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FINAL REPORT
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Automatic Charging System for Electric Vehicles-Demonstration Project

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

AIR RESOURCES BOARD
Research Division

AUTOMATIC CHARGING SYSTEM FOR ELECTRIC VEHICLES – DEMONSTRATION PROJECT

FINAL REPORT
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Section I

Executive Summary

Project Goals

The goal of this project was to demonstrate an automatic charging system on an electric vehicle (EV) as a means of enhancing the desirability of EVs.

The problem stems from the EV's short driving range per charge, which requires EV drivers to charge the vehicle's battery approximately six to eight times more often than one might have to fill a conventional car with gasoline. By eliminating most of the driver's involvement with the charging process, the automatic charging system helps to ensure that the frequency of charging operations is not a source of irritation for the driver. Perhaps even more important, the automatic charging system also insures that no opportunity to charge the EV is missed. This feature will substantially expand the capability of the vehicle, improve its reliability, and increase the service life of its battery.

The charger developed for this project offers a number of additional benefits:

- **Low cost:** The fully developed Inductran system will be far less expensive than any alternative technology because it uses efficient materials, can be built with low-cost manufacturing methods, and employs a relatively simple and straightforward control subsystem.

- **Minimal power quality issues:** Operating at line frequency, Inductran chargers do not require high-power solid-state switching to regulate the charging algorithm. Solid-state switching create very-high-frequency harmonics that can be biologically and electronically very troublesome, threatening consumer electronic devices

- **Universal charging:** The Inductran charging station can serve almost any electric vehicle, provided the size and power rating of the coupling inductors on vehicles match those of the source inductor. The source inductor's coils can be wound to suit whatever operating voltage is required. Different types and sizes of batteries can be readily accommodated by designing the coupling and the charge controller on the vehicle to suit whatever operating voltage is required.

- **High efficiency:** Inductran chargers can achieve very high efficiencies: greater than 97% at full load. The system developed for this project achieves 90% efficiency.

- **Safety:** Inductran systems are inherently safe. They contain no exposed cords, connectors, or cable, and the coil conductors in the couples are triple insulated and protected by an enclosure typically constructed of high-pressure glass/epoxy laminate. Electrical terminal and controls are encased in sealed enclosures. The system has been successfully tested while the power coupling was under water.

- **Tolerance for misalignment:** Drivers don't need to park perfectly to start the automatic charging process. A test showed that a coupling was able to transfer about 75% of its rated power when misaligned by six inches. Our driving tests showed that drivers were able to park the car correctly without repeated attempts.

The design, development, and demonstration work of this project provides a much-needed "big picture" of the ability of automatic charging to expand the market for EVs. Beyond establishing the feasibility of design, this project allowed evaluation of the more elusive "human factors" that can make or break the market acceptance of a new technology.

Approach

This project consisted of multiple tasks, performed over a period of several years, as summarized below.

Conceptual Design Study

The project team began by conducting a conceptual design study to recommend an optimal design. Described in detail in Section II of this report, the study looked at a number of issues, such as the control subsystem, the driver interface, and the power rating. It also evaluated two potential charging station configurations—drive-over or bumper-mounted--for ease of use, ease of mounting the equipment on the vehicle, manufacturing, retail, and installed costs, aesthetics, etc. Upon completion of this study, the team recommended the driver-over configuration, outlined a QA/QC plan for its manufacture, and estimated it could be competitive with other EV supply equipment (EVSE).

Detailed Design

With approval from the advisory committee to proceed with the drive-over configuration, the project team began the detailed design stage. This resulted in detailed drawings and specifications to support fabrication of the charging system, modifications of the demonstration EV to interface with the system, installation of the charging station, and system testing. This included reviewing with experienced fabricators the manufacturing and assembly costs for all components to ensure that the project would be free from undue complexity or expense. The team then fabricated an engineering-test power coupling and tested it with variable output to a load bank and battery to determine the maximum output of the coupling; the coupling's tolerance for misalignment; power factor, power quality, and voltage/current characteristics, and the charger's efficiency. These tests all showed that the system would meet design, performance, and operational expectations.

Fabrication and Installation of the Prototype

After receiving approval from the advisory team on the detailed design, the project team fabricated a prototype, working with experienced fabricators who have manufactured many other Inductran products, and who agreed to participate in the QA/QC procedures. Specifically, BV Producing Machining of Petaluma, CA, manufactured the charging system components and S. Stephanos, Consultants assembled and tested the electronic assemblies. Finished components were then pretested as feasible and then incorporated into the charger prototype by technicians, overseen by design engineers. During this time, the test bed EV was modified to accommodate the charging subsystem on the vehicle.

Testing

The project team developed a test plan to evaluate critical operating characteristics, as well as consumer acceptance factors. After the project review team approved the plan, testing was conducted at CAVTC; an ARB-qualified independent laboratory in Hayward, CA equipped to conduct exhaust and evaporative emissions tests and a previous in-use compliance contractor. The test plan and details of the testing are found in Appendix A. Generally, results were favorable, showing that the charging mechanism performed to its design specifications in a real-world application and drivers expressed overall satisfaction with the automatic charging procedure.

Demonstration

The next project phase was a field demonstration. The primary purpose of this demonstration was to learn more about the market potential of the automatic charging system by monitoring its performance—and driver reactions to using the system--in everyday use. The demo also provided an opportunity to gather additional data, such as kWh and vehicle range per charge, the charger's tolerance for parking misalignment, charging time, etc.

The demonstration of the system was delayed and hampered by some problems with the EV. Several cells in the sealed lead acid battery developed faults that compromised the range capability of the vehicle. The vehicle was sent to the manufacturer for the needed cell replacements, since access to the battery in this vehicle required special handling devices. In order to prevent further problems and to protect against the possibility of a fire, the depth of discharge of the battery was not allowed to drop below 50%. It was also found that the vehicle and charging system electronics imposed a continual parasitic load on the battery even when the vehicle was parked, which tended to compromise the data relating to the vehicle's energy consumption on the road.

The BKI team and the ARB/SCAQMD advisory team decided to conduct the field demonstration at CAVTC, using trained CAVTC technicians as drivers. The BKI team then developed a demonstration plan, which was approved by the advisory team, and initiated the demonstration at CAVTC. The demonstration plan is available in Appendix B, and a summary of the demonstration can be found in Section VI.

Findings

In a six-week trial of the automatic charger, CAVTC drivers used the EV for their daily tasks and exposed the system to trials of varying distances. Drivers were asked to record vital data in a driver's log. This included the trip distance, kWh used, charging time, state-of-charge levels of the on-board battery, and parking tolerances in relation to the charger itself. Drivers were also asked to record their impressions of the charger's performance. In general, drivers found the automatic charger easy to use and felt that public perception would match their experience.

Overview of the Project and the Work Product

The project work was performed in the period from May 1997 through October of 1999. The "drive-over" arrangement that was used for the prototype charging system was selected after closely comparing its concept with one for a "bumper-mounted" arrangement. The project team also had to resolve challenges to the basic structure of the project by members of the advisory committee. The challenges that were resolved included the suggestion that the project be modified to develop a high frequency system rather than the use of the low frequency system as was originally proposed; the alteration of the project so that the inductive power coupling would only provide power to automakers' own on-board charging systems rather than being a complete automatic charging system as specified; and the use of an off-board charger instead of an on-board charger. ARB managers concurred that the low frequency system enhanced the ease of using the charging system and its cost effectiveness, that the use of only an inductive power coupling rather than an inductively coupled charging system would put small EV manufacturers at a serious disadvantage, and that the project goal would not be well served by an off-board charger. The project then proceeded as originally planned. These efforts at altering the project goals and scope added over three months to the schedule for the project.

A new design was used in housing the inductors that kept them from contacting their enclosures in an attempt to reduce the transmission of sound to the outside environment. Tests revealed that this technique was not effective, and numerous experiments were made with other potential noise reducing methods and materials. Sound levels ranged from a low of approximately 56 dB to a maximum of approximately 67 dB. Levels of 60 dB and below were apparently acceptable to most bystanders, although the system was typically operated in configurations that produced about 64 dB. The sound level from a nearby Nissan charger was measured at 54 dB. This issue could not be fully resolved because of limited schedule time and resources, although the experiments indicated that reaching a sound level below 60 dB in a fully developed charging system could be achieved.

It was discovered in the course of testing the prototype charging system that its installation on the EV had resulted in a serious increase in the energy being dissipated in the coupling inductor. Power that was being supplied to activate the vehicle's electronics far exceeded the expected amount, and included a substantial content of very troublesome high frequency ripple. Energy was also extracted from the coupling by stray magnetic flux that heated nearby steel components of the EV. These added losses in the coupling caused the thermal destruction of the coupling's coil winding, which required that the coupling coil be rewound and the inductor moved farther from adjacent steel components. It also required that the coupling's power output be reduced from more than 6.6 kW to 6.3 kW in order to constrain its temperature rise. The 4.5% reduction in power had a relatively small effect on typical charging cycles, since the charging time during which peak power is being used is typically less than half of the charging cycle time and does not affect the balance of the cycle.

The schedule time that was consumed in constraining the thermal problem in the coupling required that the demonstration phase of the project be reduced in order to fit within the available project resources, as was agreed to by all the concerned parties. The shortened time also prevented the completion of work to reduce the sound emitted by the charger and the work to nullify affects on the coupling of high frequency harmonics from the vehicle's electronics.

The coupling inductor was designed to utilize aluminum coil conductors as a weight saving measure, but the schedule would not allow the extra time that was required to procure it. Copper conductor was used instead with a weight penalty of about 10 pounds. The total weight added to the vehicle was approximately 91 pounds.

The results of engineering tests of the charging system are tabulated in Table 1. They indicate that other than a slight reduction in maximum power capability, the system met the functional requirements for a fully capable automatic charging system. The charging algorithm was easily altered several times during the tests by reprogramming the programmable logic controller in the system. The system never failed to operate automatically during the engineering tests, it proved to be as tolerant of parking inaccuracies as had been predicted, and its controls were easily used and understood.

The specifications of the charging system as it was constructed are summarized in Table 1.

TABLE 1.
Prototype Charging System Characteristics

Characteristic	As Built	Design Target
Maximum charging power	6.3 kW	6.6 kW
Input voltage	240, 60 Hz	240, 60 Hz
Maximum input current	40 amps	40 amps
Required operator training	none	None
System efficiency	90%	90% minimum
Ease of use		
Required parking accuracy	+/- 5" (approx.)	max. tolerance
On/off control	automatic	Automatic
Projected installed cost in large quantities	$2945.00	Competitive
Sound level	64 dB (typical)	<60 dB
Voltage harmonic distortion	2.5% (@ max. load)	3%
Current harmonic distortion	18% (@ max. load)	Minimal
Power factor	95% (@ max. load)	90%
Weight added to EV	91 lbs.	70 lbs.

The demonstration cycles of the EV and charging system are summarized in Table 2.

TABLE 2.
Charging System Demonstrations

Number of automatic charging/parking cycles		29/30	
	max.	**min.**	**avg.**
Miles per trip	46.00	5.00	17.70
Travel time per trip, minutes	115.00	15.00	49.40
Energy charged to EV, kWh	16.00	3.00	7.60
kWh/mile	1.00	0.28	0.43
Charging time, hours	2.76	0.94	1.70
Number of monitored parking operations		30	
Number of successful parking operations on first attempt		25	
Number of unsuccessful first parking attempts		5	
Number of successful second parking attempts		5	

Vehicle's alignment offsets from the charging station (inches):

In 30 successful attempts:	**max.**	**min.**	**avg.**
lateral offset	3.50)	0	1.45
longitudinal	8.12	0.38	3.31
In 5 unsuccessful attempts:			
lateral offset	7.00	1.75	5.40
longitudinal offset	17.25	1.88	6.15

Conclusions and Recommendations

The Inductran prototype foreshadows promise for development of commercial automatic charging systems. As demonstrated in the field tests, drivers quickly learned to align the vehicle correctly, and agreed that the ease of charging far outweighed any parking considerations. This finding is consistent with comments from drivers of industrial EVs that use automatic charging. These people report greatly appreciating the reliability of the system and the confidence that vehicles would always be ready for use, just through constant opportunity charging.

There's every reason to believe that these benefits can be easily transferred to the consumer sector. With inductive charging readily available at worksites, downtown areas, and shopping and entertainment centers, consumers won't have to count round-trip mileage before taking the electric vehicle. And they know that every time they park at home, their vehicle will receive a charge, priming the batteries for the next trip and generally ensuring the overall health of the battery by helping avoid deep discharges.

The project participants recommend that CARB and SCAQMD consider taking the existing charger design and moving forward with a production prototype. For applications with passenger EVs, a different, more reliable vehicle should be considered. However, the participants feel that the automatic charger would be a good match for other applications such as industrial equipment and airport ground support equipment—applications ripe for a greater penetration of electric equipment. The automatic charger also would be ideal for fleet applications where similar vehicles would share a common charger. This would eliminate the need for modifications of the inductor windings to match different vehicle types. The participants also believe that the noise and heat generated by the charger make it less than ideal for residential applications, another reason to recommend its use in industrial and fleet settings.

Section II

Conceptual Design Study

Summary

The project team developed a conceptual design for implementing an inductively coupled automatic charging system under Task 1 of this contract. Specifically, the team focused on the design elements of integrating the Inductran automatic charging system into the EV selected for this project, the AC Propulsion Saturn EV, provided by the South Coast Air Quality Management District (SCAQMD).

The report begins with an overview of the inductive charging system. It then presents two mounting options—the bumper-mounted system and the drive-over system—and recommends the most favorable arrangement. Following this presentation, the report discusses the benefits of the low-frequency system chosen for this project over other possible automatic charging systems.

The quality assurance/quality control guide included in the original report on the design study can be found in Appendix C.

Design Objectives

The design of the automatic charging system meets a number of important design criteria specified in the RFP. Foremost, the system starts and stops the charging process automatically, eliminating the need for any driver intervention. Easy to use and extremely safe, it is also consumer-friendly. Further, it is anticipated that all applicable codes and standards can be met in the construction of the charger, and that the charger will likely have a benign effect on the utility's power system. Finally, we estimate that the installed cost of the unit should be equivalent to that of standard electric vehicle charging equipment. The sections below will discuss these features in greater detail.

The Automatic Charging System

The automatic charging system consists of two systems:

- An on-board charging system that contains an inductive power coupling, a charge controller, and a control electromagnet
- An off-board charging station that contains the source inductor, the electrical controls for the incoming power from the utility service, and an articulated suspension that allows the source inductor to move against the vehicle's inductor

When the vehicle parks in a charging station, the on-board charging system initiates a charging cycle, rectifies the incoming power from ac to dc through the inductive power coupling, monitors and regulates the charging voltage, and terminates the charging cycle when the battery is fully charged or when the vehicle prepares to leave the charging station. Figure 1 provides a schematic view of the charging system.

The Inductive Power Coupling

The coupling inductors in the charging station and on the vehicle consist of a laminated steel core and a coil winding around the central portion of the core. The core is rectangular in plan view and in the shape of a shallow "U" in elevation.

Current flowing in the coils causes ac magnetic flux to flow through the cores and to pass in and out of the legs of the "U" (i.e., the poles) and across the clearance airgap that separates the inductors. This magnetic flux induces voltage in every turn of the inductor coils as it flows through the magnetically linked cores. The number of turns in the coils is chosen so that the induced voltage in the source inductor's coil matches the input voltage, and the induced voltage in the vehicle inductor's coil is sufficiently high to charge the vehicle's battery.

The magnetic flux that flows through the cores of the coupling inductors when ac power is turned on creates an attractive force between the inductors. If needed, this force can be used to pull the inductors together against separating rubber pads.

Vehicle Alignment

The driver takes the first step in the charging cycle by parking the vehicle in a charging station and aligning the source inductor in the station and the on-board inductor accurately enough to allow effective power transfer. A number of aids can make alignment easier and more precise. In one experiment, for example, the driver visually lined up a small index on the hood of the vehicle with an alignment reference in the charging station. This method was very easy for the

Schematic Diagram of an Inductran Charging System

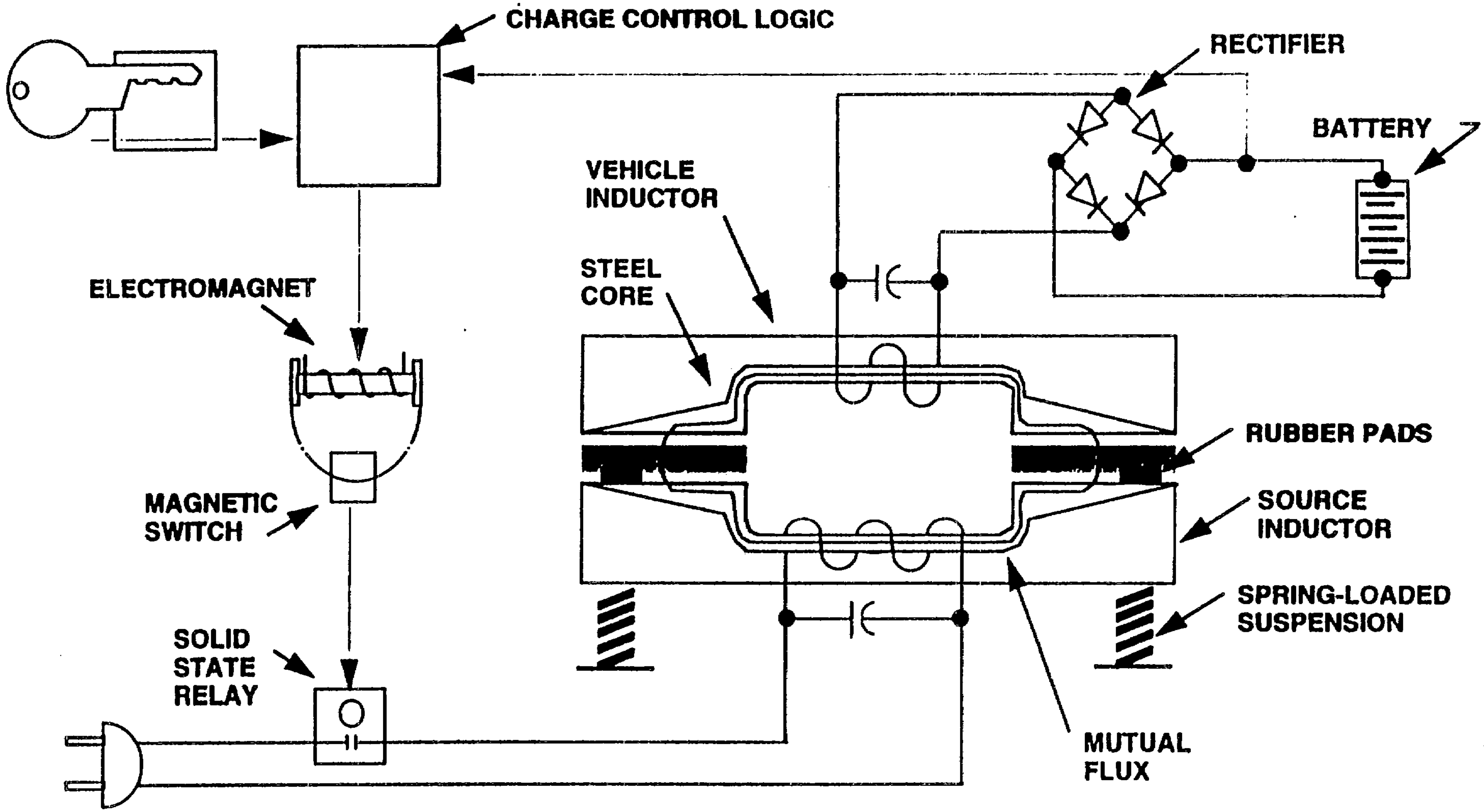

Figure 1

driver to use and understand, and resulted in accurate lateral positioning of the vehicle. Industrial systems have used markers in the pavement beside the vehicle's path to show the driver when the vehicle is the correct longitudinal position. Several other alignment methods have been considered during Task 1 and appear to be feasible. These methods and possibly other new concepts will be further investigated in the next project task.

Control Functions in the Charging System

Charging cycles are automatically initiated when the driver parks the vehicle in a charging station and turns the key switch off. The system responds by energizing a control electromagnet located on the vehicle, yet near the off-board charging station. Upon sensing magnetic flux from the electromagnet, a magnetic switch in the off-board charging station activates a solid-state relay that controls input power to the charging station. The flux pattern of the electromagnet is designed to operate the magnetic switch only if the vehicle is within the positional tolerance of the charging station.

This system automatically controls the battery charging process. Specifically, the electromagnetic characteristics of the power coupling limit the current flowing into a deeply discharged battery to the maximum rated current of the coupling and limit the maximum charging voltage to suit the particular battery. This regulating process is a highly reliable passive control method that requires no maintenance or adjustments. In contrast, most other chargers use complex and often troublesome electronic controls to accomplish these functions.

The coupling will deliver only its rated current, no matter how low the voltage of a deeply discharged battery might be, until the charging voltage approaches the maximum charging voltage for the particular battery. When the voltage approaches the maximum, the coupling's output characteristic changes to a constant voltage. The coupling maintains this constant voltage until the charging current drops to a low value as the battery reaches a fully charged condition. The output voltage then rises and indicates this condition. Sensing the rise, the charger controls turn the system off.

The basic charging controls can easily be modified to incorporate other control functions. For example, the controls can accommodate "time of day" charging, which allows charging only during hours of low demand on the utility system, when electricity rates are lowest. Another optional function is to prevent charging if the electrical demand in the household exceeds a particular limit.

Several types of digital communication links between the vehicle and the charging station (e.g., infrared, RF, ultrasonic) can be used to identify the vehicle in the station for monitoring, recording, and billing for the charging energy.

These control functions need only generate a low-level signal to activate the solid-state relay that turns the charging station on or off.

Driver Control and Display Panel

A manually operated switch in the driver's control/display panel allows the driver to stop a charging cycle for any reason. The panel graphically displays the magnitude of the charging current, which indicates the degree to which the battery has been charged.

The charger controls on the vehicle will include programmable electronic logic that will accommodate additional control functions that might be found desirable in the course of testing and demonstrating the automatic charging system.

Interfacing Requirements Between the Charging System and the Battery

The battery pack in the proposed demonstration vehicle is a sealed lead-acid battery of the absorbent glasmat (AGM) type, otherwise known as a valve-regulated lead-acid (VRLA) battery. When charging this type of battery, care must be taken to maintain even distribution of voltage among the individual batteries that make up the battery pack. VRLA battery manufacturers recommend using circuits in parallel with the individual batteries to bypass some fraction of the charging current around batteries that exhibit too high a voltage as they are being charged. Circuits to perform this function will therefore be provided in the charging system.

Operating Characteristics

Universality

The Inductran system can be a universal charging system provided the power rating of the coupling inductors on the vehicle does not exceed that of the source inductor. That is, the charging station can operate with any line voltage and serve vehicles with different battery voltages provided the source and vehicle inductors are wound to suit whatever operating voltage is desired for the battery system on board the vehicle. Different types and sizes of batteries can be readily accommodated by designing the coil in the coupling and the charge controller on the vehicle to suit the battery charging requirement and algorithm.

Efficiency

Previous versions of Inductran chargers have achieved efficiencies of over 90%, the goal of this project. The efficiency of the Inductran system is at the discretion of the system's designer. Losses in the system are primarily resistive losses in coil windings and losses from diode voltage drops in the silicon bridge rectifiers. Coil losses are constrained to low values by using conservative current densities in the coil conductors and taking advantage of design techniques that minimize current in the coils. Systems have ranged in efficiency from approximately 86% to 97%. The system developed for this charger will meet or exceed the 90% efficiency requirement at full load.

Power Rating of the Charging System

As specified in the RFP, the charging station developed in this project will use Level 2 (40 amps at 240 volts) electrical service. The power rating adopted for charging systems on this electrical service is 6.6 kW, which will be the target of the design in this prototype charging system.

Power Factor

The power factor of the chargers is generally in the mid 80–90% range. This characteristic can be influenced in the design process, as the parameters involved can be controlled by the system designer.

Harmonic Content

The harmonic content in the input current to charging systems has recently become an issue of much interest. Harmonics tend to increase the "iron" losses in the cores of utility system transformers, increase the resistive and other parasitic losses in electrical lines, and in some cases cause radiation of electromagnetic energy. The severity of these effects from a particular harmonic is highly dependent on the frequency involved. Core losses increase approximately as the square of frequency, so that the loss from one hundredth of a percent of ripple harmonic at 100 kHz would cause approximately the same loss, as would 10% of 180 Hz harmonic.

Some chargers use solid-state switching at frequencies from 360 Hz to over 100 kHz, which can create square current wave forms rich in high-frequency harmonics. Thus, the fundamental switching frequency is of concern, and higher frequency harmonics can be even more troublesome. Cables that carry currents that include high-frequency harmonics—in effect antennas—must be rigorously shielded to prevent radiation. Utility services that carry input current containing high-frequency ripple can be especially troublesome in a home environment, because the house wiring functions as an antenna that can radiate interference into computers and other sophisticated communication and control devices in the home. This kind of radiation from solid-state motor controllers in EVs has been known to randomly operate radio-controlled gates and other devices.

The Inductran charging system does not use solid-state power switches. The interface with the utility electrical service is generically very similar to that of the typical single-phase electric motor, whose low-frequency harmonics are rarely of concern. There is no possibility of troublesome radiated energy from faulty cables or current ripple, since any measurable harmonics are far below even the VLF radio frequency band, which extends down to 3 Hz.

Optional Charging Configurations

Inductran's inductively coupled charging systems have been implemented in a variety of configurations on industrial vehicles. Interfacing the charging system with a particular vehicle requires carefully considering not just where sufficient useful space might be available, but also several other important issues. Surveying and evaluating the options for arranging the charging system on the chosen vehicle is thus the first step in arriving at an optimal system design.

The automobile chosen as the demonstration vehicle in this project is a 1995 Saturn sport coupe, which is to be equipped with a (nominal) 6.6 kW automatic charging system. This vehicle has some unique constructional features. It does not, however, differ substantially from other automobiles in ways that are apt to affect the location, size, and mounting method of the charging system on the vehicle.

An initial survey of the Saturn coupe allowed elimination of some of the arrangements used or considered in industrial vehicles. For example, the coupling can't be mounted under the "engine" or passenger compartments because the space under these areas is not large enough to accommodate the coupling inductor and still maintain adequate ground clearance. The coupling should not be mounted below the rear of the car, because this would require locating the off-board charging station on the pavement where the wheels of the car could run over it. The coupling should not be located on the rear bumper, as this would require backing the car into the station, which would limit visibility of the station and make steering awkward.

The initial survey of all the possible arrangements identified two superior options (see Figure 2). One option would center the vehicle's power coupling on the front "bumper" with the pole surfaces of the inductor in a vertical plane. The second option calls for mounting the power coupling below the car, close to the front of the car. The project team explored each of these options and conducted engineering analyses of the power coupling configurations that would be required. They also prepared arrangement and perspective drawings to better assess the appearance and ease of mounting of each option.

The team considered the following issues in exploring the two options:

- Is the mounting arrangement of the coupling inductor on the vehicle likely to also be suitable for use on automobiles and vans from other manufacturers?
- Can the coupling inductors and their enclosures be designed to withstand the physical abuse and environmental exposure they might encounter in the particular arrangement?

- Does the arrangement increase the difficulty of parking the vehicle in a charging station with the required positional accuracy?
- Is the appearance and size of the charging system and the effort to install it in a typical garage likely to be acceptable to consumers?
- Is the projected production cost of the charging system in the arrangement significantly different from that for the system in the alternative arrangement?
- Does the arrangement have significant implications with respect to the performance, durability, or reliability of the charging system?

Below are summaries of conclusions about these issues for the two arrangement options.

The Bumper-Mounted Charging System Arrangement

The bumper-mounted charging system arrangement is shown in drawing SD10002 and in Figure 3. The charging station, shown in drawing SD10003, consists of an electrical enclosure bolted to the pavement and a source inductor supported by a rotating arm that is pivoted in the enclosure.

An electromagnet in the vehicle charging system is automatically energized when the vehicle parks in the station, the vehicle's keyswitch is turned off, and the coupling inductors are mated. A magnetic switch attached to the source inductor turns the charging station on when it senses magnetic flux from the electromagnet on the vehicle.

The charging station is a relatively compact assembly, as shown in drawing SD10003. Because the height to the top of the source inductor is only about 18 inches, this unit would be unobtrusive in a typical garage. The coupling inductors are 34 inches long and 7 inches high, with a narrow, attractively curved appearance.

The source inductor is supported by an arm. This arm can rotate freely about its support in the electrical enclosure below it, which serves as the base of the charging station. The arm allows the source inductor to move at least 6 inches against its spring loading after the vehicle inductor contacts the rubber pads on the source inductor. Flexible cables transfer power to the source inductor from the controls in the enclosure. The flexible cables pass upwards through a sealing gland in the shaft to which the support arm is attached and through the arm to connect to sealed terminals on the bottom of the inductor.

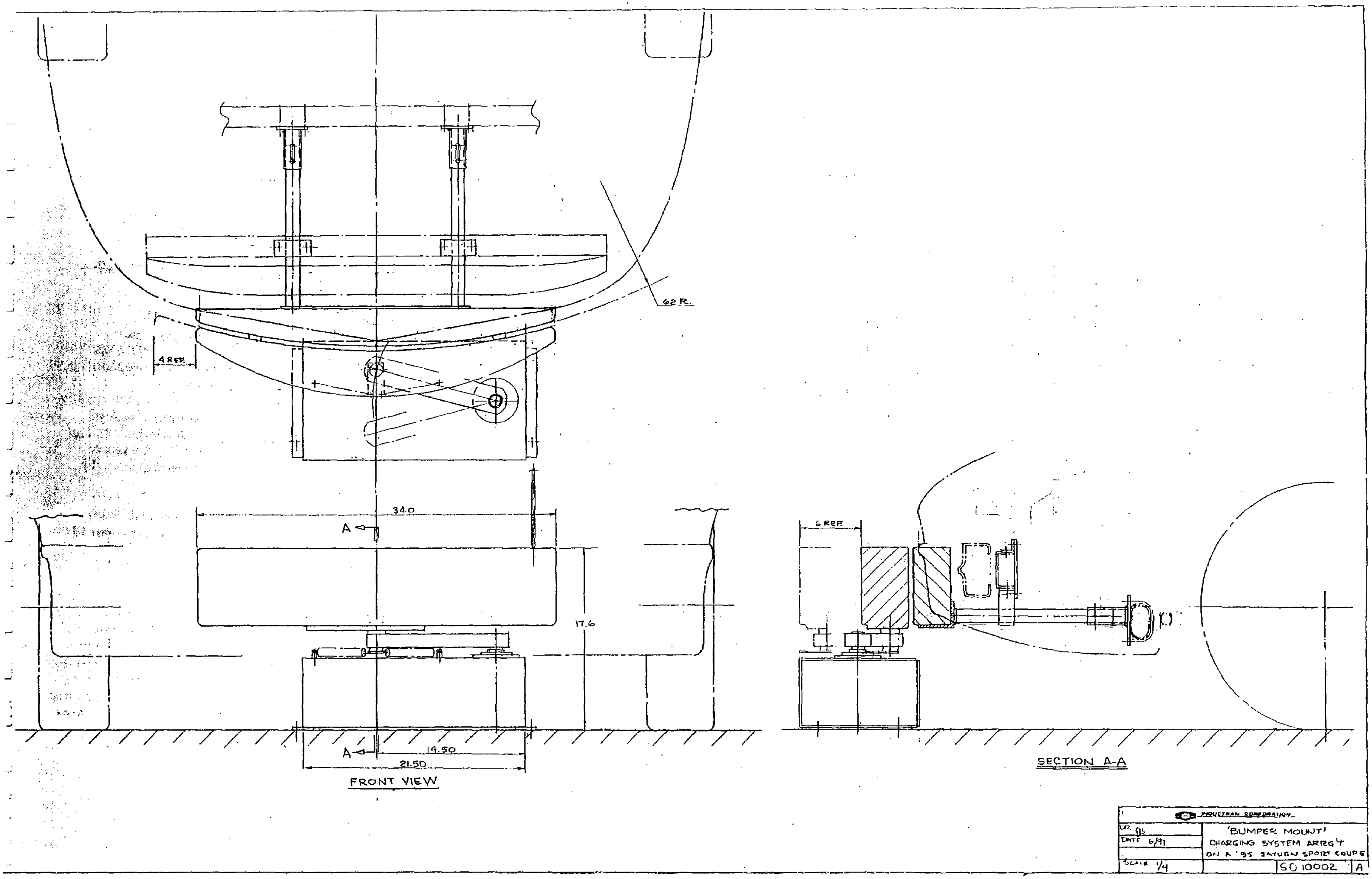
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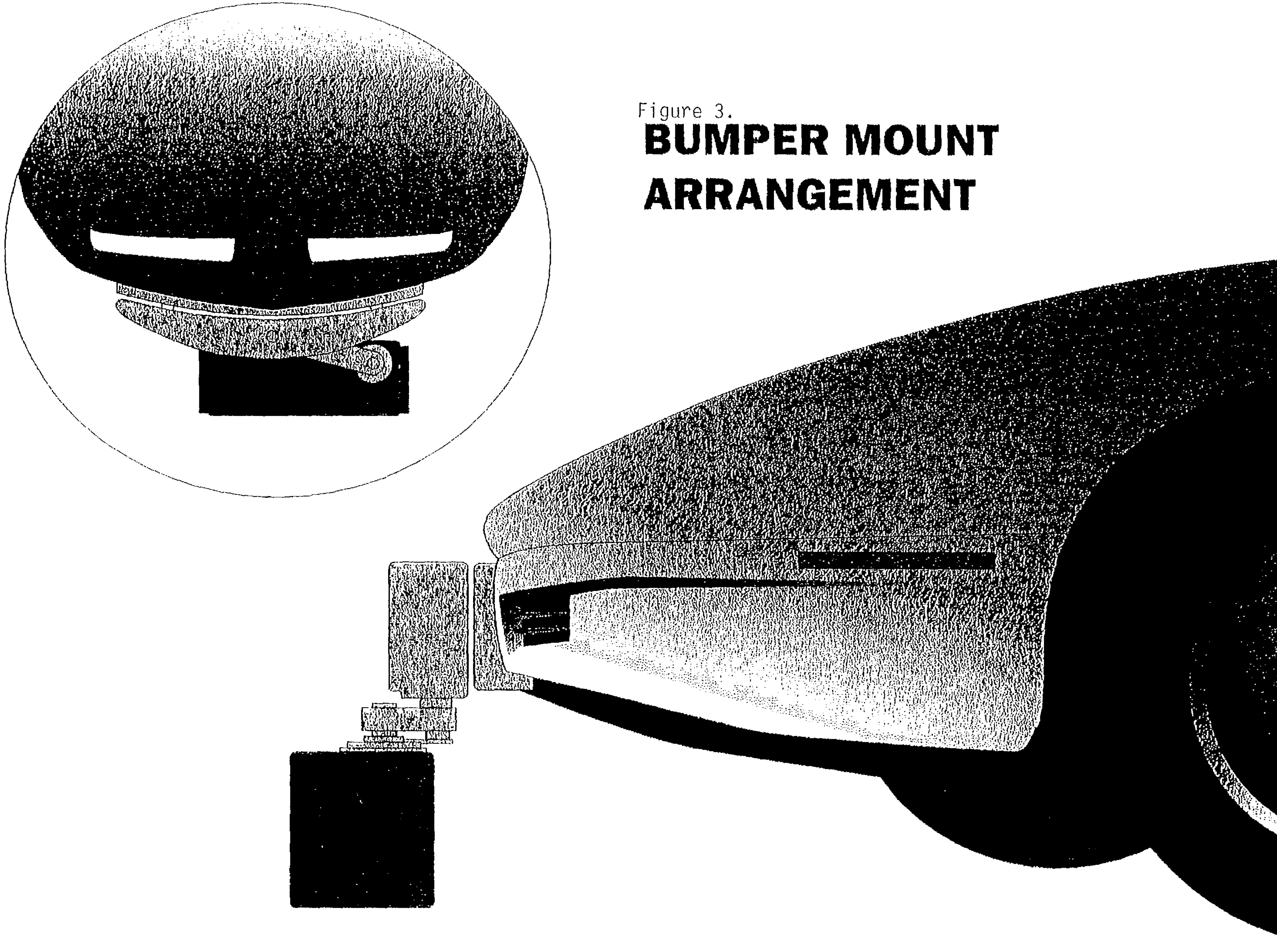
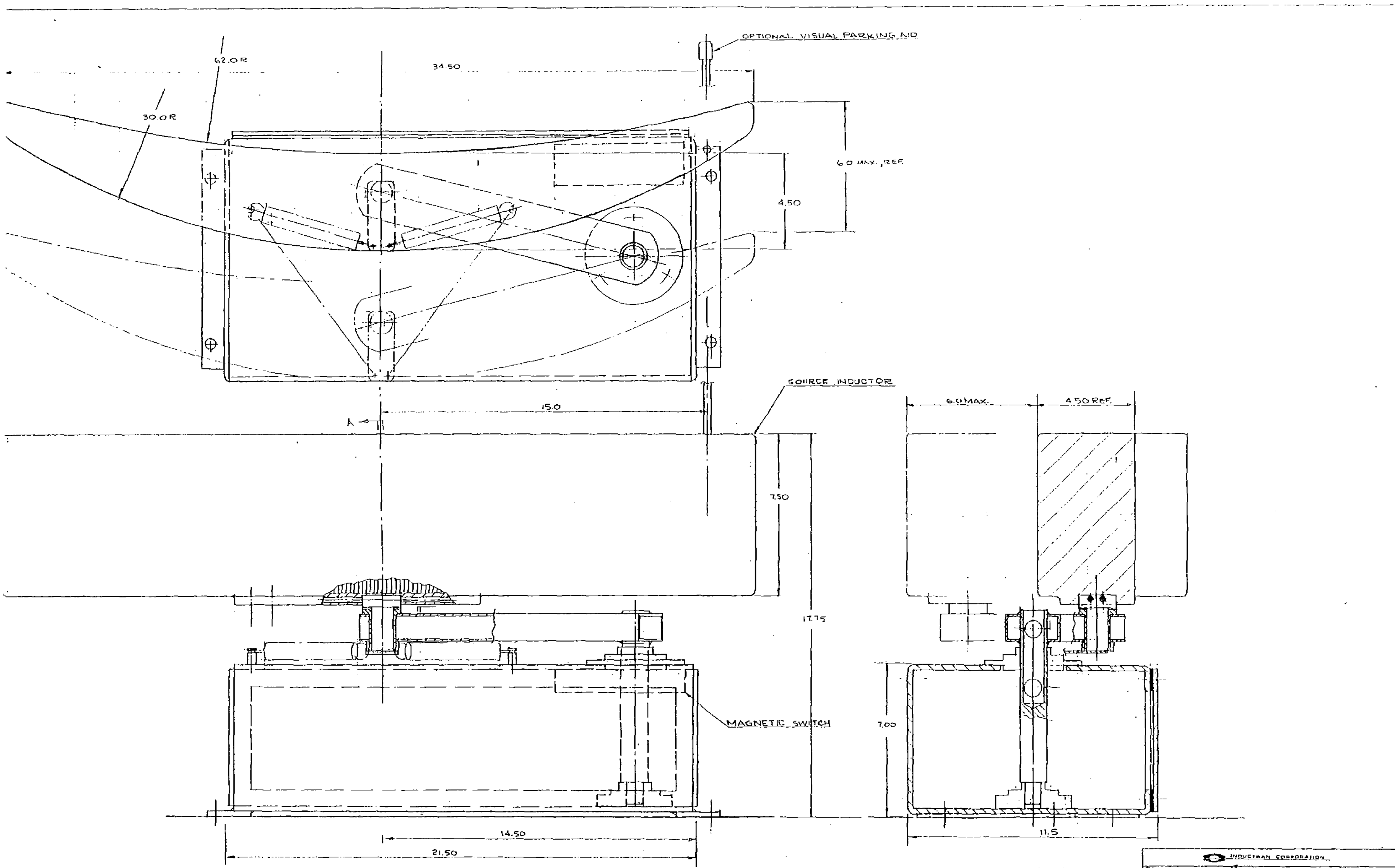
Figure 3.
BUMPER MOUNT ARRANGEMENT





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Design Issues

Installation of the coupling inductor on the vehicle

A narrow, curved coupling inductor is set into the plastic fascia that covers the energy-absorbing foam and the metal bumper beam in the front of the vehicle. The slim inductor is designed to blend smoothly into the front of the vehicle, and could be painted in the same color as the vehicle. As shown in the arrangement drawings, the inductor is supported by two parallel tubular shafts that are slidably clamped in supporting blocks that are bolted to the cross beam behind the bumper beam, and by end fittings attached to a frame crossmember. The end fittings would allow the tubular support shafts to slide rearward with only frictional restraint in the event that a frontal impact on the inductor were severe enough to compress the foam layer behind the inductor and deflect the bumper beam.

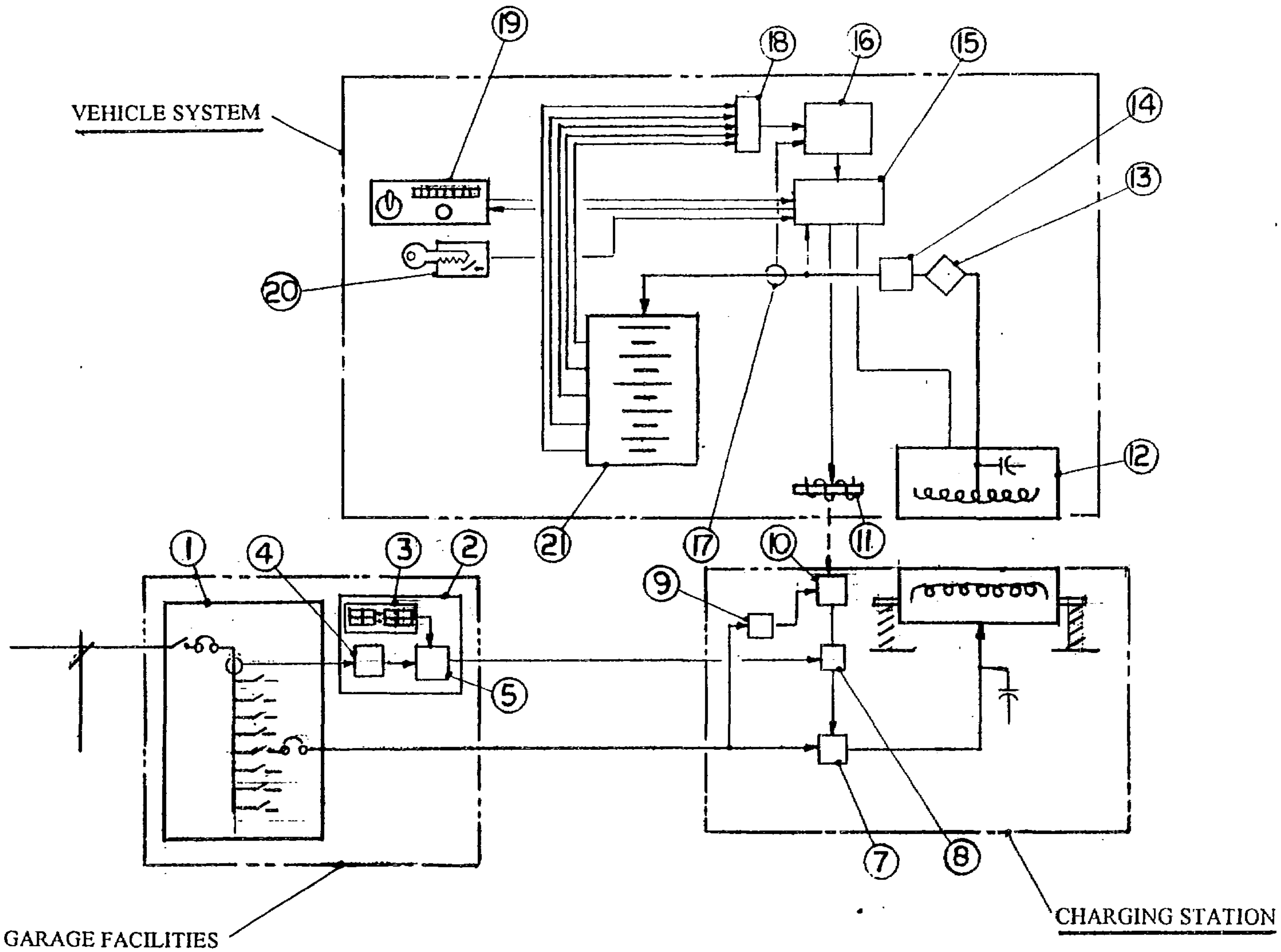
Although the mounting hardware would be specific to particular cars, the convex surface of the inductor would permit attachment to the curved front surface of most new cars without detracting from their appearance. The radius of curvature of the inductor is shorter than that of the front of the car so that the convex central region of the inductor projects outward beyond the car's front surface.

Charging station installation

The electrical enclosure is a sturdy welded aluminum box with a removable front panel for servicing and installation. The enclosure houses the electrical controls for the charging station, which are shown in the block diagram of the system, Figure 4. Installing the charging station requires only bolting the enclosure to the concrete floor of the garage, and connecting the 240 volt, 40 amp electrical service to the station through a rigid or flexible conduit entry into the electrical enclosure.

Physical protection

The central portion of the vehicle inductor in this arrangement would be subjected to periodic impacts from other vehicles during parking. Therefore, the inductor would be designed to be even more rugged than the typical inductor. The laminated steel core of the inductor would be bonded with a resilient adhesive, rather than with the hard adhesive normally used, and the central region of the inductor would be potted solidly with silica-filled resin and protected on the front surface by an extra layer of high-pressure laminate board. The resulting inductor assembly would be developed and tested to confirm that it would be more rugged and durable than the original structure that occupied that position.



1	Electrical load center
2	Optional charging cycle controller
3	Time clock
4	Load current sensor
5	Charging cycle logic
6	Source inductor
7	Solid state power relay
8	Logic control relay
9	Low-voltage transformer
10	Magnetic switch
11	Control electromagnet
12	Vehicle inductor
13	Rectifier
14	Filter
15	PLC
16	Sensor interface PCB
17	Current sensor
18	Battery voltage sensors
19	Driver's control/display panel
20	Keyswitch
21	Battery pack

Figure 4. BLOCK DIAGRAM OF THE AUTOMATIC CHARGING SYSTEM

Safety

The driver does not normally touch any component of the system. A small control/display panel lets the driver switch off the normal automatic control system of the charging system. This low-voltage device presents no possible electrical hazard.

A magnetic force pulls the inductors together when the system turns on. Because this force is relatively modest, little harm would result if someone were to put their hand between the inductors at the time of turn on. Moreover, recent authoritative studies have shown that there are no known health hazards associated with stray magnetic fields. For example, a report of a three-year study released in 1996 by the national Research Council stated that "no conclusive and consistent evidence shows that exposure to residential electric and magnetic fields produce cancer, adverse neurobiological effects or reproductive and developmental effects"[1]. Therefore, the low fields that are close to the coupling (which is not proximate to any area occupied by people) are not a significant safety issue.

The electrical conductors from which the inductor coils are wound are highly protected. For safety, they are triple-insulated with high-temperature epoxy wire insulation; vacuum-pressure-impregnated with hard electrical epoxy resin; and protected by a layer of fiberglass laminate board. These and other protections ensure against electrical discharge in severe events.

For example, a catastrophic frontal collision that caused both the cables carrying charging current from the inductor and a cable carrying battery current to simultaneously short to the vehicle structure would not result in an electrical discharge through the shorted cables. This is because the rectifier in the charge controller isolates the charger's cables from the battery. If there were an undetected cable short, and the charging system were started up later, the inductor would deliver approximately its rated current into the short. However, it would do so at essentially zero voltage and power, so that little harm would result.

Alignment

This charging system arrangement offers the advantage of maintaining the charging station within the driver's field of view until the vehicle is almost completely parked, making it easier to align the vehicle laterally. As in the alternate arrangement, several means could be used to aid longitudinal positioning.

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[1] "Closing the Book: Are power-line fields a dead issue?" *Scientific American*, March 1998.
"Scientists See No Risk in EMFs," *New York Times*, November 1, 1996.
"Study Zaps Power-Line Cancer Link," *Los Angeles Times*, July 3, 1997.

Relative cost to manufacture

The curved inductors in this arrangement results in several adverse cost implications:

- The tooling required to clamp the thin, flexible laminations in the inductors' cores into a curved shape as they are bonded together with adhesive would be more costly than the tooling for the flat inductors in the alternative arrangement.
- The labor costs of the bonding operation would be slightly higher because the narrow cores would contain a few more laminations than the wider cores in the alternate arrangement.
- The cost of manufacturing the enclosures for the inductors would be higher because of increased tooling costs, the extra costs for the manufacture of curved fiberglass parts rather than straight ones, and the cost associated with providing the extra ruggedness in the vehicle inductor assembly.
- The cost of installing the vehicle inductor would be higher because making the vehicle inductor capable of transferring impact forces to the bumper translates into more parts and greater complexity.

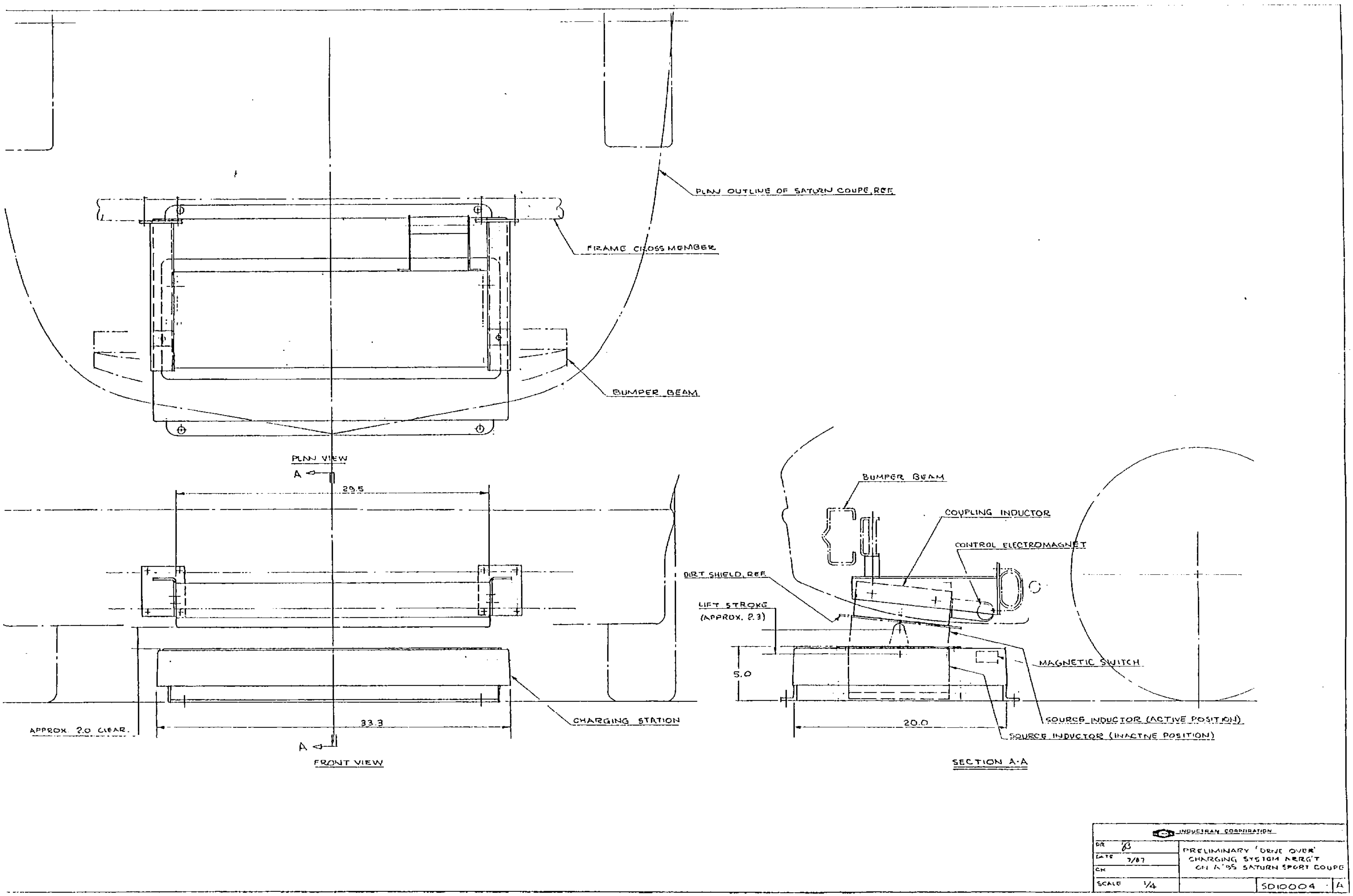
Performance

The projected performance of the bumper-mounted charging station should not differ significantly from that of the alternate arrangement. Although the reliability will be excellent, this arrangement could be less reliable if the ruggedness and impact-absorbing ability of the vehicle inductor were less than expected. On the other hand, the stand-mounted source inductor would keep the inductor above any accumulation of snow, water, or debris—a potential advantage in exterior installations. As a further advantage, this arrangement allows easy inspection of both inductors before and during operation, permitting quick detection of any damage or mechanical malfunction.

The Drive-Over Charging System Arrangement

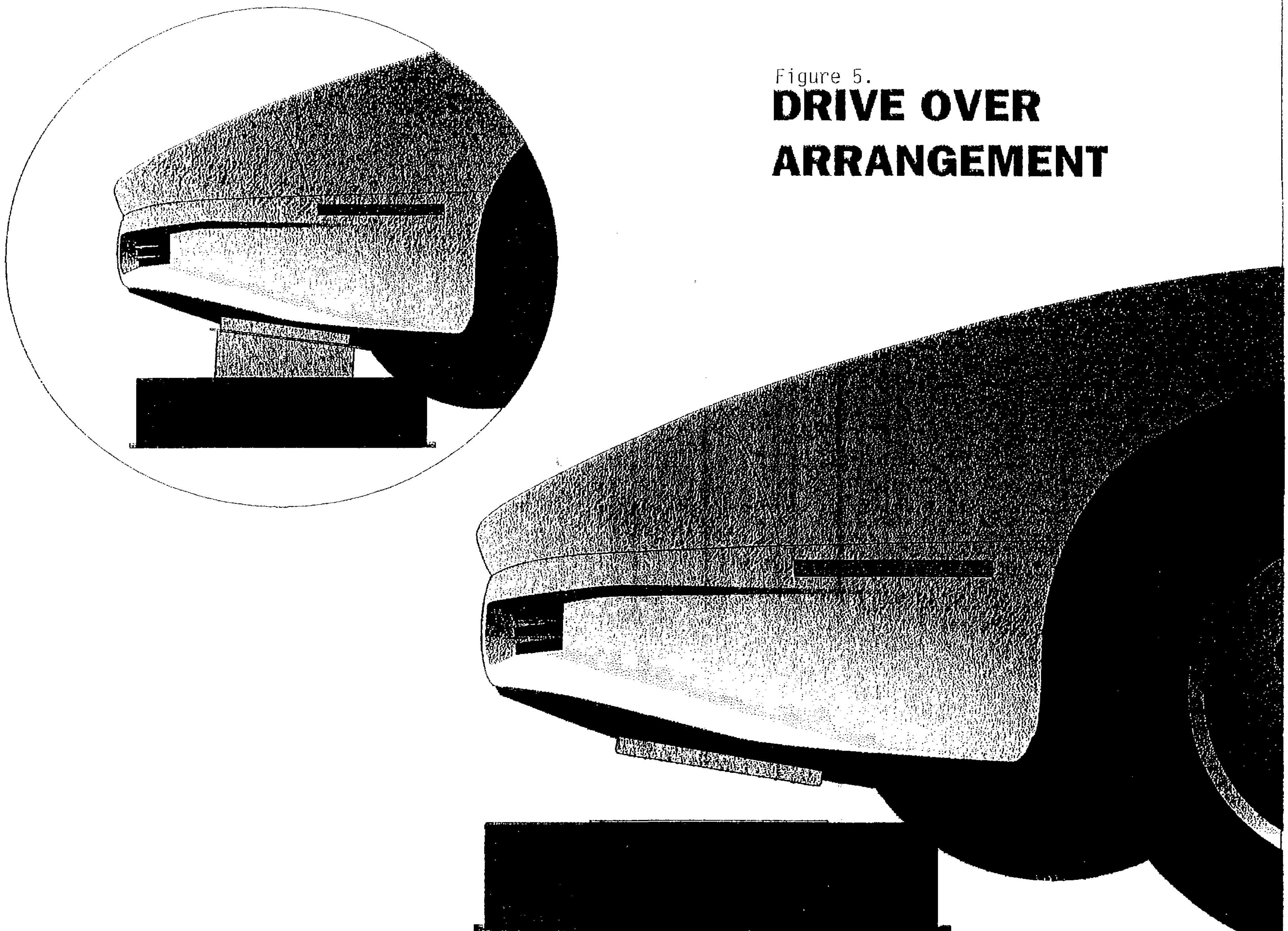
The drive-over charging system arrangement is shown in drawing SD10004 and in Figure 5. The charging station consists of a rectangular assembly that is five inches in height, which provides sufficient vertical clearance between the top of the source inductor and the bottom of the vehicle inductor as the vehicle drives over the charging station.

All electrical controls for the station, other than the magnetic switch, are within a sealed cavity in the source inductor's housing. The cover for the base of the cavity is an aluminum heatsink that transfers power losses in the inductor and controls to the outside air. A flexible cord connects the electrical service between the articulated inductor and the point where the conduit for the electrical service enters the unsealed housing for the station.



PLAN OUTLINE OF SATURN COUPE, REF.
FRAME CROSS MEMBER
BUMPER BEAM
PLAN VIEW
A
29.5
CHARGING STATION
APPROX. 2.0 CLEAR.
33.3
A
FRONT VIEW
BUMPER BEAM
COUPLING INDUCTOR
CONTROL ELECTROMAGNET
DIRT SHIELD, REF.
LIFT STROKE
(APPROX. 2.3)
5.0
MAGNETIC SWITCH
SOURCE INDUCTOR (ACTIVE POSITION)
SOURCE INDUCTOR (INACTIVE POSITION)
20.0
SECTION A-A
INDUCTRAN CORPORATION
DR
DATE 7/87
CK
SCALE 1/4
PRELIMINARY 'DRIVE OVER'
CHARGING SYSTEM ARRG'T
ON A '95 SATURN SPORT COUPE
SD10004
A

Figure 5.
DRIVE OVER ARRANGEMENT



The source inductor assembly is recessed into the center of the housing for the station, as shown in the drawing. The source inductor is mounted in a suspension inside of the housing. This suspension allows the inductor to be pulled upward by magnetic forces in the coupling until it contacts the lower surface of the vehicle inductor. The suspension is spring loaded in the upward direction, so that the modest magnetic forces in the coupling can lift the source inductor as much as three inches when the station turns on. Further, the suspension design allows the source inductor to accommodate the slope of the lower plane of the vehicle inductor in both the axial and lateral directions.

A rubber sheet covers the top of the inductor and projects beyond the inductor on all four sides. The sheet serves to seal the clearance gap between the inductor and the surrounding housing when the charging station is in its rest (lowered) position.

In the drive-over arrangement, it is not necessary to limit the width of the inductor to the height of the bumper. Thus, the drive-over arrangement allows use of shorter, wider inductors, which provides a cost advantage. Further, because the inductor enclosures are not easily visible and thus are not required to be of aesthetic design, they can be simple, economic rectangular assemblies fabricated from fiberglass board.

The housing for the charging station consists of a welded frame constructed from aluminum extrusions with a thermoformed plastic cover. The cover material is suitable for outdoor exposure, and the housing's color, texture, and shape enhance the appearance of the station.

Design Issues

Installation of the coupling inductor on the vehicle

The drive-over arrangement appears to be compatible with the configurations of most new cars. These cars usually have an "air dam" below and behind the bumper, which creates a volume between the dam and the first structural crossmember in which the coupling inductor could be mounted. The vehicle inductor and control electromagnet in this arrangement are mounted to existing structural members on the vehicle using light-weight brackets as shown in arrangement drawing.

Installation of the charging station

The drive-over charging station arrangement requires less garage floor area than the alternate arrangement because the station is below the vehicle, rather requiring additional length beyond the vehicle. The system is also less conspicuous because of the low profile of the charging station. Further, the shape and color of the charging station will be carefully designed to enhance the attractiveness of the product. The inductor houses the electrical controls for the charging station, which are shown in the block diagram of the system, Figure 4. Installing the charging station requires only bolting the housing to the concrete floor of the garage, and connecting the 240 volt, 40 amp electrical service to the station through a rigid or flexible conduit entry into the electrical enclosure.

Physical protection

The top surface of the source inductor in the charging station will be exposed to the environment, which on occasion will be outdoors. This surface is designed to be covered with a sheet of elastomer, which provides the designer with a choice of suitable materials. Neither the source nor the vehicle inductor will be subjected to impacts that could occur in the alternate arrangement. Thus, conventional inductor enclosures and inductor designs should be well suited to this application.

Safety

Safety issues are essentially the same in the drive-over arrangement as for the bumper-mounted arrangement. However, the over-drive arrangement provides a safety advantage by placing the vehicle inductor under the vehicle, which further isolates the power coupling from any possibility of contact by people.

Alignment

In the drive-over arrangement, the charging station is lost from the driver's view as the vehicle parks in the charging station. A visual aid may therefore be required to help the driver park the vehicle within the desired positional tolerances of the inductive power coupling. Several low-cost, straightforward visual aids have been tested or proposed that are easy to understand and to use.

Relative cost to manufacture

The projected production cost of the charging system in the drive-over arrangement is lower than in the alternate arrangement. Development and tooling costs would also be significantly lower because the coupling configuration is simpler, and because some important design techniques can be borrowed from proven designs of industrial chargers.

Performance

There are no apparent reasons for differences in performance between the alternate arrangements and the reliability of the charging systems in the two arrangements should be excellent. The reliability of the charging system in the drive-over arrangement may be somewhat better because the coupling inductors are subjected to less physical abuse in operation. It must be anticipated that exterior charging stations may be submerged in water or snow, and will be subjected to the effects of ultraviolet and high temperatures during summers.

However, appropriate designs will ensure excellent reliability despite these conditions.

Preferred Mounting Arrangement

An analysis of the relative merits of the alternative charging system arrangements indicated that the electromagnetic, electrical, and control functions of the charging system are not significantly affected by the choice of arrangement. The analysis therefore focused on other criteria that could be influenced by the arrangement choice: operating convenience, added weight, ease of installation, appearance, durability, reliability, safety, and costs, as discussed below.

Operating Convenience

The operation of the automatic charging system adds only one new responsibility for the driver: parking the vehicle in the charging station with more than usual care. To ensure proper operation, the inductors in the power coupling require lateral positional accuracy of approximately +/- 5 inches in the bumper-mounted arrangement and +/- 4.5 inches in the drive-over arrangement. The longitudinal positional tolerance in the bumper-mounted arrangement would be +/- 6 inches, and about +/- 3 inches in the drive-over arrangement. The ease of parking the vehicle thus favors the bumper-mounted arrangement.

Weight Added to the Vehicle

The preliminary designs for the charging system in the two arrangements indicate vehicle system weights of approximately 69 lb and 70 lb, including the vehicle inductor assembly and support structure, charge controller assembly, driver control/display panel, and power and control cabling. Thus, there is no significant difference in the weight added to the vehicle in the two arrangements.

Approximately one-third of the energy used by the vehicle on the highway is related to its weight. Adding 70 lb to a 3000-lb vehicle could be expected to increase its energy consumption by about 0.8%.

Ease of Installation

Installation of the charging station in either arrangement is similar and straightforward: the charging station needs to be bolted in place on the garage floor and connected to an electrical service. However, installing the vehicle inductor in front of the bumper is more difficult and time consuming than installing it under the front of the vehicle, as can be discerned from an inspection of the arrangement drawings. The balance of the installation—installing the charge controller and driver control/display panel—is essentially the same in both arrangements. Thus, ease of installation clearly favors the drive-over charging system arrangement.

Appearance

The vehicle's appearance is not changed by the installation of the drive-over charging system, while the bumper-mounted charging system would substantially affect—and possibly detract from—the appearance of the front of the vehicle. The appearance consideration thus favors the drive-over arrangement.

Durability

The charging system will be subjected on occasion to extreme outdoor environments, abusive treatment, oils and greases, and severe impacts from roadway debris, as well as mechanical wear and tear and thermal cycling from thousands of charging cycles. There is no apparent significant difference in the charging system arrangements that would make one or the other more vulnerable to the effects of these kinds of stresses.

The bumper-mounted inductor could be subjected to an increased incidence of impacts. However, its enhanced ruggedness should ensure its durability, despite this possibility.

Reliability

Since the electrical operation of the alternate chargers is essentially the same, any differences in reliability would be due to differences in the mechanical components. The articulation of the source inductor involves more work in the case of the drive-over arrangement because the weight of the inductor has to be raised and lowered, which is not the case with the bumper-mounted system. The arrangements also have different suspension systems. In the bumper-mounted system, the source inductor is supported by a cantilevered arm and a rotating shaft, while in the drive-over system the source inductor is lifted directly by four spring loaded belts. There does not appear to be any basis for projecting differences in the reliability of the two suspension methods, both of which are amenable to conservative design and reliable operation.

Safety

A hallmark feature of inductively coupled charging systems is their inherent operational safety. There are no exposed electrical conductors, and this automatic inductive charging system is far safer than any system that requires handling of an electrical cord carrying high voltages or high-frequency current. As another important safety advantage, this system cannot deliver more than its designed current, even in the case of a hard short circuit.

Remaining safety concerns are those that exist in any high-power electrical system, including the thermal effects from an electrical component that might fail in service. Adequate over-current protection with circuit breakers or fuses guards against most such hazards. However, excessive temperatures can also result from components whose impedance increases due to an internal failure. In industrial charging systems for people movers where the ultimate in safety is desired, thermal switches have been used to protect against the possibility of excessive temperatures in coupling inductors. These protections can be provided in the designs of both arrangement options.

Cost

Because the retail price is a major factor in the consumer acceptance of the automatic charging system, the BKI/Inductran team conducted a cost analysis for the Inductran system. Results are provided for three price points: the cost of manufacturing a single prototype unit for both configurations, the cost of producing 1,000 units, and the cost of producing 10,000 units.

	Prototype Cost Estimate		**Estimated Retail Price**		
	Drive Over	**Bumper Mount**	**1000 Units**	**10,000Units**	
Item			**Cost/unit**	**Cost/unit**	
Vehicle					
Vehicle Inductor	$7,000	$7,850	$1,200	$480	
Vehicle Mounting Members	$500	$830	$75	$25	
Charge Controller	$5,500	$5,500	$800	$320	
Electromagnet	$350	$350	$95	$45	
Subtotal	**$13,350**	**$14,530**	**$2,170**	**$870**	
Station					
Source Inductor	$6,500	$7,500	$1,100	$460	
Passive Suspension	$2,500	$2,500	$400	$170	
Source Control	$1,200	$1,200	$600	$350	
Magnetic Sensor	$900	$900	$430	$45	
Subtotal	**$11,100**	**$12,100**	**$2,530**	**$1,025**	
Auto Charger Cost	**$24,450**	**$26,630**	**$4,700**	**$1,895**	
Tooling	**$0**	**$0**	**$45,000**	**$100,000**	
Total Per Unit Cost	**$24,450**	**$26,630**	**$4,745**	**$1,905**	
Installation					
Vehicle	$480	$980	$240	$240	
Charging Station	$1,000	$1,000	$800	$800	
Subtotal	**$1,480**	**$1,980**	**$1,040**	**$1,040**	
Per Unit Installed Cost	**$25,930**	**$28,610**	**$5,785**	**$2,945**	
Notes:					
Vehicle installation for retail units assumes 4 hours of technician time @$60.00/hr.					
Additional hours are assumed for installing the prototypes.					
Retail charging station installation costs assumed similar to average costs for EVSE installation					
and additional $200 for prototype.					
Retail price estimates are for the drive-over inductive system.					

Prototype costs

As shown, the bumper-mounted system will cost about $2,200 more to produce and $500 more to install than would the drive-over system. At this stage in development, it is too early to accurately identify the difference in the retail price between the two design options.

Preliminary retail cost forecast

As shown, the forecast retail price of the automated charging system is $1,905, with a total installed cost of $2,945, assuming a production run of 10,000 and including the cost for production tooling. Thus, the Inductran charging station installed cost should be equivalent to that of standard electric vehicle supply equipment (EVSE). An incremental cost of $240 is forecast for installing the vehicle inductor on the vehicle.

The retail price forecasts were based on prototype vs. unit costs of an industrial inductive 1.6 kW charging system constructed for General Motors. Although that charger was smaller than the charger for this project, information from that project provided guidance on unit pricing reductions and larger production volumes.

Summary of the Analysis

Table 1 shows the results of the analysis to determine the best charging system arrangement. The bumper-mounted arrangement enjoys a moderate advantage in only one of the eight areas analyzed, while the drive-over arrangement offers a major advantage in two areas and a moderate advantage in an additional area. There appears to be little difference with respect to four of the analysis criteria. The drive-over arrangement therefore is the best choice.

The analysis also showed that some design effort should be devoted to enhancing the ease of positioning the vehicle, particularly in the longitudinal direction. The next project phase includes a significant effort to quantify the positional tolerance that should be provided for the typical driver, and to evaluate optional means of visually, electronically, or mechanically helping drivers easily and accurately position their vehicle in charging stations.

Table 1. Relative Effectiveness of Alternate Charging System Arrangements

Characteristic	Drive-Over	Bumper-Mount
Operating Convenience		✔✔
Added Weight on The Vehicle	•	•
Ease of Installing the System	✔✔✔	
Appearance	✔✔	
Durability	•	•
Reliability	•	•
Safety	•	•
Cost	✔✔✔	
Total	✔✔✔✔✔✔✔✔	✔✔

✔ = slight advantage
✔✔ = moderate advantage
✔✔✔ = major advantage
• = little or no difference

Benefits of the Inductran System

During the Task 1 investigation, the project team responded to two specific concerns raised about use of the Inductran system:

- A high-frequency system might be a better choice than the Inductran low-frequency (60 Hz) system, because higher-frequency equipment weighs less.
- As an in-ground system, Inductran would not be able to operate in harsh rain and snow conditions.

As discussed below, the team concluded that the Inductran system offers numerous advantages over a high-frequency system, including lower costs, greater tolerance for misalignment in the autodocking process, and a more benign potential effect on the utility system.

Lower Cost

Using utility frequency (60 Hz) allows construction of the inductive coupling from the same inexpensive materials used in electrical transformers. Coupling production costs are therefore comparable to those for a transformer with a similar power rating. The retail price for such transformers is about $3.00–$4.00

per pound; thus, the retail price of the inductive coupling in high production volume could drop to as low as $400–$500. In addition, a 60 Hz charging system enables the use of uncomplicated, less-expensive control subsystems as well as less-expensive manufacturing methods.

Tolerance of Misalignment

A 60 Hz inductive coupling can easily and inexpensively be made large enough to provide generous alignment tolerance between the vehicle and the charging station. Raising the frequency to minimize weight results in the need for very precise alignment (e.g., the Hughes paddle must slide into a slot), which makes automatic charging highly complex and so far unattainable (e.g., GM's unsuccessful laser-guided system). A high-frequency system would thus require a complex mechanism to align and engage the small coupling—increasing both cost and system complexity, and seriously degrading system reliability and ruggedness.

The alternative approach—increasing the size of the coupling of a high-frequency system to provide adequate alignment tolerance—is equally undesirable. This approach would make the coupling extremely expensive and virtually unmarketable due to the need for larger amounts of the costly materials required in high-frequency electromagnetic devices, such as ferrite cores and specialized conductors. Moreover, as coupling size increases, so does the size of the shielding required to prevent radiating electromagnetic interference (EMI), which would further increase system cost and complexity.

Less Impact on Power Quality

Chargers that use solid-state switching to convert 60 Hz to high frequency typically radiate radio frequency energy because the abrupt switching generates a wide spectrum of harmonics that extends far into the RF spectrum. These chargers have to be rigorously shielded to prevent this radiation. Despite this precaution, however, some high-frequency harmonic content is usually conducted back into the utility electrical service.

Electric power supply carrying high-frequency ripple can be especially troublesome in the home environment because the house wiring functions as an antenna that can radiate interference into computers and other sophisticated communication and control devices.

By contrast, the Inductran charging system poses little risk of degrading utility power quality because it does not use solid-state switching.

Weight Penalty

The low-frequency Inductran system weighs more than would a comparable high-frequency system. However, the entire weight of the 6.6 kW charging system to be developed for this project will account for only about 2% of the total vehicle weight and will increase the energy consumption of the vehicle less than 1%.

Experience with industrial systems has consistently shown that automatic charging results in increased charging during idle periods—which extends the range of the electric vehicle, typically by a large multiple of the weight penalty. Thus, automatic charging substantially increases the usefulness of the EV, and the small investment in extra weight is acceptable.

Tolerance to Harsh Environments and Abuse

Low-frequency automatic charging systems have firmly established their ability to operate in extremely severe environments and under abusive conditions. In-ground Inductran chargers are now operating safely and reliably in outdoor environments where they are exposed to both snow and ice.

Low-frequency systems hold several advantages over high-frequency systems in severe operating environments. The coupling inductors are rigorously sealed and have successfully operated under water. Further, low-frequency systems have no components that are sensitive to extreme environmental temperatures. The inductors are rugged enough to absorb severe impacts without damage, and sufficiently durable to withstand continual scuffing and abrasion.

For charging stations that are mounted horizontally on the pavement in an area subject to severe snow or ice storms, a straightforward and inexpensive solution is to add low-power resistive heating elements with thermostatic switches in the inductors, such as those successfully used in roof gutters or walkways for de-icing purposes.

Discussion

Though enlightening, the debate over the pros and cons of low-frequency vs. high-frequency designs is outside the scope of this project. The goal of this project is to demonstrate the viability of automated charging *per se* by building, testing, and demonstrating an automated charging system. Its purpose is not to define an optimal system design.

This said, a 60 Hz system provides significant advantages, as noted above. Further, a low-frequency system allows quicker, less-expensive development of a working prototype to serve as a benchmark for evaluating the performance and cost tradeoffs of alternative designs, including solid-state high-frequency chargers.

Specifically, this system will enable us to evaluate automated technology in terms of "human factors," i.e., the driver's ability to "dock" the EV within allowable tolerances, the frequency of misalignment, the effectiveness of parking guides, the impact of misalignment on charger efficiency, and whether drivers like an automated approach.

Most important, this system will demonstrate whether automated charging is possible at a reasonable cost and with minimal driver interaction. Once the feasibility and utility of automated charging is established, then additional issues leading to system refinements can be investigated. However, until the practicality of automated charging is demonstrated, it would be grossly inefficient to design an expensive, user-unfriendly, high frequency system for the sake of weight reduction. A high-frequency system would add complexity and cost to the project before the practicality of automatic charging and its appeal to consumers has been determined. Reducing the system's weight would be of limited value if—due to smaller tolerances, harmonic characteristics, and higher costs—the high-frequency charger is unattractive to the market.

Section III

Detailed Design Description

Objective of the Design

The objective of the design was to create a prototype charging system that could be used to test and evaluate the efficacy and desirability of automatic charging systems for electric cars.

Design approach

A design approach was taken that was significantly different than the one used for Inductran Corporation's industrial charging systems. This was done in order to try to meet the objective with a prototype charging system that could appeal to typical EV drivers, and which could satisfy the cost and functional requirements of automobile manufacturers and the marketplace. The design for the prototype charging system thus had to consider issues relating to consumer acceptance, such as ease and simplicity of use, suitability to the environment of a typical home garage, and cost. The design considered particular issues such as weight and mechanical and electrical interfaces with cars, and adaptability to serial production.

The design also was significantly influenced by the requirement that the charging system comply with specified electrical characteristics such as power factor, efficiency, and harmonic distortions in the electrical supply to the system.

Prototype systems such as this charging system must of necessity be manufactured without the benefit of production tooling. System components thus had to be designed to be producible with typical machine shop and sheet metal shop equipment and procedures, and electronic assemblies had to be designed to use simple printed circuit boards and a commercial programmable logic controller.

Description of the Operation of the Automatic Charging System

The charging system automatically initiates a charging cycle when a car parks within the charging station's tolerance for misalignment (+/- 5" long-wise and +/- 6" short-wise, see figure 6) and the driver turns off the key switch. A wand is attached to the station that provides a visual aid to help the driver park the car accurately.

An electromagnet on the car is activated when the key switch is turned off, and the charging station turns on when the electromagnet's field is sensed in the charging station. If the car is not in a charging station or the station had not turned on for some anomalous reason, the electromagnet is pulsed several times at intervals to ensure that a charging cycle could not be activated.

Charging power is transferred magnetically, i.e., without electrical contact, to the car through an inductive power coupling when the charging station is activated. The power coupling consists of two inductors, one on the car and one in the station. The source inductor in the charging station is magnetically lifted into operating position when the station turns on, since the vertical clearance between the inductors must be small when the coupling is active. The size and electromagnetic properties of the coupling are designed so that the electromagnetic field generated by the source inductor is broad enough to allow for power to be transferred between the inductors even when they are misaligned by over 5" in either direction, a tolerance for misalignment which has been found to be adequate in previous charging systems and which was demonstrated to be adequate in this project.

A charge controller assembly on the car conditions the AC power for battery charging, and the charging cycles are monitored and controlled by a programmable logic controller and associated PC board in the assembly. Once initiated, a charging cycle will continue until the control logic senses that the battery is fully charged, or that the car's key switch has been turned on in preparation for driving the car away. The controller supplies or removes power to the electromagnet in order to turn the charging system on or off.

Manual control switches in a charge control assembly in the car allow the driver to deactivate the charging system, or to periodically request an equalizing charge for conditioning the battery. A charging current indicator is also provided in the charge control assembly.

The automatic operation of the charging system assures that charging opportunities will never be missed, which enhances the reliability of the car and the service life of its battery.

General Arrangement of the Charging System

The general arrangement of the charging system is shown in drawing SD 10007. The system's major components are a charging station over which the vehicle parks when it is to be charged, and a subsystem on the vehicle that receives, conditions, and controls the charging power that is supplied from the charging station.

Charging station

The arrangement of the charging station is shown in drawing SE10008. The station is a rectangular assembly with a rugged plastic frame and a thermoformed cover that rests on the floor. It houses the source inductor for the power coupling and the electrical controls for the station.

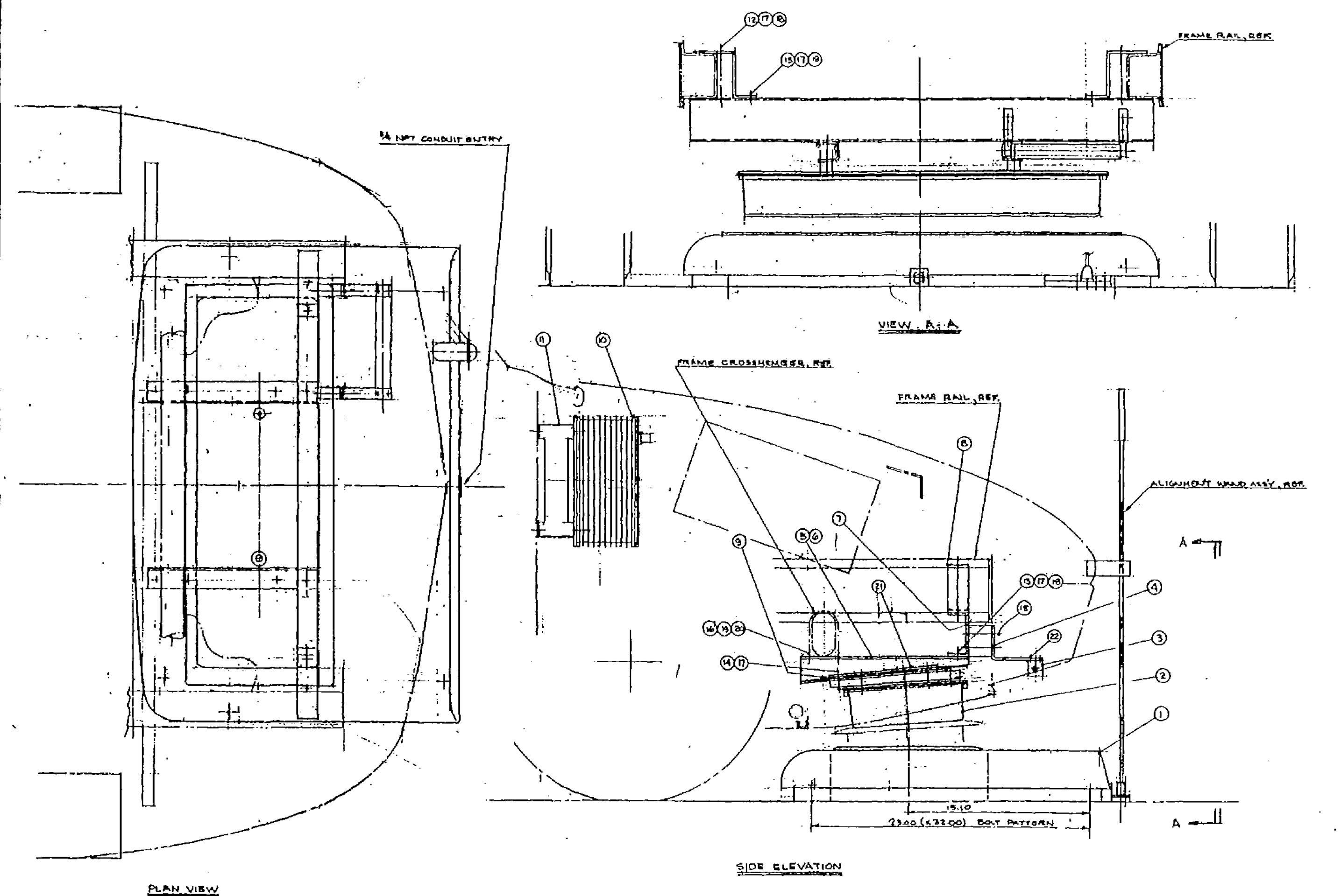
Magnetic flux links the source and vehicle inductors in the power coupling when the charger turns on. The flux creates an attractive force between the inductors that helps to lift the source inductor into contact with the vehicle inductor. An upward force is also applied to the inductor assembly by the two coil springs that parallel it, since the magnetic force alone is not sufficient to lift the inductor.

The station's electrical controls are mounted on an aluminum plate in an enclosed area in the frame of the charging station. They include a sensitive magnetic switch whose output activates the solid state relay that controls the power to the station. The switch reacts to the magnetic field from the control electromagnet on the vehicle. Several AC capacitors are also included in the electrical controls whose function is to improve the power factor in the electrical service to the system.

A wand is attached to the station to assist the driver in parking within the positional tolerance of the system. The wand is a flexible fiberglas rod that supports a reflector that is easily visible to the driver and is directly in line with the driver's position. The reflector provides the driver with a precise sense of the car's lateral position with respect to the charging station and the obvious movement of the wand when bumped by the car indicates that the car is in the correct longitudinal position.

Vehicle subsystem

The vehicle inductor assembly, drawing SD10009, is located under the front of the car with its lower surface approximately six inches above the road. It is supported by a frame that is attached to structural members in the car with clamped joints that do not require holes to be drilled in the car, making the installation process simple and quick.



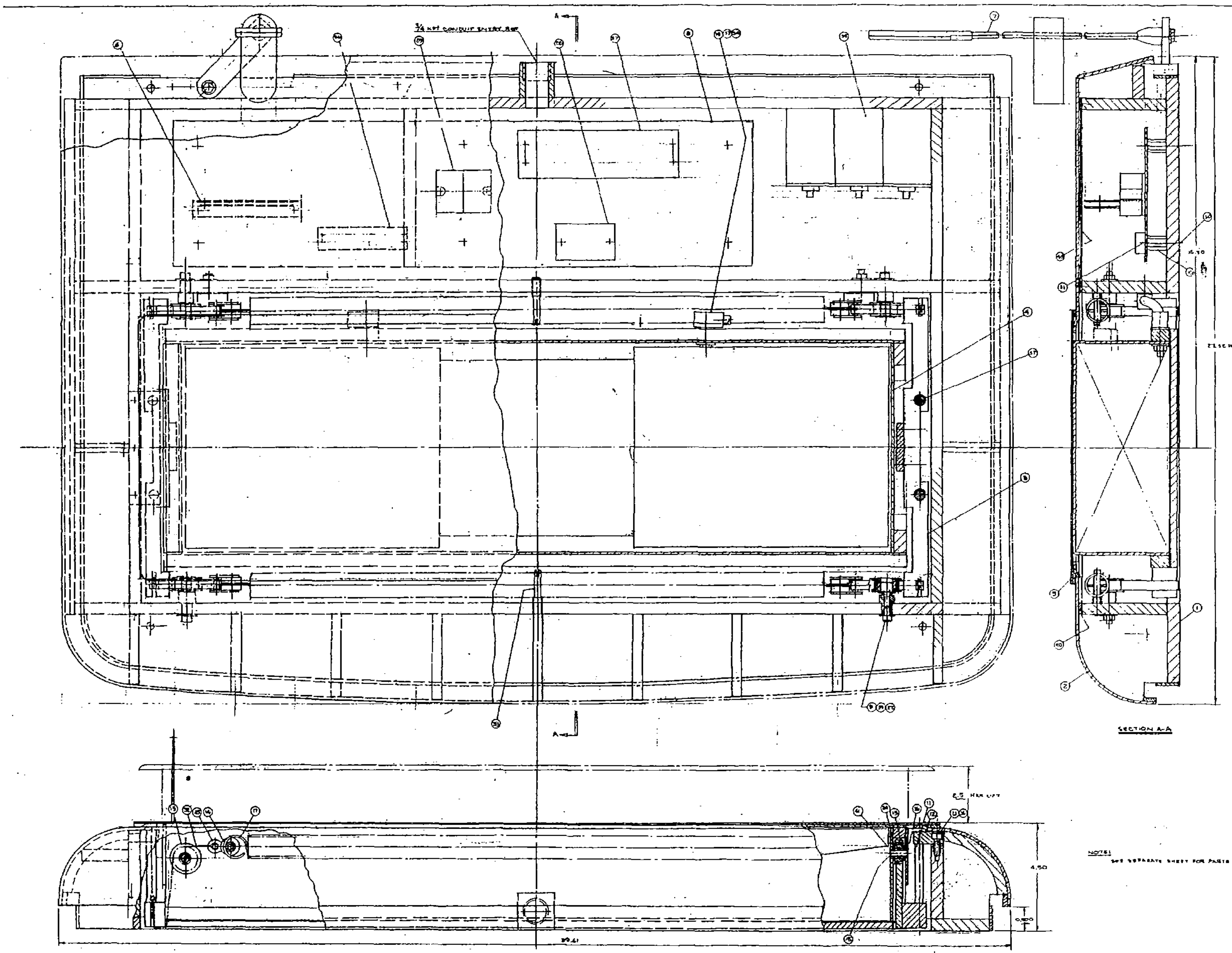
ITEM	DESCRIPTION	DRAWING	QTY
1	CHARGING STATION ASSEMBLY	SD 10008	1
2	VEHICLE INDUCTOR ASSEMBLY	SD 10009	1
3	CONTROL ELECTROMAGNET ASSY	SB 10032	1
4	E/M BRACKET	SA 10031	1
5	SUPPORT BRACKET, RIGHT	SB10032-1	1
6	SUPPORT BRACKET, LEFT	SB10032-2	1
7	SUPPORT CHANNEL	SA 10033	1
8	CLAMP BRACKET	SA 10034	2
9	SOFT PAD	(NO DWG.)	2
10	CONTROLLER ASS'Y	SD 10011	1
11	CONTROLLER SUPPORT	SA 10063	2
12	CAP SCREW, 5/16-18 x 4 1/2	——	2
13	" " , 5/16-18 x 3/4	——	4
14	" " , 5/16-18 x 1	——	4
15	PAN HD. SCR, 10-24 x 2 1/2	——	8
16	U-BOLT	SKB 668-1	2
17	SAE FLAT WASHER, 5/16	——	10
18	HEX NUT, 5/16-18	——	10
19	SAE FLAT WASHER, 1/4	——	4
20	HEX NUT, 1/4-20	——	4
21	STRAP	SKB 199-5	2
22	PAN HD. SCR, 10-24 x 3/8	——	4

POLYTRAN CORPORATION

AUTOMATIC EV CHARGING SYSTEM ASSEMBLY

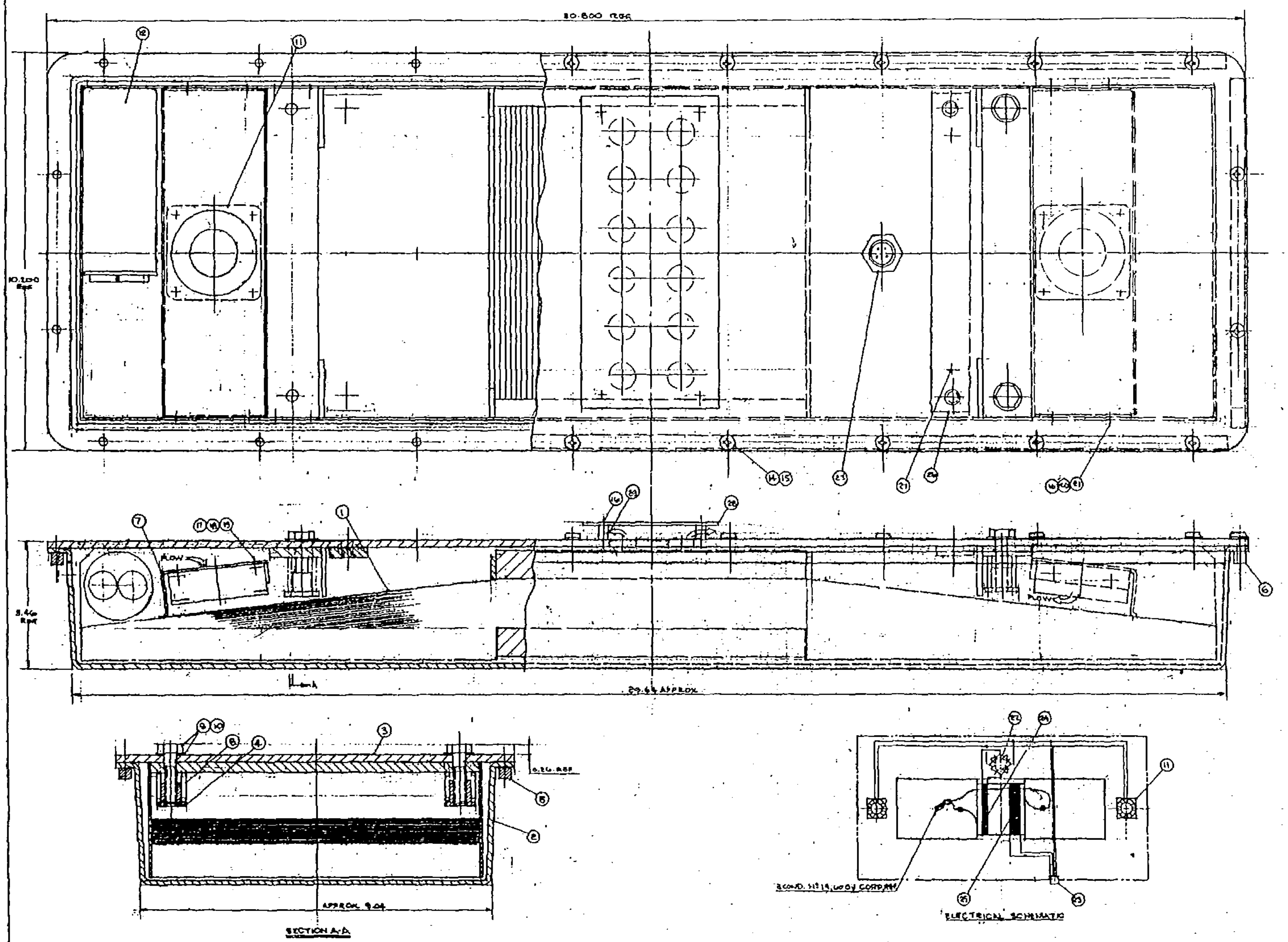
DR. JS
DATE 2/08
SCALE 1/4
MAT'L —

SD10007 D



NOTES:
SEE SEPARATE SHEET FOR PARTS LIST

DATE 2/98	AUTOMATIC EV CHARGING SYSTEM
SCALE 0.18	CHARGING STATION ASSEMBLY
—	
—	96 1008 D



ITEM	DESCRIPTION	DRAWING	QTY
1	INDUCTOR SUB ASSEMBLY	SD10012	1
2	PAN	SC10014	1
3	TOP PLATE	SA10015	1
4	SPRING NUT (8)	SA10016	4
5	SIDE BOLTING STRIP	SA10017	2
6	END BOLTING STRIP	SA10018	2
7	FAN HOUSING	SB10018	2
8	COMP. SPRING, 0.72 OD, 0.06 WIRE, 1.15 LONG		
	ASSOC. SPRING Nº C0720-056-1250	—	4
9	PLATED HEX CAP SCR., 5/16-24 x 1.25	—	4
10	" FLAT WASHER, 5/16	—	4
11	FAN, 2.4 SQ., 12VDC, NMB 2410NL-04W-B50	—	2
12	CAPACITOR, 35 MF, 440V	—	1
13			
14	PLATED PHIL. PAN HD. SCR., 10-24 x 5/8	—	20
15	" FLAT WASHER, Nº 10 x 0.437 OD	—	20
16	" PHIL. PAN HD SCR., 8-32 x 7/8	—	12
17	" " " " " , 4-40 x 7/8	—	8
18	" Nº 4 LOCK WASHER	—	8
19	" 4-40 HEX NUT	—	8
20	" Nº 8 LOCK WASHER	—	8
21	" 8-32 HEX NUT	—	8
22	BRIDGE RECTIFIER, 15 AMP, 100V MIN.	—	1
23	CONNECTOR, CONXALL 4282-6SG-300	—	1
24	6 TURN, 24 GA. MAG. WIRE COIL	—	1
25	48 " " " " " "	—	1
26	SUPPORT STRAP	SKP1138-3	2
27	F.H. SCREW, 10-24 x 1/2	—	4
28	1/16 G10 SHEET, 2.5 x 8.0	N.D.	1
28	1/4 OD. ALUM. TUBE x 3/8 LONG	—	4

INDUCTRAN CORPORATION

DR. B	AUTOMATIC EV CHARGING SYSTEM
DATE 1/88	VEHICLE INDUCTOR ASSEMBLY
SCALE 0.75	
CHK. —	
	SD 10009 D

The charge controller assembly, drawing SD 10011, is supported by brackets that are attached to the firewall of the car with sheet metal screws. The controller contains a rectifier for the incoming AC power from the inductive coupling, and a printed circuit board and programmable logic controller to monitor and control the charging cycle.

The control electromagnet is attached to the support frame for the vehicle inductor in a position over the magnetic switch in the charging station.

A charge control assembly, drawing SA10080, is mounted above the car's electronic controls on top of the battery tunnel beside the driver's seat (not shown in drawing SD10007).

Description of the Detailed Designs of System Components

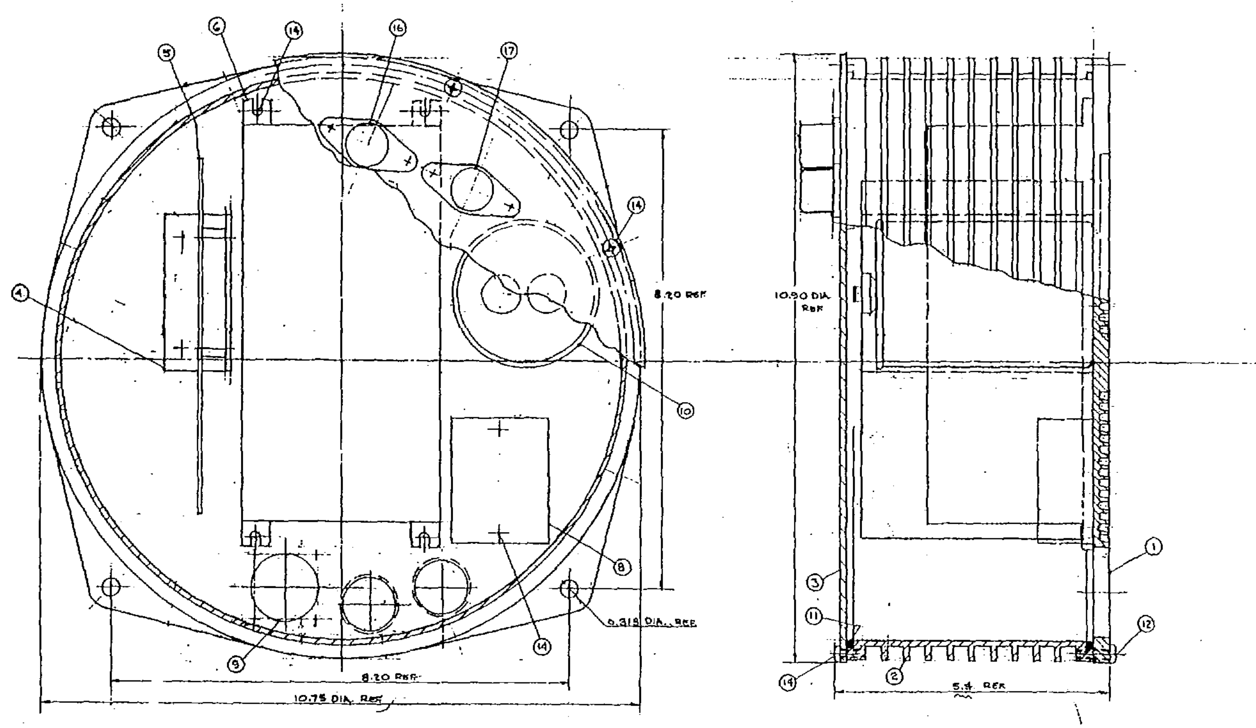
Charging station

Charging station frame and cover

The frame is fabricated from parts made of rigid PVC plate that were bonded together with solvent/ cement to construct a rugged, flexible, non-conducting, and corrosion resistant structure. This design allows the frames to be fabricated inexpensively in modest quantities because of the relatively low costs of the PVC plate, the use of a computer controlled water jet to rapidly cut the parts to close tolerance outlines, and the quick and easy assembly of the frame with solvent cemented joints.

The frame was designed with a well for the source inductor, and a watertight enclosure for the electrical controls for the charging station.

The cover for the charging station is thermoformed from plastic sheet. The prototype was fabricated from ABS sheet in order to present an attractive colored and textured outer surface. The cover could be fabricated in production quantities from colored PETG (glycol-modified polyethylene terephthalate) plastic sheet in order to obtain its exceptional impact resistance along with some other desirable physical properties. PETG plastic sheet is now widely used in the automotive industry due to its cost effectiveness compared to acrylic or polycarbonate. Colored PETG sheet was not available on short notice for the prototype system.



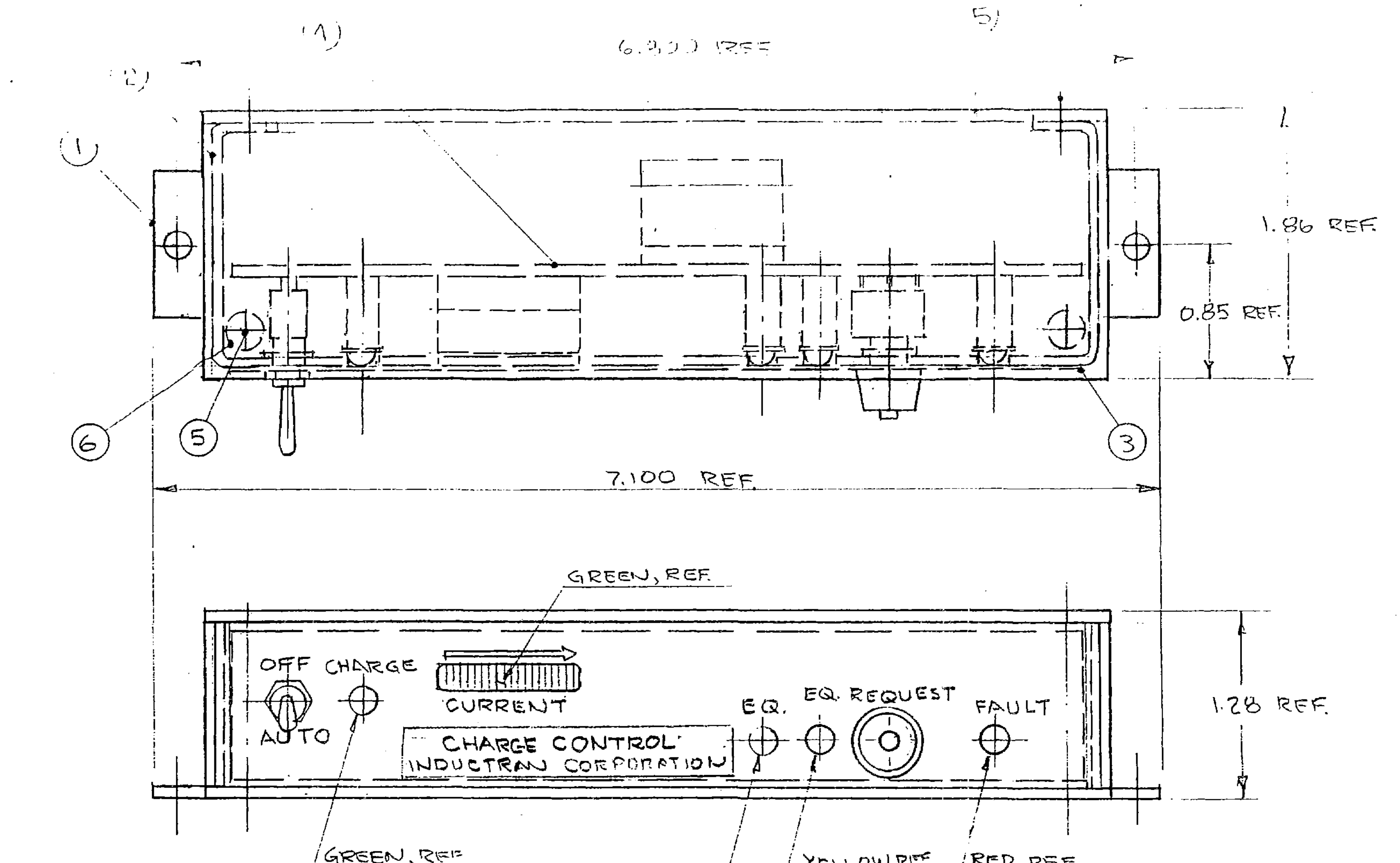
ITEM	DESCRIPTION	DRAWING	QTY
1	BASE PLATE	SC 10086	1
2	WALL TUBE	SB 10037	1
3	COVER PLATE	SA 10038	1
4	BOARD BRACKET	SA 10035	1
5	INTERFACE BOARD ASSY	SC 10040	1
6	PLC, PLC DIRECT DL205, D204B. BASE	—	1
7			
8	DIODE BRIDGE RECTIFIER, 60 AMPS, 1200 VOLTS	—	1
9	CIRCULAR PLASTIC CONNECTOR, AMP Nº 206045-1	—	1
10	AC CAPACITOR, 440 VOLT, 45 µF	—	1
11	O-RING, BUNA, 10.010 x 1/8 CROSS SECTION	—	2
12	PAN HD. PHIL. SCR, 8-32 x 1/2, STAINLESS STL.	—	8
13			
14	PHIL. PAN HD. SCR, 8-32 x 3/8, STAINLESS STL	—	20
15		—	[illegible]
16	BUSS TYPE HPF FUSEHOLDER WITH 8A, 600V. FUSE	—	1
17	" " " " " 1/2 A, " "	—	1

POLYTRAN CORPORATION

DR	[illegible]
DATE	2/98
SCALE	FULL
MAT'L	NOTED

AUTOMATIC EV CHARGING SYSTEM
CONTROLLER ASSEMBLY

SD10011 D



ITEM	DESCRIPTION	DNG.	REQD
1	PANEL HOUSING		1
2	PANEL		1
3	PANEL FACE	—	1
4	PC BOARD ASSY		1
5	8-32 x 1/4 F.H. SCR, PLATED	—	6
6	SPACER, .25 DIA. x 1.0, 8-32 THD, AL	—	2

INDUCTRAN CORPORATION
P.O. BOX 1127, ORINDA, CA 94563

DR. B	CHARGE CONTROL ASSY
DATE 7/98	
SCALE FULL	
TOL. —	5A10080 — A

Source inductor assembly

The source inductor consists of a "U" shaped steel core around which is wound the main copper coil. A small auxiliary coil winding is wound on top of the main coil to provide power for two small fans in the inductor assembly.

The steel core is constructed from thin laminations of electrical steel sheet that are bonded together with epoxy resin. The completed inductor is impregnated with a hard, heat resistant epoxy resin and cured at high temperature during a vacuum/pressure impregnation ("VPI") process after the coils have been wound on the core. This provides additional electrical insulation, fills and seals voids in the coil, and enhances the structural strength, rigidity, and heat resistance of the inductor.

The source inductor is enclosed in a plastic housing in order to minimize its weight, to avoid eddy current losses that would occur in a metal housing, and to provide a non-conducting, non-corroding structure. The enclosure's top and sides are cold formed from a polycarbonate sheet, while its bottom and ends are fabricated from pieces of "G10" high strength fiberglas/epoxy laminate.

The inductors in Inductran's industrial chargers are encased in G10 sheet that is bonded directly to the inductors, but the inductors in this new design are encased in a separable housing. The intent of the new design was to reduce the sound emitted from the inductor by isolating its vibrations from the outer housing. This arrangement required that two small fans be provided in the housing to remove the heat from the inductor's coil, since the outer surfaces of the housing are not effective in transferring heat to the outside environment. The fans are arranged to draw air from a shielded opening in one end of the inductor housing and to exhaust it from a similar opening in the other end. The new, separable housing design resulted in only a minor reduction in sound level and the fans and cooling pathways had to be modified during testing to increase the amount of cooling provided, as discussed in Section V.

Source inductor suspension

The inductor assembly is supported at its ends by self-aligning bearings in sliding frames. The bearings allow the assembly to rotate along both of its horizontal axes in order to align itself when it is lifted into contact with the lower surface of the inductor assembly on the car.

The attractive magnetic forces between the vehicle and source inductors are assisted in lifting the source inductor towards the vehicle inductor by two coil springs. The forces from the coil springs are transferred to the sliding frame of the source inductor by short pieces of timing belt, which are connected on one end to one of the coil springs and on the other end to the sliding frame. The length of the highly durable timing belt can be adjusted to allow for variation in the weight of and magnetic forces developed by individual inductors, as well as variations in forces developed by individual springs.

The electrical connections between the movable inductor assembly and the charging station's electrical controls are made through short cables. The cables that were used have a finely stranded conductor with rubber insulation so that they can flex without impeding the lifting motion of the inductor.

Electrical controls for the charging station

The electrical controls consist of a sensitive magnetic switch, a solid state relay, a small low voltage transformer, and two terminal blocks that are mounted on an aluminum plate. The magnetic switch is a proprietary Inductran product that is designed to be activated from a distance of six inches or more by a control electromagnet on the vehicle. Its low voltage output controls the operation of the solid state relay that switches the 240-volt electrical service to the charging system.

The aluminum plate also serves as a heat sink for the solid state relay.

Vehicle Subsystem

Vehicle inductor assembly

The vehicle inductor assembly includes the inductor, an enclosure, two small cooling fans, a capacitor, and a small bridge rectifier for the power for the fans.

The construction of the inductor on the car is closely similar to the source inductor. The main coil windings differ because the voltages to/from the inductors are different, and the vehicle inductor has two additional small coil windings, one of which supplies power at approximately 100 volts and more than an ampere to the electronics on the car; the other supplies low voltage to the inductor cooling fans.

The enclosure for the inductor consists of a bottom pan that is thermoformed from PETG sheet, and a G10 (fiberglas) top plate. These materials were chosen because of their impact resistance and strength. As is the case with the source inductor, the separable enclosure was used with the intent to isolate the inductor's vibrations from the outer surfaces as a means of moderating sound emissions from it.

Inlet ventilation holes are provided at each end of the housing, and exhaust holes are provided in the center of the top plate. Cooling air is drawn into the housing by a fan in each end of the enclosure. The air flows along the top surfaces of the steel core and coil to exit through the exhaust holes.

Tapped holes are provided in an aluminum strip under the top plate for the bolts that fasten the assembly to its supporting structure.

Charge controller assembly

The charge controller assembly is housed in a cylindrical aluminum enclosure whose outer diameter was machined to provide cooling fins for dissipating the heat from electronic components in the enclosure. The assembly includes a bridge rectifier for the charging current, a programmable logic controller (PLC), a printed circuit board assembly, and an AC capacitor. A multi-pin connector for control wiring, and two fittings for cables that bring AC power in and take DC power out are provided in the base plate of the enclosure. Two fuses are provided in the cover plate.

The PLC is programmed to determine when to turn the charging system off, or to extend the charging cycle when an equalizing cycle has been requested from the control panel in the car. The program in the PLC utilizes an algorithm in which either the decline of charging current to a very low value, or a rate of decline in charging current that approaches zero will trigger the start of a timed final portion of the charging cycle. The timed final charging period provides a preset (but easily reprogrammed) amount of charging energy to assure that the battery has been fully charged without the possibility of excessive overcharge.

The timed finishing charge was used—rather than using a fixed value of either battery voltage or charging current—as an indication of a fully charged battery. Factors such as battery temperature and the character of the preceding discharge cause those parameters to vary widely, so that the alternative that is used in other chargers is to substantially overcharge the battery to assure that a full state of charge has been reached. Extensive operating tests will be required to prove or disprove the merits of the selected algorithm.

An AC capacitor is mounted in the charge controller assembly so that it can be easily changed to a different value in order to alter the power coupling's current/voltage characteristic relationship.

Control electromagnet

The control electromagnet is a 9.5-inch long solenoid with a steel core whose length determines the tolerance of the charging system for lateral misalignments between the centerlines of the charging station and the car. The magnetic switch that controls the charging station will not be activated and the charger will not start if the misalignment on either side of centerline is larger than half of the length of the electromagnet.

The longitudinal tolerance for displacements is determined by the strength of the electromagnet's field, which was designed to be of a magnitude similar to the lateral tolerance.

Charge control

The charge control assembly is a small rectangular chassis, approximately six x one x two inches, with a control/display panel on its front surface. This control assembly has a toggle switch for either setting the charger for automatic operation, or turning the system off. An LED next to the switch indicates when the charging system is in operation.

An LED bar graph in the middle of the panel indicates the relative amount of charging current being provided to the battery.

A momentary contact push button switch in the panel is provided for entering an equalizing request, which causes an indicator LED to turn on. A second LED indicator turns on when the equalizing cycle automatically begins.

Section IV

Retail Price Analysis

Cost Analysis Results

Because the retail price is a major factor in the consumer acceptance of the automatic charging system, the BKI/Inductran team conducted a cost analysis for the Inductran system. Results are provided for three price points: the cost of manufacturing a single prototype unit, the cost of producing 1,000 units, and the cost of producing 10,000 units.

	Prototype Cost Estimate	Retail Price Estimate	
Item	Drive Over Unit	1,000 Units cost/unit	10,000 Units cost/unit
Vehicle			
Vehicle inductor	$7,000	$1,200	$480
Vehicle mounting members	$500	$75	$25
Charge controller	$5,500	$800	$320
Electromagnet	$350	$95	$45
Subtotal	**$13,350**	**$2,170**	**$870**
Station			
Source inductor	$6,500	$1,100	$460
Passive suspension	$2,500	$400	$170
Source control	$1,200	$600	$350
Magnetic sensor	$900	$430	$45
Subtotal	**$11,100**	**$2,530**	**$1,025**
Total charger system cost	**$24,450**	**$4,700**	**$1,895**
Tooling	**$0**	**$45,000**	**$100,000**
Total per unit cost	**$24,450**	**$4,745**	**$1,905**
Installation			
Vehicle	$480	$240	$240
Charging station	$1,000	$800	$800
Subtotal	**$1,480**	**$1,040**	**$1,040**
Per unit installed cost	**$25,930**	**$5,785**	**$2,945**

Notes: Vehicle installation assumes 8 hours of technician time @$60.00/hr for the prototype and 4 hours for retail unit
Charging station installation costs assumed similar to average costs for EVSE installation and additional $200 for prototype.

Preliminary Retail Cost Forecast

As shown, the forecast retail price of the automated charging system is $1,905, with a total installed cost of $2,945, assuming a production run of 10,000 and including the cost for production tooling. Thus, the Inductran charging station installed cost should be equivalent to that of standard EVSE. An incremental cost of $240 is forecast for installing the vehicle inductor on the vehicle.

The retail price forecasts were based on prototype vs. unit costs of an industrial inductive 1.6 kW charging system constructed for General Motors. Although that charger was smaller than the charger for this project, information from that project provided guidance on unit pricing reductions and larger production volumes. The price estimates listed in the previous table were also derived from numerous discussions with equipment suppliers along with estimates based on Inductran's previous experience in designing and installing industrial charging infrastructure. Equipment suppliers were queried about unit costs at different supply levels, including the 1,000 and 10,000 unit levels cited in the table.

A major fraction of the total cost of Inductran charging systems is the cost of the inductors. The inductors include steel cores that are an epoxy-bonded assembly of many blanked and formed laminations of electrical steel sheet. The sheet is relatively expensive since it is made of a special alloy and is thoroughly annealed and coated with an inorganic insulation. Quotations from a supplier of the steel for various quantities indicated that the cost of the sheet would drop by almost two-thirds in high quantity purchases.

Coils made of heavily insulated square copper or aluminum wire are would around the cores, and the assembly is then vacuum pressure impregnated (VPI'd) in order to strengthen it and provide an extra protective layer of hard, high temperature insulation. These costs are strongly affected by the degree to which the processes are tooled for serial production. The cost estimate reflects Inductran's experience in producing inductors in small, medium, and large quantities.

The inductors are finished by encasing them in a protective enclosure made of a material that provides impact resistance, electrical insulation, and weather/environmental resistance. This charging system used formed plastic housings of polycarbonate and PETG that were attached to a fiberglas laminate base plate. The design of the enclosure would be simplified for production, based on the experience gained in building and testing this prototype system. Cost estimates were obtained from suppliers of the prototype components.

The charging station in the prototype system, which had been designed by a skilled industrial designer, was a radical departure from other Inductran systems since it strongly considered aesthetics required for consumer acceptance rather than the purely functional designs of Inductran industrial charging systems. The pleasingly curved surfaces of the station's enclosure were achieved economically by fabricating a solvent cemented frame with parts made from rigid PVC plate that had been cut to shape by a computer controlled water jet machine. The frame was provided with an attractive, impact resistant vacuum formed plastic cover. The manufacturing processes are adaptable to inexpensive serial production methods.

The cost estimates for the electrical/electronic components of the system, and for assembly and testing the system were extrapolated from data from previous charging systems that were functionally similar to this system.

A small allowance was made for tooling used to produce the prototype system, while the 1,000 quantity estimate projected the use of "soft" tooling and the 10,000 quantity estimate projected the use of well developed and considerably more expensive "hard" tooling.

Section V

Summary of Prototype Tests

Summary

Numerous tests were performed during integration of the charging system. The purpose of many of the tests was to optimize the performance of the system with regard to issues such as the targeted electrical characteristics and emitted sound level. Numerous alterations to the system were made and tested in order to achieve reasonable compromises between those issues and the desire to provide maximum charging power output.

Tests of the power coupling

Inductran's power couplings are custom products that are designed to suit packaging requirements, the electrical service to the system, and the desired performance characteristics. Inductor dimensions, input and output current and voltage, tolerance for misalignment, sound level, power factor, and harmonic content in the input power are examples of requirements in particular applications.

Variables such as the number of turns in the coil windings of the coupling inductors, the number of laminations in their cores, the compensating capacitance that is used in parallel with the coils, and the airgap between the inductors influence the performance characteristics. Numerous tests had to be made in order to assess and trim those characteristics. In this case the variables were first trimmed during bench testing, i.e. with the coupling off of the car, and trimmed again after the coupling had been installed on the car.

Bench tests of the first pair of (unpackaged) inductors indicated that the power output of the inductive coupling was slightly lower than projections had indicated. The inductors were modified to increase their power handling capabilities, and subsequent tests showed that the modified inductors could deliver more power than the specifications for the system called for.

Source inductor suspension

The source inductor assembly did not initially lift and mate reliably with the vehicle inductor in the first operating tests of the charging system. The cause was determined to be excessive friction in bearings in the belt sprockets for the timing belts that transfer spring forces to the inductor assembly, and in the self aligning journal bearings that support the inductor at each of its ends. The journal bearings in the four belt sprockets and in the two end bearings were replaced with needle bearings in order to solve this problem.

Rather than lifting evenly, one end of the source inductor assembly tended to lift into contact with the vehicle inductor while the other end did not. Providing two slotted posts to capture and anchor the counterbalance springs at their midpoints solved this problem. This assured that the spring force at any of the four lift points would not be reduced if the other end began lifting first.

Charge controller assembly

The controller was exercised during charging tests to assess the adequacy of the charge control algorithm. The magnitude of the charging current and the rate of change of the charging current that initiate the timed finishing charge, and the length of the finishing charge were easily altered by revising the parameters in the software in a lap top computer, and then downloading the alterations into the PLC in the charge controller. The magnitude of the current that starts the finishing charge was set at approximately 3 amps and the duration of the finishing charge was set at one half hour.

Several minor electronic problems in the PC board in the controller were found and corrected during testing. Most of the problems were attributable to having to interface with the electronic systems on the vehicle whose details were not available during the design of the charging system.

Tests of the Charging System

Initial tests of the completed and installed charging system indicated that the system could exceed the charging power specification, although the power was significantly less than had been achieved with the coupling off of the car. Further testing with the vehicle inductor on and off of the car revealed that increased losses with the vehicle inductor on the car seriously affect the charging power delivered to the battery.

As initially installed, the inductor assembly was only about two inches away from a sway bar on the car that paralleled the inductor. Magnetic field from the vehicle inductor caused losses in the bar that were sufficient to heat it, and adversely affected the output of the coupling. The inductor mount was modified in order to move the inductor approximately two inches farther away from the bar, and a magnetic shield made from thin laminations of electrical steel was attached between the bar and the inductor. The losses from coupled magnetic field in the bar no longer heated it, but the coupling's characteristics were still affected, particularly with respect to the coupling's maximum power output. Although these losses are external to the power coupling, they cause additional losses in the inductor coil because of additional load current, and extra core losses because of increased magnetic flux density in the affected area.

The maximum power output of the charger as it was finally trimmed is approximately 6.3 kW. As noted above, the maximum power was determined not by the coupling's capability, but was deliberately limited to constrain the temperature rise in the vehicle inductor. The coupling in maximum trim can transfer more than 7 kW, but its temperature rose unacceptably in this trim. The losses and the temperature rise were much higher than has been the case in other Inductran charging systems.

The power required to support the vehicle's electrical system during charging was also found to be a significant loss. The requirement had been characterized by the vehicle's manufacturer as a 100 volt "signal" voltage that was initially supplied by a very light winding that was wound on the outer surface of the vehicle inductor's coil. This winding severely overheated during tests, and caused the destruction of the conductor insulation on the main coil winding because the load in the winding was found to exceed 100 watts instead of being just a signal voltage.

Individual Test Results

The following figures illustrate the individual test results.

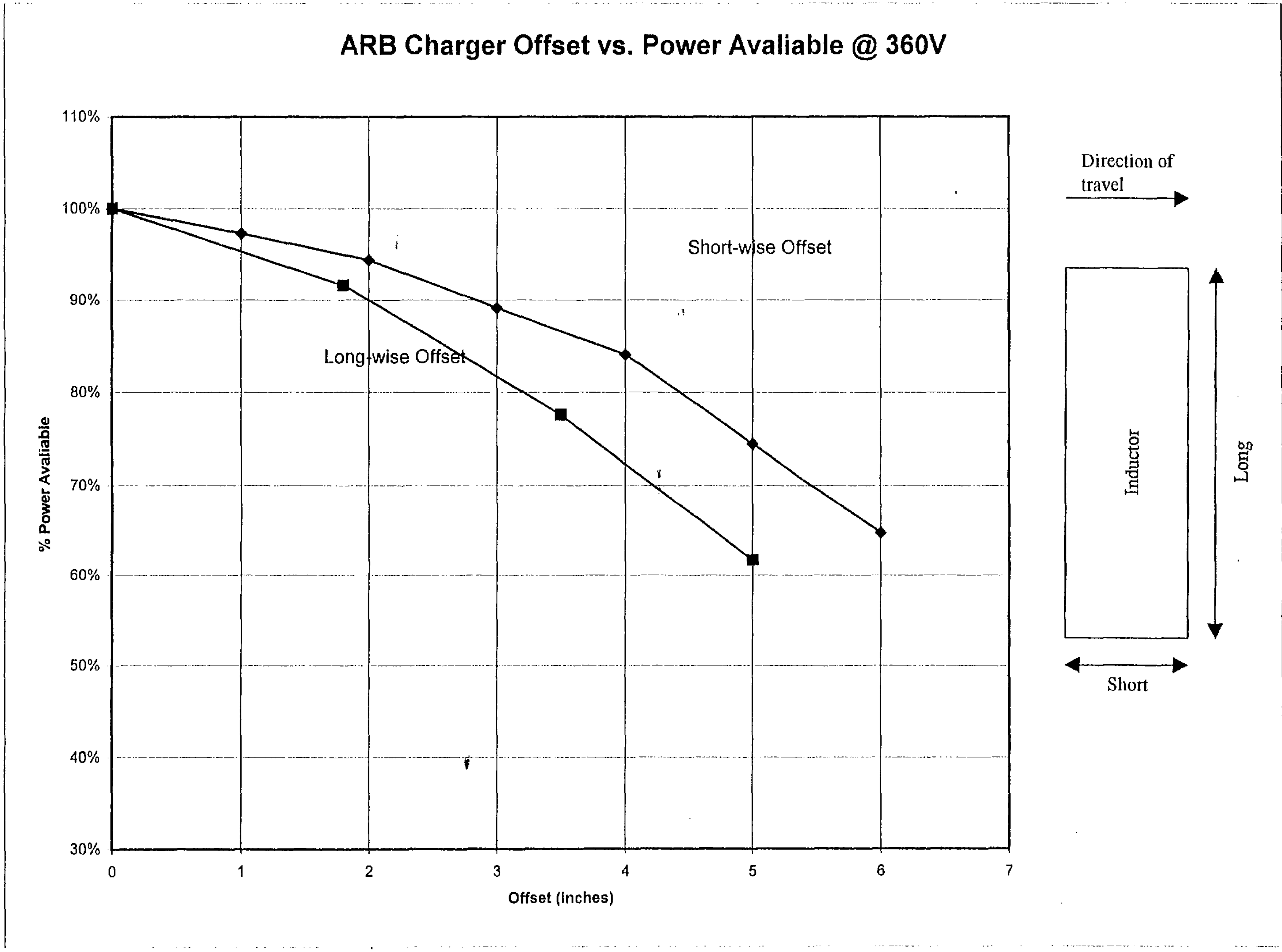
Tolerance for misalignment

The tolerance of the power coupling for misalignments was tested by offsetting the vehicle and source inductors by measured increments and recording the output from the coupling. Figure 6 shows that the coupling would deliver sufficient though reduced power for charging with misalignments approaching six inches on either horizontal axis. The charging system's controls are designed to permit the system to turn on with misalignments of approximately 4.7 inches.

Voltage versus current characteristic of the charging system

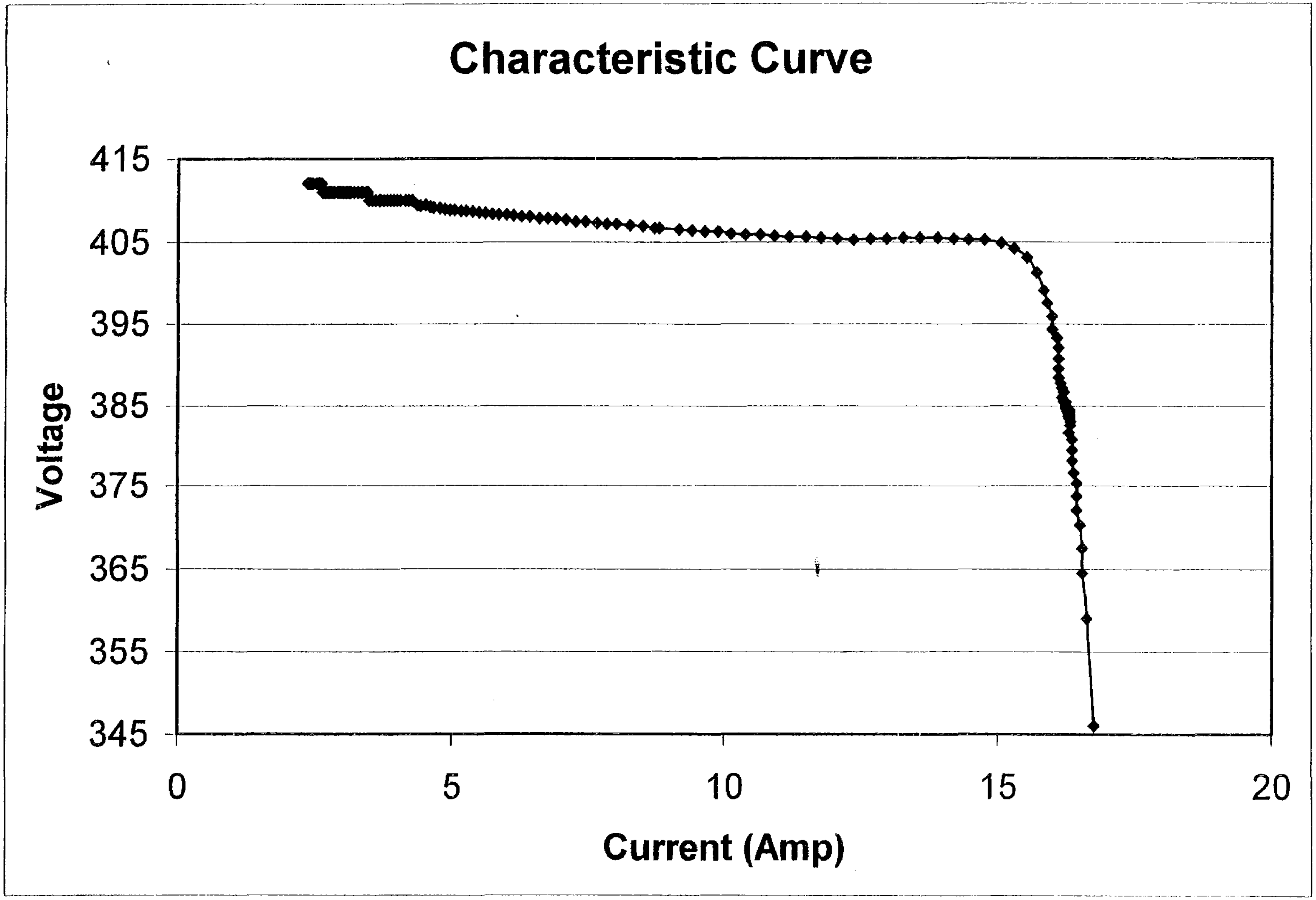
The charger delivers a roughly constant current exceeding 16 amps until the voltage rises to about 405 volts, as illustrated in Figure 7. The system then provides a relatively constant voltage that rises less than two percent to 412 volts

Figure 6


ARB Charger Offset vs. Power Avaliable @ 360V
110%
100%
90%
80%
70%
60%
50%
40%
30%
% Power Avaliable
0
1
2
3
4
5
6
7
Offset (inches)
Short-wise Offset
Long-wise Offset
Direction of travel
Inductor
Long
Short

6

Figure 7



Characteristic Curve
415
405
395
385
375
365
355
345
Voltage
0
5
10
15
20
Current (Amp)

at charge termination. This characteristic is well suited to charging systems since the constant current portion limits the output power of the charging system to suit the rating of its electric service, while the constant voltage portion protects the battery from a destructive over-voltage condition, which in this case would start at 420 volts.

Current versus time in a charging cycle

The rated capacity of the sealed lead acid battery in the vehicle is 45 amp hours at a two hour rate, and the charged amp hours in this cycle were approximately 11 during the constant current portion of the cycle and 11.5 amp hours during the constant voltage portion for a total of 22.5 amp hours (Figure 8).

The rated capacity of the sealed lead acid battery in the vehicle was 45-ampere hours at a two-hour discharge rate. The amp hours charged in the cycle shown in Figure 8 totaled 22.5 amp hours, which is the area under the curve, i.e. amps x minutes /60 min. per hour. The first 40 minutes were in the (high) constant current portion of the characteristic curve shown in Figure 7. When the charging voltage approached the gassing limit of the battery, the charger automatically shifted to the constant voltage portion of the characteristic curve, and the charging current steadily decreased as the battery approached a fully charged state during the last 110 minutes of the charging cycle. This charging system had been trimmed to limit the maximum charging current to 16.3 amps, which is less than its full capability in order to constrain the temperature rise in the vehicle inductor to assure the durability of the insulation on the coil conductors.

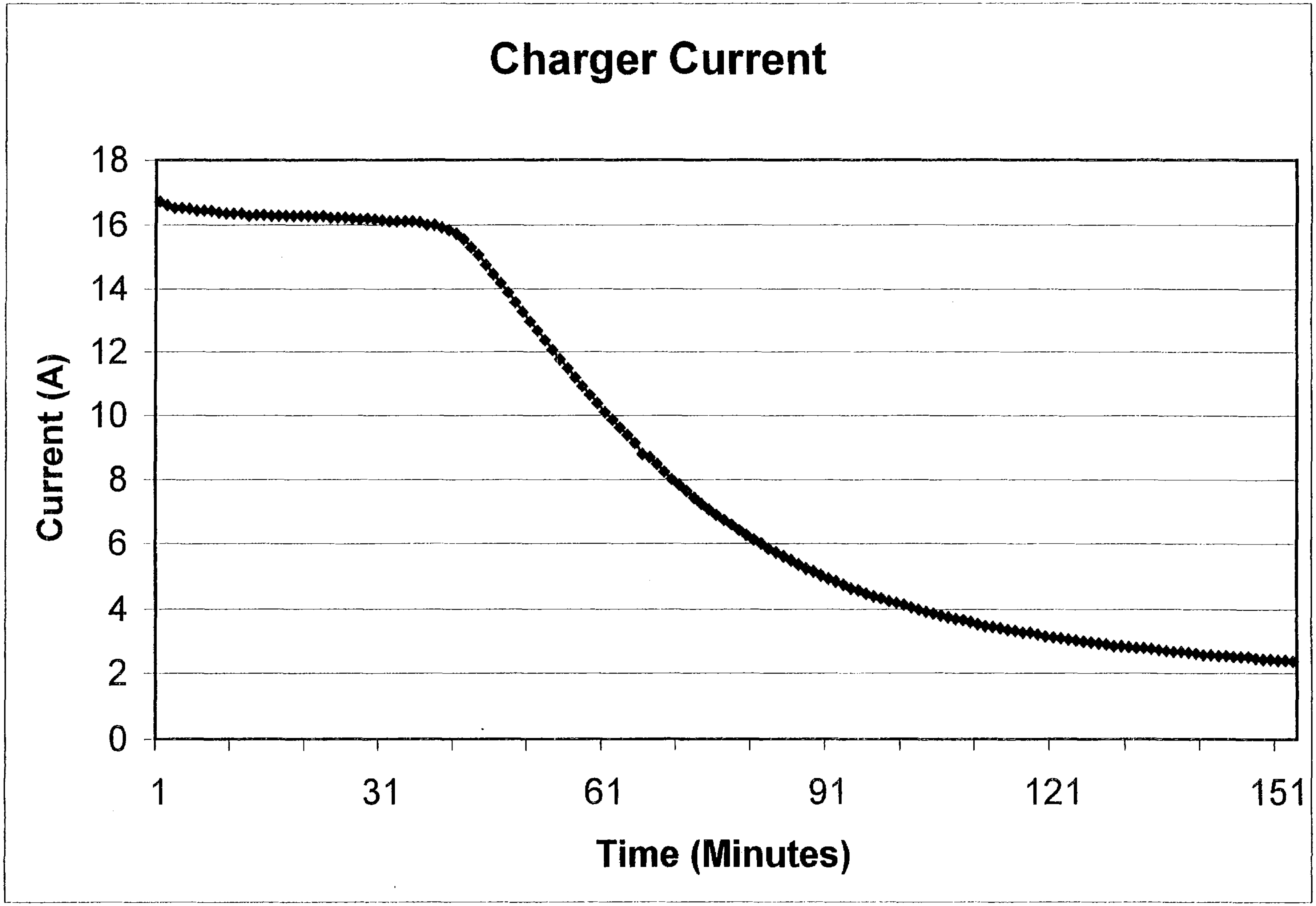
45 amp hours of battery capacity at a 2 discharge rate is a measure of the capacity of the battery in electric vehicle service, since a full discharge of a battery typically takes approximately two hours of driving, e.g. a range of 80 miles at an average of 40 mph. The cited charging energy of 22.5 amp hours indicates that the battery was at an approximate 50 percent state of charge when the charging cycle began.

Losses in the inductive power coupling cause its temperature to rise, and the losses and the rate of rise are proportional to the power being coupled. The power coupling was adjusted so that it coupled less power than its full capability in order to reduce the maximum temperature reached during a charging cycle to a level that was well within the temperature rating of the electrical insulation on the coil conductors.

System efficiency versus time in a charging cycle

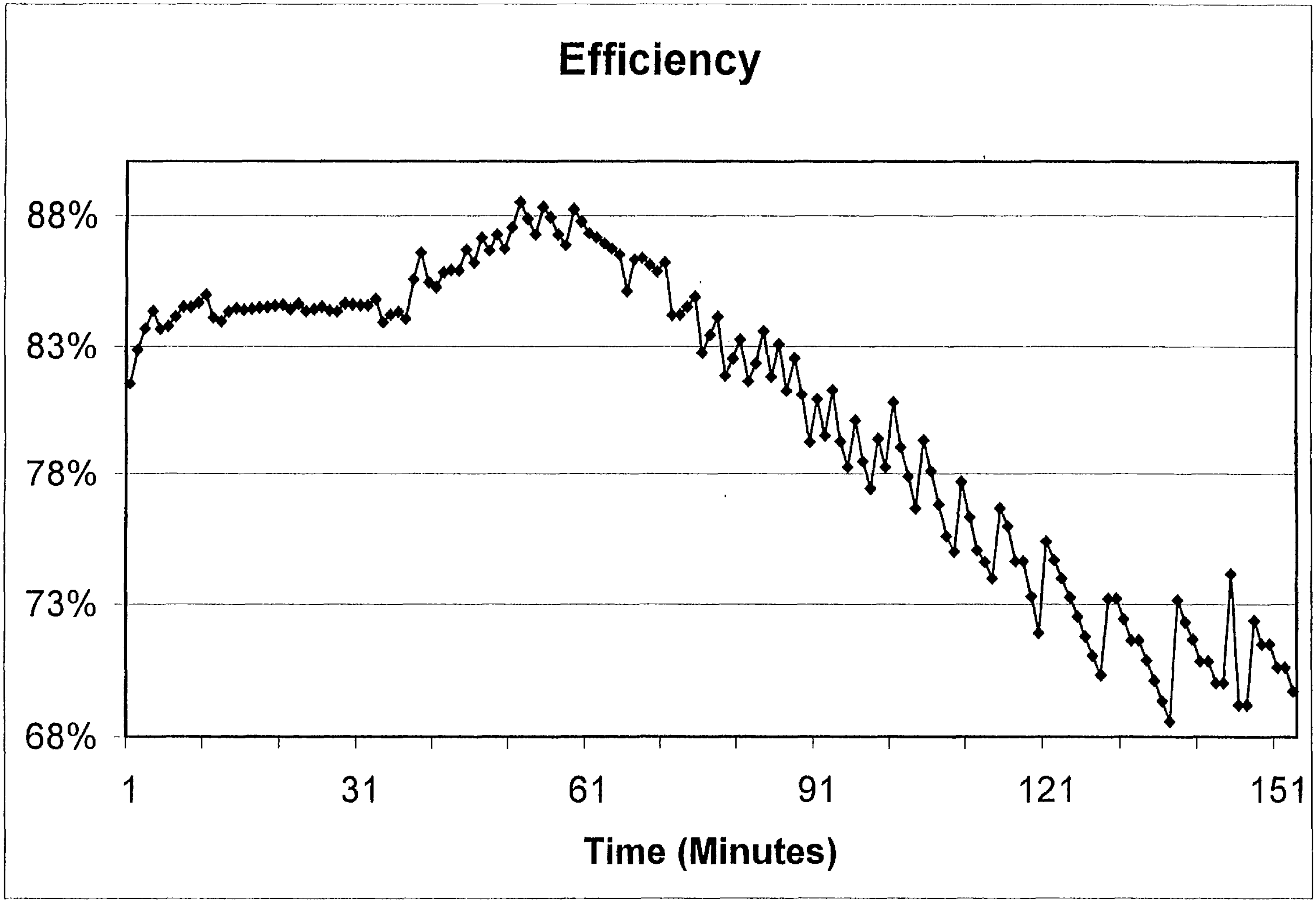
The influence of the additional losses when the vehicle inductor is installed on the vehicle are apparent in the figure, since these losses are highest during the

Figure 8



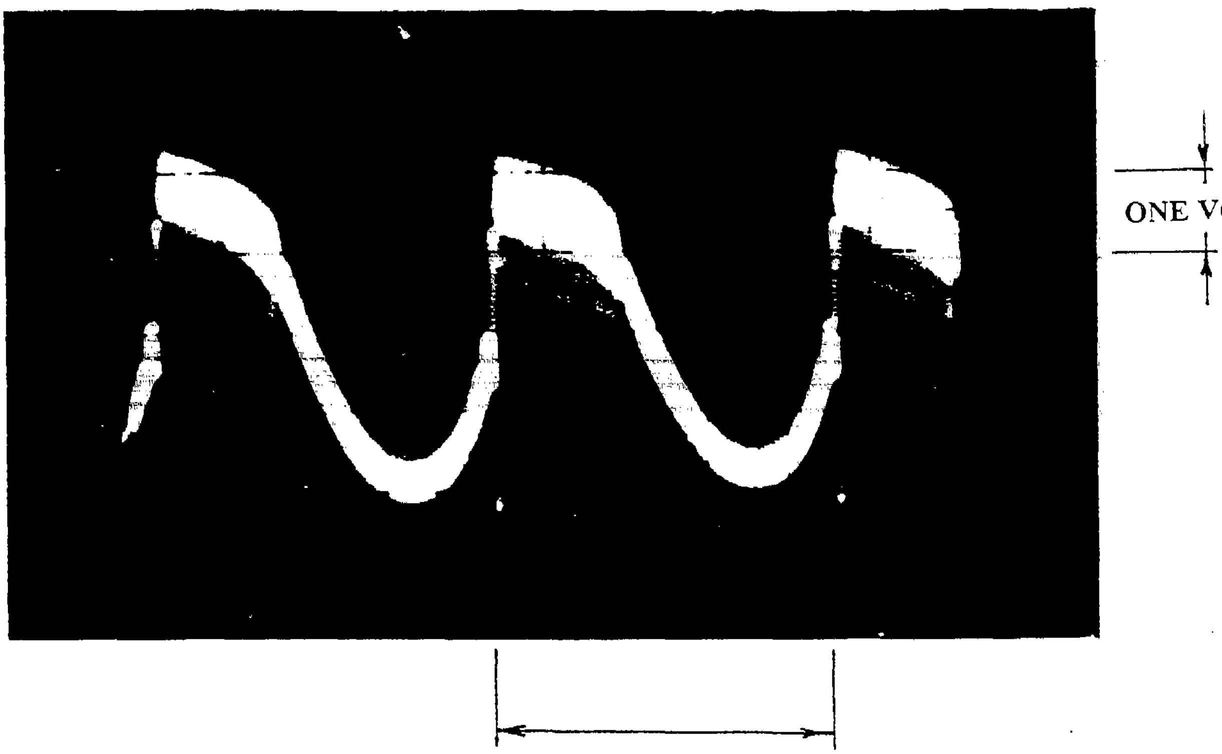
Charger Current
Current (A)
18
16
14
12
10
8
6
4
2
0
1
31
61
91
121
151
Time (Minutes)

Figure 9



9

Figure 10



CHARGING VOLTAGE RIPPLE

constant (high) current portion of the charging cycle when efficiency is usually near its maximum value. Figure 9 shows that the efficiency rose to its maximum of 88 percent when the current began to decrease after 40 minutes of charging. The electrical load of approximately 100 watts from the vehicle's electronics reduced the efficiency indicated in the figure by at least two percent.

The control electronics in the vehicle typically consume slightly more than 100 watts, which would have been difficult to measure concurrently with the total charging power measurement. Since the charging power at maximum efficiency was approximately 5 kW, the 100 watts represented an unaccounted for additional load on the charging system of approximately 2 percent.

Ripple in the charging voltage

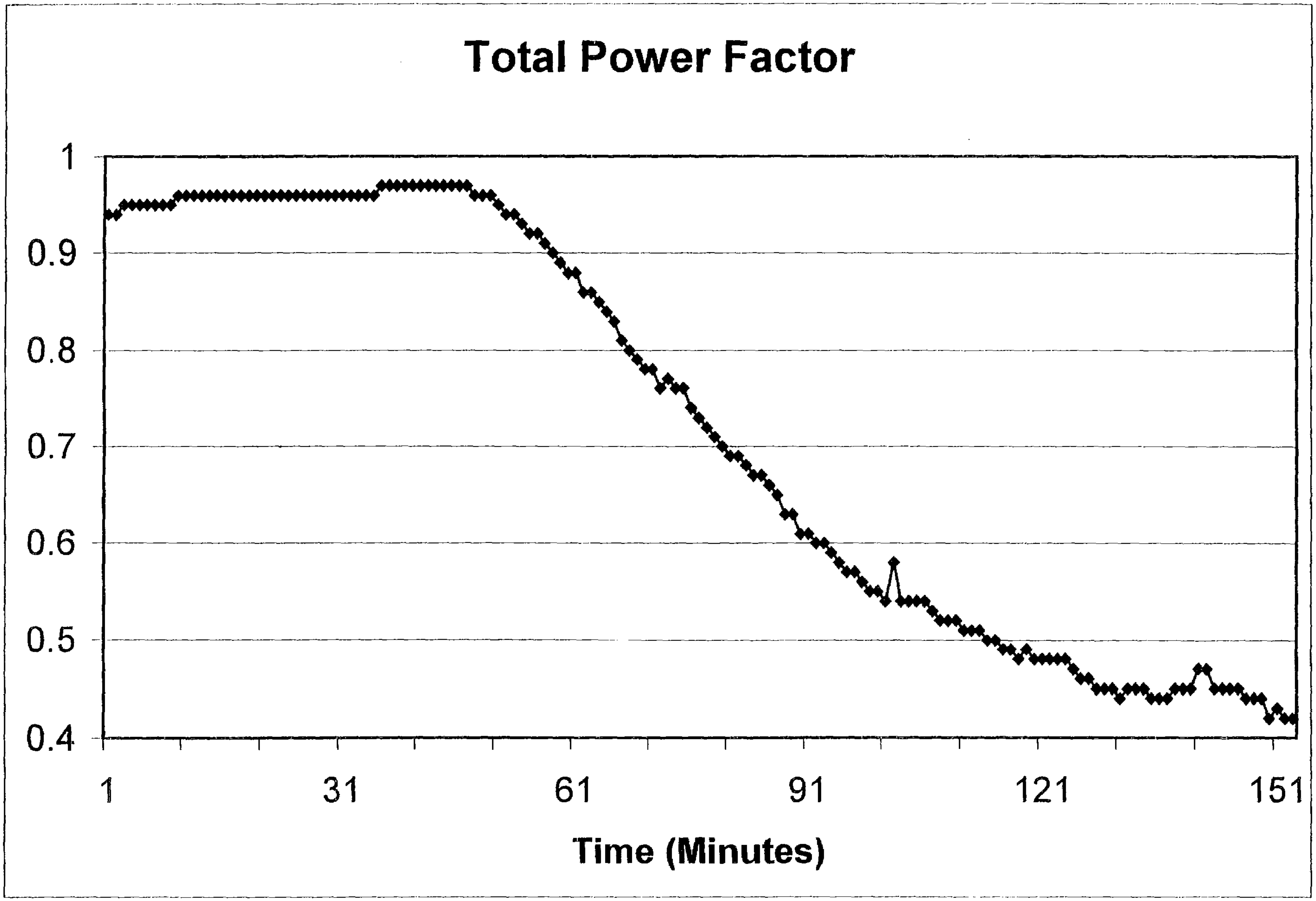
Figure 10 is an oscilloscope display of the ripple on the charging voltage that shows that there is approximately three volts of high frequency voltage superimposed on the 60 Hz ripple voltage in the charger's output. The high frequency ripple is produced by switching power supplies in the vehicle's electronic assemblies and/or the charge controller. The power associated with these switching supplies is small relative to the charging power, but the ratio of the switching frequency to the charging frequency is on the order of 100:1. Since eddy current losses in steel laminations, coil conductors, and metal components are a function of frequency squared, the losses caused by the high frequency ripple may have been substantial. There is no practical way to separate this loss and measure it. However, providing appropriate filters in the interface with the vehicle's electronics could substantially reduce the eddy current loss.

It would be very difficult to make a meaningful estimate of the eddy current losses that were caused by the high frequency component in the charging current. The geometry and conductivity of the materials in which eddy currents were induced strongly influence the losses and a variety of components with those differences were involved

Power factor during a charging cycle

Figure 11 shows that the power factor remained high, above 95 percent, during the portion of the charging cycle when most of the charging energy was provided and the output power of the charger was highest. The power factor decreased as the output declined, since the reactive component in the power remains relatively constant during the charging cycle.

Figure 11


Total Power Factor
1
0.9
0.8
0.7
0.6
0.5
0.4
1
31
61
91
121
151
Time (Minutes)

Current harmonic distortion during a charging cycle

The distortion remained at approximately 18 percent during the high power portion of the charging cycle and rose as the charging current declined, as illustrated in Figure 12. The effect of the rising distortion on the utility service is moderated because the power and current in the input electrical service decreases as distortion rises.

Harmonic distortion is caused by higher frequency current components than the line frequency in the total current. It increases eddy current and hysteresis losses in electromagnetic structures such as transformers. Its presence in electrical loads thus has undesirable effects on the electrical distribution system.

Voltage harmonic distortion during a charging cycle

Figure 13 shows that total voltage distortion in the input electrical service remained at approximately 2.2 percent during the high power portion of the charging cycle, and rose to approximately 4 percent as charging current declined.

Assessment of the Detailed Design

The following assessments are based on the experience gained in installing and testing the system and its components.

Packaging

The appearance of the inductor assemblies is better than that of the inductor assemblies in Inductran's industrial charging system. The plastic enclosures for the inductors are visually pleasing because they provide rounded edges and are without joints.

The inclusion of cooling fans in the inductor assemblies provided adequate cooling for the source inductor, but not for the vehicle inductor because losses in that inductor were much higher than anticipated.

The packaging for the charge controller assembly proved to be satisfactory, enclosing the PLC and other components in a housing of reasonable size, good appearance, and with adequate heat dissipation with natural convection.

The little charge control assembly in the car blends well aesthetically with the battery status display and control above which it is mounted, and is easily visible and operable by a driver.

Figure 12

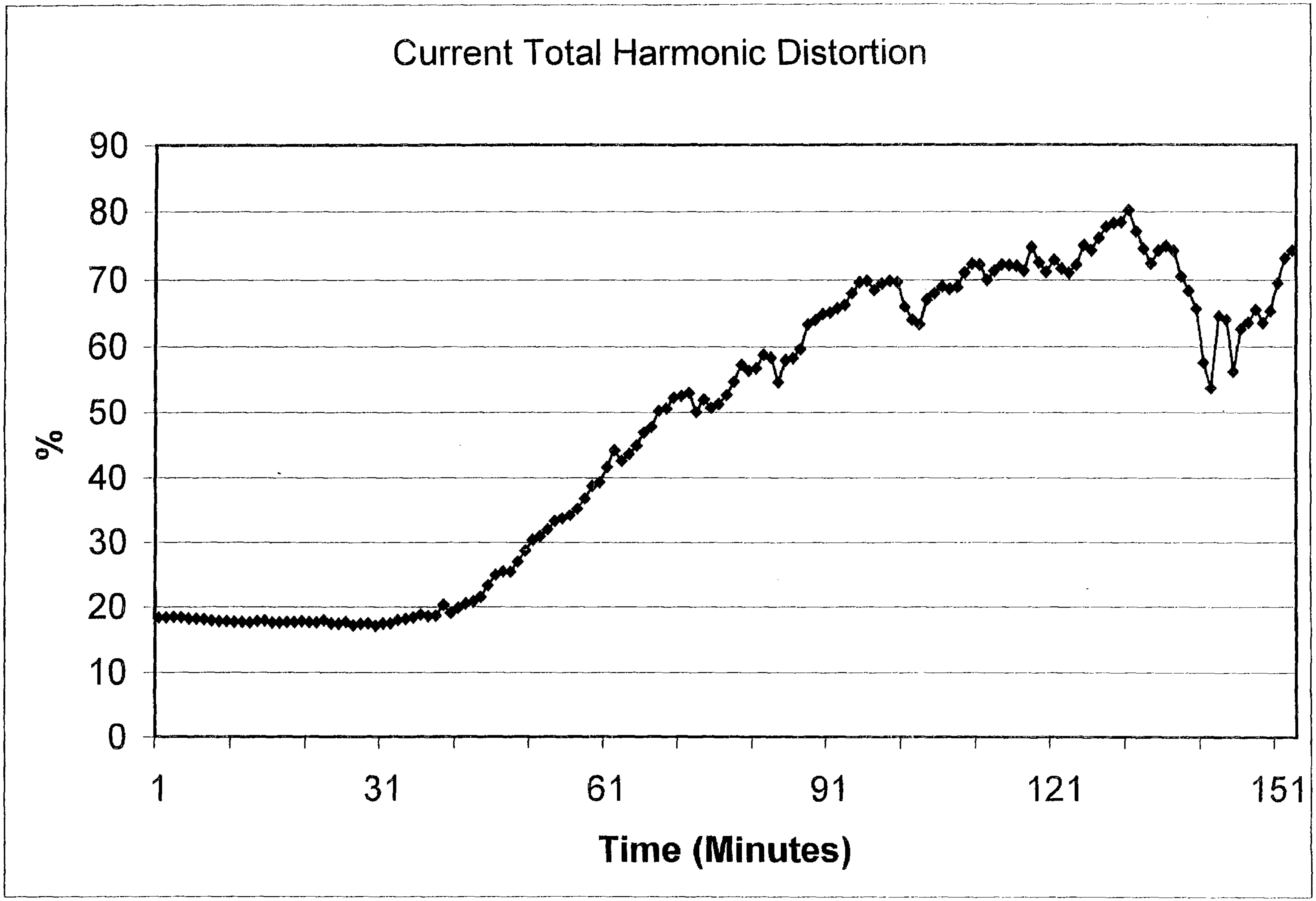
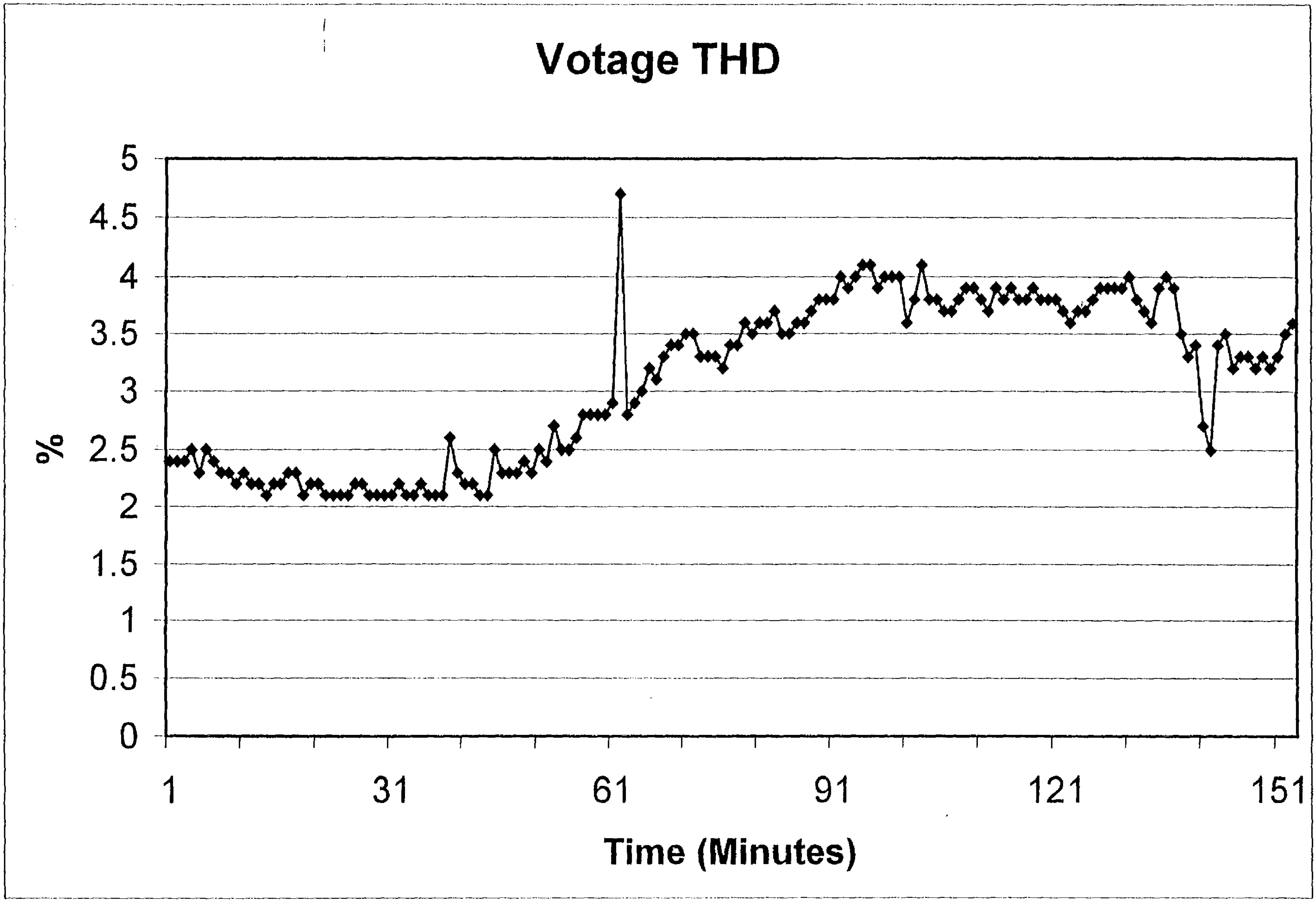

Current Total Harmonic Distortion
90
80
70
60
50
40
30
20
10
0
%
1
31
61
91
121
151
Time (Minutes)

Figure 13



Installation

Given the experience of having installed the prototype system, subsequent installations would be quickly and easily made. The charging station assembly needs only to be set in place on a garage floor and connected to an electrical service to become operational.

The supporting structure for the vehicle inductor can be clamped into place without requiring any drilling or welding, after which the inductor assembly can be fastened to it with four bolts.

The controller assembly can be quickly attached to the firewall of the car with four self-tapping sheet metal screws. The power cables to/from the controller are connected within the assembly, so that the cover plate must be removed to gain access for that purpose. Little time and effort is required to do this.

Installing the charge control in the car requires only removing four existing screws from the mounting flange for the car's battery status control/indicator, reinstalling them through the mounting bars for the charge control, and routing a small control cable to the controller assembly on the firewall.

Weight of the vehicle subsystem

The prototype system components on the vehicle weighed approximately 91 pounds, including the vehicle inductor assembly, the charge controller, supporting structure, and charge control assembly. The weight could have been reduced by approximately 10 pounds had the project schedule afforded the time to procure aluminum coil conductors for the inductors rather than copper.

Sound level

The attenuation of noise from the inductors as a result of using separable enclosures for the inductors was not fully realized. Low frequency noise is very difficult to block with lightweight enclosures, as was confirmed in system tests.

The sound emitted by the charging system was found to increase with charging voltage. It was also found to be substantially affected by the design of the foam rubber pads that were used to cushion the contact between the coupling inductors. With very soft pads the peak level at final voltage was 56 dB with the hood closed. With firmer and more durable pads the level was 71 dB with the hood open, which indicated that the sound level with the hood closed would have approximated 64 dB, which is suitable for industrial charging systems but might be problematic for some home garage environments.

An effective sound attenuating material that is applied to surfaces as a thin membrane has just been introduced to the market. It may provide a means of further reducing the emitted sound level.

Charging power

The charging power was reduced to approximately 6.3 kW from the system's maximum capability in order to constrain the temperature rise in the vehicle inductor. Increased power without additional temperature rise could be provided by reducing or eliminating losses caused by electrical loads from the vehicle's electronics, and by slight modifications to the designs of the coupling inductors.

Efficiency

The efficiency of the charging system was lower than the 93-95% efficiency of typical Inductran chargers. The efficiency was reduced by losses in the vehicle structure and power consumed by the vehicle's electronics. Losses in the power coupling were also atypically high, which may have been caused by eddy current losses in the larger than usual coil conductors that were used.

As noted in previous sections of the report, the magnitude of eddy current losses is dependent on the geometry and conductivity of the affected materials. The losses are increased as size increases, and since unusually large coil conductors were used, those losses would have been larger than they otherwise would have been.

Harmonic distortion

The harmonic distortions in the electrical service were of reasonably low magnitude during high power portions of charging cycles. At low power the distortions became a higher percentage of the input.

Projected Design of an Advanced Automatic Charging System for Production

The experience gained in the project provides a firm basis for designing a charging system with enhancements to improve its suitability as a consumer product. Projections indicate that the advanced design would reduce the vehicle subsystem's weight by approximately a third, and that emitted sound would be less than 60 dB. The total harmonic distortion, efficiency, and power factor would be substantially improved. Most of these improvements would be attributable to the addition of an inexpensive power conditioner between the incoming electrical service and the inductive coupling.

Section VI

Field Demonstration

Summary

The automatic charger was tested in real-world conditions for a period of six weeks at the Clean Air Vehicle Technology Center (CAVTC) in Hayward. CAVTC staff drove the Saturn EV for differing distances and then returned to the facility where the automatic charger was housed. Each trip ended with an attempt to park the vehicle correctly over the charger. For each of the 30 tests, the driver completed a log (see Appendix D) which recorded the trip distance, vehicle energy use, and vehicle placement in relationship to the charger.

The demonstration of the system was delayed and hampered by some problems with the EV. Several cells in the sealed lead acid battery developed faults that compromised the range capability of the vehicle. The vehicle was sent to the manufacturer for the needed cell replacements, since access to the battery in this vehicle required special handling devices. In order to prevent further problems and to protect against the possibility of a fire, the depth of discharge of the battery was not allowed to drop below 50%. It was also found that the vehicle and charging system electronics imposed a continual parasitic load on the battery even when the vehicle was parked, which tended to compromise the data relating to the vehicle's energy consumption on the road.

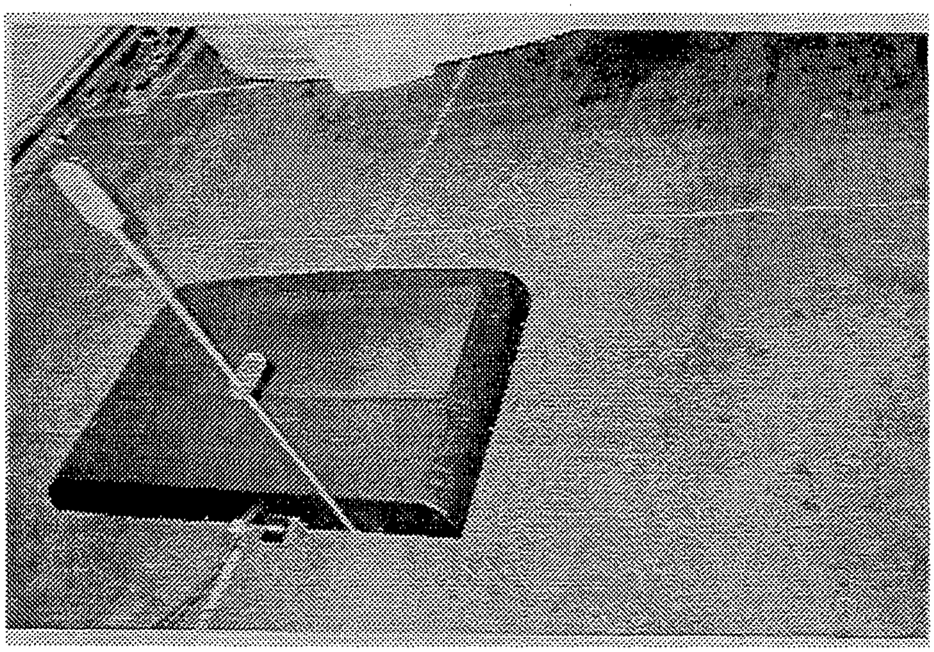
A test program was created that called for trips of different lengths to be conducted each week. In particular, each week there were two 5-mile round trips, two 15-mile round trips, and one 30-mile round trip. The demonstration was conducted at CAVTC due to the ample covered space needed for the charger and the parking bay, along with its repair facilities. CAVTC technicians were chosen to conduct the tests. Their familiarity with vehicle systems, and EVs in particular made them logical candidates to conduct the tests. The drivers, led by CAVTC systems control director Jim Rowen, were given an orientation by the BKI/Inductran project team. They were given background on the project, shown how the driver logs were to be completed, and performed hands-on demonstrations of the meters and parking alignment measurement devices. A copy of the orientation meeting agenda is included in Appendix B.

Test participants were asked to observe the performance of the automatic charger in order to answer the following questions: did the charger begin automatically when the vehicle was parked and the key was turned off? If not, how long did it take? Drivers were asked to measure the alignment of vehicle in the prescribed space based on markers placed on the floor. Whether or not the charger started when the ignition key was turned off, the driver was required to go outside the vehicle and measure the distance between alignment lines placed on the floor and markers that were placed at several points on the vehicle before re-positioning the vehicle.

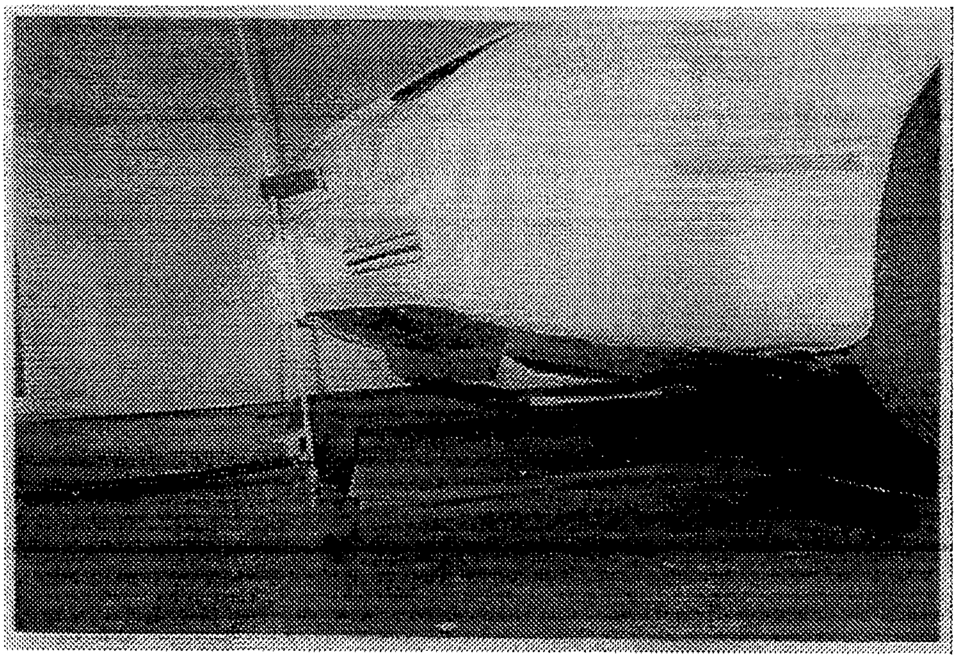
Of the 30 tests conducted, the charger started automatically on the first parking attempt 25 times. In each of the five remaining tests, the operator only required one additional attempt to correctly park the vehicle over the charger.

Test Setup

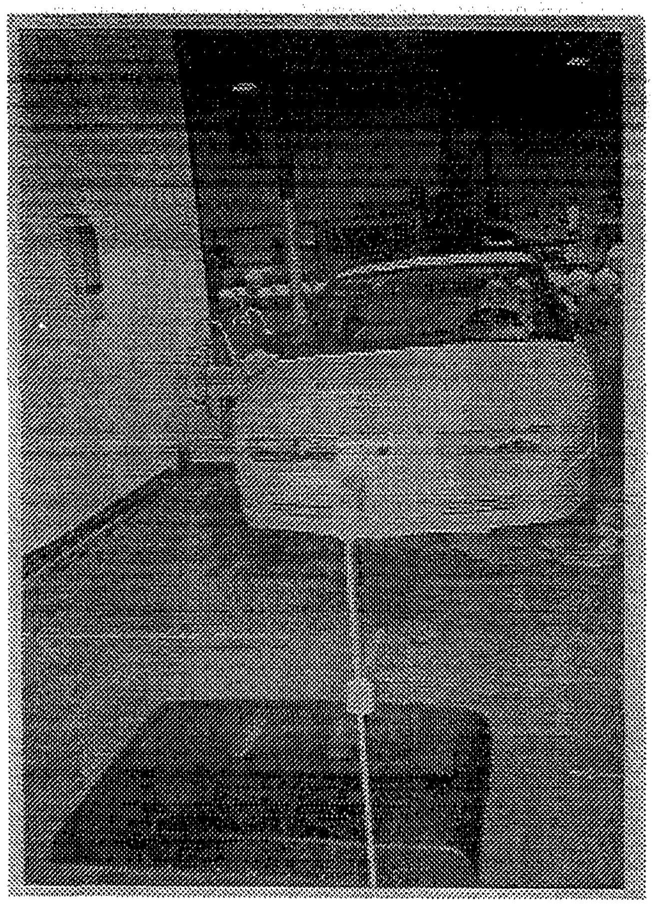
The charger was installed on the floor of a work bay at CAVTC. The charger was equipped with an hour meter to record actual charging time in hours. A wall meter connected to a separate circuit measured electricity used by the charger. The following photo shows the charger in place in the work bay. The Saturn EV is at the top of the photo. The parking guide (wand) and the charger's hour meter (directly to the left of the guide) are also visible along with the connection to the wall meter.



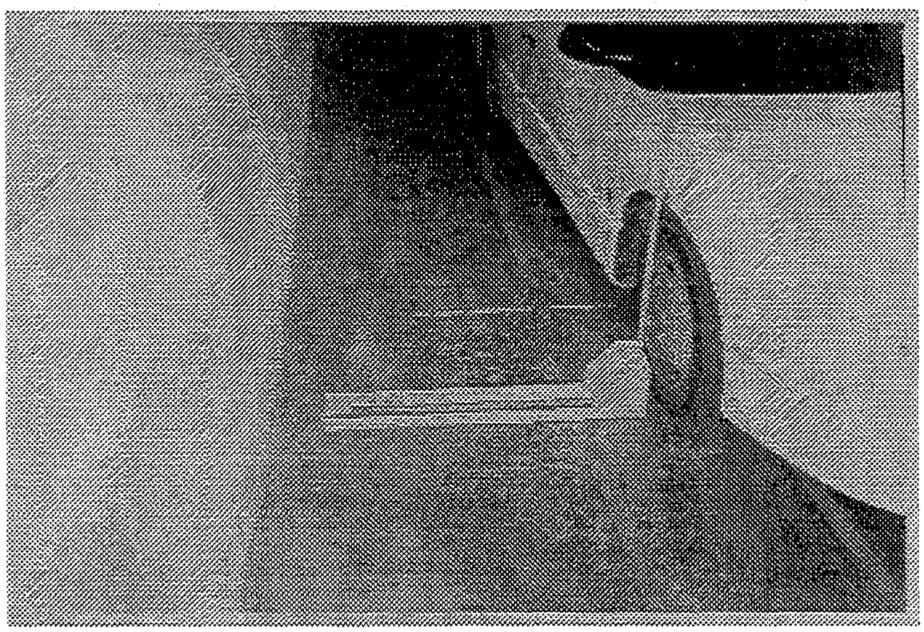
The next photo depicts the Saturn EV in position over the charger, with the charger engaged to the vehicle component.



The following photo shows the entire work bay, including the charger and vehicle.



To measure the vehicle's alignment over the charger, guidelines were taped to the work bay floor and corresponding marks were affixed to the vehicle. Measurements were performed at the right side and rear of the vehicle. The following photo shows the guidelines on the floor along with a measuring stick. The mark on the vehicle's wheel well is also visible.



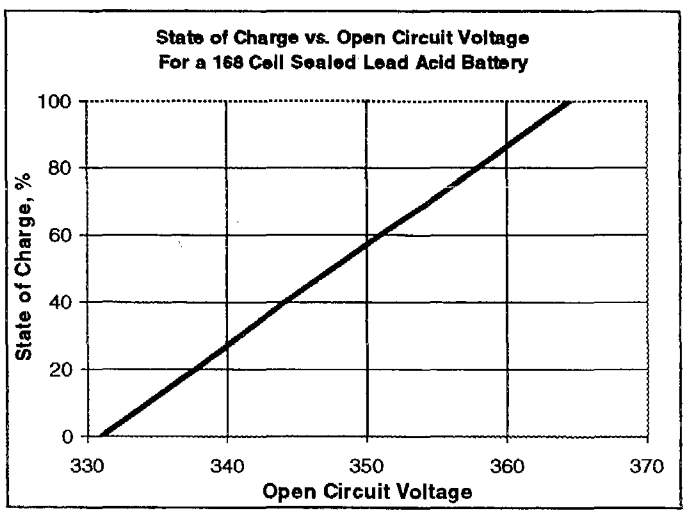
Test Results

Two of the goals of this project were to assess the feasibility and ease of use of a vehicle charger that engages automatically, without driver interface. As shown during the prototype tests and described in Section V, the automatic charging concept was proven to be feasible and practical. What the demonstration hoped to prove was the acceptance of the system from a driver's point of view and the consistency of operations over a prolonged time period.

Traditional plug-in EV chargers were designed to provide a fueling experience that was as similar as possible to liquid fueling infrastructure. The automatic charger was designed so that the driver would simply park the vehicle in a designated spot, turn off the key, and walk away. When comparing the automatic charger performance to those of more traditional plug-in chargers, it should be noted that problems have remained as plug-in chargers have evolved and matured. For example, there remains a communications problem between chargers and new vehicle types as they are introduced in the market. According to anecdotal information gathered by Edison EV, the Toyota RAV-4 EV has constant problems communicating state-of-charge levels with the General Motors ATV inductive chargers that are common throughout California. General Motors chargers have also experienced communications problems with other non-GM EVs. This illustrates the inherent problems associated with having vehicle makers also manufacturer chargers. Other problems associated with common plug-in chargers are difficulties completing charges due to battery overheating and the ability to hold a charge in an unused vehicle for a period of more than two days.

In comparison, some of the problems uncovered during the prototype tests and demonstration of the automatic charger (i.e., overheating, holding a charge, communications with the vehicle system display system) are similar to those described in the previous paragraph. The automatic charger does hold out some promise due to the fact that third-party companies, independent of the vehicle makers can manufacture it.

In general, the charger performed during the demonstration similarly to how it did during the prototype testing. No new issues relevant to the charger design were uncovered during the demonstration. What problems did occur during the demonstration can be traced mostly to the vehicle and its battery pack, as described in the beginning of this Section. In particular, the vehicle's state-of-charge (SOC) indicator lights failed midway through the test period, making it difficult for the operator to accurately ascertain the level of power remaining in the battery pack. This was remedied by the use of the following graph that employed an algorithm to chart the SOC by plotting it against the open circuit voltage.



Source: Linden, Handbook of Batteries and Fuel Cells, Figure 15.3

Another problem that delayed the completion of the tests was caused by a transmission fluid leak. Drivers also noted that the on-board battery did not hold a full SOC when the vehicle sat idle overnight. This was assumed to be a fault of a vehicle system since the charger completed a full charging cycle before automatically turning off. In other incidences, operators noted that a SOC indicator for a certain cell did not light. It was impossible to tell whether this was a problem with the cell, the indicator, or the charger. In several instances, operators needed to press the "reset" button on the dashboard in order to start the vehicle.

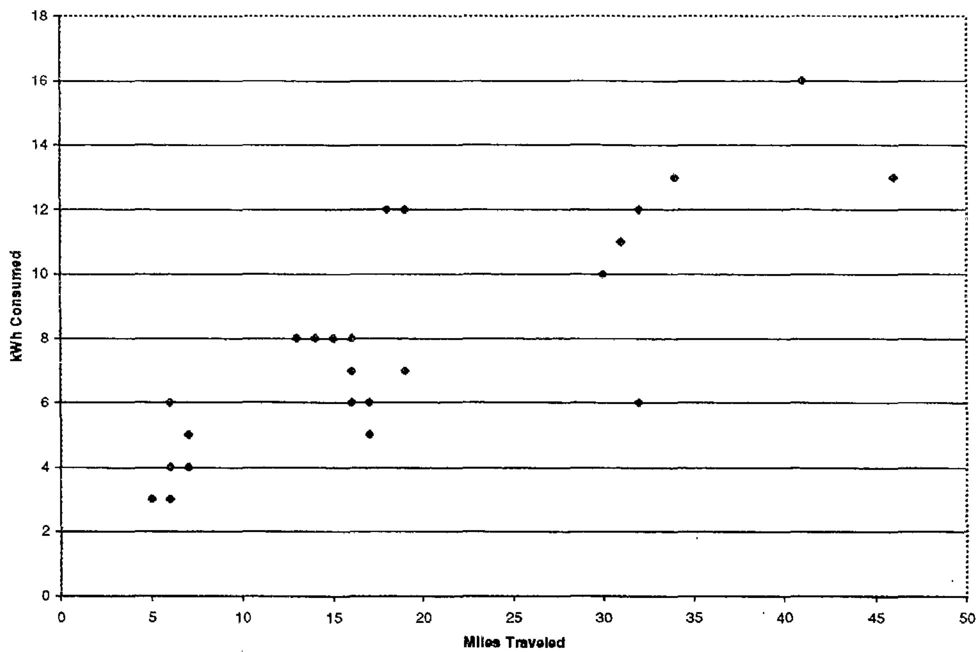
After the completion of each test drive, the charger succeeded in replenishing the open circuit voltage to 360V. We believe that any loss of charge that occurred before the next test can be attributed to the battery on the vehicle and its inability to hold a charge for a prolonged period of idleness. The actual length of inactivity and its relationship to the drain of power from the battery was not measured or analyzed.

Thirty tests were completed and drivers were asked to complete the log included in Appendix D. The following table summarizes the individual tests. Since readings from the wall meter (kWh) and charger's hour meter were measured for the interim between tests, those readings have each been moved up one test and the readings for test 30 were kept blank.

Test number	Date	Miles Traveled	Test Time (minutes)	Electricity Used (kWh)	Charging Time (Hours)	kWh per Mile	Parking Attempts
1	9/3	41	50	16	2.76	0.390	1
2	9/9	14	70	8	1.97	0.571	1
3	9/9	7	22	5	1.17	0.714	1
4	9/13	18	65	12	2.39	0.667	1
5	9/14	16	85	6	1.25	0.375	1
6	9/15	15	55	8	1.55	0.533	1
7	9/15	13	30	8	1.62	0.615	1
8	9/20	6	18	6	1.36	1.000	1
9	9/20	34	34	13	2.64	0.382	1
10	9/21	6	40	4	1.00	0.667	2
11	9/22	6	19	3	0.51	0.500	1
12	9/23	16	35	7	2.31	0.438	2
13	9/23	6	30	3	2.31	0.500	1
14	9/27	7	28	5	1.43	0.714	1
15	9/27	30	86	10	1.99	0.333	1
16	9/28	32	85	12	2.38	0.375	2
17	9/28	17	30	6	1.39	0.353	1
18	9/29	31	45	11	2.19	0.355	1
19	9/29	19	115	12	2.38	0.632	1
20	9/29	17	30	5	1.32	0.294	1
21	9/30	16	90	8	1.74	0.500	1
22	9/30	16	51	7	1.47	0.438	1
23	10/4	32	95	6	1.76	0.188	1
24	10/12	6	30	3	0.99	0.500	2
25	10/13	7	14	4	1.21	0.571	1
26	10/14	16	65	8	1.49	0.500	2
27	10/14	19	40	7	1.38	0.368	1
28	10/15	46	60	13	2.39	0.283	1
29	10/15	5	15	3	0.94	0.600	1
Average		17.72	49.38	7.55	1.70	0.426	

Electricity Consumption

The test setup at CAVTC allowed for the measurement of electricity consumed for each vehicle charging cycle. An isolated circuit with meter provided electricity to the charger. Drivers logged the meter reading before and after each charge. Measured against miles traveled, kWh consumed per test are shown graphically in the following x-y scatter graph:



As the graph illustrates, there is a decent correlation between miles traveled and kWh consumed. As best evidenced by comparing the beginning and ending data points, kWh consumed tends to increase as miles traveled increases. This is normal in any fuel consumption analysis.

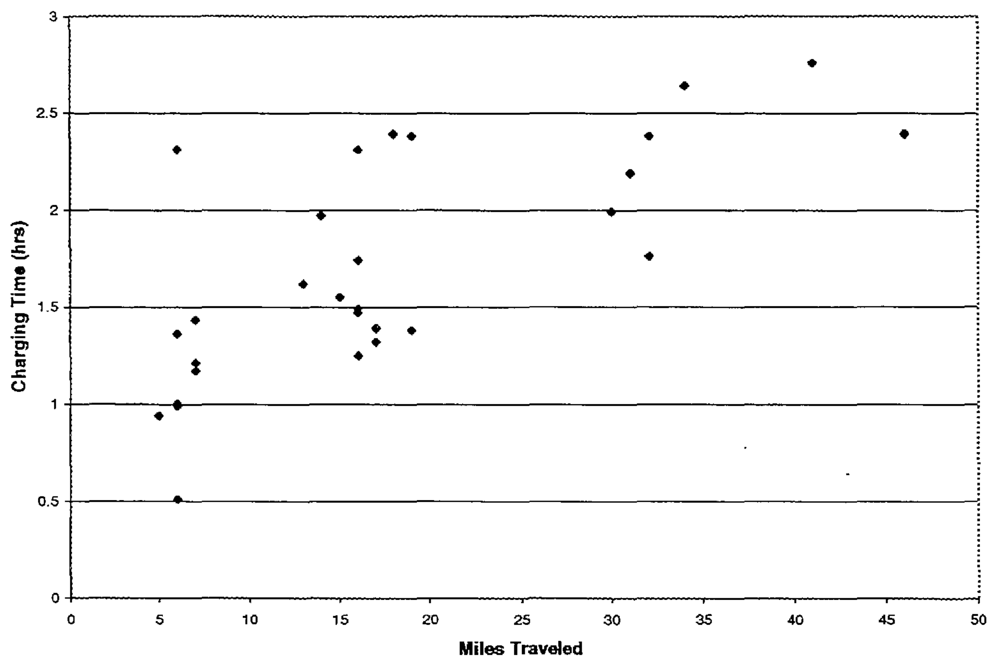
Plug-in EV chargers use approximately 19.8 kWh for lead acid batteries and 30-40 kWh for nickel metal hydride batteries (assuming a 6.6 kW charger) to fully replenish a battery. Due to the restrictions and limitations detailed earlier in this Section, the battery on the Saturn EV was never discharged below 50%, and most tests were short trips with minimal discharge. Therefore, comparing electricity use, *per se* is not a viable parameter for comparison. A comparison of the performance of the automatic charger/Saturn EV to other passenger EVs is better done through an examination of fuel efficiency.

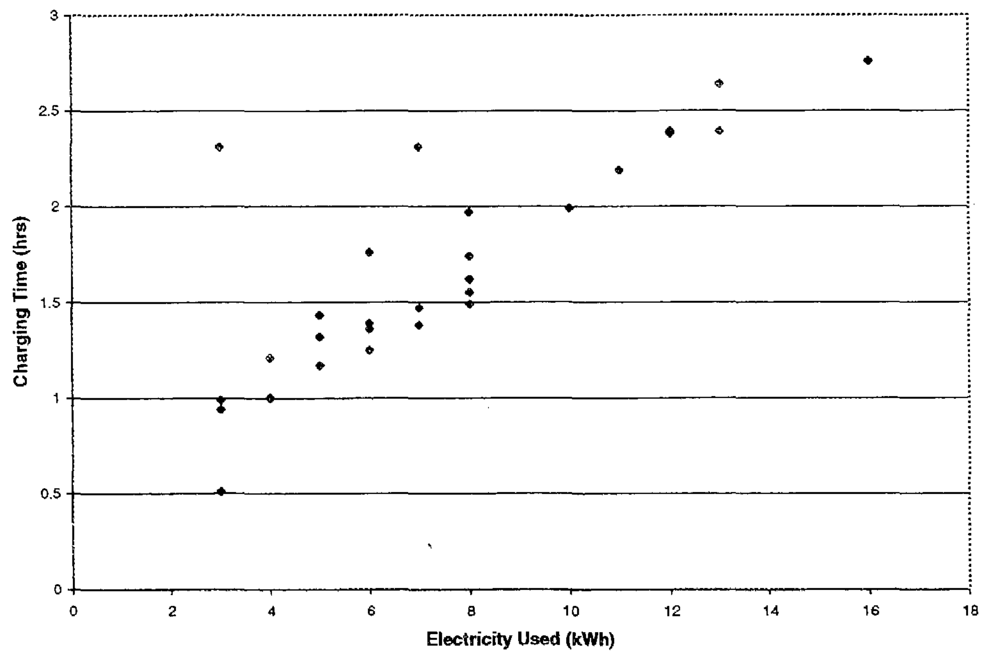
Fuel Efficiency

The data collected during the demonstration also allowed for the measurement of fuel efficiency. It must be noted, however, that fuel efficiency in EVs is a measurement of the complete fueling system. This means that the electricity used in the entire charger/vehicle system—from the charger to the wheels—is included in any computation. As shown in the test data table, fuel economy for the demonstration averaged 0.426 kWh per mile traveled. According to Pacific Gas & Electric Company, the fuel efficiency of original equipment manufacturer (OEM) vehicles currently available in California (such as the GM EV1, Honda EV Plus and the Toyota RAV-4 EV) ranges from 0.23 to 0.44 kWh per mile, depending on the vehicle and battery type. This shows that the fuel economy of Inductran charger/Saturn EV combination was roughly comparable to that of current OEM vehicles.

Charging Time

As shown in the test data, the amount of time required to replenish the vehicle batteries ranged from a low of 30.6 minutes (for a 6-mile trip that used 4 kWh) to a high of 165.6 minutes (for a 41-mile trip that used 16 kWh). As anticipated, the amount of time needed to replenish the batteries generally corresponded with the miles traveled and kWh used. The following graphs illustrate these comparisons.





Plug-in EV chargers currently in use typically require 3 to 5 hours to replenish their batteries.

In this demonstration, it is difficult to prescribe any trends or anomalies to either the vehicle or the charger. Since the charger was a prototype, and had not been used previously with the on-board AC Propulsion battery system, it is impossible to tell whether subsequent demonstrations would yield the same results. However, since the main goal of this project was to demonstrate the feasibility on the automatic charger, questions of efficiency are posed more as intellectual curiosity. Future demonstrations could be conducted to evaluate whether the automatic charger system is more efficient than traditional plug charging systems.

Analysis of Parking Tolerance

As set out in the Demonstration Plan (see Appendix B), a major goal of the trial was to measure the parking tolerance of the automatic charger in real life conditions. Since this parameter is vital to the successful operation of the charger, CAVTC personnel were careful to take lateral and longitudinal measurements for each parking attempt.

Of the 30 tests conducted, the charger started automatically when the key was turned off in 25 of the tests. In each of the remaining 5 tests, the charger started on the second attempt. No test required more than two attempts to start the charger. After each parking attempt—whether successful or not—measurements were taken of the vehicle's distance from a grid that was affixed to the floor. The grid was taped around the entire circumference of the vehicle. Three measuring points were marked on the vehicle: one above the right front wheel well, one above the right rear wheel well, and one in the middle of the rear bumper. A measuring device was constructed that allowed the driver to place it at the three measuring points and record the distance between the vehicle and the grid line (see photo 4 earlier in this section). Therefore, the distances recorded on the driver logs (Appendix D) were not the distance from the charger but from the floor grid.

The measurement at the rear bumper ("Rear") depicts longitudinal distance. If parked completely forward in the parking space, the "Rear" measurement would be 21 inches from the grid line. The two measurements on the right side of the vehicle allow for the calculation of the vehicle's lateral offset in the parking space. When perfectly aligned laterally, the distance to the grid line from the right side of the vehicle is 6.5 inches.

The following table includes the measurement data for each parking attempt. The final column, "Right Side Difference," shows the entry angle. Zero equates to a perfectly lateral parking attempt. A positive number equates to a parking angle with the nose of the car being aligned left of center in the parking space. A negative number equates to a parking angle with the nose of the car aligned right of center in the parking space.

		Successful Attempt			Unsuccessful Attempt			Right Side
Test	Driver	Rear	Right Front	Right Rear	Rear	Right Front	Right Rear	Difference
1	Boon	17.1875	7.625	6.5				1.125
2	Gil	16.5	8.75	7.5				1.25
3	Jim	17	7.5	6.875				0.625
4	Mark S.	17.625	6.25	5.125				1.125
5	Gil	12.875	9.375	7.75				1.625
6	Boon	17	6.75	4.375				2.375
7	Lance	20.625	8.5	8.875				-0.375
8	Lance	20.375	5.875	5.875				0
9	Jim	17.5	4.375	6.625				-2.25
10	Jim	17.25	4.75	4.125	15.25	12.375	12.75	0.625
11	Lance	20.875	5.875	5				0.875
12	Gil	9.75	10	12.625	3.75	8.25	4	-2.625
13	Jim	15.375	3.75	4.875				-1.125
14	Gil	19.25	6.5	5.875				0.625
15	Glen	17	9	8				1
16	Jim	17.875	5.625	9	19.125	0.125	2.75	-3.375
17	Jim	18.25	5.375	6.5				-1.125
18	Boon	17.875	8.375	7.375				1
19	Jim	20	4.75	5.25				-0.5
20	Jim	17.625	6	6.5				-0.5
21	Mark G.	18.375	8.875	9.125				-0.25
22	Jim	18	7.625	9.25				-1.625
23	Lance	18.125	7	9.125				-2.125
24	Gil	19.125	6.25	4.625	17.125	13.5	12	1.625
25	Glen	19	6.5	1.25				5.25
26	Mark G.	18.75	7.875	6.75	19	12.5	11.625	1.125
27	Jim	18.875	3.75	3				0.75
28	Jim	17.875	6.125	6.125				0
29	Gil	16.375	10	8.25				1.75
30	Mark G.	18.25	7.875	6.75				1.125
	Average	17.685	6.896	6.629				

The parking data indicates that for the successful parking attempts, the charger tolerated longitudinal differences of an average of 3.315 inches and lateral differences at the front of the vehicle of 0.396 inches.

The five unsuccessful attempts can be explained as follows:

- Test 10 – vehicle was parked too far left of the charger
- Test 12 – vehicle was parked short of the charger
- Test 16 – vehicle was parked too far right of the charger
- Test 24 – vehicle was parked too far left of the charger
- Test 26 – vehicle was parked too far left of the charger

The tests give a big picture of the acceptable parking tolerances. While the vertical parking guide precluded parking too far forward of the charger, the average successful parking attempt placed the vehicle 3 and 1/3 inches short of the perfectly centered position. The lateral parking measurements show that the average successful attempt was angled with the nose 0.27 inches to the left of the rear and the entire vehicle approximately 1 inch left of center. As can be seen in the table above, longitudinal parking attempts up to 11 inches short of ideal were tolerated and lateral tolerances measured up to 6 inches.

Driver Observations

After the test period was completed, the drivers were asked their impressions of the entire driving/parking experience. In a roundtable session, all of the participating drivers indicated that they became more adept at parking the vehicle correctly as they completed more attempts. They all also indicated that the entire parking procedure felt more comfortable with each attempt. Each also felt that their performance would undoubtedly improve the more they parked the vehicle. Everyone agreed with the proposition that overall, the automatic charging system is easy to use and that the general public would have little trouble getting accustomed to the parking procedure.

There was one instance (test 13) where the driver didn't think that the charger provided a full state-of-charge but he did not investigate before starting a new charging cycle. The other negative comments related to the vehicle performance and the fact that the state-of-charge lights stopped operating in the middle of the test period. None of the drivers indicated any displeasure with the actual process of parking correctly over the charger.

When asked how helpful the parking guide was, all of the drivers responded that it was essential for longitudinal positioning and very helpful for lateral positioning. Several drivers indicated that it was very difficult to ascertain the exact position of the charger as the vehicle advanced forward, especially in lieu of the fact that the on-board inductor housing is not positioned at the furthermost point of the vehicle. The presence of the parking guide allowed them to move forward confidently and quickly. The lateral position of the parking guide also was extremely helpful to the correct positioning of the vehicle. Most drivers felt that positioning the vehicle laterally was easier due to better site lines but the parking guide provided extra security. Again, the more the drivers used the vehicle, the easier they found the parking experience. The fact that only five tests required more than one parking attempt attests to the driver's ability and the design/placement of the charger.

Appendix A

Test Plan

Objective of the Plan

1. Introduction

The Research Division of the California Air Resource Board (CARB) is sponsoring a project to demonstrate an automatic charging system for electric vehicles. This test plan is part of the project's Task 4 deliverable: *Development of a Test Plan and Testing of the Prototype,* as defined in the technical proposal.

During the first three phases of the project, the project team developed a conceptual design, completed the detailed design, and fabricated and installed the prototype charger. This fourth phase deals with testing the prototype in a controlled environment. During the fifth and final phase, the prototype charger will be tested and operated in a consumer environment.

1.1 Objective

This test plan has been developed to demonstrate the ability of the prototype charger to meet the design criteria developed in the technical proposal. The proposed tests will measure and evaluate a wide range of critical operating characteristics. The tests will also examine factors important to consumer acceptance, such as ease of use and audible noise level.

1.2 Scope

The test plan addresses issues within the following areas, as identified in the technical proposal:

- Power quality
- Efficiency and performance
- Electromagnetic fields (EMF)

- Safety
- Ease of installation and use.

In addition, to ensure that the fifth phase of the project (operation in a consumer environment) proceeds as smoothly as possible, the test plan also addresses preliminary in-use testing.

1.3 Requirements

The requirements for each test were established by the technical proposal. Table 1.3 summarizes these requirements. Table 1.3 also lists the conditions of each test; in the proposal, these conditions were assumed but not specified.

1.4 References

The test plan refers to the following documents.

Technical Proposal, Automatic Charging System for Electric Vehicles: Demonstration Project. Prepared for State of California Air Resources Board by Bevilacqua-Knight, Inc., October 31, 1996.

IEEE Standard 519-1992, *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.*

EPRI Protocol for Measuring Magnetic Fields from Electric Vehicle Systems, EPRI Report TR-106537-3254, November 1996.

UL 2202, *Standard for Electric Vehicle (EV) Charging System Equipment,* January 1997.

UL 2231-2, *Outline of Investigation for Personnel Protection System for Electric Vehicle (EV) Supply Circuits, Part 2: Particular Requirements for Protective Device for Use in Charging Systems,* July 1996.

Table 1.3: Test Requirements

	Requirement	Type of Test	Data Needed	Conditions	Comparison Reference
A	**Power Quality**				
A.1	Power Factor	true and displacement power factor	power factor at various power levels	from 10% to 100% of full power at regular intervals	none
A.2	THD	total harmonic distortion	total harmonic distortion	from 10% to 100% of full power at regular intervals	IEEE Std 519-1992
A.3	TDD	total demand distortion	total demand distortion	from 10% to 100% of full power at regular intervals	IEEE Std 519-1992
A.4	DC Output Ripple Voltage		scope trace	at full power	none
B	**Efficiency And Performance**				
B.1	Charger Efficiency Curve	efficiency vs. time	input ac power, output dc power	at regular intervals during charge cycle	90%
B.2	Charging Profile	voltage vs. time	battery voltage	at regular intervals during charge cycle	none
B.3		power vs. time	input ac power, output dc power	at regular intervals during charge cycle	6.6 kW minimum
B.4		current vs. time	output dc current	at regular intervals during charge cycle	none
B.5	Overcharge Factor		total charge removed, total charge replaced	at end of charge	none
B.6	End of Charge Determination		observation and comment on accuracy	at end of charge	none
B.7	Audible Noise Level		noise level in dB	at full power and finishing rate	none
B.8	Charging Time		from 10% SOC to full charge	at end of charge	none
B.9	Alignment Tolerance	maximum power output vs. offset	longitudinal and lateral	at 2 inch intervals	none
C	**EMF**				
C.1	Low Frequency Magnetic Field (dc to 3kHz)	magnetic field measurement	longitudinal and lateral, centerline	at full power and finishing rate, at 1 ft intervals at front and side of car nearest the charger	none; report and compare to UK limit of < 10^{-4} tesla

	Requirement	Type of Test	Data Needed	Conditions	Comparison Reference
D	Safety				
D.1	UL 2202 and UL 2231 requirements	inspection only; no qualification testing	checklist per UL standard's design guidelines		inspection report; no qualification test
D.2	Ergonomics		user report		report only
E	Ease of Installation and Use				
E.1	Conduct Actual Installation	exterior dimensions and weight	engineering data		none
E.2		user interface	engineering data		none
E.3		ease of use	user reports		none
E.4		installation techniques	installation report		none
F	In-Use Testing				
F.1	Install in Vehicle of Project Participant	real-life performance	knowledge of any unforeseen problems	two weeks	none

2. Testing

The best way to acquire most of the data for requirements A (power quality) and B (efficiency and performance) is by running the battery charger through its complete charging cycle, and recording all the necessary data in one continuous sequence. The proposed overall test procedure is therefore to conduct a complete charging cycle test, followed by the additional tests necessary to fulfill the testing requirements:

2.1.1 Complete charging cycle test *(A.1–A.3; B.1–B.6; B.8)*
2.1.2 Audible noise level test and ripple waveform recording *(B.7, A.4)*
2.1.3 Alignment tolerance test *(B.9)*
2.1.4 EMF emission test *(C.1)*
2.1.5 Safety and ergonomics test *(D.1, D.2)*
2.1.6 Ease of installation and use test *(E.1–E.4).*

Finally, preliminary in-use testing will be conducted to pave the way for consumer testing:

2.1.7 In-use test *(F.1).*

Basic equipment required in common by all the tests is listed in section 2.1. Sections 2.1.1 through 2.1.7 detail the procedure, data to be obtained, and specialized equipment for each test. Section 2.1.8 is a summary of the specialized equipment used.

2.1 Test Equipment and Procedures

The testing will be carried out at CAVTC, an ARB-recognized vehicle emissions testing laboratory in Hayward, using repeatable tests and procedures that meet the strictest quality standards. All testing will be performed in a vehicle provided by ARB.

Basic equipment to be used throughout the testing includes:

- 220 Vac power source for the battery charger
- 110 Vac power source for the instruments
- Dummy load for discharging the battery.

2.1.1 Complete Charging Cycle Test

2.1.1.1 Test Procedure

a. Charge the battery until it reaches 100% state of charge as determined by the charger.
b. Connect an automatic data recording watt meter to the ac power input to the battery charger and to the charging input to the battery pack.
c. Discharge the vehicle battery pack to below 10% state of charge (SOC) and record the discharge current at regular intervals to determine the total charge removed.
d. Charge the battery through its complete charging cycle until its SOC reaches 100% and is turned off automatically by the charger's charge termination logic.
e. Calculate and plot the required data.

2.1.1.2 Data Obtained

Measured data, all recorded at a maximum 15-minute interval:

- ac voltage, current, and input power
- Total power factor, displacement power factor
- Total voltage harmonic distortion
- Total current harmonic distortion
- Total demand distortion
- dc battery voltage and charging current

Calculated data:

- dc power
- Efficiency
- Total charge removed and returned
- Overcharge factor

2.1.1.3 Test Equipment

- Automatic recording power meter that can handle ac and dc and calculate all the required data

2.1.2 Audible Noise Level Test and Ripple Waveform Recording

2.1.2.1 Test Procedure

The audible noise level test and the ripple waveform recording are not related, but will be performed at the same time because both are short procedures and both need to be done at the full power level and finishing rate at the end of the charge cycle.

These two tests can either be performed while the battery is passing through the appropriate power level during the charging cycle test or independently after the charging cycle test is finished.

If the tests are performed independently, a dummy load will be used to control the state of charge in order to get the battery to accept the appropriate power level.

Ripple content will be determined from the graphic recording of the charger output waveform.

Audible noise will be determined in an open environment by measuring the noise with a sound level meter with sensitivity extending to a minimum of 40dbA or less.

2.1.2.2 Data Obtained (both at full power and at finishing rate):

- Scope trace of battery voltage
- Peak-to-peak voltage reading of scope trace
- Acoustic noise level measurement at center line of charger (both lateral and longitudinal), 3 feet above ground and 6 feet away.

2.1.2.3 Test Equipment

- Oscilloscope
- Sound level meter

2.1.3 Alignment Tolerance Test

2.1.3.1 Test Procedure

a. Fully discharge the battery, or put a dummy load in place so that charger is delivering maximum power at perfect alignment.
b. With no longitudinal offset, measure and record the power output as the coupling offsets laterally at two-inch increments.
c. Repeat the test with no lateral offset, measuring and recording the power output as the coupling offsets longitudinally at two-inch increments.

2.1.3.2 Data Obtained

- Power level at all the offset conditions

2.1.3.3 Test Equipment

- dc power meter or dc volt and amp meter
- Ruler

2.1.4 EMF Emission Test

2.1.4.1 Test Procedure (performed both at full power and at finishing rate)
Magnetic field will be measured using a gauss meter. The measurement will be done at the centerline of the charger, both laterally and longitudinally, at the air-gap level at one-foot intervals from 1 foot to 10 feet away.

2.1.4.2 Data Obtained

- Magnetic field data on the two axes in 3 foot intervals beyond the vehicle perimeter

2.1.4.3 Test Equipment

- Gauss meter (F.W. Bell model 4048)

2.1.5 Safety Test

2.1.5.1 Test Procedure
Safety of Design: UL 2202 and UL 2231 are the two documents on which the safety review are based. Since this is only a prototype, there is no plan to conduct a full-scale qualification test. A review of the design will be done based on the "Construction" section of these two documents.

Ergonomics: A user report will document the ergonomic issues that impact the safe usage of the charger; no formal test procedure is required.

2.1.5.2 Data Obtained:
Safety of Design:
- Checklist of the issues considered in the review

Ergonomics:
- User report

2.1.5.3 Test Equipment
- None required

2.1.6 Ease of Installation and Use Test

2.1.6.1 Test Procedure
Engineering drawings will be produced along with related data, to document the as-built dimensions, weight, and user interface. During installation and during preliminary use, observations will be recorded

2.1.6.2 Data Obtained
- Engineering drawing and data documenting the charger's dimensions and weight, plus the user interface
- Installation report documenting the issues found during installation
- User report documenting issues related to ease of use

2.1.6.3 Test Equipment
- None required

2.1.7 Preliminary In-Use Test

2.1.7.1 Test Procedure
The charger will be observed during two weeks of regular use by a knowledgeable user.

2.1.7.2 Data Obtained
- User report documenting all issues encountered during use

2.1.7.3 Test Equipment
- None required

2.2 Specialized Test Equipment Summary

The following special equipment, or equivalent, will be used during the test:

- Sound Level Meter, Extech Model 407735
- Hall Effect Gauss/Tesla Meter, F.W. Bell Model 4048
- Digital Volt Meter, Fluke Model 70
- Recording Power Analyzer, BMI Model 3060
- Oscilloscope, Tektronic Model 2211

2.2 Test Matrix

Table 2.2 summarizes the final data to be obtained from each required test and cross references the test plan sections to the required tests.

Table 2.2: Cross Reference between Requirements and Tests

Test ID	Test Name	Final Data Obtained	Test Plan Section
A.1	Power Factor	power factor vs. charging power	2.1.1
A.2	THD	THD vs. power	2.1.1
A.3	TDD	TDD vs. power	2.1.1
A.4	DC Ripple	magnitude of ripple and scope trace @ full power	2.1.2
B.1	Efficiency	efficiency charging power	2.1.1
B.2	Charge Voltage	voltage charging power	2.1.1
B.3	Charge Power	power vs. time	2.1.1
B.4	Charge Current	current vs. time	2.1.1
B.5	Overcharge Factor	% additional charge needed	2.1.1
B.6	End-of-Charge Indication	appropriateness	2.1.1
B.7	Audible Noise	noise levels at various locations	2.1.2
B.8	Charging Time	duration in hours	2.1.1
B.9	Alignment	% power vs. offset	2.1.3
C.1	Magnetic Field	field at various locations	2.1.4
D.1	UL 2202 & 2231 safety	checklist	2.1.5
D.2	Ergonomics	user report	2.1.5
E.1	Dimensions	engineering data	2.1.6
E.2	User Interface	engineering report	2.1.6
E.3	Ease of Use	user report	2.1.6
E.4	Installation Technique	installer report	2.1.6
F.1	In-Use Test	preliminary real-world results	2.1.7

3. Test Schedule and Responsibility

The prototype tests will be performed after the charging unit is completely assembled and the engineering and functional tests have been completed and accepted. The target date is August 1998.

The tests will be performed at the CAVTC facility at Hayward. Testing will be overseen by Kenneth Tenure of BKI, Jack Bolger of Inductran, and Brian Ng of Brian Ng Engineering.

Appendix B

Demonstration Plan

Automatic Charging System Demonstration Plan

Task 5 of the Automatic Charging System for Electric Vehicles: Demonstration Project involves conducting a field demonstration of the prototype charger. On the basis of the technical proposal, BKI has developed the following demonstration plan for review by ARB and SCAQMD project management. Once approved, the plan will serve as the foundation for the field evaluation of the automatic charging system.

Purpose

The primary purpose of this demonstration will be to evaluate two critical issues:

- How well does the automatic charger perform in field use? Does it start automatically after the car is parked correctly and the key is turned off? Does it stop automatically when the battery is fully charged?
- How easy or difficult is it to align the vehicle when parking to ensure automatic operation of the charger? What level of alignment precision is required for automatic start-up of the charger?

This information will provide a sharper picture of the charger's commercial prospects. Specifically, it will show whether the charger would meet real-world expectations about performance, and whether EV drivers would find the charger a desirable convenience.

Approach

The automatic charger will be demonstrated at the Clean Air Vehicle Technology Center (CAVTC) in Hayward, California. CAVTC technicians who are experienced in on-road vehicle demonstrations and data collection will drive the vehicle, recording data on each vehicle trip in a driver log (see attached).

Several technicians will be asked to operate the vehicle. By switching drivers, the demonstration will show the extent to which ease of alignment is a problem for novice users, and whether (and how quickly) driver alignment skills improve. All drivers will receive a brief training from the BKI/Inductran team. Training will cover the demonstration goals, the weekly driving requirement, correct reading of meters, and how to complete the driver log (see attached training agenda).

At minimum, we will collect data for 30 vehicle trips. Data on shorter trips will be especially helpful in determining if the charger starts and stops automatically at the appropriate moments. Data on longer trips is not as critical toward meeting the demonstration goals. However, as such data will help demonstrate the charger's operating characteristics with a more depleted battery, some longer trips will be scheduled. The weekly driving requirement will be as follows:

- Two trips at least 5 miles in length, round trip
- Two trips at least 15 miles in length, round trip
- One trip 40 miles in length or until the battery alarm sounds (whichever comes first)

To ensure that the weekly driving requirement is met, each week the demonstration manager will check and record the types of trips made on a weekly driving log (attached) and assign any needed trips.

The demonstration will continue for 30 trips, or 1-½ months at one trip per working day. The overall demonstration duration will be shorter if the vehicle is used for more than one trip per working day. As one technician anticipates commuting in the vehicle (provided he lives within a safe distance), this may be easily possible. Passengers are allowed, but not required. No night driving is required.

Some limitations of the AC Propulsion Saturn EV will constrain the demonstration scope. For example, the batteries will not tolerate a discharge to 20% state of charge (SOC), which limits some demonstration procedures. Further, the vehicle's on-board SOC gauge determines SOC based only on vehicle operation. This prohibits use of a load bank to discharge the vehicle and accurately determine SOC.

Data Collection

Table 1 below shows the types of data that will be collected, and the purpose, measurement tool, and timing for collecting each of data type. Most data will be collected by drivers using a driver log. The exception is driver satisfaction data, which will be gathered both via comments on the driver logs as well as through interviews with drivers at the end of the demonstration.

Data Analysis and Reporting

At completion of the driving and data collection phase, BKI will analyze the data to fully examine the issues being explored through this demonstration:

- Automatic start-up and shut-down of the charger at the appropriate times
- Ease of parking alignment

- Number of attempts per driver to consistently achieve acceptable parking alignment
- Charger tolerance for parking misalignment

We'll also report on results from interviews with drivers. As noted above these analyses will be relevant to determining the charger's commercial prospects.

In addition, we will analyze kWh and time needed to charge the battery pack, to learn more about the interaction of the charger with this battery pack. In addition, we'll examine the vehicle and charger operating data to determine if they reveal any important or relevant trends that could affect the charger's acceptance as a commercial product. We'll also evaluate any performance or operating anomalies, and try to identify the causes and appropriate fixes.

BKI will summarize its findings in a memo and submit the memo and the data to ARB and SCAQMD for review. After incorporating any reviewer comments, BKI will submit a final memo. BKI will also include the demonstration data and analysis in its final report.

Driver Training Agenda

August 31, 1999
3:30 pm
CAVTC, Hayward, CA

In the Conference Room

1. Intro to demonstration (Holly Larsen)
    - What the demo is evaluating
    - What the demo is not evaluating
    - Weekly trip requirements
    - What drivers need to do

2. Intro to the automatic charger (Sally or Jack Bolger)
    - Inductive vs. conductive charging
    - How the charger operates
    - What to look out for

3. Driver instructions (Jim Rowen)

- What to look out for when using the vehicle
- Intro to the driver's log: when to fill out what

In the Garage

4. Doing the measurements (Jim)

- Reading the kWh meters (hands-on trials)
- Reading the hour meter
- Reading the on-board LED display
- Measuring parking alignment

Weekly Driving Log

Minimum Trip Lengths	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
5-mile round trip						
5-mile round trip						
15-mile trip round trip						
15-mile trip round trip						
30-mile round trip						

Table 1. Data Collection Strategy

Type of Data	Factors Determined by Collecting Data	Measurement Tool	When to Collect
Charger Performance			
Charger startup (yes, no)	Charger system problems; parking guidance device problems	Driver determination	After turning off key
Charge startup delay of more than 5 seconds from key turnoff	Charger system problems	Driver determination	After turning off key
Charge duration	Operating characteristics, commercial feasibility	Hour meter attached to charger	Start and end of charge
Energy required for charge (kWh)	Operating characteristics, energy cost to charge	kWh meter attached to wall	Start and end of charge
Anomalies	Charger system or battery problems	Driver determination	As needed
Vehicle/Battery Performance			
Vehicle mileage	Mileage per charge	Vehicle odometer	Start and end of operating vehicle
Vehicle state of charge	Battery problems; SOC meter problems; battery self-draining problems	On-board LED state of charge display	Start and end of operating vehicle
Time of day, date of battery charging	Time between charges	Clock, calendar	Start and end of vehicle charge
Anomalies	Battery, vehicle, or charger system problems	Driver determination	As needed
Ease of Aligning Vehicle			
Driver name	Alignment problems with novice drivers, alignment improvement with operating frequency	na	Start of operating vehicle
Number of docking attempts before charger startup	Parking guidance system problems; charger system problems	Parking alignment tool to measure vehicle distance from correct position; analysis of data will reveal parking angles.	After parking
Driver satisfaction	Commercial feasibility	Driver interview	As needed during demonstration; end of demonstration

Appendix C

Quality Assurance/Quality Control Plan

Objective of the Plan

The quality assurance/quality control (QA/QC) plan describes the considerations and activities that will be implemented to ensure that the prototype system produced for this project achieves the objectives. The plan also includes a preliminary set of QA/QC procedures to ensure that production systems consistently meet the quality standards reflected in the prototype system.

A primary QA/QC task will be to ensure that the system components meet the quality and performance requirements of a product seeking broad consumer acceptance. Another goal will be to ensure that the prototype system satisfies applicable codes and standards relating to EV infrastructure and the construction of electrical equipment. Finally, the prototype system must be successfully operated with minimal driver interaction.

QA/QC Plan for the Prototype System

Implementation of the Plan

Responsibility for the achieving the objectives of the QA/QC plan will be assigned to an appropriate individual who has the required technical skills to deal with the issues and system components, as discussed in the sections below. The types of employees involved in the process include the following:

- Design engineering supervisor
- Manufactured and purchased components inspector
- Prototype test supervisor
- Charging system final test supervisor

QA/QC Issues, Effort, and Equipment for Components and Subsystems

QA/QC issues relate to the charging system components and subsystems to be produced, assembled, and installed, including:

- Source inductor assembly, including sealed enclosure and electrical control components
- Vehicle inductor assembly, including enclosure
- Charging station enclosure
- Source inductor articulation subsystem
- Charge controller (vehicle-mounted subassembly)
- Magnetic switch
- Control electromagnet
- Vehicle operator controls and instruments

Specific issues that must be dealt with in the production of these components and subsystems include the following:

Fit and finish

Satisfactory fit and finish will typically require the efforts of design engineers, receiving inspectors, engineering test supervisors, and the system test supervisor. QA/QC efforts will include visual inspections and measurements of key parameters. Equipment required to assure compliance will include:

- Inspection instruments used by machine shops, such as surface plates, vernier calipers, and micrometers
- Visual aids such as illuminated magnifiers
- A surface roughness gauge and standard

Electrical integrity

Assurance of satisfactory electrical integrity will typically require the efforts of the design engineer, engineering prototype test supervisor, system test supervisor, and QA/QC supervisor. QA/QC efforts will include high-potential tests where appropriate, and design and implementation of grounding, terminal spacings, conductor enclosures, and environmental electrical protection as required by codes. Equipment required for this effort will include a "hi-pot" tester and a high-quality multimeter, current sensor, and digital temperature sensor.

Environmental integrity

Assurance of satisfactory environmental integrity will require the efforts of design engineers, receiving inspectors, and the QA/QC manager. External components of the charging system may be exposed to the full range of possible outdoor environmental conditions, and must be constructed of, or protected by, materials suited to those conditions. Components internal to the system may be subjected to water and temperature extremes caused by either the environment or electrical losses, and must be constructed of materials suited to this set of conditions.

Equipment required will include a digital temperature sensor. Moreover, the system engineering supervisor, engineering prototype test supervisor, and system test supervisor will need considerable familiarity with the relevant characteristics of metal and plastic materials, such as corrosion resistance, temperature resistance, and ultraviolet resistance.

Structural integrity

Responsibility for ensuring the structural integrity will reside primarily with the mechanical engineering supervisor during the design of the system. The supervisor of engineering prototype tests will also play an important role in testing the structural adequacy of the designs.

Controls and instruments

Quality assurance of controls and instruments will be a cooperative effort that will involve evaluations by the supervisor of engineering prototype tests, supervisor of system tests, and QA/QC manager. Evaluations will include the ease of interpretation of displays by users, and the ease of use and absence of ambiguities in system controls.

Electrical performance

Responsibility for confirming the electrical capabilities and characteristics of the system will reside with the electrical engineering supervisor. Capabilities include achieving the specified charging power and the targeted charging algorithm. Characteristics to be assessed and confirmed include the specified minimum power factor, efficiency, and harmonic content.

These capabilities and characteristics will be initially tested on prototype components by the supervisor of the engineering prototype tests, and later confirmed by the supervisor of final system tests. Equipment required will include meters capable of measuring and recording input and output current, voltage, power, power factor, and harmonic content.

QA/QC Issues, Effort, and Equipment for the Assembled and Installed Charging System

QA/QC will include a close overall inspection of the assembled system. In particular, this inspection will determine whether the design goals regarding human interactions with the system have been met, including:

- The vulnerability of the station to unintended or deliberate abuse
- The ease of use of the system, including the suitability of controls and instruments
- The installation procedure for the charging station and for the vehicle system
- Sound level from the operating system

The QA/QC manager will complete the QA/QC process, including carefully observing final system tests, reviewing test data, and analyzing the acquired data. This manager will also write a summary report of issues that were dealt with and recommendations for changes in translating the prototype design and manufacturing methods to production status. The system will then be handed off to the manager of the operational tests that will follow.

QA/QC Plan for Production Charging Systems

Many system quality issues will have been resolved in designing, fabricating, and testing the prototype. Therefore, the QA/QC plan for production systems is focused on ensuring that every system is of the quality and performance demonstrated in the prototype system.

The plan seeks to accomplish the following:

- Standardize manufacturing processes to ensure that specified tolerances and fits and finishes are maintained
- Ensure consistent quality and specifications of materials and purchased components
- Meet performance specifications, including adjustments of control set points
- Detect and correct performance anomalies
- Ensure the absence of detectable flaws in fit and finish of completed systems

The following procedures will be implemented to accomplish these goals:

Manufacturing Processes

Operation sheets will be developed that detail the sequence of operations to be performed when manufacturing components to achieve the tolerances and finishes required by production detail drawings. Ancillary processes such as plating and heat treating will be specified according to appropriate industrial standards. Inspection reports and procedures will be specified to ensure and document conformance with the required product quality.

Material and Purchased Component Quality and Specification Compliance

Receiving inspection procedures will be established and followed to ensure that items received are as ordered. Many items will require only a simple visual inspection. Specialized items, however, may require either a manufacturer's documentation of specification compliance or tests or measurements to confirm that they meet procurement specifications. Receiving reporting procedures will allow tracing of procurement details and will document required inspections.

Performance Specification Compliance

This QA/QC procedure will require that the charging systems are exercised in simulated charging cycles. The charging systems' input and output electrical characteristics (voltage, current, and power) are the major indicators of the performance quality of the system. These characteristics will be defined and documented by loading the system being tested with a variable load bank in parallel with a test battery, and then exercising the systems through its full operating range.

This process will allow:

- Verification and adjustment of control set points
- Verification of the power factor and efficiency of the system
- Checking of controls and displays
- Verification of harmonic content in the electrical service to the charging system as needed (does not require routine checking)

A standard test reporting form will be developed to ensure that the required test procedures are followed and documented.

Fit and Finish of Completed Systems

A standard inspection form will be developed to ensure that inspectors conduct all inspections required to ensure the flaw-free appearance of finished systems and follow standard remedial procedures to correct and detected flaws.

Appendix D

Field Demonstration Documentation

The completed driver logs along with a weekly summary of the field demonstration results follow in this Appendix.

Clean Air Vehicle Technology Center

Saturn EV Driver Log

Driver: Boonchanh Oupaxay

Test Number - 001

Charger Hour Meter: _ 4 1 5 4

Date: 0 9 / 0 3 / 9 9

Wall Meter: _ 0 0 2 2 1

Time In: 1 5 : 0 5
Time Out: 1 4 : 1 5 > 50 min

Odometer In: _ 1 3 2 0 8
Odometer Out: _ 1 3 1 6 7
Total Miles: 0 0 0 0 4 1

State of Charge In ☐☐☐☐☐☐☐☒☒
State of Charge Out ☒☐☐☐☐☐☐☐☐
F 1/2 E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐
2. Was there more than a five second delay? Yes ☐ No ☒
3. Did it take more than one attempt to park in the correct position Yes ☐ No ☒

Please fill in the distance chart below upon return, for both successful and/or additional attempts. (up to four)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	17 3/16	7 5/8	6 1/2
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
If **yes**, please explain:

5. Were you satisfied with the charger performance? Yes ☐ ? No ☐
If **no**, please explain:

6. Were you satisfied with the vehicle performance? Yes ☐ ? No ☐
If **no**, please explain: Reported not liking the feel of the car at all. Got very "sluggish" toward end of test.

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Gil Rodriguez

Test Number 002

Charger Hour Meter: 00044130

Date of test: 09/09/99

Wall Meter 60237

Time In: 10:20
Time Out: 09:10 > 70

Odometer In: 013222
Odometer Out: 013208
Total Miles: 14

State of Charge In ☐☐☐☐☐☐☐☐☒
State of Charge Out ☐☐☐☐☐☐☒☐☐
F ½ E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐

2. Was there more than five second delay? Yes ☐ No ☒

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	16 ½	8 ¾	7 ½
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
If yes, please explain:

5. Were you satisfied with the charger performance? Yes ☐ No ☒
If no, please explain: Because There was only a quarter of charge

6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
If no, please explain: but every Time I stepped on The accelerator There was a humming noice and it was Kind of irritating and The brakes only work about 80%, also The right

Please use back of this sheet if necessary for more comment space.

Turn signal light does not work.
Other than That The car drives comfortable
it was a good driving experience, I would not mi[illegible]
to drive it again.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Jim Rowen

Test Number 003

Charger Hour Meter: 0004627

Date of test: 09/09/99

Wall Meter 000245

Time In: 15:52
Time Out: 15:30 >22

Odometer In: 13229
Odometer Out: 13222
Total Miles: 7

State of Charge In ☐☐☐☐☐■☐☐
State of Charge Out ☐☐☐■☐☐☐☐
F ½ E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐

2. Was there more than five second delay? Yes ☐ No ☒

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	17"	7 1/2"	6 7/8"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☒ No ☐
   If yes, please explain: Turn signal: In cabin, either direction of use on turn signal lights only the left side indicator

5. Were you satisfied with the charger performance? Yes ☒ No ☐
   If **no**, please explain:

6. Were you satisfied with the vehicle performance? Yes ☐ No ☒
   If **no**, please explain: Too cramped, small driver side seat.

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Mark Scesny

Test Number 004

Charger Hour Meter: 4744

Date of test: 9/13/99

Wall Meter 00250

Time In: 16:35
Time Out: 15:30 >1:05

Odometer In: 013247
Odometer Out: 013229
Total Miles: 18

State of Charge In ☐☐☐☐☐☐☐☐☐
State of Charge Out ■☐☐☐☐☐☐☐☐
F ½ E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐

2. Was there more than five second delay? Yes ☐ No ☒

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	17 5/8	6 1/4+	5 1/8
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ■
If **yes**, please explain:

5. Were you satisfied with the charger performance? Yes ■ No ☐
If **no**, please explain:

6. Were you satisfied with the vehicle performance? Yes ■ No ☐
If **no**, please explain:

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Gil Rodriguez

Test Number 005

Charger Hour Meter: 00049.83

Date of test: 9/14/99

Wall Meter 000262

Time In: 11:50

Time Out: 10:25 → 1:25

Odometer In: 13263

Odometer Out: 13247

Total Miles: 16

State of Charge In ☐■☐☐☐☐☐☐☐

State of Charge Out ■☐☐☐☐☐☐☐☐

F ½ E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐
2. Was there more than five second delay? Yes ☐ No ☒
3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	12 7/8	9 3/8	7 3/4
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
   If yes, please explain: ______
5. Were you satisfied with the charger performance? Yes ☒ No ☐
   If no, please explain: ______
6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
   If no, please explain: ______

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Boondrenh Oupacay

Test Number 006

Charger Hour Meter: 51:08

Date of test: 09/15/99

Wall Meter 006268

Time In: 11:25

Time Out: 10:30 7:55

Odometer In: 013278

Odometer Out: 013263

Total Miles: 15

State of Charge In ☐■☐☐☐☐☐☐☐

State of Charge Out ■☐☐☐☐☐☐☐☐

F ½ E

1. Did charger start immediately when key was turned off? Yes ■ No ☐
2. Was there more than five second delay? Yes ☐ No ■
3. Did it take more than one attempt to park in the correct position? Yes ☐ No ■

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	17"	6 3/4"	4 3/8"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ■
   If yes, please explain:
5. Were you satisfied with the charger performance? Yes ■ No ☐
   If no, please explain:
6. Were you satisfied with the vehicle performance? Yes ■ No ☐
   If no, please explain:

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: [handwritten name]

Test Number 007

Charger Hour Meter: 5263

Date of test: 9/13/99

Wall Meter 0 0 2 7 6

Time In: 14:59

Time Out: 15:25 >30

Trip Roads 12.3

Odometer In: 1 3 2 9 1

Odometer Out: 1 3 2 7 8 .

Total Miles: 1 3

State of Charge In ☐☐☐☒☐☐☐☐

State of Charge Out ☒☐☐☐☐☐☐☐

F ½ E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐
2. Was there more than five second delay? Yes ☐ No ☒
3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	26 5/8	8.5	8 7/8
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☒ No ☐
   If yes, please explain: Burning Smell (parking brake not fully released)
5. Were you satisfied with the charger performance? Yes ☒ No ☐
   If no, please explain:
6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
   If no, please explain:

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Lance Remington

Test Number 008

Charger Hour Meter: 54.25

Date of test: 9/20/99

Wall Meter 0 0 ~~3 8 4~~ 284

Time In: 10:12
Time Out: 9:54

Odometer In: 1 3 2 9 7
Odometer Out: 1 3 2 9 1
Total Miles: 6

Trip 5.8 mi.

State of Charge In ☐☐☐☑☐☐☐☐
State of Charge Out ☐☐☑☐☐☐☐☐
F **½** **E**

1. Did charger start immediately when key was turned off? Yes ☑ No ☐
2. Was there more than five second delay? Yes ☐ No ☑
3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☑

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	20 3/8	9 5 7/8	5 7/8 ??
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☑
   If yes, please explain: ______

5. Were you satisfied with the charger performance? Yes ☑ No ☐
   If no, please explain: ______

6. Were you satisfied with the vehicle performance? Yes ☑ No ☐
   If no, please explain: ______

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

R

Saturn EV Driver Log

Driver: Jim Rowey

Test Number 009

Charger Hour Meter: 5561

Date of test: 9/20/99

Wall Meter 000290

Time In: 14:29

Time Out: 13:55

Odometer In: 013331

Odometer Out: 013297

Total Miles: 34

State of Charge In ☐☐☐☐☐☐☐☐■

State of Charge Out ☐☐■☐☐☐☐☐

F ½ E

1. Did charger start immediately when key was turned off? Yes ■ No ☐

2. Was there more than five second delay? Yes ☐ No ■

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ■

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	17½	4 3/8	6 5/8
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ■
If yes, please explain: ______

5. Were you satisfied with the charger performance? Yes ■ No ☐
If no, please explain: ______

6. Were you satisfied with the vehicle performance? Yes ■ No ☐
If no, please explain: ______

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Jim Rowen

Test Number 010

Charger Hour Meter: 58:25

Date of test: 9/21/99

Wall Meter 00303

Time In: 08:45

Time Out: ~~07:40~~ 08:05 >40

Odometer In: 013337

Odometer Out: 013331

Total Miles: 6

State of Charge In ☐☐☐☐☐☐☐☐☐ All out

State of Charge Out ☐☐☐☐☐☐☐■☐

F ½ E

1. Did charger start immediately when key was turned off? Yes ☐ No ■
2. Was there more than five second delay? Yes ■ No ☐
3. Did it take more than one attempt to park in the correct position? Yes ■ No ☐

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	15 1/4"	12 3/8"	12 3/4
2	17 1/4"	4 3/4"	4 1/8"
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ■ No ☐
   If yes, please explain: After full night of charge, the SOC indicator only show 2 bottom lights lit. The charger was down and off.
5. Were you satisfied with the charger performance? Yes ☐ No ■
   If no, please explain: Don't know whether it is the charger or batteries that prevented a full SOC.
6. Were you satisfied with the vehicle performance? Yes ☐ No ■
   If no, please explain: Don't like where the "Forward", "Neutral" & Reverse buttons are located. I can't see which one is selected because of the steering wheel spoke.

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Lance

Test Number 011

Charger Hour Meter: 59.25

Date of test: 9/22/99

Wall Meter 0 0 0 3 0 7

Time In: 10:44
Time Out: 10:25 } 19

Odometer In: 0 1 3 3 7 3
Odometer Out: 0 1 3 3 7 7
Total Miles: 6

State of Charge In ☐☐☐☐☐☐■☐
State of Charge Out ☐☐☐☐☐■☐☐
F ½ E

345V

1. Did charger start immediately when key was turned off? Yes ■ No ☐

2. Was there more than five second delay? Yes ☐ No ■

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ■

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	20 7/8	5 7/8	5"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ■
   If yes, please explain:

5. Were you satisfied with the charger performance? Yes ■ No ☐
   If no, please explain:

6. Were you satisfied with the vehicle performance? Yes ☐ No ■
   If no, please explain: Over night charge only showed the three lowest SOC lights lit. Voltage was 345 V but dropped to 320 V ~~upon~~ by the time of return.

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Gil Rodriguez

Test Number 012

Charger Hour Meter: 59:76

Date of test: 09/23/99

Wall Meter 00310

Time In: 08:20
Time Out: 07:45 >35

Odometer In: 013359
Odometer Out: 013343
Total Miles: 16

State of Charge In ☐☐☐☐☐☐☐☐☒ 320V
State of Charge Out ☐☐☐☐☐☐☒☒☒ 345V
F ½ E

1. Did charger start immediately when key was turned off? Yes ☐ No ☒

2. Was there more than five second delay? Yes ☒ No ☐

3. Did it take more than one attempt to park in the correct position? Yes ☒ No ☐

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	3 3/4	8 1/4	4"
2	9 3/4	10	12 5/8
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
   If **yes**, please explain:

5. Were you satisfied with the charger performance? Yes ☒ No ☒
   If no, please explain: SOC only 3 lights

6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
   If **no**, please explain:

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

R

Saturn EV Driver Log

Driver: Jim Rowan

Test Number 013

Charger Hour Meter: 62:07

Date of test: 09/23/99

Wall Meter 0 0 3 1 7

Time In: 12:20
Time Out: 11:50 > 30

Odometer In: 0 1 3 3 6 5
Odometer Out: 0 1 3 3 5 9
Total Miles: 6

State of Charge In ☐☐☐☐☐☐☐☒ 340V
State of Charge Out ☐☐☐☐☐☐☐☒ 360V
F ½ E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐
2. Was there more than five second delay? Yes ☐ No ☒
3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	15 3/8"	3 3/4	4 7/8"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☒ ~~No ☒~~
   If yes, please explain: Have noticed that battery cell #28 is often lit or flickering red, when all other cell indicator lights are out at start of test
5. Were you satisfied with the charger performance? Yes ☒ No ☐
   If no, please explain: Doesn't seem to be getting a full charge before the charger shuts off.
6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
   If no, please explain:

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Gil Rodriguez

Test Number 014

Charger Hour Meter: 63:34

Date of test: 09/27/99

Wall Meter 00320

Time In: 07:26
Time Out: 06:58 28

Odometer In: 013372
Odometer Out: 013365
Total Miles: 7

State of Charge In ☐☐☐☐☐☐☐☐■ 340
State of Charge Out ☐☐☐☐☐☐☐■☐ 345
F ½ E

1. Did charger start immediately when key was turned off? Yes ■ No ☐
2. Was there more than five second delay? Yes ☐ No ■
3. Did it take more than one attempt to park in the correct position? Yes ☐ No ■

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	19 1/4"	6 1/2"	5 7/8"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ■
   If yes, please explain: ____________
5. Were you satisfied with the charger performance? Yes ■ No ☐
   If no, please explain: ____________
6. Were you satisfied with the vehicle performance? Yes ■ No ☐
   If no, please explain: ____________

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Glen Munoz

Test Number 015

Charger Hour Meter: 64:77

Date of test: 09/27/99

Wall Meter 00325 (5)

Time In: 12:06
Time Out: 10:40 >86

Odometer In: 013402
Odometer Out: 013372
Total Miles: 30

State of Charge In ☐☐☐☐☐☐☐☐☐ 335 (?? ont)
State of Charge Out ☐☐☐☐☐■■■ 360
F ½ E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐

2. Was there more than five second delay? Yes ☐ No ☒

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	17"	9"	8"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? ~~Yes ☒~~ No ☒
If yes, please explain: ______

5. Were you satisfied with the charger performance? Yes ☒ No ☐
If no, please explain: ______

6. Were you satisfied with the vehicle performance? Yes ■ No ☐
If no, please explain: ______

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

R

Saturn EV Driver Log

Driver: Jim Rowen

Test Number 016

Charger Hour Meter: 66:76 (1.99)

Date of test: 09/28/99

Wall Meter # 00335 (10)

Time In: 09:50
Time Out: 08:25 >85

Odometer In: 013434
Odometer Out: 013402
Total Miles: 32

State of Charge In ☐☐☐☐☐☐☐☐ 325V (ON LIGHTS)
State of Charge Out ☐☐☐■■■■■ 350V
F ½ E

1. Did charger start immediately when key was turned off? Yes ☐ No ☒
2. Was there more than five second delay? Yes ☒ No ☐
3. Did it take more than one attempt to park in the correct position? Yes ☒ No ☐

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear "	Right Front	Right Rear
1	19 1/8	1/8"	2 3/4"
2	17 7/8"	5 5/8"	9"
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☒ No ☐
   If yes, please explain: Battery cell light #28 on almost constantly

5. Were you satisfied with the charger performance? Yes ☒ No ☐
   If no, please explain:

6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
   If no, please explain:

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

R

Saturn EV Driver Log

Driver: Jim Rowen

Test Number 017

Charger Hour Meter: 69:14 (2:38)

Date of test: 9/28/99

Wall Meter 002347 (12)

Time In: 14:25
Time Out: 13:55 (30)

Odometer In: 013451
Odometer Out: 013434
Total Miles: (17)

State of Charge In ☐☐☐☐☐☐☐☐☐ 330 V
State of Charge Out ☐☐☐☐☐☐☐☐■ 360 V
F ½ E

1. Did charger start immediately when key was turned off? Yes ☑ No ☐

2. Was there more than five second delay? Yes ☐ No ☑

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☑

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	18 1/4	5 3/8	6 1/2
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☑
If yes, please explain: ______

5. Were you satisfied with the charger performance? Yes ☑ No ☐
If no, please explain: ______

6. Were you satisfied with the vehicle performance? Yes ☑ No ☐
If no, please explain: ______

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

R

Saturn EV Driver Log

Driver: ~~Lance Remington~~ Boon

Test Number 018

Charger Hour Meter: 70.53 (.39)

Date of test: 09/29/99

Wall Meter 000353 (6)

Time In: 09:45
Time Out: 09:00 745

Odometer In: 013482
Odometer Out: 013451
Total Miles: 31

State of Charge In ☐☐☐☐☐☐☐☐☐ 330V
State of Charge Out ☐☐☐☐☐☐☐☐☐ 360V
F ½ E

* NO SOC LIGHTS

1. Did charger start immediately when key was turned off? Yes ☒ No ☐

2. Was there more than five second delay? Yes ☐ No ☒

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	17 7/8	8 3/8	7 3/8
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
   If yes, please explain:

5. Were you satisfied with the charger performance? Yes ☒ No ☐
   If no, please explain:

6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
   If no, please explain:

Please use back of this sheet if necessary for more comment space.

COMMENT ON BACK

810

Comment: The SOC lights did not operate at all. Not at start of test drive not after. Keeping an eye on the voltage meter shows the range of 330V to 360V and the car drives like it is charged enough to do highway speeds and local road traffic. At about 25-28 miles into a trip the battery module monitors start to light and one gets an audio beep when accellerating in the 40 amp range. Cells 20, 23 & 28 always seem to be the first to react.

Clean Air Vehicle Technoloyg Center

R

Saturn EV Driver Log

Driver: Jim Rowen

Test Number 019

Charger Hour Meter: 72:72 (2:19)

Date of test: 09/29/99

Wall Meter 000364 (11)

Time In: 15:18
Time Out: 13:15 → 1:15

Odometer In: 013501
Odometer Out: 013482
Total Miles: 19

State of Charge In ☐☐☐☐☐☐☐☐☐ 350V
State of Charge Out ☐☐☐☐☐☐☐☐☐ 360V
F ½ E

ALL OUT

1. Did charger start immediately when key was turned off? Yes ☒ No ☐

2. Was there more than five second delay? Yes ☐ No ☒

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	20"	4 3/4"	5 1/4"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☒ No ☐
   If yes, please explain: Battery temp went up to 50°C when normally 20-30°C.

5. Were you satisfied with the charger performance? Yes ☒ No ☐
   If no, please explain:

6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
   If no, please explain:

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Jim Rowen

Test Number 020

Charger Hour Meter: 74:16 (1.44)

Date of test: 09/29/99

Wall Meter 000372 (8)

Time In: ~~20:00~~
Time Out: 19:30 } 30

Odometer In: 01518
Odometer Out: 01501
Total Miles: 17

State of Charge In ☐☐☐☐☐☐☐☐☐ 350V
State of Charge Out ☐☐☐☐☐☐☐☐☐ 360V
F ½ E

☆ ALL OUT

1. Did charger start immediately when key was turned off? Yes ☒ No ☐

2. Was there more than five second delay? Yes ☐ No ☒

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	17 5/8	6"	6½
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
If yes, please explain: ______

5. Were you satisfied with the charger performance? Yes ☒ No ☐
If no, please explain: ______

6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
If no, please explain: ______

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Mark Gonzales

Test Number 021

Charger Hour Meter: ~~[illegible]~~ 75:48 (1.32)

Date of test: 09/30/99

Wall Meter 000377 (5)

Time In: 14:00 ~~10~~
Time Out: 12:30

Odometer In: 013534
Odometer Out: 013518
Total Miles: 16

State of Charge In ☐☐☐☐☐☐☐☐☐ 340V
State of Charge Out ☐☐☐☐☐☐☐☐☐ 355V
F ½ E

NO LIGHTS

1. Did charger start immediately when key was turned off? Yes ☒ No ☐
2. Was there more than five second delay? Yes ☐ No ☒
3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	18 3/8"	8 7/8"	9 1/8"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
   If yes, please explain: ______
5. Were you satisfied with the charger performance? Yes ☒ No ☐
   If no, please explain: ______
6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
   If no, please explain: ______

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

022

Saturn EV Driver Log

Driver: Jim Rowen

Test Number

Charger Hour Meter: 77:22 (1.74)

Date of test: 09/30/99

Wall Meter: 000385 (8)

Time In: 18:11

Time Out: 17:20 (51)

Odometer In: 013550

Odometer Out: 013534

Total Miles: 16

State of Charge In ☐☐☐☐☐☐☐☐☐ 340V

State of Charge Out ☐☐☐☐☐☐☐☐☐ 360V

ALL OUT   F   ½   E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐

2. Was there more than five second delay? Yes ☐ No ☒

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	18"	7 5/8"	9 1/4"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☒ No ☐
   If yes, please explain: ALL SOC LIGHTS OUT - One must push the dash board reset switch to turn on the vehicle

5. Were you satisfied with the charger performance? Yes ☒ No ☐
   If no, please explain:

6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
   If no, please explain:

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Lance Remington

Test Number 023

Charger Hour Meter: 78:69 (1:47)

Date of test: 10/04/99

Wall Meter 0 0 0 3 9 2 (7)

Time In: 09:50
Time Out: 08:25 (95)

Odometer In: 01358 2
Odometer Out: 01350
Total Miles: 32

State of Charge In □□□□□□□□□ 320V
State of Charge Out □□□□□□□□□ 350V
A/C OUT
F ½ E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐

2. Was there more than five second delay? Yes ☐ No ☒

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	18 1/8"	7"	9 1/8"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
If **yes**, please explain:

5. Were you satisfied with the charger performance? Yes ☒ No ☐
If **no**, please explain:

6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
If **no**, please explain:

Please use back of this sheet if necessary for more comment space. OVER

Clean Air Vehicle Technoloyg Center

DATA REPORT
~~Saturn EV Driver Log~~

Driver: Jim Powers

Test Number 023A

Charger Hour Meter: 82:04

Date of test: 10/12/99

Wall Meter 00405

Time In: 08:30
Time Out: 08:30

Odometer In: 013582
Odometer Out: 013582
Total Miles: 000

State of Charge In ☐☐☐☐☐☐☐☐
State of Charge Out ☐☐☐☐☐☐☐☐
F ½ E

1. Did charger start immediately when key was turned off? Yes ☐ No ☐

2. Was there more than five second delay? Yes ☐ No ☐

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☐

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1			
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☐
   If **yes**, please explain: ______

5. Were you satisfied with the charger performance? Yes ☐ No ☐
   If **no**, please explain: ______

6. Were you satisfied with the vehicle performance? Yes ☐ No ☐
   If **no**, please explain: ______

[redacted] back of this sheet [redacted] for more comment [redacted]

OVER

Transmission fluid resavor had to be re-filled is located below the Electronic enclosure. Because of the time between charges, had to push the vehicle off the charger area then return it to trigger a fresh charge. Data on front collected to account for charger & wall meter differences.

[signature]

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Gil Rodriguez

Test Number 024

Charger Hour Meter: 83.76 (1.76)

Date of test: 1/6/1/21/99

Wall Meter 000411 (6)

Time In: 16:10
Time Out: 15:40 (30)

Odometer In: 013588
Odometer Out: 013582
Total Miles: 6

State of Charge In ☐☐☐☐☐☐☐☐☐ 345V
State of Charge Out ☐☐☐☐☐☐☐☐☐ 360V
F ½ E

ALL OUT

1. Did charger start immediately when key was turned off? Yes ☐ No ☒
2. Was there more than five second delay? Yes ☐ No ☒
3. Did it take more than one attempt to park in the correct position? Yes ☒ No ☐

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	17 7/8"	13 1/2"	12"
2	19 1/8"	6 1/4	4 5/8"
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
If yes, please explain: ______

5. Were you satisfied with the charger performance? Yes ☒ No ☐
If no, please explain: ______

6. Were you satisfied with the vehicle performance? Yes ☐ No ☐
If no, please explain: ______

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Glen D. Mund

Test Number 025

Charger Hour Meter: 84:95 (.99)

Date of test: 10/13/99

Wall Meter 0 0 4 1 4 X (3)

Time In: 11:29 am (14)
Time Out: 11:15 am

Odometer In: 13595
Odometer Out: 13588
Total Miles: (7)

State of Charge In ☐☐☐☐☐☐☐☐☐ 330V
State of Charge Out ☐☐☐☐☐☐☐☐☐ 350V
F ½ E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐

2. Was there more than five second delay? Yes ☐ No ☒

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	19"	6 ½"	1¼"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
If yes, please explain:

5. Were you satisfied with the charger performance? Yes ☒ No ☐
If no, please explain:

6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
If no, please explain: But it needs power stiring

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Mark Gonzales

Test Number 026

Charger Hour Meter: 85.96 1.21

Date of test: 10/14/99

Wall Meter 0 0 0 4 1 8 (4)

Time In: 13:05
Time Out: 12:00 (65)

Odometer In: 0 1 3 6 1 1 (16)
Odometer Out: 0 1 3 5 9 5
Total Miles: 16

State of Charge In ☐☐☐☐☐☐☐☐☐ 340
State of Charge Out ☐☐☐☐☐☐☐■☐ 355V
F ½ E

1. Did charger start immediately when key was turned off? Yes ☐ No ☒
2. Was there more than five second delay? Yes ☒ No ☐
3. Did it take more than one attempt to park in the correct position? Yes ☒ No ☐

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	19"	12 1/2"	11 5/8"
2	18 3/4"	7 7/8"	6 3/4
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☒ No ☒
If yes, please explain: The car now turns on without having to push the dash board reset button

5. Were you satisfied with the charger performance? Yes ☒ No ☐
If no, please explain:

6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
If no, please explain:

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Jim Rowen

Test Number 027

Charger Hour Meter: 87.45 (149)

Date of test: 10/14/99

Wall Meter 000426 (8)

Time In: 16:05
Time Out: 15:25 (40)

Odometer In: 013628
Odometer Out: 013611
Total Miles: (17)

State of Charge In ☐☐☐☐☐☐☐☐ 348
State of Charge Out ☐☐☐☐☐■☐☐ 360V
F ½ E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐

2. Was there more than five second delay? Yes ☐ No ☒

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	18 7/8"	3 3/4"	3"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
If yes, please explain: ____

5. Were you satisfied with the charger performance? Yes ☒ No ☐
If no, please explain: ____

6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
If no, please explain: ____

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Jim Rowen

Test Number 028

Charger Hour Meter: 88:83 (138)

Date of test: 10/15/99

Wall Meter 000433 (7)

Time In: 11:40
Time Out: 10:40 (60)

Odometer In: 013674
Odometer Out: 013628
Total Miles: (46)

State of Charge In ☐☐☐☐☐☐☐☐☐ 240V
State of Charge Out ☐☐☐☐☐☐■☐☐ 350V
F ½ E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐

2. Was there more than five second delay? Yes ☐ No ☒

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	17 7/8	6 1/8	6 1/8
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
   If yes, please explain: ____________

5. Were you satisfied with the charger performance? Yes ☒ No ☐
   If no, please explain: ____________

6. Were you satisfied with the vehicle performance? Yes ☐ No ☒
   If no, please explain: Had to use the reset button to start

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Gil Rodriguez

Test Number 029

Charger Hour Meter: 91126 (2:39)

Date of test: 10/15/99

Wall Meter 000446 (13)

Time In: 15:50
Time Out: 15:35 (15)

Odometer In: 013679
Odometer Out: 013674
Total Miles: (5)

State of Charge In ☐☐☐☐☐☒☒☒ 340V
State of Charge Out ☐☐☐☐☒☒☒☒ 360V
F ½ E

1. Did charger start immediately when key was turned off? Yes ☒ No ☐
2. Was there more than five second delay? Yes ☐ No ☒
3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☒

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	16 3/8"	10"	8 1/4"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
   If yes, please explain: ______

5. Were you satisfied with the charger performance? Yes ☒ No ☐
   If no, please explain: ______

6. Were you satisfied with the vehicle performance? Yes ☒ No ☐
   If no, please explain: ______

Please use back of this sheet if necessary for more comment space.

Clean Air Vehicle Technoloyg Center

Saturn EV Driver Log

Driver: Mark Gonzales

Test Number 030

Charger Hour Meter: 92:20

Date of test: 10/15/99

Wall Meter 0 0 0 4 4 9 (3)

Time In: 17:44
Time Out: 17:30 (14)

Odometer In: 0 1 3 6 8 5
Odometer Out: 0 1 3 6 7 9
Total Miles: (6)

State of Charge In ☐☐☐☐☐☐☐☐☐☐
State of Charge Out ☐☐☐☐☒☒☒☒☒ 360V
F ½ E

1. Did charger start immediately when key was turned off? Yes ☐ No ☐

2. Was there more than five second delay? Yes ☐ No ☐

3. Did it take more than one attempt to park in the correct position? Yes ☐ No ☐

Please fill in the distance chart below upon return for both successful and/or additional attempts. (up to four attempts)

Distance Chart			
Attempt #	Rear	Right Front	Right Rear
1	18 1/4"	7 7/8"	6 3/4"
2			
3			
4			

4. Any battery or performance anomalies/problems during the trip? Yes ☐ No ☒
If yes, please explain:

5. Were you satisfied with the charger performance? Yes ☐ No ☒
If **no**, please explain: Charger did a momentary start up then dropped. Turned the vehicle on and repositioned slightly to right in stall and the charger come on.

6. Were you satisfied with the vehicle performance? Yes ☐ No ☐
If **no**, please explain:

Please use back of this sheet if necessary for more comment space.

ARB / Inductran
Weekly Project Chart

Date: 10/15/99		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Totals
5 Mile Round Trip	Test #	002	007	010	013	024	029	
	Driver	Gil	Lance	Jim	Jim	Gil	Gil	
	Miles	14	13	6	6	6	5	50
	Total Time	70	30	40	30	30	15	215
	W Meter	16	8	13	7	6	13	63
	Charger	2.76	1.55	2.64	2.31	1.76	2.39	13.41
	Attempts	1	1	2	1	2	1	8
5 Mile Round Trip	Test #	003	008	011	014	025	030	
	Driver	Jim	Lance	Lance	Gil	Glen	Mark G.	
	Miles	7	6	6	7	7	6	39
	Total Time	22	18	19	28	14	14	115
	W Meter	8	8	4	3	3	3	29
	Charger	1.97	1.62	1.00	2.31	.99	.94	8.83
	Attempts	1	1	1	1	1	1	6
15 Mile Round Trip	Test #	004	006	017	20	022	028	
	Driver	Mark S.	Boon	Jim	Jim	Jim	Jim	
	Miles	18	15	17	17	16	46	129
	Total Time	65	55	30	30	51	60	291
	W Meter	5	6	12	8	8	7	46
	Charger	1.17	1.25	2.38	1.44	1.74	1.38	9.36
	Attempts	1	1	1	1	1	1	6
15 Mile Round Trip	Test #	005	012	019	21	026	027	
	Driver	Gil	Gil	Jim	Mark G.	Mark G.	Jim	
	Miles	16	16	19	16	16	19	102
	Total Time	85	35	115	90	65	40	430
	W Meter	12	3	11	5	4	8	43
	Charger	2.39	.51	2.19	1.32	1.21	1.49	9.11
	Attempts	1	2	1	1	2	1	8
30 Mile Round Trip	Test #	001	009	015	016	018	023	
	Driver	Boon	Jim	Glen	Jim	Boon	Lance	
	Miles	41	34	30	32	31	32	200
	Total Time	50	34	86	85	45	95	395
	W Meter	Start	6	5	10	6	7	34
	Charger	Start	1.36	1.43	1.99	1.39	1.47	7.64
	Attempts	1	1	1	2	1	1	7

	Miles	Time	Wall Meter	Charger	Attempts
Totals	520	1446	215	48.35	35

Notes:
1. Driver is the vehicle operator.
2. Miles is total miles driven for this test.
3. Total Time is the time away from charger in minutes.
4. W Meter is kWh wall meter reading required for charge (kWh at start minus kWh of prior test). Test # 001 test start reading is 221 kWh.
5. Charger is charge duration for the test (Charger reading at start minus prior tests reading). Test # 001 start reading is 41.54.