ELECTRIC VEHICLE BATTERY SYSTEMS

To Anju, Anita, and Aarti

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ELECTRIC VEHICLE BATTERY SYSTEMS

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IPR2025-00152
Tesla EX1014 Page 4

TABLE OF CONTENTS

ACKNOWLEDGMENTS ix

1 ELECTRIC VEHICLE BATTERIES 1
Electric Vehicle Operation 2
Battery Basics 4
Introduction to Electric Vehicle Batteries 4
Fuel Cell Technology 14
Choice of a Battery Type for Electric Vehicles 18

2 ELECTRIC VEHICLE BATTERY EFFICIENCY 23
Effects of VRLA Battery Formation on Electric Vehicle Performance 23
Regenerative Braking 24
Electric Vehicle Body and Frame 24
Fluids, Lubricants, and Coolants 25
Effects of Current Density on Battery Formation 25
Effects of Excessive Heat on Battery Cycle Life 35
Battery Storage 35
The Lithium-ion Battery 39
Traction Battery Pack Design 41

3 ELECTRIC VEHICLE BATTERY CAPACITY 43
Battery Capacity 43
The Temperature Dependence of Battery Capacity 44
State of Charge of a VRLA Battery 46
Capacity Discharge Testing of VRLA Batteries 51
Battery Capacity Recovery 53
Definition of NiMH Battery Capacity 54
Li-ion Battery Capacity 58
Battery Capacity Tests 60
Energy Balances for the Electric Vehicle 64

IPR2025-00152
Tesla EX1014 Page 5

4 ELECTRIC VEHICLE BATTERY CHARGING 69
Charging a Single VRLA Battery 69
Charge Completion of a Single VRLA Battery 69
Temperature Compensation During Battery Charging 72
Charging NiMH Batteries 74
Rate of Charge Effect on Charge Acceptance Efficiency of Traction Battery Packs 74
Environmental Influences on Charging 80
Charging Methods for NiMH Batteries 81
Charging Technology 87
Battery Pack Corrective Actions 91

5 ELECTRIC VEHICLE BATTERY FAST CHARGING 95
The Fast Charging Process 95
Fast Charging Strategies 98
The Fast Charger Configuration 101
Using Equalizing/Leveling Chargers 105
Inductive Charging—Making Recharging Easier 111
Range Testing of Electric Vehicles Using Fast Charging 113
Electric Vehicle Speedometer Calibration 114

6 ELECTRIC VEHICLE BATTERY DISCHARGING 115
Definition of VRLA Battery Capacity 117
Definition of NiMH Battery Capacity 119
Discharge Capacity Behavior 123
Discharge Characteristics of Li-ion Battery 127
Discharge of an Electric Vehicle Battery Pack 128
Cold-Weather Impact on Electric Vehicle Battery Discharge 130

7 ELECTRIC VEHICLE BATTERY PERFORMANCE 133
The Battery Performance Management System 133
BPMS Thermal Management System 137
The BPMS Charging Control 141
High-Voltage Cabling and Disconnects 148
Safety in Battery Design 150
Battery Pack Safety—Electrolyte Spillage and Electric Shock 153
Charging Technology 155
Electrical Insulation Breakdown Detection 157
Electrical Vehicle Component Tests 157
Building Standards 159
Ventilation 159

8 TESTING AND COMPUTER-BASED MODELING OF ELECTRIC VEHICLE BATTERIES 161
Testing Electric Vehicle Batteries 163
Accelerated Reliability Testing of Electric Vehicles 167
Battery Cycle Life versus Peak Power and Rest Period 171
Safety Requirements for Electric Vehicle Batteries 188

APPENDIX A: FUEL CELL PROCESSING TECHNOLOGY FOR TRANSPORTATION APPLICATIONS: STATUS AND PROSPECTS 191
APPENDIX B: VEHICLE BATTERY CHARGING CHECKLIST/LOG 205
APPENDIX C: DAY 1/2/3 RANGE AND CHARGE TEST LOG 207
APPENDIX D: SPEEDOMETER CALIBRATION TEST DATA LOG 209
APPENDIX E: ELECTRIC VEHICLE PERFORMANCE TEST SUMMARY 211

BIBLIOGRAPHY 215

INDEX 221

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IPR2025-00152
Tesla EX1014 Page 9

1 ELECTRIC VEHICLE BATTERIES

Road vehicles emit significant air-borne pollution, including 18% of America's suspended particulates, 27% of the volatile organic compounds, 28% of Pb, 32% of nitrogen oxides, and 62% of CO. Vehicles also release 25% of America's energy-related CO_2, the principle greenhouse gas. World pollution numbers continue to grow even more rapidly as millions of people gain access to public and personal transportation.

Electrification of our energy economy and the rise of automotive transportation are two of the most significant technological revolutions of the twentieth century. Exemplifying this massive change in the lifestyle due to growth in fossil energy supplies. From negligible energy markets in the 1900, electrical generation now accounts for 34% of the primary energy consumption in the United States, while transportation consumes 27% of the energy supply. Increased fossil fuel use has financed energy expansions: coal and natural gas provide more than 65% of the energy used to generate the nation's electricity, while refined crude oil fuels virtually all the 250 million vehicles now cruising the U.S. roadways. Renewable energy, however, provides less than 2% of the energy used in either market.

The electricity and transportation energy revolution of the 1900s has affected several different and large non-overlapping markets. Electricity is used extensively in the commercial, industrial and residential sectors, but it barely supplies an iota of energy to the transportation markets. On the other hand oil contributes only 3% of the energy input for electricity. Oil usage for the purpose of transportation contributes to merely 3% of the energy input for electricity. Oil use for transportation is large and growing. More than two-thirds of the oil consumption in the United States is used for transportation purposes, mostly for cars, trucks, and buses. With aircraft attributing to 14% of the oil consumption, ships and locomotives consume the remaining 5%. Since the United States relies on oil imports, the oil use for transportation sector has surpassed total domestic oil production every year since 1986.

IPR2025-00152
Tesla EX1014 Page 11

The present rate of reliance and consumption of fossil fuels for electrification or transportation is 100,000 times faster than the rate at which they are being created by natural forces. As the readily exploited fuels continue to be consumed, the fossil fuels are becoming more costly and difficult to extract. In order to transform the demands on the development of energy systems based on renewable resources, it is important to find an alternative to fossil fuels. Little progress has been made in using electricity generated from a centralized power grid for transportation purposes. In 1900, the number of electric cars outnumbered the gasoline cars by almost a factor of two. In addition to being less polluting, the electric cars in 1900 were silent machines. As favorites of the urban social elite, the electric cars were the cars of choice as they did not require the difficult and rather dangerous handcrank starters. This led to the development of electric vehicles (EVs) by more than 100 EV manufacturers.

However, the weight of these vehicles, long recharging time, and poor durability of electric barriers reduced the ability of electric cars to gain a long-term market presence. One pound of gasoline contained a chemical energy equivalent of 100 pounds of Pb-acid batteries. Refueling the car with gasoline required only minutes, supplies of gasoline seemed to be limitless, and the long distance delivery of goods and passengers was relatively cheap and easy. This led to the virtual disappearance of electric cars by 1920.

ELECTRIC VEHICLE OPERATION

The operation of an EV is similar to that of an internal combustion vehicle. An ignition key or numeric keypad is used to power up the vehicle's instrumentation panels and electronic control module (ECM). A gearshift placed in Drive or Reverse engages the vehicle. When the brake pedal is released, the vehicle may creep in a fashion similar to an internal combustion vehicle. When the driver pushes the accelerator pedal, a signal is sent to the ECM, which in turn applies a current and voltage from the battery system to the electric motor that is proportional to the degree to which the accelerator pedal is depressed. The motor in turn applies torque to the EV wheels. Because power/torque curves for electric motors are much broader than those for internal combustion (IC) engines, the acceleration of an EV can be much quicker. Most EVs have a built-in feature called regenerative braking, which comes into play when the accelerator pedal is released or the brake pedal is applied.

IPR2025-00152
Tesla EX1014 Page 12

This feature captures the vehicle's kinetic energy and routes it through the ECM to the battery pack. Regenerative braking mimics the deceleration effects of an IC engine.

An appealing quality of EVs is that they operate very quietly. For the most part, the handling and operation of commercial EVs is comparable to their internal combustion counterparts.

Electric Vehicle Components

The major components of the EV are an electric motor, an ECM, a traction battery, a battery management system, a smart battery charger, a cabling system, a regenerative braking system, a vehicle body, a frame, EV fluids for cooling, braking, etc., and lubricants. It is important to look at the individual functions of each of these components and how they integrate to operate the vehicle.

Electronic Drive Systems

An EV is propelled by an electric motor. The traction motor is in turn controlled by the engine controller or an electronic control module. Electric motors may be understood through the principles of electromagnetism and physics. In simple terms, an electrical conductor carrying current in the presence of a magnetic field experiences a force (torque) that is proportional to the product of the current and the strength of the magnetic field. Conversely, a conductor that is moved through a magnetic field experiences an induced current. In an electric propulsion system, the electronic control module regulates the amount of current and voltage that the electric motor receives. Operating voltages can be as high as 360 V or higher. The controller takes a signal from the vehicle's accelerator pedal and controls the electric energy provided to the motor, causing the torque to turn the wheels.

There are two major types of electric drive systems: alternating current (AC) and direct current (DC). In the past, DC motors were commonly used for variable-speed applications. Because of recent advances in high-power electronics, however, AC motors are now more widely used for these applications. DC motors are typically easier to control and are less expensive, but they are often larger and heavier than AC motors. At the same time, AC motors and controllers usually have a higher efficiency over a large operational range, but, due to complex electronics, the ECMs are more expensive. Today, both AC and DC technologies can be found in commercial automobiles.

IPR2025-00152
Tesla EX1014 Page 13

BATTERY BASICS

A battery cell consists of five major components: (1) electrodes—anode and cathode; (2) separators; (3) terminals; (4) electrolyte; and (5) a case or enclosure. Battery cells are grouped together into a single mechanical and electrical unit called a battery module. These modules are electrically connected to form a battery pack, which powers the electronic drive systems.

There are two terminals per battery, one negative and one positive. The electrolyte can be a liquid, gel, or solid material. Traditional batteries, such as lead-acid (Pb-acid), nickel-cadmium (NiCd), and others have used a liquid electrolyte. This electrolyte may either be acidic or alkaline, depending on the type of battery. In many of the advanced batteries under development today for EV applications, the electrolyte is a gel, paste, or resin. Examples of these battery types are advanced sealed Pb-acid, NiMH, and Lithium (Li)-ion batteries. Lithium-polymer batteries, presently under development, have a solid electrolyte. In the most basic terms, a battery is an electrochemical cell in which an electric potential (voltage) is generated at the battery terminals by a difference in potential between the positive and negative electrodes. When an electrical load such as a motor is connected to the battery terminals, an electric circuit is completed, and current is passed through the motor, generating the torque. Outside the battery, current flows from the positive terminal, through the motor, and returns to the negative terminal. As the process continues, the battery delivers its stored energy from a charged to a discharged state. If the electrical load is replaced by an external power source that reverses the flow of the current through the battery, the battery can be charged. This process is used to reform the electrodes to their original chemical state, or full charge.

INTRODUCTION TO ELECTRIC VEHICLE BATTERIES

In the early part of 1900s, the EV design could not compete with the plethora of inventions for the internal combustion engine. The speed and range of the internal combustion engines made them an efficient solution for transportation. By the middle of the 1900s, discussions about the impending oil supplies, the growing demands of fossil fuels began to rekindle the inventions of alternate energy systems and discovery of alternate energy sources. By the mid-1970s, oil shortages led to aggressive development of EV programs. However, a temporarily stable oil supply thereafter and a rather slow advancement in

IPR2025-00152
Tesla EX1014 Page 14

battery charge terminations can be enabled at the same time. The charge electronics uses A/D converters to measure peak voltage to within a 2 mV range. This value is less than 0.6% of the voltage of a battery during charging on a per cell basis.

Alternately, IC makers offer different charge techniques. Charge electronics combines programmable, constant-current based fast charging with overvoltage protection for NiMH batteries. Unlike typical detection methods, such as the $-\Delta V$ or dT/dt methods, the charger controller detects an inflection point d^2V/dt^2. This point is reached by the charged battery at approximately 90% capacity and occurs when the battery voltage increase tends to accelerate. This detection mechanism is NiMH battery friendly as it detects the overcharge process at an early stage.

Upon detection of the inflection point, the charger continues the charge current for another 20-minute period. This is followed by a trickle charge phase to maintain a full charge. In order to prevent an inaccurate voltage measurement, the charging is halted, briefly, while a voltage measurement is taken. In addition, the charge control may include options for automatic predischarge of the battery pack, timed charging, and the choice of use of a switched mode power supply.

CHARGING TECHNOLOGY

With electric vehicles (EVs) comes the EV recharge infrastructure, both for public and private, or domestic use. This infrastructure includes recharging units, ventilation requirements, and electrical safety features suited for both indoor and outdoor charging stations. As an example of the developments, to ensure the safe installation of charging equipment, changes have been made to State of California Building and Electrical codes.

Charging Stations

During EV charging, the charger transforms electricity supplied by the local utility into energy compatible with the vehicle's battery pack voltage requirements. According to the Society of Automotive Engineers (SAE), the complete EV charging system consists of the equipment required to both condition and transfer energy from a constant-frequency, constant-voltage source or network to direct current. The direct current is required for the purpose of charging the battery and/or operating the EV electrical systems (e.g., EV interior preconditioning,

traction battery thermal management, onboard vehicle computer). The charger communicates with the battery management system and/or monitor (BMON). The management system and/or BMON in turn calculates how much voltage and current is required to charge the battery system.

Charging is accomplished by passing an electrical current through the battery to reform its active materials into their high-energy charge state. The charging process is basically a reverse of the discharging process. Current is forced to flow back to the traction battery pack. This current initiates a chemical reaction in the opposite direction. The algorithm by which this is achieved differs depending upon the battery type and due to the variations in their chemical compositions.

The EV is connected to the EV supply equipment (EVSE), which, in turn, is connected to the local utility. The National Electrical Code (NEC) defines this equipment as the ungrounded conductors, grounded conductors, equipment grounding conductors, EV couplings and connectors, attachment plugs, and all other fittings, devices, power outlets, or accessories installed specifically for the purpose of delivering energy from the utility wiring to the EV.

For residential or private and most public charging locations, there are two power levels: Level I and Level II. Level I or convenience charging, allows for charging the traction battery pack while the vehicle is connected to a 120 V, 15 A branch circuit. A complete charging cycle takes anywhere from 10 to 15 hours to be completed. This type of charging system uses the common grounded electrical outlets and is used when Level II charging is unavailable. Level II charging takes place while the vehicle is connected to a 240 V, 40 A circuit, dedicated solely for EV traction battery charging purposes only. At the Level II voltage and current levels, a full charge takes from 3 to 8 hours, depending on battery type. In order to sustain the Level II power requirements, EVSE must be hardwired to the premises wiring.

A third power level, Level III is any EVSE with a power rating greater than Level II. Most Level III charging systems are located off the vehicle platforms. Level III charging is defined as the EV equivalent of a commercial gasoline service station. In this case, a Level III charging station can successfully charge an EV in a matter of minutes. To accomplish Level III charging, the equipment must be rated at power levels from 75 to 150 kW. The Level III requires supply circuit to the equipment be rated at 480 V, 3 ϕ and between 90 to 250 A. However, the supply circuit for the Level III charge may be even larger in capacity. The equipment is to be handled by specially trained personnel.

IPR2025-00152
Tesla EX1014 Page 16

All EV infrastructural equipment, at all power levels, are required to be manufactured and installed in accordance with published standards documents such as: NFPA (NEC Article 625), SAE (J1772, J1773, J2293, others), UL (2202, 2231, 2251, others), IEEE/IEC, FCC (Title 47–Part 15), and several others.

Coupling Types

The EV system will be connected to the vehicle by the general public in all weather conditions. There are currently two primary methods of transferring power to EVs: (1) conductive coupling and (2) inductive coupling.

In the conductive coupling method, connectors use a physical metallic contact to pass electrical energy when they are joined together. Specific EV coupling systems—connectors paired with inlets—have been designed that provide a nonenergized interface to the charger operator. Thus, not only is voltage prevented from being present before the connection is completed, the metallic contacts are completely covered and inaccessible to the operator.

In the inductive coupling method, the coupling system acts as a transformer. AC power is transferred magnetically, or induced, between a primary winding, on the supply side, to a secondary winding, on the vehicle side. This method uses EV infrastructure that converts standard power-line frequency (60 Hz) to high frequency (80,000 to 300,000 Hz), reducing the size of the transformer equipment. The inductive connection is developed primarily for EV applications, though it has been applied to other small appliances.

In both conductive and inductive coupling, the connection process is safe and convenient for all users.

Charging Methods

There are three primary methods of charging EV batteries: (1) constant voltage; (2) constant current; and (3) a combination of the two.

Most EV charging systems use a constant voltage for the initial portion of the charging process, followed by a constant current for the finish. Most of the battery capacity is restored during the constant-voltage portion of the charging cycle. The constant-current portion of the charge cycle, commonly referred to as a trickle charge, serves to slowly top off the battery at a rate sufficiently slow to prevent the off-gassing of either hydrogen or oxygen from the electrolyte.

batteries are operated in enclosed cabinets, without fans or a heating system, the cabinets must be vented or the small emissions of hydrogen will build up to dangerous explosive levels.

In addition, space requirements should also be considered during EV battery pack design. Flooded Pb-acid batteries require 32% more space than their equivalent VRLA battery. The additional space requirements are due to rack requirement and the need to provide space to access the battery for maintenance purposes. Thus when it comes to deciding the most suited Pb-acid battery technology for EVs, the VRLA battery provides the greatest benefits to the user.

COLD-WEATHER IMPACT ON ELECTRIC VEHICLE BATTERY DISCHARGE

As seen with temperature characteristics of the traction battery, low temperature limits the battery discharge and useful available capacity. For commercial viability and customer acceptance, EVs need to operate reliably over a wide climatic range. The cold weather deterioration of range is well known, however, it is important to identify and quantify the causes of battery pack degradation. Once the solutions have been identified, it is important to pursue the solutions to eliminate the causes.

The EV performance under cold temperature conditions is analyzed by installing instrumentation on the vehicle to measure the electrical energy entering and leaving the battery pack. Energy consumed is measured for the system controller, climate or HVAC, and the vehicle accessories.

As part of the early phase of the test plan, it is important to develop a test plan and procedure. The necessary hardware required for the test should be installed to observe the battery capacity and SOC characteristics of the traction battery pack. In addition, it is useful to evaluate the new EV lubricant and tires. Understanding of the winter condition HVAC and accessory loads is also useful in determining the EV performance under cold temperature conditions. While gaining an understanding of the HVAC and accessory loads, it is important to evaluate the correction factors developed during the course of the EV analyses.

The cold weather performance tests are performed at 55 mph driving condition on a level concrete road. The driving profiles used during the performance tests include at least four different drivers with no specific instructions. The battery pack is tested several times during the day of the test. The battery pack tests are then repeated two to three times during the week. All tests of the battery pack performance are termi-

nated when the end-of-test criterion has been reached.

Some of the observations of the cold weather performance on a compact size EV using VRLA batteries are:

1. Aerodynamic drag effect makes a significant impact on cold weather performance. The power required is about 10% higher at 20°F than at 70°F. The aerodynamic drag increases owing to higher air density (for a given drag coefficient) as the battery pack temperature increases.

2. Losses associated with EV lubricants are low at low-operating temperatures. Better performance lubricants are required to reduce the viscous losses.

3. Road traction losses increase under cold weather operating conditions. Newly developed EV battery tires, operating at 50 psi, provide good performance and low rolling resistance at warmer operating temperatures. Further development of battery tires for cold-weather performance will reduce rolling resistance losses.

4. On road traction power required at 0°F is 60% higher than at 70°F. The traction power is indexed to power required at ambient temperature of 70°F. The ratio of power at different ambient temperatures is referenced to 70°F to maintain 55 mph EV speed.

5. Wet versus dry traction power of the EV increases to more than 5% on the wet road. Power required on a wet road to maintain EV speed at 55 mph is approximately 60 mph.

Varying driver profiles impact the EV cold-weather performance as each driver has a different profile. Some drivers are interested in comfort while some of the drivers are interested in distance and performance. The heater accessory power consumption is 1,800 W and the low beam headlights and taillights power consumption is 300 W.

Assuming that the 10 kWhr energy is supplied during the EV driving, at an ambient temperature of 70°F, the compact EV travels 75 miles at 55 mph. Under the same load conditions, the EV travels 50 miles at 55 mph at 20°F. Thus the range of the EV is reduced at a lower temperature.

The battery pack differential—temperature difference—between the ambient and the battery pack is large. In most cases the temperature differential is 15 to 40°C above the ambient temperature. The pack temperature differential is observed to be larger at lower ambient temperatures than at higher ambient temperatures.

The effective battery pack energy diminishes significantly when the Pack Capacity (Whr) tests are conducted at cold temperatures. This is

owing to the battery pack temperature and the reduced battery capacity resulting from a higher current draw at higher power requirements. It is important to develop a battery thermal control system to maintain the battery pack temperature within limits.

EV driving range is impacted by temperature. At 55 mph speeds, the vehicle range reduces from 100 miles at 70°F, to 75 miles at 40°F, to 55 miles at 20°F, down to 44 miles at 0°F. This range reduction is due to cold temperature effects on battery pack performance.

When the HVAC system is in use, and the compact size vehicle is being driven at 55 mph, the range reduces to 40 miles. The battery pack in this mode is being maintained at 70°F.

When the HVAC and the Pb-acid battery is under discharge under cold temperature conditions, the range of the EV is reduced to 35 miles at 20°F and 22 miles at 0°F.

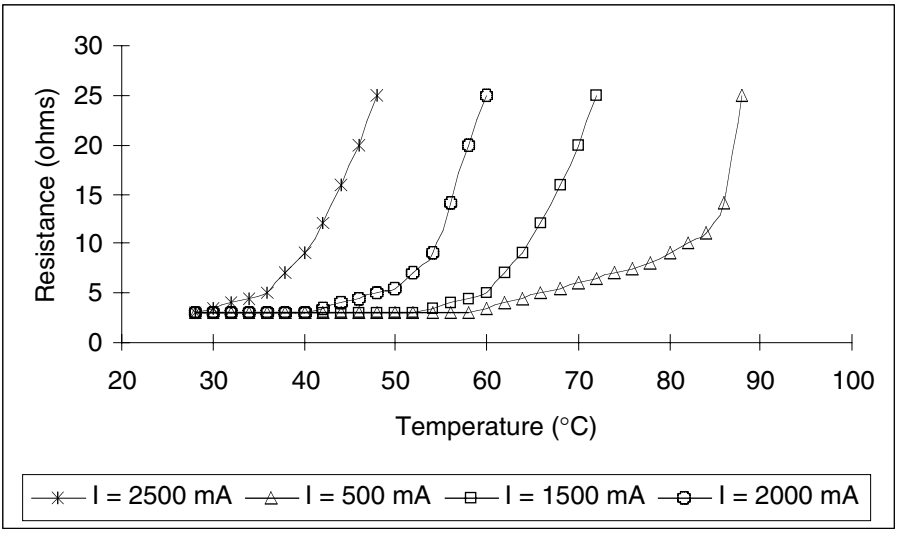
The compact EV has a range of 100 miles at steady 55 mph at an ambient temperature of 70°F. Typically, the vehicle consumes 140 Whr/mile at 70°F for propulsion only. The vehicle consumption increases to to 245 Whr/mile at 0°F (75% more).

Assume a gasoline-powered vehicle gets 30 miles/gallon at 55 mph—that's about 1,100 Whr/mile.

If the compact EV power consumption increases by 105 Whr/mile at 0°F, its efficiency would be reduced only 9% to 27.3 miles/gallon. Engine coolant and exhaust system heat may actually reduce the losses.

The compact EV losses may be broken down into component losses. The drive unit mechanical losses are primarily related to the gear train, while electrical losses are related to the alternating current (AC) motor and power inverter. Battery losses are not included. The other chassis losses are due to drive shaft, residual brake drag, and wheel bearings. HVAC is the heating, ventilation, and air conditioning system using a heat pump.

Figure 7–2 PPTC thermistor profile at varying current densities.



with insignificant rise of battery cell temperature. After 40 minutes, the battery temperature rises at a rate of 11°C/minute. After 44 minutes, the battery voltage and temperature rises. The temperature increase is at a rate of 20°C/minute. The external cell temperature reaches 85°C before stabilizing at 80°C. The maximum cell temperature of 85°C is 30°C below the temperature reached by the battery cell without a PPTC thermistor protection.

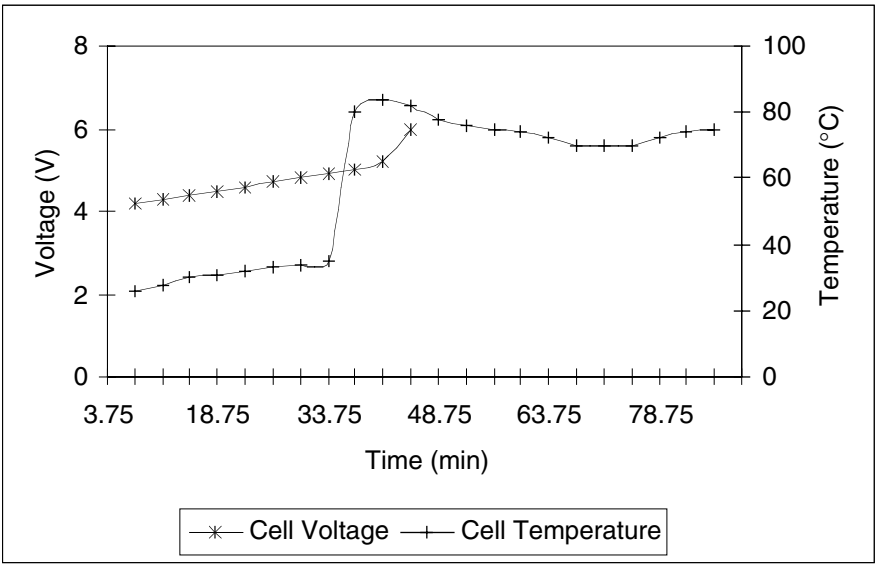
The PPTC thermistor operating at a low temperature limits the charge current close to the functional pack operating temperature as shown in Figure 7–3. The PPTC thermistor resets itself when the battery pack temperature rises, owing to excessive sunlight exposure. This feature prevents the battery pack from being disconnected owing to nuisance tripping at high battery pack temperatures.

The BPMS Charge Indicator

The battery charge indicator or fuel gauge should provide the actual battery capacity and nominal battery capacity readings. This indication is represented as:

- A miles-to-go indicator or a fuel gauge
- An economy range indicator in terms of kWhr/mile or kWhr/km

Figure 7–3 PPTC thermistor voltage/temperature characteristics.



- A warning light or an audible signal for a battery in a dangerous or faulty condition requiring immediate servicing as a "maintenance required" command

This condition should not be capable of being bypassed without a reset and disengagement of the battery pack from the traction controller module. The available energy or capacity of fully formed traction battery can be divided into three portions. The first portion of the capacity is the energy that can be restored or replenished by charging. The second portion of the traction battery energy is the available energy under the present conditions of SOC, discharge, and temperature. The third portion of the traction battery energy is the unusable energy owing to crystalline oxide formation, also known as memory. Both VRLA and NiMH batteries exhibit this memory effect.

While the SOC indicator or fuel gauge is useful, the gauge is reset to 100% each time the battery pack is recharged. The gauge shows a 100% each time regardless of the individual battery's state of health. This leads to a serious miscount of the battery pack energy being shown as 100% after a full charge, when in fact the charge acceptance has dropped down

CHARGING TECHNOLOGY

With EVs comes the EV recharging infrastructure, both for public, domestic, and private use. This charging infrastructure includes recharging units, ventilation, and electrical safety features for indoor and outdoor charging stations. To ensure the safe installation of charging equipment, changes have been made to building and electrical codes.

Charging Stations

During EV charging, the charger transforms electricity from the utility into energy compatible with the vehicle's battery pack. According to Society of Automotive Engineers (SAE), the full EV charging system consists of the equipment required to condition and transfer energy from the constant-frequency, constant-voltage supply network to direct current. For the purpose of charging the battery and/or operating the vehicles electrical systems, vehicle interior preconditioning, battery thermal management, onboard vehicle computer, the charger communicates with the BMON. The BMON dictates how much voltage and current can be delivered by the building wiring system to the EV battery system.

Charging of the battery pack is passing an electrical current through the battery to reform its active materials to their high-energy charge state. The charging process is a reverse of the discharging process, in that current is forced to flow back through the battery, driving the chemical reaction in the opposite direction. The algorithm by which this is accomplished is different for each battery type due to the variations in the batteries' chemical components.

The EV is connected to the Electric Vehicle Supply Equipment (EVSE), which in turn is connected to the building wiring. The National Electrical Code (NEC) defines this equipment as the conductors, including the ungrounded and grounded, equipment grounding conductors, the EV connectors, attachment plugs of all other fittings, devices, power outlets, or apparatus installed specifically for the purpose of delivering energy from the premise wiring to the EV.

For residential and most public charging locations, there are two power levels that will be used: Level 1 and Level II. Level I, or convenience charging, occurs while the vehicle is connected to a 120 V, 15 A branch circuit, with a complete charging cycle taking anywhere from 10 to 15 hours. This type of charging system uses the common grounded electrical outlets and is most often used when Level II charging is

unavailable. Level II charging takes place while the vehicle is connected to a 240 V, 40 A circuit that is dedicated for EV usage only. At this voltage and current level, a full charge takes from 3 to 8 hours depending on battery type. EVSE for this power level must be hardwired to the premises wiring.

A third power level, Level III, is any EVSE with a power rating greater than Level II. Most of the Level III charging system is located off the vehicle platform. During Level III charging, which is the EV equivalent of a commercial gasoline service station, an EV can be charged in a matter of minutes. To accomplish Level III charging, it is likely that this equipment may be rated at power levels from 75 to 150 kW, requiring that the supply circuit to the equipment be rated at 480 V, 3 ϕ, 90 to 250 A. Supply circuits may require to be even be larger. Only trained personnel should handle this equipment.

All EVSE equipment, at all power levels, are required to be manufactured and installed in accordance with published standards documents such as: NFPA (NEC Article 625), SAE (J1772, J1773, J2293, others), UL (2202, 2231, 2251, others), IEEE / IEC, FCC (Title 47–Part 15), and several others.

Coupling Types

EVSE can be connected to the EV by the general public under all weather conditions. There are currently two primary methods of transferring power to EVs: (1) conductive coupling, and (2) inductive coupling.

In the conductive coupling method, connectors use a physical metallic contact to pass electrical energy when they are joined together. Specific EV coupling systems—connectors paired with electrical inlets—have been designed that provide a nonenergized interface to the charger operator. Thus, not only is the voltage prevented from being present before the connection is completed, the metallic contacts are also completely covered and inaccessible to the operator.

In the inductive coupling method, the coupling system acts as a transformer. AC power is transferred magnetically, or induced between a primary winding, on the supply side to a secondary winding on the vehicle side. This method uses EVSE that converts standard power-line frequency (60 Hz) to high frequency (80 to 300 kHz), reducing the size of the transformer equipment. The inductive connection is developed primarily for EV applications, though it has been applied to other small appliances.

In both conductive and inductive coupling, the connection process is safe and convenient for all EV applications.

IPR2025-00152
Tesla EX1014 Page 24

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IPR2025-00152
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IPR2025-00152
Tesla EX1014 Page 29

INDEX

AB_2/AB_5 alloys, 9
Absorbed glass mat (AGM) batteries, 7–8, 34, 98; *See also* Valve regulated lead-acid batteries
Accelerated reliability testing, 167–71
Acceleration, 2, 59, 63–64, 66, 182–83
Accidents, 149–50, 154, 167, 189–90
AC conductance tests, 92–93
Acid spills, 151
AC impedance tests, 92–93
AC motors, 3
Active equalization, 141–42
Adhesion of active paste, 31
Aerodynamic drag, 65, 131, 182
AGM (absorbed glass mat) batteries, 7–8, 34, 98; *See also* Valve regulated lead-acid batteries
Air emissions, 187, 191, 193, 201–2
Air-flow models, 138–40
Alkaline fuel cells (AFC), 199
Alternating current (AC) motors, 3
Ambient temperature model, 139
Ampacity, 52
ANSI/IEEE 450 standard, 53, 60–64
Antimony, in Pb-acid batteries, 6, 34–35
Arrenhius equation, 179
Auxiliary power units (APUs), 68, 186–87
Auxiliary systems, 170, 185

Batteries; *See also names of individual battery types*
  choice of, 18–21
  definition and components, 4
  power calculation, 184–85
  safety design, 150–53, 188–90
  smart, 147–48
  USABC on, 4–5
  12 V auxiliary, 148–49
Battery acceptance test, 60–62
Battery condition indicators, 146
Battery degradation, fast charging and, 108–10; *See also* Cycle life
Battery modules, 4, 140–41; *See also* Battery packs
Battery monitors (BMONs), 88, 103, 127, 136, 147–48, 155
Battery packs
  capacity determination, 118–19
  charging/discharging patterns, 117–19, 128–30, 136
  cold temperature, 131–32
  components monitored during testing, 169
  design, 41–42, 133, 140–41
  insulation breakdown detection, 157
  nonuniform temperature, 117, 177
  state of charge calculations, 48
  thermal management, 137–41
  voltage calculation, 176
  voltage cut-off point, 118
  weak cells, 61, 126, 133–34
Battery Performance Management System (BPMS), 133–48
  charge indicators, 144–46
  charge protectors, 142
  charging control, 141–48
  charging/discharging monitoring, 134–35
  components, 134
  design analysis, 140–41
  diagnostics control, 147–48
  model of, 135–36
  thermal management, 137–41, 152
  thermistors, 142–45
  typical configuration, 136–37
Battery performance test, 60–62
Battery scaling, 188
Battery service capacity test, 60
Battery testing, 161–90; *See also* Electric vehicle testing
  capacity discharge, 51–53
  charge completion on oxidation, 166

IPR2025-00152
Tesla EX1014 Page 31

conductance, 92–93
constant current discharge, 164
constant power, 164
core battery performance, 163–66
crash tests, 189
cycle life, 171–73
fast charge, 166
NiMH modeling, 174–76
partial discharge, 165
peak power, 164
performance/acceptance, 60–62
recommendations, 173–76
service capacity, 60
standloss, 165
testing approach, 161–62
thermo-electrochemical model, 176–88
variable power discharge, 115, 164
vibrations, 166
Battery vibration test, 166
BMONs (battery monitors), 88, 103, 127, 136, 147–48, 155
Boost charges; *See* Equalization charges
Bottom-pour casting, 32
BPMS; *See* Battery Performance Management System
Braking, regenerative, 2–3, 24, 68, 134, 183
Braking system component monitoring, 170–71
Breakdowns, vehicle, 168
Building codes, 90, 159

Calcium, in Pb-acid batteries, 6, 34–35
Capacity, battery, 43–68
ampacity, 52
battery acceptance test, 60–62
Battery Performance Management System, 135–36
battery performance test, 60–62
battery service capacity test, 60
calculation, 187–88
charge rate *vs.*, 76, 96, 106–7
C ratings, 54–57, 119–20
definitions, 54–57
during discharge, 51–53, 119–20, 123–27
fuel gauges, 145–46
grid corrosion and, 31
Li-ion batteries, 58–59
NiMH batteries, 39, 54–57, 123–27
positive *vs.* negative electrodes, 82
recovery, 53–54
360-second discharge test profiles, 62–63
state of charge regulation and, 49
sulfation, 35, 52
temperature dependence, 44–46, 118–19, 135, 177
variable power discharge test, 62–63
VRLA batteries, 117–19
weak cells, 61, 126
Capacity discharge testing, 51–53
Carbonate, molten, 16
Carbon compounds, in Li-ion batteries, 10
Carbon monoxide, in fuel cells, 197
Casings, 14, 31
Catalysts
benefits of, 33–34
platinum, 15, 17, 192, 195, 197
Catalytic converters, 187
Cathodes, 10, 13, 26, 30; *See also* Electrodes
C1(T) criterion, 83–84
Cell polarity reversal profile, 125–26
Cells, number of, 41
Cell voltage, 120
Charge acceptance rates
during fast charging, 96–97, 106–7
fuel gauges and, 145–46
heat dissipation, 180
inefficiencies, 81
modeling, 175
Charge completion on oxidation test, 166
Charge indicators, 144–46
Charge switching method, 79–80
Charging, battery, 69–94; *See also* Charging stations; Fast charging; Overcharging
during accelerated reliability testing, 168
Battery Performance Management Systems, 134, 141–48
charge acceptance rates, 81, 96–97, 106–7, 145–46, 175, 180
charge completion on oxidation test, 166
charge protectors, 142–44
checklist/log, 205
components monitored during testing, 169
constant current, 172–73, 179–81
constant current-constant voltage, 69–71, 86, 89, 98–99, 172
couplers, 89, 111–12, 151–52, 156
cycle life and, 172
data storage on, 136–37
depolarization enhancement of, 146–47
efficiency calculations, 94
environmental influences on, 80–81
equalization, 32–33, 71, 93–94, 105–8, 118, 141–42
excessive, 35–36
inadequate, 36
inductive, 111–12

inflection point detection, 87
intelligent chargers, 85–87
Li-ion batteries, 12, 39–40
maximum power, 50
NiMH batteries, 74, 78, 81–87
overview, 4, 155
rate terminology, 95
safety considerations, 90–91
shunts, 141
smart batteries, 147–48
standard receptacles, 103
state of charge calculations, 47–48
temperature-based termination methods, 78–80, 83–85
temperature compensation, 34–35, 70–73
temperature sensing, 74–78
trickle, 86, 89, 96, 109–10
ventilation, 90–91
VRLA batteries, 34–35, 69–71
Charging stations
charger controls, 102–4, 148
couplers, 89, 111–12, 151–52, 156
fast charging, 103–5
inductive charging, 111–12
power levels, 88–89, 155–56
prerequisites, 104–5
required equipment, 87–88
Circulating-liquid thermal management system, 140
Clamp voltage, during charging, 69–71, 73
Clean Air Act, 202–3
Cobalt oxides, 10–11, 13
Cold weather; *See also* Temperature
discharge capacity, 123–24, 130–32
driving range, 131–32
fast charging, 98
fuel gauges, 146
performance tests, 130–31
state of charge calculations, 48
Collectors, copper/aluminum foil, 14
Compressed natural gas (CNG), 17–18
Conductance tests, 92–93
Conductive coupling, 89, 156
Constant current charge method, 172–73, 179–81
Constant current-constant voltage (CI-CV), 69–71, 86, 89, 98–99, 172
Constant current discharge test, 164
Constant power test, 164
Containment systems, 151
Coolants, 25, 140
Cooling of batteries, 77, 92, 172–73
Copper oxide catalysts, 197
Corrosivity, 151
Costs
battery amortization, 171
battery maintenance, 8
fuel cell stacks, 192, 195–96
hydrogen research, 19
internal combustion engine powertrain, 17
Li-ion battery production, 20–21
NiMH production, 21
operating, 171
platinum catalyst, 17, 192
repair, 168
Couplers, charge, 89, 111–12, 151–52, 156
Crashes, 149–50, 154, 167, 189–90
C ratings, 54, 119–20
Current, battery, 49–50, 94
Current density, 25–35
Cycle life
charge method and, 172
definition, 53
depth of discharge, 53–54
Li-ion batteries, 19–20
NiMH batteries, 38–39
peak power demand and, 171–72
rest periods and, 171–73
VRLA specifications, 44

Daimler-Chrysler, 5, 18, 197, 212
DC (direct current) motors, 3
Deceleration, 149, 183–84
Dendrite formation, 11, 40, 109–10
Department of Energy (DOE), 193
Depolarization, charge enhancement, 146–47
Depth of discharge (DOD)
battery resistance, 58
charge capacity and, 109
cycle life, 53–54
discharge rate and, 56–57
modeling, 175, 188
temperature dependence, 46
Diagnostics control, 147–48
Diffusion coefficient calculation, 179
Direct current (DC) motors, 3
Discharge current, 43–44, 45
Discharging, 115–32
Battery Performance Management System, 134–35
capacity during, 51–53, 119–20, 123–27
capacity ratings and, 54
cold weather impacts, 123–24, 130–32
data storage on, 136–37
discharge tests, 51–53, 115–17, 164–66

end-of-discharge voltage, 126–27
Li-ion batteries, 12, 127–29
load voltages *vs*. capacity, 119–20
NiMH batteries, 56–58, 121–27, 175
partial, 109, 165
power calculation, 41, 50–51
pulses, 124, 128–29
temperature and, 58, 115–17, 122
termination of, 124–27
voltage profiles, 55–58, 121–26
Disconnects, high-voltage, 149–50
DOD; *See* Depth of discharge
Downtime, vehicle, 168
Drag losses, 65–68, 131
Driveshaft power, 181–83
Driveshaft torque, 182–83
Drive train efficiency, 67, 170
Driving conditions
battery discharge, 115–17, 128–29
change in resistance, 65
depth of discharge, 58
heat calculations, 138
during reliability testing, 167–71
state of charge during, 47
twenty-step test profile, 63
wet, 131
Driving range, 24, 113–14, 130–32, 211–13; *See also* Efficiency, battery
Durability tests, 157
Dynamic Stress Test (DST), 115–17, 165
Dynamometer tests, 162

Efficiency, battery, 23–42
charging, 94
elevated temperatures, 28–29, 35
EV body and frame, 24–25
factors affecting, 24
failure modes of VRLA batteries, 31–35
fuel cells, 16–17, 194
NiMH battery formation, 26–31
regenerative braking, 24
Efficiency, vehicle, 66–67
Electrical safety, 151–52
Electrical utilities, fast charging and, 110–11
Electric bus isolation, 149
Electric motors, 3
Electric shock, 153–54, 157, 189
Electric vehicle batteries; *See* Batteries; *names of individual battery types*
Electric vehicles (EVs)
air emissions, 202
body and frame materials, 24–25
charging times, 102, 112
components, 3
electronic drive systems, 3
energy balances, 64–68
fast charging range testing, 113–14
fluids, lubricants, and coolants, 25
headlights and taillights, 131
heaters, 131
lubricants, 130–31
motor power, 183
need for, 2, 4–5
operation, 2–3
overall charging efficiency, 94
performance models, 181
performance test summary, 211–13
reliability/durability tests, 157, 167–71
speedometer calibration, 114, 209
tires, 130–31
Electric vehicle supply equipment (EVSE), 88
Electric vehicle testing
accelerated reliability, 167–71
cold weather performance, 130–31
crash, 189
driving range, 113–14
Dynamic Stress Test, 115–17, 165
endurance, 158
extended life, 158
freeway driving, 212–13
operating life, 158
performance safety and abuse, 167
range and charge test log, 207
reliability/durability, 157, 167–71
special performance, 165
specific model results, 211–12
standloss, 165
sustained hill-climb power, 165–66
thermal performance, 166
urban driving, 62, 211–12
Electrodes
cathodes, 10, 13, 26, 30
membrane-electrode-assembly, 195
memory effects, 147
oxidation, 27–28
passivation layer, 53–54
reactions at, 174
surface etching, 30
weight of, 42
Electrolysis
during charging phase, 7, 74, 108–10
with complete discharge, 124–25
in fuel cells, 15
gas buildup, 109
in VRLA batteries, 33, 108–10

Electrolytes
in absorbed glass mat batteries, 7
activity variations, 98
additives, 153
boiling points, 151
during charging phase, 7
conductivity, 59, 92, 179
corrosive, 151
forced circulation, 174
in fuel cells, 16
leakage during storage, 38
overcharging and, 11
over-discharge, 124–25
polymers, 10–14, 16, 195, 199
safety design, 150–51, 153–54
spillage during crashes, 189–90
sulphuric acid, 6
temperature and, 35, 162
types of, 4
Electronic control module (ECM), 2–3, 67, 127
Electronic drive systems, 3
Emissions, 187, 191, 193, 201–2
End-of-discharge voltage (EODV), 126–27
Energy consumption calculations, 64–68
Energy densities, 12–13, 20, 42, 44
Energy equations, 188
Engine efficiency, 67–68
Entropy changes, 97
Environmental concerns
air emissions, 187, 191, 193, 201–2
Li-ion *vs*. NiMH batteries, 11
manganese *vs*. cobalt or nickel, 59
EPIC performance summary, 212
Equalization charges
active, 141–42
battery packs, 93–94
in fast charging, 105–8
magnitude, 32–33
to prevent over-discharges, 118
single VRLA batteries, 71
Etch treatments, 30
Ethanol, in fuel cells, 193, 196
Europe, fuel cells in, 194–95
EVs; *See* Electric vehicles
Extended life tests, 158

Failure modes, battery
battery storage conditions, 37
excessive charging, 35–36
inadequate charging, 36
overview, 33
VRLA batteries, 31–35

Fast charging, 95–114
battery degradation, 108–10
charge acceptance ability, 96–97
charger configuration, 101–5
constant current-constant voltage method, 98–99
dendrite formation, 109–10
electrical utilities and, 110–11
equalization charges, 105–8
fast charge test, 166
feedback control, 100
heat production, 97–98, 101
inductive, 111–12
limitations of, 105–6
maximum voltage-maximum current profiles, 101–3
NiMH batteries, 84
overcharging, 96–97, 107–9
prerequisites, 104–5
process overview, 95–98
range testing, 113–14
strategies, 98–101
temperature and, 97, 100, 108–9
ultra-fast, 86
USABC goal for, 166
voltage/current profiles, 99–100
Federal Urban Driving Schedule (FUDS), 115, 123, 164–65
Field emission transistors (FETs), 142
Flame arrestors, 7–8
Float charge, 34
Flooded batteries, 6, 129–30, 151, 173
Fluids, EV, 25
Ford Motor Company, 5, 211–12
Ford Ranger test summary, 211–12
Fossil fuel use, 1–2
Freeway driving tests, 212–13
FUDS (Federal Urban Driving Schedule), 115, 123, 164–65
Fuel cell technology, 191–204
advantages of, 191–92, 198
air emissions, 191, 193, 201–2
alkaline, 199
batteries, 197–98
catalysts, 200
comparison of technologies, 198–201
cost reductions, 17, 192, 195–96
Daimler-Chrysler concept, 18, 197
DOE bus, 193
efficiency ratings, 194
fuel cell stacks, 192, 195
fuel economy, 193
ionomeric membranes, 200
market entry strategies, 203–4

molten carbonate, 16
next generation objectives, 193
overview, 14–18
phosphoric acid based, 16, 199
polymer electrolyte, 16, 195, 199–201
proton exchange membrane fuel cells, 15, 17, 194–95, 198–99
recent developments, 192–94
solid oxide, 16, 199
Fuel gauges, 144–46
Fuel stack technology, 192
Fuel vaporizers, 18

Gas diffusers, 200–201
Gasoline, in fuel cell technology, 196–97
Gel technology batteries, 7–8
General Motors, 5, 196
Glass mat batteries, 7–8, 34, 98
Graphite, 10, 40, 200
Graves, Sir William, 14–15
Gravitational power, 182
Grid corrosion, 31–32
Grid growth, 31–32
Ground-fault circuit interrupter devices, 90, 149, 152

Hall effect sensors, 136
Headlights, 131
Heat capacity, 75–76, 101
Heat dissipation, 180–81, 197
Heaters, 131
Heat generation models, 138–39, 177–81
Heating, external, 77
Heat pumps, 25
Heat transfer coefficients, 178–81
Heat transfer models, 138–39, 178–81
High-pressure gas atomization, 10
High-speed data bus (HSDB), 136–37, 147–48
High-voltage wiring systems, 148–50
Hissing, during fast charging, 98
Honda Motor Company, 5
HVAC system, 132
Hybrid vehicles, 68, 127, 186–87
Hydride electrodes, 9
Hydrogen
combustible levels, 91, 159
in fuel cells, 15–17, 191
in NiMH batteries, 26, 39–40, 124–25
production from gasoline, 18
storage of, 17
vehicle requirements, 198–99
ventilation requirements, 90–92, 129–30, 159
in VRLA batteries, 30–31, 33
weak cells, 133

Impacts, 149–50, 154, 167, 189–90
Impedance tests, 92–93
Inductive charging, 111–12
Inductive coupling, 89, 112, 156
Inertia power, 182
Inertia switch disconnects, 149
Infrastructure Working Council (IWC), 90, 159
Installation resistance, 91–92
Insulation breakdown detection, 157
Intelligent chargers, 85–87
Internal combustion engines, 68, 201
Inverter/system controller, 184
Ionic conductivity, 179

Japan, fuel cells in, 194–95
Joule's law heating, 180

Knee, of discharge curve, 56

$LaNi_5$ alloys, 9
Lead-acid batteries; *See also* Valve regulated lead-acid batteries
absorbed glass mat, 7–8, 34, 98
crash tests, 189
flooded, 6, 129–30, 151, 173
formation process, 23
gel technology, 7–8
maintenance costs, 8
overview, 6–8
Lead oxide, 6
Lead sulphate, 6, 28, 54
Li-ion batteries
advantages, 19
capacity, 58–59
cathode materials, 10–11
cell shape, 127–28
characteristics, 20
charging, 12, 39–40
cobalt oxides, 10–11, 13
cycle life, 19–20
dendrite formation, 11, 40
discharge characteristics, 127–29
heat generation models, 178–79
history of development, 13

intercalation materials, 10–11, 40
overview, 10–13
rocking-chair design, 11–12
self-discharge rate, 19
solid-state, 12, 19–21
storage, 39–40
Swing system, 13
$LiMn_2O_4$, 59; *See also* Manganese oxides
Li-polymer batteries, 4, 13–14
Lithium intercalated graphitic carbons, 10, 40
Lower cutoff voltage (LCV), 41
Low-maintenance batteries, 6
Lubricants, 25, 130–31
Lucent Technologies round cells, 6

Magnesium alloys, 25, 40
Maintenance, battery, 6, 8, 60–61
Manganese oxides, 10, 13, 21, 59
Maximum temperature cut-off method, 78–79
MCFC (molten carbonate fuel cells), 16
M&E assembly, 199–200
Meltdowns, 92
Membrane-electrode-assembly (MEA), 17, 195, 199–200
Memory effect, 145, 147; *See also* Dendrite formation
Methanol, in fuel cells, 192, 196
Mid-point voltage (MPV), 39, 56, 121–22, 126
Models
air-flow, 138–40
ambient temperature, 139
Battery Performance Management System, 135–36
charge acceptance rates, 175
depth of discharge, 175, 188
driveshaft power, 181–83
electric vehicle performance, 181
heat generation, 138–39, 177–81
heat transfer, 138–39, 178–81
NiMH batteries, 174–76
polarization resistance, 176
thermo-electrochemical, 176–88
vehicle operation, 139
Modular AGM batteries, 8
Module specifications, 42
Molten carbonate fuel cells (MCFC), 16
Motors, power and torque of, 4, 66–67, 183–84
MPV (mid-point voltage), 39, 56, 121–22, 126

National Electrical Code (NEC), 88, 90
National Electric Vehicle Infrastructure Working Council (IWC), 90, 159
National Highway Transportation and Safety Association (NHTSA), 188
Negative temperature coefficient (NTC) thermistors, 76–77, 142
Nickel cadmium (Ni-Cd) batteries, 8–9, 26; *See also* NiMH batteries
Nickel oxides, 10
NiMH batteries
activation and formation, 29–30
advantages, 19
capacity, 39, 54–57, 123–27
cell pressure, 175
charge acceptance, 175
charge protectors, 142–44
charging, 74, 78–79, 81–87
C ratings, 119–20
current density, 26–27
depth of discharge, 175
discharge termination, 124–27
discharge voltage profiles, 56–58, 121–26
electrode oxidation, 27–28
fast charging, 84
heat capacity, 75
heat generation rate modeling, 162, 178–81
hydrogen storage, 9, 39–40
intelligent chargers, 85–87
manufacturing process, 9–10, 21
mathematical model, 174–75
maximum charge temperature, 78–79
memory effect, 145, 147
overcharging, 78–82, 85, 180–81
oxygen generation, 174–75
polarization resistance model, 176
resistance during discharge, 64
self-discharge rate, 19
slow charging, 82–84
state of charge, 175
storage, 37–39
temperature effects, 29, 56, 58, 77–79, 123–24, 176
termination of discharge, 124–27
vehicle performance test summaries, 211–13
Nissan Motor Company, 5
NTC thermistors, 76–77, 142

Ohmic drop (IR), 99
Open circuit voltage (OCV), 11, 16, 46–47
Operating life tests, 158

Overcharging
  charge protectors, 142, 153
  charge termination methods, 78–80
  fast charging, 96–97, 107–9
  Li-ion batteries, 11
  NiMH batteries, 78–82, 85, 180–81
  VRLA batteries, 69, 71, 73
Over-discharging, 118, 125–26, 153
Overgassing, 73, 109
Overnight charging, 82–84, 110–11
Oversizing, 62
Oxygen
  in NiMH cells, 174–75, 180–81
  release during charging, 80–81
  in VRLA batteries, 33

PAFC (phosphoric acid based fuel cells), 15–16, 53, 199
Parallel connections, 41, 120
Partial discharge test, 165
Partial oxidation (POX) reactors, 18, 196–97
Partnership of New Generation of Vehicles, 203
Passivation layers, 53–54, 59
Paxton and Newman model, 174–75
Pb-acid batteries; *See* Lead-acid batteries; Valve regulated lead-acid batteries
Peak load hours, charging during, 110–11
Peak power test, 164
Peak voltage detect (PVD), 86–87
PEFC (polymer electrolyte fuel cells), 195, 199–201
PEMFC (proton exchange membrane fuel cells), 15, 17, 194–95, 198–99
Perfluorocarbon sulfonic acid, 200
Performance, battery, 60–62, 133–59; *See also* Battery Performance Management System
Performance safety and abuse test, 167
Performance test summary, 211–13
Peukert relationship, 44, 135, 188
Phosphoric acid based fuel cells (PAFC), 15–16, 53, 199
Pilot circuit disconnects, 149–50
Pilot line, 157
Platinum catalysts, 15, 17, 192, 195, 197
Polarity reversals, 61, 125–26
Polarization resistance model, 176
Pollution, 1, 14, 187, 191, 193, 201–2
Polyethylene oxide, 14
Polymer electrolyte fuel cells (PEFC), 195, 199–201
Polymer positive temperature coefficient (PPTC) thermistors, 142–45
Polypropylene, 151
Polyvinylidene fluoride, 151
Porosity, 53–54, 173
Potassium hydroxide, 16
Potential differences; *See* Voltage
Power
  constant power test, 164
  cut-off voltages and, 124–25
  density, 17, 20, 44
  driveshaft, 181–83
  DST power profiles, 115–17
  from the engine, 68
  fuel cell requirements, 198
  generator, 186–87
  inertia, 182
  inverter/system controller, 184
  maximum discharge, 50
  maximum recharge, 50
  motor, 183
  peak power test, 164
  sustained hill-climb power test, 165–66
  traction, 131, 184–85
  variable power discharge test, 164
Power gains, 68
Power losses
  road inclination, 66
  rolling resistance, 65–66
  system controller/engine inefficiency, 67
  transmission inefficiencies, 66–67
  vehicle acceleration, 66
POX (partial oxidation) reactors, 18, 196–97
Preferential oxidation (PROX), 18
Prelyte, 7
Pressure, 74–75, 82, 109, 175
Proton exchange membrane fuel cells (PEMFC), 15, 17, 194–95, 198–99
Proton Exchange Technology (PET), 192
PTFE, in fuel cells, 200–201

Ragone plots, 19, 127–28
Range testing, 113–14; *See also* Driving range
RAV4 performance summary, 212–13
Receptacle jacks, 104
Rechargeable batteries, 9
Recombination, 7, 32
Reconditioning charges, 53
Rectifier modules, 104
Regenerative braking, 2–3, 24, 68, 134, 183
Reliability/durability tests, 157, 167–71

IPR2025-00152
Tesla EX1014 Page 38

Resistance
  average, 49
  discharge and, 64
  installation, 91–92
  instantaneous *vs*. delayed, 55
  NiMH cells, 121
  steady-state, 55
  thermistor, 77, 142–44
Resistive load units, 52, 61
Rest periods, battery, 171–73
Ripple current, 94
Road inclination losses, 66
Rocking-chair design, 11–12
Rolling resistance losses, 65–66, 182

Safety
  battery design, 150–53
  battery requirements, 188–90
  charging equipment, 90–91
  electrical, 151–52
  electric bus isolation, 149
  electric shock, 153–54
  electrolyte spillage, 153–54
  high-voltage disconnects, 149–50
  inductive charging, 111–12
  intrinsic materials hazards, 152–53
  Li-ion batteries, 12
  Li-polymer batteries, 14
  performance safety and abuse test, 167
  water presence, 112
Scaling, 188
Self-discharge rates, 19, 32–33, 35–39, 62, 96, 165
Separators, 6, 42
Series connections, 41, 71–73, 120
Short circuiting, 152–53
Shuttlecock design, 11–12
Silica gel, 7
Simplified Federal Urban Driving Schedule (SFUDS), 123, 165
Six-minute rate, 95
Size, battery pack, 42
Smart batteries, 147–48
SOC; *See* State of charge
Society of Automotive Engineers (SAE), 87, 90, 148
Solid oxide fuel cells (SOFC), 16, 199
Solid state batteries, 12–14
Sony Corporation, 12
Spare batteries, 62
Special performance test, 165
Specific capacity, 58–59
Specific Discharge Power, 124–25, 128
Specific energy, 44, 59, 173
Specific gravity, 6
Speed, maximum, 185–86
Speedometer calibration, 114, 209
Standloss test, 165
State of charge (SOC)
  benefits of regulation, 47–48
  calculation of, 49–51
  definition, 46, 175
  from open circuit voltage, 46–47
Steam reformer-based fuel processors, 196
Storage, battery, 35–39
Sulfation, 35, 52
Sulphuric acid, 6, 98, 101
Sulphur removal, in fuel cells, 197
Sustained hill-climb power test, 165–66
Switching inverter modules, 104
System controller efficiency, 67–68

Teflon, in fuel cells, 200–201
Telecom applications, 35
Temperature; *See also* Cold weather
  ambient temperature model, 139
  battery capacity and, 44–46, 118–19, 135, 177
  during charging, 34–35, 70–73, 100
  during discharge, 46, 58, 115–17, 122
  distribution modeling, 176–88
  efficiency, 28–29, 35
  electrolytes, 35, 162
  during fast charging, 97, 100, 108–9
  float charge and, 34
  heat dissipation, 180–81, 197
  heat generation models, 138–39, 177–81
  heat transfer models, 138–39, 178–81
  midpoint voltage and, 56, 122
  modeling, 138–39, 176–88
  NiMH batteries, 27, 29, 77–79, 123–24, 176
  nonuniform, 117, 177
  polarization resistance, 176
  reduction in life, 34–35
  sensors, 74–78, 142–45
  solid state Li-ion batteries, 12
  termination methods, 78–80, 83–85
  thermal management system, 137–41
  thermal performance test, 166
  thermal runaway, 92
  VRLA batteries, 26, 28–29, 34–35, 44–46, 137–38

Terminal posts, 4, 31–32
Thermal capacity, 138
Thermal impedance, 75
Thermal management systems, 137–41, 152, 172–73
Thermal performance test, 166
Thermal runaway, 34, 92, 152, 162, 177–78
Thermistors, 74–78, 142–45
Thermo-electrochemical model, 176–88
Thevenin equivalent circuits, 54, 120
360-second frames, 62–63
Time constants, 55
Tin alloys, 35, 53
TiN_2 alloys, 9
Tires, 130–31, 183
Torque, 4, 66–67, 182–83
Torque converter speed, 66–67
Torque converter torque, 66–67
Toyota Motor Corporation, 5, 212–13
Traction batteries; *See* Batteries; *names of individual battery types*
Traction power, 131
Transmission efficiency, 66–67
Trickle charging, 86, 89, 96, 109–10

U. S. Advanced Battery Consortium (USABC), 5, 21, 115, 166
Ultra-fast charging, 86
Urban driving tests, 211–12
Urban driving time power test, 62

Valve regulated lead-acid (VRLA) batteries
  absorbed glass mat, 7–8, 34, 98
  advantages, 5–7, 18–19, 129–30, 151
  capacity definition, 117–19
  capacity discharge testing, 51–53
  capacity recovery, 53–54
  catalysts in, 33–34
  charge protectors, 142
  charging, 34–35, 69–71
  computer simulations, 162
  current density, 26
  cycle life, 44
  discharge tests, 63–64, 116–17
  electrolysis, 33, 108–10
  end of formation, 30–31
  equalization charging, 71
  failure modes, 31–35
  fast charging, 98–99
  formation and EV performance, 23–24
  heat capacity, 101
  hydrogen, 30–31, 33
  maximum power calculation, 50
  memory effect, 145
  overcharging, 69, 71, 73
  self-discharge rate, 19
  series connections, 71–73
  state of charge calculations, 46–51
  storage, 36–37
  temperature and, 28–29, 34–35, 44–46, 77, 98, 137–38
  USABC performance requirements, 43–44
  voltage, 60–61
Vanadium oxide, 13
Variable power discharge test, 115, 164
VARTA Li-metal oxide/carbon system, 13
Vehicle acceleration power losses, 66
Vehicle endurance test, 158
Vehicle operational model, 139
Vehicles, electric; *See* Electric vehicles
Vehicle tire limit, 183
Ventilation, 90–92, 129–30, 140, 152, 159
Vibration test, 166
Voltage
  average, 49
  during charging, 74–75, 99–100
  clamp, 69–71, 73
  cut-off points, 41, 118, 124
  discharge profiles, 55–58, 119–26
  end-of-discharge, 126–27
  fuel cells, 16
  Li-ion batteries, 11
  under load, 119–20, 184–86
  mid-point, 39, 56, 121–22, 126
  minimum, 185–86
  NiMH battery packs, 176
  no-load, 135
  overview, 6–7
  profile calculation, 50–51
  resistance-free, 98, 100
  thermistor, 77, 145
  transition voltage restoration current, 84
  variation during formation cycles, 27
Voltage peak method, 97
VRLA batteries; *See* Valve regulated lead-acid batteries

Water loss, 32, 34–35
Weak cells, 61, 126, 133–34
Wheel bearing losses, 182
Zero-emission vehicles, 191, 193, 202–3
Zinc oxide catalysts, 197
Zinc precipitation, 109
Zr-oxide, solid doped, 16