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Reclamation of Automotive Batteries:

Assessment of Health Impacts and Recycling Technology

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

AIR RESOURCES BOARD
Research Division

RECLAMATION OF AUTOMOTIVE BATTERIES: ASSESSMENT OF HEALTH IMPACTS AND RECYCLING TECHNOLOGY

Contract No. 93-323
Final Report

Task 1: Assessment of Recycling Technology

Prepared For:

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and

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ABSTRACT

This final report for Task 1: Assessment of Recycling Technology provides an assessment of current electric vehicle (EV) battery recycling technology for the California Air Resources Board (CARB) and CalStart. As a result of CARB's requirements for the sale of zero-emissions vehicles (ZEVs) beginning in 1998, it projected that California's on-road fleet of EVs will increase significantly between the years of 1998 and 2003. The purpose of the Task 1 effort was to examine approximately ten different candidate EV battery technologies based on their performance and recyclability and to develop a ranking of the batteries based on these examinations. The batteries evaluated were lead-acid (all types), nickel-cadmium, nickel-iron, nickel-metal hydride, sodium-sulfur, sodium-nickel chloride, lithium-iron disulfide, lithium-ion, lithium polymer, and zinc batteries (zinc-air and zinc-bromine). The results of Task 1 will assist in determining where efforts should be focused in establishing new recycling facilities and developing cleaner technologies. Presently recycling facilities for lead-acid batteries are located in California. A nickel-containing battery recycler exists in Pennsylvania, but additional capacity will probably be required for these batteries. Minimal capacity exists to accommodate zinc-air and various lithium batteries. A facility located in British Columbia, Canada recycles lithium batteries. However, additional facilities will almost assuredly be necessary if lithium batteries are used extensively in EVs. A market assessment was performed to find what markets exist, if any, for the recycled products. This assessment also helped to determine if it would be feasible for recycling efforts to rely on the sale of the product to sustain themselves, or if a battery deposit would be necessary to subsidize the process. The value of materials from recycled batteries is not stable enough to fully support recycling efforts. Therefore, we recommend that a deposit of $100 to $150 should be levied on light-duty vehicle batteries to ensure that these batteries are returned for recycling. All of the batteries under study exhibit the characteristic of hazardous waste in California, and are therefore subject to strict regulations, but this status could change with the finalization of a new EPA rule, the Universal Waste Rule. In the final ranking of the batteries' performance and recyclability, lithium-ion batteries are rated highly for performance, but score only average in terms of recyclability, since only one facility currently recycles this battery and the recycling products may flood the market. Similarly, lithium-polymer batteries are rated very well for performance but poorly for recyclability, since large EV sizes of this battery are not even produced yet, let alone recycled. Lead-acid batteries are rated the highest for recyclability but are ranked poorly on performance. Nickel-metal hydride batteries are rated with moderately high marks for both performance and recyclability. It should be noted that the rankings and scores generated in this report are intended for comparative and qualitative use only. The assessment methodology used in this report is based on current technology and the limited data that is available. Task 2 (Assessment of Health Impacts) for this study will provide an overall assessment of health and hazard impacts of deploying each battery type. The analysis will result in a ranking of the batteries will account for toxic and hazard attributes associated with each battery's potential recycle and disposal chain.

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SECTION 1

INTRODUCTION

California's ability to meet its air quality goals depends on its ability to lower the exhaust emissions of its on-road vehicle fleet. The California Air Resources Board's (CARB's) Low Emission Vehicle Rules will decrease emissions through the phased introduction of vehicles meeting increasingly stringent exhaust emission standards. In particular, the required introduction of zero-emission vehicles in 1998 will begin an important shift in both the vehicle emissions inventory and in the new vehicle choices afforded Californians. Yet these emission reductions will not arrive without raising other environmental, economic, and social issues. Battery-powered electric vehicles, currently the only technology envisioned to meet the zero-emission requirements, appear to force a number of tradeoffs in order to attain low vehicle emissions. Some of these tradeoffs involve vehicle characteristics, such as range, size, and economics. Volume 2 of this study also evaluates the environmental effects and human health hazards associated with widespread use of rechargeable battery technologies.

Of course, rechargeable batteries have been in widespread vehicle use for many decades. The conventional lead-acid battery present in vehicles today is one of the technologies which may be adopted for electric vehicles. Why, then, does the advent of electric vehicles raise seemingly new questions about the efficacy of rechargeable batteries? For several reasons: first, all batteries capable of powering a car contain hazardous constituents, and careless disposal would release these constituents into the environment. Second, the existing battery recycling infrastructure — including lead-acid battery recycling — may not accommodate the batteries powering these vehicles, due to volume, technology, or market constraints. Furthermore, an electric vehicle will use many more batteries than a conventional vehicle, through both the number of batteries necessary to power it, and the number of times the batteries will need to be replaced. Finally, it is difficult to predict which battery technology or technologies are going to be successful in the electric vehicle marketplace, leaving a great deal of uncertainty regarding what sorts of new environmental and economic forces will be brought to bear in only a few years. For all these reasons, the impact of electric vehicle battery waste on the environment is a major concern.

California is in the advantageous position of knowing precisely when these vehicles will enter the marketplace, and in approximately what numbers. Therefore the state can pave the way for electric vehicles, facilitating the recycling process and infrastructure through legislative and regulatory means, if necessary. The state can also encourage technology development toward those batteries likely to be beneficial in performance, cost, and environmental dimensions. This report will provide the information basis which will allow the Air Resources Board to ensure that electric vehicles remain a critical step in its efforts to improve California's environment.

SECTION 2

TASK 1: ASSESSMENT OF RECYCLING TECHNOLOGY

Because no single type of battery has been agreed upon by electric vehicle developers as "optimal," several potentially viable batteries are currently in developmental stages ranging from commercial to advanced research. Several types of advanced lead-acid batteries are currently being developed, such as the sealed bipolar lead-acid battery (SBLA). By 1998, the SBLA battery has the potential for achieving a moderate energy and high power density (55 Wh/kg at 80% depth of discharge (DOD) and more than 1 kW/kg for more than 1,000 cycles), and a lifetime of 5 to 10 years. Batteries used commercially for other purposes, such as nickel-metal hydride batteries, may be adapted for vehicle use, and entirely new batteries, such as the lithium polymer, are being researched for vehicular purposes. Table 1 lists the specifications for batteries being examined for electric vehicles. In this assessment, approximately ten battery types will be studied in detail, including lead-acid (all types), nickel-cadmium (NiCd), nickel-iron (NiFe), nickel-metal hydride (NiMH), sodium-sulfur (NaS), sodium-nickel chloride (Na-$NiCl_2$), lithium-iron disulfide ($LiFeS_2$), lithium ion (Li-ion), lithium-polymer (Li-polymer) and zinc batteries (Zn-air and Zn-Br).

The United States Advanced Battery Consortium (USABC) defines near term as 1993-1997, mid term as 1998 to early 2000s, and long term as after the early 2000s. USABC funds batteries based on their potential to meet goals defined for each of these time periods. However, for purposes of this study of recycling impact, near term is defined as 2000, mid term as 2005, and long term as 2010, to allow for actual battery introduction and use.

While the California Air Resources Board (CARB) Zero Emission Vehicle (ZEV) mandate requires the introduction of zero emission vehicles from the seven largest manufacturers beginning in 1998, they have also established a credit system which allows for ZEV credits to be generated for either excess or early vehicle introduction. Credits generated as early as 1993 hold their full value and are not discounted until the year 2000. Mandated manufacturers are likely to phase into the market or purchase credits from early market vehicle manufacturers. It is generally expected that advanced lead-acid batteries will predominate in certified ZEVs introduced before 1998.

Beginning in 1998, batteries are likely to include advanced lead-acid and nickel-metal hydride. NiCds will also be available during this time period. By 2000, available battery types could also include sodium-nickel chloride and sodium-sulfur. Electric vehicle (EV) batteries that look promising for 2003 and beyond include lithium-ion, improved nickel-metal hydride, and potentially lithium polymer.

2.1 CANDIDATE BATTERY TECHNOLOGIES FOR ELECTRIC VEHICLES

2.1.1 Lead-Acid Batteries

Traditional liquid electrolyte lead-acid batteries have been in use since the 1850s and are fast becoming a technology of the past. Lead-acid batteries produced for conventional starting,

Table 1. Batteries under development for electric vehicle use[1]

System	Specific Energy (Wh/kg) (C/3)	Peak Power (W/kg) (80% DOD)	Energy Efficiency (%)	Battery Life (cycles) (C/3 & C/2)	Self - Discharge (% per 48h)	Production Cost (US$/kWh)[2]	Operating Temperature (°C)[3]	Ability to Fast Charge[3]	Commercial Availability[3]	Existing Recycling Facilities[3]
Acidic aqueous solution										
Lead Acid	30 to 50	100 to 300	>80	500 to 1,500	0.6	70 to 150	Ambient	Yes	Now	Yes
Sealed Bipolar Lead-Acid	55	450	NA	1000+	<15	150	-30° to 65°C	Yes	NA	Yes
Zinc/bromine	70 to 80	35 to 100	75	200 to 2,000	40	100	20° to 40°C	No	No	No
Alkaline aqueous solution										
Nickel cadmium	50 to 60	130 to 235	75	2,000	2	300	Ambient	Yes	Now	Yes
Nickel-metal hydride[4]	70 to 80	175	>70	800+	>10	200	-30° to 60°C	<1h	1995	Yes
Nickel-iron	40 to 60	80 to 150	60	500 to 2,000	3	150	Ambient	Yes	1993/4	Yes
Aluminum/air	220 to 300	160	<50	NA	NA	NA	NA	NA	No	No
Iron/air	100	90	60	500+	NA	50[1]	NA	NA	No	No
Zinc/air	120 to 200	30 to 80	60	600+	NA	85	Ambient	No	No	Yes[6]
Molten Salt										
Sodium-sulfur	90 to 120	130 to 180	85	500+	0	250	350°C	Yes	1995	No
Sodium-nickel chloride	90 to 130	60 to 130	NA	1,000+	NA	250	300°C	Yes	No	No
Lithium-iron sulfide	60 to 130	100 to 200	80	1,000+	NA	150	450°C	Yes	No	Yes[7]
Solid State										
Lithium polymer	85 to 130	80 to 85	80 to 85	100+	0.03	100[1]	Ambient to -120°C	NA	NA	Yes[7]
Lithium-ion[8]	108	216		800+	<1[9]	NA	Ambient to 60°C	Yes[5]	1998	NA
USABC Goals[10]										
USABC mid-term	80 to 100	150 to 200	75	600	<15	150	-30°to +65°C	<6h	1995 required	Required
USABC long-term	200	400	80	1,000	<1	100	-40° to +85°C	3 to 6h	1998 required	Required

1. Reference 1
2. Reference 2
3. Reference 3
4. Reference 4
5. Reference 5
6. Reference 6
7. Reference 7
8. Reference 8
9. Reference 9
10. United States Advanced Battery Consortium

NA = Not available.

lighting, and ignition (SLI) applications are now available in sealed maintenance-free versions that now dominate the market. As noted by the CARB, improved lead-acid batteries in conventional ignition applications have increased energy density 25 percent and battery life 500 percent over the past three years [10]. Lead content has also been reduced over time. When considered for electric vehicle application, however, these flooded traction lead-acid batteries present numerous disadvantages. They are heavy and have low energy densities, they require frequent watering, they generate gases when recharging, and they contain electrolyte in a liquid form.

The lead-acid battery in the deep cycle marine battery configuration has been the battery of choice for most EV enthusiasts, providing a range of 40 to 50 miles in a converted vehicle at a reasonable cost.

2.1.2 Tubular Lead-Acid Batteries

Some conventional lead-acid batteries are constructed with a tubular plate design. The batteries are composed of rows of porous tubes, with long coaxial lead-alloy spines, which are fixed to a header bar. The tubes are made of woven or braided fiberglass sheaths and filled with paste slurry. The tubes are capped at the open end with a plastic plug. Tubular plate technology has the advantage of having greater surface area and more acid than flat plate batteries, which results in a higher energy density and a more efficient use of active material. Advances in tubular lead-acid technology have been made by decreasing the diameters of the spines and the sheaths, which allows for more tubes per plate. This has increased the energy density and nearly doubled the driving [1, 11].

Tubular lead-acid modules have been manufactured by Chloride Electric Vehicles Systems Ltd. Although the modules have a relatively high cycle life (1,000 cycles), they fall below the USABC mid-term goals in most respects, exhibiting poor energy efficiency (68%), low specific energy (33 Wh/kg), low peak power (91 W/kg), and a long recharge time [12].

2.1.3 Advanced Sealed Lead-Acid Batteries

Sealed lead-acid batteries have been in production for almost two decades. They employ traditional lead-acid chemistry and do not require watering. In sealed batteries, gases from charging and discharging recombine with chemicals in the battery, eliminating free electrolyte and significant dry gases resulting from overcharge. Valve-regulated sealed lead-acid (VRLA) batteries offer increased safety, power and life over flooded batteries, which contain excess electrolyte to reduce the need for maintenance and frequent watering. They are maintenance-free, are lighter weight, and are usable in any position [13, 14].

With the advent of the EV market, lead-acid battery manufacturers are aggressively pursuing improvements in their products. For example, GNB, a national manufacturer and recycler of lead-acid batteries, claims a 25 percent improvement in specific energy and a 50 percent improvement in battery life since 1990. The Optima battery has shown particular promise in an EV conversion developed by Alan Cocconi, achieving close to a 100-mile range in both urban and highway drive cycles. The Optima employs a cylindrical design and a lead paste and has a relatively low cost of about $1,500 per battery pack (for 28 12-volt batteries). GNB, Optima, Delco Remy, Exide, Trojan, Sonnenschein, and Gates Energy Products, among others, are actively participating in lead-acid battery development for EV applications [10, 14].

Lead-acid batteries are well-regulated and have an established recycling infrastructure, allowing manufacturers of advanced lead-acid batteries to move forward with manufacturing.

2.1.4 Quasi-Bipolar Lead-Acid Batteries

Quasi-or Semi- bipolar refers to the particular construction and design of the lead-acid battery. This design employs lead plates, stacked in pairs, alternating positive and negative polarities, with each pair separated by a glass mat. Each set of pairs constitutes a "module" that can be interconnected to provide the desired voltage capacity for the battery pack. Electrosource, Incorporated (ELSI), based in Texas, has been developing a quasi-bipolar battery which includes a lightweight mesh grid woven with a fiberglass and lead "yarn", pressed into a plate to become the battery storage element. The term "bipolar" refers to the design of the lead plates, which contain both the positive and negative electrodes on a single plate. This advanced lead-acid configuration offers increased power and energy, a maintenance-free extended cycle life, and the relatively low cost of a lead-acid battery [13, 15, 16].

Another advantage of this configuration is a shorter recharging time. Conventional lead-acid batteries require about 4 to 6 hours for a full charge (from 80% depth of discharge, 220 volt charge). Electrosource claims their quasi-bipolar battery can recharge to half capacity in 8 minutes and take a full charge in half an hour.

This battery is in pilot production in Texas and is currently being evaluated in vehicles. It is likely to be available in the near-term. If produced in large volumes, it will likely be cost competitive with existing lead-acid technology both in vehicles and other conventional applications [17].

2.1.5 Sealed Bipolar Lead-Acid Batteries

Bipolar lead-acid technology has been in development for several years as a secondary battery in several applications, including EVs. The bipolar design incorporates short lengths of glass fibers in the positive active material with a coating of stannic oxide to create conductivity. Both positive and negative electrodes are placed on the same plate, reducing travel distance for the electric current.

SBLA batteries have been tested successfully at the multi-cell level (Arias Research has tested several 12 V modules in the laboratory), but full-size battery packs are not yet available for testing in the laboratory or in vehicles. While SBLA batteries fall short of meeting the USABC mid-term goals for specific energy, they have the advantage of maintaining high power density even at a low state of charge. This advantage would result in an increase in range for EVs over conventional lead-acid batteries by ensuring good acceleration/performance even at low states of charge. SBLA batteries also promise a long cycle life, and, in laboratory tests, have demonstrated close to 1,500 cycles measured at the cell level.

SBLA batteries are smaller and lighter, with higher energy and power density than conventional batteries. However, their pressurized plate construction has presented manufacturing challenges that are currently being addressed but have not yet been resolved. When available, they will offer a long cycle life at low cost without maintenance [10, 14, 15].

Several companies have been developing the original battery concept that originated at the Jet Propulsion Laboratory. Arias Research, Pinnacle Research, Johnson Controls, and Trojan Battery Company, among others, are developers of the bipolar lead-acid battery technology [15].

2.1.6 Nickel-Cadmium Batteries

Nickel-cadmium batteries are used widely in electronics applications. They operate at ambient temperatures and demonstrate greater power and energy density than lead-acid batteries. Their most appealing feature for use in electric vehicles is their longer cycle and calendar life. To date, the non-sealed version of the NiCd battery, which requires watering, has delivered the best performance. Currently, SAFT, a major NiCd battery manufacturer located in France, is demonstrating a sealed version of the NiCd battery which shows promise of reaching full performance [10]. However, thus far their high cost has prevented their wide scale use in vehicles [18].

Older NiCd batteries, which had sintered nickel electrodes, required a 20 to 30 percent overcharge to achieve a full state of charge, and have encountered problems with a "memory effect." When subject to frequent short discharges, they would "forget" their full energy capability and would require reconditioning to recover. They often required frequent watering and as much as 30% overcharge in order to be fully charged. New plastic bonded nickel electrodes do not exhibit this problem and can be deeply or partially discharged without adverse effects.

While NiCds are popular in other countries, they have had limited success in the U.S. In one of the most comprehensive demonstrations of EVs and infrastructure in New Rochelle, France, NiCds have been the battery of choice. In Japan, NiCds have been the primary battery used in demonstration vehicles. In general, NiCds are more appealing in countries with high gasoline prices. However, in the United States, two factors have diminished the potential for the role of NiCds in a large EV market. The cost of NiCds compares unfavorably with relatively inexpensive gasoline, and there is a general reluctance to commit to an increase in cadmium use, however well-managed. Furthermore, while the high cost of NiCds is balanced by a long life, it adds substantially to the initial cost of the EV, exacerbating an existing market barrier [19].

SAFT, ACME, and Japan Storage Battery are the major world producers of NiCds. SAFT is pursuing the EV market for their batteries, and is already manufacturing purpose-built EV battery monoblocks for test vehicle fleets in France [20].

2.1.7 Nickel-Iron Batteries

Nickel-iron batteries have been used widely in vehicle applications. They require periodic watering which has become a disadvantage in today's competitive battery market. NiFe batteries also produce more gas when charging than an unsealed lead-acid battery, creating safety issues for charging in enclosed spaces. Moreover, NiFe batteries require a 30 to 40 percent overcharge to achieve a full charge, resulting in a very poor efficiency rating. NiFe batteries are resilient when overcharged or discharged and can withstand demanding duty cycles. Their weight makes NiFe batteries more suitable for medium- and heavy-duty vehicles [10, 15, 21, 22].

NiFe batteries operate at ambient temperatures and provide a higher specific energy and longer life than lead-acid batteries. While they have a comparatively high initial cost, they could be cost competitive on a life-cycle basis [22].

There have been recent and concerted efforts to develop a nickel-iron battery for EVs. EPRI, Eagle Picher and the U.S. Department of Energy have sponsored programs to develop a sealed version of this battery for use in electric vehicles, but they have not experienced sustained success. Westinghouse is also developing a version of this battery [22].

2.1.8 Nickel-Metal Hydride Batteries

Nickel-metal hydride batteries have been in use since 1970 in electronics applications including computers and cameras. Now in test vehicles with major auto makers and EV upgraders, they have the advantage of high specific energy and long cycle life. An important feature of nickel-metal hydride batteries is that they can be fully discharged with very little impact on battery life. They operate at ambient temperature and do not require maintenance [23].

Nickel-metal hydride batteries are being developed by SAFT, Ovonics, and Panasonic (Japan). Both SAFT and Ovonics batteries are being funded by the USABC and share similar contents: nickel, nickel hydroxide, chromium, vanadium, titanium, zirconium, potassium hydroxide, manganese, and hydrogen. Ovonics has signed an agreement with General Motors for the purpose of producing their batteries in the near term [24, 25].

CARB's recent tests of a converted vehicle with nickel-metal hydride batteries indicate dramatic improvements in range and performance over lead-acid batteries. In a converted gasoline vehicle, the range is extended to over 140 miles, combining both highway and urban driving cycles. In a purpose-built vehicle, unofficial tests indicate a range in excess of 200 miles [26].

2.1.9 Sodium-Sulfur Batteries

Sodium-sulfur batteries have been in development for over 25 years. Ford Motor Company was the initial developer of this battery in the 1960's and 70's. Silent Power (UK), Asea Brown Boveri (Germany), Powerplex Technologies, Incorporated (Canada) and Yuasa Battery Company (Japan) have recently developed this technology. Asea Brown Boveri (ABB) recently discontinued funding for their sodium-sulfur battery development. However, the USABC is currently funding Silent Power's further development of the sodium-sulfur battery, in addition to conducting a production plant feasibility study [15, 27].

Sodium-sulfur batteries offer increased energy when compared to conventional Pb-acid batteries, considered an advantage because energy corresponds to vehicle range. Sodium-sulfur batteries employ molten sodium as the negative electrode, sulfur-sodium polysulfide as the positive electrode and a solid sodium plus ion-conducting electrolyte. Because the batteries operate at very high temperatures (300-350°C) battery developers have designed a thermal management system that encases the battery so that it does not feel hot to the touch. However, the existing thermal management system takes up 40 percent of the battery packÕs mass. When not in use for extended periods of time (i.e., several hours or more), the battery must be plugged in to maintain an adequate level of heat. If the battery temperature drops too far, the battery "freezes", and permanent damage can result. The temperature requirements of the battery will demand readily available infrastructure for "plugging in" when parked as well as continuous energy at low levels to maintain heat [16, 28].

Sodium-sulfur batteries have a potentially high cycle life but only about a three-year proven calendar life, and they are expensive relative to lead-acid batteries. It is for these reasons that they have been considered for high mileage, high use fleet applications. Frequent use and cycling could make this battery economical [22, 28].

Sodium-sulfur batteries are currently being demonstrated in vehicles. Over 20 cars and vans have been operated using these batteries over the last five years in Germany and Canada. In 1994, Ford introduced about 70 Ecostar vans into delivery application demonstrations throughout the U.S. Although there have been isolated incidents of non-injury battery fires with at least two of these test vehicles, the vehicles have performed well [28, 29]. Ford has since upgraded the battery control software and incorporated hardware changes to prevent battery fires in the future.

2.1.10 Sodium-Nickel Chloride Batteries

Like sodium-sulfur batteries, the sodium-nickel chloride battery is a high temperature battery. The sodium-nickel chloride battery depends on a relatively lower temperature, 250-300°C, for conductivity. AEG (Germany) and Beta Research and Development (UK) are developing this battery for use in EVs. Sodium-nickel-chloride batteries have higher energy density to provide increased range, but they have somewhat limited power density at low states of charge, impeding acceleration [15, 30]. Continuing work in the area of power density indicates the potential for improvement.

This thermal technology employs sodium as the negative electrode, nickel chloride as the positive electrode, and a beta alumina solid electrolyte with a molten sodium tetra-chloro-alumina secondary electrolyte. It differs from sodium-sulfur in its tolerance of heat loss. The sodium-nickel-chloride battery can be left unplugged for extended periods of time without incurring damage but must be heated to operating temperature before driving is resumed [10, 31].

Materials for this battery could potentially be available at a low cost, depending on economies of scale. AEG is currently producing the battery in a pilot plant in Germany, and Mercedes-Benz has been testing this battery in their electric vehicles. According to AEG, early demonstrations have shown a calendar life of five years or 50,000 miles, and a cycle life exceeding 1,000 cycles. AEG has stated their intention to provide batteries to the EV market as soon as feasible [23].

2.1.11 Lithium-Metal Disulfide Batteries

Lithium-metal disulfide batteries also operate at high temperatures of 400 to 450°C. They are currently in use in lawnmower applications. The metal electrode is either aluminum disulfide or iron-disulfide; the second electrode is lithium. This battery has the advantage of storing more energy in less space, resulting in a size of only one-third to one-fifth the size of lead-acid batteries, while providing comparable energy [14, 15].

With its high energy, lithium-metal disulfide batteries promise range comparable to gasoline vehicles. However, full size batteries have not yet been constructed and issues of component cost, sensitivity to over-charge and deep discharge, and the impact of corrosion on cycle and calendar life remain.

Battery design for the disulfide system originated at Argonne National Laboratory (ANL) as a monosulfide battery using a porous magnesium oxide or boron nitride separator and a potassium and lithium chloride electrolyte. Research is currently continuing at ANL. In the U.S., SAFT America has a contract with USABC to develop a lithium-iron-disulfide bipolar version to meet their long term battery goals, and Westinghouse also has a continuing program [10, 27].

In Japan, the Ministry of International Trade and Industry (MITI) is funding the Lithium Battery Energy Storage Technology Research Association to develop lithium battery technologies. The Association will receive about $150 million for a ten-year research and development program [5, 10, 24, 32].

2.1.12 Lithium-Ion Batteries

Recent developments in lithium battery technology coupled with the commercial success of Sony's lithium-ion secondary cell have re-energized interest in the potential of this battery to power electric vehicles. Every major battery company in the U.S., Asia and Europe, as well as suppliers for anode and cathode materials, are working on lithium-ion technology, an indication of the excitement about this battery's potential.

In the lithium-ion battery, metallic lithium is replaced with a lithium-ion cell using a carbon intercalation anode with a lithium cobalt oxide cathode. This "Rocking Chair" cell is considered to be safer and to have a longer cycle life than lithium metal combinations. As well as promising a higher level of consumer safety, lithium-ion batteries are good candidates for rapid recharging and have shown a life of over 1,000 cycles in laboratory tests, with a predicted calendar of at least 5 years. To assure long life and safety, multi-cell applications will require a sophisticated battery management system to control charge and discharge.

Initial cost projections for lithium-ion are estimated at two times the cost of nickel-metal hydride and four times the cost of nickel-cadmium due to the cost of the cathode materials. Development on alternative cathode materials is occurring at a rapid pace in an attempt to meet this cost challenge with less costly materials [5, 10, 24, 32, 33].

2.1.13 Lithium Polymer Batteries

Lithium polymer batteries, still in the development stage, show promise for high performance and low cost. Lithium polymer batteries operate at ambient temperatures, but they generate heat during charging and discharging. Developers are challenged to find a way to dissipate this heat without damaging the polymer electrolyte [15, 16, 24].

Early laboratory tests indicate lithium polymer batteries have the potential for a high cycle life, as well as a long calendar life. Developers expect that they will allow vehicle ranges of over three hundred miles on a single charge. That feature coupled with a low cost would minimize the range differential between battery- and gasoline-powered vehicles. Yuasa Battery Company with Canada Hydro Quebec and 3M, W.R. Grace (USABC contract), Valance Technology, Sonyo Electric Company, and Matsushita Battery Industrial Company, among others, are all developing this battery technology [21, 23, 34, 35].

2.1.14 Zinc-Bromine Batteries

The development of zinc-bromine batteries accelerated in the 1960s when the problems of electrical short circuiting and poor efficiency were overcome with technical advances. In the 1980s, this battery achieved over 2,000 charge cycles in laboratory tests. Exxon continued work on this battery and developed the first full size rechargeable pack for demonstration in the Ford ETX electric van. Although Exxon discontinued its development effort, Johnson Controls is continuing to make advances in design, materials and thermal management.

Zinc-bromine batteries offer high specific energy for extended EV range, but they have low power and a short cycle life. They have been demonstrated in vehicles and have performed well for short periods of time. Current versions of this battery require electrolyte to be pumped through the battery with an external pump. The pumping process decreases battery efficiency and leaves the external pump, which contains bromine gases, vulnerable to damage and gas release [16, 36].

Zinc-bromine batteries are being developed by Johnson Controls, Incorporated and Powercell, Incorporated. If technical advances continue, this battery could offer a low cost [10].

2.1.15 Zinc-Air Batteries

Zinc-air batteries offer high energy density for extended EV range at half the cost of lead-acid batteries, but they have low power density and a short life. They have been considered as a battery to be coupled with an additional power source such as a high power battery or possibly even a future mechanical power source. Zinc-air batteries require scrubbers, which are bulky, to purify the air electrodes [23].

Southern California Edison Company has demonstrated a Chrysler van coupling Dreisbach Electromotive Incorporated (DEMI) zinc-air batteries with nickel-cadmium batteries with limited success [10, 15].

Another version of this battery technology requires mechanical recharging that would result in a canister of depleted electrolyte in the form of a zinc slurry. Developers intend for the slurry to be exchanged at a service station. This would require an extensive infrastructure for consumer use that has not yet been explored for California or the U.S. According to Electric Fuel Limited of Israel, Germany has indicated an interest in this version of the battery and has placed an order for 25,000 of these batteries [15, 24].

Other developers and researchers of zinc-air technology include Pinnacle Research Institute, Lawrence Berkeley Laboratory, Westinghouse, and Energy Resource Corporation [15].

2.2 EXISTING RECYCLING INFRASTRUCTURE

Recycling infrastructures in the United States currently exist only for lead-acid, NiCd, NiFe, and to some degree NiMH batteries. Of the batteries discussed in this study, only lead-acid batteries are used universally in automobiles. Automotive NiCd batteries are commercially produced, but are only used in a small number of prototype EVs. The existing infrastructure for lead-acid batteries is capable of accommodating all types of lead-acid batteries, including advanced lead-acid and SBLA. Forty-two states currently have legislation requiring that spent lead-acid batteries be recycled and that they be accepted by battery retailers and/or wholesalers in exchange for new lead-acid batteries. A summary of state laws regarding the return of spent lead-acid batteries is found in the Appendix [37].

Lead-acid batteries have been actively recycled since the 1920s [38]. In most states, they are now banned from municipal solid waste landfills, but relaxed regulations have made the recycling system so accommodating that lead-acid batteries are now being recycled at a rate of about 95% [37]. Consumers simply return spent batteries to an authorized retailer, wholesaler, service center, collection center, or directly to the recycler. The retailer or wholesaler is not required to obtain a hazardous waste generator or storage permit, but simply sends the batteries to a secondary lead smelter for reclamation. In California, however, the shipment must be accompanied by a Bill of Lading, which identifies the name and address of the generator (owner of the collection center) and the transporter, the number of batteries in the shipment, and the date of shipment. Transporters of lead-acid batteries are not required to register themselves as hazardous waste transporters, and do not need to fill out manifest papers to accompany the shipment [37]. Regulation begins only when the batteries reach the recycler.

As the current regulations stand, all batteries presently on the market, as well as those under development for EVs, meet the characteristic definition of hazardous waste, and would be subject to extensive hazardous waste transportation, treatment, and disposal regulations. Only vehicular lead-acid batteries currently enjoy the regulatory exemptions regarding collection and transport necessary to facilitate the convenient recycling system already in place for these batteries. There is hope, however, that other batteries may soon share the same benefits as lead-acid batteries. The EPA has introduced the "Universal Waste Rule" (40 CFR, Part 273), which will exempt all types of batteries and certain household hazardous wastes and recalled pesticides from parts of the Resource Conservation and Recovery Act (RCRA). When finalized, the new rule will waive certain restrictions that are presently placed on batteries. Manifests will not be required for shipments of spent batteries, and generators and transporters of spent batteries will not be required to register for an EPA identification number. The Universal Waste Rule is expected to be finalized in January 1995 [39]. The new rule will not take effect, however, immediately after its finalization. Because it is not a federal law, which would preempt existing state laws, but only a federal rule, most states would not be required to adopt the rule if it is more lenient than their existing code, since most states, including California, have authority to adopt environmental regulations stricter than those at the federal level. The new rule would appear in the federal code soon after its finalization, but it may take several months to several years before each state decides whether or not to adopt it. California could make a bold step in this respect, since it is often the state that leads the nation in the environmental arena.

A list of existing lead-acid recycling facilities in the U.S. is given in Table 2, along with their current capacities and estimated future capacities. GNB and RSR Corporation are the two recyclers of lead-acid batteries in California, together processing 12-13 million spent lead-acid batteries per year in California alone (over 200,000 tons). A significant percentage of these batteries are from out-of-state. By 1995, both companies estimate that together they will be able to handle nearly 300,000 tons of spent lead-acid batteries per year. Projected increases in spent lead-acid batteries in California, based upon a scenario in which all EVs are lead-acid powered, are shown in Figure 1. Even assuming that 100% of electric vehicles sold in California will be run on lead-acid batteries, and accounting for varying battery life between internal combustion vehicle (ICV) batteries (four years) and EV batteries (2 years), the projected amount of spent lead-acid batteries for 2005 is only 262,344 tons. GNB and RSR estimate that they will be able to handle that amount by next year. Currently both facilities receive lead-acid batteries from sources other than passenger vehicles as well as from out-of-state. They are restricted from much further expansion of their facilities by the South Coast Air Quality Management District (SCAQMD). In fact, GNB is under an abatement order of the SCAQMD which limits GNB's production to 90% of full capacity. Therefore, in order to accommodate increases in demand beyond 2005, the two companies may need to cut back on their out-of-state business and/or consider other recycling processes, such as electrowinning, which have fewer air emissions [40, 41]. It is important to note, however, that while electrowinning processes produce fewer air emissions, they do produce greater amounts of wastewater as a result of the washing techniques used (see discussion of lead-acid recycling, Section 2.3.1). As a trade-off for reduced air emissions, these facilities would most likely need additional wastewater treatment capacity.

A more likely scenario involves a certain percentage of the new EVs being powered with NiCd batteries. A study performed by the Cadmium Council, Inc. estimates that commercially available EV NiCds, manufactured by such companies as the French owned SAFT-NIFE, and the German owned DAUG-Hoppecke, could power as much as 40% of the new EV fleet in California and in several northeastern states which have also passed similar ZEV laws. The only existing NiCd recycler in North America is INMETCO of Ellwood City, Pennsylvania. All other NiCd recyclers are located in Europe, Japan, and Korea. For a complete list of NiCd recyclers and their capacities,

Table 2. Existing battery recycling facilities

Recycler Name	Location	Battery Type Recycled	Recycling Technology Used	Recycling Cost per Ton (U.S.$)	Current Recycling Rate tons/yr	Estimated Capacity (1995 or later) (tons/yr)
ToxCo[1]	B.C., Canada	Lithium	Hydrolysis	4000-8000	830	
Recovery & Reclamation[2]	Pecos, TX	Zinc	Physical Separation	Not Disclosed	12,000	18,000
GNB[3]	Los Angeles Dallas, TX Columbus, GA	Pb-Acid	Smelting	400-500	105,000	168,000
RSR Quemetco, Inc.[4]	City of Industry, CA Dallas, TX	Pb-Acid	Smelting	400-500	100,000	150,000
Sanders Lead	Troy, AL	Pb-Acid	Smelting	NA	NA	NA
Skuylkill Metals	Baton Rouge, LA Forest City, MO	Pb-Acid	Smelting	NA	NA	NA
Refined Metals	Indianapolis, IN Memphis, TN	Pb-Acid	Smelting	NA	NA	NA
The Doe Run Company[5]	Boss, MO	Pb-Acid	Smelting	400-500	130,000	185,000
~~Kinsbursky Bros.[6]~~	~~Anaheim, CA~~	~~Pb-Acid/NiCd~~	~~Only Dismantling~~	~~200-500~~	~~24,000~~	~~48,000~~
Japan Recycle Center[7]	Japan/Korea	NiCd	Pyrometallurgical	500-1,500	3,000	~5,000
Toho Zinc Co.[7]	Japan	NiCd	Pyrometallurgical	500-1,500	2,000	not limited
Kansai Catalyst[7]	Japan	NiCd	Pyrometallurgical	500-1,500	500-1,000	~2,000
INMETCO[8]	Pennsylvania	NiCd/NiFe/NiMH	Pyrometallurgical	600-800	2,250	10,000
SAFT/NIFE[7]	Sweden	NiCd	Pyrometallurgical	1,500	1,500	No expansion plans
SNAM/SAVAM[7]	France	NiCd	Pyrometallurgical	490	6,600	8,800
TNO[7]	The Netherlands	NiCd	Hydrometallurgical	1,670	~800	~1,600
Hydrometal[7]	Belgium	NiCd	Hydrometallurgical	1,670	100-150	~300

1. Reference 7
2. Reference 6
3. Reference 40
4. Reference 41
5. Reference 42
6. Reference 43
7. Reference 44
8. Reference 45

NA = Not available.

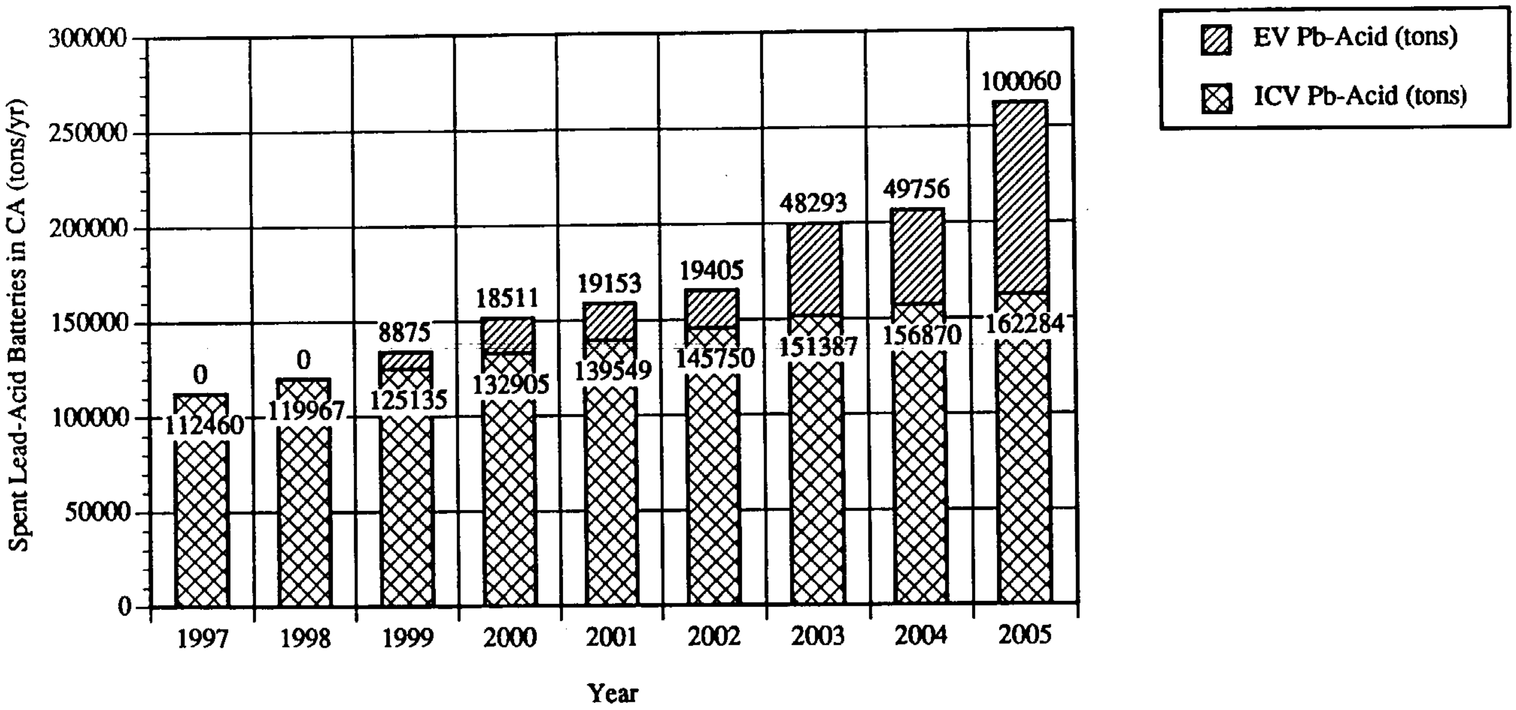


Figure 1. The tonnage of California-generated lead-acid batteries is projected to increase due to continued conventional vehicle growth and EV recycling. This scenario assumes 100% of EVs are powered by lead-acid batteries. Recycling capacity in the state is expected to grow from the current 200,000 to 300,000 tons/yr by 1995.

see Table 2. The combined capacity of all the world's NiCd recyclers is presently about 26,000 tons per year with expansion capabilities up to 44,000 tons. At this time, however, none of the existing facilities are at full capacity. It is estimated that they are only receiving about 11,000 tons per year. If 40% of California's new EVs would be NiCd powered, with an average NiCd life of 7 years, then there would be an increase in recyclable NiCd batteries in California of about 8,800 tons by the year 2005, and about 46,000 tons by 2010. Existing facilities could accommodate the near-term increase, but may encounter difficulty meeting increases beyond the near-term. In addition, small sealed cell and industrial NiCds are currently only being recycled at a rate of 21% worldwide, with an additional 41,400 tons annually that are not being recycled. With expanded recycling of these batteries plus the influx of EV NiCds, expansion of facilities in the U.S. will become a necessity. INMETCO now handles only 2,250 tons of nickel containing batteries, including NiCd, NiFe, and a small percentage of NiMH batteries; it is permitted to handle only 10,000 tons. As a further hindrance, an agreement of the International Basel Convention is placing barriers on the exportation of hazardous waste from the country of origin [46, 47].

To date, there is no comprehensive collection system for nickel-cadmium batteries in the U.S. since they do not benefit from regulatory exemptions as lead-acid batteries do. For example, California's hazardous waste laws do not prohibit businesses from using electric vehicles powered by nickel-cadmium batteries and sending those batteries to INMETCO in Pennsylvania for recycling. However, in order to transport spent nickel-cadmium batteries, the business would have to register itself as a hazardous waste generator, fill out manifests, hire an EPA registered transporter, pay taxes, and file reports just as all hazardous waste generators do. These hurdles are quite significant for a business that is not otherwise a generator, and most such businesses would simply not bother with the expense and the learning necessary to accomplish these tasks correctly, and would probably opt not to buy electric vehicles. However, if the battery recycling process were as simple as the lead-acid battery recycling process, in which the batteries are simply taken back by the retailer or dealer installing the new batteries, the recycling process would remain transparent to the user and there would be no disincentive associated with battery handling. At this time, large quantity generators of hazardous waste (those generating more than 1,000 kg per month) must obtain an EPA hazardous waste generator identification number from the state environmental agency. This number must appear on the manifest which accompanies the batteries from the point where they are first declared waste to the final disposal or recycling destination. The transporter of the batteries must be an EPA registered hazardous waste hauler with an appropriate identification number. The ultimate recycling, processing, or disposal facility must have an EPA treatment, storage, or disposal (TSD) facility permit. Each party involved in the "cradle-to-grave" path must receive, sign, and maintain for three years, a copy of the manifest. The signatures help to guarantee that the batteries are classified, packaged, shipped, and handled correctly and aid in determining legal responsibility in the event of a violation [48].

Several cities in 14 states (AL, FL, KS, KY, MI, MN, MO, NH, NJ, NY, PA, VA, WY, and WA) have pilot collection programs for household battery waste (dry cell batteries only, of all chemistries); but in many of these plans, the batteries are simply sent to a hazardous waste landfill or incinerator [49]. States that adopt such collection programs can enact Pilot Project rules which temporarily render the RCRA manifest rules null and void for batteries. It is not known whether these rules allow for the collection of automotive and EV batteries, as this depends on how the state defines the term 'battery' within the rules. The Portable Rechargeable Battery Association (PRBA) has developed a program for the nationwide collection of small sealed cell NiCd batteries generated in consumer waste (Figure 2). The program will be administered by a company called the Rechargeable Battery Recycling Corporation (RBRC). The RBRC will sell licenses to use the RBRC seal to NiCd battery manufacturers who wish to participate in the program. Consumers can then return used NiCd batteries to designated retail collection points. From the collection centers

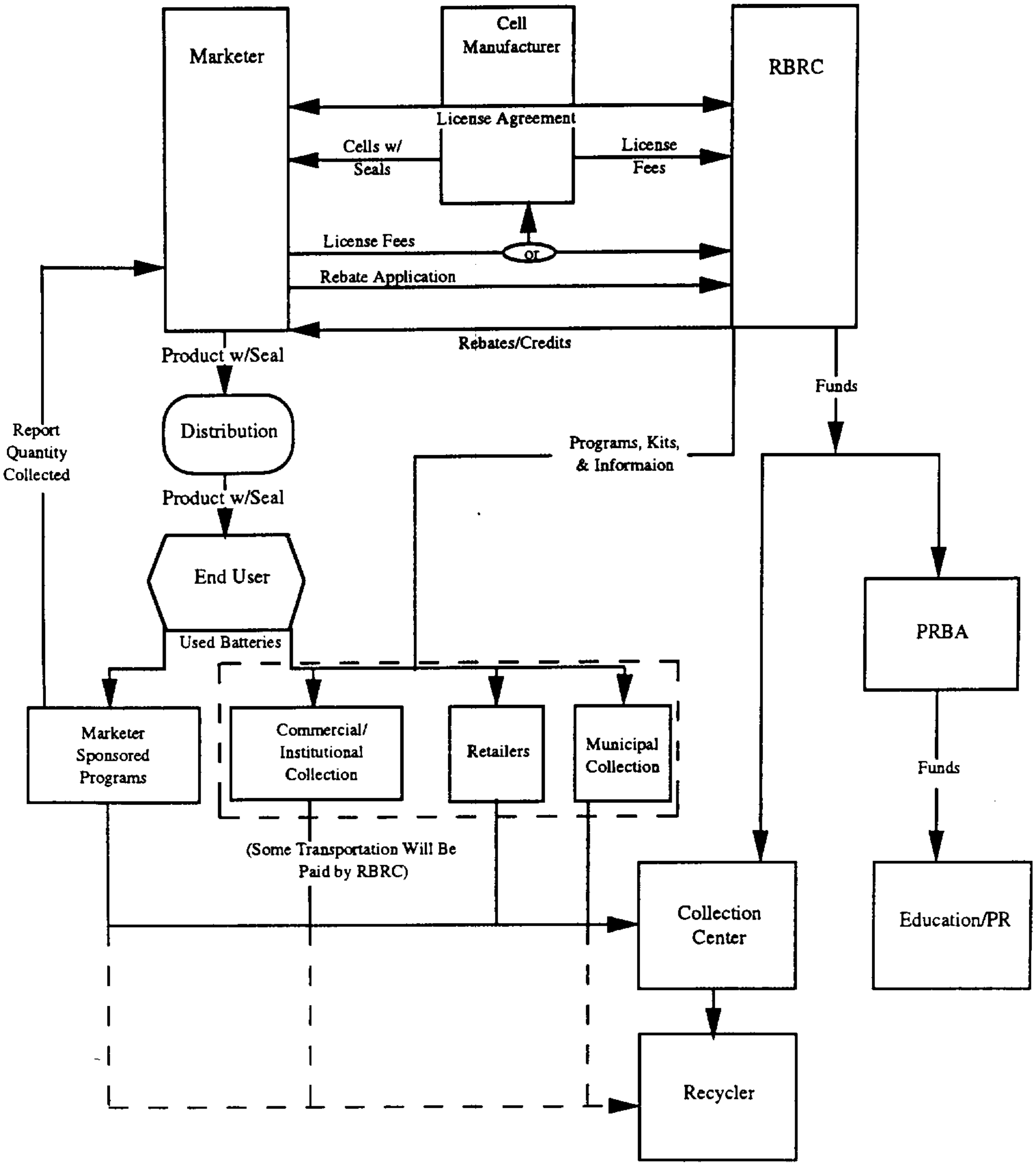


Figure 2. RBRC National Battery Collection Program funding and operations

they will be transported to recyclers [50, 51]. The program was originally slated to begin September 1, 1994, pending the adoption by the EPA of the Universal Waste Rule, which will exempt household hazardous waste and batteries of all types from regulation until the waste reaches the recycler. This would enable much smoother retail collection, since collection centers would not be required to have hazardous waste generator or storage permits or manifest the shipment of the batteries. The final ruling on Part 273 is anticipated by January of 1995. Since Part 273 has not been adopted before the scheduled start of the RBRC program, the RBRC has selected 13 states to be part of the first phase of the program. These states are Maryland, Wisconsin, Minnesota, and the states that make up the Northeast Recycling Council (NERC), Connecticut, Delaware, Maine, Massachusetts, New Hampshire, Pennsylvania, Rhode Island, and Vermont. Thus far Minnesota and New Jersey have adopted the RBRC program. In the event that the Universal Waste Rule does not pass as expected, it is likely that the states with existing successful collection programs will extend those programs rather than end them. Other states that do not currently have pilot collection programs could expedite matters by adopting pilot programs while the Universal Waste Rule is under regulatory review in those states. Although the RBRC program does not initially plan to encompass the collection of industrial and automotive NiCd batteries (the program only covers small sealed cell NiCds), they will be in active discussions with EV battery manufacturers to encourage them to participate in the program [47, 50].

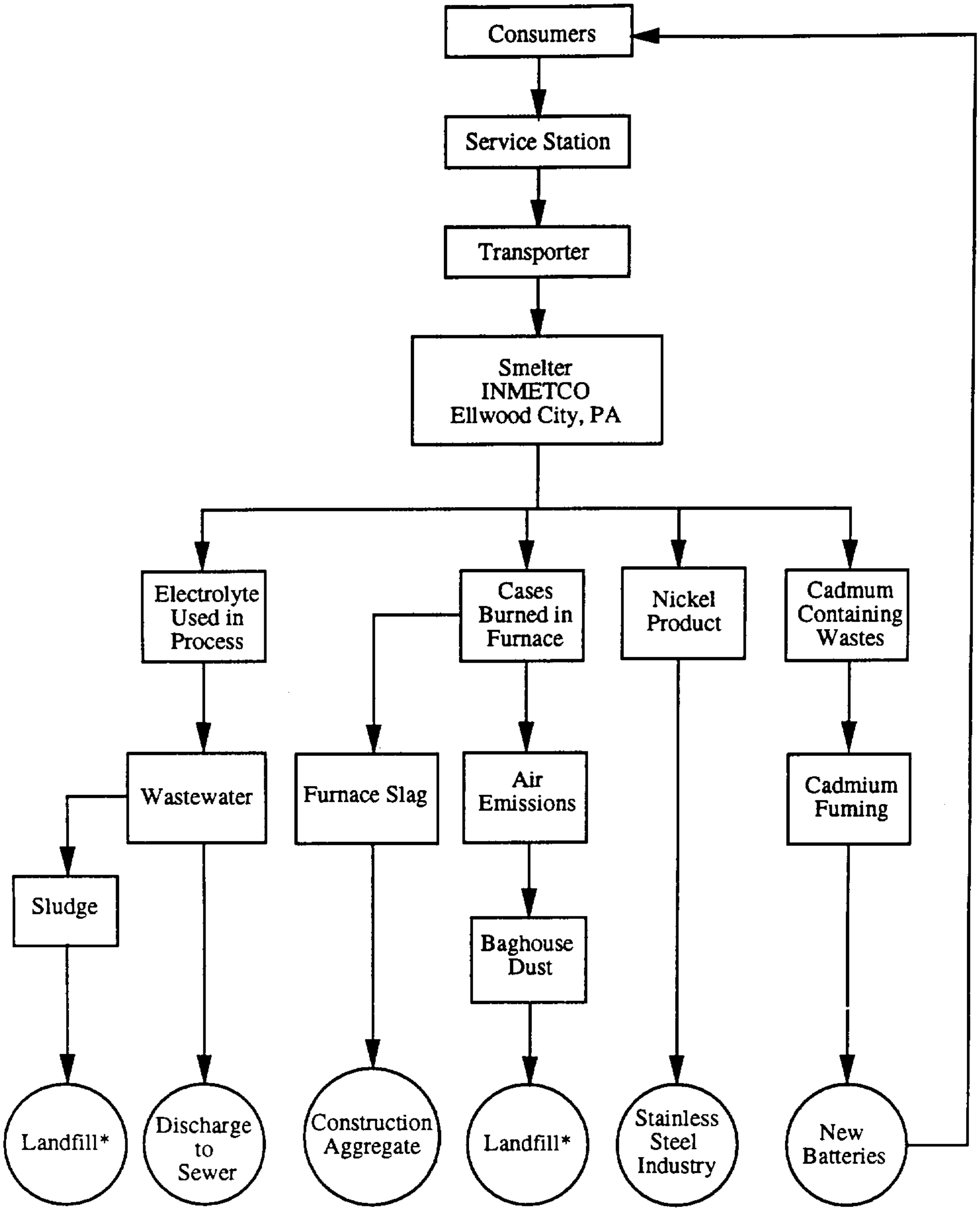
Figure 3 shows how a possible collection infrastructure for NiCd batteries might look if Part 273 is adopted. The service station/collection center depicted in Figure 3 could collect batteries of different chemistries and separate them for shipment to their respective recycling facilities if the batteries are labeled properly so that their chemistry is easily identifiable. Japan is experimenting with a color coding system to identify NiCd batteries by a uniformly accepted color imprinted on the battery case [47]. A state regulation requiring color labeling would facilitate more efficient collection and retrieval of spent batteries. Color codings would be universally understandable, regardless of language. A system like this could be adopted internationally, such as color coded symbols that are used today for hazardous materials.

2.3 RECYCLING TECHNOLOGIES

2.3.1 Lead-Acid

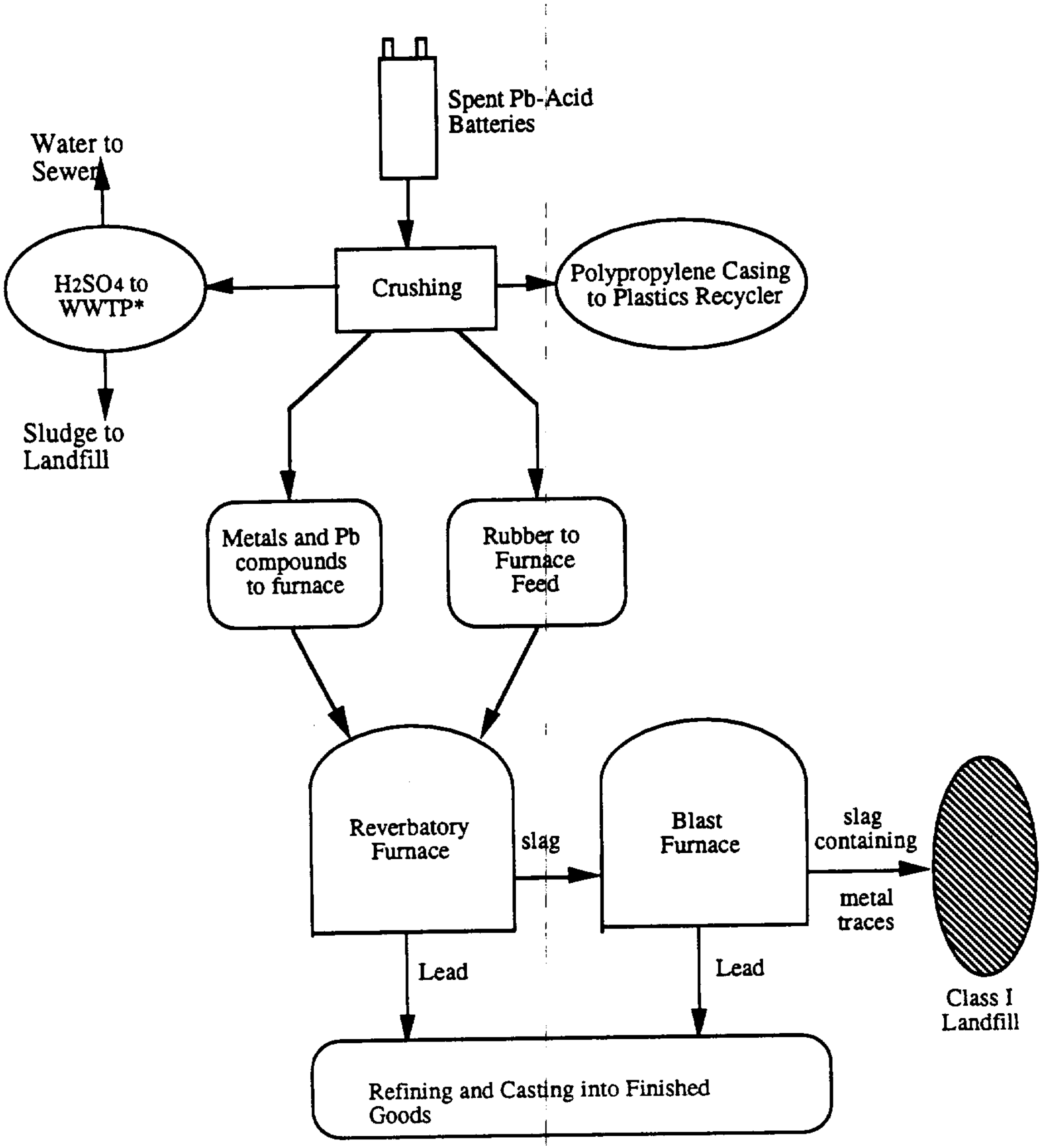
2.3.1.1 Smelting

The conventional method to recover lead from spent lead-acid batteries is smelting. The process of secondary lead smelting is a well developed technology. As batteries come into the smelting plant, they are first broken and separated into constituent parts, which are then sent to different processes for further treatment. At GNB, for example, batteries are conveyed onto a hammermill where they are broken open, and the component parts are separated (Figure 4). The sulfuric acid electrolyte is neutralized and sent to a wastewater treatment plant (WWTP) for pH adjustment, clarification, and filtration. The treated water is then discharged to the Los Angeles County sewer. The remaining solids are separated into four parts. Polypropylene cases are sold to a plastics recycler for remanufacture as battery cases and other consumer products. Rubber cases are substituted as feed for the furnace. The metals and lead compounds are sent into the reverbatory furnace. The metal compounds form a slag which separates from the compounds. The metals are removed and further refined. The remaining slag and lead compounds are sent to a blast furnace. Lead is recovered from the blast furnace, and another slag residue, containing traces of metals, is sent to a Class 1 Hazardous Waste Landfill. The metals recovered from furnaces are sent to the refinery, after which they are made into finished products, such as new lead-acid batteries [40]. The Doe Run Company, a secondary lead smelter in Missouri, adds a different twist to the



* Municipal or Class 1 Hazardous Waste Landfill, depending on composition.

Figure 3. Possible nickel-cadmium battery infrastructure road map



*WWTP = Wastewater Treatment Plant

Figure 4. GNB's lead-acid battery recycling process

battery separation process. Instead of neutralizing the sulfuric acid, which produces a sludge that usually ends up in a landfill, they convert the acid to pure anhydrous sodium sulfate. This can be used in the manufacture of laundry detergents and glass. Doe Run produces about 8,000 tons of sodium sulfate per year from spent battery electrolyte [43].

2.3.1.2 Electrowinning

In the late 1970s, RSR Corporation patented an electrowinning process to recover lead without toxic air emissions. In the early 1980s, RSR successfully ran a pilot plant, and it now plans to build a full scale plant with a capacity of 36,000 tons/yr near its existing smelting plant in Indianapolis. Most of the air pollution from smelting results from the high temperature pyrometallurgical processes used to treat the lead paste to remove sulfur. The RSR process uses wet chemistry to remove the sulfur and precipitate the lead out from the paste. The process begins with battery wrecking (Figure 5), which involves first removing the acid electrolyte and sending the drained batteries to a roll crusher. The pieces are sent to a sink-float separator, where the floating polypropylene cases are removed for recycling. The paste and metals sink and are scraped off by a drag conveyor. The paste and metals are separated so that the paste, which contains 54% $PbSO_4$, 40% PbO_2, 2% metallic Pb, and 4% other constituents, may be desulfurized (Figure 6). The insoluble $PbSO_4$ is converted to $PbCO_3$, which is even more insoluble, by addition of Na_2CO_3, according to the following reaction:

$$PbSO_4 + Na_2CO_3 \rightarrow PbCO_3 + Na_2SO_4$$

The $PbCO_3$ thus formed and the PbO_2 from the original paste are decomposed to soluble PbO by heating in a drying oven above 325°C. After drying, the PbO is leached in a H_2SiF_6 electrolyte according to the following reaction:

$$PbO + H_2SiF_6 \rightarrow PbSiF_6\ H_2O$$

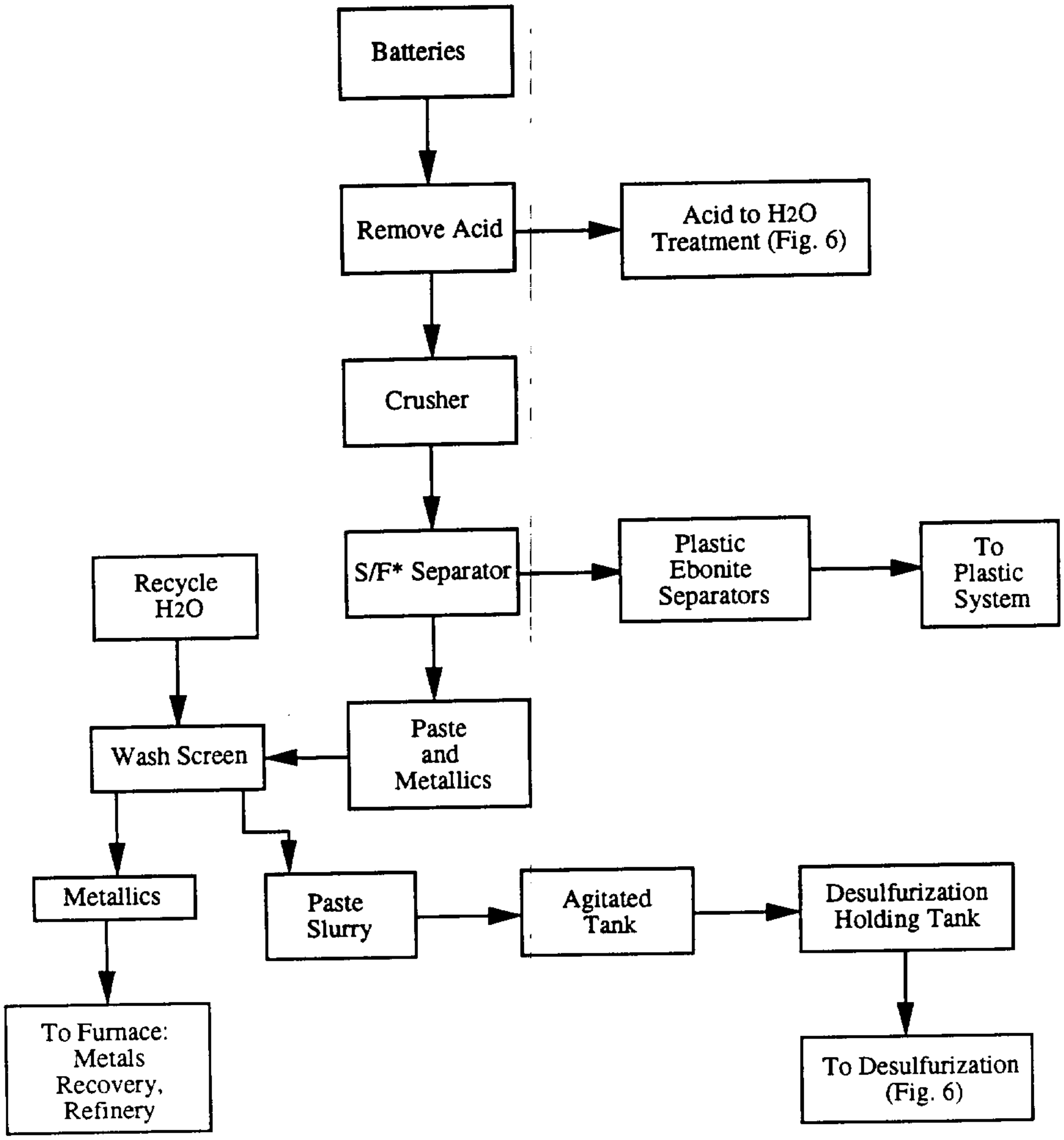
The pregnant electrolyte is then sent to the electrowinning process, which employs RSR's patented PbO_2 coated graphite anodes. The current density at the pilot plant was 100 A/m^2, with a cell voltage of 2.5 V. One potential problem in the electrowinning process is the formation of insoluble PbO_2 on the anode, as follows:

$$4e^- + 2PbSiF_6 + 2H_2O \rightarrow PbO_2 + Pb + 2H_2SiF_6$$

RSR has overcome this problem by adding small amounts of arsenic to the electrolyte, thereby changing the reaction to:

$$4e^- + 2PbSiF_6 + 2H_2O \rightarrow 2Pb + 2H_2SiF_6 + O_2$$

The oxygen produced is vented to the atmosphere. The lead recovered is more than 99.99% pure and was produced at an output rate of 100 tons/day in the pilot plant [52]. In late 1994, GNB began conducting a laboratory scale study of a lead-acid electrowinning process, which is focusing on the effects of various electrolytes on the life of the electrowinning anodes. If the study is successful, efforts will move towards establishing a pilot plant [40].



* S/F = Sink/Float

Figure 5. RSR's lead-acid battery wrecking and paste separation process (Reference 52)

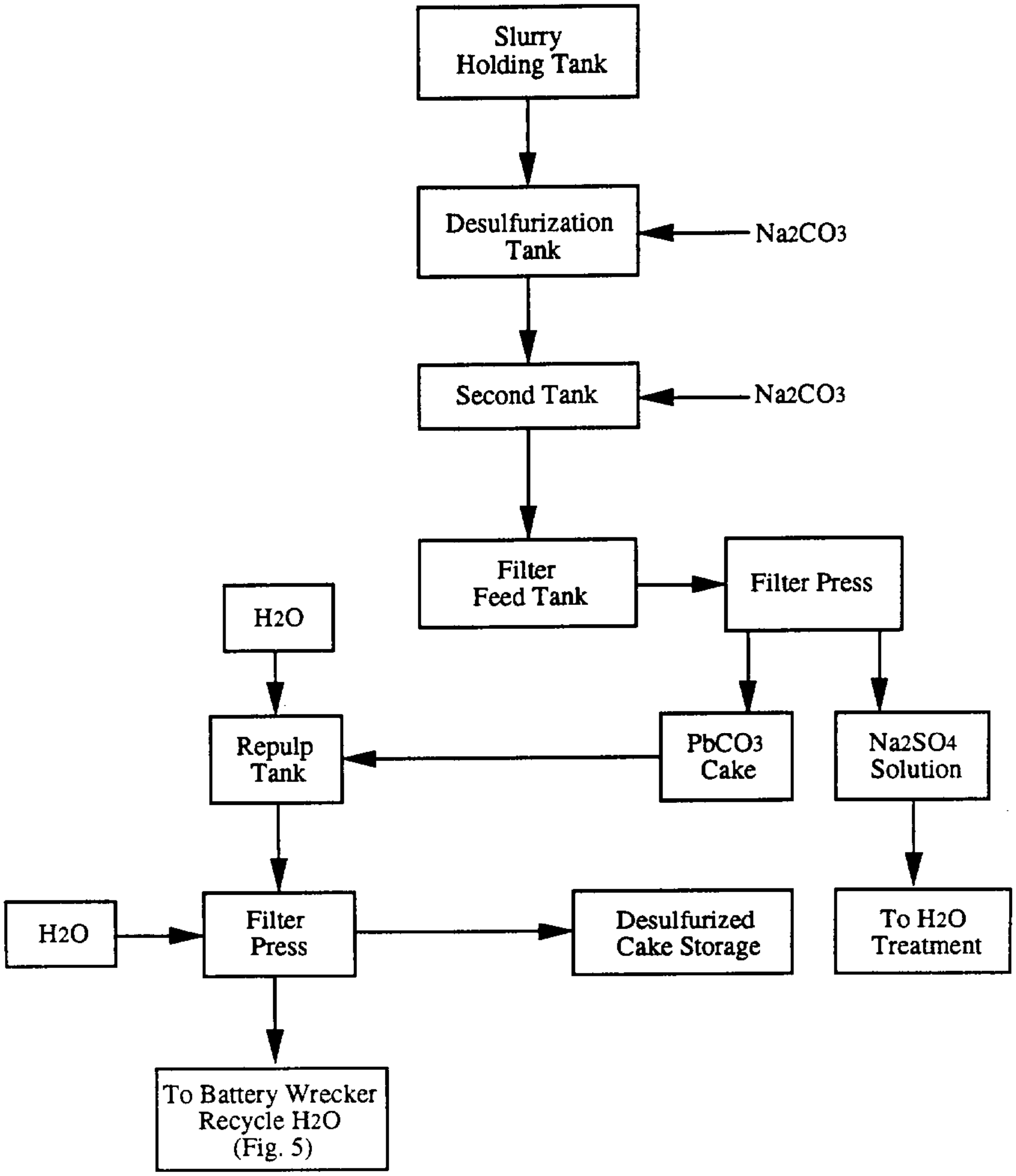


Figure 6. RSR's lead-acid battery paste desulfurization process (Reference 52)

In addition to smelting and electrowinning, EPRI is working on technologies to extend the life of lead-acid batteries. Electrosource, Inc., of Austin, Texas, in a collaboration with EPRI, is developing an advanced lead-acid battery that promises to last three to four times longer, provide 50% to 80% greater specific energy, and deliver two to three times more power for better acceleration than conventional lead-acid batteries. Called the Horizon®, the battery gets its name from its design. The plates are oriented horizontally, rather than vertically, to eliminate electrolyte stratification and shedding of the active material from the grids. The Horizon® can be recycled using current recycling technology for conventional lead-acids. After extensive research, scientists at Electrosource and EPRI are confident that the Horizon® will be able to meet several of the USABC mid-term goals for EV batteries. Researchers at Electrosource and EPRI expect the Horizon® to be in commercial production by 1995 [53].

2.3.2 Nickel-Cadmium

INMETCO recycles NiCd batteries (Figure 7) by sending them through a shredder and conveying the shredded material to a pelletizing disk. The pellets are then sent to the rotary hearth furnace (RHF), which operates at 2,300°F. The RHF reduces the oxidized metals to metallic form. The reduced metallic pellets are transferred to the submerged electric arc furnace (EAF), the smelter. The pellets are smelted to extract the metal components. The molten metal is then cast into so-called "pigs" for use as a stainless steel remelt alloy. Only the nickel is reclaimed from NiCd batteries at INMETCO. Cadmium is not reclaimed at this facility for recycling, but is collected from the flue dust in pollution control devices and is sent to other refining operations for reclamation. The process also produces a non-hazardous slag which is sold as a construction aggregate. Since INMETCO is not solely a battery recycler, but is primarily a stainless steel recycler, they also accept NiFe batteries to reclaim the nickel and iron for use in the remelt alloy. INMETCO's thermal recovery technology has been determined by the EPA to be the best demonstrated available technology (BDAT) [54].

By contrast, the SNAM/SAVAM facility in France and the SAFT plant in Sweden are dedicated NiCd battery recyclers (Figure 8). The SNAM/SAVAM facility breaks down each battery into the constituent parts and produces a nickel product, a cadmium product, and separated casings. The polypropylene casings are recycled. The cadmium is vaporized and condensed to a liquid, where it is then cast into ingots or sticks at more than 99% purity. It may then be further refined to 99.99% purity and sold. The nickel is recovered as ferronickel for use in stainless steel [44].

2.3.3 Nickel-Iron

Although other automotive batteries under development for use in electric vehicles either do not have existing recycling facilities or are not being actively recycled, small sealed cell and industrial NiFe batteries are already being processed at the INMETCO facility, using the same process used for NiCds. The products are used in the same stainless steel remelt alloy, and sold to the stainless steel industry. Thus the technology exists to recycle the automotive variety of this battery [54]. Currently the capacity is very limited, as INMETCO is presently the only facility in the U.S. accepting this battery type, but the company has expressed a willingness to devote more of its existing capacity to EV battery recycling, which would include NiCd, NiFe, and NiMH batteries [55].

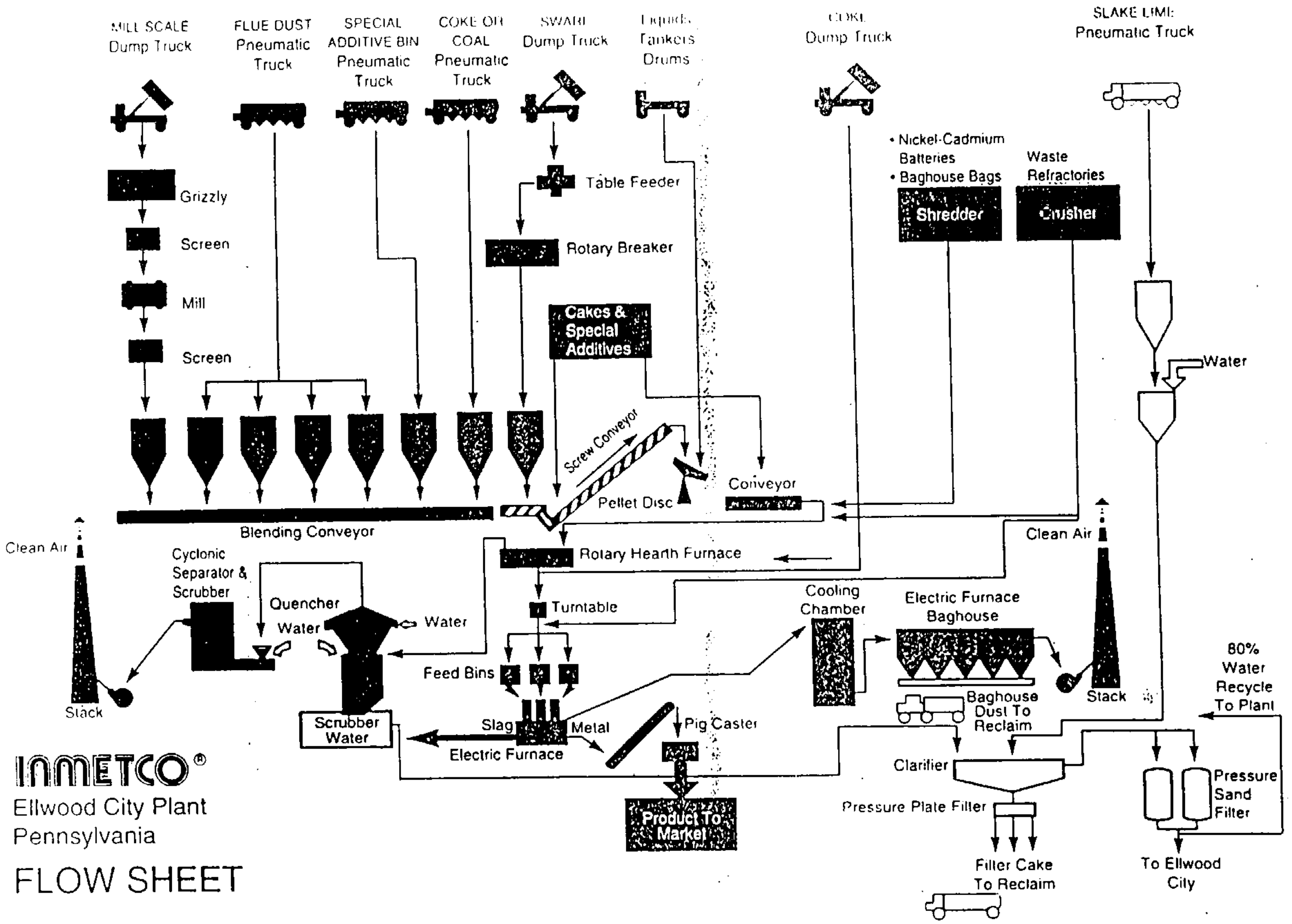


Figure 7. INMETCO NiCd process flowsheet (Reference 54)

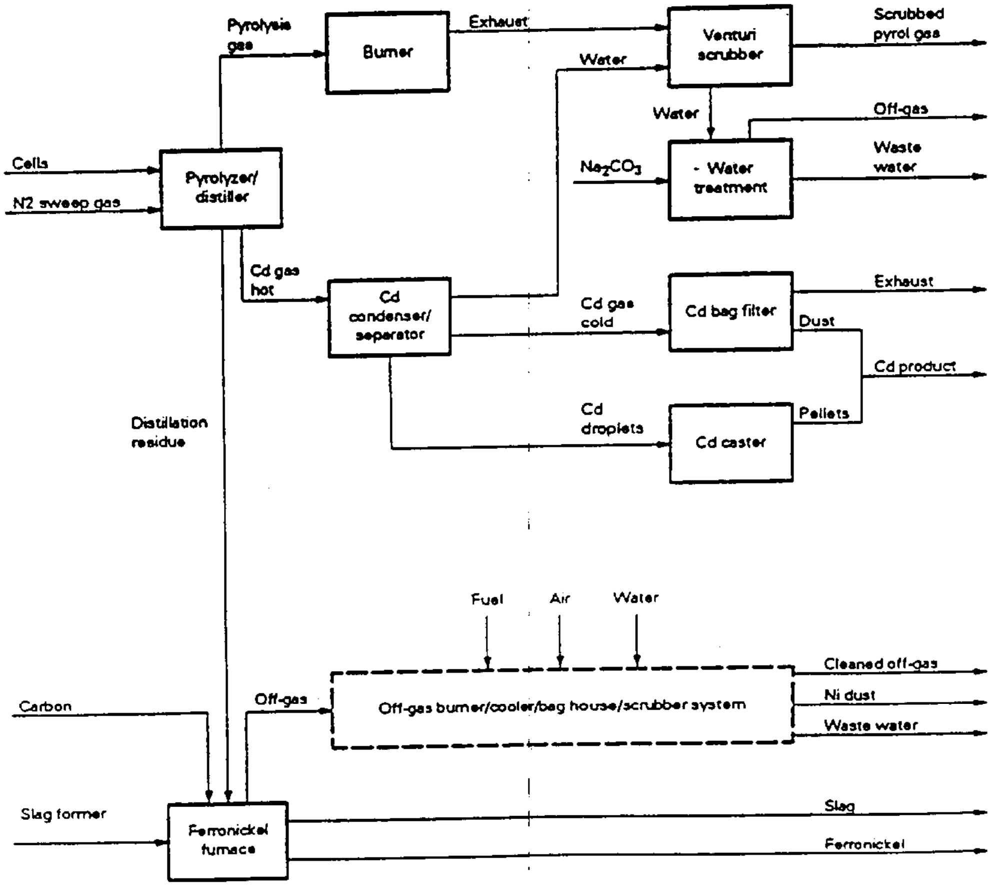


Figure 8. SNAM/SAVAM/NiCd process flowsheet (Reference 55)

2.3.4 Nickel-Metal Hydride

NiMH batteries have been difficult to recycle because of their contents. Two types of NiMH batteries are produced, AB_2 and AB_5 types. AB_2 types usually contain some mix of Fe, Cr, Co, Mn, Ni, Ti, V, Zr, and Al. AB_5 types contain a mix of Ni, Fe, Cr, Co, Mn, Al, and the rare earth metals, known as misch metal. However, the exact make-up of the metal hydrides is often not known, and is sometimes proprietary information. According to the U.S. EPA toxicity characteristic leaching procedure (TCLP) test, NiMH batteries have been determined to be non-hazardous at the federal level. The TCLP test determines a waste's toxicity based on how much will leach out of a landfill into the surrounding soil or groundwater. If the leachate amount exceeds a certain limit, the waste is defined as toxic. The results of this test are shown in Table 3 [56]. However, California and the European Community have established stricter toxicity levels, and the limits for nickel concentration in waste would classify NiMHs as hazardous. Columns 9 and 10 of Table 3 are the limits of the California Soluble Threshold Limit Concentration (STLC) procedure and the Total Threshold Limit Concentration (TTLC) procedure, respectively. These tests are similar in purpose to the federal TCLP test, but the waste extraction procedures of the California tests are more effective and thorough than the federal test.

Limited capacity exists today to recycle NiMH batteries. Existing NiCd recycling plants could handle a small amount of NiMH batteries. The INMETCO plant has the ability to recover Ni, Fe, V, Co, Cr, and Mn, all of which are typically found in NiMHs. These metals could be recovered in ingots and sold to the stainless steel industry. The Zr, Ti, and Al also found in NiMH batteries would most likely not be recovered at the facility, but would be disposed of in the metal slag. Switzerland's Recymet plant, which handles unsorted household batteries, could accept some NiMH batteries but would require process modifications to recover V, Zr, Ti, and Cr. The SAVAM facility in France could accept NiMH batteries, but probably cannot recover metals other than Ni and Fe at this point. Clearly, the existing facilities will not be able to feasibly recover all of the valuable metals found in NiMH batteries, based on their processes now in use. Due to the political expediency and increasingly strict regulations regarding export of hazardous waste, additional capacity to recycle NiMH batteries in the U.S. will be needed if these batteries are produced on a large scale.

Table 3. TCLP results of metals found in conventional and NiMH batteries[1] (all TCLP results are reported in mg/L)

	Alkaline	Mercury	NiCd	AB_5	AB_2	EPA HWL[2]	EC HWL[3]	CA STLC Limit[4]	CA TTLC Limit (mg/kg)[4]
Cd	0.20-1.20	<0.01	48-290	0.01-1.41	<0.01-0.08	1.0	0.5	1.0	100
Cr (VI)	<0.05	<0.05	<0.05	0.16-0.24	0.09-0.23	5.0	0.5	5.0	500
Hg	0.01-0.12	92	<0.01	<0.002	<0.002	0.2	0.2	0.2	20
Ni	0.07-0.35	0.36	62-160	610-920	320-590	None	2.0	20.0	2,000

1. Reference 56.
2. EPA HWL = EPA Hazardous Waste Limit for the TCLP.
3. EC HWL = European Community Hazardous Waste Limit (proposed for 9/18/92).
4. Reference 57. STLC = Soluble Threshold Limit Concentration; TTLC = Total Threshold Limit Concentration.

New processes designed specifically for the recycling of NiMH batteries have been researched by the U.S. Bureau of Mines (USBoM) and Teledyne Wah Chang Albany (TWCA), of Albany, Oregon. Two possible NiMH recycling options are shown in Figures 9 and 2-10. The first process, developed by the USBoM, involves shredding the batteries, washing to remove the KOH electrolyte, and dissolving the metals in an acid digester to selectively precipitate the metals. This process leaves some undissolved nonhazardous solid residues, such as the battery insulators, which are disposed of in a municipal solid waste landfill. The products would be salts of nickel, cobalt, and the rare earth metals. There are no air emissions produced by this process, and the acid solution can be treated to levels of the primary drinking water standards for metals and pH, and discharged to a municipal sewer [58].

The second alternative, developed by TWCA, requires shredding the batteries and washing to remove the KOH. The drained batteries are then gravimetrically sorted into organic and metallic components by density-based flotation. The metallics are dried and melted, producing an alloy rich in nickel. The slag would contain Zr, Ti, and Al. Some potential uses for this alloy are in certain nickel-based or steel alloys, which would require further refining [56].

Whatever option is employed will be based on economics [56]. NiMH battery manufacturers are hopeful that the stainless steel and specialty steel industries will be able to absorb the products of NiMH recycling. Researchers at USBoM and TWCA believe that this view is overly optimistic, since the quality of the alloy produced will be low, and it will be in competition with higher grade alloys produced by other recycling processes.

2.3.5 Sodium-Sulfur

A typical sodium-sulfur (NaS) battery contains steel, aluminum, copper, ceramic insulation, sodium, sodium polysulfides, chromium compounds, sulfur, alumina, and graphite. Based on these components, NaS batteries would be considered hazardous by EPA. Sodium and sodium sulfides are hazardous because of their reactivity and corrosivity. Sodium polysulfides are considered corrosive in the molten state, but could be corrosive in the solid state if they come in contact with water. In California, NaCl and Na_2CO_3 are considered hazardous based on toxicity, since results of fish bioassays have proven that these salts have an LD_{50} less than 5,000 mg/kg, which is the limit listed in 22 CCR 66261.24 (a)(3) [59]. In addition, there is a human safety problem with transporting molten sodium at an operating temperature of 350°C on a passenger vehicle. There have been incidents of the cell packs catching fire inside a vehicle. Furthermore, sodium polysulfides could be hazardous because of their corrosivity. The only concentration standard that applies to NaS batteries is for chromium (Cr), which could be toxic based on the TCLP test. Even though hexavalent Cr is more toxic than trivalent Cr, the standard (5 mg/L) regulates total chromium, because trivalent Cr can oxidize to the hexavalent form in the environment. Depending on whether or not the Cr concentration exceeds the standard, recovery of Cr may or may not be necessary from a regulatory standpoint, but is preferred from an environmental standpoint.

Several treatment and disposal processes have been researched at Sandia National Laboratories for NaS batteries, but the process chosen will depend on regulatory requirements, environmental impacts, and economic factors [60]. One potential process could recover sodium tetrasulfides through direct recycling, but the market for these is small and the price low. Another process could indirectly recover sodium dithionite ($Na_2S_2O_6$â$2H_2O$) through reclamation/recycling. Sodium dithionite has a much larger market and a higher price [60]. From an environmental and regulatory viewpoint, direct recycling is preferred because it can be exempted from certain RCRA permits if the process meets the EPA definition of recycling. But in order for the process to meet

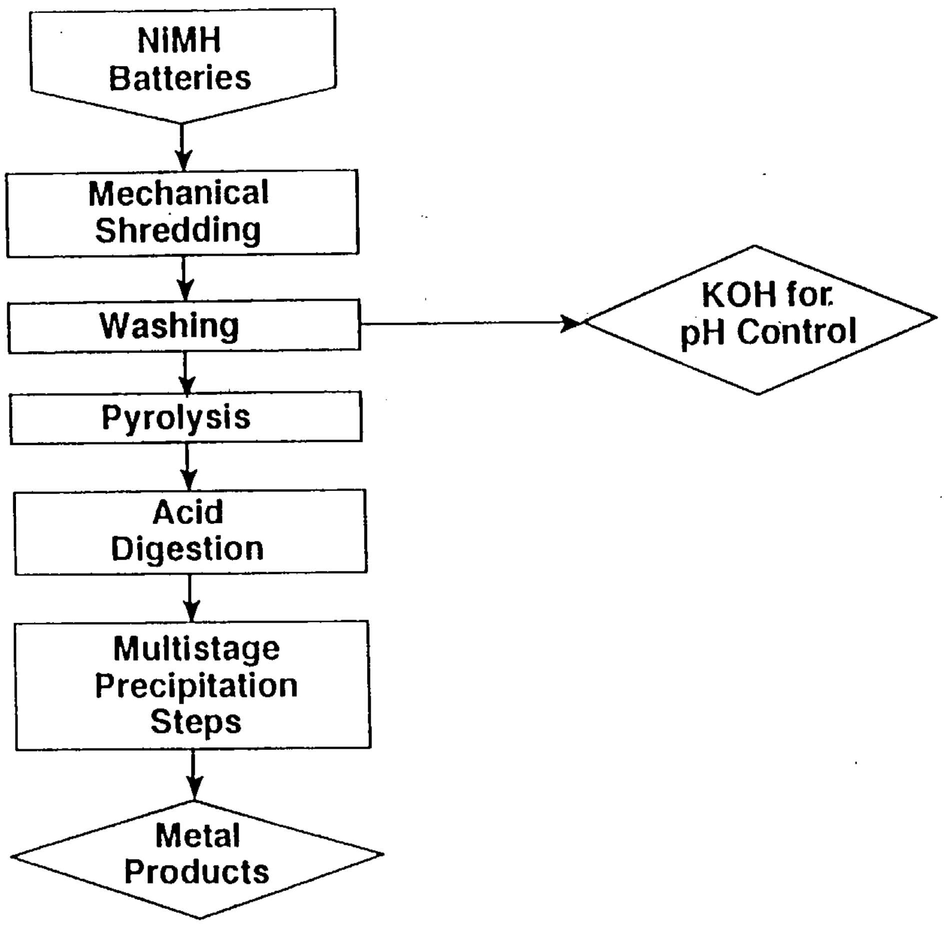


Figure 9. U.S. Bureau of Mines hydrometallurgical process for recycling NiMH batteries (Reference 56)

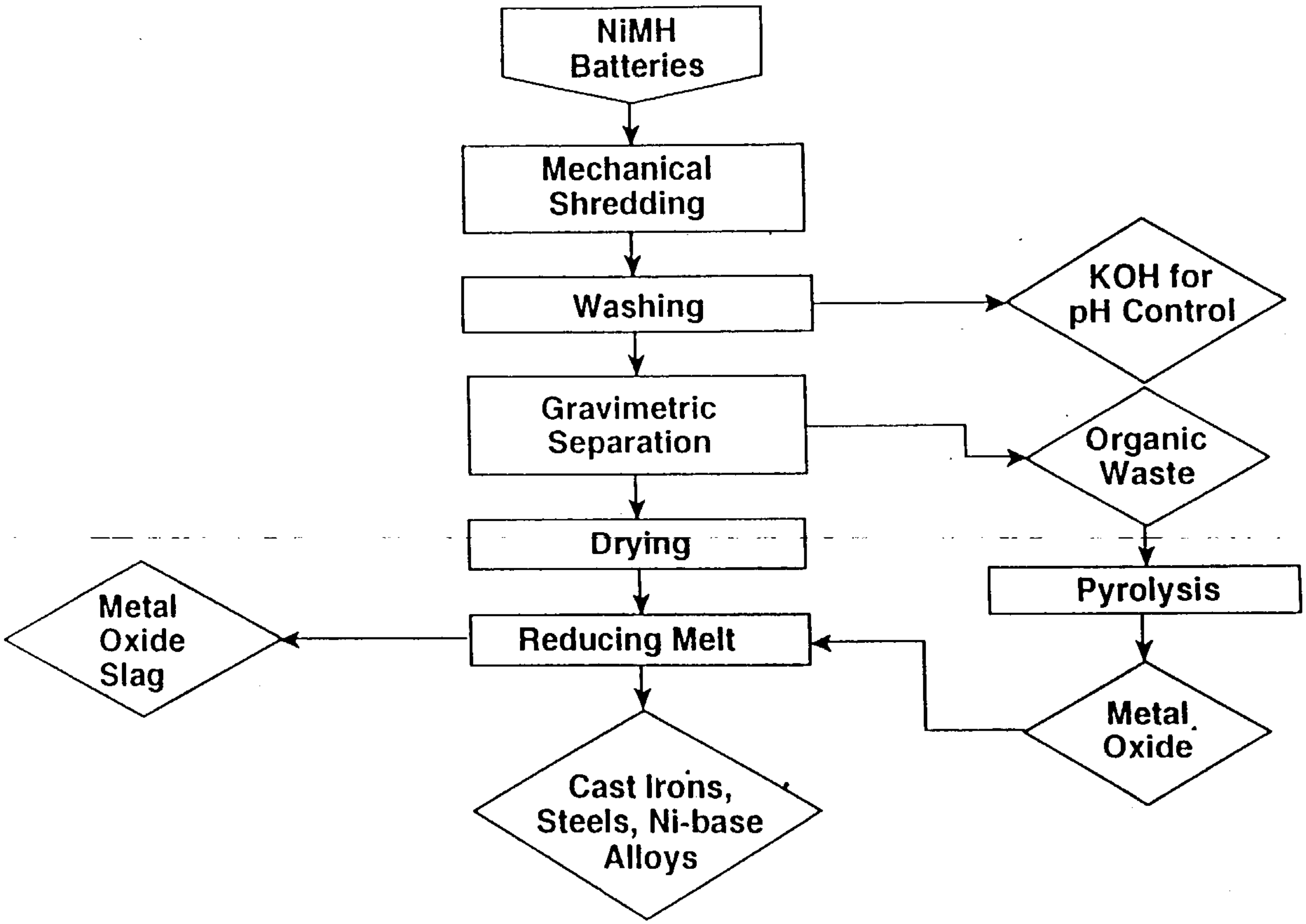


Figure 10. TWCA process to recycle NiMH batteries by melting (Reference 56)

the definition, a market must exist for the end product of that process. The processes studied at Sandia are described below.

1. Recovery of Sodium Polysulfides: The cells are crushed to recover sodium polysulfide. Addition of excess sulfur oxidizes any Na_2S_3 to Na_2S_4. The polysulfides are dissolved in water, and the aqueous solution is dried and drummed for shipping. This process may require a RCRA permit if no market for the Na_2S_4 exists [60, 61]. Sodium polysulfides had a limited market in the past for use in color dyes. However, since the reunification of Germany, the former East Germany has been able to provide cheaper materials for color dyes, thus squeezing sodium polysulfides out of this market [62].

2. Sodium Recovery/Sulfur Reclamation: Prior to disassembly, the cells are charged, although recharging may be only 90% efficient. The cells are heated to 100°C, and the sodium is removed from the battery matrix. The outer cell container is then removed, and the sulfur is hydrotreated to yield H_2S. The H_2S is oxidized, via the Claus process, to elemental sulfur. If a market for this product exists, no permit would be required. In addition, the hazardous products could be reused by battery manufacturers without further processing. If removal of chromium were required (based on results of the TCLP), a RCRA permit would be necessary [60, 61].

3. Oxidation of Polysulfides to form Sodium Sulfate, Sulfur, and Sodium Chloride: The cells are discharged to yield Na_2S_3, though discharging will not be 100% efficient because some cells are electrically isolated. The cells are opened and sodium hypochlorite (NaOCl) is added. This oxidizes the polysulfides to sodium sulfate and elemental sulfur. The solution is filtered, and Na_2SO_4 and NaCl are produced. A potential market for these products exists, and if they are sold for reuse, no permit would be required. However, the products are not hazardous, and could thus be landfilled or incinerated. In this case, a permit would be required [60, 61].

4. Acidic Oxidation and Claus Process to Yield Sodium Sulfate and Elemental Sulfur: The cells are discharged as above. The cells are then opened and sulfuric acid is added to form sodium sulfate, H_2S, and elemental sulfur. The H_2S is oxidized, via the Claus process, to elemental sulfur. This product is not hazardous, and could thus be reused or landfilled/incinerated. The landfill/incineration option would necessitate a permit [60, 61].

In addition to the previous work at Sandia, Silent Power in the United Kingdom has developed and recently patented a process for recycling NaS batteries. The process, depicted in Figure 11, is very similar to number 4 above. The advantage of this process over the Sandia process is that the cells can be in any state of discharge when they are shredded. The process would probably meet the EPA definition of recycling since there is a market for sodium sulfate and elemental sulfur [63]. Little has been published so far on the Silent Power process, since it has only recently been developed. Unfortunately, although the chemistry for all of these processes has been worked out, the cost feasibility of recycling NaS EV batteries on a grand scale has not been studied to a satisfactory degree.

In the past, Asea Brown Boveri (ABB), who is working with Ford on the Ecostar van project to develop NaS batteries, operated a pilot scale recycling plant in Germany. In their process, the outer stainless steel casings were removed and sold as stainless steel scrap. The inner cell casings, composed of aluminum with a thin chromium inner lining, were punctured and the cells were placed in a hot paraffin bath at 110°C to melt out the sodium. The recovered sodium was of very high

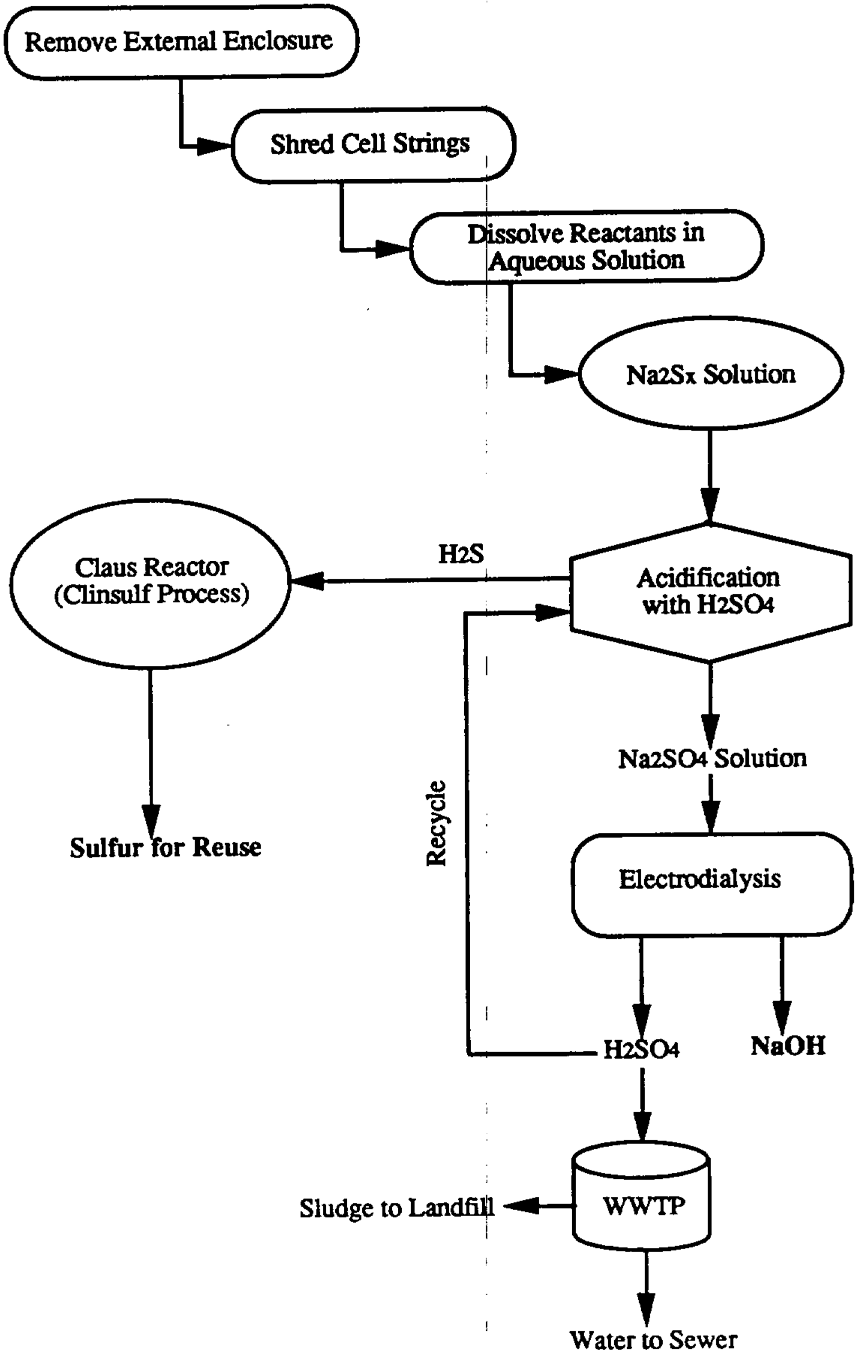


Figure 11. Silent power sodium-sulfur acidification process

purity and could be sold back to the sodium metal industry. The aluminum casings could be sold to aluminum recyclers, and the remainder of the cells were incinerated. ABB has since closed the recycling plant in Germany and does not have plans to begin producing NaS batteries commercially after the completion of the Ford contract [62].

2.3.6 Sodium-Nickel Chloride

Since sodium-nickel chloride batteries are not yet in commercial or pilot scale production, any processes for recycling these batteries are in preliminary developmental stages at this point. One process for recycling sodium-nickel chloride batteries, which has been tried successfully on a laboratory scale, involves a joint venture between German companies Mercedes-Benz and AEG. This process involves breaking the batteries open in the discharged state to separate the materials. In the discharged state, the batteries contain NaCl, nickel powder, $NaAlCl_4$, and ceramic. In the event of incomplete discharge, there may also be some residual $NiCl_2$ remaining. The soluble compounds, such as $NiCl_2$, NaCl, and $NaAlCl_4$, are dissolved in a leaching solution. Nickel chloride is precipitated out of solution as nickel sulfide using H_2S. The nickel sulfide is then returned to a metallurgical process to extract the nickel metal. The NaCl and $NaAlCl_4$ are removed by crystallization and can be reused in new batteries. The nickel powder, steel casing scrap, and ceramics are separated by sieving and magnetic separation. The nickel powder and steel casings are sent for further pyrometallurgical treatment. AEG reports a 90% salvage rate for the nickel powder, which is at least 95% pure on a laboratory scale. The ceramic may be disposed or reused in new batteries. The next step in the development of this process is a scale-up to a pilot plant after commercial production of the AEG "ZEBRA" sodium-nickel chloride battery. Commercial production is expected to begin in time for the 1998 mandate [64].

Another possible method of recycling Na-$NiCl_2$ batteries is based on their similar structure to NaS batteries. The materials could be recovered by recharging the batteries, as in process 2 above, to remove the elemental sodium from the battery matrix. The $NiCl_2$ could be removed after the cell container is broken open. These materials may need to be further purified or processed. If the products are pure enough, they may be able to be reused in new Na-$NiCl_2$ batteries.

2.3.7 Lithium Batteries

A U.S. company, Toxco, with a facility located in British Columbia, Canada, has been recycling military size and household lithium batteries since September 1993. Toxco has received $LiSO_2$, $LiFeS_2$, Li vinyl chloride, $LiMnO_2$, and a very small quantity of Li polymer batteries in sizes ranging from AAA up to 250 lbs. The process is based on a hydrolysis reaction. The batteries are first frozen in liquid nitrogen at -320°F for three to four hours to reduce the reactivity of the lithium. The reactivity at -320°F is only a minute fraction of the reactivity at room temperature, so the batteries are essentially inert at that temperature. They are then fed on a conveyor to the shredder. From the shredder they proceed to an aqueous reaction tank where the various lithium compounds are reduced to LiOH. Carbon dioxide is added to convert the lithium to lithium carbonate. Other agents can also be added to produce other insoluble lithium salts, such as lithium sulfide. The metal and plastic cases are separated from the solution where they can be sold to recyclers. Other packaging materials are not separated from the salt solution. The entire solution is sold to the cement industry as an additive for concrete, because the salts increase the elasticity of the concrete. It is not necessary to separate the carbon black and other cell materials from the lithium salts, because they are simply burned off in the cement kiln. Toxco has achieved salvage rates of about 65% of the total input as a recovered, salable product, with the remaining 35% being non-hazardous solid waste or offgases. The process apparently generates no hazardous air emissions or wastewater. All of the process water is repeatedly reused. The solid waste produced passes the TCLP test and can be safely and legally disposed of in the United States or Canada. Currently Toxco can accommodate about 50,000 to 90,000 batteries per month with weights ranging from size AAA to 250 lbs. The average battery weight in the process input is now around 2.5 lbs, so the facility is handling between 1,000 to 2,000 tons annually and anticipates no major problems with expansion. Facilities were difficult to permit in the United States, since there were previously no similar facilities to compare it to for an environmental impact study. Now that the plant has been operating successfully, it may be easier to establish additional plants in the U.S., if public opposition to location of facilities in their immediate vicinity (the "Not In My Back Yard" or NIMBY factor) can be overcome. The process has been approved by the U.S. EPA, Environment Canada, and the Ministry of British Columbia [7].

2.3.8 Zinc Batteries

Zinc-air batteries produce zinc oxide in the discharged state. Recovery and Reclamation, a company based in Texas, processes small household and industrial railroad sized zinc-air batteries. The process is simple and involves no smelting, so there are no toxic air emissions. The batteries are simply broken open, and the cells are washed with KOH to flush off the ZnO. The ZnO/KOH solution is then run through a filter press to remove the KOH. When the ZnO has dried, it can be sold to a zinc company, such as U.S. Zinc, or to a plating company [6]. Metallic zinc can be recovered from ZnO either through smelting or electrowinning, but secondary zinc is usually recovered by smelting and distillation.

2.4 MARKET ASSESSMENT

The economic feasibility of recycling is as important as the development of recycling technology. A battery recycling system can either be market-driven or regulation-driven. In the market-driven scenario, the material values upon reclamation support the recycling costs. In the regulatory scenario, the recycling adds a net cost to the system. This cost may be borne directly by the user, through disposal fees or higher battery costs, or it may be subsidized by the government. While a market system is generally preferable because it minimizes administrative waste and will evolve to the least-cost recycling system, it depends on consistently high material prices which may not exist for many battery constituents under study. In addition, a market-driven system may not result in the highest possible percentage of battery components being recycled.

Market conditions for metals and other products of battery recycling will affect the success of a battery recycling program. Prior experience with newspaper and plastic recycling programs has shown that collection of the material is only the first step in establishing a recycling program. A market must also exist for recycled materials. For instance, mandates that established a minimum recycled content help provide a market for recycled paper and plastic. In the case of aluminum cans, recycling success varies with the market price of aluminum. Deposits on bottles and cans help to further recycling incentives by increasing the values of the collected materials and helping to finance collection operations. Another obstacle to recycling paper, bottle glass, and cans is the low unit value for containers and paper. In contrast, copper wire and bulk aluminum are readily recycled because scrap values make recycling (and even theft) quite cost attractive. Among currently recycled materials, the issue of market demand has been resolved to some extent for recycled newspaper, plastic, and glass through mandated use of recycled products. In the case of aluminum, the post recycling use of aluminum has never been an issue since aluminum is an industrial commodity that is used on a large scale. Only a low market price in prior years has curtailed collection activities.

Recycled products from batteries can be categorized by their degree of processing during recycling. The following categories apply to batteries:

1. Pure metals or materials (lead, cadmium, sodium, sulfur)
2. Metal alloys (ferronickel alloys)
3. Partially processed materials (casing chips, cadmium dust, metal, etc.)
4. Waste materials (furnace slag, Na_2S_3, treated electrolyte)

To begin our market assessment, we projected a scenario for the near-term (year 2000), mid-term (year 2005), and long-term (year 2010) EV market in California. For each battery, we estimated what percentage of the EV market it might attain, based on the current state of development, the battery technology, the current recycling status, projections from battery manufacturers, and the extent of support the battery receives from auto manufacturers, researchers, and the USABC. Table 4 summarizes these estimated projections for light-duty vehicles (LDV) in California. A view of the market saturation of each type of battery at the end of its useful life is depicted in Figure 12. This graph shows a projection of the raw tons of spent batteries from California vehicles that will be available for recycling of all battery types, which is useful to evaluate if the recycled products will flood the market. It also serves as an aid in determining if additional recycling capacity will be needed.

2.4.1 Lead-Acid

The existing system for lead-acid battery recycling is largely regulation-driven. In most states, the recycling of lead-acid batteries is mandated and a deposit is required on purchases of all new lead-acid batteries. However, the market does play a large role in the efficiency of lead-acid recycling. Secondary lead smelting has been profitable at times, but throughout the past few decades, the commodity prices of lead have fluctuated, making it difficult to economically maintain a high rate of recycling. During the 1980s, the price of primary lead dropped dramatically, causing several secondary smelters to go out of business. The rate of lead-acid battery recycling fell from 85% to 69%, but currently the rate is assessed at around 95% [38]. The market for secondary lead exists, and under economically favorable conditions, lead-acid battery recycling presents a closed loop market. Newly manufactured lead-acid batteries today contain nearly 70% secondary lead, and it is expected that lead-acid batteries will still dominate the battery market for conventional vehicles.

2.4.2 Nickel-Cadmium/Nickel-Iron

Nickel-cadmium batteries could be a major contender for near-term EV use since the EV models can be commercially developed today and the NiCd recycling infrastructure is already well established. Today, only a small fraction of NiCds produced are the automotive type. Whether or not NiCd batteries will be able to significantly penetrate the EV market depends on the world supplies and prices of nickel and cadmium, the markets for recovered materials, and environmental concerns regarding cadmium toxicity.

The main market for the recovered nickel from NiCd, NiFe, and NiMH batteries is for use in a ferronickel alloy used in the production of stainless steel. The current domestic demand for ferronickel is about 16,500 U.S. tons per year [65]. If NiCds power only 5% of the EV fleet up to the year 2000, as predicted in Table 4, then there should be about 990 tons of recyclable NiCds in the year 2005 and about 1000 tons in the year 2007 (after this year, the amount of remaining NiCds

Table 4. Summary of EV battery market share estimates

Battery	Estimated Market Potential		Estimated Market Share of New LDVs & MDVs (%)		
	Maximum Long Term Market	Comment	Near Term 2000	Mid Term 2005	Long Term 2010
Lead-Acid	100	Current market share	38	0	0
Sealed Bipolar Lead-Acid	70	Now in pilot production	15	10	6
NiCd	40	Cadmium Council estimate, expensive	5	0	0
NiMH-AB_2	30	Performs as well as NiCd but less toxic. Pilot plant being built.	10	10	7
NiMH-AB_5	30	Performs as well as NiCd but less toxic. Pilot plant being built.	10	10	7
NaS	50	Supported by Ford	2	0	0
Na-$NiCl_2$	50	Built by AEG for Mercedes	0	0	0
LiFeS	20	Long term substitute for Na-$NiCl_2$ corrosion problems	0	0	0
LiFeS2	30	Disulfide has higher energy, corrosion problems	0	0	0
Zn/Air, Al/Air	10	Primary battery, not rechargeable	0	0	0
Li Polymer	50	Promising long-term battery, some current military applications	0	30	50
Li Ion	50	Low cost, high energy. Currently used in motorcycles and consumer products.	20	40	30
New light- and medium-duty EVs in California			37,595	203,350	217,440

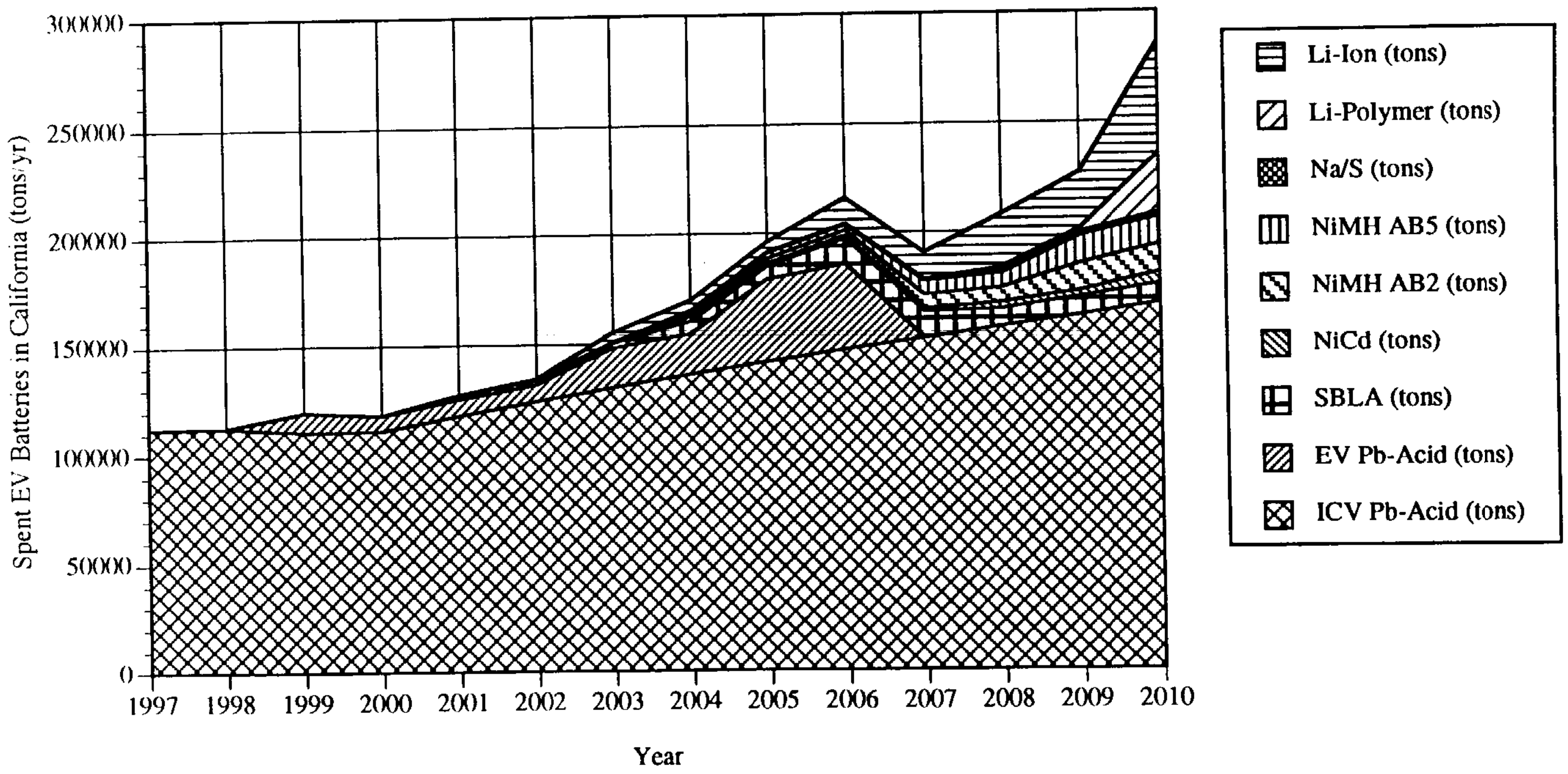


Figure 12. Level of market saturation from California spent EV batteries

should be insignificant). INMETCO is presently producing about 22,800 tons annually of a stainless steel remelt alloy containing nickel, iron, and chromium from various sources, including nickel containing batteries [54]. The demand from the U.S. stainless steel industry is expected to rise by about 2 or 3% per year in the near future. The present price for nickel is near an all-time low (near U.S. $3.00/lb) [47] because Russia recently entered the global market and just opened up its large nickel reserves. However, economists are optimistic that the price will begin to rise soon, as demands for nickel are increasing in the U.S. and Asia. Total U.S. demand for all nickel forms is estimated at 144,000 U.S. tons [65]. The nickel usage in batteries currently accounts for only a very small fraction of this demand [66]. In 1989, the estimated world nickel reserves were approximately 54,000,000 tons, with large untapped deposits still available. The resources exist to supply the electric vehicle market, but there is some doubt as to whether or not there will be enough demand for the secondary nickel.

The cadmium supply is more difficult to analyze because cadmium is a by-product of zinc refining. Thus, the supply of cadmium is a direct function of the demand for zinc. NiCd batteries account for over 60% of the demand for cadmium [67]. The Cadmium Association of London, and the Cadmium Council, Inc. of North America have developed a forecast for the global cadmium supply and demand. In this study, an upper and a lower projection were made on the number of total EVs worldwide and the number of NiCd powered EVs worldwide to simulate a maximum potential demand scenario. Table 5 shows these projections and the anticipated demand for cadmium from EV use. Table 6 summarizes the total cadmium demand, including demand from other industries. Table 7 presents the expected growth in the zinc production, with the corresponding cadmium supply. It is anticipated that the efficiency of cadmium recovery from zinc will increase, thus improving the zinc:cadmium ratio. The total world supply, including centrally planned economies, secondary cadmium, and cadmium from EV battery recycling is shown in Table 8. Comparing the total demand and the total supply, there should be enough cadmium to supply between 40 to 50% of the EV market, at least for the near term. The question remains as to whether or not the demand will be high enough to make recycling economical. The assumption

Table 5. The Cadmium Association forecast of worldwide cadmium demand for EVs[1]

Year	1995	1998	2001	2003
Total No. Vehicles				
• Upper projection	50,000	400,000	700,000	900,000
• Lower projection	30,000	150,000	300,000	450,000
% NiCd Share	20%	30%	45%	50%
No. of NiCd Vehicles				
• Upper projection	10,000	120,000	315,000	450,000
• Lower projection	6,000	45,000	135,000	225,000
Cadmium Demand @ upper projection	@ 15 kWh per vehicle [3.15 kg Cd/kWh] @ 47.25 kg Cd/vehicle			
Year	1995	1998	2001	2003
Upper Projection (tons Cd)	473	5,670	14,884	21,263

1. Reference 67.

Table 6. The Cadmium Association summary of worldwide cadmium demand from all sources (data in tons)[1]

Year	1995	1998	2001	2003
EV Demand	521	6,250	16,410	23,442
Estimated Non-EV Demand	22,180	20,950	19,850	17,640
Total Demand	22,700	27,200	36,260	41,100

1. Reference 67.

Table 7. The Cadmium Association summary of worldwide zinc production and related cadmium production[1]

Year	10^3 Tons Zn	lb Cd/ton Zn	Cadmium Supply (tons)
1991	5,957	6	17,871
1992	5,914	6	17,742
1993	5,718	6	17,154
1994	5,833	6	17,499
1995	6,081	6	18,243
1996	6,418	6.2	19,896
1997	6,539	6.2	20,271
1998	6,649	6.2	20,612
1999	6,952	6.4	22,246
2000	7,007	6.4	22,422
2001	6,842	6.6	22,579
2002	6,787	6.6	22,397
2003	6,897	6.6	22,760

1. Reference 67.

Table 8. The Cadmium Association summary of worldwide cadmium supply from all sources (data in tons)[1]

Year	1991	1995	1998	2001	2003
Primary Supply					
• Market Economy Countries	17,871	18,243	20,612	22,579	22,760
• Centrally Planned Economies	4,532	4,716	4,860	5,006	5,107
• Supplementary Cadmium Supply	—	—	2,547	2,758	2,787
Secondary Cadmium Supply	1,100	2,500	3,900	6,600	9,400
EV Battery Recycling	—[2]	—[2]	—[2]	—[2]	2,200
Total Supply	23,503	25,459	31,919	36,943	42,254

1. Reference 67.
2. EV battery recycling not yet begun in these years, based on NiCd battery life of roughly 7 years. EVs enter world market in 1995.

is that recycling cadmium will be necessary to supplement the supply of primary cadmium. With expanded use of NiCds in EVs and in portable equipment, the demand for cadmium should rise sharply. If secondary cadmium can be used to make new NiCd batteries, as secondary lead is used to make new lead-acid batteries, then the recycling of NiCd batteries should be able to create and sustain its own market.

2.4.3 Nickel-Metal Hydride

Markets for secondary NiMH products are difficult to find. Many of the markets where products of NiMH recycling could be sold have very strict process input purity requirements. It is clear from research that has been conducted at the Bureau of Mines and TWCA that all of the metals in the hydrides will not be able to be recovered economically with the current state of recovery technology. Some of the metals will simply fall out as slag, while others will be incorporated into a nickel-vanadium-ferroalloy and be sold to the most probable market, the steel industry. NiMH batteries will be present in much larger quantities than NiCds, according the predictions in Table 4. By 2005, there could be close to 4,900 tons of spent NiMHs available for recycling, and as much as 25,300 tons in 2010, with a nickel content between 15% and 50%. Due to the large supply of ferronickel from nickel containing batteries in addition to the supply from other steel scrap, it may be difficult for nickel battery recycling to sustain itself solely on the stainless steel market.

Other materials that could be produced from NiMHs are nickel salts, vanadium, titanium compounds, zirconium compounds, rare earth metals, and potassium compounds. Nickel salts, such as nickel chloride, nickel sulfate, and nickel carbonate, do not have a very large or expanding market. The domestic nickel chloride demand is near 8,000 metric tons. Presently, France and Finland are supplying about 90% of the production. There do not appear to be new markets for $NiCl_2$, and demand for the current markets has not been rising. The total demand for nickel sulfate and nickel carbonate together is only about 3,400 metric tons. Nickel sulfate, mainly used in nickel plating, has been imported from Finland and Belgium for many years in fairly constant quantities. Nickel carbonate has traditionally been used for pH control and metal finishing, and could also be used for electrogalvanizing. Unfortunately, the recycled nickel carbonate would not be able to meet the feedstock purity requirements for electrogalvanizing, which would be the case with most of the metal products of NiMH recycling [65].

The remaining products of NiMH battery recycling do not appear to be very marketable. The titanium compounds produced in recycling would not meet the concentration requirements for feedstocks for the manufacture of titanium dioxide. Zirconium compounds could be used to produce glass refractories, but the industry only accepts secondary materials when there is a supply shortage. The rare earth metals would be far too expensive to recover separately. The only possibility at this point would be to produce a misch metal, which contains an undesirable $Al(OH)_3$ impurity. Rare earth metal producers feel that the secondary misch metal would not be a suitable feedstock. The potassium product recovered would be potassium chloride, which is used in fertilizers. However, the recycled material contains a high concentration of sodium chloride, which may make this material undesirable to the fertilizer market. Vanadium may have a market in the steel industry, but it would probably be more feasible to recover this in the alloy, rather than to try and separate it into a pure form [65].

2.4.4 Sodium-Sulfur/Sodium-Nickel Chloride

The only readily salable products of NaS and Na-NiCl2 battery (also classified together as sodium-beta batteries) recycling are sodium chloride, sodium sulfate, soda ash (sodium carbonate), and nickel metal (the market assessment of nickel has been discussed previously in the sections relating to NiCd, NiFe, and NiMH batteries). Sodium polysulfides have no real market value, and their final destination would probably be a landfill. Sodium chloride production and consumption have remained steady around 36,000 and 39,000 metric tons respectively. Uses of this product are in the chemical industry, food and agriculture, ice control, and water treatment. Soda ash production increased by about 18% between 1980 and 1989, while consumption remained stable around 6.5 million metric tons. Soda ash is used primarily in glass, but is also used in soaps and detergents and in the chemical industry. Both production and consumption of sodium sulfate have dropped by about 30% since 1980. The largest use of sodium sulfate is in soaps and detergents, accounting for about 45% of the market demand, with pulp and paper and glass making up the remainder of the demand. The total demand for all three compounds in 1989 was 46.2 million metric tons. Our market scenario of EVs in California (Table 4) predicts that by 2000, sodium-beta batteries will account for only 2% of the EV market. Based on this assumption, there would only be about 360 tons of spent sodium-sulfur batteries in 2005 and about 2,000 tons of spent sodium-sulfur batteries in 2010. These usage figures are based on sodium sulfur batteries entering the market in 1998 and supplying 2% of new LDVs and MDVs between 1998 and 2005. The amount of spent sodium-beta batteries on the market in any given year will probably not overwhelm the market [68, 69].

2.4.5 Lithium Batteries

Recycled products from lithium batteries can easily be sold to the cement or ceramics industry. The lithium salts help to give these materials better flexibility and expandability. Toxco, a lithium battery recycler in British Columbia, has reported no difficulty in selling their lithium carbonate product based on the purity of the salt. The cement industry does not require a high purity feedstock, since any impurities will be burned off in the kiln. The demand for cement has risen from 70,000,000 metric tons in 1980 to 83,000,000 metric tons in 1989, but the percentage of this associated with a demand for lithium salts is unknown. Other uses of lithium compounds are in the aluminum industry, in air conditioning, greases and lubricants, synthetic rubber, specialty glass, and in new batteries. Whether or not recycled lithium can be reused in batteries remains to be seen, as the larger industrial and automotive sizes have not been significantly manufactured or recycled up to this point. Based on our EV market scenario (Table 4), lithium batteries will enter the market in 1998, altogether powering about 20% of the new EVs. For the near-term, lithium-ion batteries are expected to prevail over the other types of lithium batteries. Determining the amount of available lithium battery scrap is difficult, since the weight of lithium-ion EV batteries can only be estimated at this time. However, if the predictions of Tables 4, A4, and A5 prove accurate to any degree, additional recycling plants will almost surely have to be sited in the United States. Based on these assumptions, there could be as much as 77,000 tons of spent lithium batteries on the market by 2010. It is also difficult to determine if the amount of lithium scrap that will be available will all be salable, based on market conditions, or whether it will have to be landfilled. Total domestic consumption of lithium for all uses has remained stable around 3,000 metric tons. It appears that the supply of lithium battery scrap may exceed the demand for lithium of all types. Unless other uses of lithium are found, such as recycling it back to batteries, a large portion of the lithium scrap may end up in landfills [68, 69].

2.4.6 Zinc Batteries

There are many markets in which secondary zinc could be sold. The main market for zinc is galvanizing, with zinc-based alloys and brass and bronze production as strong second and third markets. Between 1970 and 1980, zinc consumption decreased slightly, but between 1980 and 1990, consumption increased steadily. Production has also been on a steady rise since 1980, but the demand still far exceeds production. This trend explains the steady rise in the market price since 1970, both in the U.S. and on the London Metal Exchange. Table 9 shows the total U.S. production and consumption figures along with market price for 1970, 1980, and 1989. It is not expected that zinc-air batteries will flood the market with secondary zinc to the extent that the supply will exceed the demand. Our market share scenario indicates that zinc-air batteries will not even significantly impact the market. These batteries have a theoretical life of around fifteen years, so they will not be recycled for many years after their introduction. In 1980, the total demand for zinc scrap from all users was 183,000 metric tons [68]. Even if 10% of the near-term EV fleet were powered with zinc-air batteries, this would represent only about 2,400 tons of spent batteries, with an average zinc content of 45%. Thus, the battery scrap would make up only a small fraction of the recent demand for zinc scrap. Thus, problems are not anticipated in absorbing the supply from zinc battery recycling.

2.5 ISSUES FOR BATTERY RECYCLING

2.5.1 Establishing Battery Recycling

Encouraging the recycling of batteries involves two main issues. The first concern is facilitating transport of the battery to a central collection point. This is primarily affected by the size of the deposit and the rules governing the deposit system (Sections 2.5.1.1 through 2.5.1.3). The second issue is whether recycling should be pursued as an alternative to other disposal alternatives available. The primary consideration is whether recycling, mandated as such, will distort the evolution of the battery market by burdening some technologies more than others (Sections 2.5.2 through 2.5.2.6). A summary of the main issues in the pages that follow appear in Table 10.

2.5.1.1 Getting the Batteries to Central Collection Points

The size of the batteries, the number of electric vehicles, and the disposal issues associated with the batteries' component elements strongly indicate that a systematic effort to provide for centralized collection of used batteries is needed. The two techniques commonly used to insure battery return are legal prohibitions and incentives.

Legal prohibitions. A legal prohibition on the free disposal of batteries in landfills and other consumer dump sites would require enforcement. In all likelihood, the prohibition would be only

Table 9. Domestic zinc production and consumption: 1970, 1980, 1989

	1970[1] (metric tons)	1980[2] (metric tons)	1989[2] (metric tons)
Total Production	870,000	380,000	805,000
Total Consumption	1,420,000	1,154,000	1,340,000
Price (U.S.$/kg): United States	340	830	1,830
Price (U.S.$/kg): London (LME)	290	760	1,690

1. Reference 70.
2. Reference 69.

Table 10. Establishing an electric vehicle battery market with assurance of used battery collection and recycling summary of issues[1]

Objective	Options	Problems/Issues	Recommendations
Get batteries to collection points.	1. Rely on market value of scrap 2. Require deposit	Option 1 will have variable effects depending on battery types and fluctuating commodity prices. Option 2 will require collection and administration of significant funds.	Deposit of $100 to $150 recommended for LDVs, higher for MDVs and HDVs. Legislative guidance, hearings, and workshops on use of deposit fund are needed.
Insure maximum possible battery return without inciting theft.	1. Closed return system 2. Open return system	Option 1 would require battery registration to establish battery ownership before refund. Option 2 would possibly make it too easy to obtain cash for stolen batteries.	Public hearings and workshops needed to get a better sense of implications of each system
Ecourage maximum number of collection points without excessive burden to vendors or manufacturers.	1. Each vendor collects and refunds deposits on used batteries only for those types sold 2. Vendors are made to collect all types, issue refund, and ship to an appropriate disposal or recycling facility	Option 1 may decrease the number of returned batteries. Option 2 may be burdensome to firms. Collection efficiency will be affected by the structure of the used battery market (both legal and illegal), and will be variable by battery technology.	Public hearings and workshops needed
Encourage battery material recycling.	1. Set "closed loop" recycling targets 2. Set "open loop" recycling targets 3. Set targets on a case by case basis	Options 1 and 2 have the virtue of simplicity but will have discriminatory effects on battery technologies. Option 3 could be cumbersome and contentious.	Public hearings and workshops needed

[1] Reference 71.

partially effective. Some enforcement would be needed to prevent the collection and illegal disposal of large numbers of batteries. However, minimizing the need for enforcement is clearly advantageous to society.

Incentives. An incentive system will provide for higher return rates at lower cost to society overall. There are two possible kinds of incentives: requiring a deposit when the battery is first purchased, or relying upon the battery's scrap or recycling value. A disincentive, such as charging a disposal fee for the old batteries to purchasers of new ones (in imitation of the charge sometimes levied for the disposal of used engine oil) would be counterproductive to recycling.

Relying on a possible scrap value will not provide for systematic and dependable battery collection, because some batteries will have higher scrap value than others. Unless the materials used in the battery are valuable, prices for recovered battery elements will provide only minimal incentive for battery return. Due to materials market fluctuations, the incentive may vary from year to year. In addition, there will be wide discrepancies in the cash value of the recycled components among the various battery technologies.

A mandatory deposit at the time the battery is purchased would ensure that all batteries were returned to central collection points. Mandatory deposits are currently in effect in California for car batteries, and recycling has achieved a 95% return rate. The appropriate size of the deposit merits some evaluation.

2.5.1.2 Deposit Size

The desired size of the battery deposit will have to take into account several different factors, some of which will be discussed later, in Section 2.5.2.6. This discussion will focus on the balance to be struck between (1) reducing incentives for theft and (2) assuring an adequate return rate. In the following sections, we will suggest that a deposit on the order of $100 for light duty vehicles will be adequate to accomplish the second objective without unduly encouraging theft. Appropriate deposits for medium duty and heavy duty vehicles, which require 2 times and 4 times the battery capacity, might be $200 and $400, respectively.

Theft

As the electric vehicle market expands, used batteries will be in demand. Even today's vehicles are readily stolen and taken to "chop shops" for the resale of parts. The EVs of tomorrow may be easy to steal because of their size. The battery will, at least with some technologies, constitute a high-value item (possibly worth thousands of dollars) that may be readily sold on the black market. Stationary applications may develop for these batteries which could widen the demand for them on the black market.

Currently sound equipment worth as little as $100-$200 is a frequent target of opportunity for theft. Batteries sufficient to power an LDV will be considerably more difficult to remove and carry (on the order of 1,000 lbs.) but they could provide a tempting target for more sophisticated auto thieves.

It is possible that the resale value of stolen batteries on the black market will, by itself, generate battery theft. In this case, the effect of the deposit on theft will be partially determined by the rules governing the deposits and partially determined by the size of the deposit relative to the black market value of the batteries. An "open return policy," where anyone who turns a battery in to a collection point is eligible to receive a deposit refund, would most facilitate the collection of batteries but, if the deposit is too high, would also promote theft. A "closed return policy" whereby only the original buyer of the battery is allowed to collect the deposit, would discourage theft but would also require an expensive administrative burden, perhaps leading to the equivalent of a vehicle-specific title or pink slip for batteries. The closed return policy would have the effect of freezing out of normal collection/disposal channels the portion of batteries that enter the black market, either through vehicle theft or specifically targeted battery theft.

Scenario 1: "Open Return" Deposit Policy

In this scenario, anyone who shows up at a collection point with a battery is entitled to a refund. Thieves will sell into the black market if the price is higher, or to the collection point, where the established deposit value will set a floor price for all used batteries. Therefore, the higher the deposit, the greater the incentive to steal the batteries. The policy objective is to set a deposit price level which strongly encourages the return of used batteries without encouraging theft.

Users of stolen batteries would have no problem returning them for the deposit when the battery life was ended. The "open return" policy would not address the social problem of battery theft, but it would provide a strong incentive to make sure all batteries are disposed of in an environmentally safe manner.

Scenario 2: "Closed Return" Deposit Policy

In this scenario, we hypothesize that a computerized battery registration is in effect statewide. The owner of the battery can trade in a battery only by providing proof of original purchase.

Stolen batteries would less readily be sold to collection points. Purchasers of stolen batteries, after having used them, would have no means to return them legally. The batteries would probably be abandoned or disposed of in an illegal manner.

A registration/enforcement technique such as this might diminish the social problem of battery theft, which would then be driven by the black market value of the batteries, but increase the environmentally unsafe disposal of batteries.

A "closed return" deposit policy would also have the effect of discouraging freelance collectors of batteries. Special permits, however, might be given to auto dismantlers and others to turn in large quantities of batteries for the deposit. An unlicensed individual who turned in a large number of batteries in the course of the year would enter the database many times and could potentially be targeted by enforcement authorities as a "fence" for a stolen battery operation.

It should be underscored that a "closed return" deposit system would not prevent battery theft. It would merely reduce, without eliminating, the stealing of batteries for the express purpose of selling them back to the deposit system. It would cause problems for the buyers of the stolen batteries, who might not be aware of their provenance. The "closed return" system might effectively eliminate from environmentally safe collection and disposal the fraction of illegally procured batteries.

Legal Salvage Operations

Many batteries will be returned through normal auto dismantling and scrapping operations, as they are today. The deposit-related problem is to ascertain what the scrap value of an electric vehicle would be.

Today, older vehicles are worth about $50-$150 in scrap depending on their size, weight, and construction. In major urban areas this value is not sufficient to encourage all owners to return their vehicles to scrap yards. However, it is sufficient to support towing operations that are specialized in the removal of abandoned vehicles.

We know, therefore, that at an average value of $100 per vehicle (1) many people will still not turn the vehicle in on their own, and (2) the fee is sufficient to support specialized collection services.

Battery-powered vehicles will be no different, but their scrap value may be less. They will be composed of plastics and composites which may be recyclable but not fetch a salvage price equivalent to steel. This would increase the number of abandoned vehicles in the long run, and also decrease the incentives for firms specialized in vehicle collection to bring the abandoned EVs in for proper disposal.

A battery deposit could be a surrogate for scrap metal value. That is, the battery deposit could be set high enough to insure that the incentive to bring the batteries to a collection point is at least as high as the current incentive to return a vehicle. If the total vehicle/battery value is too low, the incidence of abandoned vehicles will increase, and the efficiency of collection by specialized firms will decrease below current levels. If the battery deposit is set too high, it may act as an incentive for theft, as discussed above.

It should be pointed out that in the current system of abandoned vehicle collection, the incentive to bring in a vehicle decreases with its distance from a major urban center, where automobile dismantling and scrapping facilities are typically located. The early generation of EVs, due to range considerations, are not likely to venture far from the urban centers. But later models at greater distances from auto dismantling facilities might be abandoned rather than returned, and there will be insufficient economic incentive to tow them in. Depending on the battery technology, EVs abandoned to the elements may pose health or environmental risks significantly greater than today's vehicles. If this is the case, then a higher battery deposit or other incentive for the collection of abandoned vehicles in remote areas might be necessary [72].

Growth of a Deposit Pool

If a fee on the order of $100 is collected per EV in operation a sizable fund of money will result. This fund will be constituted of (1) the actual deposit; (2) earned interest on the deposit funds; and (3) lost deposits from batteries which haven't been returned.

As can be seen in Figure 13, the income from the battery deposit pool will rise to significant dimensions if forecasts prove accurate. The income from the deposit fund will reach or exceed $2-3 million annually in the year 2002-2003. By 2010, it will be nearly $8.2 million, growing to $12 million by 2015. These estimates are based on a number of assumptions about interest rates and the number of vehicles in use, as well as size of deposit by vehicle (see the breakdown in Table 11). A higher deposit size would generate increased income: $150 per light-duty vehicle would not be excessive and if scaled for the other vehicle types would result in a 50% increase. The income

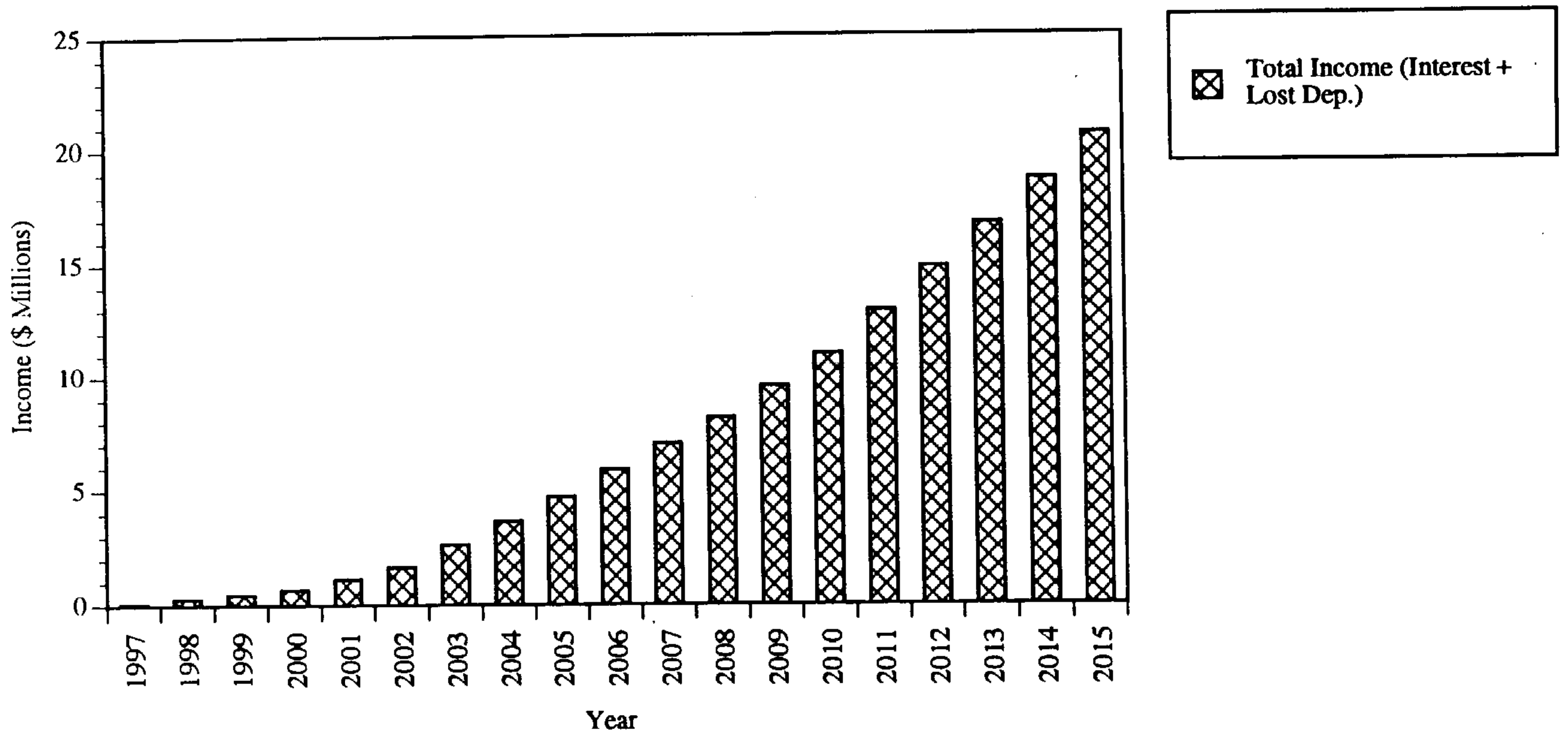


Figure 13. Income from battery deposits — interest income plus deposits on claims due to lost batteries (Reference 71)

Table 11. Analysis of battery deposit fund income[1]

Year	New Vehicles	Total Electric Vehicle Population				Income from Battery Deposits				
		LDVs	MDVs	HDVs	Total EVs	Total Battery Deposits (Millions)	Interest Received (Millions)	Batteries Not Returned	Income from Lost Deposits (Millions)	Total Income (Interest + Lost Dep.)
1997	1,722,632	17,226	200	20	17,446	1.77	0.09	0	0	0.09
1998	1,751,977	52,266	1,080	40	53,386	5.46	0.27	0	0	0.27
1999	1,781,311	87,560	2,520	60	90,140	9.28	0.46	0	0	0.46
2000	1,810,738	123,161	3,900	110	127,171	13.14	0.66	0	0	0.66
2001	1,837,506	213,873	6,420	160	220,453	22.74	1.14	0	0	1.14
2002	1,863,129	305,055	10,020	210	315,285	32.59	1.63	0	0	1.63
2003	1,890,059	488,944	16,320	260	505,524	52.26	2.61	0	0	2.61
2004	1,917,075	673,499	25,259	310	699,068	72.53	3.63	0	0	3.63
2005	1,944,701	852,790	34,139	360	887,289	92.25	4.61	872	0.09	4.70
2006	1,974,344	1,029,880	42,959	410	1,073,249	111.74	5.59	2,669	0.27	5.86
2007	2,004,244	1,204,095	51,720	440	1,256,255	130.93	6.55	4,507	0.46	7.01
2008	2,034,347	1,376,142	59,159	470	1,435,771	149.63	7.48	6,359	0.66	8.14
2009	2,063,716	1,547,742	66,120	470	1,614,332	168.19	8.41	11,023	1.14	9.55
2010	2,093,395	1,719,784	72,839	470	1,793,093	186.73	9.34	15,764	1.63	10.97
2011	2,123,640	1,894,071	78,059	470	1,972,600	205.21	10.26	25,276	2.61	12.87
2012	2,154,028	2,072,224	82,198	470	2,154,892	223.85	11.19	34,953	3.63	14.82
2013	2,184,133	2,256,874	83,638	470	2,340,982	242.60	12.13	44,364	4.61	16.74
2014	2,216,788	2,450,100	82,438	470	2,533,008	261.69	13.08	53,662	5.59	18.67
2015	2,243,271	2,649,854	81,296	470	2,731,620	281.43	14.07	62,813	6.55	20.62

[1] Reference 71.

Assumptions

- One "battery" per vehicle.
- LDV requires $100 deposit per vehicle, MDV and HDV reqire $200 and $400, respectively.
- Five year life on all batteries, batteries are exchanged for new ones.
- Eight year vehicle life: 95% of batteries are returned and deposit is refunded.
- 5% of batteries are not returned, deposit is lost by the consumer (i.e., available for payout).
- Interest (5% annually) and lost deposits are paid out in the year in which they occur.

generation of the fund could exceed $18 million in 2015 on a fund size of $137 million. The non-returned battery portion (estimated at 5%) would provide nearly half of the expected fund income yield, interest bearing investments providing the rest.

The fund's size and related income stream will be proportionate to the vehicles in circulation. Recent events surrounding California's negotiations over the Federal Implementation Plan and State Implementation Plan indicate that the fleet average HC requirement under the ZEV-LEV program could fall from 0.062 HC/g/mi. in 2007 to 0.025 HC/g/mi. If this change is adopted, the EV portion of the light duty vehicle fleet could rise faster. The battery deposit fund would be considerably larger than forecast here.

It would be wise to make provision for the use of these funds at an early date, as the degree of controversy of how to use the funds will be proportional to the quantity of the money in the deposit pool. This section will briefly review some critical aspects of the deposit fund's operation.

1. Who will hold the money? Battery vendors or manufacturers might hold the deposits. The interest income would likely be kept by the vendor, and the fund might provide an asset against which they could borrow. This approach has the advantage that the deposits could be returned directly to the consumer by the vendor at the time a battery is turned in. There would be a risk of losing the funds to business closings, embezzlement, or bankruptcies. Attempts to monitor the size of the deposit pool, collect interest, or ensure fair return of deposits to the customer could provide an expensive administrative burden (e.g., where would the refunds come from if a manufacturer, or even an entire technology, went bankrupt?).

   An alternative approach would be to have the State Board of Equalization collect the deposits in much the same way that sales tax is collected today. The money could be held in a special account, possibly in an instrument such as state bonds. The disadvantage is that either the customer or the vendor would have to apply to the state for a refund at the time the battery is returned. The deposit pool's liability in the event of the bankruptcy of a manufacturer would be covered.

2. Who will profit from the interest income? The interest income could be given back to consumers upon handing in their batteries, i.e., deposit + interest. This might be necessary to preserve the value of the deposit as a return incentive if battery lives reach the point (e.g., 10 years) where inflation could significantly diminish the value of the deposit. At 3% inflation per year, the real value of a $100 deposit after 10 years is $73.74. Higher inflation rates would lower the real value even further; to the extent that inflation occurs, the incentive power of the deposit will erode, leading to a lower incentive to return the batteries.

   Alternative uses for the income stream from the bond fund might be to fund research and development of electric vehicle technology, including better batteries or fuel cells. Or, the money might be used to develop better waste disposal and recycling for batteries. A "dedicated use" for the funds would be more effective for the future of electric vehicles than having the income go into the general state revenue fund.

   A final possibility is that the income stream from the fund could be turned back to the vendors in proportion to their sales; or it might be lent to them to help them develop their recycling operations. Returning the money to the battery vendors/manufacturers has the virtue of giving participants in a difficult, potentially high-risk market a slender increase in their total return.

3. Who will keep the funds from non-returned batteries? If the current non-return rate for lead-acid batteries is maintained, 5% of all batteries will "disappear" from the system. The distributional issues and options are the same as for the interest income.

   The deposit fund will have to make a determination as to when a battery is presumed "missing in action" for the purposes of the deposit. This will vary depending on the technology of the battery. A time period two standard deviations from the average battery life (by definition covering 95 % of the batteries) of each technology type would provide a conservative margin for the fund to declare a battery "missing in action" The deposit money could either be left in the fund, to add to the principal which generates the interest income used to finance electric vehicle-related research and development, or released directly to that research (or other activity).

2.5.1.3 Conclusion Regarding Deposit Necessity and Size

Given a choice between requiring a deposit or relying on the recycling value of the battery, a deposit is necessary because the recycling value of the different battery technologies reviewed in this report is not stable enough, nor in all cases high enough, to insure the regular collection of all battery types under all price conditions. Automobile scrappage is an example of recycling which is driven by the market value of the metal, but one consequence of relying on this technique is that when scrap metal prices are low, vehicles accumulate on the streets or in wrecking yards. Because of the environmental hazards, some battery technologies should not be allowed to accumulate.

A firmly established system for collection of deposits would add regularity and predictability to battery collection. Deposits could be uniformly used to insure battery collection regardless of battery type. Not all battery types will be fully recyclable, but getting the batteries to central collection points will at least permit them to be disposed of according to the particular disposal hazards each type represents.

This report recommends that the deposit for the battery pack per vehicle be set roughly equivalent to the current scrapping value of old cars ($100-$150). This fee would not be enough to encourage all customers to bring their vehicles/batteries to an appropriate disposal site, but it would support a vehicle/battery recovery system roughly equivalent to today's operations for the towing and scrapping of abandoned vehicles. Yet it is low enough that the battery deposit would not constitute, in itself, a value that would make the batteries a special target of opportunity for theft. The value of the battery deposit would be neither particularly greater nor lesser than the value of other systems on the automobile, such as the sound system and tires.

The deposit pool of funds that will grow as a result of the operation of a deposit system to insure used battery collection will represent a significant fund of money, though at its inception it will be relatively modest. One possible use of such a fund is to encourage electric vehicle technology, or more specifically, battery recycling. Other uses might be determined during the legislative review process.

The choice between setting up an "open return" deposit system and a "closed return" deposit system will need to be made as a result of public process and further consultation with the general public and with experts, particularly law enforcement agencies and insurance companies.

2.5.2 Competitive Impacts of a Recycling Requirement

Regulatory requirements will have unequal impacts on market participants. Policy decisions about the necessity and extent of hazardous material reclamation and recycling will affect the competitive positions of firms, because not all firms will be equally capable of meeting the same requirements. Moreover, the ability of firms to meet recycling or other disposal requirements will vary with time as well as with technology. That is, a firm may be able to employ certain kinds of reclamation techniques only after a certain number of years of operation, when the volume of returned batteries reaches a certain threshold level.

It is assumed in this section that all batteries will be disposed of in a manner consistent with federal and state requirements. These requirements may have discriminatory effects, but they are already in place. The specific issue here is whether the recycling requirement as such can be applied uniformly to all battery technologies.

2.5.2.1 Recycling: Content Targets and Definitional Problems

The current best model of battery recycling is the lead-acid battery industry. The 95% return rate to recycling centers is admirable and a significant step; moreover, virtually the whole lead-acid battery is relatively cost effective to recycle.

Should this therefore be the model of all other battery designs? Not necessarily. The disposal of some batteries may pose worse problems for the environment and the public health than the current lead-acid technology. A 95% return rate might not be sufficient, for example, to ameliorate the more significant hazards posed by NaS or other molten salt batteries. For high hazard batteries, special deposit, return or registration requirements might be necessary. Or, a high performing battery may have very low impact disposal consequences, but it might be recyclable only at great cost, or there might be high risk environmental consequences associated with the recycling technology. It would not make sense to impose a 100% content recyclability on such a technology if that requirement meant keeping the battery off the market, or imposing an exorbitant entry cost on it.

In addition, there can be no definitive rule concerning "open loop" or "closed loop" recycling. The lead-acid battery is a "closed loop" recycling process where a portion of the next generation of batteries can be made from the previous generation. By contrast, in the NiCd battery the reclaimed nickel cannot be used in the next generation of batteries, but it can be used as a ferronickel in stainless steel. The nickel is recycled into another market: an "open loop." Still other battery components may be relatively innocuous but have no prospect other than a landfill.

2.5.2.2 Impact of Regulations

Regulations must always have a competitive impact. Battery deposit requirements in the range of $100 to $150 will make it incrementally more difficult to sell EVs. This effect, however, will probably not be as important as the variable competitive impacts of collection and recycling requirements on battery manufacturers or vendors.

The two major areas of discriminatory impacts will be in distribution/collection facilities and in processing.

2.5.2.3 Distribution/Collection Facilities

The infrastructure for the sale and recuperation of lead-acid battery technology is already in place. Vendors are potentially major collection sites, as are automobile dismantlers.

In the usual battery replacement operation, an EV owner will buy the same kind of battery from a vendor and a vendor will take the old one. However, the replacement battery may not use the same technology as the original. For example, a NiCd manufacturer may design a NiCd replacement battery for a vehicle originally sold with a lead-acid battery. But if vendors do not take batteries of other types or from other manufacturers, then there will be an incremental expenditure of effort which will discourage some people from taking the time to find out where they can dispose of their batteries. As a result, many batteries may end up in backyards or garages.

This situation may sound improbable but in fact may occur rather frequently. A large secondary battery market may develop, and not all of these batteries will be returned to vendors at the time of replacement. This scenario may occur for the following reasons:

1. As performance of their battery pack decreases, some owners may choose to "unload" their used battery packs before they are totally unusable, so they can enjoy the superior performance of a "fresh" battery pack. They may sell their used battery packs to other buyers in the usual arenas: flea markets, classified ads, etc. An owner of an aging EV, which happens to have a relatively new battery pack, may try to sell the battery and scrap or abandon the vehicle itself. Sodium-beta batteries, if they last for their currently maximum predicted lives of 16 years, will outlive many of the vehicles they are placed in and enter the secondary market through various routes.

2. Battery manufacturers will attempt to manufacture compatible battery types. The first wave of EVs will probably be dominated by lead-acid technology. But those vehicles are not necessarily going to be lead-acid vehicles for their whole lives. Rival battery manufacturers may attempt to design or retrofit for the existing market. If a breakthrough occurs, EV owners might flock to the new battery technology without necessarily buying new EVs.

3. Battery packs may be sold as "single units." That is, one way to imagine an EV battery is several large batteries contained in one large plastic case. While in use, these batteries would always be together. Their removal and replacement might require several strong people, a forklift, hoist, or other specialized tool.

Partial battery pack replacement may, however, emerge as a possibility. Manufacturers may choose to make the batteries easier to manipulate in common use, so that both professional and home mechanics will easily be able to replace them. An EV's total battery pack could therefore be composed of (for example) four or five (or more) physically separate units. This would reduce the high consumer deterrent effect of a $1,000 to $3,000 full battery pack replacement, and permit phased replacement of the individual battery units. The effect on recycling would be to encourage home battery switching and increase the number of batteries circulating independently of their original vehicles.

Thus, a large number of batteries may circulate in the secondary market. Consumers will arrive at various collection points expecting that their particular battery type will be accepted for a deposit refund. If the collection system allows vendor/collection points to discriminate against battery types, than the less-used battery types will have more difficulty being returned.

Difficulty in returning the less-used battery types could result in a competitive disadvantage for some manufacturers. On the other hand, it is also true that a vendor of a less-frequently used battery type might not want the trouble of serving as a collection point for a more numerous rival battery technology. A lithium battery vendor who has made necessary arrangements for the collection and shipment of lithium batteries may find it unfair to have to cope with lead-acid batteries both because it is inconvenient and because his/her own battery handling and storage equipment might not be appropriate.

There is no prior experience for resolving this issue. In New York, supermarkets are allowed to, and in most cases do, refuse deposit refunds to consumers who arrive with bottles that are for products not sold at that store. Automated machines which collect these bottles, crush or shred them in situ, and issue a deposit refund slip, are equipped with sensor systems to reject inappropriate bottles. The result is that consumers often (though not always) leave rejected bottles in the stores' trash cans. These orphaned bottles therefore escape collection and are landfilled.

A deposit system that allows discrimination at the point of collection will have such an effect. The deterrent effect of the deposit will be diminished if partial battery pack replacement is possible. An EV owner who is trying to dispose of 1/5 of a total battery pack (perhaps with a deposit value of $20) will not necessarily want to drive across town to get rid of an unusual or rare battery type which has been refused by a nearby vendor/collection point. A number of possible alternative disposal options are available, including abandoning the battery at some site or heaving it into a nearby store's dumpster. The negative environmental impact of the landfilled battery will be dependent on the technology of that particular battery. The frequency of such practices will vary inversely with the size of the deposit and directly with the difficulties (and costs) associated with getting the right battery to the right collection point.

Unfortunately, neither deposit fees nor open return of all battery types will guarantee a 100% retrieval rate, but it is clear that anything done to reduce obstacles faced by consumers will increase the rate of battery return.

2.5.2.4 Recyclability Requirements

In addition to the deposit fee, the question of recycling options is probably the major market organization issue to be faced by regulatory agencies in implementing the ZEV requirement. The popular conception of recycling, as symbolized by the universal symbol of three arrows arranged in a circle and printed on many containers, reflects what we term "closed loop" recycling: the product is made, used, and the recoverable portions of the product are processed and sent back to be reincorporated into the next generation of product. Of the current technologies in wide-spread use, the lead-acid battery comes closest to representing this ideal in EV technology.

In reality, however, recycling offers challenges which are specific to each product. When the end result of reprocessing a product results in a pure marketable commodity, such as silver, aluminum, or steel, it is superfluous for recycling advocates to mandate the reincorporation of recovered materials back into the same product. For example, there is little to be gained, from the point of view of conserving resources, in mandating that 50% or 100% of new automobile steel content come from the previous generation of automobiles. The "open loop" recycling of steel in the international market will permit efficient allocation.

Some materials may require "open loop" recycling because the product is changed in use and is no longer suitable for its first use. The nickel in a NiCd battery is best reused as ferronickel in stainless steel. It so happens there is a market for this recovered material; but if there were no such market, requiring the full recycling of the nickel back into the next generation of NiCd batteries would effectively be regulatory discrimination against the development of this technology.

One could in theory impose a "closed loop" recycling requirement. This has been done with plastic bottles, where the recycled plastic is not cost-effective relative to new plastic. The market for recycled bottle plastic must be created by regulations. Although there no doubt is variability among bottle manufacturers which makes this requirement more difficult in some cases than in others, the plastic bottle market is much more homogeneous than the expected EV battery market.

This lack of homogeneity means that even a sophisticated regulation that required "closed loop" recycling as a first option and "open loop" recycling as a second option would still have discriminatory effects: Lithium recycling could meet "open loop" requirements, but the nitrogen freezing process needed to render the lithium inert could be a fundamental cost disadvantage relative to lead-acid or NiCd recycling.

2.5.2.5 The Regulatory Issue

Assume that all state and federal standards needed to protect the environment and the public health are met by all battery technologies. Add to the goal of safe disposal a recycling requirement. This may reflect concerns about landfill space or the possibility of long-term waste degradation not currently covered by regulations; or, perhaps, a concern that enforcement will not reach full compliance.

The question regulators may have to face is whether to impose significant cost disadvantages for the express purpose of recycling a battery even if the effect is to raise costs prohibitively or discourage the introduction of a technology that may guarantee much wider acceptance of EVs and help clean the air.

There is no one requirement, such as full closed-loop recycling, full open-loop recycling, mixed closed- and open-loop, partial recycling (10%, 50% of materials), etc., which can effectively be written at this time to cover all the different permutations of recycling possibilities. Many of the batteries are not even in production yet, and their eventual cost cannot be precisely determined even starting with the assumption of raw materials only, much less adding in recovery and recycling requirements [73].

Furthermore, the elements of time and market share are a component of cost. A firm that cannot envision recycling for 1% of the market may be able to do so 5 years later if it has 10% of the market. If the firm immediately captures 20% of the market, it may be able to introduce recycling on very short order. Also, recovery and recycling technology will evolve in the normal course of process innovation.

Should it be shown that a given battery technology, in spite of good performance characteristics in a vehicle, poses an extreme risk in the disposal end of its life, then it might be wise to prohibit it from use until such time as the disposal problems are more satisfactorily resolved.

2.5.2.6 Recycling as a Reasonable Objective: Recommendations

To avoid discriminatory cost impacts on desirable new battery technologies, recycling will have to be evaluated as a "desirable and reasonable goal" towards which all manufacturers should be expected to make progress. This goal will have to be weighed against the full range of issues associated with disposal, cost effectiveness and vehicle performance, etc. Progress towards the goal of recycling in all vehicle technologies will only occur if it is required and part of the legal conditions for participating in the market. Otherwise, recycling will only occur in such battery types as have reclaimable components that can readily be marketed or reused, and even so, such marketing and reuse may depend on fluctuating raw commodity prices.

The regulatory process will have to be flexible enough to evaluate each battery technology depending on:

1. The kinds of disposal problems it represents
2. The costs of the various disposal/recycling options
3. The contribution each battery type may make to getting cost-effective, long-range, high-performing EVs into general use
4. The extent to which market penetration and development time may change or improve the prospects for more stringent recovery/recycling requirements
5. Such miscellaneous health and pollution issues involved in procurement, processing, transport of raw materials, transport of the finished product to the consumer, potential safety hazards in use, and problems relating to the recovery and transport of the used batteries to recycling or disposal facilities, as may arise with regard to each battery type

This would indicate that some kind of public process would be necessary to evaluate a new battery technology and determine the appropriate disposal or recycling for that technology. Moreover, these arrangements would have to be reviewed periodically; review could be triggered by time (e.g., every 5 years), by market share (e.g., when 2% is reached or exceeded) or by units sold (e.g., when 10,000 batteries have been sold). The process should be designed to centralize and expedite the decision-making and permitting by the air, water, solid waste, and hazardous materials authorities, allowing the applicants to address all of these issues at one time.

If the vehicle battery market proves highly competitive, with many technology types in use, the equity issue among battery producers will be an object of contention. Arguments will be advanced by successful manufacturers that prospective competitors ought to meet stringent processing requirements, in the hope that a new market entrant will find "recycling equality" a prohibitive barrier to market entry. Permitting hearings may provide platforms for the makers of one battery technology to describe the supposed dangers or defects of a rival. It would be preferable for the regulatory authority to have an advisory board of non-industry experts whose testimony or "report of findings" could be used as a source of disinterested opinion during the permit process.

Arguably, manufacturers might prefer a simple, make-or-break objective, such as 50% closed-loop recycling, to the regulatory process proposed here. This seems unlikely to be effective, given the wide variety of technologies and their high variability with regard to toxic or hazardous components and eventual disposal problems. It would seem advisable however for the question of how to achieve reasonable progress towards recycling of all battery types to be put before the interested parties (environmentalists, waste treatment/landfill authorities, automobile manufacturers, battery manufacturers, etc.) in workshops and public hearings at the earliest possible date.

We should also note that even though the current legislative tendency has been to exempt batteries in household waste streams from recycling or hazardous waste requirements under RCRA, the proliferation of battery recycling of all types under the ZEV requirement may provide an opportunity to collect consumer dry cells. There are a significant number of disposal risks associated with these [74]. The opportunity to take care of the dry cell waste problem while organizing large-scale collection and disposal/recycling of ZEV batteries should, perhaps, not be passed up.

2.6 REGULATORY ASSESSMENT

As has become apparent with small nickel-cadmium battery recycling efforts, hazardous waste disposal requirements can have a significant damping effect on well-intentioned recycling proposals. In addition, any new recycling facilities will have to obtain appropriate operating permits, which may include land use, air, and water permits in addition to hazardous waste generator or transportation, storage, or disposal permits. In order to facilitate more effective battery recycling, all of the pertinent regulations need to be addressed to determine how the current system could be modified to better accomplish this task.

2.6.1 Overview of RCRA Regulations

Subtitle C of RCRA governs the management of hazardous waste. This subtitle details the requirements for permitting, operations, cleanup, and disposal, and lists the criteria established by EPA for identifying hazardous waste. A waste is listed as a characteristic waste if it exhibits one or more of the following: ignitability, corrosivity, reactivity, or toxicity. EPA has also established hazardous waste numbers, listed in 40 CFR Part 261, for wastes from specific and nonspecific sources. Characteristic waste categories are assigned the following numbers: ignitable-D001; reactive-D002; corrosive-D003, and toxic-D004-D043. The toxicity characteristic is determined by the toxicity characteristic leaching procedure (TCLP) test. All of the batteries discussed in this study, except lead-acid, would be categorized as hazardous waste, either based on the metals or electrolyte content [75].

Certain hazardous wastes, such as lead-acid batteries, are exempted from RCRA. If the waste is hazardous, the volume generated must be monitored to determine if the generator can be declared a conditionally exempt small quantity generator (CESQG—those generating less than 100 kg/month), a small quantity generator (SQG—those generating between 100 and 1,000 kg/month), or a completely regulated generator (producing more than 1,000 kg/month). Each class of generators are subject to different levels of RCRA requirements. SQGs, producing more than 100 kg, but less than 1,000 kg in a calendar month, are not required to obtain a RCRA hazardous waste generator permit, but are required to label all hazardous waste and manifest all shipments through an authorized hazardous waste hauler, and send them to an authorized treatment, storage, and disposal (TSD) facility. Fully regulated generators are required to obtain a RCRA permit as well as obey all the rules of manifesting and using registered transporters and TSDs [75].

All domestic shipments of hazardous waste must be manifested and shipped with an EPA registered hazardous waste hauler. Registered hazardous waste haulers are restricted from accepting non-manifested waste. The manifest system is a way to track waste along its path from generator to transporter to TSD and to assign responsibility at each stage of its journey. The manifest must be signed by the generator, each transporter, and the owner/operator of the TSD. Each person must keep a copy of the manifest for three years. Once the shipment has reached the final destination, an additional copy must be sent back to the generator. The generator and the owner/operator of the TSD must also file a biennial report to the EPA, which contains all the pertinent identification numbers and shipping dates, and quantities and descriptions of all hazardous waste shipped [75].

For international shipments of hazardous waste, any person wishing to export the waste must receive written consent from the receiving country (the consignee). The EPA must also receive a notice of intent to export and an Acknowledgment of Consent, which is a cable from the U.S. embassy in the receiving country expressing the consent of the consignee to receive the waste. The notice of intent to the EPA must contain a full description of the waste; the export frequency of waste; the quantity; the points of entry to and departure from all countries en route; a description of the TSD in the receiving country, the method of treatment, and method of shipment; and the name and location of the consignee and alternate consignees, if any have been specified. The shipment must be accompanied by the Acknowledgment of Consent and a manifest containing the name and address of the consignee and any alternate consignees. The exporter must require that the consignee sign the manifest upon receipt of the shipment. The signed copy should be returned to the exporter. All rules of the receiving country regarding transport, treatment, storage, and disposal of hazardous waste apply [75].

Owners and Operators of TSDs must obtain RCRA part A and part B permits, which describe the types and amounts of waste treated, the treatment process used, and the types and amounts of wastes that are stored and/or disposed of. The types of storage containers must also be identified and may be subject to further regulation. They are required to keep extensive records of their activity, emissions, and waste discharges. Some must perform emissions monitoring and groundwater monitoring. All federal and local air and water regulations apply, and emissions standards are often stricter for TSDs because of the nature of the materials they process [75].

California hazardous waste management regulations are nearly identical to the federal RCRA regulations except the contaminant levels of the California TTLC and STLC tests are stricter than the federal TCLP limits in some cases. The Hazardous Waste Control Law (HWCL) is found in the Health and Safety Code §§25100-25249. The listed hazardous wastes and the TTLC and STLC contaminant regulations are detailed in Title 22 of the California Code of Regulations (CCR) §66261.24 [57]. Paragraphs 66262 contain the rules on hazardous waste shipping, although they follow the RCRA rules [76].

2.6.2 Air Quality Standards

TSD facilities that incinerate hazardous waste are subject to further regulation by RCRA. Facilities that use thermal treatment, such as smelters or other pyrometallurgical devices, to recover materials must meet the following emissions standards:

- Principal Organic Hazardous Constituents (POHCs) must be destroyed or reduced by 99.99%
- Carbon Monoxide (CO) emissions must not exceed an hourly rolling average of 100 ppmv
- Hydrocarbons (HCs) are not to exceed 20 ppmv
- Particulate Matter (PM) emissions are not to exceed 180 mg/dscf or 0.08 gr/dscf

- HCl emissions should not be greater than 7 mg/m^3 and Cl_2 gas should not exceed 0.4 mg/m^3

- Toxic metal emissions standards are based on the metal being emitted, the stack height, terrain, and the land use of the surrounding area [77]

These are national standards, and any state or local regulations which may be different will also apply and may, in some cases, supersede the above standards [77].

In the Clean Air Act (CAA), the EPA set forth national ambient air quality standards (NAAQS), which are summarized in Table 12, in order to prevent the continued deterioration of air quality. Some states, such as Pennsylvania, where INMETCO is located, adopted these standards into their own environmental codes, while others, such as California, have developed even stricter standards. California ambient air quality standards (CA-AAQS) are also shown in Table 12 for comparison.

Ambient air quality standards are not source specific, but are set up for regional compliance purposes. Each state must issue a state implementation plan (SIP) to demonstrate how it will meet the ambient standards. In California, emissions standards for stationary sources are set by each regional air quality management district and are coordinated by CARB into the SIP. The standards are usually specific to the nature of the industry and the type of sources or equipment [76]. GNB and RSR, the two southern California secondary lead smelters, are under the jurisdiction of the SCAQMD.

Table 12. National and California ambient air quality standards

Criteria Pollutant	NAAQS		CA-AAQS
	Primary Standard	**Secondary Standard**	**Primary Standard**
CO	9 ppm — 8 hr avg. 35 ppm — 1 hr avg.	None	9 ppm — 8 hr avg. 20 ppm — 1 hr avg.
PM_{10}	150 $\mu g/m^3$ — 24 hr avg. 50 $\mu g/m^3$ — AAM[1]	Same Same	50 $\mu g/m^3$ — 24 hr avg.
Pb	1.5 $\mu g/m^3$ — 3 mo. avg.	None	1.5 $\mu g/m^3$ — 1 mo. avg.
NO_2	0.053 ppm AAM[1]	Same	0.25 ppm — 1 hr avg.
O_3	0.12 ppm — 1 hr avg.	Same	0.09 ppm — 1 hr avg.
SO_2	80 $\mu g/m^3$ — AAM[1] 365 $\mu g/m^3$ — 24 hr avg.	1,300 $\mu g/m^3$ — 1 hr avg.	0.25 ppm — 1 hr avg. 0.04 ppm — 24 hr avg.
Total suspended particulate (TSP)	75 $\mu g/m^3$ — AAM[1] 260 $\mu g/m^3$ — 24 hr avg.	60 $\mu g/m^3$ AAM[1] 150 $\mu g/m^3$ — 24 hr avg.	none
H_2S	None	None	0.03 ppm — 1 hr avg.
Vinyl Chloride	None	None	0.010 ppm — 24 hr avg.
Sulfates	None	None	25 $\mu g/m^3$ — 24 hr avg.

1. AAM = Annual Arithmetic Mean.

Any facility that issues air contaminants into the atmosphere is required to obtain a permit and incorporate emissions control devices into the facility vents. New sources, in addition to the permit, are also subject to a new source review by the local air district to determine if that facility may safely operate within that district's emissions inventory or whether it must obtain offsets to do so. Offsets are used when a new source exceeds a threshold limit. Facilities whose emissions are less than the limit may bank their offsets, trade, or sell them [76].

The Federal Clean Air Act has also established National Emissions Standards for Hazardous Air Pollutants (NESHAPS), covered under 40 CFR, Part 61 [78]. Of interest to battery recycling may be the standard for mercury of 2300 g/day from mercury ore processing plants or mercury cell chlor-alkali plants. California has additionally established control measures for certain toxic air contaminants. Hexavalent chromium emissions, for example, must be reduced by 95-99.8%, depending on the process emitting the chromium [78]. CARB is also planning to add control measures for cadmium and cadmium compounds, and nickel and nickel compounds. In addition, California facilities with potential emissions face extensive inventory requirements. California Assembly Bill 2588 (AB 2588), the Air Toxics "Hot Spots," Information and Assessment Act of 1987, defines a list of over 450 toxic air contaminants in the AB 2588 appendix A-1, and requires emissions inventories of toxics from all facilities with A-1 listed substances in quantities greater than the reportable quantities. The reportable quantities depend on the contaminant and are listed in the AB 2588 Appendix A-1.

Pennsylvania, where the INMETCO recycling facility is located, has incorporated the NAAQS for CO, PM_{10}, Pb, NO_2, O_3, SO_2, and TSP as well as the federal NESHAPS into its own state code, and has the additional standards shown in Table 13.

Air quality regulation in Pennsylvania is centralized under the Pennsylvania Department of Environmental Resources. Each county of Pennsylvania may be subject to different degrees of regulation, depending on its history of compliance. Lawrence County, where INMETCO is located, has historically had difficulty meeting the PM_{10} standards.

As is the case with California, emissions standards for criteria and hazardous air pollutants are source specific. They must be determined for each region, for each facility, and for each source in that facility, based on the emissions inventories of each region. Like California, Pennsylvania

Table 13. Pennsylvania ambient air quality standards[1]

Contaminant	Concentration			
	1 Year	30 Days	24 Hours	1 Hour
Settled Particulate	0.8 mg/cm^2/mo.	1.5 mg/cm^2/mo.	–	–
Beryllium	–	0.01 μg/m^3	–	–
Sulfates	–	10 μg/m^3	30 μg/m^3	–
Fluorides	–	–	5 μg/m^3	–
H_2S	–	–	0.005 ppm	0.1 ppm

1. Reference 79.

also practices emissions reduction offsets for new sources and allows banking, trading, and selling of offsets [79].

2.6.3 Wastewater Management

To protect the quality of our nation's waters, the EPA passed the Federal Water Pollution Control Act, also known as the Clean Water Act (CWA), in 1972 to protect navigable waters. Under the Safe Drinking Water Act (SDWA), the EPA set minimum standards to be maintained to protect drinking water. The primary drinking water standards for inorganic contaminants are listed in Table 14. California also passed the Water Quality Act (WQA), which in many cases exceeds the standards of the CWA. In California, Proposition 65 prohibits discharging any known carcinogens or chemicals known to cause reproductive harm to any potential drinking water supply. A list of 300 such chemicals is found in Title 12 of the California Code of Regulations, §12000 (b) and (c) [80].

The state agency which governs water quality in California is the State Water Resources Control Board (SWRCB), which is part of Cal/EPA. Under the CWA, any facility which discharges pollution to navigable waters must have a permit. The permitting mechanism is known as the National Pollution Discharge Elimination System (NPDES), and the EPA has granted the SWRCB authority to administer the NPDES program in California. Each regional water quality control board defines "beneficial uses" of water in that region, and establishes objectives to protect the

Table 14. National primary drinking water standards for inorganic contaminants[1]

Contaminant	Maximum Contaminant Level (MCL), mg/L	Secondary MCL, mg/L
Arsenic	0.05	—
Barium	1.0	—
Cadmium	0.001	—
Total Chromium	0.05	—
Copper	1.3	1.0
Lead	0.05	—
Manganese	—	0.05
Mercury	0.002	—
Nickel (proposed)	0.10	—
Fluoride[2]	4.0	2.0
Zinc[2]	—	5.0
Nitrate[2]	10	—
Selenium	0.01	—
Silver	0.05	0.10

1. Reference 81.
2. Reference 82.

beneficial uses. In California, any proposed discharge to a receiving body, other than a sewer, must be reported to the SWRCB. If the receiving body is a surface water, the facility needs a NPDES permit, which stipulates protective discharge limits. If the protective limits cannot be met, the discharge is prohibited. Permit discharge conditions are based on the assimilative capacity of the receiving water and the water quality objectives [76].

TSDs and recycling facilities are also required to have a stormwater runoff discharge permit. This requires facilities to develop a stormwater pollution prevention program, to monitor stormwater collection systems, and to eliminate illegal stormwater discharges to the sewer [76].

Discharges to a sewer require a permit of the local sanitation district which imposes discharge limits. The following are typical discharge limits and conditions imposed by a sanitation district [76].

Constituent	**Discharge Limit (mg/L or ppm)**
Arsenic	1.0
Cadmium	0.8
Total Chromium	2.5
Copper	2.0
Lead	0.6
Mercury	0.01
Nickel	2.0
Silver	0.5
Zinc	5.0

- Temperature may not exceed 150°F
- pH must be between 6 and 11.5
- Total Suspended Solids (TSS) may not exceed 500 mg/L
- Five day biochemical oxygen demand (BOD_5) may not exceed 600 mg/L
- Total Dissolved Solids (TDS) may not exceed 1,000 mg/L or the TDS of the potable water supply by more than 250 mg/L, whichever is greater

EPA has also stipulated pretreatment standards for categories of industries. Title 40 CFR, Part 403 contains general regulations for new and existing sources. Of interest to battery recycling may be Part 413-electroplating, 414-organics and plastics, 415-inorganics, 420-iron and steel manufacturing, 421-nonferrous metals manufacturing, and 424-ferroalloy manufacturing. Facilities within these categories must treat their effluent before discharging it to the sewer, in order to protect the wastewater treatment plant operations and effluent [76].

2.6.4 Facility Siting Regulations

Locating a new battery recycling facility must be based on several environmental, economic, and human factors. Before any permitting can begin, the site must be assessed for possible contamination from previous occupants. If contamination is found, the site must first be remediated. As part of the permit application process, the site must be zoned to assure that it is located in an appropriate area, i.e., agricultural zones, commercial zones, industrial zones, residential zones, and recreational zones. Proper zoning assures the public welfare and reduces the consequences of the NIMBY syndrome. Conditional Use Permits (CUPs) can be granted to allow some flexibility in the zoning ordinances, provided that the facility meets the conditions of the permit, which account for public safety, for the duration of operation. The CUP application requires very specific information on the nature of the operation and a list of contacts, as well as information on the present use of all the property within a 500 foot radius of the site [76].

There are several agencies involved in the permit approval process. The local water sanitation district issues conditional permits for discharging to the local sewer, based on the nature of the operation, the chemicals used, and the volume and composition of the wastewater discharged. The local air quality control district must ascertain whether or not the site is within a nonattainment area. If it is, the district must determine what offsets are required before it can issue permits. The local water quality control board must assess the impact of the proposed facility on surface or groundwaters. If discharges to land or surface waters are inevitable, the board must set discharge limitations. Any above ground storage tanks are also under the jurisdiction of the local water board. The local hazardous materials (hazmat) administering agency must also receive the facilities hazmat inventory, as required by the community-right-to-know law. Information on the storage areas and handling of hazmat is also required. Additionally, if the operation is identified as posing potentially significant environmental impacts, the California Environmental Quality Act (CEQA) requires that an Environmental Impact Report (EIR) be written. All of the local agency permits must be approved before the planning and zoning committee can approve the application for a land use permit. Government Code §§65850-65850.2 contains the regulations for planning and zoning [76].

The land use decision of the lead local agency will determine if the applicant may continue with the hazardous waste facility project. The lead local agency is that local agency which has the responsibility to approve a hazardous waste facility. The specific agency may vary by city or county. The applicant may appeal the decision of the lead local agency, under the Tanner Appeal Process (Health and Safety Code, Chapter 6.5, Article 8.7, §§25199-25199.14). This process allows the applicant to appeal the land use decision of the lead local agency if the decision was made before the environmental impact report was certified, or if conditions of the decision would be so restrictive that it is almost as if the facility were disapproved. In order to appeal, the applicant must already have obtained all the necessary, pre-construction, state-level permits. Concerned citizens may also appeal a land use decision, if they feel that the conditions of the approval do not adequately safeguard their health and environment. The appeal board acts in place of the lead local agency, and may overturn the decision made by the lead local agency if it finds the proposed facility to be in compliance with all of the local environmental policies, if the facility has all the necessary, pre-construction, state-level permits, and if the appeal board has identified a definite need for the facility. The appeal board has the authority to require the lead local agency to reverse its decision [83].

2.6.5 OSHA and Cal/OSHA

The Federal Occupational Safety and Health Act (OSHA) was passed in 1970, with the basic doctrine of guaranteeing safe and healthful working conditions for every working man and woman in the country. In 1972, California signed the Cal/OSHA into law, stipulating the same or more stringent regulations as the Fed/OSHA. Under Cal/OSHA, any employer in the state of California, regardless of the type of business, has the following rights and responsibilities:

Employers have the right to:

- Receive free educational and training services from the state on matters of worker health and safety
- Petition for a change in the existing rules or standards
- Participate in advisory committees and public hearings to amend existing standards
- Request a variation on the requirements
- Be present during a facility inspection by the Division of Occupational Safety and Health (DOSH)
- Dispute abatement requirements, citations, or penalties
- Be protected by law, should trade secrets be revealed as the result of a DOSH inspection
- Obtain Material Safety Data Sheets (MSDS) from the manufacturer of any hazmats which employees may come into contact with

Employers have the responsibility to:

- Maintain a safe and healthful workplace for all employees
- Abide by all OSHA standards, regulations, orders, and rules
- Provide for employee training in safe work habits and special practices for any job which may present worker hazards
- Provide hazmat training and inform workers of contaminants to which they may be exposed, and the permissible exposure levels (PEL)
- Allow employee access to their personal medical and exposure records
- Visibly post, at the place the violation occurred, any citations incurred for violations
- Post the Cal/OSHA "Safety and Health Protection on the Job" notice
- Permit employees to be present at any monitoring or measuring of hazard exposure
- Notify an employee when he/she has been exposed to a contaminant at a level above the PEL, and to inform the employee of how to proceed
- Keep reports and records of injuries, illnesses, exposures, and various categories required by OSHA
- Develop an illness and accident prevention plan
- Make employee injury and illness records accessible to employees

Employees have the right to:

- A safe and healthful workplace
- General training and specific training regarding job hazards
- View all MSDSs and receive information from the employer about any hazards to which he/she may be exposed
- Refuse to do any job that violates the Labor Code or OSHA
- Be present during monitoring and measuring of hazard exposure
- Be informed if he/she has been exposed to a hazardous substance at a level above the PEL
- View and copy exposure and medical records of any employees
- Lodge an anonymous complaint with the DOSH to request a site inspection
- Have an employee representative at all DOSH inspections
- View any citations received by the employer
- View the injury and illness records
- Petition for a revision to any OSHA standards
- Take part in appeal proceedings
- Be notified of an application for a variation in OSHA standards and take part in the hearings
- Be present or represented at permit safety conferences

Employees have the responsibility to:

- Abide by all OSHA regulations, rules, and orders
- Not tamper with, remove, or destroy safety equipment, notices, or safeguards
- Not interfere with other employees who may be using safety equipment or safeguards
- Use the proper safety equipment provided for their protection

2.6.6 Additional Comments on Regulatory Concerns

In addition to governmental regulations, a significant barrier to the establishment of new sources in California is the public's NIMBY attitude. It is the opinion of recyclers in California that NIMBY will be more of a barrier than governmental regulations in siting any new battery recycling facilities in California. Citizens have the right, under the Tanner Appeal Process, to appeal any land use decision that involves land in their community, if they believe that the decision neglected some necessary conditions to protect their health and environment. Therefore, it will be important to consider the expansion and upgrading of existing facilities to accommodate larger volumes of waste and different types of battery waste, in addition to building new facilities. Under the existing regulatory structure in California, it may certainly be possible to allow new facilities to come on line. It may be easier to simply expand and upgrade existing facilities.

2.7 BATTERY RANKING

Each battery type is ranked separately according to overall recycling technology and battery performance. The purpose of the battery performance ranking is to identify which batteries are likely to be used in EV applications in the near term or have excellent prospects for long term vehicle application. The ranking of candidate EV battery recycling will also assist in determining which batteries will be evaluated further as part of a health hazard assessment. Recycling weighting factors are estimated for attributes under the following categories:

- Battery performance
- Battery recycling
    - Recycling technology
    - Recycling infrastructure
    - Market conditions
    - Regulatory constraints

2.7.1 Battery Performance Ranking

A weighting factor is assigned to each attribute to reflect the relative importance of each attribute and to take into account double counting of related factors. Table 15 shows the battery performance attributes with their weighting factors. Initial battery cost was not included in the market ranking criteria, because cost estimates are unreliable at this point and the effect on vehicle price is difficult to predict. Similarly, health and hazardous attributes are not included in the initial screening in order not to prejudice the outcome of the health/hazard assessment. Each battery is scored on a scale of 1 to 5 for each performance and recycling related attribute. Where possible, scoring was based upon quantitative criteria. A score of 5 indicates the best performance or characteristics, and a 1 indicates the worst performance or characteristic.

2.7.1.1 Battery Performance Attributes

The scoring for battery performance attributes are shown in Table 16.

1. *Specific Energy.* Specific energy is a measure of a battery's energy content per unit weight, and is an important attribute because it dictates how far a vehicle can travel for a given battery weight. Because range limitations are the major issue with EV implementation, specific energy is weighted heavily. The higher a battery's specific energy, the higher its score.

Table 15. Battery performance ranking attributes

Battery Performance	Weighting Factor
Commercial status	2
Specific energy	5
Specific power	4
Rechargeability	3
Charge holding ability/Stand alone loss	1
Battery life	2
Energy Efficiency	2
Total	17

Table 16. Technical battery ranking criteria

Ranking Score	Specific Energy (Wh/kg) (C/3)	Specific Power (W/kg) (80% DOD)	Self Discharge (% per 48 hr)	Battery Life (years)	Commercial Status	Rechargeability	Efficiency (%)
5	>100	>400	<1	>8	Currently available in EVs	Electrical	>95
4	71 to 100	251 to 399	1 to 5	5 to 8	Available in 2 yrs.		85-94
3	51 to 70	151 to 250	6 to 9	3 to 4	Available in 5 yrs.		75-84
2	31 to 50	100 to 150	10 to 12	2 to 3	Available in 10 yrs.	Chemical	65-74
1	≤30	<100	>12	<2	> 10 yrs.	Not Rechargeable	<65

2. *Specific Power.* Specific power is a measure of a battery's ability to deliver energy and the EV's ability to accelerate rapidly. This attribute is important because it affects the EV's driveability and consumer appeal.

3. *Charge Holding Ability/Stand Alone Loss.* Charge holding ability is important because self discharge increases the battery size requirement if the vehicle is to be parked away from a charger for any significant amount of time. Excessive self discharge or heating requirements also contributes to excessive electricity use and consequently higher operating costs.

4. *Battery Life.* Battery life affects the vehicles' operating cost as well as the life cycle recycling requirement. Increased battery life will have a direct impact on the recycling requirement for batteries. Although many of the advanced batteries are relatively expensive, their longer life offsets the initial battery cost.

5. *Commercial Status.* Commercial status characterizes the batteries' prospects for being used in an EV due to current commercial success, on-going research efforts, or promising prospects in demonstration vehicles with significant industrial backing. The highest score is given to lead-acid batteries which are already procured commercially. Batteries that are receiving significant industrial support also score well in terms of commercial status, such as those funded by the USABC, including NiMH and NaS. Longer-term batteries, including the lithium polymer battery, which do not yet have a definitive commercial release timeline, receive relatively lower scores.

6. *Rechargeability.* Rechargeability provides a substantial degree of convenience for EV batteries. While it could be conceivable that a battery could be replaced at a service station for every "fueling" event, such an approach would have limited consumer appeal. Electrically rechargeable batteries score better in this assessment than those with replaceable chemicals, because the inherent advantages of overnight home recharging combined with the lack of infrastructure for replacing battery chemical makes electrically rechargeable batteries more desirable.

7. *Energy Efficiency.* Like poor charge holding ability, a poor energy efficiency of the battery can lead to excessive electricity use and higher operating costs. It will also present an inconvenience to the consumer to have to recharge the battery more often.

8. *Battery Life Cost.* Some batteries may appear expensive based on the initial purchase price and replacement price, but the longer lives of several of the advanced batteries can significantly offset the perceived high costs. While this attribute is not included in the ranking, since costs are difficult to accurately predict at this point for some batteries and will almost certainly change with fluctuating metal prices, the estimated market prices of batteries warrant some discussion. Prices are gauged in US$/kWh/yr to show how the purchase price of the battery will be distributed over its lifetime. For light duty vehicles, lead-acid batteries actually are the most expensive option at this time, because of the short life of only two years. The life costs are summarized in Table 17 for light-, medium-, and heavy-duty vehicles.

2.7.2 Recycling Ranking Attributes

The attributes used to rank overall battery recycling are shown in Table 18.

2.7.2.1 Recycling Technology

Recycling technology assesses the current state of battery recycling. Scoring criteria are shown in Table 19.

1. *Ease of Battery Dismantling.* The ease of dismantling the batteries before recycling is integral to the overall ease of recycling the battery. Lead-acid batteries with plastic casings are the easiest types of batteries to dismantle, as they are simply placed in a chopper or shredder. Batteries with metal casings are more difficult and may require special treatment or equipment.

   Preliminary preparatory steps may need to be taken before the battery can be dismantled or handled for recycling. For example, the lithium in all types of lithium batteries is highly reactive. Therefore, these batteries must be frozen in liquid nitrogen to render the lithium essentially inert or be handled in an inert environment. NaS and

Table 17. Battery life costs

Battery	US$/kWh/yr (LDV)	US$/kWh/yr (MDV)	US$/kWh/yr (HDV)
Lead-Acid	55	55	55
Sealed Bipolar Lead-Acid	50	50	75
Nickel-Cadmium	43	75	—
Nickel-Metal Hydride	34	50	—
Zinc-Air	12	17	—
Sodium-Sulfur	42	63	—
Sodium-Nickel Chloride	32	50	—
Lithium-Iron Disulfide	30	50	—
Lithium-Polymer	20	34	—

Table 18. Battery recycling ranking attributes

Attribute	Weighting Factor
<u>Recycling technology</u>	
Ease of battery dismantling	3
Fraction of output that is recyclable/reusable	5
Fraction of output as hazardous waste	5
Scale of technology	4
Size of batteries handled	3
<u>Recycling infrastructure</u>	
Existing recycling facilities	2
Existing collection infrastructure	2
Distance to recycler	1
<u>Market considerations</u>	
Market for recycled products	3
Value of product	2
Disposal costs	1
<u>Regulatory constraints</u>	
Hazardous material status	1
Toxic metals content	1
Difficulty in permitting new or expanded facilities	2
Effect of air emissions on permitting	1
Total	36

Table 19. Recycling technology ranking criteria

Ranking Score	Ease of Dismantling	% Output Recyclable/ Reusable	% Output as Hazardous Waste	Scale of Technology	Size of Batteries Handled
5	Simple; Mechanical only	>90%	<10%	Commercial	>200 kg
4	Discharge	>75%	<25%	Pilot	>50 kg
3	Cooling	>50%	<50%	Bench	>10 kg
2	Removal of extraneous systems	>25%	<75%	—	Dry cell consumer size or button
1	Stabilization/deep freeze	<25%	<75%	Not developed	Not recycled

other molten salt batteries may need to be cooled and/or discharged before disassembly for safety reasons. An important consideration is how the large voltages across the electrodes of EV battery modules will affect electrical dismantling equipment. Furthermore, many of the batteries currently in development may have rather sophisticated elements such as heat transfer elements or software that preclude recycling or make it much more difficult. Ideally, batteries being developed for EVs should be designed with recycling in mind at the end point of the product's useful life.

2. *Fraction of Output that is Recyclable/Reusable.* Aside from the environmental goals of reducing the total waste stream from recycling processes, a high percentage of recyclable or reusable material will make the recycling process more profitable, whereas a high fraction of waste output will only increase the disposal costs. A process that produces more waste than recyclable material will also have difficulty gaining public acceptance, as recycling has a better public image than disposal or incineration.

3. *Fraction of Output that is Hazardous Waste.* A high fraction of hazardous waste will significantly increase disposal costs and will increase the regulatory burden on the process. Batteries that produce high amounts of hazardous waste from recycling receive low scores.

4. *Scale of Technology.* Recycling technologies are ranked on the current state of development of the technology. Technologies already operating on a commercial scale, such as lead-acid recycling, receive the highest score. Technologies that are only in pilot scale or bench scale receive respectively lower scores. Batteries that are currently not recycled at all score the lowest.

5. *Size of Batteries Handled.* The size of the batteries currently being recycled is an important indication of the need for scale-up and process refinement. The batteries handled in existing recycling facilities may be significantly smaller in size than future EV batteries. Dismantling and shredding equipment may need to be modified to accommodate the rather large sizes of EV battery packs. A shredder that normally handles only small dry cell or button batteries could certainly not accommodate an 800 lb NiCd monoblock sent through it. Large-size batteries that are already recycled receive the highest scores, and those that are not recycled at all receive the lowest score. It is assumed that batteries which are only recycled on a pilot or bench scale, such as

the NaS battery, are of the larger EV battery size. Therefore, those batteries scored the highest in this category.

2.7.2.2 Recycling Infrastructure

Establishing a viable recycling infrastructure in California could be vital to the economic success of the EV program in the state. It would certainly be more economical to recycle spent batteries in-state, for several reasons: (1) to reduce the regulatory steps that would be involved with shipping waste out-of-state, (2) to reduce the costs of recycling by minimizing transportation costs, and (3) to create jobs in California. The guidelines used to score batteries in this category are shown in Table 20.

1. *Existing Recycling Facilities.* Batteries are ranked on the availability of existing recycling facilities. Existing recycling facilities in California and the U.S. are a crucial step to creating a viable recycling infrastructure for EV batteries. For this reason, lead-acid batteries score highest because recyclers and battery breakers are already operating in California. NiCds rank next highest because a recycling facility operates in the U.S.

2. *Existing Collection Infrastructure.* Batteries score well in this category if there is an adequate number of collection centers for that battery type. Lead-acid batteries exclusively receive the highest score, since, in most states, consumers may return their spent lead-acid batteries to the point of purchase, or some other retail collection center. NiCds score second-highest in this category, since the Portable Rechargeable Battery Association (PRBA) has begun the initial stages of their NiCd collection program under the direction of the Rechargeable Battery Recycling Corporation (RBRC), which may in the future encompass EV batteries. Most other battery types receive low scores, since they are not being actively collected.

3. *Distance to Recycler.* Batteries for which recycling facilities exist in California are ranked highest in this category, as proximity minimizes transportation costs. Batteries with recycling facilities located within North America are ranked second, and facilities in Europe and Asia are third and fourth, respectively. Batteries for which no commercial scale recycling facilities exist score the lowest.

Table 20. Recycling infrastructure ranking criteria

Ranking Score	Existing Recycling Facilities	Existing Collection Infrastructure	Distance to Recycler
5	California	Excellent	California
4	North America	Good	North America
3	Worldwide	Fair	Europe
2	Developing	Poor	Asia
1	None	Not developed	None

2.7.2.3 Market Considerations

The condition of the market can make or break a recycling operation. Even in cases where recycling is largely regulation driven, as in the case of lead-acid batteries, the market can have devastating effects. In the 1980s, the price of lead experienced a significant drop at several points during the decade, causing many smelters to go out of business. In addition, a market for the recycled product must exist in order for the recycling effort to sustain itself. Regulations requiring a certain percentage of recycled material in new products are helpful, but their effectiveness is limited if the recycled product is not suitable for reuse. The ranking criteria surrounding market considerations are detailed in Table 21.

1. *Market for Recycle Products.* The market for recycled products affects the success of recycling battery components. Batteries with "closed loop" metal consumption, in which recycled product metals are used to produce the same type of battery, are less likely to be affected by shifts in the market demand for recycled products. For example, in both lead-acid and NiCd battery recycling, lead and cadmium are almost completely recovered and can be used to meet the demand for new battery materials. Therefore, the issue of recycled metals flooding the market is not relevant for batteries that produce pure metals from the recycling process.

   Secondary markets for recycling products are more affected by fluctuating market demand than are the closed-loop markets. Nickel, for example, is usually recovered as a ferronickel alloy and sold to stainless steel producers. Recovered lithium is sold as an additive to the cement industry. In contrast, products such as sodium polysulfides and recovered misch metals have virtually no market, and are given the lowest score.

2. *Value of Product.* The higher the intrinsic demand for a product of recycling, the more sustainable is recycling of a given battery type. In general, the rarer the metal, the higher and more constant its market value. For the most current battery metals prices, see Table 22.

   Other metals have a market value that fluctuates greatly depending of a number of other factors. In the case of nickel, Russia's opening of its vast nickel reserves has pushed the world market price to an all-time low.

   Cadmium has also recently experienced a decline in price partly attributable to increasingly stringent environmental regulations. Furthermore, cadmium is obtained as a co-product of zinc mining, and its supply is therefore linked with the demand for zinc. Similarly, lithium demand is closely tied to the primary aluminum industry. Other products, including sodium or sulfur, have fairly consistent low market values.

3. *Disposal Costs.* Associated disposal costs are high if the battery has a high percentage of unrecyclable material, or if the recycling process yields a product with no market. The fraction of the waste that must be disposed of as hazardous waste adds to the disposal costs.

2.7.2.4 Regulatory Constraints

Regulatory considerations are difficult to weigh, since the regulations governing battery recycling could change almost completely during the first part of 1995 with the finalization of the Universal Waste Rule. This rule will make recycling easier for consumers, as they will be allowed

Table 21. Market ranking criteria

Ranking Score	Market for Recycle Product	Value of Product	Disposal Costs
5	Closed Loop	\$11 to \$20/lb	No disposal
4	—	\$6 to \$10/lb	
3	Secondary	\$2 to \$5/lb	Municipal Waste
2	—	\$0.50 to \$1/lb	
1	No Market	<\$0.50/lb	Hazardous Waste

Table 22. Market value of metals and products of recycling

Metal	Price (U.S. \$/lb) 1989[1]	Price (U.S.\$/lb) Current[2]
Al	0.89	0.847
Cd	6.35	0.45
Cu	1.30	1.33
Fe/Steel	0.256	0.069
Pb	0.34	0.27
Li (Li_2CO_3)	1.63	2.00
Mischmetal	12.35	12.68
Ni	6.30	3.54
Na (Na_2SO_4)	0.043	0.04
S	0.044	0.022
Sn	4.13	2.45
V (V_2O_5)	4.50	1.43
Zn	0.83	0.474

1. Reference 69.
2. Reference 85.

to transport their own spent batteries to collection centers or recyclers. Collection centers will be able to operate more smoothly as well, with less red tape to work through in order to store and ship batteries. Currently, all spent batteries are classified as hazardous waste, with only one regulatory exemption for the collection, storage, and transportation of lead-acid batteries. Therefore, in most categories, lead-acid batteries are given the highest score based on their exempt status, and all other battery types are ranked equally second-highest, because it is likely that they could also be granted exempt status in the near future. The ranking of various attributes related to regulatory constraints are listed in Table 23.

1. *Hazardous Materials Status of Spent Batteries.* At the present, all batteries are classified as hazardous materials, except for lead-acid batteries, which are exempt from hazardous waste constraints. The collection, storage, and transportation of hazardous materials is governed by RCRA. However, all batteries are expected to become exempt from these requirements pending finalization of the Universal Waste Rule, so they are given scores almost as high as lead-acid batteries.

2. *Toxic Metals Content.* The batteries are also ranked according to their toxic metals content, since handling toxic metals will pose constraints on the operations of recycling facilities. Toxic metals are defined as those identified by the federal TCLP test, listed in 40 CFR, Part 261.24, and by the California STLC and TTLC tests, listed in 22 CCR, Part 66261.24. These metals include antimony, arsenic, cadmium, chromium, iron, lead, lithium, nickel, sodium, sulfur, tin, and zinc. Toxic metals contents were based on the material safety data sheets for the batteries under study here [85]. OSHA, the Clean Air Act (CAA), the Clean Water Act (CWA), RCRA regulations, as well as state environmental and local air, water and waste regulating boards impose restrictions on facility operations that deal with hazardous emissions, effluents, storage, or handling.

Table 23. Regulatory ranking criteria

Ranking Score	Hazardous Materials Status	Toxic Metals Content	Difficulty of Permitting New or Expanded Facilities	Effect of Air Emissions on Permitting
5	Currently exempt	<5%	No environmental impacts/permits not required	No significant air emissions
4	To be exempted per Universal Waste Rule	5 to 25%	—	Produces significant emissions of criteria pollutants in an attainment area
3	—	26 to 50%	—	Produces significant criteria pollutants in a nonattainment area
2	—	51 to 75%	Process creates public opposition	Produces TACs and/or significant amounts of criteria pollutants in a severe or extreme nonattainment area
1	—	>75%	Located in California	Produces significant amounts of TACs

3. *Difficulty in Permitting New or Expanded Facilities.* Permitting a recycling facility can prove to be a nearly insurmountable regulatory obstacle in some cases. The difficulty of permitting a given process depends upon the potential health and hazard impacts of the material, the local regulatory environment, and the public concern towards the facility. Environmental regulations differ from state to state and even within each state. California is widely regarded as having the most stringent, all-encompassing environmental regulations of any state; they often prove restrictive to new businesses with the potential to produce pollution. Furthermore, public opinion, when directed against a particular project, can effectively deny a facility permit approval during the public review process. Public opinion is influenced greatly by the "NIMBY" syndrome. For example, a lithium recycler in British Columbia tried initially to locate a facility at several sites in the U.S. Although the process received approval from the U.S. EPA, local opposition prevented the company from locating in the U.S.

4. *Effect of Air Emissions on Permitting.* Recycling processes which produce air pollutants are subject to additional regulatory constraints. New sources of air pollution must obtain a permit to construct and must comply with New Source Performance Standards (NSPS) as well as either Best Available Control Technology (BACT) or Lowest Achievable Emission Rate (LAER). The BACT requirement applies to emissions in areas that are in attainment with the National Ambient Air Quality Standards (NAAQS), while the LAER requirement applies to sources of emissions in nonattainment areas.

Processes which produce significant amounts of Toxic Air Contaminants (TACs), as defined by CARB (pursuant to the provisions of AB 1807 and AB 2728), are subject to stringent regulations and control requirements, including use of Maximum Achievable Control Technology (MACT). A current list of TACs can be found in the Appendix. All of the federal Hazardous Air Pollutants (HAPs) are included in the California list of TACs. Because of stringent regulations for toxic air pollutants, some processes that produce air toxic emissions, such as smelters, are very difficult to permit. Pyrometallurgical processes used in metal (and thus battery) recycling use smelters; however, for most battery types, electrowinning or electric arc melting furnaces are available material recovery options. The region in which a facility is located also affects the difficulty of the permitting process. Locating a new source in an area that is classified as an extreme or severe nonattainment area for criteria pollutants requires obtaining offset emissions and greatly increases the complexity of the permitting.

If the batteries are already recycled using a process such as an electric arc furnace, electrowinning, or another wet chemistry process, as in the case of zinc-air batteries, it is assumed that any new or expanded facilities for these batteries will use the same process. These batteries therefore score well in this category. If the technology exists to recycle batteries in a more air-friendly manner, even if the battery is currently recycled via smelting, such as lead-acid, these batteries also score well, assuming that all new facilities will use the cleaner process.

2.7.3 Ranking Scores

Table 24 shows the ranking of batteries for each of the attributes in Tables 17, 19, 20, 22, and 23. Each battery attribute was compared to the ranking criteria laid out in the above tables and given the appropriate score based on those criteria. To calculate the total score, the individual score for each attribute was multiplied by the weighting factor for that attribute, and the sum was taken of the product of weighting factor and attribute score.

Table 24. Battery ranking scores

Attribute	Weighting Factor	Convent. Pb-acid	Sealed Bipolar Pb-acid	NiCd	NiMH	Na/S	Na-NiCl
Performance Atrtribute							
Commercial status	2	5	4	5	4	3	3
Specific energy	5	2	2	3	4	4	4
Specific power	4	2	5	3	3	3	2
Rechargeability	3	5	5	5	5	5	5
Charge holding ability	1	5	3	4	2	2	3
Battery life	2	2	2	4	4	4	4
Energy efficiency	2	3	3	3	3	1	1
Score	—	58	66	70	71	65	62
Recycling Ranking Attribute							
Ease of battery dismantling	3	5	5	5	5	4	4
Fraction of output that is recyclable/reusable	5	5	5	5	5	4	5
Fraction of output as hazardous waste	5	5	5	5	5	5	5
Scale of existing technology	4	5	5	5	5	4	3
Size of batteries currently handled	3	4	4	4	4	4	1
Existing recycling facilities	2	5	5	4	4	1	2
Existing collection infrastructure	2	5	5	4	4	1	1
Distance to recycler	1	5	5	4	4	1	1
Market for recycled product	3	5	5	3	3	3	3
Value of product	2	1	1	1	1	1	1
Disposal costs	1	1	1	1	3	1	1
Hazardous material status	1	5	5	4	4	4	4
Toxic metals content	1	2	2	4	3	5	5
Difficulty in permitting new or expanded facilities	2	1	1	2	2	2	2
Effect of air emissions on permitting	1	4	4	5	5	4	5
Score	—	153	153	146	147	119	114

Table 24. Battery ranking scores (concluded)

Attribute	LiFeS	LiFeS2	Li Polymer	Li-Ion	Zn/air	Al/air	Fe/air	ZnBr	Max. Score
Performance Attribute									
Commercial status	1	1	1	3	1	1	1	1	5
Specific energy	4	4	5	5	5	5	4	3	5
Specific power	3	3	1	3	1	4	2	2	5
Rechargeability	5	5	5	5	5	1	1	2	5
Charge holding ability	3	3	5	5	NA	NA	NA	1	5
Battery life	4	4	4	4	4	4	4	4	5
Energy efficiency	1	1	4	1	1	1	1	3	5
Score	62	62	67	73	(56)	(56)	(43)	46	95
Recycling Ranking Attribute									
Ease of battery dismantling	1	1	1	5	5	5	5	5	5
Fraction of output that is recyclable/reusable	5	5	5	5	5	5	5	5	5
Fraction of output as hazardous waste	5	5	5	5	5	5	5	5	5
Scale of existing technology	5	5	1	3	5	1	1	5	5
Size of batteries currently handled	4	4	1	3	4	NA	NA	2	5
Existing recycling facilities	4	4	1	3	4	1	1	4	5
Existing collection infrastructure	1	1	1	1	1	1	1	1	5
Distance to recycler	4	4	1	2	4	1	1	4	5
Market for recycled product	3	3	3	3	5	5	5	5	5
Value of product	3	3	3	3	1	2	1	1	5
Disposal costs	3	3	3	3	3	3	3	3	5
Hazardous material status	4	4	4	4	4	4	4	4	5
Toxic metals content	5	5	5	5	2	5	5	2	5
Difficulty in permitting new or expanded facilities	2	2	2	2	2	2	2	2	5
Effect of air emissions on permitting	5	5	5	5	5	5	5	5	5
Score	135	135	101	132	146	(114)	(112)	140	180

NA = Not available.

( ) = Score reflects lack of data for one or more attributes.

$$\textit{Total Score} = \sum (\textit{Weighting Factor} \times \textit{Individual Attribute Score})$$

It should be noted that the rankings and scores associated with each battery performance and recycling technology are intended for comparative and qualitative use. The assessment methodology used in this report is based solely on current technology; assignment of ranking scores involved decisions that were based on the limited data that is available. The results given here should be viewed within this context.

Lead-acid batteries receive the highest score for recyclability because they are a commercial product and have the most widely established recycling infrastructure Zinc batteries scored high for recyclability, since large industrial sized versions of this battery are being recycled in Texas, and the process produces very little, if any, hazardous waste or hazardous air pollutants. NiMH and NiCd batteries are ranked next since INMETCO is recycling NiCds and small amounts of NiMH batteries in Pennsylvania. NiMHs score higher than NiCds since they are less hazardous than NiCds. The lithium batteries receive fairly high marks for recyclability, since the process used in Canada produces no air emissions and the wastewater is recycled back into the process. They are rated lower than zinc since the batteries must be exported to Canada. Lithium polymer batteries are scored poorly for recyclability since virtually no one even produces them in large sizes. Overall the sodium beta batteries are rated poorly in terms of recyclability, since the market for these recycled products is not favorable, and their recycling efforts have only been on a pilot or bench scale and involve incineration. The other molten salt batteries are given low scores for recyclability since there are no known recyclers for these battery types.

The lithium ion and polymer batteries are ranked well for performance, with significant research still being conducted in these areas. Although data on the energy efficiency of lithium-ion batteries is not available, they receive a conservatively low score of 1 (one) in this category. However, even with such a conservative score for this attribute, they still achieve the highest performance score. Sodium-beta batteries are rated average for performance.

The performance scores for the molten salt batteries, which include NaS, Na-NiCl$_2$, LiFeS, and LiFeS$_2$, require some clarification, as their scores do not follow the ranking criteria exactly. Sodium-sulfur is given a score of 2 for charge-holding ability, although it exhibits 0% self-discharge, because if left unplugged for extended periods of time, the battery "freezes" and must be reconditioned. The other molten salt batteries are not as severely damaged by freezing as sodium-sulfur, but they must be heated to the full operating temperature before driving resumes. Keeping these batteries at such high temperatures results in greater energy use to recharge the battery, and thus all of the molten salt batteries receive the lowest scores for energy efficiency. The air and zinc batteries are scored the lowest for performance, and there does not appear to be much research support for these batteries in EV applications. The category of charge-holding ability for all of the metal-air batteries is left blank, due to lack of sufficient information needed to make a reasonable estimate. The performance and recycling scores are listed in descending order in Tables 25 and 26.

Table 25. Summary of battery performance scores

Battery Technology	Performance Score
Lithium-Ion	73
Nickel-Metal Hydride	71
Nickel-Cadmium	70
Lithium Polymer	67
Sealed Bipolar Lead-Acid	66
Sodium-Sulfur	65
Lithium-Iron Sulfide	62
Lithium-Iron Disulfide	62
Sodium-Nickel Chloride	62
Conventional Lead-Acid	58
Zinc-Air	(56)
Aluminum-Air	(56)
Zinc-Bromine	46
Iron-Air	(43)

Table 26. Summary of battery recycling scores

Battery Technology	Recycling Score
Conventional Lead-Acid	153
Sealed Bipolar Lead-Acid	153
Nickel-Metal Hydride	147
Nickel-Cadmium	146
Zinc-Air	146
Zinc-Bromine	140
Lithium-Iron Sulfide	135
Lithium-Iron Disulfide	135
Lithium-Ion	132
Sodium-Sulfur	119
Sodium-Nickel Chloride	114
Aluminum-Air	(114)
Iron-Air	(112)
Lithium Polymer	101

SECTION 3

CONCLUSIONS AND RECOMMENDATIONS

There are still many unanswered questions about the fate of EV battery recycling in California, which can only be answered as the future unfolds. In the forum of this study, we have attempted to assess the ability of California and the nation to accommodate the electric vehicle battery waste that will be generated by the timed introduction of EVs in California. The use of EVs is intended to better the environmental quality in the state, and therefore great care should be taken to ensure that their use does not actually deteriorate environmental quality through careless disposal of batteries or through unsound recycling practices.

It is still somewhat early to determine which batteries will ultimately fill the market, although we have made reasonable predictions as to which technologies will be favored, namely lithium-polymer, lithium-ion, and nickel-metal hydride. No matter which batteries are used, recycling must be considered as the final destination for batteries, and should be included as part of the battery design. Batteries in development should be tested for toxicity as well as performance, and samples of the recycled product should be tested for purity and for hazardous materials content to determine if markets are available for the product. Battery compositions must be verified by chemical assay in order to determine how they will be affected by environmental regulations. Even if certain batteries may not be considered hazardous, recycling should still be considered necessary to recover valuable metals and conserve raw materials.

The assumptions and predictions made in this report are intended to assist regulatory bodies in determining if additional recycling capacity is needed in California. If it is found that such capacity is needed, it will be necessary to assess the economic feasibility of establishing new plants. For lead-acid batteries, there appears to be enough capacity to handle increases up to the year 2010, although if lead-acid plays a greater role in the EV market than is expected, it may be necessary for in-state recyclers to turn away some out-of-state batteries. Nickel-containing batteries may be present in large quantities, possibly exceeding 30,000 tons by 2010. If this proves true, it will be necessary to establish more recycling capacity for these battery types. INMETCO is permitted to handle only 10,000 tons of nickel batteries. While there are other NiCd recyclers in the world, they are not all equipped to accept NiMH batteries. In addition, it is politically, socially, and environmentally preferable not to ship hazardous waste out of the country. Sodium and zinc batteries will most likely not be present in large numbers. The capacity for zinc recycling listed in Table 2 will probably suffice. There is currently no full-scale recycling plant that accepts sodium-beta batteries, but given the relatively small market share that is anticipated for these batteries, it may not be economical to establish a dedicated sodium-beta battery recycler. Lithium batteries may prove to be a problem if additional plants cannot be located in the United States. Lithium-ion and lithium-polymer batteries together could generate as much as 77,000 tons of waste by 2010. The single plant in Canada will certainly not be adequate to accommodate the anticipated large quantities of lithium batteries. Additional facilities will surely be needed, preferably in the United States.

Most recycling technologies today are still in developmental stages, with the exceptions of secondary lead smelting, which has been practiced since the early part of the century, and nickel-cadmium smelting. The evolving trend is turning away from technologies such as smelting, which produce significant amounts of air pollution, in favor of more air friendly technologies, such as electrowinning and other hydrometallurgical processes. However, the tradeoff involved with this switch in technologies is the production of far greater amounts of wastewater. Certainly for the South Coast Air Basin (SCAB), air quality is of primary concern; in such severe non-attainment areas, wet chemical processes will be preferred.

It is evident that many batteries will not be able to support a closed loop recycling system such as the lead-acid battery system in which as much as 70% of the new batteries are produced from recycled lead. The quality of many recycled products will simply be too poor for them to be reused in battery electrodes, and they will have to be sold to secondary markets where those can be found. In such cases, recycling efforts will not be able to rely solely on the sale of their product to be sustainable. We recommend that a deposit be levied on new battery sales, both as an incentive for consumers to return the batteries, and to generate an income which could subsidize recycling efforts. A deposit of $100 is recommended for all light-duty vehicle batteries, and $200 and $400 for medium-duty and heavy-duty vehicle batteries, respectively.

The regulatory environment for batteries could change within a very short time. At the present all spent batteries except lead-acid batteries are considered hazardous waste and are fully subject to RCRA regulations. With the final ruling of the Universal Waste Rule, all spent batteries could share the same exemptions. However, new TSD facilities will still face the same strict requirements for facility permitting, air emissions permitting, and wastewater discharge permitting. In certain areas, such as the SCAB, processes with heavy air emissions will be more difficult to permit than processes such as electrowinning, which produce virtually no toxic air emissions. Public opposition will still be a strong factor to contend with, no matter what the process, or how safe the EPA may determine it to be. This can only be dealt with in the usual arenas of public hearings. However, regardless of which batteries are eventually chosen to power EVs, cleaner recycling technologies such as electrowinning should be pursued not just for the immediate and long-term environmental benefits, but also so that public opposition can be more rationally and logically considered.

REFERENCES

1. Rand, D.A.J. "Batteries for Road Electric Vehicles: Systems in Competition with Nickel-Cadmium." *Nickel-Cadmium Battery Update '92*, the Cadmium Association, London, 1992.

2. Consultations with the Air Resources Board, Mobile Source Division, May 1994.

3. Cook, M. and H. Morrow. "Market Prospects for Nickel-Cadmium Batteries in Electric Vehicles." *Metal Bulletin Monthly*, April 1992.

4. Ovshinsky, S.R., M.A. Fetcenko, and J. Ross. "A Nickel Metal Hydride Battery for Electric Vehicles." *Science*, Vol. 20, April 9, 1993.

5. Consultation with Steve Albu, Mobile Source Division, California Air Resources Board, El Monte, California, September 29, 1994.

6. Consultations with William Meador, President, Recovery and Reclamation, Inc., Pecos, Texas, August, September, and October 1994.

7. Consultations with William McLaughlin, President, Toxco, Claremont, California, September and October 1994.

8. Sarre, G., M. Broussely, and R. Staniewicz. "Lithium-Carbon (Lithium-Ion) Battery System for Electric Vehicles," presented at the 12th International Electric Vehicle Symposium, Anaheim, California, December 5-7, 1994.

9. Guyomard, D., and J.M. Tarascon. "Rocking-Chair or Lithium-Ion Rechargeable Lithium Batteries", *Advanced Materials*, Vol. 6, No. 5, 1994.

10. Consultations with Juan Osborne, Mobile Source Division, California Air Resources Board, El Monte, California, September and October 1994.

11. Linden, D. *Handbook of Batteries and Fuel Cells*, New York: McGraw-Hill, 1984.

12. "SAFT and the Electric Vehicle," DAI/MKT/093, February 1991.

13. Electrosource Incorporated, Presentation on Technology Readiness and Potential Market at the Sacramento Municipal Utility District, Sacramento, California, Spring 1993.

14. "1994 Low-Emission Vehicles and Zero-Emission Vehicle Program Review", Staff Report, California Environmental Protection Agency, Air Resources Board, Mobile Source Division, April 1994.

15. "Transportation Energy Storage Technology Research at Southern California Edison Strategy and Plan", Southern California Edison Research, Development and Demonstration Department, November 1993.

16. "Electric Vehicle Battery and Fuel Cell Research and Development Program", Status Report, U.S. Department of Energy, Electric and Hybrid Propulsion Division, August 1989.

17. Consultations with Michael Wirsch, Electric Vehicle Program Manager, Sacramento Municipal Utility District, Sacramento, California, September and October 1994.

18. "Nickel Cadmium Batteries, The Performance Choice for Electric Vehicles", The NiCd Information Center, Reston, Virginia, July 1993.

19. "La Rochelle Electric Vehicle Program Feedback and Power Management," PSA Peugeot Citro'n, presentation to the electric Transportation Coalition States Initiative Subcommittee Meeting, Pittsburgh, Pennsylvania, August 11, 1994.

20. "SAFT: The Electric Vehicle Comes of Age." SAFT brochure, 1993.

21. "Electric Vehicles for the 90's," *EPRI Journal*, April/May 1991.

22. "Transportation Program Planning Document", Electric Power Research Institute, May 1993.

23. United States Advanced Battery Consortium, program documents, 1991-1993.

24. Consultations with Naum Pinsky, USABC Representative, Transportation Research, Southern California Edison Company, Los Angeles, California, September and October 1994.

25. Ovonics Presentation on Nickel-Metal Hydride Battery Technology at the California Air Resources Board Low Emission Vehicle Biennial Review Workshop, El Monte, California, March 25, 1994.

26. "Test Results from an Ovonic Battery Company Nickel-Metal Hydride (Ni-MH) Powered Solectria Force Electric Vehicle." California Air Resources Board, July, 1994.

27. "Battery Testing at ANL", William H. DeLuca, Palo Alto, CA, January 22, 1991

28. "ABB High Energy NaS Battery: Questions and Answers", Asea Brown Boveri, November 1993.

29. Ford Motor Company Presentation on Ecostar performance at the California Air Resources Board Low Emission Vehicle Biennial Review Workshop, El Monte, California, March 25, 1994.

30. "Technical Support Document: Zero-Emission Vehicle Update", California Environmental Protection Agency, Air Resources Board, Mobile Source Division, April 1994.

31. AEG Presentation on Sodium-Nickel Chloride Battery Technology at the California air Resources Board Low Emission Vehicle Biennial Review Workshop, El Monte, California, March 25, 1994.

32. Staniewicz, R.J., A.S. Gambrell, and G. Castro. "Lithium Like Rechargeable Battery," SAFT R&D Center, Maryland, presented at the 36th Power Sources conference, Cherry Hill, New Jersey, June 1994.

33. Mayer, S.T., J.H. Feikert and J.L Kaschmitter. "Cycle Life Testing of Lithium-Ion Batteries for Small Satellite LEO Space Missions," prepared for the U.S. Department of Energy, Office of Transportation Technology, UCRL-JC-114996, August 16, 1993.

34. Matsushita Press Release, MEP-92-10, May 7, 1992.

35. "The Transportation Program, Realizing the Promise of Electric Transportation", Electric Power Research Institute, 1991.

36. Consultations with Andy Burke, Institute for Transportation Studies, University of California, Davis, August 1994.

37. "Summary of Lead-Acid Battery Laws," Battery Council International, July 1994.

38. "Seizing the Environmental Initiative." GNB Incorporated, Brochure, 1992.

39. Consultation with Charlotte Mooney, Environmental Protection Agency, Washington, D.C., August 10, 1994.

40. Consultations with William McKusky, Environmental Engineer, GNB Incorporated, Los Angeles, California, August, September, and October 1994.

41. Consultations with Al Lospinoso, President, RSR Corporation, City of Industry, California, August, September, and October 1994.

42. Consultations with Lou Madgits, Raw Materials Manager, The Doe Run Company, Boss, Missouri, August 1994.

43. Consultations with Todd Coy, the Kinsbursky Brothers, Anaheim California, July, August, September 1994.

44. Morrow, H. "The Recycling of Nickel-Cadmium Batteries," *The Battery Man*, October 1993.

45. Consultations with John Liotta, National Account Manager, INMETCO, Ellwood City, Pennsylvania, August and September 1994.

46. Consultations with Hugh Morrow, Director, The Cadmium Council, Reston, Virginia, July - October 1994.

47. Consultation with Jeff Bagby, Finance and Seal Administrator, The Rechargeable Battery Recycling Corporation, September 29, 1994.

48. Onuska, J.C., M.E. Schweers, and P.A. Whitver. "Programs for Collecting, Packaging, Transporting and Reclaiming Spent Nickel-Cadmium Batteries." Presented at the Fifth International Seminar on Battery Waste Management, Deerfield Beach, Florida, 1993.

49. "Used Dry Cell Batteries: Is a Collection Program Right for Your Community?" EPA/530-K-92-006, December 1992.

50. Portable Rechargeable Battery Association, National Battery Collection Program Outline, July 1993.

51. Rechargeable Battery Recycling Corporation, The RBRC License Agreement - Index of Exhibits, 1994.

52. Prengman, R.D. and H. McDonald. "RSR's Full Scale Plant to Electrowin Lead From Battery Scrap," RSR Corporation, Date?.

53. Moore, T. "Producing the near-term EV battery." *EPRI Journal*, April/May 1994.

54. "INMETCO: Making Metals a Reusable Resource." INMETCO Brochure, 1993.

55. Consultations with John Onuska, Environmental Health and Safety Manager, INMETCO, Ellwood City, Pennsylvania, August and September 1994.

56. Knoll, C.R., S.M Tuominen, R.E. Walsh, and J.R. Peterson. "Recyclability of Nickel Metal Hydride Rechargeable Batteries." Presented at the Fourth International Rechargeable Battery Seminar, Deerfield Beach, Florida, March 1992.

57. California Environmental Protection Agency, Title 22, California Code of Regulations, Parts 66261.20 - 66261.24.

58. Consultation with Glen Palmer, U.S. Department of the Interior, Bureau of Mines, Salt Lake City, Utah, August 22, 1994.

59. Consultations with Terry Escarda, California Department of Toxic Substances Control, Sacramento, California, January 4, 1995.

60. Corbus, D. "Environmental, Health, and Safety Issues of Sodium-Sulfur Batteries for Electric and Hybrid Vehicles, Volume 2: Battery Recycling and Disposal." National Renewable Energy Laboratory, September 1992.

61. Consultations with Rudy Jungst, Sandia National Laboratories, Albuquerque, New Mexico, September and October 1994.

62. Consultation with Malcolm Shemmans, Asea Brown Boveri, Toronto, Canada, October 6, 1994.

63. Consultations with James Rasmussen, Silent Power Ltd., at the Ad Hoc Electric Vehicle Battery Working Group, Recycling Sub-Working Meeting, Washington, D.C., August 29-30, 1994.

64. Hammerling, H., C.H. Dustmann, and H. Boehm. "Zebra Batteries to Power Tomorrow's Electric Vehicles." AEG Corporation, Presented at the Electric Vehicle Conference and Trade Show, Honolulu, Hawaii, December 1993.

65. Sabatini, J.C., E.L. Field, I-C. Wu, M.R. Cox, B.M. Barnett, and J.T. Coleman. "Feasibility Study for the Recycling of Nickel Metal Hydride Electric Vehicle Batteries", A.D. Little, Inc. for National Renewable Energy Laboratory, January 1994.

66. Morrow, H. "Developing the Nickel-Cadmium Electric Vehicle Market in North America," *Nickel-Cadmium Battery Update '92*, the Cadmium Association, London, 1992.

67. Cook, M.E. "Cadmium: Supply, Demand, and the Electric Vehicle," Presented at the Ninth International Minor Metals Seminar, Budapest, May 1993.

68. *Minerals Yearbook, Volume 1: Metals and Minerals*, U.S. Department of the Interior, 1980.

69. *Mineral Commodity Summaries 1990*, U.S. Bureau of Mines.

70. *Kirk-Othmer Encyclopedia of Chemical Technology*, 3rd Edition, New York: J. Wiley & Sons, 1984.

71. Nowell, Greg. J.T. Nowell and Co., 1994.

72. Sawyer, J.W. *Automotive Scrap Recycling: Processes, Prices, and Prospects*, Baltimore, MD: Johns Hopkins University Press, 1974.

73. Meltzer, M., M. Callahan, and T. Jensen. "Metal-Bearing Waste Streams: Minimizing Recycling and Treatment," Park Ridge, NJ: Noyes Data Corporation, 1990.

74. Hurd, D.J., D.M. Muchnick, et.al., "Recycling of Consumer Dry Cell Batteries," Park Ridge, NJ: Noyes Data Corporation, 1993.

75. Environmental Protection Agency, Title 40 Code of Federal Regulations, Parts 261-264.

76. *California Environmental Compliance Handbook*, published by the California Chamber of Commerce, 1992.

77. *BNA-Air Pollution Control*, Section 125:8351, "RCRA Standards for the Combustion of Hazardous Waste," published by the Bureau of National Affairs, Inc., 1994.

78. Environmental Protection Agency, Title 40 Code of Federal Regulations, Part 61.

79. *BNA-Air Pollution Control*, Section 111:5301, "State Policies: Pennsylvania," Published by the Bureau of National Affairs, Inc., 1994.

80. California Environmental Protection Agency, Title 12, California Code of Regulations, Parts 12000 (b) and (c).

81. Tchobanoglous, G. and E.D. Schroeder. *Water Quality*, Reading, Massachusetts: Addison-Wesley, 1987.

82. U.S. EPA, Office of Drinking Water, "Fact Sheet: Drinking Water Regulations Under the Safe Drinking Water Act," May 1990.

83. California Health and Safety Code, Chapter 6.5, Article 8.7, "Procedures for the Approval of New Facilities," Parts 25199 - 25199.14.

84. *Cal/OSHA Handbook*, published by the California Chamber of Commerce, 1990.

85. Consultations with Carol Sharp, Librarian, U.S. Department of the Interior, Bureau of Mines, Salt Lake City Research Center, Salt Lake City, Utah, October 17, 1994.

86. Electric Vehicle Battery Material Safety Data Sheets, complied for Arizona Public Service Company by Electric Transportation Applications, Glendale, Arizona.

87. Martin C. "CalETC Utility EV Penetrations and Vehicle Splits." Letter from Cece Martin of the California Electric Transportation Coalition, February 26, 1993.

LIST OF ACRONYMS

AAM	Annual Arithmetic Mean
ABB	Asea Brown Boveri. A German owned company which conducted research on sodium-sulfur batteries.
ANL	Argonne National Laboratories. A U.S. government laboratory located in Argonne, Illinois
BACT	Best Available Control Technology
BCI	The Battery Council International. A trade association for lead-acid battery manufacturers, distributors, and recyclers.
BDAT	Best Demonstrated Available Technology
BOD_5	Five-day Biochemical Oxygen Demand. A measure of organic pollution in wastewater.
CAA	Clean Air Act
CA-AAQS	California Ambient Air Quality Standards
CARB	California Air Resources Board. Division of the California Environmental Protection Agency which governs air quality regulations in California.
CCR	California Code of Regulations
CEQA	California Environmental Quality Act
CESQG	Conditionally Exempt Small Quantity Generator. Generates less than 100 kg of hazardous waste per month.
CFR	Code of Federal Regulations
CUP	Conditional Use Permit. A permit to locate and operate a facility within specified conditions.
CWA	Clean Water Act
DEMI	Dreisbach Electromotive, Inc. A German owned company which develops zinc-air batteries.
DOD	Depth of Discharge. This specifies how fully a battery is charged.
DOSH	Division of Occupational Safety and Health
EAF	Electric Arc Furnace
EIR	Environmental Impact Report
ELSI	Electrosource, Inc. A Texas-based company developing advanced lead-acid batteries.
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute. A research organization funded by U.S. utility companies.
EV	Electric Vehicle
HAPs	Hazardous Air Pollutants
HCs	Hydrocarbons
HDV	Heavy Duty Vehicle
HWCL	Hazardous Waste Control Law
HWL	Hazardous Waste Limit
ICV	Internal Combustion Vehicle
KOH	Potassium hydroxide electrolyte
LAER	Lowest Achievable Emissions Rate

LD_{50}	Lethal Dose. Dose at which fifty percent of the test population dies.
LDV	Light Duty Vehicle
LEV	Low Emission Vehicle
LiFeS	Lithium-iron sulfide battery
$LiFeS_2$	Lithium-iron disulfide battery
Li-ion	Lithium-ion battery
Li-polymer	Lithium-polymer battery
MACT	Maximum Achievable Control Technology
MDV	Medium Duty Vehicle
MITI	Ministry of International Trade and Industry (Japan)
MSDS	Material Safety Data Sheet. Specifies quantities of hazardous materials present in a product, and specific hazards associated with the handling of the product.
NAAQS	National Ambient Air Quality Standards
$Na\text{-}NiCl_2$	Sodium-nickel chloride battery
NaS	Sodium-sulfur battery
NERC	Northeast Recycling Council. Composed of representatives from ten northeastern states.
NESHAPS	National Emissions Standards for Hazardous Air Pollutants
NiCd	Nickel-cadmium battery
NiFe	Nickel-iron battery
NIMBY	Not In My Back Yard. Public opposition to the location of facilities in their immediate vicinity.
NiMH	Nickel-metal hydride battery
NPDES	National Pollution Discharge Elimination System. Permit system for wastewater discharge.
NSPS	New Source Performance Standard
OSHA	Occupational Safety and Health Act
Pb-acid	Lead-acid battery
PEL	Permissible Exposure Limit
PM	Particulate Matter
PM_{10}	Particulate Matter below 10 micrometers in diameter
POHCs	Principle Organic Hazardous Constituents
PRBA	Portable Rechargeable Battery Association. A trade association for NiCd battery manufacturers and customers.
RBRC	Rechargeable Battery Recycling Corporation. A company established by the PRBA to facilitate collection and recycling of consumer size NiCds.
RCRA	Resource Conservation and Recovery Act
RHF	Rotary Hearth Furnace
SBLA	Sealed Bipolar Lead-Acid battery
SCAB	South Coast Air Basin. The region consisting of Los Angeles, Orange, Riverside, and San Bernardino counties.
SCAQMD	South Coast Air Quality Management District. A regional agency responsible for air quality in the SCAB.
SDWA	Safe Drinking Water Act
SIP	State Implementation Plan. Plan that demonstrates how a state will implement new environmental regulations in order to achieve attainment.
SLI	Starting, Lighting, and Ignition battery
SQG	Small Quantity Generator. Generates between 100 and 1,000 kg of hazardous waste per month.
STLC	Soluble Threshold Limit Concentration

SWRCB	State Water Resources Control Board. Administers the NPDES system in California.
TACs	Toxic Air Contaminants
TCLP	Toxicity Characteristic Leaching Procedure test
TDS	Total Dissolved Solids
TSD	Treatment, Storage, and Disposal facility
TSP	Total Suspended Particulate (in air)
TSS	Total Suspended Solids (in water)
TTLC	Total Threshold Limit Concentration
TWCA	Teledyne Wah Chang Albany (Albany, Oregon)
UK	United Kingdom
USABC	United States Advanced Battery Consortium. Auto industry, electric utility, and government-funded research effort.
USBoM	United States Bureau of Mines
VRLA	Valve-Regulated sealed Lead-Acid
WQA	Water Quality Act
WWTP	Wastewater Treatment Plant
ZEV	Zero Emission Vehicle
Zn-air	Zinc-air battery
Zn-Br	Zinc-bromine battery

APPENDIX A

Table A-1 shows a summary of state and some local laws regarding lead-acid battery recycling and disposal. The table was compiled in July 1994 by the Battery Council, International (BCI), the trade association for lead-acid battery manufacturers, distributors, and recyclers which drafted the lead-acid battery recycling legislation that most states adopted.

Table A-2 shows a breakdown of the projected electric vehicle population in California from 1997 to 2015 taking retired vehicles into account. An average life of 8 years for LDVs, 10 years for MDVs, and 9 years for HDVs was assumed Numbers for light duty vehicles are based on vehicle inventory models, EMFAC and BURDEN, developed by CARB. MDV numbers are based on an earlier study performed by the California Electric Transportation Coalition. The heavy duty population was developed by the principal authors of this report. The electrical energy consumption is arrived at by the following equation:

$$Electrical\ Energy(GW/yr) = \frac{\#\ vehicles \times mi/yr \times energy\ consumption\ (kWh/mi)}{10^6\ kWh/GWh}$$

This calculation was performed for each vehicle weight class, for each year.

Table A-3 shows the calculations behind Figure 1. The vehicle numbers follow those from Table A-2. The total number of internal combustion vehicles show an average of 2% growth per year, which is in agreement with the BURDEN inventory. The tons of recyclable lead-acid batteries were based on a two year life for lead-acid batteries in EVs and a four year life in ICVs. The batteries in new vehicles for each year were assumed to be spent after one lifetime and therefore available for recycling, i.e., batteries introduced in EVs in 1998 would be recycled in 2000, and those introduced in ICVs in 1998 would be recycled in 2002, and so on.

Table A-4, which shows the calculations behind Figure 12, follows the same guidelines and assumptions as Table A-3, except it shows the projections for all the battery types in this study. The battery weights and estimated calendar lives are taken from Table A-5. The percentages of each battery present are based on the market share estimates established in Table 4.

Table A-5 is an extended version of Table 1, showing the battery specifications for all three vehicle weight classes. The vehicle range and energy consumption are estimates and extrapolations in most cases, as this data is difficult to generalize for all vehicles in a class, since it tends to vary with each vehicle. Therefore this data should not be assumed to be accurate, or in agreement with vehicle manufacturers' data. The battery weight, the maximum theoretical life, and the specific battery weights were arrived at by calculations, and should also not be assumed to be accurate. Much of the data for lithium-ion batteries is not yet available, as it has not been published, or could not yet be disclosed. The following equations show how the values in this table were derived:

$$\mathit{Battery\ Weight} = \frac{\mathit{mi/charge} \times \mathit{kWh/mi}}{\dfrac{\mathit{Wh/kg}}{1{,}000\ \mathit{Wh/kWh}}} \times \left[1 + \frac{\mathit{self\text{-}discharge}}{2} \right]$$

$$\mathit{Max.\ Theoretical\ Life} + \frac{\mathit{mi/charge}}{\mathit{mi/yr}} \times \mathit{life\ in\ charges}$$

$$\mathit{Specific\ Battery\ Weight}\ (\mathit{g/mi}) = \frac{(1\ \mathit{kg} \times 1{,}000\ \mathit{g/kg})}{(\mathit{mi/yr} \times \mathit{life\ in\ years})}$$

$$\mathit{Specific\ Battery\ Weight}\ (\mathit{g/kWh}) = \frac{\mathit{g/mi}}{\mathit{kWh/mi}}$$

Table A-1. Summary of state lead-acid battery laws

State/County	Effective Date	BCI Model	Deposit[a] Trade/All	Split of Deposit	Deposit Refund Period	Point-of-Sale Sign[b]
Arizona[c]	9/27/90	Yes	$5 (T)	100% Retailer	30 days	Retailer
Arkansas	7/1/92	Yes	$10 (T)	100% Retailer	30 days	State
California	1/1/89	Yes				No
Conneticut[d]	10/1/90	Yes	$5 (T)	100% Retailer	30 days	Retailer
Florida[e]	1/1/89	Yes				No
Georgia	1/1/91	Yes				Retailer
Hawaii	1/1/90	Yes				State
Idaho[f]	7/1/91	Yes	$5 (T)	100% Retailer	30 days	Retailer
Illinois	9/1/90	Yes				Retailer
Indiana	1/1/91	Yes				Retailer
Iowa	7/1/90	Yes				Retailer
Kansas City,[g] Missouri	3/14/90	Yes				Retailer
Kentucky	7/13/90	Yes				Retailer
Lousiana	9/1/89	Yes				Retailer
Maine[h]	10/30/89	Yes	$10 (T)	100% Retailer	7 days	State
Massachusetts	12/31/90	No[i]				No
Michigan[j]	4/1/90	Yes				State
Minnesota	10/4/89	Yes[k]	$5 (T)	100% Retailer		State
Mississippi	7/1/91	Yes				State
Missouri	1/1/91	Yes				State
Nebraska	9/1/94	No[i]				
Nevada	1/1/92	No[i]				No

Table A-1. Summary of state lead-acid battery laws (continued)

State/County	Effective Date	BCI Model	Deposit[a] Trade/All	Split of Deposit	Deposit Refund Period	Point-of-Sale Sign[b]
New Hampshire	1/1/91	No[i]				No
New Jersey	10/9/91	Yes				Retailer
New Mexico	12/31/91	No[i]				
New York	1/1/91	Yes	$5 (T)	100% Retailer	30 days	Retailer
North Carolina	1/1/91	Yes				Retailer
North Dakota	1/1/92	Yes				No
Oklahoma	9/1/93	Yes[l]				Retailer
Oregon[m]	1/1/90	Yes				Retailer
Pennsylvania	7/26/89	Yes				State
Rhode Island	1/1/89	Yes[n]	$5 (T)	80% State 20% Retailer	7 days	No
South Carolina[o]	5/27/91	Yes	$5 (T)	100% Retailer	30 days	State
South Dakota[p]	7/1/92	Yes				No
Tennessee	7/1/90	Yes[q]				No
Texas[r]	9/1/91	Yes				State
Utah[s]	1/1/92	Yes				Retailer/Wholesaler
Vermont	6/17/94	Yes				Retailer
Virginia	7/1/90	Yes				State
Washington	7/23/89	Yes	$5 (T)	100% Retailer	30 days	State
West Virginia	4/6/94	Yes[t]				Retailer/Wholesaler
Wisconsin[u]	1/1/91	Yes				State
Wyoming	6/8/89	Yes				State

Footnotes for Table A-1

a This refers to a deposit in lieu of a trade-in (T), or a deposit on all batteries.

b This refers to whose responsibility it is to make the educational signs, the state or the retailer. A "No" indicates that there is no sign requirement.

c Arizona requires all lead acid batteries sold must be labeled with a universally accepted recycling symbol. Arizona also requires that State agencies and political subdivisions comply with the battery recycling law.

d Retailers in Connecticut must take back batteries one-for-one at the point of sale.

e Florida requires the collection of a $1.50 fee per battery at the retail level.

f Idaho requires all lead batteries sold to be labeled with a universally accepted recycling symbol. In addition, batteries used in motorcycles, off-road recreation vehicles, or lawn and garden equipment are exempt from the deposit in lieu of a trade-in requirement.

g The ordinance of Kansas City, Missouri, requires that retailers take back up to 3 batteries not at the point of sale, and it requires that junk batteries be stores in "an adequately ventilated enclosure in good repair that protects its contents from any precipitation, etc." Any spilled acid must be immediately collected and neutralized.

h Main requires the collection of a $1 fee per battery at the retail level.

i New Hampshire, New Mexico, Nevada, and Massachusetts placed a ban on the landfilling and incineration of lead batteries only. Nevada will allow lead battery disposal at state "permitted" facilities, however. See also footnotes "k" and "t."

j Michigan's deposit provision becomes effective 7/1/95. The deposit will be $6 in lieu of a trade-in, with a 30-day refund period, and $0.03 of every $6 will accrue to the retailer.

k Minnesota now requires that retailers take back up to 5 batteries not at the point of sale.

l Oklahoma requires that retailers of lead acid batteries post and maintain a sign at or near the point of display or sale to inform the public that lead-acid batteries are accepted for recycling.

m Oregon required that until 12/31/93 retailers had to accept at least 1 battery from consumers; since that date, retailers have been allowed only to accept batteries one-for-one at the point of sale.

n Rhode Island also requires that retailers be paid no less than $1 for a junk battery. This commonly is referred to as a "handling fee."

o South Carolina requires retailers to collect a $2 fee for lead batteries sold to the ultimate consumer. The retailer may retain 3 percent of the collected fees to cover administrative costs. Fees collected by the state treasurer are to be deposited into a Solid Waste Management Trust Fund. Small sealed lead-acid batteries are now exempt from the fee and BCI model provisions; however, a study on the recycling of these batteries is required. See S.C. Code Ann. §44-96-40 (23).

p South Dakota requires wholesalers and retailers to "accept, on a one-for-one exchange basis, used lead-acid batteries and . . . ensure the propoer handling and disposal of the batteries." Further, after July 1, 1995, all lead-acid batteries shall be eliminated from landfilled wastes.

Footnotes for Table A-1 (continued)

q Tennessee prohibits landfills or incinerators in the state from accepting lead-acid batteries for incineration or disposal. Further, lead-acid battery retailers must accept used lead-acid batteries as trade-in batteries.

r Texas requires the collection of a $2 fee for batteries of less than 12 volts, and, a $3 fee for batteries of 12 or more volts. Exempted from the fee is any battery that is: (1) rated at less than 10 ampere hours; (2) Sealed so that no access to the interior of the battery is possible without destroying the battery; and (3) with dimensions (sum of height, width and length) less than 15 inches. The fees are to be collected by any wholesaler or retailer who sells a battery not for resale. To cover administrative costs, the dealer may retain $0.025 per unit. All remaining money, less 4 percent to cover state administrative costs, goes to the state comptroller to be placed in a waste remediation fund.

s Utah requires retailers to take back a maximum of two used lead batteries from customers.

t West Virginia requires retailers and wholesalers to collect used lead-acid batteries from customers and to post point-of-sale signs.

u Wisconsin law allows retailers to charge a $5 deposit in lieu of a trade-in, and to charge $3 for taking a battery.

k Nebraska placed a prohibition on only the landfilling of lead batteries. See also footnote "i."

w Several states have adopted separate household battery recycling laws that include provisions strictly applicable to small sealed lead-acid batteries. These states are California, Florida, Illinois, Iowa, Maine, Maryland, Minnesota, New Hampshire, New Jersey, New York, Oregon, Rhode Island and Vermont. However, the laws described above apply to automotive lead-acid batteries only.

Lead-Acid Battery Definitions by State

Arizona	"(A) battery with a core of elemental lead and a capacity of six or more volts which is suitable for use in a vehicle or boat."
Arkansas	"(A) battery with a core of elemental lead and a capacity of six or more volts."
California	"(A)ny battery which is primarily composed of both lead and sulfuric acid, with a capacity of six volts or more, and which is used for any of the following purposes: 1) as a starting battery which is designed to deliver a high burst of energy necessary to crank an engine until it starts; 2) as a motive power battery which is designed to provide the sources of power for propulsion or operation; 3) as a stationary standby battery which is designed to be used in systems where the battery acts as a source of emergency power, serving as a backup in case of failure or interruption in the flow of power from the primary source."
Connecticut	"(A) lead-acid battery or a motor vehicle battery"
Florida	Under the recycling provisions, the term lead-acid battery is undefined. Under the battery free provisions, the term is defined as follows: "(T)hose lead-acid batteries designed for use in motor vehicles, vessels, and aircraft, and includes such batteries when sold as a component part of a motor vehicle, vessel, or aircraft, but not when sold to recycle components."
Georgia	The term lead-acid battery is undefined; however, the law applies only to lead-acid vehicle batteries. . ."
Hawaii	The term lead-acid battery is undefined, however, the law applies to "motor vehicle or other lead-acid batteries. . ."

Footnotes for Table A-1 (continued)

Idaho	"(A) battery with a core of elemental lead and a capacity of six or more volts which is suitable for use in farm equipment, a motor vehicle or a boat. Batteries only suitable for motor cycles, off-road recreation vehicles or lawn and garden equipment are exempt from the fees in this chapter."
Illinois	"(A) battery containing lead and sulfuric acid that has a nominal voltage of at least six volts and is intended for use in motor vehicles."
Indiana	"(A) battery that: 1) contains lead and sulfuric acid; and 2) has a nominal voltage of at least six volts."
Iowa	The term lead-acid battery is undefined.
Kansas City	"Any battery that consists of lead and sulfuric acid, is used as a power source, and has a capacity of six (6) volts or more."
Kentucky	The term lead-acid battery is undefined.
Lousiana	The term lead-acid battery is undefined; however, the law applies to "motor vehicle batteries or other lead-acid batteries. . ."
Maine	"(A) device designed and used to store electrical energy through chemical reactions involving lead and acid."
Mass.	The term lead battery is undefined and unqualified in the regulation.
Michigan	"(A) storage battery in which the electrodes are grids of lead containing lead oxides that change in composition during charging and discharging, and the electrolyte is dilute sulfuric acid."
Minnesota	The term lead-acid battery is undefined and unqualified in the law.
Mississippi	The term lead-acid battery is undefined; however, the law applies to "motor vehicle batteries or other lead-acid batteries. . ."
Missouri	"(A) battery designed to contain lead and sulfuric acid with a nominal voltage of at least six volts and of the type intended for use in motor vehicles and watercraft."
Nevada	The term lead-acid battery is undefined, however, the law applies to "motor vehicle batteries."
New Hampshire	The term lead-acid battery is undefined; however, the law applies to "motor vehicle or wet cell batteries."
New Jersey	"(A) lead-acid electric storage battery designed for use in motor vehicles, aviation equipment or marine vessels."
New Mexico	The term lead-acid battery is undefined and unqualified in the regulation.
New York	"(A)ny battery with a capacity of six or more volts which contains lead and sulfuric acid and which is used as a power source in a vehicle."

Footnotes for Table A-1 (concluded)

N. Carolina	The term lead-acid battery is undefined; however, the law applies to "motor vehicle batteries or other lead-acid batteries. . ."
N. Dakota	The term lead-acid battery is undefined.
Oklahoma	"(A) lead-acid electrical device used in boats, planes and motor vehicles."
Oregon	The term lead-acid battery is undefined.
Pennsylvania	The term lead-acid battery is undefined; however, the law applies to "motor vehicle batteries or other lead-acid batteries. . ."
R. Island	"(B)atteries used in any vehicle, or of a capacity of six (6) volts or more, and of one hudred fifty (150) pounds or less in weight, and like batteries in stationary uses."
S. Carolina	"(A)ny battery that consists of lead and sulfuric acid, is used as a power source, and has a capacity of six volts or more, except that this term shall not include a small sealed lead-acid battery which means a lead-acid battery weighing twenty-five pounds or less, used in non-vehicular, non SLI (starting, lighting, ignition) applications."
S. Dakota	The term lead-acid battery is undefined.
Tennessee	The term lead-acid battery in undefined. Limited portions of the law apply only to "automobile batteries" while other portions of the law appear to be more broad.
Texas	Under the recycling model provisions, the term lead-acid battery is undefined; however, the law applies to "motor vehicle batteries or other lead-acid batteries. . ." Under the battery free provisions, the term is defined as follows: "any battery with a capacity of six or more volts which contains lead and sulfuric acid."
Utah	The term lead-acid battery is undefined; however, the law applies to any "motor vehicle battery or other lead-acid battery. . ."
Vermont	"Lead-acid battery means a battery that contains lead and sulfuric acid and is used as a power source." Nevertheless, the law exempts small sealed lead-acid batteries from coverage.
Virginia	The term lead-acid battery is undefined; however, the law applies to any "motor vehicle battery or other lead-acid battery. . ."
Washington	"(B)atteries capable for use in any vehicle, having a core consisting of elemental lead, and a capacity of six or more volts."
W. Virginia	"lead-acid battery means an encasement which contains or contained lead and sulfuric acid to produce an electrical charge."
Wisconsin	The term lead-acid battery is undefined; however, the law applies to any "motor vehicle battery or other lead-acid battery. . ."
Wyoming	The term lead-acid battery is undefined; however, the law applies to any "motor vehicle battery or other lead-acid battery. . ."

Table A-2. California projected electric vehicle population

Year	New Vehicles[1]	% LDV EVs[1]	New LDV EVs[1]	Accumulated LDV EVs	Retired LDV EVs[1]	Total LDV EVs[1]	New MDV EVs[2]	Retired MDV EVs	Total MDV EVs	New HDV EVs	Retired HDV EVs	Total HDV EVs	Electrical Energy (GWh/yr)		
													LDV EVs	MDV EVs	HDV EVs
1997	1,722,632	1	17,226	17,226	0	17,226	200	0	200	20	0	20	45	1	2
1998	1,751,977	2	35,040	52,266	0	52,266	1,080	0	1,280	20	0	40	136	7	3
1999	1,781,311	2	35,626	87,892	332	87,560	1,439	0	2,720	20	0	60	228	14	5
2000	1,810,738	2	36,215	124,107	946	123,161	1,380	0	4,100	50	0	110	320	21	9
2001	1,837,506	5	91,875	215,982	2,109	213,873	2,520	0	6,620	50	0	160	556	34	13
2002	1,863,129	5	93,156	309,139	4,083	305,055	3,600	0	10,220	50	0	210	793	53	17
2003	1,890,059	10	189,006	498,144	9,201	488,944	6,300	0	16,520	50	0	260	1,271	86	21
2004	1,917,075	10	191,708	689,852	16,353	673,499	8,939	0	25,459	50	0	310	1,751	132	25
2005	1,944,701	10	194,470	884,322	31,533	852,790	8,880	0	34,339	50	0	360	2,217	179	29
2006	1,974,344	10	197,434	1,081,756	51,877	1,029,880	8,820	0	43,159	50	20	390	2,678	224	31
2007	2,004,244	10	200,424	1,282,181	78,086	1,204,095	8,761	200	51,720	50	20	420	3,131	269	34
2008	2,034,347	10	203,435	1,485,616	109,474	1,376,142	8,520	1,080	59,159	50	20	450	3,578	308	36
2009	2,063,716	10	206,372	1,691,987	144,245	1,547,742	8,400	1,439	66,120	50	50	450	4,024	344	36
2010	2,093,395	10	209,340	1,901,327	181,542	1,719,784	8,100	1,380	72,839	50	50	450	4,471	379	36
2011	2,123,640	10	212,364	2,113,691	219,620	1,894,071	7,739	2,520	78,059	50	50	450	4,925	406	36
2012	2,154,028	10	215,403	2,329,093	256,869	2,072,224	7,739	3,600	82,198	50	50	450	5,388	427	36
2013	2,184,133	10	218,413	2,547,507	290,632	2,256,874	7,739	6,300	83,638	50	50	450	5,868	435	36
2014	2,216,788	10	221,679	2,769,186	319,086	2,450,100	7,739	8,939	82,438	50	50	450	6,370	429	36
2015	2,243,271	10	224,327	2,993,513	343,659	2,649,854	7,739	8,880	81,296	50	50	450	6,890	423	36

	LDV	MDV	HDV
Average annual mileage	13,000	13,000	40,000
Average energy consumption (kWh/mi)	0.20	0.40	2.00

[1] BURDEN 7F, new LDV Populations, CARB.
[2] Reference 87.

Table A-3. Worksheet for Figure 1

Year	New Vehicles	% LDV EVs	No. of New EVs (LDV)	No. of New EVs (MDV)	No. of New EVs (HDV)	No. of New ICVs	Baseline No. of ICVs (LDV)	Accumulated ICVs (LDV)	Retired ICVs	Total ICVs	Pb-Acid wt., LDV (lbs)
1997	1,722,632	1	17,226	200	20	1,705,186	24,000,000	25,705,186	0	25,705,186	1,007
1998	1,751,977	2	35,040	1,080	20	1,715,837	24,000,000	27,421,023	0	27,421,023	1,007
1999	1,781,311	2	35,626	1,439	50	1,744,195	24,000,000	29,165,218	562,889	28,602,330	1,007
2000	1,810,738	2	36,215	1,380	50	1,773,093	24,000,000	30,938,312	559,983	30,378,328	1,007
2001	1,837,506	5	91,875	2,520	50	1,743,061	24,000,000	32,681,372	784,353	31,897,019	1,007
2002	1,863,129	5	93,156	3,600	50	1,766,323	24,000,000	34,447,695	1,133,329	33,314,366	1,007
2003	1,890,059	10	189,006	6,300	50	1,694,703	24,000,000	36,142,398	1,539,666	34,602,732	1,007
2004	1,917,075	10	191,708	8,939	50	1,716,379	24,000,000	37,858,776	2,002,729	35,856,047	1,007
2005	1,944,701	10	194,470	8,880	50	1,741,301	24,000,000	39,600,077	2,506,685	37,093,392	1,007

Year	lb/ton	Pb-Acid wt., MDV (lb)	Pb-Acid wt., HDV (lb)	Tons EV Pb-Acid On-Road	Tons EV Pb-Acid as Waste	Pb-Acid wt., ICV (lb)	Tons ICV Pb-Acid On-Road	Tons ICV Pb-Acid as Waste	Total Tons Recyclable Pb-Acid
1997	2,000	1,514	5,045	8,875	0	35	449,841	112,460	112,460
1998	2,000	1,514	5,045	18,511	0	35	479,868	119,967	119,967
1999	2,000	1,514	5,045	19,153	8,875	35	500,541	125,135	134,010
2000	2,000	1,514	5,045	19,405	18,511	35	531,621	132,905	151,416
2001	2,000	1,514	5,045	48,293	19,153	35	558,198	139,549	158,703
2002	2,000	1,514	5,045	49,756	19,405	35	583,001	145,750	165,155
2003	2,000	1,514	5,045	100,060	48,293	35	605,548	151,387	199,680
2004	2,000	1,514	5,045	103,418	49,756	35	627,481	156,870	206,626
2005	2,000	1,514	5,045	104,764	100,060	35	649,134	162,284	262,343

Assumptions:

- Battery Pack weights = [Range (mi.)]*[Energy Consumption (kWh/mi)]/[Specific Energy (kWh/kg)]*[1+(Self-discharge coefficient/2)].
- Values shown in Table A-5.
- Conventional Pb-Acid batteries weigh 16 kg.
- Conventional Pb-Acid batteries in ICVs have a 4-year life, so new conventional Pb-Acid batteries will not be recycled for 4 years.
- One fourth of the baseline conventional Pb-Acid batteries in ICVs are recycled each year, based on a 4-year life.
- Conventional Pb-Acid batteries in EVs have a 2-year life, so batteries in new EVs are recycled after 2 years.
- Prototype and test EVs on the road prior to 1998 account for 1% of the LDV market.

Table A-4. Market saturation of EV batteries

Year	New Vehicles	% EVs	No. of New EVs (LDV)	Accumulated LDV EVs	No. Retired EVs (LDV)	No. of Net New LDV EVs	No. of New EVs (MDV)	No. of Retired EVs (MDV)	No. of Net New MDV EVs	% of Pb-Acid LDVs &MDVs	% of SBLA LDVs & MDVs
1997	1,722,632	1	17,226	17,226	0	17,226	200	0	200	100	0
1998	1,751,977	2	35,040	52,266	0	52,266	1,080	0	1,080	38	15
1999	1,781,311	2	35,626	87,892	332	87,560	1,439	0	1,439	38	15
2000	1,810,738	2	36,215	124,107	946	123,161	1,380	0	1,380	38	15
2001	1,837,506	5	91,875	215,982	2,109	213,873	2,520	0	2,520	38	15
2002	1,863,129	5	93,156	309,139	4,083	305,055	3,600	0	3,600	38	15
2003	1,890,059	10	189,006	498,144	9,201	488,944	6,300	0	6,300	38	15
2004	1,917,075	10	191,708	689,852	16,353	673,499	8,939	0	8,939	38	15
2005	1,944,701	10	194,470	884,322	31,533	852,790	8,880	0	8,880	0	10
2006	1,974,344	10	197,434	1,081,756	51,877	1,029,880	8,820	0	8,820	0	10
2007	2,004,244	10	200,424	1,282,181	78,086	1,204,095	8,761	0	8,761	0	10
2008	2,034,347	10	203,435	1,485,616	109,474	1,376,142	8,520	1,080	7,440	0	10
2009	2,063,716	10	206,372	1,691,987	144,245	1,547,742	8,400	1,439	6,961	0	10
2010	2,093,395	10	209,340	1,901,327	181,542	1,719,784	8,100	1,380	6,720	0	6

Year	% of NiCd LDVs & MDVs	% of AB2 LDVs & MDVs	% of AB5 LDVs & MDVs	% of Na/S LDVs & MDVs	% of Na-NiCl2 LDVs & MDVs	% of Li-Poly LDVs & MDVs	% of Li-Ion LDVs & MDVs	No. of New EVs (HDV)	No. of Retired EVs (HDV)	No. of Net New HDV EVs	% of Pb-Acid HDVs
1997	0	0	0	0	0	0	0	20	0	20	100
1998	5	10	10	2	0	0	20	20	0	20	55
1999	5	10	10	2	0	0	20	50	0	50	55
2000	5	10	10	2	0	0	20	50	0	50	55
2001	5	10	10	2	0	0	20	50	0	50	55
2002	5	10	10	2	0	0	20	50	0	50	55
2003	5	10	10	2	0	0	20	50	0	50	55
2004	5	10	10	2	0	0	20	50	0	50	55
2005	0	10	10	0	0	30	40	50	0	50	0
2006	0	10	10	0	0	30	40	50	20	30	0
2007	0	10	10	0	0	30	40	50	20	30	0
2008	0	10	10	0	0	30	40	50	50	0	0
2009	0	10	10	0	0	30	40	50	50	0	0
2010	0	7	7	0	0	50	30	50	50	0	0

Table A-4. Market saturation of EV batteries (continued)

Year	% of SBLA HDVs	No. of New ICVs (LDV)	Baseline No. of ICVs (LDV)	Accumulated ICVs (LDV)	No. of Retired ICVs (LDV)	Total ICVs (LDV)	Pb-Acid wt., ICV (lb)	No. of EVs (LDV)	Pb-Acid wt., LDV (lb)	SBLA wt. , LDV (lb)	NiCd wt., LDV (lb)
1997	0	1,705,186	24,000,000	25,705,186	0	25,705,186	35	899,681,499	1,007	783	1,130
1998	45	1,715,837	24,000,000	27,421,023	0	27,421,023	35	959,735,797	1,007	783	1,130
1999	45	1,744,195	24,000,000	29,165,218	562,889	28,602,330	35	1,001,081,535	1,007	783	1,130
2000	45	1,773,093	24,000,000	30,938,312	559,983	30,378,328	35	1,063,241,483	1,007	783	1,130
2001	45	1,743,061	24,000,000	32,681,372	784,353	31,897,019	35	1,116,395,675	1,007	783	1,130
2002	45	1,766,323	24,000,000	34,447,695	1,133,329	33,314,366	35	1,166,002,796	1,007	783	1,130
2003	45	1,694,703	24,000,000	36,142,398	1,539,666	34,602,732	35	1,211,095,610	1,007	783	1,130
2004	45	1,716,379	24,000,000	37,858,776	2,002,729	35,856,047	35	1,254,961,648	1,007	783	1,130
2005	100	1,741,301	24,000,000	39,600,077	2,506,685	37,093,392	35	1,298,268,733	1,007	783	1,130
2006	100	1,768,040	24,000,000	41,368,117	3,110,882	38,257,234	35	1,339,003,207	1,007	783	1,130
2007	100	1,795,009	24,000,000	43,163,125	3,811,304	39,351,821	35	1,377,313,752	1,007	783	1,130
2008	100	1,822,342	24,000,000	44,985,468	4,552,529	40,432,938	35	1,415,152,845	1,007	783	1,130
2009	100	1,848,894	24,000,000	46,834,362	5,268,866	41,565,496	35	1,454,792,375	1,007	783	1,130
2010	100	1,875,906	24,000,000	48,710,268	5,952,395	42,757,873	35	1,496,525,554	1,007	783	1,130

Year	AB2 wt., LDV (lb)	AB5 wt., LDV (lb)	Na/S wt., LDV (lb)	Na-NiCl2 wt., LDV (lb)	Li-Poly wt., LDV (lb)	Li-Ion wt., LDV (lb)	lb/ton	No. of EVs (MDV)	Pb-Acid wt., MDV (lb)	SBLA wt., MDV (lb)	NiCd wt., MDV (lb)
1997	1,236	1,236	924	1,007	880	900	2,000	200	1,514	1,177	1,617
1998	1,236	1,236	924	1,007	880	900	2,000	1,080	1,514	1,177	1,617
1999	1,236	1,236	924	1,007	880	900	2,000	1,439	1,514	1,177	1,617
2000	1,236	1,236	924	1,007	880	900	2,000	1,380	1,514	1,177	1,617
2001	1,236	1,236	924	1,007	880	900	2,000	2,520	1,514	1,177	1,617
2002	1,236	1,236	924	1,007	880	900	2,000	3,600	1,514	1,177	1,617
2003	1,236	1,236	924	1,007	880	900	2,000	6,300	1,514	1,177	1,617
2004	1,236	1,236	924	1,007	880	900	2,000	8,939	1,514	1,177	1,617
2005	1,236	1,236	924	1,007	880	900	2,000	8,880	1,514	1,177	1,617
2006	1,236	1,236	924	1,007	880	900	2,000	8,820	1,514	1,177	1,617
2007	1,236	1,236	924	1,007	880	900	2,000	8,761	1,514	1,177	1,617
2008	1,236	1,236	924	1,007	880	900	2,000	8,520	1,514	1,177	1,617
2009	1,236	1,236	924	1,007	880	900	2,000	8,400	1,514	1,177	1,617
2010	1,236	1,236	924	1,007	880	900	2,000	8,100	1,514	1,177	1,617

Table A-4. Market saturation of EV batteries (continued)

Year	AB2 wt., MDV (lb)	AB5 wt., MDV (lb)	Na/S wt., MDV (lb)	Na-NiCl2 wt., MDV (lb)	Li-Poly wt., MDV (lb)	Li-Ion wt., MDV (lb)	No. of EVs (HDV)	Pb-Acid wt., HDV (lb)	SBLA wt., HDV (lb)	New Tons ICV Pb-Acid On-Road
1997	1,822	1,822	1,309	1,428	1,200	1,228	20	5,045	3,920	449,841
1998	1,822	1,822	1,309	1,428	1,200	1,228	20	5,045	3,920	479,868
1999	1,822	1,822	1,309	1,428	1,200	1,228	50	5,045	3,920	500,541
2000	1,822	1,822	1,309	1,428	1,200	1,228	50	5,045	3,920	531,621
2001	1,822	1,822	1,309	1,428	1,200	1,228	50	5,045	3,920	558,198
2002	1,822	1,822	1,309	1,428	1,200	1,228	50	5,045	3,920	583,001
2003	1,822	1,822	1,309	1,428	1,200	1,228	50	5,045	3,920	605,548
2004	1,822	1,822	1,309	1,428	1,200	1,228	50	5,045	3,920	627,481
2005	1,822	1,822	1,309	1,428	1,200	1,228	50	5,045	3,920	649,134
2006	1,822	1,822	1,309	1,428	1,200	1,228	50	5,045	3,920	669,502
2007	1,822	1,822	1,309	1,428	1,200	1,228	50	5,045	3,920	688,657
2008	1,822	1,822	1,309	1,428	1,200	1,228	50	5,045	3,920	707,576
2009	1,822	1,822	1,309	1,428	1,200	1,228	50	5,045	3,920	727,396
2010	1,822	1,822	1,309	1,428	1,200	1,228	50	5,045	3,920	748,263

Year	Tons Spent ICV Pb-Acid	New Tons EV Pb-Acid On-Road	Tons Spent EV Pb-Acid	New Tons SBLA On-Road	Tons Spent SBLA	New Tons NiCd On-Road	Tons Spent NiCd	New Tons AB2 On-Road	Tons Spent AB2	New Tons AB5 On-Road
1997	112,460	8,875	0	0	0	0	0	0	0	0
1998	119,967	7,043	0	2,171	0	1,034	0	2,264	0	2,264
1999	125,135	7,300	8,875	2,263	0	1,065	0	2,333	0	2,333
2000	132,905	7,395	7,043	2,293	18	1,079	0	2,364	0	2,364
2001	139,549	18,373	7,300	5,662	2,171	2,697	0	5,907	0	5,907
2002	145,750	18,929	7,395	5,833	2,263	2,777	56	6,085	98	6,085
2003	151,387	38,044	18,373	11,700	2,293	5,594	102	12,254	131	12,254
2004	156,870	39,320	18,929	12,091	5,662	5,777	146	12,662	2,291	12,662
2005	162,284	0	38,044	8,234	5,833	0	1,245	12,827	2,431	12,827
2006	167,375	0	39,320	8,347	11,700	0	1,152	13,005	2,566	13,005
2007	172,164	0	0	8,460	12,145	0	1,278	13,184	6,252	13,184
2008	176,894	0	0	8,564	8,234	0	2,957	13,348	6,571	13,348
2009	181,849	0	0	8,672	8,347	0	2,632	13,519	12,490	13,519
2010	187,066	0	0	5,301	8,460	0	5,339	9,573	12,651	9,573

Table A-4. Market saturation of EV batteries (concluded)

Year	Tons Spent AB5	New Tons Na/S On-Road	Tons Spent Na/S	New Tons Na-NiCl2 On-Road	Tons Spent Na-NiCl2	New Tons Li-Poly On-Road	Tons Spent Li-Polymer	New Tons Li-Ion On-Road	Tons Spent Li-Ion
1997	0	0	0	0	0	0	0	0	0
1998	0	338	0	0	0	0	0	3,286	0
1999	0	348	0	0	0	0	0	3,383	0
2000	0	353	0	0	0	0	0	3,429	0
2001	0	882	0	0	0	0	0	8,578	0
2002	98	908	14	0	0	0	0	8,826	133
2003	131	1,829	19	0	0	0	0	17,784	4,480
2004	2,291	1,888	342	0	0	0	0	18,351	4,544
2005	2,431	0	362	0	0	27,268	0	37,186	4,757
2006	2,566	0	382	0	0	27,649	0	37,704	11,724
2007	6,252	0	931	0	0	28,033	0	38,228	12,213
2008	6,571	0	978	0	0	28,387	1,598	38,711	24,308
2009	12,490	0	1,746	0	0	28,753	1,588	39,210	25,723
2010	12,651	0	1,771	0	0	48,485	27,247	29,753	49,928

Assumptions:

- Battery Pack weights = [Range (mi.)]*[Energy Comsumption (kWh/mi)]/[Specific Energy (kWh/kg)]*[1+(Self-discharge coefficient/2)]
  Values shown in Worksheet 1.
- Conventional Pb-Acid batteries weigh 35 lb.
- Conventional Pb-Acid batteries have a 4-year life, so new conventional Pb-Acid batteries will be recycled after 4 years.
- One fourth of the total conventional Pb-Acid batteries are recycled each year, based on a 4-year life.
- Battery weights and lives are taken from Table A-5.
- Recycling begins after one battery lifetime has elapsed.
- Batteries produced in a given year are recycled after one effective lifetime.
- No stockpiling of spent batteries from year to year.

Table A-5. Summary of battery specifications

Battery Type		Range (mi/charge)	Energy Consumption of EV (kWh/miles)	Specific Energy (Wh/kg)	Self-Discharge Coefficient (%)	Battery Weight (kg)	Mileage per Year (mi/yr)	Total Cycle Life (charges)	Max. Theoretical Life (years)	Estimated Life (years)	Specific Battery Weight (g/mi)	Specific Battery Weight (g/kwh)
Pb - Acid	LDV	80	0.2	35	0.60	458.51	15,000	600	3.20	2.00	15.28	76.42
	MDV	60	0.4	35	0.60	687.77	15,000	600	2.40	2.00	22.93	57.31
	HDV	40	2	35	0.60	2,292.57	40,000	800	0.80	2.00	28.66	14.33
Pb - Acid (Sealed Bi-Polar)	LDV	130	0.2	45	0.60	579.51	15,000	800	6.93	3.00	12.88	64.39
	MDV	95	0.4	45	0.60	846.98	15,000	800	5.07	3.00	18.82	47.05
	HDV	50	2	45	0.60	2,228.89	40,000	1000	1.25	2.00	27.86	13.93
Ni - Cd	LDV	140	0.2	55	2	514.18	15,000	2000	18.67	7.00	4.90	24.48
	MDV	100	0.4	55	2	734.55	15,000	2000	13.33	4.00	12.24	30.61
	HDV		2	55	2	0.00	40,000	2000	0.00	0.00	0.00	0.00
Ni-Metal-Hydride AB_2	LDV	190	0.2	71	10	561.97	15,000	1000	12.67	6.00	6.24	31.22
	MDV	140	0.4	71	10	828.17	15,000	1000	9.33	4.00	13.80	34.51
	HDV		2	71	10	0.00	40,000	1000	0.00	0.00	0.00	0.00
Ni-Metal-Hydride AB_5	LDV	190	0.2	71	10	561.97	15,000	1000	12.67	6.00	6.24	31.22
	MDV	140	0.4	71	10	828.17	15,000	1000	9.33	4.00	13.80	34.51
	HDV		2	71	10	0.00	40,000	1000	0.00	0.00	0.00	0.00
Na - S	LDV	240	0.2	120	10	420.00	15,000	800	12.80	6.00	4.67	23.33
	MDV	170	0.4	120	10	595.00	15,000	800	9.07	4.00	9.92	24.79
	HDV		2	120	10	0.00	40,000	800	0.00	0.00	0.00	0.00
Na - Ni - Cl_2	LDV	220	0.2	110	10	420.00	15,000	1000	14.67	8.00	3.50	17.50
	MDV	150	0.4	110	10	572.73	15,000	1000	10.00	5.00	7.64	19.09
	HDV		2	110	10	0.00	40,000	1000	0.00	0.00	0.00	0.00
Li - Fe - S	LDV	220	0.2	95	10	486.32	15,000	600	8.80	5.00	6.48	32.42
	MDV	150	0.4	95	10	663.16	15,000	600	6.00	3.00	14.74	36.84
	HDV		2	95	10	0.00	40,000	600	0.00	0.00	0.00	0.00
Li - Fe - S_2	LDV	220	0.2	160	10	288.75	15,000	600	8.80	5.00	3.85	19.25
	MDV	150	0.4	160	10	393.75	15,000	600	6.00	3.00	8.75	21.88
	HDV		2	160	10	0.00	40,000	600	0.00	0.00	0.00	0.00
Li - Polymer	LDV	220	0.2	110	0.03	400.06	15,000	400	5.87	5.00	5.33	26.67
	MDV	150	0.4	110	0.03	545.54	15,000	400	4.00	3.00	12.12	30.31
	HDV		2	110	0.03	0.00	40,000	800	0.00	0.00	0.00	0.00
Li-Ion[a]	LDV	220	0.2	113	1.00	391.33	15,000	1000	14.67	5.00	5.22	26.09
	MDV	150	0.4	113	1.00	533.63	15,000	800	8.00	4.00	8.89	22.23
	HDV		2	113	1.00	0.00	40,000		0.00	0.00	0.00	0.00
Zn - Air	LDV	450	0.2	150	0.00	600.00	15,000	600	18.00	7.00	5.71	28.57
	MDV	320	0.4	150	0.00	853.33	15,000	600	12.80	5.00	11.38	28.44
	HDV		2	150	0.00	0.00	40,000	600	0.00	0.00	0.00	0.00

[a] Data are estimates based on limited available information.

Table A-6. Toxic air contaminant identification list (April 1993)

Category I

Acetaldehyde
Acetamide
Acetonitrile
Acetophenone
2-Acetylaminofluorene
Acrolein
Acrylamide
Acrylic acid
Acrylonitrile
Allyl chloride
4-Aminobyphenyl
Aniline
o-Anisidine
Asbestos
Benzene (including from gasoline)
Benzidine
Benzotrichloride
Benzyl chloride
Biphenyl
Bis(2-ethylhexyl)phthalate (DEHP)
Bis(chloromethyl)ether
Bromoform
1,3-Butadiene
Cadmium (metallic and cadmium compounds)
Calcium cyanamide
Caprolactam
Captan
Carbaryl
Carbon disulfide
Carbon tetrachloride
Carbonyl sulfide
Catechol
Chloramben
Chlordane
Chlorine
Chlorinated dioxins and dibenzofurans
Chloroacetic acid
2-Chloroacetophenone
Chlorobenzene
Chlorobenzilate
Chloroform
Chloromethyl methyl ether
Chloroprene
Chromium VI
Cresols/Cresylic acid
o-Cresol
m-Cresol
p-Cresol
Cumene
2,4-D. salts and esters
DDE
Diazomethane
Dibenzofurans
1,2-Dibromo-3-chloropropane
Dibutylphthalate

1,4-Diclhorobenzene(p)
3,3-Dichlorobenzidene
Dichloroethyl ether
1,3-Dichloropropane
Dichlorvos
Diethanolamine
N,N-Diethyl aniline
Diethyl sulfate
3,3-Dimethoxybenzidene
Dimethyl carbamoyl chloride
Dimethyl formamide
1,1-Dimethyl hydrazine
Dimethyl phthalate
Dimethyl sulfate
4,6-Dinitro-o-cresol, and salts
2,4-Dinitrophenol
2,4-Dinitrotoluene
1,4-Dioxane
1,2-Diphenylhydrazine
Epichlorohydrin
1,2-Epoxybutane
Ethyl acrylate
Ethyl benzene
Ethyl carbamate
Ethyl chloride
Ethylene dibromide
Ethylene dichloride
Ethylene glycol
Ethylene imine
Ethylene oxide
Ethylene thioures
Ethylidene dichloride
Formaldehyde
Heptachlor
Hexachlorobenzene
Hexachlorbutadiene
Hexachlorocyclopentadiene
Hexachloroethane
Hexamethylene-1.6-diisocyanate
Hexamethylphosphoramide
Hexane
Hydrazine
Hydrochloric acid
Hydrogen fluoride
Hydroquinone
Inorganic arsenic
Isophorone
Lindane
Maleic anhydride
Methanol
Methoxyxhlor
Methyl bromide
Methyl chloride
Methyl chloroform
Methyl ethyl ketone

Methyl hydrazine
Methyl iodide
Methyl isobutyl ketone
Methyl isocyanate
Methyl methacrylate
Methyl tert butyl ether (MTBE)
4,4-Methylene bis(2-chloroaniline)
Methylene chloride
Methylene diphenyl diisocyanate
4,4-Methylenedianiline
Naphthalene
Nickel and nickel compounds
Nitrobenzene
4-Nitrobiphenyl
4-Nitrophenol
2-Nitropropane
N-Nitroso-N-methylures
N-Nitrosodimethylamine
N-Nitrosomorpholine
Parathion
Pentachloronitrobenzene
Pentachlorophenol
Phenol
p-Phenylenediamine
Phosgene
Phosphine
Phosphorous
Phthalic anhydride
Polychlorinated biphenyls (PCBs)
1,3-Propane sultone
beta-Propiolactone
Propionaldehyde
Propoxur
Propylene dichloride
Propylene oxide
1,2-Propyleneimine
Quinoline
Quinone
Styrene
Styrene oxide
2,3,7,8-Tetrachlorodibenzo-p-dioxin
1,1,2,2-Tetrachloroethane
Tetrachloroethylene
Titanium tetrachloride
Toluene
2,4-Toluene diamine
2,4-Toluene diisocyanate
o-Toluidine
Toxaphene
1,2,4-Trichlorobenzene
1,1,2-Trichloroethane
Trichloroethylene
2,4,5-Trichlorophenol
2,4,6-Trichlorophenol
Triethylamine

Table A-6. Toxic air contaminant identification list (April 1993) (concluded)

Category I (continued)

- Trifluralin
- 2,2,4-Trimethylpentane
- Vinyl acetate
- Vinyl bromide
- Vinyl chloride
- Vinylidene chloride
- Xylenes
- o-Xylenes
- Polycyclic Organic Matter
- m-Xylenes
- p-Xylenes
- Antimony compounds
- Arsenic compounds
- Beryllium compounds
- Cadmium compounds
- Chromium compounds
- Cobalt compounds
- Raionuclides (including radon)
- Coke Oven Emissions
- Cyanide compounds
- Glycol Ethers
- Lead compounds
- Manganese compounds
- Mercury compounds
- Fine mineral fibers
- Nckel compounds
- Selenium compounds

Category II

- Diesel exhaust
- Environmental tobacco smoke
- Inorganic lead
- Dialkylnitrosamines

Category III

- Acetone
- Aluminum
- Ammonia
- Ammonium nitrate
- Ammonium sulfate
- Barium compounds
- Benzoyl chloride
- Bis(2-ethylhexyl)adipate
- Bromine compounds (inorgainc)
- Butyl acrylate
- Butyl benzyl phthalate
- Carbon black extracts
- Chlorinated fluorocarbons
- Chlorine dioxide
- Chlorophenols
- Copper compounds
- Creosotes
- Crystalline silica
- Cumene hydroperoxide
- Cyclohexane
- Decabromodiphenyl oxide
- Diaminotoluene
- Dicofol
- Gasoline vapors
- Glutaraldehyde
- Hexachlorocyclohexanes
- Hydrogen sulfide
- Isopropyl alcohol
- 4,4'-Isopropylidenediphenol
- Molybdenum trioxide
- n-Butyl alcohol
- Nitric acid
- Nitrilotriacetic acid
- Peracetic acid
- 2-Phenylphenol
- Phosphouric acid
- Propene
- sec-Butyl alcohol
- Silver compounds
- Sodium hydroxide
- Sulfuric acid
- Terephthalic acid
- tert-Butyl alcohol
- Thiourea
- 1,2,4-Trimethylbenzene
- Zinc compounds

Category I contaminants are those that are already considered to be toxic by CARB, and include all of the federal HAPs. These are defined in Assembly Bills 1807 and 2728. Category II contaminants are under consideration to be identified as TACs. Category III contaminants are those that are being considered for listing under Category II.