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National Renewable Energy Laboratory
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Preface

Recent advances in the development of nickel metal-hydride (Ni-MH) batteries have resulted in an interest in utilizing this technology for propulsion in electric vehicles (EVs). In 1992, a cost-shared contract for the development of Ni-MH EV batteries was awarded to Ovonic Battery Company (OBC) by the United States Advanced Battery Consortium (USABC). Recently, SAFT America Inc. also received a cost-shared contract from the USABC to develop Ni-MH EV batteries. A primary goal of these contracts is to facilitate the commercialization of the Ni-MH battery for EVs, and an important part of the commercialization of any technology is an assessment of environmental, health, and safety (EH&S) issues. This report examines the EH&S issues associated with the use of the Ni-MH battery technology as the energy source in EVs.

The Analytic Studies Division prepared this report for the Electric and Hybrid Propulsion Division of the Office of Transportation Technologies in the U.S. Department of Energy (DOE). The report is intended to help DOE determine the direction of its research, development, and demonstration program for Ni-MH technology, and it is one part of DOE's program to work with industry to commercialize Ni-MH batteries for EVs. Previous EH&S reports were prepared by the Analytic Studies Division for sodium-sulfur EV batteries. Because the assessment of EH&S issues for advanced EV batteries is an ongoing task, future studies will build on the analysis contained in this report and previous reports.

We are indebted to many people who helped obtain information for this report. We would like to thank Dennis Corrigan of Ovonic Battery Company (OBC) for supplying information on OBC Ni-MH EV batteries and helping us understand the technology. We would also like to thank John Smaga of Argonne National Laboratories, who helped us understand some of the technical aspects of Ni-MH EV batteries, and Andy Altemos, who helped with the analysis of shipping regulations for Ni-MH EV batteries. And we also thank Helen Cost of Chrysler Corporation for her support. Finally, we thank Ken Heitner and Dana O'Hara of DOE for their leadership and support in directing and sponsoring the EH&S program and these assessments, and Ray Sutula of the DOE for support and guidance regarding Ni-MH EV battery research.

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Executive Summary

An analysis of the environmental, health, and safety (EH&S) issues for any new technology is an important part of the commercialization of that technology. This is particularly true of transportation-based technologies, such as advanced batteries for electric vehicles (EVs), because safety is a critical factor for consumer acceptance. Because many EV batteries contain wastes considered hazardous by the Environmental Protection Agency (EPA), it is also important to consider environmental issues associated with battery systems, such as the end-of-life recycling or reclamation of EV batteries. The purpose of this report is to identify important EH&S issues for nickel metal-hydride EV batteries and to assess where testing and further analysis are needed.

EH&S issues are discussed in two separate sections in this report: health and safety, and environment. Health and safety issues involve human contact with Ni-MH EV batteries and their constituents, whereas environmental issues concern the potential impacts on the environment due to the manufacturing, use, and disposal of Ni-MH EV batteries. The health and safety section of this report discusses cell and battery safety, workplace health and safety, shipping, and in-vehicle safety. The environmental section examines the recycling of Ni-MH EV batteries and discusses environmental regulations governing emissions from the manufacture of Ni-MH EV batteries.

In general, the findings of this report are that Ni-MH EV cells and batteries present few health and safety risks. The nontoxic nature of the electrode materials of the Ni-MH EV cell helps minimize the health and safety hazards of Ni-MH EV cells and batteries. The risk of cell rupture from the generation of high internal cell pressures is minimized through careful cell design that includes a pressure release vent for venting of internal gases above specified pressure thresholds. In addition, the design of Ni-MH EV cells minimizes the chance of hydrogen gas venting; venting is primarily limited to oxygen gas. Test data were presented for Ni-MH EV cells under different failure modes (e.g., short-circuiting); in some cases individual cells would vent, in no cases did any of the cells explode or rupture.

Workplace health and safety were discussed in this report in the context of chemical health hazards. Occupational Safety and Health Administration (OSHA) standards were used as a benchmark for evaluating workplace health and safety and were presented in the report for the different materials contained in Ni-MH EV cells. Nickel and nickel compounds contained in Ni-MH EV batteries are of primary concern for workplace exposure during Ni-MH EV battery operations (e.g., manufacture), since the National Toxicology Program considers nickel and nickel compounds probable carcinogens. However, workplace exposure for these substances should be within acceptable limits as long as OSHA standards for workplace exposure are met.

The section on shipping of Ni-MH EV batteries indicated that Ni-MH EV batteries would probably be classified as "nonspillable" batteries and, therefore, be exempt from many of the Department of Transportation (DOT) regulations for hazardous waste transport. However, because specific tests for making this determination are required, it is recommended that shipping take place under the more stringent "spillable" requirements until the testing can be completed. Further regulatory relief is available if the batteries meet the “dry” criteria, (i.e., not capable of leaking or spilling any free liquid if the battery is ruptured). Providing the batteries can meet the dry criteria and providing they pose no other transport hazards, such as the generation of excessive heat, they would not be subject to DOT regulation at all.

No major in-vehicle safety issues were identified that uniquely applied to Ni-MH EV batteries. However, various in-vehicle safety issues that applied to all EV batteries were analyzed. Although these issues were not unique to Ni-MH EV batteries, they are important issues that must be addressed for EVs regardless of battery type.

The environmental concerns associated with Ni-MH EV batteries, like the health and safety risks, were also considered small. The main environmental issue discussed was the recycling of Ni-MH EV batteries. Test results showed that Ni-MH AB_2 -type EV batteries would not be considered a hazardous waste under existing EPA regulations, although they would be considered hazardous under California state and European Community environmental regulations.

In addition to analyzing the EH&S issues for Ni-MH batteries, this report also includes an overview of the EH&S issues for other nickel-based EV batteries. The other nickel-based systems consist of the following battery types: nickel-cadmium (Ni-Cd), nickel-iron, nickel-hydrogen, and nickel-zinc. Three main EH&S issues were identified for nickel-based EV batteries: venting characteristics; toxicity of battery materials; and the hazardous waste status of spent batteries.

Although the nickel-based battery systems share many common EH&S characteristics, several important differences were identified in this report. For example, differences in OSHA standards for workplace exposure to cadmium and nickel were analyzed, and test results for Ni-Cd batteries were presented that showed that Ni-Cd batteries are considered hazardous wastes under EPA regulations. In contrast, Ni-MH AB_2-type batteries are only considered hazardous under California state regulations and by European Community regulations.

Although the EH&S issues for Ni-MH EV batteries were, in general, considered small, this report makes a number of recommendations for future work in the area of EH&S for Ni-MH EV applications. Because battery safety is such an important aspect of the commercialization process of EVs, the adoption of formalized safety testing procedures could help promote the safety aspects of EV batteries. In addition, conducting safety tests by an independent testing organization would help promote the safety aspects of EV batteries. Safety tests, such as drop tests, fire tests, and abusive overcharging and overdischarging tests, should be conducted on Ni-MH EV batteries (as well as on other EV batteries) to determine how they would react to accidents such as collisions, fires, and battery charger malfunctions (some of this testing has been performed by Ovonic Battery Company).

As advanced batteries begin to be integrated with the vehicle platforms in prototype and commercial EVs, increased in-vehicle testing should be carried out to demonstrate compliance with the existing regulations and standards and to bolster public acceptance of the new product. In addition, such testing will help guide the development of batteries and vehicles to ensure that they will be capable of compliance.

Because Ni-MH batteries would be exempt from DOT shipping regulations if they can meet the dry criteria, it is recommended that testing be undertaken to determine if the criteria can be met. If Ni-MH batteries can meet the dry criteria, no other testing would be necessary. If the dry tests are conducted and the batteries cannot meet the criteria, tests should then be conducted to determine if the batteries meet the nonspillable requirements. If the batteries can meet the nonspillable criteria, they would need only be protected against short circuits and be securely packaged in accordance with DOT regulations. No other transport requirements would apply.

Although it is generally agreed that recycling is a preferred alternative to disposal, there is no information on the costs for recycling Ni-MH EV batteries, and there is no guarantee that recycling will cost less than disposal; hence future work needs to be conducted to determine feasible cost-effective recycling processes for Ni-MH batteries. The National Renewable Energy Laboratory is currently studying how to estimate recycling costs for Ni-MH EV batteries. It is recommended that this activity be conducted for other advanced EV batteries as well. If recycle costs for EV batteries are high (e.g., no net profit through recycling), then this could jeopardize the commercial potential of EV batteries.

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Introduction

Nickel metal-hydride (Ni-MH) batteries share many common features with other nickel-based batteries, such as nickel-cadmium (Ni-Cd). The Ni-MH system uses a positive electrode that is very similar to that of the Ni-Cd system. However, advances in the performance of the Ni-MH technology, as well as recent environmental, health, and safety (EH&S) concerns regarding the use of cadmium in the workplace and the disposal of cadmium-bearing wastes, have focused attention on the potential for Ni-MH batteries to replace Ni-Cd batteries in many applications.

There are a number of different companies that are involved with the development of Ni-MH batteries for a wide variety of applications, including small-scale commercial appliances, aerospace applications, and electric vehicles (EVs). Nearly all of the major battery companies, including Japanese companies, either have announced some type of Ni-MH product or are in the development stage of a product (Coates 1992). Recent advances in Ni-MH technology have focused attention on the potential for Ni-MH batteries to power EVs. A limited number of Ni-MH EV batteries have been produced, but most of the research for Ni-MH EV technology is still being conducted at the cell level. This report describes the EH&S issues for Ni-MH EV cells and batteries and concentrates primarily on the Ni-MH EV technology being developed at Ovonic Battery Company (OBC) as part of a cost-shared contract with the United States Advanced Battery Consortium (USABC).[1]

This report comprises four parts, in addition to a reference section and three appendices. The four main parts are: Part I - Health and Safety Issues for Ni-MH EV Batteries; Part II - Environmental Issues for Ni-MH EV Batteries; Part III - General EH&S Characteristics of Nickel-Based EV Batttery Systems; Part IV-Conclusions. Health and safety issues discussed in Part 1 involve human contact with Ni-MH EV batteries and their constituents, whereas environmental issues discussed in Part 2 concern the potential impacts on the environment of the manufacturing, use, and disposal of Ni-MH EV batteries.

The health and safety section discusses cell and battery safety, workplace health and safety, shipping, and in-vehicle safety. An overview of the health and safety categories is shown in Figure 1, including the categories analyzed and the primary regulations governing each category. The first chapter, on cell and battery safety, describes the key safety hazards associated with Ni-MH cells and the cell and battery design features that address those hazards. A brief overview of workplace exposure to chemical health hazards for Ni-MH battery processes (e.g., manufacturing) is presented in the second chapter. In the third chapter, regulations governing the shipment of Ni-MH batteries are discussed. Finally, the last chapter discusses in-vehicle safety considerations for Ni-MH EVs.

An overview of the environmental section is shown in Figure 2, which summarizes the key environmental issues for the primary life-cycle stages of Ni-MH EV batteries and the primary regulations governing each stage. The recycling of Ni-MH EV batteries is given particular emphasis in the environmental section. The first chapter discusses Environmental Protection Agency (EPA) regulations affecting Ni-MH EV battery manufacturing. The second life-cycle stage for Ni-MH EV batteries consists of emissions associated with vehicle charging. These emissions are primarily from electric utilities that supply electricity for Ni-MH EV battery charging and are not dealt with in this report because they are being analyzed in a different

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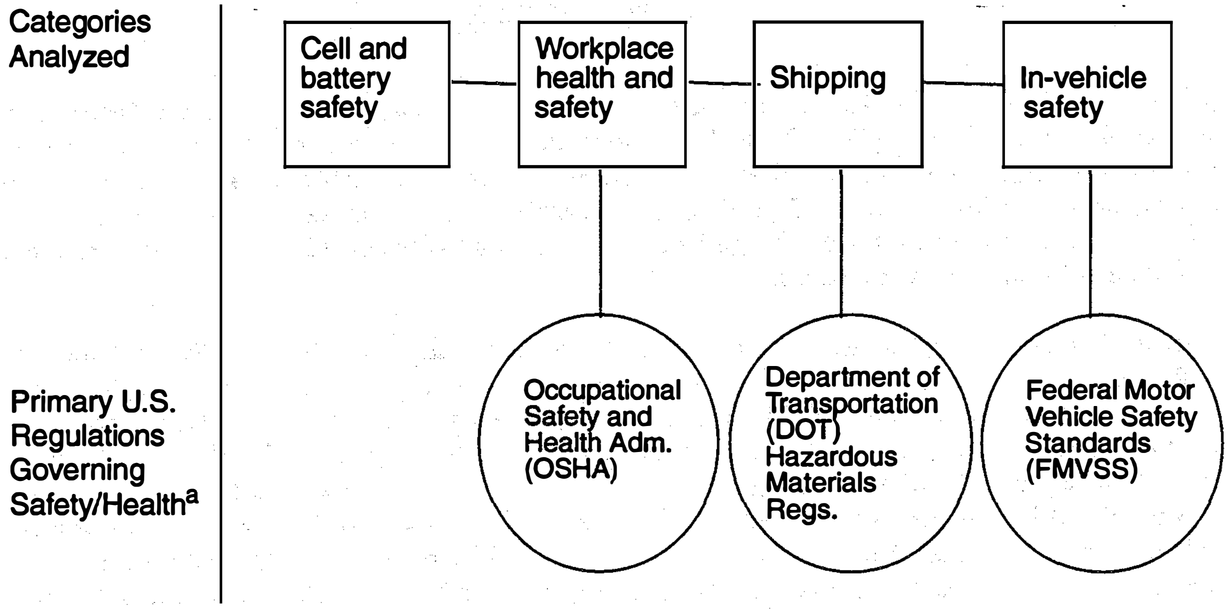
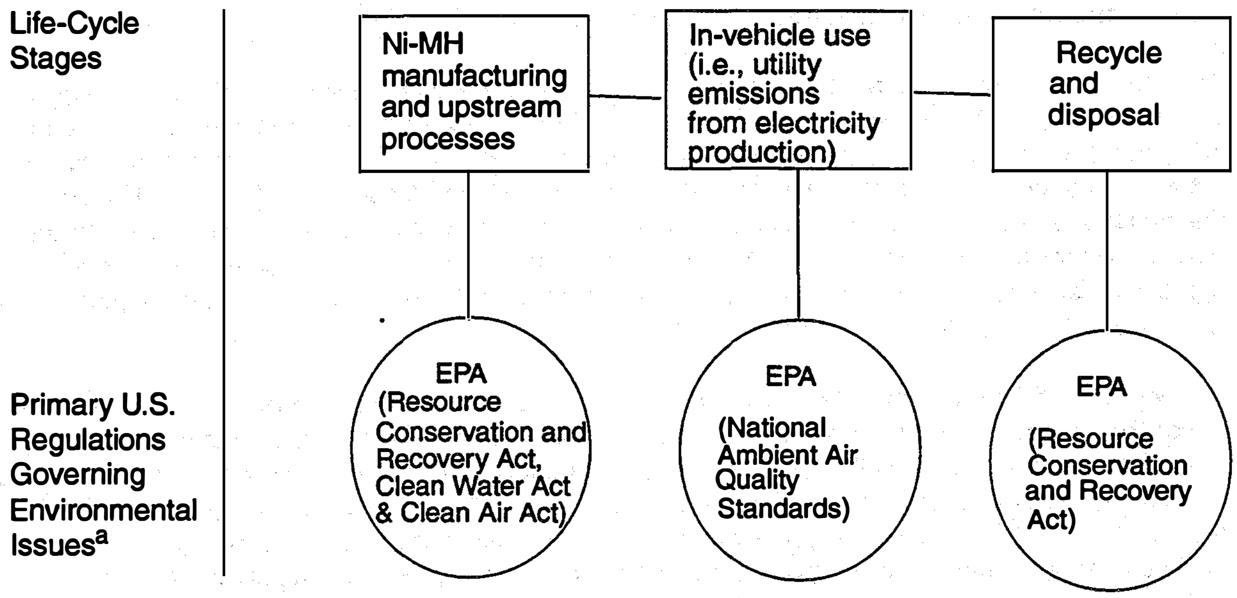
[1] SAFT America Inc. was recently awarded a contract by the USABC to develop its Ni-MH EV technology; however, because this contract was awarded only recently, SAFT-America's technology is not included in this report.



[a] The regulations identified are considered the primary regulations, but other regulations or standards may exist. For example, the Society of Automotive Engineers also sets standards related to in-vehicle safety, and the United Nations has adopted regulations governing the international shipment of hazardous materials. All applicable regulations are discussed that relate to the different aspects of EH&S for Ni-MH EV batteries.

Figure 1. Health and safety categories and governing regulations for Ni-MH EV batteries



[a] The regulations identified are considered the primary regulations, but other regulations or standards may exist. .

Figure 2. Environmental stages and governing regulations for Ni-MH EV batteries

study.[1] In the last chapter of the environmental section, Ni-MH EV battery recycling and disposal are evaluated in terms of the regulations set forth by the EPA for managing hazardous wastes. Different recycling processes are discussed, and test results for determining the regulatory status of spent Ni-MH batteries are presented.

The third section of this report consists of a brief overview of the EH&S issues affecting nickel-based EV batteries. The nickel-based EV batteries analyzed include Ni-MH, Ni-Cd, nickel-iron, nickel-hydrogen, and nickel-zinc. Specific regulatory requirements for Ni-Cd batteries are presented in this section, and the primary EH&S issues for nickel-based EV batteries are identified.

Finally, the conclusion of this report discusses some of the future work that is required to ensure that EH&S issues are fully addressed for Ni-MH EV batteries.

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[1] A total energy cycle analysis is being conducted for EVs by the Department of Energy that will estimate emissions for the primary life-cycle processes for selected EV battery technologies. In addition to estimating power plant emissions from EV charging, other upstream (e.g., manufacturing) and downstream (e.g., recycling) emissions may be analyzed.

Part I - Health and Safety Issues for Ni-MH EV Batteries

Cell and Battery Safety

Background

A nickel metal-hydride (Ni-MH) battery for electric vehicles (EVs) consists of many electrically interconnected cells and a battery enclosure. System components peripheral to the battery itself, such as the battery controller, affect battery safety but are not considered in this report. Because the Ni-MH technology is relatively new for EV applications, only a limited number of Ni-MH EV batteries have been manufactured and tested, so data on Ni-MH battery safety are limited. Therefore, the emphasis in this section is on cell safety, although battery safety is also discussed.

The science and technology of rechargeable metal hydrides began about 1970 with the discovery that the intermetallic compound lanthanum-nickel ($LaNi_5$) could be easily hydrided and dehydrided at room temperature with modest pressure increases. Although the nickel metal-hydride technology has been in existence for some time, it was not until recently that this technology was developed for commercial applications, such as computers and cellular telephones. (Safety concerns for small-scale applications of the Ni-MH technology are similar to those of the widely commercialized nickel-cadmium (Ni-Cd) technology, which has had a good safety record since its commercialization [Crompton 1990].)

The positive electrode of a Ni-MH cell is a nickel-hydroxide electrode, which is the same as in many of the other nickel batteries (e.g., Ni-Cd). The negative electrode is a metal hydride electrode, which contains different metals that can store hydrogen (other materials may also be included in the hydride to prevent corrosion or enhance hydrogen storage). The specific composition of the metal hydride depends on the specific battery application and manufacturer. The Ni-MH technology typically uses an aqueous potassium hydroxide electrolyte. The electrolyte is often referred to as a "starved electrolyte" because there is no free electrolyte; all of the electrolyte is contained in the porous electrodes or in the material that separates the electrodes (i.e., the separators).

Sealed prismatic cells are typical for Ni-MH EV batteries, as opposed to the cylindrical-shaped cells (e.g., C cells) used for small-scale commercial applications. Prismatic cell containers are typically constructed from stainless steel, although other materials may be used. Ni-MH EV batteries are fitted with a resealable pressure release vent so that cells can vent if internal pressures build up. Because Ni-MH EV batteries are not high temperature batteries, they do not require a sophisticated thermal management system like some other advanced EV batteries (e.g., sodium-sulfur batteries), although they do require some form of cooling. The Ni-MH cell operates according to the following reactions at the electrodes:

Negative Electrode: $\text{Alloy} + H_20 + e^- \text{ <--------> } \text{Alloy[H]} + OH^-$

Positive Electrode: $Ni(OH)_2 + OH^- \text{ <--------> } NiOOH + H_20 + e^-$

Overall reaction: $\text{Alloy} + Ni(OH_2) \text{ <--------> } \text{Alloy[H]} + NiOOH$

Charging proceeds from left to right; discharging from right to left. The intrinsic voltage of the Ni-MH cell is approximately 1.2 V (Eager and Puglisi 1992).

The following sections discuss the major safety issues associated with Ni-MH cells and batteries. Safety is discussed primarily in terms of risks, as opposed to hazards. A hazard is a source of risk; it is a substance or action that can cause harm. Risk, on the other hand, is the possibility of suffering harm from a hazard

(Cohrssen and Covello 1989). For example, even though the hazards associated with exposure to some battery cell materials can be substantial, the risks involved in using various battery electrodes can be minimized through careful design, engineering, and testing. This section provides a qualitative analysis of the hazards and risks that must be addressed before Ni-MH EV batteries can be deployed on a commercial scale.[1]

Although electrical integrity at the battery level is critical and electrical hazards associated with a Ni-MH battery (or any high energy battery) must be acknowledged, the emphasis of this assessment is on the chemical and structural integrity of the individual cells that make up a Ni-MH battery. However, because of the large number of cells that make up a battery, safety at the cell level cannot always be extrapolated to the battery level; hence, a distinction should be made between cell safety and battery safety. In addition, a further distinction is made in this report between battery safety under normal operating conditions and safety under catastrophic events such as collisions.

Intrinsic Material Hazards of Ni-MH Cells

Many elements and alloys store hydrogen reversibly, most notably titanium-iron, manganese-nickel, lanthanum-nickel (also known as AB_5), and the metal hydrides developed by the Ovonic Battery Company (OBC), which are known as AB_2 (AB_2 and AB_5 are crystal structure designations). The AB_2 and AB_5 hydrides are the most common alloys used for Ni-MH applications (several patents have been applied for that involve different hydride alloys). The AB_2 alloy used by OBC is the primary hydride alloy considered in this discussion on EV cell and battery safety.

The positive electrode of a Ni-MH battery consists of nickel hydroxide, and the negative electrode is made up of a metal hydride. The AB_2 hydrides developed by OBC are based on proprietary hydrogen storage materials consisting primarily of vanadium, titanium, zirconium, nickel, and chromium. The electrolyte is an aqueous water-based solution of 30% potassium hydroxide with a lithium hydroxide additive; it is contained in a conventional separator system (Ovshinsky et al. 1992).

Table 1 shows the major hazards associated with the different constituents of a Ni-MH cell based on the AB_2 hydride. (Although the hazards for the AB_5 hydride are not shown, it should be noted that this alloy may be pyrophoric, i.e., highly flammable; the AB_2 hydride is not pyrophoric.) It should be stressed that hazards, not risks, are shown in Table 1. For example, although a single high exposure to nickel hydroxide can be harmful, exposure to nickel-hydroxide dust or fumes from a NiMH EV battery is unlikely because the nickel-hydroxide is in a metal form and is enclosed within individual cells; hence, the risk of injury from this particular hazard is minimized.

Appendix A contains more detailed safety information on the constituents discussed previously. When considering toxicity data on hazardous substances, it is important to note the difference between acute toxicity and chronic toxicity. Acute toxicity is the ability of a chemical to cause systematic damage as the result of short-term exposure. Chronic toxicity involves long-term, low-level exposure in which the rate of chemical exposure is greater than the capacity of the body to eliminate the substance or render it harmless (Kavianian and Wentz 1990). Chronic health effects result from long-term exposure to a substance, such as the exposure of workers to a substance in a manufacturing plant that utilizes that material for its

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[1] This section on cell and battery safety does not constitute a formal risk analysis. A formal risk analysis usually includes the following: Estimates of the amounts, frequencies, and locations of the release of hazardous materials; duration of exposures to the hazardous materials; estimates of the percentage of the population exposed and dosage-response relationships for exposure; and a quantitative estimate of the risk (Cohrssen and Covello 1989).

Table 1. Hazardous Chemical Species Associated with a Nickel Metal-Hydride Cell[a]

Species	Safety Concern
Nickel hydroxide	*Probable carcinogen.* Lung damage may result from a single high exposure or repeated lower exposures. Skin contact may cause skin allergy.
Potassium hydroxide	Extremely corrosive.
Hydrogen gas[b]	Extremely flammable. Explosive.
AB_2 alloy	Generally nontoxic; however, if materials are acid-dissolved or treated chemically to form water-soluble compounds of nickel or chromium, then these water-soluble compounds of nickel or chromium, then these water-soluble compounds may be carcinogenic. Dust finer than 100 mesh can be flammable. Hot or burning metal can produce toxic fumes. (Evolves hydrogen above 100°C. Reactions with oxidizers or chlorine will generate hazardous reaction products such as metal oxide dust and fumes or corrosive and toxic metallic chlorides.)

[a] It should be noted that hazards, not risks, are shown in Table 1; actual risks in Ni-MH cells from these hazards would be greatly minimized due to a number of reasons discussed in the text. Because metals will be bound in the alloy, the hazards for the AB_2 alloy itself are the most applicable to Ni-MN safety, as opposed to the hazards for individual metals. However, hazards of individual metals are discussed in the section on workplace exposure.

[b] Hydrogen is usually part of a OH^- radical or bound to the alloy, although hydrogen gas can be produced from cells under certain conditions, which are described in a later part of this chapter.

Source: Lewis 1992.

manufactured products. Worker exposure to Ni-MH EV battery manufacturing is discussed in a later section of this report.

Ni-MH Cell Failure Modes

Safety concerns of Ni-MH EV cells are fewer than safety concerns about many other advanced EV cells. The safe utilization of Ni-MH cells in small-scale commercial applications during the past few years (e.g., C cells) contributes to their overall safety record. Although OBC has been able to scale up their smaller Ni-MH cells to large prismatic-shaped EV cells and retain the performance characteristics (Fetcenko et al. 1992), the safety characteristics of Ni-MH C cells and Ni-MH EV cells, although similar, should not be considered identical because of size and design differences.

Hazards of Ni-MH cells are, in general, low because of the stable nature of the electrode materials used in a Ni-MH cell and because of the use of a starved electrolyte. The starved electrolyte minimizes the risk associated with electrolyte spillage that is possible in cells with a "freestanding electrolyte." With a starved electrolyte, the surface tension forces (e.g., capillary effect) keep the electrolyte bound in the battery separators and the porous electrodes. For example, Ni-MH EV cells that have been cut open and separated into individual components will retain their electrolyte unless active measures are taken to remove it. Hydrogen gas, which is extremely flammable and explosive, may be produced and subsequently vented from individual cells during cell failure modes (e.g., exposure of cells to high heat). However, Ni-MH cells are designed to minimize the potential for hydrogen gas evolution within cells. In the rare case that hydrogen gas is vented from a cell, appropriate design considerations that allow for the dispersion of the gas from the battery and vehicle minimize any risks associated with hydrogen flammability. Nevertheless, one potential hazard exists with a Ni-MH *cell*: pressure buildup in a cell causing the cell to burst or rupture. The risks associated with pressure buildup in a cell and subsequent cell burst are small because the pressure release vent on a cell is designed to open before cell pressures would cause the cell to burst or rupture.

Cell Design to Prevent Above-Normal Cell Pressure

The Ni-MH cell container, or can, serves as a final barrier between the cell and the battery enclosure; it is typically made out of stainless steel, although other materials may be used. The strength of stainless steel provides an adequate barrier to prevent rupture of the cell in all but extreme situations. High cell pressure may result from the buildup of gas in a cell. Both hydrogen and oxygen could potentially build up the internal pressure of a Ni-MH cell, and if not properly vented, cause the cell to burst.

A key safety design feature of a Ni-MH cell is the pressure release vent. This is a vent that is set to release at a certain pressure above the normal operating pressure of the cell. It is usually made up of a rubber gasket that gets moved backwards as the internal pressure of the cell increases. Upon reaching a certain pressure, which is about 7.5 atmospheres (Smaga 1993) in an EV cell, the gasket opens and the cell is free to vent. Elevated pressures generally occur only on overcharge. Ovonic's Ni-MH EV cells operate at ambient pressure during normal charge and discharge, except during overcharge, when pressures may reach 2–3 atmospheres. Quick charging of Ni-MH EV cells results in the highest internal cell pressures.

Ni-MH EV cells can withstand more than 50% overcharge (at a C/7 rate) and more than 20% overdischarge, (at a rate of C/3) without excessive pressure buildup and subsequent venting (Ovshinsky et al. 1993). This tolerance to overcharging and discharging increases the safety of the Ni-MH EV cell. Many other types of EV cells do not have this overcharge and overdischarge protection and may be destroyed under these circumstances.

Ni-MH cells are largely tolerant to overcharging and over discharging. However, *severe* overcharging or overdischarging, such as that associated with a potential malfunction of a battery controller or charger during a quick charge, could result in a build up of cell gases and subsequent cell pressures that would cause a cell to vent. The pressure release vent is the key safety feature that allows Ni-MH EV cells to alleviate the potential hazard of pressure build up.

To understand why and under what circumstances a Ni-MH cell might evolve gases faster than they can recombine in the cell, the cell reactions for overcharging and cell reversal are presented in Table 2; the basic charge and discharge reactions are also shown for reference (Venkatesan et al. 1988).

During overcharging, the nickel hydroxide electrode becomes fully charged, generating oxygen gas, which recombines at the negative electrode, thereby generating heat. At low charge rates, it is possible to continuously overcharge a Ni-MH EV cell without adverse effects because of the oxygen recombination reaction (Venkatesan et al. 1993). At higher charge rates, the pressure within a Ni-MH cell is proportional to the rate of overcharge. Above certain charge rates, oxygen is produced at a faster rate than it can recombine, and the internal cell pressure increases until the pressure release vent threshold is reached. At that time, the cell safely vents the accumulated oxygen, and the internal pressure decreases to ambient pressure. Cell safety testing, such as deliberate overcharging that results in testing of the pressure release vent, allows the safety of a Ni-MH cell to be assessed for this potential failure mode.

Table 2. Cell Reactions for Overcharging and Overdischarging

	Positive	Negative
Charge/discharge	$Ni(OH)_2 + OH^- \longleftrightarrow NiOOH + H_2O + e^-$	$Alloy + H_2O + e^- \longleftrightarrow Alloy[H] + OH^-$
Overcharge	$4OH^- \longrightarrow 2H_2O + O_2 + 4e^-$	$2H_2O + O_2 + 4e^- \longrightarrow 4OH^-$
Overdischarge	$2H_2O + 2e^- \longrightarrow H_2 + 2OH^-$	$H_2 + 2OH^- \longrightarrow 2H_2O + 2e^-$

During overdischarge, hydrogen gas is generated at the positive electrode; it then recombines at the negative electrode. At very high levels of overdischarge, all the hydrogen cannot recombine at the negative electrode. Severe overdischarge can result in increased pressure from hydrogen gas buildup and subsequent venting of the cell through the pressure release vent. Cell safety testing, such as deliberately overdischarging the cell, allows the safety of the cell to be assessed for this potential failure mode.

Cell Testing

Ni-MH EV cells are still a very new technology, so testing on a large scale has begun only recently. Table 3 summarizes the results of safety tests that were carried out by OBC on its Ni-MH EV cells. The cells were subjected to various abuse tests such as overdischarge, direct short-circuit, extended high rate overcharge, and exposure to high temperatures.

Battery Design and Safety

Although the safe use of Ni-MH batteries for vehicular propulsion begins with cell safety, a battery consists of many hundreds of mechanically and electrically interconnected cells in an enclosure and introduces additional safety concerns not necessarily considered on the cell level. Because of the competitive nature of this new technology, little information is available on Ni-MH battery designs, and most of this information is proprietary. Nevertheless, battery safety is briefly discussed from a generic standpoint (i.e., no specific battery configurations or designs are presented).

Important components of battery design include the following: electrical networking; electrical insulation; battery enclosure, including any thermal management requirements; and electrical and mechanical interfaces with battery controllers and chargers.

A good electrical network design will accommodate cell failure with minimal effect on battery performance. Many EV battery designs for other advanced battery technologies allow for cell failures to be isolated within cell modules, resulting in the loss of a minimum amount of cells under such circumstances. For some EV batteries, cell modules may be individually monitored electrically to detect charge imbalances caused by cell failure or cell aging. However, this type of cell module monitoring should not be required for Ni-MH EV batteries because of the safe performance of Ni-MH cells under overcharge and overdischarge scenarios.

For example, because more than 100 cells in series are needed for the battery pack voltages of 200–300 V typical of modern EVs, slight imbalances in the state of charge of the cells are likely to occur. These imbalances could be caused by environmental factors, such as cell-to-cell temperature gradients across a battery pack, and not necessarily by variations in individual cell capacities. At the end of charge, cells at a higher state of charge can be exposed to severe overcharge. At the end of discharge, cells at a lower state of

Table 3. Safety Tests for NI-MH EV Cells (supplied by OBC)

Test Description	Results
1. Greater than 100% overcharge of 35 Ah cells at rates ranging from C/5 to C/10.	Cell temperatures rose to around 40°C. In some cases, venting occurred. No damage to the cell or immediate detrimental effect on the performance was observed.
2. A 70% overdischarge of several 35 Ah cells at the C/3 rate followed by a 30-second discharge pulse at the C/3 rate driving the cells deep into reversal.	The temperature rose to about 35°C. The pressure generated was insufficient to open the pressure release vent. No damage to the cell or immediate detrimental effect on the performance was observed.
3. Exposure of charged 50 Ah cells to flames from a butane torch.	After 1 minute the cells started venting, some escape of steam was observed. The cells vented safely after about 1 minute. No fire or explosions occurred.
4. Exposure of 50 Ah cells to flames from a butane torch during active overcharge at the C/10 rate. Cells were heated until cell cases were red hot.	The cells vented safely after about 1 minute. Later steam and then smoke vented, indicating internal charring of the separator. No fire or explosions occurred.
5. Exposure of 50 Ah cell overdischarged 30% to flames from a butane torch.	Normal venting. Later steam and then smoke vented, indicating internal charring of the separators. No fire or explosions occurred.
6. Exposure of 50 Ah cell to flames from a butane torch during active overdischarge at the C/10 rate.	Normal venting. Later steam and then smoke vented, indicating internal charring of the separators. No fire or explosions occurred.
7. Direct shorting of several fully charged 50 Ah cells.	Measurements of current indicated up to 1800 A during shorting. Current dropped to 400–500 A, which was maintained for around 5 minutes. External cell temperatures rose to about 150°C. The cells safely vented. Venting started at around 2 minutes into the tests. More vigorous venting occurred around 5 minutes into the tests.

charge can easily be overdischarged by the remainder of the cells in the pack. Yet under both these conditions, Ni-MH EV cells will normally be tolerant to the amount of overcharge or discharge (Venkatesan et al. 1993). This was discussed previously for individual cells. However, should these cells be *severely* overcharged or overdischarged, then they would vent through the pressure release vent; the battery pack should be designed to allow for the safe venting of cells. (In addition, it might be helpful to monitor which cells in a battery pack have vented through their pressure release vents.)

Ni-MH battery systems must be designed so that individual cells can vent without gases building up pressure within the battery enclosure. OBC Ni-MH batteries are designed to generate predominantly oxygen rather than hydrogen. However, in the unlikely event that hydrogen gases are vented, battery systems must be designed to disperse the gas from individual cells so that it does not accumulate in the battery enclosure[1] or in the vehicle. To avoid the accumulation of hydrogen that could potentially lead to hydrogen explosions, batteries should not be placed in enclosed spaces without adequate ventilation. The ventilation required for cooling the battery pack could be sufficient to dissipate any vented hydrogen gas from a Ni-MH battery pack. Because Ni-MH cells vent hydrogen upon heating, Ni-MH battery packs should also be designed for a worst case scenario, such as a fire, in which heating up of the battery could cause many cells to vent hydrogen within a short period of time.

Other important aspects of battery design include electrical insulation, battery enclosure, and electrical and mechanical interfaces with battery controllers. Electrical insulation, although generally considered a standard precaution in any type of storage battery, is extremely important for high energy advanced EV batteries because of the high current levels generated by the battery pack. Although safety standards exist for the electrical insulation of lead-acid storage batteries (SAE 1986), no such standards currently exist for EV batteries. Prismatic Ni-MH EV cells have been constructed using stainless steel as a container for the cell, but the use of other insulator materials could increase the overall electrical insulation of a Ni-MH battery pack.

Battery enclosures are also an important part of overall safety for a Ni-MH EV battery. Although generally considered an ambient temperature battery, Ni-MH batteries do generate heat at specific times, such as during overcharging or parts of the discharge cycle; hence, thermal design parameters should be incorporated into Ni-MH EV battery enclosures (current OBC Ni-MH battery designs utilize air cooling for the battery pack). In addition to providing the thermal and gas management required for a battery, battery enclosures should be designed to meet existing safety guidelines and practices (e.g., batteries should be properly secured).

Electrical and mechanical interfaces with battery chargers and controllers should be designed to meet all appropriate standards and guidelines, including all electrical safety practices and good engineering design criteria. For small Ni-MH commercial cells, the design of charging systems for Ni-MH batteries is generally similar to the design of Ni-Cd charging systems (Eager and Puglisi 1992). Charge termination schemes are based on detecting temperature or voltage characteristics that occur when a battery has reached a charged state. Temperature cutoff, incremental temperature rise, voltage decrement, and voltage plateau all have been evaluated as charge termination schemes for Ni-MH batteries (Eager and Puglisi 1992). Because of the subtlety of detecting the voltage and temperature peaks at full charge, it is possible that unexpected ambient temperature excursions or noise within the system could mask the cutoff signal (Eager and Puglisi 1992). Therefore, methods of charge termination for Ni-MH EV batteries should be multiple and redundant, if possible.

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[1] Evacuation of hydrogen gas is essential to the safe operation of electric vehicles. One incident was reported for a lead-acid EV where inadequate ventilation of hydrogen gas lead to a pick-up truck exploding (Hayden 1981). Although lead-acid hydrogen gassing is different than hydrogen generation in Ni-MH batteries, this example illustrates the caution required in venting hydrogen. This is discussed further in the section on in-vehicle safety.

Conclusions

In general, the safety risks associated with Ni-MH EV cells are small. Internal pressure buildup within a cell and subsequent cell rupture were identified as a potential safety hazard for Ni-MH EV cells. The primary safety design feature that addresses this potential hazard is the pressure release vent on a Ni-MH cell, which opens at an elevated pressure and allows the gases to vent. This safety design feature minimizes the risk associated with this hazard. A potential safety hazard for Ni-MH EV *batteries* is the possible accumulation of hydrogen in the battery enclosure from cells that have vented. While the design of OBC Ni-MH cells minimizes the chance of hydrogen venting, battery packs should be adequately ventilated to further minimize risks.

Workplace Safety and Health Issues for Ni-MH EV Batteries

Background

Occupational health and safety issues include occupational injuries and diseases, risk assessment, engineering control systems, air containments, emission controls, electrical safety, work practices, materials handling, industrial toxicology, system safety, and product liability. However, this section on workplace health and safety issues focuses only on workplace exposure to substances that may present chemical hazards. Other occupational health and safety issues, although extremely important, have been well understood by battery manufacturers. Furthermore, most of these issues are not specifically unique to Ni-MH EV battery manufacturing but are applicable to battery manufacturing in general (or just manufacturing in general).

There has been an increasing concern with workplace exposure to chemical hazards. This section gives an overview of the regulations governing workplace exposure to chemical substances contained in Ni-MH batteries that present potential health hazards. It is assumed that workplace exposure to these chemicals would primarily take place during the manufacture of Ni-MH batteries, but workplace exposure could also take place during upstream processes (e.g., smelting of metals) as well as during the recycling and disposal of batteries or during battery maintenance.

Chemical Hazard Characterization

Chemical hazards fall into two broad categories: physical hazards and health hazards. Materials that present physical hazards include combustible liquids, flammable gases, all compressed gases, pyrophoric materials, explosives, organic peroxides, oxidizers, and other related materials. Chemical health hazards, which are the focus of this section, are harder to define because they may affect people differently, and their effects may be hard to separate from nonoccupational health hazards.

Chemical health hazards can be divided into two broad categories of acute and chronic hazards. Acute health hazards usually cause a measurable effect soon after a single exposure. Chronic health hazards, on the other hand, produce permanent health effects as a result of repeated exposures over a long period of time.

Chemical health hazards from battery manufacturing may be associated with the following types of substances: corrosives, irritants, toxic chemicals, and carcinogens. Irritants are chemicals that cause skin, eye, or lung irritation. Toxicity of chemicals is normally determined by conducting tests on laboratory animals; specific criteria have been established in terms of dose response characteristics for rats that categorize a substance as toxic or highly toxic. Carcinogens are chemicals that have been known to cause cancer or have the potential to cause cancer in humans, as recognized by any of the following:

- International Agency for Research on Cancer (IARC)
- Annual report published by the National Toxicology Program (NTP) of the U.S. Public Health Service
- Regulations by the Occupational Safety and Health Administration (OSHA) (29 CFR 1910 Subpart Z).

Different standards and recommendations exist for workplace exposure to chemical substances. For example, the National Institute for Occupational Safety and Health (NIOSH) publishes recommended exposure limits for many toxic substances, and the American Conference of Governmental Industrial Hygienists (ACGIH) publishes threshold limit values (TLVs) for toxic substances. OSHA standards may be expressed differently than NIOSH and ACGIH standards (e.g., OSHA's 8-hour time-weighted average versus ACGIH's TLV). OSHA standards are the most comprehensive regulations for chemical health hazards in the workplace and are described in the following section as they pertain to toxic or carcinogenic substances contained in Ni-MH EV batteries.

Occupational Safety and Health Act Regulations

Air contaminant standards for the working place as established by OSHA exist for nickel and nickel compounds (including nickel hydroxide), manganese fumes, chromium (as metal), vanadium (as vanadium pentoxide - V_2O_5), titanium (as titanium dioxide - TiO_2), and zirconium. Although short-term exposure limits exist for some of these substances, only the OSHA time-weighted average permissible exposure limits (TWA PELs) are discussed. The TWA PEL is the more common OSHA standard and that is why it is presented here. A TWA PEL is an employee's average airborne exposure in any 8-hour work shift of a 40-hour work week (*Federal Register* 1989). The TWA PELs established for these compounds are as follows: insoluble nickel—1.0 mg/m^3; nickel hydroxide—1.0 mg/m^3; manganese fumes—1.0 mg/m^3; chromium—1.0 mg/m^3; vanadium pentoxide—0.05 mg/m^3; titanium dioxide—5.0 mg/m^3; and zirconium compounds—5.0 mg/m^3. Some of these compounds may not be present in the manufacturing of Ni-MH cells (e.g., vanadium pentoxide).

Of the TWA PELs listed, only the nickel and chromium levels are based on carcinogenic criteria. The NTP considers nickel a probable carcinogen and chromium a known carcinogen. The manganese limit was set to protect against poisoning, lung damage, and pneumonia. Vanadium limits are based on its potential to cause chronic bronchitis and chronic lung inflammation (*Federal Register* 1989).

Chemical Health Hazards for Ni-MH Battery Constituents

Table 4 summarizes the chemical health hazards for the different constituents found in Ni-MH EV batteries. Both physical and chemical health hazards for a specific chemical are summarized on the material safety data sheet (MSDS). A MSDS is a worker's guide to the safe use of a chemical. Appendix A contains an MSDS for the OBC AB_2 alloy.

Table 4. Summary of Health Hazards for Nickel Metal-Hydride Battery Constituents

Species	Safety Concern
Nickel hydroxide	*Probable carcinogen.* Lung damage may result from a single high exposure or repeated lower exposures. Skin contact may cause skin allergy.
Nickel	*Probable carcinogen.* Skin contact may cause skin allergy.
Chromium	*Confirmed carcinogen* (only for hexavalent chromium). Chromium particles can irritate the eyes.
Vanadium	Exposure may irritate the eyes, nose, throat, and air passages.
Titanium	Flammable.
Zirconium	Flammable.
Potassium hydroxide	Corrosive.
Manganese	Human systemic effects by inhalation. Skin and eye irritant. Dust may be pyrophoric in air.
Hydrogen	Extremely flammable.

Source: Lewis 1992.

Shipping Requirements for Nickel Metal-Hydride Batteries

Introduction

This section examines the shipping regulations that govern the shipment of Ni-MH batteries. It is important to note that the transport regulatory processes examined are reviewed within the context of assessing the necessary steps needed to provide for the domestic and international transport of Ni-MH batteries. The need for such an assessment was determined by DOE upon the announcement of United States Advanced Battery Consortium (USABC) supported research toward the commercialization of Ni-MH batteries at OBC.

Domestic Requirements

The offering for transportation of hazardous materials within the United States—either for purely domestic transport or for international transport—is governed by the Department of Transportation (DOT) Hazardous Materials Regulations. These regulations are codified in Title 49 of the Code of Federal Regulations (49 CFR), Parts 100–179. Under these regulations, a hazardous material is defined as any "substance or material...which has been determined by the Secretary of Transportation to be capable of posing an unreasonable risk to health, safety, and property when transported in commerce...."

Before any chemical, device, (including any type of battery) or any other product may be offered for transport or be transported in the United States (either for purely domestic shipment or for international shipment), it must be determined that the material or device does not pose inherently unacceptable levels of risk in transport. Materials posing such risks are referred to as "forbidden" materials in the DOT regulations. Section 173.21 of the DOT regulations provides a qualitative description of the types of materials considered to pose such inherent risks in transport as to be forbidden from transport altogether. Included as forbidden materials are:

1. Electrical devices that are likely to create sparks or generate a dangerous quantity of heat, unless packaged in a manner that precludes such an occurrence; and

2. Packages that give off flammable gas or vapor, released from a material not otherwise considered a hazardous material (e.g., a flammable liquid), that is likely to create a flammable mixture with air in a transport vehicle.

Therefore, batteries posing such inherent risks (as packaged for transport) would be unacceptable for transport. Examples would include charged batteries in which short circuits could result in the generation of dangerous quantities of heat, unless packaged to prevent such an occurrence (such as by protecting terminals from short circuit) or batteries capable of evolving dangerous quantities of flammable gases. No quantitative criteria are provided in the regulations to define "dangerous" quantities of heat or gas, so it is necessary that a subjective judgment be made based on the packaging and manner in which the batteries are prepared for transport, and on the conditions likely to be encountered in transport.

Based on the information contained in the section on cell and battery safety, Ni-MH EV batteries may be designed to meet the two criteria listed above and thus would not be considered “forbidden materials”; however, it is the responsibility of the battery manufacturer to prove that these two criteria are met for a specific battery design.

Provided that a Ni-MH battery has been determined not to be a forbidden material, it is possible that, because of the nature of the "starved electrolyte" design, the battery will not only be permitted for transport, but will not be subject to the DOT regulations in transport. For such batteries in which the battery fluid is contained in the battery separators and electrodes, DOT provides regulatory relief if the battery meets the criteria of a “dry” battery (will not exhibit the release of any free liquid if the battery is ruptured or cracked). In a number of letters issued by DOT, a dry battery has been defined on the basis of the following criteria:

> If .... the batteries are of such a design that no flow of battery fluid would occur if the batteries were ruptured or cracked, and there is no free liquid, we would consider these batteries to be “dry" and, therefore, not subject to the (Hazardous Materials Regulations) HMR. (DOT 1988).

It is recommended, therefore, that testing be conducted on Ni-MH battery designs to determine if the dry criteria can be met. If the criteria cannot be met, or if the decision is made to ship Ni-MH batteries before the testing can take place, the following discussion further details the domestic regulatory requirements.

Part 172 of the regulations contains a hazardous materials table that lists materials that are considered to be hazardous in transportation. In addition to substances (liquids, solids, and gases), the table also lists a number of articles or devices (e.g., certain types of batteries) that contain hazardous materials and are, therefore, considered hazardous for purposes of transport. For each listed substance or article, the hazardous materials table provides a four-digit identification number (usually prefaced by the letters "UN") and indicates the hazard class and the required packaging, and provides other information such as required hazard labels and indications of whether, and in what quantities, the listed material may be transported aboard an aircraft.

Part 173 of the regulations defines the various "hazard classes" of materials. If a material meets the definition of one of these hazard classes, it is subject to regulation in transport—whether or not it is specifically listed by name in the hazardous materials table. For those materials meeting the definition of one or more of these hazard classes, but not specifically listed by name in the hazardous materials table, the table contains "generic" listings based on the hazards presented by the material in question (e.g., "corrosive liquid, n.o.s.,"[1] "flammable solid, n.o.s.," or "hydrides, metal, n.o.s.") that prescribe the regulatory requirements applicable to the transport of any material meeting the generic description.

With respect to the hazardous materials table in Part 172, one of the entries for articles listed is

Batteries, wet, filled with alkali, ***electric storage.***

The hazard class indicated for this entry is Class 8 (corrosive), and the identification number provided is UN 2795. In order to qualify for shipment under this entry, the regulations provide that the batteries concerned may contain no hazardous materials other than materials meeting the definition of Class 8. Because Ni-MH batteries contain a potassium hydroxide solution electrolyte—an alkali, corrosive (Class 8) liquid—these batteries are candidates for transport under the above entry. However, before it can be definitively established that it is appropriate to ship Ni-MH batteries according to the requirements applicable to this entry in the hazardous materials table, it must first be ascertained that the batteries contain no other substance classified as a hazardous material under the DOT regulations. In order to make this decision, it must be determined whether any of the component materials in the batteries are listed by name in the hazardous materials table and, if not, whether any of the component materials meet the definition of one of the DOT-regulated hazard classes as presented in Part 173 of the DOT regulations.

Certain materials that may be present in these batteries, for example titanium and zirconium powders, dry, are listed in the hazardous materials table and classed as Division 4.1 (flammable solids). However, indications are that when combined with other materials and converted into the physical form in which they are present in the batteries, and when surrounded by an electrolyte, these materials would not exhibit the characteristic hazards associated with Division 4.1. In addition, further indications are that these battery components do not meet the definition of any class of hazardous materials as prescribed in Part 173 of the DOT regulations when shipped as a completed battery, including electrolyte.

Based on these premises, according to the DOT definitions, the only hazardous material present in these batteries (when filled with an electrolyte) is the potassium hydroxide electrolyte. This being the case, the batteries would be eligible to be transported under the entry for **UN 2795 - "Batteries, wet, filled with alkali."** However, it is noted that in the event that a battery is to be shipped without an electrolyte, or if the individual components were shipped separately, it would be necessary to definitively determine that these components, in solid form, do not meet the definition of any class of hazardous materials under the DOT regulations. The applicable definitions and classification tests and criteria are presented in Part 173 of the DOT regulations.

The DOT provisions governing the transport of alkali-filled batteries establish two "categories" of batteries, and it is the category into which a particular battery design falls that establishes the specific transport requirements that apply. These two categories are termed "spillable batteries" and "nonspillable batteries."

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[1] The abbreviation "n.o.s." stands for "not otherwise specified." When a particular material meeting the definition of a hazardous material is not specifically listed by name in the hazardous materials table, the regulations applicable to the n.o.s. or generic entry in the table apply to the corresponding specific hazard class, packing group, and subsidiary hazard, if any, of the material.

Paragraph 173.159(d) of the DOT regulations presents the performance standards that are used to determine if a battery qualifies as nonspillable.

Under the provisions of 173.159(d), an alkali-filled battery is considered nonspillable if it is capable of withstanding the following two tests without leakage of battery fluid:

1. Vibration test. The battery must be rigidly clamped to the platform of a vibration machine, and a simple harmonic motion having an amplitude of 0.8 mm (0.03 inches), with a 1.6 mm (0.063 inches) maximum total excursion must be applied. The frequency must be varied at a rate of 1 Hz/minute between the limits of 10 to 55 Hz. The entire range of frequencies and return must be traversed in 95±5 minutes for each mounting position of the battery. The battery must be tested in three mutually perpendicular positions (to include testing with fill openings and vents, if any, in an inverted position) for equal time periods.

2. Pressure differential test. Following the vibration test, the battery must be stored for 6 hours at 24°C±4°C (75°F±7°F) while subjected to a pressure differential of at least 88 kPa (13 psi). The battery must be tested in three mutually perpendicular positions (to include testing with fill openings and vents, if any, in an inverted position) for at least 6 hours in each position.

A summary of the DOT requirements applicable to the transport of both nonspillable and spillable alkali-filled batteries follows.

Nonspillable Batteries. Batteries meeting the requirements for determination as nonspillable batteries **are not subject to any DOT transport requirements provided they are**

1. Protected against short circuits

2. Securely packaged.

Spillable Batteries. In contrast to nonspillable batteries, spillable batteries eligible to be shipped under the entry **"batteries, wet, filled with alkali, electric storage"** (UN 2795) must comply with the detailed requirements found in the regulations, (e.g., packaging, marking, shipping papers, labeling, etc.). For example, provision for packaging large, "industrial-type" batteries is provided in paragraph (c)(1) of 173.159. When packed without other materials:

> Electric storage batteries, protected against short circuits and firmly secured to skids or pallets capable of withstanding the shocks normally incident to transportation, are authorized for transportation by rail, highway or water. The height of the completed unit must not exceed 1.5 times the width of the skid or pallet. The unit must be capable of withstanding, without damage, a superimposed weight equal to two times the weight of the unit or, if the weight of the unit exceeds 907 kg (2000 pounds), a superimposed weight of 1814 kg (4000 pounds). Battery terminals must not be relied upon to support any part of the superimposed weight.

Note that the above packaging specifications for spillable batteries are not authorized for domestic transportation by aircraft. The largest battery authorized for transportation by passenger aircraft is 25 kg. For cargo-only aircraft, a battery packaged so that the gross weight of the package offered for transport does not exceed 400 kg is theoretically possible. However, in such case, the packaging (with the battery inside) would be required to meet UN Packaging Group III performance tests, and it is not certain that this level of packaging performance could be achieved with such a heavy battery. If UN performance tested packaging is not used, the largest battery permitted on a cargo-only aircraft is 34 kg (75 pounds). As a result of these packaging considerations, if it is necessary to transport Ni-MH batteries by aircraft, and they are determined to be spillable, a "DOT exemption" may be required.

The remainder of the DOT requirements applicable to the transport of spillable batteries are relatively straightforward, and are similar to those that apply to all hazardous materials. Packages containing the batteries, or, the batteries themselves, if transported "unpackaged" on pallets as described above, would be required to bear CORROSIVE labels and to be marked with the proper shipping name and UN number (i.e., **"UN 2795 batteries, wet, filled with alkali"**), as required by Subparts E and D, respectively, of the DOT regulations. Vehicles, rail cars, and freight containers in which batteries are transported would normally be required to bear "CORROSIVE" placards on each side and each end as required by Subpart F of the regulations. Battery shipments would have to be described and certified on a shipping paper in accordance with the requirements of Subpart C of Part 172, and the emergency response information requirements in Subpart G of Part 172 would apply. All employees involved with any aspect of the transportation of these hazardous materials must be trained as required by Subpart H of Part 172. In certain cases, persons offering such batteries for transport are required to register with DOT and pay a registration fee (annually) before batteries are offered.

DOT Shipping Classification for Ni-MH Batteries

If the batteries cannot meet the dry criteria, the requirements of DOT's hazardous materials regulations apply. It was determined that the only hazardous material in the Ni-MH batteries (when filled with an electrolyte) is the potassium hydroxide electrolyte itself. This conclusion was reached after assessing the battery constituents, the form in which they are present in the battery, and the effect of the electrolyte on the constituents. Although, in powder form, some of the hydride constituents (e.g., titanium and zirconium powders, dry) are considered to be hazardous under DOT regulations, indications are that when the constituents are combined, converted to a solid physical form, and contained in an electrolyte, they do not meet the definition of any of the hazardous materials classes prescribed in Part 173 nor are they listed as a combined substance in the hazardous materials table. However, it is noted that if a battery or battery components are to be shipped unassembled and void of the electrolyte, it is important that the solid materials in the battery be tested (according to the tests specified in DOT Regulations, Part 173) to definitively determine their status under the regulations as a combination of substances, in solid form.

Concerning determination of whether a battery is spillable or nonspillable, it is likely that Ni-MH battery designs will meet the nonspillable criteria because of their design characteristics. However, the nonspillable tests should be run and the determination made by the manufacturer before shipping under nonspillable provisions. And, because Ni-MH battery designs can vary, it is important to appropriately assess each design to ensure compliance with the nonspillability requirements.

In the near term, Ni-MH batteries could be shipped under the **batteries, wet, filled with alkali, *electric storage*** entry under the spillable requirements. Recommended work for the future includes testing to determine if the battery can be classified as dry, and if not, testing to determine nonspillable status.

International Requirements

The international requirements applicable to the transport of Ni-MH batteries by cargo vessel are promulgated by the International Maritime Organization (IMO), and those applicable to the international transport by air are promulgated by the International Civil Aviation Organization (ICAO). The IMO is a specialized agency of the United Nations concerned primarily with the promotion of safety in shipping and the prevention of marine pollution from ships. The IMO regulatory system for shipping hazardous materials is known as the International Maritime Dangerous Goods Code (or the IMDG Code) (IMO 1992). The ICAO promulgates rules for the safe transportation of hazardous materials by air and has established its own set of regulations, the ICAO Technical Instructions for the Safe Transport of Dangerous Goods by Air (ICAO 1993).

IMDG Code Provisions

With respect to transport by cargo vessel, the IMDG Code requirements are quite similar to the DOT requirements, except that no relief is provided based on the usage of a "starved electrolyte." Therefore, batteries must be shipped as "hazardous," containing electrolyte, subject to the IMDG Code requirements. The hazardous materials listing in the IMDG Code also contains the entry "BATTERIES, WET, FILLED WITH ALKALI, electric storage" (Class 8, UN 2795). Based on the premise that the only hazardous component of the batteries is the potassium hydroxide electrolyte, the batteries would be shipped according to the requirements applicable to this entry. The basic packaging and labeling requirements for alkali-filled batteries are found on IMDG Code page 8120.

Like the DOT regulations, the packaging requirements for alkali-filled batteries in the IMDG Code provide for the transport of large batteries. When batteries are packed in a wooden slatted crate, the IMDG Code prescribes no maximum gross weight limitation on the size of the battery. The marking, labeling, placarding, and shipping-paper requirements are the same as provided in the DOT regulations.

Also like the DOT regulations, the IMDG Code provides certain relaxations in the transport requirements for batteries that are determined to be nonspillable on the basis of successfully passing certain performance tests. However, the IMDG Code exceptions for such batteries are much less generous than the DOT exception for nonspillable batteries, generally only relieving the shipper of the requirement to label batteries and freight containers with the "CORROSIVE" label and placard, respectively. Such batteries must be transported under the listing **"BATTERIES, WET NON-SPILLABLE"** (UN 2800). The basic packaging and labeling requirements for these batteries may be found on IMDG Code page 8121.

IMO Shipping Classification for Ni-MH Batteries

Although the IMDG Code does not currently offer an exception for “dry” batteries, it is expected that the code will be updated on January 1, 1995, to do so. Thus, in 1995, providing that the batteries are not considered a forbidden material, they would be excepted from the IMDG Code if proven to be dry, and would need only be protected against short circuits and securely packaged if deemed to be nonspillable. In the meantime, batteries should be shipped under the spillable provisions until nonspillability can be determined.

ICAO Technical Instructions

The ICAO Technical Instructions, unlike the IMDG Code, contain the same exception for dry batteries as the DOT regulations; that is, "if the batteries are of such a design that no flow of battery fluid would occur if the battery were ruptured or cracked, and there is no free liquid," the batteries would be considered dry and not subject to the Technical Instructions when transported by air.

Furthermore, if future testing confirms that Ni-MH batteries are nonspillable, the ICAO Technical Instructions provide significant regulatory relief. The standards for determining if a battery is either dry or nonspillable are identical to those provided for in the DOT regulations. Nonspillable batteries, of any size, are permitted to be transported by both passenger and cargo aircraft when they are protected against short circuits and securely packed in strong outside packagings. Such “strong outside packagings” are not required to be tested and certified to UN performance standards. Packages containing nonspillable batteries must, however, be labeled and marked "CORROSIVE" and the shipment described and certified on a shipping paper, as required by the Technical Instructions.

The ICAO Technical Instructions also contain a listing for the entry **"BATTERIES, WET, FILLED WITH ALKALI, electric storage"** (Class 8, UN 2795). In the spillable battery category, the quantity limits on, and the required packagings for these batteries could pose a problem for shipping large Ni-MH batteries internationally by aircraft. In particular, as in the DOT regulations, the largest battery authorized for transportation by passenger aircraft is 25 kg and by cargo aircraft is 400 kg. The ICAO rules also require these batteries to be packaged in packaging tested and certified to UN Packing Group III performance standards, and, as indicated earlier, it is not certain that this level of packaging performance could be achieved with such a heavy battery. Unlike the DOT regulations, non-UN-tested-and-certified packaging is not permitted for any spillable battery—regardless of battery size.

Because of these packaging considerations, and because it is assumed that near-term shipping of Ni-MH batteries should take place under spillable provisions, an exemption may be required to enable large Ni-MH batteries to be transported internationally by aircraft. The exemption procedures in the ICAO Technical Instructions specify a cumbersome and lenthy process requiring that any such exemption be issued by all countries concerned with the shipment—including the countries of origin, destination, transit (if any), and overflight, as well as the country in which the aircraft carrying the shipment is registered.

ICAO Shipping Classification for Ni-MH Batteries

As with DOT, if the batteries cannot meet the dry criteria, the requirements of ICAO's Technical Instructions apply. However, if a Ni-MH battery is capable of meeting the requirements for a nonspillable battery, significant regulatory relief is available, and the need for an exemption due to weight and packaging constraints would be alleviated. As was mentioned previously, the weight and packaging constraints apply only in the spillable category.

Conclusions

If testing confirms that Ni-MH batteries are dry, or do not release any free liquid if the battery is ruptured or cracked, they would be excepted from DOT and ICAO regulation providing they are not considered to be forbidden materials. This same exception will also be instituted in the IMDG Code beginning January 1, 1995, after uniform dry criteria are incorporated into the IMDG Code.

If the batteries do not meet the dry criteria, then testing can take place to determine nonspillability. The tests to determine nonspillability are identical for DOT, ICAO, and IMO. Those tests include a vibration and pressure differential test, both of which are discussed in detail in this chapter under Domestic Requirements.

The following is a brief description of each agency's spillable and nonspillable regulatory requirements, including a discussion on the regulatory relief obtained in the nonspillable classification. In general, it is concluded that shipping of Ni-MH batteries should take place under spillable provisions until testing can take place to confirm either dry or nonspillable classification. If international air transport is anticipated, dry and/or nonspillable classification is particularly important because of the weight and packaging limitations in the spillable provisions.

DOT

If Ni-MH batteries meet the nonspillable criteria, they need only be protected against short circuits and securely packaged—no other regulatory requirements would apply. In contrast, if shipped under the spillable classification, detailed requirements on packaging, marking, shipping papers, labeling, and other considerations would apply.

ICAO

Nonspillable batteries, of any size, are permitted to be transported by both passenger and cargo aircraft when they are protected against short circuits and securely packed in strong outside packagings. Such "strong outside packagings" are not required to be tested and certified to UN performance standards. Packages containing nonspillable batteries must, however, be labeled and marked "CORROSIVE," and the shipment described and certified on a shipping paper, as required by the Technical Instructions.

In contrast, the ICAO Technical Instructions specify weight and packaging limitations on spillable batteries. These weight and packaging considerations could pose a problem for shipping large Ni-MH batteries internationally by aircraft because the largest battery authorized for transportation by passenger aircraft is 25 kg and by cargo aircraft is 400 kg. These size limitations could result in the need for an exemption, a lengthy and cumbersome process under the ICAO Technical Instructions. The ICAO rules also require that these batteries be packaged and certified to UN Packing Group III performance standards, which might be difficult to achieve with such a heavy battery.

IMO

Although the IMDG Code provides relaxations for nonspillable batteries, it generally only relieves the shipper of the requirement to label batteries and freight containers with the "CORROSIVE" label and placard, respectively. The IMDG Code packaging requirements for spillable batteries are detailed, but do provide for the shipment of large batteries without requiring UN packaging certification.

In-Vehicle Safety

Background

The issue of in-vehicle safety may be the single most important environmental, health, and safety concern for EVs from the standpoint of consumer acceptance. According to a *Business Week*/Harris poll, 99% of those surveyed rated safety as "very important" or "somewhat important" when deciding which car to buy (Treece et al. 1990). Inasmuch as public acceptance is a primary determinant of the commercial success of a new technology, the penetration of EVs into vehicle markets may be severely hindered by a perception (justified or not) that they are unsafe.

This section briefly reviews the safety concerns associated with EV use as identified by previous analyses and discusses the applicable regulations and standards.[1] In addition, the discussion presented here seeks to clarify issues that were previously identified as requiring further characterization (Mark 1992), such as

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[1] This analysis summarizes the discussion in a related report (Mark 1992) on the in-vehicle safety aspects of sodium-sulfur batteries for EVs where the issues are transferrable between the two different battery types. In addition, because there have been regulatory developments since the time the previous report was sent to press, this discussion updates some of the regulatory analysis provided in the earlier document.

crashworthiness and electrolyte spillage. While the primary focus of this report is to assess the safety issues of EVs operating on Ni-MH batteries, most of the hazards described in this in-vehicle safety section are generic to EVs and can be thought of as applicable to a wide range of battery types and designs. The only hazards identified as specific to Ni-MH batteries are those associated with the chemical composition of the batteries, discussed in the section on chemical hazards; all other hazards are EV-generic. As that section points out, the risks associated with the chemical hazards of Ni-MH batteries are small, and thus *EVs operating on Ni-MH batteries do not pose any significant, unique hazards when compared with EVs operating on other battery types.*

Potential Hazards and Applicable Regulations and Standards

Conventional internal combustion engine vehicles (ICEVs) have benefitted from years of development in which the hazards inherent in the storage and use of combustion fuels, as well as from vehicle operation, have been minimized. Vehicle developers will most certainly build upon this experience in designing EVs; however, there are several hazards unique to EV use that require further characterization. In specific, these unique hazards result from the use of high voltage battery and drive systems, the chemical hazards associated with some of the battery materials, operational differences that may result from battery use, and changes in vehicle mass or structure as a consequence of range-extension design efforts. Each of these issues is discussed in more detail in the following sections, along with a review of the regulations or standards that attempt to address these hazards.

With respect to regulations, the National Highway Traffic Safety Administration (NHTSA) under the U.S. Department of Transportation is responsible for all safety regulations of motor vehicles. Its role is to monitor adherence to the Federal Motor Vehicle Safety Standards (FMVSS), conduct safety investigations, and propose new standards when necessary. The FMVSS, published in 49 CFR Part 571, set minimum standards for motor vehicle safety performance and are intended to protect the public against unreasonable risk of crash occurrence and crashes resulting in death or serious injury.

Certification of compliance with the FMVSS must be provided by the manufacturer, and all vehicles sold must have a certification label verifying that the vehicle meets all FMVSS or listing the exemptions that the vehicle may have. NHTSA conducts surveillance testing of vehicles already on the market to monitor the auto manufacturers.

In December 1991, NHTSA issued an Advanced Notice of Proposed Rulemaking (ANPRM) regarding new and amended FMVSS that would apply to EVs. The purpose of the advanced notice (Docket 91-49, Notice 1) was to solicit comments on the issues identified in the ANPRM and opinions as to whether NHTSA should consider rulemaking to address these issues. A total of 46 organizations commented on the regulations, and, taking these responses under advisement, NHTSA has more recently published a Notice of Proposed Rulemaking (NPRM) stating the adjustments to the FMVSS that it plans to promulgate. In general, changes to the existing FMVSS under the NPRM (Docket 91-49, Notice 3) are minimal; however, the fact that NHTSA has decided not to regulate a number of unique issues posed by EVs does not reflect an opinion that EV-specific hazards do not exist, but rather that such issues need not be regulated at this point. These issues and the agency's conclusions were published in a general notice to the *Federal Register*, dated November 18, 1992 (Docket 91-49, Notice 2).

In addition to the regulations set forth by NHTSA, a handful of organizations are in the process of drafting standards or guidelines relevant to EV charging, maintenance, and operation.[1] In particular, the Society of Automotive Engineers (SAE) is currently sponsoring an EV Forum to investigate standards for several aspects of EV safety. Two major safety-related initiatives include subworking groups on high voltage vehicle wiring and on vehicle charging. Finally, the DOE-sponsored Ad Hoc EV Battery Readiness Working Group continues to support a subworking group on In-Vehicle Safety. The subworking group maintains a forum for discussing operational, maintenance, and charging safety issues; acts as both an industry and government advisory group; and addresses particular issues of interest to DOE and industry alike (e.g., the recent NHTSA regulatory activities). Because the activities of these (and other) organizations are still under way, no definitive standards or guidelines have been set to date; however, the following sections will attempt to discuss the current status of these activities as they apply to the specific hazards identified.

Electrical Hazards

The typical battery for traction applications operates at between 100 and 350 V, depending on the specific battery type and design (Brown and Hall 1982; Rowand 1992; EVP July 1, 1992; EVP June 15, 1992; EVP June 1, 1992; EVP May 1, 1992; and EVP February 1, 1992). In contrast with the typical 12-V battery used in an ICEV for starting, lighting, and other small electrical loads, this poses a potentially lethal shock hazard, particularly during charging and maintenance, and in the event of a severe collision. Preventive measures might include electrically isolating the batteries and motor from the conductive components of the vehicle (e.g., the chassis), installing tamper-proof covers on the batteries to limit exposure during nonskilled maintenance, providing a mechanism for disabling the drive power circuitry during routine maintenance, and ensuring that insulating and protective material surrounds high-voltage components.

At the present time, there are no regulations specifically governing the charging or maintenance of EVs nor are there specific rules regarding these activities. As discussed above, an SAE EV Forum is currently investigating charging issues and, together with the Electric Power Research Institute (EPRI), is authoring an article for the 1996 National Electrical Code (NEC) handbook regarding charging practices. The article will recommend procedures and practices for wiring, connectors, and location of chargers, in addition to considering garage ventilation requirements.

Chemical Hazards

During normal operation and charging, no exposure to the chemical compounds within the Ni-MH battery will occur,[2] and the chemical risks associated with high-energy crashes (such as electrolyte spillage or hydrogen evolution from overheating) are small.[3]

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1. There are many other organizations involved in investigating the technical, economic, and infrastructural issues related to EV usage; however, the majority of these are not currently considering establishing standards related to in-vehicle safety.
2. Because the potentially hazardous materials comprising Ni-MH batteries (e.g., nickel compounds) are contained in solid form, these substances pose no direct risks during in-vehicle use. In addition, because the Ni-MH cell design incorporates a "starved" electrolyte, there is little or no potential for electrolyte spillage as in the case of many other battery designs.
3. The chemical hazards associated with cell failure modes are discussed in detail in the section on cell and battery safety.

Although NHTSA considered the possibility of rulemaking to set standards for the release of battery materials from EVs, it has decided that regulatory action was not appropriate at this time; however, it reserves the right to consider regulations in the future pending further research (NHTSA 1992).

Operational Hazards

Performance

Although the majority of components in an EV are identical to those found in a conventional vehicle, the replacement of the internal combustion engine with an electric propulsion system effects a number of important mechanical and operational changes. The performance of EVs is a high priority for potential battery and vehicle manufacturers because it may be a key factor in consumer acceptance. EVs that are not capable of accelerating at the same rate as ICEVs or cannot obtain sufficient maximum speeds might present minor risks in certain traffic situations (e.g., merging onto a highway). However, there currently exists a wide range of performance within the conventional automobile fleet, and there is no indication that future EVs will be incapable of achieving levels within that range. In fact, the efforts on the part of General Motors to create a two-seater sport EV (the Impact) operating on lead-acid batteries are aiming for a design goal of a 0–60 mph (0–97 km/h) acceleration in 8 seconds (Vettraino 1991), demonstrating the potential for EVs to be designed to meet high performance criteria.

Typical batteries used for traction applications can weigh from 300–800 kg[1] (Rowand 1992; EVP July 1, 1992; EVP June 15, 1992; EVP January 15, 1992; EVP March 15, 1992; SAFT n.d.), which presents a unique weight management issue for vehicle designers. In EVs converted from ICEVs, the replacement of the conventional engine and transmission with an electrical system can alter the amount and distribution of weight in the vehicle, resulting in changes in maneuverability from a different center of mass, increased loading on the suspension system, and larger inertial forces. In addition, the increased weight of a conversion EV will increase the loading on the braking system, and sudden stops may require larger braking distances. Such crash avoidance problems have not been systematically addressed at this point because commercially available EVs have been able to meet the applicable safety standards. Where deemed necessary, innovative weight distribution techniques have been used in some vehicle designs (e.g., the use of large, flat battery trays to distribute battery weight, placement of the batteries over the wheels for enhanced traction, battery shock absorption systems). Manufacturers of dedicated EVs, who are designing vehicles from the ground up, will have much more latitude in constructing vehicles that effectively address such crash avoidance problems.

Braking

To extend the range of EV operation, most vehicle designs are expected to incorporate regenerative braking. In such a system, the mechanical braking energy is converted into electricity by running the motor as a generator to partially recharge the battery (in other words, the vehicle wheels are now driving the motor). This increases the charge of the battery and is similar to transmission braking experienced in an ICEV, in which the drive system is also used to slow the vehicle. Regenerative braking is capable of providing large amounts of braking energy, limited only by the rate of battery recharge (the higher the recharge rate, the greater the braking effect).

Theoretically, it is possible to operate an EV over most driving cycles almost entirely with regenerative braking; however, the effect of regenerative braking is minimal at lower speeds (the lower limit at which

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[1] These are values reported in the literature for existing and near-term batteries, and they strongly depend on the type and design of the battery and vehicle. Advanced batteries are expected to reside at the lower end of this range, if not below.

regenerative braking is no longer effective varies from vehicle to vehicle, with estimates ranging from 3–25 mph (5–40 km/h) (Mark 1992). In addition, if the vehicle's batteries are fully charged, regeneration does not occur, although this situation will be particularly rare because a portion of the batteries' energy must always be expended in order to get the vehicle moving in the first place. In these cases, and in sudden stops when the requisite braking energy is high, regenerative braking will probably need to be supplemented with a conventional service brake system. In addition, it is not clear at this early date in vehicle design how powerful an effect standard regenerative braking will be or whether conventional service brakes will also need to be deployed during normal stops (as well as during the unique situations outlined above). In any event, use of regenerative braking should not involve any undue safety hazards.

In addition to the use of regeneration, EV braking systems may vary from those on conventional vehicles because many service brake systems may be electrically activated. It is therefore possible that loss of electrical power due to low battery charge or electrical malfunction might affect the ability to slow or stop the vehicle. Current FMVSS and related testing procedures on braking requirements include verbiage on transmission braking effects and hydraulic brake systems that do not encompass the use of regenerative braking and electric brake systems. NHTSA has issued a Supplementary Notice for Proposed Rulemaking (SNPRM) stating supplemental rules for a new standard proposed in 1991, FMVSS No. 135: Passenger Car Brake Systems, which has yet to be finalized. The SNPRM (Docket 85-06, Notice 7) discusses EV braking systems and how they might be covered under the new regulation. The majority of the supplementary proposed rules relate to definitions and adjustments to testing procedures outlined in the NPRM for conventional vehicles. In general, no matter what braking system configuration is used (regenerative, electrical, and/or hydraulic), EVs will be expected to comply with the regulations already proposed under Standard No. 135 under all operating conditions, including both fully charged and nearly depleted batteries.

Crashworthiness

Crashworthiness is a paramount issue for consumers when it comes to vehicle safety, and considerable attention continues to be devoted in the automotive industry to the hazards associated with vehicle collisions. Although EVs are expected to perform similarly to conventional vehicles, the use of batteries for energy storage presents three unique issues of importance to EV designers with respect to crashworthiness: (1) battery movement, (2) increased weight of EVs converted from ICEVs, and (3) changes in mass or structure in dedicated EV designs.

Battery Movement

Because typical batteries can weigh from 300–800 kg, EVs will require a substantial retaining structure to ensure that the batteries do not break free and become mobile during a crash. Tests of early retrofitted EVs indicated that battery tie-downs were not always adequate because some batteries in the vehicles tested by NHTSA in the early 1980s were able to break free during the crash test (Peirce 1981). This presents a considerable hazard not only to the occupants of the crashed vehicle but also to passengers of other vehicles and to pedestrians in the surrounding area. Although some early model conversion vehicles did not perform adequately in retaining their battery packs, these were in the minority. This issue does not present a significant problem for vehicle designers today as long as adequate controls over battery movement are employed.[1]

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1. Batteries do not necessarily have to be stationary during a crash. In fact, a controlled "direction" of battery movement during a crash might be determined to be an effective crash energy management technique.

Crash Energy Management

There are two primary risks to the safety of occupants involved in a high energy crash: (1) collision of the occupant with the interior of the vehicle (e.g., the windshield, steering column, dashboard) and (2) deformation of the vehicle such that severe encroachment of the passenger compartment occurs. The first risk is primarily mitigated through the restraint system (seat belts, air bags) and passenger compartment design (padding, larger distances between occupants and major interior structures) and will not be discussed in this report because it is not unique to EVs. On the other hand, the mass and structural changes expected for EVs do present unique crash energy management issues with relation to the second risk, vehicle deformation.

Because crashworthiness is a major focus of vehicle manufacturers, design techniques used to reduce the risks from crashes have become quite sophisticated over the last few decades. This section does not attempt to survey all of the available crash energy management methods but rather offers a simplistic view of crashworthiness to highlight the potential differences in vehicle safety design and performance that might result from changes in mass and/or structure in EVs.

In a high speed collision involving a fixed object or another vehicle, large amounts of kinetic energy must be absorbed by one or more of the objects. In the case of a collision with a fixed object, such as a wall, the majority of the crash energy will be absorbed by the vehicle itself. This is accomplished through deformation of the vehicle structure, and a stiffer vehicle structure will be associated with less overall deformation and therefore less risk to the occupant compartment, while less stiffness will increase the amount of deformation required to absorb the crash energy. Increased stiffness can be achieved through adding support structures to the vehicle (beams, barriers, etc.) or through the use of more resilient materials, as discussed further below. It is important to recognize, however, that stiffness is only one element in an integrated crashworthiness design, and many other factors impact the safety of the vehicle. For example, although deformation can result in intrusion of the occupant compartment, it also plays a positive role in absorbing crash energy, thereby reducing the deceleration rate experienced by the occupants. Increasing stiffness as a stand-alone design technique[1] would therefore reduce the absorption benefits of the vehicle materials and trade a decrease in the overall deformation (i.e., protection of the occupant compartment) for an increase in the occupant deceleration rate (resulting in greater speeds of impact with the vehicle interior).

Converted Vehicles

The majority of EVs operating today and in the near-term are expected to be conventional vehicles that have been retrofitted with an electric drive train and battery storage system. The replacement of the internal combustion engine with the electric system usually increases the weight of the vehicle by at least 10% (NHTSA 1993), primarily as a result of the batteries. A higher mass means that the EV will have greater kinetic energy than an ICEV operating at the same speed. This increased kinetic energy, if absorbed by a vehicle with the same structural stiffness as before conversion, will result in an increased deformation of the vehicle structure.

Currently, vehicles must meet FMVSS Nos. 204 and 208, which set standards for maximum rearward displacement of the steering column, as well as limits on the impact to the head, thorax, and legs of test dummies during a 30 mph (48 km/h) rigid barrier crash test. Commercially available EVs will also be required to comply with the standards, and test data on early model conversion vehicles indicate that this will be possible, oftentimes without any structural changes made to the vehicle (Peirce 1981). In some cases, however, compliance with the federal standards may require that the vehicle be reinforced or slightly

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[1] i.e., without any modifications to the passenger restraint system or occupant compartment design.

redesigned. Enhancement of the front-end structure through reinforcement beams or barriers has been used in some designs (Rosenkrands, Singh and Harmahendar 1980), while innovative shock absorption units for the increased battery mass have been used in others (Palvoelgyi and Stangl 1990). In either case, achieving adequate crash energy management through additional structures will generally increase the weight of the vehicle even further, although newer materials may be able to play an important role in low-weight structural additions.

Dedicated Vehicles

EVs designed from the ground up will most likely be optimized such that the maximum amount of range can reasonably be achieved from the battery pack. This will require a number of energy saving measures, such as regenerative braking, aerodynamic design, and low resistance tires. Perhaps most important for reducing the load on the battery system will be an overall vehicle weight reduction. Using traditional materials and conventional vehicle structures, weight reduction could mean decreased structural strength for the vehicle and might result in decreased crashworthiness. Instead, EV designers have been focusing on newer materials, such as composites or aluminum, to achieve the desired structural integrity while reducing vehicle weight.

In addition to structural integrity, dedicated EVs that are designed to be lightweight for performance considerations will have a disadvantage in collisions with heavier vehicles on the road.[1] This is explained by the lower "mass aggressiveness" of the lighter vehicle. Two vehicles of the same mass and driving at equal speeds will essentially stop one another in a head-on collision because their momentums are identical; however, a head-on collision of a 500-kg car and a 1200-kg car, both traveling 50 km/h, will result in both cars moving in the direction of the heavier car at a speed of 20.6 km/h following the crash. Thus, the resultant velocity change, a major parameter in determining the severity of injury to the vehicle occupants, is only 29.4 km/h for the heavier ("mass aggressive") vehicle and 70.6 km/h for the lighter vehicle (Kaeser 1992). From the standpoint of the occupants in the heavier vehicle, this is a benefit; however, the opposite is true for the occupants of the vehicle with lower mass aggressiveness.

In addition to the relative masses of the vehicles, the relative stiffness of the vehicle structures is important in a vehicle-to-vehicle collision. If the smaller vehicle is more resilient than the heavier vehicle and does not deform as easily, the larger vehicle will absorb some of the energy of the crash through deformation, and the resultant deleterious impact on the lighter vehicle will not be as great. Should the opposite hold true, i.e. the lighter vehicle deforms more readily than the heavier, then the overall effect of the crash on the lighter vehicle will be large. This presents unique problems for a vehicle fleet in which a mix of large and small vehicles exists, particularly if the larger vehicles begin to be designed to be more resilient to deformation for increased safety. Certainly, a wide range of mass and structural stiffness already exists in the vehicle fleet, and it is not clear at this time if future low mass EVs will fall within these ranges or be of even lighter weight than most existing vehicles. What does appear to be important, however, is that low mass EVs are structurally resilient enough to provide adequate crash protection in collisions with fixed barriers as well as with other vehicles.

There are limited published crash data on late model dedicated EVs; however, the available literature suggests that crashworthiness standards can be met through a combination of structural reinforcement techniques and occupant restraint systems. One vehicle that has been recently designed and demonstrated in Europe is the Horlacher, a small two-seater prototype commuter vehicle, developed by a Swiss company of the same name, that incorporates a hollow fiberglass composite beam structure called an "impact belt." The impact belt is built into the structure at bumper level around the circumference of the vehicle and

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[1] Although not discussed here, this is also true for lightweight conventional vehicles.

provides a low weight, stiff barrier to protect against impacts. Testing of the vehicle indicated very low overall deformation when compared with other dedicated EV designs (Kaeser 1992). This, of course, is only one vehicle design, and EV designers will undoubtedly continue to develop alternatives that effectively manage crash energy and provide acceptable levels of safety in the future.

Conclusions

This chapter sets the stage for identifying the challenges facing battery manufacturers (electrical and chemical hazards) and vehicle designers (electrical and operational hazards, crashworthiness). As stated earlier, the majority of these issues relate to the entire family of EVs, and EVs operating on Ni-MH batteries should not present significant hazards different from EVs operating on other battery types. In addition, this section concludes that the generic hazards identified for all EVs, namely electrical hazards, operational hazards, and crashworthiness, should not pose undue risks given that the appropriate safety standards are met.

Part II - Environmental Issues for Ni-MH EV Batteries

Introduction

Environmental impacts can occur in the different phases of a Ni-MH EV battery life cycle. Life-cycle processes for Ni-MH EV batteries include mining, milling, smelting, and refining of metallic materials for electrode components, manufacturing of inorganic chemicals and other materials for electrolytes and other hardware components, battery assembly processes, operation and maintenance of batteries, and recycling and disposal of used batteries. The main emphasis in this section is on the recycling and disposal of spent batteries because this has been identified by environmental regulatory agencies as the life-cycle phase for which environmental impacts are the greatest. However, a brief discussion is first presented on the regulatory requirements for Ni-MH EV battery manufacturing.

Ni-MH Battery Manufacturing Processes

Background

The manufacturing of Ni-MH EV batteries will result in air, solid waste, and liquid waste emissions. These emissions are briefly discussed in this section, and the applicable EPA regulations that govern these emissions are identified. Because no large-scale Ni-MH EV battery manufacturing plants exist, no specific information on plant emissions is available. Air emissions are regulated by the EPA under the Clean Air Act, which was amended in 1990 to include a list of 189 hazardous air pollutants. Solid waste, as described further in the section on recycling, is regulated by the EPA under the Resource Conservation and Recovery Act (RCRA). Finally, liquid effluent emissions are regulated by the EPA under the Clean Water Act. These regulations are briefly described below.

Regulations Affecting Ni-MH EV Battery Manufacturing

Clean Air Act

Title III of the Clean Air Act Amendments (CAAA) of 1990 includes a list of 189 hazardous air pollutants for which emissions must be reduced. Included among this list are three compounds that may be contained in Ni-MH EV batteries: nickel compounds, chromium compounds, and manganese compounds. However, Title III of the CAAA only regulates these pollutants for "major sources." A major source is defined as a source that emits more than 10 tons per year (tpy) (9.1 metric tonnes) or more of any hazardous pollutant (i.e., one of the 189 regulated pollutants), or 25 tpy (22.7 metric tonnes) or more of any combination of regulated hazardous air pollutants. Other criteria exist for defining major sources, but they would not apply to Ni-MH EV battery manufacturers. Because no non-lead-acid battery manufacturers are currently considered "major sources," it is unlikely that Ni-MH EV battery manufacturers would emit any of the three hazardous air pollutants, mentioned previously, above the 10 tpy (9.1 metric tonnes) and 25 tpy (22.7 metric tonnes) thresholds; therefore, Ni-MH EV battery manufacturers would probably not be considered major sources under Title III of the CAAA.

Under the CAAA, EPA has established *categories of sources* of hazardous air pollutants. The categories are for specific industries (e.g., petroleum and natural gas production and refining) and for specific processes (e.g., surface coating processes); they are sources for which EPA intends to promulgate regulations in the next 10 years. Lead-acid battery manufacturing is the only battery manufacturing process listed (U.S. EPA November 1990).

Clean Water Act

Regulations promulgated by EPA under the Clean Water Act are somewhat similar to those under the CAAA. Categorical industries are identified by EPA regulations for which categorical local limits exist for pollutant discharges into sewer systems. Ni-Cd battery manufacturing is not listed as a categorical industry, and because Ni-MH batteries are considered less toxic than Ni-Cd batteries, it is doubtful that Ni-MH EV battery manufacturing would fall under this jurisdiction.

Resource Conservation and Recovery Act

Manufacturing plants of Ni-MH EV batteries would have to comply with all regulations for the disposal of wastes defined as hazardous under RCRA. EPA regulations under RCRA are described further in the next section on recycling and disposal, as well as in Appendix C. Disposal of hazardous wastes from Ni-MH EV battery manufacturing would not require any special permits because, with the exception of the potassium hydroxide, none of the constituents in a Ni-MH EV battery are considered hazardous under RCRA. Any excess potassium hydroxide could be used in the facility to neutralize wastewater and hence would not be significant from a hazardous waste standpoint.

Recycling of Ni-MH Batteries

Background

Recycling and disposal of spent Ni-MH batteries are important issues that must be addressed as part of the commercialization process of Ni-MH batteries. The use of Ni-MH batteries in EVs will result in significant environmental benefits, such as improvements in air quality, and the disposal of spent batteries should not detract from those benefits. The only hazardous material in a Ni-MH battery, as defined by EPA regulations governing waste disposal, is the corrosive potassium-hydroxide-based solution comprising the electrolyte. Although it would be legal to remove the electrolyte from Ni-MH batteries and then dispose of the battery in a landfill, this practice is not encouraged for two reasons: (1) environmental considerations encourage recycling wastes and (2) valuable metals can be recovered and therefore conserved by recycling or reclaiming Ni-MH batteries.

In addition to environmental considerations, a main reason for recycling Ni-MH EV batteries is economics. To meet the USABC cost goal of $150/kWh, valuable metals from spent Ni-MH EV batteries should be recycled to battery grade materials and reused by battery manufacturers or sold at the market price. Although disposal, as well as recycling, of Ni-MH EV batteries is discussed in this section, recycling of Ni-MH EV batteries will probably be a requirement for economic reasons (Butler 1993); however, disposal of Ni-MH EV batteries may be an option during the initial phase of Ni-MH EV battery commercialization when there are fewer batteries for disposal. It should be noted that not all constituents of a battery will necessarily be recycled (e.g., battery insulation), and the emphasis in this section is on the recycling of metals contained within a Ni-MH EV battery.

This section on recycling of Ni-MH batteries discusses EPA standards for the disposal, recycling, or reclamation of Ni-MH battery constituents. Test data for Ni-MH batteries are presented that demonstrate that Ni-MH batteries are not considered a hazardous waste under EPA regulations, although they would be considered a hazardous waste in California because of stricter regulations implemented on the state level. Existing battery recycling processes are discussed, as well as the permitting requirements for battery recycling facilities. Finally, potential recycling options for Ni-MH batteries are reviewed, and future information needs for the development of Ni-MH recycling processes are identified.

Regulations for Determining the Hazardous Classification of Ni-MH Battery Products

A heightened awareness of environmental concerns has resulted in an increased interest in how wastes are disposed. Under existing EPA regulations, hazardous wastes cannot be disposed of in landfills. Recycling or reclamation of wastes (hereafter, the term recycling includes reclamation), as opposed to disposal, is a primary objective of the EPA; hence, the recyclability of new products is always an important consideration.

Solid waste disposal in the United States is regulated under RCRA, and it is the responsibility of the EPA to develop regulations to carry out and enforce RCRA. The primary objectives of RCRA are to protect human health and the environment and to conserve valuable material and resources (Haney and Casler 1990). Previous analyses have examined the impact of RCRA on EV battery recycling (Corbus 1992a). Appendix C presents an overview of RCRA regulations pertaining to the recycling of EV batteries.

EPA defines a waste as hazardous if it exhibits any of the following characteristics: ignitability, reactivity, corrosivity, and toxicity (see Appendix C for definitions). Toxicity is a particularly important hazardous waste characteristic because, unlike the other three hazardous characteristics that can often be removed from a waste through specific treatment processes (e.g., neutralizing corrosive wastes), toxic materials are always considered hazardous if they are above certain EPA standards. Toxic materials can be removed from a waste, whereby the remaining waste can be rendered nonhazardous, but the toxic materials themselves are still considered hazardous. These toxic materials can be recycled, as is done with lead-acid batteries, and to a lesser extent with Ni-Cd batteries.

The disposal of batteries that contain hazardous wastes is difficult because of EPA regulations that ban hazardous waste land disposal (U.S. EPA June 1990a). These regulations require that all hazardous wastes containing toxic metals be treated to EPA leachate levels before disposal. Table 5 lists the main contaminants regulated *for toxicity* by the EPA that may be found in different types of batteries. The concentrations listed are the maximum concentrations allowable in a waste before it is considered hazardous by the EPA.

Table 5. EPA Hazardous Waste Limits for Toxic Wastes[a]

Contaminant	Maximum concentration (mg/L)
Arsenic	5.0
Cadmium	1.0
Chromium	5.0
Lead	5.0
Mercury	0.2
Silver	5.0

[a] EPA has promulgated standards for other toxic contaminants but they are not listed here because they are not found in batteries.

An EPA test procedure known as the toxicity characteristic leaching procedure (TCLP) is used to determine the leachability of materials (e.g., metals) from a waste; wastes that leach metals at or above the concentrations listed in Table 5 are considered hazardous by the EPA. The TCLP test is used as an indication of the amount of toxic metals that could leach out under conditions similar to those found in a landfill. (See Appendix C for more information on the TCLP test.)

Nontoxic hazardous wastes, such as corrosive wastes, may be specifically listed by name as a hazardous waste by the EPA or may be determined to be hazardous by various EPA rules or test methods. For example, an aqueous waste that has a pH less than or equal to 2 or greater than or equal to 12.5 is considered a corrosive waste.

There is a provision in RCRA that allows individual states to pass regulations that are stricter than those adopted by the EPA. Within California, hazardous waste is defined in Health and Safety Code Sections 25117 et seq. and in Chapter 11, Division 4.5, Title 22, California Code of Regulations. California has different and more strict requirements than the TCLP test; the regulations used to determine toxicity in California are called the Waste Extraction Test (WET) regulations. The WET regulations contain standards for nickel as follows: soluble threshold limit concentration of 20 mg/L; and total threshold limit concentration of 2000 mg/kg. In contrast to California nickel regulations, the European Community (EC) hazardous waste regulations also include a hazardous waste standard for nickel of 2 mg/L.

Hazardous Classification of Ni-MH Battery Products

To date, TCLP testing has been conducted for two different types of AB_2 alloys (Knoll et al 1990). These tests were carried out by Teledyne Wah Chang Company, a major metals supplier located in the United States. The following alloys were tested (compositions in weight percent): composition 1—40.9 vanadium (V), 20.5 nickel (Ni), 20.2 zirconium (Zr), 9.0 chromium (Cr), 8.4 titanium (Ti), and 1.0 manganese (Mn); composition 2—22.7 V, 35.9 Ni, 25.4 Zr, and 16.0 Ti (Knoll et al. 1991). These specific compositions are not necessarily the same as those that would be used in EV Ni-MH cells, but they are close enough to give a good indication of whether current AB_2-type alloys, such as the one being developed by OBC for Ni-MH EVs, would pass the TCLP test. These compositions were selected to cover most of the wide range of possible nickel and vanadium levels and to include typical chromium and manganese levels (Knoll et al. 1991).

Before TCLP testing, batteries were crushed and screened to less than 325 mesh. To simulate the effect of incineration, samples were oxidized by heating in air at 535^{0} C for 2 hours. The resultant samples, from both cycled (i.e., used) and uncycled (i.e., new) batteries, were subject to the TCLP; the test results are shown in Table 6 (Knoll et al. 1991). Table 7 compares the TCLP test results for cadmium, chromium, and nickel with EPA, California, and EC environmental regulations.

The results of the TCLP tests for Ni-MH AB_2- type batteries show that all metals leach at concentrations below EPA standards. Except for nickel and copper, cycled batteries showed higher concentrations than uncycled batteries. All concentrations were below EPA hazardous waste limits. However, nickel concentrations for Ni-MH batteries are above the standards set by California and by the EC; hence, spent Ni-MH batteries would be considered hazardous wastes in California and Europe.

Table 6. Leachability of Metals from AB_2 -Type Batteries (All TCLP results are reported in mg/L)

Metals	Cycled	Uncycled	Uncycled/Oxidized
Cadmium	0.078	>0.010	>0.010
Chromium	0.230	0.09	1.0
Copper	48	79	22
Iron	530	210	210
Manganese	1.94	1.2	1.09
Nickel	320	590	320
Vanadium	>0.05	>0.05	52
Zinc	>0.02	>0.02	0.17
Mercury	>0.002	>0.002	>0.002

Table 7. Comparison of TCLP Test Results for Ni-MH Batteries with EPA and European Community Regulations (All TCLP results are reported in mg/L)

Metals	Ni-MH[a]	EPA Standard	EC Standard[b]	California Regulations[c]
Cadmium	>0.01–0.08	1.0	0.5	1.0
Chromium	0.09–0.23	5.0	0.5	5.0
Nickel	320.0–590.0	None	2.0	20.0

[a] Results are reported for AB_2 alloys that contain small amounts of cadmium; it should be noted that Ovonic Battery Company alloys will not contain any cadmium.

[b] European Community Hazardous Waste Limit.

[c] California regulations use a different test to determine toxicity that is more stringent than the TCLP test.

Source: Knoll et al. 1992.

Permitting Requirements for Ni-MH Battery Recycling Facilities

Because Ni-MH batteries do not contain any *toxic* hazardous wastes as defined under RCRA regulations, they could be disposed of in a landfill after their corrosive electrolyte was removed. Disposal of Ni-MH batteries should not require a RCRA permit for the *treatment and disposal* of hazardous wastes because the corrosive electrolyte could be reused in the plant (e.g., to neutralize wastewater) and hence, it could be recycled or reused. Recycling Ni-MH batteries should not require a RCRA *treatment and disposal* permit either. However, recycling or disposal of Ni-MH EV batteries may require a RCRA *storage* permit because batteries would have to be stored before being recycled or disposed. A RCRA storage permit is much easier to obtain that a RCRA treatment and disposal permit. Because RCRA treatment and disposal permits are costly and time consuming to obtain (up to five years in some cases), not having to obtain a RCRA treatment and disposal permit would greatly facilitate Ni-MH EV battery recycling.

Recycling of Ni-MH Batteries

The preferred method for Ni-MH battery disposal is recycling. The main reasons for recycling spent Ni-MH batteries are economics, environmental protection, and conservation. However, basic conditions must be met in order for recycling to be economical, environmentally safe, and practical. These conditions include (1) sufficient quantity of spent batteries for recycling, (2) high enough concentration of recyclable materials so that they can be reused/reclaimed, (3) a market for the recovered materials, and (4) availability of a treatment process with justifiable energy requirements and low environmental impacts (e.g., low emissions and process residues). It will be important to evaluate the development of Ni-MH battery treatment processes according to the previous conditions.

The first two conditions for recycling feasibility stated previously would be affected by the number of Ni-MH EVs deployed and by the cycle life of the battery. Because the cycle life of a Ni-MH EV battery is estimated to be relatively long, the generation of spent Ni-MH EV batteries and hence, of recyclable materials, would be lower than for a different EV battery with a shorter cycle life and the same EV deployment.

Of primary importance in the recycling of Ni-MH batteries is the separation of some of the valuable strategic metals that are contained in the battery. For example, the alloys used in the hydride can contain significant percentages of costly or strategic metals such as vanadium, zirconium, and chromium, plus less costly metals such as nickel, iron, titanium, or manganese. The market price for recycled Ni-MH metals will vary, hence, different markets for Ni-MH recycle products should be evaluated and the price sensitivities of those markets investigated.

Existing Recycling Facilities

The majority of battery recycling plants are for lead-acid batteries because of the large volume of lead-acid batteries that are collected and available for recycling. There are very few facilities presently available for recycling batteries other than lead-acid batteries. No facilities currently exist for recycling Ni-MH batteries. Existing recycling processes for non-lead-acid batteries are just beginning to be commercialized, and they are not designed to recover the individual metals contained in Ni-MH batteries. For example, whereas some Ni-Cd battery recycling processes may be partially applicable to recycling Ni-MH batteries, none of these processes recycles all the individual metals of the Ni-MH battery. However, existing processes that do not result in the recycle of all the individual metals in a Ni-MH EV battery may be appropriate during the early phase of commercialization, and some processes might have the potential to recycle all of the individual Ni-MH metals with some given modifications to the process. Some of the non-lead-acid battery recycling facilities are described here.

INMETCO, an existing pyrometallurgical plant in the United States, uses high-temperature metal recovery (HTMR) (Onuska Jr. 1991) to recycle various non-lead-acid batteries and is currently evaluating this process for the recycling of Ni-MH batteries. EPA suggests HTMR as a treatment for the disposal of cadmium-containing batteries (U.S. EPA June 1990b). The process basically consists of the following: (1) feed preparation that includes shredding the batteries and washing to remove the electrolyte, (2) partial reduction of metal oxides in a rotary hearth furnace operated at 1260°C, and (3) melting and final reduction in a smelting furnace operated at 1400° to 1600°C. Of the metals associated with a Ni-MH battery, it appears that nickel, iron, vanadium, chromium, and manganese could be recovered in small ingots and sold to iron-based producers (Knoll et al. 1991). Other metals, such as zirconium and titanium, would be contained in the nonhazardous slag produced by the HTMR process; the slag could be used as fill for road base or other similar uses. The drawback to this process is that the metals would not be recovered in their original form, so the recycled products would not be worth as much, and primary metals would not be conserved.

It appears that a plant in Switzerland, operated by a company called Recymet, could also recycle/reclaim Ni-MH batteries. The process basically consists of the following steps: (1) pyrolysis at 550°C followed by condensation of mercury, (2) shredding and washing to remove manganese, zinc, and graphite, (3) magnetic-induction separation to remove iron and graphite, and (4) electrolysis to separate the remaining metals (Antenen and Burri 1992). This process could accept Ni-MH batteries, but modifications would be needed to reclaim some of the metals such as vanadium, zirconium, titanium, and chromium. As with the first recycling process described previously, the drawback to this process is that valuable or strategic metals are not recovered in their primary form (e.g., vanadium and zirconium). Hence, these metals would not be conserved, and the recycled product would be worth less than if the metals were recycled individually.

There are other recycling/reclamation facilities for non-lead-acid batteries in France (SAVAM) and Sweden (SAFT NIFE) that are starting to recycle non-lead-acid batteries; some of these might be able to accept Ni-MH batteries. However, like the two processes described previously, they presently are not equipped to recycle the different primary metals contained in Ni-MH batteries.

To date, none of the recycling plants for non-lead-acid primary batteries have done well economically. A significant factor has been a low collection rate for primary (e.g., consumer) batteries. The economics of recycling batteries is based on a number of different factors, including the price of the metals being recovered, and these prices fluctuate. For example, secondary lead smelters that reclaim lead from lead-acid car batteries are heavily affected by price fluctuations for lead. Recycling facilities benefit from an "economy of scale" in terms of the number of batteries being recycled; in other words, more batteries for recycling often translates into better economics. As the market penetration of Ni-MH batteries increases, the economic feasibility for a dedicated Ni-MH recycling facility will improve. However, the market penetration of Ni-MH EV batteries will have to be large before there are enough batteries to economically justify a dedicated Ni-MH recycling facility. Whereas consumer battery recycling has not been able to recycle a very large percentage of the total batteries available for recycle in the United States, EV battery recycling, including Ni-MH EV battery recycling, should recycle a high percentage of the total batteries available for recycle because of the special handling requirements needed for EV batteries (i.e., their size reduces the risk of mismanagement) and because of differences in the regulatory requirements for handling of the batteries (some states do not mandate that consumer batteries be recycled).

Depending on the economics, it is envisioned that the first Ni-MH EV batteries would either be recycled in existing non-lead-acid battery recycling plants (e.g., Ni-Cd facilities) or merely disposed of in a landfill (if there were no economic incentives to recycle these batteries). As more Ni-MH EV batteries became available for recycling, the economics of Ni-MH battery recycling could justify dedicated Ni-MH recycling plants. Because consumer Ni-MH batteries probably could be recycled with Ni-MH EV batteries, the market penetration of consumer Ni-MH batteries could help the overall economics of Ni-MH EV battery recycling.

The question of who pays for recycling a Ni-MH EV battery is important because the costs are usually significant. The costs of consumer battery recycling in Switzerland are passed on to the consumer through a preliminary disposal fee (Antenen and Burri 1992). The fee is clearly indicated on the battery and varies with the weight of the battery; fees are usually about 10% of the purchase price of a battery. The collected fees are transferred by the retailers to a nonprofit organization founded by Swiss battery manufacturers and retailers, who contract recycling to battery recycling companies that have a fixed price for recycling based on the weight of the batteries. Thus, all companies and groups that collect used batteries can send them to recycling companies without paying for the recycling. Figure 3 shows a schematic of the Swiss battery recycling setup. This type of arrangement should be evaluated for Ni-MH EV battery recycling.

Because battery recycling and disposal costs can be a significant part of the total cost of a Ni-MH EV battery, it will be important to estimate these costs in the near future and to study different mechanisms for financing them.

Potential Recycling Options for Ni-MH Batteries

Because the metals contained in a Ni-MH battery have a wide range of melting and boiling points, their recovery through various pyrometallurgical processes should be evaluated. Chemical processes, such as a nickel extractive metallurgy technology (e.g., solvent extraction/ion exchange, acidic or alkali leaching followed by electrowinning) may also be applicable to Ni-MH battery recycling. Whether these types of processes can be done economically remains to be evaluated.

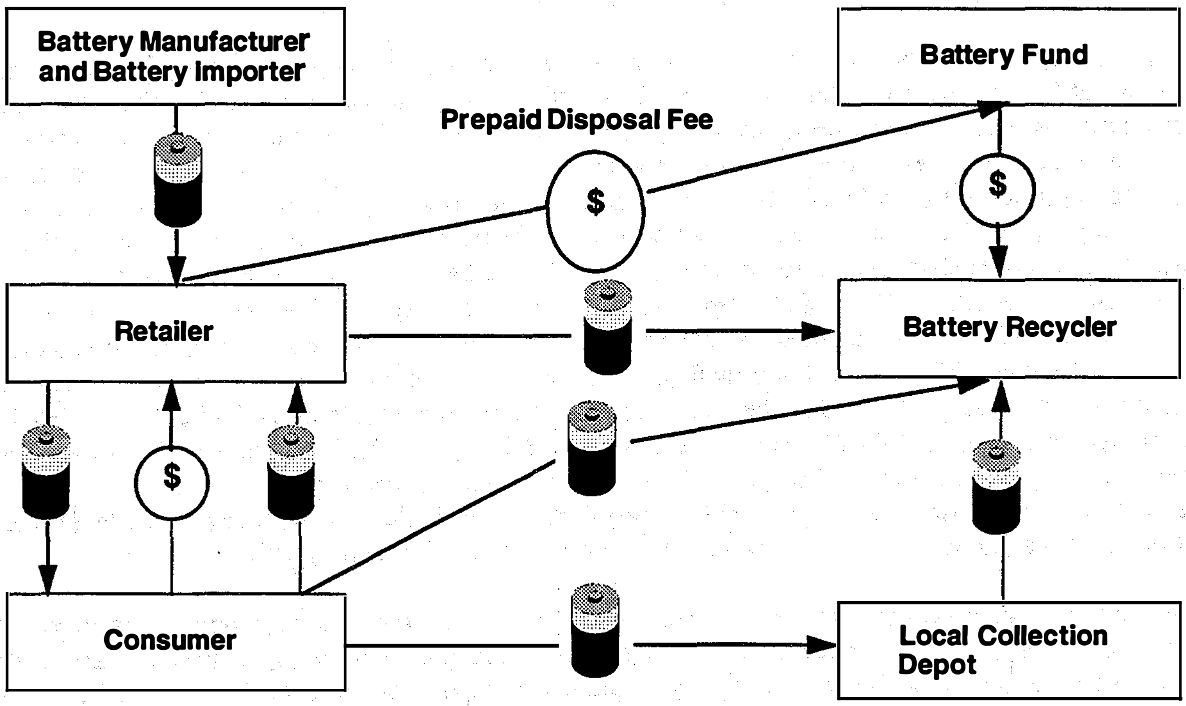

Figure 3. Financing of consumer battery recycling in Switzerland

One recycling option that has been proposed for Ni-MH batteries is shown in Figure 4 (Knoll et al. 1992). This process consists of mechanically shredding cells to expose the interior of cells and washing them to remove the potassium hydroxide before dissolving the metals in an acid digester. The dissolved metals then are selectively removed from the acidic solution by precipitation processes. Any components not dissolved in the acid are separated for treatment as a solid waste (Knoll et al. 1991).

Conclusions

Test results were presented that showed that Ni-MH AB_2-type EV batteries would not be considered a toxic hazardous waste under existing EPA regulations. However, Ni-MH EV batteries would be considered a toxic hazardous waste under State of California and EC environmental regulations. Existing recycling processes were evaluated for Ni-MH EV batteries. Although it appears that some of these processes might be applicable to Ni-MH EV batteries, none of these processes would currently be able to recycle Ni-MH EV batteries and produce the original individual metals contained in the batteries (e.g., vanadium). While it is generally agreed that recycling is a preferred alternative to disposal, cost-effective recycling processes for Ni-MH batteries have yet to be evaluated.

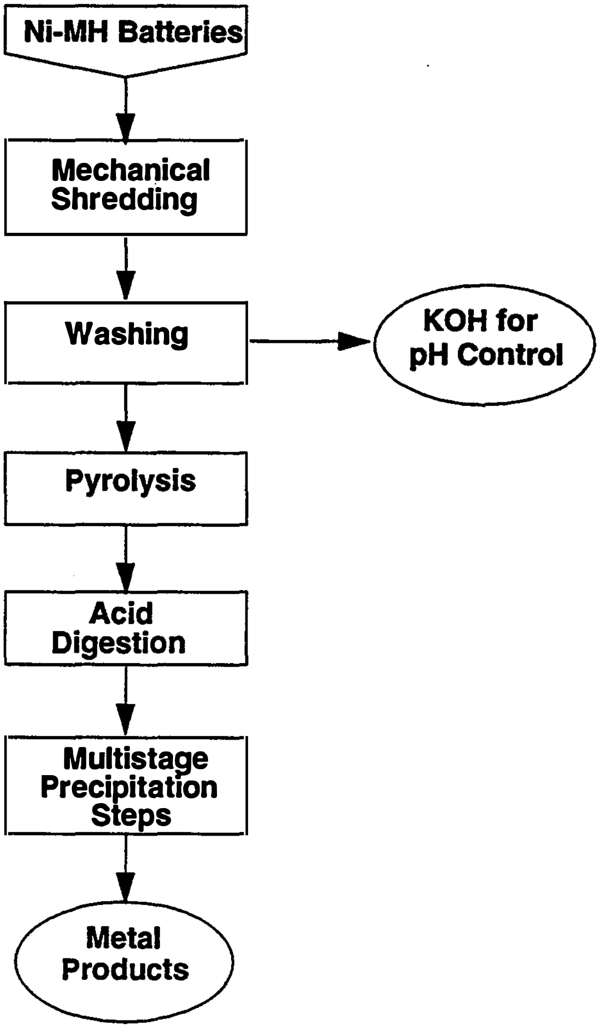

Figure 4. Proposed recycling process for Ni-MH batteries

Part III - General EH&S Characteristics of Nickel-Based EV Battery Systems

Introduction

This section describes some of the general EH&S issues for nickel-based EV batteries. The nickel-based systems include the following battery types: Ni-MH, Ni-Cd, nickel-iron (Ni-Fe), nickel-hydrogen ($Ni-H_2$), and nickel-zinc (Ni-Zn). All nickel systems are based on the use of a nickel-oxide active material that undergoes one valence change from charge to discharge and vice versa. In addition to sharing the same type of positive nickel electrode, nickel-based systems also have many other common characteristics, such as the use of an alkaline electrolyte that contains potassium hydroxide. All nickel-based batteries are ambient temperature batteries and have the same closed circuit voltage of 1.2 V, except for the Ni-Zn cell, which has a closed circuit voltage of 1.6 V.

Three main EH&S issues were identified for nickel-based EV batteries: venting characteristics; toxicity of battery materials; and the hazardous waste status of spent batteries. These three characteristics are described below.

Venting Characteristics of Nickel-Based Systems

Venting characteristics of nickel-based batteries vary as to whether a battery is sealed or nonsealed. Nonsealed batteries may vent gases at anytime, although gassing is highest during charging. Sealed batteries only vent during failure modes (e.g., abusive overcharging of Ni-MH EV batteries) when the safety pressure vent releases for individual cells. Table 8 lists the different nickel-based EV battery systems and their venting characteristics.

Both sealed and nonsealed batteries can vent hydrogen. Hydrogen gas is a highly flammable and explosive gas, so safety precautions to minimize the risks from vented hydrogen gases are required for nickel-based EV batteries. Vented cells may generate hydrogen gas during charging, hence, adequate ventilation should be provided and caution should be taken to eliminate any potential source of ignition near the location of hydrogen venting. Sealed batteries are usually considered safer than nonsealed batteries because hydrogen gassing is much less likely to occur, but both vented and nonvented systems can be designed to be safe. Internal cell pressures may build up in sealed cells during failure modes, so safety precautions must be taken to allow abnormally high pressures to vent. This is done by designing sealed nickel-based EV cells with pressure release vents.

Table 8. Venting Characteristics of Nickel-Based EV Batteries

Battery Type	Sealed/Nonsealed	Gassing Rate on Charge for Nonsealed Batteries (in cc/h per rated 100 Ah capacity) (NAVSEA 1992)
Ni-MH	sealed	NA (pressure release valve)
Ni-Cd	both sealed & nonsealed[a]	2500 for nonsealed (last 20% of charge)
Ni-Fe	nonsealed	2500 (last 20% of charge)
$Ni-H_2$	sealed	NA (pressure release valve)
Ni-Zn	nonsealed	50 (last 20% of charge)

[a] Recent Ni-Cd EV battery designs have started using sealed cells.

The dangers associated with hydrogen gas should not be overlooked in nickel-based EV battery designs. Hydrogen-oxygen flames can accelerate to the point of detonation, and high speed flames are the most difficult to quench (Eagle Picher 1983). In addition to safety measures that prevent hydrogen gas buildup (e.g., adequate ventilation mechanisms), flame arrestors specifically designed for hydrogen-oxygen flames should be considered for battery and vehicle designs. Hydrogen gas detection mechanisms should also be evaluated for battery and vehicle designs. Cell and battery safety design features should be incorporated into both sealed and nonsealed nickel-based EV batteries to minimize the risks associated with hydrogen gassing.

Sealed nickel family EV batteries rely on oxygen recombination mechanisms to control oxygen gas formation and may use hydrogen recombination mechanisms (e.g., Ni-MH cell) or other methods to control hydrogen gas formation. Hence sealed nickel-based batteries do not require their electrolyte to be refilled periodically as do the nonsealed batteries. Safety precautions for hydrogen gas should be taken during maintenance of nonsealed batteries (e.g., watering of Ni-Fe EV batteries).

Toxicity of Nickel-Based EV Battery Constituents

The chapter on workplace health and safety issues for Ni-MH EV batteries discussed some of the chemical safety hazards for Ni-MH battery constituents. A benchmark for evaluating these hazards was the existence of OSHA standards for different battery constituents. The magnitude of the OSHA standard (i.e., how strict it is) and the specific chemical health hazard that the OSHA standard addressed (e.g., carcinogen, irritant) were also important indications of the degree of risk associated with a given substance.

Nickel compounds are considered probable carcinogens by the National Toxicology Program. Because all nickel-based EV batteries contain a nickel-based positive electrode, they all share the chemical health hazard related to nickel compounds. The only other identified carcinogen among the nickel-based EV batteries is cadmium.

The OSHA limit for cadmium is very strict. In September 1992, OSHA promulgated a new time-weighted average permissible exposure limit (TWA PEL) for cadmium of 5.0 *micrograms* per cubic meter (*Federal Register* 1992) (OSHA TWA PELs were discussed previously in the section on workplace exposure.) The old cadmium standard was 0.1 mg/m^3; hence, the new standard is stricter by two orders of magnitude and reflects recent concerns about the extreme toxicity of cadmium. (For reference, the OSHA standard for nickel is 1.0 mg/m^3.)

As long as manufacturing processes meet OSHA standards, the workplace exposure to chemical health hazards is acceptable; i.e., OSHA regulations are presumed to establish safe levels of chemical exposure for workers. However, OSHA standards will be much harder to meet for substances that are considered highly toxic or carcinogenic. For example, OSHA cadmium TWA PELs are much stricter than nickel TWA PELs. Although the final impact of the new OSHA standard on Ni-Cd manufacturing in the United States has yet to be determined, it will probably require Ni-Cd manufacturers to retrofit plants with new equipment to meet this standard. Originally there was concern among the three U.S. Ni-Cd battery manufacturing facilities that they might have to close because of the difficulty in complying with this standard (American Metal Market 1990).

Even though chemical health hazards for cadmium and nickel should be about the same for facilities meeting OSHA standards (i.e., because OSHA regulations should ensure a safe level of exposure), the *risks* associated with these two substances may be different because risks would include periods of noncompliance with OSHA standards, such as accidents or equipment malfunctions. During periods of noncompliance with OSHA standards, risks would be higher for more toxic substances. This report does not include a risk assessment for worker exposure to cadmium or nickel in the workplace, so the degree of risk posed by these substances in EV battery manufacturing processes cannot be compared.

Other nickel-based constituents were not considered to pose serious chemical health hazards. The two other nickel-based battery electrode materials not yet discussed, iron and zinc, are considered mild irritants (Lewis 1992). Iron oxide and zinc oxide are regulated by OSHA as respirable metal dusts, for which the TWA PEL is 10 mg/m^3.

Recycling and Disposal of Nickel-Based EV Batteries

The recycling and disposal of spent EV batteries has been identified as one of the most important life-cycle stages of EV batteries in terms of environmental impacts (Corbus 1992b). All nickel-based EV batteries would be considered hazardous wastes by the EPA because of the batteries' corrosive electrolyte. However, the corrosive electrolyte can be removed from a battery to render it nonhazardous.

In the chapter on recycling and disposal of Ni-MH batteries, six *toxic* materials (arsenic, cadmium, chromium, lead, mercury, and silver) were discussed for which the EPA has promulgated hazardous waste standards based on toxicity. *Toxic* hazardous wastes are often considered more of an environmental problem than nontoxic hazardous wastes (e.g., corrosive hazardous wastes). (See the chapter on recycling for a more in-depth discussion on toxic hazardous wastes.) Testing for toxicity is determined by using the EPA's toxicity characteristic leaching procedure (TCLP).

TCLP test results for Ni-MH consumer batteries are discussed in the chapter on Ni-MH recycling and disposal. TCLP tests for Ni-Cd consumer batteries have also been conducted. The results of TCLP tests carried out by a major metal supplier in the United States for both Ni-MH and Ni-CD consumer batteries are shown in Table 9, along with the corresponding EPA, European Community (EC), and California regulations. Although the TCLP test results are for consumer batteries, they give a good indication of test results for Ni-MH (AB_2 -type) and Ni-Cd EV batteries because EV battery materials would be similar, as would the leaching properties of the EV battery materials.

The results of the TCLP tests for Ni-MH batteries show that all metals leach at concentrations below EPA standards. This is not true for Ni-Cd batteries, which are shown to leach cadmium at levels above EPA standards. Nickel concentrations for Ni-MH batteries are above the standards set in California and by the EC, hence, spent Ni-MH batteries would be considered hazardous wastes in California and Europe. Although TCLP testing has not been conducted for the three other nickel-based batteries, Ni-Fe, Ni-H_2, and Ni-Zn, they would probably also be considered hazardous wastes in California and Europe because of nickel concentrations; however, their electrode materials do not contain any substances regulated by the EPA under RCRA, so their electrode materials would not be considered toxic hazardous wastes by the EPA. (It was not determined if these three batteries, Ni-Fe, Ni-H_2, and Ni-Zn, contained nonelectrode materials, such as chromium, that could be significant in TCLP tests.)

Recycling or disposal of nickel-based EV batteries, other than Ni-Cd batteries, may require a RCRA *storage* permit (because they are considered hazardous based on their corrosive electrolyte), but they would not require a RCRA *treatment and disposal* permit. Because RCRA treatment and disposal permits are costly and time consuming to obtain (up to five years to obtain in some cases), not having to obtain a RCRA treatment and disposal permit would greatly facilitate recycling of nickel-based EV batteries, with the exception of Ni-Cd batteries. Recycling of Ni-Cd EV batteries would probably require a RCRA *treatment and disposal* permit because of the cadmium contained in the batteries. Permitting requirements could be different in California for nickel-based EV batteries because nickel is considered a hazardous waste in this state. (See Appendix C for information on RCRA permitting requirements.)

Table 9. Comparison of TCLP Test Results for Ni-MH and Ni-Cd Consumer Batteries with EPA, European Community, and California Regulations (All TCLP results are reported in mg/L)

	Ni-MH[a]	Ni-Cd	EPA Standard	EC Standard[b]	California Regulations[c]
Cadmium	>0.01–0.08	48.0–290.0	1.0	0.5	1.0
Chromium	0.09–0.23	>0.05	5.0	0.5	5.0
Nickel	320.0–590.0	62.0–160.0	None	2.0	20.0

[a] Results are reported for AB_2 alloys that contain small amounts of cadmium; it should be noted that OBC alloys will not contain any cadmium.

[b] European Community Hazardous Waste Limit.

[c] California regulations use a different test to determine toxicity that is more stringent than the TCLP test.

Source: Knoll 1992.

Large Ni-Cd industrial batteries, such as those that have been used in railroad and mass transit cars, are recycled because EPA regulations forbid their disposal in a landfill. For example, SAFT-NIFE currently sends its large Ni-Cd industrial batteries to Sweden for recycling. Ni-Cd EV batteries would also have to be recycled. Although Ni-Cd batteries are considered a hazardous waste and Ni-MH batteries are not, the near-term economics of Ni-Cd EV recycling appear to be more attractive because of the existing Ni-Cd recycling infrastructure. In terms of environmental impacts of hazardous waste disposal, if all nickel-based EV batteries are recycled, then the environmental impacts should be small because no toxic wastes would be disposed.

Other EH&S Issues for Nickel-Based EV Batteries

The exact regulatory status of shipping different types of nickel-based batteries should be determined. The shipment of sealed batteries may be easier because they probably would be classified as "nonspillable batteries," and the regulatory requirements for nonspillable batteries are much less stringent than for spillable batteries. (Nonsealed nickel-based EV batteries may also qualify as nonspillable batteries.) The specific tests for determining whether a battery is spillable or nonspillable are described in the chapter on shipping. The nickel-based EV batteries do not pose any unique in-vehicle safety issues except those related to hydrogen gas hazards. Hydrogen venting was discussed previously in the chapters on cell and battery safety and in-vehicle safety. Nickel-based EVs do have a number of in-vehicle safety issues that they share in common with other EVs, and these were discussed in depth in the section on in-vehicle safety.

Part IV - Conclusions

Summary

This report analyzed the key EH&S issues for Ni-MH EV batteries. In general, the health and safety hazards associated with Ni-MH EV batteries are small. The nontoxic nature of the electrode materials of the Ni-MH EV cell help minimize the health and safety hazards of Ni-MH EV cells and batteries.

Internal pressure buildup within a cell was identified as a potential cell safety hazard. The primary safety design feature of a Ni-MH EV cell that addresses this potential hazard is the pressure release valve, which minimizes the risk associated with this potential hazard. The accumulation of hydrogen gas within the battery enclosure was identified as a potential Ni-MH EV *battery* safety hazard. Ni-MH EV batteries should incorporate design features that minimize the hazards associated with hydrogen gas accumulation.

Workplace health and safety were also addressed in this report. Although nickel and nickel compounds are considered probable carcinogens, meeting OSHA standards for exposure to these compounds in the workplace should provide for a safe work environment.

In the shipping section, it was concluded that if testing confirms that Ni-MH batteries are dry (i.e., do not release any free liquid if the battery is ruptured or cracked), they would be exempted from DOT and International Civil Aviation Organization (ICAO) regulations. The same exception also will be instituted in the International Maritime Organization (IMDG) Code beginning January 1, 1995, after uniform dry criteria are incorporated into the IMDG Code. If the batteries do not meet the dry criteria, then testing can take place to determine nonspillability. The tests to determine nonspillability are identical for DOT, ICAO, and IMO, including vibration and pressure differential tests. Regulatory relief is available under DOT, ICAO, and IMO nonspillable provisions, but is most significant under ICAO and DOT regulation—nonspillable batteries need only be protected against short circuits and be securely packaged. ICAO further requires that the outside packaging be "strong," but does not require that it meet UN performance standards. A nonspillable classification is particularly important for international air transport because restrictive weight and packaging constraints exist in the spillable category. In general, it was concluded that shipping of Ni-MH batteries should take place under spillable provisions until testing can take place to confirm either dry or nonspillable classification.

In-vehicle safety was the last topic under health and safety. No major in-vehicle safety issues were identified that uniquely applied to Ni-MH EV batteries, except those hazards associated with hydrogen gases. However, various in-vehicle safety issues that applied to all EV batteries were analyzed. Although these issues were not unique to the Ni-MH EV batteries or nickel-based EV batteries, they are important issues that must be addressed for EVs regardless of battery type.

The environmental concerns associated with Ni-MH EV batteries were also considered small. The main environmental issue that was discussed in this report was the recycling of Ni-MH EV batteries. Test results were presented that showed that Ni-MH AB_2-type EV batteries would not be considered a hazardous waste under existing EPA regulations, although they would be considered hazardous under California and European Community (EC) environmental regulations. Although recycling of Ni-MH EV batteries is preferred over disposal, from an environmental standpoint, the economics of recycling Ni-MH EV batteries needs to be evaluated to determine if recycling will be feasible.

The other nickel-based EV batteries share many common EH&S characteristics with Ni-MH EV batteries. However, there are also some differences in the EH&S characteristics of the nickel battery family. Many of these differences were identified in this report. For example, differences in OSHA standards for workplace exposure to cadmium and nickel were analyzed, and test results for Ni-Cd batteries were presented that showed that Ni-Cd batteries are considered hazardous wastes under EPA regulations. In contrast, Ni-MH AB_2-type batteries are only considered hazardous under California and EC regulations.

Recommendations for Future Work

This report highlighted a number of areas in which additional work should be conducted. As Ni-MH EV batteries approach commercialization, it will be important to perform more cell and battery safety testing. In particular, safety test data on full Ni-MH EV battery packs would be useful. Safety tests, such as drop tests, fire tests, and abusive overcharging and overdischarging tests, should be conducted on Ni-MH batteries to determine how they would react to accidents such as collisions, fires, and battery charger malfunctions. Because battery safety testing is such an important aspect of the commercialization process of EVs, the adoption of formalized safety testing procedures could help promote the safety aspects of EV batteries. In addition, carrying out safety tests by an independent testing organization could help promote the safety aspects of EV batteries.

As advanced batteries begin to be integrated with the vehicle platforms in prototype and commercial EVs, increased in-vehicle testing for safety should be carried out to demonstrate compliance with the existing regulations and standards and to bolster public acceptance of the new product. In addition, such testing will help guide the development of batteries and vehicles to ensure that they will in fact be capable of compliance.

Because much of these data have traditionally been proprietary, the federal government can encourage greater cooperation within the private sector and between government and industry through joint-funding ventures, working groups (such as the Ad Hoc EV Battery Readiness Working Group), and consortia (such as the U.S. Advanced Battery Consortium). In particular, DOE can work with industry groups and DOT's National Highway Traffic Safety Administration to consider, in more detail, the specific crashworthiness issues posed by the use of converted or dedicated EVs, to establish any supplemental testing procedures necessary, and to facilitate information exchange through collecting and disseminating test data in a common data base. In addition, DOE should continue to consider working with standards-making organizations to develop appropriate EV standards for charging and maintenance.

Because Ni-MH batteries would be exempted from DOT and ICAO shipping regulations if they can meet the dry criteria (i.e., they will not leak any free liquid if the battery is ruptured or cracked), it is recommended that testing be undertaken to determine if the criteria can be met. If Ni-MH batteries can meet the dry criteria, no other testing would be necessary. If the dry tests are conducted and the batteries cannot meet the criteria, tests should then be conducted to determine if the batteries meet the nonspillable requirements under which significant regulatory relief is available under the DOT and ICAO regulations. IMO also provides regulatory relief under the nonspillable requirements, but it is more limited. Because the battery manufacturer is ultimately responsible for providing test data to prove that the batteries are either dry or nonspillable, it is recommended that the testing take place at an independent testing facility retained by the manufacturer.

Future work is needed in the area of recycling and disposal of Ni-MH EV batteries. Even though it is generally agreed that recycling is a preferred alternative to disposal, cost-effective recycling processes for Ni-MH batteries have yet to be evaluated. In addition to identifying feasible recycling processes, future studies should also estimate recycling costs for potential recycling processes because a determination cannot be made as to whether recycling or disposal of Ni-MH EV batteries is more economical until costs are evaluated. The National Renewable Energy Laboratory is currently conducting a study to estimate recycling costs for Ni-MH EV batteries. This will include identifying feasible recycling processes for

Ni-MH batteries, as well as reviewing market outlets for Ni-MH recycle products and estimating the sensitivities of these markets to fluctuations in metal supplies. Finally, general design criteria for Ni-MH EV cell and battery packs should be evaluated to determine the impact of the design on the ease of dismantling the cell and batteries (i.e., design for recyclability) for recycling.

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Appendix A

Toxicity Data for Ni-MH Battery Constituents

Excerpts from Ovonic Battery Company's Material Safety Data Sheet for Nickel Metal-Hydride Powder

SECTION 1 - IDENTIFICATION

Product:	OVONIC HYDRIDE POWDER
Synonyms:	None
Chemical Family:	Metallic hydride

SECTION 2 - INGREDIENTS

Chemical Components	C.A.S. No.	%	OSHA Exposure Limits (mg/m^3) Table Z-1-A final Rule	
			STEL	TWA
Vanadium, V	7440-62-2	15-45	--	0.05 (as V_2O_5)
Nickel, Ni	7440-02-0	15-45	--	1
Zirconium, ZR	7440-67-7	15-45	10	5
Titanium, Ti	7440-32-6	5-25	--	5 (as respirable T_iO_2 dust)
Chromium, Cr	7440-47-3	5-20	--	1 (as metal)
Colbalt, Co	7440-48-4	0-10	--	0.1
Manganese, Mn	7439-96-5	0-5	3	1
Aluminum, Al	7429-90-5	0-5	--	5 (as respirable dust)
Hydrogen, H	1333-74-0	0-0.2	--	--

SECTION 3 - PHYSICAL DATA

Boiling Point:	Not applicable
Vapor Pressure:	0 mm Hg at 20^{o}C
Vapor Density:	Not applicable
Solubility in Water:	Insoluble
Specific Gravity (H_2O = 1):	5.0 to 7.2
Melting Point:	1700^{o}C
Evaporation Rate	Not applicable
Appearance and Odor:	Metallic grey particles, odorless

SECTION 4 - FIRE AND EXPLOSION HAZARD DATA

Flash Point:	Not applicable
Auto-Ignition Temperature:	Not applicable
Flammability Limits in Air:	Dust finer than 100 mesh can be flammable
Extinguisher Media:	Class D Fire Extinguisher. Fire can be controlled by smothering with dry sand.
Special Fire Fighting Procedures:	Class D Fire - Do not use water.
Fire and Explosion Hazards:	Hot or burning metal can produce toxic fumes. Use self contained breathingapparatus operated in positive pressure mode if the fire involves vanadium containing metal or oxide.

SECTION 5 - HEALTH HAZARD DATA

Primary Route of Entry:	Inhalation, ingestion
Effects of Overexposure:	Acute - None known Chronic - None known
Emergency First Aid Procedure:	Eye Contact - Normal procedures for foreign object. Inhalation - Normal procedures for inert dust.
Toxicity Data:	These materials are non toxic. If the material is acid-dissolved or treated chemically to form water soluble compounds of nickel or chromium, then possibly carcinogenic behavior of these water soluble materials must be considered in any handling, processing or disposal procedures.

SECTION 6 - REACTIVITY HAZARD DATA

Stability:	Stable at room temperature.
Hazardous Polymerization:	Does not occur.
Incompatibility:	The material should be kept away from oxidizers. The hydride may react violently with chlorine above 180°C and may react with oxygen to form water.
Hazardous Decomposition Products:	Evolves hydrogen above 100°C. Reactions with oxidizers or chlorine will generate hazardous reaction products such as metal oxide dust and fumes or corrosive and toxic metallic chlorides.

SECTION 7 - SPILL, LEAK AND DISPOSAL PROCEDURES

Handling Procedures and Equipment: Keep dry. Do not stir up dust by cleaning an area with an air hose. Do not use vacuum cleaner to clean up dust - potential explosion of dust and air mixture.

Storage Requirements: Keep dry. Cleanliness and good housekeeping are important to minimize oxide dust levels. Eating and smoking should not be permitted in areas where metal hydride dusts are present. Wash hands thoroughly before eating, smoking or using toilet facilities.

Spill or Leak Procedures: No special procedures.

Waste Disposal: Disposal of in accordance with Federal, State and Local regulations.

Environmental Hazards: None in alloy form.

D.O.T. Proper Shipping Name: UN 1325 - Flammable Solid, NOS

SECTION 8 - SPECIAL PROTECTIVE MEASURES

Respiratory Protection: Wear appropriate NIOSH approved respirator if dust or fume exposure levels are exceeded.

Protective Clothing: None

Eye Protection: Dust goggles help prevent eye irritation.

SECTION 9 - SPECIAL PRECAUTIONS

Other precautions: None known

DISCLAIMER OF EXPRESSED AND IMPLIED WARRANTIES

The data in this Material Safety Data Sheet relates only to the specific material designated herein and does not relate to use in combination with any other material or in any process. The information set forth herein is based on technical data that Ovonic Battery Company believes to be reliable. It is intended for use by persons having technical skill and at their own discretion and risk. Ovonic Battery Company makes no warranties, expressed or implied, and assumes no liability in connection with any use of this information. Nothing herein is to be taken as a license to operate under or a recommendation to infringe any patents. Any use of this data or information must be determined by the user to be in accordance with Federal, State and Local laws and regulations.

Ovonic Battery Company assumes no responsibility and makes no warranty, expressed or implied, representation, promise or statement as to the completeness, accuracy or currency of any data so provided.

Appendix B

Safety Tests for Ovonic Battery Company's Ni-MH C Cells

(Supplied by Ovonic Battery Company)

The intrinsic safety of the Ovonic NiMH technology has been exhaustively demonstrated over several years now for consumer cells. In the laboratory at OBC, we have deliberately subjected consumer cells to a variety of abusive tests to investigate potential safety problems:

1. Heat cells on a hot plate at 250 C in the charged and discharged states for over 2 hours. Proper venting occurred in response to the pressure increase after about 20 minutes. Cell shorting occurred after about 90 minutes due to melting of the nylon separators. No explosions.

2. Continuous overcharge of cells at the 3 C rate for 7 hours. Proper venting occurred after 1 hour. No explosions.

3. Continuous overcharge of cells at the 10 C rate. Cell shorting occurred after 2.5 minutes. Proper venting occurred after 4 minutes. No explosions.

4. Forced overdischarge of cells at 3, 5, and 10 C rates. Proper venting occurred. Steady state temperature rise to 160 C. No explosions.

5. Deliberate short circuit across the terminals of cells. Discharge through internal resistance complete in about 3 minutes. Temperature rise to 190 C in 7 minutes. No explosions.

6. Connect cells to a 12 V car battery for extreme high rate overcharge and overdischarge. Cells immediately went to open circuit. No explosions.

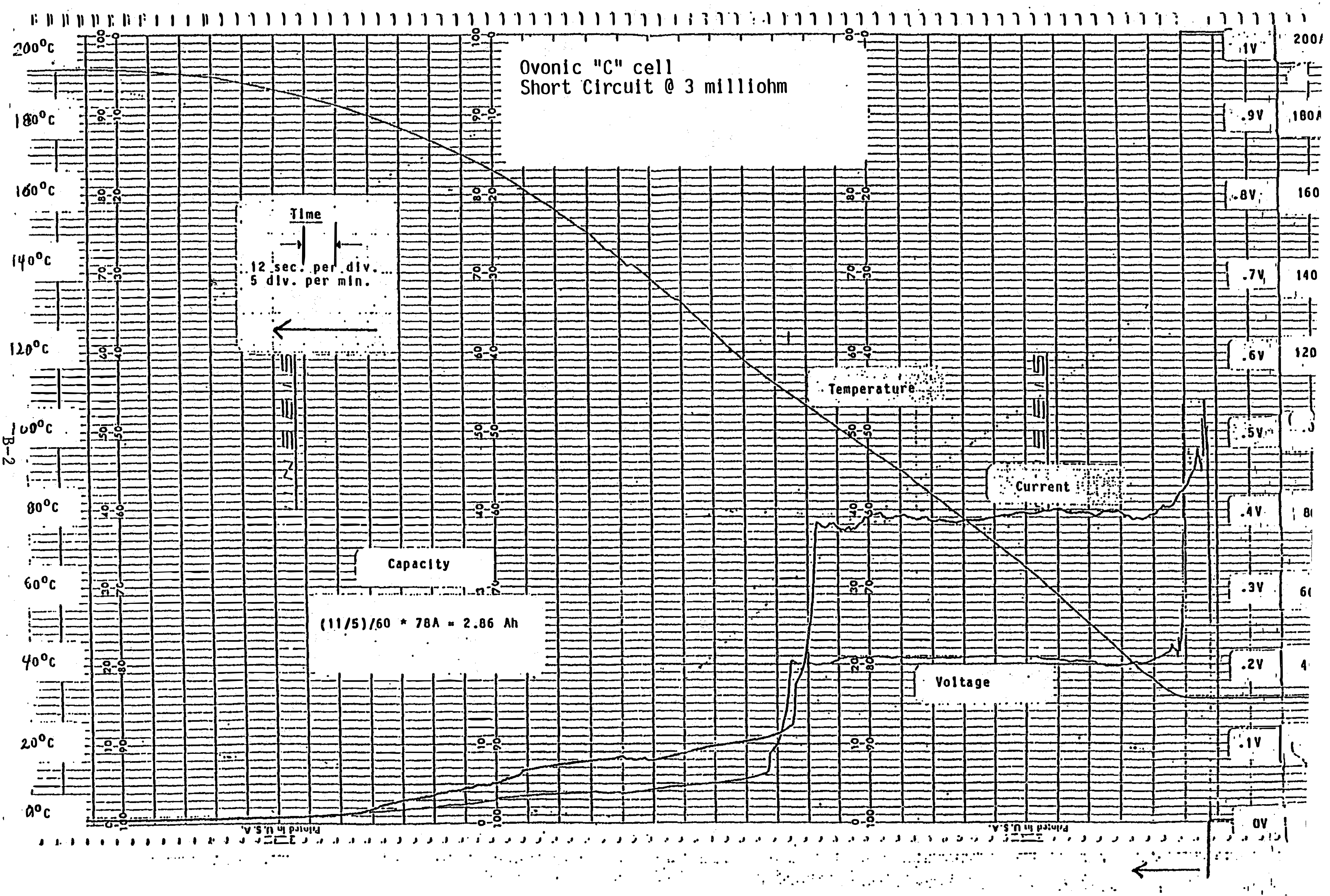
7. Repeated 20% overcharge of cells at the C/2 rate. Repeated up to several hundred times with no apparent damage to cells or detrimental effect on performance.

8. Repeated 15% overdischarge of cells at the C/2 rate. Repeated up to several hundred times with no apparent damage to cells or detrimental effect on performance.

9. Exposure of cells in the charged and discharged condition to an open flame. Proper venting occurred with no explosions.

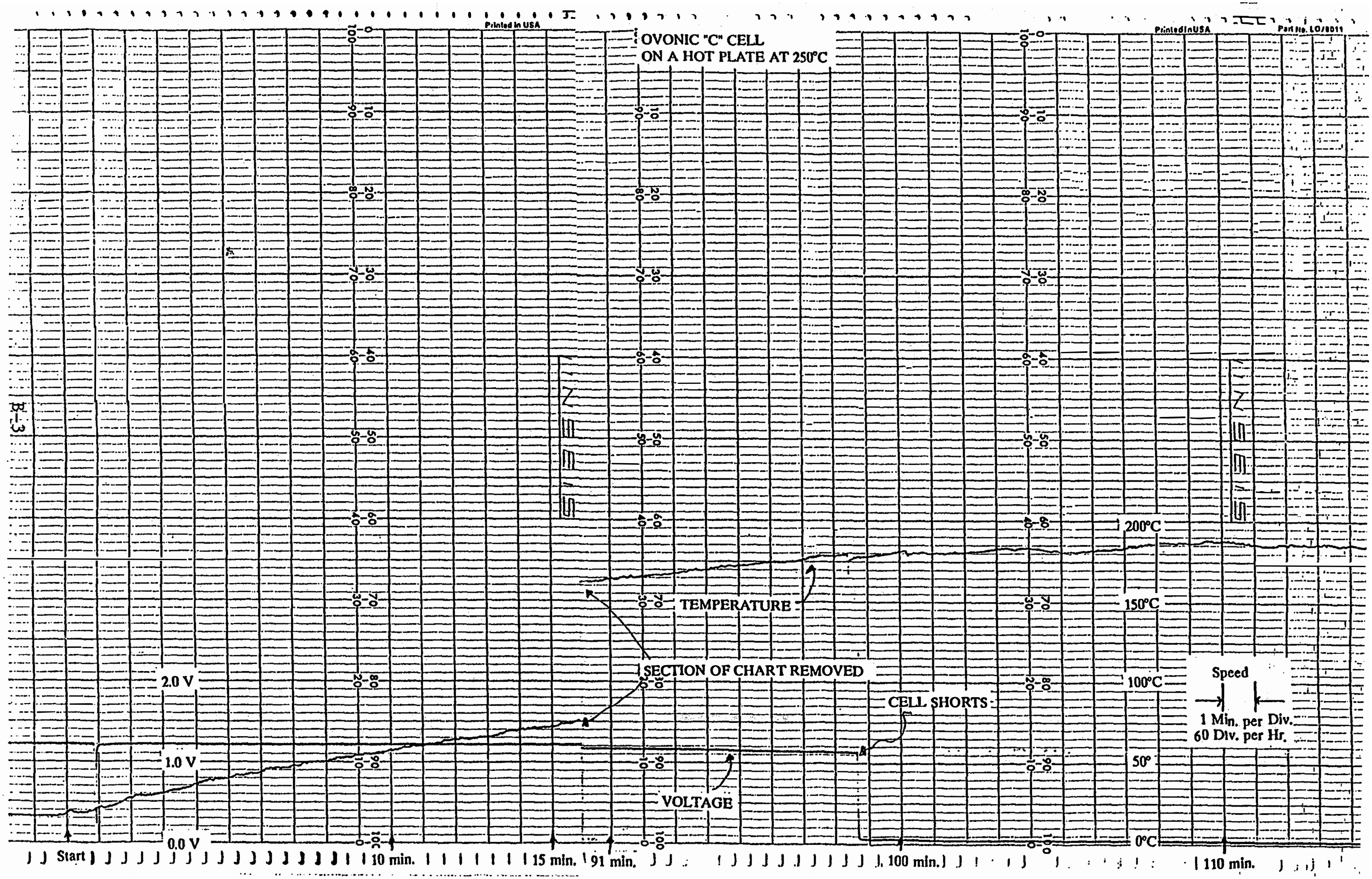
In competitive analysis of competing NiMH products using AB_5 alloys, some explosions occurred on hot plate tests. Further, AB_5 alloy electrodes spontaneously ignite when removed from cells. This does not occur with OBC alloys.

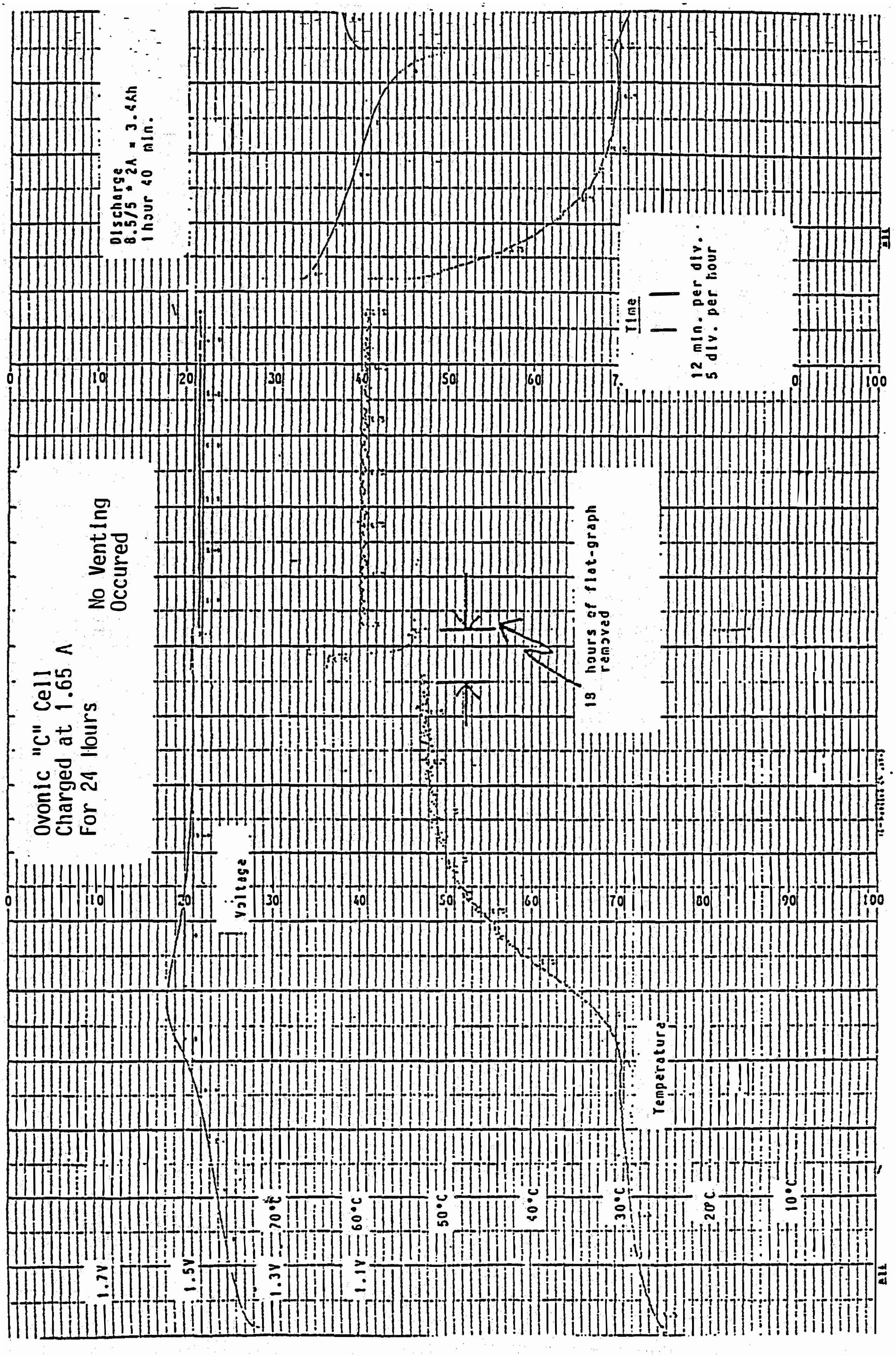
OBC licensees have been subjected OBC consumer cells to an exhaustive variety of tests including the 8 tests listed in the attached table entitled NiMH Safety Verification Testing For Consumer Cells. Their conclusion is that Ovonic NiMH cells showed similar failure characteristics to NiCd cells and present no additional safety issues.

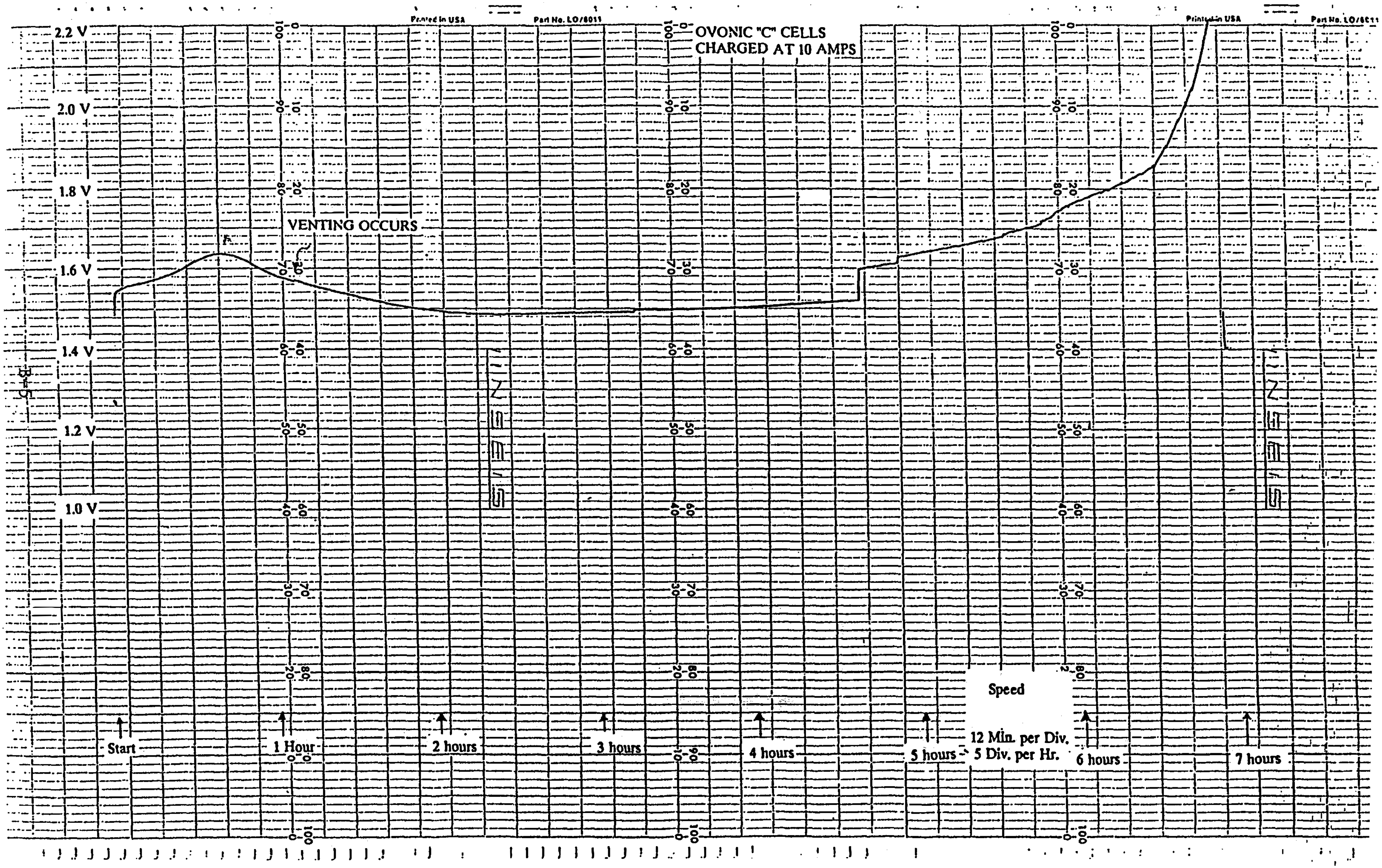


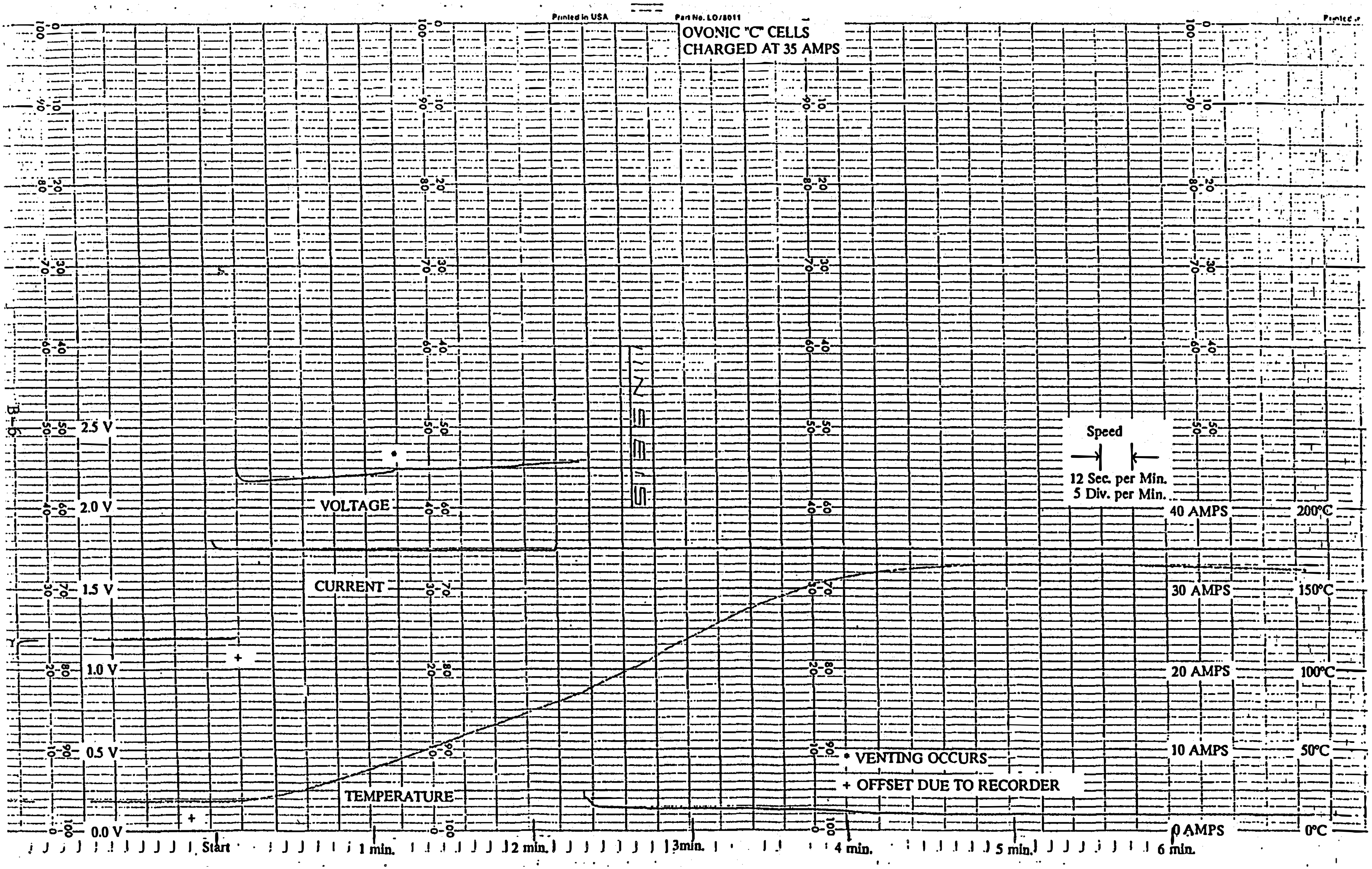
Ovonic "C" cell
Short Circuit @ 3 milliohm

(11/5)/60 * 78A = 2.86 Ah

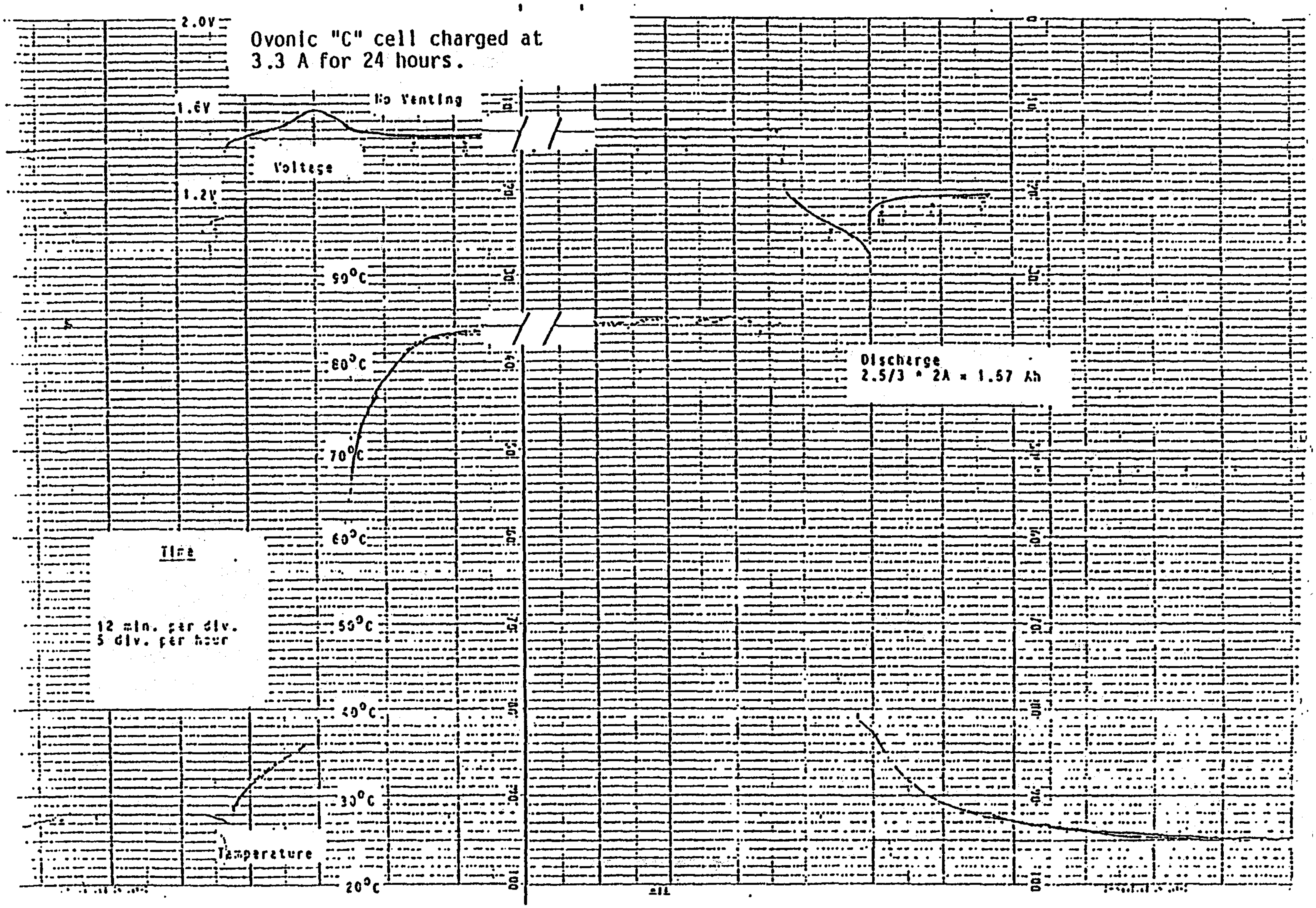

OVONIC "C" CELL
ON A HOT PLATE AT 250°C
TEMPERATURE
SECTION OF CHART REMOVED
CELL SHORTS
VOLTAGE
2.0 V
1.0 V
0.0 V
200°C
150°C
100°C
50°
0°C
Speed
1 Min. per Div.
60 Div. per Hr.
Start
10 min.
15 min.
91 min.
100 min.
110 min.
Printed in USA
Part No. LO/8011


Ovonic "C" Cell
Charged at 1.65 A
For 24 Hours
No Venting
Occured
Discharge
8.5/5 * 2A = 3.4Ah
1 hour 40 min.
18 hours of flat-graph
removed
Time
12 min. per div.
5 div. per hour
Voltage
Temperature
0
10
20
30
40
50
60
70
80
90
100
1.7V
1.5V
1.3V
1.1V
70°C
60°C
50°C
40°C
30°C
20°C
10°C

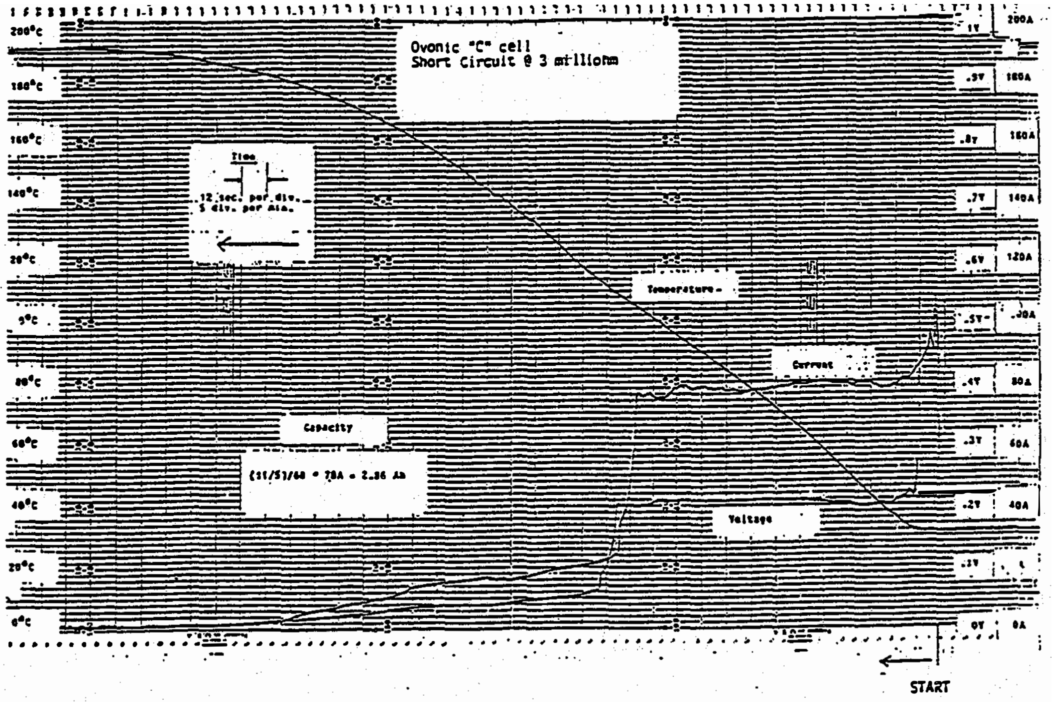

OVONIC "C" CELLS
CHARGED AT 10 AMPS
2.2 V
2.0 V
1.8 V
1.6 V
1.4 V
1.2 V
1.0 V
VENTING OCCURS
Start
1 Hour
2 hours
3 hours
4 hours
5 hours
6 hours
7 hours
Speed
12 Min. per Div.
5 Div. per Hr.
Printed in USA
Part No. LO/6011



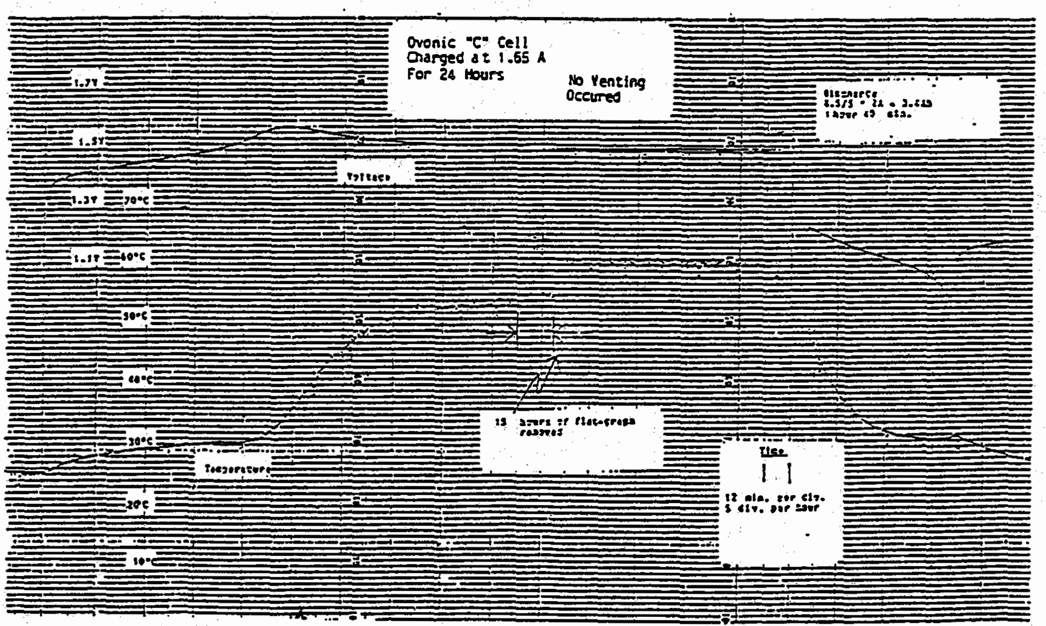
OVONIC "C" CELLS
CHARGED AT 35 AMPS



Ovonic C cell Overcharged at C Rate (3.3 Amps)



Short Circuit Behavior (Ovonic C cell through 3 milliohm load)



Ovonic C cell Overcharged at C/2 Rate (1.65 Amps)

Appendix C

Overview of RCRA Regulations Pertaining to EV Battery Recycling and Disposal

Overview of RCRA Regulations Pertaining to EV Battery Recycling and Disposal

Background

Ni-MH EV batteries would only be considered hazardous based on the corrosive electrolyte. Since this could easily be neutralized in the facility disposing of or recycling these batteries, the recycling and disposal of Ni-MH batteries should be exempt from most RCRA regulations for hazardous wastes. Nevertheless, an overview of RCRA regulations is given in this appendix.

Solid waste in the United States is regulated under the Resource Conservation and Recovery Act (RCRA). RCRA was passed in 1976 as an amendment to the Solid Waste Disposal Act. The primary objectives of RCRA are to protect human health and the environment and to conserve valuable material and resources. The requirements contained in Subtitle C of RCRA cover the management of hazardous wastes.

It is the responsibility of the U. S. Environmental Protection Agency (EPA) to develop regulations to carry out and enforce RCRA. Hazardous waste regulations enforcing RCRA can be found in Volume 40 of the Code of Federal Regulations (40 CFR), Parts 260-281. Volume 40 of the Code of Federal Regulations is updated once a year to reflect new rulings. Most states have the authority from the federal EPA to operate their own hazardous waste programs. States that have this authority may adopt their own hazardous waste regulations, which must be at least as stringent as the EPA regulations.

RCRA Regulations Impacting EV Battery Storage and Disposal

RCRA regulations that affect battery disposal are discussed below. This is not a comprehensive list of all the RCRA requirements that will affect EV battery disposal, but an overview of some of the more important requirements and provisions.

Listed and Characteristic Wastes. A solid waste is considered a hazardous waste (and therefore subject to RCRA requirements) if it is either a "listed " waste under 40 CFR Part 261 Subpart D, or a "characteristic" waste. A waste is listed as a hazardous waste based on the process from which the waste was generated and/or the constituents found in the waste. A characteristic waste exhibits any one or more of the following hazardous characteristics: ignitability, corrosivity, reactivity, or toxicity.

Waste Manifesting and Treatment, Storage, and Disposal Facilities. RCRA regulations require that a hazardous waste be tracked from its generation to its final disposal. Final disposal takes place at a licensed treatment, storage and disposal (TSD) facility. This "cradle-to-grave" approach incorporates a tracking system whereby the waste is accompanied by a manifest as it exchanges hands from generators to transporters through to its disposal at a TSD facility. The manifest system assigns responsibility for the hazardous waste to someone at each stage of its handling, with the TSD facility being the last link in a manifest system under RCRA. The recordkeeping and reporting requirements associated with the manifest system are burdensome.

TSD facilities are defined in 40 CFR Part 260.1 and explained in depth in Part 264. A TSD facility encompasses three different functions:

Treatment. Any method, technique, or process, including neutralization, designed to change the physical, chemical, or biological character or composition of any hazardous waste so as to neutralize such waste, or so as to recover energy or material resources from the waste, or so as to render such waste nonhazardous, or less hazardous, safer to transport, store, or dispose of, or amenable for recovery, storage or reduced in volume.

Storage. The holding of hazardous waste for a temporary period, at the end of which the hazardous waste is treated, disposed of, or stored elsewhere.

Disposal. The discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including groundwaters (40 CFR 260.1).

Federal versus State Authorization. EPA may delegate authority to individual states to operate a state hazardous waste program in lieu of part or all of the federal hazardous waste program, yet EPA still retains certain oversight authority in states with EPA-authorized hazardous waste programs. State regulations must be as stringent as the federal regulations and may be more stringent if the state desires. Most states have been granted authority to administer their own state hazardous waste programs, and these programs may vary significantly from state to state. Although the EPA requires that state regulations be as stringent as the federal regulations, in many cases state hazardous waste requirements are less stringent than the federal requirements because of the procedures by which the regulations are interpreted and enforced. Differences in state hazardous waste programs may have an effect on where companies choose to locate their TSD facilities.

Hazardous Waste Export Requirements. 40 CFR Part 262.51 contains regulations for the export of hazardous waste. Exporters of hazardous waste must comply with stringent notification, recordkeeping, and manifesting requirements. New regulations may be adopted in the future that further restrict hazardous waste exports.

Exclusion from RCRA Requirements

Certain waste treatment processes may be excluded from all or parts of the RCRA regulatory requirements. RCRA exclusions that may be applicable to the treatment, storage, and disposal of spent EV batteries are discussed below.

Recycling of Hazardous Wastes. Hazardous wastes that are recycled (known in RCRA as recyclable materials) may be exempt from all or parts of the RCRA regulations. RCRA regulations for recycling of hazardous wastes are complex and are subject to interpretation by the EPA or state environmental agencies. EPA is also changing the recycling regulations, which may make recycling for certain materials easier in the future.

It is usually necessary to know the specifics of the treatment process and how the recycled products are to be reused or disposed of to determine whether RCRA regulations apply for a specific waste. Recycling via use and/or reuse involves the return of a waste material either to the originating process as a substitute for an input material or to another process as an input material. "A material is 'reclaimed' if it is processed to recover a useful product or if it is regenerated. Examples include the recovery of lead values from spent batteries and the regeneration of spent solvents" (40 CFR Part 261.1). In general, recycling by use and/or reuse is exempt from RCRA, while recycling by reclamation is often subject to RCRA. Materials are not regulated under RCRA when they can be shown to be recycled by being: "1) Used or reused as ingredients in an industrial process to make a product, provided the materials are not being reclaimed; or 2) used or reused as effective substitutes for commercial products; or 3) returned to the original process from which they are generated, without first being reclaimed" (40 CFR Part 261.2 [e][1][i-iii]).

The regulatory interpretation of recycling is sometimes difficult to understand. EPA encourages recycling, yet it is very sensitive to treatments that are merely called recycling in order to evade regulation. From an EPA perspective, the issue of whether an activity is considered legitimate recycling involves assessing whether the secondary material is "commodity-like." The main environmental considerations are (1) whether the secondary material truly has value as a raw material/product (i.e., is it likely to be abandoned or mismanaged rather than being recycled), and (2) whether the recycling process (including ancillary storage) is likely to release hazardous constituents (or otherwise pose risks to human health and the environment) that are different from or greater than the processing of an analogous raw material/product.

Overview of RCRA

The RCRA statute is divided into ten subtitles:

Subtitle A - General Provisions
Subtitle B - Office of Solid Waste; Authorities of the Administrator
Subtitle C - Hazardous Waste Management
Subtitle D - State or Regional Solid Waste Plans
Subtitle E - Duties of the Secretary of Commerce in Resource Recovery
Subtitle F - Federal Responsibilities
Subtitle G - Miscellaneous Provisions
Subtitle H - Research Development, Demonstration, and Information
Subtitle I - Regulation of Underground Storage Tanks
Subtitle J - Demonstration Medical Waste Tracking Program.

Subtitle C establishes a comprehensive management program to regulate hazardous waste from generation through disposal. Subtitle C contains the majority of the requirements for RCRA permitting, operations, cleanup and closure; it includes EPA criteria for identifying hazardous waste. Subtitle C contains the regulations that will govern the disposal of any hazardous materials from spent EV batteries.

Under Subtitle C, one must determine whether the solid waste generated is a hazardous waste not excluded from regulation. If the waste is a hazardous waste subject to regulation, then the volume of the waste generated must be calculated. Calculating the volume of the hazardous waste allows one to properly classify the process as either a conditionally exempt small quantity generator (CESQG - generates less than 100 kilograms per month of hazardous waste), a small quantity generator (SQG - generates less than 1000 kilograms per month of hazardous waste), or a fully regulated generator. Each type of hazardous waste generator is subject to a different level of RCRA notification and operational requirements.

Listed below are definitions of selected terms from the Subtitle C RCRA regulations that may be applicable to EV battery disposal.

Characteristic Waste - A solid waste that is a hazardous waste because it exhibits one or more of the following hazardous characteristics: ignitability, corrosivity, reactivity, or toxicity.

Disposal - The discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including groundwater.

EPA Hazardous Waste Number - A number EPA assigns to the following types of waste: waste that is hazardous by definition; hazardous waste listed in 40 CFR 261 Subpart D from specific and nonspecific sources identified by EPA (F,K,P,U); and characteristic waste identified in 40 CFR 261 Subpart C, including wastes with ignitable (D001), reactive (D002), corrosive (D003), and EP toxic (D004-D0017) characteristics.

Hazardous Waste - Includes those solid wastes that (1) are not excluded from the definition of hazardous waste, (2) are listed as hazardous wastes by EPA, (3) exhibit one or more of the characteristics of hazardous waste (see also characteristic waste), or (4) are mixed or derived from a listed hazardous waste.

Land Disposal - Includes, but is not limited to, placement in a landfill, surface impoundment, wastepile, injection well, land treatment facility, or salt dome formation intended for disposal purposes. Land disposal facilities are a subset of TSD facilities.

Land Disposal Restrictions - Also known as the land ban, these restrictions under RCRA prohibit any land disposal of untreated hazardous wastes, unless a national capacity variance has been granted for a specific waste.

Leachate - Liquid, including any suspended components in the liquid, that has percolated through or drained from hazardous waste.

Listed Waste - Wastes listed as hazardous under 40 CFR Part 261 Subpart D. A waste is listed as a hazardous waste based on the process from which the waste was generated and/or based on the constituents found in the waste (see also characteristic waste and delisting).

Manifest - The “cradle-to-grave” paperwork that must accompany a shipment of hazardous waste as it moves from the generator to the transporter and eventually to the TSD facility. The generator originates and signs the manifest (EPA form 8700-22 and, if necessary, EPA form 8700-22a) in accordance with the instructions included in the Appendix to 40 CFR Part 262.

Part A Permit Application or Part A - The first part of the two-part RCRA permit application that TSD facilities must submit to the authorized regulatory agency (EPA or the state).

Part B Permit Application or Part B - The second and more complicated part of the two-part RCRA permit application required for owners/operators of TSD facilities. Applicants must submit a Part B in narrative form to the designated agency and include detailed treatment of a wide range of activities and procedures needed for their facilities to demonstrate proper protection of human health and the environment.

Pollution Prevention - Any source reduction or recycling activity that results in reduction of the total volume of hazardous waste, reduction of toxicity of hazardous waste, or both, as long as that reduction is consistent with the goal of minimizing the present and future risks to public health and the environment.

Research, Development, and Demonstration (RD&D) Permit - May be issued to a hazardous waste treatment facility that proposes new and innovative or experimental treatment technologies for which there are as yet no permit standards.

Storage - The holding of hazardous waste for a temporary period, at the end of which the hazardous waste is treated, disposed, or stored elsewhere. Facilities are required to have a RCRA permit for storage of hazardous waste for more than 90 days; storage for less than 90 days does not require a RCRA permit (this applies to generators who store waste).

TSD Facility - A facility that treats, stores, and/or disposes of hazardous wastes.

Toxicity Characteristic Leaching Procedure (TCLP) - The analytical method that is used to determine whether or not a waste is a characteristic hazardous waste based on toxicity. The TCLP is also necessary to comply with provisions of land disposal restrictions as well (see also toxicity characteristic rule).

Toxicity Characteristic (TC) Rule - This rule replaces the Extraction Procedure toxicity test (EP TOX) with the TC test to determine whether or not a waste is a characteristic waste based ontoxicity. The new TC test requires analysis of 25 organic compounds in addition to the eight metals (including chromium) and six pesticides that were subject to the EP TOX test.

Transporter - A person transporting, within the United States, hazardous waste that requires a manifest. On-site movement of hazardous waste does not apply. Transporters must comply with 40 CFR Part 263.

Treatment - Any method, technique, or process, including neutralization, designed to change the physical, chemical, or biological character or composition of any hazardous waste so as to neutralize such waste, or so as to recover energy or material resources from the waste, or so as to render such waste nonhazardous, or less hazardous, safer to transport, store or dispose of, or amenable for recovery, amenable for storage, or reduced in volume.

Treatment Standards - Standards that hazardous wastes must meet prior to land disposal. A treatment standard generally expresses a treatment technology as concentration limits to give generators flexibility in choosing treatment options. Note that concentration limits are based upon the best demonstrated available technology (BDAT) for a particular waste or similar waste.

Waste Minimization - Generators and TSD facilities operating under RCRA permits are required to certify annually that they have waste minimization plans in place and that the plans are being implemented at their facilities (see also pollution prevention).

Characteristics of Hazardous Wastes. A solid waste is a hazardous waste if it exhibits any of the following characteristics: ignitability, corrosivity, reactivity, or toxicity. The methods for determining whether a waste exhibits any of the above characteristics are described in 40 CFR Parts 261.21-261.24. Specific properties defining characteristic wastes that may be applicable to EV battery constituents are described below (see 40 CFR Part 261.2 for a complete list of definitions for characteristic wastes).

Ignitability - Properties defining ignitability include (1) a substance that is not a liquid and is capable, under standard temperature and pressure, of causing fire through friction, absorption of moisture, or spontaneous chemical changes; and, when ignited, burns so vigorously and persistently that it creates a hazard; (2) a substance that is an oxidizer as defined in 49 CFR 173.151 (40 CFR 261.21). A solid waste that exhibits the characteristic of ignitability has the EPA hazardous waste number of D001.

Corrosivity - Properties defining corrosivity include (1) an aqueous waste that has a pH less than or equal to 2 or greater than or equal to 12.5 and (2) a liquid that corrodes steel (SAE 1020) at a rate greater than 6.35 mm per year at a test temperature of 55°C as determined by the test method specified in NACE (National Association of Corrosion Engineers) Standard TM-01-69 (40 CFR 261.22). A solid waste that exhibits the characteristic of corrosivity has the EPA hazardous waste number of D002.

Reactivity - Properties defining reactivity include a substance that (1) reacts violently with water, (2) forms potentially explosive mixtures with water, (3) when mixed with water, generates toxic gases, vapors, or fumes in a quantity sufficient to present a danger to human health or the environment, or (4) is a cyanide or sulfide bearing waste that, when exposed to pH conditions between 2 and 12.5, can generate toxic gases, vapors, or fumes in a quantity sufficient to present a danger to human health or the environment (40 CFR

261.23). A solid waste that exhibts the characteristics of reactivity has the EPA hazardous waste number D003.

Toxicity - A solid waste exhibits the characterististic of toxicity if, using the toxicity characteristic leaching procedure (TCLP), concentrations in the extract of a representative sample of the waste are above the EPA standards for any of the 25 organic compounds, eight metals, or six pesticides for which standards exist.

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This report identifies important environment, health, and safety issues associated with nickel metal-hydride (Ni-MH) batteries and assesses the need for further testing and analysis. Among the issues discussed are cell and battery safety, workplace health and safety, shipping requirements, and in-vehicle safety. The manufacture and recycling of Ni-MH batteries are also examined. This report also overviews the "EH&S" issues associated with other nickel-based electric vehicle batteries; it examines venting characteristics, toxicity of battery materials, and the status of spent batteries as a hazardous waste.

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