

INTELLICHARGE

Hostile Environment Battery Chargers



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Abstract

This paper details the design and construction of a new type of battery charger optimized for use in humanitarian demining. It is our objective to design a battery charging system that is not only feasible, but also marketable to the humanitarian demining community. To succeed, the system must overcome the shortcomings in existing battery chargers that have prevented their successful deployment.

We begin by detailing the conditions under which deminers work, including the climate, work patterns, and treatment of equipment. We describe the techniques we used to collect information from demining organizations, and highlight problems with existing demining equipment.

Background knowledge on rechargeable batteries and solar cells is necessary to fully understand the design problem. We present a concise explanation of both of these technologies, correcting a number of common misunderstandings. The limitations of currently available battery chargers are also examined.

The Intellicharge System offers a cost-saving alternative to the ongoing use of disposable batteries. After providing an overview of the design, justification is given for our conceptual decisions. The mechanical and electrical design details are then fully disclosed, including complete engineering drawings and circuit board layouts. Every detail of the design is consistent with the original objectives of the project.

Following the discussion of the design, we explain how the System could be manufactured on a commercial scale. Assembly procedures for major components are examined in detail. The quantity at which molding structural components becomes more cost efficient than machining them is also calculated. A thorough analysis of production costs is provided, along with a complete bill of materials and detailed final assembly procedures.

The ultimate goal of the Intellicharge System is to save money for humanitarian demining organizations. Two cost-benefit analyses are presented, demonstrating the economic viability of the Intellicharge System in different usage scenarios.

Brief Description of Design

The Intellicharge System is designed to meet the needs of most humanitarian demining organizations. It is capable of quickly charging large numbers of batteries under difficult operating conditions. It can operate from almost any source of power and automatically sets itself to the correct voltage range. Under typical operating conditions, the current design will charge eight 4,000mAh D-size batteries in about an hour. The next revision of the design will charge eight 8,000mAh D-size batteries in the same amount of time.

The System is designed to be shipped and stored without a transport case, and is built to withstand shock, vibration, and repeated impacts. The System is completely waterproof, even when disassembled.

All of the components used in the Intellicharge System have been specifically chosen to resist the effects of oil, dirt, sand, and abrasive grit. Since the System is convection-cooled, there are no fans or ventilation slots to get plugged

The Intellicharge System is designed to be serviced in the field, and can be completely disassembled with only two wrenches. Other than the six nuts that hold it together, there are no small parts to get lost or damaged. The whole System is modular, so replacing parts is also greatly simplified

The Intellicharge System measures 29.6cm x 40.4cm x 8.8cm, and weighs about 7kg. It contains eight **Cell Charger Modules (CCM)** and one **Autoranging Power Converter (APC)** Module. All nine modules slide into spaces within a structural frame, called the Chassis. Two aluminum heat sinks bolted onto either side of the Chassis hold the nine modules in place. The entire unit is fixed to a stainless steel plate with a sturdy handle. The plate has holes punched through it to facilitate bolting or screwing onto any flat surface, horizontal or vertical.

Each Cell Charger Module is an independent battery charger. The user plugs a power source into the APC Module, which then outputs a regulated supply of 12 volts DC to the eight CCM's. Each of the eight chargers operates independently. If one were damaged, the other modules would continue to function normally.

The current CCM design can test, charge, and monitor a single D-size battery. In the future, three more variations of the CCM will be designed to charge a C-size, 9-volt, or two AA-size batteries. In the case of the AA-size module, the two batteries will still be tested and monitored independently.

All Cell Charger Modules will be interchangeable so that the Intellicharge System can be used with any combination of eight CCM's, simultaneously charging D, C, 9-volt, and AA size batteries.

Major Achievements

To succeed at this project, we had to adapt solutions from a wide variety of unrelated industries. The Intellicharge System has the following advantages over currently available battery chargers:

- The Autoranging Power Converter which permits the use of virtually any power source, even those with fluctuating and/or intermittent output
- Independent, microprocessor-controlled battery chargers which:
 - o allow the charging of odd numbers of batteries, inserted at random and removed as required
 - o identify non-rechargeable batteries as well as damaged, open or shorted rechargeables
 - o prevents overcharging of batteries, even with mixed battery types and varied levels of discharge
 - o can condition nickel-cadmium batteries in a fraction of the time that other battery chargers require
 - o use simple LED indicators to clearly display the status of each battery
- Translation-lock battery holders which make it virtually impossible for batteries to fall out of the charger, allowing the device to be mounted vertically in a vehicle and operated while in motion
- Potted, conduction-cooled electronics which make the Intellicharge System impervious to water while facilitating rapid cooling
- Modular construction which simplifies component replacement and allows customization of the System to each users needs

While further testing and development is needed before field testing can begin, most of the major design obstacles have already been overcome.

1 Introduction

1.1 Humanitarian Demining

Humanitarian demining is the tedious, precise, and potentially dangerous job of removing anti-personnel and anti-vehicle landmines from post-conflict areas.



Figure 1-1: A Deminer at Work [1].

This process often involves the removal of rockets, grenades, and other unexploded shells, in addition to the landmines. Such devices are collectively referred to as UXO.

Landmines are a global problem, and present in countries spread across the entire planet. As a result, humanitarian demining organizations work under a diverse set of social, economic, and climatic conditions.



Figure 1-2: Landmine Affected Countries [2]

Every demining organization is unique. They use different equipment, different **Standard Operating Procedures (SOP's)**, and often have different overall goals. Any equipment marketed to these organizations must be versatile enough to satisfy the needs of many different groups.

1.2 Chargers for Humanitarian Demining

As part of the process of getting the mines out of the ground, almost every demining organization uses portable metal detectors. Most of these detectors are designed to run from standard “Consumer Size” batteries, in particular, C-size and D-size batteries. [3]. Each detector takes between 3 and 8 of these batteries, and they can last anywhere from 2 to 5 days under heavy usage. [4].

It is not unusual for a single group of deminers to have dozens of detectors in use at once. As a consequence, many organizations go through thousands of disposable batteries every month. For many, the cost of batteries is a significant and ongoing expense. [5, 6].

Properly deployed, modern rechargeable batteries could offer a significant cost savings to many humanitarian demining organizations. Unfortunately, there are several obstacles to successful deployment of this technology.

First, the batteries used must have high enough capacity to run the detectors for a reasonable length of time. The batteries must also be able to withstand vibration during transport and tolerate charging under hot conditions. Most consumer grade batteries cannot meet these demands. A complete discussion of batteries is presented in Section 3.

Second, a low cost, reliable source of electrical power is needed to serve as an energy source from which to charge the batteries. Since deminers often work in remote locations far away from conventional wall outlets, finding a suitable source of power becomes an interesting challenge. Power source options are discussed in Sections 4 and 5.

Finally, a charger is needed that can quickly charge large numbers AA, C, D-size, and 9-volt batteries. The charger has to be reasonably priced, efficient, waterproof, and highly durable. The design of such a device forms the basis of this report.

The description of our design starts in Section 7.

2 Problem Definition

There are hundreds of different battery chargers on the market today; hundreds that are *not* being used in demining operations.

Our design had to be an exception. To develop a marketable device, we asked demining operators what it was they wanted.

2.1 Demining Industry Contacts

Only with relentless determination were we able to contact deminers and demining operators from all over the world. On their responses we based our perception of the design problem.

With the information gathered, a list of key design requirements was compiled. We also gained some important insights into the day-to-day operations of humanitarian demining operations, and into the failures of existing technology to meet their needs.

For determining the needs of end-users, our primary source of information was the MgM Forum. The forum is a mailing list facilitated by *Stiftung Menschen gegen Minen* (The Humanitarian Foundation of People Against Landmines). By posting questions, as well as a survey, to the forum we initiated our correspondence with 12 different individuals of various backgrounds.[7-17]

Valuable input was also received from the judges of the Mines Action Canada Technology Research Competition. In addition to answering our specific questions, key requirements for a successful battery charger were highlighted in their comments on past submissions to the competition. [18,19].

A few people with extensive demining experience were also found within Canada. Bill McAuley and Steve Stamp both served as Canadian peacekeepers in Bosnia. The two enabled us to put our research into context by enlightening us to common demining procedures and aspects of the humanitarian demining industry as a whole. [20,21] We also interviewed two Kosovar women. They were traveling across the Canada to speak about their experiences working as deminers with Norwegian People's Aid. [22]

Once we had a general idea of where we wanted to take our design, we called up several companies that manufacture demining equipment and discussed their experiences designing equipment for

Humanitarian Demining. This input also helped our design process.

2.2 Design Requirements

There are five design criteria that we see as absolutely essential to the marketability of the Intellicharge Battery Charging System. Each was mentioned by the contest judges and repeated by the many other people we talked to. The device must:

- Indicate each battery's charge state in a reliable and unambiguous manner.
- Charge batteries quickly enough to keep up with the rapid rate at which demining operations deplete them.
- Be fully functional at the extreme temperatures and humidity levels.
- Be able to run off of vehicle batteries, generators, solar panels and AC mains.
- Be of sufficient physical durability to withstand the rough, heavy usage prevalent in demining operations.

Despite the numerous differences between one demining operation and the next, there was a surprising degree of consistency in the responses we received. Expanding on the five critical requirements listed above, it was generally agreed that the battery charger should:

- Be highly reliable.
- Withstand exposure to dust, humidity, mud, rain, and sand.
- Adapt to various battery sizes and chemistries.
- Require minimal operator training.
- Automatically reject damaged and/or non-rechargeable batteries.
- Charge a set of batteries in four hours or less.
- Offer the user the choice of mounting it on a flat surface that is either horizontal or vertical.
- Be capable of operating while mounted in a vehicle.
- Be capable of operating from "dirty" and/or intermittent power sources.
- Have a minimal number of switches, buttons, and indicator lights.
- Be possible to disassemble and reassemble with common tools.
- Have a reasonable price tag.

The Intellicharge Battery Charging System meets every one of the requirements listed above.

2.3 Common Pitfalls

Beyond the main design requirements, there are other factors that must be considered when designing equipment that is intended to be used in the field:

- Small parts are easily lost.
- Parts can become contaminated with mud, grit, and dirt.
- Electrical connectors are usually small and difficult to work with.
- Threads can get stripped and/or eroded by sand, damaging the device.
- Seals fail, resulting in damage due to rain or humidity.

Numerous steps were taken to mitigate the problems above: The components of the Intellicharge System are large and durable so that they are easy to handle. The electronics inside the Intellicharge System are encased in thermally conductive potting. There are no seals in the design. All components are waterproof and easy to clean.

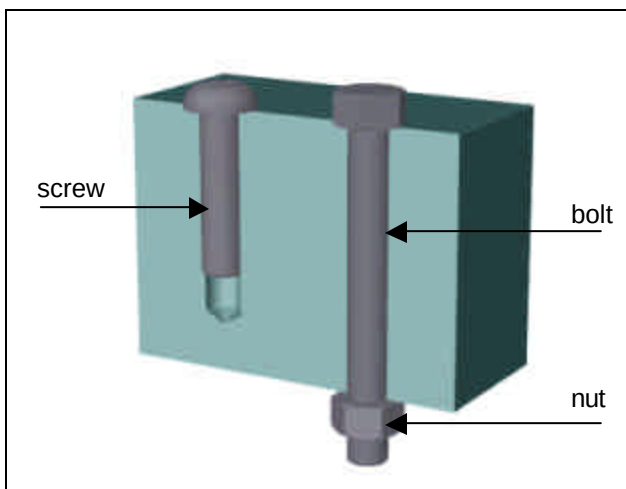


Figure 2-1: Clarification of Screws and Bolts

Threaded fasteners could not be avoided entirely and the system does contain six, standard sized nuts. Nuts and bolts were used instead of screws because, when the threads wear out, both parts of the fastener can be replaced.

The difference between bolts and screws is sometimes misunderstood. To clarify: bolts are used with nuts; screws are inserted into a threaded hole on the device itself (Figure 2-1).

Threads will erode; it is only a matter of time. If screws were used there would have to be threads on the battery charging device itself. Damaged nuts

and bolts are far less expensive to replace than an entire battery charger.

2.4 Working Conditions

Through our interviews and email correspondence, important points were raised that helped us understand the design problem at hand. [16]. Each of the following generalizations were made by at least three different people working in the humanitarian demining industry.

At most demining operations:

- Multiple sources of power such as generators, vehicles, and AC mains are available.
- When used, generators are typically run for four hours each day, usually in the evening.
- Power sources are not reliable. Generators break down and AC mains switch off without notice.
- Banks of vehicle batteries are often used as back-up power supplies.
- Deminers start work early so that they can avoid the mid-day heat.
- Mine detectors are left on continuously throughout the working day.
- Equipment is frequently handled roughly and/or abused.
- Equipment is taken apart and cleaned, or otherwise maintained, on a weekly basis. At least a minimal level of maintenance is done every day.
- Operators are accustomed to fixing things themselves. It can be assumed that at least some people within the organization have mechanical expertise.
- Organizations usually own more than one type of mine detector. Different types of mine detectors often require different sizes of batteries.
- It is usually slow and very expensive to ship in replacement parts for equipment.
- Operators are willing to pay more money for equipment that offers higher performance and greater reliability.

3 Background on Battery Technology

The most expensive component of any large scale recharging operation is the batteries, not the charger. [23].

Proper selection of *batteries*¹ for a given application is crucial to the success of the project. The decision to use a given chemistry of battery must be made on a case-by-case basis taking the full scope of the organization into account. Different equipment, different operating conditions, and different user expectations make some batteries better suited than others for a given set of working conditions and usage patterns.

There are at least six different chemistries of rechargeable batteries widely available to consumers:

- Rechargeable Alkaline [RAM]
- Nickel-cadmium [NiCd]
- Nickel-metal-hydride [NiMH]
- Lead-acid [PbSO₄]
- Lithium-ion [LiI]
- Lithium-polymer [LiP]

Unless an organization is willing to build custom battery adapters, modify circuitry, or fabricate external battery packs, battery selection is greatly simplified:

To work in a device that is designed to run off of typical, consumer-sizes of batteries, the battery has to have a terminal voltage of 1.2 to 1.65 volts, and it has to meet ANSI dimensional standards.

There are only three battery chemistries that meet both of these requirements: Nickel-cadmium, Nickel-metal-hydride, and Rechargeable Alkaline.

While Rechargeable Alkaline batteries are inexpensive and widely available, they also have two serious drawbacks: a complete charge cycle takes at least 16 hours, and, each battery can only be recharged about 20 times (with a considerable decrease in capacity each time). [24].

Because of their long recharge time and short service life, rechargeable alkalines are not suitable for use in humanitarian demining operations. Their usage will not be discussed further.

¹ A "battery" and a "cell" are not, technically, the same thing. Please refer to Section 3.6.

3.1 The Alkaline Battery

Disposable alkaline batteries are the battery of choice for many demining organizations thanks to their low cost, high capacity, and long shelf life.

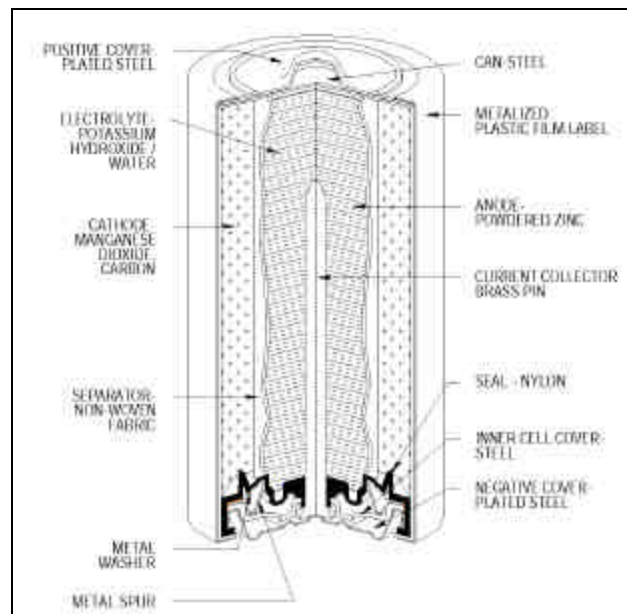


Figure 3-1: Construction of an Alkaline Battery. [25].

A typical Dsize battery has a capacity of 18,000mAh and costs around \$1.50 USD when purchased in quantity [26]. A cylindrical-construction alkaline consists of a steel can containing a powdered zinc anode and a manganese dioxide based cathode. The two electrodes are separated by a thin layer of non-woven fabric which is saturated with a potassium hydroxide based electrolyte. Connection to the powdered zinc anode is made with a brass current collector pin.

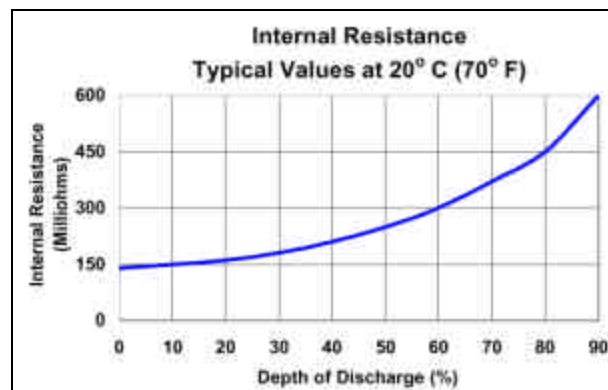


Figure 3-2: Alkaline Internal Resistance. [27].

This construction gives the battery a high internal resistance, typically starting at around 150 milliohms and progressively increasing over the service life of the battery. The internal resistance varies with temperature, and also the rate at which the battery is being discharged.

The internal resistance of the battery has a significant impact on its performance. While a typical D-size alkaline *technically* has a capacity of 18,000mAh, a large portion of this capacity can only be used if the battery is discharged very slowly. [28]. With modern electronic devices, this is rarely the case.

Many electronic devices, such as handheld two-way radios and certain metal detectors, place a significant load on the battery. In these applications, alkalines may only last 30% longer than a typical NiMH battery.

When powering loads with extremely high current draw, the internal resistance of an alkaline battery causes a large portion of the battery's stored energy to be dissipated as heat. As a result, alkaline batteries can actually have a shorter service life than comparable NiCd or NiMH rechargeables. A good example of this is powering a camera flash. In this application, NiMH batteries typically last 40% longer than alkalines. [29].

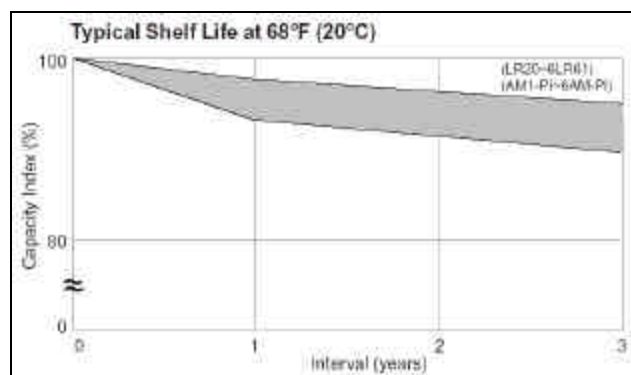


Figure 3-3: Alkaline Self-Discharge. [30].

One benefit of alkaline batteries is that they have a very low rate of self-discharge. Most alkaline batteries can be stored for years without losing a significant portion of their energy, even at elevated temperatures. This makes alkaline batteries well suited for standby applications, where the batteries and the device they power are stored for long periods of time between uses.

While alkaline batteries cannot be recharged and are not suitable for extremely high current

applications, they still represent the best choice for many users.

3.2 The Nickel-Cadmium Battery

The nickel-cadmium battery, or "NiCd", has a completely different construction from alkaline-chemistry batteries and very different electrical characteristics.

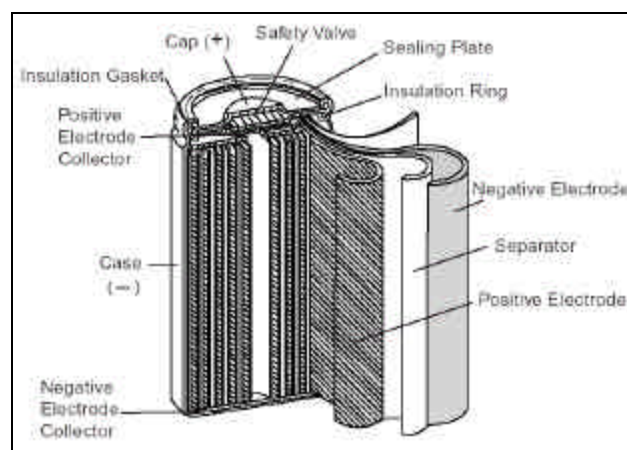


Figure 3-4: Construction of a NiCd Battery. [31].

A typical D-size NiCd battery has a capacity of 4,400mAh and costs roughly \$9.00USD when purchased in quantity. [32]. Under perfect conditions, it can be recharged thousands of times.

The cylindrical-construction NiCd consists of a stainless steel can containing a positive plate, which uses nickel hydroxide as its active material, and a negative plate which uses a cadmium compound. A separator made of a thin non-woven fabric is placed between the plates and is saturated with an alkaline electrolyte, typically potassium hydroxide.

A safety valve is used to vent the battery if the internal pressure becomes dangerously high. The valve is integrated into the top of the can beneath the positive terminal.

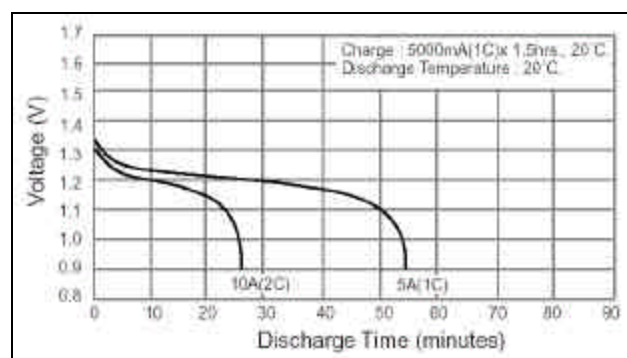


Figure 3-5: NiCd Discharge Curve. [33].

NiCd batteries have several electrochemical characteristics that differentiate them from other chemistries. First, NiCd batteries have very low internal resistance, allowing the battery to be charged or discharged very quickly and to hold its terminal voltage constant over most of the battery life.

Second, NiCd batteries exhibit a drop in terminal voltage and an increase in temperature when the battery reaches capacity during charging. This phenomenon is most noticeable when the batteries are charged at a rate greater than 0.5C (i.e.: half the capacity of the battery per hour). [34].

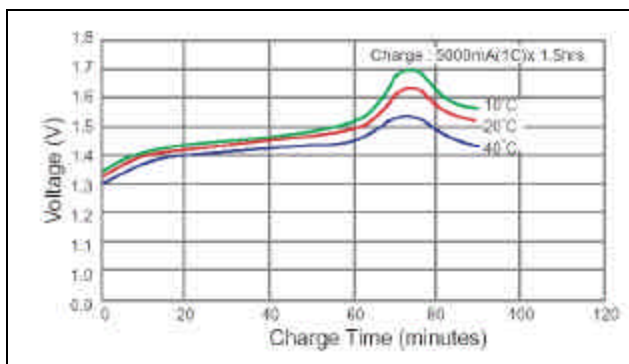


Figure 3-6: NiCd Charging Curve. [35].

Third, NiCd batteries have a high rate of self-discharge, and it increases with the temperature at which they are stored. A typical NiCd will retain 80% of its energy after 2 months in storage at 20°C. If the temperature is increased to 45°C, the energy retained drops to just 20%. [31].

Because of this high self-discharge rate, NiCd batteries are best suited for applications where they can be used soon after charging, rather than being left in storage for long periods of time.

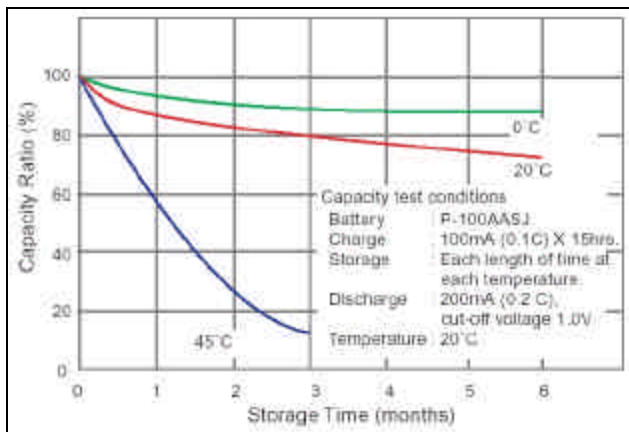


Figure 3-7: NiCd Self Discharge with Temp. [31].

Fourth, NiCd batteries have an exceptionally long cycle life when properly maintained. Most manufacturers rate their NiCd batteries for 1,000 charge/discharge cycles, but substantially longer lives can often be achieved. [36].

The capacity of a properly maintained NiCd drops slowly over the course of its service life, reaching about 83% after 500 cycles.

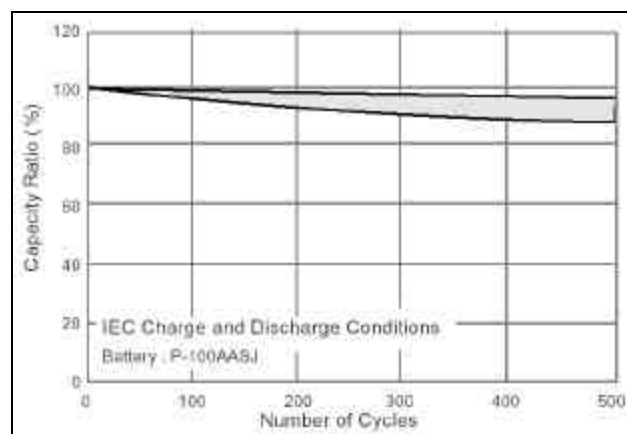


Figure 3-8: NiCd Capacity Loss with Age. [31].

Some D-Size NiCd's can be fast-charged, others cannot.

NiCd batteries exhibit a behavior called voltage depression, also known as the "memory effect".

If repeatedly recharged after being only partially discharged, a NiCd will begin to grow metallic crystal formations between its plates. These eventually start to act as microscopic short circuits between the plates, resulting in decreased capacity. This phenomenon is commonly referred to as the "memory effect."

In order to counter the memory effect, NiCd batteries occasionally have to be "exercised." That is, they must be completely discharged and then fully recharged. This causes the crystal formations to dissolve into the electrolyte. Since the charge process is much faster than the rate of crystal growth, it takes many partial charge-discharge cycles for the crystals to re-form.

NiCd batteries should be exercised, at most, once every 30 uses. More frequent cycling reduces the service life of the battery. [37].

3.3 The Nickel-Metal-Hydrate Battery

The nickel-metal-hydrate battery, or “NiMH”, uses a similar construction to NiCd based batteries with different electrochemical ingredients.

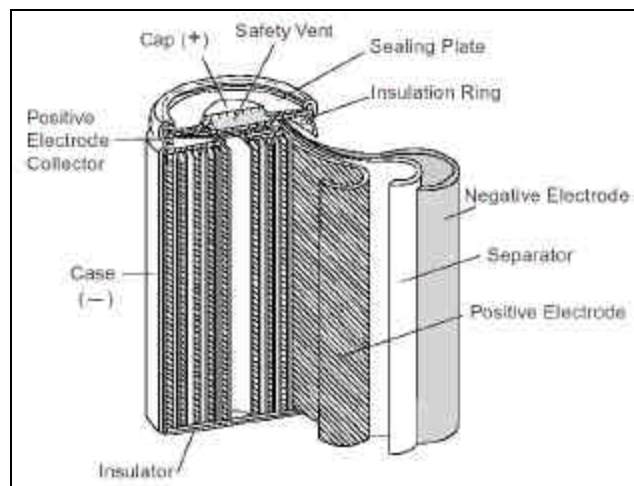


Figure 3-9: Construction of a NiMH Battery. [38].

A cylindrical-construction NiMH consists of a stainless steel can containing a positive plate, which uses nickel hydroxide as its active material, and a special hydrogen-absorbing alloy for the negative electrode. A separator made of a thin non-woven fabric is placed between the plates and is saturated with an alkaline electrolyte consisting mainly of potassium hydroxide.

A safety valve is integrated into the top of the can to vent the battery if the internal pressure becomes dangerously high.

NiMH batteries offer 30-40% higher capacity than comparable sized NiCd's, but at the expense of durability and cycle life. [39].

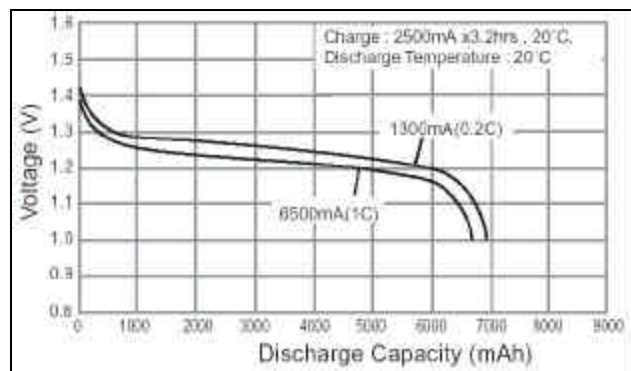


Figure 3-10: NiMH Discharge Curve. [40].

Many of the electrical characteristics of NiMH batteries are similar to those of NiCd's.

NiMH batteries have very low internal resistance, allowing them to be charged and discharged very quickly. As with a NiCd, the NiMH holds its terminal voltage constant over almost its entire charge life.

During charging, the terminal voltage drops and the battery temperature increases rapidly when the NiMH battery reaches capacity. However, at elevated temperatures the magnitude of the voltage drop is far lower than that of a NiCd. With charge rates lower than 0.5C, it is almost nonexistent. [41].

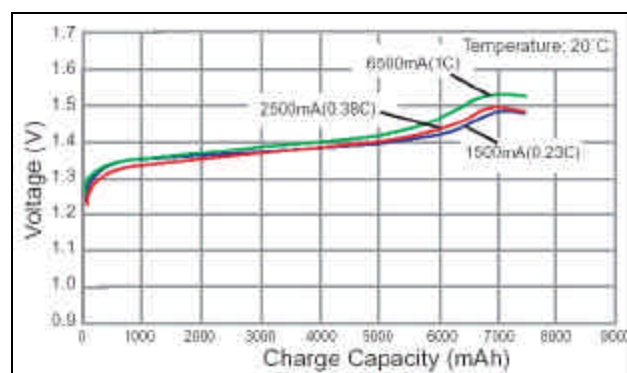


Figure 3-11: NiMH Charging Curve. [42].

In addition, the charging process for a NiMH battery becomes very inefficient for low charge rates as the temperature of the battery is increased. A typical NiMH will charge to full capacity with a 0.1C charge rate at 20°C. If the temperature is increased to 45°C, the capacity ratio drops to just 65%. If the charge rate is now increased to 1.0C, the capacity ratio increases to 96%. [43].

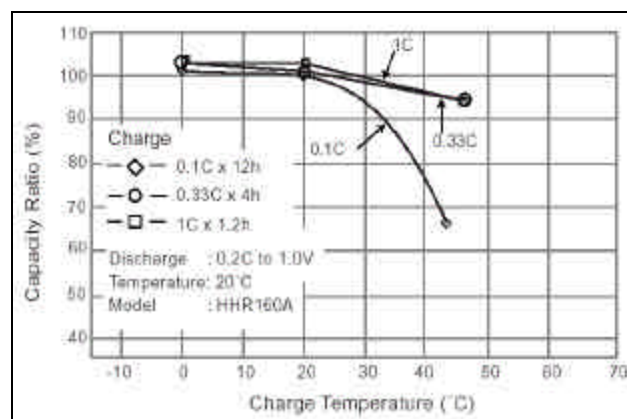


Figure 3-12: NiMH Capacity Loss with Temp. and Charge Rate. [44].

Due to the voltage drop and capacity ratio effects, NiMH batteries usually cannot be slow-charged. If slow-charging is attempted, there is a serious risk of overcharging the battery. A NiMH battery is quickly

and severely damaged by overcharge, resulting in a permanent loss of capacity. [46].

Self-discharge in most NiMH batteries is comparable to that of NiCd's. A typical NiMH loses about 3% of its energy per day when stored at 45°C. [45].

NiMH batteries are especially difficult to charge properly at high temperatures, and usually cannot be charged at temperatures higher than 45°C.

NiMH batteries exhibit a memory effect similar to that experienced with NiCd batteries. While it is less pronounced than with NiCd's, NiMH batteries should occasionally be put through a complete charge-discharge cycle as a preventative measure. [46].

One of the major strikes against NiMH batteries is their short cycle life. The performance of a typical NiMH battery begins to fall off quickly after 300 cycles, and is made even worse by high operating temperatures. [47].

The short cycle life combined with the marginal (30%) increase in capacity and significant increase in cost means that for a given investment in batteries, NiMH batteries will deliver a far lower total amount of energy over their lives than comparable batteries, such as NiCd's. This is reflected in the much higher Cost Per Cycle figure listed in Table 3-1.

3.4 End of Life in NiCd and NiMH

Even with proper maintenance, NiCd and NiMH batteries will eventually wear out. It is also possible for batteries to be damaged by misuse.

Worn-out or damaged batteries usually show four distinct modes of failure:

- Significantly Reduced Capacity
- High Rate of Self-Discharge
- Internal Short
- Open Circuit

3.4.1 SIGNIFICANTLY REDUCED CAPACITY

With continued use, the capacity of a NiCd or NiMH battery will slowly decrease over time. This results in shorter run times for equipment powered by the battery.

If a NiCd or NiMH battery is overcharged, or discharged at an extremely high rate, the heat generated may boil the electrolyte. This causes the battery to vent electrolyte until the internal pressure

reaches a safe level. The loss of electrolyte causes significant loss of capacity. The problem is compounded if the safety vent does not re-seal correctly and continues to leak electrolyte.

When a battery can only hold 70% of its rated capacity, it is usually considered defective, and should be replaced.

3.4.2 HIGH RATE OF SELF DISCHARGE

In batteries that have been damaged or are approaching the end of their service life, the insulator separating the electrodes can begin to break down, causing short circuits between the electrodes. This should not be confused with the previously explained "memory effect".

The short circuits greatly increase the self-discharge rate of the battery, causing it to quickly lose any stored energy. This condition cannot be corrected, and batteries showing this behavior should be replaced.

3.4.3 INTERNAL SHORT

A short circuit between the electrodes of a NiCd or NiMH battery is an end-of-life failure. It occurs in batteries with manufacturing defects or batteries at the end of their service life.

While it is often possible to melt or "zap" an internal short by applying a high amperage current pulse to the battery, doing so causes serious damage to the battery. Batteries "repaired" in this manner will not function reliably and should not be used.

3.4.4 OPEN CIRCUIT

An open circuit between the electrodes of a NiCd or NiMH battery is also an end-of-life (EOL) failure. It occurs in batteries with manufacturing defects, or batteries that have been damaged by misuse.

This condition is usually caused by failure of one of the connecting strips between the battery electrodes and the external terminals. This can happen by physical impact, or by the connecting strip melting from excessive current draw. An open-circuit failure can also occur if the battery has lost almost all of its electrolyte.

These conditions cannot be corrected, and batteries showing this behavior should be replaced.

3.5 The Right Battery for the Job

All of the previously discussed batteries have unique advantages and disadvantages that make them the best candidate for a given application.

For operations that use their equipment lightly with long periods of storage in between, non-rechargeable alkalines are probably the best choice. The cost of buying and managing a rechargeable battery system it is difficult to justify for such a light use application.

For users with more demanding requirements, the choice lies between nickel-cadmium and nickel-metal-hydride batteries.

As can be seen in table 31, NiMH batteries have the highest capacity, and require exercising less frequently than NiCd's. They also have the highest initial cost, and lowest cycle life, resulting in the highest cost per cycle.

NiCd batteries have a lower capacity than NiMH's, but also a much lower initial cost and much longer cycle life, resulting in the lowest cost per cycle. They do, however, need to be exercised more frequently than NiMH batteries.

Table 3-1: Comparison of NiCd and NiMH.

	NiCd	NiMH
Gravimetric Energy Density (Wh/kg)	45-80	60-120
Cycle Life (to 75% of initial capacity)	1500	300 to 500
Fast Charge Time	1h typical	1h +
Overcharge Tolerance	moderate	low
Self-discharge / Month (room temperature)	20%	30%
Vibration Resistance	Moderate	Low
Charging Temperature	Up to 60°C	Up to 45°C
Maintenance Requirement	30 to 60 days	60 to 90 days
Typical Battery Cost (US\$, reference only)	\$10.00 (1.5V, D)	\$17.00 (1.5V, D)
Cost per Cycle (US\$)	\$0.009	\$0.04

For some users, having the longest run time electrochemically possible is the greatest motivating

factor. These users will probably want to use NiMH Batteries.

The Intellicharge System includes automatic battery exercising hardware, and is capable of operating at a sustained high temperature, simplifying the use of NiCd's and allowing charging of high-temperature NiCd's at high operating temperatures.

We recommend the use of NiCd batteries over NiMH batteries for almost all applications. Despite the reduced capacity and the possible disposal problems that come with these batteries, they are the clear winner in terms of durability, reliability, service life, and cost

A comparison of battery characteristics is listed in Table 3.1.

3.6 Charging Nickel-Chemistry Batteries

Because NiCd and NiMH batteries have similar charge-discharge behavior, both types of batteries can be charged using the same electronics. Trickle charge rate aside, a well designed charger doesn't have to be able to tell NiCd and NiMH batteries apart, it just has to be able to tell when both types of batteries have reached capacity.

As mentioned earlier, both NiCd and NiMH batteries exhibit an increase in terminal voltage as the battery is charged, and a decrease or plateau in terminal voltage once the battery has reached capacity (exceeded, actually). A charger can use this phenomenon to tell when the battery is full, and to stop the charge cycle. This technique is called **Negative Differential Voltage (NDV)**. [48].

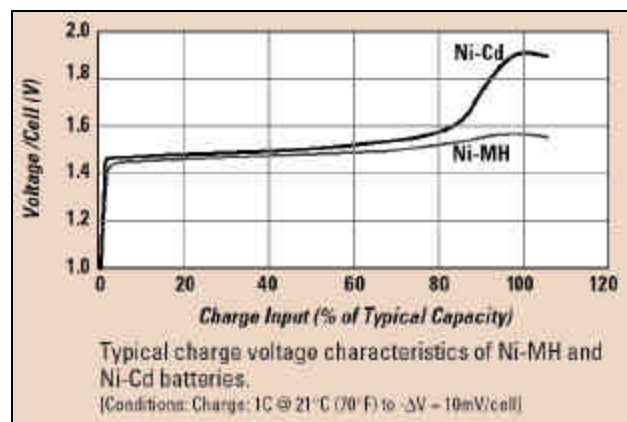


Figure 3-13: Charge vs. Voltage for NiCd / NiMH. [47].

Unfortunately, there is a minor problem. NiMH batteries have a much lower voltage drop than

NiCd's, and at charging temperatures over 45°C it might not even be measurable. Accordingly, a charger using this phenomenon alone could miss the voltage drop and overcharge the battery.

Another characteristic of both NiCd and NiMH batteries is that the temperature of the battery increases rapidly as the battery approaches capacity. More specifically, the *rate of change of temperature* increases.

By measuring the temperature of the battery when it is first placed in the charger, subtracting it from the temperature measured during the charge process, and comparing the rate of increase of the temperature readings, a charger can use this second phenomenon to tell when the battery is full and to stop the charge cycle. This technique is called **Differential Temperature (DT)**. [48].

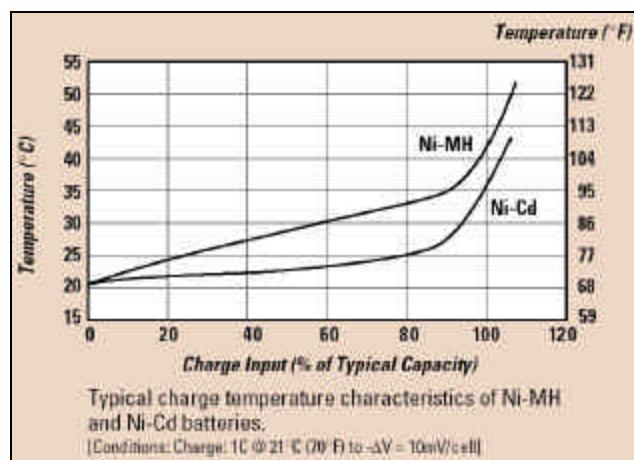


Figure 3-14: Charge -vs.- Temp For NiCd / NiMH. [47].

Unfortunately, there are several possible problems with this technique as well. First, a NiMH battery gets much hotter much faster than a NiCd. A charger using this technique alone could prematurely end the charge cycle on NiMH batteries.

Second, if the charger is left outside on a cloudy day and the sun comes out, the temperature increase could also end the charge cycle ahead of schedule.

Clearly, neither of these techniques alone will provide satisfactory results when charging both NiMH and NiCd batteries outdoors using the same charger.

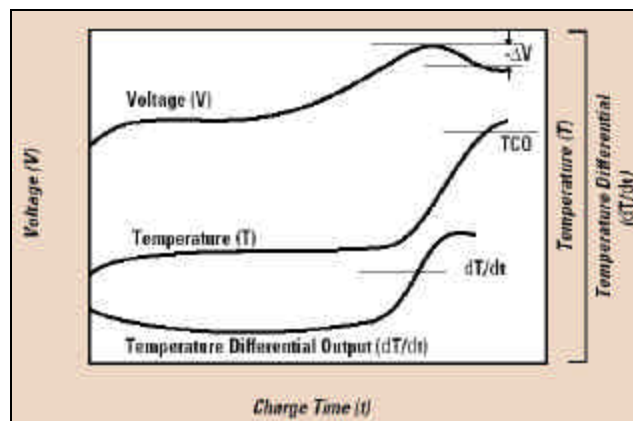


Figure 3-15: Combined NDV and DT Algorithms. [47].

By combining both NDV and DT techniques, it's possible to end the charge cycle for both NiCd and NiMH batteries at the right time with a high degree of accuracy. [52].

A charger using this algorithm simultaneously monitors the temperature and terminal voltage of the battery under charge. The NDV trigger threshold is set to a very low value, allowing the weak response of a NiMH battery to be detected. When the controller detects a temperature rise in synchronization with a drop or plateau in terminal voltage, it ends the charge cycle. [47].

Because both measurements are used as part of the decision process, false triggering by sunlight or noise in the voltage measurement circuitry is avoided. The algorithm can be expanded to take ambient temperature, elapsed time, and expected battery capacity into account.

At the very least, the device should have a safety timer that terminates the charge cycle after a certain maximum time period has elapsed.

Figure [3-16] and Table [3-2] show this algorithm optimized for the Panasonic brand (both NiCd and NiMH) rechargeable batteries.

Table 3-2: Suggested Calibration Data. [43].

(1) Rapid charge current	Max. 1CmA to 0.5CmA
(2) Rapid charge transition voltage restoration current	0.2 to 0.3CmA
(3) Rapid charge start voltage	Approx. 0.8V/cell
(4) Charge terminating voltage	1.8V/cell
(5) -ΔV value	5 to 10mV/cell
(6) Battery temperature rising rate dT/dt value	1 to 2°C/min
(7) Maximum battery temperature TCO	60°C (for L-A, L-flatA and SC sizes) 55°C (for A, AA and D sizes) 50°C (for OA, AAA and prismatic sizes)
(8) Initial -ΔV detection disabling timer	5 to 10 min
(9) Thicke current (after rapid charge)	0.033 to 0.05CmA
(10) Rapid charge transfer timer	60 min
(11) Rapid charge timer	90 min (at 1CmA charge)
(12) Total timer	10 to 20 hours
(13) Rapid charge temperature range	0 to 40°C

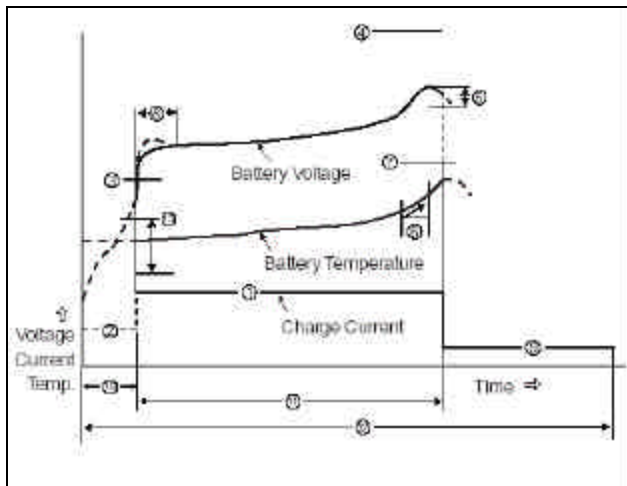


Figure 3-16: NDV / DT Algorithm Critical Points. [43].

3.7 Technically Speaking

To be technically accurate, there is a difference between a cell and a battery.

A cell is a single electrochemical assembly with one anode and one cathode that generates a voltage dependant on the electrochemical system it uses.



Figure 3-17: Cells Labeled as Batteries

A Battery consists of two or more cells connected together to increase the voltage or current capacity of the assembly. Therefore, a 1.5 volt D-size “battery” is actually a cell, while a 9 volt “battery” (containing six 1.5V cells wired in series) truly is a battery.

It seems that most, if not all, manufacturers label their products as batteries regardless of what is actually inside them.

Throughout this report, we will refer to D, C, and AA-cells as batteries, adopting the naming system used by the manufacturers.

4 Background on Solar Power

One major obstacle to the widespread deployment of rechargeable batteries in humanitarian demining is finding a reliable power source from which to charge them. More often than not, deminers have to work in rural or underdeveloped areas, far from an AC wall outlet

To function in the demining environment, a battery charger has to be able to work with unconventional sources of power, and to overcome the unique challenges that they represent. This section of the report explores the power sources available at a typical demining operation, and examines the specific challenges involved in using each source.

4.1 Solar Panels

Past entries have categorized solar panels based on their molecular structure, differentiating between monocrystalline, multicrystalline, and amorphous cells. With advances in technology, classification is no longer so simple.

Manufacturers now use all sorts of proprietary technology to enhance their products. [49,50]. One large manufacturer layers three thin-film narrow band amorphous solar cells on top of each other to produce power densities approaching that of a polycrystalline cell. [51]. Another large manufacturer uses a proprietary Edge-defined film fed growth process to significantly enhance the power output of their polycrystalline cells. [52].

A more realistic way to list solar panels is based on their intended use: Fixed installation, semi permanent, and foldable.

4.2 Rigid Photovoltaic panels

The absolute highest power output per dollar ratio comes from rigid PV (photovoltaic) panels. [53].

A rigid PV panel is intended for permanent installation, either on the roof of a building or bolted to some kind of support structure. Most of these panels are surprisingly durable, rated to survive 200km/h winds and 25mm hailstones impacting at terminal velocity. [54].

For maximum efficiency, rigid PV panels usually have tempered glass fronts. The glass front will crack if the panel is dropped on a hard surface.



Figure 4-1: NCL Panels With Road Case. [55]



Figure 4-2: NCL Road Case Closed. [56].

By adding a road case that doubles as a support frame, a rigid PV panel can be used as a portable energy source, as shown in this system from NCL Solar. [57].

The durable road case allows glass-fronted panels to survive normal transport and handling. The integrated frame allows them to be angled towards the sun, and prevents them from being blown over by wind. In many countries, this is an important consideration.

Below is a list of typical market prices for rigid PV panels (as of Apr 17, 2002) ranked by dollars per watt:

Table 4-1: Price Comparison of Rigid PV Panels. [After: 58].

Supplier	Brand Name	Watts	Min Qty	US\$/Panel	US\$/Watt
Solatron Technologies	Photowatt	100	2	\$399.00	3.99
Cheapest Solar	Siemens	90	1	\$360.00	4.00
Alternative Energy Store	Matrix	80	2	\$320.00	4.00
Advance Power Co	Siemens	90	2	\$360.00	4.00
Alternative Energy Store	Matrix	75	2	\$302.50	4.03
Solatron Technologies	Photowatt	95	2	\$389.00	4.09
Solatron Technologies	Photowatt	90	2	\$369.00	4.10
Alternative Energy Store	Matrix	105	2	\$434.50	4.14
Advance Power Co	BP Solar	120	2	\$500.00	4.17
Sun Electronics	Kyocera	80	4	Call	4.30

4.3 Semi Permanent Panels

The next best power output per dollar ratio comes from shatterproof PV panels. This class of panels is more durable than rigid PV. They're designed to be moved from one location to another, or even mounted on moving platforms such as boats and RV's (campers). These panels fall into two categories, rigid PV with a shatterproof front and thin-film flexible panels.

Shatterproof front panels, such as the units below manufactured by BP Solar, are highly durable. They can take repeated impacts without cracking. [59]. Their plastic fronts will "frost" if the panel is constantly abraded against other equipment.

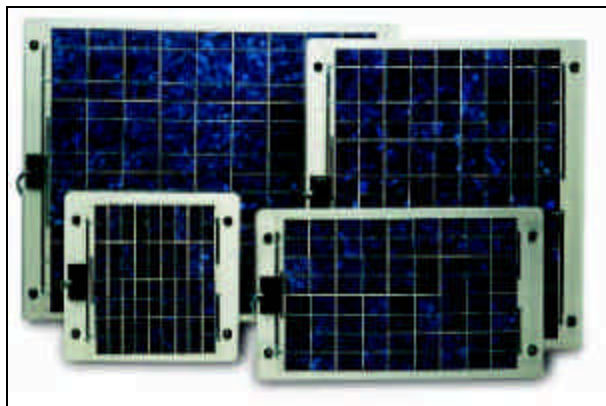


Figure 4-3: BP Solar Shatterproof PV Panels. [60].

The high durability comes at the price of higher cost, reduced output, and shorter service life due to weathering of the plastic glazing film.

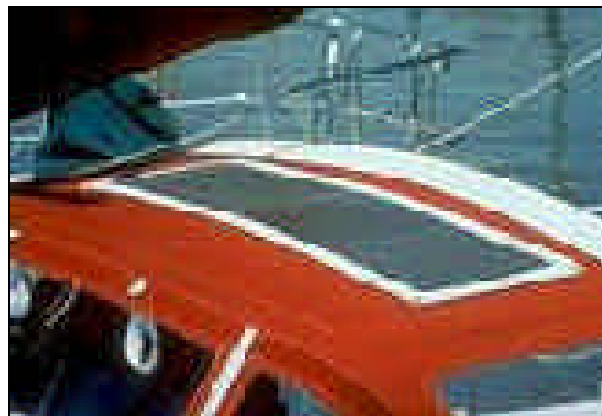


Figure 4-4: Flexible PV Panel on Boat. [61].

Flexible solar panels use thin-film amorphous solar cells layered atop one another to generate electricity. These panels can have surprisingly high power output because each layer of cells is "tuned" to absorb light of a different wavelength. By bonding the cells to a thin sheet of stainless steel and covering them with a flexible polymer, its possible to make a somewhat flexible solar panel. [49, 50, 62].

These panels cannot be rolled up like a rug or folded like a piece of paper, but they will bend to fit a curved surface, like the roof of a bus.

Because the panels have few rigid parts, and contain almost no oxidizable metals, they are highly resistant to corrosion and vibration. They can still be damaged if driven over by a vehicle or repeatedly stepped on.

In general, flexible solar panels are more expensive and have significantly lower power output than either shatterproof or glass fronted rigid PV modules.

Current (as of May 5, 2002) retail prices for shatterproof, flexible PV panels are listed in the table below.

Table 4-2: Shatterproof and Flexible PV Pricing. [After: 63].

PHOTOVOLTAIC PANELS		Price	Shipping
PVUS5	Unisolar 5 watt PV panel	65.00	9.00
PVUS11	Unisolar 11 watt PV panel	124.00	9.00
PVUS21	Unisolar 21 watt PV panel	149.00	12.00
PVUS32	Unisolar 32 watt PV panel	198.00	14.00
PVUS42	Unisolar 42 watt PV panel	245.00	16.00
PVUS64	Unisolar 64 watt PV panel	364.00	22.00
PVUSF5	Unisolar 5 watt flexible PV panel	89.00	9.00
PVUSF11	Unisolar 11 watt flexible PV panel	145.00	9.00
PVUSF32	Unisolar 32 watt flexible PV panel	289.00	14.00

4.4 Foldable PV Panels

Some applications require a solar panel that can be quickly folded up and stowed away, then quickly redeployed at another location. The panels in this category are designed for military and high-end consumer applications where cost is a secondary concern.



Figure 4-5: UniSolar Foldable PV Panel. [64]



Figure 4-6: NCL Solar Folding PV Panel. [After: 65].

One such system, manufactured by NCL Solar, produces a peak power output of 10.8 watts.

List Price: \$650.00 USD.

Another larger System, made by Uni-Solar, produces a peak power output of 30 watts.

List Price: \$780.00 USD.

Unfortunately, neither of these systems are well suited for powering solar battery chargers. Their high cost and low output are not justified by the increase in portability that a folding system offers.

Because these panels are mounted on either a plastic or fabric substrate, they are far less durable than a shatterproof PV panel, and much less resistant to weathering. While it is true that, as advertised, either of the foldable panels could still work after being riddled with bullet holes, they would only continue to do so for a limited time. Following a puncture, the expensive flexible PV cells would quickly be destroyed by reaction with water from rain and moisture in the air.

In most locations, a foldable PV panel would have to be draped over some kind of rigid support so it could be pointed at the sun. Since the support (e.g.: a wooden board) would have to be transported along with the panel, it would completely defeat the purpose of making the panel foldable in the first place.

In the context of powering an affordable and reliable battery charger, foldable PV panels are a terrific example of something that looks great on paper, but is just not practical in the field.

4.5 Disadvantages of Solar Power

Just because solar panels are reliable, low maintenance energy conversion devices, does not mean that they are reliable sources of power.

For a solar panel to work properly, it must be correctly sized for the intended load and receive large amounts of high intensity sunlight. This may not be a problem in countries such as Sudan, but it can be a major challenge in other mine-affected countries.

For example, consider an operation such as the Cambodian Mine Action Center, mentioned in the Mines Action Canada 2000 Technology Competition Judges' comments. Based on the detectors they have in use, this operation would need 108 4,400mAh batteries charged per day. [19].

$$108 \times 1.3 \times 4.44 \times 2 = 1,264.77$$

It will take over 1,200 watt-hours of energy per day to charge those batteries, assuming the charger and charging process runs at 50% efficiency.

Using satellite data from NASA and a very rough calculation, we can say that the average daily insolation in Cambodia is about 4.5kW/m², with a peak insolation of about 700W/m². [66].

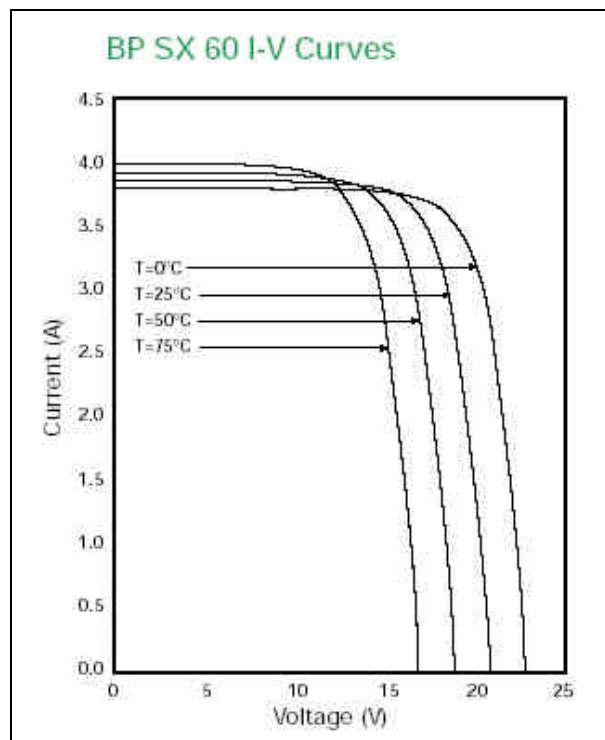


Figure 4-7: BP SX 60 Curves @ 1KW/m². [67].

Under these conditions, a typical rigid PV Panel, such as the BP Solar BP-SX-60 pictured above, will only generate about half the power output it is rated for.

Assuming that 30% of the daily insolation happens during the early morning and late evening, when the light intensity is too low to get any power out of the panel. And assuming that the remainder of the day, the panel runs at its rated 11.5% efficiency [67], and has 0.516m² area, we get:

$$(1 - 0.3) \times 4500 \times 0.116 \times 0.5160 = 188.4 \text{ Wh/Day}$$

That's 188.4 Watt-hours per 60-watt panel per day. To get 1,200 WH/day will require seven panels.

Then there is the possibility that it could be raining or overcast for a few days in a row. In order to still be able to charge batteries, electrical power from the solar panels will have to be stored using a bank of lead-acid batteries. Assume we want to have 3 days of electricity storage:

$$3 \times 1,264 = 3,792 \text{ WH storage}$$

$$3,792 / 12 = 316 \text{ AH battery capacity}$$

316 Amp-Hours of battery capacity at 12 volts. That is the equivalent of six, 55 amp-hour, 12 volt storage batteries. Assuming that the charging process is 75% efficient, and that we want our battery bank to be able to charge up in four days while still charging the metal detector batteries, we need:

$$3,792 / (0.75 \times 188.4 \times 4) = 6.72 \approx 7$$

Seven additional solar panels added to the system, bringing the total to fourteen panels.

$$(14 \times 270) + (6 \times 171) + (149) = \$4,955.00$$

The completed solar array, including the charge controller, will cost over \$4,955.00 USD, measure almost (3m x 3m), (10ft. x 10ft.), and including the batteries, weigh over 762lbs (346kg).

Compared to the size, weight, and cost of this system, other sources of power begin to look very attractive.

These calculations are rough estimates, and would have to be verified with on-site measurements before building the system. What they are intended to illustrate is that solar power may not be the best choice for all demining operations.

5 Alternatives to Solar Power

5.1 Generators

Many demining operations use a portable generator as a power source while working in the field. Since the generator is noisy and consumes fuel, most operations only run their generators for 4 hours per day. [15,16,68].

Many generators, (especially older ones operating in harsh climates) produce a noisy AC waveform loaded with brush noise, harmonics, and voltage spikes. The frequency of the AC signal will vary with the speed of the engine, and the voltage could fluctuate by +/- 10 volts.

The industry collectively refers to this as “dirty power”. Sensitive electronics operating from this kind of input require extensive noise filtering and wide range power regulation circuitry. [69].

A much more dangerous situation can happen with a “do it yourself” unregulated generator where the engine throttle position is manually adjusted. If the generator throttle is set for a heavy load and the load is then disconnected, the engine will quickly spin up to maximum speed. In some cases, this can cause the output voltage to increase by 50%. For a generator operating at 240 volts, the voltage could suddenly increase to 360V. [69].

Another problem with generators is the fact that they are usually run for only four hours. This is only $\frac{1}{4}$ of the time needed to slow charge a NiCd battery.

Because of the voltage fluctuations, variable frequency, noise spikes and interruptions in power, most consumer grade battery chargers don't work reliably when run from a generator. In addition, many commercial-grade chargers could sustain damage from the power spikes and overvoltage conditions.

If a charger is to be run reliably from dirty power, it has to be specifically designed to handle it.

5.2 Vehicle Power

Every modern vehicle needs some sort of battery to power the starter, and either an alternator or magneto to keep it charged. Both of these can be used as a power source while the vehicle is running and the battery can be used as a power source when the engine is switched off. Properly utilized, even a small vehicle alternator can supply hundreds of watts of power. [70].

Some users like to add a second battery to their vehicles. The auxiliary battery charges while the engine is running, and powers loads when the engine is off. This allows the full capacity of the auxiliary battery to be utilized without having to worry about leaving enough power to start the vehicle.

Designing a battery charger that can run from the majority of vehicle power systems is not easy. The voltages used in vehicle charging systems range from 12 to 48 volts.

Most North-American vehicles use 12-volt electrical systems, while many European vehicles (in particular Land Rovers) use 24-volts. [71]. Certain heavy-duty vehicles use 42 or 48 volt electrical systems. Some vehicles even have onboard AC inverters, which supply either 120 or 240 volts AC output. [72].



Figure 5-1: Wall-Mounted Electronics in MGM Vehicles. [72].

There are several conditions that occur in vehicle power systems which complicate the design of electronics operating from them.

Most batteries behave as unregulated power sources, especially under heavy load. A good example of this is when someone climbs into the vehicle and starts it up. When the starter is engaged, it places a massive load on the battery, causing its terminal voltage to drop. That's why the headlights dim when you start your car.

This drop can cause battery chargers operating from the vehicle battery to reset, starting the charge cycles over again.

Vehicle alternators do not function as filtered DC supplies. They output a rectified sine wave, which for most purposes can be thought of as a string of DC pulses. Even when connected across a large vehicle battery, the pulses still produce significant amounts of noise in the vehicle electrical system. If

the brushes in the alternator are worn, or the diodes in its rectifier damaged, the alternator can also emit intense bursts of switching noise as the brushes arc to the slip rings. Often, this interferes with the vehicle's radio causing a condition known as "alternator whine".

One of the worst possible situations happens when the user starts the vehicle then disconnects the battery while the engine is running. Unless the vehicle has computerized engine control, the engine will continue to operate. This leaves the entire vehicle electrical system, as well as anything connected to it, exposed to the raw, unfiltered power supplied by the alternator. Most consumer grade chargers designed for low voltage input do not have sufficient input power filtering to handle this, and would sustain damage in this situation.

If a charger is to be run reliably from real world vehicle power systems, it has to be carefully designed to handle all of the situations that are likely to occur.

5.3 AC Mains

Deminers operating in some mine-affected countries have access to AC mains. In some cases, they are even hard wired directly to the demining camp. [20,21,22]. Just because a facility is supplied with commercial power does not mean it is suitable for running sensitive electronics. The voltage, frequency, and quality of AC power vary widely from one location to the next.

AC mains have two conditions that can stress electronic equipment.

First, under periods of intense loading the voltage coming from the power grid can sag, sometimes by a significant amount. This condition is known as a "brown out" and often makes the news if it happens in a large North American city.

In countries with a less developed power infrastructure, brownouts can happen on a daily basis. Every time compressor X at factory Y starts up 20 km down the line, the voltage for everyone on the circuit drops for 10 seconds, and there is nothing anyone can do about it.

A second condition that equipment has to deal with is voltage transients, more commonly known as "power surges".

Many things can cause transients on a power line, including switching activities at the substation, and

distant lightning strikes. Transients can be lumped into two categories: large ones, and small ones.

Small transients can happen on a regular basis. Any device used to protect against them should be intrinsically self-resetting. One common method of handling transients is to bypass the power input of the device using a pair of counteracting Zener diodes. When a transient hits the device, the diode pair breaks down, shorting out the input. At the end of the AC cycle (1/120 second later) the input crosses the zero point, causing the diode pair to reset. This prevents the circuit breaker from blowing.

Large transients require a different form of protection. Devices are typically protected from large transients using a Metal Oxide Varistor (MOV). An MOV basically is powdered rust sandwiched between two metal plates. When hit with a large transient, the incoming pulse arcs through the rust causing it to fuse together. This creates a direct short circuit across the MOV terminals which are capable of dissipating a large amount of power.

While MOV's are capable of absorbing massive power transients, they can only take a single hit, after which they remain shorted and have to be replaced

5.4 Concluding Remarks on Power

A well designed universal input battery charger can save money for deminers by allowing them to run the device from the power sources available, instead of having to adapt existing sources to suit the charger. However, the problems associated with each common type of power source must be considered in that battery charger design.

6 Current Battery Charging Technology

Before embarking on the design of a new type of battery charger, we spent a considerable amount of time researching chargers that are currently being manufactured. Most battery chargers fall into one of two distinct categories: Personal Chargers, and Industrial Chargers.

6.1 Personal Chargers

The personal charger is sold in attractive packaging and is offered for sale along side such products as digital cameras, cell phones, and portable music players. These chargers are usually low in cost and perform well when used for the application intended. They are designed to be operated indoors at room temperature.

Only fast chargers (those with a cycle time of less than two hours) are suitable for use in the humanitarian demining environment. If the charge time is any slower it could be difficult or impossible for the charger to tell when to end the charge cycle on NiMH batteries. If the charger uses a trickle charge (16 hours+ charge time) charging could be controlled by a timer, but the unit will take too long to be practical.

While there are many consumer grade fast chargers available for AA, AAA, and 9-volt size batteries, we have yet to find a consumer grade charger that does C or D size batteries in less than six hours.

If a charger was to be built that could charge a D size battery in an hour, it would need electronics much more powerful, and proportionately more expensive, than those for AA-batteries. Because most consumers use D-size batteries for things like toys or flashlights, charging time is not a priority, especially if it means increasing the price of the charger. Accordingly, manufacturers build slow, low cost chargers for C and D size batteries.

Below are examples of some of the better consumer grade chargers currently on the market.

The Alltek AT-5798 charger, pictured above, can charge four 4,400mAh D-size NiCd's in about six hours, and includes battery-conditioning circuitry. A complete discharge-charge cycle takes 18 hours. It includes a country-specific AC adapter. [74].

List Price: \$37.99 USD



Figure 6-1: Alltek AT-5798 (left) and Maha C-204F. [74, 75].

The Maha C-204F charger pictured above can charge four AA size 1,200mAh NiMH batteries in as little as 1 hour. It also includes conditioning circuitry to exercise the batteries. It includes a country-specific AC adapter, and can be run from 12-volt power sources. [75,76].

List Price: \$22.97 USD.

6.2 Industrial Chargers

Industrial chargers are built for repetitive use on large fleets of batteries. Available in single or multi-bay configurations, industrial chargers are designed to charge a specific battery or pack for a specific piece of equipment. They are usually sold by the Original Equipment Manufacturer (OEM).

A battery pack is an assembly containing several batteries, usually wired in series. This increases the storage capacity and output voltage of the pack.

Battery packs simplify operations in an industrial environment because they reduce the number of components in a system. A radio that uses six AA-size batteries can be powered by a single 6-cell pack, taking five extra parts out of circulation.

While industrial grade fast chargers are available for hundreds of different styles of custom battery packs, we have yet to find a charger that does C or D size batteries. The reason is simple: most industrial users use battery packs, not individual batteries.

Shown below are examples two industrial charging systems.



Figure 6-2: Cell-Con 18 Bay Smart Charger. [77].

The system pictured in Figure 6-2 simultaneously charges eighteen radio battery packs. That's the equivalent of 108 AA size batteries.



Figure 6-3: PowerStream 16 Bay 800 W SLA Charger. [78].

The system pictured in Figure 6-3 simultaneously charges sixteen sealed lead-acid batteries with a combined power output of 800 watts. Note the four large cooling fans inside the case. This device is waterproof, but only when the case is closed.

6.3 Humanitarian Demining Chargers

Metal detectors used in humanitarian demining use consumer style batteries in an industrial environment. Because of this, an industrial charger that accepts consumer style batteries is required.

Based on our research, we have only been able to locate two devices that do this, only one of which is still being manufactured.

6.3.1 THE SAIC UPM

The first device was called the SAIC Universal Power Manager and was developed in cooperation

with the US Military in 1998. It was then offered to the demining community. [79].

Based on the information we were able to obtain, the system had an input voltage range of 3-30 volts DC and 100 to 240 volts AC. It could output a constant charging voltage of 2 to 30 volts DC at up to 2 amps. It weighed 1kg and had external dimensions of 17 x 12 x 5.5 cm.

The SAIC Power Manager could charge any chemistry of battery, including lithium. It included advanced system and battery diagnostic routines. The user programmed it for the battery type and capacity being charged. [80].

The SAIC Power Manager could charge up to eighteen batteries at a time but, since it only had one output, all of them had to be wired in series. That meant all of the batteries had to be at the same level of charge to avoid overcharging less-discharged batteries.

The SAIC UPM never caught on. It was discontinued in 2000.

6.3.2 THE MINELAB F-SERIES CHARGER

The only industrial battery charger left on the market that handles consumer style batteries is the Minelab F-Series charger. [4].

The Minelab system can charge eight D-size 4,400mAh NiMH rechargeables in three hours. For users of NiCd batteries, it includes a discharge circuit for draining the batteries. This process takes about eight hours, after which the charge cycle begins automatically. [81].

Batteries are charged as two groups of four, and loaded into the charger from the front. Inside the charger are four metal tubes similar to the body of a flashlight. The batteries are inserted into the tubes and locked in place with the end cap.

The Minelab charger operates off three ranges of power input: 11-14VDC, 23-28VDC, and 85-250VAC. If a voltage outside these ranges is applied to the device, it will not operate. [69].

The DC ranges are connected to the charger using a military style connector, while the AC ranges are connected using a standard "modular" power cord. [83].

All of the electronics in the Minelab charger are hardened against dirty power. Thermal cutoffs shut

down the unit if it begins to overheat. The device is water resistant but not waterproof. It is not designed for use in wet environments.

List Price: \$400.00 USD [84].



Figure 6-4: The Minelab F-Series Charger. [81].

6.4 Discussion of Shortcomings

While the Minelab F-Series charger is probably the best charger currently available for humanitarian demining that handles ANSI standard size batteries, there are several opportunities for improvement on this device.

For instance, users of the Minelab charger unfamiliar with the English language may find the performance of the charger somewhat disappointing. The Minelab charger features two large black buttons prominently located on the front of the unit. Unfortunately, these buttons are used to *discharge* the batteries.

The tubular construction of the charger's battery compartments could lead to heat buildup problems when the unit is used in hot environments. The batteries are inside a tube which is inside a case. Air that is around the batteries and in-between the tube and the case acts as an effective insulator.

Heat generated by the batteries during charging cannot easily escape to the outside atmosphere. Consequently, the rate at which the batteries can be charged is limited. Under extremely hot conditions the device may be unable to charge the batteries at all.

Since the Minelab charger has separate low voltage and high voltage power inputs, it is the users responsibility to ensure the correct power source is connected to the correct input.

While the connectors on the charger prevent the high voltage cable from being plugged into the low voltage connector, they do not prevent the *other* end of the cables from being connected to the wrong power source, especially if the ends are cut off.

This situation makes it possible to connect the low range input to a high voltage power source, damaging the charger.

The Minelab charger is water resistant, but not completely waterproof. If the charger was exposed to heavy rain or prolonged condensing humidity, water could enter the Chassis and cause damage to the electronics.

Despite these shortcomings, the MineLab F-Series charger surpasses, by far, every other system we have seen to date.

7 Design Overview

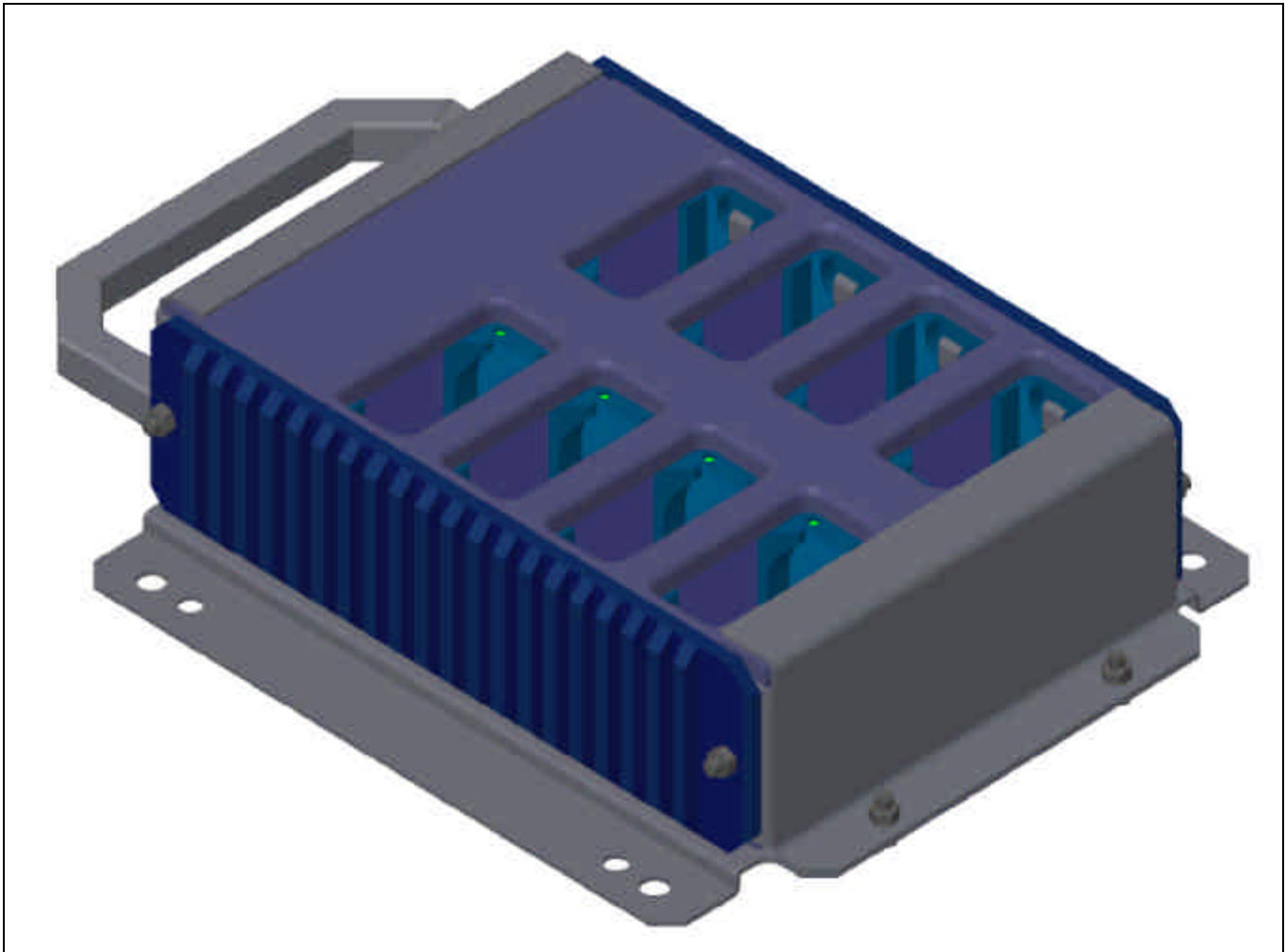


Figure 7-1: Isometric View of the Intellicharge Battery Charging System

7.1 General Description

The Intellicharge System is unlike any battery-charging device we have found. Measuring 29.6cm x 40.4cm x 8.8cm, the System weighs about 7kg (15.4 pounds). The next version the design will likely be slightly smaller and as much as 2kg lighter. Considering how much this device is able to accomplish, its current design is relatively compact.

The System is designed to be shipped and stored without a transport case. It is designed to resist shock, vibration, and repeated impacts. The System is completely waterproof, even when disassembled.

All of the components used in the Intellicharge System have been specifically chosen to resist the effects of dirt, sand, and abrasive grit. There are no

fans or ventilation slots to get plugged. Every component can be safely washed with water.

All of the external components are made from either plastic or non-rusting metals. All of the System's parts are also fungus resistant.

The Intellicharge System is designed to be serviced in the field. The entire device can be completely disassembled with only two wrenches. Other than the six nuts that hold it together, there are no small parts to get lost or damaged. The whole System is modular, so replacing parts is also greatly simplified.

After providing brief overview of the assembly, the design will be discussed in further detail. The conceptual, mechanical, and electrical aspects of the design will be covered.

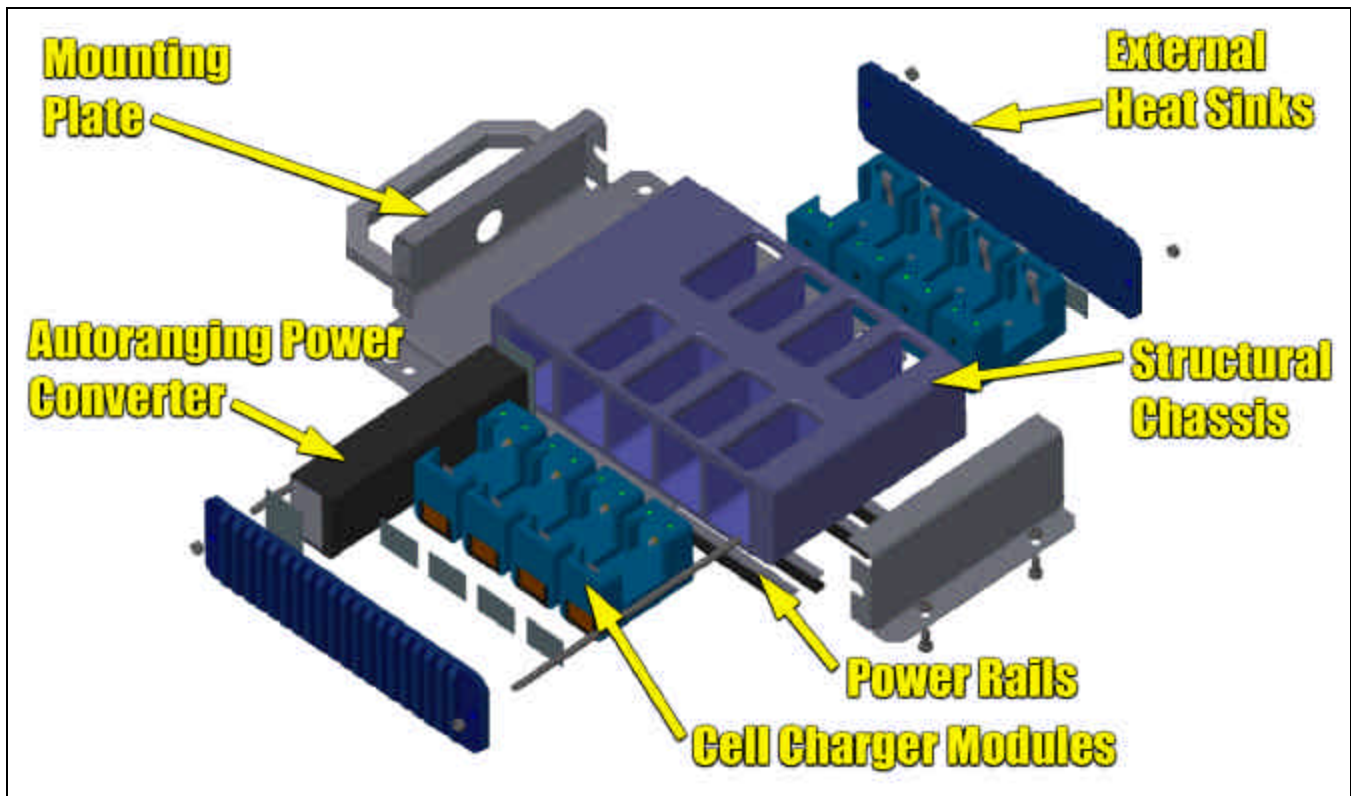


Figure 7-2: Exploded, Labeled View of Intellicharge System

7.2 Design Overview

The major components in the Intellicharge System are labeled in Figure 7-2. The System contains eight **Cell Charger Modules (CCM)** and one **Autorangeing Power Converter (APC)** Module. All nine modules slide into spaces within a structural frame, called the Chassis. Two aluminum heat sinks bolted onto either side of the Chassis hold the nine modules in place. The entire unit is fixed to a stainless steel mounting plate with a sturdy handle.

7.2.1 POWER DISTRIBUTION

Each CCM is an independent battery charger. They all receive power from the APC. The user plugs a power source into the APC Module, which then converts the electricity into a regulated supply of 12 volts DC. Output from the APC is distributed to the CCM's by four stainless steel Power Rails. Figure 7-3 illustrates the overall view of this topology.

The Power Rails connect to the APC using corrosion resistant, high reliability spring contacts. Every CCM is equipped with a similar pair of spring contacts that engage with the energized Power Rails, allowing the it to draw power from the APC.

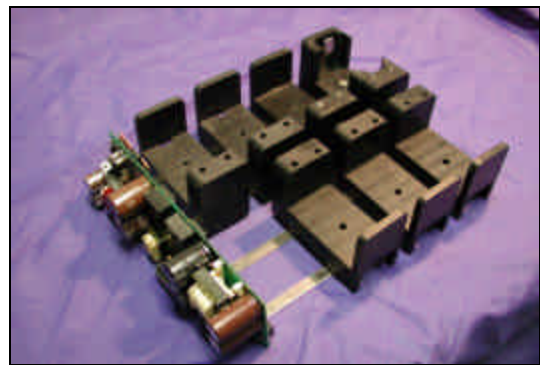


Figure 7-3: Power Distribution Topology



Figure 7-4: Cell Charger Module in Use

7.2.2 HEAT MANAGEMENT

Heat generated by the APC is transferred internally to a copper heat spreader that then conducts the heat outwards to the External Heat Sinks on either side of the APC Module. Similar heat spreaders are on the Cell Charger Modules, as well. Thermal Interface Pads bridge the air gap between the heat spreaders and the External Heat Sinks, providing a low resistance path for heat to flow through (Figure 7-2, Figure 7-5).

When the System is disassembled, the pads can be peeled off and reused. If they ever become dirty, they can be washed with water (Figure 7-6). [86].

7.2.3 CELL CHARGER MODULES

Each CCM is a highly efficient, single-cell battery charger (Figure 7-4). Each CCM is completely self-contained, both electrically and mechanically. If one unit malfunctions, the others will continue to operate normally. Since the CCM's are electrically independent, some units can be used to discharge batteries while others are charging them. By using different modules, sized for different battery types, the Intellicharge System can be used to charge different sizes of batteries at the same time.

A key feature of each CCM is the translation-lock battery holder (Figure 7-7). When a battery is inserted into the Cell Charger Module, it translates laterally towards the negative battery contact. This moves the end of the battery below the holder, locking it into place. Once locked, the battery is nearly impossible to shake loose from the holder. This unique feature allows the System to be mounted in a vehicle and used as it travels over rough terrain. The batteries will not fall out.

7.2.4 POWER INPUT

Power enters the System through a watertight military connector molded into the potting of the APC (Figure 7-8). Though people we spoke to in the demining community requested screw terminals, we had to use this style of connector to meet UL regulations [85].

Because the body of the connector is sunken into the charger, the cord will rip out of the connector before the connector pulls out of the APC, thus preventing damage. The watertight connector can be opened up and the wires quickly reattached. [87].

The charger is not intended to be hung from its power cord but we have been warned that some deminers will to do this anyhow [ref 4]. The handle can be used as a strain relief. Wrap the cord around the handle twice, then knot it. The handle also serves the purpose of shielding the connector from impacts.



Figure 7-5: Applying a Thermal Interface Pad



Figure 7-6: Washing a Thermal Interface Pad



Figure 7-7: Translation Lock Battery Holder



Figure 7-8: Mounting Plate & Power Input Connector

7.2.5 ASSEMBLY OF THE SYSTEM

The Power Rails run along the bottom of the Chassis (Figure 7-9) and are insulated from the Mounting Plate by strips of potting compound that are poured into the assembly. Since the potting compound does not adhere to the HDPE case, the power rails can still be removed if necessary.

The CCM's load into the Chassis from the sides with their heat spreaders facing outwards. If a Charger Module is inserted backwards its spring contacts will not align with the power rails, preventing it from being reverse-powered. A module inserted backwards can be easily removed, even if it is inserted upside down.

If the APC is inserted backwards, the power input connector will face inwards, preventing the power source from being connected. If the APC is inserted upside down, its spring contacts will not make contact with the power rails. These features prevent the APC from connecting to the power rails with reverse polarity.

After all of the modules have been properly loaded into the Chassis, a Thermal Interface Pad is placed over each module's heat spreader (Figure 7-5, Figure 7-10). This allows efficient heat transfer between the module and the External Heat Sinks. If a user disassembles the System and leaves out the pads during reassembly, circuitry inside the APC and Cell Charger Modules will shut them down before they overheat.

To finish assembly, the External Heat Sinks are placed on each side of the Chassis and bolted in place (Figure 7-11). Normally, this can be done using only one wrench. If the fasteners have been secured using thread locking compound, two wrenches are needed to break the seal.

Once the System is assembled, access ports cut in the front of the Chassis allow the batteries to be inserted and removed. Figure 7-12 shows our prototype of the System. In the production version, the edges of the access ports will be beveled to improve access to the batteries for users wearing gloves or who simply have big hands.

When the Chassis is attached to the Mounting Plate, a hole behind the handle lines up with the power input connector on the APC (Figure 7-8). This allows the watertight connector to be plugged in and its locking ring engaged, securely attaching it to the charger.



Figure 7-9: Assembling the Power Rails



Figure 7-10: Loading Cell Charger Modules Into Chassis



Figure 7-11: Securing the External Heat Sinks



Figure 7-12: Cell Charger Visible Through Access Port

8 Conceptual Design

The Intellicharge Battery Charging System represents a number of improvements over current battery charger designs. The three that shaped the fundamental, conceptual design of the Intellicharge System are:

- Durable, open construction that eliminates the need for an external casing
- Modular design that charges batteries independently
- Autoranging Power Converter that allows virtually any power source to be used for charging batteries

These three concepts were formed at the earliest stages of development and made up the framework in which we created the rest of the design and are expanded upon below.

8.1 Open Construction

8.1.1 CONVENTIONAL BATTERY CHARGERS

As with most electronics, battery chargers generally consist of fragile electronic components packed inside a protective, outer casing. Conventional battery chargers usually have a two-part, plastic outer shell. These two parts are either permanently bonded or screwed together. High-durability, industrial-grade chargers usually have casings that latch shut, like suitcases, but these must remain open while the charger is in operation so that the unit can dissipate heat.

Conventional battery chargers, however, are unsuitable for use in humanitarian demining.

Humanitarian demining operators do require battery chargers that can be easily shipped from place to place. They also need battery chargers that can operate *while* being shipped from place to place. A battery charger in a suitcase only looks portable if you never thought of mounting it inside of an off-road vehicle.

It is interesting to note why suitcase-style battery chargers must be kept open while operating. Most batteries cannot be charged when they reach temperatures greater than 60°C. The considerable heat generated by the battery charger must somehow be dissipated. The thick case acts as an effective insulator and any such battery charger typically requires at least one fan to circulate air throughout it.

Enclosing the Intellicharge System within a thinner protective case would have been counter-productive. The case would not have offered any protection from impact but would have still trapped heat, if only because it traps air.

Heat is not transferred “through” air the way it can be transferred through aluminum. This is an important concept to understand. Hot air just expands, rises, and drifts away from heat sources, carrying that heat *away* with it. Fans cool objects down by moving the hot air away even faster. People feel colder when it's windy because they keep heating up air around them and that air just keeps getting blown away. This form of heat transfer is known as **convection**.

Conduction is how heat is transferred through solids. For example, when an iron rod is left with one end in a campfire and the entire rod gets warm, it is because conduction has occurred.

Any pocket of air trapped within a device is a marvelous insulator because neither conduction nor convection is able to occur. Conversely, air that is free to move is an excellent thing to transfer extra heat into because it keeps rising, drifting away, and taking heat along with it.

To allow air to move, most electronics have vents, if not fans as well. While these allow air to circulate, vents and fans also allow water, salt, and dirt into the device. The outer case then compounds the problem by trapping the water or debris inside, with the electronics.

8.1.2 AN ALTERNATIVE

To hold the components of the battery charger and absorb impact, the Intellicharge System fits around a frame, which we refer to as the **Structural Chassis**. All components are designed to resist fungal growth as well as corrosion due to water, salt, and moderately strong acids or bases. Components on the outside of the Chassis are also designed to withstand repeated impact.

Sacrificing efficient heat loss in an attempt to shelter the Intellicharge System from the environment seemed to be a failure-prone strategy. Instead, we chose to make an open-construction, waterproof device that could withstand exposure to the environment.

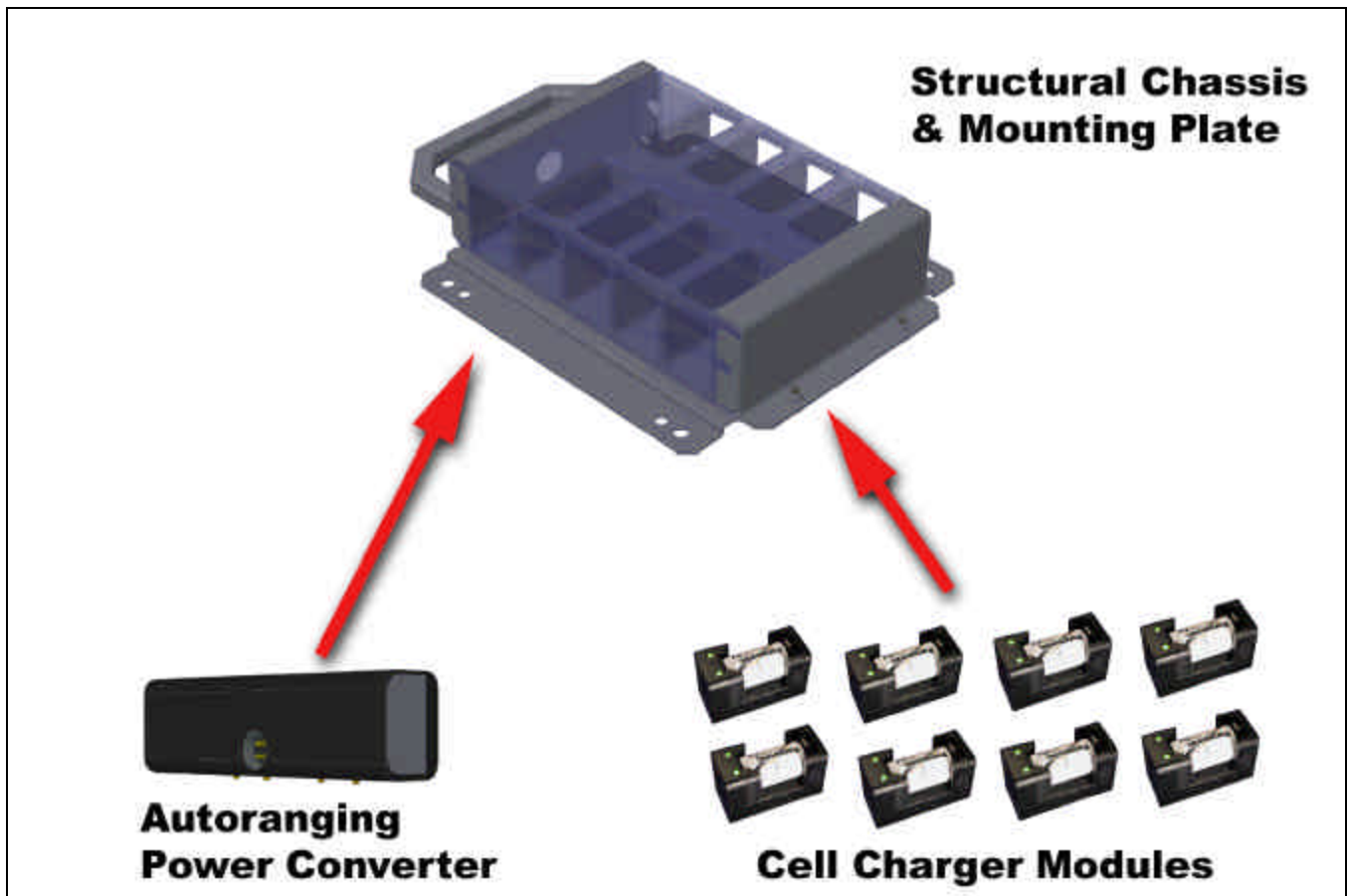


Figure 8-1: Hierarchical Diagram showing Modularity of the System

When the Intellicharge System is used outside in the rain, water is free to run over and in-between any of the major components.

The only sensitive parts that a battery charger really needs are the electronics on the circuit boards. For electronic designs built to withstand exposure to high temperatures and corrosive liquids, we looked to automotives. There we found a host of fragile electronics safely encased in various types of corrosion-resistant, thermally conductive potting compounds.

Encasing electronics in potting compound seals them off from moisture and corrosive products without relying on failure-prone gaskets and o-rings. Nor does it require high-precision manufacture. Most importantly, the potting replaces the any air around the electronics. Conduction through the compound, or metal heat spreaders embedded in the compound, draws thermal energy away from the electronics to external heatsinks, where it can then be released to the surrounding atmosphere.

The use of a frame, rather than an case, made the design of all the components highly interdependent. Allowing batteries as well as battery contacts to remain exposed to the open atmosphere also limited the number of available design options. While the open design of the Intellicharge System has restricted us to certain structural properties, it has also lead to the construction of a safer, durable, and more effective product.

8.2 Modular Design

Modular construction detailed in Figure 8-1, is one of the highlights of the Intellicharge System. It offers numerous, important advancements over conventional charger topologies:

- it makes the System field repairable, using spare replacement modules. The Intellicharge System can be disassembled, failed components can be replaced, and the entire device can be reassembled in a few minutes, even in the pouring rain.

- it allows cost reduction through duplication. Eight identical Cell Chargers are used, each built into identical battery holders.
- it lets the user customize the System by replacing Dsize Charger Modules for 9 volt, C-cell, or AA-cell modules.
- it is required for any charger with potted electronics. A one-piece charger filled with epoxy, would become a \$600 doorstop as soon as a single component failed. The modular design keeps the fault contained so that only the one module that failed needs to be replaced.

8.3 Autoranging Power Converter

Most battery chargers are only designed to operate from a specific, limited range of voltages. If the power input supplied to the charger is outside this range, the charger will not function properly and could be damaged.

Most consumer grade battery chargers are designed to work at either 120 or 240 volts AC input +/- volts. Higher end industrial chargers usually have a wider input range of 90-270 volts. This is called a

“universal input” supply because it will, theoretically, run from any residential wall outlet, the world over.

In humanitarian demining, end users usually do not have a wall outlet available to power battery chargers. Chargers built for this application need a very wide input range to be able to utilize as many different power sources as possible.

One such charger, the Minelab F series, has three ranges of input: 11 to 14 volts DC, 23 to 28 volts DC, and 85 to 270 volts AC. The user manually selects the range by connecting to the appropriate power input jack on the back of the device. [83].

The **Autoranging Power Converter (APC)** used in the Intellicharge System takes this concept one step further. Rather than have a number of different power inputs, the System has a single input connector and automatically adjusts itself for the correct input voltage. This ability is called “autoranging.”

The APC will work on any input in the range, AC or DC. This gives users greater flexibility and simplifies operation.

9 Mechanical Design

The mechanical design of the Intellicharge System will be considered to include:

- Layout optimization for the mechanical components and assemblies.
- Evaluation of, and final decision upon, method of manufacture.
- Determination of dimensional and geometric details of all components.
- Selection of materials used to build the components within the design.
- Assurance of durability, structural integrity.
- Management of waste heat.

There are six major component groupings in our design:

- Autoranging Power Converter (APC)
- Cell Charger Modules (CCM's)
- Structural Chassis
- Mounting Plate
- Power Distribution Components
- Heat Management Components

These groups of components function together to ensure the mechanical and electrical integrity of the System. The mechanical design aspects of the APC Module are also common to the CCM's, so it does not warrant a separate discussion for its mechanical design. For each of the other five component groups listed above, the following will be provided:

- A physical description of the component or components
- A discussion of design considerations that are particular to that component or group of components
- The reasoning used in material selection



Figure 9-1: Front View of Structural Chassis

9.1 Structural Chassis

9.1.1 CURRENT CHASSIS DESIGN

The **Structural Chassis** is a rectangular, plastic, structural frame designed to hold the System together while dampening impacts. Figures 9-1 and 9-2 show the current design of the Chassis from different views. Key features of the Chassis include:

- Eight access ports in the top surface, allowing access to batteries.
- Four cavities in either side to contain the Cell Charger Modules (CCM's).
- One cavity for the APC that goes through the entire width of the Chassis.
- Four slots on the bottom surface for the Power Rails.
- Two, ¼ inch diameter (6.35mm) holes through the entire width of the Chassis for threaded rods
- A hole on one end for access to the APC's power input connector.
- Slight recessions at each end to accommodate the Mounting Plate.

Of the features listed above, the last two have not been mentioned before. For simplicity, those two features were omitted from the prototype, which is otherwise fully functional. The detail drawing used to machine the prototype is provided in the Technical Appendices at the end of the report.

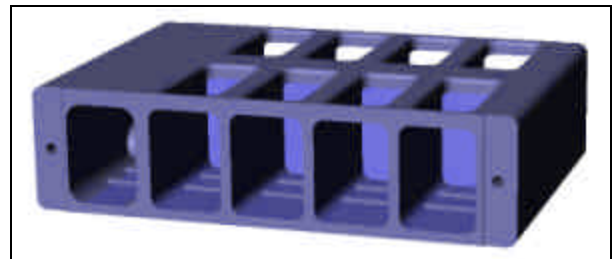


Figure 9-2: Rendering of Current Chassis Design

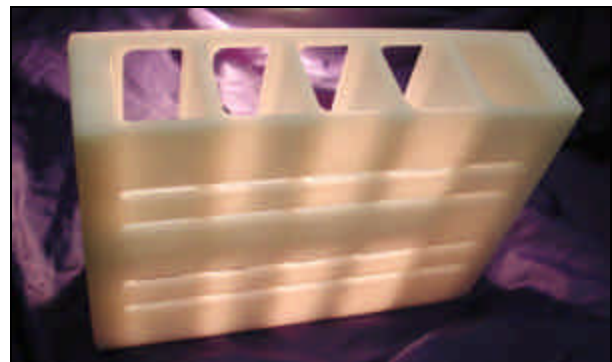


Figure 9-3: Rear View of Structural Chassis

The Intellicharge System can be mounted horizontally or vertically. Throughout the report, the “top” of the unit will be considered to be its uppermost surface when it is lying horizontally (Figure 9-4).

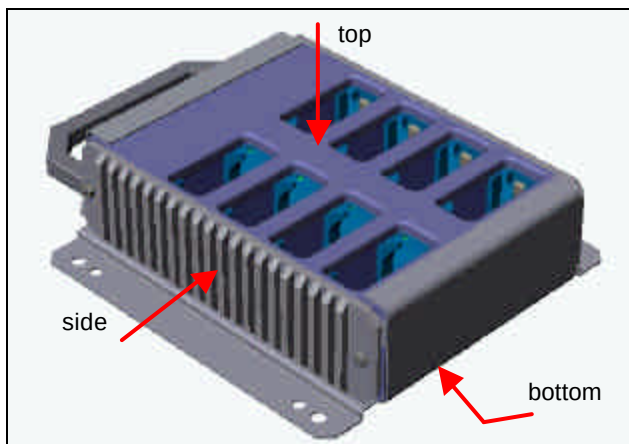


Figure 9-4: Orientation of the Chassis

9.1.2 DESIGN RELIANT ON OTHER PARTS

At the very least, the Chassis must be able to contain the combined volume of the Cell Charger Modules and APC, with some material left for structural rigidity.

The largest batteries the System will be expected to charge are D-size batteries.

Accordingly, the Chassis has to be able to fit eight Cell Charger Modules, each of which is capable of holding a D-size battery, plus an APC large enough to power them.

By designing a System that can charge the largest battery expected, the System is inherently able to accommodate smaller batteries as well.

9.1.3 MATERIAL SELECTION

Selecting the optimal material from which to manufacture the Chassis was a surprisingly difficult problem. The first decision was whether to make it from metal or plastic.

Most metals are very strong. This allows the Chassis to be made with relatively thin walls. Metal is also thermally conductive, so the Chassis could be used, at least to an extent, as a heat sink for the electronics. Unfortunately, metal cannot be molded – at least not in the complexity needed for our design. This means that every Chassis would have to be

individually machined, at a cost of several hundred dollars per piece.

In addition, metal has poor dampening qualities. Shock from an external impact would transfer right through a metal case, placing stress on internal components. Since the charger will be used in wet locations, the Chassis would have to be made from either anodized aluminum or stainless steel. Though obtaining the raw materials for machining metal is cheaper than for machining plastic, the plastic can be molded once in production. The prototypes may be cheaper to make in metal, but at the going rate of \$50Cdn/hr for machining time, it is not practical to machine production quantities of the Chassis.

Another important reason for using plastic for the Chassis is that it acts as a dampener when the System is subjected to impact or vibration.

While there are hundreds of thousands of plastics, we are limited to fairly high strength, widely available materials that maintain their physical properties up to temperatures of about 100°C.

Reasonable choices are hence limited to HDPE (High Density Polyethylene), ABS (acrylonitrile butadiene styrene), and PVC (polyvinyl chloride). Since the additives used to make PVC resistant to impact can be a food source for fungus [88,89], we were left with just two choices: HDPE and ABS.

For our prototype System, we chose to make the Chassis from HDPE because of its waxy texture that very little adheres to. [90]. Just as Teflon frying pans are easy to clean, mud is easily wiped off of HDPE.

We chose to make the Cell Charger Modules from ABS so we could solvent-weld the parts together. The potting compound we chose also adheres aggressively to ABS. It is also a harder material than HDPE, so it makes something of a protective barrier around the batteries and electronics.

When the System is dropped, the Chassis will deform slightly and dissipate the impact. It is the electronics that we do not want to constantly exposed to bending, twisting, or buckling.

9.2 Heat Management Components

9.2.1 BRIEF TECHNICAL BACKGROUND

A "heat sink" is anything that cools a System by collecting and dissipating heat. In electronic design, heat sinks often are blocks of aluminum with fins along one side.

An **active heat sink** has a fan that continually moves air past its fins. This type of heat sink is said to be cooled by **forced convection**.

If there is no fan moving air past the heat sink, then it is called a **passive heat sink**. A passive heat sink is cooled by **free convection**.

The Intellicharge System is cooled entirely by free convection. Heat generated by the electronics is dissipated into the air by the two **External Heat Sinks**, made from aircraft grade aluminum.

9.2.2 HEAT MANAGEMENT COMPONENTS

9.2.2.1 *What is Hot and What Stays Cool*

Each Cell Charger has four major heat-producing components: a Power Regulator, a Schottky Diode, and two MOSFETS. One MOSFET produces heat while the battery is charging, the other while the battery is being exercised. To keep the battery cool, heat must be removed from these components and dissipated to the surrounding atmosphere.

Furthermore, a Digital Temperature Sensor is located beneath the battery (Figure 9-5). For it to accurately measure the battery temperature, it must be thermally insulated from the Cell Charger and heat must transfer to it easily from the battery.

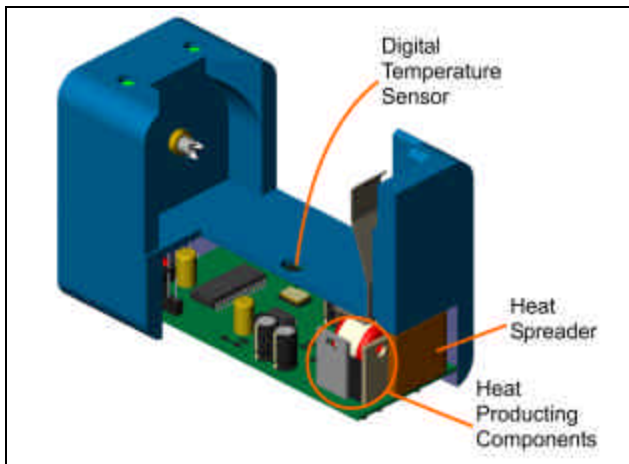


Figure 9-5: Cut-Away View of Cell Charger



Figure 9-6: Securing the Heat Spreader



Figure 9-7: Installing a Thermal Interface Pad

9.2.2.2 *Dissipation of Heat from the Cell Charger*

Inside the CCM, the heat producing components are located at the outside edge of the circuit board and bonded to a copper Heat Spreader using Loctite 315 thermally conductive adhesive. Because the layer of thermal adhesive is both highly conductive to heat and very thin, the bond produced is of very low thermal resistance.

Heat from the heat producing components flows into the copper heat spreader. From there, the heat is conducted to the External Heat Sinks (Figure 9-10).

If the External Heat Sinks were simply pressed against the Heat Spreaders, a small but very significant air gap would result. This would greatly limit the flow of heat between the Heat Spreader and the Heat Sink. To solve the problem, a Thermal Interface Pad is placed between the components, bridging the gap and maximizing heat transfer. (Figure 9-7)

The corners of the Heat Sinks are beveled at a 45° angle. Sharp, right angles, would have produced high stress concentrations whenever the System is dropped or struck on one of its Heat Sinks.

9.2.2.3 Thermal Interface Pads

The 3M 5509 Thermal Interface Pad material is a flexible silicone based thermal transfer sheet. It is an excellent conductor of heat, an electrical insulator, and it is completely waterproof. The Thermal Interface Pads can be repeatedly peeled off the heat spreaders and stuck back into position with little wear. If they get dirty, they can be washed with water.

In humid (or worse yet, salty) atmospheres, an electrolytic reaction can occur between copper and aluminum. The Thermal Interface Pads cover the entire outside surface of the heat spreader preventing this reaction from occurring.

When the bolts on the External Heat Sinks are tightened they compress the Heat Sink against the Heat Spreader. The Thermal Interface Pad deforms, filling displacing any air between the Heat Sink and the Heat Spreader as it conforms to the irregularities on the two surfaces.

9.2.2.4 Heat Dissipation from the APC Module

The APC Heat Spreader is very similar to that used in the Cell Charger Modules. Affixed to the underside of the APC circuit board, it stretches across the length of the APC before bending up at either ends where it presses against the Thermal Interface Pads. See Figure 9-8.

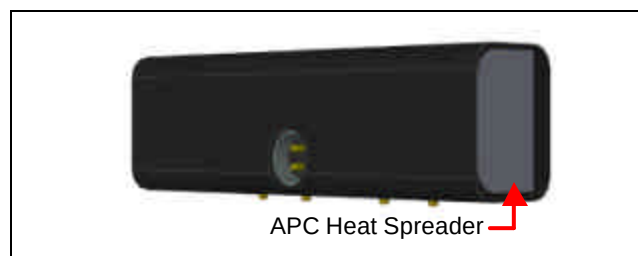


Figure 9-8: View of APC Showing Heat Spreader

9.2.2.5 Accommodating the Temperature Sensor

The Digital Temperature Sensor is affixed to its own, small circuit board that insulates it from the heat generated by the Cell Charger.

To protect the sensor, and to conduct heat between it and the battery, the space around it is filled with a highly thermally conductive potting compound. Measurement of the battery temperature thus can be fast and accurate.



Figure 9-9: Potting Applied to Sensor

9.2.3 CHOICE OF MATERIALS

The Heat Sinks are made of anodized, common 6061-T6 Aluminum. Though reasonably corrosion-resistant, aluminum may oxidize in salty, wet environments. Anodizing the Heat Sinks is a simple, effective way to reduce oxidization. [91]. The CCM Heat Spreaders will be copper, another common medium for transferring heat.

Aluminum's availability, high thermal conductivity (166.9W/mK [92]), lightweight and reasonably low price make it a popular heat sink material. Aluminum will also be used for the APC Heat Spreader. Anodizing the Spreader would be redundant since it is not exposed to corrosive elements.

Anodized aluminum was chosen for the Heat Sinks because unlike other reasonably priced heat conductors, it is sufficiently durable and corrosion-resistant to be used externally.



Figure 9-10: External Heat Sink. Inset: Beveled Corner

Copper's superior thermal conductivity (300-400W/mK) made it the preferred material for quickly transferring heat from the Cell Chargers to the Heat Sinks. [92]. There are other materials, such as silver, that have higher thermal conductivities than either copper or aluminum but they are prohibitively expensive. [89].

The potting compound chosen for the CCM and APC Modules is a mixture of Loctite Hardener 3163 and Resin 3142. It was chosen for its thermal conductivity, hardness, reasonable price, and ability to bond to ABS. [93].

The potting over the temperature sensor is 3M 2707. It contains small flakes of aluminum to give it an exceptionally high thermal conductivity. At roughly \$50 for a 37mL tube, it is only suitable for use where small quantities are required.

9.2.4 INTEGRATION INTO THE SYSTEM

The chosen location of the Heat Sinks had tremendous ramifications on the rest of the design. Essentially, the decision came down to deciding what path heat would follow as it exited the Intellicharge System.

The design of the Cell Charger Modules, the Chassis, and the overall layout were largely determined by the decision to direct heat from the electronics out through the sides of the unit. In responding to questions about why the design is the way it is, the design will often trace back, eventually, to the chosen location of the Heat Sinks.

9.2.5 TOP MOUNTED HEAT SINKS

Had we decided to send waste heat out the top of the device, the Cell Chargers would have had to have been beside the batteries. (If the charger was at one end of the battery, it would be difficult to connect it to both battery terminals. If it was below the batteries, heat generated in the Cell Chargers would have too great of a distance to travel to the External Heat Sinks.)

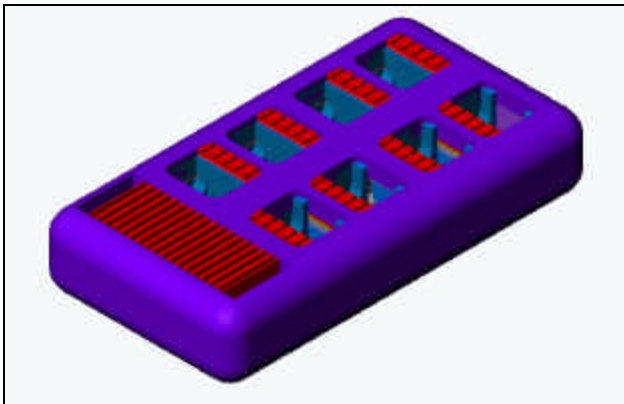


Figure 9-11: System with Top Mounted Heat Sinks
[from Archives of Early Intellicharge Designs]

The option of having Heat Sinks on top was eliminated partly because of space considerations. Knowing that some of the components needed for the Cell Charger would be about 1.5cm tall, it was realized in the early stages of design that the Cell Charger would add almost 2cm, or $\frac{3}{4}$ inch, to one of the three overall dimensions of the CCM. When on the bottom, the Cell Chargers add 2cm to the overall height of the Intellicharge System. If all eight batteries had a Cell Charger beside them, the Cell Chargers add about 8cm (3 inches) to the overall length of the Intellicharge System. (2cm x 4 modules = 8cm)

The volume added by the Cell Chargers is about the same either way.

2cm x 20cm x 30cm = 1200cm³ added to the bottom
8cm x 20cm x 7cm = 1120cm³ added to the side

Increasing the length of the device increases its weight; however; by necessitating a larger Mounting Plate. Molding such a long Chassis would also have increased the size and cost of the mold unnecessarily.

The second reason why top-mounted Heat Sinks were not used is that each of the nine modules would have to have its own individual Heat Sink. Large Heat Sinks across the tops of Charger Modules would have blocked off the access ports through which the batteries are taken in and out.

Individual Heat Sinks not only increase the cost of each module but they limit the total surface area available for dissipating heat. When the size of heat sinks is reduced, and the amount of heat generated stays the same, the temperature of the heat sinks increases.

A high heat sink temperature is problematic for two reasons. Firstly, it could burn someone if it got too hot. In an informal test involving a curling iron and a thermometer, the curling iron (presumably, aluminum) reached 76°C before it was too hot to hold on to. All exposed surfaces of the Intellicharge System should be kept cooler than that. Secondly, heat travels from hotter places to cooler places. The cooler a heat sink remains, the more heat can be transferred to it from the electronics.

9.2.6 BOTTOM MOUNTED HEAT SINKS

Once resolved to putting the Cell Charger in the bottom of the CCM, it seemed tempting to pull the heat downward, into the Mounting Plate. From there, the heat could either be conducted into the mounting surface (the table or wall that the unit was mounted on), or it could be transferred to the air if any was allowed to circulate beneath the unit.

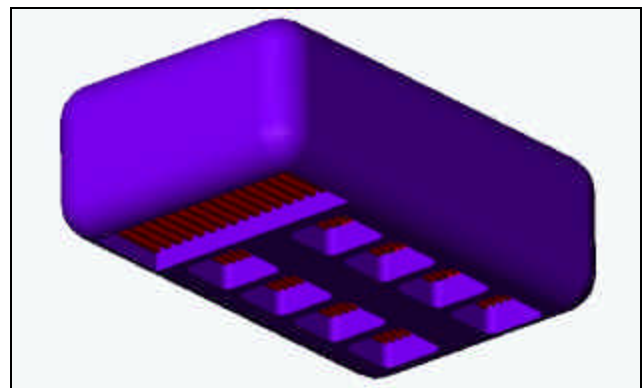


Figure 9-12: Bottom Mounted Heat Sinks
[from Archives of Early Intellicharge Designs]

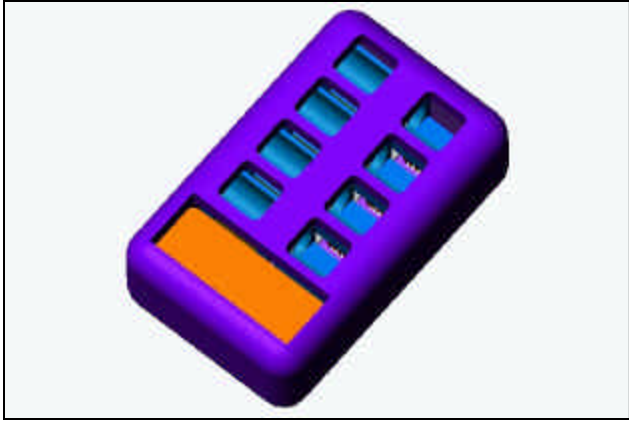


Figure 9-13: Bottom Mounted Heat Sinks (top view)
[from Archives of Early Intellicharge Designs]

Relying on heat transfer into the mounting surface would not be acceptable. The mounting surface would probably not be something designed for heat dissipation. Moreover, it is not known what else the mounting surface is used for, or what ramifications there may be if it got hot.

Secondly, the Intellicharge System relies on free convection, which involves allowing heat to rise. Unless the charger was mounted vertically, it would be hard for hot air to escape.

9.2.7 SIDE MOUNTED HEAT SINKS

Directing heat through the sides of the device avoids all of the problems mentioned above, encountered when sending heat in other directions. Advantages of placing one Heat Sink on either side of the Chassis include:

- Cell Charger electronics can remain on the underside of the CCM's and still be close to a Heat Sink
- Heat Sinks could also form two of the outer walls of the Chassis
- Heat Sinks provide additional structural rigidity

The decision to use one Heat Sink on either side of the Chassis affected several other aspects of the Intellicharge System's design.

9.2.8 MAINTAINING ADEQUATE HEAT LOSS

The prediction of heat transfer relies heavily on empirical data. The thickness, length, and number of fins on the Heat Sink were chosen arbitrarily for the initial prototype. There are too many unknown variables at this time to make meaningful calculations.

During future testing, we plan to fully analyze heat transfer out of the Cell Charger Modules. We will accurately measure the heat generated by the electronics within the module and the portion of the heat that actually is conducted through the Heat Spreaders to the Heat Sinks, how much transfers to the battery, and how much dissipates elsewhere.

From there, we can better approximate the behavior of heat within the charger to find a combination of dimensions that is both effective and logistically sound. The design is, by nature, an iterative process and it may be necessary to prototype several additional sets of Heat Sinks and Heat Spreaders before finalizing the design.

Effectiveness can be confirmed by testing the entire System, loaded with eight batteries, in a simulated tropical climate. There are a number full environmental testing chambers that we hope to obtain access to for these tests. Failing that, a regular laboratory oven could be used. Tins of water would be evaporated inside it first to increase the humidity.

To decrease the heat transferred to the battery, the following variables are within our control to adjust:

- CCM Heat Spreader dimensions
- CCM Heat Spreader material
- APC Heat Spreader dimensions
- APC Heat Spreader material
- Heat Sink dimensions
- Thickness of the insulating ABS polymer between the Cell Charger and the battery
- Power output of the Cell Charger

Even within the last two months, new electrical components have entered the market that would further reduce the size of the Cell Charger while increasing its efficiency. Furthermore, the smaller the electronics, the larger we can make the Heat Spreaders, and the faster heat can be transferred away from the batteries.

It is impractical to redesign a device every time the electronics industry makes a small technological advancement, but if all of the easier options have been exercised and heat loss is still too slow, then updating the electronics could be a possibility.

A significant reduction in heat generation could potentially allow economizing decisions to be made in the design of the Heat Spreaders and Heat Sinks.

9.2.9 CHOOSING PASSIVE HEAT TRANSFER

A fan directed at the Heat Sinks and/or batteries would increase the rate of heat loss. However, a fan could also become clogged with dirt, damaged by sand, or wrecked by rain. Not only would a fan be prone to failure, it would also increase the size, cost, and weight, and energy consumption of the System.

Of course, the use of a fan is not prohibited by the mere fact that there is none pre-installed on the Intellicharge System. If heat was significantly limiting the charge-rate of the batteries, users could place a standard, consumer-grade fan by their Intellicharge System. Such a fan could be easily replaced when necessary.

Few computerized devices conduct heat directly to their exterior. If the device has any cooling considerations at all, there will typically be a fan that pulls air into the device, or just slots in the outer casing to allow hot air to escape.

The open design of the Intellicharge System prevents heat from building up inside any closed area. The Heat Sinks on the exterior of the device also allow it to make the most out of any air circulation.

9.3 Cell Charger Module

9.3.1 PHYSICAL DESCRIPTION

The Cell Charger Housing is the plastic body of the CCM. It holds the battery, the positive and negative battery contacts, two LED lights, the Cell Charger (a circuit board), a digital temperature sensor, and the Heat Spreader. Collectively, this assembly is called the Cell Charger Module (CCM).

The negative battery contact is a spring-loaded pin manufactured by Connect2it LLC., with a “4 Point Crown” tip (Figure 9-14). The pointed plunger is heavily nickel-plated brass and the ring at the base of the plunger is gold plated [120,122].

The Connect2it contacts are specialized corrosion-resistant contacts designed to withstand long-term use in harsh environments.

The positive battery contact is made of bent stainless steel sheet. The reasons for choosing these two contacts will be made clarified in Section 9.3.3.

Mechanically, the CCM has two functions: maintain electrical contact at either end of the battery, and hold the battery firmly in place.

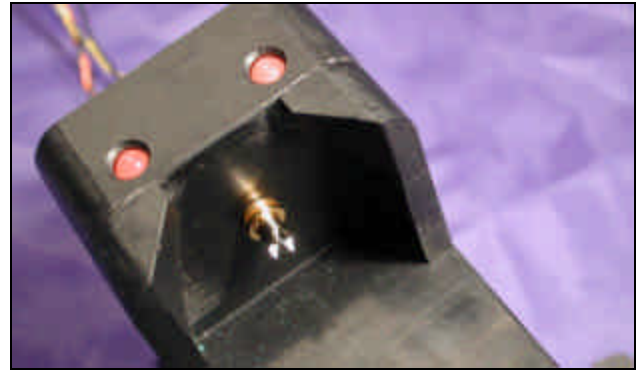


Figure 9-14: Detail of Negative Battery Contact



Figure 9-15: Detail of Positive Battery Contact

In a broader sense, the main reasons for the existence of the CCM are quite different: simplify the replacement of parts, and allow for customization of the design. These roles will be discussed before moving on to the mechanical functionality of the CCM.

9.3.2 VERSATILITY IN BATTERY SIZE

Based on our research we estimate that roughly 50% of the mine detectors currently on the market use D-size batteries. Of the remaining 50%, perhaps about half of those detectors use C-cells. The rest use 9-volt or AA-size batteries. [3, 20-22, 94-117]

Furthermore, demining organizations often use several different models/brands of mine detector, each of which uses a different size battery.

The CCM presented here is designed to hold a single D-size battery. It is our intent to eventually design three more Cell Charger Modules for charging one 9volt battery, one Gcell, or two AA-cells. They will all have the same overall dimensions so that they are interchangeable within the System.

9.3.3 FUNCTIONALITY OF THE CCM

A primary functional requirement of the CCM is to hold the battery firmly in place while making secure electrical contact with both of its terminals.

Section 2.2, Design Requirements, specifies that the System must be capable of operating while mounted vertically in a vehicle and shaken violently as the vehicle moves over rough terrain. However, it also must be easy to take batteries in and out of the Intellicharge System.

Finding a means of holding onto the battery firmly without impeding a user's access to the batteries was an interesting challenge.

The geometry was complicated further by the fact that "standard" batteries are far from actually being standard. To meet ANSI specifications, a D-size battery can be anywhere from 2.343 to 2.421 inches in length (59.51 to 61.49mm) and 1.268 to 1.346 inches in diameter (32.20 to 34.19mm). The ranges of acceptable dimensions for 9-volt, C-size, and AA-size batteries are comparable to those for D-cells. [118].

9.3.3.1 Battery Holders

The term, "**battery holder**" often refers to a standard, off-the-shelf component that consists of a piece of plastic molded to fit one or two batteries as well as positive and negative battery contacts.

Standard battery holders sell for about \$0.60 USD and work well for the low-usage, consumer-grade devices that they are generally made for. An example of a mass-produced battery holder is shown in Figure 9-14.



Figure 9-16: A Low Cost Battery Holder

A battery holder might also be custom built into a device. Whether the device charges batteries or is powered by them, it must have one or more battery holders.



Figure 9-17: Battery Holder in a Consumer Grade Fast-Charger



Figure 9-18: Battery Holder in an Industrial Flashlight

Battery chargers and battery-powered devices all have certain design traits in common, which is why it is sometimes useful to talk about typical battery *holder* design instead of typical battery *charger* design.

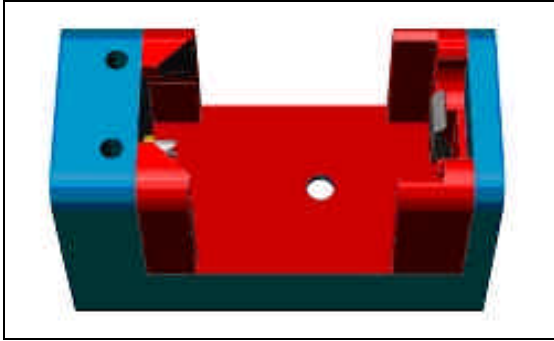


Figure 9-19: The Intellicharge Battery Holder



Figure 9-20: Inserting a Battery (Stage 1)



Figure 9-21: Inserting a Battery (Stage 2)



Figure 9-22: Inserting a Battery (Stage 3)

9.3.3.2 *Translation-Lock Battery Holder*

Our “battery holder,” consists of all parts of the CCM that are related to holding the battery. In Figure 9-19, the “battery holder” is the entire red portion, plus the two battery contacts.

Batteries are inserted into our battery holder at a downward angle towards the negative, Connect2it, battery contact. See Figure 9-20.

As the battery presses into the plunger of the spring contact, it can slide downward, into the holder (Figure 9-21).

Once the battery is inside the holder, the positive contact pushes the battery inwards towards the Connect2it contact. This causes the negative end of the battery to slide beneath the chamfered holder assemblies, locking it into place (Figure 9-22).

Since the battery is secured on the positive end by the positive contact, and on the negative end by the built-in battery “cradle,” the battery cannot be removed by pulling it outwards away from the Cell Charger Module. Once locked, the battery is extremely difficult to shake loose from the holder.

Only by angling the battery upwards can it be freed. To do this, the negative, Connect2it battery contact has to be pushed in while the battery is tilted forward. This is actually quite easy to do. Most people can get the batteries in and out with 1 hand.

Other battery holders can be found that work in a similar manner. They even have similar looking positive battery contacts. What makes the Intellicharge battery holder design unique is the exaggerated translation of the battery.

Conventional battery holders only need the cell to slip about half a millimeter (0.02in.) before it is free to slide out from beneath the ledges of the battery holder. The Intellicharge battery holder requires the battery to translate by about 2mm (0.08in.).

The Intellicharge Battery holder will accommodate the full range of ANSI D-size batteries.

The battery holder shown in the photos is only a prototype. The production version of this contact will be formed differently than the one shown in the photo (discussed in Section 16.2, Future Design Plans).

9.3.4 MANUFACTURABILITY

In production, the Cell Charger Housing would be injection molded. Because molds are costly, the prototypes for testing have been machined from a solid block of plastic. Consequently, the initial design was made in such a way that it can be machined, not molded.

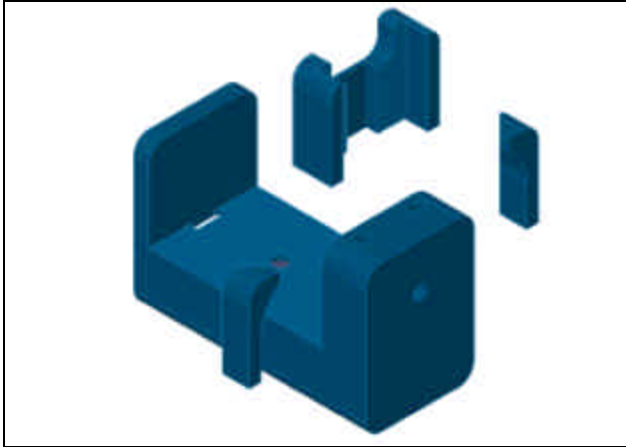


Figure 9-23: Machined Components of Cell Charger

The most significant difference between the molded and machined versions of the Cell Charger Housing is that the machined one must be made in four parts. Figure 9-21.

Because the Cell Charger Housing is made of ABS polymer (acrylonitrile butadiene styrene), the pieces can be solvent welded together without compromising the strength of the final part. When injection molded, solvent welding is not necessary. In fact, molding the small parts individually is problematic because they are too small to easily hollow out, yet too thick to mold.

9.3.5 MATERIAL SELECTION

The compound selected for filling the Cell Charger Module was Loctite 3142 Thermally Conductive Resin, combined with Loctite 3163 High Adhesion Hardener. [93]. This combination was chosen because it was:

- Affordable
- Available
- Thermally conductive
- Hard but not brittle (90 Shore D Hardness, comparable to ABS at 100 Shore D)
- Safe enough to mix ourselves
- Able to set within 24 hours at room temperature

9.4 Power Rails and Contacts

9.4.1 POWER RAILS AND NOT WIRES

The four Power Rails are strips of 16 Gauge ($\frac{1}{16}$ in. or 1.6mm thick) stainless steel sheet that conduct electricity from the APC (Autoranging Power Supply) to the eight CCM's.

If wires were used for this task, they would have to be soldered to each module. Two wires would have to run from each Cell Charger Module to the APC, thus creating 32 potential failure points. Furthermore, assembly or disassembly of the System would be prohibited.

While the Power Rails themselves are simple enough, the overall design of the Intellicharge System depends heavily on how the Power Rails are incorporated into the design. Where the Power Rails are located, and how electrical contact is made with them, were difficult decisions to make.

9.4.2 ELECTRICAL CONTACTS

To ensure reliable electrical contact, it is not sufficient for metal components to be merely touching. The two surfaces must be free of corrosion and pressed firmly against each other.

In addition, the electrical contacts between the Rails and each of the modules had to meet a number of criteria:

- Highly corrosion resistant.
- Long cycle life, will not fatigue.
- Reliable, yet non-permanent contact.
- Minimal space requirements.
- Physically durable.
- Able to carry 2 amps, minimum.
- Able to exert a reasonable amount of force on the Rails, to ensure electrical contact.

It had been thought that spring loaded contacts would be the best way to ensure electrical contact without compromising the ease of disassembling and reassembling the System. However, finding springs of appropriate size, shape, material, and stiffness was exceedingly difficult.

The contacts eventually chosen were suggested by Scott Smith, Technical and Mechanical Project Coordinator of the NGO, MgM Demining. [119].

Connect2it, high-durability spring contacts are advertised as battery contacts, though they are used in a wide assortment of portable, outdoor electronics. [120].

The contact is 15mm long when fully extended and has a spring-loaded plunger that can contract almost 5mm into the contact body. Figure 9-22 shows a rendering of this high-cycle, resilient, gold plated contact. [121-123].

Connect2it has sold slightly smaller versions of this contact for use on the Hubble Space Telescope. Similar contacts are used for a wide range of military applications, including battery chargers. [121].

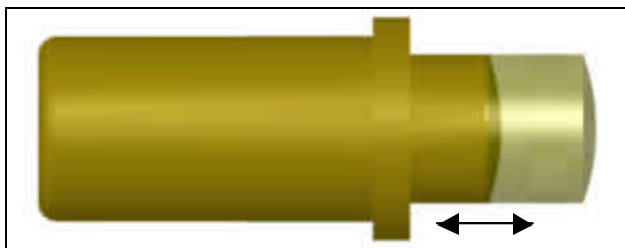


Figure 9-24: Connect2it High Durability Spring Contact

The contacts are easy to obtain, costing between \$1.32 to \$1.95 USD each, depending on quantity purchased. [121]. No minimum order is necessary. A similar, Connect2it contact was also selected as the negative battery contact.

The only other obvious mechanism, besides a different type of spring, that could have applied the necessary force to press two contacts together, would be bolts.

As much as possible, we have eliminated threaded fasteners (i.e.: nuts, bolts, and screws) from the design because they:

- Are quickly eroded by sand.
- Usually require tools to disassemble, which may not be readily available.
- Are small and easy to lose.
- Can be difficult to replace, especially when a specific size and thread is required.
- Are time-consuming to disassemble or assemble.
- Require considerable room for hands and/or tools to access them.

Fortunately, the array of battery contacts available from Connect2it made it possible for us to select a viable alternative. The next decision was where to put them.

9.4.3 POWER RAIL LOCATION

The location of the Power Rails influences the CCM and Chassis designs, as well as the overall layout of the unit.

In choosing the location of the Power Rails, consideration was given to preserve the following:

- Manufacturability of the Chassis
- Manufacturability of the Cell Charger Modules
- Proper insulation of all electrically energized components
- Ease of assembly/disassembly
- Functionality of the other components

In our current design, the four Power Rails all lie flat in slots cut through the bottom of the Chassis, underneath the Cell Charger Modules.

Had one or more Rail ran along either side of the System (between the Heat Sink and the Chassis) then they would had to have been well insulated from the Heat Sinks to prevent them from shorting. Most electrical insulators are also very good thermal insulators. This would have interfered with the operation of the Heat Sinks. Attempting to resolve the combined needs of the Power Rails and the Heat Sinks greatly complicated the design problem.

Placing the Power Rails down the center of the device would not have been beneficial either. At first, the center seemed like the most obvious location. Two Rails, one above the other, could have made contact with all eight CCM's.

However, as shown in Figure 9-25, center-located Power Rails were problematic for a number of reasons.

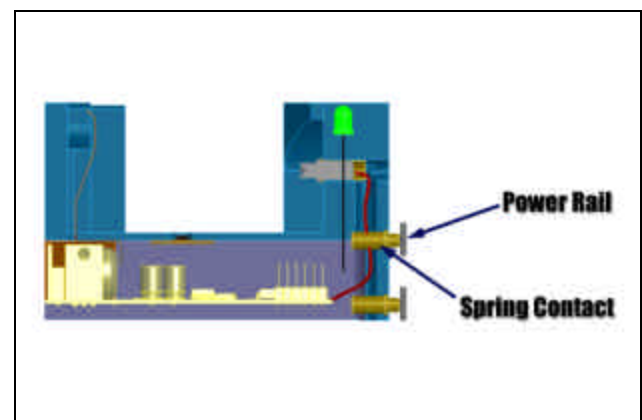


Figure 9-25: CCM Arrangement if Rails were Centered

Holes would either have to be made in the Cell Charger Housing for the contacts to go through (which would have significantly complicated the mold for the Housing) or else that entire wall of the Housing would need to be removed, making it difficult to pour the potting or to consistently place the contacts in their proper locations.

Moreover, having both of the contacts anywhere but soldered to the circuit board would require additional wires, which creates considerable bulk. By deduction, that left the option of putting the Rails on the bottom of the Chassis.

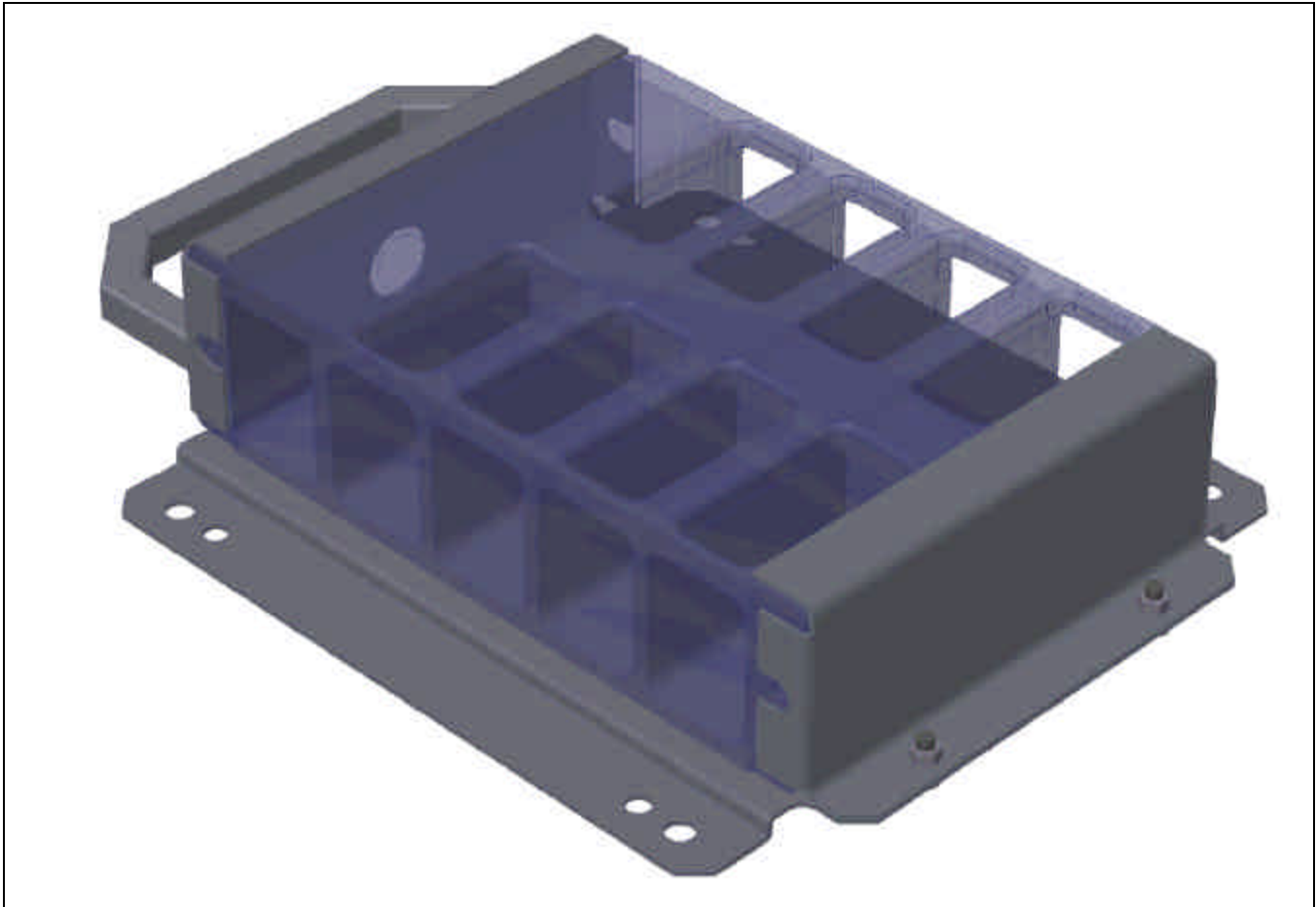


Figure 9-26: Chassis Inside Two Piece Mounting Plate

9.5 Mounting Plate

The Mounting Plate provides a hard outer shell to an otherwise soft plastic charger. Combined with the aluminum External Heat Sinks, five of six faces are covered with metal, leaving only the plastic of the front of the charger exposed.

The Mounting Plate also incorporates the handle of the charger, and it allows the charger to be easily mounted to any flat surface.

The Mounting Plate is made from two pieces of 14 gauge stainless steel, attached together using bolts.

Tabs on the Mounting Plate fit behind the External Heat Sinks and are compressed between the Heat Sinks and the Chassis when the fasteners are engaged. This greatly increases the strength and rigidity of the System.

The handle is made up of 5 pieces of square stainless tubing MIG welded together, then to the Mounting Plate.

10 Electrical Design – Autoranging Power Converter

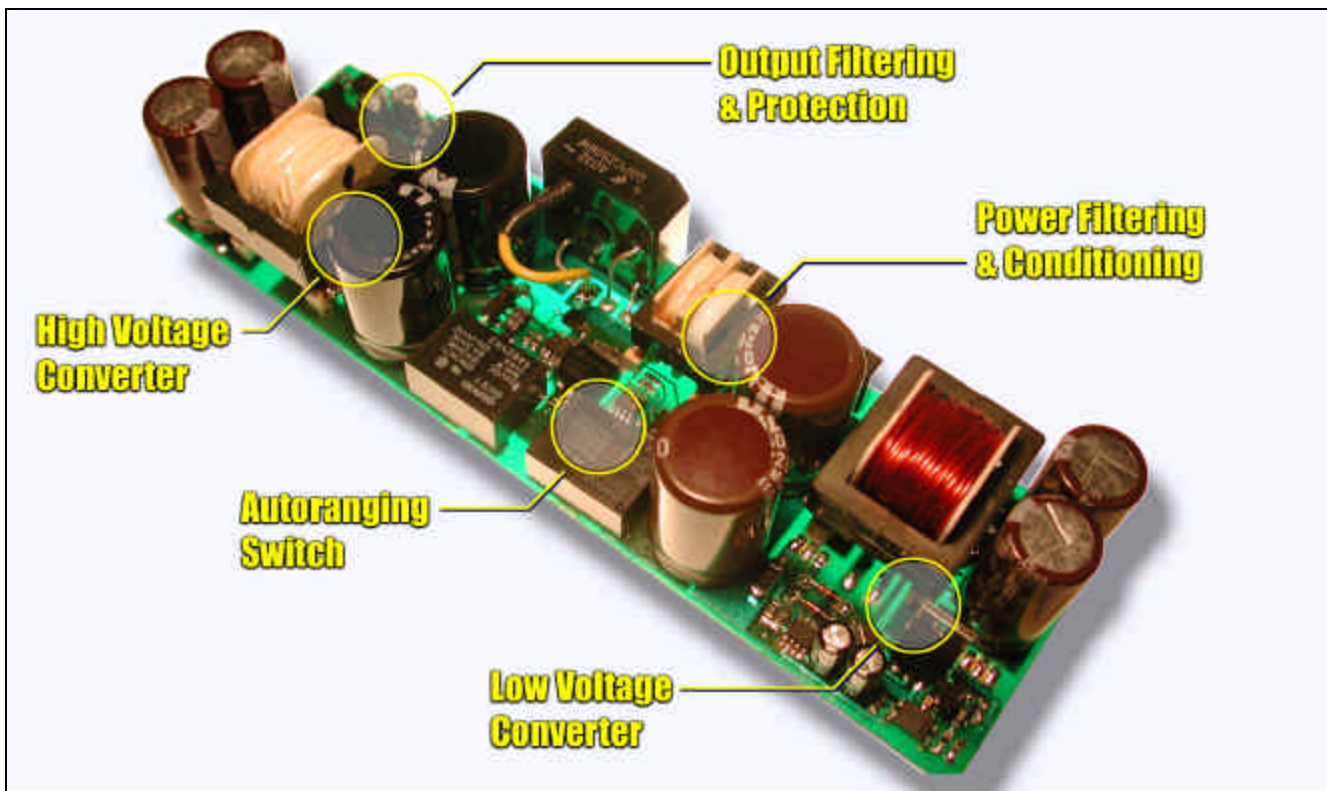


Figure 10-1: Autoranging Power Converter PCB Before Potting

10.1 General Description

Most computerized devices use some kind of power supply to convert the voltage supplied by the power source to a level suitable for running the internal circuitry.

The Intellicharge System required the development a new type of power supply; a power supply capable of operating from 10-300 volts AC or DC with noisy and intermittent power sources.

Measuring only 19.5 x 6 x 4cm and weighing less than 600 grams, the APC is designed specifically for use under the conditions deminers work in

The power conversion circuitry used in the APC is highly efficient, minimizing waste heat generation to keep the System cool. In spite of this, all of the components used in the module are rated for continuous operation at 105°C, allowing it to operate under the most hostile conditions.

The power supply is also auto ranging, so unlike other wide input range chargers, the Intellicharge System only needs one input power connector.

The user can never damage the System by connecting the power source to the wrong input. It is impossible to plug the power source in backwards because the input connector only has two terminals and their polarity does not matter (it is “polarity agnostic”).

The **Autoranging Power Converter (APC)** uses a number of techniques to achieve such a high level of functionality. Heavy input power filtering, oversized filter capacitors, and extremely large input diodes are used to make the System resistant to dirty power.

Two wide range switching power converters and an autoranging circuit (effectively, a switch between the two) are used to give the supply its large working range and high operating efficiency. One of the converters handles the high voltage (HV) range, the other handles the low voltage (LV) range.

This section of the report will provide an overview of the APC. It will detail the main components, and explain their operation. Construction of the prototype and results of testing will also be discussed.

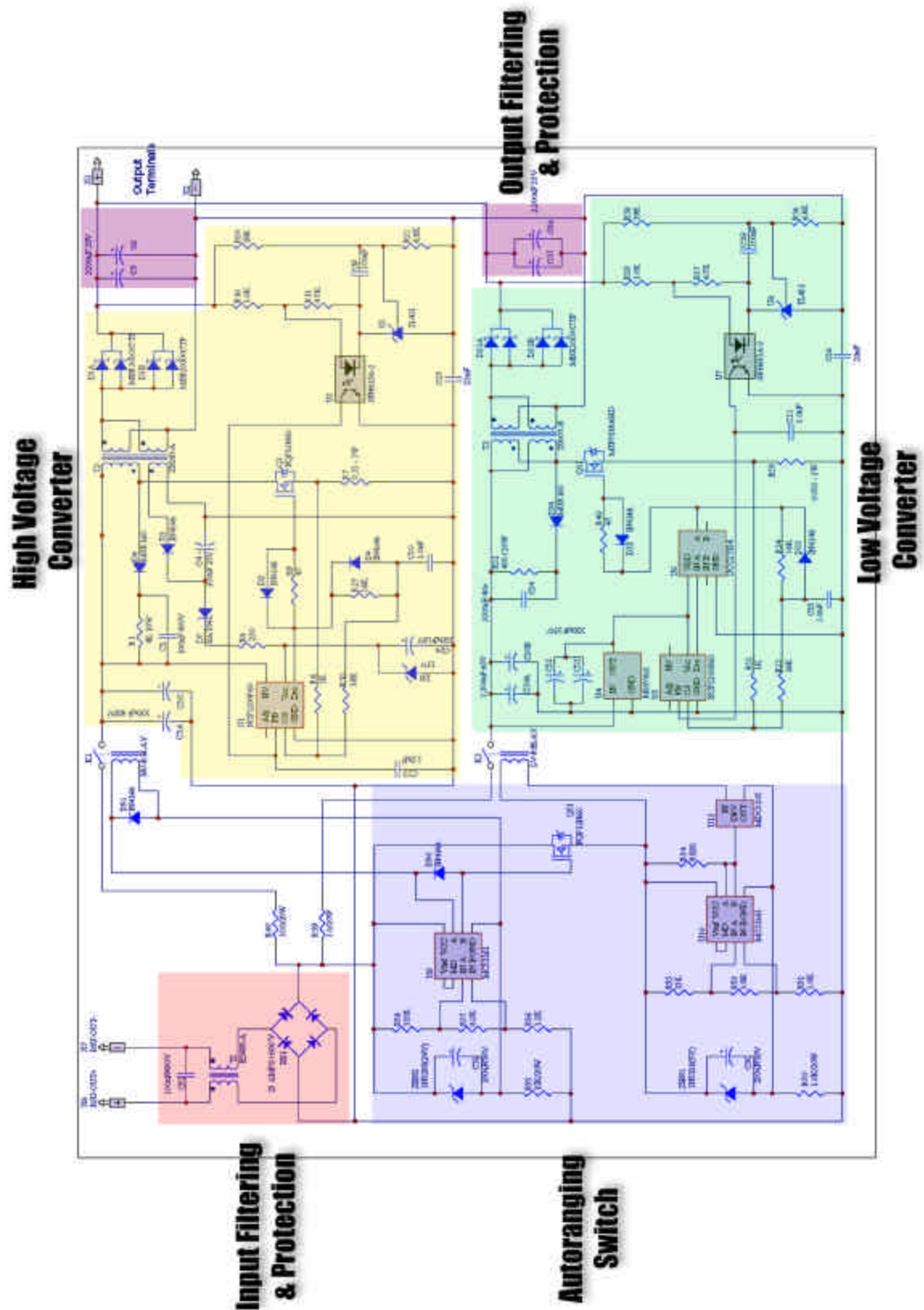


Figure 10-2: Circuit Diagram of APC Divided into Regions

10.2 Power Filtering & Conditioning

Since the APC must run from noisy, intermittent sources of power possibly containing voltage spikes and high frequency (HF) interference, the input power must be heavily filtered before distribution to the rest of the supply.

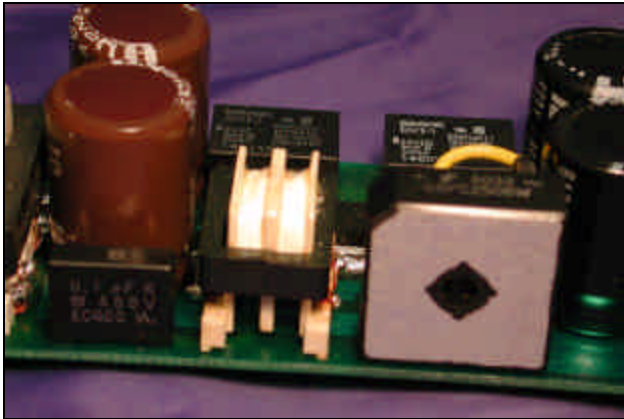


Figure 10-3: Detail of Power Filtering Components

This is a difficult task, because the input voltage can be up to 300 volts and the input current can be up to 6 amps. The filter circuitry must be able to accommodate the peak current as well as the peak voltage, but it must also be as small and inexpensive as possible.

For this application, we chose to use a common mode choke and parallel bypass capacitor to form a low-pass filter. Combined with the bulk capacitors in the input stage of each converter, this provides effective noise filtering at the APC input.

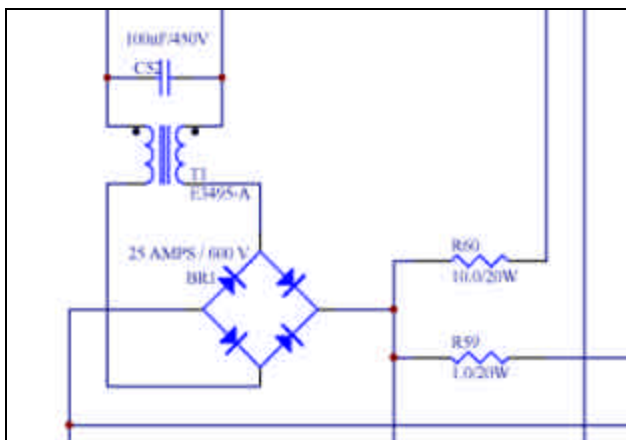


Figure 10-4: Schematic of Power Filtering Components

The schematic in Figure 10-4 shows a common mode choke, T1, that blocks high frequency noise from entering the supply. Efficacy is further

enhanced by the action of capacitor C52 and resistor R1. After initial filtering, the input power is rectified by BR1 and filtered by C1 to give an input suitable for the autoranging switch.

BR1 is an industrial grade bridge rectifier rated for 600 volts at 25 amps continuous load. It can withstand repeated **surge currents of up to 300 amperes**. [125]. A rectifier with such high ratings was required to prevent failures if the supply was run from a pulsed DC source such as an automotive alternator with a faulty rectifier. The high voltage rating is necessary to handle unregulated (speed adjusted manually) AC generators, some of which could drift up to over 400VAC if the load was suddenly removed.

Two power resistors, R1 and R2 (10 ohm-20 watt and 1.0 ohm-20 watt, respectively) are used to limit the rate at which the bulk capacitors in each of the power converters can charge. This limits the inrush current through the bridge rectifier and relays when the supply is first plugged in. With the bulk capacitors in either converter completely discharged and the maximum rated voltage applied to the supply, the peak inrush current will not exceed the ratings of either the bridge rectifier or the relays. This prevents the failure of these components, even under adverse conditions.

In the future, we plan to replace these resistors with “soft-start” devices, to further increase efficiency.

10.3 Autoranging Switch

The autoranging switch takes the output from the power-conditioning block and routes it to the appropriate flyback converter. If the voltage is below

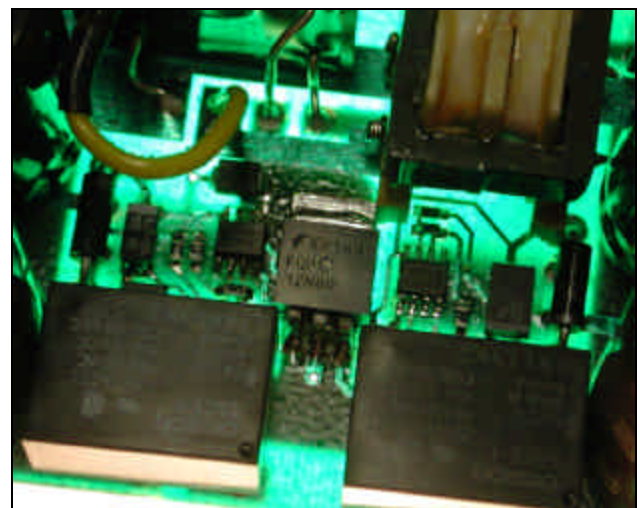


Figure 10-5: Autoranging Switch Components

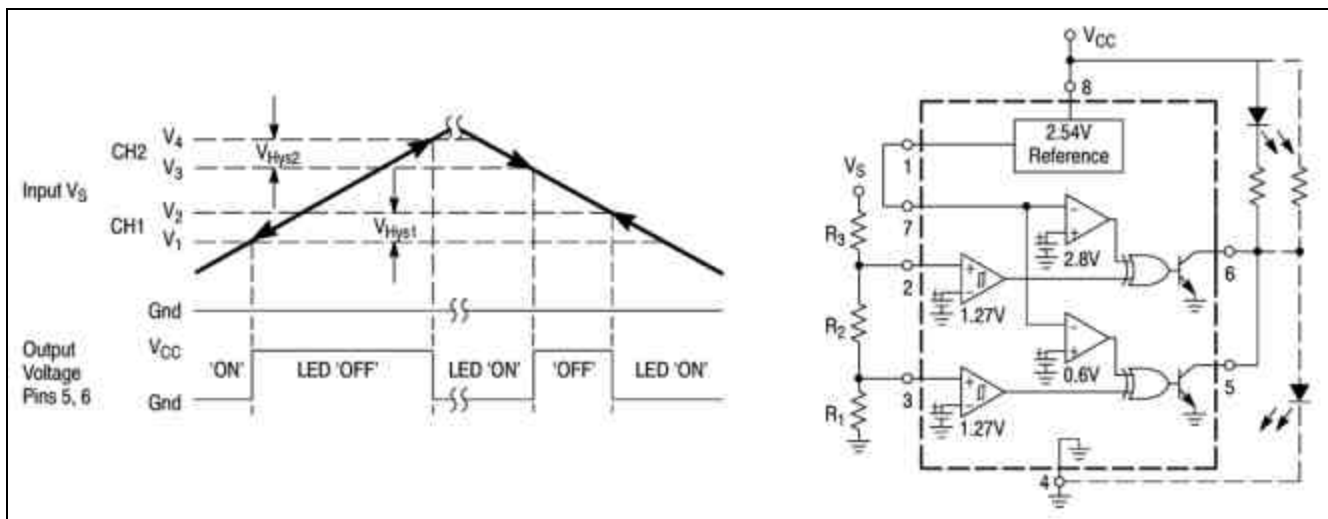


Figure 10-6: MC33161 Internal Configuration and Graph of Typical Voltage Response. [126].

48 volts, it is routed to the low converter, otherwise it is routed to the high converter. The ranges of the

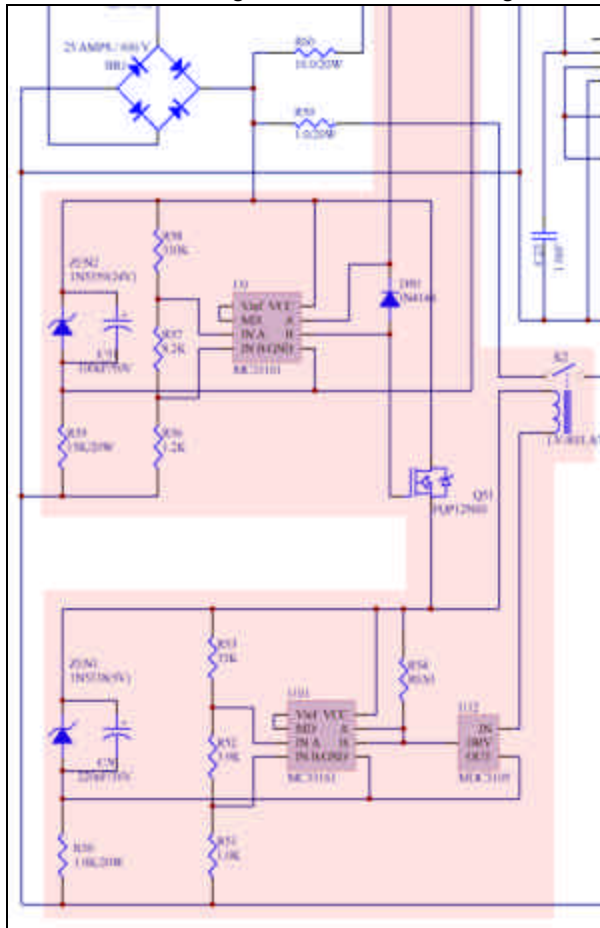


Figure 10-7: Schematic of Autoranging Circuitry

converters overlap by at least 5 volts, giving a good safety margin for the switch. If the input voltage is below 10 volts, the power supplies will be disconnected from the power source. Likewise, if the input voltage exceeds 300 volts, both supplies will be disconnected.

As designed, the autoranging switch should be able to withstand static overvoltage conditions in excess of 500 volts. This is different from the interrupting rating, however. If the HV supply relay is already activated and the input voltage then suddenly jumps to 500 volts, the relay might not be able to disconnect in time to prevent arcing. Note, that by "suddenly," we mean less than half a second, much faster than an unregulated generator could ramp up.

The autoranging switch uses two OnSemi MC33161 universal voltage monitors (U9, U10) to perform the voltage selection function. Each voltage monitor is connected across the power input of the supply using a Zener diode (ZEN1, ZEN2) in series with a resistor (R50, R55), forming a shunt regulator.

The shunt regulator on the top voltage monitor operates at 24 volts, while the shunt regulator on the bottom voltage monitor operates at 5 volts.

When the top voltage monitor detects an input voltage in the range of 300-48 volts, it activates relay K1, applying power to the high voltage converter. If the input voltage drops below 48 volts, the voltage monitor switches on Q51, a 600 volt MOSFET, which applies power to the shunt regulator of the lower voltage monitor. Even with input voltages as

low as 10 volts, the upper shunt regulator can provide sufficient current to run U9 and keep Q51 switched on. [126, 127].

If the lower monitor senses an input voltage between 10 and 48 volts, it activates relay K2, applying power to the low voltage converter. If the voltage is below 10 volts, relay K2 will not be activated, leaving the APC in standby mode.

Because the top voltage monitor “locks-out” the bottom one, it is not possible for both flyback converters to be activated at the same time.

More likely than not, someone will eventually connect the APC to a power source that sits right at the changeover voltage of the autoranging switch. The power source will probably be dirty or intermittent, causing its output voltage to fluctuate. This situation could cause some types of autoranging switches to repeatedly switch between the high voltage and low voltage supplies, damaging the relays.

Our design has several features to prevent this from happening.

First, the shunt regulator on each voltage monitor has a large filter capacitor across the Zener diode, sufficient to power both the monitor and the relay it drives for several seconds. This prevents false activation when run on intermittent power.

Second, each of the voltage monitors has built in hysteresis. If the voltage shifts out of the range of one of the converters, it usually has to stay there for several seconds before the voltage monitor will trigger. However, this is a voltage proportional delay. If the input power jumps from 40 to 300 volts, the switch will trigger almost instantaneously.

To increase the life of the autoranging switch, a bypass diode has been placed across the coil of each of the relays. This prevents the back-EMF generated by the relay coil from stressing the switching transistor in the voltage monitor when the relay is switched off.

10.4 Low Voltage Converter

The low voltage power converter (shown in Figure 10-8), consists of a flyback converter **specifically optimized to run from solar panels** but versatile enough to run from many other power sources, such as vehicle power systems and battery banks.

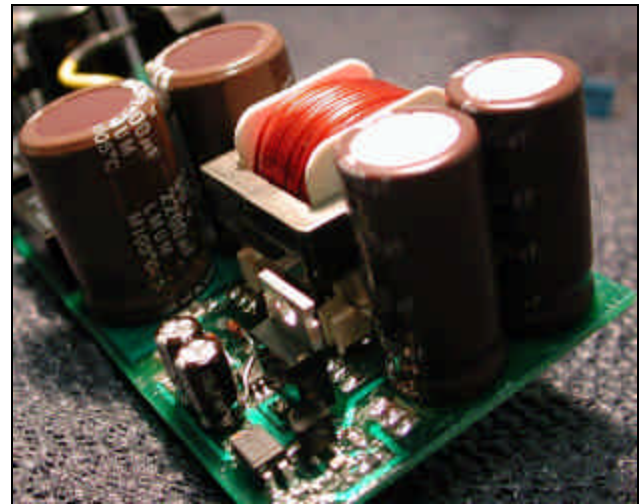


Figure 10-8: Detail of Low Voltage Converter

All of the components within the converter have been selected for maximum efficiency, reducing the size of the solar array needed to charge a given number of batteries.

10.4.1 BULK CAPACITORS

By their nature of operation, switching power supplies draw their input power in pulses. The bulk capacitors function as an energy reservoir, storing input power and releasing it on demand to the supply.

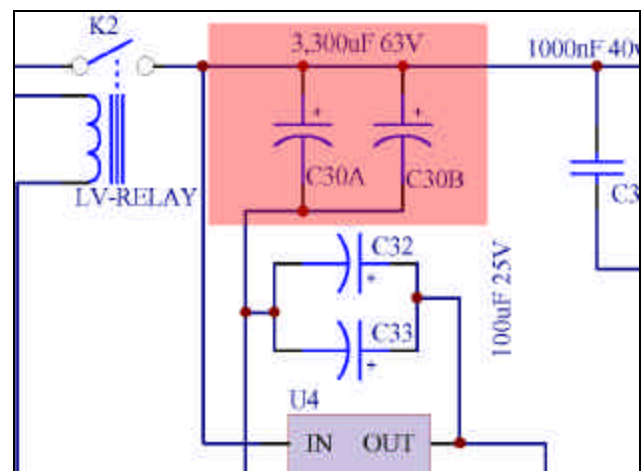


Figure 10-9: Bulk Capacitors in the Low Voltage Converter

For this application, we chose Illinois Capacitor 338LMU063M2DC 3,300 μ F 63V 105C Snap-in capacitors. [128].

These parts were selected for their small size, low **Effective Series Resistance (ESR)** and high temperature rating. We chose to use two 3,300 μ F capacitors. These are roughly double the size normally used in comparable designs. The larger capacitor size allows the converter to better cope with variable and intermittent power. We used two parts instead of one large capacitor to maximize the surge current of the bank, and to allow the capacitors to fit in the space available.

These capacitors are rated for use at 105 C with a 2000 hour **Mean Time Before Failure (MTBF)**. If we keep the operating temperature below 75°C, the life increases to over 20,000 hours. By using a capacitor with a high temperature rating, even though the supply runs at a lower temperature, we can greatly extend the MTBF of the supply. [129].

10.4.2 INTERNAL REGULATOR

The internal regulator is used to convert the input voltage of the supply to the 12-volt operating voltage of the **Pulse Width Modulation (PWM)** controller and MOSFET driver.

For this application, we selected an OnSemi MC7812BT fixed voltage regulator. [130]. This device is a linear regulator and operates over a wide voltage range. In general, linear regulators are quite inefficient, but since the control circuitry draws only a small amount of power, power usage and waste heat generation are kept under control. During testing, it didn't even require a heat sink.

Looking at the schematic, there are two large electrolytic capacitors connected across the output of the regulator. On the actual circuit board, these capacitors are located directly beside the PWM controller and the MOSFET driver, and connected across their power inputs. The capacitors provide the power pulses needed by these devices during switching of the MOSFET.

10.4.3 PWM CONTROLLER

The PWM controller controls the switching action of the MOSFET. It generates variable duty cycle pulses based on the voltages present on its FB and CS pins. By varying the duty cycle of the pulses, it is possible to control the output voltage of the power supply.

We chose an OnSemi NCP1200 as the PWM controller for our supply. The NCP1200 uses a standard current mode architecture where the switch-off time is dictated by the peak current setpoint. It contains many of the support components typically needed in a switching supply, including timing components, feedback devices, and a low pass filter. This significantly reduces the size and complexity of the control circuitry within the supply, lowering costs while increasing reliability.

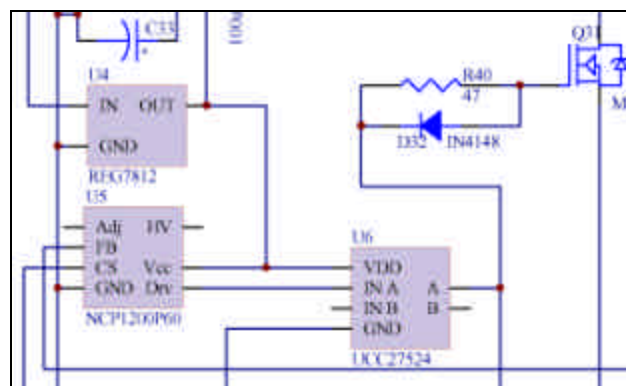


Figure 10-10: Schematic of PWM Controller.

The NCP1200 also implements pulse skipping when the supply is lightly loaded, which reduces standby power draw. It also incorporates electronic short-circuit protection.

If the output of the supply is shorted, the controller will sense it and shut off the output. This eliminates the need for *user replaceable* fuses in the output of the supply. [131]. (A non-replaceable "catastrophic-failure" fuse is still required to meet UL regulations).

All of the above features make the NCP1200 a very desirable part for our application.

10.4.4 MOSFET AND DRIVER

Because the LV Converter must be able to operate from power inputs as low as 10 volts, the MOSFET controlling the flow of current to the primary of the transformer must be able to handle large amounts of current. Technically speaking, this means that the MOSFET must have a large junction size and will have a correspondingly large gate capacitance.

On the other hand, the power supply must also be able to operate from input voltages as high as 48 volts. At this voltage, the MOSFET has to be switched very rapidly in order to produce pulses short enough to control the output voltage.

Switching a large MOSFET at a high rate of speed requires short pulses of a very high current, about 3.5 amps in our case. During initial testing, we found this is far more than the PWM controller is capable of supplying.

The MOSFET driver takes the low current drive signal from the PWM controller and boosts it so that the MOSFET can operate at the required speed. Without the MOSFET driver, the MOSFET would never fully be switched on or off if the supply was operating with a high input voltage. That is, the MOSFET would operate in **linear mode**. This would cause the MOSFET to dissipate a tremendous amount of heat, shortening its lifespan and greatly reducing power supply efficiency.

For this application, we selected a Texas Instruments UCC27324 4-AMP Dual Non-inverting high speed MOSFET driver. This component supplies adequate drive power for the MOSFET. [132]

10.4.5 FLYBACK TRANSFORMER

The flyback transformer (pictured in Figure 10-11) is one of the most critical components in the power supply. Its electromagnetic properties determine or affect almost every supply characteristic.



Figure 10-11: Winding the LV Flyback By Hand

For the LV supply, we used the same core and bobbin as a stock Coilcraft Z9007-B Flyback. [133]. This greatly simplifies matters should we decide to have Coilcraft wind a batch of our transformers for a production run of chargers.

This size of core kept size and cost under control while allowing sufficient room for our windings. The transformer we designed has 4 primaries in parallel using 20-gauge wire, and 4 secondaries in parallel also using 20 gauge wire. The turns ratio is 1:1.3. The primary inductance is about 60 μ H.

We had to use parallel windings because of the operating frequency of the transformer. The supply has a switching frequency of 60kHz. At frequencies this high, a phenomenon called the “skin effect” begins to affect electrical conductors. Basically, the current switches so quickly that the electrons never have time “soak” all the way into the conductor. If thick wire had been used for the windings, only a narrow band around the outside would ever see current flow. Twenty-gauge wire is the thickest we can use and still have full wire utilization. [135, 136].

Between the primaries and secondaries of the transformer, there are 5 layers of Mylar tape. This provides about 2,500 volts of isolation between the windings.

10.4.6 OUTPUT RECTIFICATION & FILTERING

The output of the flyback transformer is rectified by D31A and D31B, and then filtered by C37 and C38. All of these components have been selected for their high efficiency and high reliability.

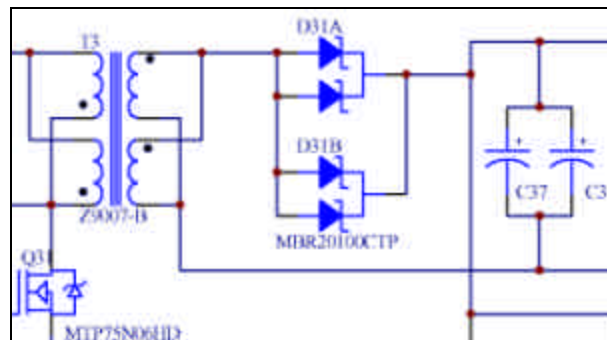


Figure 10-12: LV Converter Output Diode and Caps

Parallel OnSemi MBR20100CTP Schottky diodes are used to reduce heat generation. [136]. The capacitors are Illinois Capacitor 228RZM035M low ESR 105°C high ripple parts, and are placed in parallel to further increase their ripple current capacity. [137]. As with the bulk capacitors on the supply input, we are using high temperature rating parts at lower temperatures to increase the MTBF of the supply.

10.4.7 OUTPUT VOLTAGE REGULATOR

The components in the output regulator monitor the output of the supply and adjust it to ensure that it is within a safe range.

The most important part of this module is U8, which functions as a programmable Zener diode. Using resistors R36 and R38, we can program U8 to break down (start conducting) at almost any voltage we

want. [138]. In our design, we have it set for 12.6 volts.

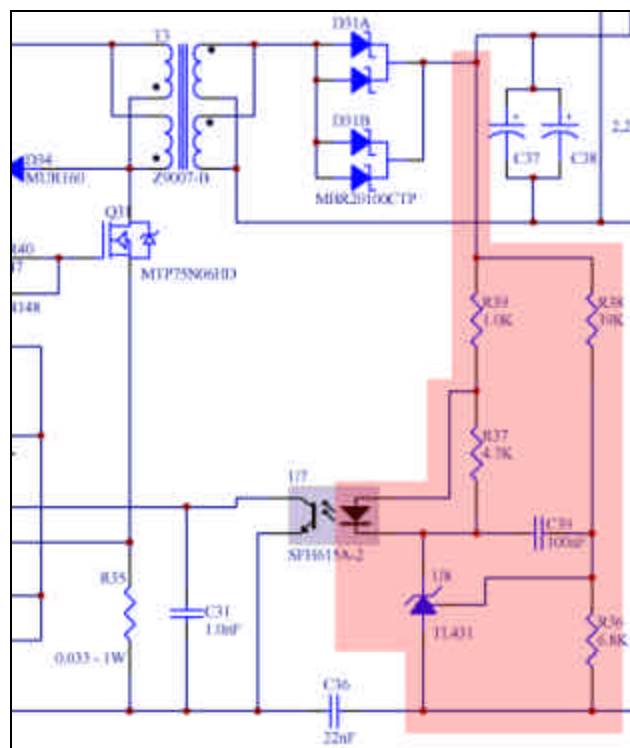


Figure 10-13: Schematic of Output Voltage Regulator

When the output voltage of the power supply exceeds 12.6 volts, U8 breaks down and starts to conduct. This switches on the optoisolator, signaling the PWM controller to reduce the output voltage of the supply.

To avoid burning out the optoisolator, R37 and R39 form a voltage divider that steps down the output voltage of the power supply to a level the optoisolator can use. For our application, this is about 3 volts. Capacitor C39 is used to stabilize the voltage regulator, preventing it from oscillating.

10.4.8 OPTOISOLATOR

The optoisolator is responsible for transmitting control signals from the voltage regulator block to the PWM controller while keeping the circuits electrically isolated from one another.

Inside the optoisolator are a LED light source and a light sensitive phototransistor. When power is applied to the LED, it illuminates the phototransistor, switching it on. This makes it possible for a signal to be sent from one circuit to another without any electrical connection between them. In our case, the optoisolator provides almost 5,000 volts of isolation. [139].

Since the primary and secondary windings of the flyback transformer are also isolated, there is no electrical connection between the input and output sides of the power supply.

The electrical isolation of the input and output is legally required. It prevents an electrical shock from the output of the APC even if it is connected to a high voltage input and even if the control circuitry inside the supply has failed. A non-isolated supply would not comply with international electrical regulations.

10.4.9 CURRENT FEEDBACK & CONDITIONING

The PWM controller in our supply uses a current sense resistor in series with the MOSFET and flyback transformer primary. When the MOSFET first switches on, the waveform present across the current sense resistor contains a voltage spike. The voltage spike can falsely trigger the current comparator in the PWM controller, causing it to switch off prematurely.

To avoid this problem, the PWM controller ignores the first 250ns of input from the current sense resistor during each switching cycle (measured from when the controller first sends the signal to switch on the MOSFET). This technique is called **Leading Edge Blanking**, or, LEB. [140].

Even with the use of a high current MOSFET driver, there is still a considerable delay between when the PWM controller sends a signal to switch on the MOSFET and when the MOSFET actually gets switched on. This delay uses up the entire LEB interval, allowing the PWM controller to get hit with the voltage spike. This usually causes the system to go metastable, crippling the converter.

We solved this problem by adding an RC network between the current sense resistor and the PWM controller. Together, these components integrate the current sense signal, absorbing the voltage spike and preventing false triggering of the current comparator. This modification allows the supply to function efficiently and reliably, even with a highly variable input voltage.

10.4.10 PRIMARY FEEDBACK CLAMP

When the MOSFET switches off at the end of a cycle, the magnetic field inside the flyback transformer collapses, transferring the stored energy to the transformer secondaries. During this process, the rapidly changing magnetic field also creates a high voltage pulse across the transformer primary.

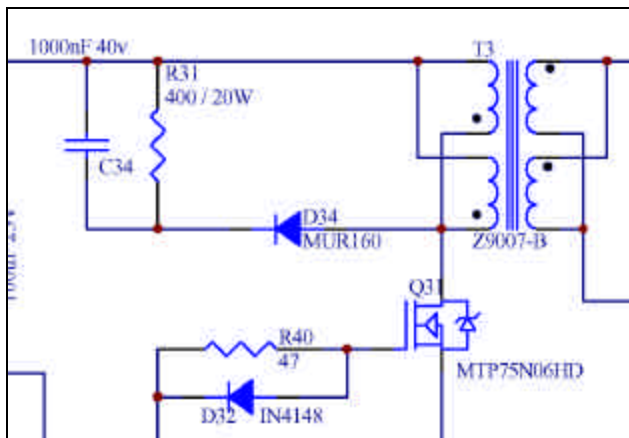


Figure 10-14: LV Converter Primary Clamp.

To prevent damage to the MOSFET, D34 and C34 are used to catch the high voltage pulse and dissipate it through resistor R31. This keeps the reverse voltage placed across the MOSFET at a safe level.

Even though the MOSFET contains a clamping diode to absorb reverse voltage pulses, it is not sufficient to do so on a repeated basis within the context of our design. The added primary feedback clamp circuitry increases the lifespan of the MOSFET while only slightly reducing overall efficiency.

10.5 High Voltage Power Converter

10.5.1 USE OF REFERENCE DESIGN

The high voltage converter used in our prototype APC was modeled after a reference design described in OnSemi application note “AND8076/D”. [141].

This design required extensive modifications before it could be used in our application. It did not come with a PCB layout and was not designed for our voltage range.



Figure 10-15: Detail of High Voltage Converter

10.5.2 BULK CAPACITORS

The HV Power Converter uses two Illinois Capacitor 220μF 450V 105°C capacitors as its bulk capacitor bank. [142]. As with the LV supply, these parts were chosen specifically for their small size, low ESR and high temperature rating.

By using a capacitor with a high temperature rating, even though the supply runs at a much lower temperature, we can greatly extend the MTBF of the supply.

10.5.3 AUXILIARY REGULATOR

Because of the 48-360 volt input range, the HV Converter uses an auxiliary winding on the flyback transformer to power the PWM controller instead of a linear regulator. While the NCP1200 PWM controller has a built-in regulator that can function from 90-300 volts, it is not sufficient for the lower portion of the input voltage range (48-90V), and cannot supply enough current to efficiently drive the MOSFET that we have chosen. [131, 140].

Because the power coming from the auxiliary winding is AC at 60kHz, we have to use a two-stage process to rectify and regulate it before delivery to the control circuitry. See Figure 10-16.

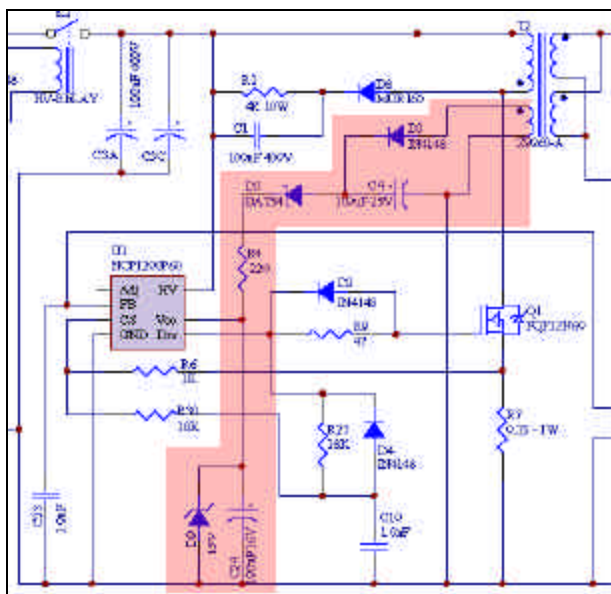


Figure 10-16: HV Converter Aux Winding PSU

First, power from the winding is rectified using a high-speed diode, D7, and stored in a low ESR aluminum-polymer capacitor, C4. This provides a DC supply, but no voltage regulation.

The output from this section of the board is routed to D9 and R4, which act as a shunt regulator. C24 is connected in parallel with D9 to stabilize the output. Together, these components allow a stable, voltage regulated supply to be drawn from the auxiliary winding.

Since the power supply for the controller comes from a winding on the flyback transformer, startup of the supply when power is first applied can be problematic. The NCP1200 has built in circuitry to deal with this.

When the NCP1200 first switches on, it enters a state called “hiccup mode” where it draws current from its HV input line and uses it to switch on the MOSFET. Using the MOSFET, the controller applies short pulses of power to the flyback transformer primary, generating voltage pulses across the transformer’s auxiliary winding. After several pulses C4 and C24 charge to working voltage. At this point, the PWM controller exits hiccup mode and commences normal operation. [131].

10.5.4 PWM CONTROLLER

As with the LV converter, the HV converter uses an OnSemi NCP1200 as the PWM controller for the supply.

10.5.5 MOSFET

We have chosen to oversize the MOSFET both in terms of voltage and current rating to increase the efficiency and reliability of the supply, and to give it the required input range.

Because the MOSFET used in the HV converter has to handle ten times less current than the converter, its gate capacitance is much lower, allowing it to be driven directly by the PWM controller.

There are many MOSFETS available that will meet the requirements of this supply. We chose a Fairchild Semiconductor FQP12N60 because of its low cost. [143].

10.5.6 FLYBACK TRANSFORMER

For the HV converter, we selected a Coilcraft core and bobbin identical to that used in the LV converter.

The transformer we designed has 1 primary wound using 22-gauge wire, an auxiliary winding wound with 24-gauge wire, and 4 secondaries in parallel using 20 gauge wire. The turns ratio is 1:0.322. The primary inductance is about 350µH.

This construction is similar to the transformer used in the OnSemi reference design, but it uses thicker wire for the primary. The air gap in the transformer core has been adjusted to lower the inductance. As with the LV power converter we had to use parallel windings in the secondary because of the operating frequency of the transformer.

Between the primary and secondaries of the transformer, there are 5 layers of Mylar tape. This provides about 2,500 volts of isolation between the windings.

10.5.7 OUTPUT RECTIFICATION & FILTERING

The HV converter uses the same rectification circuitry as the LV converter. The only difference is that the Schottky diodes are rated for 200 volts instead of 100 volts. [136].

As with the LV converter, two parts (4 diodes total) are used in parallel to reduce heat generation. The capacitors are double sized to handle power fluctuations and have a 105 C temperature rating, to increase the MTBF of the supply.

10.5.8 OUTPUT VOLTAGE REGULATOR

The output voltage regulation circuitry is identical to that used in the LV converter.

10.5.9 OPTOISOLATOR

The optoisolator in the HV converter is the same component as used in the LV converter.

10.5.10 CURRENT FEEDBACK & CONDITIONING

The PWM controller used in the HV converter supply requires the same feedback conditioning circuitry as used in the LV converter, but for a different reason.

Since the gate capacitance of the MOSFET used in this supply is actually quite small, the PWM controller can switch the MOSFET from “off” to “on” very quickly. Because the input voltage to the supply can be very high (360 VDC) and the inductance of the flyback transformer has to be very low (350μH so it can function at 48 volts) the PWM controller can generate massive current pulses in the transformer primary. Operating this way, the supply could generate large amounts of electromagnetic radiation that might interfere with radios, computers, and other electronics near the charger. [131, 140, 141].

To prevent this from happening, R9 is used to limit the current flow into the MOSFET, slowing its transition time. D2 is used to allow the MOSFET to still switch off quickly, minimizing heat dissipation.

Because R9 increases the time it takes for the MOSFET to switch on, it once again causes the waveform across the current sense resistor, R7, to exceed the **Leading Edge Blanking (LEB)** interval of the PWM controller.

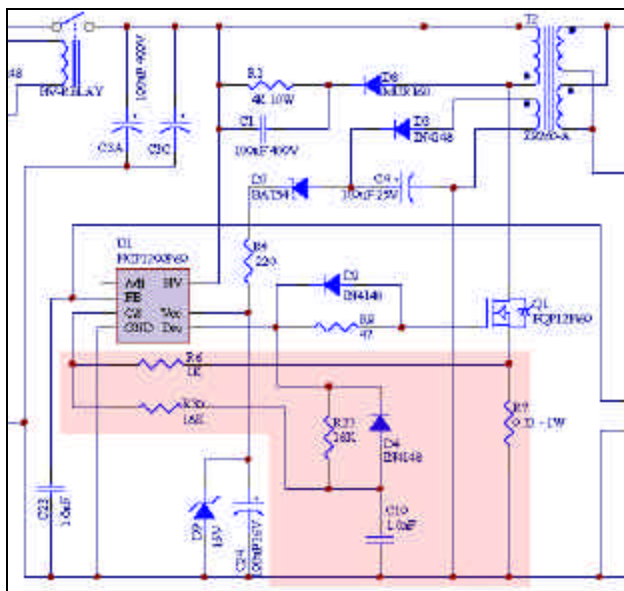


Figure 10-17 HV Converter RC Network

This will cause the problems previously described for the Low Voltage Converter. In addition, it would probably cause the power supply to go metastable.

As in the Low Voltage Converter, the problem was solved by adding a diode-bypassed RC network between the current sense resistor and the PWM controller. This removes the voltage spike during switch-on of the MOSFET.

10.5.11 PRIMARY FEEDBACK CLAMP

As with the LV converter, the HV converter requires a clamping network on the flyback transformer primary. This network is used to prevent the high voltage flyback pulse across the primary of the transformer from causing damage to the MOSFET. Diode D8, resistor R1, and capacitor C1 are used to catch the high voltage pulse and dissipate it through the resistor. This keeps the reverse voltage placed across the MOSFET to a safe level.

Even though the MOSFET contains a clamping diode to absorb reverse voltage pulses, it is not sufficient to do so on a repeated basis within the context of our design. The added primary feedback clamp circuitry increases the lifespan of the MOSFET while only slightly reducing overall efficiency.

10.6 Output Filtering & Protection

As designed, the output of the APC is fairly resistant to damage by external loads. By the design of the PWM controller circuitry, the output is already current limited. If it is short circuited, the supply will simply switch off its output until the fault is corrected.

Because of the large filter capacitors across the supply output, the circuitry is highly resistant to electrostatic discharge, and will tolerate an external power source connected across the output of up to 35 volts without damaging the supply.

10.6.1 REVERSE POWERING

One of the few conditions the APC is not resistant to is having an external power source, such as a car battery, connected backwards across the output of the supply while it is switched off. Doing this would destroy the filter capacitors and Schottky diodes in the output section of the power supply. When the APC is being used in the Intellicharge System, this situation should never arise because the user cannot connect external loads to the APC while it is installed in the charger.

If a more versatile and durable APC is desired for other applications, additional circuitry may be added to the APC to prevent this problem. The easiest way to resolve it would be to place a relay in series with the output of the supply. When the APC is switched

off, the relay would disconnect it from the output terminals, preventing the supply from being reverse-powered while it is switched off.

10.6.2 ADDITIONAL FILTERING

At present, filtering on the output of the APC consists of the filter capacitors in the output section of each supply. This should prove adequate for powering the Cell Chargers, but switching noise in the output of the supply could cause interference with surrounding electrical equipment. If this happens, it may be necessary to add an inductor to the supply output to attenuate the interference.

10.7 APC Status LED Lights

An APC user interface will be added to future versions of the Intellicharge System design. It will consist of just two “Status LED’s” mounted near the input connector for the supply.

A LED in series with a current limiting resistor will be connected across the output of the Internal Regulator in the Low Voltage Converter, and across the auxiliary winding shunt regulator in the High Voltage Converter. During normal operation, the LED corresponding to the converter that is in operation will light up. If the input is over/under voltage, neither of the LED’s will light up. If the output of the supply is short-circuited, the LED corresponding to the converter that is in operation will pulse at a rate of roughly 3Hz.

11 Electrical Design – Cell Charger

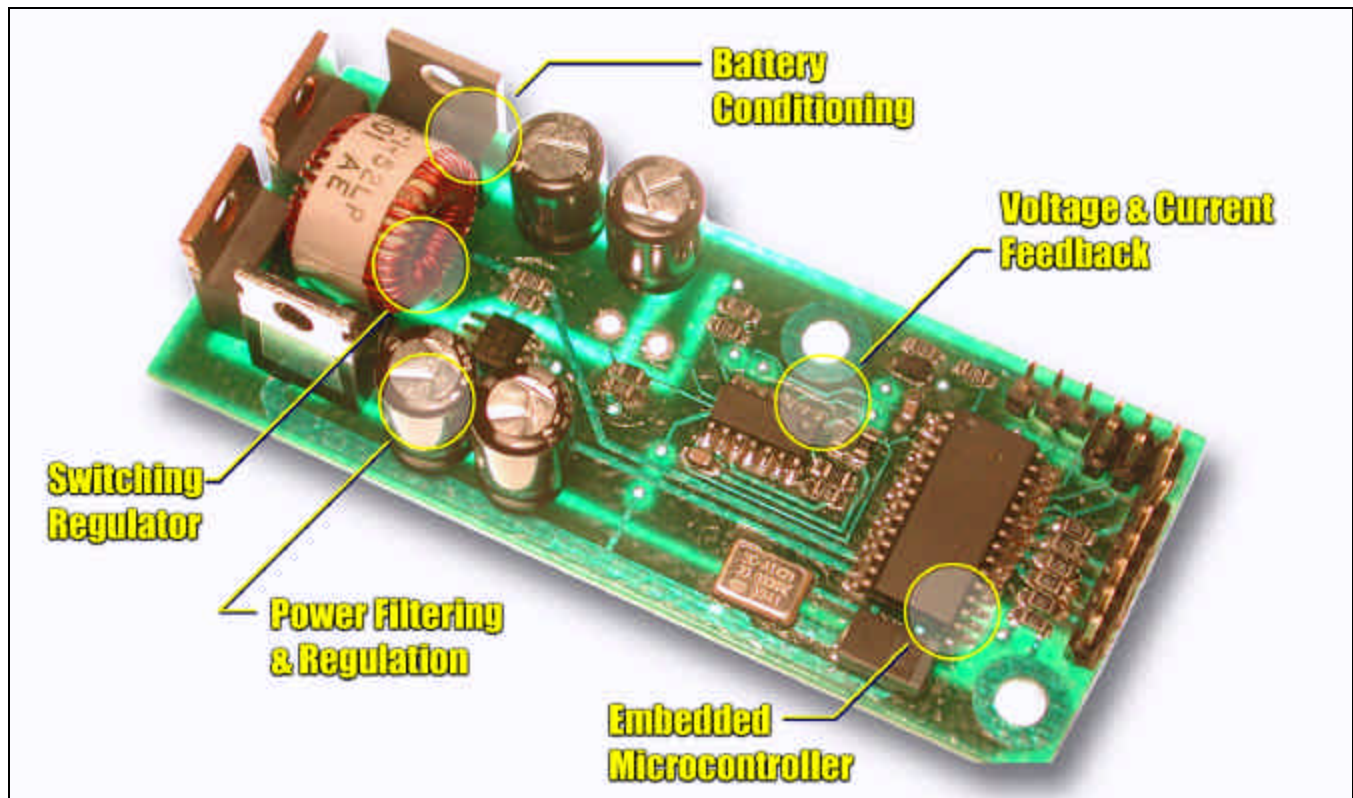


Figure 11-1: Main Components of the Cell Charger

11.1 General Description

Unlike most battery chargers, which charge their batteries in series and at the same time, the Intellicharge System uses eight independent battery chargers to service each battery individually.

This approach offers a number of benefits, including the ability to charge odd numbers of batteries, insert them at random and remove them as required. Furthermore, all of this can be done without disrupting the other batteries in the System.

It also lets the System identify non-rechargeable batteries inserted into the charger, and to identify damaged, open, or shorted rechargeables.

While small in size, the Cell Charger is powerful and efficient, designed to charge batteries at 4,000mA, with an output of up to 8,000mA at reduced efficiency.

The Cell Chargers use both NDV and DT methods to end the charge cycle, and include a top-up charge phase as well as post-charging trickle mode to

ensure every battery leaves the charger in top condition.

Every Cell Charger also includes conditioning circuitry for exercising NiCd batteries. This process can be initiated manually, or it can be done automatically on randomly selected batteries. Since the process is computer controlled, discharging can take as little as 60 minutes, without compromising battery life.

Each Cell Charger contains seven main electronic blocks:

- Input Power Filtering and Regulation
- The CPU (Embedded Microcontroller)
- The Switching Regulator
- Voltage and Current Feedback
- Thermal Monitoring
- Battery Conditioning
- ICSPi Interface

These blocks will now be discussed in detail.

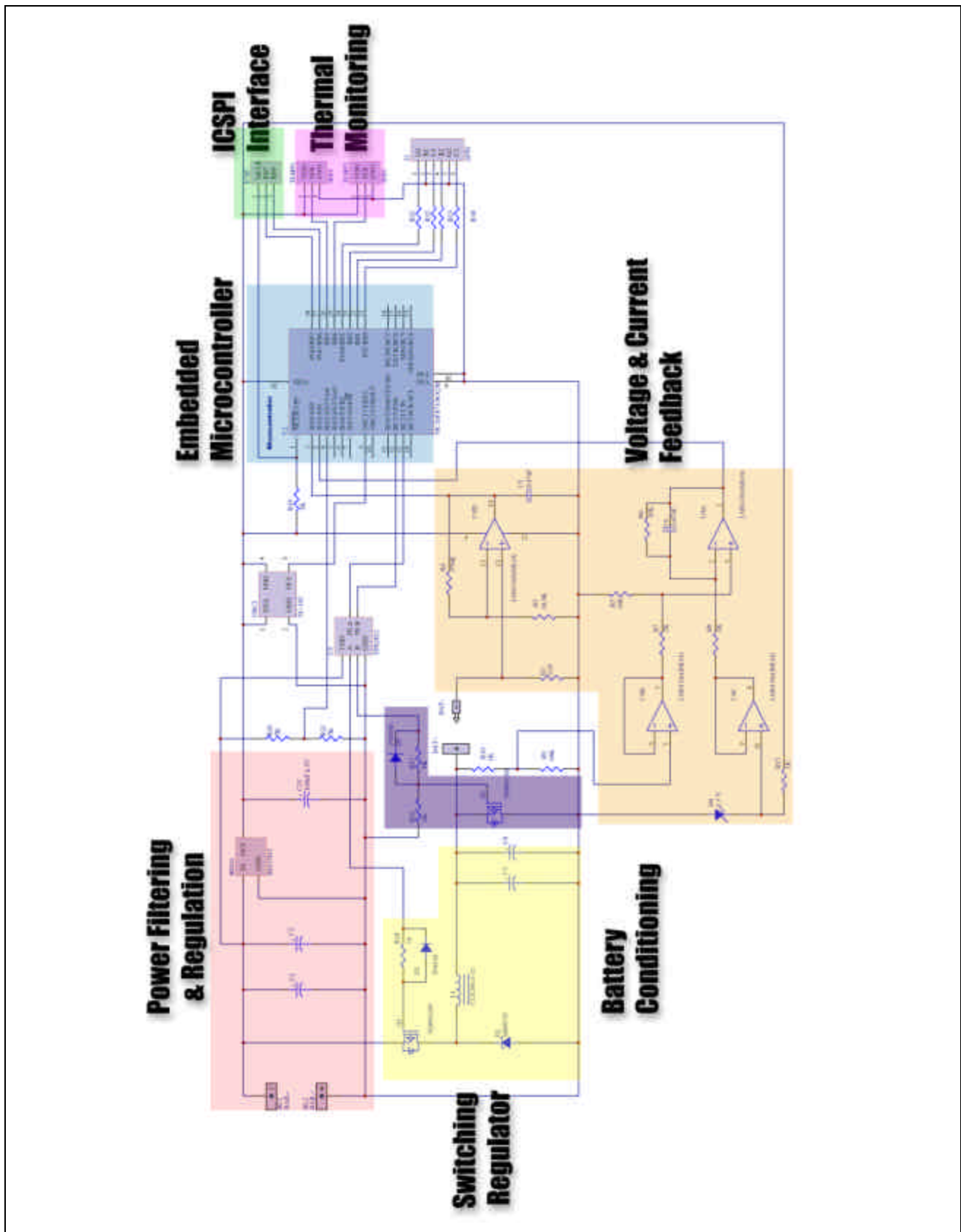


Figure 11-2: Cell Charger Circuit Diagram Divided into Regions

11.2 Input Power Filtering & Regulation

The Cell Chargers are designed to operate from a 12-18 volt power source, even though the CPU runs at 5 volts and the battery is charged at 1.2-1.5 volts.

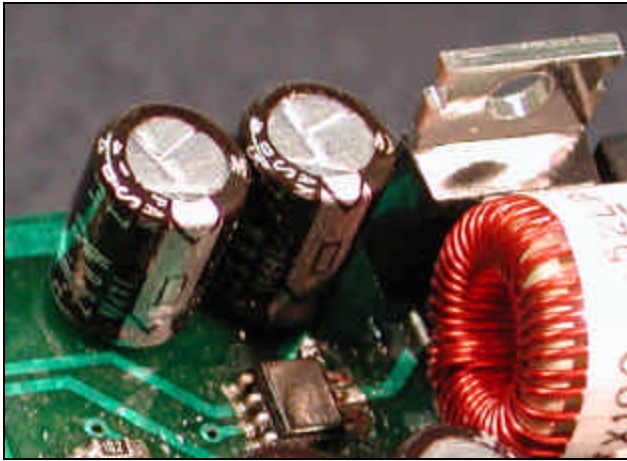


Figure 11-3: Input Filter and Regulator Components

Due to the current rating of the spring contacts and the resistance of the power rails, it is not practical to distribute a lower voltage to the Cell Chargers. The 12 to 18 volt range also makes it possible to run the Cell Chargers directly from a solar panel if one wanted to build a low cost charger without the APC.

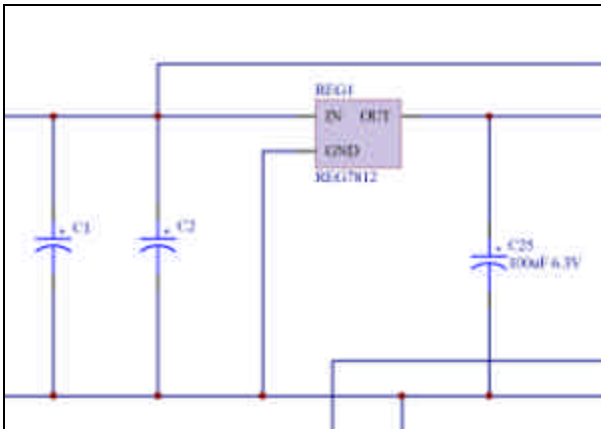


Figure 11-4: Schematic of Regulator Components

Input power to the Cell Charger, taken directly from the power supply rails, is filtered by electrolytic capacitors C1 and C2, and then fed into regulator REG1 to generate the 5 volt supply for the CPU, clock module, and Op-Amps. REG1 is a linear regulator and as such has poor efficiency. Since the CPU, clock module and op-amps only draw about 100mW of power, power usage and waste heat generation are not a concern. [130].

Looking at the schematic, we can see that C25 is connected across the output of the regulator. On the circuit board, this component is located directly beside the CPU, and provides the necessary peak current pulses to stabilize the voltage across the CPU.

11.3 Embedded Microcontroller

All of the functions of the Cell Charger are controlled by the CPU. For this design, we have selected a Microchip PIC16F83 microcontroller. [144].

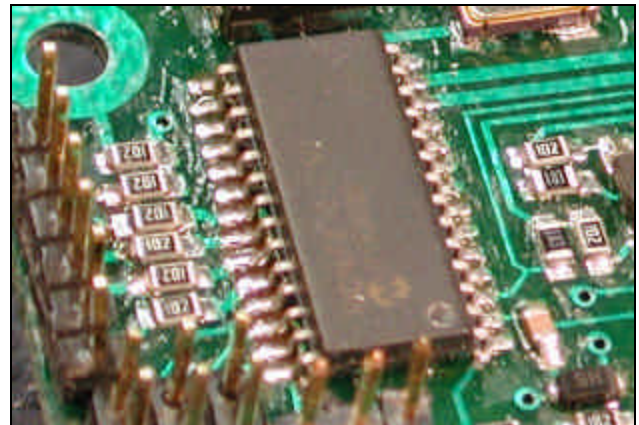


Figure 11-5: Detail of Embedded Microcontroller.

There are several key advantages to using the Microchip PIC16F83 microcontroller:

- The device is relatively inexpensive.
- The program code is stored in flash memory, which can be updated electronically and programmed after the device has been soldered to a circuit board.
- The device has an on-board PWM module, which can be used to drive a switching power supply.
- The device has five built-in analog-to-digital converters.
- The device has high current output lines, which can directly drive LED's.
- The device runs at 20MHz, which is necessary for realtime control of a switching regulator.
- The device has built-in power-on and watchdog timers, allowing it to automatically reset in case of a program error or power interruption.

As configured within our circuit, the output of the PWM module is used to control the switching regulator that charges the battery. Three of the ADC lines are used: one to monitor the current through

the battery, one to measure the voltage across the battery, and one to monitor the input voltage to the Cell Charger. Four of the output lines are used to drive the Bi-color LED's that inform the user of the status of the battery.

Details of the firmware that runs on the CPU are discussed in Section 12 of the report.

11.4 The Switching Regulator

The Cell Chargers use a buck-mode switching regulator to reduce the input to the Cell Charger to the 1.2-1.5 volt output needed to charge the battery.

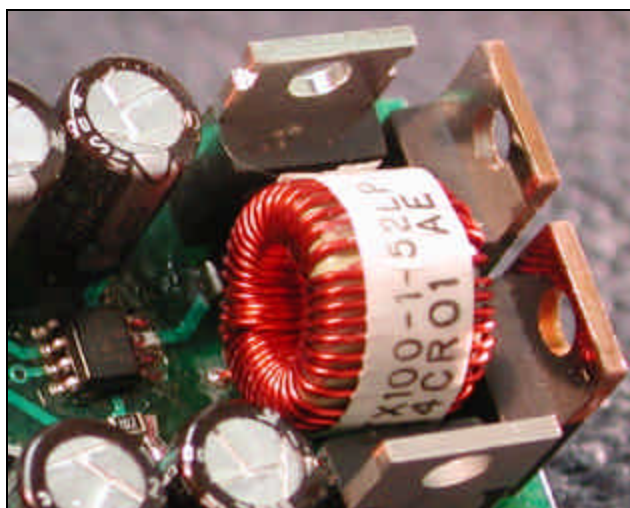


Figure 11-6: Switching Regulator (3 Amp Version)

The buck regulator consists of a power MOSFET, Q1; a toroidal inductor, L1; and a Schottky diode, D1. The output of the regulator is filtered by capacitors C3 and C4 before it is applied to the battery.

In our System, the switching regulator is driven by the PWM output of the CPU. Current flow through the battery is monitored using current sense resistor R2. The signal across R2 is fed into the charge current scaling Op-Amp U4-D and then sent to ADC port 0 on the CPU. Using this feedback voltage, the CPU can accurately control current flow through the battery. Based on the feedback signal at ADC port 0, the operating system sets the duty cycle of the PWM module.

11.4.1 MOSFET AND DRIVER

Because the switching regulator must be able to handle an output current of up to 8 amps with an output voltage of only 1.4 volts, the MOSFET controlling the flow of current in the switching regulator must have an extremely low “on” resistance. This translates to a large, high current, low voltage MOSFET. After considerable experimentation, we decided to use the same MOSFET as used in the LV power supply of the APC.

The PWM output from the CPU is not designed to directly drive power MOSFETS. The signal must first be amplified by a MOSFET driver. Since the CCM switching regulator only operates at 20kHz, the MOSFET does not have to switch as quickly as the LV Converter, and a much smaller MOSFET driver can be used. For this application, we chose a Texas Instruments TPS2812 high-speed 2-amp driver. [145]. This part is able to handle the necessary drive current, while reducing the total production cost of the Cell Charger Modules.

The 5-volt output of the on-board linear regulator is not high enough to properly drive the MOSFET. To fix this, the driver draws its power directly from the input filter capacitors. Because the input lines to the driver are isolated, they can be safely driven by the 5V output of the CPU without causing problems with latch-up.

11.4.2 POWER INDUCTOR

The power inductor used in the switching regulator consists of 30 turns of 20-gauge wire wound on a 22mm toroidal core. The inductance is about 50 μ H. Bonded to the heat spreader with thermally conductive adhesive, this design can handle a continuous current of up to 8 amps.

While more difficult to produce than a standard rod shaped or GI core inductor, the toroid has several advantages. First, it packs the most inductance in the smallest amount of space possible. Second, it has a tightly coupled, closed magnetic circuit.

All of the magnetic flux produced by the inductor stays inside the inductor. It does not radiate outwards and interfere with surrounding electronics. This was a major concern with the CCM circuit boards, because the power inductor is located only 16mm from the sensitive op-amps used for current and voltage scaling.

The core used in our design is identical to that used in a Coiltronics CTX100-1-52LP inductor. This greatly simplifies matters should we decide to have

Coiltronics wind a batch of our inductors for a production run of chargers.

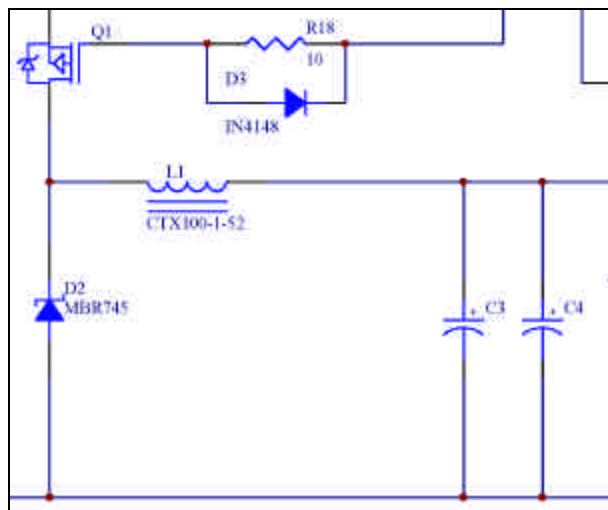


Figure 11-7: Schematic of Switching Regulator

11.4.3 SCHOTTKY DIODE

The Schottky diode used in the switching regulator has the lowest voltage drop that we could find in heat sinkable diodes. The part selected was an OnSemi MBR745, which has a forward voltage drop of 0.4 volts @ 25°C, and decreases to 0.2 volts as the junction temperature approaches 85°C. [146].

Minimizing the voltage drop across the Schottky diode is crucial to the efficient operation of the switching regulator. During negative portion of the switching cycle, the energy stored in the inductor flows through the diode, and the voltage drop across it represents a loss. With a 0.4-volt drop, and driving a 1.3-volt output, the diode consumes 23% of the output power. Fortunately, current only flows through the diode during half of the switch cycle, reducing the actual loss to 11.5%.

Many buck regulators also incorporate a second Schottky diode on the output side of the inductor. This was not feasible in our design due to the voltage drop introduced by the diode. Had we included this second diode in our circuit, it would have consumed almost 23% of the output power of the regulator.

11.4.4 CONTROLLER

It is unusual to use, as we did, the CPU to drive the regulator instead of a dedicated switching regulator controller. Unlike a linear regulator, the output of a switching regulator fluctuates slightly depending on the point within the switching cycle it is measured at. In many applications, this is not a problem, but when

that voltage is being monitored for a 1 millivolt drop to signal the end of the charge cycle, it quickly becomes one.

Normally, voltage ripple can be mitigated by using large filter capacitors, and possibly inductors, on the output side of the supply. Because the CCM regulator has an output current of up to 8 amps, the capacitors and inductors necessary to control the ripple would have filled the entire electronics compartment.

One way around this problem is to ignore the ripple and just sample the battery voltage in synchronization with the switching regulator. In order to accurately measure the battery voltage using this technique, it must be sampled right after D3 has finished conduction, but before Q1 switches back on and starts the next cycle.

Initially, we tried using a dedicated switching regulator IC to control Q1, but quickly discovered that we could not synchronize it with the CPU well enough to get usable battery voltage readings. The regulator has to be driven by the CPU so that the voltage across the battery can be sampled at the correct time.

11.5 Voltage and Current Feedback

One of the most important parts of the Cell Charger module is the voltage and current feedback circuitry.

This group of components measures the voltages present at the current sense resistor and battery terminals, amplifies and conditions the signals, and then delivers them to the CPU. Considering the low levels and narrow margins of these signals, this is a nontrivial task.

The main component in the VCF block is U4, a four channel Op-amp. For this application, we chose a National Semiconductor LM6134AIM 4 channel op-amp. [147]. Many other parts could have been used, but we felt the Fairchild part provided a good balance of performance, usability, and cost. The high slew rate and wide bandwidth of this part are required for an arc-suppression system discussed later in the report.

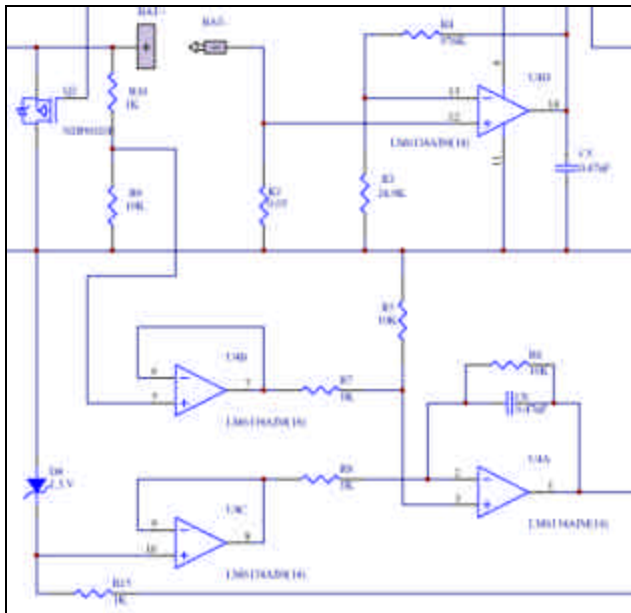


Figure 11-8: Schematic of VCF Block

In our design, two of the Op-amp channels are configured to act as non-inverting buffers. They simply isolate the output signal from the input without changing its level. The first channel acts as the cell voltage buffer. Its input is tied to the positive battery terminal. The second op-amp functions as the voltage reference buffer. Its input tied to the output of Zener diode D4.

D4 is a 1.5-volt Zener diode in series with a 1K resistor, configured to act as a shunt regulator.

The third channel is configured to act as a difference amplifier. The output of channels 1 and 2 are fed to the inputs of channel 3. The op-amp takes the difference between the voltages, amplifies it, and sends the result to ADC input 1 of the CPU.

The fourth channel of the op-amp is configured to act as a high-gain amplifier. The input of this channel is the very low voltage across the current sense resistor. The op-amp amplifies it, and then sends the result to ADC input 0 of the CPU.

We based this comparator scheme on a similar circuit used in a 1997 Microchip Inc. reference design. [148].

11.6 Thermal Monitoring

Since the Cell Chargers are required to charge batteries under widely varying temperatures, any design has to include temperature monitoring.

Each Cell Charger has two built-in temperature sensors. One monitors the temperature of the battery, and the other monitors the temperature of the heat spreader.

The CPU uses temperature readings from these sensors to make decisions about the charging process. The temperature reading from the battery compartment is used to decide if it is too hot or too cold to charge the battery.

Because of the need for high accuracy, wide operating temperature range, and the fact that the sensors are located near sources of interference, we chose to use digital temperature sensors.

The part we selected for this application is a Maxim MAX6576 Period/Frequency output digital temperature sensor. It communicates with the CPU using a 1-Wire™ serial interface, greatly simplifying wiring. The MAX6576 has a working temperature range of -40°C to $+150^{\circ}\text{C}$. It has guaranteed $\pm 3^{\circ}\text{C}$ ($\pm 1^{\circ}\text{C}$ typical) accuracy over the 0°C to 70°C range, with $\pm 5.0^{\circ}\text{C}$ accuracy over the -20°C to $+100^{\circ}\text{C}$ temperature range. [149]. This is more than adequate for our design.

If this part proves to be inadequate in field use, our design allows us to upgrade to a Maxim MAX6629 12 bit digital temperature sensor. It communicates with the CPU using a three wire serial interface.

The MAX6629 has a working temperature range of -40°C to $+150^{\circ}\text{C}$. It has guaranteed $\pm 1^{\circ}\text{C}$ ($\pm 0.2^{\circ}\text{C}$ typical) accuracy over the 0°C to 70°C range, and $\pm 2.3^{\circ}\text{C}$ accuracy over the -20°C to $+100^{\circ}\text{C}$ temperature range. [150].

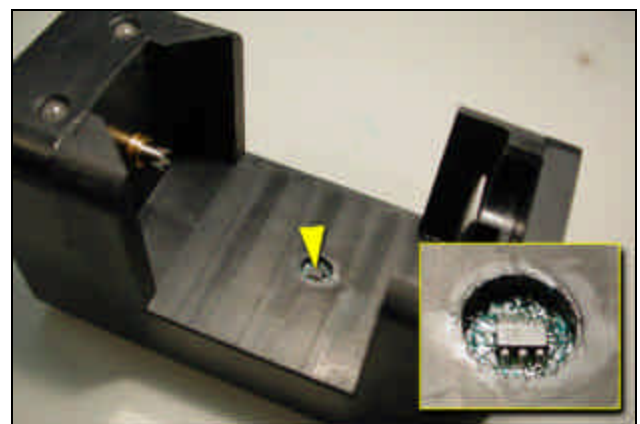


Figure 11-9: Digital Temp Sensor Mounted in CCM

11.7 Battery Conditioning

For some working environments, NiCd chemistry rechargeables are the only battery that can withstand the operating and environmental demands.

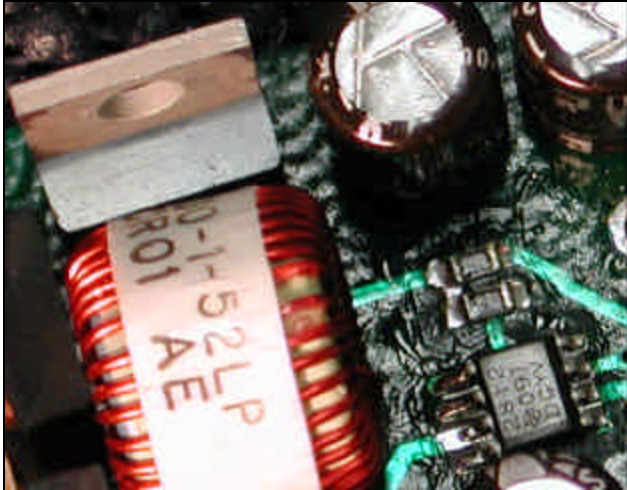


Figure 11-10: Detail of Battery Conditioning MOSFET

Because NiCd batteries can develop voltage depression or “memory effect” during use, each Cell Charger contains discharge circuitry to allow the batteries to be exercised.

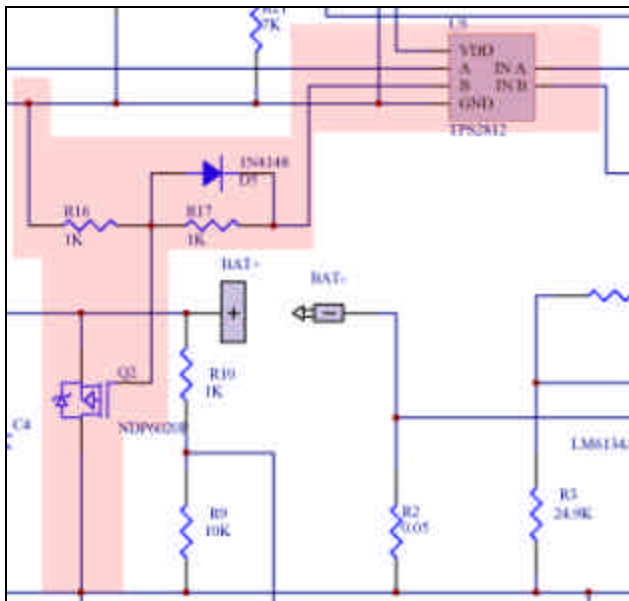


Figure 11-11: Schematic of Battery Conditioning Components

This has been implemented by connecting a power MOSFET across the battery terminals and using a voltage divider to bias it into linear mode. By using this technique, we can replace a \$4.29 US twenty-

watt heat sinkable power resistor with a \$0.78 US power MOSFET that works just as well.

Looking at the schematic, you will notice that one leg of the voltage divider is bypassed with a diode, and connected to one channel of the MOSFET driver. This forces the MOSFET to run in linear mode when it is on, but allows us to bypass the voltage divider when we want to switch it off. This allows the MOSFET to be switched off *very* quickly.

The quick turn-off time is used for arc suppression at the battery contacts, should the user remove the battery while it is discharging.

Throughout the discharge cycle, the CPU samples the battery voltage thousands of times per second. If the battery voltage suddenly drops, as it would if the battery were pulled away from the positive contact, the CPU immediately stops the discharge.

This feature quenches an arc at the battery contacts almost instantaneously, before it can do any damage. After an arc-quench, the CPU continues to monitor the voltage at the battery contacts. If it returns to normal within 1 second, the discharge process is resumed.

How the operating system allows for battery conditioning is described in Section 12.4.

11.8 ICSP Interface

The In-Circuit Serial Programming Interface, or ICSP, is one of the most important features of the Cell Charger. It allows the assembled and potted Cell Chargers to be **reprogrammed in the field** using either a laptop computer or a small, inexpensive (\$30) data transfer module about ½ the size of a deck of cards.

These data transfer modules can be mailed out to end users as required. To reprogram a Cell Charger, they simply plug the data transfer module into a 3-pin jack on the back of the Charger Module and push a button. Programming takes 30 seconds. Similar techniques are already in use for upgrading the operating systems in point-of-sale terminals, vending machines, and even high-end mine detectors. [104].

Using a data transfer module, the entire contents of the flash memory of the Cell Charger can also be downloaded to another computer for analysis. This allows the System to be used in ways never possible with conventional chargers.

11.8.1 UPGRADES

Every year, the batteries available constantly change. Their capacities increase, and new chemistries are introduced. Because the Cell Charger is controlled entirely by the operating system stored in the flash memory, it can be re-programmed to deal with new battery chemistries.

11.8.2 CUSTOMIZATION

Because the operating system is loaded on to the Cell Chargers after they have been built, it is possible to change the programming of each charger to suit the needs of the user. For example, say an organization has thousands of NiCd batteries in use and wants to charge them. The charger algorithms could be further optimized for NiCd chemistry. Or how about a user that, for some reason, wants to charge rechargeable alkaline batteries. By modifying the operating system loaded on their chargers, we could program the Intellicharge System to charge this type of battery.

11.8.3 STATISTICS

During operation, the CPU of the Cell Charger records performance and usage information to a section of its internal flash memory. This information can be downloaded by the user and used for management purposes.

12 Electrical Design – Cell Charger Operating System

12.1 General Description

Because the Cell Chargers are run using a microcontroller, it is the software loaded on to the microcontroller that determines almost all of the behaviors of the system.

While the operating system described in this report is for D-size batteries, the Cell Chargers can also be used to charge C, AA, and 9-volt batteries. The principals behind the algorithms are essentially the same for each.

12.1.1 CHOICE OF LANGUAGE

Because of the complexity of the operating system, it was not realistic to even attempt to code it in a low-level assembly language. Had we done so, it would have taken a prohibitive amount of time to write it and even longer to find all of the mistakes. If we ever wanted to change or update the software in the future, it also would have been proportionally difficult to go through the code again and revise it.

We wrote the operating system for the Cell Chargers in C, and used a specialized, highly optimized compiler/assembler to convert it to the program code for the CPU. This greatly reduced development time, produced small, efficient code, and maximized our time spent developing it.

Source code for the charger operating system is available on our website. www.intellicharge.com

12.1.2 FUNCTIONS OF THE OPERATING SYSTEM

The description of the operating system is broken into its six major functions:

- Battery Qualification
- Charging Algorithm
- Battery Conditioning
- Calibration
- Regulator Control
- Safety Assurance

The following Sections, 12.2 to 12.7, will cover the functions listed above.

12.2 Battery Qualification

After the user puts an arbitrary battery into the Charger Module, the Cell Charger must decide whether the battery can be recharged and if it needs recharging.

To accomplish this, the Intellicharge system uses some of the battery identification techniques outlined in US Patent 6,191,551 owned by Research In Motion (RIM) Inc. [151].

Our use of these techniques does not infringe on the RIM patent because the Intellicharge system is not powered by the batteries it charges. In addition, we have implemented additional tests that were not possible in the RIM design.

12.2.1 BATTERY VOLTAGE TEST

For this test, the CPU reads the battery voltage compares it to the threshold voltage of 1.396V.

During this test, 16 samples of the battery voltage are taken and averaged together. The purpose of this is to remove any noise that may be present in the readings.

If the average voltage is below the threshold value, then the battery voltage test is considered successful and the CPU proceeds to the Internal Resistance test. If the voltage is equal to or above the threshold value, the user is alerted that the battery inserted into the charger is either a non-rechargeable, or simply does not need recharging.

This test works because most fully charged alkaline and lithium batteries have voltages above the threshold value. Furthermore, most fully charged NiCd and NiMH batteries have a terminal voltage in this neighborhood. Therefore, the battery voltage test detects both fully charged NiCd and NiMH batteries, preventing overcharging, as well as non-rechargeable batteries.

12.2.2 INTERNAL RESISTANCE TEST

The IR test measures the internal resistance of the battery to determine its chemistry. Due to their construction, NiCd and NiMH chemistry batteries have very a very low internal resistance. This allows them to be differentiated by the test. **This test identifies “shorted” or “open” NiCd and NiMH batteries.**

The Internal Resistance test works by using the switching regulator to send three current pulses through the battery. For each pulse, the terminal voltage is measured and stored to memory.

- First pulse: test current I1 of 500mA for 100ms. Measures terminal voltage V1.
- Second pulse: test current I2 of 750mA for 100ms. Measures terminal voltage V2.
- Third pulse: test current I3 of 1000mA for 100ms. Measures terminal voltage V3.

The average of $(V1 / I1)$, $(V2 / I2)$, and $(V3 / I3)$ is a rough approximation of the internal resistance of the battery.

If the value is between 5 and 60 milliohms, the test is considered a success.

The CPU waits 5ms and then repeats the test cycle.

The test cycle is repeated eight times. If at least five of the tests are successful, the CPU moves to the timed charge test. Otherwise it alerts the user that the battery cannot be charged.

12.2.3 TIMED CHARGE TEST

After the battery has passed the first two tests, the controller proceeds to the timed charge test. **This test identifies fully charged NiCd and NiMH batteries**, as well as any non-rechargeable batteries that have made it past the first two tests.

Test charging of the battery is enabled at 4,000mA for five seconds. After five seconds, the CPU measures the voltage of the battery, recording 16 samples and averaging them to eliminate noise.

If the measured voltage exceeds a threshold value of 1.553 volts, the CPU immediately stops charging and alerts the user.

If the measured voltage is below 1.553 volts, the CPU waits 1.5 seconds, and then repeats the 5-second test charge cycle.

If, after 16 cycles, the threshold voltage is still below 1.553 volts, the battery is considered to be a NiCd or NiMH chemistry battery needing charging. The CPU then proceeds with the normal charging algorithm.

The value of 1.553 volts was selected as the threshold value because most NiCd and NiMH D-cells, when charged for five seconds at a rate of 4,000mA, have terminal voltages that rise to less than 1.553V. However, NiCd and NiMH batteries that are not ready to be recharged have terminal voltages that are above 1.553V. Thus the test identifies NiCd or NiMH chemistry batteries needing recharging, as well as any non-rechargeable batteries that have made it past the first two tests.

12.3 Charging Algorithm

Charging batteries under field conditions is not easy. Especially considering that the charger has to work with both NiCd and NiMH batteries, and that the characteristics of these batteries change as they age.

12.3.1 TEMPERATURE DEPENDENCE

After the battery in the charger has been identified as a NiCd or NiMH chemistry battery that needs charging, the charger gives a “green light” informing the user that the battery is being charged. Before actually applying a charge current to the battery, the system waits for 2 minutes to ensure that the battery compartment temperature sensor has warmed or cooled to the same temperature as the battery. The system then takes a temperature reading.

If the battery temperature is below 0°C or above 50°C, the system will give a red light condition and not charge the battery. If the temperature is between 0°C and 40°C, the charger will begin charging at full rate of 4,000mA, and if the temperature is between 40°C and 50°C the charger will begin charging at half rate (2,000mA). In addition, the charging rate may be reduced based on the temperature of the Cell Charger’s heat spreader, but never below 0.5C.

During charging, the CPU uses the battery compartment temperature as feedback for the charging process. The CPU stores the battery compartment temperature when the charge cycle was started, and compares it to the battery compartment temperature as the battery is charged. During charging, the battery will, of course, warm up and the battery compartment temperature will rise. The CPU monitors the rate at which the temperature changes, and when there is a sudden increase it

knows the battery has probably reached capacity. This is called differential temperature sensing.

The temperature sensor on the heat spreader is used for thermal lockout and charge rate throttle-back. Charge rate throttle-back is a technique used by our design to do the “best job possible given the current operating conditions”. If the temperature of the heat spreader is below +50°C, the Cell Charger will charge the battery at the maximum current allowed.

So long as the battery and the heat spreader remain at a safe temperature, the CPU will continue charging at this rate until the battery is charged or something begins to heat up. If the heat spreader temperature exceeds 50°C, the Cell Charger will slowly reduce its charging rate until it either reaches the minimum allowed charge rate, or the temperature of the heat spreader stops rising.

If the charger has bottomed out at the minimum charge rate, it will permit the temperature of the heat spreader to rise to up to 80°C. If the temperature of the heat spreader exceeds 80°C, the CPU will give up, stop charging the battery, and enter sleep mode. **The temperature of the battery is never allowed to exceed 50°C.**

12.3.2 ENDING THE CHARGE CYCLE

The Intellicharge system uses a combination of Negative-Differential-Voltage (NDV) and Differential-Temperature (DT) sensing to determine the correct time to stop charging the battery. The use of both methods in combination are required, as neither one will function reliably on its own under the expected operating conditions. A time-out mechanism is also incorporated as a safety measure.

As a NiCd or NiMH battery is charged with a constant current, its terminal voltage slowly increases during the charging process. When the battery reaches capacity, the rate of voltage change decreases, indicating that charging should be stopped.

NiCd and NiMH batteries have different NDV signatures, and they vary with operating temperature. The typical voltage drop of a NiCd will be around 30mV. With a NiMH, especially if the temperature is over 40°C, the change in voltage may be virtually nonexistent. NiMH batteries that have been stored for long periods of time may also exhibit a false NDV event during the first few minutes of charging. [34].

The Cell Chargers incorporate several mechanisms to deal with these problems. First, the system uses an op-amp to “window” the battery terminal voltage before sending it to the CPU. This allows the system to detect voltage fluctuations as low as 1mV. [148, 152].

Second, the system ignores NDV events that occur during the first few minutes of charging, preventing false triggering by depleted NiMH batteries. Finally, the system takes the battery temperature into account when determining the end point of the charge cycle.

As a NiCd or NiMH battery is charged, its temperature will slowly rise during the charging process. When the battery has reached capacity, the rate of change of temperature will rise sharply, indicating that the battery is charged. This technique is known as Differential Temperature (DT) Sensing. Unfortunately, temperature rise detection is not a completely reliable process. Moving the charger from a cool location to a warmer one while it is charging, or perhaps even the sun shining on the charger could raise the battery compartment temperature and falsely trigger the system.

As such, the Cell Chargers use a combination of NDV and DT sensing to decide when to end the charge cycle.

It should also be noted that neither of these methods work well at charge rates of less than 0.5C. Accordingly, the minimum charge current for the system is 2,000mA.

12.3.3 TOP-UP CHARGE

The level to which a NiCd or NiMH battery can be charged varies with the temperature that the battery is charged at. At high temperatures, a battery may only have 70% charge acceptance meaning that, after the charge cycle has been ended by NDV and DT monitoring, it is still only charged to 70% of its capacity.

To deal with this problem, following initial fast charging, the battery is allowed to cool for several minutes (monitored by the battery compartment temperature sensor). After which, providing that the battery temperature has dropped to a safe level, the system will apply a 1,000mA timed topping charge to the battery, to fill up the remaining capacity.

12.3.4 TRICKLE CHARGE

Both NiCd and NiMH batteries experience self-discharge. This is especially noticeable at high temperatures. A trickle charge is used to counter the self-discharge of the battery, and to fill the small amount of capacity that may remain after the top-up phase. Following the top-up charge, the Cell Charger allows the battery to cool for several minutes, and then applies a trickle charge to the battery.

In general, NiCd batteries are quite forgiving in terms of trickle charge current. NiMH batteries are not. If a NiMH battery is left in a charger with too high a trickle charging current, the battery could be overcharged and damaged. The recommended trickle charge for a NiMH battery is 0.05C. For a 4,000mAH battery this is 200mA.

12.4 Battery Conditioning

For end users using NiCd batteries, it may be necessary to condition the batteries in order to prevent problems with voltage depression (also known as “memory effect”). In many applications, voltage depression may not be a problem, and if it becomes one, the batteries only have to be exercised, on average, about once every 30 cycles to eliminate it. Performing a full discharge cycle before every battery is recharged would waste time and reduce the service life of the batteries.

The Intellicharge system offers two methods to deal with this problem.

Under the first method, the system can be programmed to discharge batteries on command. When enabled, this feature is activated by inserting a battery into the Cell Charger Module, pulling it away from the positive contact for one second, and then “tapping” the positive contact against the positive terminal three times. The charger will flash the status lights to confirm. After ensuring that the battery isn’t a non-rechargeable, it will begin the discharge cycle. Using the rugged battery contacts as a switch eliminates the need for a “discharge” button, and is almost impossible to trigger accidentally.

Under the second method, the system can be programmed to perform a discharge cycle at random on 1 out of every 30 batteries charged. This may be more convenient when charging large numbers of batteries. If the user needs the batteries as soon as possible, a Cell Charger performing a randomly initiated discharge may be stopped by pulling the battery away from the positive contact, holding it for

one second, and releasing it. At this point, the Cell Charger will immediately begin the normal charge cycle.

The discharge cycle takes about one hour, temperature and battery permitting. As the battery is discharged, the CPU will automatically adjust the discharge rate based on the temperature of the battery and the temperature of the Cell Charger heat spreader, ensuring both remain at a safe level. The maximum discharge rate is about 4,000mA, since the rate is controlled by the MOSFET, it is not voltage dependent. A number of precautions are taken to prevent contact arcing if the battery is pulled away from the positive contact during the discharge process, either by accident or to stop the discharge cycle.

For end users using NiMH batteries exclusively or for users in situations where the discharge capability otherwise presents a problem, both discharge methods can be disabled.

12.5 Calibration

A quick survey of the battery manufacturer catalogs sitting in our lab shows D-size NiCd batteries ranging from 1,800mAH to over 4,400mAH and D-size NiMH batteries ranging from 1,500mAH to 6,600mAH. Some of these batteries can be fast charged and some cannot. Some of these batteries can be charged at up to 65°C while others will only work at 45°C.

There are two important issues raised by this:

The first issue is setting the safety time-out for fast charging. If the timeout were set for ½ hour, then when the 1,800mAH battery is at maximum capacity, the 6,600mAH NiMH would be at less than 30% charge.

The second issue is setting the maximum safe charging temperature. If the maximum charging temperature is set at 45°C so the charger is safe for the low temperature batteries, an end user that wants to use it in an extremely hot location with high temperature batteries will get extremely slow charge rates.

Calibration parameters stored in the flash memory of each Cell Charger solves this problem. By setting the calibration parameters, we can build a “custom” charger for each user, specifically optimized for the batteries they are using.

Eight Cell Charger Modules can be programmed in under ten minutes, and the system can be re-programmed as often as needed. This can be done in the field using a data transfer module, or at base camp using a laptop computer.

For users who either don't know the specifications of the batteries they are using, or are using several different kinds of batteries simultaneously, the system can be programmed with "generic" parameters that will work with most batteries, but under penalty of reduced performance.

In the future, we plan to give the system the ability to "learn" the characteristics of new batteries. Under this approach, the user would insert a sample "good" battery into the charger, and the charger would run a series of tests to determine necessary operating parameters.

12.6 Regulator Control

Because all of the voltage measurements taken during charging must be synchronized with the switching regulator, the CPU controls this device. A number of application notes published by the CPU manufacturer, Microchip Technology Inc, describe this control scheme. [148, 153, 154].

The Microchip PIC16F873 has a built in hardware module used for generating PWM signals. By simply writing a value to the device's control register, we can set both its frequency of operation and the duty cycle of its pulses. The PWM module also has a countdown register, so we can determine when it is going to send out the next pulse.

The PIC16F873 has five built in ADC ports. On this processor, an ADC port takes in a signal from 0 to 5 volts, and generates a numeric value corresponding to the voltage. The hardware has 12-bit resolution, so we can sense 4,096 different values, or, 0.00122-volt increments. The ADC value is acquired by simply reading the appropriate ADC port.

When the charge cycle is initiated, or we want to send current through the battery for testing, the switching regulator is activated by writing a duty cycle to the PWM module. This in turn causes Q1 to be activated, and the regulator to begin sending current into the battery.

As previously discussed, current flow into the battery is measured by the current flow resistor, conditioned by the VCF Block, and sent to the ADC port of the CPU. This provides the CPU with a feedback signal proportional to the current flowing into the battery.

This value is read from the ADC port and multiplied by a correction constant to get the actual current flowing into the battery.

If the current flow through the battery is too high, the CPU reduces the duty cycle of the PWM module. If the current flow is too low, the CPU increases the duty cycle of the PWM module.

The C compiler that we used to write the operating system includes special functions for interfacing to the CPU's ADC and PWM modules. This makes the switching regulator controller relatively simple to code.

12.7 Safety Assurance

The operating system used for the Cell Chargers incorporates a number of safety mechanisms to prevent damage to the charger, batteries, and user.

12.7.1 TEMPERATURE

Over and above how they are used as part of the charging process, the CPU uses readings from the temperature sensors to maintain the charger at a safe operating temperature.

During charging, the CPU constantly monitors the temperature of the heat spreader assembly. If this temperature begins to rise above 80°C, the cell CPU will "throttle" the charge rate, slowly decreasing it until the temperature of the heat spreader stops rising. The CPU will not permit the temperature of the heat spreader to exceed 100°C. If it does, and if the system is operating at the minimum permitted charge rate or is in the top-up charge stage, the system will stop charging until the temperature of the heat spreader falls below 80°C.

In the event of a runaway CPU failure, the system also has a hardware thermal cut out. If the temperature of the heat spreader exceeds 125°C, the thermal shutdown of the main voltage regulator will activate, disconnecting power to the CPU and control circuitry. [130].

12.7.2 ARC SUPPRESSION

The CPU incorporates a special algorithm to prevent arcing at the battery contacts when the battery is removed unexpectedly during conditioning.

Throughout the discharge cycle, the CPU samples the battery voltage thousands of times per second. If the battery voltage suddenly drops, as it would if the battery were pulled away from the positive contact, the CPU immediately stops the discharge. This

feature quenches an arc at the battery contacts almost instantaneously, long before it can do any damage.

After an arc-quench, the CPU continues to monitor the voltage at the battery contacts. If it returns to normal within 1 second, the discharge process is resumed. Note that the stainless steel positive battery contact will resist arcing better than other metals.

12.7.3 CYCLIC REDUNDANCY CHECK

The operating system of the Cell Charger is stored in the flash memory of its CPU. While flash memory is generally quite reliable, it is possible for the stored instructions to be damaged if the CPU is hit by a high energy particle such as a cosmic ray, decay product from a radioactive source, or simply by spontaneous failure of one of the memory cells. [155].

If the damaged memory cell contained a critical instruction, it could cause the charger to undercharge batteries, overcharge batteries, or short out the other chargers in the system. In such a case, it is vital that the Cell Charger be prevented from operating.

Using techniques described in Microchip Technologies application note "AN730", each Cell Charger performs a Cyclic Redundancy Check (CRC) on its program memory every time it is powered up. [156]. This process only takes a fraction of a second to complete. If any of the memory cells have been damaged, the CRC will detect the damage, lock out the switching regulator and conditioning MOSFET, and, if possible, alert the user that the operating system has been damaged (e.g. cause the LED's to flash red).

13 Electromechanical Design

The physical construction of the electrical assemblies used in the Intellicharge System is an important element of the overall design. This construction ultimately determines the capabilities and specifications of the charger. Size and manufacturability directly affects the price of the finished system.

All of the electrical assemblies used in the Intellicharge system have been built to meet three important design criteria. First, they must occupy the minimum volume possible. The size of the electronics has a direct effect on the size of the modules, and the cost of the system.

Second, the assemblies must be as efficient as possible. This requires careful placement of the power components, and careful high current path design.

Finally, the assemblies must be as inexpensive as possible to manufacture. That means that we are limited to 2 layer circuit boards and cannot use any exotic, high performance components.

13.1 Surface Mount Components

The first decision we made was to use as many surface mount components in the design as possible. Surface mount components more than double the density of a typical circuit board. They use much smaller packages than their through-hole counterparts, and don't require holes through the board for leads. Consequently, components can be mounted on both sides of the board without interfering with each other.

Had we tried to build the charger using only through-hole parts, the Cell Chargers would have been at least double the size. [157].

13.2 Components Bonded to Heat Sinks

Since the modules used within the design are filled with potting compound to make the waterproof, all of the major heat producing components must be conduction cooled. That affects the case styles of these components and their placement on the board.

The MOSFETS, Schottky diodes, Voltage Regulators, and Power Resistors used in the design all have TO-220 style cases for easy mounting to the heat spreaders. In the Cell Charger, all of the heat

producing components are clustered at one end of the board, so they can be attached to the heat spreader. In the APC, all of the heat producing components are mounted on the back side of the circuit board, so they contact the heat spreader running across the back of the device once it is assembled.

13.3 High Current Loops

Switching power supplies have large current pulses with very sharp edges flowing within the power supply circuit. To increase efficiency and minimize the generation of EMI, the high current loops in the APC and Cell Charger Modules had to be carefully designed. [158].

Designing high-density circuit boards with high current tracks, mixed mode signals and sensitive voltage measurement circuitry proved to be very challenging.

We used two techniques to optimize the high current loops. First, we placed all of the affected components in close proximity, minimizing track length. Second, we used planar tracks to maximize the width and decrease resistance. [159].

We used large ground planes to control noise leakage into the sensitive operational-amplifiers in the Cell Chargers, and the current feedback loops in the APC. In many cases, we had to add decoupling capacitors to the ground plane to control spurious noise on control signal traces. [160, 161].

Layouts for the Autoranging Power Converter and Cell Charger printed circuit boards are shown in Figure 13-1 and Figure 13-2. Complete engineering drawings of these boards are provided in the technical appendices.

13.4 PCB Layout Drawings

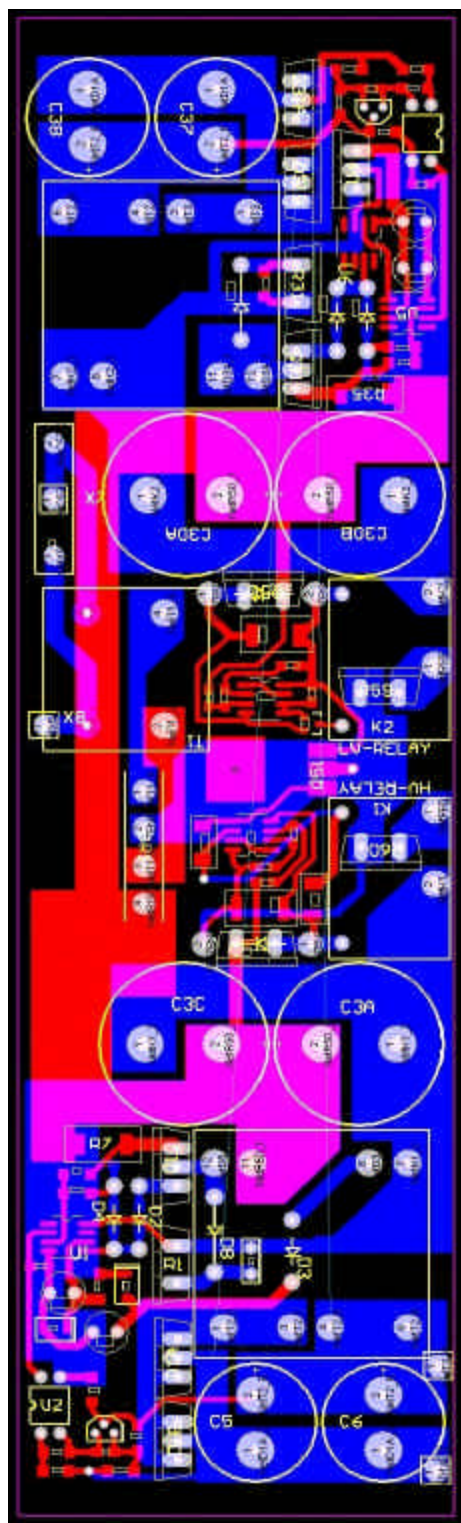


Figure 13-1: PCB Layout for the APC
(Approximate Scale 1:1)

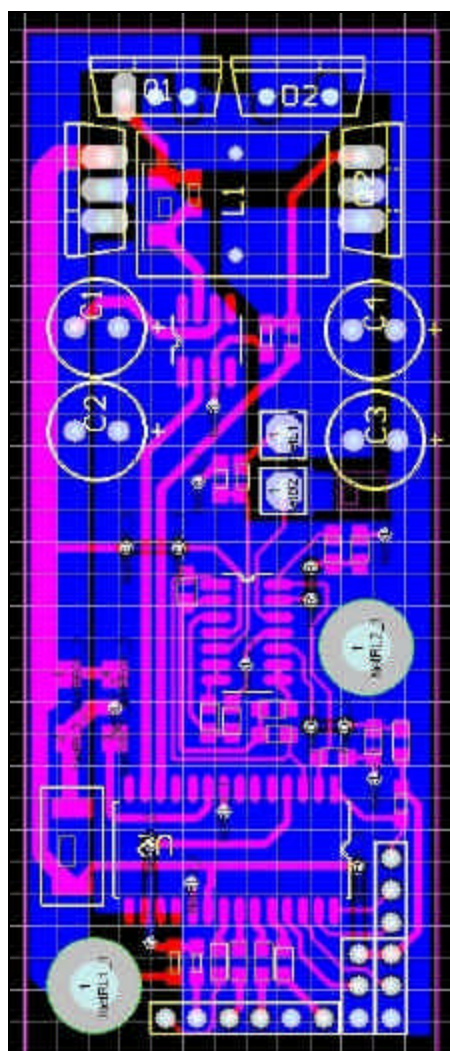


Figure 13-2: PCB Layout for Cell Charger
(Approximate Scale 3:1)

14 Production

For the Intellicharge system to succeed, it must be practical to manufacture the system for profit in commercial quantities.

The system was designed while in constant communication with suppliers and manufacturers. Throughout the design process, we have taken many steps to reduce the cost of components used in the system.

Once the design is complete, budgetary pricing must be obtained for every component used. After that, final assembly time must be calculated, and the cost of capital factored in. Only then can an accurate manufacturing cost be determined.

Budgetary pricing has been received for all components used in the **current** version of the design. Manufacturing and assembly costs have been estimated using the information gathered thus far.

The largest of the initial set-up costs are the two injection molds for the Chassis and the Cell Charger Housing. Estimated prices for these are given. The cost of the Intellicharge System, **excluding tooling costs**, is then estimated.

14.1 Mechanical Components

If every component in the Intellicharge system were manufactured in a machine shop, the cost of the Chassis and Cell Charger Housing alone would exceed \$400.00USD. While this may be acceptable for field testing and prototypes, it is prohibitively expensive at production quantities. We have investigated injection molding as a lower-cost alternative to machining.

Injection molding requires a complicated, custom-built injection mold for each component produced. A typical injection mold can cost anywhere from \$5,000USD to \$75,000USD.

The reason the molds are so expensive is because they have to be from large blocks of hardened tool steel. One mold that we were shown was used to make eight plastic coat hangers. It was approximately 4 feet x 3 feet x 8 inches (1.2m x 0.9m x 0.2m).

For this project, we contacted three different injection-molding companies. We sent them our completed drawings, and then met with them to discuss how molding costs could be minimized. After some minor adjustments, we obtained budgetary pricing.

Pictured in Figure 14-1 and Figure 14-2 are two rendered versions of preliminary impressions of what the molded Cell Charger Housing might look like, as provided by Draeder Manufacturing in Edmonton, Canada. Further discussion will be necessary before a usable, molded design is generated. We expect that the final mold would be simpler (and less expensive) than what they are currently envisioning.

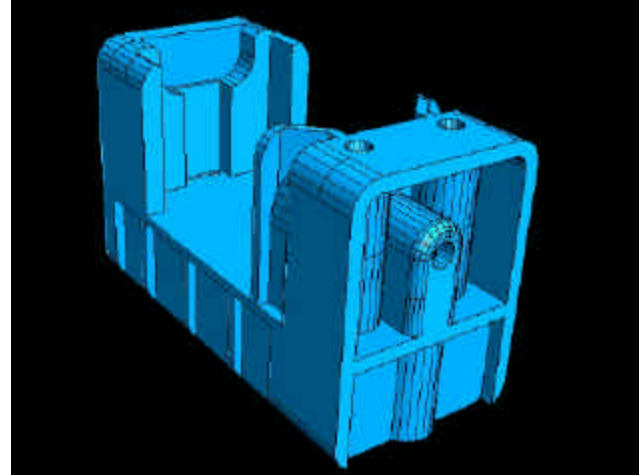


Figure 14-1: Preliminary Impression of Molded Design (Isometric View) [164]

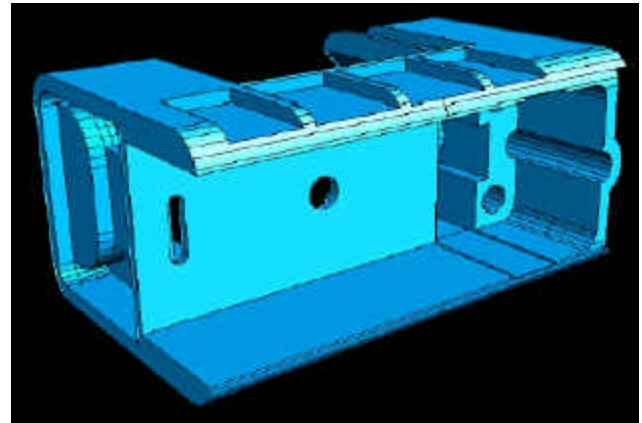


Figure 14-2: Preliminary Impression of Molded Design (Bottom View) [164]

Based on budgetary pricing received to date, the mold used to produce the Chassis will cost between \$30,000 and \$40,000CDN. (\$20,000 and \$26,000USD). The mold used to produce the Cell Charger Housings will cost between \$20,000 and \$25,000CDN (\$13,000 and \$16,250USD).

Once ordered, fabrication and testing of the molds will take up to 12 weeks.

After the initial cost of the mold, the per-part cost of the Chassis will be about \$5.00CDN (\$3.25USD). The per-part cost of the Cell Charger Housings will be as much as \$1.50CDN (\$0.98USD). The above costs include the plastic.

The minimum run on the Cell Charger Housing could be as much as about 1000 pieces. The minimum run for the Chassis could be closer to 400, because each part takes longer to mold.

To compare machining to molding, we make the optimistic assumption that the Chassis and eight Cell Charger Housings could be machined in ten hours. The going rate for machining time is about \$50CDN/hour, so that would make the total labor costs of machining \$500CDN.

\$50/hour x 10 hours = \$500CDN (or \$422USD)

The solid blocks of plastic required for machining would cost about \$150CDN, based on what we paid for our prototypes. The total cost to machine the parts, in Canadian dollars, is estimated as:

Machined Cost = \$(500 + 150) x N

where N is the number of Intellicharge Systems produced.

To mold the parts, the cost would be:

Molded Cost = \$40,000 + \$5xC + \$25,000 + \$1.50xH

where C is 400, the minimum number of Chassis we can have molded and H is the minimum number of Cell Charger Housings we can have made.

Hence:

Molded Cost = \$40000+\$5x400+\$25000+1.50x1000
= \$68,500

So the breakeven-quantity, when the cost of molding is equal to the cost of machining, can be found by:

\$68,500 = \$(500+150) x N = \$650 x N

N = $\frac{\$68,500.00}{\$650.00} = 105.4$

At quantities of 106 or greater, molding would be less expensive than machining. The major simplifying assumptions in this estimation are:

- ten hours of machine time are sufficient to make one Chassis and eight Cell Charger Housings
- eight Cell Charger Housings are needed per Chassis
- all Cell Charger Housings are for the same size of battery

Budgetary pricing has not yet been received for additional sizes of Cell Charger Housings. Since only the inner layers of the mold would have to be changed (the rest of the Cell Charger Housing mold could be used more than once) the price would be considerably less than the first Cell Charger Housing mold.

14.2 Mechanical Components Bill of Materials

Table 14-1: BOM for Mechanical Components of the Intellicharge System

All prices are listed in U.S. dollars.

PART NO.	MANUF. PART NO.	DESCRIPTION	QTY.	UNIT COST	TOTAL	MIN.	MANUFACTURER
3-07C-11		Cell Charger Housing	8	1.00	8.00	1000	Intellicharge
3-11B-11		Heat Spreader, Material + Fab.	8	2.09	16.72	8	Intellicharge
3-12B-11		Positive Battery Contact, Material + Fab.	8	1.13	9.04	8	Intellicharge
9-05-40	260B-S04-157-288-591	4pt Crown Contact 28.8oz	8	2.16	17.28	1	Connect2it
9-06-40	260B-A05-157-144-591	Radius Tip Contact 14.4oz	16	1.95	31.2	1	Connect2it
9-07-40		1/2"length spring contact receptacle	8	0.70	5.60	1	Connect2it
3-05B-10		Structural Chassis	1	3.25	3.25	400	Intellicharge
3-06A-10		Power Rails, Material + Fab.	4	0.69	2.76	4	Intellicharge
3-14A-10		Back Plate Assembly, Materials + Fab.	1	23.70	23.70	1	Intellicharge
9-10-10		1/4" 20UNC threaded stainless rods	2	5.00	10.00	1	Bolt Supply
9-11-20		Stainless 1/4"-20UNC nuts	6	0.15	0.90	1	Bolt Supply
9-12-20		Stainless Bolts 1/4" 20UNC x 1/2" long	2	0.26	0.52	1	Bolt Supply
				TOTAL	\$127.96		

14.3 Cell Charger Module Bill of Materials

Table 14-2: BOM for Cell Charger Components

All prices are listed in U.S. dollars.

PART NO.	MANUF. PART NO.	DESCRIPTION	QTY.	UNIT COST	TOTAL	MIN.	MANUFACTURER
FILL-CPD	3141 Potting	Thermally conductive potting	0.03	0.025	0.00075	4000	Loctite
	3163 Hardener	Hardener for potting compound	0.01	0.04	0.0004	1000	Loctite
SENS-FIL	TC 2707	Thermally conductive epoxy	0.05	0.688	0.0344	444	3M Canada
HS-GLUE	315 Thermal Glue	Self Shimming Heat Sink Glue	0.1	1.21	0.121	30	Loctite
HS-PAD	5509 Pad	Thermally conductive pad	2	0.404	0.808	3750	3M Canada
LED1	LTL-30EFJP	Bi-Color Red/Green LED 3PIN	2	0.094	0.188	1000	Lite-On Semi
C1, C2	NRSZ221M16V	220µF 16V Thru Hole Elect	2	0.11	0.22	1000	NIC Components
C3, C4	NRSZ471M6.3V	470µF 6.3V Thru Hole Elect	2	0.09	0.18	1000	NIC Components
U6	UCC27325	4 AMP MOSFET Driver	1	1.08	1.08	50	Texas Inst
D3, D5	1N4148	High Speed High Cond Diode	2	0.017	0.034	1000	Fairchild Semi
Q2	FQP12N60	10.5A 600 Volt N MOS TO-220	1	1.08	1.08	1000	Fairchild Semi
Q1	MTP75N06HD	75A 60V N Channel MOS TO-220	1	1.813	1.813	50	OnSemi
D2	MBR745	7.5A 45V Schottky Rectifier	1	0.533	0.533	50	OnSemi
OSC1	SC-1420	20MHz Surface Mount Osc	1	0.85	0.85	1000	NEL Freq Controls
IND1	CTX100-1-52LP	100µH 2.4A Toroidal Inductor	1	0.89	0.89	50	Coiltronics
REG1	MC7805CT	1A 5V Regulator TO220 Package	1	0.319	0.319	50	OnSemi
U2	PIC16F873-SO	4K Flash CPU SOIC Package	1	3.21	3.21	100	Microchip Inc
TMP1, 2	MAX6576	1 Wire Serial Temp Sensor	2	0.61	1.23	1000	Dallas-Maxim
SENS1	AVX P50MCT-ND	0.05 OHM Current Sense	1	0.62	0.62	10	AVX Components
U4	LM6134AIM	General Purpose Dual Op-Amp	1	1.58	1.58	100	National Semi
R1-R10	2206 Series Resistors	Various 1/8W SMT Resistors	19	0.01	0.19	1000	Ohmite
C5, C6	2206-2208 Size Caps	Various Low Value SMT Caps	2	0.03	0.06	1000	Kemet
PCB	PCB	Printed Circuit Board Fabrication	1	2.53	2.53	10	APC
LOAD	LOAD	Load and Solder Components	1	1.30	1.30	1	
				TOTAL	\$18.87		

At \$18.87USD each, eight Cell Chargers will cost 8 x \$18.87 = \$150.96

14.4 Autoranging Power Converter Bill of Materials

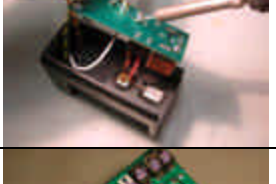
Table 14-3: BOM for the Autoranging Power Converter

All prices are in U.S. dollars.

PART NO.	MANUF. PART NO.	DESCRIPTION	QTY.	UNIT COST	TOTAL	MIN.	MANUFACTURER
FILL- CPD	3141 Potting	Thermally Conductive Potting	0.3	0.025	0.0075	4000	Loctite
	3163 Hardener	Hardener for Potting Compound	0.1	0.04	0.004	1000	Loctite
HS-GLUE	315 Thermal Glue	Self Shimming Heat Sink Glue	0.1	1.21	0.121	30	Loctite
HS-PAD	5509 Pad	Thermally conductive Pad	8	0.404	3.232	3750	3M Canada
T1	H7019-A	8 A 0.79mH Common Mode Choke	1	5.82	5.82	1	Coilcraft
T2	Custom	LV Supply Flyback	1	4	4	1	Coilcraft
T3	Custom	HV Supply Flyback	1	4	4	1	Coilcraft
ZEN1	1N5338	5 Volt 5 Watt Zener Regulator	1	0.206	0.206	1000	OnSemi
ZEN2	1N5359	24 Volt 5 Watt Zener Regulator	1	0.206	0.206	1000	OnSemi
D2,4,32,33,50,51	1N4148	High Speed High Cond Diode	6	0.017	0.102	1000	Fairchild Semi
D7	BAT54	Small Signal 30V Schottky	1	0.128	0.128	3000	OnSemi
D8, D34	MUR160	Rectifier 1A 600V Ultrafast	2	0.159	0.318	1000	OnSemi
U3, U8	TL431ACLP	Adjustable Shunt Voltage Regulator	2	0.253	0.506	98	OnSemi
U1, U5	NCP1200P60	Switching PSU Controller 60KHz	2	0.048	0.096	1000	OnSemi
U9, U10	MC33161	Dual Voltage Monitor	2	0.867	1.734	98	OnSemi
U2, U7	SFH615A -2	5.3KV Opto, High Reliability	2	0.13	0.26	100	Vishay
U12	MDC3105	Integrated Relay Driver	1	0.159	0.159	3000	OnSemi
U6	UCC27325	4 AMP MOSFET Driver	1	1.08	1.08	50	Texas Inst
K1	G5CE-1-DC24	120V 15A SPST Relay 24V Coil	1	2.64	2.64	10	Omron
K2	G5CE-1-DC5	120V 15A SPST Relay 5V Coil	1	2.56	2.56	10	Omron
Q1, Q51	FQP12N60	10.5A 600 Volt N MOS TO-220	1	1.08	1.08	1000	Fairchild Semi
Q31	MTP75N06HD	75A 60V N Channel MOS TO-220	1	1.813	1.813		OnSemi
BR1	GBPC2506W	25A 600V Bridge GBPC Case	1	2.55	2.55	1000	Fairchild Semi
U4	MC7812CT	1A 12V Regulator TO220 Package	1	0.319	0.319	50	OnSemi
D1A-D2B	MBR20100CT	100V 20A Schottky TO-220	4	0.759	3.036	50	OnSemi
C52, C1	P10755-ND	0.1µF 450V Poly Cap	2	0.34	0.68	10	Panasonic
C34	EF1105-ND	1.0µF 100V Poly Cap	1	0.53	0.53	10	Panasonic
C25, 36	P225255-ND	22nF 2500V Isolation cap	2	0.31	0.62	1000	Kemet
C3A,B	107LBA400M2BD	100µF 450V 105C Electrolytic	2	1.98	3.96	1	Illinois Cap
C30A,B	338LMU063M2BD	3300µF 63V 105C Electrolytic	2	2.31	4.62	1	Illinois Cap
C5,6,37,38	228LSR035M	2200µF 35V 105C Electrolytic	4	1.32	5.28	1	Illinois Cap
C32, 33, 4	NRSZ101M25V6.3X11	100µF 25V 105C Electrolytic	3	0.09	0.27	1000	NIC
C50, 24	NRSZ221M16V6.3X11	220µF 16V 105C Electrolytic	2	0.11	0.22	1000	NIC
C51	NRSZ101M50V6.3X11	100µF 50V 105C Electrolytic	1	0.11	0.11	1000	NIC
R60	TAH20P010RJ-ND	10 Ohm 20 Watt Power Resistor	1	2.45	2.45	10	Ohmite
R59	TAH20P001RJ-ND	1 Ohm 20 Watt Power Resistor	1	2.45	2.45	10	Ohmite
R55	TAH20P15K0J-ND	15K 20 Watt Power Resistor	1	2.45	2.45	10	Ohmite
R50	TAH20P1K00J-ND	1K 20 Watt Power Resistor	1	2.45	2.45	10	Ohmite
R1	TAH20P4K00J-ND	4K 20 Watt Power Resistor	1	2.45	2.45	10	Ohmite
R31	TAH20P470RJ-ND	470 Ohm 20 Watt Power Resistor	1	2.45	2.45	10	Ohmite
R7	PT.33UCT-ND	0.33 Ohm 1 Watt Current Sense	1	0.96	0.96	10	AVX
R35	PT.033UCT-ND	0.033 Ohm 1 Watt Current Sense	1	0.96	0.96	10	AVX
LED1	LTL-30EFJP	Bi-Color Red/Green LED 3PIN	2	0.094	0.188	1000	Lite-On Semi
Various	2206 Series Resistors	Various 1/8W SMT Resistors	24	0.01	0.24	1000	Ohmite
Various	2206-2208 Size Caps	Various Low Value SMT Caps	5	0.03	0.15	1000	Kemet
PCB	PCB	Printed Circuit Board Fabrication	1	10.96	10.96	10	APC
LOAD	LOAD	Load and solder components	1	10.00	10.00	1	
				TOTAL	90.43		

14.5 Final Assembly

Once the circuit boards have been loaded and soldered, and the mechanical parts fabricated, they still have to be assembled into a working system. If not carefully planned, final assembly can greatly increase the manufacturing cost of a system. All of the modules in the Intellicharge system are designed for fast assembly. Listed below are all of the final assembly steps for the system, along with assembly times.

	<u>Glue CCM Heat Spreaders</u> Attach the copper heat spreaders to the circuit board for each Cell Charger Module using Loctite 315 Self Shimming Thermal Adhesive.	4 minutes /8 parts
	<u>Program Test Code</u> Using the PIC programmer and adapter, program each of the Cell Charger Module circuit boards with test code. (The adapter in this photo has been wired to reverse the pin-out of the programmer ZIF socket, allowing it to function as depicted.)	8 minutes /8 parts
	<u>Solder/Install Negative Contact</u> Solder the negative battery contact holder to its connecting wire, and thread it into the Cell Charger Housing.	6 minutes /8 parts
	<u>Solder/Install Positive Contact</u> Using nickel-bonding flux, solder the positive battery contact to its connecting wire and thread it into the Cell Charger Housing.	6 minutes /8 parts
	<u>Secure Temp Sensor/Positive Contact</u> Using the alignment jig and the 3M epoxy mixing gun, secure the temperature sensor and positive battery contact into place.	4 minutes /8 parts
	<u>Solder All Wires Into Place</u> Solder the LED's, Temp Sensor, Battery Contact wires, and the Spring Terminals into place. Apply power to the Cell Charger and ensure the test sequence runs properly. If so, proceed to potting.	36 minutes /8 parts
	<u>Glue APC Heat Spreader/Attach Connectors</u> Apply Loctite 315 Self Shimming Thermally Conductive Adhesive to all power components including the bridge rectifier. Slide PCB into heat spreader. Solder input power connector and spring contacts in place	15 minutes
	<u>Mix Potting Compound</u> Using the pre-calibrated measuring containers, mix a batch of potting compound	5 minutes

	<u>Fill Cell Charger Modules and APC</u> Carefully fill each module with potting compound, ensuring that all trapped air is released. You should have NO left over compound. If you do, something has air trapped inside it. When finished, place modules in oven.	8 minutes
	<u>Fill Battery Compartment Temp Sensor Cavity</u> Using the 3M epoxy mixing gun, fill the battery compartment temperature sensor cavity with 3M TC-2707 thermally conductive epoxy. Ensure the epoxy fill is level with the bottom of the battery compartment.	2 minutes /8 parts
	<u>Program Operating System</u> Using the ISCPI adapter, program each of the filled Cell Charger Modules with either the generic operating system or customized code specified by the end user.	8 minutes /8 parts
	<u>Prep and Install Thermal Interface Pads</u> Cut the required size Thermal Interface Pads from the sheets supplied, and stick them to the heat spreaders on the Cell Charger Modules.	4 Minutes
	<u>Insert Power Rails</u> Insert the Power Rails into the back of the chassis, and then fill the space behind them with potting compound.	2 Minutes
	<u>Load Modules Into Chassis</u> Slide the APC and all of the Cell Charger Modules into the chassis	2 Minutes
	<u>Bolt Heat Sinks in Place/Attach Mounting Plate</u> Bolt the External Heat Sinks in place, and install the mounting plate. Plug the system in and test it.	5 Minutes
	TOTAL	121 MIN

Taking the cost of labor to be \$15.00CDN/hour (the approximate going rate for a Canadian undergraduate engineering student), the labor cost of assembly is:

$$\text{Labor Cost of Assembly} = \frac{121\text{min.}}{60\text{min/h}} \times \$15/\text{h} = \$30.25\text{CDN} (\$19.66\text{USD})$$

14.6 Calculation of Per-Unit Cost

Combining the cost of the mechanical components (\$127.96), the cost of the electrical components (\$150.96+90.43), and the cost of final assembly (\$19.66) the cost of each Intellicharge System works out to \$389.01USD. This does not include capital costs for production set-up.

The dollar amount has to be taken in context. The design presented is a first iteration. **Future revisions will significantly reduce the overall price.**

Furthermore, the closest comparable charger on the market (The Minelab Fseries charger), has a list price of \$400.00 USD. The Intellicharge system offers double the charging speed of the Minelab charger, allowing it to charge twice as many batteries in the same amount of time. In addition, the

Intellicharge system is Autoranging and completely waterproof.

Based on our knowledge, to date, of the market for high-durability chargers and the capabilities of the Intellicharge system, we feel that an 8bay unit can be sold for \$600.00USD so long as its performance and reliability can be proven.

It is not uncommon for a large demining organization to go through thousands of disposable batteries each month. Even if the system cost twice as much, it could still pay for itself within a matter of months when used as part of a properly managed rechargeable battery program.

The next section of the report examines the potential savings a demining organization could achieve by switching to rechargeable batteries and using the Intellicharge system to charge them.

15 Cost Savings Analysis

The purpose of the Intellicharge system is to save money for the organizations that purchase it. Two hypothetical demining operations are examined. Their battery usage and how much money they might be able to save by using the Intellicharge System are roughly estimated.

However, some factors are beyond our ability to predict at this time. How long the Intellicharge System will run before requiring replacement parts can only be estimated through field testing. Labor costs incurred through use of the System cannot be estimated until more is known about typical wages, worker-abilities, and operating procedures.

15.1 Organization A

15.1.1 SCENARIO DESCRIPTION



Figure 15-1: Political Map of Mozambique Region [165].

Below is a description of the working conditions at the (fictitious) Organization A.

"I have just come back from Mozambique where our guys are really struggling with this whole battery story.

We send a team of deminers out from our camp and down the track to the actual minefield (we prefer not to live in them!). We leave at about 06:00 and finish the day at about 14:00 to beat the heat and avoid accidents due to fatigue.

The detectors work non-stop all day. At the end of the day, we load it all up and take it back to camp.

In camp, the genset usually runs from 12:00 to 14:00 for fridges during midday and from 18:00 to 22:00 for charging, lights, and video/TV if present. The result is that there is NOT a 10 or 14-hour mains present to charge stuff properly.

On top of that, the last time I was in camp, the genset packed up and we had no AC for over a week. "



Figure 15-2: The Ebinger EBEX 421 GC Detector [3].

Detectors

Sixteen Ebinger EBEX 420 GC detectors. Each detector takes eight C-size batteries. Alkaline batteries last about 4 days in this detector. [166].

Power

Generator at base camp. They have two light trucks, one remains at the camp most of the day, and the other is frequently on the road picking up supplies.

Current Battery Usage

640 C-size batteries per month.

Satellite Climate Data

Table 15-1: Average Recorded Air Temperatures in Mozambique [167].

Air temperature (°C)													
Latitude -17 Longitude 37	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
10 Year Average	24.4	24.2	23.6	22.7	21.0	19.6	19.5	20.3	22.6	24.9	25.1	24.8	22.7
El Nino Year (1987)	24.2	24.3	24.4	22.5	21.3	18.7	18.8	21.3	24.6	25.4	26.9	26.8	23.2
La Nina Year (1988)	25.2	24.2	24.2	23.2	21.4	20.8	20.6	20.1	22.3	25.0	23.6	23.6	22.8

Table 15-2: Average Wind Speeds Recorded in Mozambique [168].

Wind speed (m/s)													
Latitude -17 Longitude 37	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
10 Year Average	1.37	1.37	1.34	1.49	1.56	1.78	1.82	1.95	2.04	2.10	1.87	1.52	1.68
El Nino Year (1987)	1.36	1.27	1.20	1.48	1.56	1.79	1.76	2.09	2.11	2.22	2.11	1.63	1.71
La Nina Year (1988)	1.40	1.27	1.36	1.44	1.60	1.85	1.84	1.76	2.04	2.00	1.94	1.47	1.66

Table 15-3: Average Insolation Recorded in Mozambique [169].

Insolation at available GMT times (kW/m ²)													
Latitude -17 Longitude 37	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Average@0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Average@3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Average@6	0.38	0.33	0.33	0.35	0.28	0.24	0.23	0.28	0.38	0.47	0.47	0.42	
Average@9	0.76	0.71	0.73	0.74	0.65	0.59	0.61	0.70	0.82	0.85	0.83	0.77	
Average@12	0.55	0.56	0.57	0.59	0.49	0.44	0.45	0.51	0.59	0.57	0.56	0.53	
Average@15	0.12	0.13	0.10	n/a	n/a	n/a	n/a	n/a	0.25	0.18	0.10	0.10	
Average@18	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
Average@21	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	

Table 15-4: Average Frequency of Near-Overcast Skies Recorded in Mozambique [170].

Frequency of near-overcast skies at available GMT times (%)													
Latitude -17 Longitude 37	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
>= 70% @0	58.9	56.6	39.2	17.5	12.8	8.90	10.8	6.43	5.78	14.0	31.9	52.3	
>= 70% @3	52.8	49.0	30.9	12.5	10.2	8.71	12.5	7.26	4.94	13.4	28.6	47.9	
>= 70% @6	59.1	55.7	44.8	28.4	23.6	27.1	24.7	22.3	21.8	34.2	46.8	52.7	
>= 70% @9	62.1	59.4	46.9	34.1	34.6	37.8	34.5	37.4	35.1	54.1	56.4	57.3	
>= 70% @12	69.4	68.2	58.4	42.2	41.8	48.1	52.0	53.8	47.2	63.4	68.5	71.7	
>= 70% @15	74.9	73.2	54.7	22.5	19.6	19.5	22.9	19.3	14.9	25.1	46.2	62.7	
>= 70% @18	72.8	66.3	50.5	20.0	15.1	14.0	15.4	12.2	6.28	18.9	38.2	57.8	
>= 70% @21	67.2	64.2	44.1	17.5	12.0	9.99	13.5	8.75	5.82	15.0	34.3	55.5	

15.1.2 ANALYSIS OF OPERATION A

This operation uses 640 C size cells per month. At \$1.00USD per battery, operating costs are \$640.00 US / month.

The climate in the region is cool enough to use NiMH batteries, but due to the frequency with which the batteries will be cycled, NiCd's are a better choice.

The region receives enough sunlight to make solar power an option, but due to the frequency of cloudy days, more panels will be required and auxiliary storage batteries will have to be added increasing the cost of the system.

This camp runs their generator six hours a day, enough time for an Intellicharge system to change six sets of batteries.

15.1.2.1 Option 1: Run from Generator

Recommended Batteries. *References: [32, 171].*

Panasonic P-280DR Rapid Charge NiCd. 2800mAH capacity, 50°C operating temperature, \$6.14 USD/battery. 128 batteries for fleet + 32 spares.

These batteries should last two days in the detector specified.

Battery cost: **\$982.40 USD**

Recommended Charger

Two Intellicharge, 8-bay systems.

Charger Cost: **\$1,200.00 USD**

Total System Cost: **\$2,182.40**

Expected Battery fleet life

500 cycles. 5 working days/week, charged every other working day yields a service life of: 3.84years.

Execute as follows:

- Divide metal detectors into two groups of eight detectors.
- Divide the 128 fleet batteries into two groups of 64 batteries. Use spray paint to mark the batteries, different color for each group.
- Alternate the charging. Group 1 gets charged Monday, Group 2 on Tuesday, Group 1 on Wednesday, and so on.
- During the 4-hour evening generator run, use both chargers simultaneously to charge 16 batteries/hour, 64 batteries total in 4 hours.
- On the last weekend of every month, run all of the batteries through a deep discharge/charge conditioning cycle to prevent the "memory effect" from occurring.

Results

Payback Period: **3.41 Months**

Savings over 1 set of batteries: **\$29,491.00 USD**

15.1.2.2 Option 2: Run from Solar Panels

Recommended Batteries. *References: [32, 171].*

Panasonic P-280DR Rapid Charge NiCd. 2800mAH capacity, 50°C operating temp, \$6.14 USD/battery. 128 batteries for fleet + 32 spares

Battery cost: **\$982.40 USD**

Recommended Charger

Two Intellicharge, 8 bay systems.

Charger Cost: **\$1,200.00 USD**

Recommended Battery Bank. *Reference: [172].*

Four OPTIMA D34/78 12 Volt, 55AH Deep cycle Batteries. \$171.USD/ea

These batteries hold enough power to run the two Intellicharge Systems for four days if it is cloudy.

Battery Cost: **\$684.00 USD**

Recommended Solar Panels. *Reference: [58].*

Four PhotoWatt 100 Watt PV panels

These solar panels are powerful enough to restore the battery bank quickly, should it get depleted after several days of cloud.

Panel Cost: **\$1,600.00 USD**

Recommended Charge Controller. *Reference: [173].*

Trace Engineering C40 40 Amp solar charge controller.

Charge Controller Cost: **\$159.00 USD**

Total System Cost: \$4625.40

Execute as for Option 1, except:

- Use the solar panels charge the battery bank during the day
- Run the Intellicharge Systems from the battery bank during the evenings.

Results

Payback Period: **7.22 Months**

Savings over 1 set of batteries: **\$29,491.00 USD**

15.2 Organization B

15.2.1 SCENARIO DESCRIPTION



Figure 15-3: Political Map of Cambodia Region [174].

Below is a description of the working conditions at the (fictitious) Organization B.

"We use Minelab F-Series metal detectors, and each of them takes 4 D-size batteries. Alkaline batteries last five days in these detectors."

We have 18 detectors in a platoon and 3 platoons on a site. That means 216 batteries in use at a site at the same time. Each site goes through 864 batteries per month. Since we work on at least five sites at any given time, we go through 4,320 batteries per month!

We are a large, centralized organization with a head office, several service depots, and a number of local field offices. Our main office and service depots have AC mains, but sometimes the electricity shuts off for a few hours during the day. The main office and two of the field depots have generators.

We have a fleet of light trucks that we use to transport people and equipment from site to site. On a typical day, the work crews meet at either the service depots or the field offices, from there they carry their equipment out to the work sites.

At the end of the day, they return with their equipment and drop it off at the service depots or field offices. Nobody stays at the work sites during the night"



Figure 15-4: The Minelab F4 Mine Detector [3].

Detectors

270 Minelab F4's. Each detector takes four D-size batteries. Alkaline batteries last 5 days in this detector. [166].

Power

AC Mains at main office and 4 service depots. Generators at main office and two service depots. Small fleet of light trucks, one or two are usually parked at each job side. The others are constantly driving about moving people and equipment from one location to another.

Current Battery Usage

4,320 D-size batteries per month

Satellite Climate Data

Table 15-5: Average Air Temperature Recorded in Cambodia [175].

Air temperature (°C)													
Latitude 13 Longitude 104	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
10 Year Average	25.2	27.4	28.4	28.2	26.7	25.6	25.1	25.1	25.1	24.6	23.4	23.1	25.6
El Nino Year (1987)	26.1	27.3	29.7	29.4	27.2	26.2	25.2	25.7	25.3	25.1	24.4	20.7	26.0
La Nina Year (1988)	24.8	27.9	29.0	26.8	26.4	25.3	25.3	25.3	25.5	24.4	23.0	22.2	25.5

Table 15-6: Average Wind Speeds Recorded in Cambodia [176].

Wind speed (m/s)													
Latitude 13 Longitude 104	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
10 Year Average	2.66	2.39	2.06	1.63	1.35	1.65	1.54	1.67	1.27	1.53	2.31	2.68	1.89
El Nino Year (1987)	2.74	2.39	2.14	1.78	1.38	1.53	1.72	1.45	1.28	1.35	2.04	2.92	1.89
La Nina Year (1988)	2.41	2.33	2.08	1.50	1.32	1.51	1.38	1.35	1.12	1.60	2.77	2.72	1.84

Table 15-7: Average Insolation Recorded in Cambodia [177].

Insolation at available GMT times (kW/m ²)													
Latitude 13 Longitude 104	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Average@0	n/a	n/a	0.22	n/a	0.11	0.08	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Average@3	0.46	0.41	0.49	0.53	0.55	0.44	0.47	0.38	0.39	0.45	0.47	0.46	
Average@6	0.62	0.64	0.63	0.64	0.65	0.56	0.61	0.48	0.49	0.54	0.56	0.60	
Average@9	0.31	0.35	0.34	0.33	0.34	0.28	0.32	0.25	0.24	0.25	0.24	0.27	
Average@12	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Average@15	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Average@18	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Average@21	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table 15-8: Average Frequency of Near-Overcast Skies Recorded in Cambodia [178].

Frequency of near-overcast skies at available GMT times (%)													
Latitude 13 Longitude 104	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
>= 70% @0	10.3	6.42	16.3	38.1	58.3	67.9	65.6	77.0	65.3	57.1	29.6	8.83	
>= 70% @3	10.9	11.2	28.7	46.2	58.1	69.2	70.1	79.2	74.0	64.9	29.7	10.8	
>= 70% @6	18.7	34.4	56.4	66.6	59.1	70.4	69.8	81.0	68.4	62.5	36.8	17.3	
>= 70% @9	16.6	16.4	37.3	61.0	73.2	81.2	79.3	88.4	79.9	61.3	36.8	19.7	
>= 70% @12	9.02	8.69	27.3	49.6	77.0	86.0	84.1	88.3	83.3	63.6	36.6	13.6	
>= 70% @15	8.68	9.76	23.8	50.2	73.0	84.7	82.9	86.4	81.0	61.8	36.0	10.8	
>= 70% @18	9.16	8.96	21.4	50.3	76.3	84.0	80.1	87.8	80.6	64.7	37.9	12.1	
>= 70% @21	10.7	11.1	19.4	46.7	68.6	77.5	74.0	82.8	74.9	60.4	37.4	13.2	

15.2.2 ANALYSIS OF OPERATION B

This operation uses 4,320 D-size batteries per month. At \$1.50 USD per battery, their battery costs are \$6480.00 US / month.

The climate in the region is cool enough to use NiMH batteries, but NiCd's will provide better performance in the long run and are more resistant to abuse than NiMH's.

This operation is so large it requires centralized battery management. Because the organization has a number of service depots, each location can be used as a battery distribution point.

Since all of their service facilities have AC Mains power, the selection of a power source is greatly simplified. Had there been no electrical power at the service facilities, a fairly large solar array could have been installed at each facility, providing electricity both for charging batteries and lighting the building. Local weather, usage patterns and user expectations would have to be carefully evaluated before attempting such an installation.

With 4,400mAh rechargeable batteries, a Minelab F4 will run for 3 days between charges. [69].

Recommended Batteries. *References: [32, 33].*

Panasonic P-500DR Rapid Charge NiCd. 4,400mAh capacity, 50°C operating temp, Bought at 100pc discount \$7.52 USD/battery. 1,440 batteries for fleet + 100 spares

Battery cost: **\$11,656.00 USD**

Recommended Charger

Five Intellicharge, 8-bay systems. One system per site.

Charger Cost: **\$3,000.00 USD**

Total System Cost: \$14,656.00 USD

Execute as follows:

- For each jobsite, assign a supply depot to charge its batteries.
- Divide the 54 detectors at each jobsite into three groups of 18 detectors.
- Mark each group of detectors with a different color of paint.
- Each jobsite will need four groups of 72 batteries. At any given time, three of these sets will be inside the detectors, and the fourth set will be at the supply depot, getting charged.
- Mark each group of batteries with a different color of paint so they can be readily identified.
- Each night, send a truck out from the supply depot to the jobsite to deliver a fresh set of 72 charged batteries, and pick up the most discharged set from the work crew.
- Return discharged batteries to the supply depot for charging. Repeat this daily, rotating the sets of batteries.
- On the last workday of every month, run the current set of batteries through a conditioning cycle to the "memory effect" from occurring.
- In an 8 hour workday, the Intellicharge System can charge 64 batteries. Charge eight more over night so that 72 batteries can be charged every day. This allows battery needs to be met with only one Intellicharge System per site.

If the AC mains power fails at any point during charging, the charger will go into sleep mode until it is restored, then resume charging where it left off when power is restored.

In the event of an extended power outage, the Intellicharge System can be run from a vehicle battery. Should that battery also be needed for a vehicle, the engine should be started every two hours to prevent the Intellicharge System from overly discharging it.

Results for the operation described above, excluding labor costs:

Payback Period: **2.26 Months**
 $(14,656.00 / 6,480.00) = 2.26$

Batteries get cycled 5 times each month.
 $(20/3) \times (4/3) = 5$

Savings over 1 set of batteries (assuming a 250 cycle life on each NiCd) = **\$311,040.00 USD**

15.3 Synthesis

Looking at the two case studies outlined above, the savings achieved was roughly proportional to the size of the organization.

Of course, the calculations made are only rough approximations. Field trials using real chargers, real detectors, and real batteries working under realistic operating conditions would be needed for more realistic projections.

The sample calculations do illustrate, however, that significant savings could be possible under the right conditions.

16 Future Design Plans (Mechanical)

16.1 Evaluation of Chassis Design

Since development of the Intellicharge System began, a great deal has been learned about designing components made of molded plastic and bent sheet metal.

We are not satisfied with the current designs of the Chassis and Mounting Plate, but we are confident in our ability to improve on them. Further investigation into both manufacturing processes and user priorities will help us make the design decisions that we are facing.

16.1.1 TWO PRIMARY CONCERNS

The current Chassis design is functional, and at quantities well over 200, the cost to manufacture it would not necessarily be prohibitive. However, we believe the overall cost of the Chassis could still be reduced anywhere from, 15% to 40%.

For example, making large holes in the bottom of the Chassis, directly below the Modules and the power input connector, would eliminate the use of mold inserts. Representatives at local injection molding companies have indicated to us that the mold inserts are a significant portion of the estimated mold price.

The second issue of importance is the use of long threaded rods to hold the System together. The rods are difficult to replace. Moreover, rods only threaded on the ends would have to be used, which further limits the users options. If threaded along the whole length, the threads of the rod could cut into the plastic and weaken the chassis.

In addition, the deep, thin holes must be machined. They cannot be molded.

16.1.2 ALTERNATIVES TO THREADED RODS

The use of these rods was originally selected as a temporary means of assembling our machined prototype. The molded version was to have four long thread inserts.

During continued research and development, we have seen a number of devices, of otherwise excellent quality, ruined by structural failure at the thread inserts. Another alternative would be preferred.

To maintain effective heat transfer between the Heat Spreaders and the Heat Sinks, there must be a

considerable amount of force pressing these parts together. There are two rough ideas that we are investigating.

One approach could be to let the Mounting Plate hold the Heat Sinks loosely in place and use a spring to push the modules outward. Removing the modules may require removal the Mounting Plate. As a result, a small bend in the Mounting Plate could also prevent insertion or removal of the Heat Sinks.

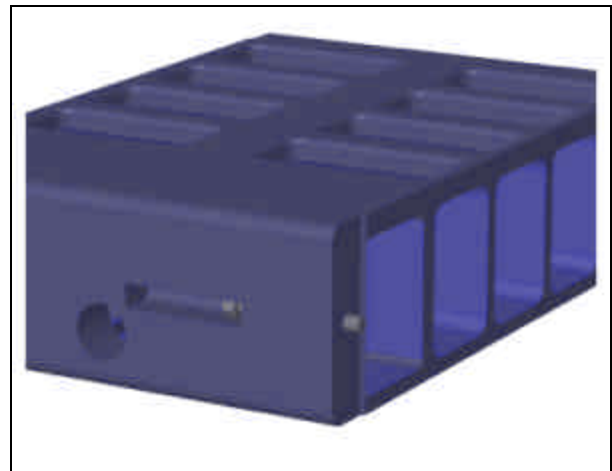


Figure 16-1: Proposed Fastener Modifications

A second approach could be to replace each threaded rod with two bolts. Slots either on the inside or the outside of the Chassis would allow the bolts to be inserted into the present locations of the Heat Sinks. The slots could be lined with strips of stainless steel sheet to protect the plastic. The bolts would protrude from the Chassis in the same places that the threaded rods do now. Figure 16-1 illustrates this concept.

Unfortunately, this design would involve additional mold inserts. A minimal amount of machining for final features on the Chassis could prove the most economical approach, depending upon the quantity produced.

16.2 Battery Contacts and Mud

16.2.1 POSITIVE BATTERY CONTACT

In theory, the stainless steel, positive battery contact is intended to have only the most minimal deflection. It acts more as a rigid ledge to hold down the positive end of the battery than as a spring. Its ability to deflect slightly allows it to move with the battery

when it is shaken and accommodates the range in standard battery dimensions.

During testing, the prototype contact deflected too easily. The prototype did confirm that the geometry of our battery holder would indeed allow the easy removal and insertion of batteries, but the contact had to be somewhat contorted with a couple pairs of pliers before it would hold the battery as firmly as we had hoped. It still allowed us to test the concept behind our design, but our adapted prototype would not have worked perfectly with every brand of D-cell batteries. The geometry of the battery holder seems to serve its functions, however.

A stiffer spring at the battery's negative end would reduce the "amount of spring" required at the stainless steel, positive battery contact. The Connect2it negative battery contact will be upgraded to a 28.8oz. spring from the 10.8oz springs, which were sent to us as samples. Besides the force in the spring, these contacts are identical.

16.2.2 MUD AND BATTERY CONTACTS

The Connect2it, 4 Point Crown battery contacts are actually advertised as "self-cleaning." Similar pointed tips are used for testing circuit boards on an assembly line in situations where the boards are covered with a thick layer of contaminants (masking compound, flux, thermal grease, etc.).

The positive battery contact design could, admittedly, get covered with mud. Consideration has been taken to avoid mud-related complications during operation, but testing would be required to see how successful it is.

First, the positive contact has an open profile. Unlike many similar battery contacts, the metal does not bend about itself, forming a loop (Figure 16-3).

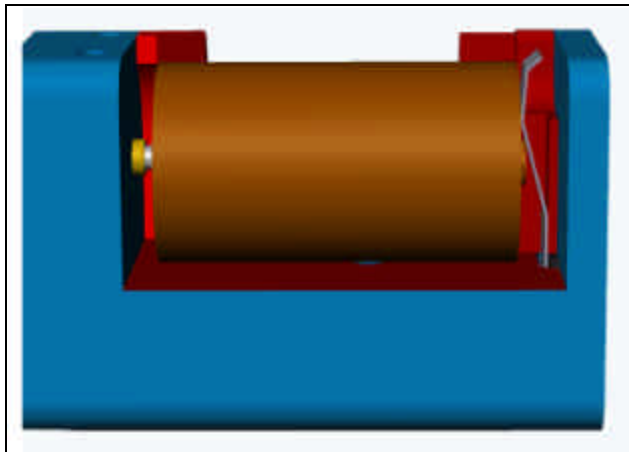


Figure 16-2: Partial Cut-Away View of Battery Holder

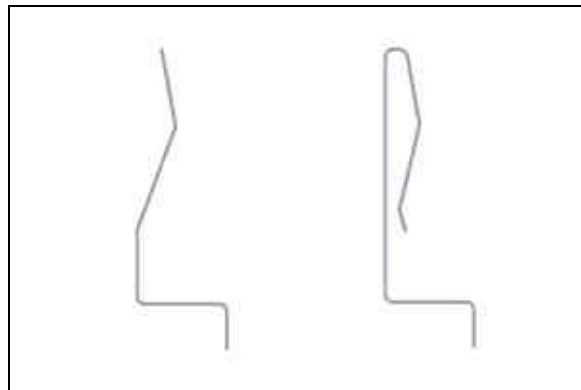


Figure 16-3: Alternative Battery Contacts

Second, the battery will be under more compressive force than what is usual for battery holders. The force helps the battery push through the any grime on the contact.

Third, the surfaces are not parallel. It is the edge of the battery that must push against the contact. While not as sharp as the points of a Connect2it battery contact, the edge is more likely to push through the dirt than a flat face.

Fourth, any dirt stuck behind the contact will have little effect on its functionality, because the contact is not intended to deflect much anyhow.

16.3 Last Wrench to Throw

Drainage. All of our early designs contained some sort of drainage; an escape route for the water that could be pouring down from the sky, right into our battery charging system.

Of course the water will seep out of the device all on its own, eventually, but not fast enough. Our concern is not with water damage but with the inconvenience of a wet battery charging unit and, more significantly, the unwanted tropical guests that tend to proliferate in stagnant pools of water.

Drainage holes could be molded or machined into the Chassis without any great difficulty. We decided several months ago that we would shelve the drainage issue for the time being so that we could focus on the other aspects of our design. It is our intent to include some provision for drainage once the Chassis design is closer to be finalized.

17 Future Design Plans (Electrical)

17.1 900kHz Switching Regulators

While the switching regulators used in the Cell Charger modules serve the purpose, there is much room for improvement in the design.

As it stands, the architecture of the PIC16F873 microcontroller and the frequency at which it operates limits the operating frequency of the switching regulator to 20kHz.

This requires a very large inductor and very large filter capacitors for the device to operate. Heat buildup in the inductor also limits the current output of the cell charger.

By using a dedicated switching regulator controller that has a “sync” output pin which is tied to the controller’s clock, and then connecting that pin to a divide-by-100 counter, it is possible to get a usable synchronization signal from the regulator.

When this signal is connected to an interrupt line on the PIC16F873, and the correct code added to the interrupt service routine, it is possible to get the device to sample the battery voltage and current at the correct time, every time.

By having the switching regulator operate at 900kHz, the size (and cost) of the components used drops dramatically. Figure 17-1 shows the components used in the first switching regulator design on the left, and the much smaller components in the latest design revision on the right.



Figure 17-1: Switching Regulator Components

17.2 Greatly Reduced Size

Many manufacturers of components used in the first version of our design have now started to offer the components in much smaller case sizes. This allows us to fit many more components on the same area of a Printed Circuit Board (PCB).

This will allow us to re-design the printed circuit boards to be far smaller and compact than the initial versions, especially if we decide to use four-layer boards. It is not unrealistic to expect a 75% reduction in the size of the electronics packages following the next round of electrical design revisions.

This will translate into significant reductions in manufacturing costs, as well as allowing the size of the charger as a whole to be reduced significantly.

18 Conclusion

Less than a year into the development of our battery charging system, we have already met the most challenging of the design criteria and prototyped the current version of the system.

The Intellicharge System already brings battery charging technology much closer to being a viable option for demining operations. Significant achievements of the design include:

- An entirely new approach to battery charging technology that is able to charge batteries at an optimal rate with superior reliability by using individual chargers with carefully planned, “intelligent” algorithms.
- A promising new design of a battery holder that combines physical durability with ease of access, all while holding batteries firmly in place.
- Development of the first (to the best of our knowledge) autoranging power supply on a battery charger.
- Opening of the door to a new approach to battery charger design by eliminating the need for an outer case.
- Clarification of what the humanitarian demining community needs in a battery charger. If not finished our exploration of the problem yet, we can still offer a head start to any future developers of battery charging technology.

We feel that the Intellicharge System has the potential to become a highly successful product. However, to continue the development and testing of the System, we are now seeking the support and guidance of interested members of the demining community.

The next steps in the development of the Intellicharge System design are:

- Receive feedback on the design presented within this report and, with that feedback, reevaluate our design.
- Consider the extent of necessary changes and set a time line for the next full design revision.
- Rework the Chassis design to improve manufacturability and water drainage as well as to address potential concerns over the current usage of fasteners.
- If worthwhile, use finite element method to simulate the Intellicharge System under

dynamic loading to assess how certain design revisions would influence the device's physical durability.

- Continue discourse with members of the demining community to correct, clarify, and/or support our recommended modes of incorporating the Intellicharge System into demining operations (includes further discussion of how the System is best mounted, who operates it, how and when).
- Make minor refinements to the electrical design to optimize efficiency before testing the heat loss through various components of the Intellicharge System. Adjust heat-transferring components accordingly.
- Refine the positive battery contact for functionality and resilience to mud.
- Determine the extent of resources that can be made available to us, what additional resources are needed, and a strategy for securing those additional resources.
- Continue research into military and industrial standards for testing to clarify and support quantifiable targets for the final design.

19 Author Biographies

Carl Roett



In addition to his contributions to the computer and electrical design of the Intellicharge system, Carl is also a full-time Computer Engineering student at the University of Calgary in Canada. He will graduate with his Bachelor of Science in May 2003.

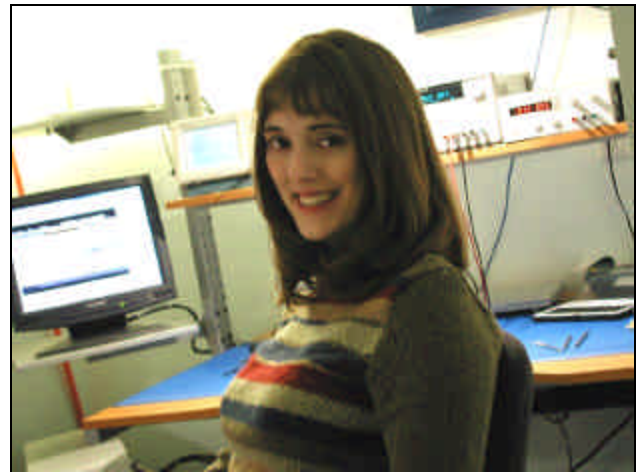
For the past six years, Carl has been the proprietor of HyperLight Research. HyperLight repairs, maintains, and resells a wide variety of specialized electronic equipment, from robotic lighting systems for discotheques to high-powered industrial lasers.

Carl will be continuing development of the electrical systems used in the Intellicharge system as the design continues to evolve into a marketable product.

The best way to contact Carl is by E/mail.

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Tara Dorscher



Tara Dorscher graduated in April of 2002 from Mechanical Engineering at the University of Calgary. She currently works as a design engineer at Red Flame Hot Tapping Services in Red Deer, Alberta.

Tara previously gained design experience during her 15-month internship at Ryan Energy Technology Inc. (May 2000 to July 2001). Ryan provides both Measuring and Logging While Drilling services to the directional drilling industry.

Tara will be continuing work of the thermal and mechanical aspects of the design while working towards lowering the manufacturing costs of the system.

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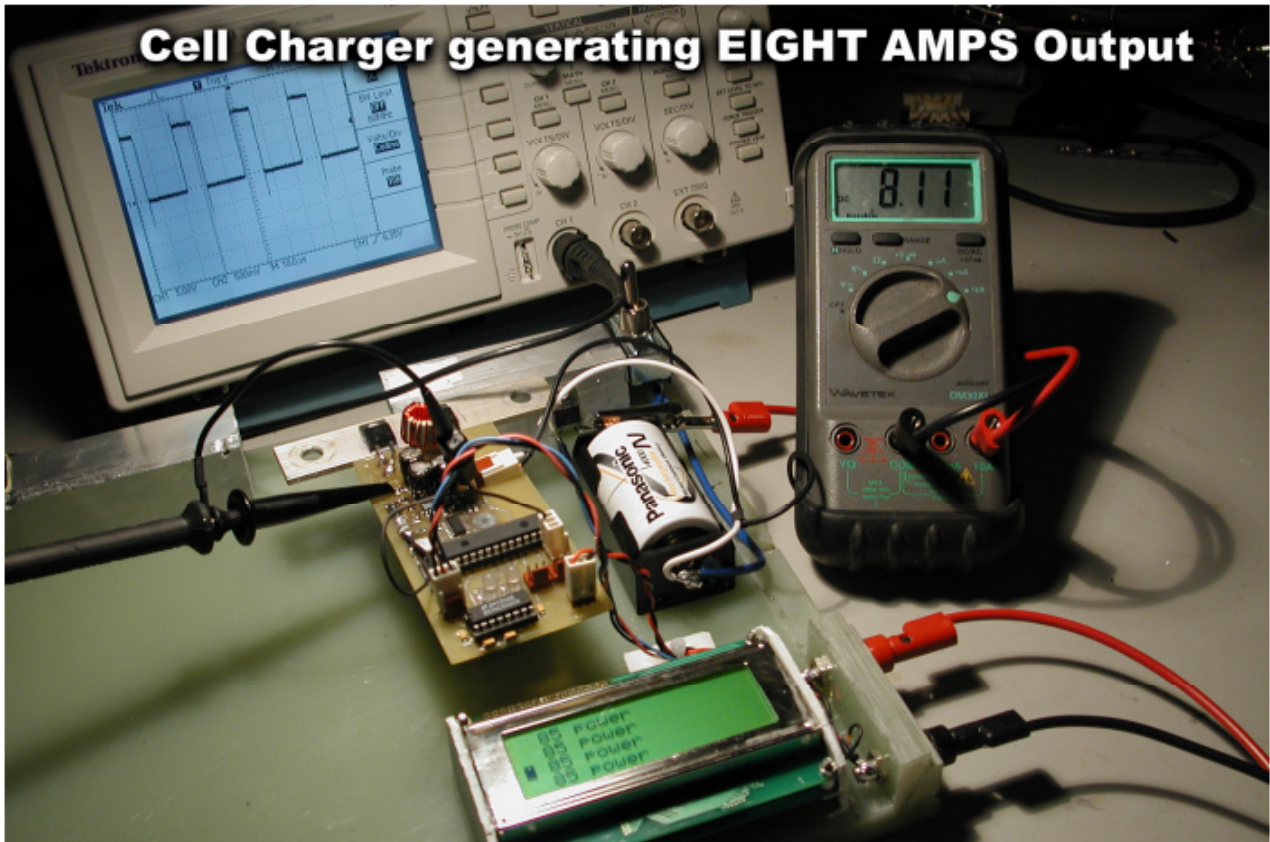
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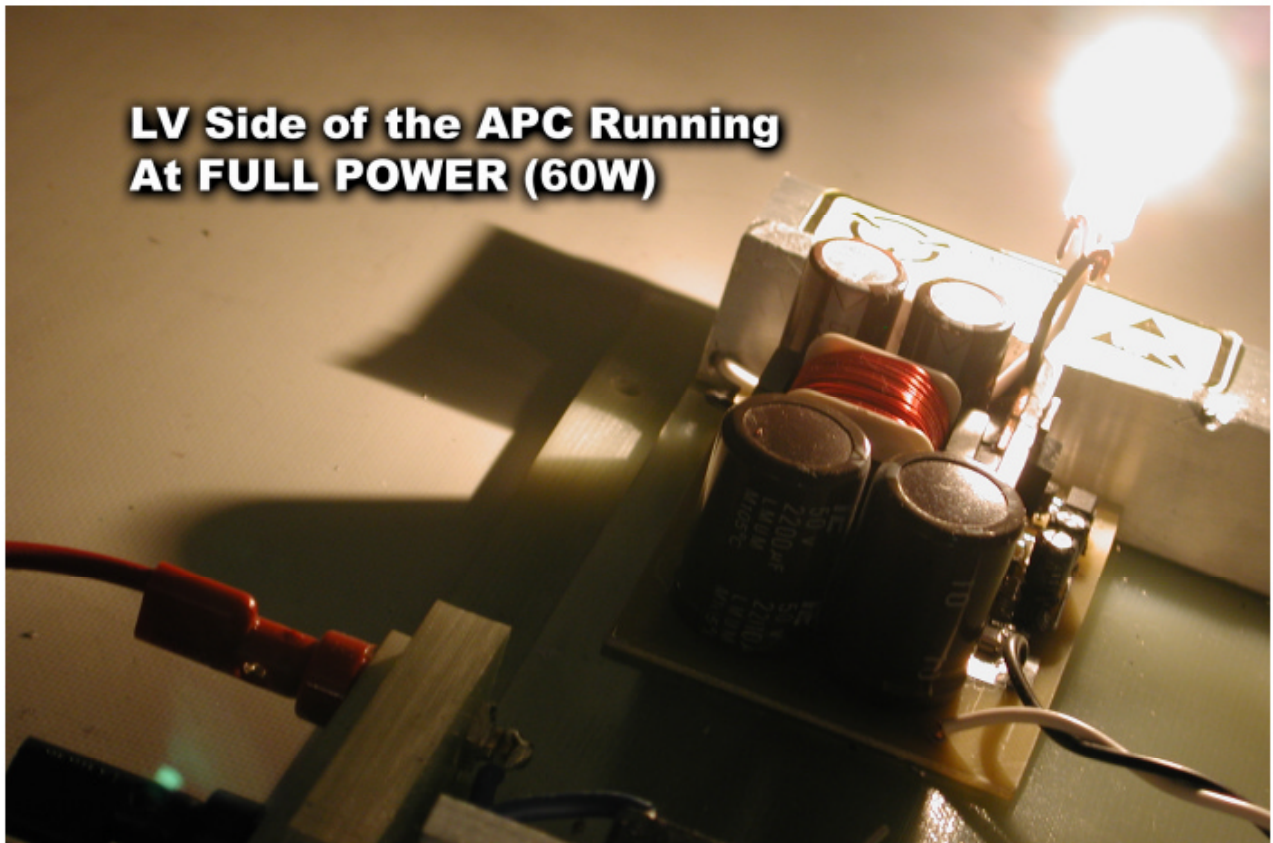
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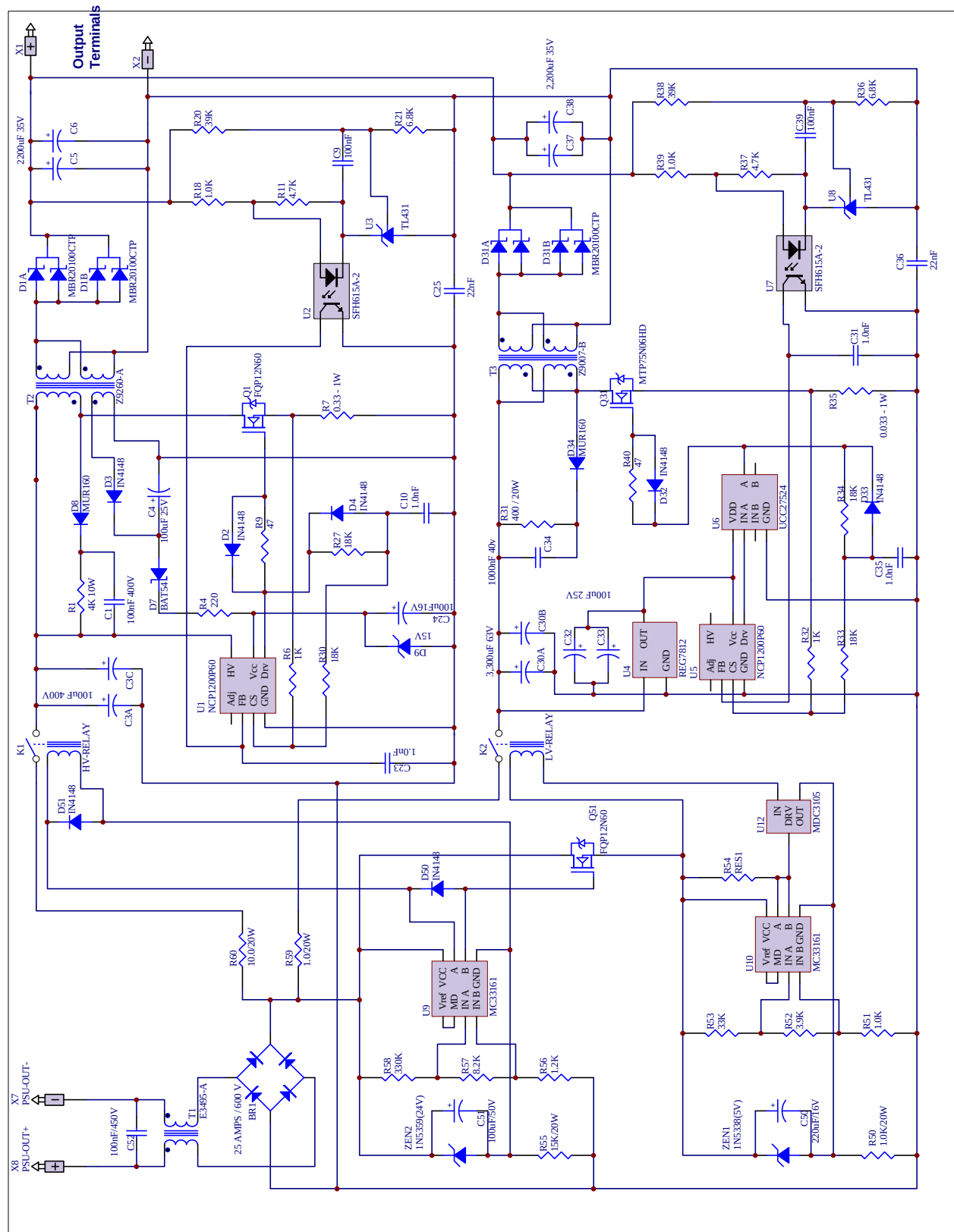


Cell Charger generating EIGHT AMPS Output



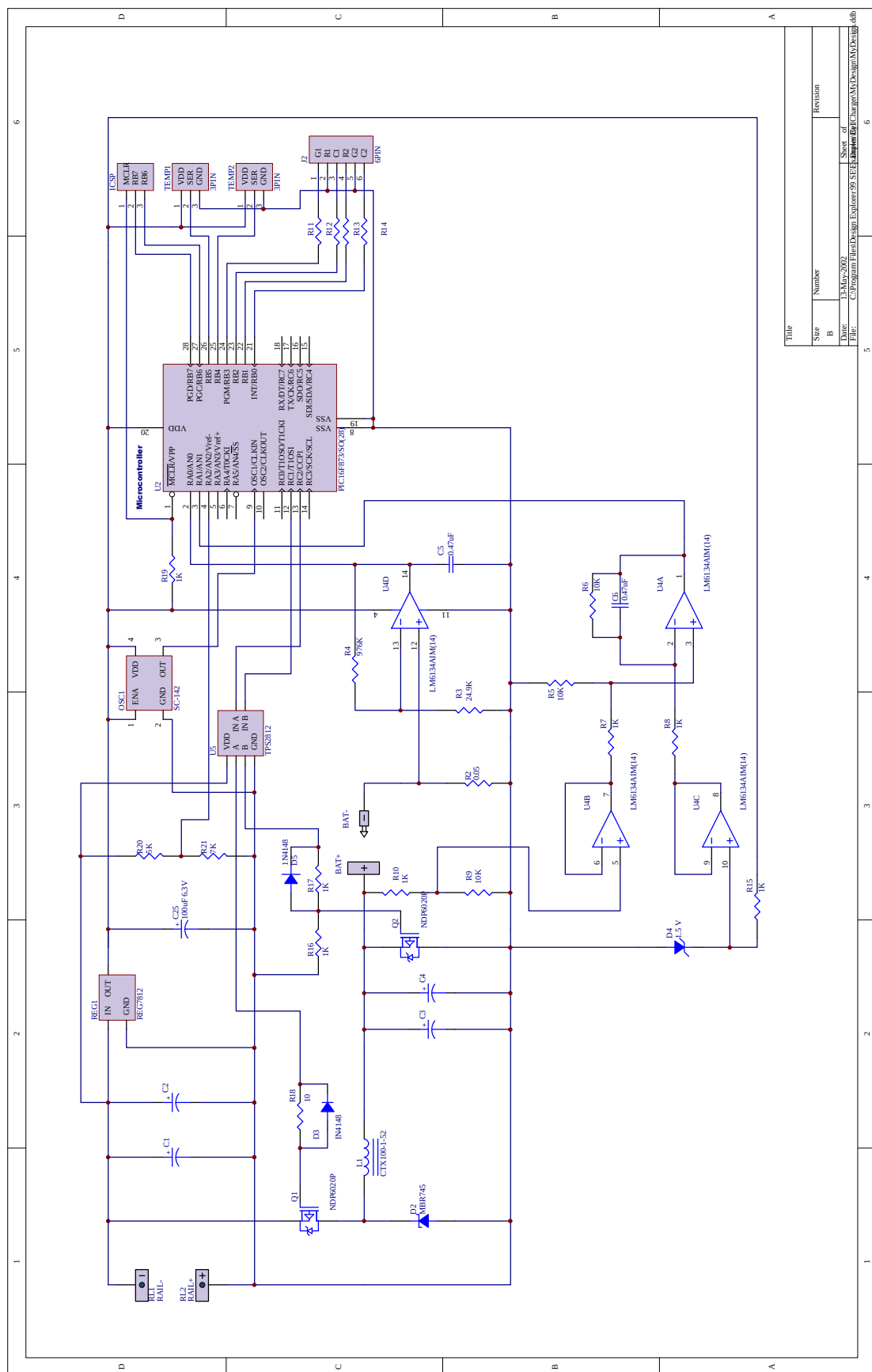
**LV Side of the APC Running
At FULL POWER (60W)**





Autoranging Power Converter Bill of Materials

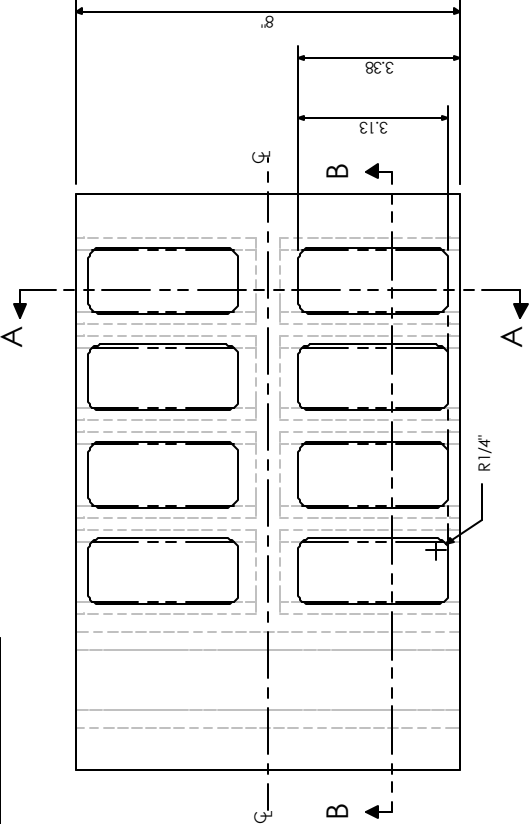
	MANUF. PART NO.	DESCRIPTION	QTY.	UNIT COST	TOTAL	MIN.	MANUFACTURER
FILL-CPD	3141 Potting	Thermally Conductive Potting	0.3	0.025	0.0075	4000	Loctite
	3163 Hardener	Hardener for Potting Compound	0.1	0.04	0.004	1000	Loctite
HS-GLUE	315 Thermal Glue	Self Shimming Heat Sink Glue	0.1	1.21	0.121	30	Loctite
HS-PAD	5509 Pad	Thermally conductive Pad	8	0.404	3.232	3750	3M Canada
T1	H7019-A	8 A 0.79mH Common Mode Choke	1	5.82	5.82	1	Coilcraft
T2	Custom	LV Supply Flyback	1	4	4	1	Coilcraft
T3	Custom	HV Supply Flyback	1	4	4	1	Coilcraft
ZEN1	1N5338	5 Volt 5 Watt Zener Regulator	1	0.206	0.206	1000	OnSemi
ZEN2	1N5359	24 Volt 5 Watt Zener Regulator	1	0.206	0.206	1000	OnSemi
D2,4,32,33,50,51	1N4148	High Speed High Cond Diode	6	0.017	0.102	1000	Fairchild Semi
D7	BAT54	Small Signal 30V Schottky	1	0.128	0.128	3000	OnSemi
D8, D34	MUR160	Rectifier 1A 600V Ultrafast	2	0.159	0.318	1000	OnSemi
U3, U8	TL431ACLP	Adjustable Shunt Voltage Regulator	2	0.253	0.506	98	OnSemi
U1, U5	NCP1200P60	Switching PSU Controller 60KHz	2	0.048	0.096	1000	OnSemi
U9, U10	MC33161	Dual Voltage Monitor	2	0.867	1.734	98	OnSemi
U2, U7	SFH615A-2	5.3KV Opto, High Reliability	2	0.13	0.26	100	Vishay
U12	MDC3105	Integrated Relay Driver	1	0.159	0.159	3000	OnSemi
U6	UCC27325	4 AMP MOSFET Driver	1	1.08	1.08	50	Texas Inst
K1	G5CE-1-DC24	120V 15A SPST Relay 24V Coil	1	2.64	2.64	10	Omron
K2	G5CE-1-DC5	120V 15A SPST Relay 5V Coil	1	2.56	2.56	10	Omron
Q1, Q51	FQP12N60	10.5A 600 Volt N MOS TO-220	1	1.08	1.08	1000	Fairchild Semi
Q31	MTP75N06HD	75A 60V N Channel MOS TO-220	1	1.813	1.813		OnSemi
BR1	GBPC2506W	25A 600V Bridge GBPC Case	1	2.55	2.55	1000	Fairchild Semi
U4	MC7812CT	1A 12V Regulator TO220 Package	1	0.319	0.319	50	OnSemi
D1A-D2B	MBR20100CT	100V 20A Schottky TO-220	4	0.759	3.036	50	OnSemi
C52, C1	P10755-ND	0.1µF 450V Poly Cap	2	0.34	0.68	10	Panasonic
C34	EF1105-ND	1.0µF 100V Poly Cap	1	0.53	0.53	10	Panasonic
C25, 36	P225255-ND	22nF 2500V Isolation cap	2	0.31	0.62	1000	Kemet
C3A,B	107LBA400M2BD	100µF 450V 105C Electrolytic	2	1.98	3.96	1	Illinois Cap
C30A,B	338LMU063M2BD	3300µF 63V 105C Electrolytic	2	2.31	4.62	1	Illinois Cap
C5,6,37,38	228LSR035M	2200µF 35V 105C Electrolytic	4	1.32	5.28	1	Illinois Cap
C32, 33, 4	NRSZ101M25V6.3X11	100µF 25V 105C Electrolytic	3	0.09	0.27	1000	NIC
C50, 24	NRSZ221M16V6.3X11	220µF 16V 105C Electrolytic	2	0.11	0.22	1000	NIC
C51	NRSZ101M50V6.3X11	100µF 50V 105C Electrolytic	1	0.11	0.11	1000	NIC
R60	TAH20P010RJ-ND	10 Ohm 20 Watt Power Resistor	1	2.45	2.45	10	Ohmite
R59	TAH20P001RJ-ND	1 Ohm 20 Watt Power Resistor	1	2.45	2.45	10	Ohmite
R55	TAH20P15K0J-ND	15K 20 Watt Power Resistor	1	2.45	2.45	10	Ohmite
R50	TAH20P1K00J-ND	1K 20 Watt Power Resistor	1	2.45	2.45	10	Ohmite
R1	TAH20P4K00J-ND	4K 20 Watt Power Resistor	1	2.45	2.45	10	Ohmite
R31	TAH20P470RJ-ND	470 Ohm 20 Watt Power Resistor	1	2.45	2.45	10	Ohmite
R7	PT.33UCT-ND	0.33 Ohm 1 Watt Current Sense	1	0.96	0.96	10	AVX
R35	PT.033UCT-ND	0.033 Ohm 1 Watt Current Sense	1	0.96	0.96	10	AVX
LED1	LTL-30EFJP	Bi-Color Red/Green LED 3PIN	2	0.094	0.188	1000	Lite-On Semi
Various	2206 Series Resistors	Various 1/8W SMT Resistors	24	0.01	0.24	1000	Ohmite
Various	2206-2208 Size Caps	Various Low Value SMT Caps	5	0.03	0.15	1000	Kemet
PCB	PCB	Printed Circuit Board Fabrication	1	10.96	10.96	10	APC
LOAD	LOAD	Load and solder components	1	10.00	10.00	1	
				TOTAL	90.43		



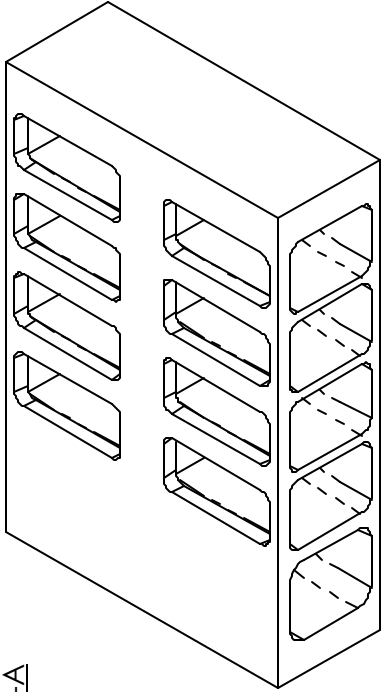
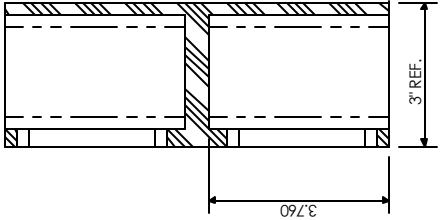
14.3 Cell Charger Module Bill of Materials

	MANUF. PART NO.	DESCRIPTION	QTY.	UNIT COST	TOTAL	MIN.	MANUFACTURER
FILL-CPD	3141 Potting	Thermally conductive potting	0.03	0.025	0.00075	4000	Loctite
	3163 Hardener	Hardener for potting compound	0.01	0.04	0.0004	1000	Loctite
SENS-FIL	TC 2707	Thermally conductive epoxy	0.05	0.688	0.0344	444	3M Canada
HS-GLUE	315 Thermal Glue	Self Shimming Heat Sink Glue	0.1	1.21	0.121	30	Loctite
HS-PAD	5509 Pad	Thermally conductive pad	2	0.404	0.808	3750	3M Canada
LED1	LTL-30EFJP	Bi-Color Red/Green LED 3PIN	2	0.094	0.188	1000	Lite-On Semi
C1, C2	NRSZ221M16V	220µF 16V Thru Hole Elect	2	0.11	0.22	1000	NIC Components
C3, C4	NRSZ471M6.3V	470µF 6.3V Thru Hole Elect	2	0.09	0.18	1000	NIC Components
U6	UCC27325	4 AMP MOSFET Driver	1	1.08	1.08	50	Texas Inst
D3, D5	1N4148	High Speed High Cond Diode	2	0.017	0.034	1000	Fairchild Semi
Q2	FQP12N60	10.5A 600 Volt N MOS TO-220	1	1.08	1.08	1000	Fairchild Semi
Q1	MTP75N06HD	75A 60V N Channel MOS TO-220	1	1.813	1.813	50	OnSemi
D2	MBR745	7.5A 45V Schottky Rectifier	1	0.533	0.533	50	OnSemi
OSC1	SC-1420	20MHz Surface Mount Osc	1	0.85	0.85	1000	NEL Freq Controls
IND1	CTX100-1-52LP	100µH 2.4A Toroidal Inductor	1	0.89	0.89	50	Coiltronics
REG1	MC7805CT	1A 5V Regulator TO220 Package	1	0.319	0.319	50	OnSemi
U2	PIC16F873-SO	4K Flash CPU SOIC Package	1	3.21	3.21	100	Microchip Inc
TMP1, 2	MAX6576	1 Wire Serial Temp Sensor	2	0.61	1.23	1000	Dallas-Maxim
SENS1	AVX P50MCT-ND	0.05 OHM Current Sense	1	0.62	0.62	10	AVX Components
U4	LM6134AIM	General Purpose Dual Op-Amp	1	1.58	1.58	100	National Semi
R1-R10	2206 Series Resistors	Various 1/8W SMT Resistors	19	0.01	0.19	1000	Ohmite
C5, C6	2206-2208 Size Caps	Various Low Value SMT Caps	2	0.03	0.06	1000	Kemet
PCB	PCB	Printed Circuit Board Fabrication	1	2.53	2.53	10	APC
LOAD	LOAD	Load and Solder Components	1	1.30	1.30	1	
				TOTAL	\$18.87		

X	PROTOTYPE	TLD
-	PRODUCTION	-
-	OBSOLETE	-



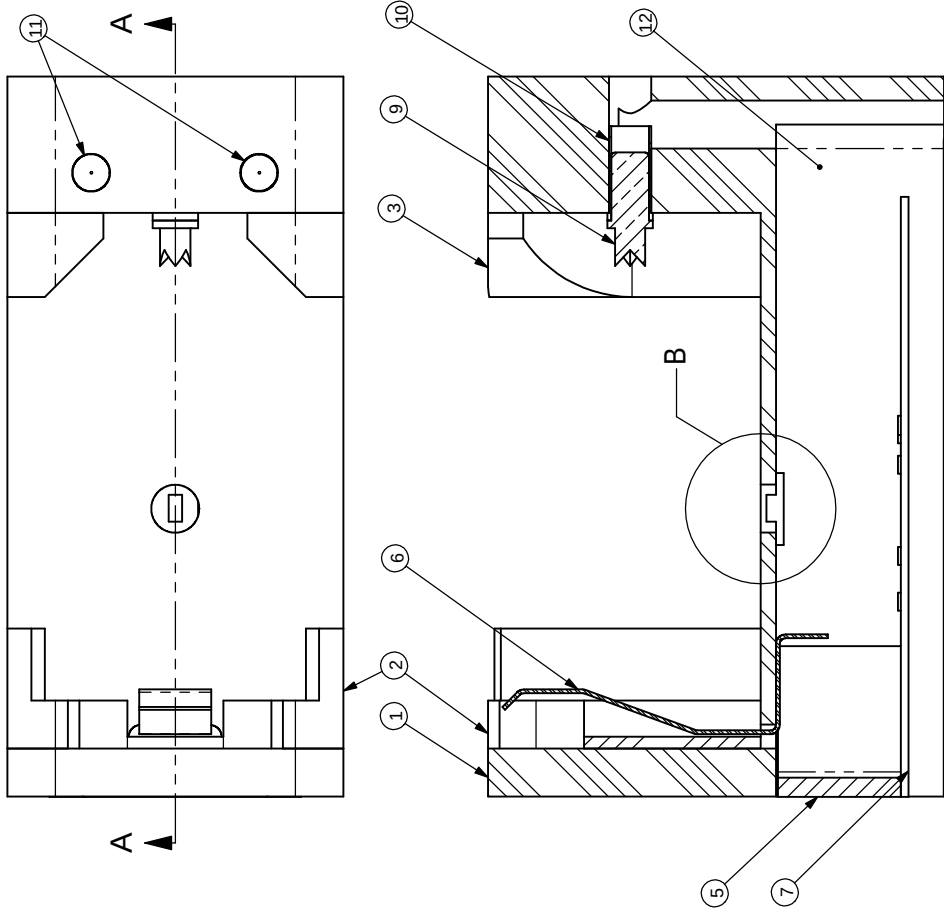
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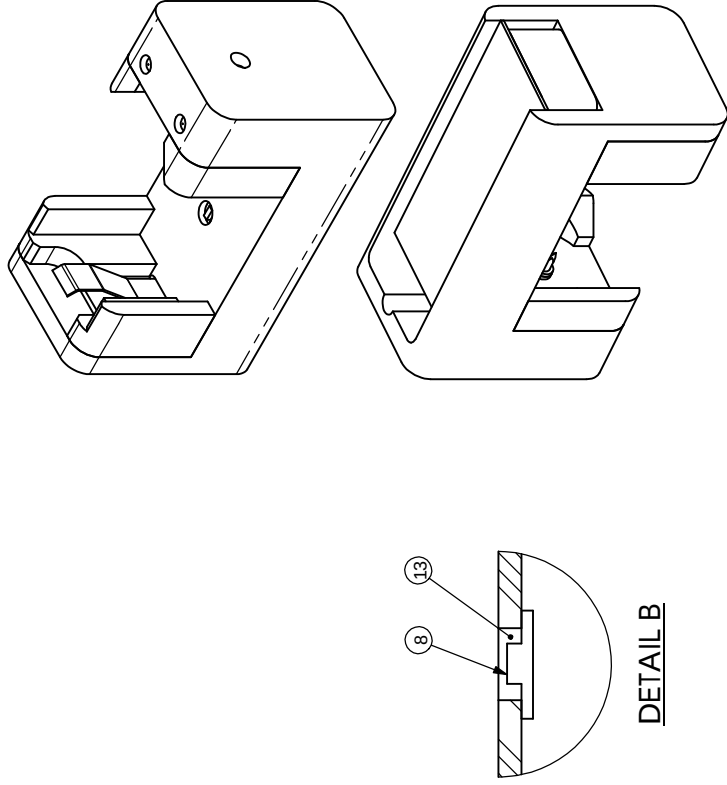
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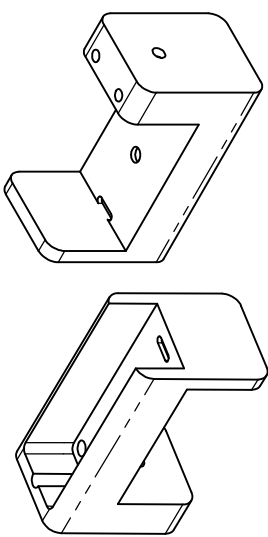
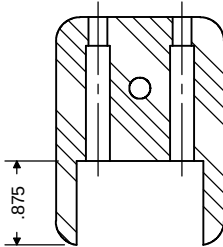
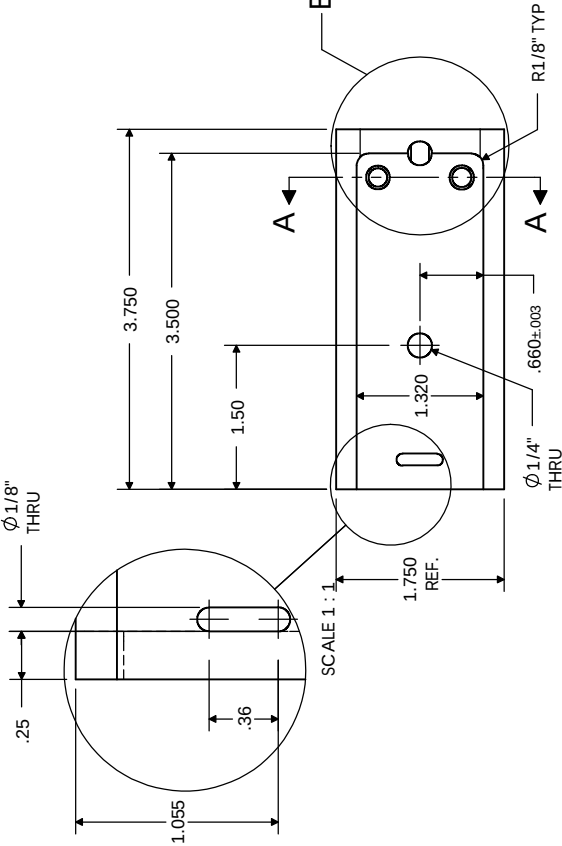
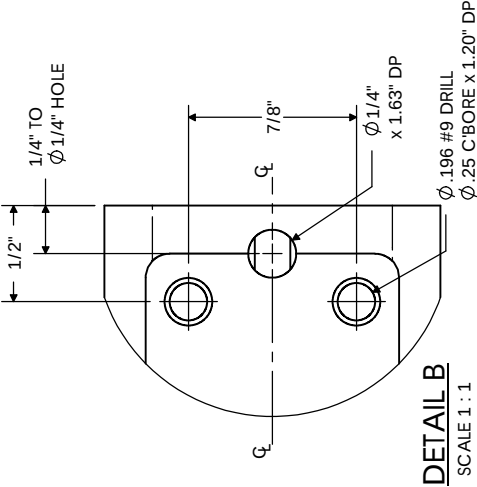
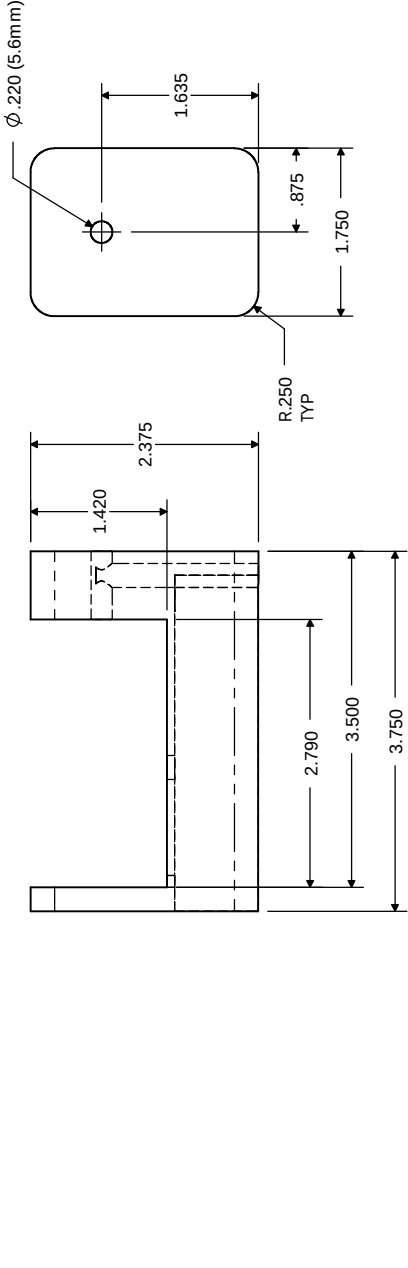


SECTION A-A



DETAIL B

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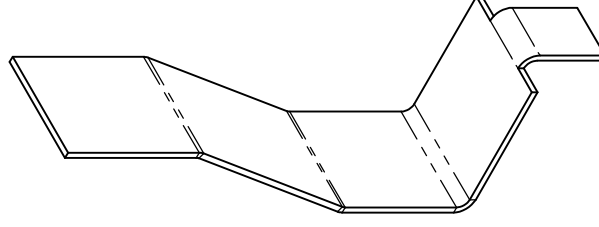
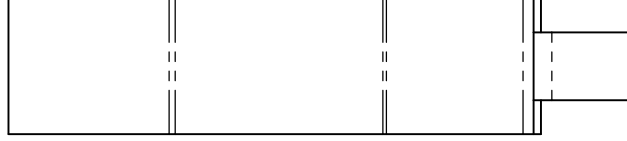
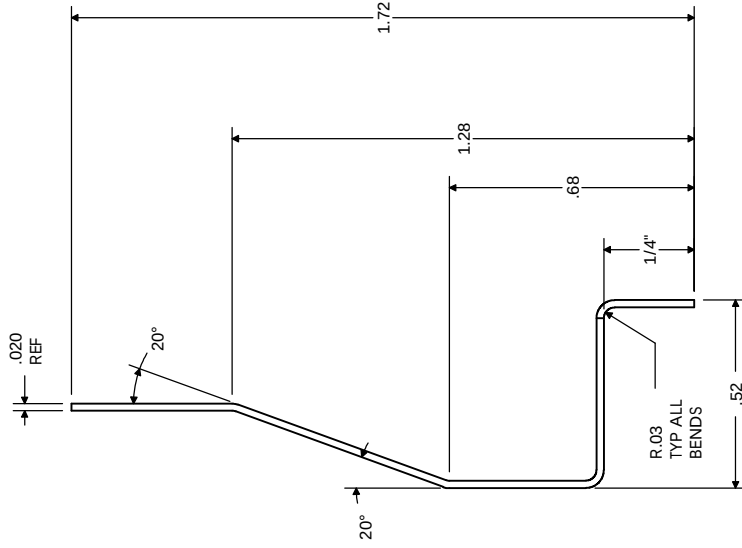
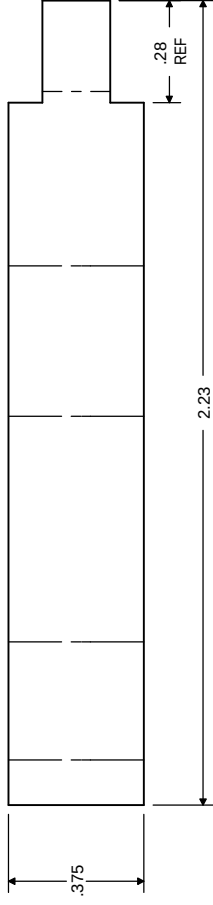
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GROUP #14
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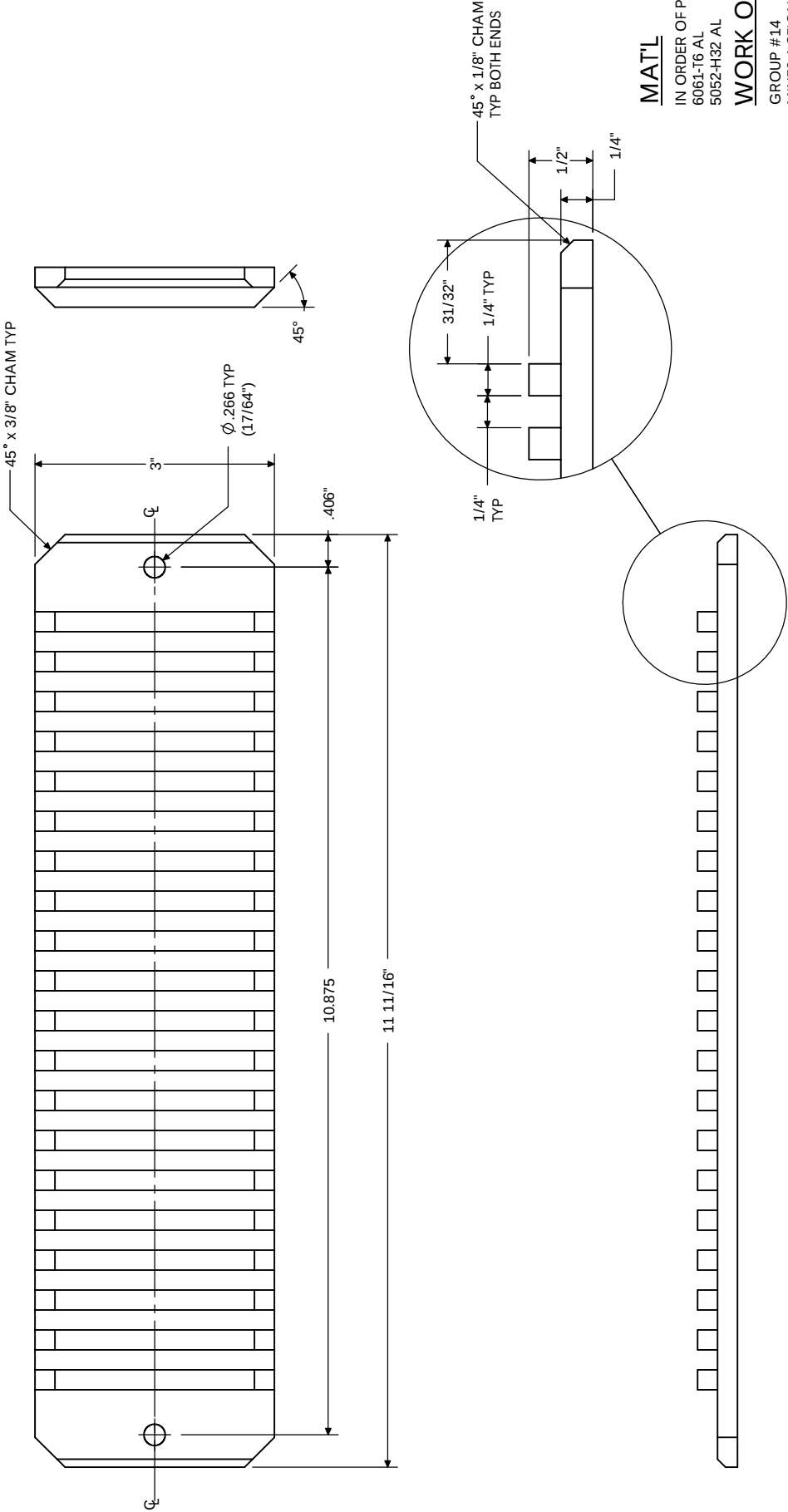
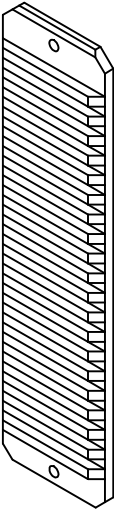
26 Ga. SS SHEET

WORK ORDER

GROUP #14
MINES ACTION CANADA

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X	PROTOTYPE	TLD
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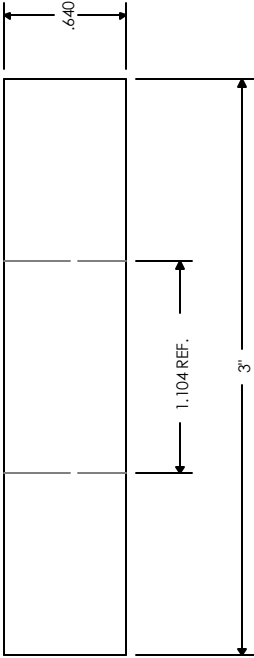


MAT'L
 IN ORDER OF PREFERENCE:
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 5052-H32 AL
WORK ORDER
 GROUP #14
 MINES ACTION CANADA

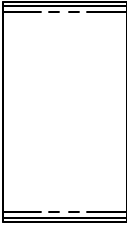
--	---	----	--	ALL DIMENSIONS IN INCHES					INTELLICHARGE Hostile Environment Battery Chargers 652 Willingdon Blvd. S.E. Calgary AB T2J 2B4 PH: (403) 585-1437 EMAIL: dorscher@intellicharge.ca WEBSITE: www.intellicharge.ca	DRAWN BY:	TLD	DATE:	2002/02/24		
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--	DISTANCE BETWEEN BOLT HOLES WAS INCORRECT		2002/02/28	TLD						APPROVED BY:	TLD	DATE:	2002/02/24		
--	OVERALL LENGTH WAS 11-7/8"		2002/02/24	TLD						PART NAME HEAT SINK & CATEGORY: BCG					
A1	DRAWN ON SOLIDWORKS 2001		2002/02/24	TLD						PART NUMBER: 3-10A1-10					
REV.	DESCRIPTION		DATE	BY						FILE NAME: 3-10A1-10.SLDDRW				SCALE: 1:2	SHEET: 1 of 1

X	PROTOTYPE	TLD
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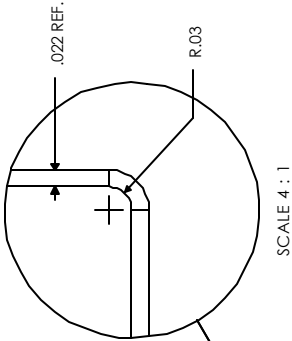
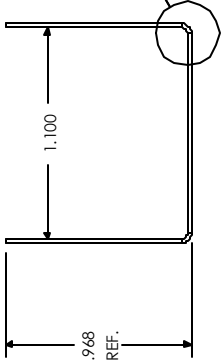
FLAT PATTERN



BENT
FRONT VIEW



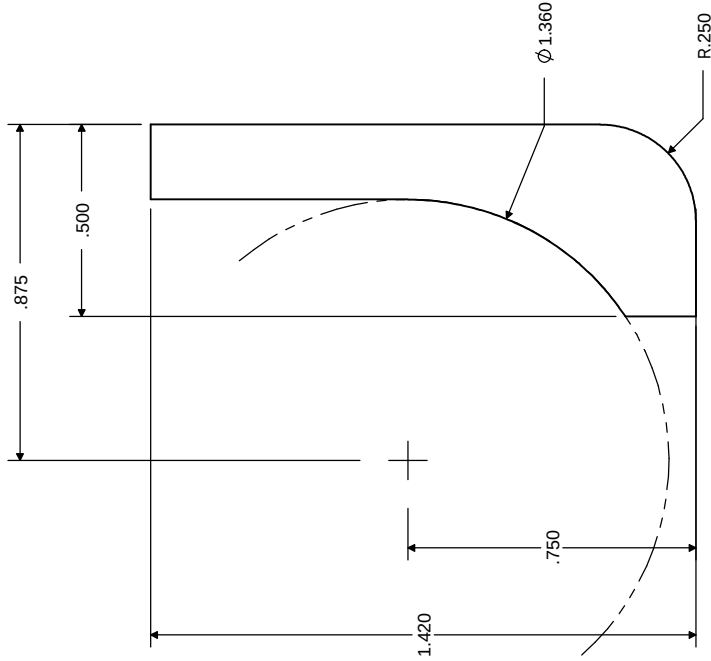
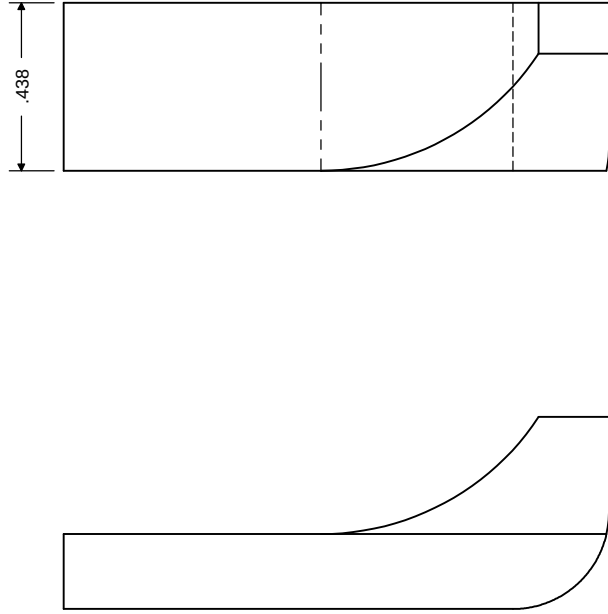
BENT
TOP VIEW



MAT'L
24 Ga. COPPER SHEET

WORK ORDER
GROUP #14
MINES ACTION CANADA

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				---/--/---		---		PART NAME HEAT SPREADER & CATEGORY: CCM							
A		DRAWN ON SOLIDWORKS 2001		2002/02/23		TLD		PART NUMBER: 3-11A-11				SCALE: 1:1			
REV.		DESCRIPTION		DATE		BY		FILE NAME: 3-11A-11.SLDDRW				SHEET: 1 of 1			

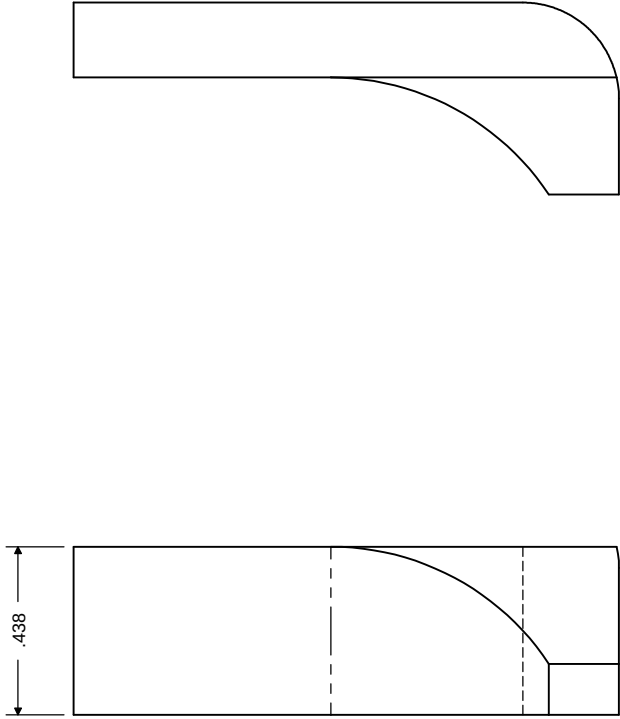
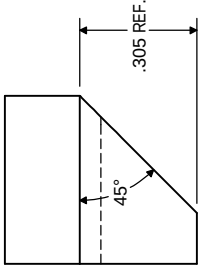
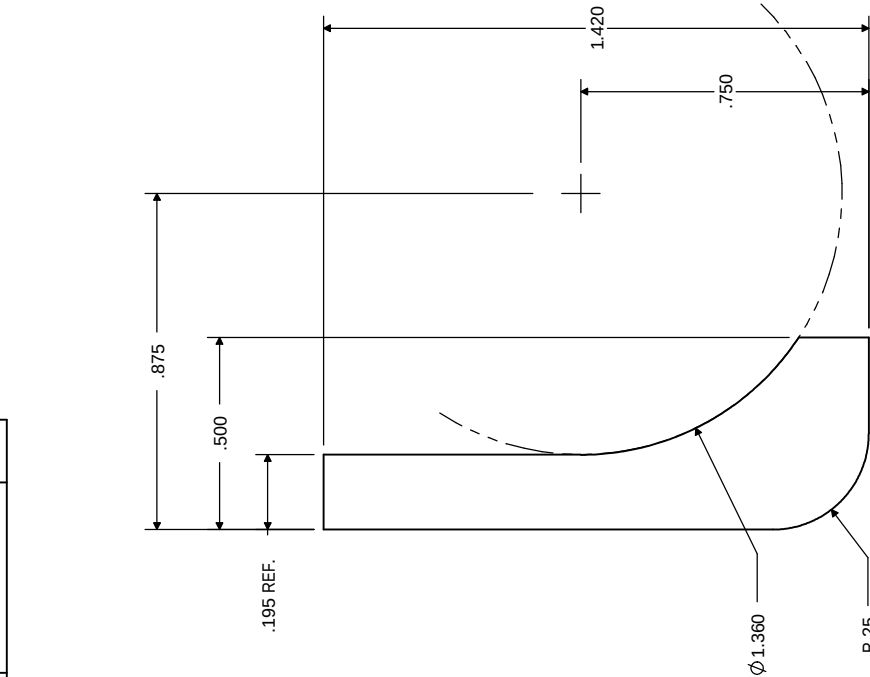


MAT'L
ABS
NOTE

THIS PART IS THE MIRROR
IMAGE OF PART NO. 3-09B1-11

--	---		----/--/----	--	ALL DIMENSIONS IN INCHES USE THE FOLLOWING TOLERANCES UNLESS OTHERWISE STATED: LINEAR FRACTIONS ± 1/32" X.XX ± 0.01" ANGULAR X° ± 30'	INTELLICHARGE Houston Environment Battery Chargers 652 Willingdon Blvd. S.E. Calgary AB T2J 2B4 PH: (403) 585-1437 EMAIL: dorscher@intellicharge.ca WEBSITE: www.intellicharge.ca	DRAWN BY:	TLD	DATE:	2002/02/18
--	---		----/--/----	--			CHECKED BY:	TLD	DATE:	2002/02/23
B2	WIDTH WAS 5/8in. ANGLE WAS 40deg.		2002/03/14	TLD			APPROVED BY:	TLD	DATE:	2002/02/23
--	CORRECTED AN OUT-OF-SYNC DIMENSION		2002/03/29	TLD			PART NAME & CATEGORY: NEGATIVE BATTERY CRADLE - RIGHT CCM			
A2	DRAWN ON SOLIDWORKS 2001		2002/02/18	TLD			PART NUMBER: 3-09B2-11			
REV.	DESCRIPTION		DATE	BY			FILE NAME: 3-09B2-11.SLDDRW			
									SHEET:	1 of 1

X	PROTOTYPE	TLD
-	PRODUCTION	-
-	OBSOLETE	-



NOTE

THIS PART IS THE MIRROR
IMAGE OF PART NO. 3-09B2-11

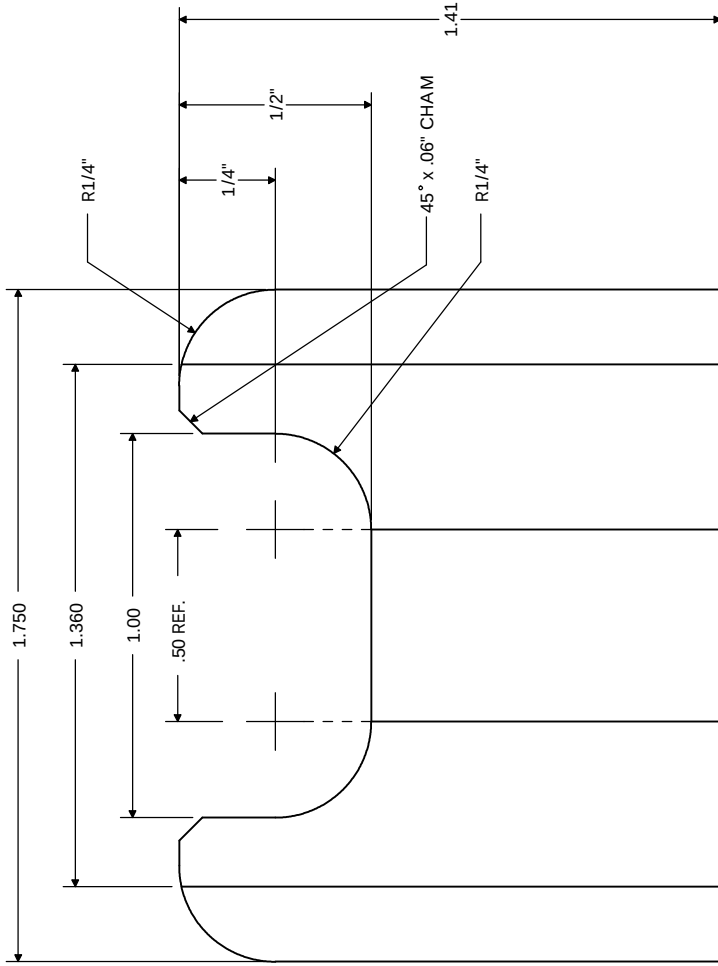
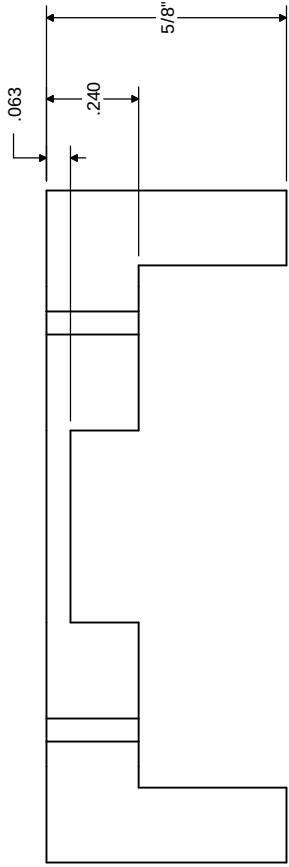
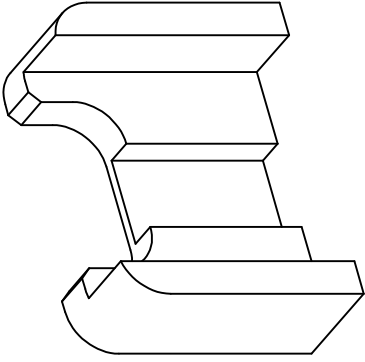
MAT'L

ABS

REV.	DESCRIPTION	DATE	BY	ALL DIMENSIONS IN INCHES	
--	---	----/--/--	--	USE THE FOLLOWING TOLERANCES UNLESS OTHERWISE STATED:	
--	---	----/--/--	--	LINEAR FRACTIONS $\pm 1/32"$ X.XX $\pm 0.01"$ X.XXX $\pm 0.005"$	
B1	WIDTH WAS 5/8in. ANGLE WAS 40deg	2002/03/14	TLD	ANGULAR X° $\pm 30'$	
--	ADDED MOUNTING HOLE NOTE, FIXED PART NAME	2002/02/23	TLD		
A1	DRAWN ON SOLIDWORKS 2001	2002/02/18	TLD		
REV.	DESCRIPTION	DATE	BY		

INTELLICHARGE Hostile Environment Battery Chargers		DRAWN BY:	TLD	DATE:	2002/02/18
652 Willingdon Blvd. S.E. Calgary AB T2J 2B4 PH: (403) 585-1437 EMAIL: dorschel@intellicharge.ca WEBSITE: www.intellicharge.ca		CHECKED BY:	TLD	DATE:	2002/02/21
PART NAME: NEGATIVE BATTERY CRADLE - LEFT & CATEGORY: CCM		APPROVED BY:	TLD	DATE:	2002/02/21
PART NUMBER: 3-09B1-11		SCALE: 2:1			
FILE NAME: 3-09B1-11.SLDDRW		SHEET: 1 of 1			

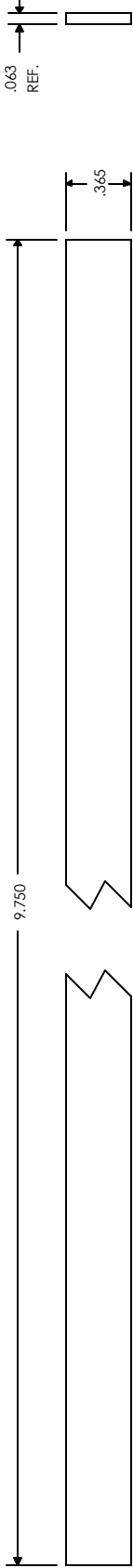
X	PROTOTYPE	TLD
-	PRODUCTION	-
-	OBSOLETE	-



MAT'L
ABS

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X	PROTOTYPE	TLD
-	PRODUCTION	-
-	OBSOLETE	-



MAT'L

16 Ga. STAINLESS STEEL SHEET

WORK ORDER

GROUP #14
MINES ACTION CANADA

						ALL DIMENSIONS IN INCHES		INTELLICHARGE Hostile Environment Battery Chargers		DRAWN BY: TLD		DATE: 2002/02/23	
						USE THE FOLLOWING TOLERANCES UNLESS OTHERWISE STATED:		652 Willingdon Blvd. S.E. Calgary AB T2J 2B4		CHECKED BY: TLD		DATE: 2002/02/24	
						LINEAR FRACTIONS ± 1/32"		PH: (403) 585-1437		APPROVED BY: TLD		DATE: 2002/02/24	
						X.XX ± 0.01"		EMAIL: dorscher@intellicharge.ca					
						X.XXX ± 0.005"		WEBSITE: www.intellicharge.ca					
						ANGULAR X° ± 30'		PART NAME RAIL					
								& CATEGORY: BCG					
A		DRAWN ON SOLIDWORKS 2001		2002/02/23		TLD		PART NUMBER: 3-06A-10				SCALE: 1:1	
REV.		DESCRIPTION		DATE		BY		FILE NAME: 3-06A-10.SLDDRW				SHEET: 1 of 1	