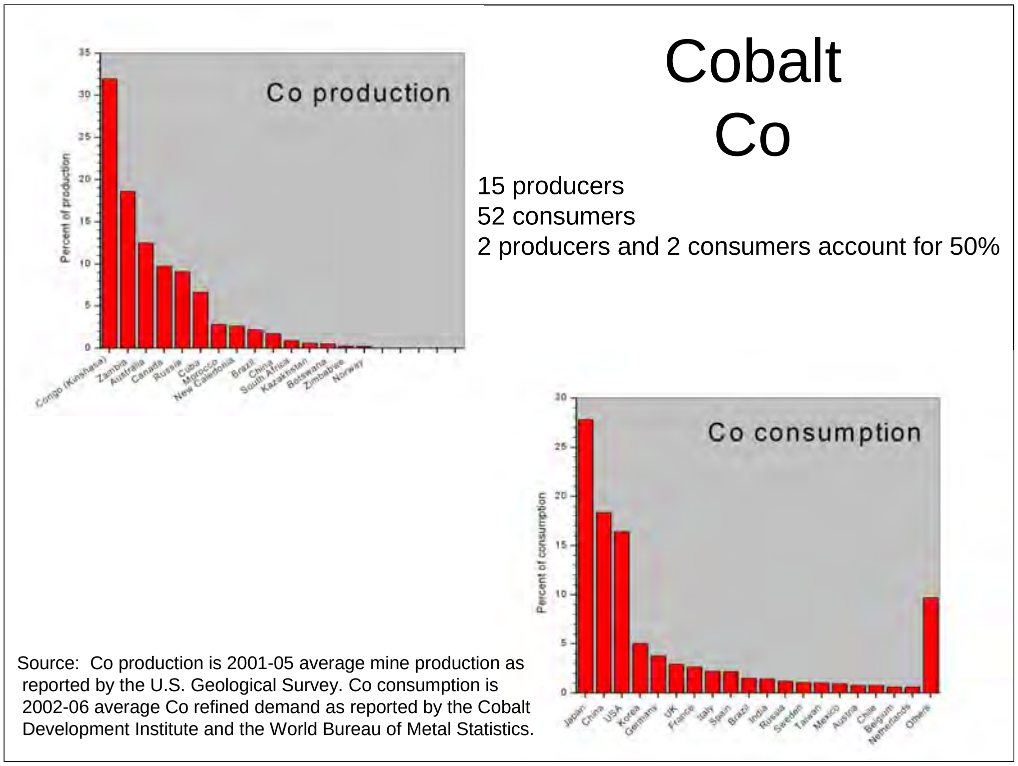
Cadmium
Cd

27 producers
21 consumers
4 producers and 2 consumers account for 50%

Source: Cd production is 2002-06 average Cd refinery production as reported by the U.S. Geological Survey. Cd consumption is 2002-06 average Cd refined consumption as reported by the World Bureau of Metal Statistics.

Among 27 cadmium-producing countries, the leading 3 producers (China, Korea, and Japan) each account for a similar amount of production and together account for about 39% of world production.

Among 21 cadmium-consuming countries, the leading consumer (China) accounts for about 30% of consumption; the leading 2 consumers (China and Belgium) account for more than 50% of world consumption.



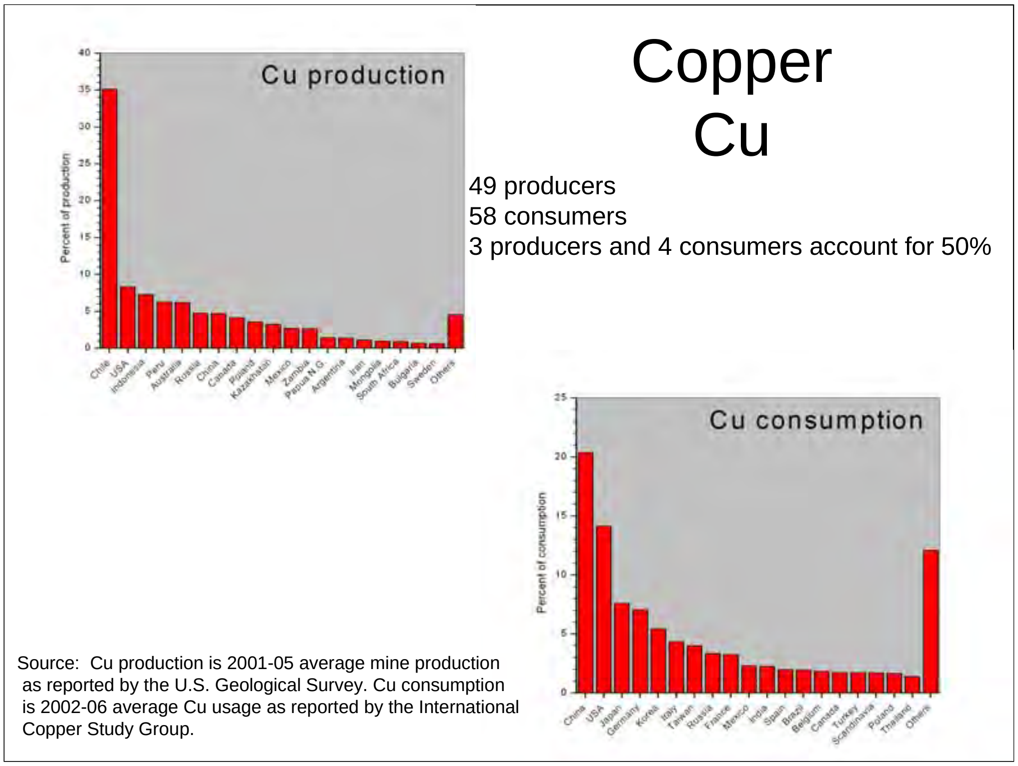
Cobalt
Co

15 producers
52 consumers
2 producers and 2 consumers account for 50%

Source: Co production is 2001-05 average mine production as reported by the U.S. Geological Survey. Co consumption is 2002-06 average Co refined demand as reported by the Cobalt Development Institute and the World Bureau of Metal Statistics.

Among 15 cobalt-producing countries, the leading producer [Congo (Kinshasa)] accounts for about 30% of production; the leading 2 producers [Congo (Kinshasa) and Zambia] account for about 50% of world production.

Among 52 cobalt-consuming countries, the leading consumer (Japan) accounts for about 30% of consumption; the leading 2 consumers (Japan and China) account for almost 50% of world consumption.



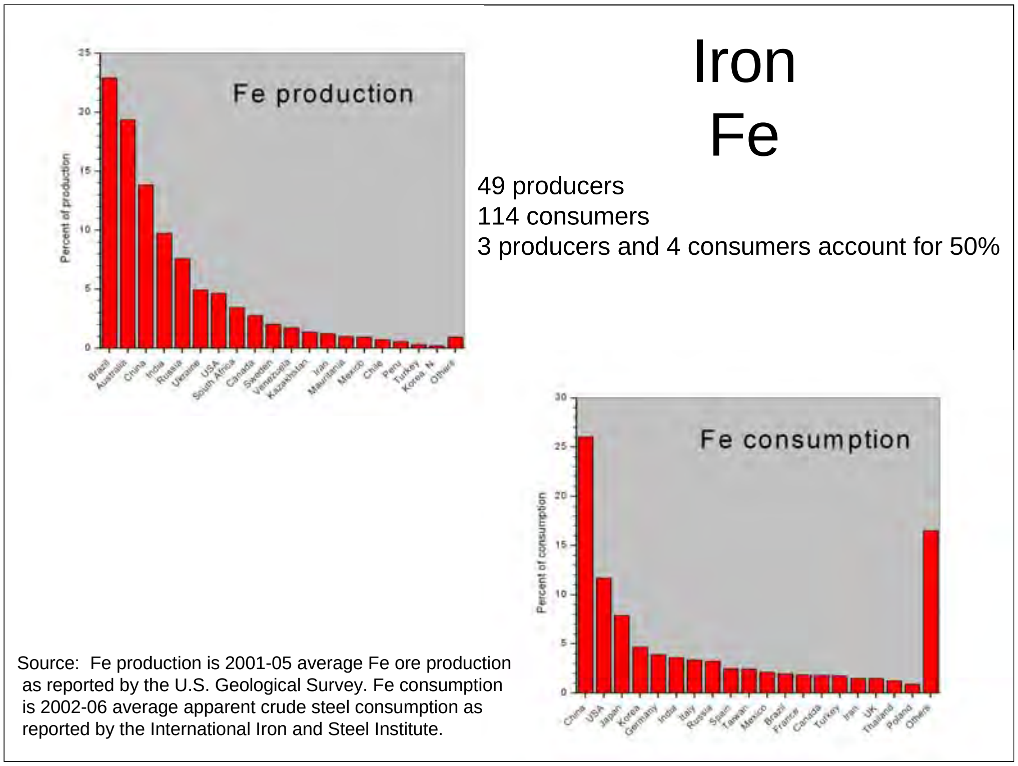
Copper
Cu

49 producers
58 consumers
3 producers and 4 consumers account for 50%

Source: Cu production is 2001-05 average mine production as reported by the U.S. Geological Survey. Cu consumption is 2002-06 average Cu usage as reported by the International Copper Study Group.

Among 49 copper-producing countries, the leading producer (Chile) accounts for more than 30% of production; the leading 3 producers (Chile, the United States, and Indonesia) account for about 50% of world production.

Among 58 copper-consuming countries, the leading consumer (China) accounts for about 20% of consumption; the leading 4 consumers (China, Japan, Germany, and the United States) account for about 50% of world consumption.



Iron
Fe

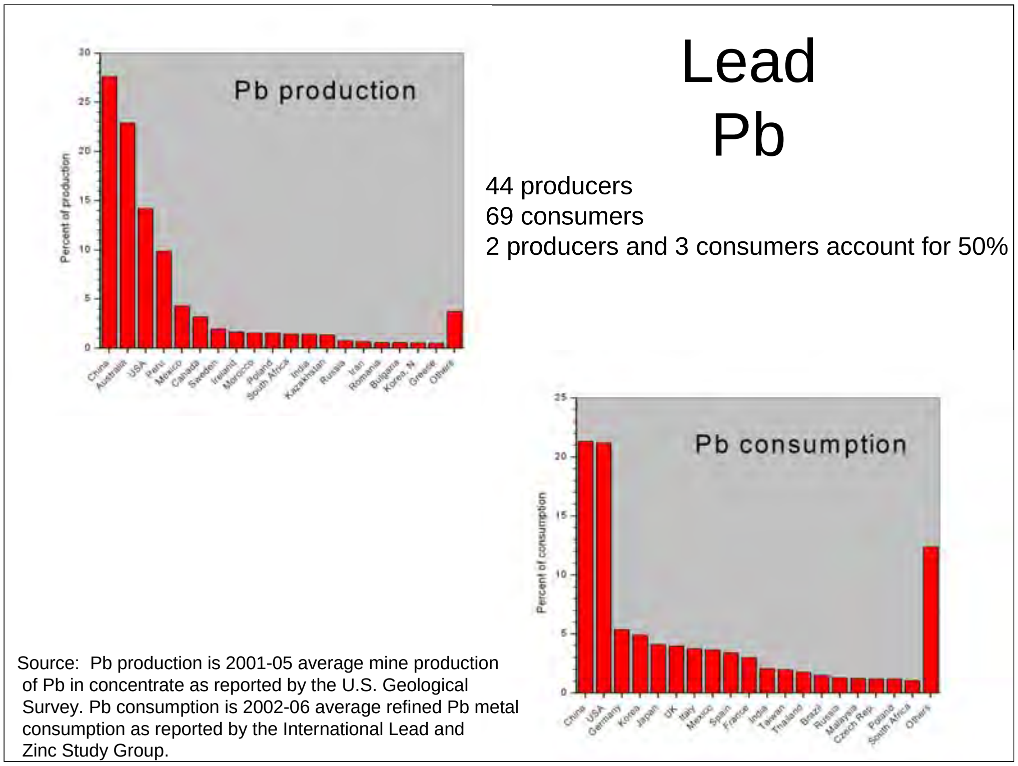
49 producers
114 consumers
3 producers and 4 consumers account for 50%

Source: Fe production is 2001-05 average Fe ore production as reported by the U.S. Geological Survey. Fe consumption is 2002-06 average apparent crude steel consumption as reported by the International Iron and Steel Institute.

Among 49 iron ore-producing countries, the leading 3 producers (Brazil, Australia, and China) account for more than 50% of production.

Among 114 iron (in the form of steel)-consuming countries, the leading consumer (China) accounts for about 25% of consumption; the leading 3 consumers (China, United States, and Japan) account for about 50% of world consumption.

[Percent of iron production is based on the iron ore production measured in contained iron. Percent of consumption is based on gross weight of steel production; however, 60% of U.S. steel production is by EAF using scrap instead of iron ore.]



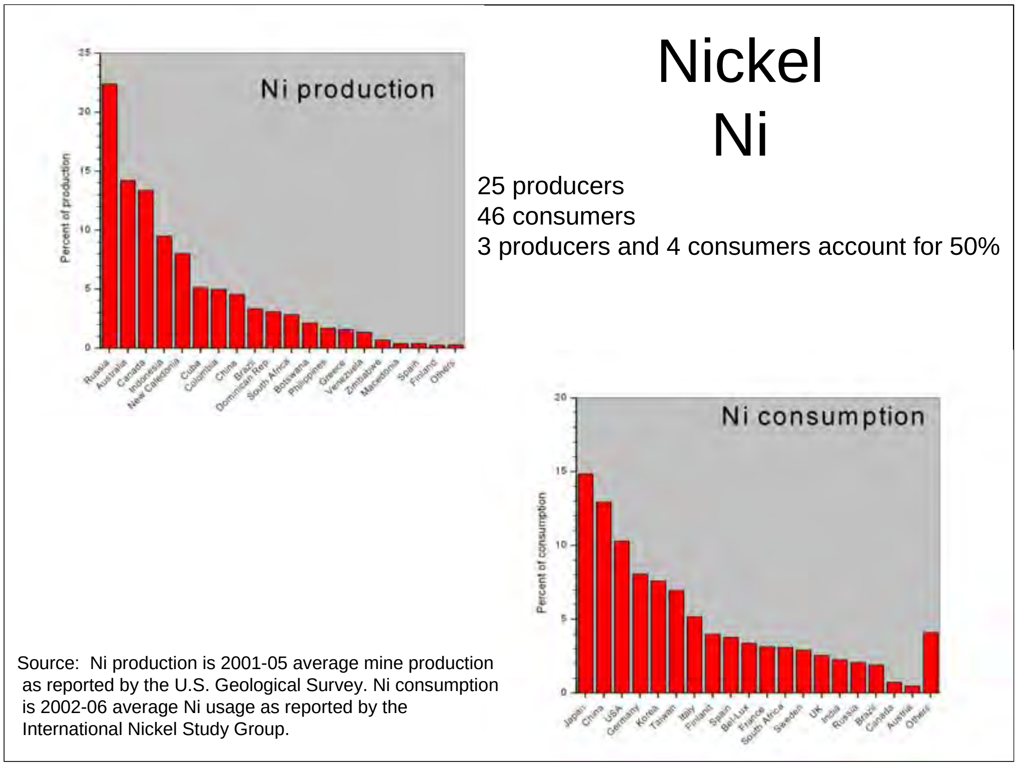
Lead
Pb

44 producers
69 consumers
2 producers and 3 consumers account for 50%

Source: Pb production is 2001-05 average mine production of Pb in concentrate as reported by the U.S. Geological Survey. Pb consumption is 2002-06 average refined Pb metal consumption as reported by the International Lead and Zinc Study Group.

Among 44 lead-producing countries, the leading producer (China) accounts for about 25% of production; the leading 2 producers (China and Australia) accounted for about 50% of world production.

Among 69 lead-consuming countries, the leading 2 consumers (China and the United States) each account for more than 20% of consumption; the leading 3 consumers (China, the United States, and Germany) account for about 50% of world consumption.



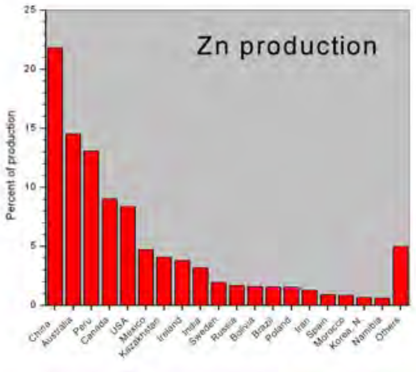
Nickel
Ni

25 producers
46 consumers
3 producers and 4 consumers account for 50%

Source: Ni production is 2001-05 average mine production as reported by the U.S. Geological Survey. Ni consumption is 2002-06 average Ni usage as reported by the International Nickel Study Group.

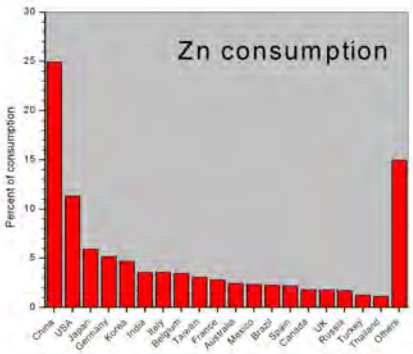
Among 25 nickel-producing countries, the leading producer (Russia) accounts for about 22% of production; the leading 3 (Russia, Australia, and Canada) producers account for about 50% of world production.

Among 46 nickel-consuming countries, the leading 3 consumers (Japan, China, and the United States) account for 37% of consumption; the leading 4 consumers (Japan, China, the United States, and Germany) account for about 50% of world consumption. In 2007, China overtook Japan as the leading consumer of nickel.



Zinc
Zn

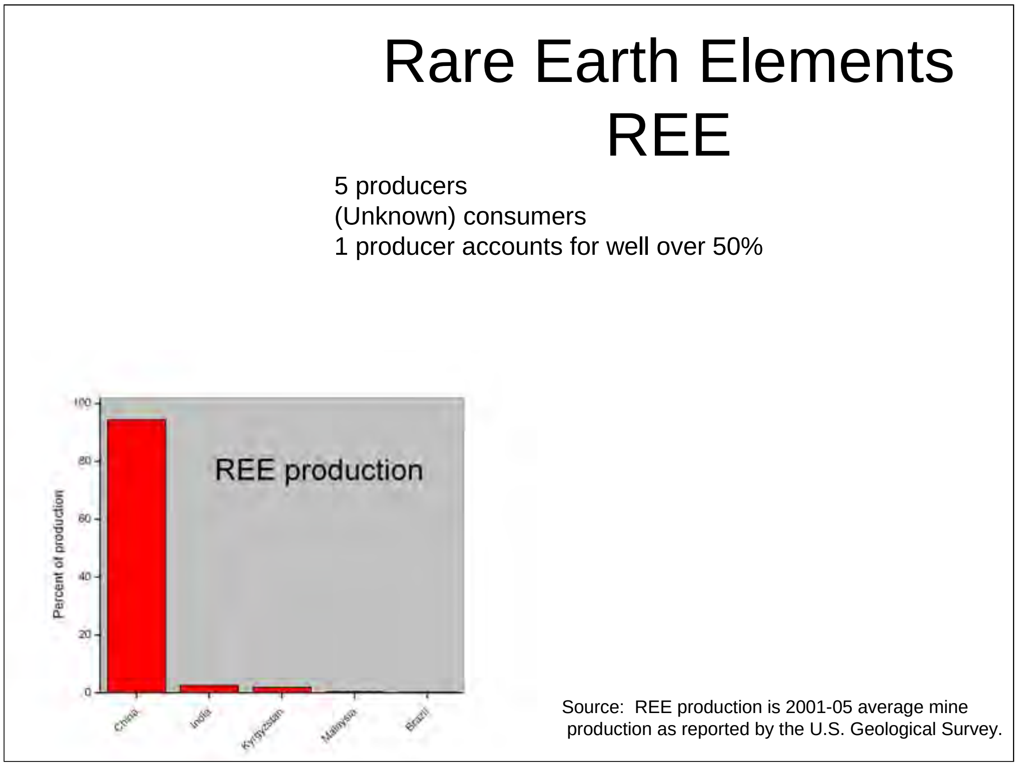
42 producers
73 consumers
3 producers and 4 consumers account for 50%



Source: Zn production is 2001-05 average mine production of Zn in concentrate and direct shipping ore as reported by the U.S. Geological Survey. Zn consumption is 2002-06 average refined Zn metal consumption as reported by the International Lead and Zinc Study Group.

Among 42 zinc-producing countries, the leading producer (China) accounts for more than 20% of production; the leading 3 producers (China, Australia, and Peru) account for about 50% of world production.

Among 73 zinc-consuming countries, the leading consumer (China), accounts for about 25% of consumption; the leading 4 consumers (China, the United States, Japan, and Germany), account for about 50% of world consumption.



Rare Earth Elements REE

5 producers
(Unknown) consumers
1 producer accounts for well over 50%

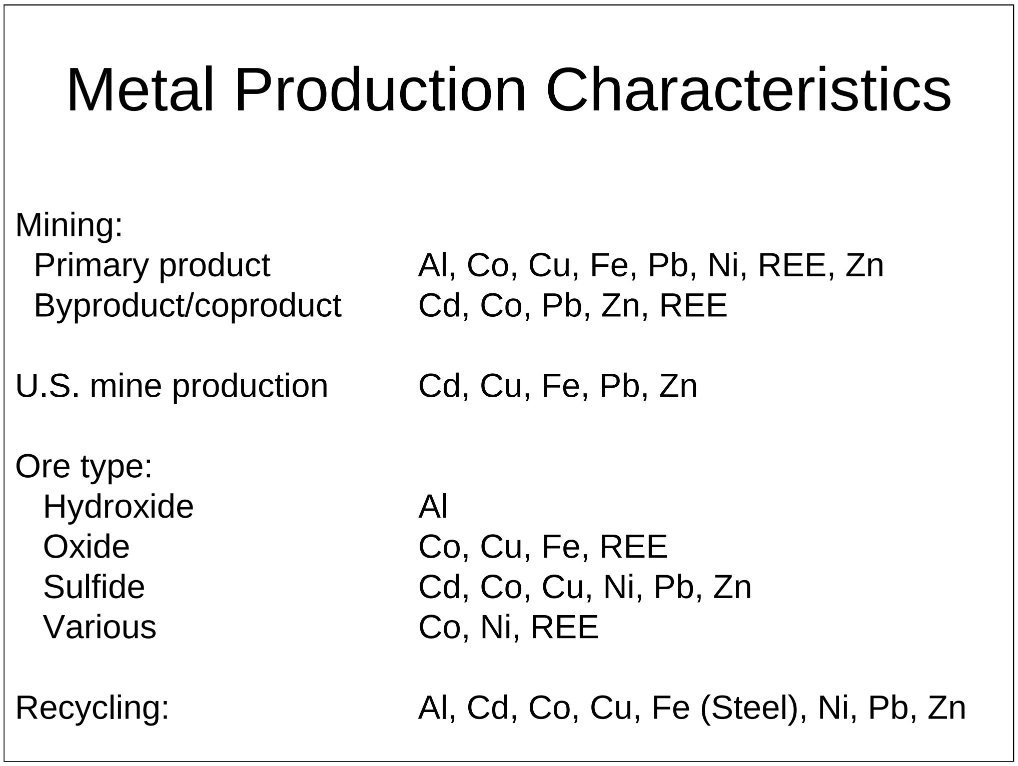
Source: REE production is 2001-05 average mine production as reported by the U.S. Geological Survey.

Among five rare earth-producing countries, the leading producer (China) accounts for more than 90% of production.

(Rare earths consumption data were not available.)

Al, Cd, Co, Cu, Fe, Ni, Pb, REE, and Zn Commodity Characteristics

Look at the characteristics and prices of these metals. The price of metals with similar characteristics may have similar influences. For example, the price of a byproduct metal could be influenced by the price of the metal of which it is a byproduct; or, metals that are produced in the same geographic area could be affected by the same environmental event, such as an earthquake or storm, or change in business operating conditions, such as labor relations or taxes.



Metal Production Characteristics

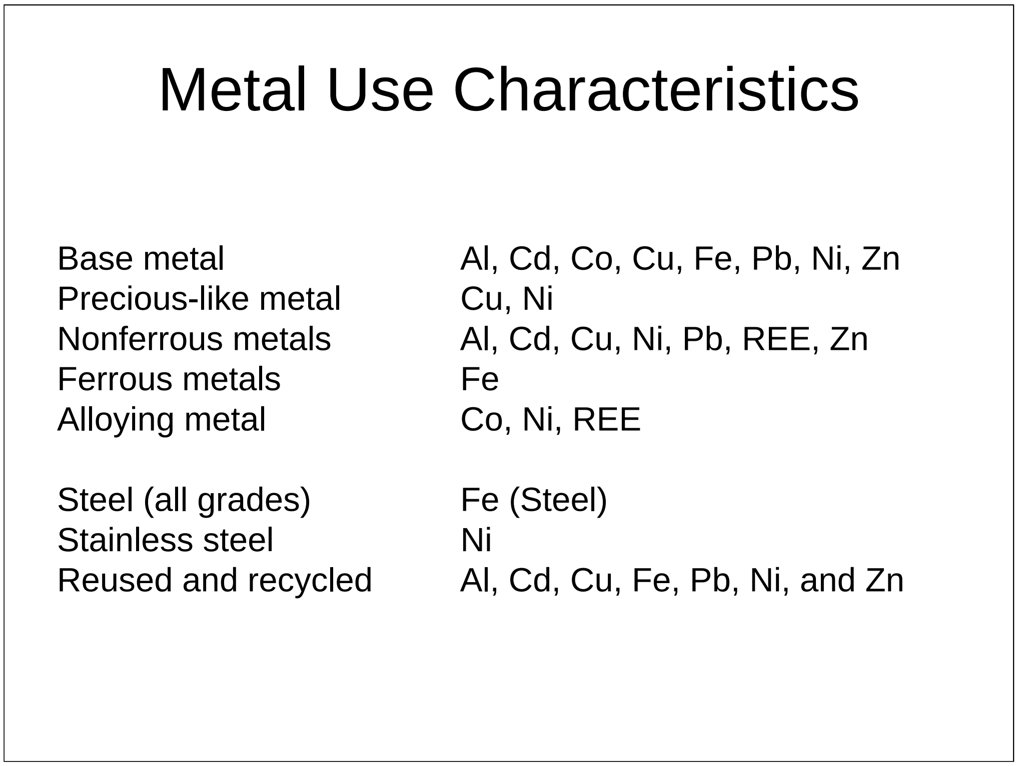
Mining:	
Primary product	Al, Co, Cu, Fe, Pb, Ni, REE, Zn
Byproduct/coproduct	Cd, Co, Pb, Zn, REE
U.S. mine production	Cd, Cu, Fe, Pb, Zn
Ore type:	
Hydroxide	Al
Oxide	Co, Cu, Fe, REE
Sulfide	Cd, Co, Cu, Ni, Pb, Zn
Various	Co, Ni, REE
Recycling:	Al, Cd, Co, Cu, Fe (Steel), Ni, Pb, Zn

Generally, metal ores are mined, beneficiated, and then processed to extract metal. Mining factors affect the production cost, and, therefore, the price of metals. It must be considered whether the metal is mined as primary product, byproduct, or coproduct. If it is a primary product, production can more easily respond to price changes. Byproduct metal production depends on the primary products' market conditions, byproduct market conditions, and fluctuations of byproduct ore grade and recovery rates. (Byproduct may be recovered to remove a detrimental impurity.) For example, cadmium is generally produced as a byproduct of zinc production.

Cadmium, copper, iron, lead, and zinc are produced (mined) domestically; aluminum, cobalt, nickel, and rare earths are not.

Recycling markets contribute a significant amount to the production of Al, Cd, Co, Cu, Fe (steel), Ni, Pb, and Zn. Indeed, industry has integrated these recycled materials into process streams to the degree that they are now essential feed materials and commodities. There are large, active markets for used aluminum, copper, iron (steel), lead, nickel, and zinc for recycling. Cd and Ni are recovered from recycled Ni-Cd batteries.

[Recycling is used here in the sense of post-consumer recovery and reuse. Metal scrap generated in the production process is generally reintegrated into the production process stream.]



Metal Use Characteristics

Base metal	Al, Cd, Co, Cu, Fe, Pb, Ni, Zn
Precious-like metal	Cu, Ni
Nonferrous metals	Al, Cd, Cu, Ni, Pb, REE, Zn
Ferrous metals	Fe
Alloying metal	Co, Ni, REE
Steel (all grades)	Fe (Steel)
Stainless steel	Ni
Reused and recycled	Al, Cd, Cu, Fe, Pb, Ni, and Zn

Al, Cd, Co, Cu, Fe, Pb, Ni, and Zn are base metals; Cu and Ni are precious-like metals in the sense that they have been the object of speculative investment as are gold, silver, and platinum-group metals; Al, Cd, Cu, Ni, Pb, REE, and Zn are nonferrous metals; and Co and Ni are primarily alloying elements.

The leading use of Fe is to make steel. Ni is used in significant amounts as an alloying element in stainless steel. Co and Ni are used as base metals and alloying elements in superalloys. Co and Ni are used in batteries: Co in lithium-ion batteries and Ni in Ni-Cd batteries. REE are used primarily as oxides; however, mischmetal (a natural mixture of REE) is an alloying agent in steel and nickel-hydride battery alloys. Individual REE are added to superalloys. Cd, Ni, and Pb are used to make batteries.

Al, Cd, Co, Cu, Ni, Pb, steel, and Zn have significant recycle production and scrap metal markets.

Factor Classification

All commodities, everywhere
Some commodities, everywhere
All commodities, limited geographic area
Some commodities, limited geographic area

Economic events such as world wars, national industrial growth, the Asian financial crisis (1997-98), recessions, and inflation have affected metal prices. Technologic developments, such as the growth of power and communication industries that require copper wire or the subsequent transition to wireless communication, also affect metal prices.

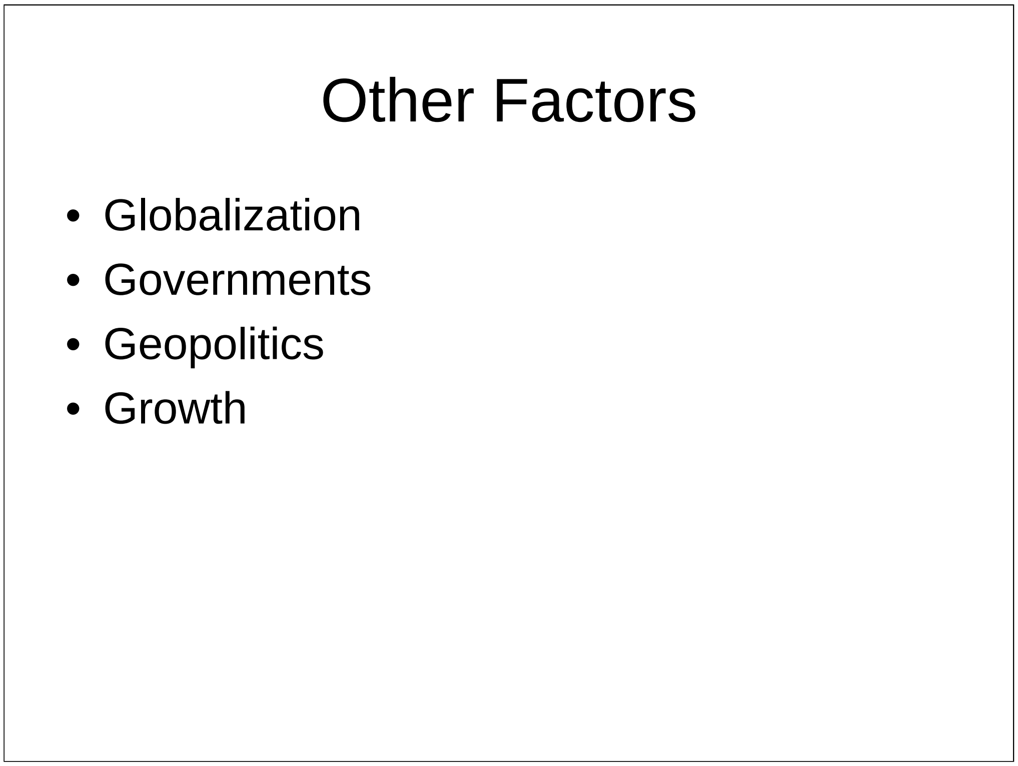
Commodity-specific events such as the construction of new production facilities or processes, new uses (or the discontinuance of historical uses), unexpected mine or plant closures (natural disaster, supply disruption, accident, strike, and so forth), or industry restructuring all affect metal prices.

Effects are in the present regardless of the event; however, the duration of effects may vary. The duration of a strike is usually substantially shorter than that of a war. A natural disaster may be shorter than a strike. The extent and duration of an event affect price through supply and demand.

Factors Affecting Price

- Scarcity
- Supply-demand balance
- Stocks and rate of use
- Actual or anticipated supply disruption
- Earnings, market performance, expectations
- Investment level

Generally, business analysts say that supply-demand balance determines price; investment analysts say that expectations play an important role in determining price; commodity analysts say that price increases as the number of weeks of supply in stocks diminishes; and financial market analysts say that increased speculative investment in metals causes the price to rise.



Other Factors

- Globalization
- Governments
- Geopolitics
- Growth

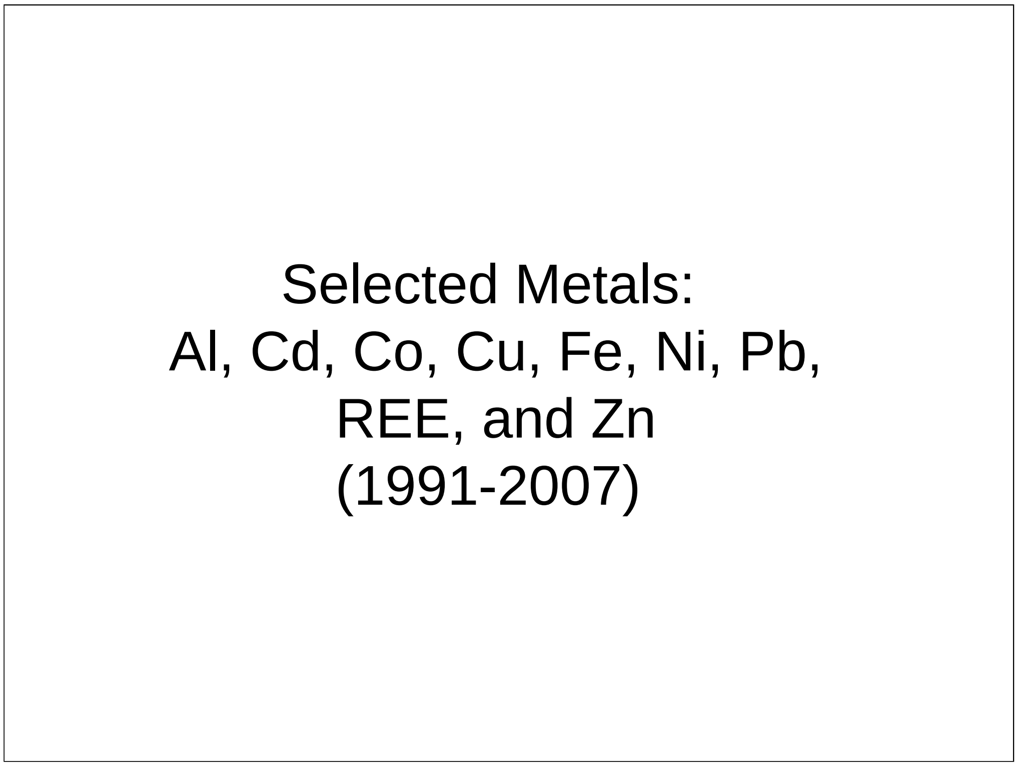
Globalization is important because many countries now play a role in metal production and consumption. Events in any of those countries could affect metal price. Events between countries, such as changes in currency exchange rates, play a role.

Governments set trade policy (implementation or suspension of taxes, penalties, and quotas) that affect supply by regulating (restricting or encouraging) material flow. They set the rules for resource extraction. They are a source of demand when they build stockpiles and a source of supply when they dispose of them.

Geopolitical events involving governments or economic paradigms and armed conflict can cause major changes. Historically, there have been two world wars and restructuring of national economies. There is no reason to believe that such events will not happen again. That these events have happened is reason to ask "What will happen and where?" and "Which metals will be affected?"

Businesses grow and reorganize. Despite the best business planning, demand can get ahead of supply when new production facilities come onstream late or do not perform as expected. Supply can get ahead of demand when a capacity increase exceeds the downstream industry's ability to absorb the potential new production.

There is also a national economic growth factor. Societies, as they develop, demand metals in a way that depends on their current economic position. For example, development in a country that is constructing road, rail, public utility, and building infrastructure would make a greater demand on metals use than would the development of a country that has nearly adequate amounts of transportation, housing, and basic services.



Selected Metals:
Al, Cd, Co, Cu, Fe, Ni, Pb, REE, and Zn
(1991-2007)

Now look at production, consumption, stocks, and price of these selected metals in a more recent time period.

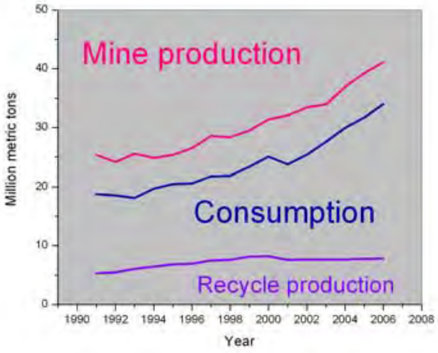
Stocks are a buffer between production and consumption. Stock changes indicate the imbalance between production and consumption.

Aluminum
Al

Aluminum is the second leading metal produced after iron. The United States is a major alumina and aluminum producer but does not produce bauxite and is a leading consuming country. [2006 world mine production: Al (in bauxite) was 47 Mt-contained Al (178 Mt-Bauxite ore @ 0.50 Al_2O_3/ore @ 0.529 Al/Al_2O_3); and Fe (in iron ore), 945 Mt-contained Fe (1,800 Mt-ore).]

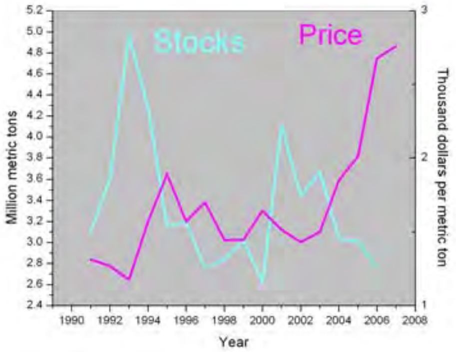
[Al data sources: Al mine production is Al content of bauxite world mine production as reported in the Bauxite and Alumina chapter of the USGS Minerals Yearbook. Al consumption is Al refined consumption as reported by the WBMS in WMS. Al recycle production is Al secondary production as reported by the WBMS in WMS. Al stocks are metal exchange (LME, COMEX, Shanghai Metal Exchange, and Tokyo Commodity Exchange), country, and U.S. strategic stockpile stocks as reported by the WBMS in WMS. Al price is Al ingot average U.S. market spot price as reported in the Aluminum section of the USGS Mineral Commodity Summaries.]

Aluminum
Al



World mine production, consumption,
and recycle production

Aluminum stocks and price



Source: See statement of Al data sources.

Aluminum mine production (estimated as world bauxite production times 0.5 units of alumina per unit bauxite times 0.52 units of aluminum per unit of alumina) and consumption (of Al metal) generally have been rising since 1992.

Aluminum price and stocks usually change in opposite directions. Al stocks rose sharply from 1991 through 1993 while price dropped. Since 2002, the aluminum price rose, closing 2007 at a historic high.

Al content of bauxite production exceeds Al metal consumption because about 15% of bauxite production is consumed for uses other than Al metal production; about 5% is directly consumed (for example, for uses such as abrasives, chemicals, cement, proppants, refractories, and in steel mills as a flux additive) and about 10% is used to make alumina that is consumed for uses other than Al metal production (for example, for uses such as abrasives, cement, ceramics, chemicals, and refractories).

[Note: Stocks are London Metal Exchange (LME) plus New York Commodities Exchange (COMEX) plus country plus National Defense Stockpile (NDS) stocks for December of year as reported by World Bureau of Metal Statistics.]

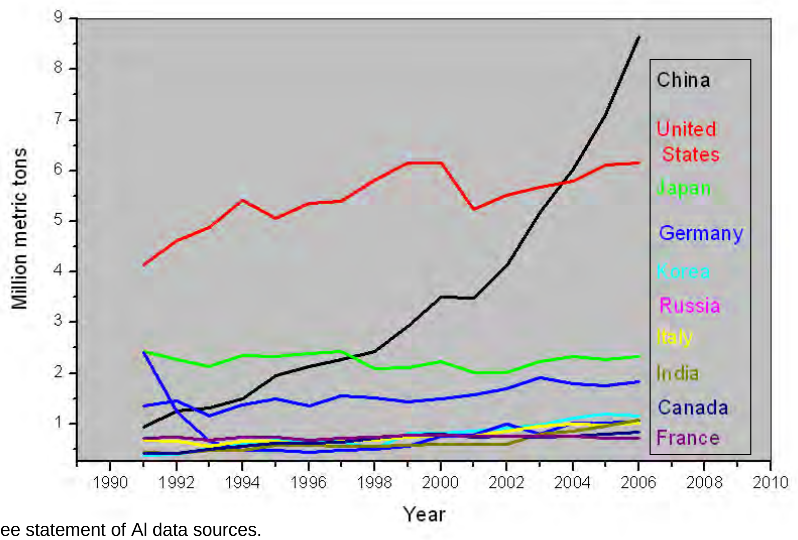
Cadmium
Cd

Cadmium is primarily produced as a byproduct of zinc mining and mostly is used to make batteries, an application that is declining. Its use as a plating metal to protect against corrosion by sacrificial oxidation also has been declining.

[Cd data sources: Cd mine production is Cd world refinery production as reported in the Cadmium chapter of the USGS Minerals Yearbook. Cd consumption is Cd refined consumption as reported by the WBMS in WMS. Cd stocks are country and U.S. strategic stockpile stocks as reported by the WBMS in WMS. Cd price is New York dealer Cd metal average annual price as reported in the Cadmium section of the USGS Mineral Commodity Summaries.]

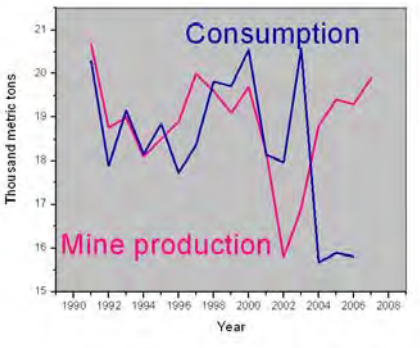
Aluminum
Al

Leading aluminum consumers



Source: See statement of Al data sources.

Aluminum consumption by most of the leading consumers has been steady during the 1991-2006 period. Among the leading consumers, only China has increased consumption significantly.



Cadmium
Cd

World mine production and consumption

Cadmium stocks and price

Source: See statement of Cd data sources.

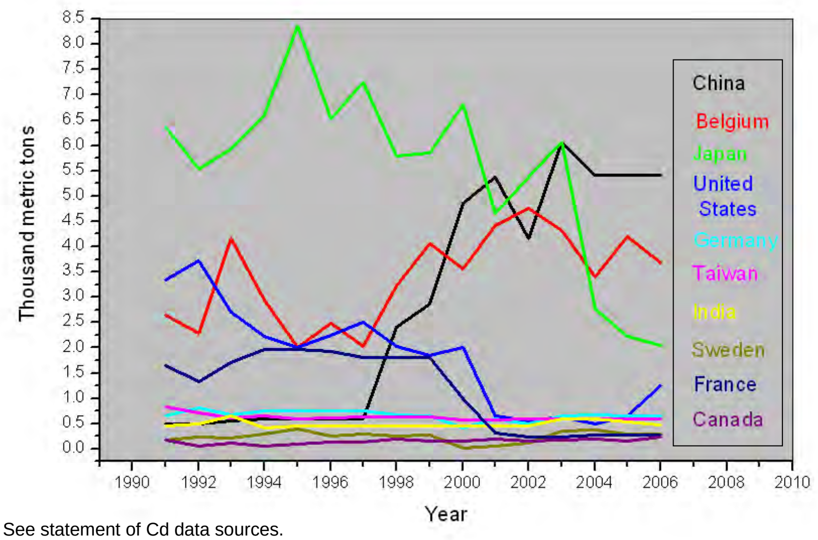
Cadmium mine production, as represented here by cadmium refinery production, was similar to consumption until 2003, when production increased and consumption declined. Cadmium price has been rising since 1999 following a stock decline trend since 1996. Mine production did not respond to change in consumption from 2001-02, which may have resulted from the byproduct status of cadmium. Zn production declined during that time period.

The overall decline in 1991-2003 Cd consumption to 2004-06 Cd consumption may be associated with the substitution of non-Cd-containing batteries for Cd-containing batteries and the European Union Batteries Directive that was expected to reduce portable NiCd battery use in the near future.

[Stocks are country and National Defense Stockpile (NDS) stocks as reported by World Bureau of Metal Statistics for December of year.]

Cadmium
Cd

Leading cadmium consumers



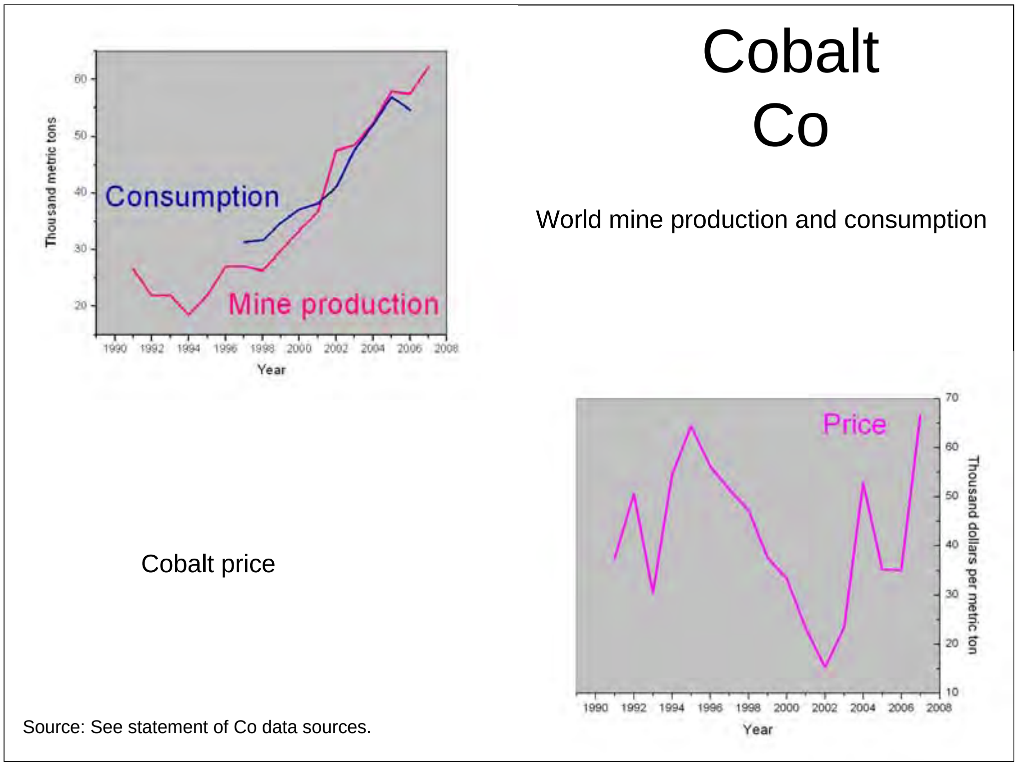
Source: See statement of Cd data sources.

In the early 1990s, Japan was the leading consumer of cadmium; however, Japan's consumption has since declined significantly. U.S. cadmium consumption has declined, too. China and Belgium became the leading cadmium consumers by 2006. The rise in Cd consumption by China and the decline in the United States and Japan are associated with the relocation of battery manufacturers to China.

Cobalt
Co

Cobalt is mined as a primary product and recovered as a byproduct of copper and nickel production.

[Co data sources: Co mine production is Co world mine production as reported in the Cobalt chapter of the USGS Minerals Yearbook. Co consumption is refined Co apparent demand as reported by the CDI and the WBMS in Annual Cobalt Statistics. Co price is Co cathode average annual price as reported in the Cobalt section of the USGS Mineral Commodity Summaries.]



Cobalt
Co

World mine production and consumption

Cobalt price

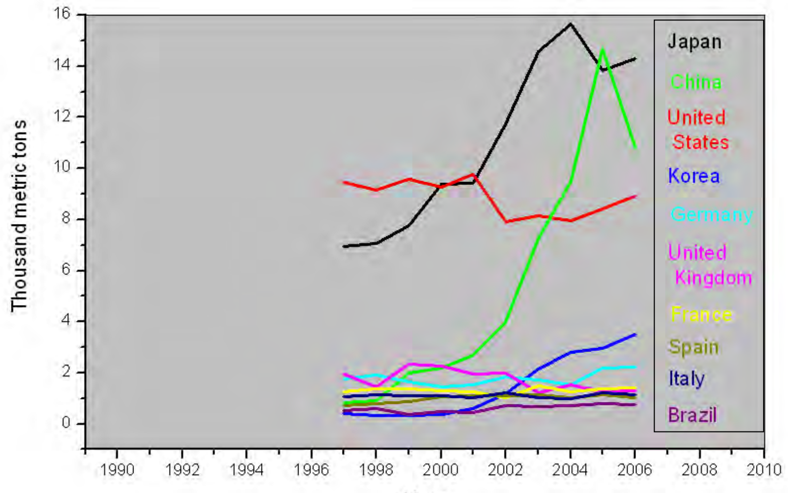
Source: See statement of Co data sources.

Cobalt production and consumption have increased steadily since 1994.

Despite the steady increase of production and consumption during the time period, cobalt price dropped between 1996 and 2002, indicating that the rate of production was more than adequate to meet the rate of consumption.

Leading cobalt consumers

Cobalt
Co



Source: See statement of Co data sources.

Japan and the United States were leading cobalt-consuming countries over the entire time period; however, from 1999 to 2005, China’s consumption grew from that of a leading consumer to the leading consumer.

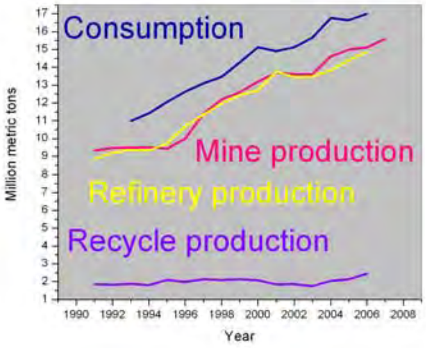
[China’s consumption decline from 2005 to 2006 may have resulted from consumption of stocks, which is not included in consumption shown in the graph.]

Copper
Cu

Copper is produced from an oxide or sulfide ore, which is converted to copper metal. The United States produces a significant amount of copper and is a leading copper consumer.

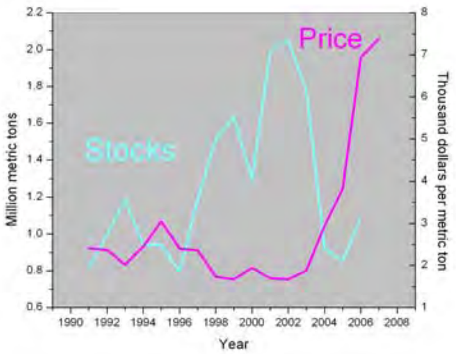
[Cu data sources: Cu mine production is Cu world mine production as reported in the Copper chapter of the USGS Minerals Yearbook. Cu consumption is Cu world usage reported by the ICSG. Cu recycle production is Cu secondary refinery production as reported by the ICSG. Cu stocks are metal exchange (LME, COMEX, and Shanghai Futures Exchange) and selected merchant stocks as reported by the ICSG. Cu price is average domestic producer Cu cathode price as reported in the Copper section of the USGS Mineral Commodity Summaries.]

Copper Cu



World mine production, refinery production, consumption, and recycle production

Copper stocks and price



Source: See statement of Cu data sources.

Copper production and consumption have increased steadily since 1991.

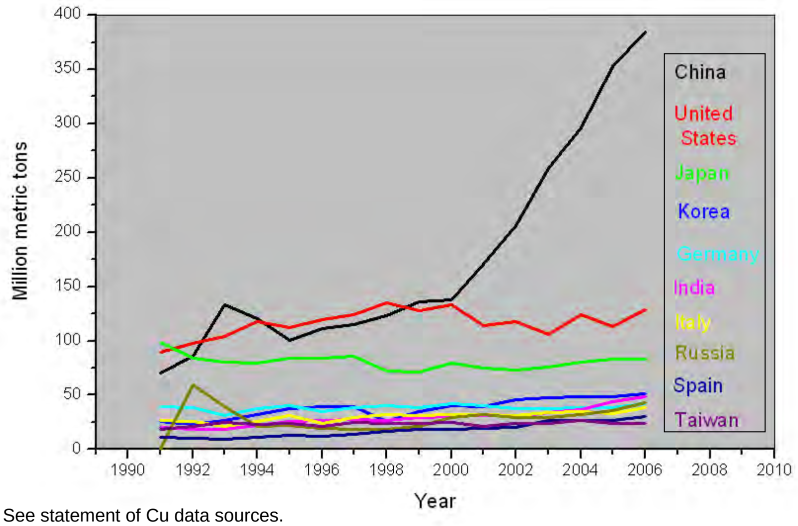
On only two occasions during the 1991-2006 period did both annual average price and year-end stocks change in the same direction. These were in 1995-96 and 2005-06 when both stocks and price increased.

The price drop in 1995-96 followed the discovery in 1996 that a rogue trader had used trading company money to maintain the price of copper. Copper is traded internationally on three commodity exchanges, and production, consumption, and stock information is readily available. The copper market is relatively transparent in that a change in supply or demand is reflected in price, while an excess of production over consumption results in higher stock levels, and a deficit of production relative to consumption results in lower stock levels. Recessions result in reduced demand; additional supply can be delayed by long lead times for the construction of new facilities.

Like that of the other metals, world copper mine production and consumption increased while the copper price trend declined between 1991 and 2003. The stocks-price graph suggests that demand exceeded production in 2003 when stocks dropped to near historic low levels and the price rose.

Copper
Cu

Leading copper consumers



Source: See statement of Cu data sources.

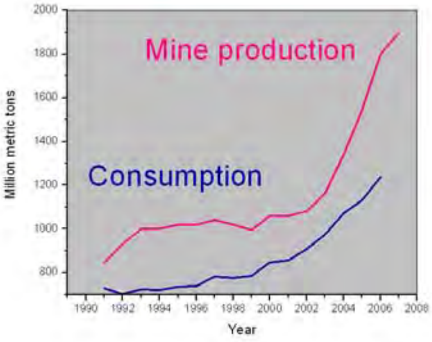
Among the leading copper consumers, China has increased consumption significantly. Consumption by the other leading consumers has changed little during the 1991-2006 period. The 1997-98 decline in Korean copper consumption was associated with the Korean financial crisis.

Iron
Fe

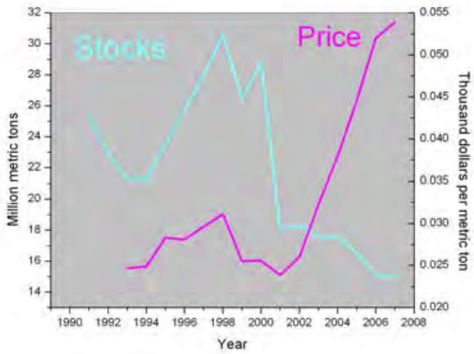
As measured by mine production, iron is the leading metal commodity. As measured by production, iron (steel) recycle production and iron slag production are the second and third leading metal commodities.

[Fe data sources: Fe mine production is Fe content of Fe ore world production as reported in the Iron Ore chapter of the USGS Minerals Yearbook. Fe consumption is raw steel world production as reported in the Iron and Steel chapter of the USGS Minerals Yearbook. Fe stocks are mine, dock, and consuming plant Fe ore stocks, excluding byproduct ore as reported in the Iron Ore section of the USGS Mineral Commodity Summaries. Fe price is Fe ore price estimated from the reported value of Fe ore at mines as reported in the Iron Ore section of the USGS Mineral Commodity Summaries. 2001-05 average world production of mined iron was 692 Mt-contained Fe, and steel production was 979.8 Mt, suggesting that the 2001-05 average recycled component of world steel production was 290 Mt (=979.8-692). Slag production in the same time period was 300-400 Mt, based on the Iron and Steel Slag section of Mineral Commodity Summaries 2007 reported production of 200-240 Mt/yr-iron slag, 115-180 Mt/yr-steel slag.]

Iron
Fe



World mine production and consumption



U.S. iron ore stocks and price

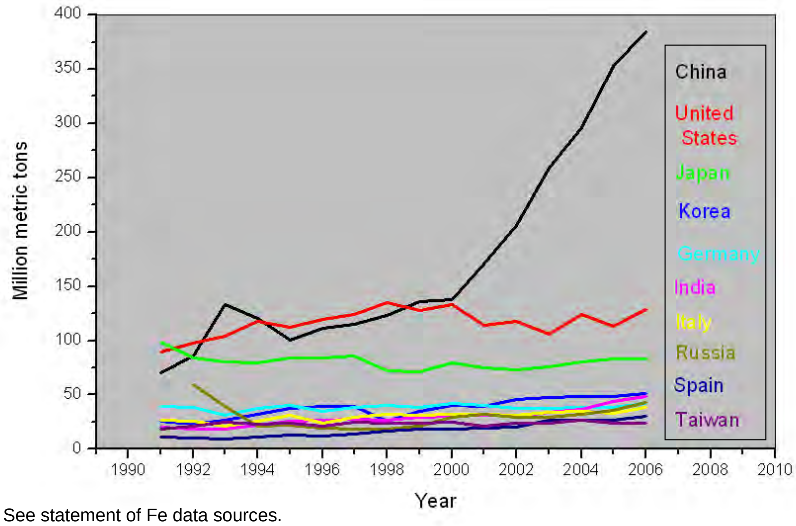
Source: See statement of Fe data sources.

Iron mine production and consumption have increased during the 1991-2006 period, strongly since 2002.

The figure shows U.S. stocks and iron ore price. U.S. stocks and price do not appear to change in opposite directions as they do for aluminum and copper until 2001, after which price rose while stocks declined. Possibly, U.S. stocks and price reflected North American (that is, regional) iron ore and steel markets, where a number of iron ore mines reduced production or went out of business, causing the inventory decline before 2001. After 2001, consumption of iron ore by China began to influence the North American market as China's consumption of other metals affected those metals' markets.

Leading iron (steel) consumers

Iron
Fe



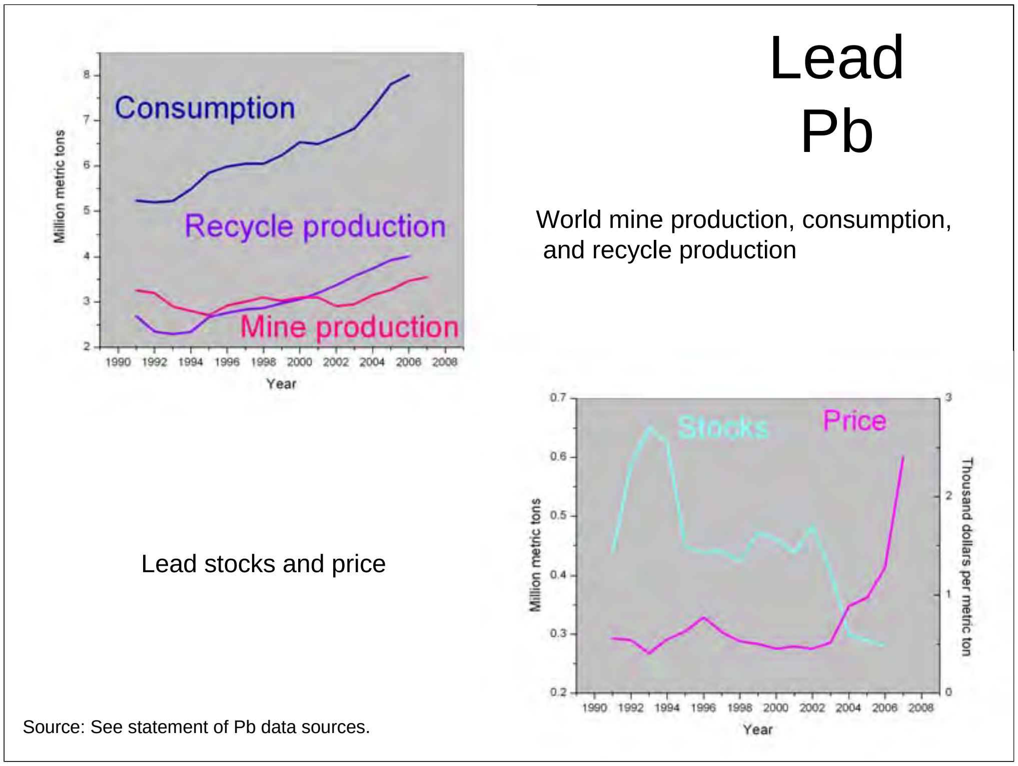
Source: See statement of Fe data sources.

Among the significant consumers of iron (as measured by steel consumption), only China showed significant growth during this 1991-2006 period. The 1997-98 decline in Korean iron consumption was associated with the Korean financial crisis.

Lead
Pb

Lead is mined as a primary product. A large fraction of lead production is through recycling.

[Pb data sources: Pb mine production is world mine production of Pb in concentrate as reported in the Lead chapter of the USGS Minerals Yearbook. Pb consumption is refined Pb metal consumption as reported by the ILZSG in Lead and Zinc Statistics. Pb recycle production is secondary world lead refinery production as reported by the USGS in the Lead chapter of the Minerals Yearbook. Pb stocks are LME, commercial (consumer, merchant, and producer), and U.S. strategic stockpile stocks as reported by the ILZSG in Lead and Zinc Statistics. Pb price is North American Pb producer average price as reported in the Lead section of the USGS Mineral Commodity Summaries.]



Lead
Pb

World mine production, consumption, and recycle production

Lead stocks and price

Source: See statement of Pb data sources.

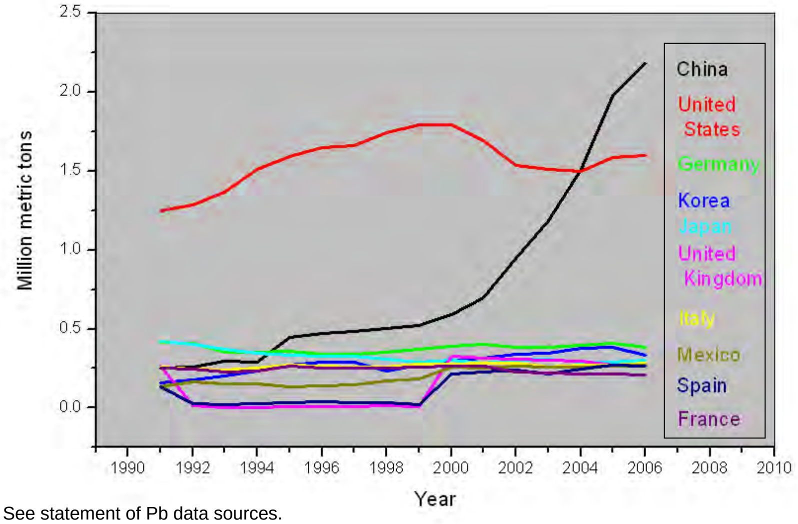
Lead mine production and consumption increased during the 1991-2006 period. Notice that, for lead, recycle production is about the same magnitude as mine production.

After a significant rise in lead stocks from 1991 through 1994, lead stocks declined during the 1994-2006 period. The price increased dramatically from 2003 through 2007.

[Lead stocks are producer, consumer, merchant, and LME stocks for the end of December of year as reported by the ILZSG.]

Lead
Pb

Leading lead consumers



Source: See statement of Pb data sources.

During the 1991-2006 period, China moved from being a significant to being the leading consumer of lead. China's growth was strongest from about 2000 to 2006.

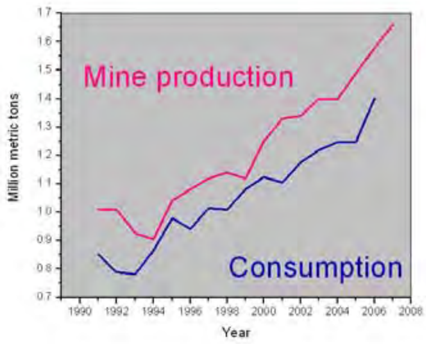
Nickel
Ni

Nickel is mined in a variety of mineral forms from which nickel extraction is complex and deposit dependent. About one-half of U.S. nickel consumption goes into stainless and alloy steel, and most of the rest goes into nonferrous alloys (copper, brass) and superalloys (nickel-based and nickel-containing, cobalt-based alloys).

[Ni data sources: Ni mine production is Ni world mine production as reported in the Nickel chapter of the USGS Minerals Yearbook. Ni consumption is Ni consumption as reported by the INSG in World Nickel Statistics. Ni stocks are LME stocks as reported by the INSG in World Nickel Statistics. Ni price is average annual LME Ni price as reported in the Nickel section of the USGS Mineral Commodity Summaries.]

Nickel
Ni

World mine production and consumption



Nickel stocks and price

Source: See statement of Ni data sources.

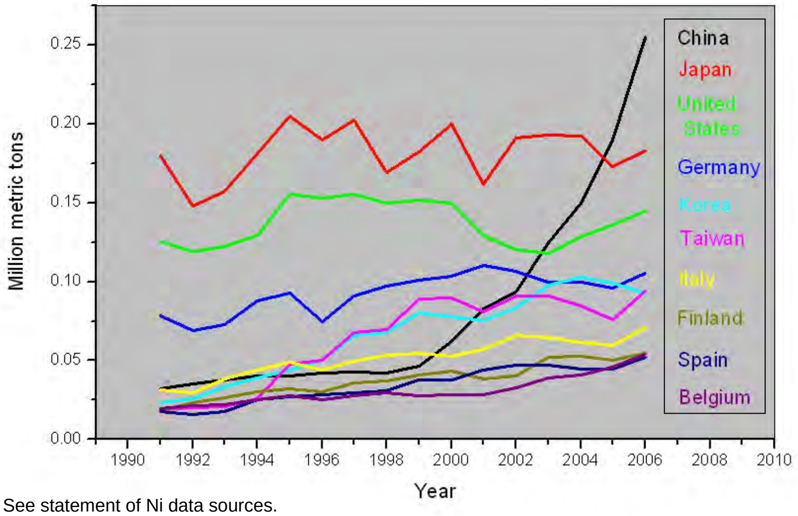
After a brief decline at the beginning of the 1991-2006 period, nickel mine production and consumption have increased.

World nickel stocks increased between 1991 and 1994, after which they have generally declined.

Following the dissolution of the Soviet Union in 1991, Ni stocks were built up until 1994, even as mine production declined. Glenbrook Nickel Company's mine (Nickel Mountain, OR) and smelter (Riddle, OR), the sole remaining primary nickel production operations in the United States, closed following the nickel price decline from 1991 through 1993. From 2001 to 2003, both stocks and price increased, suggesting involvement by investment funds. Several consecutive years of nickel demand growth have drawn down (LME) stocks to historically low levels.

Nickel
Ni

Leading nickel consumers



Source: See statement of Ni data sources.

World nickel consumption has been increasing as has that of China and Germany, who are among the leading consumers. During the 1995-2006 period, China moved from being a significant to being the leading consumer of nickel.

Rare Earth Elements
REE

The rare earth elements are a group of 17 elements comprising the 15 lanthanides, scandium, and yttrium—a variety of elements that tend to occur together in minerals.

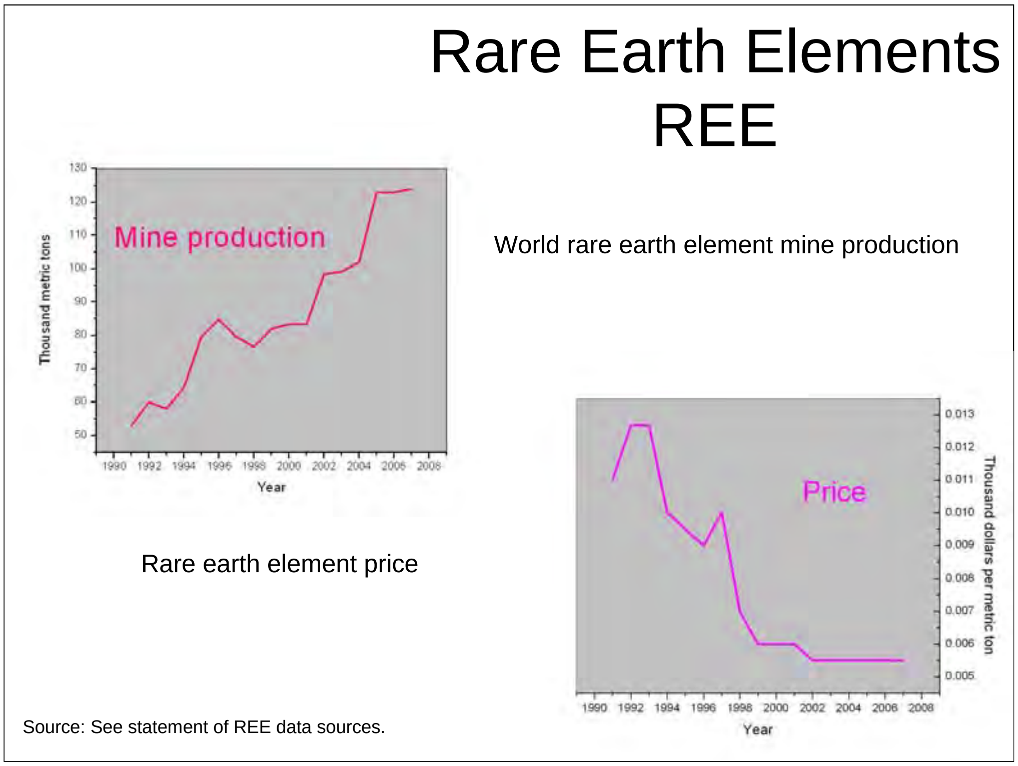
The large number of elements represented by the REE moniker indicates an even greater variety of diverse uses. Ce, Gd, La, Nd, Pr, and Sm are used in glasses—Ce and Nd to absorb ultraviolet and Gd, La, and Sm to absorb infrared. Eu is used in the red phosphor in television tubes. Nd is used in magnets.

[REE data sources: REE estimated world mine production Rare Earths chapter of the USGS Minerals Yearbook. REE price is price of metal content of mischmetal as reported in the Rare Earths section of the USGS Mineral Commodity Summaries.]

Zinc
Zn

Zinc is produced as a primary product, byproduct, and also has a significant secondary component to production.

[Zn data sources: Zn mine production is Zn content of Zn concentrate and direct shipping ore world production as reported in the Zinc chapter of the USGS Minerals Yearbook. Zn consumption is Zn refined metal consumption as reported by the ILZSG in Lead and Zinc Statistics. Zn recycle production is Zn Western world recovery of Zn as reported by the ILZSG in Lead and Zinc Statistics. Zn stocks are LME, commercial (producers, consumers, and merchants), and U.S. strategic stockpile stocks as reported by the ILZSG in Lead and Zinc Statistics. Zn price is aluminum average LME cash price as reported in the Zn section of the USGS Mineral Commodity Summaries.]



Rare Earth Elements REE

World rare earth element mine production

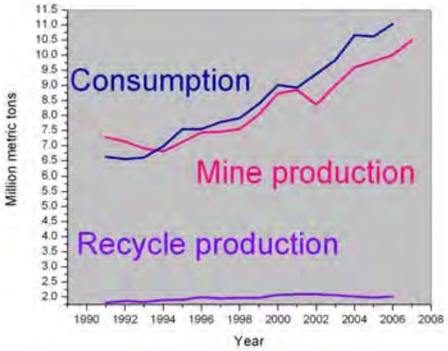
Rare earth element price

Source: See statement of REE data sources.

Rare earth element production, like that of other metals described before, has been increasing during the 1991-2007 period; however, unlike the other metals, price has been declining. Owing to its strong economic impact, the materials and items that China consumes have been getting more expensive while the price of materials and items that China produces has been getting cheaper. Generally, that translates into the cost of raw materials going up and the cost of consumer products going down; however, in this case, China is by far the leading producer of this raw material, so its price is not rising at the end of the time period as are the prices of other metals. The price of most REE in 2007 rose significantly (not shown in figure) as a result of increased Chinese consumption and China’s enactment of export controls. In response to the rising price, Mountain Pass Mine, CA, restarted processing stocks of REE concentrate.

Consumption and stocks data for rare earths are not available. Rare earth production has shifted to China from the United States. China now produces over 90% of world supply.

Zinc
Zn



World mine production, consumption, and recycle production

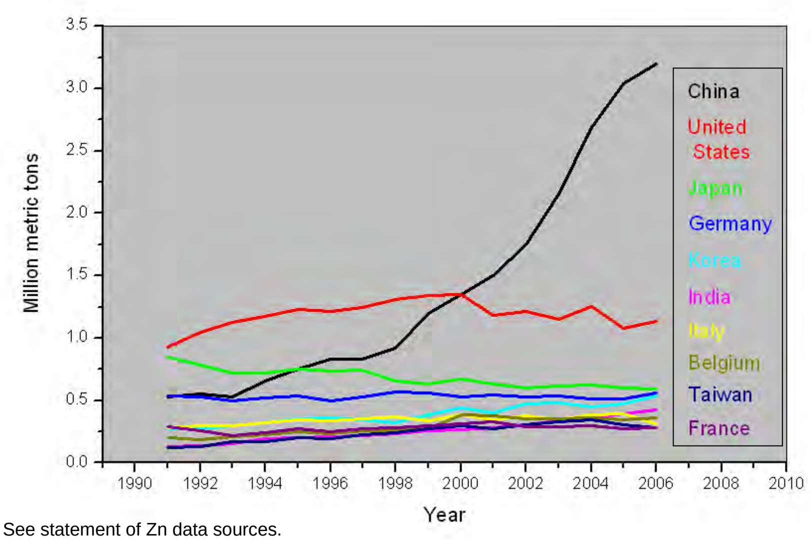
Zinc stocks and price

Source: See statement of Zn data sources.

Zinc consumption has risen after a brief decline from 1991 through 1994, a period during which stocks increased. Zinc mine production and consumption generally increased during the 1991-2006 period. The stock changes before 2003 were associated with small price changes compared to the rapid stock decline and price rise that started in the 2003-04 period.

Zinc
Zn

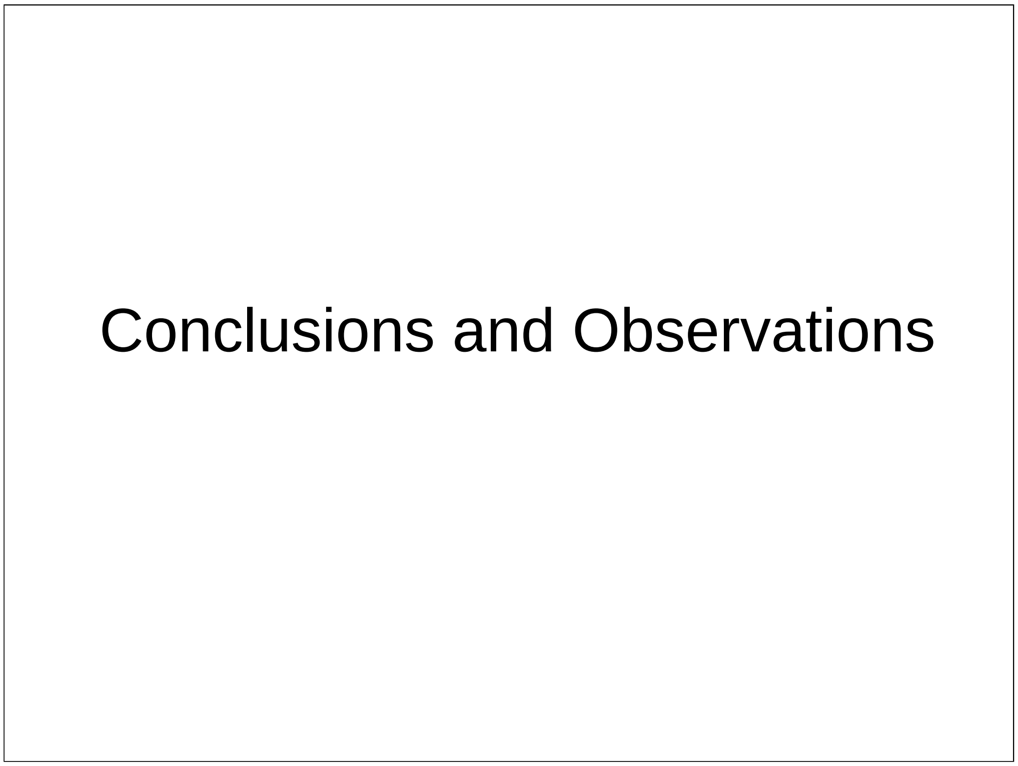
Leading zinc consumers



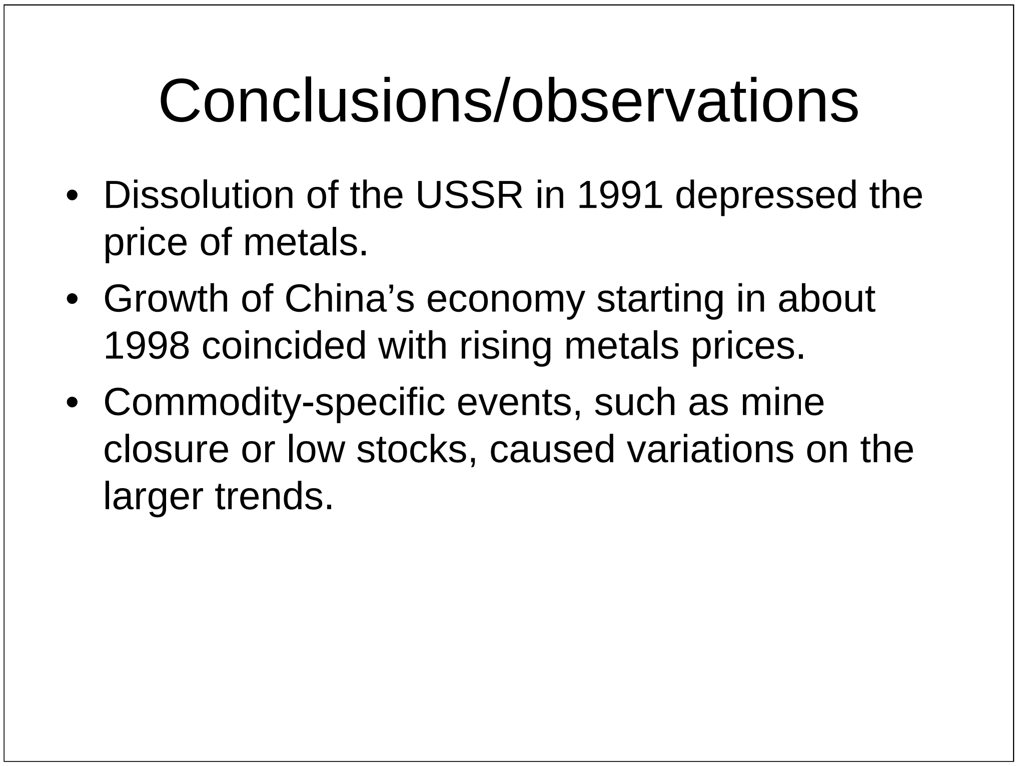
Source: See statement of Zn data sources.

China moved from being a significant consumer to being the leading consumer of zinc during the 1991-2006 period.

During 2001 in the United States, there was a general downturn in the economy and a 20% decline in automobile sales. These events affected the steel industry, where nearly 60% of U.S. zinc is consumed to make galvanized steel. Reduced consumption in the United States contributed to increased stocks in that year shown on p. 48.



Conclusions and Observations



Conclusions/observations

- Dissolution of the USSR in 1991 depressed the price of metals.
- Growth of China’s economy starting in about 1998 coincided with rising metals prices.
- Commodity-specific events, such as mine closure or low stocks, caused variations on the larger trends.

Two major events that affected metal prices during the 1991 to 2007 period—dissolution of the Soviet Union in 1991 and consumption growth in China starting in about 1998—may be associated with the following trends common to many metals: production declines followed by declining prices in the early part of the period that were coincident with dissolution of the Soviet Union, and rising production and dramatically increasing prices at the end of the period that were coincident with economic growth in China. Dissolution of the Soviet Union reduced demand and added to supply. Sustained demand growth in China exceeded world growth in supply and support infrastructure (electrical power, transportation), causing stock depletion and rising prices.

For those metals for which world consumption data are available (Al, Cd, Co, Cu, Fe, Ni, Pb, and Zn), China is a major, growing consumer. For those metals for which world stocks data are available (Al, Cd, Cu, Ni, Pb, and Zn), stocks are at or near historic low levels. Since China’s growth is that of its general economy, one would expect the stocks of other mineral commodities (Co and REE) to be affected in the same way.

It appears that dissolution of the Soviet Union in 1991 resulted in the integration of Eastern and Western stocks into a world market, where they caused prices to drop. Lower prices may have caused marginal producers to stop production, leaving the metal production industry less able to meet Chinese demand. In addition, the leading consumer at the time (United States) was in recession from July 1990 through March 1991.

In 2005, copper stocks reached the lowest level since 1996; in 2006, nickel stocks reached the lowest level over the entire 1991-2006 period.

China-United States Share of Selected Metals Markets
(5-year average)

Metal	China Share	China Rank	U.S. Share	U.S. Rank	Comment
Aluminum					
Ore production	10%	3	--	--	Australia, #1 (36%) Brazil, #2 (12%)
Alumina	11%	2	8%	3	Australia, #1 (29%)
Smelter production	20%	1	9%	4	Russia, #2 (12%), Canada #3 (10%)
Consumption	21%	1	20%	2	Japan, #3 (8%)
Cadmium					
Ore production	14%	1	7%	7	Korea, #2 (13%)
Consumption	31%	1	4%	4	Belgium, #2 (13%)
Cobalt					
Ore production	2%	10	--	--	Congo, #1 (32%)
Consumption	18%	2	16%	3	Japan, #1 (28%)
Copper					
Ore production	5%	7	8%	2	Chile, #1 (35%)
Smelter production	14%	1	5%	5	Chile, Japan #2, 3 (12%)
Refinery production	12%	2	9%	3	Chile, #1 (18%)
Consumption	20%	1	14%	2	Japan, #3 (8%)

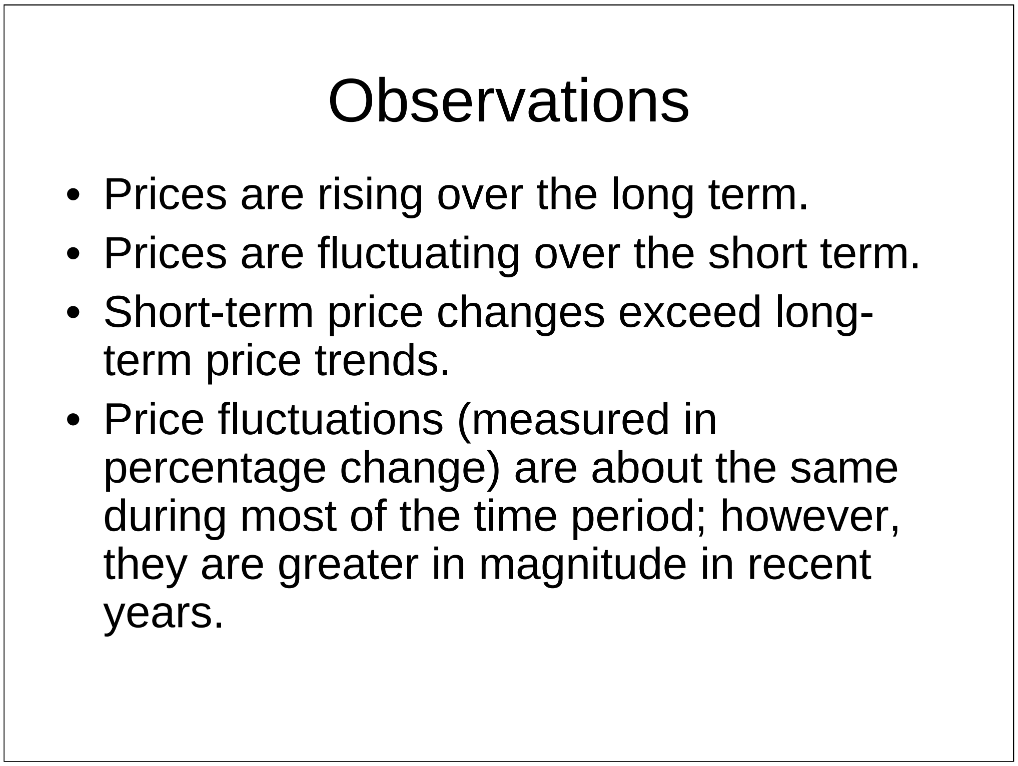
Today, China has the second largest economy after that of the United States. China's impact on the mineral and metals markets is greater than its proportional economic size might indicate because China, unlike developed countries, is building infrastructure, a process that is mineral and metal intensive.

Notice that in this list of China's and the United States' share of and rank in the production and consumption of these metals, China ranks mostly number 1; the United States ranks number 2 or lower for all of these metals.

China-United States Share of Selected Metals Markets—continued
(5-year average)

Metal	China Share	China Rank	U.S. Share	U.S. Rank	Comment
Nickel					
Ore production	5%	8	--	--	Russia, #1 (22%)
Plant production	5%	6	--	--	Russia, #1 (21%)
Consumption	13%	2	10%	3	Japan, #1 (15%)
Zinc					
Production	22%	1	8%	5	Australia, #2 (15%)
Consumption	25%	1	11%	2	Japan, #3 (6%)
Steel (all grades)					
Production	24%	1	10%	3	Japan, #2 (11%)
Consumption	23%	1	13%	2	Japan, #3 (8%)
Stainless steel					
Production	13%	2	9%	3	Japan, #1 (16%)
Consumption	22%	1	11%	3	Japan, #2 (11%)

China became the leading stainless steel producer in 2006.



Observations

- Prices are rising over the long term.
- Prices are fluctuating over the short term.
- Short-term price changes exceed long-term price trends.
- Price fluctuations (measured in percentage change) are about the same during most of the time period; however, they are greater in magnitude in recent years.

Historically, nominal metal prices have trended upward, whereas constant dollar prices have not changed significantly. These trends may not be apparent over short time periods because of the amplitude and duration of price fluctuations. Looking at frequently quoted prices (such as those in the trade journals that report prices daily or weekly or commodity exchanges that quote prices even more frequently) obscures long-term trends.

Cost of production sets the lower limit for sustainable prices. Supply-demand considerations, such as plant openings and closings or unexpected events such as industrial accidents or natural disasters, influence short-term price variations. Global events such as wars, recessions, inflation, or economic growth influence longer term trends.

Conclusions and Observations

- The U.S. once dominated the market but no longer.
- China’s GDP growth was 11% in Q1 2007.

In terms of the consumer market, the time when the U.S. economy was the predominant influence on price has changed to one in which consumption is shared. China, in particular, is a growing participant (that is, processor and consumer) in the world market. China reported 11% GDP growth in the first quarter of 2007, which some economists interpret as an overheating economy. To determine what effect this will have on metal prices, we must answer the question “Is this the China miracle or the China bubble?” Or “For how long will this be the China miracle and when will it turn into the China bubble?” Sustained growth in China means sustained demand for these metals and high prices until suppliers and infrastructure expand to accommodate the new level of demand.

China’s demand for metal results partly from infrastructure expansion in China. At first, infrastructure expansion is metal and material intensive, because China starts with little infrastructure. After roads, bridges, tunnels, and buildings are built, China’s expansion will likely turn to less material-intensive development such as in entertainment, health care, and communications. As India grows, its greater GDP will make it more influential in the world market. As China moves away from material-intensive development, India may be moving into material-intensive development. Thus, India may replace China as the material-intensive developing country in the near future.

Current Events with Potential Price Impacts

- Moderation of China’s economic growth
- Increase in India’s economic growth
- Steel industry consolidation
- Global warming and carbon sequestration
- Rising energy costs
- Value of the U.S. dollar

Metal prices are affected by factors external to the metals industry. The metals industry is a part of the world and national economies, so changes in those economies can affect metals’ prices.

Some situations that could affect prices in the near future include possible export limitations on chromite ore from India and South Africa, changes in China’s economic growth, and continued Indian economic growth.

Global warming is becoming an issue. High fuel prices raise transportation and production costs. Independent of any metal industry factors, the price of metals changes with the changing value of the U.S. dollar, which has been generally declining. As a result of these factors, the price of metals has been trending upward.

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Appendix 1. List of Abbreviations

Al	aluminum
Cd	cadmium
Ce	cerium
CDI	Cobalt Development Institute
Co	cobalt
COMEX	New York Commodity Exchange
Cu	copper
EAF	electric-arc furnace
Eu	europium
Fe	iron
GDP	Gross domestic product
Gd	gadolinium
ICSG	International Copper Study Group
ILZSG	International Lead and Zinc Study Group
INSG	International Nickel Study Group
k	kilo (10^3)
Korea	Republic of Korea
k$/t	thousand (current, nominal, not-inflation-adjusted) dollars per metric ton
k1998$/t	thousand (constant, deflated, inflation-adjusted) dollars per metric ton
La	lanthanum
LME	London Metal Exchange
M	mega (10^6)
MCS	Mineral Commodity Summaries
Mn	manganese
Mo	molybdenum
Nd	neodymium
Ni	nickel
Pb	lead
Pr	praseodymium
REE	rare earth elements
Sm	samarium
t	metric ton
U.S.	United States
USGS	U.S. Geological Survey
WBMS	World Bureau of Metal Statistics
WMS	World Metal Statistics
yr	year
Zn	zinc
$	U.S. dollar

ATTACHMENT 3

Cobalt Statistics, U.S. Geological Survey, Last Modification: November 19, 2009.

COBALT STATISTICS[1]
U.S. GEOLOGICAL SURVEY
[All values are in metric tons (t) cobalt content unless otherwise noted]
Last modification: November 19, 2009

Year	Primary production	Secondary production	Mine shipments	Government shipments	Imports	Exports	Stocks	Reported consumption	Apparent consumption	Unit value ($/t)	Unit value (98$/t)	World mine production	World refinery production
1900					20				20	4,930	97,000		
1901					20				20	5,590	110,000	180	
1902					30				30	5,600	106,000	540	
1903					20				20	6,050	110,000	640	
1904					10				10	6,210	113,000	540	
1905					20				20	6,060	110,000	450	
1906					10				10	5,940	108,000	450	
1907					20				20	4,680	82,000	910	
1908					70				70	230	4,300	1,360	
1909					5				5	2,920	53,000	1,450	
1910	0				5				5	1,270	22,000	1,000	
1911	0				200				200	300	5,200	820	
1912	0				260				260	320	5,400	860	
1913	0				70				70	1,390	22,900	820	
1914	0				110				110	2,470	40,300	360	
1915	0				70				70	3,180	51,200	230	
1916	0				110				110	3,220	48,200	410	
1917	0				170				170	3,890	49,600	360	
1918					240				240	3,900	42,100	450	
1919					70				70	4,770	45,000	360	
1920					120				120	6,150	50,000	360	
1921					70				70	6,450	58,600	180	
1922					120				120	6,590	64,000	820	
1923	0				193				193	5,950	56,700	640	
1924	0				128				128	5,810	55,400	1,090	
1925	0				185				185	5,450	50,900	1,090	
1926	0				291				291	5,260	48,300	820	
1927	0				308				308	5,120	47,800	1,180	
1928	0				371				371	5,140	48,900	1,180	
1929	0				550				550	4,940	47,100	1,360	
1930	0				360				360	4,990	48,900	1,270	
1931					186				186	3,620	38,800	910	
1932	0				137				137	3,000	35,800	1,090	
1933					349				349	2,550	32,000	1,270	
1934					454				454	2,350	28,600	1,450	
1935					529				529	2,530	30,100	2,000	
1936					717				717	2,780	32,600	2,720	

COBALT STATISTICS[1]
U.S. GEOLOGICAL SURVEY
[All values are in metric tons (t) cobalt content unless otherwise noted]
Last modification: November 19, 2009

Year	Primary production	Secondary production	Mine shipments	Government shipments	Imports	Exports	Stocks	Reported consumption	Apparent consumption	Unit value ($/t)	Unit value (98$/t)	World mine production	World refinery production
1937					787				787	3,140	35,500	3,800	
1938					567				567	3,030	35,000	4,500	
1939					1,210				1,210	3,100	36,400	4,500	
1940	40		40		1,910				1,940	2,620	30,600	5,000	
1941	150		150		2,120	20			2,250	2,600	28,800	4,000	
1942	210		190		1,940	40			2,100	2,220	22,200	3,500	
1943	210	20	220		2,050	160		1,780	2,140	2,920	27,600	4,200	
1944	240	21	160		1,710	180		1,810	1,710	4,200	38,900	3,900	
1945	320	14	380		2,090	10		1,680	2,470	3,660	33,200	4,700	
1946	150	4	150		1,570	5		1,860	1,710	3,400	28,300	3,500	
1947	187	2	198		3,720	0		1,880	3,920	2,920	21,400	5,000	
1948	198	9	170		4,000	1	852	2,280	3,330	3,040	20,500	6,100	
1949	150	7	197		3,380	10	621	2,130	3,810	3,550	24,300	5,900	
1950	232	57	193		4,130	10		3,760	4,990	3,670	24,800	7,170	
1951	267	406	221		4,690	5	438	4,510	4,870	4,420	27,600	8,440	
1952	438	621	254		6,820	25	491	4,910	7,620	5,000	30,700	10,100	
1953	398	699	577		7,820	20	545	4,880	9,020	5,070	30,900	11,300	
1954	652	358	733		7,650	140	538	3,330	8,610	5,470	33,200	13,100	
1955	842	233	787		8,500	170	589	4,420	9,300	5,460	33,300	13,300	
1956	1,150	179	1,200		7,070	140	564	4,340	8,330	5,570	33,400	14,400	
1957	1,500	165	1,490		7,880	70	443	4,150	9,590	4,410	25,600	14,400	
1958	1,820	161	1,820		6,870	80	396	3,420	8,820	4,360	24,600	12,600	
1959	1,060	118	1,050		9,640	30	636	4,490	10,500	3,930	22,000	14,800	
1960		109			5,520	80	842	4,050	5,340	3,390	18,600	14,200	
1961		81			4,760	90	820	4,350	4,770	3,280	17,900	14,400	
1962		94			5,640	90	671	5,110	5,790	3,210	17,400	17,100	
1963		112			4,770	90	498	4,780	4,970	3,180	16,900	14,500	
1964	492	67		332	5,640	49	644	4,830	6,340	3,190	16,800	17,800	
1965	538	39		1	6,990	53	1,630	6,170	6,520	3,480	18,000	19,000	
1966	551	22		346	8,540	45	2,900	6,440	8,140	3,420	17,200	21,800	
1967	530	54		2,810	3,730	91	2,970	6,340	6,960	4,370	21,300	20,500	
1968	533	65		2,250	4,110	644	2,670	5,900	6,620	4,500	21,100	19,600	17,100
1969	455	149		2,720	5,860	679	2,330	7,080	8,850	4,070	18,100	20,200	18,000
1970	316	31		2,340	5,630	670	2,600	6,060	7,380	4,880	20,500	24,200	21,300
1971	313	57		763	4,950	166	2,370	5,670	6,140	4,810	19,400	25,100	22,400
1972	0	89		2,700	6,310	586	2,060	6,410	8,830	5,230	20,400	24,800	20,300
1973	0	120	0	3,890	8,730	634	4,170	8,500	9,990	6,480	23,800	29,400	23,100

COBALT STATISTICS[1]
U.S. GEOLOGICAL SURVEY
[All values are in metric tons (t) cobalt content unless otherwise noted]
Last modification: November 19, 2009

Year	Primary production	Secondary production	Mine shipments	Government shipments	Imports	Exports	Stocks	Reported consumption	Apparent consumption	Unit value ($/t)	Unit value (98$/t)	World mine production	World refinery production
1974	0	122	0	4,050	7,310	611	4,290	8,560	10,700	7,520	24,900	30,900	24,800
1975	0	155	0	2,880	3,000	802	3,150	5,800	6,380	9,280	28,100	30,800	20,800
1976	0	149	0	3,040	7,480	794	4,020	7,480	9,000	9,410	27,000	21,400	18,800
1977	0	230	0	67	7,960	404	3,570	7,520	8,310	11,900	32,100	21,500	20,800
1978	0	470	0	0	8,630	702	2,730	9,070	9,240	22,000	54,900	26,800	24,700
1979	0	531	0	0	9,070	329	3,470	7,890	8,530	53,300	120,000	29,900	28,500
1980	0	537	0	0	7,390	264	3,400	6,950	7,740	51,600	102,000	31,300	30,200
1981	0	441	0	-1,060	7,070	378	3,800	5,300	5,680	36,900	66,100	30,700	25,800
1982	0	395	0	-1,300	5,840	270	3,390	4,290	5,070	25,300	42,700	24,600	19,300
1983	0	328	0	-120	7,810	374	4,050	5,130	6,980	14,900	24,300	37,900	18,100
1984	0	399	0	-2,450	11,500	304	5,110	5,870	8,060	19,000	29,800	40,900	23,700
1985	0	408	0	-721	8,030	292	5,480	5,620	7,060	23,800	36,100	47,400	27,500
1986	0	1,200	0	0	5,570	454	4,060	6,480	7,740	16,200	24,100	50,200	31,400
1987	0	1,030	0	0	8,830	366	5,560	6,670	7,990	14,700	21,100	41,200	28,000
1988	0	1,020	0	0	7,050	543	5,260	7,230	7,830	16,200	22,300	43,800	26,400
1989	0	1,180	0	0	5,790	889	4,550	7,030	6,800	17,300	22,700	42,900	26,400
1990	0	1,230	0	-108	6,530	1,340	3,220	7,560	7,640	18,200	22,700	42,300	27,300
1991	0	1,580	0	0	6,920	1,540	2,400	7,220	7,790	25,100	30,100	33,300	25,200
1992	0	1,620	0	0	5,760	1,420	1,760	6,400	6,590	47,400	55,100	28,000	21,500
1993	0	1,610	0	289	5,940	795	1,460	6,480	7,350	31,300	35,300	21,900	16,600
1994	0	1,840	0	1,500	6,780	1,360	1,490	7,500	8,730	42,200	46,400	18,000	20,000
1995	0	1,870	0	1,550	6,440	1,300	1,080	7,590	8,970	58,300	62,400	24,500	23,300
1996	0	2,280	0	2,050	6,710	1,660	1,070	7,990	9,380	56,400	58,600	26,200	25,600
1997	0	2,750	0	1,620	8,430	1,570	1,090	9,160	11,200	46,300	47,000	27,400	27,100
1998	0	3,080	0	2,310	7,670	1,680	1,000	9,380	11,500	44,200	44,200	36,300	31,400
1999	0	2,700	0	1,530	8,150	1,550	1,160	8,660	10,700	33,700	33,000	33,900	33,100
2000	0	2,590	0	2,960	8,770	2,630	1,120	8,980	11,700	29,700	28,100	39,300	36,000
2001	0	2,810	0	3,050	9,410	3,210	1,330	9,540	11,800	23,300	21,500	46,300	38,700
2002	0	2,750	0	524	8,450	2,080	1,140	8,270	9,830	17,100	15,500	53,700	40,800
2003	0	2,130	0	2,380	8,080	2,710	1,010	8,030	10,000	20,600	18,200	54,600	43,200
2004	0	2,300	0	1,630	8,720	2,500	1,210	8,990	9,950	43,400	37,400	60,300	48,500
2005	0	2,030	0	1,110	11,100	2,440	1,190	9,150	11,800	33,600	28,100	66,200	54,100
2006	0	2,010	0	260	11,600	2,850	1,180	9,280	11,000	30,700	24,800	69,800	53,800
2007	0	1,930	0	617	10,300	3,100	1,310	9,320	9,630	54,600	42,900	72,600	53,300
2008	0	1,930	0	203	10,700	2,850	1,160	8,810	10,100	68,400	51,800	75,900	57,600

[1] Compiled by D.A. Buckingham (retired) and K.B. Shedd.

Data are calculated, estimated, or reported. See notes for more information.

Cobalt Worksheet Notes

Data Sources

The sources of data for the cobalt worksheet are the mineral statistics publications of the U.S. Bureau of Mines and the U.S. Geological Survey—Minerals Yearbooks (MYB) and its predecessor, Mineral Resources of the United States (MR); Mineral Commodity Summaries (MCS) and its predecessor, Commodity Data Summaries (CDS); and Mineral Facts and Problems (MFP). In addition, some data came from U.S. Bureau of Mines Information Circular 8103 (IC 8103), Cobalt—A Materials Survey, (U.S. Bureau of Mines, 1962). The years of publication and corresponding years of data coverage are listed in the References section below. Blank cells in the worksheet indicate that data were either not available or were withheld in order to avoid disclosing proprietary data.

Primary Production

The data are U.S. mine production. Prior to 1940, U.S. cobalt mine production was intermittent and, with some exceptions, generally very low in volume; a consistent data series is not available. Data are not available for the years 1900–09, 1918–22, 1931, and 1933–39. Data for the years 1940–46 represent estimated recoverable cobalt content derived by using an estimated average recovery rate of 63.5 percent for cobalt. This average was calculated from recoverable cobalt and cobalt content for the years 1947–50. Data for the years 1947–59 are published recoverable cobalt content from the MYB. Production data are withheld for the years 1960–63 in order to avoid disclosing proprietary data. Data for the years 1964–71 are mine production from the 1975 MFP. After 1971, there was no mine production; the data are “0.”

Secondary Production

U.S. scrap consumption was used to estimate secondary cobalt production. Prior to 1943, data are not available. Data for the years 1943–45 are from IC 8103. Data for the years 1946 to the most recent are from the MYB, but include unpublished revisions for 1988, 1992–96, and 1999–2002.

Shipments

Shipments data are not available prior to 1940. Data for the years 1940–59 are mine shipments. Data for the years 1940–46 represent estimated recoverable cobalt content derived by using an estimated average recovery rate of 64.6 percent for cobalt. This average was calculated from the cobalt content and recoverable cobalt content of mine shipments for the years 1947–50. Data for 1947–59 are recoverable cobalt content. All mine shipments data are from the MYB. Data for the years 1960–61 are withheld in order to avoid disclosing proprietary data. For the years 1962–72 mine shipments data are not available. The U.S. Government began stockpiling cobalt in the early 1940s. Data for the years 1964 to the most recent are net U.S. Government stockpile shipments. Negative numbers for these shipments indicate net U.S. Government acquisitions. Data for the years 1964–77 are from the 1975 and 1980 MFP. Data for the years 1978–89 and 1991 to the most recent are from the MCS. Datum for 1990 is from the MYB.

Imports

Data are cobalt imports for consumption. Imports data include various types of cobalt materials, such as alloys, matte, oxides, ores and concentrates, salts and compounds, unwrought metal, waste and scrap, and other. These data are reported in gross weight for the years 1900–22 and cobalt content for the years 1923 to the most recent. By using gross weights and cobalt contents reported for the years 1923–30, an estimated weighted average cobalt content of 73.1 percent was calculated and used to estimate the cobalt content of imports for the years 1900–22. Data for the years 1964 to the most recent exclude cobalt alloys, ores, and concentrates. Import data for the years 1989 to the most recent exclude matte, waste, and scrap. Data for 1984–85 and 1990 include cobalt destined for the National Defense Stockpile. Data are from the MR and the MYB.

Exports

Data are not available prior to 1941. Cobalt exports data include alloys, oxides, ores and concentrates, salts and compounds, waste and scrap, and unwrought metal, and exclude semifabricated, wrought cobalt, and cobalt articles. Cobalt content data for the years 1942–48 and 1951–52 are estimated based on the estimated cobalt content of each material, alloys, metal, and scrap (estimated to be mostly metal), 90 percent; ores and concentrates, 2 percent; oxides, 70 percent; and salts and compounds, 30 percent. Exports for the years 1949–50 and 1953–63 are estimated to be mostly scrap with a cobalt content of about 10 percent. Gross weight data for the years 1941–63 came from the MYB. Exports for the years 1964–79 are estimated cobalt content from the 1975 and 1980 MFP. Exports for the years 1980 to the most recent are estimated cobalt content from the MYB.

Stocks

Stocks data are not available prior to 1948 and for the year 1950. All stocks data are for the end of the calendar year, so beginning stocks are defined as the previous year stocks, and ending stocks are defined as the current year stocks. Stocks data for the years 1948–49 and 1951–64 are consumer stocks; data for the years 1965 to the most recent are industry stocks. Data are from the following sources: 1948–53, CDS; 1954–64, MYB; 1965–72, MFP (1975); 1973–82, MCS; 1983–85, and 2000, previously unpublished revisions; and 1986–99 and 2001 to the most recent year, MCS.

Reported Consumption
Data represent reported cobalt consumption in the United States to make products such as alloys, cemented carbides, and a variety of chemical applications. Data are based on company reports to the U.S. Bureau of Mines and the U.S. Geological Survey and may include estimates for non-respondents. Reported consumption data are not available prior to 1943. Cobalt materials included during various time periods are as follows: 1943–45, metal, chemical compounds (oxide and cobalt-nickel compound only), purchased scrap, and ore used directly in magnets and other industrial applications; 1946–53, metal, chemical compounds (organic and inorganic), purchased scrap, and ore and alloy; 1954 to the most recent year, metal, chemical compounds (organic and inorganic), and purchased scrap. Data for the years 1943–87 and 1992 to the most recent are from the MYB. Data for the years 1988–91 are previously unpublished revisions.

Apparent Consumption
Cobalt apparent consumption data prior to 1940 are cobalt imports data only. Prior to 1940, U.S. cobalt mine production was intermittent and, with some exceptions, generally very low in volume; secondary production, exports, and U.S. government shipments were assumed to be negligible or zero; and there is no information available to assess changes in stocks levels. Apparent consumption for the years 1940–63 was estimated using the following equation:

APPARENT CONSUMPTION = MINE SHIPMENTS + SECONDARY PRODUCTION + IMPORTS – EXPORTS ± STOCK CHANGES + GOVERNMENT SHIPMENTS.

Because primary cobalt production and mine shipments data for the years 1960–61 were withheld and were not available for the years 1962–63, an estimate of 500 metric tons (t) was used for calculating apparent consumption and rounded to three significant figures. This estimate reflects a contraction of the domestic cobalt industry during this time period. Apparent consumption for the years 1964 to the most recent was estimated using the following equation:

APPARENT CONSUMPTION = PRIMARY (MINE) PRODUCTION + SECONDARY PRODUCTION + IMPORTS – EXPORTS ± STOCK CHANGES + GOVERNMENT SHIPMENTS.

Unit Value ($/t)
Unit value is defined as the value of 1 t of cobalt apparent consumption. For the years 1900 to the most recent, estimation of the cobalt unit value is calculated on an annual basis from the U.S. dollar (expressed as current dollars) value of imports divided by cobalt content of those imports. Estimation of unit value is based on import data because the greatest part of apparent consumption is imported. U.S. cobalt import quantity and value data are from the MR and the MYB.

Unit Value (98$/t)
The Consumer Price Index conversion factor, with 1998 as the base year, is used to adjust unit value in current U.S. dollars to the unit value in constant 1998 U.S. dollars.

World Mine Production
Data represent the cobalt content of refined products or the cobalt content, recoverable cobalt content, or recovered cobalt content of mined ores, concentrates, or intermediate products depending on the producing country and year. The blank cell in the worksheet indicates that data for the year 1900 were not available. Production estimates for the former Soviet Union are not included prior to 1961. Data for the years 1901–36 are from IC 8103. Data for the years 1937–97 are from the MYB. Data for the years 1998–2003 are previously unpublished revisions. Data for the years 2004 to the most recent are from the MYB.

World Refinery Production
Blank cells in the worksheet indicate that data were not available for the years 1900–67. Data for the years 1968 to the most recent are from the MYB and represent the cobalt content of refined cobalt products. U.S. production data are included in the total for the years 1969–71, and 1975–83. No U.S. production data are reported for the years 1968, 1972–74 and after 1983.

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For more information, please contact:

USGS Cobalt Commodity Specialist

ATTACHMENT 4

Bureau of Mines Information Circular/1993 (IC9350), The Materials Flow of Cobalt in the United States.

IC 9350

BUREAU OF MINES
INFORMATION CIRCULAR/1993

The Materials Flow of Cobalt in the United States

By Kim B. Shedd

UNITED STATES DEPARTMENT OF THE INTERIOR

Information Circular 9350

The Materials Flow of Cobalt in the United States

By Kim B. Shedd

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES

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CIP

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

g/mt	gram per metric ton	mt/yr	metric ton per year
mt	metric ton	%	percent

THE MATERIALS FLOW OF COBALT IN THE UNITED STATES

By Kim B. Shedd[1]

ABSTRACT

An initial evaluation of the flow of cobalt-containing materials in the United States was prepared. The following aspects of materials flow were included: cobalt released as a result of mining and processing other metals and minerals; scrap generation and subsequent recycling or cobalt recovery; and cobalt losses resulting from the generation of wastes, dissipative uses, and disposal of used products. Where possible, estimates were made to quantify the amount of cobalt lost from the materials flow.

More than 2,000 metric tons (mt) of cobalt are released annually from mining and mineral processing in the United States, including 480 mt of cobalt in coal produced in the United States. Metallurgical industries examined in this study have well-established recycling or cobalt recovery practices. The petroleum industry recycles spent catalysts, and some chemical catalysts are also recycled.

Losses generated during cobalt chemical and powder processing were estimated at 50 mt to 80 mt of cobalt annually. Losses from alloy processing and the manufacture of parts and products were estimated to be 360 mt. These industrial losses are greatly outweighed by an estimated 2,780 mt of cobalt consumed in the United States each year to make products that will ultimately be disposed.

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[1] Physical scientist, U.S. Bureau of Mines, Washington, DC.

INTRODUCTION

The U.S. Bureau of Mines has initiated a series of studies on the flow of materials resulting from the production and use of various commodities. The purpose of this study was to prepare an initial evaluation of the flow of cobalt-containing materials in the United States. Aspects of materials flow considered for the study included cobalt released during the mining and processing of other metals and minerals; scrap generation and subsequent recycling or cobalt recovery; and cobalt losses resulting from the generation of wastes, dissipative uses, and disposal of used products. Where possible, estimates were made to quantify the amount of cobalt lost from the materials flow.

Estimates of cobalt consumed by various industries were made from data published in the Bureau's Minerals Yearbook (*1*).[2] In most cases, consumption in the present study represents an average of 2 to 3 years of data ending in 1989. The Bureau's consumption data represent the amounts of cobalt reported by U.S. industries to make superalloys, magnetic alloys, cemented carbides, catalysts, paint driers, etc. The Bureau does not collect data on how these products are used or whether they are used in the United States or exported.

Because of trade flows between the United States and other parts of the world, identification of the actual amounts of cobalt in final products used in this country is much more difficult. The cobalt content of imports and exports of consumer products is not available. If a significant portion of cobalt-containing products is exported, then downstream distribution of those materials in the United States will be overestimated. Conversely, if significant amounts of cobalt-containing products are imported into the United States, then the distribution of cobalt in those products will be underestimated. An example of the latter case is cobalt in magnets. The estimate for cobalt lost through disposal of magnets in used products given later in this report is based only on the cobalt content of magnetic alloys produced in the United States. A realistic estimate of cobalt in magnets produced elsewhere and imported into this country both separately and in products was not feasible.

Many of the estimates for scrap recycling and losses were based on information in two earlier studies, one by the National Research Council's National Materials Advisory Board in 1983 (*2*), and one by Inco Research and Development under contract for the U.S. Bureau of Mines in 1980 (*3*). Supplemental references were used where available. The Bureau of Mines' Albany Research Center has also done research on materials flows and recently published a report on cobalt (*4*). As in the current study, the Albany study relied heavily on reference 2. The authors generated estimates for quantities of cobalt used, recycled, or lost during U.S. production of cobalt-containing products in 1987. The approach of the current study was slightly different from that of the Albany study. The emphasis of the current study was on the total flow of cobalt-containing materials in the United States. In addition to cobalt flows during processing and manufacturing, the current study also addressed cobalt losses during mining and mineral processing, from the burning of fossil fuels, from dissipation during use, and from disposal after use.

It was not always possible to determine the final distribution of cobalt-containing materials. Wastes can be downgraded,[3] stockpiled, exported, or discarded. Some reports do not distinguish between downgraded cobalt and environmental losses, because for the purpose of their studies both represent a loss of usable cobalt. Therefore, a portion of the cobalt listed as "losses" in this study may have been incorporated into other materials flows via downgrading, or it may no longer be present in the United States, because it was exported.

The author recognizes that technological changes, such as changes in recycling practices and cobalt uses, since the cited references were written may have caused changes in the materials flow. However, it is hoped that the results of the current study will give an estimate of the relative magnitudes of cobalt lost from various sectors of the U.S. cobalt flow and will provide a starting point for further studies on this subject.

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[2] Italic numbers in parentheses refer to items in the list of references preceding the glossary at the end of this report.

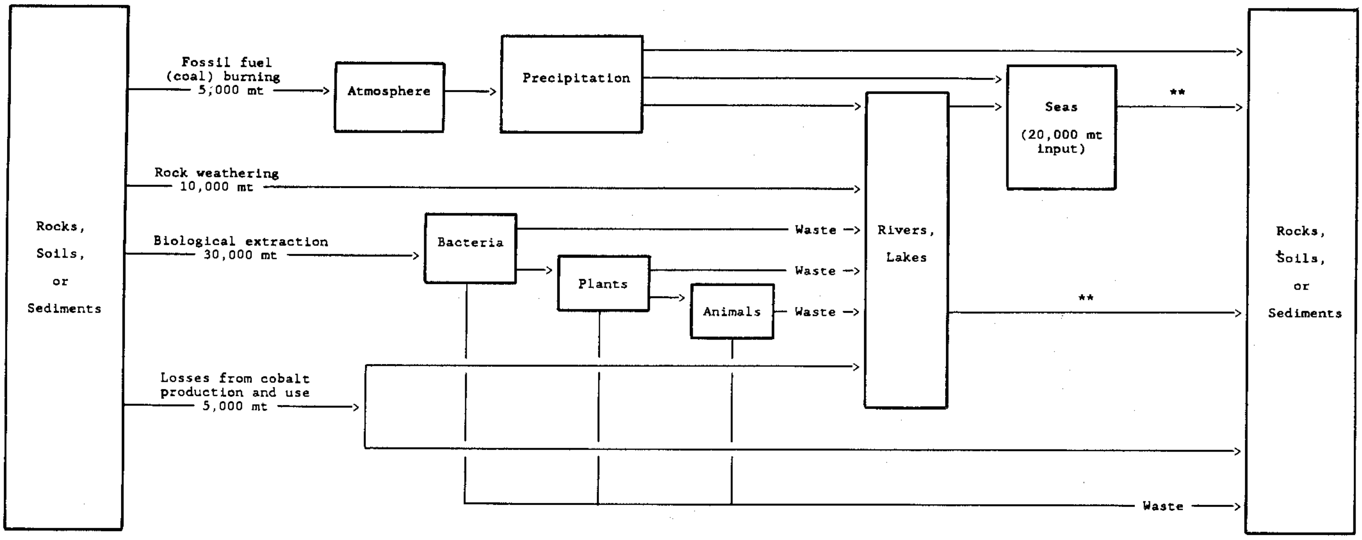
[3] A glossary of terms is included at the end of this report.

THE ANNUAL GLOBAL COBALT CYCLE

The flow of cobalt through the global environment was characterized by Donaldson, et al. (*5-6*). An adaptation of Donaldson's "cobalt cycle" is presented as figure 1. Donaldson estimated that on a global scale, 50,000 mt of cobalt enter the environment each year. Most of this cobalt is released through the natural processes of rock weathering (20%) and biological extraction (60%). Biological extraction refers to the biochemical processes in which cobalt is extracted from rocks and soils by bacteria and other microorganisms. An important example is the conversion of inorganic cobalt to cobalamins—vitamin B_{12} coenzymes. These processes occur in various environments including the rumen fluids of ruminant animals, soils, nodules of leguminous plants, dairy products, marine sediments, and seawater (*7*).

The remaining 20% of global cobalt release is attributed to industrial emissions. One-half of the industrial emissions is thought to originate from the burning of fossil fuels, primarily coal. The other one-half of industrial emissions is released during the annual production and use of 25,000 mt of cobalt. Six percent of the global cobalt releases result from its use as a metal and 4% result from chemical and other uses.

Donaldson attributed only minimal releases to worldwide mining and refining of cobalt. Because cobalt is produced as a byproduct, and recovery of nickel, copper, or platinum is the principal concern, cobalt recovery rates would not be expected to be as high as recovery rates for the principal metals. In cobalt-producing operations, cobalt recoveries from milling ores to concentrates range from less than 10% when little effort is made to recover the cobalt, to greater than 80% when cobalt recovery is emphasized (*8*). Therefore, 20% to 90% of the cobalt originally present in the ore is lost to the tailings during beneficiation. Following beneficiation, further losses occur when concentrates are processed to recover the metals. As one example, cobalt losses to the slag phase are high when nickel sulfide concentrates are smelted to form matte (*9*). Compilation of overall recovery rates for each cobalt-producing operation to estimate an average worldwide rate is beyond the scope of the present study. If the overall worldwide cobalt recovery from ore to refined metal is roughly estimated as 50%, then the amount of cobalt lost during its production would equal the amount produced. Therefore, on a global basis, 25,000 mt of cobalt would be lost each year from the production of 25,000 mt of metal.



** Biological extraction, adsorption on sediments, or chemical precipitation.

Figure 1.—The annual global cobalt cycle. Adapted from references (*5*) and (*6*).

Adding this estimated loss from cobalt production to Donaldson's estimates for global releases increases the total global release of cobalt to 75,000 mt/yr. In addition, the ratio of natural emissions versus industrial emissions changes from Donaldson's estimate of 80% natural/20% industrial to roughly equal amounts released from natural processes and industrial processes. The breakdown of individual components would then be as follows: 40% from biological extraction, 13% from weathering, 7% from fossil fuels, 4% from metal use, 3% from chemical and other use, and 33% from ore and metal production (table 1).

Additional cobalt would be lost from mining and refining operations where cobalt is present, but is not produced as a primary product or byproduct. Examples of cobalt released in the United States during the production of other metals are discussed in the following section.

Table 1.—Global sources of cobalt to the environment (metric tons cobalt per year)

Source	Amount
Natural emissions:	
Biological extraction	30,000
Weathering of rocks and soils	10,000
Volcanic emissions	small
Industrial emissions:	
Fossil fuels	5,000
Metal use	3,000
Chemical and other use	2,000
Ore and metal production	25,000
Total	75,000

Source: References (5) and (6), except for "ore and metal production," this study.

ANNUAL U.S. COBALT MATERIALS FLOW

The present-day flow of cobalt-containing materials in the United States can be divided into four general industry/consumer stages: mining and refining operations/fossil fuels, chemical and powder processing, fabricate/manufacture, and use. The general flow of cobalt materials is shown in figure 2, from raw materials to products,

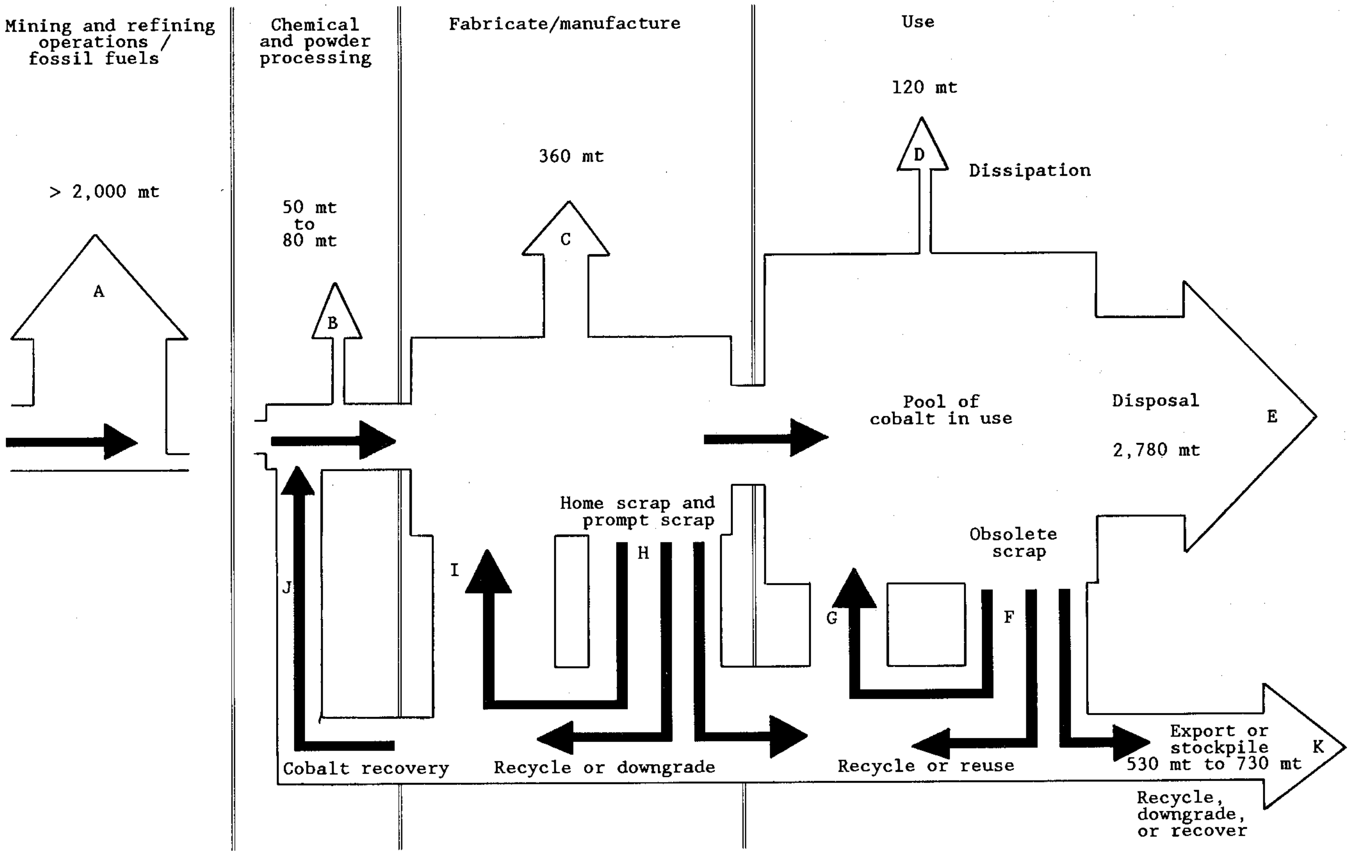


Figure 2.—Current annual U.S. cobalt materials flow.

left to right. Flows of cobalt recovery and recycling were identified, and depicted as black right-to-left arrows at the bases of the industry/consumer stages. Losses of cobalt from each stage were identified, and are represented by white up-arrows. Two white arrows at the "end" of the cobalt materials flow diagram represent additional ways that cobalt leaves the U.S. cobalt materials flow. The relative sizes of the boxes at each industry/consumer stage and the relative sizes of the white arrows are intended to represent relative quantities of materials. Descriptions of losses and recycling flows are presented in table 2.

Table 2.—Cobalt losses and recycling flows in the United States

Designation on figure 2	Description
A	Cobalt released during mining and refining and from burning fossil fuels.
B	Cobalt lost during chemical and powder processing.
C	Cobalt lost during alloy production and/or product manufacture.
D	Dissipative cobalt losses during use.
E	Cobalt lost from the disposal of products following use.
F	Cobalt-containing products leaving the flow following use.
G	Recycled products reentering the flow without reprocessing.
H	Home scrap and prompt scrap leaving the flow.
I	Scrap reentering the flow during alloy production or product manufacture.
J	Scrap reentering the flow during chemical and powder processing.
K	Loss to the U.S. flow via export or stockpile of materials or products.

MINING AND REFINING OPERATIONS/ FOSSIL FUELS

The United States is not considered a cobalt producer. The last significant byproduct cobalt mine production ceased at the end of 1971, and the one U.S. cobalt refinery stopped processing imported nickel-cobalt matte in late 1985. However, small amounts of cobalt are sometimes associated with other ores and metals being produced in the United States such as lead, copper, gold, zinc, ferronickel, iron ore, and coal. Most of the cobalt in these ores is separated from the primary minerals or metals during beneficiation or metallurgical processing. When ore containing cobalt is treated, the cobalt reports to mill tailings; smelter slags, mattes, drosses, or flue dusts; residues or other products of metallurgical processing. These materials are sometimes stockpiled. Unless recovered in other countries from exported materials, this cobalt does not reenter the U.S. cobalt flow. In some cases, cobalt is not separated from the primary product during processing and remains in the final product. Coal and ferronickel are two products that can contain varying amounts of cobalt. Cobalt in U.S. coal is discussed below. Cobalt in ferronickel (generally less than 1%) would report to steel and possibly also to wastes associated with steel manufacture. Three examples of cobalt flows associated with current U.S. metal and mineral production are presented below.

Missouri Lead Ores

In 1988, 86% of U.S. primary lead production was from the Missouri Lead Belt. Based on an estimated 0.015 weight percent cobalt in these ores (*10*), and an annual mine production of 5.4 million mt of ore (*11*), over 800 mt of cobalt was mined, but not recovered, in 1988. Roughly one-half of this cobalt reported to mill tailings. The remainder was distributed among various concentrates, and ultimately reported to mattes, residues, and other materials generated from lead, zinc, and copper operations (fig. 3). The mattes, residues, etc., are discarded, stockpiled, or exported (*12*). If stockpiled, they are temporarily out of the U.S. flow. If exported, they have left the U.S. flow. Therefore, the estimates reported in figure 3 should be considered potential losses whose final placement (in the United States or elsewhere) is not known.

Copper Leach Solutions

Cobalt is associated with some of the copper ores in Arizona, New Mexico, and Utah (*13*). In processing these ores, most of the cobalt accumulates in flotation mill tailings and/or in spent copper leach solutions produced from heap-leaching dumps of low-grade ores. No estimates of cobalt in copper mill tailings are currently available. The spent copper leach solutions have been investigated as a potential source of cobalt. U.S. Bureau of Mines researchers estimate that spent leach solutions from five domestic sources could produce more than 900 mt of cobalt each year (*14*).

Coal

Trace amounts of cobalt are also present in fossil fuels such as coal and oil. As discussed previously, an estimated 7% to 10% of cobalt emissions into the global environment are from the burning of fossil fuels. U.S. coals are estimated to contain an average cobalt content of 0.6 g/mt (*15*). The cobalt is associated with sulfide minerals present in the coal. Based on 0.6 g/mt of cobalt in coal, the 800 million mt of coal consumed in the United States in 1989 (*16*) could have contained 480 mt of cobalt. In order to meet emission standards, coal powerplants either use

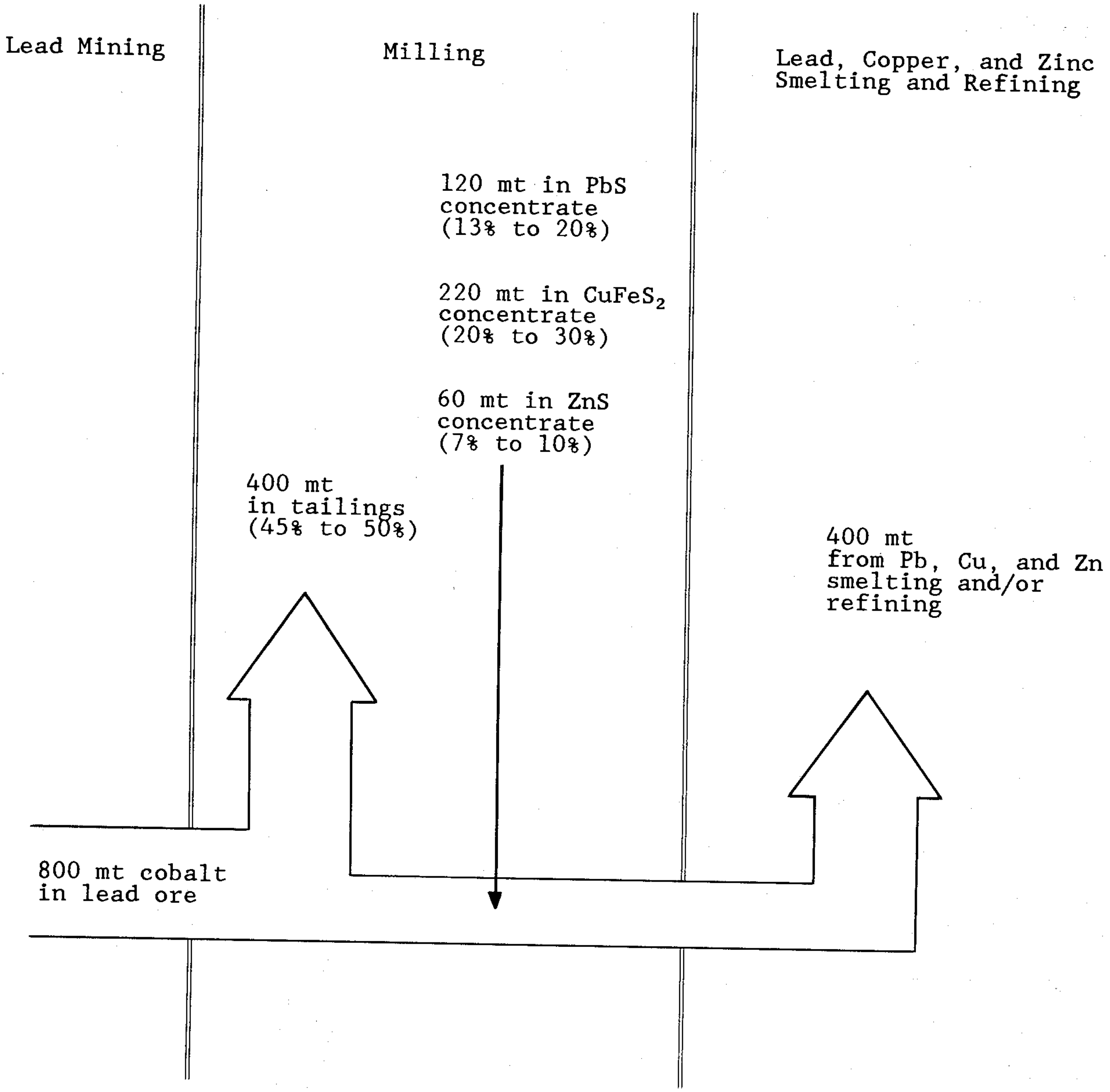


Figure 3.—Cobalt released annually from Missouri lead ores. Adapted from reference (*10*).

processed coal or clean their emissions with scrubbers. Therefore, cobalt in some coals would be removed during coal processing, and cobalt in other coals would most likely report to the fly ash produced during combustion and be captured by antipollution devices.

For this study, losses associated with coal production and use are included with losses from metal mining and refining operations. Based only on these three examples, a minimum of 2,000 mt of cobalt is released each year from these sources (A on figure 2).

CHEMICAL AND POWDER PROCESSING

Chemical and powder processing industries manufacture cobalt chemicals and/or powders from imported cobalt metal and/or cobalt-containing scrap. Examples of scrap feed materials include cemented carbide scrap and catalyst residues. At this stage in the cobalt materials flow, when scrap is the feed material, cobalt is recovered—separated from other metals present in the scrap and residues. For example, cobalt in cemented carbide scrap can be separated from tungsten carbide and reprocessed to make pure cobalt metal powder. The products from these industries—cobalt chemicals and powders—are consumed to make products in the fabricate/manufacture stage, used directly in the use stage, or exported (fig. 2).

Chemical and powder processing are assumed to be fairly efficient and to have low losses. Cobalt yields of 98% for powder processing and 97% for chemical processing have been reported *(17)*. Based on a rough estimate of 2,600 mt of U.S. chemical and powder production, losses would be only 50 mt/yr to 80 mt/yr (B on figure 2).

FABRICATE/MANUFACTURE

This stage of the cobalt flow diagram represents many individual industries that consume cobalt to manufacture a wide variety of products. Examples of products include jet engine parts, magnets, cemented carbide tool inserts, catalysts for petroleum refining, paints, and porcelain enamel products. Raw materials used in this part of the cobalt industry include imported cobalt (metal, powder, and chemicals), cobalt from U.S. chemical and powder processors, and cobalt-containing scrap.

Recycled scrap can constitute a significant portion of the raw materials for some industries (I on figure 2). In the case of superalloy processing, this scrap can originate from various stages of the cobalt flow diagram. Scrap originating from the fabricate/manufacture stage (H on figure 2) can either be home scrap or prompt scrap. Scrap can also originate from the use stage (F on figure 2) as used jet engine parts (obsolete scrap).

Products from the fabricate/manufacture stage are either used in the United States or exported. Losses from this stage are labeled C on figure 2. The 360 mt of cobalt lost from this stage is the sum of estimated losses from individual industries discussed later in this report.

USE

This stage of the cobalt flow represents cobalt-containing products that are still being used, regardless of the year in which they were manufactured. It can be viewed as a pool of use where newly manufactured products join products still in service. The length of time a product remains in the "use pool" varies depending on the product, and can change over time with changes in technology or conditions of use.

In addition to U.S. products, imports of cobalt-containing products also enter the "use pool." Cobalt-containing materials or products leave the use pool in four ways: dissipation, disposal, recycling or cobalt recovery, and exporting or stockpiling. Dissipation is defined as losses occurring during use or as a result of use (D on figure 2). Attrition of cemented carbides during machining operations, mining, or drilling, and the dispersal of cobalt agricultural supplements from the soil to plants to animals are examples of dissipation. For the purpose of this study, paint is not counted as a dissipative use, although some losses in paint could be considered as such. An estimated 120 mt of cobalt are lost each year in the United States from dissipation.

The second way cobalt can leave the use pool is by disposal (E on figure 2). Disposal is the conveyance of cobalt-bearing items or materials to landfills. These cobalt-containing products are removed from the materials flow without recovering the cobalt or recycling the product. In some products, recycling or cobalt recovery might be possible, if collection, recycling technology, and economics were amenable. For instance, cobalt-containing magnets could be recycled if they were collected from obsolete equipment, sorted by alloy type, and returned to magnet alloy melters. In other products, recycling or recovery of cobalt is nearly impossible. The main reason for this is the extremely low cobalt content in these products. Many cobalt chemical applications, such as paint and rubber additives, are essentially nonrecyclable. A sum of the estimates for individual industries discussed later in this report gives a total of 2,780 mt of cobalt consumed each year in the United States to make products that will ultimately be disposed.

The third route to leaving the use pool is through recycling or cobalt recovery. In some cases, materials are recycled without reprocessing and return almost immediately to the "use pool" (flow labeled F to G on figure 2). For example, homogeneous catalysts used in some chemical processes are separated from the product and then reused on-site. A small fraction of magnets from consumer products may be reused without remelting. In most cases, however, cobalt-containing products are recycled at an earlier stage in the materials flow. For example, used jet engine parts are cleaned up by scrap processors and returned to alloy melters (I on figure 2). Most used magnets would also be recycled by remelting at the alloy processing stage. Cobalt recovery from obsolete products is done by chemical and powder processors (J, see also "Chemical and Powder Processing" above).

The final way cobalt can leave the U.S. use pool is by exporting or stockpiling. Cobalt-containing exports range from materials such as scrap metal and processing residues to finished products, such as alloys or consumer goods. Stockpiled materials represent cobalt temporarily removed from the U.S. flow. These materials may be later reintroduced to the flow via recycling or metal recovery, or leave the flow via disposal or export. K on figure 2 represents cobalt contained in exported scrap and exported or stockpiled residues. Estimation of the cobalt contained in exported finished products was not practically feasible.

ANNUAL COBALT FLOWS IN INDIVIDUAL CONSUMING INDUSTRIES

SUPERALLOYS

The largest use of cobalt is in superalloys, which are alloys designed to resist stress and corrosion at high temperatures. The main use for superalloys is in aircraft turbine engine parts, but they are also used in other applications, such as turbines in electric powerplants, helicopter rotors, and prosthetic implants. The superalloy industry involves many stages, beginning with the initial melting of raw materials, through various fabrication stages, ending with machining or other processing to make a final part. Superalloys can be categorized as three main types depending on the primary fabrication method used in their production: wrought superalloys, cast superalloys, and superalloys made by powder metallurgy. The material flows and resultant losses in these three ways of making superalloys differ. Estimates for materials flows in the production of wrought and cast superalloys follow. Insufficient data were available to estimate materials flows in the production of superalloys by powder metallurgical techniques.

Large volumes of scrap are generated in the production of wrought and cast superalloys. In 1980 (*18*), only 27% of the raw materials melted to produce wrought superalloys was contained in the finished products. The remaining 73% ended up as waste or scrap. In the production of cast superalloys, 32% of the raw materials was contained in finished products and 68% ended up as waste or scrap.

The superalloy industry recycles a high percentage of the scrap it generates. The melts for wrought alloys were estimated to contain 47% home scrap, 13% purchased scrap (3% prompt scrap and 10% obsolete scrap), and 40% primary metal (*19*). This agrees with more current estimates by a wrought alloy producer (*20*). Melts for cast alloys were estimated to be composed of 8% home scrap, 47% purchased scrap (39% prompt scrap and 8% obsolete scrap), and 45% primary metal.

The quality of the scrap produced at various stages in the superalloy industry will influence the ability to recycle it. Uncontaminated well-identified solids and processed turnings are most likely to be recycled. Other types of scrap, such as dusts, furnace scale, sludges, and slags, tend to be composed of more than one alloy type and can be contaminated or highly oxidized, thus complicating recycling efforts. In the case of materials like melt-shop smoke, metal prices determine whether the material is recycled or landfilled (*21*).

Some cobalt-containing scrap is not recycled to the superalloy industry, but is instead downgraded to other alloys such as steels. These alloys reenter the use pool, although their cobalt content is greatly diminished. Superalloy scrap is also exported, or can be processed to recover individual elements such as cobalt and nickel. A diagram showing the flow of scrap materials in the superalloy industry is shown in figure 4.

The annual cobalt materials flow diagram for the superalloy industry is shown in figure 5. This diagram represents a combination of the wrought and cast superalloy industries based on a ratio 2:1 for the amount of primary cobalt in wrought versus cast superalloys (*22*). The raw materials input to alloy processing includes primary cobalt, purchased scrap (prompt and obsolete), and home scrap. Industry averages for the percent of each raw material were provided (*3*), and are shown in table 3 and figure 5. The amount of primary cobalt plus purchased scrap was estimated to be 2,850 mt from an average consumption of cobalt in superalloys (*1*). The total cobalt input to superalloy processing was estimated to be 4,385 mt, based on the assumption that the primary cobalt and purchased scrap represented 65% of the total. Additional estimates for the quantities of materials recycled, lost, downgraded, and exported were similarly derived from published percentages (*2-3*).

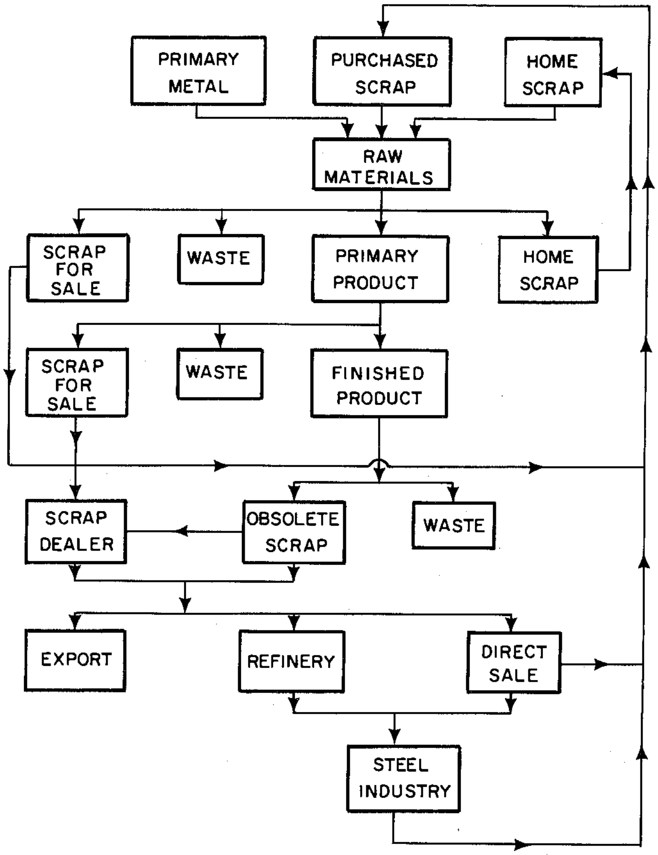


Figure 4.—Flow of scrap materials in the superalloy industry. Source: Reference (*3*).

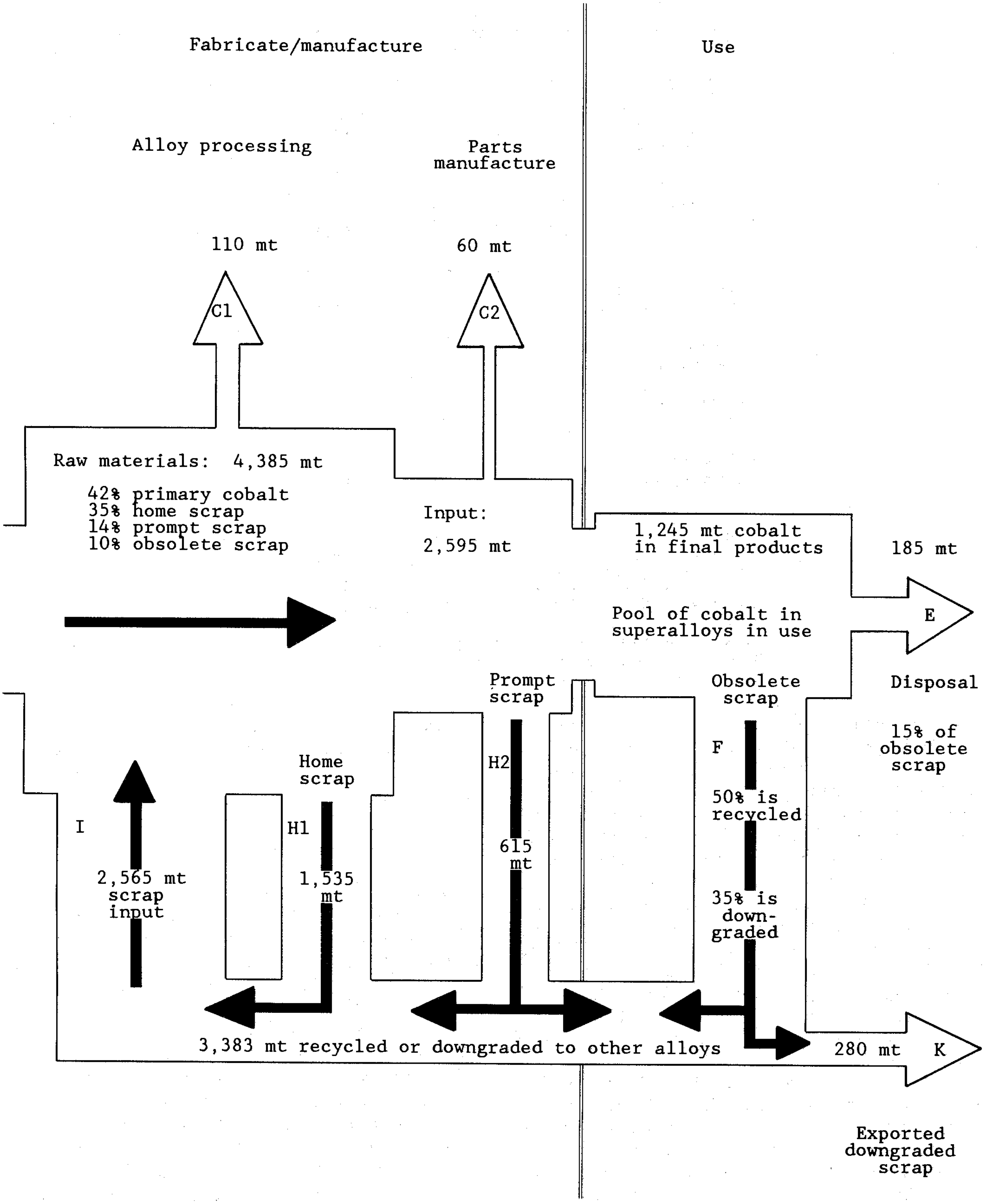


Figure 5.—Annual cobalt flow in the superalloy industry (wrought and cast superalloys).

Table 3.—Annual flow of cobalt materials in the superalloy industry[1]

	Percent[2]	Quantity, (metric tons)	
Superalloy processing:			
Raw materials input:			
Primary metal	42	1,820	2,850
Purchased scrap:			
Prompt	14	615	
Obsolete	10	415	
Home scrap	35	1,535	
Total	100	4,385	
Waste	[3]2-3	-110	
Downgraded scrap	[3]3	-145	
Home scrap generated	[3]35	-1,535	
Parts manufacture:			
Input materials		2,595	
Waste	[4]2-3	-60	
Prompt scrap generated	[3]14	-615	
Downgraded scrap	[4]26	-675	
Final products:			
Contained cobalt	[3]29	1,245	
Totals:			
Waste	[3]4	170	
Downgraded scrap	[3]19	820	
Exported downgraded scrap	[5]34	280	

[1] Data may not add to totals shown because of independent rounding.
[2] From reference (2) or (3).
[3] Percent of raw materials input to superalloy processing.
[4] Percent of input materials to parts of manufacture.
[5] Percent of downgraded scrap.

An estimated 2% to 3% of the total 4,385 mt of cobalt melted is lost as wastes during alloy processing, and 2% to 3% of the 2,595 mt of cobalt input to parts manufacture is lost as wastes, resulting in a total loss of 4% of the initial raw materials melted. Nineteen percent of initial raw materials is downgraded, representing a loss of usable cobalt, but not an environmental loss. Thirty-four percent of the downgraded scrap was thought to have been exported. In terms of obsolete scrap, in the early 1980's, only one-half of the obsolete scrap generated in a given year was thought to have been recycled to superalloys, 35% was downgraded to steels, and 15% was lost, presumably through disposal (*23*). If this disposal rate has not improved, as much as 185 mt of the cobalt used each year to produce superalloy parts would eventually be disposed of following use.

The estimates in table 3 and figure 5 do not take into account technological changes that may have occurred since the early 1980's. For instance, the relative amounts of primary cobalt in wrought and cast superalloys have changed, and the fraction of superalloys produced by powder metallurgy was not taken into account. In addition, the influence of the price of cobalt on scrap recycling was not taken into consideration. However, the average percent of scrap in the raw materials melt was not expected to increase without a major breakthrough in alloy melting or refining technology (*24*).

MAGNETS

Magnetic alloys are another important use for cobalt. Various permanent and soft magnetic alloys contain cobalt, but the largest use is in Alnico permanent magnets. In 1983, an estimated 90% of the cobalt consumed in magnetic alloys was used to make Alnico and iron-chromium-cobalt alloys (*25*). However, the iron-chromium-cobalt alloys represented only a very small portion of this cobalt use. The remaining 10% of the cobalt used in magnets went to the production of samarium-cobalt magnets.

Most Alnico magnets are formed by casting, although some are made by powder metallurgical techniques. Iron-chromium-cobalt alloys are either cast to size or cast to an ingot that is then rolled and/or drawn to its final shape or to a form that can be cut. Samarium-cobalt magnets are usually formed by powder metallurgical processes.

Most of the home scrap generated in the production of cast and wrought magnets is recycled. Minor losses might occur during reprocessing of grinding sludges, and some manufacturing scrap may be downgraded. Sludges produced from manufacturing samarium-cobalt magnets by powder metallurgical techniques are either lost or reprocessed to recover the samarium or both the samarium and cobalt.

In 1989, roughly 860 mt of cobalt was used in the United States to produce magnetic alloys. Estimates for cobalt lost through wastes and downgrading during alloy processing and magnet manufacture were made based on estimates for wrought and cast magnet production (*2*). Industry averages of 4% waste and 4% downgraded scrap during alloy processing and 3% waste from magnet manufacture were used to develop figure 6. These estimates do not take into account technological changes that have occurred since the early 1980's. For instance, in 1987 as much as 20% of all cobalt used in magnet manufacture would have been processed by powder metallurgical techniques, based on the relative amounts of cobalt consumed to make samarium-cobalt and Alnico magnets (*26*). Other areas for further study include changes in the relative proportions of cast and wrought magnet production, changes in the recycling rates of magnet scrap, and uses of other cobalt-containing scrap as feed for magnet manufacture.

In any case, losses from manufacturing are thought to be greatly outweighed by losses from disposal of magnet-containing products. It is estimated that only a small portion of cobalt-containing magnets are recycled after use. Two examples are magnets recovered prior to the disposal of leased equipment, such as telephones or computer disk drives, and large magnets identified and recovered by specialty scrap dealers. Most of these magnets would be remelted and reenter the cobalt flow at the alloy processing stage (I on figure 6). A small fraction might be reused without remelting (flow F to G on figure 6).

The 765 mt loss attributed to disposal on figure 6 assumes that all used magnets are disposed. Further research is necessary to refine this estimate. As mentioned above, some cobalt-containing magnets are recycled following use. In addition, other cobalt-containing magnets would be downgraded if not removed prior to the recycling of products such as automobiles. As with other cobalt uses, data on the cobalt content of imported and exported magnets are not available. Therefore, the amount of cobalt in magnets disposed of in the United States may be greater or less than 765 mt, depending on the net trade flow. Cobalt imported and exported in magnets, either alone or in products such as electrical equipment, could be significant, but would be very difficult to quantify.

CEMENTED CARBIDES

Cemented carbides are wear-resistant materials used for a wide range of industrial applications including metal-cutting, metal-working, mining, and oil and gas well drilling. An estimated 550 mt of cobalt metal powder is used each year to make cemented carbides. Powder processing on figure 7 represents the industries that make pure cobalt powder from metal or scrap. Losses during powder processing are discussed in the "Chemical and Powder Processing" section of this report.

In the fabricate/manufacture stage cobalt and tungsten carbide powders are blended together and sintered to produce cemented carbide parts. Reject parts and scrap are segregated and recycled. Losses are thought to be negligible at this stage (*27*).

Cemented carbides are designed for wear-resistance, so dissipative losses from attrition during use are expected to be low. An estimated 70% of cemented carbide is used to make cutting tool inserts. These inserts lose their cutting edge after less than 1% of their mass has been used (*28*). The remaining 30% of cemented carbides are used in mining and wear-resistant applications, which may suffer losses up to 30% during use. Based on this information, overall cobalt losses due to attrition are estimated to be no more than 50 mt/yr.

The greatest losses from cemented carbides are likely to be from the proportion of obsolete scrap that is not recycled. These losses were estimated from information on recycling in the cemented carbide industry. An estimated 30% to 40% of the cobalt consumed to produce cemented carbides originates from cemented carbide scrap (*29*), and most of this scrap is obsolete scrap from consumers (*30*). The ability to recycle used cemented carbides varies depending on the consuming industry. Estimates of recycling limits for cemented carbides from various industries, as identified in the early 1980's, are presented in table 4.

Table 4.—Estimated recycling limits for cemented carbide scrap (percent)

Application	Theoretical maximum	Probable practical limit	Practical limit in the early 1980's
Cutting tool inserts	95	60	40
Brazed tools	75	40	15
Oil drilling	90	85	80
Coal mining	65	50	15
Mining	85	85	65
Wear parts	90	85	80

Source: Reference (*2*).

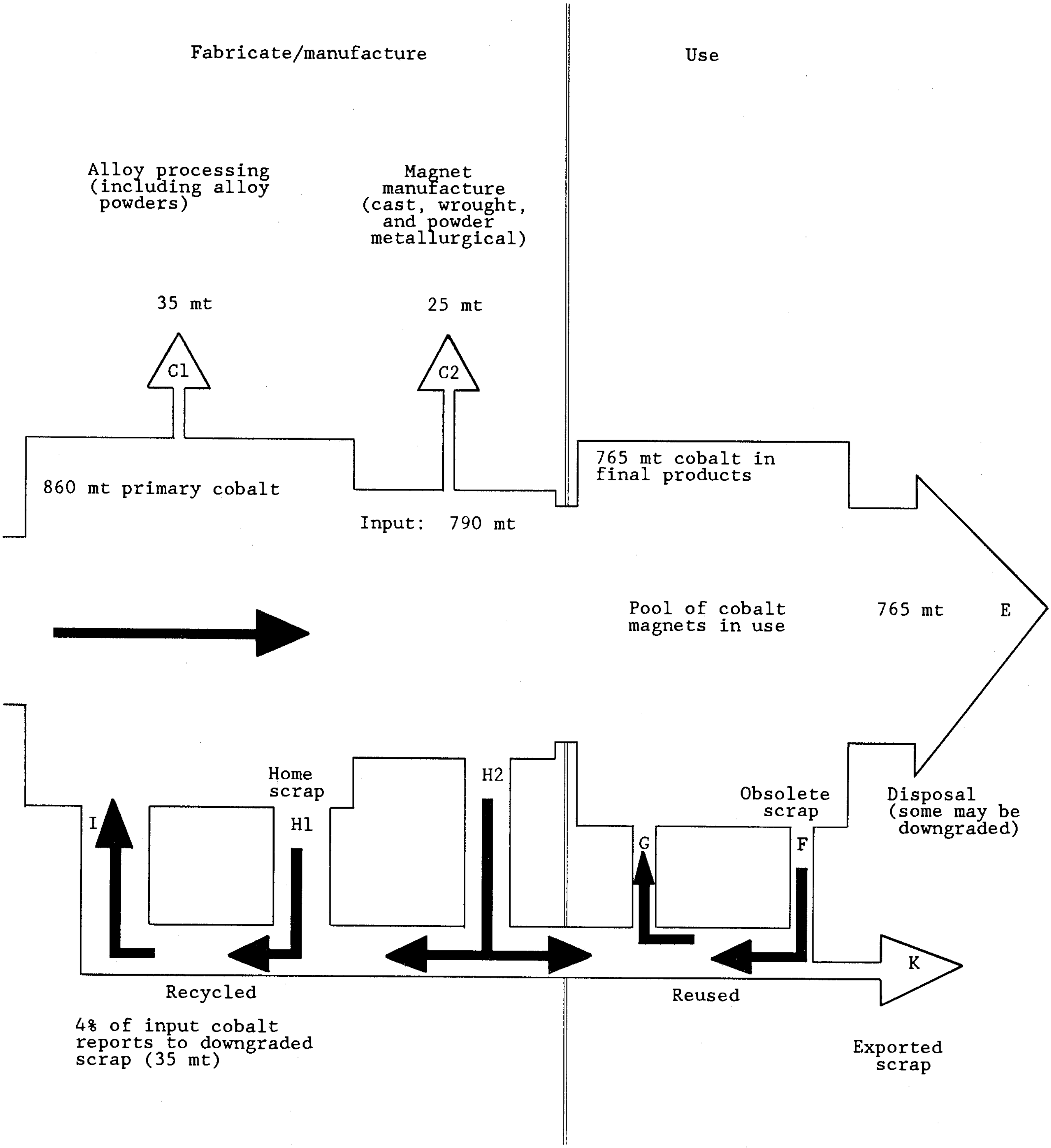


Figure 6.—Annual cobalt flow in the magnet industry.

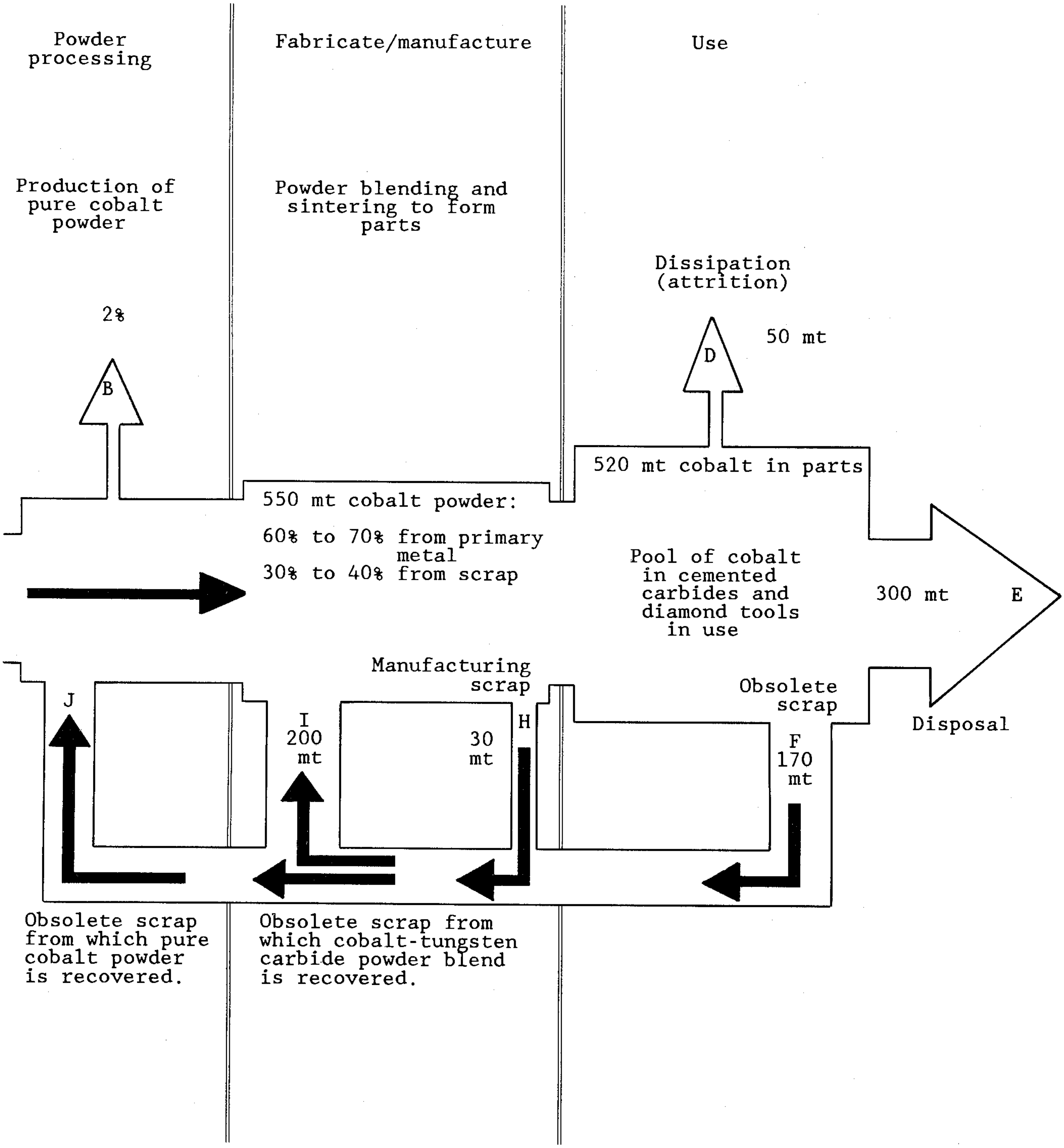


Figure 7.—Annual cobalt flow in the cemented carbide industry.

Recycling occurs at various stages in the cemented carbide industry. In addition to the recycling of obsolete scrap already discussed, almost all "manufacturing scrap" is recycled (*31*). Home scrap represents approximately 5% of the raw materials consumed to make cemented carbides (*32*).

Cemented carbide scrap can be broken down for recycling by various processes. Reclaimed powders from some processes can be reused directly to make new cemented carbide parts in the fabricate/manufacture stage (I on figure 7). The "zinc process," as modified by the Bureau of Mines, is one of the most important direct methods for recycling cemented carbides. U.S. annual capacity for recycling by the zinc process is 2,200 mt of cemented carbide (*33*) (roughly 220 mt of cobalt). In the late 1980's, U.S. annual secondary production using the zinc process was estimated at 600 mt of blended powder (*34*). This would have contained roughly 60 mt of cobalt.

A second recycling option is the use of chemical processes that break down cemented carbides to yield pure cobalt powder and tungsten carbide, tungsten, or ammonium paratungstate. A high percentage of cemented carbide scrap is recycled using chemical methods (*35*). This scrap would reenter the cobalt flow at J in the powder processing stage or I in the fabricate/manufacture stage (fig. 7). A third recycling option is to crush and grade used cemented carbides, then use the resulting material for grits, or braze it onto metals for use as an abrasive for grinding, or use it as hardfacing on construction and earthmoving machinery. Cemented carbide scrap, in the form of tungsten carbide tool inserts, has also been used by the superalloy industry as a source of tungsten (*36*). Some cemented carbide scrap could also be downgraded, when parts are not removed from scrap that is recycled to the steel industry.

As was done for other industries in this study, the net imports and exports of cemented carbides were assumed to be zero. Based on an average of 550 mt of cobalt consumed to produce cemented carbides, about 200 mt would have been from recycled cemented carbide scrap (170 mt from obsolete scrap plus 30 mt from manufacturing scrap). Of the 520 mt of cobalt in cemented carbide products, 50 mt could have been lost during use, 170 mt would be recycled, and the remaining 300 mt could have been lost by disposal. However, this estimate of discarded scrap is probably a maximum, because it does not take into account scrap consumed by superalloy melters for its tungsten values, scrap downgraded to steel, or scrap crushed to be used as abrasives or hardfacing.

MISCELLANEOUS METALLIC USES

Roughly 600 mt to 700 mt of cobalt are used each year in other metallic uses. Information on the tonnage consumed in each end use is not available. However, high-speed tool steels and hardfacing alloys use a large portion of this cobalt.

Approximately 200 mt of cobalt are consumed in tool steels. Sixteen percent of the primary cobalt melted is lost as waste from semifinished steel production and 2% of the input cobalt to tool manufacture is lost as waste during that stage (*37*). This would leave approximately 165 mt of cobalt in the final products. If 70% of the obsolete tool steel scrap is recycled or downgraded (*38*), the remaining 30% or 50 mt would be lost by disposal. Increases in production by powder metallurgical techniques and other technological changes since the early 1980's may have reduced the amount of waste generated. In addition, the amount of cobalt lost by disposal of obsolete products assumes no losses due to exports and no gains due to imports of these products.

As much as 200 mt of primary cobalt and cobalt in purchased scrap is used in the production of hardfacing alloy rods and powders (*39*). In addition to primary cobalt and purchased scrap, 8% of the raw materials originates from home scrap. During alloy processing, 6% of the raw materials melted is lost as waste, 8% becomes home scrap, and 8% is downgraded (*40*). During parts manufacture, an additional 3% of the initial raw materials is lost as waste and 29% becomes prompt scrap, leaving roughly 100 mt of cobalt in the final products. Once these products are shipped to users very little of the cobalt is returned to the cobalt flow (*41*). Some overspray and swarf generated during use might be recycled. Hardfacing on obsolete parts is not recycled for its cobalt values, although the cobalt might be downgraded if the parts are recycled to other alloys. Information on the dissipative loss of cobalt as wear during use was not available. Without further information on dissipation, disposal, and downgrading, the total estimated cobalt in final products was listed as a disposal on figure 8. As with other end uses, this estimate assumes no losses due to exports and no gains due to imports of these products.

CATALYSTS

Cobalt catalysts are used to improve the reaction rates of various processes in the chemical and petroleum industries. Approximately 700 mt, or 10%, of the cobalt consumed in the United States each year is for the manufacture of catalysts. Most of the cobalt used in catalysts is for three applications—the production of terephthalic acid (TPA) and dimethyl terephthalate (DMT), hydroformylation (the OXO process), and hydrotreating and desulfurization of petroleum. An estimated 60% is for the two chemical processes, 35% is for the petroleum catalysts, and the remaining 5% is for several other catalyst applications (*42*).

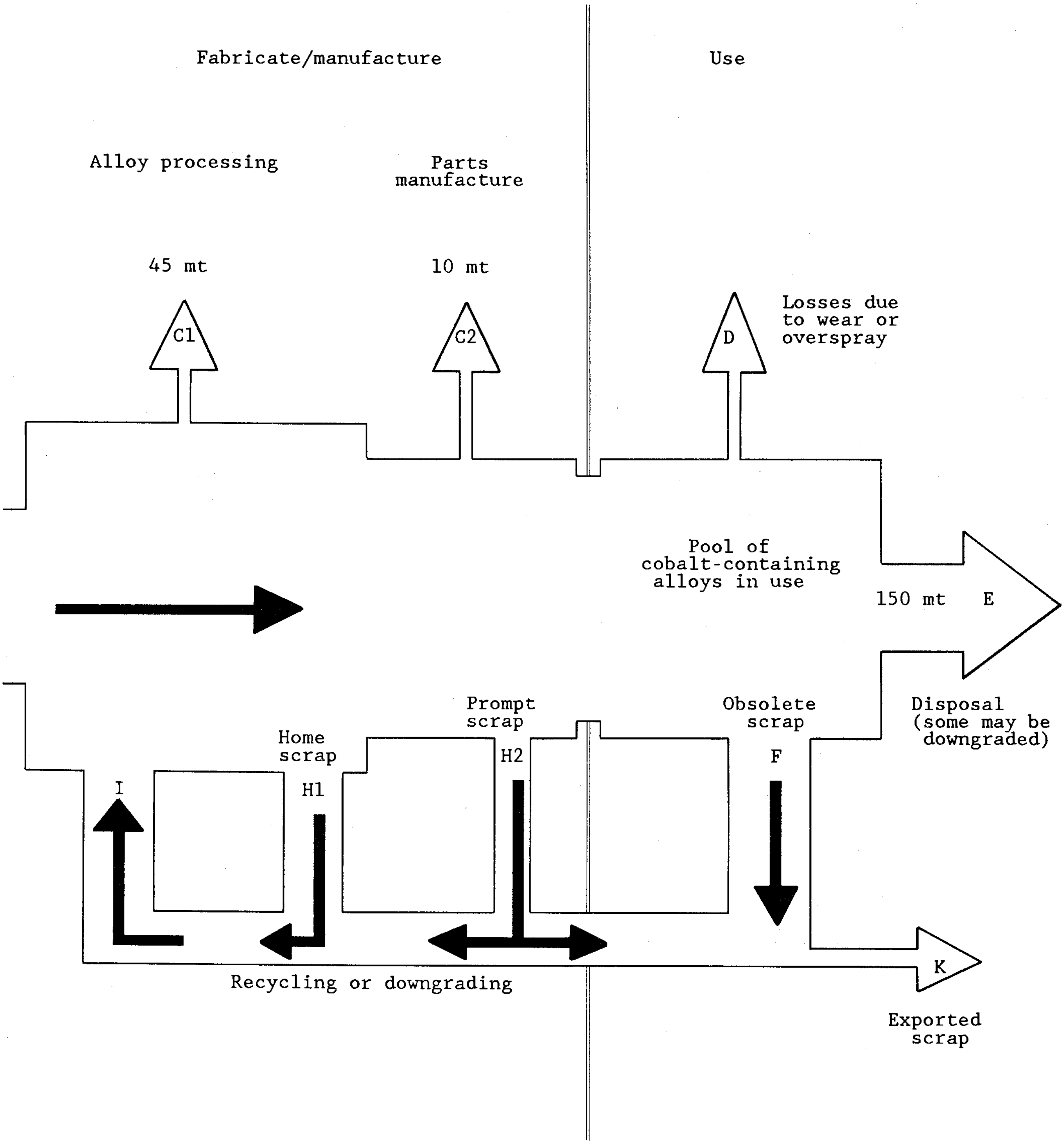


Figure 8.—Annual cobalt flow in miscellaneous metallic uses. (Losses from tool steels and hardfacing.)

In the two chemical processes, the cobalt catalyst is added as a soluble salt to the reaction mixture (homogeneous catalysis). Losses associated with the manufacture of homogeneous catalysts would be included in the "Chemical and Powder Processing" section of this report. In the production of TPA and DMT, cobalt acetate or cobalt bromide is used with manganese as a co-catalyst. TPA is an intermediate chemical used in the production of synthetic fibers and plastic films. The OXO process uses cobalt carbonyl as a catalyst in the hydroformylation of olefins to alcohols and aldehydes. The alcohols and aldehydes are then used to make plastics and detergents. For both these processes, the catalysts are separated from the product and then reused on-site. Cobalt residues are sent back to chemical processors for reprocessing to fresh catalyst material (J on figure 9). Roughly 90% of the cobalt is recovered, the remaining 10% is lost during recycle and reuse (*43*).

In the petroleum industry, hydrotreating and desulfurization processes use heterogeneous catalysts composed of cobalt and molybdenum sulfides on an alumina support. Losses associated with the manufacture of heterogeneous catalysts were estimated at roughly 3% of the cobalt consumed (*44*), or 5 mt to 10 mt of cobalt. When they become less effective, the catalysts can be regenerated for reuse, but after a number of regenerations, the catalysts are considered spent, and must be replaced. The United States currently has the capacity to process all the spent petroleum catalysts generated each year. Two U.S. metal-reclaiming facilities currently recover molybdenum, vanadium, alumina, and a mixed nickel-cobalt residue from spent petroleum catalysts. An estimated 250 mt to 450 mt of cobalt in nickel-cobalt residue is reclaimed annually from spent petroleum catalysts (*45*). Roughly one-half of the residue is exported and then refined to pure nickel and cobalt. This cobalt then reenters the world cobalt supply as primary metal. The other one-half of the residue is either stockpiled in the United States with the intention of refining the cobalt at a later date when it is economically feasible or downgraded into other products.

MISCELLANEOUS CHEMICAL USES

Driers, Pigments, Ground Coat Frit, and Others

Currently approximately 800 mt of cobalt are consumed in the United States each year to manufacture organic compounds for the drying of paints, inks, and varnishes. An additional 320 mt of cobalt is used to make inorganic pigments for paints, plastics, glass, and ceramics. There are also many other uses for cobalt chemicals. For instance, cobalt is used in ground coat frits to bond porcelain enamel to steel in cookware, appliances, and bath tubs; it acts as a decolorizer in glass, glazes, enamels, and porcelain; it improves the magnetic properties of audio and video tapes; it bonds rubber to brass-coated steel belts in radial tires; it is used in electroplating; and it is used as a moisture indicator in desiccants. These miscellaneous uses account for an additional 370 mt of cobalt used each year.

In these applications, cobalt is usually an important but very minor constituent of the final product. Dilution of cobalt makes its recovery basically impossible. Therefore, all the cobalt used in these applications is ultimately lost. This 100% loss following use greatly outweighs any losses that occur during manufacturing. Annual losses depend on the length of time the products remain in service before disposal. The fact that some of these products remain in service for decades or longer makes it very difficult to estimate disposal on an annual basis. However, since all the products will eventually be discarded, one could ignore time in service, and consider that in a given year all the cobalt used will eventually be lost.

As with other industry sectors, information on the cobalt content of imports and exports of cobalt-containing products was not available. If all the domestically produced driers, pigments, frits, etc., were used in products that stayed in the United States, and no additional products containing cobalt driers, pigments, frits, etc., were imported, then 1,490 mt of cobalt would eventually be lost in the United States. Based on a 3% loss during chemical processing (see "Chemical and Powder Processing" section), and a 5% loss during product manufacture (*46*), the remaining 1,380 mt would be lost to disposal (fig. 10). Further research would be required to determine the trade flows of cobalt in these chemical applications and to refine these estimates.

Agriculture and Feed Additives

Cobalt, as present in vitamin B_{12}, is important to the health of animals, including humans. Ruminant animals (cattle, sheep, and goats) require a certain level of cobalt in their feed to prevent anemia and death. The cobalt is converted to vitamin B_{12} by microorganisms in the animals' digestive systems. In areas with cobalt-deficient soils, cobalt must be added to the animals' diets. This can be done by adding cobalt to the soil as a fertilizer, by adding cobalt to the feedstock, or by introducing cobalt or vitamin B_{12} directly into grazing animals through various means (*47*).

Agricultural uses of materials can be considered dissipative uses—the materials are dispersed during use and are not recoverable. Similar to cobalt use in other noncatalyst chemical applications, this 100% loss as a result of use greatly outweighs any losses that might occur during production of the cobalt chemicals or feeds. U.S. cobalt consumption to produce feed additives is quite small, but is listed separately in this report to provide an example of a fully dissipative use for cobalt. Roughly 30 mt of cobalt are consumed each year by U.S. chemical processors for feed additives. Information on exports and imports of cobalt for agricultural use is not available. If all 30 mt were used in the United States, and no imported cobalt was used, then 30 mt of cobalt would be dissipated each year (fig. 11).

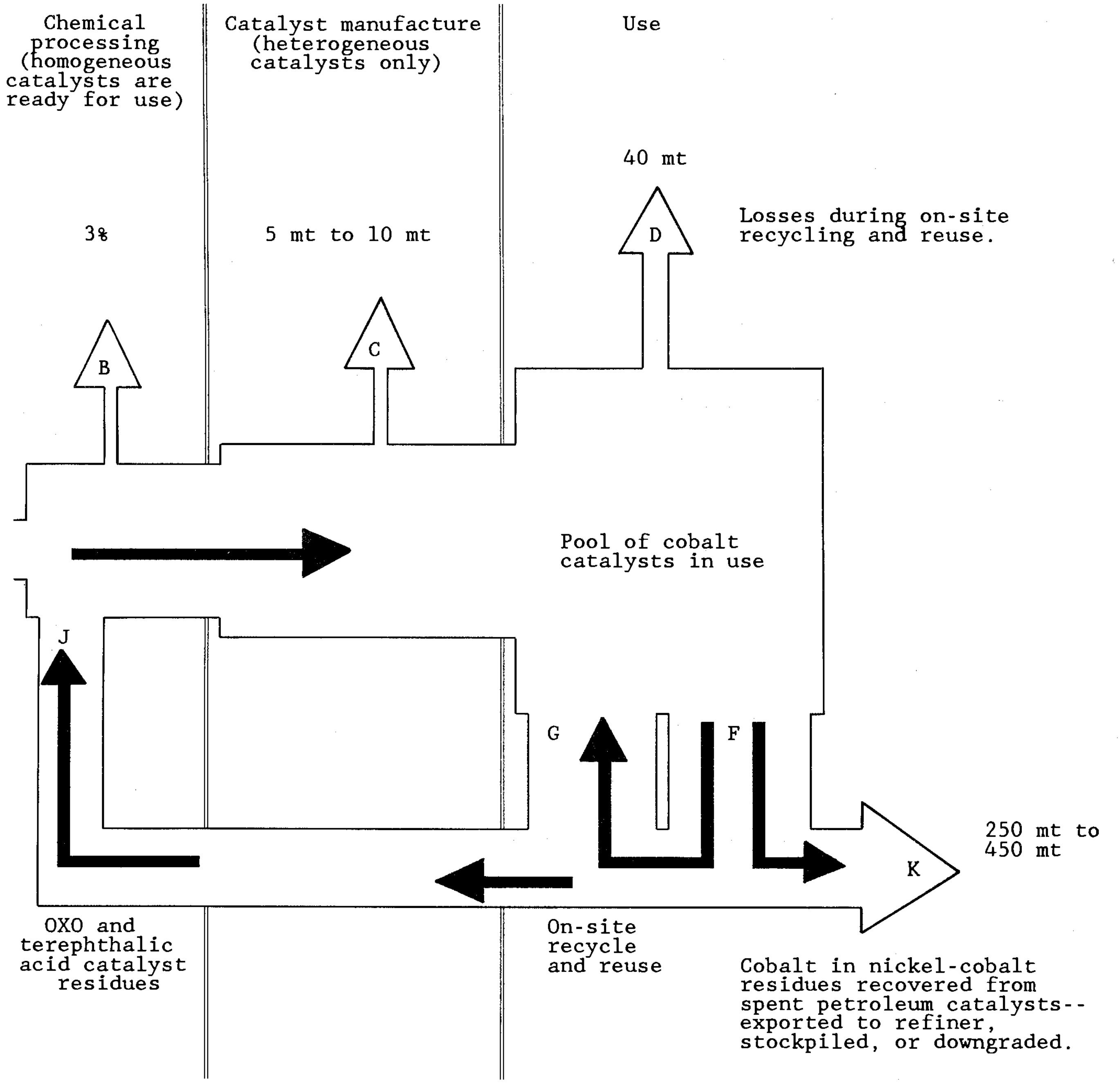


Figure 9.—Annual cobalt flow in the catalyst industry.

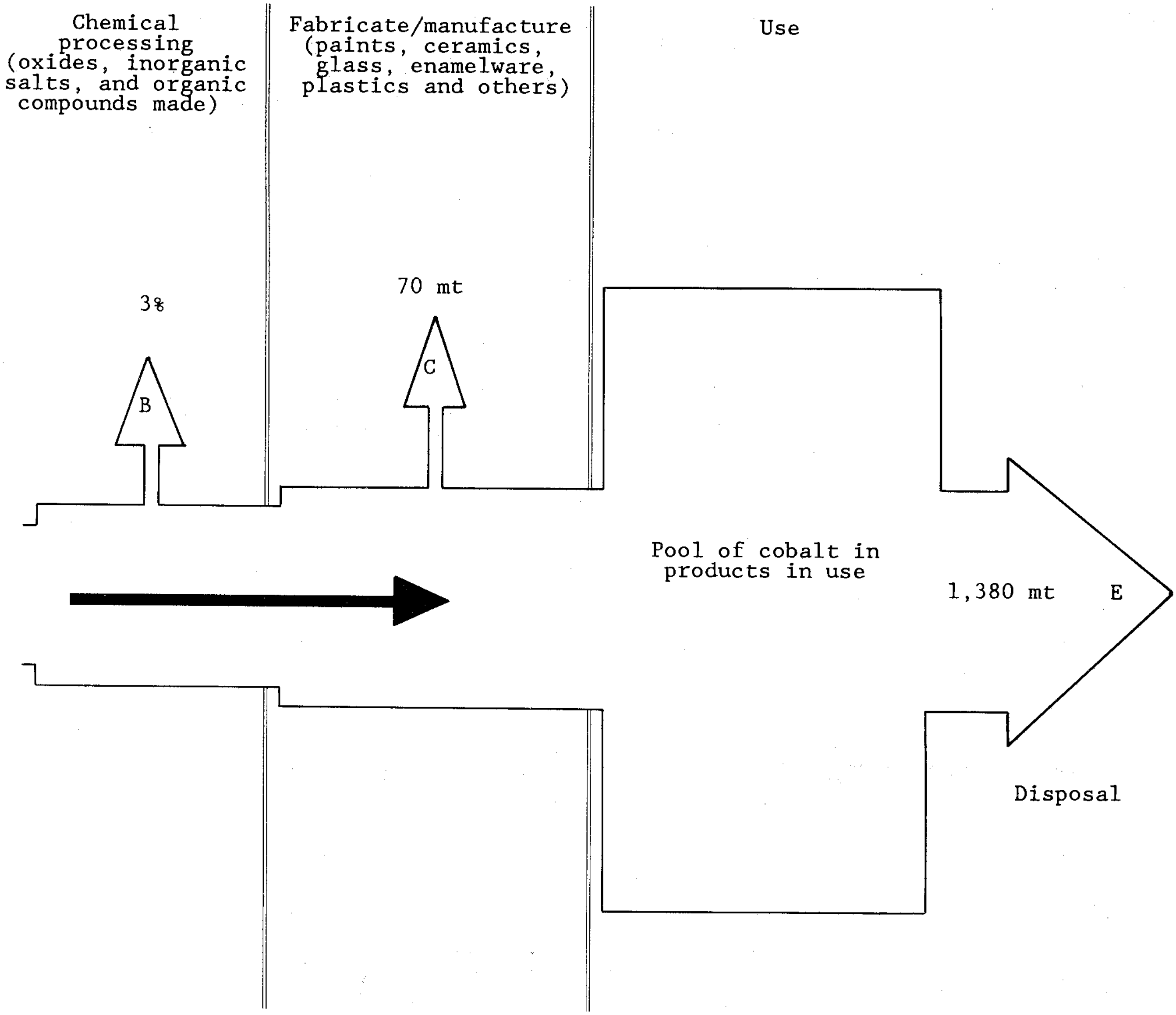


Figure 10.—Annual cobalt flow in miscellaneous chemical applications.

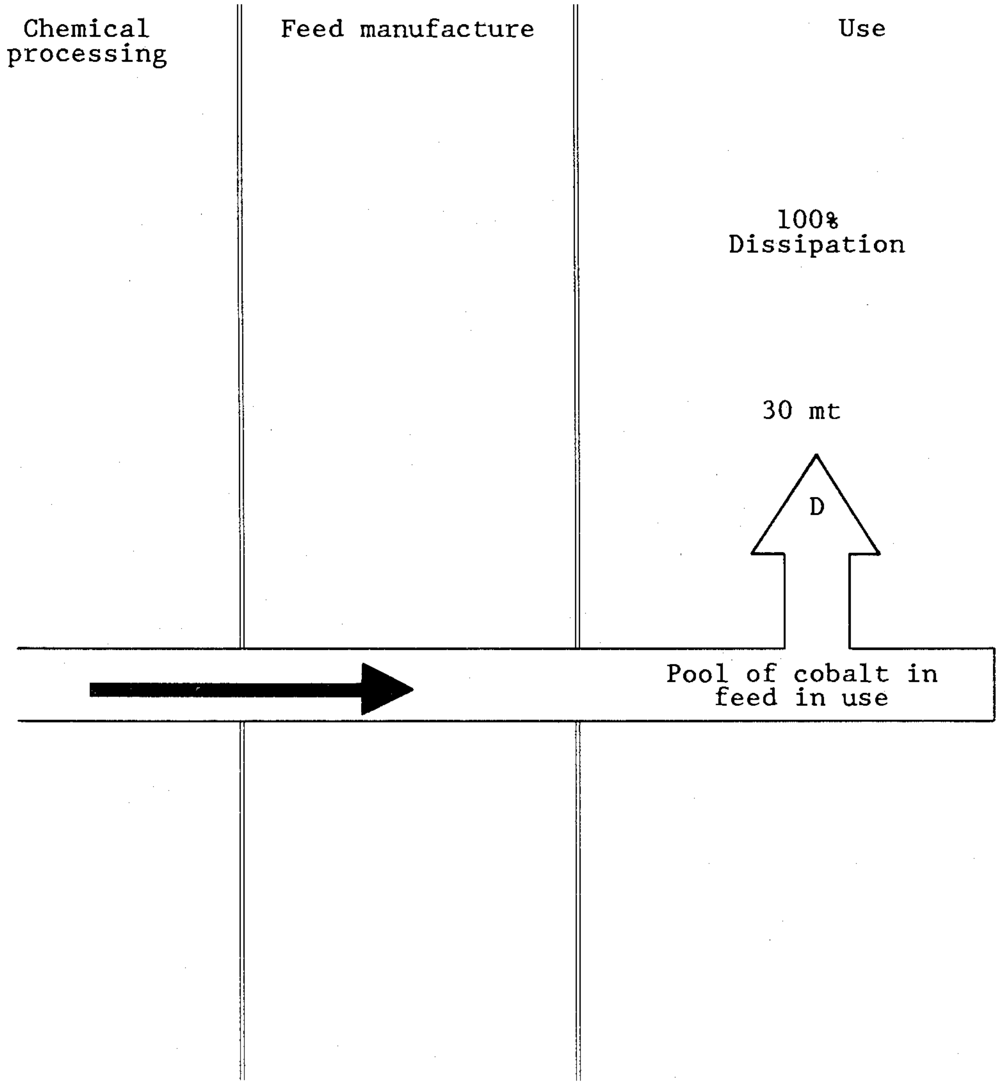


Figure 11.—Annual cobalt losses from use in agriculture and feed additives.

HISTORICAL LOSSES

Cobalt losses during consumption and use will change over time with variations in total consumption, with changes in how cobalt is used, and with changes in the price of cobalt and associated metals. Trends in total U.S. cobalt consumption over the past three decades are depicted in figure 12. Total consumption during this time period roughly paralleled economic conditions and general industrial activity. Because of its many varied applications, total cobalt consumption is the net result of the performance of many individual industries—production of military and civilian aircraft (superalloys); production of instrumentation and electrical equipment (magnetic alloys); mining, oil and gas drilling (cemented carbides); petroleum refining (catalysts); chemical processing (catalysts); etc.

Superimposed upon general economic conditions and the performance of specific industries are the effects of changing materials usage. These changes can result from various factors. For example, in the late 1970's, a sudden increase in the price of cobalt and concerns about supply vulnerability resulted in increased efforts toward cobalt conservation and substitution. A rapid decline in the use of Alnico magnets occurred at this time as a result of substitution by ferrite and samarium-cobalt magnets. Substitution in some chemical applications also occurred. Researchers examined the effects of reducing the cobalt content of various superalloys, and cobalt-base superalloys were replaced by cobalt-containing nickel-base alloys where possible (*48*).

A comparison of cobalt consumption by major industry sector at two points in time is shown in figure 13. The years 1960 and 1989 were chosen to show general trends in cobalt use. However, for each industry sector represented, considerable variation occurred in both tonnage consumed and percent of total consumption during the 30-year period. A thorough discussion of trends in cobalt consumption is beyond the scope of this paper. Generally speaking, as compared with 1960, the United States currently consumes more cobalt to produce superalloys, cutting and wear-resistant materials, and chemical and ceramic materials, and less cobalt to produce magnets and other alloys. This is true both in terms of tonnage and percent of total use.

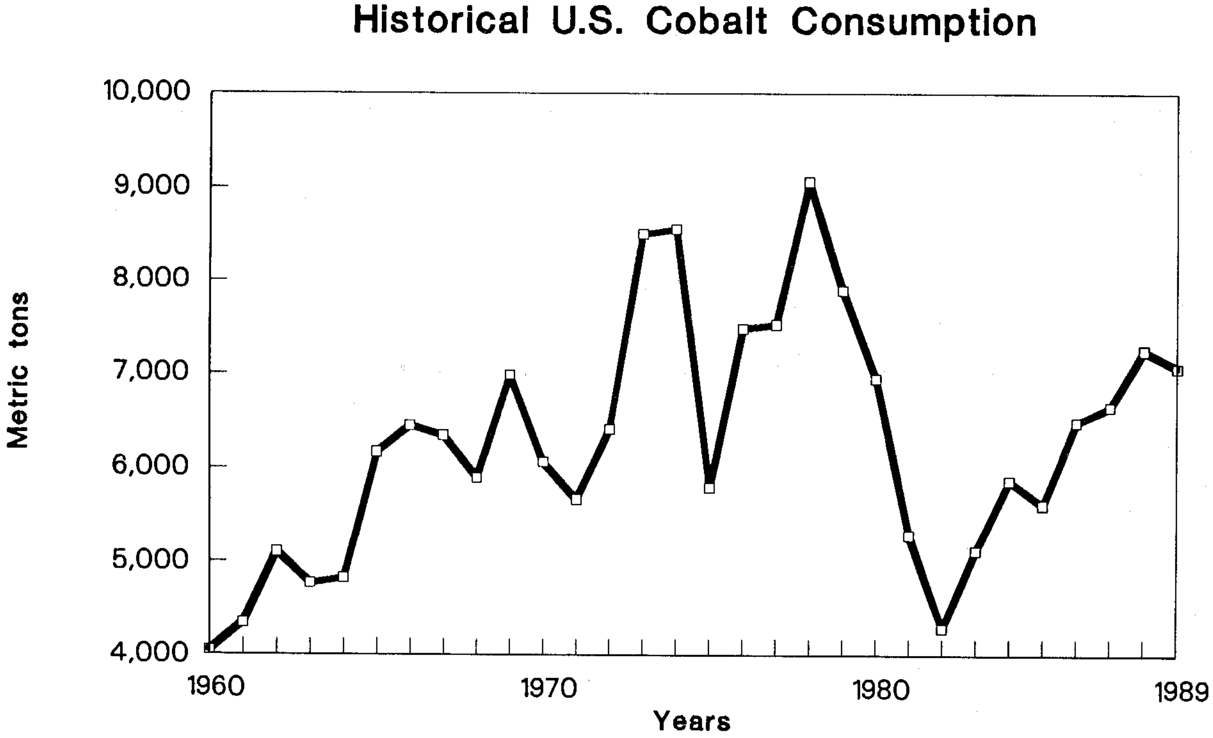


Figure 12.—U.S. reported cobalt consumption, 1960-89. Source: U.S. Bureau of Mines, Minerals Yearbooks.

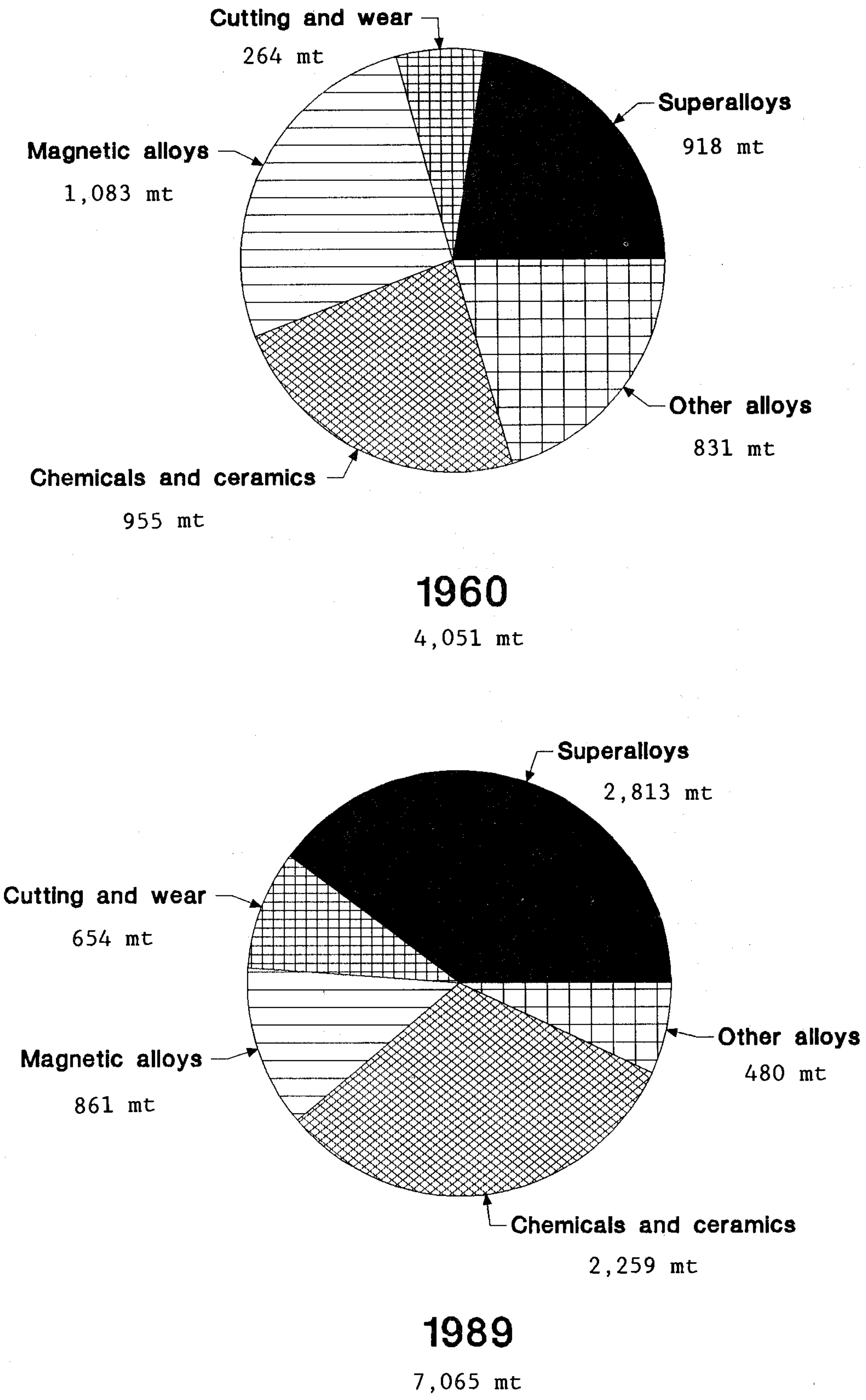


Figure 13.—Trends in cobalt use. Source: U.S. Bureau of Mines, Minerals Yearbooks.

DISTRIBUTION OF LOSSES

Information on cobalt losses is available from the U.S. Environmental Protection Agency's (EPA) Toxics Release Inventory (TRI) (*49*). TRI data are collected by the EPA as required by law under the 1986 Emergency Planning and Community Right-to-Know Act. Under the law, industries manufacturing, processing, or using certain chemicals above defined threshold limits must report estimates of emissions each year. Both "cobalt" and "cobalt compounds" (defined as "any unique chemical substance that contains cobalt as part of that chemical's infrastructure") are included in the TRI.

TRI data are divided into two types—releases to the environment (to air, water, or land) and transfers to off-site locations (municipal wastewater treatment plants or other treatment and disposal facilities). Results of the TRI for the years 1987 through 1989 are provided in tables 5 through 7. The total releases and transfers reported to EPA during this time period (table 7) are roughly equal to the combined "losses" estimated for the chemical and powder processing and fabricate/manufacture stages in the present study (fig. 2). Some mining and/or mineral processing operations are probably included in the TRI data. As a future study, an industry-by-industry comparison of TRI data with the estimates in the current study would show areas of overlap and disagreement, and might provide further insight to the quantities, character, and distribution of cobalt materials leaving the cobalt flow.

Table 5.—EPA Toxic Release Inventory data, cobalt

(metric tons, contained cobalt)

	1987	1988	1989
Releases:			
Fugitive or non-point air emissions	9	7	13
Stack or point air emissions	5	8	8
Discharge to water	6	7	6
Underground injection	0	0	0
Releases to land	9	97	108
Total	29	119	135
Transfers:			
Discharge to publicly owned treatment works[1]	4	4	5
Other off-site locations[2]	114	93	115
Total[3]	119	97	120
Grand total[3]	148	216	256

[1] Municipal wastewater treatment plants.

[2] Treatment and disposal facilities.

[3] Data may not add to totals shown because of independent rounding.

Source: U.S. Environmental Protection Agency, reference (*49*).

Table 6.—EPA Toxic Release Inventory data, cobalt compounds

(metric tons, contained cobalt)

	1987	1988	1989
Releases:			
Fugitive or non-point air emissions	6	5	6
Stack or point air emissions	16	19	28
Discharge to water	19	29	32
Underground injection	([1])	8	7
Releases to land	45	17	42
Total	86	78	115
Transfers:			
Discharge to publicly owned treatment works[2]	12	13	11
Other off-site locations[3]	193	150	198
Total	205	163	209
Grand total	291	241	324

[1] Less than 1/2 unit.
[2] Municipal wastewater treatment plants.
[3] Treatment and disposal facilities.

Source: U.S. Environmental Protection Agency, reference (*49*).

Table 7.—EPA Toxic Release Inventory data, cobalt and cobalt compounds

(metric tons, contained cobalt)

	1987	1988	1989
Releases:			
Fugitive or non-point air emissions	15	12	19
Stack or point air emissions	21	27	36
Discharge to water	25	36	38
Underground injection	([1])	8	7
Releases to land	54	114	150
Total[2]	116	197	250
Transfers:			
Discharge to publicly owned treatment works[3]	17	17	16
Other off-site locations[4]	307	243	314
Total	324	260	330
Grand total	440	457	580

[1] Less than 1/2 unit.
[2] Data may not add to totals shown because of independent rounding.
[3] Municipal wastewater treatment plants.
[4] Treatment and disposal facilities.

Source: U.S. Environmental Protection Agency, reference (*49*).

CONCLUSIONS

This study provides an initial evaluation of the flow of cobalt in the United States. The flows of cobalt-containing materials during selected mining and mineral processing operations, burning of fossil fuels, chemical and powder processing, alloy processing, and the manufacture and use of various products were identified. Where possible, estimates were made to quantify recycling rates and losses. Also identified were areas where further research is necessary to verify or improve the estimates.

Estimates of global sources of cobalt to the environment were cited from Donaldson. In terms of losses attributed to humans, on a global scale Donaldson estimated that equal quantities of cobalt are released from fossil fuel burning and from cobalt use as a metal or chemical. If we assume that losses from "cobalt use as a metal or chemical" refers to losses from the processing and manufacture of cobalt chemicals, powders, alloys, and products, and dissipation during use, but does not include losses resulting from the disposal of used products, then estimates for the United States in the present study show a similar distribution. Releases of 480 mt of cobalt were attributed to U.S. coal burning and 530 mt to 560 mt were attributed to U.S. cobalt use (50 mt to 80 mt from chemical and powder processing, 360 mt from fabricate/manufacture, and 120 mt from dissipation).

Donaldson does not attribute any significant cobalt releases to cobalt mining and refining. Preliminary estimates in the present study indicate that significant quantities of cobalt are released both during cobalt production and during the production of other metals and minerals. For example, even though the United States is not a cobalt producer, an estimated 1,700 mt of cobalt are released each year from mining and processing lead ores in Missouri and processing copper ores by heap leaching in the Western United States alone. This discrepancy between the two studies is most likely the result of a difference in definitions.

Industrial losses from cobalt chemical and powder processing, alloy processing, and parts and product manufacturing are estimated at 410 mt/yr to 440 mt/yr (50 mt to 80 mt from chemical and powder processing plus 360 mt from fabricate/manufacture). This estimate is roughly equal to releases and transfers of cobalt reported by U.S. industries to the EPA for 1987 (440 mt), 1988 (457 mt), and 1989 (580 mt).

These industrial losses are greatly outweighed by the loss of cobalt in products discarded following use. An estimated 2,780 mt of cobalt is consumed in the United States each year to make products that will ultimately be disposed. Recycling or cobalt recovery might be possible from some products currently discarded, if collection, recycling technology, and economics were amenable. Recycling of used cobalt-containing magnets are one example. In other products, such as many cobalt chemical applications, the cobalt is too diluted to make recovery feasible.

The superalloy, magnet alloy, cemented carbide, tool steel, and hardfacing industries have well-established recycling or cobalt recovery practices. These industries recycle home scrap, prompt scrap, and in some cases, obsolete scrap as well. Some metallic scrap is downgraded, but although this is a loss of usable cobalt, it is not an environmental loss. The petroleum industry has well-established recycling and metal-recovery practices for spent catalysts, and some chemical catalysts are also recycled.

Most cobalt uses are not dissipative in character. Cobalt lost from the dissipation of agricultural products, through the attrition of cemented carbides, and during the recycle and reuse of homogeneous catalysts is estimated to total 120 mt annually.

In terms of further research, a more thorough study of individual industries could be done to evaluate some of the assumptions in the present study (such as net trade flows, recycling rates, and waste generation), confirm or revise the loss estimates, and determine the effects of any technological changes since the cited references were published. As part of this study, an industry-by-industry comparison of TRI data with the estimates from the present study might provide further insight to the quantities, character, and distribution of cobalt losses.

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GLOSSARY

Cast alloys.—Alloys made from a melt that is cast into a shape.

Dissipation.—For the purpose of this study, dissipation refers to losses occurring during use or as a result of use. Attrition of cemented carbides during machining operations, mining and drilling, and the dispersal of cobalt agricultural supplements from the soil to plants to animals are examples of dissipation.

Downgrading.—The remelting of cobalt-containing alloys to make an alloy with a much lower cobalt content, such as steel. The cobalt is diluted to the level of a residual or background element in the new alloy, and does not contribute to the properties of the new alloy. Therefore, the cobalt is considered lost in terms of usable cobalt. However, it is not lost to the environment. This cobalt is still in the "use pool" and is not considered a loss for the purpose of this study.

Heterogeneous catalysts.—Catalysts that are a different phase from the reaction mixture, such as solid catalysts in a liquid reaction mixture.

Homogeneous catalysts.—Catalysts that are the same phase as the reaction mixture, such as soluble salts in a liquid reaction mixture.

Loss.—For the purpose of this study, "loss" is defined rather loosely to include various materials that leave the U.S. cobalt flow during mining and mineral processing, chemical and powder processing, manufacturing, and use. Efforts were made to distinguish between two types of losses. The first type includes losses from the U.S. cobalt flow that remain in the United States, such as industrial emissions and losses from dissipation during use or disposal following use. The second type of loss from the U.S. cobalt flow includes exports of cobalt to other countries and the transfer of cobalt to another U.S. materials flow (downgrading). Materials that temporarily leave the flow, such as stockpiled materials or scrap that leaves the cobalt flow before being recycled, are not considered losses.

Recovery.—For the purpose of this study, recovery is used to represent recycling processes that separate cobalt from other metals. The cobalt is then reused as is or is further refined. Examples of scrap materials from which cobalt is recovered include spent petroleum catalysts and some cemented carbide scrap.

Recycling.—For the purpose of this study, recycling is the reintroduction of scrap or other discarded materials to the materials flow. In the case of alloys, recycling usually involves remelting alloy scrap to make the same or another alloy. Alloy scrap can originate from various points in the cobalt cycle. Home scrap (also called revert or run-around scrap) is the scrap generated in the production of new metals, such as superalloys. This scrap is reused in the same plant in which it is generated. Prompt scrap (also called industrial, manufacturing, or new scrap) is scrap generated by metal-working industries, such as in parts manufacturing. Obsolete scrap (also called old scrap) is from products that have been in use, such as jet engine blades or cemented carbide tool inserts. Another scrap category is purchased scrap. This can be either prompt or obsolete scrap that has been bought from a scrap processor or dealer.

Wrought alloys.—Alloys suitable for forming by mechanical means at temperatures below their melting point. Ingots of wrought alloys are hot-worked into bars, sheets, or other forms. These forms are then forged into final parts.

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