

INDUSTRIAL ECOLOGY OF METALS: BARRIERS AND INCENTIVES TO CLOSING LOOPS

by

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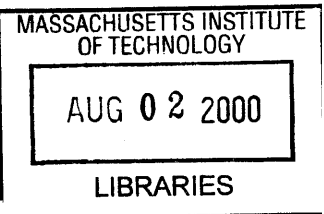
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ABSTRACT

This thesis examines the end-of-life markets for NiCd batteries and Aluminum Intensive Vehicles (AIVs) through an industrial ecology framework. Case studies were chosen to examine the general characteristics of the industrial ecology of metals, barriers and incentives to closing material loops, and policy interventions associated with loop closing.

The NiCd case shows how industry policy and public policy converge towards creation of an environmentally beneficial end-of-life market. The industry coordinated take back program was motivated by public health concern for cadmium landfill contamination. The main barriers to taking back batteries are low consumer participation, insufficient economic incentive for cadmium recovery, and ambiguous industry motivations. Public policy makers should consider subsidizing recycled cadmium prices and adding serious accountability measures to the take back system (such as a tax per unit under a recycle rate goal).

The AIV case demonstrates the effectiveness of material value economic incentives for creating and maintaining a self-sufficient recycling system. However, the current recycling system built for steel automobiles will not most efficiently recycle AIVs. Barriers to efficient recycling include inadequate aluminum alloy sorting technology and lack of coordination between firms. Public policy options are limited because recycling efficiency regulation is outside the enabling legislation of agencies, but government should assist industry coordination as much as possible.

The case studies also speak generally to loop closing policies that affect either the supply or demand for recycled material. Demand increasing policies (procurement, minimum recycled content, etc.) are more appropriate for recycling systems where a functional system is in place and the last user has sufficient incentive to return the product. On the other hand, supply increasing policies (take back, landfill ban, etc.) may be necessary for products where the last user does not have sufficient incentive to deliver the used product to the recycling system. Industry policy is useful for developing mutually beneficial technology, setting product standards, and coordinating behavior through merger and acquisition.

ACKNOWLEDGEMENTS

Two years ago, I sat along the placid shores of Lake Mendota in Madison, Wisconsin, pondering my future at one of three institutions – University of Michigan (Ann Arbor), Harvard Kennedy School of Government, and Massachusetts Institute of Technology. I chose the metaphorical “fire hose drinking fountain” we fondly call The Institute. Knowing that M.I.T. was most in line with my techno-centric academic background, I promised myself that I would keep my mind open to new ways of thinking and conceiving the world. I thank the students of the Technology and Policy Program who consistently challenge my prejudiced social paradigm.

Without a doubt, the first challenge upon arriving to M.I.T. is overcoming The Institute’s intimidating facade. My landing here was certainly softened by Larry Susskind, thanks for taking a chance on me in the beginning and continually challenging my understanding of policy. Thanks also to the Consortium on Environmental Challenges for providing support of research behind this thesis.

But my memories of M.I.T. will revolve around the home away from home at the Technology, Business, and Environment Program (specifically E40-242b). I believe strongly in the power of ordinary experience, and it was the everyday interactions with Jen, both Mikes, and Jon that have shaped my worldview of business as the most important social institution, and the natural environment as our context for physical and spiritual existence. This thesis is only a partial reflection of their importance on my life. The fact that two years ago I would hardly be able to compose or understand my thesis speaks volume to their wisdom and intelligence. Thank you Jen and John for living out and demonstrating the meaning of intellectual leadership, I will carry that with me forever.

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CHAPTER 1 – INTRODUCTION

1.1. Introduction to the Thesis

Questions of material use are fundamental to economic and environmental performance, which makes them ripe for public policy consideration. The cases studied in this thesis are no exception. Policy makers in the US Environmental Protection Agency are particularly concerned with controlling the fate of toxic or otherwise environmentally harmful materials. The Love Canal incident, a whole neighborhood had built on top of a toxic dumpsite, brought national attention to problems of irresponsible materials handling. Policy response to Love Canal and other similar situations led to statutory enactment of a several laws and a corresponding increase in the scope and importance of the US EPA.

A case chosen for this thesis looks at nickel cadmium batteries and studies public concern for toxic releases to the environment. Several critical policy questions face the United States and other NiCd battery consuming countries. The most drastic measure would call for banning nickel cadmium batteries entirely. More moderate proposals include mandatory take backs. Implementation of take back systems can be government or industry led, and must incorporate a whole host of incentives to encourage desired behavior. The industry led take back in the United States begs questions of private organizations' accountability to adequately providing public goods.

The US EPA is sometimes caught in an administrative dilemma because its mission is to protect the natural environment, while many unregulated aspects account for significant impacts. As a result, they have taken steps with the Department of Energy to increase energy efficiency in building design, industry operations, etc. The aluminum intensive automobile case focuses on increasing recycling system efficiency. However, traditional policy instruments are limited since this is an unregulated goal, raising questions about the structure of our regulatory system to handle these situations.

1.2. Industrial Ecology of Metals

There is a lot of rhetoric surrounding the idea that “waste = food.” Chemical engineers have used this idea extensively in the design of facilities for many years, where waste streams of one process serve as input streams to another process. But the practice of 1950’s style chemical engineering, while certainly resource efficient, is not often associated with “industrial ecology.” This begs the question, what is the difference between resource efficiency and industrial ecology?

Graedel and Allenby defined industrial ecology as “the study of the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural and technological evolution.” (Graedel and Allenby 1998) This statement has serious implications, namely that the world has limited resources for a given set of current and foreseeable technologies. Thus, industrial ecology is a framework for operating within limited resources.

Graedel and Allenby’s vision is significantly different than desiring the chemical engineer’s idea of resource efficiency. Industrial ecology pierces through modern day rhetoric of “win-win” for business and environment, or “eco-efficiency.” Rather, this framework is meant to force citizens of the planet to reconceive standard neo-classical economic views of resources, and the need to plan for their use throughout desired human development.

The industrial ecology of metals is the practice of using metal resources efficiently and planning for a resource-constrained world. Experts in the field of industrial ecology have suggested several guidelines in the practice of resource efficiency (Kirchain 1999):

- Dematerialization – More efficient use of a given material for a given function
- Materials Substitution – Replacement of current materials for those less scarce and more benign
- Repair, reuse, remanufacture, and recycling
- Waste mining – Use of waste streams as inputs to other processes

Resource efficiency is often accompanied by economic gain because it involves advanced technology utilization or incremental development. However, there comes a point when current and foreseeable technology cannot achieve certain resource efficiency levels – the

“win-win” opportunities run out. Planning for a resource-constrained world where technology cannot solve scarcity problems generates the most controversy arises. This kind of planning might force us to reduce resource consumption, even if the resources are being used efficiently. In other words, we may have to make conscientious tradeoffs between consumption and conservation.

The industrial ecology of metals describes metal intensive products and their ecology-like material flows. This thesis also focuses on the end-of-life market in particular. There are several characteristics that make metals an interesting subset of industrial ecology:

- Ubiquitous – Metals are used in many common products, and there are important products where the metallic fraction of total mass is quite high; e.g., automobile, white goods, cans, etc.
- High material value – Many metals are the product of sophisticated refining processes.
- High value-added capacity – Metals have the ability to be made into very valuable products.
- High value-to-volume ratio – One of the limiting factors in materials flows is the transportation costs between economic actors. Recycling becomes less feasible if transportation costs become a high percentage of the total cost structure. A high value-to-volume ratio allows for cheaper transport of bulk goods.
- Persistence – Metals maintain composition and integrity despite great temperature ranges and other conditions, allowing for greater flexibility during processing. This also gives additional incentives to manage material wastes in the case of toxic metals.
- Similar environmental concerns – Metals are a concern to the environment for usually one of two reasons, either they are inherently toxic or their refining process has adverse consequences.

1.3. Recycling Options

In the context of industrial ecology, industrial systems are often looked at in terms of material loops. Materials originate from primary fabricators, are used for various products, return for secondary processing through recycling systems, and are sold again to the product manufacturers. In this sense, materials travel through value-added industrial loops – total lifecycles.

Material lifecycles are often described in the context of a certain product, such as an automobile. Lifecycles are divided into two loop sections, upstream and downstream. The upstream section describes raw material extraction, product manufacture, distribution, and consumption. The downstream section describes collection, processing, and disposal options. Downstream systems are synonymous with the end-of-life market and recycling system. Downstream systems are the main subject of this thesis, although interrelationships with upstream activities sometimes factor into the analysis.

Downstream recycling activities are described as either “open loop” or “closed loop.” Technically, the difference is relatively simple. Closed loop recycling takes material from a given product and recycles that material so that it is used again for the same product, closing the loop on the product’s material lifecycle. Open loop recycling allows material to be recycled into other products and uses.

For example, closed loop Pb recycling would take lead-acid car batteries and re-smelt the lead to be used in new lead-acid batteries. Ideally, the only system leak would be fugitive emissions from the smelting process. Closed loop recycling has intuitive appeal because it says we only need a one-time infusion of material to create a self-sustaining value-added chain. On the other hand, open loop recycling could take leaded cathode rays tubes, recycle them, and make leaded glass for X-ray laboratories. Open loop recycling has intuitive appeal because it allows lowest cost recycling, where material takes the most economically feasible pathway.

While the technical difference is simple, the two types of recycling have very different philosophical foundations in industrial ecology. Closed loop recycling is often held as the panacea of product sustainability, since it forces society to find a self-sustaining material loop technological solution for every product. However, open loop advocates often cite an efficiency argument. Namely, open loop recycling allows for more efficient solutions, thus increasing the likelihood of industry participation. Open loop recycling is a more practical policy option for material diffusion problems such as the cathode ray example, where it is difficult to separate lead from glass.

Philosophical differences take hold in political debates over the role of industrial ecology in economic planning and environmental policy. The next section outlines policy objectives from a private and public perspective. Rhetoric of open loop vs. closed loop recycling underlies many debates in this field.

1.4. Policy Frameworks

Studying the industrial ecology of metals is not useful without consideration of policy objectives. The policy framework of this thesis uses both public policy and corporate industry policy. Industrial ecology-based planning is a mixture of both private and public objectives, and finding common policy objectives is crucial to developing a stable end-of-life management system. Private goals do not always coincide with public policy, which creates tension between regulated entities and their regulators. This thesis acknowledges such tension and will address points of policy divergence.

Corporate industry policy is the coordinated effort of two or more private enterprises towards a common goal. Industry policy is developed and operationalized with industry sector issues in mind. This type of policy utilizes formal and informal institutions, such as trade associations, partnerships, alliances, or mergers to further its interests. While industry policy addresses many different issues and is hard to generalize, industry is often looking for ways to: standardize operations, anticipate political changes, share financial risk, gain economies of scale, or create reliable information.

Public policy goals transcend private sector oriented objectives by looking at social welfare maximization. Public policy is loosely defined as the pursuit of social welfare maximization. The public policy framework used in this thesis is based on current United States policy experience, where mixed social agendas compete for resources. A common mixed social agenda is the tension between neoclassical economic theory and Rawlsian political philosophy. Where the former attempts to maximize aggregate welfare, the latter attempts to equalize distribution of welfare.

1.5. Policy Rationale for Intervention – Three Market Problems

One common policy goal is the creation and stabilization of markets for recyclates. In addition, both corporate industry policy and public policy seek to maximize resource use efficiency. While these are common goals, the means and distribution of costs and benefits are greatly debated. Most policies are first approached from a partial or general equilibrium economic framework, analyzing supply and demand relationships.

Adam Smith's "invisible hand" is supposed to allow free markets to allocate resources most efficiently. The invisible hand encourages recycling insofar as the "composition of demand effect" makes consumers move to products made with recycled goods because they are cheaper (if they are indeed cheaper). (Tietenberg 1992) But the theoretical basis for recycling also makes intuitive sense since recycling increases the effective available stock across time, thus increasing asset value.

Consider a stock "A" of recyclable metal and suppose a recycling rate "a" ($0 < a < 1.0$). Then the effective size of this metal's stock is a sum of an infinite series: A in the first year, $A * a$ the second year, $A * a^2$ the third year, etc. (Tietenberg 1992)

$$\text{Total Stock Size of Recyclable Metal} = A + A*a + A*a^2 + \dots = A/(1-a)$$

For a metal with a 50% recycling rate, the stock size will be twice the original level. A 90% recycling rate does even better, creating an effective stock size ten times the original! Therefore, an efficient market supplies only enough virgin metal to replenish demand after accounting for the recycling. Free markets have not tended to allocate recyclable material efficiently due to three common market failure problems.

First, the incentive structure for those supplying virgin materials and those supplying recycled materials is different. Primary producers are usually in the business of mining ore, refining, smelting, and distributing virgin material. On the other hand, secondary recyclers have complicated logistical problems in transportation and collection. They both compete for the same customers, but have very different cost structures. Free market competition between primary and secondary producers may easily lead to oversupply, analogous to other

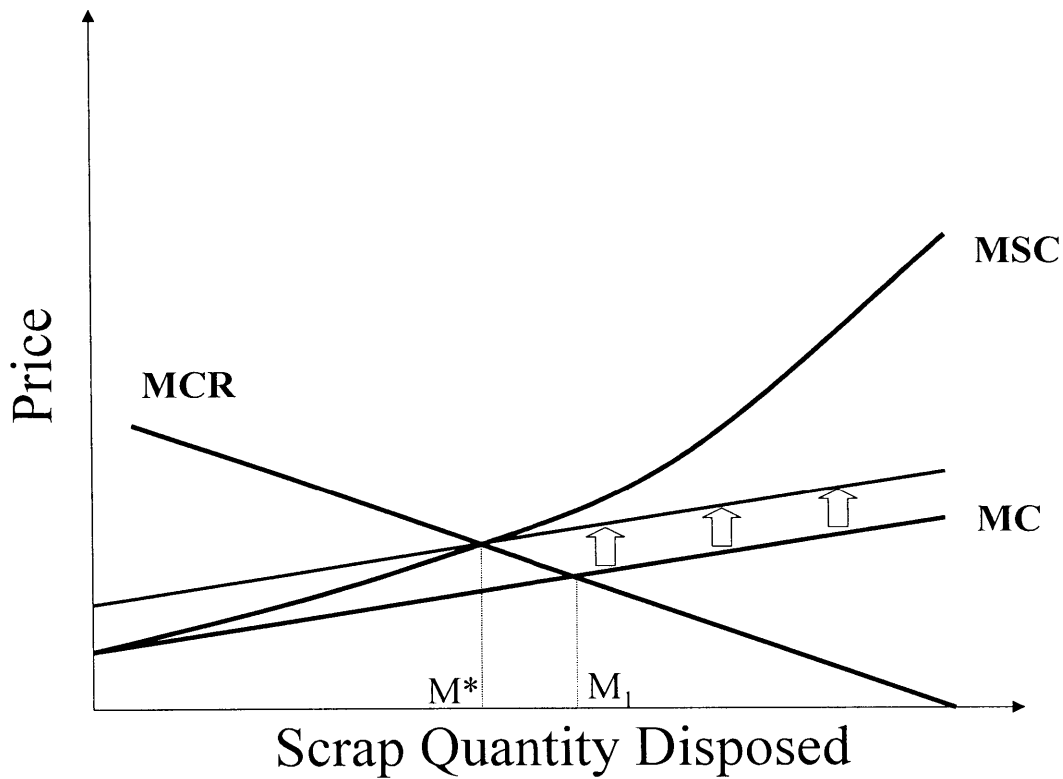
commodity markets. A plausible explanation for oversupply from primary metals producers would be the need to fill capacity utilization. Virgin metals producers operate in capital intensive industries, where utilization is often a very important goal to achieve sufficient returns. In addition, governments have subsidized and supported primary metals manufacturing, but neglected many of the secondary markets.

The second problem, often cited in the field of environmental policy, is accounting for “externalities.” Externalities are welfare reducing (or increasing) effects that are not accounted for in the price of a good – the price does not reflect its social value. (Pindyck and Rubinfeld 1998) This means a consumer does not pay for the true cost of a good, they either pay too much or too little.

Two types of externalities exist with respect to end-of-life metal materials. First, many people perceive that we consume landfill capacity too quickly (where capacity is either physical space or ability to absorb toxic material). Landfill users do not pay for the real cost because of environmental externalities from groundwater contamination, ugly landscape, etc. Landfill pricing schemes lead to inefficient disposal levels. Municipal governments often charge a fixed fee to keep administration costs down. Thus, households have little incentive to dispose less than their “quota.” Households also have little incentive to filter out hazardous waste because municipalities do not check garbage content. In either case, landfill capacity will be overused.

Figure 1.4a. shows how free markets will result in M_1 scrap disposal, where marginal cost of recycling (MCR) intersects marginal cost of disposal (MC). This level exceeds the efficient market recycling rate (M^*), where the marginal social cost (MSC) intersects the marginal cost of recycling (MCR). The marginal cost (MC) curve must be shifted up in order to achieve the market efficient recycling rate. The basic lesson is that intervention is necessary where social costs have diverged from private costs.

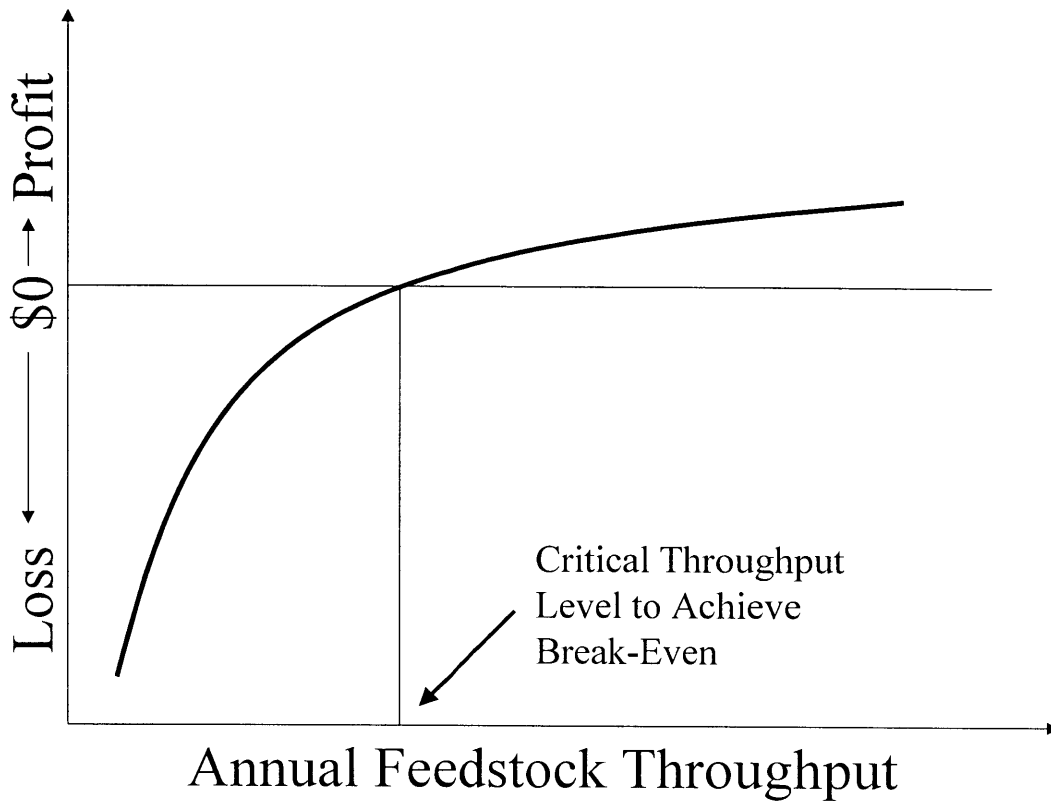
Figure 1.4a. The Efficient Amount of Recycling (Pindyck and Rubinfeld 1998)



The second externality is defined more broadly. In general, many people believe that we do not pay for the real cost of deforestation, habitat loss, water pollution, and other environmental ills related to ore extraction and metal smelting. Effectively, this puts recycled material at a competitive disadvantage with respect to virgin material.

The third market problem leading to inefficient distribution of market resources is based on an economies of scale argument. (Chen 1995) Many capital intensive industries exhibit economies of scale because fixed costs are much larger than variable costs. Therefore, the additional variable costs become a smaller fraction of the total production cost as production levels increase. In other words, marginal cost of production goes down as production increases. Figure 1.4b. shows this effect in graphical form.

Figure 1.4b. Critical Throughput – Economies of Scale Argument



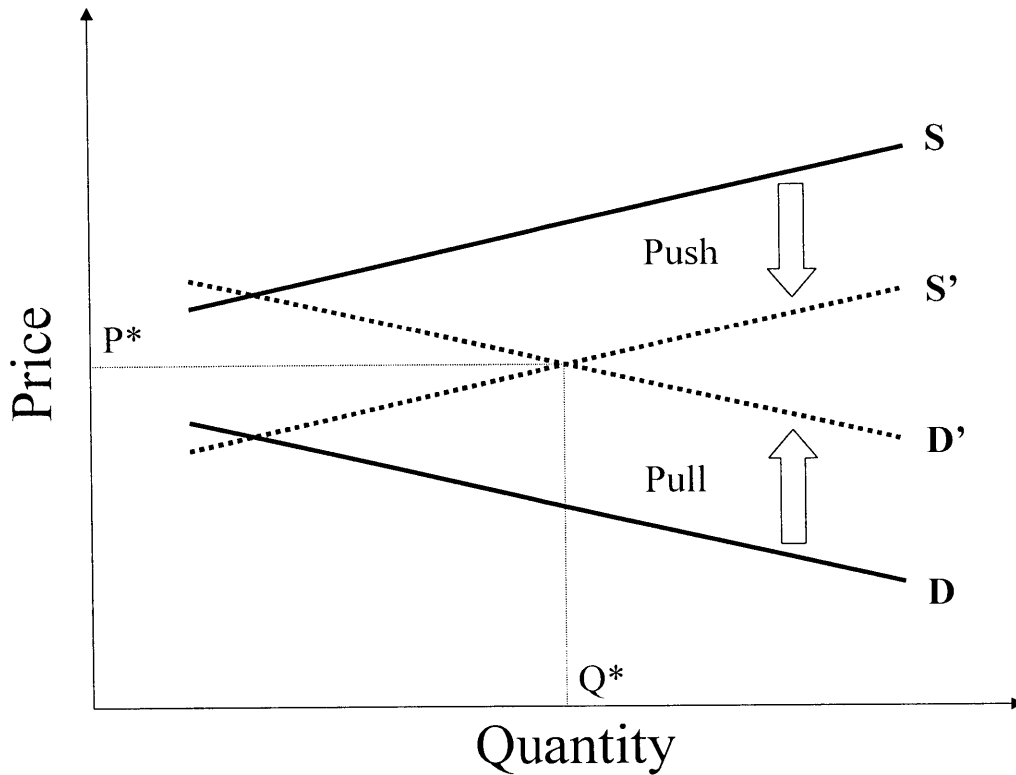
Recycling operations often follow this form of production curve since transportation costs and processing costs are usually capital intensive or have high initial costs. Policy intervention is intended to coordinate industry behavior so that critical throughput is reached in a relatively quick time horizon, minimizing unprofitable activity. This curve can also be interpreted as a function of network externalities (an individual's demand is affected by the demand of others). The proper system infrastructure will not develop if few people recycle, but the system will "mature" into a profitable enterprise once recycling becomes a norm or industry standard. Curbside recycling, for example, would be very costly if only a few people participated because the municipal government has to invest in specialized trucks, bins, and logistical management.

1.6. Policy Objectives

There are two main policy objective categories given the need for public or industry policy intervention. Policy objectives are geared toward either shifting the demand or shifting the

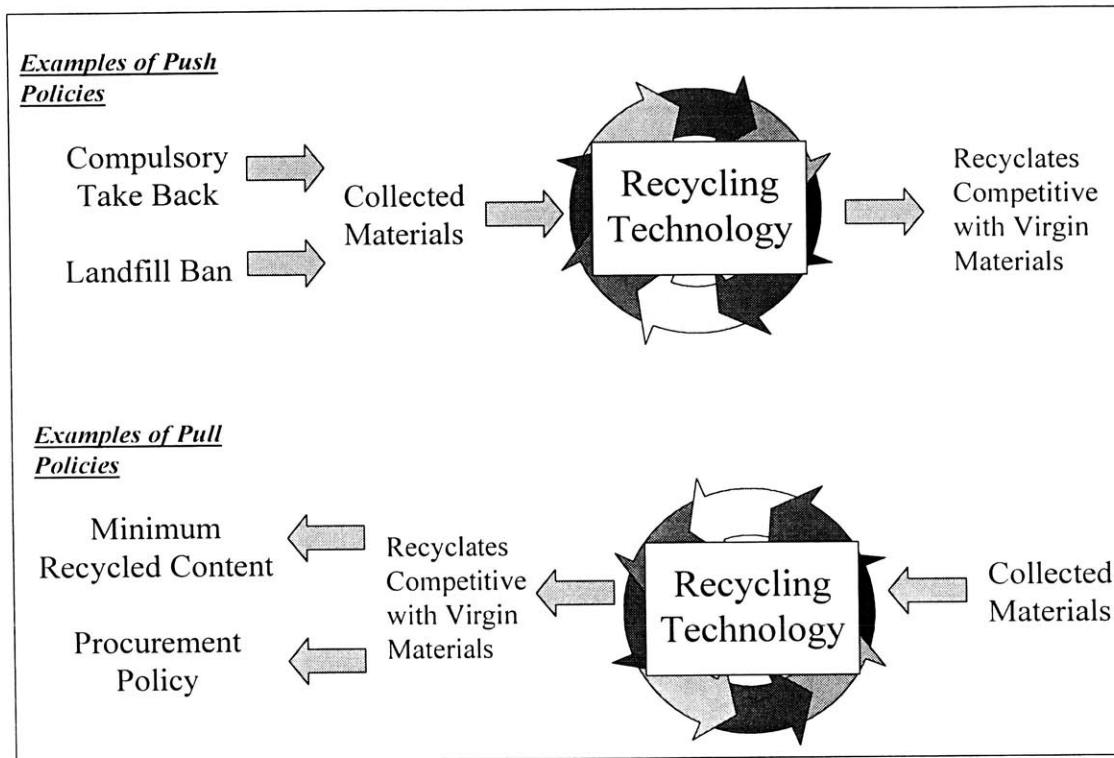
supply in a way that creates lower market clearing prices for recycled material or higher supply quantities. Figure 1.5a. shows how policy intervention can either “push” or “pull” market behavior. (Chen 1995)

Figure 1.5a. Recycling Economics



The supply shift is a policy intervention that increases the amount of recycled material, thus pushing the curve up. Take back mandates and landfill bans are two common methods of increasing the supply, “pushing” material into the end-of-life system. On the other hand, demand-side policy increases the effective demand for recycled material, or “pulling” material out of the end-of-life system (see Figure 1.5b.). The assumption behind both of these policies is that intervention will drive technological change, forcing industry to adopt more efficient technological solutions to recycling. (Chen 1995)

Figure 1.5b. Push-Pull Thinking



However, increased technology utilization or incremental change is not sufficient because policies will result in more costly operations. The goal of policy intervention is to create dynamic efficiency solutions through technological innovation and breakthroughs. The aluminum beverage can is an excellent example where policy intervention led to technological change in can composition. The result was a more recyclable can, lowering recycling costs for processors, and dramatically changing the feasibility of aluminum recycling.

In addition to policy instruments mentioned in the diagram above, deposits, taxes, subsidies, and price supports could be utilized to change material value. Analysis of these policies is not given general attention here, but will follow after presentation of the two case studies.

1.7. Case Study Selection

Comprehensively studying the industrial ecology of metals would require extensive analysis on most major metal intensive products, which is far beyond the scope of a master's thesis. Case selection considered objectives of industrial ecology and tries to find some degree of generalization.

There seems to be two major thrusts for resource conservation. First, industrial ecology seeks to minimize the associated impacts of material use through “dematerialization.” In other words, less aluminum needed for a given function corresponds to less energy requirements and emissions of toxic by-products. The aluminum intensive automobile was chosen to capture a focus on dematerialization and material substitution. The ubiquitous nature of aluminum and the automobile also force policy makers to face general questions about resource conservation and limits to human impact on the environment.

The second major thrust of resource conservation is to minimize direct environmental impacts of materials in the biological impact pathway. In many cases, this involves taking emissions of one production source and using it as a useful input to another process – “waste mining.” The case of nickel cadmium batteries was chosen to focus on this aspect of industrial ecology. Neither nickel nor cadmium are resource scarce metals, but both have serious direct health and environmental consequences in their end-of-life fate (especially when compared to steel or aluminum). The nickel cadmium battery is very difficult to dematerialize because its energy storage function is closely tied the mass of each metal.

Both case studies focus on the most important aspect of end-of-life materials management, the recycling system. Recycling systems are complex because of their non-linear relationships. Many businesses think in terms of a supplier-producer-distributor-customer relationship, but a vibrant recycling system can complicate this dynamic. Producers' design choices can affect disposal options, which then change material markets, altering suppliers' economics, which then allow producers to obtain cheaper input material, etc. Interdependencies between economic actors make decision analysis difficult. This thesis will explore complexity in the end-of-life market dynamics.

While both case studies have active end-of-life markets, it is hard to imagine two recycling systems that could be more different. The automobile recycling system is an economics-driven system and self-sustaining. Regulatory pressure stems from general landfill and resource concerns, not targeted policy intervention. On the other hand, nickel cadmium battery recycling is a recent industrial policy initiative, subsidized by producers, and subject to the threat of targeted policy intervention.

1.8. Outline of Thesis

The next two chapters describe case studies of the nickel cadmium battery and the aluminum intensive automobile. Case studies attempt a general approach to understanding the end-of-life markets – industry context, technology, and macroeconomic variables are explored. Sankey diagrams will show estimated metals flow through the economy. Chapter 4 is an analysis of the recycling systems, utilizing a basic econometric matrix to outline relationships between actors. Comparisons are drawn between the two cases, with attention given to the public policy context. Chapter 5 will describe how standard policy options might affect recycling systems. The thesis concludes with a few comments on the industrial ecology of metals and lessons learned from these cases. Specifically, the cases suggest that pull policy is more appropriate for established recycling systems, and push policies are effective for retrieving materials where no formal prior recycling system exists. A set of public policy options are recommended to enhance the recycling systems' efficiency

CHAPTER 2 – NICKEL CADMIUM BATTERY

Nickel cadmium battery recycling is nearing its sixth year of concerted effort. The battery industry's self-led initiative is an innovative approach to end-of-life product management, spawning praise from environmentalists and government alike. However, the take back system hasn't met its promised goals. Promised recycling rates of 70% have not been achieved, and target dates are continually pushed back.

Should more regulation have been promulgated, or was this really "one of those cases where government simply needed to get out of the way." (Rep. Scott L. Klug, R-Wisconsin, chief sponsor of the "Battery Act"). (Daniels 1996) Do recycling systems need more than six years to achieve desirable recycling rates? Or will the nickel cadmium problem be solved by its shrinking market share to nickel metal hydride and lithium ion substitutes?

2.1. Basics of Nickel Cadmium Batteries

2.1.1. Characteristics of the Nickel-Cadmium Battery

"Nicads" are one of several popular rechargeable, or secondary batteries. Primary batteries are single discharge cells, such as alkaline types used in many electronics. Secondary batteries, on the other hand, operate on a reversible chemical reaction. The typical composition of a NiCd battery is given below.

Table 2.1.1. – A Typical Composition of the NiCd Battery (Lankey 1998)

Material	Weight (%)
Nickel	20.20
Nickel Hydroxide	17.40
Cadmium	24.60
Cobalt	1.40
Steel and copper terminals	4.10
Lithium Hydroxide	0.70
Potassium Hydroxide	5.22
Water	11.48
Case and cover (stainless steel)	11.70
Miscellaneous plastics	3.10
Other	0.10
Total	100

Electric power is supplied by the ion exchange between nickel and cadmium plates (electrodes). An electrolyte (LiOH or KOH) is stuffed between plates and carries charges between the two plates. Many other technical modifications have been developed to enhance various performance characteristics of the battery.

2.1.2. Commercial applications

Most NiCd batteries are purchased indirectly through semi-durable electronics, such as cordless power tools and portable communication devices (cordless phones). The other sizable market is for industrial grade power supplies in trains, light rail, and emergency lighting. Nickel cadmium batteries have found a strong niche market for low-cost high power delivery services. They are projected to serve the needs of products used in extreme climactic conditions. (Lankey 1998) Table 2.1.2. shows the distribution of applications in the Japanese battery market from 1996, with approximate increasing or decreasing trends indicated.

The important consideration with respect to end-of-life management is that NiCd batteries are not often primary products, but rather an added cost to the product being purchased. This has broad ramifications for designing effective policies to facilitate take back. For example, consumers may not notice educational labels, or electronics manufacturers may oppose deposit-type strategies since higher product pricing may reduce electronic device sales.

**Table 2.1.2. – 1996 Distribution in Japanese NiCd Sales
by Application (Lankey 1998)**

Application	10 ⁶ Cells	%	Trend
Home Appliances	64	28	Stable
Office Equipment	15	7	N/A
Communications	43	19	Decreasing
Power Tools	51	22	Increasing
Round Cells	14	6	N/A
Emergency Lighting	25	11	Increasing
Other (industrial)	16	7	Increasing
Total	228	100	(Overall 2-4% growth per year)

2.1.3. Market position in the battery industry

The overall market size for rechargeable batteries has been increasing with the proliferation of portable electronic devices. Nickel cadmium batteries benefit from several desirable aspects: durability, reliable performance across temperature ranges, excellent rechargeability, fast power delivery, and cost-effectiveness. Nonetheless, other battery types have made quite an impressive dent in the NiCd market, notably the Lithium-ion and Nickel metal hydride battery. These both weigh considerably less, which has been an important consumer preference in the laptop computer and cellular phone markets.

NiCd batteries had established a very strong initial position in the rechargeable battery market, but now are facing serious competition. Because other batteries are competing very closely, we might expect to see marginal considerations swing consumer choice. Brown and Klein estimate that NiCd battery market share has decreased 15% (in relative terms) because of environmental concerns alone. (Brown and Klien 1997)

The market for rechargeable batteries is splitting into two segments – price-sensitive and performance-sensitive applications. *Performance-sensitive* applications include the laptop computer and mobile phone, where every extra operational minute derived from higher quality batteries (such as Lithium ion) is worth the extra cost. *Price-sensitive* applications favor NiCd batteries because the low selling price is important in highly competitive markets, such as cordless household phones and rechargeable flashlights. (Margolin 1995)

Assuming NiCd batteries currently have a ten percent market share (Lankey 1998), it is not expected that NiCd share would fall below five percent of the total battery market because industrial and cordless power tool applications lack economical substitutes. These two applications alone constitute roughly 50% of the current NiCd market, and the market for industrial batteries is expected to grow at 10% per year. Another prediction from the International Cadmium Association is that nickel cadmium batteries will be one of several power supply choices for electric vehicles. Even a modest electric vehicle market share would increase NiCd production by a factor of ten. (Metal Bulletin 1995) Thus, the

materials management question is not “how do we get rid of it,” but rather “how do we deal with it.”

2.2. Material Flows

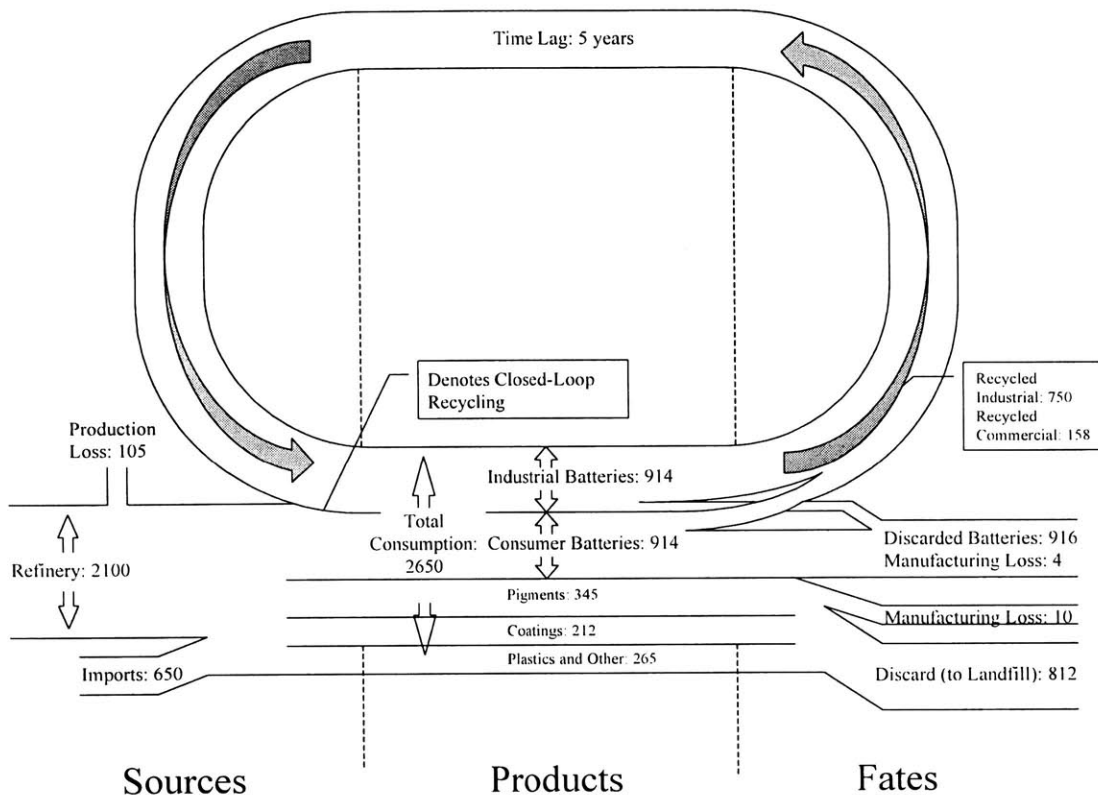
2.2.1. Cadmium

Cadmium is mostly found in a zinc-ore at low concentrations (0.3% to 0.5%), and is a by-product of zinc production. Trace amounts of cadmium are also found in other ores, making it a common low-level toxic pollutant from numerous industrial processes. Historically, cadmium use was concentrated in electroplating operations, pigments, and plastic stabilizers. Nickel cadmium batteries first appeared during World War II, and have increased in use every year since then.

Cadmium material flows are diagramed in Figure 2.2.1., including leaks to the environment. (Llewlyn 1990) While the Sankey diagram is based on 1989 and 1996 U.S. data, the general industry profile is similar today. However, as mentioned in the previous section, battery production is increasingly becoming the dominant sink of cadmium stock. Well over 50% of total cadmium production is now used for batteries in the U.S. This number is even higher for the global market at 70%. (Financial Times 1998) Figure 2.2.1. is a modification and represents an approximation of current U.S. material flows.

Cadmium is not a highly recyclable metal given its product design and typology. For example, cadmium bonded into pigments and plastic resins cannot be easily separated. Likewise, if cadmium coating represents a small portion of the total product being discarded, then it will most likely not be recycled. To date, almost all recycling has been for spent NiCd batteries. (United States Geological Survey 1999) Of the recycled batteries, 80 to 85% are from industrial types, which are more likely to be recycled because each unit has more material (and thus more value). In addition, industrial batteries are not disposed through household waste, but rather a much more regulated commercial waste stream. Estimating the recycling rate of batteries is a very difficult calculation, involving many imprecise assumptions. For example, different types of nickel cadmium batteries have different lifetimes. Therefore, it is difficult to tell what year they discard their used batteries.

Figure 2.2.1. Cadmium Sankey (metric tons)



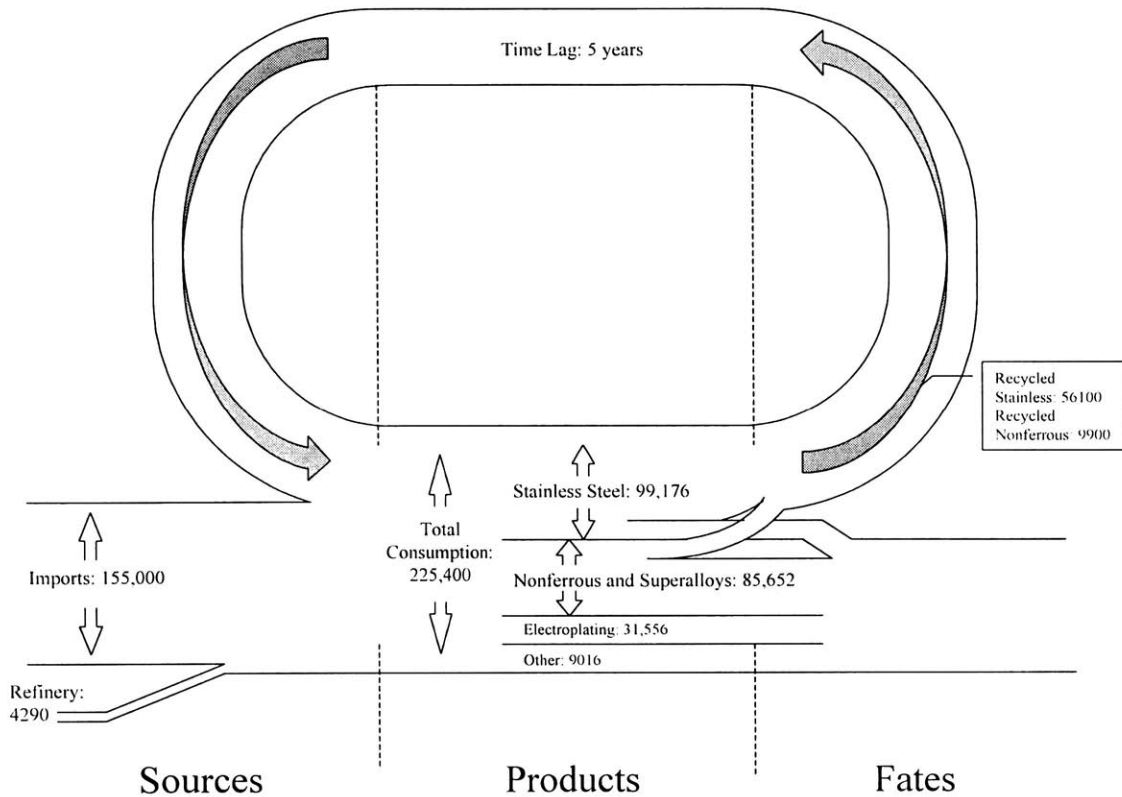
Material flows of cadmium are significantly different in other countries. Recycling rates have tended to be higher in Japan and Europe, not surprising considering their tighter regulatory environment. In addition, cadmium has been banned from certain uses in Europe, such as pigments.

2.2.2. Nickel Material Flows

Nickel is produced all over the world, with Russia leading global output. (Kuck 1997) Stainless steel consumes 65% of the world nickel supply, with another 5% for other steel alloys. Battery manufacturer demand represents a much smaller portion of global nickel demand, but this number is increasing at about 6% per year. Even so, it is not a large enough portion to be an important flow on the Sankey diagram. Demand for stainless steel is also increasing, suggesting that battery manufacturers will not be a major consumer of

nickel in the foreseeable future. (Kuck 1997) Figure 2.2.2. is a Sankey diagram for the U.S. material flows of nickel.

Figure 2.2.2. Nickel Sankey Diagram (metric tons)



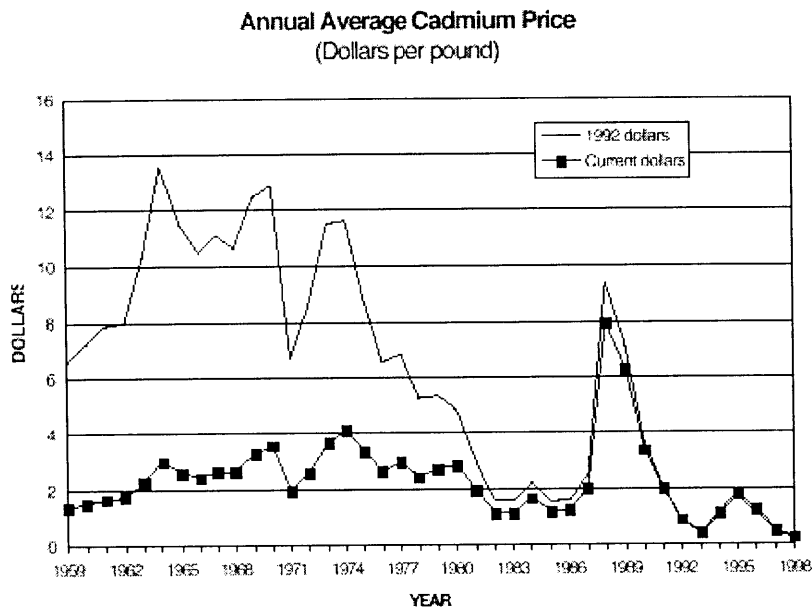
2.2.3. Nickel and Cadmium Pricing

Prices for both nickel and cadmium have been volatile (see Figure 2.2.3.), as with many commodities markets. The late 1980's were a golden time for cadmium producers, with prices well over \$6.00 per pound. This shortage was caused by the rapid growth of NiCd production. In fact, industry experts at the 1989 Sixth Cadmium Conference seriously discussed cadmium recycling as a viable solution to high prices. With 1989 recycling technology, \$3.50 per pound would allow recyclers to break even, and \$4.00 per pound would be a "good return on investment." (DiMaria 1989)

The price elevation was short lived because macroeconomic variables (such as an oversupply created by excess production in Russia) altered global conditions. The United States Defense Logistics Agency also decided to dispose of its strategic stockpile of cadmium,

increasing the supply significantly. (Chemical Marketing Reporter 1994) Recycling has also contributed approximately 11% of global production, lowering the price even more. (Financial Times 1998) Another destabilizing effect is that cadmium production is directly related to zinc demand and production.

Figure 2.2.3. Cadmium Prices (\$/lb.)



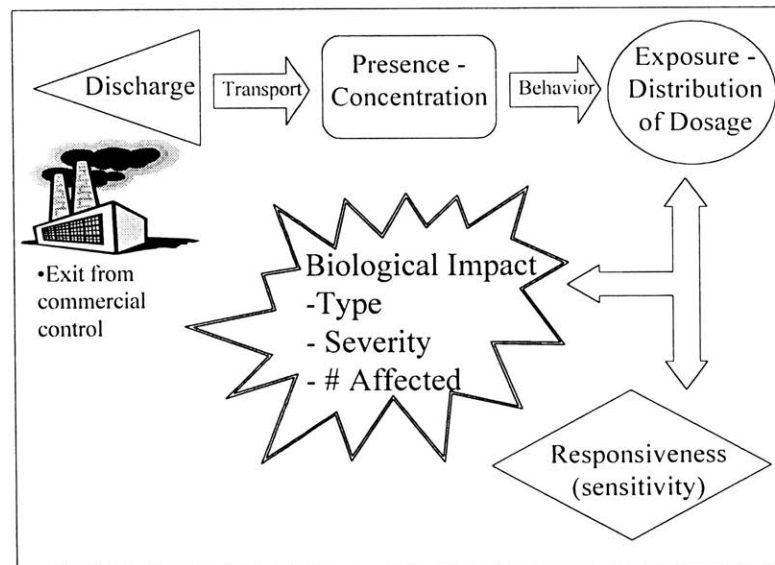
Price factors greatly determine both the price competitiveness of nickel cadmium batteries in the rechargeable market and the economic feasibility of recycling. One mid 1990's estimate puts the preferable range between \$1 and \$3; where prices above \$3 would make NiCd batteries too expensive and anything below \$1 makes recycling uneconomical.

(Environmental Information Networks 1995) Nickel does not suffer from the same complexities because battery material demand constitutes such a small fraction of the total market. Cadmium price issues are exacerbated by production in countries where little or no recycling exists, such as Russia. This prevents possible government intervention to curb production and encourage recycling.

2.3. Biological Impact Pathway

Loosely speaking, we are concerned with energy, resource conservation, and leaks in the lifecycle when referring to environmental concerns. The first two are assumed to be all other things equal, desirable goals in designing policy and corporate practice; i.e., more conservation is better. However, leaks to the lifecycle are much more difficult to understand. If a leak causes no harm, should we care? CFCs and CO₂ are two notable examples where government and industry delayed policy action because emissions were believed to be harmless. But this logic places a lot of trust in current scientific knowledge. One tool for assessing harm from leaks is the “biological impact pathway.” Figure 2.3. illustrates the biological impact pathway, and how lifecycle leaks goes through complicated interactions before final biological harm is registered. (Ashford 1980)

Figure 2.3. Biological Impact Pathway



2.3.1. Toxicity of Nickel and Cadmium

Cadmium is a toxic heavy metal. Short-term, or acute, effects include pulmonary irritation (of the lung). However, long term effects are of the most serious concern to regulators. Cadmium is considered to be a “probable human carcinogen of medium carcinogenic hazard” by the US EPA. (United States Environmental Protection Agency) In addition,

cadmium is a bioaccumulative toxin in some organs, such as the kidney. Cadmium also has teratogenic and other adverse developmental effects.

The main source of airborne exposure to cadmium comes from burning fossil fuels, smelting, and municipal waste incineration. (United States Environmental Protection Agency) Cadmium releases into water bodies come mostly from leaching landfills and wastewater of cadmium-intensive industrial activities. (United States Environmental Protection Agency Office of Water) Due to the health concerns mentioned above, cadmium is considered to be a major environmental hazard.

While cadmium is undoubtedly a problem, nickel is often an overlooked hazard in battery waste management. Nickel dusts are considered Group A carcinogens, making it more carcinogenic than lead. (United States Environmental Protection Agency) Nickel also has acute and non-carcinogenic chronic effects targeted toward the lung and kidneys, making it a “high concern” pollutant.

Main air pathways include refinery dust, municipal incinerator air pollution, and through food ingestion. Nickel is a water-borne pollutant through industrial wastewater and landfill leachate. The EPA does not consider nickel in water to be an acute danger. However, long-term exposure includes heart and liver damage, skin irritation, and decreased body weight. Nickel does not bioaccumulate, which is different from cadmium. (United States Environmental Protection Agency Office of Water)

2.3.2. Biological Impact Pathway of NiCd Batteries

The first step in a biological impact is discharge, or exit from commercial control. Nickel and cadmium are released in several ways mentioned in the previous section. Incineration and leaching of municipal waste is most pertinent to the NiCd lifecycle; and to a lesser degree, management of industrial waste streams. Both discharge pathways are difficult to control. Industrial waste streams employ pollution control technology to minimize discharge quantity, but this does not prevent inevitable releases due to inherent leaks of the manufacturing process. Discharge from municipal waste is even more difficult to control

because individual households contribute to the landfill. While regulations may ban disposal of NiCd batteries, they are essentially unenforceable.

The next step in a biological impact pathway is the transport of nickel and cadmium from the leaky system to populations. Incineration is a transport of metal from waste into airborne particles, carried by air movements in the atmosphere. The US EPA uses computer models and monitoring stations to estimate movements of air toxins. Even though the net output of airborne heavy metals may be understood, it should be noted that determining exactly how much is due to batteries is very difficult because of waste stream ambiguities.

Landfill leachate is difficult to understand from a transport perspective, since underground water behaves in unpredictable ways. However, hydrological engineers have developed methods of analyzing water movements, aided by sampling techniques. Once again, determining how much leachate contamination is due to batteries can be almost impossible to determine since municipal trash concentrations are unknown.

Environmental regulations have forced industry to carefully monitor emissions of cadmium and nickel to the environment, which makes metal transport much easier to track from industrial sources. Table 2.3.2(a) and (b) show that most of the metal released is due to metal acquisition, followed by battery manufacturing.

Table 2.3.2(a) Cadmium Emissions by Medium per kg of NiCd Batteries (Lankey 1998)

Medium	grams Cd per kg NiCd battery <u>manufactured</u>	grams Cd per kg NiCd battery <u>recycled</u>
Air	0.11	0.00095
Water	0.031	0.00038
Land	0.25	0.019
Total	0.39	0.02

Table 2.3.2(b) Cadmium and Nickel Emissions per kg of NiCd Batteries (Lankey 1998)

Life Cycle Stage	g Cd	g Ni
Raw materials acquisition	1.2	2.25
Battery manufacturing	0.39	0.5
Battery recycling	0.02	0.0125

Recycling batteries has a net positive effect on the environment if the recycled cadmium replaces virgin cadmium. For example, 0.25 kg Cd is recycled per kg NiCd battery. This saves $(1.2 \text{ g} * 0.25 \text{ kg Cd/g emission}) = .3 \text{ g Cd}$ from being released in raw material acquisition, while only producing 0.02 g Cd pollution from recycling operations – a net savings of 0.28 g Cd.

Exposure to these heavy metals is determined through behavior analysis; e.g., dermal, ingestion, etc. The greatest concerns for these metals are through inhalation of metallic dusts or vapors and ingestion through contaminated drinking water. Finally, the dose-response relationship tells us what the ultimate biological impact will be. As mentioned in the previous section, these heavy metals demonstrate several dose-response relationships: acute, chronic, carcinogenic, and teratogenic. In addition, cadmium is bioaccumulative, making it particularly dangerous in long-term exposure.

Practically, these metals are of great concern because municipal waste management is an area of great controversy and uncertainty for many countries. As landfills close, citizens wonder about leachate contamination. Alternatives to landfilling certain types of waste, such as incineration, make batteries of particular concern. Issues of environmental justice can exacerbate debates when incinerator facilities are located near poor or minority neighborhoods.

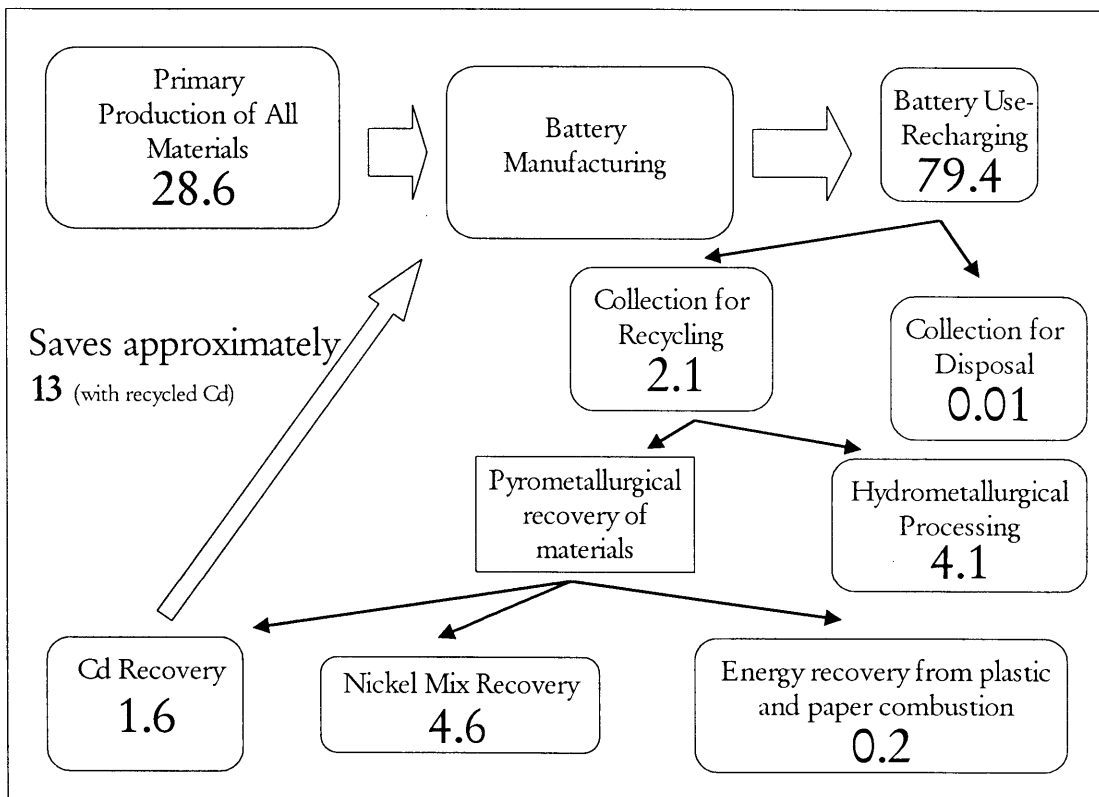
2.3.3. Energy Consumption

Experts agree that most industrial systems are best designed to be energy efficient. Energy production contributes to pollution of many forms. The traditional concern pollutants are sulfur dioxide and carbon dioxide from fossil fuel combustion, but even “clean” sources such as hydroelectric contribute to ecological disruption. Windmills can be very unsightly on a once-picturesque prairie. Thus, for the sake of this thesis, energy conservation is considered to be a positive characteristic.

The lifecycle of NiCd batteries is an industrial system. Lankey characterized the NiCd energy lifecycle in Figure 2.3.3., mapping resource extraction through manufacturing and

recycling. There are two important takeaways from Figure 2.3.3. First, more energy is tied up in the use of rechargeable batteries than all other sources combined. Second, recycling saves approximately 12.8 kilo-Watt-hours per kg NiCd batteries. These savings are significant considering the millions of pounds of NiCd batteries produced each year.¹ As a general issue, policy makers should acknowledge these features when considering alternatives. For example, mandating a switch to other (possibly less efficient) battery types may result in much higher energy demands during the use stage.

Figure 2.3.3. NiCd Energy Lifecycle (kWh per kg of NiCd battery) (Lankey 1998)



2.3.4. Resource conservation

Unlike environmental problems such as packaging waste and forest management, battery waste management has not placed an inherent emphasis on resource conservation. Nickel and cadmium are not analogous to trees and forest products. As an input to their product,

¹ One estimate states that 1.5 billion pounds of NiCd batteries were produced by the battery industry in 1997 worldwide. Energy savings from recycled cadmium could be quite significant when aggregated across industry.

the metals are not considered ecological entities. They are not the subject of preservation efforts. Resource conservation is usually the subject of concern because extraction is directly correlated to metal discharge to the environment.

Financially, there are good reasons to monitor resource stocks and flows of these metals. Nickel will most likely be a metal in high demand for quite some time because of its role in stainless steel and alloy production. Governments are wise to manage stocks of both metals to prevent price spikes experienced by the early 1990's cadmium market.

Cadmium presents a special form of resource conservation concern because it is a by-product of zinc production. Supposing all commercial cadmium applications stopped production, then zinc producers would find themselves in a peculiar position by having to manage large quantities of cadmium-containing solid waste. Under current regulations, such waste is considered hazardous, which in turn might drive up the price of zinc.

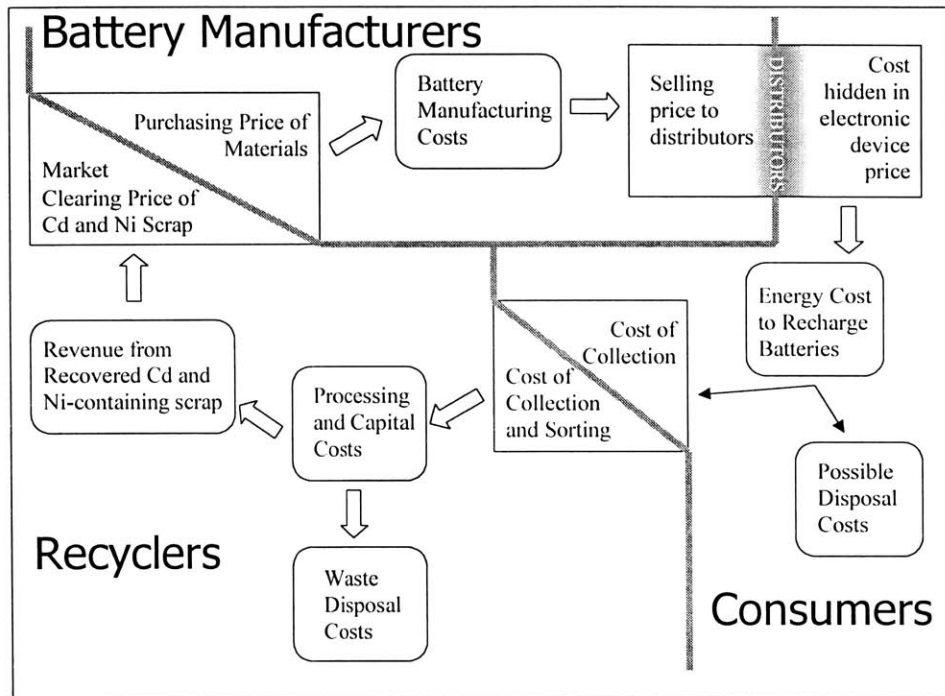
2.4. Industry Structure

2.4.1. Economic lifecycle of the nickel cadmium battery

The nickel cadmium battery has a closed loop lifecycle because cadmium recycled out of old batteries is used for new batteries. This creates much more interdependence between stages of the lifecycle. For example, dramatic increases in cadmium recycling can affect input costs for battery manufacturers. Figure 2.4.1. illustrates the lifecycle and corresponding actors, and will serve as the template for analyzing the nickel cadmium battery industry.

Nickel does not have a closed loop lifecycle because nickel from used batteries become feedstock to stainless steel production.

Figure 2.4.1. NiCd Industry Economic Lifecycle



2.4.2. Rechargeable battery manufacturing industry

The rechargeable battery industry is dominated by a small number of large producers, such as Rayo Vac, Gillette (Duracell), Sanyo, Matsushita (Panasonic), Sony, Ralston Purina (Energizer), and European manufacturers Saft and Varta. The industry structure went through dramatic change in the early 1990's, marked by mergers, acquisitions, and joint ventures. (O'Neil 1994) These companies produced the largest amount of nickel cadmium batteries, especially those for household use. There are a large number of smaller battery manufacturers that produce industrial and specialty nickel cadmium batteries. Larger companies are not structured to provide services for low volume orders.

Recent technological advances have allowed some companies to change strategic position in the rechargeable market. Duracell has made a corporate commitment to "Cadmium-Free Rechargeable Batteries," and now produces NiMH and Li-ion. (Duracell) OEM customers

of battery manufacturers are demanding more environmentally friendly alternatives. For example, Omnipoint Communication Services banned the use of NiCds in their personal communication devices. (Mooney 1998) While “you get an argument from the NiCad makers that almost everything in a NiCad battery is recycled,” one Ericsson Inc. manager retorted, “actual recycle rates are pretty low.” (Mooney 1998)

Energizer still makes nickel cadmium batteries as a low cost alternative to NiMH in all their application segments (cordless phones, camcorders, etc.). (Energizer) Energizer will not play as important of a role in the rechargeable market because they are focusing on primary (non-rechargeable) batteries and recently divested from their OEM (original equipment manufacturer) business. For example, they will not be providing batteries for mobile phone manufacturers such as Qualcomm. (Energizer 1999)

As the third largest battery manufacturer, Rayo Vac produces modest quantities of NiCd batteries and recently acquired Direct Power Plus (DPP), a rechargeable battery company with almost \$20 million in sales. This is part of an “aggressive” growth strategy in rechargeables, including nickel cadmium batteries. (PRNewswire 1998) Rayovac also saw the need to produce a low cost non-cadmium rechargeable, and has spent a sizable amount on developing a rechargeable alkaline battery called “Renewal.”

However, it is Japanese companies that have been in the forefront of rechargeable battery manufacturing. Sony, Sanyo, and Matsushita (Panasonic) have been the strategic leaders in this industry, dominating the \$5 billion market. (Financial Times Survey Edition 1999) Other major NiCd manufacturers are Saft and Varta.

2.4.3. Consumer use of nickel cadmium batteries

Household consumers tend to purchase nickel cadmium batteries through two avenues. First, they may buy batteries as single cells (AA, AAA, C, D, etc.) with some sort of cradle to recharge depleted batteries. These batteries are meant substitute the ubiquitous alkaline cell. Consumers gain by not having to purchase new batteries, but rather can just recharge their “old” ones. Rechargeable batteries suffer from higher initial costs, discouraging consumers with short financial time horizons. Another drawback is that some consumers perceive a

high information cost on learning how to use rechargeables. Common distribution routes for NiCd cell-type batteries would be in electronics and discount stores like Wal-Mart.

The other type of nickel cadmium battery is the “battery pack.” Packs are usually manufactured in more unique shapes for particular applications in specific brands or devices; e.g., the batteries in laptop computers and mobile phones. Their business strategy is much different than selling cell-types to household consumers since battery manufacturers are making the product for OEMs. The OEM may demand different characteristics or prices depending on whether the electrical device is price or performance-sensitive. Distribution routes would be similar to the distribution route of whatever electronic device is being purchased. Moreover, the battery price is often incorporated into the device price, making it difficult for consumers to exercise demand preferences across battery-sensitive characteristics. The Rechargeable Battery Recycling Corporation offers the following data on discards and recycling rates of non-industrial batteries in Table 2.4.3.

Table 2.4.3. U.S. and Canada Consumption and Recycling of NiCd (non-industrial) batteries (lb.)² (RBRC 1998)

Year	Total Recyclable Pounds Entering Waste Stream	RBRC Market Penetration	RBRC Batteries in Waste Stream	Pounds Batteries Recycled	Rate
1993	14,221,000	--	--	284,000	2%
1994	15,760,000	--	--	630,000	4%
1995	17,921,000	--	--	2,703,000	15%
1996	20,542,000	--	--	3,078,000	15%
1997	22,454,000	75%	16,840,500	3,782,000	22%
1998	23,231,000	80%	18,584,800	4,646,200	25%
1999	26,330,000	81%	21,327,300	6,398,190	30%
2000	27,917,000	82%	22,891,940	8,012,179	35%
2001	28,242,000	83%	23,440,860	9,376,344	40%
2002	28,199,000	84%	23,687,160	11,843,580	50%
2003	28,032,000	85%	23,827,200	14,296,320	60%
2004	28,035,000	86%	24,110,100	16,877,070	70%
2005	28,027,000	87%	24,383,290	19,506,792	80%

² Shaded areas represent estimates given in 1998.

Another type of consumer is the industrial purchaser, which may be through OEM or direct from the battery manufacturer. Large nickel cadmium batteries are common back-up supplies for trains. Their cost would most likely be incorporated into the train's overall price. On the other hand, hospital back-up power supplies are another common NiCd application. These might be sold as individual batteries to the hospital administration. Industrial applications are less performance sensitive because weight is not a dominant consumer preference.

2.4.4. Nickel Cadmium battery recycling technology

Recycling plays a large role in the industrial and regulatory analysis of nickel cadmium batteries since it fundamentally changes economic and environmental interactions. Its importance is well stated in a 1995 article on the rechargeable battery industry. (Margolin 1995)

“When it appeared that NiCd batteries might be withdrawn from the market because of landfill-contamination hazards they posed, the price premium for NiMH batteries was not an issue. But now that practical recycling programs have been implemented and government regulations appear to be easing, NiCd batteries are likely here to stay.”

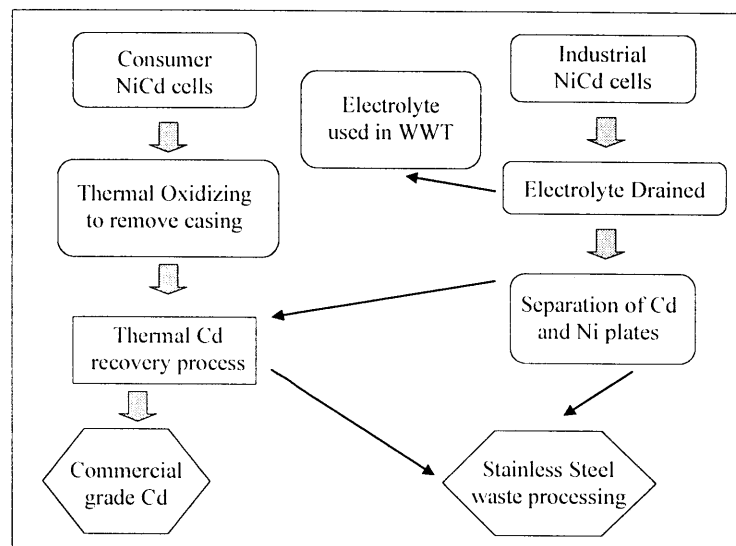
Nickel cadmium batteries are recycled in only a handful of locations around the world. Inco Ltd., a large nickel metal fabricator, owns a subsidiary company called the International Metals Reclamation Company (INMETCO). INMETCO is the only recycling facility in North America that can recover cadmium in a re-usable form. There are other facilities in Japan, Austria, Germany, Australia, and France. The French recycler, SNAM, has a capacity of 5,200 tons, and is very active in the European NiCd recycling market. (Haznews 1996)

INMETCO receives spent nickel cadmium batteries in 50-gallon drums and through the mail. The batteries must be separated by hand to ensure feedstock consistency. A major determining factor for the value of the recycled metal is final purity quality.

Cadmium from the recycling operation is used to make nickel cadmium batteries again making a closed loop with the cadmium material flow (see Figure 2.4.4.). Nickel and iron material in the battery is eventually mixed with other metal to make a stainless steel product.

The electrolyte is used in INMETCO's wastewater treatment facility to neutralize chemicals from other operations. A new \$5 million operation was installed in 1995, which made cadmium recovery feasible. The new thermal processing essentially vaporizes cadmium and recollects it in solid form, leaving a nickel-iron scrap behind. This is possible because the melting point of cadmium is lower than the nickel-iron metal. (INMETCO 2000) The following diagram illustrates the material flow in this battery processor. (Lankey 1998)

Figure 2.4.4. Battery Processing Flow (Lankey 1998)



2.4.5. Nickel Cadmium battery recycling economics

As the quote in Section 2.4.4. may suggest, survival of the nickel cadmium battery industry hinges on its ability to assuage regulators – notably, finding a politically viable solution to cadmium recycling. INMETCO received a \$100,000 grant from the Pennsylvania Solid Waste-Resource Act to develop a technology for recycling (adapted from the French recycler SNAM). The thermal processing technology was revolutionary in its ability to recover cadmium as a useful product. \$5,000,000 was invested in a 3,000-ton capacity cadmium recovery facility. (Goodwin 1995)

INMETCO already operates stainless steel waste processing, so they had existing nickel-iron recovery capabilities. Due to proprietary reasons, there are no publicly available cost data on INMETCO's operations. However, INMETCO was the subject of a dissertation done by Rebecca Lankey at Carnegie Mellon University in 1998. She developed cost and revenue estimates based on the best available information:

**Table 4.5. INMETCO Costs and Revenues (in \$)
per pound NiCd battery (Lankey 1998)**

	Cost	Revenue
Cd recovery facility operation and maintenance	-0.40	
Capital related	-0.17	
Stainless steel processing	-0.13	
Return on investment	-0.08	
Nickel-iron-chromium containing product		0.56
Cadmium product		0.19
Pre-paid mailer fees ³		0.10
Total	- 0.78	0.85

The price of nickel was assumed to be \$2.12 per pound and \$1 per pound for cadmium, which were current estimates at the time Lankey conducted her research. Since then, the price of cadmium has bottomed out at \$0.30 per pound, down from nearly \$9.00 per pound in 1988. The price change (from \$1.00 to \$0.30) in price would reduce cadmium metal revenue from \$0.19 to about \$0.06 per pound – or total revenue of \$0.72. This is below the cost of processing batteries, not a particularly advantageous business position.

On the other hand, nickel prices have not changed and contribute a much higher fraction of the total revenue. INMETCO must either demand more from per-paid mailers or stop recycling cadmium for the time being, and wait until cadmium prices are higher. Lankey suggests another option; INMETCO could try to develop technology that would extract trace amounts of cobalt from the batteries. Cobalt prices were about \$23 per pound in 1998

³ Pre-paid mailer fees include the revenue derived from other companies when they ship battery waste to INMETCO; i.e., INMETCO is paid to receive the waste.

and would net \$0.32 per pound battery. The U.S. needs cobalt for strategic reasons since they must import all cobalt from Africa.

2.4.6. PRBA and RBRC

Pre-paid mailers are a form of subsidy intervention into the economic lifecycle. INMETCO would almost certainly not be in the business of recycling NiCd batteries without subsidization. This subsidy does not necessarily come from battery manufacturers, but may come from Compaq, Radio Shack, or Black & Decker. These subsidies are the brainchild of the Portable Rechargeable Battery Association, formed in 1991 by five large battery manufacturers. Their mission is to “provide leadership in obtaining consistent domestic and international solutions to environmental and other selected issues affecting the use, recycling and disposal of small sealed rechargeable batteries.” (PRBA 2000)

Membership has increased and diversified quite a bit since 1991. There are over 80 companies representing all kinds of manufacturers and retailers in PRBA. PRBA is a trade association representing the regulatory interests of any company interfacing with nickel cadmium batteries. Its most important response to policy concerns was the creation of the Rechargeable Battery Recycling Corporation (RBRC), a nonprofit organization funded by many of the same companies in PRBA.

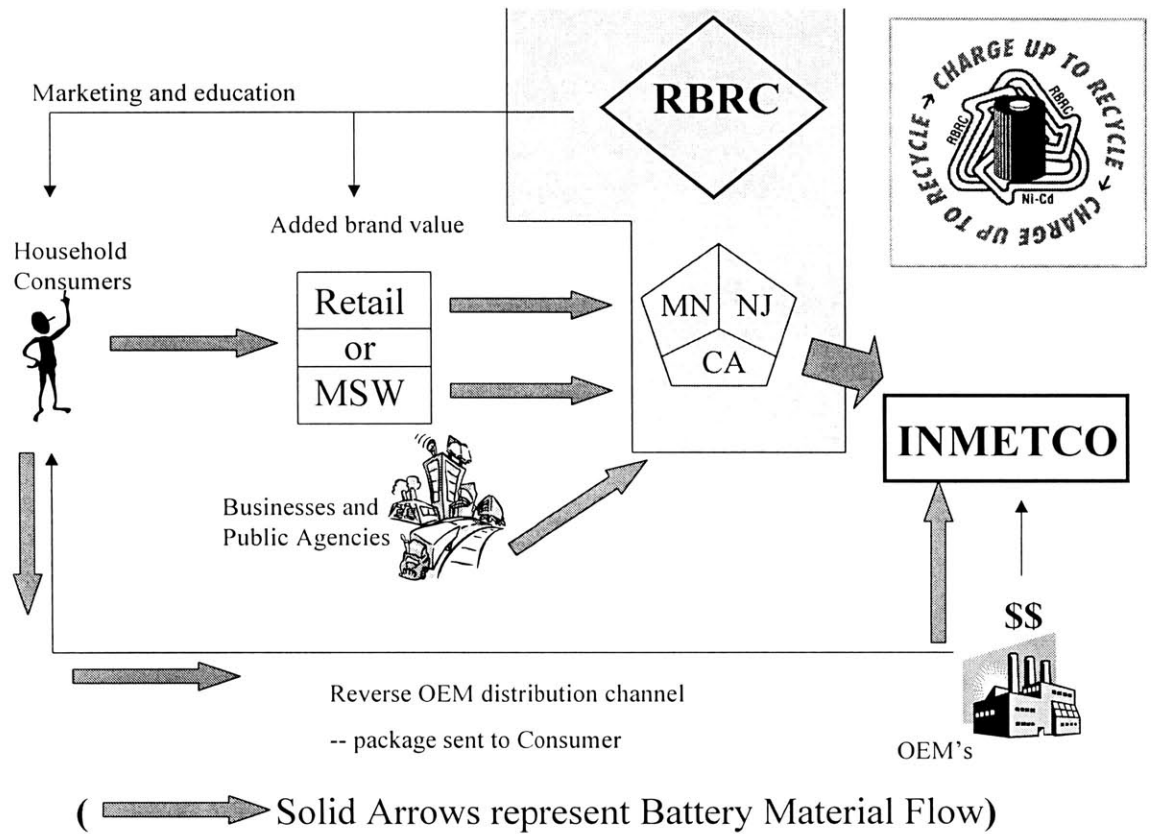
RBRC was formed as an organization for implementing collection, education, and transportation programs. The group of companies in RBRC decided that cooperation, rather than competition, was needed to successfully implement these operations. The goal in 1995 was to raise the recycle rate of small dry cell NiCd batteries from 15% to 70%. (Hachman 1995) Table 2.4.3. lists the accomplishments of RBRC and their projections for the next seven years.

2.5. Take Back System

The take back system for nickel cadmium batteries did not develop through traditional free market economic incentives. The system was a construct of centralized planning by the battery manufacturing and portable electronics industry. Although industry does not cite regulatory concern as the motivation for initiating this take back, most literature agrees that

it was created to preemptively establish an industry-led recycling effort before political pressures would result in limiting regulation. Figure 2.5. outlines basic transactions in this take back system, with the shaded area representing RBRC-subsidized activity through the “Charge Up To Recycle” campaign. The next seven sections describe the details in this system.

Figure 2.5. NiCd Take Back System



2.5.1. Overview of RBRC corporate activity

RBRC has two divisions, one that manages collection and education logistics through independent contractors, and another that administers the seal licenses and finances. In 1996, RBRC spent \$0.8 million on administration and \$4.7 million on logistics and education. Given 2,500 tons recycled, the average cost to recycle NiCd batteries is \$2200 per ton. This is approximately the same cost cited by municipal solid waste handlers to have

battery waste disposed of via private mechanisms. The program cost represents about 1% of the total NiCd battery sales. (Fishbein 1997)

RBRC signed a five-year contract with INMETCO making it the exclusive recycling vendor for RBRC's spent batteries. Three companies have been contracted to serve as collection locations: 1) Wade Environmental Industries – Atco, New Jersey; 2) US Filter Recovery Services, Inc. – Roseville, Minnesota; 3) Kinsbursky Brothers Supply, Inc. – Anaheim, California. (Fishbein 1997) A system of transportation companies have been contracted to ship batteries; e.g., UPS and commercial trucking services. RBRC-funded liability and contingent pollution insurance covers both transporters and collection service companies. (Fishbein 1997)

2.5.2. Funding and administration

RBRC's recycling system funding comes from license fees for an "eco-label." Fees are based on the weight (tonnage) produced in the previous calendar quarter and range from \$0.04 to \$0.12 per battery. (Fishbein 1997) Participating companies have input on RBRC's budget allocations and determine the precise fee levels. RBRC hired *Home Improvement* sitcom star, Richard Karn, to lead their \$1.6 million annual marketing campaign raising awareness. (Byrd 1996)

The label is licensed on a per-battery-unit basis and effectively acts as an additional cost to the consumer. Each individual battery has the RBRC logo (see Figure 2.5.2.). Charging license fees may be complicated when batteries are manufactured for OEMs. In that case, the brand name on the battery is a licensee and the brand name of the electronic device is a sub-licensee. (Fishbein 1997) RBRC logos are found on about 80% of all nickel cadmium batteries. (RBRC 2000)

RBRC highly encourages visible display of the seal, on both the battery and product. They recognize that public awareness and education is necessary to program success. In the absence of direct marketing (from *Home Improvement's* Richard Karn, for example), consumers have a narrow window of attention where they notice and internalize information portrayed on the seal.

Figure 2.5.2. RBRC Seal (RBRC 2000)



Not everybody is convinced of NiCd label effectiveness. In Germany (where there are similar recycling efforts), one environmental official noted that labels could confuse customer; moreover, consumers are not likely to recycle unless there is a financial incentive. (Haznews 1997) The label may just suggest that recycled materials are in the product (such as with paper products) or that it is recyclable – the label does not clearly address this difference. However, RBRC's seal must walk a fine line between too much information and too little information. The seal must also convey the need to recycle toxic metals without making the product look toxic itself.

2.5.3. Retail collection system

Charge Up to Recycle! is RBRC's national program to collect spent nickel cadmium batteries. In 1997, RBRC was networked to 15,000 retail collection sites. (Mooney 1997) By 1998 this number was up to 20,000 sites, and is now at 25,000. Little information is known about the distribution of collection volume across these sites. (Greczyn 1998) This program operates across borders with Canadian retailers, and now has 26 participating major retail chains. Local stores of these retail chains are incorporated in a database accessible by anyone via a 1-800 number.

These retail sites, such as Radio Shack, Batteries Plus, and Ace Hardware, sell NiCd batteries or products containing NiCd batteries. Each retail location saves spent batteries in 18-pound capacity buckets. Battery buckets have prepaid labels and are picked up by UPS for delivery. Therefore, retailers incur no direct financial cost aside from the time needed to administer collection. RBRC has made a conscientious effort to minimize the effort expended by retailers to participate in *Charge Up to Recycle!* UPS sends the buckets to the nearest of the three consolidation points. They hold onto the batteries until 10,000 to 40,000 pounds are accumulated. The collection point operator calls a trucking service after collecting over 10,000 pounds, and the batteries are shipped off to INMETCO with RBRC insurance covering possible accidental spills.

2.5.4. Community collection system

Community collection sites are another part of RBRC's *Charge up to Recycle!* program. RBRC hopes to take advantage of pre-existing municipal recyclable waste collection systems, such as common curbside collection. RBRC will pay for pick-ups from one common location in each county, provided they are at least 1,000 pounds and once per month at most. Many municipal waste collectors use 55-gallon drums to collect batteries. (Fishbein 1997)

Municipalities incur costs from sending batteries to a single collection point in the county and time spent on adding additional tasks to collection procedures. However, they may also reap significant benefits. *Charge Up to Recycle!* allows municipal waste collectors already collecting NiCd batteries to avoid costly disposal and treatment fees.⁴ For municipalities not collecting batteries, the program saves landfills from future water pollution contingencies. Incinerators also benefit from the need for less expensive pollution control devices to filter out heavy metals.

⁴ Fishbein estimates that NiCd disposal fees could cost up to \$1600 per ton. New Jersey DEP estimates that it costs \$17 million to control heavy metals from incineration emissions, and \$30 to \$45 million to control ash disposal. (Fishbein 1997) Nationwide, such costs far exceed the \$5.5 million RBRC price tag.

2.5.4. Business and public agency (BPA) collection system

Businesses, government agencies, and other institutions are prohibited from disposing NiCd batteries in their municipal waste stream because BPA's do not qualify for RCRA household waste exemptions. While enforcing this ban is difficult, RBRC hopes to reduce the incentive for illegal disposal. Businesses and agencies pay for shipping costs to one of the three collection locations and RBRC covers all other costs.

Without *Charge Up to Recycle!*, businesses and agencies pay for disposal and treatment costs. Battery Solutions, Inc. priced collection, sorting, and transportation of small cells at \$0.85 per pound and large industrial size at \$1.10. (Battery Solutions Inc. 2000) Presumably, BPA's are going to participate in *Charge Up to Recycle!* if the program is cheaper to use than traditional networks of private waste handlers.

2.5.6. Licensee collection system

The licensee fee system is meant to provide an incentive for companies to develop their own take back channels through reverse distribution programs. Companies collect batteries and ship them to INMETCO, whereby RBRC pays all other drum disposal and recycling fees. The benefit to a licensee is that they get a 75% rebate on their license fee, or somewhere around \$0.1746. (Fishbein 1997) In other words, the more a company can solve the problem by itself, the less it pays into this industry-wide take back effort.

2.5.7. Other Take Back Mechanisms

Two variations from RBRC's plan contribute to total NiCd recycling. Some electronics manufacturers, such as Compaq, offer to send their customers packages that transport a battery to INMETCO. Compaq then pays a fee of \$0.40 per pound directly to INMETCO for each battery recycled. Compaq will send packages to ship all battery types because they feel that recycling only NiCd batteries neglects legitimate environmental concerns about other battery types. (Fishbein 1997) For example, NiMH batteries contain a significant amount of nickel, which has very serious carcinogenic properties in its airborne form. INMETCO also sends out mailers to large industrial battery users and collects them for \$19.95 per container. A special bulk rate is available for \$17.95. (Simon 1996)

2.6. Government Policy

Fifteen countries across the world and nine U.S. states have landfill bans on nickel cadmium battery disposal. In 1994, the U.S. Supreme Court (*City of Chicago v. Environmental Defense Fund*) ruled that incinerated municipal waste ash containing high heavy metal concentrations is hazardous waste. Household battery discards, once exempt from regulation, now opened up the liability floodgates since batteries are considered the major source of landfill heavy metals. PRBA formed RBRC later that year.

Most major U.S. laws have some influence on nickel cadmium battery regulation, such as the Clean Water Act overseeing leachate from landfills. CERCLA (Superfund) contains provisions for both cadmium and nickel contamination, and the Clean Air Act Title III lists cadmium emissions as a hazardous air pollutant subject to very strict MACT standards. The most important legal mechanisms for the purpose of this thesis are the Universal Waste Rule (part of RCRA) and the Rechargeable Battery Management Act, although both were motivated by a plethora of state regulations on battery disposal.

2.6.1. Universal Waste Rule – A modification of RCRA

The Resource Conservation and Recovery Act is one of the most important regulatory tools for tracking and controlling the fate of hazardous materials. A key concept in RCRA is the Manifest System of tracking hazardous waste from generator to storage to transporter to final treatment and disposal. This comprehensive tracking is often called the “cradle to grave” system because someone is always responsible for the material and there is paperwork to trace any missing links back to responsible parties.

One important exemption to many RCRA rules, for very practical reasons, was household generated waste. Government policy makers realized that enforcement and monitoring of individual household waste would be impossible without an intrusion of privacy. Even so, some states imposed landfill bans on nickel cadmium batteries. These bans were political statements that states were serious about getting nickel and cadmium out of the waste stream.

BPA's are subject to RCRA regulation depending on how much waste they generate. RCRA classifies generators into three categories: very small, small, and large; each with more stringent requirements. One of the problems with respect to battery recycling is that transportation is only feasible when a large quantity has been accumulated. This would make any retailer or collection storage facility subject to more stringent regulation.

The 1995 Universal Waste Rule gave an exemption to collectors of battery waste provided that collection was intended for transportation and ultimate recycling purposes. (United States Environmental Protection Agency 1997) This gave much more flexibility to RBRC in setting up and operating the extensive network of collection points necessary for economical battery transportation to INMETCO. For example, RBRC pointed out that shipping one pound of batteries from Iowa to Pennsylvania cost \$1.00 before the Universal Waste Rule, but only cost \$0.17 after its implementation. (Fishbein 1997) Savings came from reduced manifest document generation, less liability, ability to use non-hazardous waste transporters, and saved time. As the PRBA president explained, "We have been handcuffed and shackled by certain federal and state regulations. If we go through the regulatory route, it will take several years [to approve recycling]." (Lee 1996)

2.6.2. The Rechargeable Battery Management Act of 1996

While the Universal Waste Rule modified RCRA requirements, it could not preempt state sovereignty. Therefore, states were not forced to revise their regulations or implement a system for enforcing new federal rules. While the federal government always has the ability to withhold highway funds for non-implementation, such practices add to an already strained state-federal relationship. States often don't have the resources to quickly implement federal rules. By 1996, only 36 states had updated their own policies to incorporate the Universal Waste Rule.

Later in 1996, Congress passed the Rechargeable Battery Management Act to make the Universal Waste Rule applicable to all fifty states (§ 104). The Act's general tone was focused heavily on assisting industry efforts to self-organize a recycling program. Public education and participation were cited as "key" to program success. (United States Environmental Protection Agency 1997) EPA was required to consult battery

manufacturers and ensure general implementation of recycling efforts. The Battery Management Act was clearly written with PRBA and RBRC in mind.

Title I §103 of the Battery Management Act required that manufacturers put labels on the outside of NiCd batteries, instructing consumers on proper disposal. The mandated uniform labeling scheme was supposed to homogenize diverse state requirements and raise consumer awareness. The US EPA approved RBRC's label in 1998. In addition, the Act set product specifications that ensured easy removal of batteries from electronic devices. Violation of either labeling or making batteries easily removable resulted in penalties and enforcement actions by the US EPA. (United States Environmental Protection Agency 1997)

Republicans gained landslide victories in the 1994 election, creating a majority over Democrats in both the House and Senate. It was clear that the political agenda had made a decisive shift. Republicans favored a more *laissez faire* approach to environmental protection, giving companies the freedom to implement industry environmental initiatives. Rep. Scott Klug (R-Wisconsin) and Rep. Frank Pallone (D-New Jersey) co-sponsored the Rechargeable Battery Management Act, but most support came from Republican House members. Many Democrats in Congress were not enthusiastic supporters of the Battery Management Act. In addition, the US EPA was cautious in its support for the Act because it feared that the new law would reduce care by which batteries are handled.

Response by other constituencies was not very supportive. George Dreckmann, recycling coordinator for Madison, Wisconsin, thought that "if we were to list environmental priorities, this wouldn't even be in the top 20," he said. "This isn't a tough bill, it's a no-brainer, and I don't think it accomplishes anything as far as where the industry is headed." He voiced skepticism about logistical implementation of RBRC's plan. "Studies show that consumers will participate (in recycling programs) only if it's convenient," Dreckmann said. "They will only go to a place [RBRC participating retailer] if they already had another reason to go there in the first place." (Falsani 1996)

2.6.3. European regulation

Europe, in general, has been much less open to the idea of long-term cadmium use. Sweden banned the use of cadmium in some products in 1980's. The EU also drafted proposals to ban cadmium batteries by 2008, with the strongest support from Germany. The Netherlands has also been a strong advocate of recycling batteries. They mandated a law that requires a 90% recycle rate, but to date they have only achieved a 60% rate. France recently enacted legislation requiring that all battery manufacturers have a plan for recycling their batteries by 2001, with a recycling rate of 65% by 2003. The distribution system being developed there is similar to RBRC's plan. (Haznews 1999) Belgium has one of the most stringent battery management plans, imposing a \$0.33 tax on batteries that are not being recycled at 75% by 2000. (Fishbein 1997) It seems that Belgium is the only country with a clear sanctioning system for failure to reach desired recycling rates.

Germany recently incorporated nickel cadmium batteries into the DSD (Duales System Deutschland). Starting October 1998, DSD would coordinate take back through its "green dot" logo license system, which operates similar to RBRC on a large scale (incorporating many household consumer products and packaging).

2.7. Policy Conclusions for Nickel Cadmium Recycling

The quote from Rep. Scott Klug suggests that the political climate supported less direct government intervention to handle the nickel cadmium battery problem. However, the facts of this case do not imply that an industry-led initiative is fulfilling the public need for less NiCd discards. This is not to imply that modifying RCRA was imprudent.⁵ Rather, the Universal Waste Rule redraft was a tacit commitment by the battery industry that less regulatory oversight would be rewarded with higher recycling. Keeping the context in mind, we may comment briefly on several aspects of the public policy behind this case.

First, government enacted the Battery Management Act without assuring sufficient observability and enforcement. The Act was lauded as a win-win scenario, where

⁵ Most people involved with environmental management note the recycling disincentives written into RCRA.

government got a recycling system implemented and industry was assured that nickel cadmium batteries would not be banned. Basic contract law suggests three conditions must exist for a stable agreement: (1) specificity, (2) observability, and (3) enforceability. The Battery Management Act was fairly specific in mandating that RCRA exemptions were granted only under condition of recycling system implementation. It was even more specific about requirements for the label to be placed on batteries. However, there were no conditions put on either EPA to actively observe or monitor recycling rates. Most importantly, the Battery Management Act provided few enforcement options for the government. Battery manufacturers were subject to some legal requirements regarding the label, but absolutely none regarding recycle rates.

Other countries have added accountability measures to take back legislation, as mentioned in section 2.6.3. Unfortunately, there are no readily available data on recycling rates over the last five to ten years in these countries, making policy evaluation very difficult. Thus, it is hard to definitively state that more enforcement would solve the recycling system's low recycling rates. Policy options to increase recycle rates are explored further at the end of this thesis. However, the lack of visible recycling success under enforceable conditions suggests that more ingrained problems exist. Analysis of the nickel cadmium recycling system and potential ingrained problems is presented in Chapter 4.

CHAPTER 3 – ALUMINUM INTENSIVE VEHICLE

The automobile is often lauded as the world's most recycled consumer product. However, , automobile manufacturers, metal producers, and recyclers have become concerned about the ability of current end-of-life markets to handle increased aluminum and non-metallic (plastic) content.

The automobile industry consumes almost 20% of the total aluminum market, making it an important customer. Since automobiles are heavily recycled, they constitute an even more important fraction of the secondary recycled aluminum market. Therefore, changes in the automobile industry have the potential to strongly affect secondary aluminum markets as a whole.

The case will look at the end-of-life market for automobiles and aluminum in particular.

The move to an aluminum intensive vehicle is essentially a perturbation of this complicated, interdependent system. Drawing on several analytical studies, the case will discuss how this system might respond to future aluminum material substitution. This research is the basis for examining the implications for industrial ecology of metals in terms of recycling choice – open loop or closed loop – and maximizing material value from system behavior.

3.1. The Aluminum Intensive Vehicle Basics

3.1.1. Characteristics of the AIV

While there is no scientific definition, an automobile is considered “aluminum intensive” if it contains roughly more than 700 pounds of aluminum. Several AIV's are already in production: Audi A8, Honda Acura NSX, and the Plymouth Prowler. (Ng, Miller and Tessieri 1999) The choice to use 700 pounds as a defining characteristic of AIV's is somewhat arbitrary because the aluminum content has been steadily increasing in automobile material choice. Pressures from environmental regulation of pollution and emissions, as well

as petroleum use conservation in general, is driving this material choice. Table 3.1.1a. lists the material breakdown for a standard (non-AIV) automobile.

**Table 3.1.1a. – A Typical Composition of a
2000 U.S. Automobile (non-AIV) [Ward's, 1999 #80]**

Material	Weight (lb)	Weight (%)	% Change from 1988
Plastics	412	13.5	42.7
Aluminum	340	11.1	56.2
Copper	45	1.5	-8.9
Zinc	16	0.5	-21.9
Other Ferrous	67	2.2	32.8
Iron	430	14.1	-6.3
Carbon Steel	965	31.6	-49.2
HS Steel	247	8.1	6.1
Stainless Steel	42	1.4	26.2
Glass	86	2.8	1.2
Rubber	133	4.4	-0.8
Fluid	177	5.8	-0.6
Other	96	3.1	-29.7
Total	3050	100 (rounded)	-3.8

Figure 3.1.1., from Ducker Research Company, shows how aluminum content has been steadily increasing. Even though aluminum accounts for only 11% of current automobile mass, this percentage has increased an average 4.2% per year from 1977 until 1999. (Aluminum Association 2000)

Figure 3.1.1a. Average Al Content per U.S. Vehicle (Aluminum Association 2000)

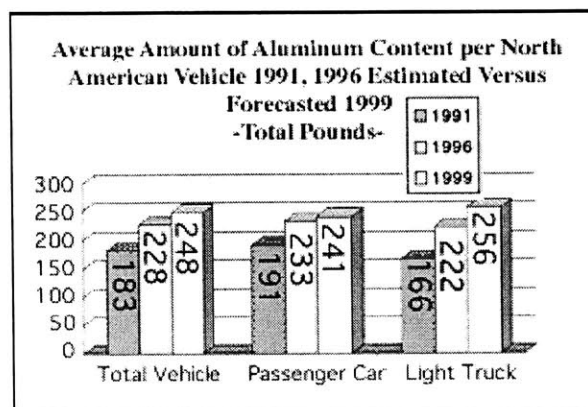


Table 3.1.1b. should give the reader a feel for where growth areas exist in specific automotive aluminum applications. The body sheet is obviously a major change for automobiles (increasing from essentially zero lb./vehicle to 500 lb./vehicle). This is one reason that wrought automotive aluminum parts will be in higher demand, increasing significantly more than cast parts.

Table 3.1.1b. Aluminum Usage in AIV's (Ng, Miller and Tessieri 1999)

Component Group	Pounds per Vehicle in 1996	Pounds per AIV in 2001 (projected)	Change (%)
Powertrain	138	241.3	75
Body sheet, hang-ons, and bumpers	4.5	492.4	10842
Structural groups, brakes, wheels, and electrical group	49.6	192.1	287
Heat exchangers, climate control units	49.3	41	-17
Interior, safety components and miscellaneous	7.1	22.5	217
Subtotal of all cast parts	189	347.3	84
Subtotal of all wrought parts	59.5	642.0	979
Subtotals classified by:			
Cast parts	189	347.3	84
Rolled parts	30.6	478.0	1462
Extruded parts	25.5	97.5	282
Forged parts	3.4	66.5	19
Total	248.5	989.3	298

Moving to AIV production will require many changes in current automobile manufacturing. For the last century, automakers have been trained to work with steel, which has different metalworking properties from aluminum. Everything from stamping to welding will have to change. While aluminum metalworking technology is well established, it will require capital investments beyond those normally involved in launching a new car line. The inherently higher value of aluminum might lead to more specialized auto parts pre-fabrication and may require less assembly costs (possibly offsetting increased capital costs). Increased part value has spin-off effects on consumers as well. Car collisions will be more expensive to repair, and insurance costs may increase.

3.1.2. Market Position

Aluminum intensive vehicles are mostly experimental at this point with only a handful of models made worldwide (in relatively small sales). However, many industry experts anticipate dramatic changes in aluminum automobile content over the next thirty years. The Partnership for New Generation Vehicles (PNGV) is a consortium working on introducing a high volume AIV-type sedan into the US market. PNGV might catalyze material shifts in other vehicle types (compact size, light trucks, etc.). Researchers at Oak Ridge Laboratory propose the following market penetration schedule. (Das, Curlee and Schexnayder 1997)

Table 3.1.2. Projected U.S. PNGV Sales and Market Share
(Das, Curlee and Schexnayder 1997)

Year	High Case			Low Case		
	Vehicle Sales (thousands)		Market Share (%)	Vehicle Sales (thousands)		Market Share (%)
	Autos	Light Trucks		Autos	Light Trucks	
2006	0	0	0	0	0	0
2010	97	75	1.0	0	0	0
2015	904	709	9.0	169	133	1.7
2020	3144	2275	29.0	517	374	4.8
2025	6146	4087	52.5	1496	995	12.8
2030	7880	4318	60.0	3939	2159	30.0

The different market demand cases are a function of two main variables, government regulation and customer demand. Government standards could be increased and necessitate material substitution. This assumption must be tempered by considering possible technology advances in engine efficiency.

The other market driver could be customer demand from fuel economy and general environmental concerns. The University of Michigan ranked these preferences in their Delphi report series, with environmental considerations and fuel economy coming in 10th and 11th place respectively out of 12 categories. (Chen 1994) Clearly, consumer demand will not be the major driver in materials substitution (unless gas prices increase significantly or pollution magnifies). The willingness to pay is just not high enough.

3.2. Material Flows of Aluminum

3.2.1. Aluminum Production

Primary aluminum is made from an energy intensive “Hall Heroult” process, whereby alumina is electrolyzed by carbon anodes. The Hall Heroult process consumes well over 13 kWh per kilo aluminum. Technological progress has significantly improved this energy efficiency over the last few decades. Anodes are consumed by reacting with oxygen atoms in alumina (Al_2O_3), giving off CO_2 among other gases. Molten aluminum is then ready for fabrication into either extruded, rolled, or cast forms.

Large countries dominate world production of aluminum (see Table 3.2.1a.), with disproportionately large production from countries with access to cheap power (such as Norway’s vast hydroelectric network). Production facilities tend to be privately owned in the developed nations. However, either state owned entities or multinational corporations constitute large producers in developing countries. The United States is similar to other countries in that a few large companies dominate production (see Table 3.2.1b.). Pending anti-trust investigation, Alcoa will control well over half of the primary aluminum production with the Alumax and Reynolds acquisitions.

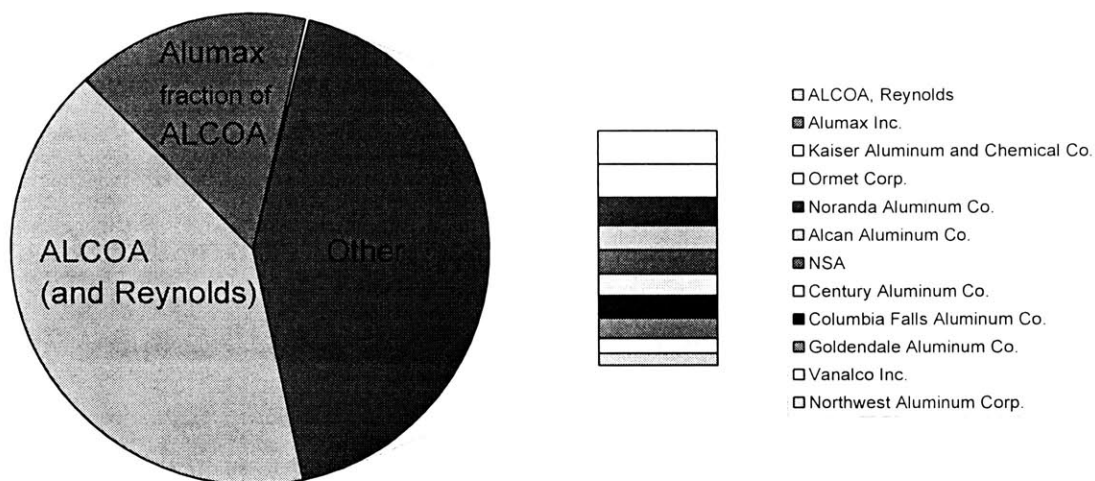
Table 3.2.1a. – 1998 World Smelter Production (United States Geological Survey 1999)

	1998 Production (thousand metric tons)	Percent of Total	Percent Change from 1997	Production per GDP (tons/million \$)
Australia	1,580	7.12	5.06	4.338
Brazil	1,200	5.41	0.00	1.598
Canada	2,340	10.54	0.43	3.908
China	2,200	9.91	9.09	2.290
France	0,420	1.89	7.14	0.293
Norway	0,950	4.28	3.26	6.511
Russia	2,960	13.33	1.69	10.701
South Africa	0,660	2.97	0.00	4.948
Venezuela	0,600	2.67	-6.67	6.316
United States	3,700	16.67	2.70	0.451
Other countries	5,550	25.00	4.68	N/A
World Total	22,200	100.00	3.60	0.7725

Table 3.2.1b – Market Concentration of U.S. Aluminum Producers (Plunkert 1998)

Company	1998 Yearend Capacity ⁶ (thousand metric tons)	Percent of Total
Alcan Aluminum Co.	186	4.42
ALCOA (pre-1998)	1,290	30.64
Alumax Inc. ⁷	651	15.55
Reynolds Metals Inc. ⁸	448	10.64
Century Aluminum Co.	168	3.39
Columbia Falls Aluminum Co.	168	3.39
Goldendale Aluminum Co.	168	3.39
Kaiser Aluminum and Chemical Co.	273	6.48
NSA	186	4.42
Noranda Aluminum Co.	215	5.11
Northwest Aluminum Corp.	82	1.95
Ormet Corp.	256	6.08
Vanalco Inc.	116	2.76
Total	4,210	100.00

Figure 3.2.1. Aluminum Market Concentration



⁶ Yearend capacity had not changed from 1996.

⁷ Alumax Inc. merged with Alcoa in 1998.

⁸ ALCOA and Reynolds have both agreed to a merger. ALCOA will acquire Reynolds stock, but retain consumer brand products under the Reynolds name. The merger is pending government anti-trust approval.

Aluminum recycling is an important part of the total flow of aluminum through economies around the world. For example, the United States depends on secondary production for approximately one third of its total supply (with the other thirds coming from domestic production and imports). The importance of recycling is underscored by the fact that scrap can be recovered into useful form for about 5-10% (about 0.65 kWh) of the energy required for primary production.

3.2.2. Aluminum Use

Aluminum has several characteristics that make it a very useful material. Most importantly, it is one third less dense than steel with a specific weight of 2.7 g/cm^3 . It tends to be less susceptible to corrosion than iron or some forms of steel because aluminum forms an oxide on its surface. Aluminum oxides do not flake or separate from the metal in the same way iron rust may. Aluminum is also a good conductor of electricity, reflects both heat and light, is nonflammable, and has desirable ductility. Sheets thin as 0.007 mm are impermeable and opaque to light. (Hydro Aluminum 1992) As with many metals, alloys can change important characteristics.

One of the most visible applications to consumers is the aluminum beverage can. The Universal Beverage Can has captured essentially the entire beverage can market. Plastic bottles compete with beverage cans, but each has comparative advantages; e.g., the can is easier to chill, while the plastic bottle can be resealed. The aluminum can contains over half recycled material and was specially designed to be closed loop recyclable; i.e., the material can be directly melted back into usable can alloys.

Aluminum has many substitutes because of its wide range of applications. In fact, its growth has occurred through replacement of other materials instead of applications to new products. Its very usefulness and broad applicability makes it susceptible to substitution unless pricing remains competitive. Copper can easily substitute aluminum in transmission wires, although it is much more expensive under current conditions. Steel and titanium can technically replace aluminum in transportation applications. High performance military aircraft use titanium because it blends aluminum's lightness with steel's strength. Aluminum

has replaced wood in a few construction applications, and competes closely in some products (such as stud materials or residential house siding).

Table 3.2.2. U.S. Aluminum Shipments by Industry (thousand tons) (Plunkert 1998)

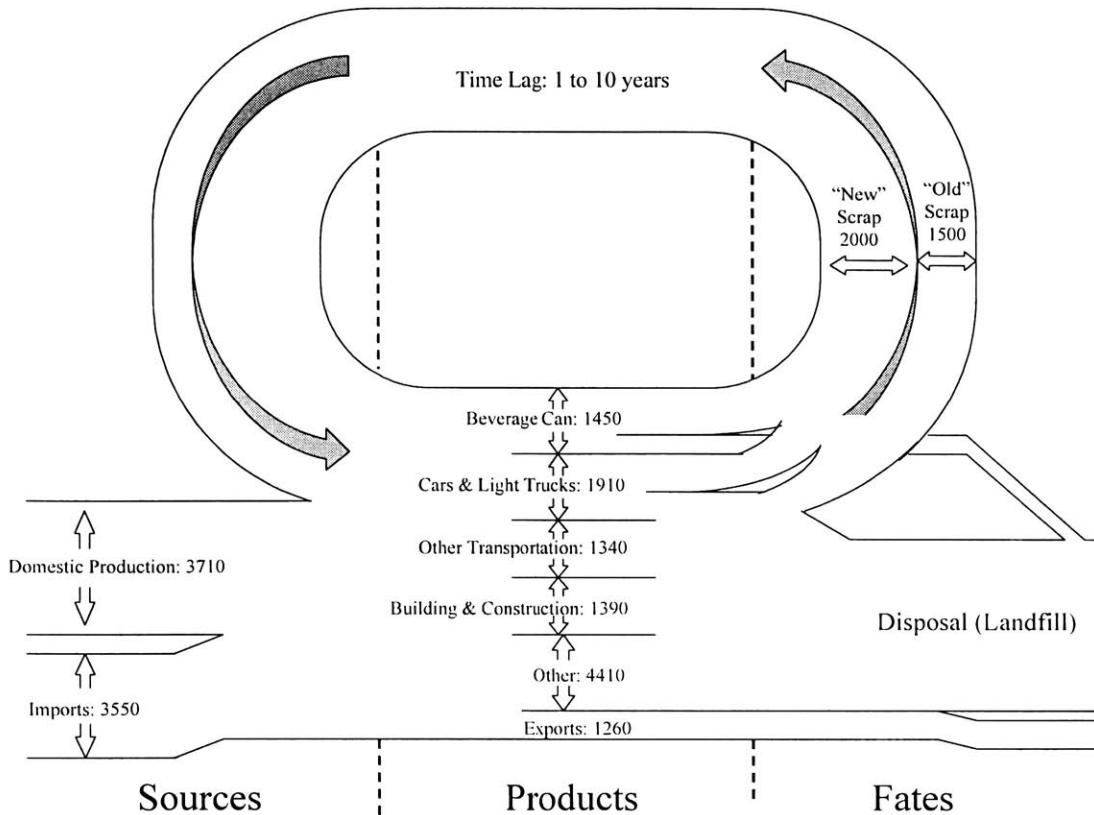
Industry	1996		1997		1998		
	Quantity	%	Quantity	%	Quantity	%	% change from 1996
Containers and Packaging	2,180	22.6	2,220	21.7	2,270	21.6	4.13
Building and Construction	1,330	13.8	1,320	12.9	1,390	13.2	4.32
Transportation ⁹ (Cars & Light Trucks)	2,640	27.5	2,990	29.2	3,250 (1,908)	30.8 (18.2)	18.77
Electrical	671	7.0	708	6.9	714	6.8	6.02
Consumer Durables	655	6.8	694	6.8	725	6.9	9.66
Machinery	596	5.9	626	6.1	629	6.0	5.25
Other	291	3.0	318	3.1	286	2.7	-1.75
Total Domestic	8,330	86.6	8,880	86.8	9,270	88.0	10.14
Exports	1,290	13.4	1,360	13.2	1,260	12.0	-2.38
Grand Total	9,610	100	10,200	100	10,500	100	8.48

The applications listed in Table 3.2.2. and other data from the USGS are used to construct a material flow Sankey diagram (see Figure 3.2.2.). (United States Geological Survey 1999)

The numbers are approximated to accommodate data discrepancies because much of this data is difficult to measure. Two important aspects must be emphasized. First, most aluminum recycling happens within industrial facilities during the manufacturing of products, accounting for the “new scrap.” Second, “old scrap” (including returned discarded products) is made up of primarily recycled beverage can aluminum and automotive aluminum. In general, aluminum recycling accounts for a significant portion of the total material flow, making it an essential facet to the overall economic landscape of aluminum supply and demand issues.

⁹ Adjustments based on the Ducker report, that 1999 passenger and light truck markets will consumer 3.815 billion pounds of aluminum.

Figure 3.2.2. Aluminum Sankey Diagram (metric tons)



Growth potential for automotive aluminum is of major interest to the aluminum industry. Given market share projections in Section 3.1.2., Oak Ridge researchers calculated expected supply and demand deviations from the base case where automobile companies use material composition close to current day specifications. The base case is also weighted for a 0.6% annual fuel economy (CAFE) improvement, which translates into a 0.2% weight reduction. The high numbers correspond to high projected growth and likewise for the low projected market share. (Das, Curlee and Schexnayder 1997)

**Table 3.2.2. Material Requirements for Aluminum-based PNGV (thousand tons)
(Das, Curlee and Schexnayder 1997)**

Material	2007	2010	2015	2020	2025	2030
Demand Increase						
Cast Aluminum	0 to 3	0 to 34	57 to 303	162 to 981	434 to 1784	1021 to 2043
Wrought Aluminum	0 to 3	0 to 34	59 to 317	479 to 1967	1160 to 2321	
Demand Reduction						
Carbon Steel	0 to 8	0 to 75	122 to 655	338 to 2052	875 to 3596	1977 to 3955
High Strength Steel	0 to 2	0 to 18	30 to 159	82 to 497	212 to 871	479 to 958
Cast Iron	0 to 2	0 to 17	28 to 150	77 to 470	200 to 823	452 to 905

Data in 3.2.1. show approximate aluminum production at about 4,000 thousand metric tons. By 2030, AIV manufacturing will require 50 to 100% more aluminum production capacity than is currently available from domestic sources. While U.S. aluminum fabricators may expand to accommodate some of this demand increase, it is highly unlikely that the industry will be able to expand and meet all AIV production needs. The ability to meet projected wrought demand increase, in particular, will be difficult to meet from domestic producers.

3.2.3. Aluminum Recycling

Secondary aluminum is often broken down into two different types: old and new scrap (see Figure 3.2.2.). New scrap is pieces of aluminum left over from various stages of aluminum production (casting, extrusion, or rolling) and product manufacturing. New scrap accounts for almost 4 billion of the 7 billion pounds of recovered aluminum. Old scrap (post-consumer materials) like the beverage can accounts for the other 3 billion pounds. (Plunkert 1998) However, old scrap has represented the largest growth area in aluminum recycling, aided by curbside pickup and other consumer take back programs.

Generally speaking, the aluminum recycling market can be split into three different segments: (Aluminum Association 1998)

- Large aluminum producers and manufacturers of wrought products, such as aluminum siding.
- Producers of secondary-specification alloy ingot.
- Toll processors, who recycle secondary metal for specific producers under contract; i.e., their product does not enter the market.

Recyclers vary greatly in size from 5,000 to 1 million tons capacity. These three types of processors perform some of five basic functions: (Aluminum Association 1998)

- Used Beverage Container (UBC) Processing – cans are recycled back into can sheet. This is a closed loop process. The beverage can is the most ubiquitous form of recycled consumer aluminum, with over 66 billion cans recycled each year – a \$990 million market in total. This market alone constitutes 1,938 million pounds of the United States' secondary aluminum, which gives the can a recycling rate of 60%. (Aluminum Association 2000)
- Specific Alloy Production – scrap from various sources are combined to make a specific alloy, usually demanded by a particular customer or product line. For example, many casting products demand very specific alloys to fulfill their intended function. The automotive industry consumes between 65 and 70% of specific alloy production.
- Remelt Secondary Ingot – a mixture of scrap made without specific attention to chemical composition. Large aluminum producers commonly use RSI.
- Deoxidation Ingot Production – aluminum recovered to create a feedstock for steel making processes.
- Dross Processing – aluminum with a high level of impurities that is treated to recover a more pure form.

Automotive aluminum recycling is considered to be an important growth area. Between 80 to 90% of the aluminum currently in cars is recycled. 60 to 70% of the aluminum in cars is from secondary material. While aluminum is only 5 to 10% of the average automobile (by weight), it accounts for 35 to 50% of the hulk body's value. (Aluminum Association 2000)

One of the persistent problems facing automobile recycling alloys incompatibility. Wrought aluminum alloys contain 0.15 to 0.40 wt-% Fe and 0.10 to 1.2 wt-% Si; whereas the cast aluminum coming from shredders contain Fe > 0.6% and Si > 7.0%. (Ng, Miller and

Tessieri 1999) The difference in composition is too great for shredder aluminum output to be “closed loop” recycled back into automobile applications. As aluminum moves into specialty markets, recycling will become more complex, and demand the evolution of niche recyclers to satisfy customer needs.

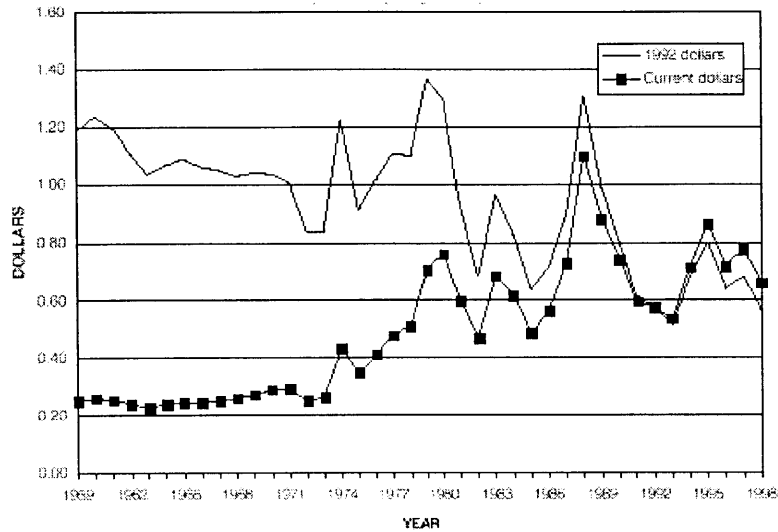
Processing specific alloys requires capital investment in function-specific technology, making this industry more risky. If customer product make-up changes, then recyclers may find it difficult to recover capital costs. As a result, aluminum processors are going through a period of consolidation because diversified processors may change operations and minimize risk.

Presence of impurities is another major issue affecting overall economic feasibility of aluminum recycling. Impurities include other metals (iron, copper, etc.), glass, combustible materials, etc. Metallic impurities change the overall value of final secondary aluminum products since additives may create undesirable characteristics. Magnesium is one impurity of particular importance because it requires special “fluxing” techniques to remove. Non-metallic impurities also raise environmental control costs, since processors have to invest in pollution control equipment to abate emissions given off by impurities.

3.2.4. Aluminum Pricing

The cost of aluminum varies greatly between countries. A per-pound cost breakdown for U.S.-produced aluminum (not including capital costs) is approximately: \$0.175 for alumina, \$0.145 for electricity, \$0.082 for labor, and \$0.148 for other costs (replacing anodes, etc.). (Das, Curlee and Schexnayder 1997) Current aluminum price ranges between \$0.60 and \$0.80 per pound, which is somewhat low compared to historical levels. The Soviet Union dissolution is the major cause for oversupply and price depression, with the recent Asian economic crisis adding to demand reduction. Figure 3.2.4. shows aluminum prices for the last 20 years.

Figure 3.2.4. Aluminum Prices (United States Geological Survey 1999)

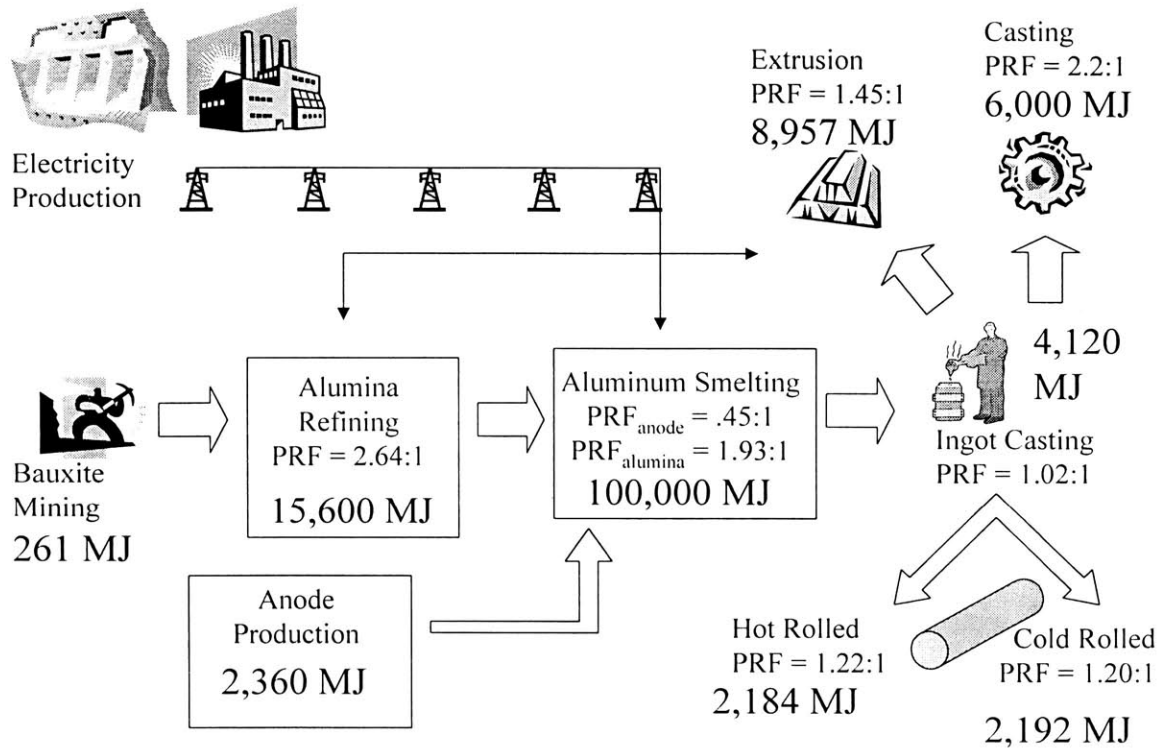


3.3. Environmental Concerns

3.3.1. Emissions and Waste from Reduction Procedure

Aluminum production, as with many other metal fabrication processes, is an environmentally intensive industry. Figure 3.3.1. gives a schematic representation of aluminum's energy lifecycle. (Roy F. Weston Inc. 1998) Each lifecycle energy consumption stage is reported in megajoules per 1000-kg product (bauxite, alumina, etc.), rather than per 1000-kg final product. This is done because there are four different products and efficiency, represented by the Product Ratio Factor (PRF), may vary depending on waste recovery processes in each facility. The PRF is a function of chemical reaction dynamics within the lifecycle stage, and can be mathematically represented by the ratio of input to 1-kg output; i.e., it takes 2.64-kg bauxite to make 1.0-kg alumina.

Figure 3.3.1. Lifecycle Stages of Aluminum Production



Carbon dioxide is increasingly becoming a pollutant of major concern to the aluminum industry. The two main sources of CO₂ are from anode reduction and associated energy expenditures. Reduction is the process by which carbon anodes remove oxygen atoms from alumina, producing about 1.5 kg CO₂ per kg molten aluminum. Most CO₂ comes from the associated energy costs, such as energy input to reduction process and transportation. These combine for about 12 kg CO₂ per kg aluminum, however this number may vary greatly depending on the energy source for reduction (hydroelectric or fossil). The aluminum industry is closely watching progress in climate change negotiations and the possibility of a carbon tax. Perfluoro carbon compounds are another set of potent greenhouse gases emitted from the smelting process. Other smelting emissions include fluorides of several varieties (which can chemically “scorch” plants near facilities), sulfur dioxide, and polycyclic organic matter (tars).

Another significant environmental concern related to aluminum production is hazardous solid waste. Alumina refining produces large quantities of iron oxide containing sludge, called “red mud.” Red mud also contains caustic soda, which can be removed in more advanced refinery systems. Over one third of bauxite input ends up as red mud. A solid waste produced from smelting is spent potliners. Potliners are containers used for the electrolytic process. Dross waste is a product of salts and molten aluminum. Salts bind to impurities and rise to the top of molten aluminum, whereby “dross” is skimmed off the top. This substance is toxic if it comes in contact with water.

3.3.3. Energy and Resource Conservation

Energy consumption is usually noted as the major environmental concern of aluminum production. Aluminum recycling is economically favorable mostly due to the fact that primary aluminum is energy intensive. It takes seven to ten times more energy to produce primary aluminum compared to secondary aluminum (depending on the kind of aluminum and recovery processes). Steel also enjoys significant energy savings since it takes two to three times more energy to make primary steel.

Resource concerns about aluminum are not generally directed towards scarcity of bauxite (or alumina), since it is a very abundant material on the earth’s crust. Conservation of aluminum through recycling is more of an effort to capture energy savings from avoiding primary production. However, if we consider landfill space as a limited resource, then aluminum use is a resource conservation issue. Landfill space conservation is a major issue in European countries.

3.4. Industry Structures

3.4.1. Automobile industry

The automobile industry is one of the most important economic sectors in most industrialized countries’ economies. This thesis looks primarily at the end-of-life recycling market for automobiles; but as mentioned before, this industry is best viewed as an interwoven cycle of activity. Section 3.4.1. will describe the important influences automobile suppliers, manufacturers, and dealers have on the industrial ecology of metals.

Automobile manufacturers are the most important factor in determining how cars move through end-of-life markets. This happens primarily through product design choice – in terms of material choice, physical material shape, durability, and how pieces are connected or located in the automobile. The suppliers are important insofar as their ability to meet product specification demands from automobile manufacturers at a low cost. Suppliers are not usually the target of regulation or external pressure to increase recyclability in the same ways as the auto manufacturers. However, supplier technology is a crucial factor in defining the economic capability of different design goals; e.g., light-weighting, reduced drag, etc.

The automobile dealer acts as a broker in this industry, contributing in many important ways. They are crucial in adding liquidity. Liquidity is needed to reduce inventory costs and enhance sales flexibility to high value production units. The dealer's liquidity demands a premium and recovered through markups charged per car. Their relationship to recycling is mostly through control of new automobile supply. Dealers also use marketing schemes to develop or take advantage of consumer preferences (including fuel economy). They are also subject to recycling legislation if deposit systems are mandated because the sticker price will be higher.

3.4.2. Automotive recycling industry operations

The recycling industry is a \$3.4 billion operation, employing over 40,000 people at 7,000 individual business establishments. (Das and Cruise 1999) Arguably, these numbers do not represent the full impact on society since automobile recycling benefits car manufacturers by stabilizing material price. In addition, recyclers provide a great service by ridding our landscape of the once daunting junked car landfill problem. About 95% of all automobiles are recovered for recycling (totaling 10 to 11 million junked vehicles per year), which is a vast improvement from the 1960's.¹⁰

There are three main actors in the recycling system: dismantlers, shredders, and non-ferrous separators. While some recycling operations combine various parts of the three functions,

¹⁰ It should be noted that while 95% of cars are recovered, about 20 to 25% of vehicle mass is lost in each recovered car. Most of this lost mass is known as automotive shredder residue (ASR).

they are considered separate for the purposes of material and economic analysis. Table 3.4.2. lists material recovery by function.

Table 3.4.2. Material Recovery Rate by Operation Type
(based on current steel-intensive automobile) (Das and Cruise 1999)

Material Type	Weight (lb.)	Material Recovery (% weight)		
		Dismantling	Shredding	Non-ferrous Separation
Carbon Steel	1526	35	64	1
High Strength Steel	369	35	64	1
Cast Iron	350	90	9	1
Cast Aluminum	178	15	20	65
Wrought Aluminum	178	15	20	65
Plastics	342	0	90	10
Magnesium	5	0	20	80
Copper	45	20	0	80
Zinc	15	0	0	100
Other materials	358	50	50	0
Total weight	3240	35%	55%	10%

Dismantlers are often the same businesses that pick up old cars from the last user. On average, the dismantler offers between \$50 and \$300 for an incapacitated automobile, but this amount may vary by the condition or quality of the car. Two kinds of parts are removed. Primary parts have either inherent material value or must be removed for regulatory reasons; e.g., the lead battery. Secondary parts have same-use value after reconditioning; e.g., radio. Secondary parts add inventory costs to the dismantler since the market for used parts is hard to determine. After removing parts from the car, a dismantler will crush the body into a “hulk,” saving space in transport to a shredder. The hulk is sold to a shredder.

Well over 10,000 dismantlers process 11 million cars per year in the United States, and over half are family-owned. (Das and Cruise 1999) Each individual business is usually small with 10 or fewer employees. (Chen 1994) Dismantlers are extremely important first players in the downstream system because they ultimately determine the ferrous and non-ferrous content of hulks. For example, dismantlers eagerly take off aluminum hubcaps, but take value away from the non-ferrous separator.

Shredders slice the hulk into fist-sized pieces and retrieve most ferrous material. Shredders can process an entire hulk in 45 seconds. A hammer mill is the major capital cost for operators, and requires extensive maintenance (6 to 8 hours per 10 to 12 hour workday). Non-metallic material, called automotive shredder residue (ASR), is usually sent to the landfill for final disposal. Ferrous material is separated by magnets and sent to electric arc furnaces or other steel industry businesses. Automobiles account for 80% of shredders input material, with the other 20% coming from “white goods.”

Non-ferrous material is sent to a separation process, which uses density-separating techniques to sort materials into different bins (for aluminum, zinc, copper, etc.). Less than a dozen stand-alone non-ferrous separators exist in the United States, despite the fact that capital costs are low. (Das and Cruise 1999) In general, non-ferrous separators are not as profitable as the other businesses in recycling. While aluminum separation is of primary concern for this thesis, it is unlikely that non-ferrous separation would be viable if it did not also separate other valuable metals.

3.4.3. Automotive Recycling Industry System Relationships

The automotive recycling industry is strongly driven by metal markets and the auto manufacturing industry. Broadly speaking, the recycling industry provides two essential services: 1) raw material price and supply stabilization, and 2) spent vehicle handling/landfill space conservation.

Merely landfilling old cars would produce a national waste problem given the millions of cars produced every year. In fact, the United States and other countries faced such a dilemma in the 1960's. The US Bureau of Mines published a 1967 report, entitled “Automobile Disposal: A National Problem,” which addressed the rapid buildup of junked cars and their increasing visibility across the national landscape. The problem was rooted in technology choice of steel makers. The basic oxygen furnace (BOF), a common technology choice during the 1960's, limited acceptable levels of input impurities. Scraped vehicles had too many other metals for the hulk value to exceed handling costs. Junk yards were able to recover the engine block and other high value parts, but the rest was left to rust and create an unsightly symbol of industrialism-gone-awry.

Although legislative proposals gained serious momentum, this dilemma was solved primarily by the new electric arc furnace (EAF) technology. The EAF could handle much higher impurity levels and had much smaller capital costs. These mini-mills benefited from lower barriers-to-entry in the scrap processing market, allowing geographic, capital budgeting, and other limitations to decrease in importance. The other technological development that helped solve the automobile disposal problem was the “shredder.” Auto shredders are mechanical systems for chopping hulks into fist-sized pieces of metal and allowed for easier magnetic separation of non-ferrous and ferrous materials.

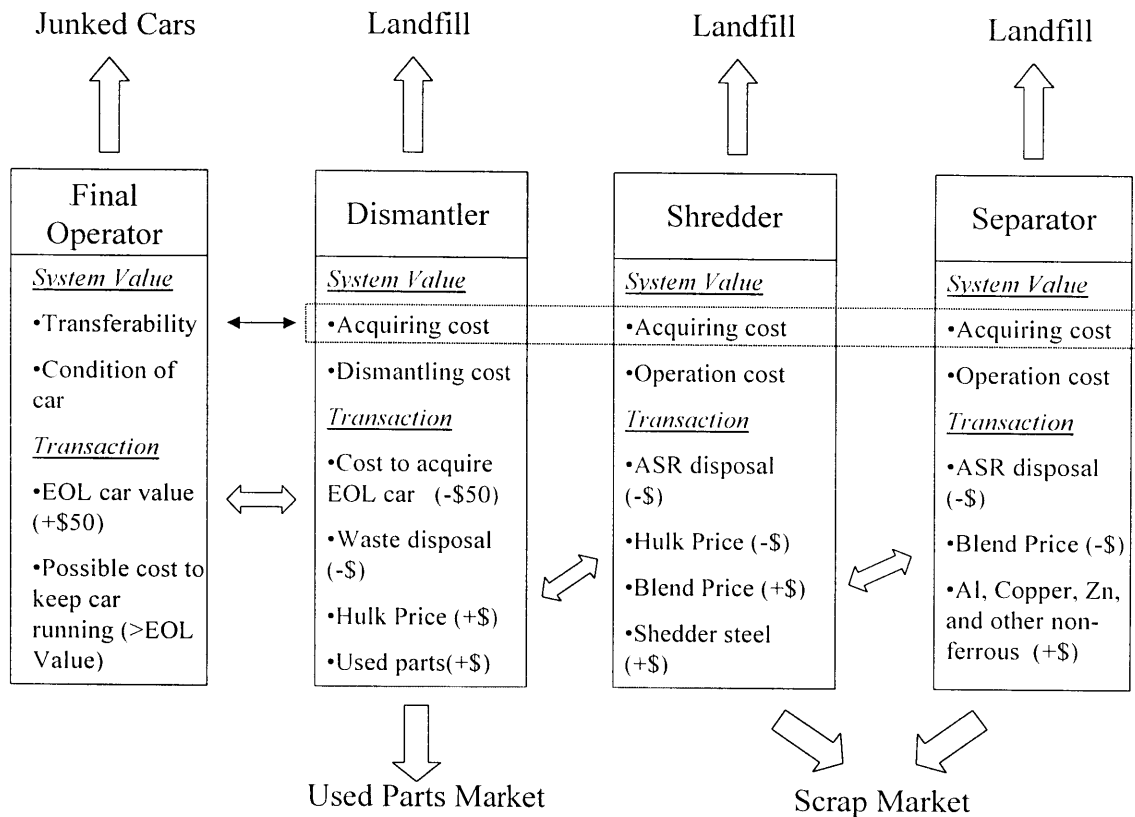
The other function of recycling is stabilization of price and supply, most evident during World War II. The surge of industrial activity during WWII led to metal shortages, including both steel and aluminum. Recycling efforts alleviated some of the supply shortages and helped keep prices down. While recent recycling has taken on an environmental persona, it undeniably aids in assuring reliable supply. As the aluminum Sankey diagram shows, automotive recycling is a significant portion of the total metal flow.

The economic lifecycle diagram (see Figure 3.4.3.) shows that the recycling system is very complicated. This diagram is a template for economic transactions between different businesses in the system. “System value” denotes internal costs or operations that do not take place in the market. These costs are a function of technology choice or supply chain management in the case of acquiring cost. The internal costs and technology choice employed by each actor help define system value because they are determining factors of how materials flow through the system. On the other hand, “transactions” refers to market transactions where clearing prices are established on not influenced by any one given firm. Transactions define the distribution of costs and benefits across actors, but do not contribute to system value.

Figure 3.4.3. condenses a lot of information about this recycling system. Transferability for the final operator refers to the end user’s knowledge about disposal options. Condition of car, which influences system value, is also reflected in the cost to keep it running. However, this is primarily an issue for dismantlers because car condition mostly influences used parts

value, not raw material value. The acquiring costs listed for dismantlers, shredders, and non-ferrous separators refer to the supply chain management costs for each firm. For example, shredders may have to spend extra money on maintaining a reliable hulk feedstock through long term contracts.

Figure 3.4.3. Recycling System Economics



3.5. Effect of Aluminum Substitution on Recycling

The high volume AIV sedan is a concept product right now, but recent industry trends suggest that aluminum has already made a significant presence in automobile material choice. CAFE and other environmental pressures may force the automobile industry to gradually move towards AIV's without the big fanfare of PNGV. While 85-90% of automotive aluminum (in the end-of-life market) is recovered for recycling, that still leaves 10-15% going

into the waste stream. The next three sections describe the efforts of researchers to understand how aluminum material substitution might change the end-of-life market.

Several open questions permeate this discussion. Will increasing automotive aluminum content reduce recycling efficiency? Can wrought supply increase fast enough to meet new demand? Is unsorted automotive aluminum recycling inefficient? If so, from who's perspective, individual firms or the system as a whole?

3.5.1. Reynolds Metals Study

Researchers from Reynolds Metals Company (now Alcoa) constructed cost models to examine the effect of increased automotive aluminum on recycling. They were primarily concerned with the PNGV model, which has approximately 25% less aluminum than the AIV in Table 3.1.1. (although in similar proportions). Of practical importance, the PNGV program set a goal of 80% recyclability; that is, 80% of the automotive aluminum is *closed loop* recycled back into a PNGV automobile.

After setting up the cost model, they analyzed 17 different scenarios varying the PNGV composition. AIV's were also considered in the models, and tended to have higher recyclability percentages. Six major conclusions came out of their study:

- 1) Separation technology of cast and wrought media is important to achieve "closed loop" material flows.
- 2) Sorting technology for different wrought alloys is important to make sure the system actualizes higher value of specific alloys. Sorting will also reduce chlorination needed to "clean" alloys in the foundry.
- 3) Auto dismantlers can profitably segregate five types of aluminum scrap (bumpers, hand-ons, engine and transmission, heat exchangers, and other media). Further separation will require too much labor costs with current technology.
- 4) Although magnesium is lighter than aluminum, material substitution to reduce magnesium increases recyclability from 67% to 79% and only sacrifices a 23-pound increase. Magnesium is considered to be an extremely undesirable impurity in aluminum alloys.
- 5) Alloy selection in product material choice is an effective way to design better recycling systems.
- 6) Design for Recycling should favor alloys that have higher tolerance to mixing.

3.5.2. Studies at the Massachusetts Institute of Technology

The Material Systems Laboratory at the Massachusetts Institute of Technology has been very active in exploring the effects of material choice. Chialin Chen wrote a Master's thesis, exploring various scenarios with systems dynamics models. (Chen 1994) The other archival resource was a Ph.D. dissertation written by Randolph Kirchain in 1999.

Chialin Chen uses systems dynamics to explore sensitivity of the recycling system to price changes, industrial designs, and public policy initiatives. Sensitivity analysis forms the bulk of his results. While this study looks primarily at material substitution of plastic and advanced composites into automobile design, some of the lessons from plastics substitution can be extended to aluminum substitution.

First, the automobile recycling industry has been well established as an economics-driven system. This would contrast to paper recycling, where collection has been subsidized by participating organizations (office collections, municipal curbside pick-up, etc.) Thus, environmental or technology mandates should be carefully administered to recognize current system incentives.

Second, the value-chain of automobile recycling is highly interdependent. A systems analysis is crucial when considering policy options and policy makers should avoid targeting single sectors for policy. Mandating "take-back" programs on the automobile producers may force them to invest in recycling capabilities outside of their expertise, such as collection and dismantling. Take-backs could force competition with existing businesses that already provide recycling services, maybe putting them out of business. The recycling system would run a risk of substituting expensive auto producer-led take-back process for efficient dismantlers.¹¹ This would increase overall recycling inefficiency and decrease value of scraped material. In a sense, automobile producers would be forced to "cannibalize" recycling system value from existing beneficial businesses.

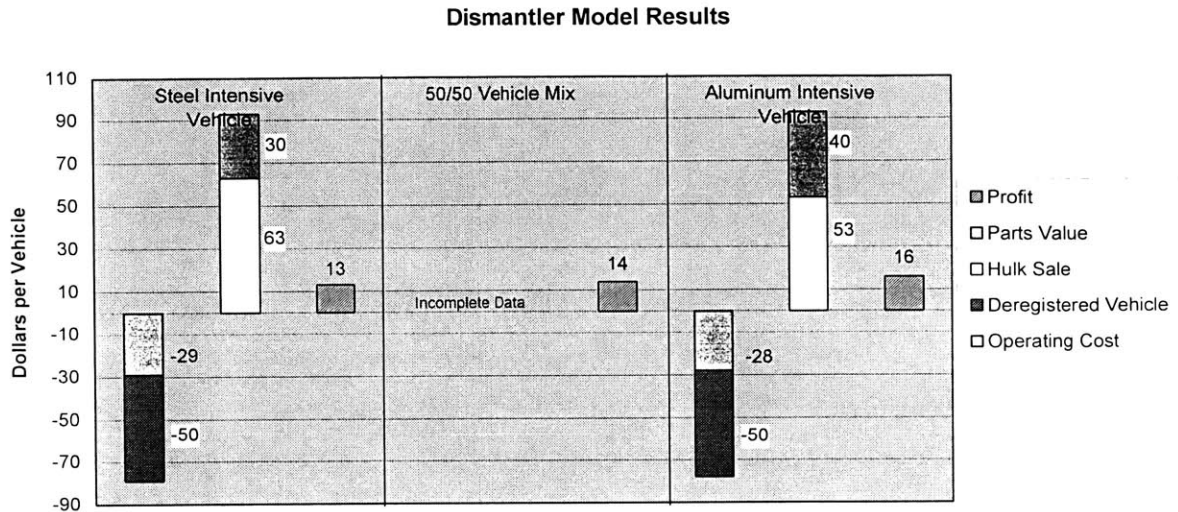
¹¹ Chen cites industry sources that suggest automobile manufacturer-led recycling would cost four times what current recyclers accomplish.

Chen also makes several suggestions for industry policy makers. Not surprisingly, the role of technology development is emphasized. After all, it was the EAF development that led to modern-day recycling. Design for Recycling initiatives are suggested, such as reducing material diversity, making pieces more dismantler-friendly, and establishing supplier and recycler partnerships.

Randolph Kirchain worked extensively with Technical Cost Modeling of materials substitution in automobiles. TCM is a bottom-up method of modeling sensitivity to various scenarios and key variables. As with many other cost models, economic scenarios are run in partial equilibrium (as opposed to general equilibrium analysis). For the purpose of his analysis, Kirchain grouped nonferrous separation with shredding. Another very important assumption is that the end user is not capable of capturing added material value; i.e. the final operator receives the same payment from dismantlers for both standard steel cars and AIVs.

Kirchain's analysis showed the importance of dismantling since the first step in a recycle process can determine material value down the remaining value chain. The Preferred Removal Set (PRS) Routine is the dismantler's protocol used to extract valuable parts from a junked automobile. Part value is not the sole determinant in the extraction decision, since parts must be removed sequentially at a substantial labor cost. "Buoyancy" is the term used to describe how attractive a part is for removal. Buoyancy equals "part value" minus "extraction cost." (Kirchain 1999) The intuitive idea is that buoyant parts float to the top of a dismantlers value preference. A comparison of various material scenarios is described in Figure 3.5.2. (Kirchain 1999)

Figure 3.5.2. Profit scenarios for different material substitutions



There are several important points to take away from these graphs. First, increased aluminum content is a positive economic change for recyclers. Second, dismantlers are not able to capture the bulk of increased material value in the system. Kirchain assumes that aluminum materials substitution will occur for parts “hidden” in the car’s structure; e.g., chassis and structural elements. In fact, the move to a 100% AIV only results in one major dismantling change of hood removal. Therefore, even though aluminum parts demand nine times the price of steel counterparts, dismantlers are not able to capitalize on material substitution because of high removal costs. (Kirchain 1999) In other words, while an AIV is more valuable from a raw materials standpoint, it has approximately the same “buoyancy.”

While dismantlers do not remove extra parts, we might expect hulk value to offset major differences. This is not the case because generally accepted business practices in the automotive recycling industry have hulk prices set at approximately five cents per kilogram, regardless of the automobile type or composition. (Kirchain 1999) Kirchain proposes that the two most sensitive dismantler “variables” are vehicle composition and hulk price.

Shredders are the major beneficiaries of aluminum substitution. However, they are selling their product to scrap metals brokers so profitability is highly sensitive to material price.

Likewise, the material composition of hulks bought from dismantlers determines the value of their final scrap product. Another material issue not discussed in great detail here is the non-metal (ASR) content and corresponding landfill prices to dispose of this waste stream. Both variables turn out to be very sensitive shredder factors.

Hulk price is a sensitive variable for shredders (as it is with dismantlers). Shredders lose \$10 profit for every penny per kg price increase. Therefore, hulk price adjustments may be one way of distributing profit windfalls between dismantlers and shredders. The likelihood of dismantlers increasing hulk price to enjoy profits depends on many economic characteristics of the recycling system.

One caveat of Kirchain's dissertation is to remember that aluminum substitution was not engineered with Design for Recycling in mind. Automobile manufacturers may choose to make their cars more "buoyant" by designing easily dismantled parts. Dismantlers would most likely respond by taking more pieces out of the automobile and lower the hulk price and weight. While dismantlers may enjoy higher profits, the shredder could be in danger of losing input material. Moreover, shredder profitability falls dramatically below 70% capital utilization rate. (Kirchain 1999)

This possibility was explored by TCM scenarios of dismantling times, with the idea that less dismantling times correspond to an automobile designed for recycling. Surprisingly, the TCM showed that dismantlers still do not remove a majority of the junked car mass at zero disassembly time. (Kirchain 1999) While this analysis is an approximation of buoyancy tests on AIVs (without DfR in mind), it definitely challenges standard assumptions about dismantler barriers to removal. Buoyancy must be a more complicated concept than merely time required to take a part out.

The AIV with an aluminum engine block presents an interesting scenario. In this case, shredders can improve profitability of the aluminum engine-AIV scenario by offering a higher hulk price (eighteen cents per kg), which would give dismantlers an incentive to remove less material (including the engine). In fact, both dismantler and shredder profit would increase. Again, Kirchain's TCM challenge standard assumptions about system

optimization. This result essentially says that both firms are better off with less part removal and dismantling, which runs against the rhetoric of increased dismantling as a solution to recycling. Dismantlers may be less efficient in processing material, giving shredders the comparative advantage.

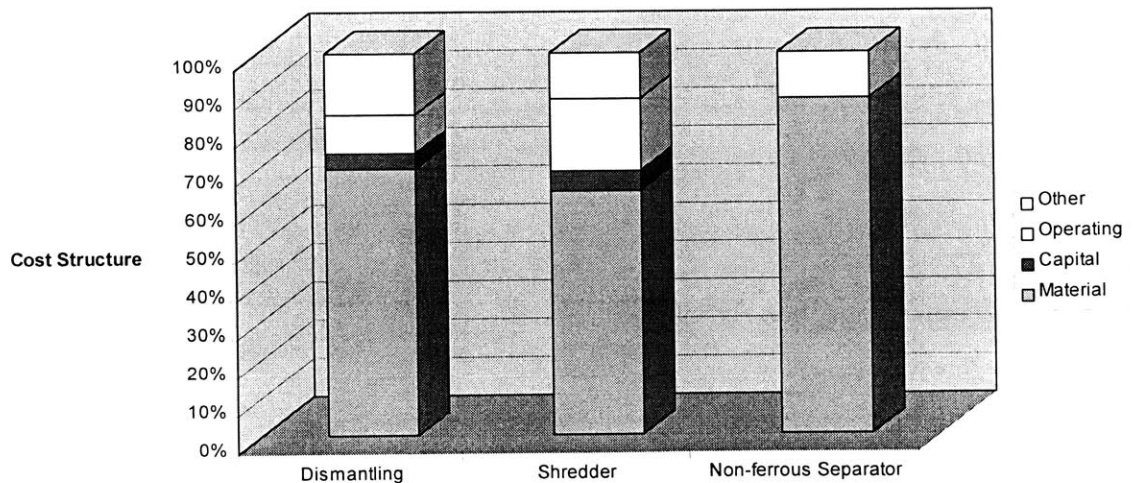
The recycling system seems to buckle when an AIV uses aluminum for its chassis and engine block. Given a moderate degree of “buoyancy,” the shredder can not pay the dismantler enough to not disassemble. This scenario would force serious changes in the shredding industry.

3.5.3. Oak Ridge National Laboratory Study

Oak Ridge Laboratory has been quite active in analyzing many transportation issues – recycling AIV’s notwithstanding. Sujit Das, T. Randall Curlee, and Susan Schexnayder published a study entitled, “Materials Used in New Generation Vehicles: Supplies, Shifts, and Supporting Infrastructure.” (Das, Curlee and Schexnayder 1997)

Base case profitability was estimated for the dismantler, shredder, and non-ferrous separator to be 30%, 64%, and 14% respectively. Although “profitability” was not precisely defined, it should suffice for the comparative purposes of this thesis. Figure 3.5.3a. presents the following cost structure for the automobile recycling industry:

Figure 3.5.3a. Cost Structure of Automobile Recycling Industry (Das and Cruise 1999)



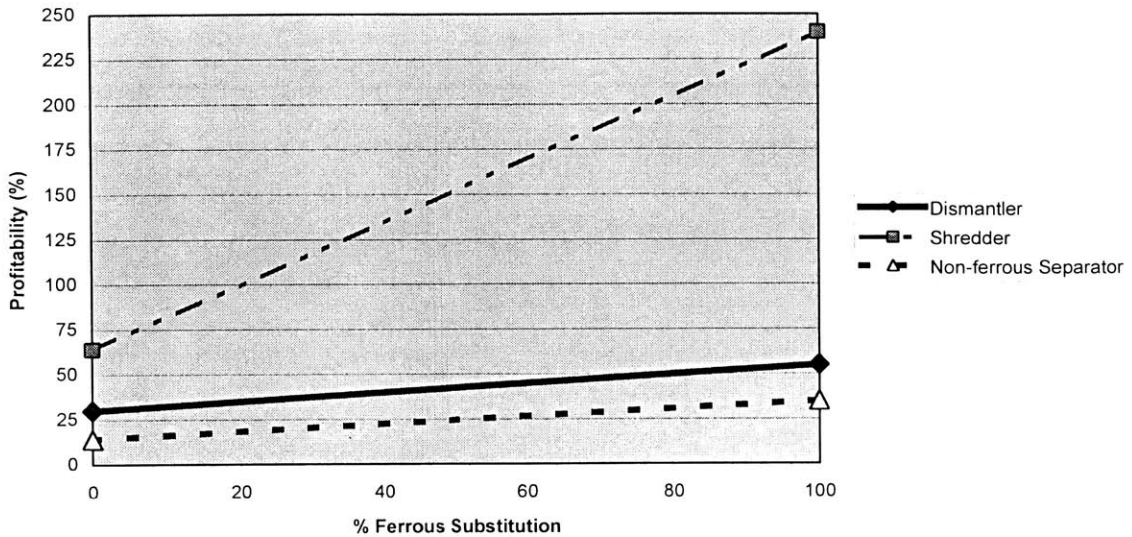
This cost structure suggests a few things about the recycling system. As the authors note, capital costs are low for each business as a fraction of the whole. Presumably, these numbers represent return of capital costs since the other costs are variable. The authors conclude that infrastructure changes will not have as large of an effect as material composition. However, it is premature to make definitive statements due to capital budgeting uncertainty. For example, return on capital costs may be low per unit, but that may occur in a situation where capital equipment is both expensive and long-lived; e.g., high barriers to entry.

Even so, the author's emphasis on material costs seems well placed. Each business' material costs are inversely proportional to their overall profitability. This seems reasonable when we see that the service provided by recyclers is to add-value to material. Processing material into more useful forms or composition enhances value-added capacity and puts the non-ferrous separator at a profit disadvantage. Aluminum recovery is not a high value-added activity.

The scenario above describes the automotive recycling system base case where steel intensive automobiles are recovered. Moving to an AIV could be good for non-ferrous separators if they can develop value-added competencies; e.g., casting and wrought separation. However, it could be bad if aluminum parts are easy to dismantle since the non-ferrous separator volume would decrease. By simplifying issues of alloy compatibility, Das and Curlee compared ferrous substitution rates to profitability (see Figure 3.5.3b).

It is immediately apparent from Figure 3.5.3b. that shredders are capturing most of the profit from having a more valuable metal flowing through the recycling system. Authors credited this to lower hulk weight and increased aluminum revenues from scrap sold to non-ferrous separators. Unfortunately, there was no further detailed discussion of this issue.

Figure 3.5.3b. Profitability vs. Ferrous Substitution (Das and Cruise 1999)



Das and Curlee performed various sensitivity analyses with a conservative estimate of an AIV (50% more aluminum than the base case). Two major conclusions were derived from the sensitivity analyses. First, if dismantlers want to take more aluminum out of cars, then they must remove between 35 and 50% of the car's total aluminum in order to retain base level profitability (30%). This is because higher investment and labor costs needed to extract aluminum parts follow increasing returns to scale. The second main conclusion is that non-ferrous separators approximately double their profitability under the 50% increased aluminum-content automobile scenario. Furthermore, their profits can substantially increase if they can separate the higher valued wrought alloys away from castings.

In summary, Das and Curlee believed that increased aluminum content would have a universally positive effect on every automobile recycling firm. However, they noted that system value maximization might not be obtained unless coordinated effort is undertaken to increase alloy separation. Nonferrous separators are seen as more effective processors in this respect, but may be hindered by pre-emptive dismantler sorting. The authors also point out that one dozen non-ferrous separators are not capable of handling the AIV, and that major infrastructure investment is needed on the short-term horizon.

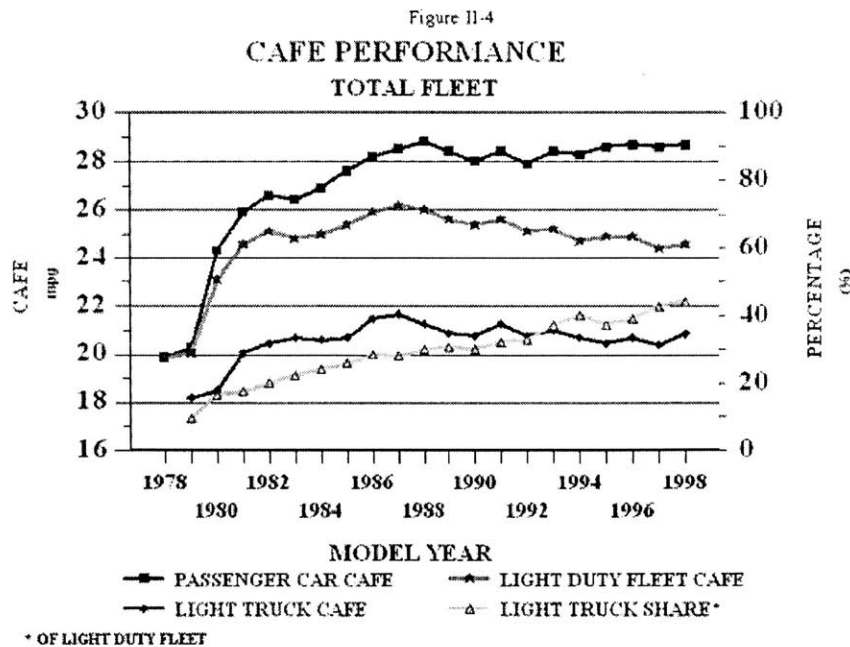
3.6. Government Policy

3.6.1. CAFE (Corporate Average Fuel Economy) Standard

CAFE standards were introduced in response to long lines at gas stations during the 1970's oil shock. The U.S. public pressured government officials to make automakers adhere to a minimum miles per gallon standard. The thinking was that car companies needed to be accountable somehow, so car fleets manufactured during times of oil abundance would not be a major problem if another oil shock occurred.

Even with the historical practice of light-weighting automobiles to meet CAFE standards, it is entirely possible that automakers may use alternative technologies. For example, hybrid automobiles are one technology solution to meeting CAFE. However, for the purpose of this thesis, it is assumed that automakers will lightweight to an AIV.

Figure 3.6.1. CAFE Standards (US Department of Transportation -- National Highway Traffic Safety Administration 1998)



3.6.2. Clean Air Act

Clean Air Act regulation promulgated under Subchapter II (Emission Standards for Moving Sources) also affects material choice for automakers. Standards are usually specified in terms of end-of-pipe pollution levels (grams) per mile. Sometimes, the auto industry was required to install new technology to meet the desired goals. The best example of such pollution control on automobiles is the catalytic converter. Weight reduction and aerodynamic designs are both ways to reduce grams/mile emissions because of gas mileage increase. A 10% decrease in drag leads to a 2% increase in fuel efficiency. (Chen 1994)

Both Clean Air Act and CAFE standards are tunable regulations, in that government agencies may adjust numerical requirements without new statutory legislation. Agency discretion is used to determine the appropriate levels, and they are given the authority to “tighten the belt” on performance. This tunable feature is one reason why CAFE standards are a high priority on the list of engineers, since the initial automobile design period may be a few years away from production. By the time a car is actually produced in large numbers, standards may have changed.

3.6.3. Partnership for a New Generation of Vehicle (PNGV)

One of the major government initiatives affecting automobile end-of-life markets is the PNGV, which is a collaborative effort between the three major U.S. automakers (Ford, Daimler-Chrysler, and General Motors). The goal is to develop an 80 miles-per-gallon family sedan without sacrificing important consumer preferences, such as safety, performance, and comfort. The program’s goal is to have a protocol automobile ready for production by 2005.

It is widely expected that the 80-mpg goal will be met in part by substituting materials, specifically aluminum or composites for steel. By introducing these new materials, car companies hope to cut the current average weight of 3200 lbs. to about 2000 lbs. PNGV is one of the most influential industry policy initiatives with respect to material substitution. One of the implicit goals is to help the automotive industry advance fuel efficiency and light-weighting without losing competitive advantage. The mechanisms for accomplishing this

goal are collective technology development, standardized solutions to industry-wide problems (such as recycling), and normalizing time to market with new product.

3.6.4. Department of Energy “Industries of the Future”

The U.S. Department of Energy entered into an agreement with members of the aluminum industry through a program called, “Industries of the Future.” This program is an effort to develop key technologies seen as critical to enhancing energy efficiency of emerging aluminum markets. The aluminum program specified five goals: scrap separation, alloy preservation and optimization, design for recycling, furnace technology, and automotive initiatives. (Aluminum Association 1998)

While the last goal has immediate implications to this thesis, the other four goals are just as important. Scrap separation has been one of the key barriers to increased recycling because process technologies often include high labor costs. Taking advantage of low-cost labor locations (such as Mexico) is often not feasible because of transportation costs. Scrap separation has an immediate impact on all downstream processes because sorting ultimately determines scrap-input quality to secondary processing. Aluminum presents unique separation difficulties because of alloy compatibility issues and the small density differentiation between alloys.

“Design for Recycling” (DfR) is one of many manufacturing practices, collectively known as “Design for X.”¹² The purpose in any design program is to intentionally emphasize a certain product characteristic. In this case, the desirable characteristic is recyclability. Recyclability is a vague guide to design and often demands coordination between competitors and suppliers to ensure total industry participation. This is because automobiles designed for recycling are goods with network externalities; i.e., one DfR car among 1000 non-DfR cars is not worth as much as one DfR car among 1000 DfR cars. Automobile dismantling is routinized according to specific protocols to minimize processing time. Dismantlers need to be able to follow one (of a limited few) routines.

¹² Other design programs include design for environment, safety, quality, etc.

The Aluminum Association specified several Design for Recycling characteristics: 1) consistency in alloy use for product parts, 2) identifying parts by alloy, and 3) designing for ease in separating parts that include or attach to other non-aluminum materials. (Aluminum Association 1998) These technological demands are intended to make recycling easier for dismantlers and reduce the alloy contamination introduced during automated non-ferrous separation processes. One possible idea includes “total car dismantling,” where large-scale facilities will take apart most (if not all) of the automobile, replacing the role of 12,000 small-scale “junk yards.”

3.6.5. European Recycling Initiatives

In general, European recycling drivers arise from higher landfill costs and resistance to waste transportation. Sweden initiated a deposit system in response to a protectionist measure, prohibiting the export of domestic steel. The ban on exports lowered steel value and made automotive recycling less profitable. This led to disposal problems similar to the U.S. in the 1960's. Germany passed a law that required car owners to obtain a certificate of disposal to stop billing of annual registration and insurance fees.

3.7. Policy Conclusions for AIV Recycling

The formal policy instruments available to government agencies are quite limited. Adjusting CAFE standards and Clean Air Act emissions limits are both effective in light-weighting the vehicle. However, the US EPA has no ability to specify how efficiency gains or light-weighting should be implemented. They are even further removed from an ability to control how such standards could affect the recycling system. Broader policy options affecting supply and demand relationships or prices seem like the only government solution. These options are discussed further in Chapter 5.

Thus, the Department of Energy and EPA initiate industry partnership programs; e.g., PNGV and “Industries of the Future.” Several characteristics of these programs limit their ability to be successful. Partnerships are voluntary agreements between industry and government, making enforcement very difficult. The incentive to uphold one's commitment depends on the value of remaining a member of the group. Partnerships act like “clubs”

because membership offers some value. In the case of PNGV, the automakers derive good will benefits from trying to create socially beneficial product choices. Research collaboration and harmonizing time-to-market reduces the risk posed by trying to create a new product. Leaving the club runs the risk of allowing competitors to potentially capitalize on a new market segment.

Government holds the key to allow partnerships with reduced anti-trust concern, but retains limited ability to enforce agreements and goals. Thus, industry will not be sanctioned by failure to reach the goals of an 80% recyclable – 80 miles-per-gallon automobile. Actually, the government may lose credibility when trying to initiate successful future partnerships. This inadvertent sanction on government for industry failure may be a disincentive for government officials to advocate socially optimal options. Instead, they may search for moderate options with higher likelihood of industry implementation.

Therefore, it is highly uncertain that either Clean Air Act or partnership policy options are going to be successful in guaranteeing an AIV efficient recycling system. A new approach may be necessary. Chapter 5 will continue this policy discussion by proposing alternative options.

CHAPTER 4 – ANALYSIS OF CASE STUDIES

This chapter presents an analysis of recycling systems in the nickel cadmium battery and aluminum intensive vehicle cases. Analysis is directed towards identifying strong and weak points in the end-of-life markets, qualitative characterization of metal intensive product recycling systems, and future areas of research. Econometric analysis is intended to add descriptive depth to the case studies. The chapter concludes with a comparative analysis of the two cases, with specific attention on comparing the public policy differences.

4.1. Econometric Analysis

One tool for concisely picturing the recycle system as a whole is by plotting the actors out on a matrix, where each square represents the interaction between two members.

Traditionally, econometricians use this sort of relationship scheme to begin involved quantitative analysis. For the purpose of this thesis, the matrix will be a talking point for descriptive analysis. Thus, while interactions focus on transactions such as sales and purchasing, “softer” economic costs and benefits are also included; e.g., customer satisfaction. Internal transactions are featured along the diagonal, such as processing technology utilization, administration, material value actualization (asset accumulation).¹³

The next two figures are econometric matrices for the nickel cadmium and aluminum intensive vehicle recycling systems. The two major constraints are that (1) the sum of each row must be greater than zero (individual profit motive), and (2) the sum of the diagonal must be greater than zero (system profit motive).

Several features stand out immediately, such as the symmetric axis along the matrix diagonal. The most notable difference between the two figures is that the AIV matrix has a simpler

¹³ Material value actualization is a form of asset accumulation in the context of an end-of-life economic system. Material flows from the end user in a one way direction, thus metal must reach a final point before it becomes an input for a process not related to the end-of-life (product manufacturing).

value chain structure, whereas the NiCd matrix has disproportionately more transactions with two actors (RBRC and INMETCO). This feature is indicative of a subsidized system, where centralized planning is necessary to coordinate collective action. The next few sections continue from this simple initial analysis.

Figure 4.1a. – Nickel Cadmium Battery Econometric Matrix

	A	B	C	D	E	F	G	H	I	J	K
A -- Retailer (as seller)	P	+									
B -- Last User	-	OC	+		+						
C -- Retailer (as collector)		+	P		+						
D -- Municipal/BPA Collector				P	+						-
E -- RBRC		-	-	-	P	-				+	
F -- INMETCO					+	P	+	+		+	-
G -- Cadmium Scrap Market						-	P			+	
H -- Ni-Fe Scrap Market						-		P	+		
I -- Stainless Steel Industry								-	V		
J -- Battery Manufacturers					-	-	-			V	-
K -- Landfill/Waste Market				+		+				+	P

Figure 4.1b. Aluminum Intensive Vehicle Econometric Matrix

	A	B	C	D	E	F	G	H	I	J	K
A -- Last User	OC	+									
B -- Dismantler	-	P	+		+						-
C -- Shredder		-	P	+		+					-
D -- Non-ferrous Separator			-	P			+				-
E -- Used Parts Market		-			V						
F -- Ferrous Scrap Market			-			P		+			
G -- Non-ferrous Scrap Market				-			P		+		
H -- Steel Industry						-		V			
I -- Aluminum Industry							-		P	+	
J -- Automobile Industry									-	V	
K -- Landfill		+	+	+							P

LEGEND		CONSTRAINTS
+	Income generating transaction	"Individual profit motive" Sum of row > 0
-	Purchasing transaction	
P	Process resources spent to extract valuable product or administer operation	"System profit motive" Sum of diagonal > 0
V	Material Value Actualization - Asset Accumulation	
OC	Opportunity Cost (cost of opportunities forgone)	

4.2. NiCd Recycling System Analysis

While the matrix in section 4.1. gives a concise view of the recycling systems, it offers little resolution of the actual details. Drawing information from the case study, we can more accurately describe the system in Figure 4.2 (see Appendix 1). The next few subsections highlight strong and weak points in the RBRC-led take back system.

4.2.1. Strong Industry Participation

Industry cooperation is strong with over 80% of all NiCd batteries bearing the RBRC seal. In addition, over 20,000 retail chains have signed up for the program across Canada and the United States. This was achieved only four years after initial implementation of the program. While industry participation is a necessary condition, it is not sufficient by itself for creating a successful recycling system.

First, achieving a stable and predictable material stream is important to turn dead batteries into profit. Capacity utilization, as in many industrial processes, is key in having an adequate return on capital for INMETCO. Second, RBRC would not have public policy legitimacy if there was low industry participation. Congress passed the Battery Management Act with the intention of aiding an industry-wide national NiCd collection program. Public concern leading to the threat of action against cadmium could easily resurface if it was perceived that RBRC was not delivering on its promise of an industry-wide take back.

4.2.2. RBRC's Role as a Trade Association

The decision for battery manufacture to participate may not be obvious from the matrix because the constraint on their row is that the horizontal sum be greater than zero. This implies that the battery manufactures would have to actualize enough material value from recycling to offset the other costs (logo license fees, mailers, etc.). The case study tells a very different story, which is why the trade association benefit makes up for the balance. Despite RBRC's lack of publicly stated purpose to assuage regulators, battery manufacturers joined the program to preempt restrictive legislation on their products. Thus, RBRC acts like a trade association in preserving the business interests of its members. This service has positive economic value by maintaining business as usual practice with product manufacture and sales activities.

The incentive for retailers to participate as collectors is a prominent feature of this matrix. Retailers are mostly concerned about preventing deposits or product bans. An added bonus occurs with the interaction between the retailer (as collector) and the end user. It is a “win-win” scenario for both parties. The end user’s need to recycle (as an environmentally aware citizen) is satisfied, and the retailer benefits by having increased store traffic and building positive rapport with potential customers. (RBRC 1999) The “win-win” situation seems to look like a positive externality in the recycling system because the price of the battery does not appear to reflect the real surplus enjoyed by both parties. A positive externality contributes to retailer and consumer participation, but is not desirable from the standpoint of battery manufacturers’ interest in minimizing logo fees.

4.2.3. Weak Consumer Participation

End consumers have little incentive to do anything other than throw their batteries into the garbage. RBRC counts on the same consumer goodwill exercised in recycling of newspaper, plastics, and glass to motivate nickel cadmium product return. This section focuses on the opportunity cost matrix cell for the end user.

Japan, the single largest producing country of NiCd batteries, has had a concerted recycling program for many years. One would expect to find a high awareness in Japan compared to other places. However, NiCd batteries elude mainstream awareness in Japan as in many other countries. The Nikkei English News published a 2000 person countrywide survey performed in late 1996 – only 50% of the respondents knew of NiCd batteries, 36.9% knew that the batteries are recyclable, and only 24.5% kept the used batteries (to recycle). (Nikkei English News 1996)

The United States, arguably the largest consumer of NiCd batteries, has an even worse awareness of recycling rechargeable batteries. RBRC sponsored an NPD Group survey to assess consumer knowledge with over 1200 sample households. The key findings were that while 95% of the households own cordless devices, only 16% recycle their batteries, and they prefer recycling and environmentally friendly activities that are easily done at home. (Business Wire 1999) 16% contrasts greatly to a 75% participation rate in bottle, can, and

newspaper recycling. The most common profile of a NiCd recycler is a married, middle-aged professional, with a college education and no children.

"What this survey points to is the great need for public education," said Ralph Millard, executive vice president, RBRC. "Our goal is to encourage portable product owners - which is 95% of the population - to learn more about their products and the power behind them. Recycling NiCd batteries is easy - just call 1-800-8- BATTERY or go online at www.rbrc.org - but getting people to take that first step is the real challenge." (Business Wire 1999)

Awareness may be explained by the *information cost* to learn about nickel cadmium batteries. One of the problematic characteristics of information costs is that consumers may not even be aware of the real cost to learn about recycling. All it takes is the perception of costly learning to prevent the consumer from taking the time to actually learn, which may actually be less than the perceived hassle. Thus, real costs also include an *inconvenience cost*. In addition, if the education information does not convey the marginal benefit to consumers from taking batteries back, then a voluntary recycling plan will have little hope of success. RBRC is limited in explaining the marginal benefit because it may make consumers backlash even more against nickel cadmium products.

Although RBRC is considering expansion of the take back to NiMH, they strategically chose to exclusively focus on NiCd battery recycling to limit program cost and coverage – there was little public concern for other rechargeables. But an exclusive recycling focus can hurt consumer understanding because they must be able to differentiate and select NiCd batteries out from all other sorts of batteries. Many consumers do not understand the extent of environmental risk posed by various technologies, so only emphasizing one type may confuse the public. Consumer psychology tends to focus on a product's service, not the product itself; suggesting that a broad battery take back may be more effective.

4.2.4. Macroeconomic Risk Exposure for INMETCO

INMETCO advanced recycling technology from cadmium removal and disposal (waste treatment) to true cadmium recovery. The technology is environmentally beneficial because cadmium can be re-used, rather than shipped off for disposal. However beneficial,

INMETCO is only able to create a marginally profitable product. Low profit margins are very undesirable when coupled with INMETCO's high operating macroeconomic risk.

First, NiCd consumption accounts for over 75% of the total cadmium material flow, and production levels heavily influence prices (see the Cadmium Sankey in Chapter 2).

INMETCO has little influence over primary cadmium production. This puts them at a disadvantage in controlling global supply and price levels. Second, recycling operations increase supply, which can contribute to price depression if cadmium demand growth is not sufficient. Third, cadmium is also a natural by-product of zinc production. As long as zinc demand is sufficient, there will be a consistent stream of cadmium available to the market. Finally, zinc (and cadmium) fabrication is subject to overproduction in developing countries and economies in transition that are looking for hard currency from battery manufacturing countries (Japan and U.S.).

4.2.5. Free Riders

A recent report by Raymond Communications, "Battery Recovery Laws Worldwide," stated that not all the RBRC participants pay their share of the \$7.5 million collection and recycling price tag. (Raymond Communications 1999) Potential for free riders arise anytime an organization (firm, group of firms, or government) provides a public good. Public goods have two characteristics – they are non-rival and non-exclusive. Non-rival goods have zero marginal cost to provide the service to one additional consumer. Non-exclusive goods are services where the producer can not exclude people from consuming it. Obvious examples of public goods are national defense and street lighting.

The RBRC program, in theory, is not a public good because it is exclusive – they charge a fee to license their logo, which then allows the battery to be recycled. However, in practice, the program operates more like a public good than one would originally think. This is because RBRC's legitimacy derives from its ability to have a broad scope. If RBRC does not attempt to recycle almost all nickel cadmium batteries, then the battery industry runs a risk of government intervention. Therefore, RBRC is reluctant to impose sanctions on members that do not pay license fees, making the recycling service less exclusive.

While the marginal cost to recycle one more battery is not theoretically zero, variable costs are arguably far less than the fixed costs to establish and maintain a national recycling organization. Another way to think of this program's non-rival character is that once the bins and collection points are created, adding one extra battery costs almost nothing. Likewise, once the trucks are shipping batteries to INMETCO, adding an additional battery is negligible.

Aside from non-paying members, RBRC could be subject to other forms of free ridership. For example, retailers may take back batteries without the RBRC seal, fearing a lost sale from turning away a conscientious consumer. Consumers who tend to recycle batteries have higher-than-average disposable income, and are very valuable customers. A retailer who refuses to accept a battery may look unconcerned with the environment. A recent RBRC poll of participating retailers corroborates these general concerns. RBRC was gauging the acceptability of expanding *Charge Up to Recycle!* to other battery types, and asked retailers what reasons they have for providing these recycling services. The top four reasons (allowing for multiple responses) were: (RBRC 1999)

- (1) Provide Customer Service – 58%
- (2) Increase Store Traffic – 55%
- (3) Comply with Law – 21%
- (4) Already Collecting and Need Program – 14%

4.3. Recycle rates are low

The previous sections describe important features of RBRC's take back program. Most of these features raised serious concerns about the system's ability to function successfully as a program for recycling 70% of small sealed batteries. The concerns are corroborated with current available information, such as recycle rates and projected goals. The goal set by RBRC is a 70% recycle rate, and has been an elusive target as Table 4.3. suggests. 1999 seemed to tell a similar story as 1998, in that the recycle rate continues to hover around 30% and goals for reaching 70% are at least 5 years away.

Table 4.3. Readjusting Goals: RBRC's timeframe for a 70% recycle rate of small cells

Date of Commitment	Target Year	Source
1995	1998	(Hachman 1995)
1996	2001	(Goodwin 1996)
1997	2002	(Mooney 1997)
1998	2004	(RBRC 1998)

The European counterpart to PRBA is the European Portable Battery Association (EPBA), and has made similar arguments for industry self-governance over cadmium bans or battery deposits. However, their goals seem to be more modest, saying that a 75% collection rate is “preposterous.” (Haznews 1998) As a result of the PDB study, RBRC has admitted the lack of consumer awareness and participation. (Market 1999) The battery industry seems to be forming consensus that voluntary take-back schemes will not produce short-term recycling rates of 70%. It is unclear, however, that the industry believes regulation can achieve such rates instead. The means to reach a 70% rate are in serious question.

Japan has been trying to increase recycling of nickel cadmium batteries for many years. One study cited in Lankey, shows an erratic recycling rate from 1980 to 1990, ranging between 15% and 30%. More data collected from 1991 to 1994 shows roughly the same. (Lankey 1998) Of the batteries being recycled, over 70% were collected through OEM reverse channel routes, and another 20% through waste collectors (non-municipal waste services). As with the US and Europe, Japan has had much more success recycling the large vented industrial NiCd batteries, but has yet to establish a reliable program for reclaiming small sealed cells.

Although consumer battery recycle rates are low, industrial batteries have been relatively more easy to recycle. The difference between industrial and consumer recycle rates batteries highlights the comments made about opportunity costs. Industrial batteries are used by businesses and public agencies, which have a strong legal incentive to not dispose of the batteries. They are regulated as hazardous waste, and must be disposed of according to strict RCRA regulations.

4.4. Aluminum Intensive Vehicle Recycling System Analysis

Once again, the matrix using symbols may not provide resolution we desire in analyzing the recycling system. Figure 4.4. (see Appendix 2) provides a descriptive look at the interactions within this system. The following subsections will give focus on specific and important aspects of this matrix.

4.4.1. Strong End User Participation

The end user's decision decides the fate of any product in an end-of-life market – either it gets recycled or thrown away. In the case of automobiles, end users have been faithful suppliers to junk yard dismantlers for over 20 years. As the case study discussed, technological breakthroughs (EAF and shredder) enabled the system to turn handsome profits from used cars. This allows dismantlers to offer \$50 or more for old cars, which has been ample compensation for end users to have their “jalopies” hauled away.

Another way of looking at this situation is to consider the end users decision as weighting of the \$50 against opportunities forgone by getting the car repaired (for more than \$50) and extending its life. The aluminum intensive vehicle would alter this tradeoff because dismantlers are willing to pay more for aluminum cars. In general, we would probably see automobiles enter the recycling system sooner. Higher transfer price between dismantler and end user would also assure a continued automobile recycling rate of 90 to 95%, possibly even increasing it.

4.4.2. Lost Aluminum Value in Future AIV

As the case study mentioned, combined wrought (sheets and extrusions) and casting material streams can only be recycled into casting material; i.e., the more valuable wrought material value is lost into casting. Recovering alloy-sensitive wrought products separate from castings would maximize value from this system. One of the limiting factors in alloy separation is that the difference between densities is too small for current automated non-ferrous technology. Thus, labor intensive dismantling seems to be the most obvious choice for alloy separation.

Getting the incentives aligned to encourage specific dismantler behavior is not easy, especially considering the decentralized junkyard industry structure. The next chapter will discuss policy options for achieving this goal. At this point, it is interesting to note that value actualization (on the econometric matrix) happens in the used scrap market, steel industry, and automobile industry. In particular, automobile manufacturers are the last point of aluminum material flow. This implies that the value of increased aluminum material can be captured by carmakers. Moreover, the value is dependent on the extent of value-added activities performed by recyclers and transfer prices. Automobile manufacturers should be thinking seriously about how to recover this infusion of aluminum material value by influencing recycler behavior and product design.

4.4.2. Dismantler/Separator Instability

As the case study discusses, infusion of aluminum (at current AIV estimates) into the recycling system is a positive economic change – profitability of all recycling operations increases. Problems arise from the fact that most material value is in aluminum parts – processing costs make steel marginally profitable compared to aluminum. As more aluminum is substituted into the car, a point is reached at which the dismantler finds it profitable to take out a lot of aluminum. So much that the shredder must actually pay the dismantler to keep it in; otherwise the shredder can not recover costs from steel alone. Shredders are more efficient than the dismantler at removing aluminum from parts buried deep in the car. Thus, total dismantling will result in less profit for both the dismantler and shredder compared to a situation where the shredder pays a dismantler to keep it in.

Another critical point is reached when aluminum is substituted in for the engine block, chassis, and body. At this point, the shredder can not pay the dismantler enough to not remove parts. The recycling system collapses to pure dismantling. Implications beyond this are unclear, but possible options include junked ferrous hulk accumulation, landfilling of a significant fraction of the automobile, and shredder subsidization (operating as waste processors). The problem is summarized as a failure in individual profit motive to create system value maximization.

4.4.3. Conflicting environmental goals

Experts in the automobile industry are familiar with the dilemma posed to them. On the one hand, government wants more fuel-efficient cars, demanding more advanced materials substitution. On the other hand, government tries to encourage efficient recycling, which is difficult to achieve because of changing inputs and diversity of economic actors in the recycling system. The two competing goals are not necessarily at odds in all instances, but must be reconciled and carefully considered.

In general, this problem points to an aspect of industrial ecology of metals. By limiting analysis to the behavior of metals in products, we have not given the related effects an equal place at the table. While industrial ecology acknowledges that resource efficiency is good because of related environmental savings, it does not necessarily provide a framework for making informed tradeoffs. For example, it may be more environmentally beneficial to reduce recyclability by a certain per cent if another aspect (such as fuel efficiency) is improved. In life cycle analysis, this problem corresponds to boundary selection – how expansive should we analyze the impacts of a certain product or process?

4.5. Comparative Analysis

It is readily apparent that the two cases offer very different stories of how metal intensive products are recycled. Comparison of the two cases offers insights on recycling system behavior and public policy response to the need for effective recycling. First, the opportunity cost for end users is much different; that is, the cost of not being able to do something other than returning the product. Alternatives to recycling drive the decision of end users and are the critical first step in the system. In addition, available opportunities are a function of many variables (possibly too expansive to list here). An unfortunate implication of heterogeneous and complicated opportunity costs is that general studies of recycling systems are also very complicated.

Second, the cases share in their limited available policy options to address recycling system efficiency. After the Battery Management Act was enacted, the US EPA had little recourse in the event of low recycling rates. This problem is even more poignant in the AIV case.

Short of major statutory reform, agencies are limited to partnerships for addressing the efficiency of an AIV recycling system. Both cases draw out a well-documented problem in administrative government – agencies enabling legislation often prevents or disallows them from addressing their public goals.

Third, current policies used in both case studies have little accountability. As mentioned in the NiCd case, industry was given significant regulatory relief without being subject to accountability measures. Short-term problems associated with effective policy implementation have already been discussed, but attention should also be given to long term problems. If *Charge Up To Recycle!* does not perform as promised within the next five to ten years, then industry's failure to provide this public good will surely be exposed. This result could undermine the public's trust in various ways. The public would not trust government to negotiate its power and capabilities with industry, even though private sector solutions and implementation can be more efficient in many cases. Also, the public would not trust industry to uphold its promises, perpetuating modern perceptions that corporate interests are alienated from social interests. These scenarios are not in the interest of government officials, industry leaders, or the public.

Fourth, industry conditions for the two cases are much different and support differentiated policy options for recycling metal-intensive products. As mentioned in section 4.2., the macroeconomic price risk has made cadmium recycling essentially unprofitable for INMETCO. Had prices remained over five dollars per pound, then incentives to recycle could open up industry led options to increase recycling rates; e.g., offering rebates for returned batteries. The AIV case is extremely complicated with respect to managing industry structure. The implications include uncertain technology development and increased difficulty in setting standards.

CHAPTER 5 – POLICY OPTIONS AND CONCLUSIONS

The final chapter develops a list of policy options for improving the nickel cadmium battery and AIV recycling systems. The econometric matrix is a useful tool for presenting a wide scope of information with the caveat that choosing a policy option requires much more detailed analysis of costs and benefits.

Generally, we can group policy options into three categories: “push” and “pull” public policy, and industry policy (see Chapter 1). The first chapter described frameworks and motivations behind different policies. The next three sections are based on matrices developed in Chapter 4. The last sections discuss merits of different policy options, and generalize their relevance to various types of recycling systems.

5.1. “Push” Policy

Push policies are aimed at increasing the supply of available recycle material by modifying consumer behavior. Increasing supply will either make recycle material cost effective where before it was not competitive with virgin material, or control the fate of materials in the end-of-life market to alter biological impact pathway. In general, push policy options include compulsory take back, fixed target recycling, landfill bans, municipal collection, production quotas, and deposits.

While some of these policies seem very similar, they are aimed at changing different types of behavior within the system. Compulsory take back forces producers to accept their products once a consumer is finished. By itself, a take back does not force recycling. Rather, it imposes a cost on the manufacturers by making them develop channels for retrieving products. RBRC is a good example of how costs have been centralized by many manufacturers, but one could imagine each individual firm also developing their own program of contractors and transportation services. In both cases, the cost ultimately is taken out of profits and/or imposed on the consumer through higher prices.

Coupling take back with a landfill ban may encourage consumers to utilize the industry take back channel. On the matrix, a landfill ban will change the opportunity cost of the last user. It will make the alternative to recycling more costly because some sort of penalty might be assessed. Thus, end users are more likely to send products into the recycling system. It is unclear how effective landfill bans are from the nickel cadmium battery case. Some states ban NiCd disposal while others do not. However, no state-by-state recycling rate difference is noted. One possible explanation is that banning NiCds is an unenforceable policy, thus failing to alter end user opportunity cost.

Fixed target recycling is another way to put teeth into a take back policy. As mentioned in the NiCd case, certain European countries have imposed fixed recycling rates with possible sanctions (tax per battery) in the case of non-compliance. While recycling rates were higher in these countries than in the United States, it is difficult to assess the degree to which fixed recycling rates changed behavior. Three general problems arise in this case. First, monitoring recycle rates is difficult. Second, picking the wrong tax level could burden consumers or encourage partial compliance (by paying the tax instead of recycling). Third, fixed recycling rates do not change the opportunity cost of end users, failing to address the weakest point in the NiCd recycling system.

Municipal collection programs have been relatively successful in recovering materials that have little or no value; e.g., glass and paper. In fact, aluminum cans often subsidize the whole program. While many cities have “hazardous waste day” collection, municipal programs for NiCd batteries have been far less successful. One possible reason is that batteries must be treated with more care than glass, plastic, and paper, making weekly curbside collection impossible. Citizens must drive to a collection site approximately once per month, making recycling more inconvenient. Mandating stronger municipal collection policies seems unrealistic and expensive.

Deposits are used to increase the price of a product, whereby the deposit is paid back after the product is returned for recycling. Deposits are a strong motivation for end users to return products because the opportunity cost to not recycle is visibly higher. A financial

mechanism with clear payoffs may be more effective than a landfill ban where relatively small sanctions (order of \$100) are almost never enforced.

The AIV case does not seem appropriate for take back or deposit policies since return rates are about 95%, and material recycling after return is over 75%. Although recycling steel intensive cars has been a historical concern (especially in Europe), aluminum is in no danger of being thrown away.

5.2. “Pull” Policy

Pull policy options increase consumer demand for recycle material. Increased demand for recycle creates a competitive market need, hopefully improving the technology and efficiency of collection and recycling. Pull policy options include minimum recycled content specifications, procurement policy, taxes on virgin material, and price supports for products containing recycled material.

The Partnership for New Generation of Vehicles, mentioned in the case study, has set a goal of 80% closed loop recycling in developing a future car design. This type of specification is a form of “pull” policy because it forces automobile manufacturers to use recycle, thus creating additional market demand for recycled automotive aluminum and steel. This could potentially have dramatic implications for wrought products. Current recycling downgrades wrought into the recycled casting quality stream. Demand for recycled aluminum wrought could force technology changes in the dismantling and separation operation.

Procurement policy is another form of pull policy. Executive Order 12873 requires agencies to implement “Federal Acquisition, Recycling, and Waste Prevention” pursuant to §6002 of the Resource Conservation and Recovery Act (RCRA). EO 12873 broadly mandates procuring agencies to prefer recovered or recycled products. The United States government is the single largest customer of many goods and could exercise significant consumer pressure for automobiles with high-recycled material content for car fleets in the Park Service, Post Office, etc. Other large customers, such as car rental companies, could use similar pressure as part of a

product differentiation strategy. One limiting factor is that automobiles are not usually differentiated across environmental characteristics, let alone recycled content.

Taxes on virgin material are technically price adjustments. However, they affect demand by effectively increasing competitive advantage of aluminum made from recycled material. In addition, tax revenue could be targeted at recycling technology and infrastructure development, reducing the need for long term government intervention. In the case of an excise tax (where aluminum producers are taxed per unit sold), the aluminum industry would place pressure on the scrap market to deliver more recycle material. They might pay a price premium for recycle scrap so long as the premium is less than the tax.

Taxes on virgin material may help improve the economic viability of INMETCO in the NiCd case. Alternatively, a negative tax (subsidy) could be used to support the price of recycled cadmium. This would help mitigate some of the macroeconomic risk exposure to international supply and overproduction problems.

5.3. Industry Policy

Industry policy is based on coordinated corporate policy or strategy between two or more firms in a competitive market. Trade associations represent many industry policy interests and have been quite active for the last century. A common industry policy taken by many associations is lobbying government officials on behalf of members' financial interests with the goal of influencing public policy. For example, chemical firms in the United States initiated the Responsible Care[®] program under the auspice of CMA (Chemical Manufacturers Association). Responsible Care[®] is a codified environmental management system aimed at establishing baseline performance levels so that irresponsible action taken by one firm will not hurt the collective industry image. Other industry policy actions suggested in this section (specific to the industrial ecology of metals) include R&D technology development, product standard specifications, merger and acquisition, and supply chain management.

Processing costs are decreased mostly through R&D, technology change, and efficiency gains. Finding a non-labor intensive solution to the alloy separation problem would dramatically change the AIV recycling system. Unlike the EAF, it seems that this particular technology solution would result from some degree of coordinated effort. Aluminum producers have the metallurgical know-how, auto producers have technical skills for implementing design changes, and auto recyclers will be the eventual separators. INMETCO has already overcome one significant technological hurdle in the NiCd case. Enhanced NiCd recycling is more a function of consumer participation and logistical planning. However, if RBRC incorporates NiMH and Li-ion batteries into the take back, then sorting technology would be important.

Product standard specification may be one technical avenue for encouraging aluminum alloy separation. The dismantler's labor and technology constraints suggest that industry-wide coordination is needed to ensure efficient recycling operation. For example, the dismantler does not have the capacity to learn a different part separation routine for each car model type.

Another industry policy option is merging or acquiring competitors to gain more control over industry behavior. Increasing the value of recycled material and parts involves policy designed to support a healthy market for aluminum alloys and other parts. One suggestion might be to encourage loop closing in automobile material flows, thus securing alloy supply and demand relationships. Automobile manufacturers could invest in recycling operations or somehow gain more influence on their activity through contracts.

One foreseeable problem with aluminum intensive cars is saturation of certain alloy markets as a consequence of material choice and/or recycling processes. In particular, the demand for casting quality aluminum may be exceeded by supply created from automotive recycling. If cast alloy markets become saturated, then the overall value of the car could decrease. The urgency for preemptive industry policy is highlighted by a 10-year lag time. That is, by the time alloy saturation is noticed in aluminum markets, there will be at least 10 years before immediate action can have an impact. Industry consolidation may assist in preventing

market saturation, but free trade barriers and macroeconomic risk will cap risk reduction by import competition.

As mentioned in the AIV case study, one possible implication of maximum aluminum substitution is recycling system collapse. If aluminum is substituted for the body, engine, and chassis, then shredders become obsolete. Social welfare implications are clearly undesirable because of steel hulk accumulation and landfill usage. Likewise, U.S. automakers would desire to remain relatively free from regulation of end-of-life vehicles. It would be in the interest of all parties for auto manufacturers to manage recycling operations as an extension of their business.

5.4. Implications for Industrial Ecology of Metals

5.4.1. Policy Preferences

The intuitive appeal of “pull” policy is that it had fixed target and flexible means. The additional demand creates incentives for recycling, while leaving the market to develop least cost means in achieving the desired recycle rate. The corollary is that “push” policies suffer from fixed means to achieve increased recycling. In addition, push policies can run the danger of creating too much recycle material, bottoming out the entire market and risking system collapse; e.g., packaging materials and the DSD system in Germany. However, this may be an unfair condemnation of push policies.

The two cases give a little more insight on the appropriateness of these two types of policy options. Generally, we see that pull policies are more effective for recycling systems where the last user has sufficient incentive to recycle and a functional system is in place. On the other hand, push policies may be necessary for products where the last user does not have sufficient incentive to deliver the expired product to the recycling system. This generalization has several justifications. First, pull policies may not be able to catalyze the formation of a recycling system where none existed before. In a sense, pull policies are incremental changes from business as usual. Second, push policies operate directly on the end user, changing their opportunity cost in the system. This is a more effective method to

initiate product return than pull policies, which must work backwards from the material demand.

Pull policies would not have worked in starting a nickel cadmium battery take back. The battery industry had an incentive to operationalize a recycling system in a short time span, and the RBRC *Charge Up To Recycle!* program more than doubled small cell recycling in four years. While RBRC-led take back may not be a sufficient condition to achieve the desirable 70% recycling rate, it seems to be a necessary condition. Therefore, some combination of push and pull may be needed to propel recycling rates to their promised levels.

The AIV case clearly shows that landfill bans or take backs are not appropriate for an operational recycling system. The problem with aluminum substitution is a matter of trying to maximize the material value in the system and protecting from possible system failure (albeit a small probability). These issues require pull policy intervention such as specifying wrought recycled content.

The case studies might imply another generalization about policy appropriateness. It seems that push policies are more appropriate for controlling the fate of substances where there exists a biological impact pathway concern. The motivation to control toxic material fate is driven by public and environmental health consequences, not resource efficiency or economic asset value maximization. Push policies are directed at pushing the supply of material from the end user through a planned recycling system, where that planned recycling system can be set up to handle toxic material. On the other hand, pull policies rely on market demand and thus some sort of material value motivation.

5.4.2. Industrial Ecology Classifications

A question begged by the obvious differences between the AIV and NiCd cases is whether the industrial ecology of metals is a useful classification when looking at end-of-life markets. Macroeconomists have already shown the importance of macro-level material flows through national resource balances. But should industrial ecology be parsed into material types (plastics, forest products, etc) when considering targeted microeconomic recycling policies?

Based on the lessons learned from this thesis, industrial ecology should not be parsed into material categories when analyzing end-of-life markets.

For example, one of the main distinguishing differences between the NiCd and AIV systems was the last user's opportunity cost. It may be suggested that the last user's opportunity cost is a useful starting point for classifying different end-of-life industrial ecologies. Nickel cadmium batteries and leaded cathode ray tubes (CRTs) have more in common than with the AIV. Both have toxicity concerns, are not readily dematerialized, and have little inherent material value to the last user. However, CRT landfill bans could be far more effective because they are not easily hidden in municipal waste streams. Therefore, opportunity costs in the two examples are very different. In terms of identifying policy opportunities, the last user's opportunity cost is far more important than product characteristics (such as material type) by themselves.

Another possible point of departure for classifying end-of-life systems would be to divide material concerns into biological impact pathway control and material value maximization. These two motivations are fundamentally different in terms of incentives, available technologies, and policy pressures.

Broadly speaking, there are two categories of characteristics describing end-of-life systems in these two cases. The list below suggests that many variables influence end-of-life markets. Industrial ecology studies should be very careful not to hastily group products together without considering such a list. The particular list developed for these case studies show that a metal product generalization is not useful.

Technical:

- Substitutability of virgin materials
- Energy ratio (primary/secondary)
- Recovery type (functional vs. material)
- Material recycling technology
- Product complexity (beverage can vs. automobile)

Economic:

- Opportunity cost of last user – “returnability”

- Inter-sectoral – how many industrial sectors does it cross?
- Inter-temporal – how long is product turnaround time (from manufacturing to disposal)?
- Value Chain characteristics
 - Market concentration of recycling actors
 - Dependency of each on one another
 - Disposal market
- Market relationships between metals (ex: Cd and Zinc)
- Market absorptency of product's recycled metal

While this thesis shows that industrial ecology of metals is not a useful classification for end-of-life markets, it is not arguing that all industrial ecology typologies are not useful. Generalizing industrial ecology may have benefits in terms of increasing the discipline's predictive capacity, but generalization must be done with care.

5.5. Implications for Public Policy

As mentioned in section 4.5., heterogeneous and complicated opportunity costs make general treatment of recycling systems very difficult. Correspondingly, it is very difficult to create policy that can handle recycling systems generally. Experience with RCRA corroborates this observation. RCRA is a broad reaching policy that affects many different material types and a vast array of products. The case studies show that specifying RCRA recycling rules across metal-intensive products would not be an appropriate policy classification. The Battery Management Act served as a model in the sense that it addressed a specific product in a specific context (NiCd batteries in the recycling market).

Limited available policy options imply need for statutory reform. The Battery Management Act needs to be amended so that the US EPA can have a more active role in administering and overseeing *Charge Up To Recycle!* One possibility includes a tax mechanism that penalizes battery manufacturers for not achieving predetermined recycling rates. For example, RBRC publicly claimed that they could achieve a 70% recycling rate. Currently, they are at least 40 percentage points below this goal, which would be subject to taxation under a new policy. Successful implementation of a tax policy would require sophisticated monitoring capacity. (Tietenberg 1992) INMETCO's "front door" would be a plausible point to keep track of returned batteries, and industry shipment can give a reasonable estimate of NiCds entering

the consumer market. However, calculating recycle rates requires subjective determinations of turnaround time and consumer retention. An adequate monitoring scheme would have to be planned very carefully. (Lankey 1998)

Perhaps the most drastic changes would occur in administrative regulation of automobile recycling systems. For example, the government could specify minimum recycled content of certain alloys in automobiles. This could correspond with the 80% recyclable goal set by the PNGV. Increasing the demand for alloy recycling could serve as a useful incentive to change firm behavior in the recycling system. However, such regulation would be a significant divergence from the government's traditional stance on regulating product characteristics (usually only done where public health impacts are concerned). A more feasible incremental change might be to use the government's procurement power to purchase AIVs that are engineered for maximum recycling.

In the same way that policy capacity must be enhanced, both cases showed the need for more accountability built into policy implementation. The tax scheme proposed above is one financial measure to increase accountability. However, the Battery Management Act should also provide for non-financial accountability, such as five-year reviews by the US EPA submitted to a Congressional Sub-Committee. There should be a formal forum for public concern to praise or criticize recycling rate progress of *Charge Up To Recycle!* Currently, RBRC has the ability to co-opt discussion on NiCd recycling because it can make unsubstantiated claims about future performance without having to be accountable to previous performance commitments.

Accountability is difficult to build into the AIV recycling case because industry has made much less binding targets. While they agreed to design an 80 miles-per-gallon car that is 80% recyclable, there were no commitments to actually producing the cars. This is a reflection of the partnership process, where the lack of government ability to mandate product specifications limits their bargaining power in negotiating PNGV goals.

Finally, policies should be sensitive to different industry conditions as mentioned in section 4.5. The most immediate policy appropriate for the NiCd case is a negative tax (subsidy) on

recycled cadmium from INMETCO. It should be an adjustable tax set so that price remains constant, thus stabilizing operations and giving better incentives for customers to return their batteries. (Lankey 1998) The AIV case is complicated by the recycling system's sheer size, diffusion, and lack of existing regulatory oversight. Certain industry actions may be appropriate, such as mergers and acquisition. Government policy could assist expedition of this process. An extreme policy could be supporting a regulated monopoly consolidation, but this course of action would require significant deliberation. The most important policy implication of the automobile recycling industry structure is that direct government intervention should not disturb transaction efficiency already built into the system.

REFERENCES

- Aluminum Association. "Aluminum Recycling Casebook: The American Aluminum Industry -- First in the World in Recycling." . (1998).
- Aluminum Association. Auto Aluminum. 2000. Aluminum Association. Available: www.autoaluminum.org. February 2000.
- Aluminum Association. Environment. 2000. Aluminum Association. Available: www.aluminum.org. February 11 2000.
- Ashford, et al. "Evaluating Chemical Regulations: Trade-off Analysis and Impact Assessment for Environmental Decision-Making." M.I.T. Center for Policy Alternative. (1980): Cambridge. 20, 22-25.
- Battery Solutions Inc. "Pricing Information". 2000. Battery Solutions Inc. Available: www.batteryrecycling.com. February 5 2000.
- BrownKlien. Design Factors for a Super High Energy Density NiMH Battery for Military Uses. Long Beach, CA, 1997. 33-36.
- Business Wire. "Wireless Products in the U.S. Boom But Green Behaviors Wane." Business Wire November 16 1999.
- Byrd, Edward. "Stars Pitch Products: Campaigns Borrow Familiar Faces." Wireless Week May, 13 1996.
- Chemical Marketing Reporter. "A Healthy Cycle." August 25 1994: 7.
- Chen, Andrew C. "A Product Lifecycle Framework for Environmental Management and Policy Analysis: Case Study of Automobile Recycling." . Massachusetts Institute of Technology, 1995.
- Chen, Chailin. "Prospects for Automobile Recycling: An Integrated Approach of Systems Dynamics and Life-Cycle Assessment." . Massachusetts Institute of Technology, 1994.
- Daniels. "Battery." Waste News May 27 1996: 3.
- Das, SujitT. Randall Cruise. "Vehicle Recycling, Regulatory, Policy, and Labeling Issues: Recycling of New Generation Vehicles." Society of Automotive Engineers. (1999): Warrendale, PA. 87-96.
- Das, SujitT. Randall CurleeSusan Schexnayder. "Materials Used in New Generation Vehicles: Supplies, Shifts, and Supporting Infrastructure." Oak Ridge National Laboratory. (1997): Oak Ridge.
- DiMaria, Eugene. "More recycling seen aid to end cadmium shortfall." American Metal Markey April 25 1989: 1.
- Duracell. . Available: www.duracell.com/Our_Company/index.html. January 25 2000.
- Energizer. . Available: www.energizer.com/products/rechargeable/products/cordless.html. January 25 2000.
- Energizer. "1999 Annual Report." Ralston Purina. (1999).
- Environmental Information Networks. NiCad, NiMH Battery Makers Debate Future Market Growth. 1995. Electric Vehicles Energy Network Online Today.
- Falsani, Cathleen. "Critics scoff at Klug bill on recycling." The Capital Times April 24 1996: 1A.

Financial Times. "Commodities and Agriculture: Cadmium is in need of a recharge." October 1 1998.

Financial Times Survey Edition. "Survey - Battery Industry." May 10 1999.

Fishbein, Bette. "Industry Program to Collect Nickel-Cadmium Batteries." INFORM. (1997): New York.

Goodwin, Morgan E. "INMETCO wins grant for battery recycling." American Metal Market July 28 1995: 11.

Goodwin, Morgan E. "New law said boon for NiCd recycling." American Metal Market May 17 1996: 1.

Graedel, Thomas E. Braden R. Allenby. Industrial Ecology of the Automobile. Upper Saddle River, NJ: Prentice Hall, 1998.

Greczyn, Mary. "EPA unveils battery label." Waste News August 24 1998.

Hachman, Mark. "Slow progress in battery recycling." Electronic Buyers News November 6 1995: 10.

Haznews. "Battery collection: voluntary or regulated?" Haznews August 1 1997.

Haznews. "Battery recycling technology: which route to take?" Haznews September 1 1996.

Haznews. "EU cadmium ban for batteries?" Haznews June 1 1998.

Haznews. "French battery industry sets up collection scheme." Haznews July 1 1999.

Hydro Aluminum. "Aluminum and ecology." . (1992). 4.

INMETCO. 2000. INMETCO. Available: www.inmetco.com. January 23 2000.

Kirchain, Randolph. "Modeling Methods for Complex Manufacturing Systems: Studying the Effects of Materials Substitution on the Automobile Recycling Infrastructure." . Massachusetts Institute of Technology, 1999.

Kuck, Peter. "Nickel." US Geological Survey. (1997).

Lankey, Rebecca L. "Management and Recycling for Nickel-Cadmium Batteries." Dissertation. Carnegie Mellon University, 1998.

Lee, Rikkie. "Battery recycling gains, Federal Law catches up." Wireless Week April 22 1996: 6.

Llewlynn, Thomas O. "Cadmium (Materials Flow)." US Department of Interior, Bureau of Mines. (1990).

Margolin, Bob. "Power Technologies: Part 2: Batteries." Electrical Engineering Times May 15 1995: 49.

Market, American Metal. "Most NiCd batteries wind up in landfills, trade group claims." American Metal Market November 18 1999: 7.

Metal Bulletin. "Cadmium future still battery dependant." June 15 1995: 9.

Mooney, Elizabeth V. "Battery business evolves from one acronym to another." RCCR Radio Communications Report November 16 1998.

Mooney, Elizabeth V. "Rechargeable Battery Recycling Corp. announces Nokia signing." RCCR Radio Communications Report March 17 1997: 19.

Ng, George John C. Miller Michael B. Tessieri. "Vehicle Recycling, Regulatory, Policy, and Labeling Issues: Aluminum Usage in the PNGV and Its Impact on the Recycling Infrastructure." Society of Automotive Engineers. (1999): Warrendale, PA. 97-119.

Nikkei English News. "Interest in NiCd battery recycling remains low." Nikkei English News December 4 1996: 12.

O'Neil, Dan. "The Secret of NiMH, NiCad, Li, Zn, and Other Ramblings on Portable Power." Photographic Trade News March 1 1994: 12.

Pindyck, Robert S. Daniel L. Rubinfeld. Microeconomics, Fourth Edition. Upper Saddle River, NJ: Prentice-Hall, Inc., 1998.

- Plunkert, Patricia A. "Aluminum." United States Geological Survey -- Minerals Information. (1998).
- PRBA, Portable Rechargeable Battery Association. 2000. Available: www.prba.org. January 25 2000.
- PRNewswire. Rayovac expands into rechargeable battery market. 1998. Available: www.rayovac.com. January 15 2000.
- Raymond Communications. Report Questions 90% Recovery Goals for Ni-Cd Batteries. 1999. Raymond Communications, Inc. Available: www.raymond.com. January 28 2000.
- RBRC. EPA certifies alternative battery recycling label: Battery Group Hopes To Increase Consumer Recycling Of Used Ni-Cd Batteries. 2000. RBRC. Available: www.rbrc.org. February 3 August 21.
- RBRC. "Looking to the Future." Charge Up To Recycle Newsletter 1999.
- RBRC. "Ni-Cd Battery Recycling - United States and Canada." Charge Up To Recycle! Newsletter 1998: 4.
- RBRC. RBRC Website. 2000. RBRC. Available: www.rbrc.org2000.
- Roy F. Weston Inc. "Life Cycle Inventory Report for the North American Aluminum Industry." . (1998): West Chester. 4.
- Simon, Bernard. "Inco Arm Gears Up to Recycle Tonnes of Batteries." The Financial Post May 30 1996: 62.
- Tietenberg, Tom. Environmental and Natural Resource Economics, 3rd Edition. New York, NY: Harper Collins, 1992.
- United States Environmental Protection Agency. Cadmium and Compounds. Technology Transfer Network - United Air Toxics Website. Available: www.epa.gov/ttnuate1/hlthef/cadmium.html. November 10 1999.
- United States Environmental Protection Agency. "Implementation of the Mercury-Containing and Rechargeable Battery Management Act." . (1997).
- United States Environmental Protection Agency. Nickel and Compounds. Technology Transfer Network - United Air Toxics Website. Available: www.epa.gov/ttn/uatw/hlthef/nickel.html. January 15 2000.
- United States Environmental Protection Agency Office of Water. Consumer Factsheet on Cadmium. Available: www.epa.gov/OGWDW/dwh/c-ioc/cadmium.html. January 15 2000.
- United States Environmental Protection Agency Office of Water. Consumer Factsheet on Nickel. Office of Ground Water and Drinking Water. Available: www.epa.gov/OGWDW/dwh/c-ioc/nickel.html. January 15 2000.
- United States Geological Survey. "Cadmium." United States Geological Survey. (1999).
- United States Geological Survey. "Mineral Commodity Summaries - Aluminum." United States Geological Survey. (1999). 23.
- US Department of Transportation -- National Highway Traffic Safety Administration. "Automotive Fuel Economy Program -- Twenty third annual report to Congress." . (1998): Washington DC.

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APPENDIX 1 – Figure 4.2. Descriptive Econometric Matrix for NiCd Take Back

	A	B	C	D	E	F	G	H	I	J	K
A - Retailer (as seller)	Shop Operation	Shelf Price of Battery +									
B - Last User	Cost of Battery ---	Opportunity Cost	Satisfy Need to Recycle +		Satisfy Need for Recycling Information +						
C - Retailer (as collector)		Improved Customer Relation-ships +	Program Implementation		Subsidized Transport & Prevent Deposit +						
D - Municipal/BPA Collector				Program Implementation	Subsidized Transport +						Possible Charge to Dispose ---
E - RBRC		Recycling Information ---	Transport Costs & PR to Prevent Deposit ---	Transport Costs ---	Program Administration ---	Fixed Fee Mailers ---				License Fee + Act as Trade Association ---	
F - INMETCO					Fixed Fee Mailers +	Manufacturing Costs +	Cadmium Revenue +	Ni-Fe Revenue +		Fixed Fee Mailers +	Possible Charge to Dispose ---
G - Cadmium Scrap Market						Cadmium Price ---	Brokering ---			Cadmium Revenue +	
H - Ni-Fe Scrap Market						Ni-Fe Price ---		Brokering	Ni-Fe Revenue +		
I - Stainless Steel Industry								Material Cost for Ni-Fe input ---	Material Value		
J - Battery Manufacturers					License Fee --- Trade Association Benefit +	Fixed Fee Mailers ---	Cadmium Purchase for new NiCds ---			Material Value	Possible Charge to Dispose ---
K - Landfill/Waste Market				Possible Disposal Revenue +		Possible Disposal Revenue +				Possible Disposal Revenue +	Landfill Maintenance Cost

APPENDIX 2 – Figure 4.4. Descriptive Econometric Matrix for AIV Recycling System

	A	B	C	D	E	F	G	H	I	J	K
A - Last User	Opportunity Cost	\$50 from Junk Yard +									
B - Dismantler	\$50 Paid to Last User ---	Towing and Dismantling	Revenue from Hulk +		Revenue from Used Parts +						Cost to Dispose Waste ---
C - Shredder		Cost to Acquire Hulk ---	Operating Cost for Hammer Mill	Revenue from Non-Ferrous Material +		Revenue from Scrap Brokers +					Cost to Dispose ASR ---
D - Non-ferrous Separator			Cost to Separate Metals ---	Operating Cost for Separators			Revenue from Scrap Market +				Cost to Dispose ASR ---
E - Used Parts Market		Cost to Buy Parts ---			Value Actualized From Parts						
F - Ferrous Scrap Market			Cost to Buy Scrap ---			Brokering		Revenue from Steel Mills +			
G - Non-ferrous Scrap Market				Cost to Buy Scrap ---			Brokering		Revenue from Aluminum Foundries +		
H - Steel Industry						Cost to Buy Scrap ---		Value Actualized			
I - Aluminum Industry							Cost to Buy Scrap ---		Processing Cost	Revenue from Metal Sales Contract +	
J - Automobile Industry									Cost for Aluminum ---	Value Actualized from Al	
K - Landfill		Revenue from Waste +	Revenue from Waste +	Revenue from Waste +							Processing Cost