Engine Generators

Compiled by Tracy Dahl

Overview

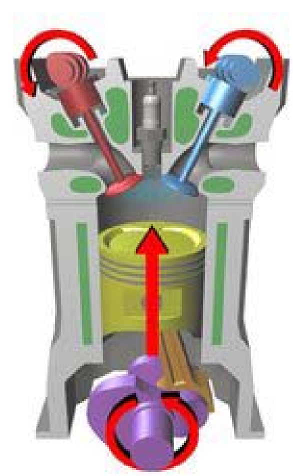
When a research project requires a high output (>4 kilowatts) of electrical power over a short duration or an on-demand power source to supplement a renewable energy system, engine-driven generators can provide a viable technological solution. The internal combustion engine is a mature technology that has been employed with great success the world over. Indeed, it is arguable that this success and the ubiquitous nature of the technology have led directly to many of the environmental crises facing our planet today. Nevertheless, the advantages of the engine-driven generator are many, and in some applications, it is the appropriate technology for the job.

The term *engine generator* is very broad and includes both internal and external combustion types, including micro-turbines. For an in-depth discussion of micro-turbines, please see http://polarpower.org and navigate to Technologies > Power Generation > Micro Turbines. A piston-type internal combustion engine refers to any engine utilizing the combustion of a fuel to push a piston within a cylinder. This reciprocal motion is changed into a more useful rotary motion by the crankshaft. This paper is restricted to a discussion on piston-type engine generators and their applicability to polar scientific research.

There is a wide range of engine-driven generators available, from portable units capable of supplying a few hundred watts of power to enormous, multi-megawatt units capable of supplying grid power for a small city. The demand for autonomous power supplies has fueled tremendous competition among manufacturers of generators. This has led to advances in the technology and generally lower prices, particularly in the portable generator market. For the purpose of this discussion, we will be focusing primarily on smaller to mid-size generator applications.

A Brief History of the Internal Combustion Engine

Although Gottlieb Daimler is typically credited with the invention of the internal combustion engine in 1885, precursors to his design date back much earlier. The first operational internal combustion engine appears to have been invented by Francois Isaac de Rivas of Switzerland in 1807. This engine used a mixture of hydrogen and oxygen for fuel. Unfortunately, this design did not find practical application, although ironically, there is currently a great resurgence of interest in hydrogen as a renewable fuel source since its combustion results in very little harmful emission. External combustion steam engines predate internal combustion engines by a significant margin, and many of the mechanical principles are common across both technologies. Like most technologies, the evolution from the first primitive engines of the past to the sophisticated engines of today was a process of incremental improvements punctuated by periodic innovative advances. Advances in metallurgy and fossil fuel mining and manufacturing ran parallel to this development and allowed for the widespread application of the technology in the modern world.



Four-stroke cut away.

Power

A discussion of engines and generators requires some background about classifications of power and how they are defined. Engine generators convert mechanical energy into electrical energy through the combustion of fuel. Engines are generally rated in *horsepower* and/or *torque.*

The term *horsepower* was coined by the Scottish engineer James Watt (1736-1819) whose name coincidentally defines the unit of electrical power (the watt, W). Horsepower is a way of talking about work in relation to time. Torque is the actual twisting force an engine can produce.

1 horsepower = 33,000 foot pounds of work per minute.
1 horsepower is equivalent to 746 watts.
1 horsepower (over the course of an hour) is equivalent to 2,545 British thermal units (BTUs).

To convert torque to horsepower: $\frac{\text{torque x revolutions per minute (RPM)}}{5{,}252}$

Engine generators are most commonly rated in watts or kilowatts (1 kilowatt = 1,000 watts). Bear in mind that most manufacturer ratings, particularly in regard to portable generators, are a bit optimistic. As an example, the Honda EB5000 generator, although rated at 5,000 watts (5 kilowatts), is rated for a continuous load of 4,000 watts (4 kilowatts). The 5-kilowatt rating is for a surge load, such as starting an electric motor. Furthermore, power must be de-rated for gains in elevation by 2% for every 1,000 feet above sea level. With this in mind, the actual continuous power rating for the EB5000 at a 6,000-foot elevation would be only 3,520 watts. Diesel generators are slightly less affected by altitude, but they must be de-rated nonetheless.

Also remember that the formulas above do not take conversion efficiency into account. For instance, the Honda EB5000 (5 kW) generator utilizes a 9 horsepower engine. Given the horsepower/watt equation given above, one would expect the engine to be capable of 6,714 watts. The reason for the discrepancy is due to the conversion efficiency from mechanical to electrical energy.

Even more pronounced is the conversion efficiency from fuel to electrical energy. One gallon of diesel fuel has an energy content of about 38 kilowatt hours. An engine generator will produce between 10 to 14 kilowatt hours per gallon. Thus, the conversion efficiencies of internal combustion engines range from 26% to 38%. The balance of the energy is expressed as waste heat. Ways to recapture some of this "wasted" energy will be discussed further on in the document.

The Honda EB5000.

Generator Aspects

Fuel Types

Perhaps the best way to classify internal combustion engines and their applicability to polar research is to first identify the type of fuel on which they are intended to run. The type of engine employed may have more to do with fuel characteristics than direct attributes of the corresponding technology.

Gasoline Engines

This is the most familiar type of engine. The 4-stroke (4-cycle) gasoline engine is found in the vast majority of automobiles and smaller generator sets. The 2-stroke (2-cycle) engine has fallen out of favor due to lower efficiency and higher emissions but is still utilized in some motorcycles, outboard motorboat engines, snowmobiles, and chainsaws due to a very favorable power-to-weight ratio. There are currently very few 2-stroke engine generators on the market. Whereas 4-stroke engines carry the lubricating oil in the crankcase of the engine separate from the combustion chamber, 2-stroke engines mix the lubricating oil in the fuel, which partly accounts for their higher harmful emission levels.

Regardless of the engine cycle, the combustion of gasoline requires a spark-type ignition system. Gasoline is introduced into the engine in an atomized state (finely mixed with air at a 15:1 ratio) via a carburetor (common to smaller engines) or fuel injection. Significant changes in elevation require re-jetting of the carburetor, or automated adjustments in the case of electronically controlled fuel injected engines (EFI), to ensure that the 15:1 ratio is maintained.

The Honda EB11000.

Gasoline is rated by octane, a measure of the ignition quality of the fuel. Contrary to popular belief, the higher the octane number, the more controlled the burn rate becomes (less explosive combustion). This is why higher-octane fuel produces less detonation (engine knocking). Octane is determined primarily by what additives are utilized in the refining process. Ethanol, or denatured alcohol (a renewable fuel), is often used in a 15% ratio to increase octane. Because it is an oxygenated fuel, this also results in lower harmful emissions. Many major cities have instituted oxygenated fuel programs for this reason. In some locations, gasoline-ethanol blends are available up to 85% ethanol (E85). However, in ratios greater than 15%, ethanol can lead to cold-starting problems and generally lower efficiency. Ethanol is also “hydrotropic” (attracted to water), which can be an important benefit in preventing minor water issues from becoming problems. Small amounts of water can be absorbed into the blended fuel and will run through the engine harmlessly. Large amounts of water will cause stratification of the fuel. Essentially, the alcohol-water mix results in a higher specific gravity than gasoline, and it will precipitate out to the bottom of the container, which is usually where the fuel pick-up for the engine is located. For polar applications, a 10% ratio (E10) of ethanol to gasoline is ideal, although either 15% ethanol or pure gasoline is also acceptable. Methanol-based MTBE fuel has deleterious effects on the environment and should be avoided. E85 or straight alcohol is not suitable for use in polar environments.

Gasoline is quite volatile and can be problematic to store in large quantities. The shelf life for gasoline is typically about 6 months before it begins to degrade, although in colder climates, the viable service life is extended considerably. Gasoline is widely available and, although classified as hazardous, is still considered suitable for air transportation when stored in appropriately rated containers.

Gaseous Fuels

The common gaseous fuels include liquid propane (LP) and natural gas (methane). Most 4-stroke, spark-ignited engines can be converted to run on these fuels with relatively little modification. Hydrogen can be utilized in an internal combustion application as well, although it is a bit more specialized and problematic to deal with. Natural gas is typically only available through a pipeline infrastructure and is therefore not suitable for most remote research applications.

LP is the gaseous fuel most suitable for use in remote applications. It burns cleanly, thereby resulting in fewer harmful emissions than gasoline or diesel, and stores well in specialized pressure tanks or cylinders. However, there are serious drawbacks associated with this utilizing this fuel:

- LP ceases to vaporize at about -40º C. European LP contains significant amounts of butane and ceases to flow at a higher temperature. These problems can be overcome through a number of methods including (controlled) heating of the fuel cylinders and/or liquid withdrawal regulators.

- One of the major combustion byproducts of LP is water vapor. Water vapor can create some significant problems in polar environments, such as ice dams plugging up exhaust systems.

- LP is considered very hazardous air cargo and technically cannot be transported on the same aircraft as passengers. It bears a Cargo Aircraft Only (CAO) designation, although waivers can sometimes be obtained.

- All gaseous fuels have a lower energy density than gasoline. Namely, if a gasoline engine is converted to run on propane, it must be de-rated by 15%. In other words, a generator rated for a (true) 5,000-watt output on gasoline would be capable of only a 4,250-watt output when fueled with LP. To refer back to the example of the Honda EB5000 again, the continuous (true) rating is 4,000 watts. This would mean that the generator, when converted to run on LP, would be capable of supplying only 3,400 watts. At a 6,000-foot elevation, the combination of de-rating for LP and altitude would result in a generator capable of producing less than 3,000 watts on a continuous basis.

- Conventional vapor withdrawal regulators rely on rubber diaphragms to regulate fuel delivery. These regulators tend to perform poorly in extreme cold.

Diesel Engines

Diesel engines do not require a spark-type ignition system but utilize the heat of compression in the cylinder to supply the ignition source. Diesel fuel is injected into the compressed air in the combustion chamber where it ignites spontaneously. To supply the heat for combustion, a diesel engine runs a much higher compression ratio than a gasoline-fired engine. As a result, these engines tend to be of much heavier construction and longer lived than a gasoline engine of similar output. These engines tend to be appreciably more fuel-efficient than gasoline engines and require less maintenance due to the absence of a spark-type ignition system. However, they also tend to be very heavy and do not lend themselves well to portable applications. The vast majority of diesel engines are of the 4-stroke design. There are a few 2-stroke diesel engines in application today; however, the design is fundamentally different from gasoline 2-stroke engines, and the lubricating oil is not mixed with the fuel.

The Cummins 800kW generator.

Diesel fuel is heavier and less volatile than gasoline and stores well for periods of up to 2 years in temperate climates. In the Polar Regions, the shelf life is nearly unlimited as long as the fuel is kept clean (more on this later). Diesel fuel is principally rated by cetane number. Similar to octane, cetane is a measure of the ignition quality of the fuel that influences starting as well as combustion roughness. The two basic grades of diesel fuel for use in piston-type engines are 1-D and 2-D. 1-D diesel fuel is more volatile and less prone to gelling at low temperatures. For use in extremely cold environments, jet fuel (Jet A-1, AN8) is often substituted for 1-D. However, because this type of fuel is intended for use in turbine-type engines requiring a lower cetane rating and no lubricity, additives are required to convert it into what is commonly referred to as DFA (Diesel Fuel Arctic). It should be noted that jet fuel is a less energy-dense fuel than either 1-D or 2-D. In other words, there are fewer BTUs or less power available in a gallon of jet fuel than in a gallon of diesel. Hence, engines must be slightly de-rated for power output when jet fuel is utilized.

For polar applications, 2-D diesel fuel should never be utilized if temperatures are expected to be below -20º F. 1-D is appropriate for temperatures down to -40º F. If consistently lower temperatures are anticipated, modified jet fuel should be utilized.

Fuel Notes

All fuels should be clean and free of water. It must flow properly in cold weather and exhibit good deposit and anticorrosion control to keep injectors and other fuel system components in proper condition. Fuel should have the minimum octane or cetane rating required by the engine manufacturer to provide good starting and combustion characteristics.

Water is a major issue for fuel storage in polar environments. Perhaps half of all engine problems experienced in the Polar Regions are caused by water contamination of the fuel. In these cold environments, ice formation in fuels containing water creates severe fuel-line and filter-plugging problems. Both gasoline- and diesel-fired engines are adversely affected by water contamination, and stringent measures must be employed to ensure this problem does not occur.

Water gets into fuel in several ways: condensation, loose caps or fittings, and, in the case of fuel stored in barrels, through the pressure changes caused by solar exposure. An exposed fuel drum top will collect snow. With adequate solar exposure, the snow on the top will melt while the pressure in the drum concurrently increases causing air to escape past the seal on the cap. As the solar exposure decreases due to diurnal variation, the pressure once again decreases thus creating a vacuum. The liquid water is then sucked past the seal on the cap and into the drum. Frequent checks of the fuel supply and draining and/or changing of fuel filters and fuel additives can all help reduce the problem, but the best approach is to avoid water contamination in the first place. Take care in the handling and storage of fuel. If fuel is to be stored in drums, store them at an angle with the openings at 9 o'clock and 3 o'clock. Better yet, invest in some low-cost yet effective drum covers to completely eliminate the problem before it occurs. When transferring fuel from drums to the generator fuel tank, use a water block type of filter.

Although ethanol can be added to gasoline, it readily absorbs small amounts of water out of the fuel and should not be added at a ratio of greater than 15%. At ratios greater than this, stratification can occur, which can lead to a host of other problems. In diesel fuel, the use of any alcohol is discouraged. However, if necessary, one pint (473 ml) per 100 gallons (379 liters) is the maximum accepted ratio. ***Note: Many engine manufacturers specifically warn against the use of alcohols due to the potentially adverse effects on pumps, seals, and flash point.***

Generators

This document assumes that the reader has some knowledge of electrical concepts. If the material presented below seems confusing, visit http://www.polarpower.org and navigate to Technologies > Power System Fundamentals to review electrical fundamentals before proceeding further. What follows in this section is not meant as an exhaustive discussion on the subject of electrical generation but, rather, as an overview of the technology the researcher is likely to encounter.

Most engine-driven generators produce *alternating current* (AC). As such, the terms *alternator* and *generator* are used somewhat interchangeably. There are some engine generators that convert the AC power to direct current

(DC) right at the source of production, either through electronic or mechanical rectification. Because most engine generators for remote scientific research will be utilized primarily as battery chargers, the AC power will need to be rectified to DC and regulated so as not to exceed battery-charging capacity. Strategies for using generators for battery charging will be discussed further on in this document.

Generators rely on the principles of *electromagnetism* to produce electricity. Essentially, if two magnets are placed so that the opposite poles are adjacent to one another and a conductor is passed through the magnetic field between them, a voltage is generated within the conductor. The voltage produced in a conductor is determined by:

- the number of conductors in the coil,
- the rate at which the conductors are moved through the magnetic field, and
- the number of magnetic lines of force or field strength produced by the magnets.

The two basic configurations for generators are *revolving armature* and *revolving field.* In the past 20 years, revolving field generators have come to dominate the industry, and our discussion will focus primarily on this technology.

Winding the coil of conductors around an iron core reduces the reluctance of the magnetic field and concentrates the magnetic lines at each end of the iron core. The result is a much stronger electromagnet. This component is typically referred to as the *rotor* and is attached to the end of the engine crankshaft. It is responsible for creating the *field* and can utilize either permanent magnets, diodes in combination with an *exciter winding,* or DC current applied through a set of *brushes.* In most generators, the iron core utilizes either two poles or four poles. The *frequency* a generator produces is determined by the speed of rotation (engine RPM) and the number of poles in the rotor. A two-pole rotor requires a 3,600-RPM rotational speed to produce a 60-cycle-per-second sinusoidal waveform (AC). This is expressed in *hertz*, or Hz. The U.S. standard frequency is 60 Hz, whereas the majority of the rest of the world uses a 50-Hz standard. A four-pole generator needs to rotate at half the speed, or 1,800 RPM, to produce the same 60-Hz frequency.

$$\text{Frequency (Hz)} = \frac{\text{P (number of poles)} \times \text{RPM}}{120}$$

Two-pole generators operating at 3,600 RPM are the most common configuration for portable applications. Because of the higher RPM, more power is available from a smaller engine. However, these generators also tend to be louder and do not last as long as four-pole/1,800-RPM generators. Most diesel-powered generators utilize the slower turning four-pole design and are more suitable for stationary applications.

Engine speed, and therefore output frequency, is controlled by the *governor.* Mechanical-type governors typically rely on a system of weights and springs, which work against one another to reach a dynamic balance. As loads are increased, engine RPM slows and the spring opens the throttle valve to supply a greater fuel-air mixture to the engine. As the speed returns to normal, the weights are thrown out with greater force, and the balance against the spring is once again reached. Although this happens quite rapidly, there is still an appreciable lag time, and precise frequency regulation is somewhat more difficult to maintain. Electronic governors continuously monitor engine RPM and can respond much more rapidly to changing loads. They also maintain a much tighter frequency control, which can be important for very sensitive electronic devices. In general, electronic governors are found only on larger stationary generators.

Although there are many variations in the basic theme, the rotating field generator is the type most commonly found in use today. The rotor, essentially a powerful electromagnet, rotates within the *stator,* the stationary or main windings of the generator. The inductive voltage created within the stator is what creates the electrical output of the generator. Frequency is controlled by engine speed and the number of poles in the rotor. Voltage is controlled by the number of windings and the strength of the electromagnet (rotor). Most generators employ some form of automatic voltage regulation to eliminate the need to manually adjust field currents to obtain voltage control. In

many generators, this is done by varying the amount of current passed to the slip rings on the rotor thereby varying the strength of the electromagnet. Brushless generators rely either on permanent magnets to establish the field or separate exciter windings and residual magnetism to initiate the process. Permanent magnet generators tend to have somewhat less accurate voltage control. This link will take you to an animation of an electrical generator, illustrating the concepts discussed in the text:
http://www.sciencejoywagon.com/physicszone/lesson/otherpub/wfendt/generatorengl.htm

The vast majority of smaller generators are *single-phase* units. This means that the AC system has a single voltage in which voltage reversals concurrently occur and are of the same alternating polarity throughout the system (1). Most residential household service in the United States is single phase, with 120 VAC and 240 VAC available. Portable generators are designed with this type of electrical system in mind. The formula for determining power output in watts for a single-phase generator is:

watts = volts x amps

A *three-phase* AC system has three individual circuits or phases. Each phase is timed so that the current alternation of the first phase is one third of a cycle (120º) ahead of the second and two thirds of a cycle (240º) ahead of the third (2). Three-phase power is commonly found in industrial settings where very large inductive loads (such as large electric motors) must be started. Common voltages are 120/208, 480, and 600 VAC. Three-phase power is typically found in large generators and only very rarely in units under a 10-kilowatt output rating. The formula for determining power output in watts for a three-phase generator is:

watts = volts x amps (averaged) x 1.73

Some generators offer re-connectable windings, which allow for single-phase or three-phase operation, and a variety of voltages. Note that when a three-phase generator is cut over to single-phase operation, the output rating must typically be reduced by one third.

Choosing a Generator

As stated above, the first criterion in selecting an engine generator should be the fuel type. If this is to be a summer-only application where the researcher is present, any fuel will do. If the generator will need to be transported by hand across difficult terrain, a portable, gasoline-fired model is ideal since a lightweight model and easy-to-handle fuel takes priority.

The Makita G1300R on the leftis a 1.3kW unit and is considered a portable model. The Honda EB5000 on the right is a 5kW unit. While still portable, it weighs nearly 200 lbs., and is more typically classified as an “industrial” generator.

If the application is to be a semi-permanent, year-round installation requiring autonomous operation, a slow-turning, efficient diesel engine might make more sense. This type of engine, while significantly heavier, also will have a much longer service interval and produce more power per gallon of fuel used. Stationary generator sets of this type are also frequently equipped with remote start functionality—an essential feature for autonomous applications.

If exhaust emissions are a concern, then a propane-powered unit may be the best choice despite the problematic nature of utilizing this fuel in Polar Regions. Propane produces the least toxic type of emissions of any hydrocarbon fuel, and when equipped with a catalytic exhaust system, the pollution emitted is fairly benign. If absolutely no emissions are permissible, hydrogen can be utilized as a fuel source. When hydrogen is combusted, the primary emission is water vapor; however, utilizing hydrogen fuel is problematic due to transportation and storage issues, the potential difficulty in locating a source, and the somewhat specialized equipment required to convert engines to run on this fuel. Also, the water vapor coming out of the exhaust tends to freeze into a block of ice in extreme cold.

Alternatively, the engine generator power source can be located a significant distance away from the research site. AC power travels fairly well over long distances with minimal voltage drop. The voltage drop amount is determined by the voltage, the conductor resistance, and the current (amps) draw. Increasing the voltage via a transformer system or increasing the size of the conductor will reduce the amount of voltage drop experienced.

If a waste heat recovery strategy is being considered, a liquid-cooled generator will be far easier to set up with a heat exchanger system than an air-cooled model. Water (or a water-glycol mix) has a thermal storage capacity an order of magnitude greater than air. An engine’s existing water pump usually has adequate capacity to integrate a heat exchanger loop.

Regardless of the type of engine generator selected, it is wise to go with a reputable manufacturer. Inexpensive generators tend to have much poorer reliability and lower efficiencies than high-end models. They are also typically louder, have greater vibration, and produce a less stable voltage and frequency than premium units.

Battery Charging

Electrical power requirements for scientific research tend to be fairly modest, requiring only a small fraction of the generator-produced power. Typically, loads range from less than 50 watts to a few hundred watts continuously. As such, it is generally impractical to run a generator capable of a several-thousand-watt output continuously to support only small and/or intermittent loads. It is not only incredibly inefficient, but fuel storage and maintenance issues become major concerns. Even when bulk fuel storage is possible, most small generators require at least an oil change every 100 hours of operation. That means that every 4th day, someone has to be on site to change out the oil. Long-run generators with larger oil reservoirs are available, which extends the interval between maintenance, but the essential problem remains. The solution is to run the generator only when necessary to charge a battery bank and/or supply power for intermittent large loads.

The battery bank provides a method for storing power for later use. When sized appropriately, it can absorb the full output capability of the generator via a quality battery charger. It also allows for the use of DC-powered instruments and equipment, which is typically a more efficient power supply for small scientific loads. More on batteries follows below.

When utilized in this manner, engine generators become a fairly efficient method for powering remote research. When combined with one or more renewable energy technologies (photovoltaics [PV] or wind power), engine run time can be reduced even further. To conserve fuel and extend battery life, renewable energy technologies provide a perfect match for this on-demand power supply. Researchers are encouraged to consider utilizing the resources already available from the environment—wind, sun, and, in a few instances, flowing water—to create an optimized system for the location. For more on combining technologies in a single power system, see the section on “Hybrid Systems” below.

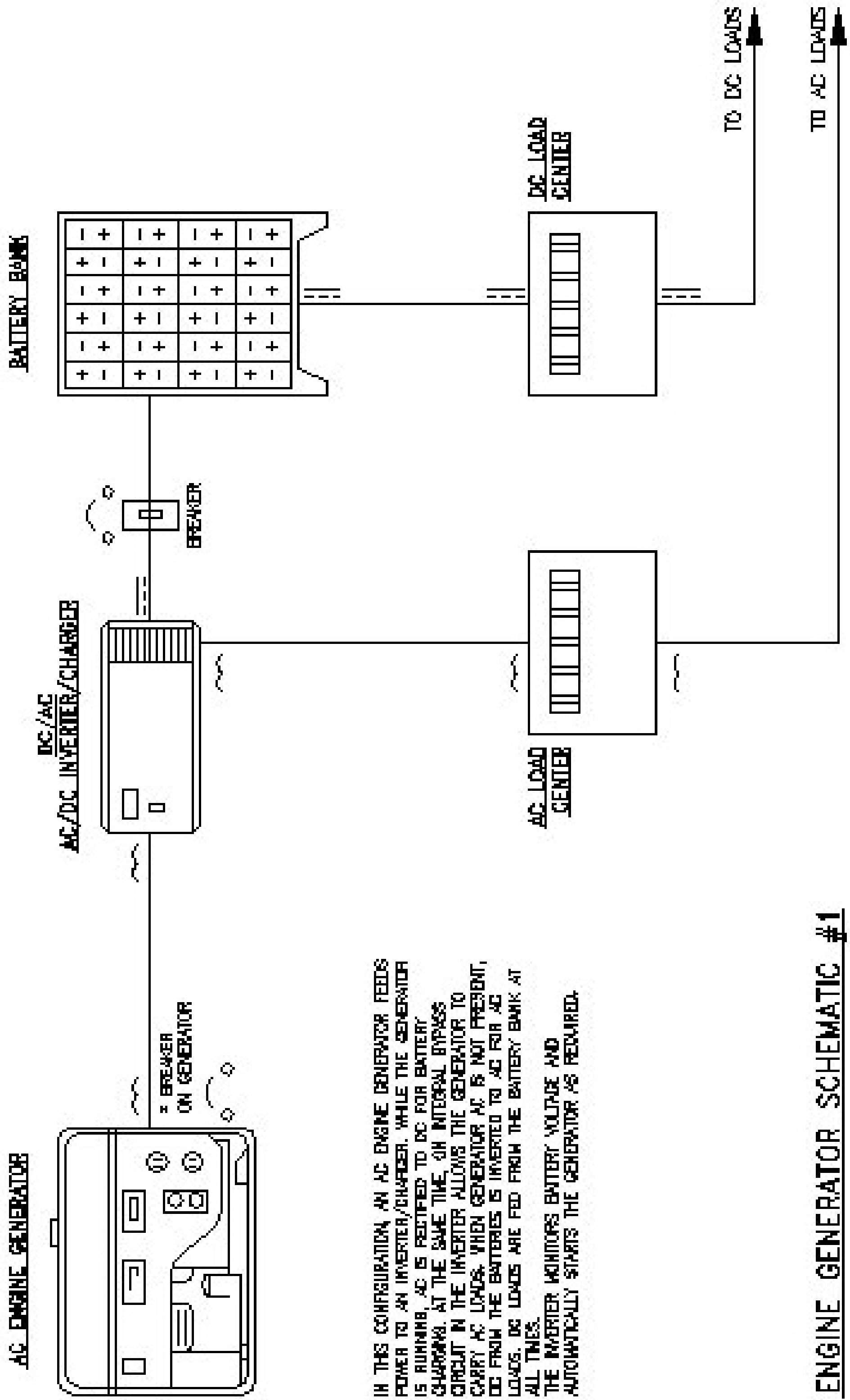
There are several vendors that offer systems capable of meeting remote researcher requirements. However, these systems tend to be somewhat generic and will likely require some customization to better meet the particular requirements of the environment and the research project. Please refer to the “Links” section of http://polarpower.org for contact information on power system vendors.

For various reasons, some researchers may choose to build their own system. Fortunately, the renewable energy industry has already developed much of the technology suitable for this type of application.

Inverters

An inverter is a device that converts DC power from the battery bank to AC power for various loads. In larger systems that incorporate components that demand AC power, an inverter must be utilized. Also, if the instrument site is located some distance from the power production site, an inverter allows for an efficient means of getting electricity to the point of use. AC is easier to transport over long distances and has become the conventional modern electrical standard.

There are several inverters available that can provide the control for managing an engine generator system. There are many inverters that combine a powerful 3-stage battery charger into the system as well as programmable set points for controlling generator operation. When battery voltage drops to a pre-determined value, the inverter will initiate a generator run cycle. The generator is automatically started and given a period of 30 seconds to several minutes to reach operating temperature and stabilize voltage and frequency. The inverter then activates the charge cycle, gradually increasing the load until the generator is near full output. Depending upon the size of the battery bank and the generator, this cycle may last from a few hours up to 8 hours. Once the charge cycle is complete, the inverter will shut down the generator and revert to inverter mode. ***Note: Even when AC power is not required, the utilization of an off-the-shelf inverter as the charger and system controller can be an expeditious and cost-effective solution.***


AC ENGINE GENERATOR
* BREAKER
ON GENERATOR
DC/AC
AC/DC INVERTER/CHARGER
BREAKER
BATTERY BANK
AC LOAD
CENTER
DC LOAD
CENTER
TO DC LOADS
TO AC LOADS
IN THIS CONFIGURATION, AN AC ENGINE GENERATOR FEEDS POWER TO AN INVERTER/CHARGER. WHILE THE GENERATOR IS RUNNING, AC IS RECTIFIED TO DC FOR BATTERY CHARGING. AT THE SAME TIME, AN INTEGRAL BYPASS CIRCUIT IN THE INVERTER ALLOWS THE GENERATOR TO CARRY AC LOADS. WHEN GENERATOR AC IS NOT PRESENT, DC FROM THE BATTERIES IS INVERTED TO AC FOR AC LOADS. DC LOADS ARE FED FROM THE BATTERY BANK AT ALL TIMES.
THE INVERTER MONITORS BATTERY VOLTAGE AND AUTOMATICALLY STARTS THE GENERATOR AS REQUIRED.
ENGINE GENERATOR SCHEMATIC #1

There are two fundamental categories of inverters, *synchronous* and *static* or *stand-alone.* Synchronous inverters are capable of being tied into the electrical *grid,* or utility power. Except in the largest of infrastructure-based systems, this type of inverter finds little application in the field of polar research. Static inverters are designed for independent, utility-free power systems and are the type used for remote research applications.

A second classification refers to the type of AC waveform they produce. Inverters are available in *square wave, modified square wave,* and *sine wave* outputs.

- Square wave inverters are inexpensive, but typically provide poor output voltage control, limited surge capacity, and significant amounts of harmonic distortion. In general, this type of inverter is inappropriate for remote scientific research applications.

- Modified square wave inverters utilize more complex circuitry to create a waveform more closely approximating a true sine wave. They are capable of handling greater surge loads and have an output with less harmonic distortion. Although capable of powering a wider range of loads, there are still issues of concern for the polar researcher. Some electronic devices can pick up inverter noise or buzz, and any device utilizing a digital timekeeper will run either fast or slow when powered by a modified square waveform.

- Sine wave inverters are best for powering sensitive electronics that require high-quality waveforms. They have little inherent harmonic distortion and typically have surge capacities double or greater than the continuous output rating. This is an important consideration if motors or other inductive loads are part of the overall power budget. Because sine wave inverters are now available in sizes from a few hundred watts to many kilowatts of output, there is little reason to consider any other type for polar research applications. ***Note: If AC power is part of the project requirement, use an inverter with a high-quality sine wave output.***

When selecting an inverter, many additional criteria must be considered:

- *DC voltage input* must match the battery voltage of the system.

- *AC power output* must be adequate to satisfy the maximum-potential-combined AC load, or all of the AC-powered equipment that might be on at one time. However, the system designer should also be cautious about over-sizing the inverter, as most operate at their maximum efficiency toward the middle to upper end of their output range.

- *Voltage and frequency regulation* should be very tight in a high-quality unit. Voltage and frequency should match the system requirements (60 Hz/120 volts for U.S. equipment and 50 Hz/240 volts for European equipment). Note that step-up or step-down autotransformers can be utilized to change output voltages if required but at the expense of a bit more power consumption.

- *Efficiency* should be high across a broad range of output levels. Some inverter manufacturers claim high efficiency levels, but they may be measured at or near maximum output where the inverter will rarely operate. Choose an inverter rated for high efficiency over a wide range of load conditions.

- *Construction* should be consistent with the application requirements. Some inverters offer a sealed design or special coatings on the electronics to enhance reliability in wet or corrosive environments. Other inverters utilize open construction with a cooling fan for increased load capacity. A limited range of marine-rated inverters is available for maritime environments.

It should be noted that inverter technology is finding increasing application as an integrated component in engine generator packages. Essentially, the engines are allowed to run at variable RPM—hence, uncontrolled frequency. The AC power is rectified to DC and then inverted back to a stable-frequency AC. The result is far greater efficiency

The Honda EU1000i.

and a completely stable frequency and voltage output. Several models of Honda and Yamaha portable generators now incorporate this technology, as do a few generators intended for the recreational vehicle (RV) market. Because the advantages are obvious, it is only a matter of time before the technology finds its way into the stationary generator market. However, incorporating an inverter into the engine generator does not obviate the need for a second inverter in an engine generator/battery system.

Battery Charger

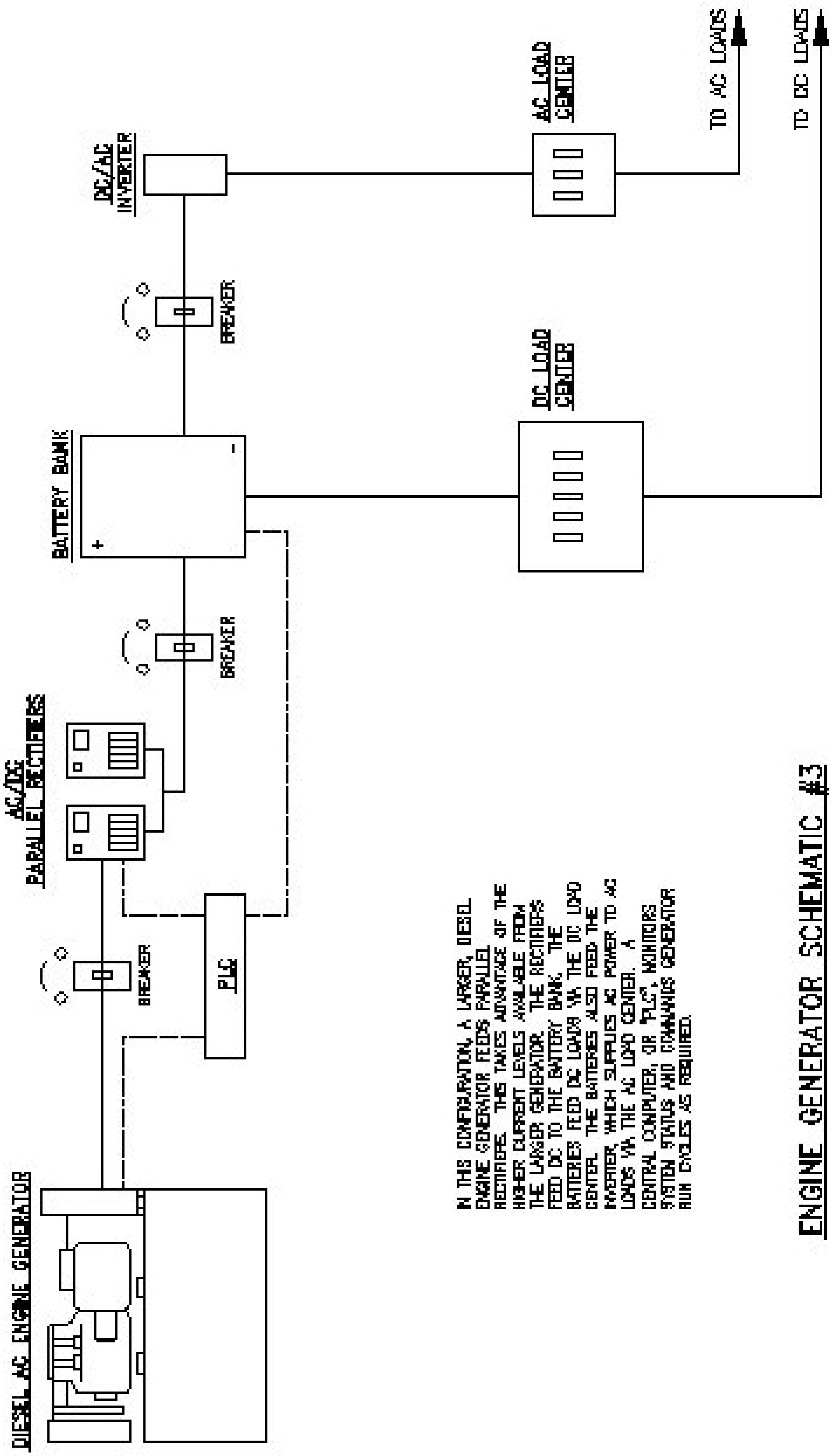
There will be many instances where a standard inverter does not fulfill the requirements of the system. If one chooses to provide a separate controller for the system rather than an off-the-shelf inverter, then a high-capacity battery charger (rectifier) will need to be employed. Standard automotive-type battery chargers are not adequate for charging a large, deep-cycle battery bank. Specialized chargers designed for the renewable energy industry and/or industrial applications are a far better choice for this application. High-end chargers allow for the programming of maximum charge rates and allow for 3-stage charging to maximize battery longevity. Manufacturers are listed in the “Links” section of http://polarpower.org.

Most inverters and battery chargers operate on 120 VAC. Most single-phase generators have a 120/240 VAC capability. In many instances, selecting the 120 VAC option on the generator means that you are utilizing only half of the generator’s windings and therefore can use only half of the available power. There are several strategies to get around this situation:

- Select a generator that has full output capability at 120 VAC. This is a premium feature and will be noted in the technical specifications. This method results in the least amount of conversion inefficiency.

- Configure the system with two battery strings and two chargers. This is an expensive option but does add a level of redundancy that can be important.

- Utilize a transformer to take the full generator output at 240 VAC stepped down to 120 VAC for use by the inverter/charger. This method is the least efficient due to losses in the conversion process; however, it does supply a well-conditioned line voltage to the charger.


DIESEL AC ENGINE GENERATOR
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ENGINE GENERATOR SCHEMATIC #3

Batteries

A battery stores electrical energy in the form of chemical energy. To be effective in an engine generator system, the electrochemical processes must work in both directions—in other words, the system must be re-chargeable.

Batteries perform three main functions in a stand-alone engine generator application:

1. *Autonomy*: By meeting the load requirements at all times, autonomy eliminates the need for continuous generator operation.

2. *A DC power supply*: Most scientific instrumentation is designed to run on DC power, which tends to be much more efficient than AC.

3. *Engine starting*: Typically, the starting battery is independent of the main battery bank. However, if it is a 12 VDC system, the main battery bank could also serve as the starting battery.

Any battery suitable for remote power applications will be a *deep-cycle* type of battery as opposed to a starting (*SLI)* type. Although these two fundamental classes of batteries may appear similar on the outside, the internal structure is quite different. SLI batteries are intended to deliver a high-amperage output for a short period of time, but repeated deep discharges cause rapid deterioration of battery performance. These batteries are typically rated in cranking amps, or cold cranking amps (CCA). Deep-cycle batteries are designed to deliver a typically lower current for the size of the battery, but they are capable of withstanding numerous deep discharges without damage.

The amount of energy a deep-cycle battery can store is referred to as its *capacity.* The unit that describes capacity is the *amp hour) .* Battery capacity is determined by the manufacturer based on a constant discharge over a period of time. Often, batteries will appear to have multiple ratings due to this rating process. The 20-hour rate (C/20) and the 100-hour rate (C/100) are referred to most frequently. When determining which battery to choose, be sure to compare all batteries at the same discharge rate.

Deep-cycle batteries vary widely in type, price, and quality. Low-cost trolling batteries represent the low end of the scale and are generally not suitable for use in remote power applications. The most expensive battery per amp hour is generally the gel-cell battery. Battery failure has often been the cause of suboptimal power system performance. Without a doubt, this is not the area to cut expenses. The battery bank for any power system must be of the highest quality available, of the correct type for the application, and of sufficient capacity to ensure that the depth of discharge does not exceed design parameters. The size of a battery bank for even relatively low-power applications can be surprisingly large, particularly if year-round autonomy is a design requirement. Cold temperatures reduce capacity but tend to extend battery life. System sizing worksheets (see the end of this document) are essential for ensuring adequate battery capacity for a given project.

The most common type of battery found in remote power systems is the lead acid battery. Although the discussion will focus on this blanket technology, other rechargeable battery types do exist, including nickel-cadmium (NiCad), nickel metal hydride (NiMH), nickel-iron (NiFe), lithium ion, and lithium polymer batteries. Of these, the NiMH and lithium polymer batteries show significant promise for broader application in autonomous power systems. These battery types demonstrate up to a four-fold greater energy density and enhanced performance across a wider temperature range, which might ultimately favor this emerging technology. NiCad batteries have been used in a few polar applications, as they have superior performance in extreme cold. However, the high price, low efficiency (about 65% vs. 85%-95% for lead acid), and restrictive charging parameters make them unsuitable for most applications. At the moment, the comparatively low prices and well-documented performance of lead acid batteries favor their continued use for remote power systems.

In the lead acid class of batteries, two specific types stand out for their applicability to polar power applications: the *gel cell* and the *absorbed glass mat (AGM).* These two types of batteries represent good choices not only due to performance characteristics but also because they are both suitable for air transportation. Because the electrolyte

Deka AGM type battery

solution in both of these battery types is immobilized, they represent a lower hazard class than standard *flooded* batteries and do not require a great deal of specialized packing before being shipped via aircraft into the field. Although the performance characteristics of flooded deep-cycle batteries may meet or exceed those of the gel-cell and AGM types, the transportation and maintenance issues can prove to be quite problematic for remote scientific research projects.

Both of these types of batteries are classed together as *valve-regulated lead acid (VRLA)* batteries. A battery charging at a high amp rating or an excessively high voltage can release gases (hydrogen and oxygen) due to an overcharge condition. In a VRLA-type battery, gases are not released during a normal, controlled charge cycle. There is a closed loop that keeps the chemical levels balanced and internal pressures below the release threshold of the valve.

One very important difference to note between gel-cell and AGM batteries is that the gel-cell battery is a plate-limited design, whereas AGM batteries are an electrolyte-limited design. This can be very important in polar applications where extremely cold temperatures are often the norm. Freezing the electrolyte solution in a battery must be avoided. It causes irreversible damage to the battery, which could lead to catastrophic failure. Also, a frozen battery cannot recharge until it has been thawed out again—not always a simple proposition in the field. Electrolytes freeze at higher temperatures as they discharge and the specific gravity decreases. AGM and flooded-cell batteries can continue to discharge until the electrolytes become severely depleted thereby resulting in a low specific gravity and a relatively high freezing point. A quality load controller somewhat obviates this concern, as it will typically incorporate a low-battery disconnect capable of opening the circuit between the battery and the load prior to the onset of problems. In a plate-limited battery, the chemical reaction that causes the flow of electrons ceases before the electrolyte specific gravity falls too low. This provides a certain measure of inherent protection by design. It is important to note, however, that gel-cell batteries are vulnerable to damage in other ways. Charging at excessively high rates can create voids in the gelled electrolyte that significantly reduces the capacity of the battery. Voltage and current must be carefully controlled and cannot exceed the C/20 rate (approximately 5% of the amp hour rating for the battery bank).

For larger systems that incorporate other charging sources such as wind turbines or engine generators, AGM batteries may be preferable due to a superior high-current rate performance (3). It is worth noting that many battery manufacturers offer both gel-cell and AGM types. Gel-type batteries have fallen somewhat out of favor in the industry in recent years, but there are still applications where this is the most appropriate technology to use. The optimal battery choice for a given research project must be determined on a case-by-case basis, but generally speaking, AGM batteries are considered superior for use with engine generators due to their ability to be charged at a high current rate.


Industrial battery stacks offer the ability to reconfigure voltages based on 2 volt cells. They can also allow for a lot of energy storage in a compact space.

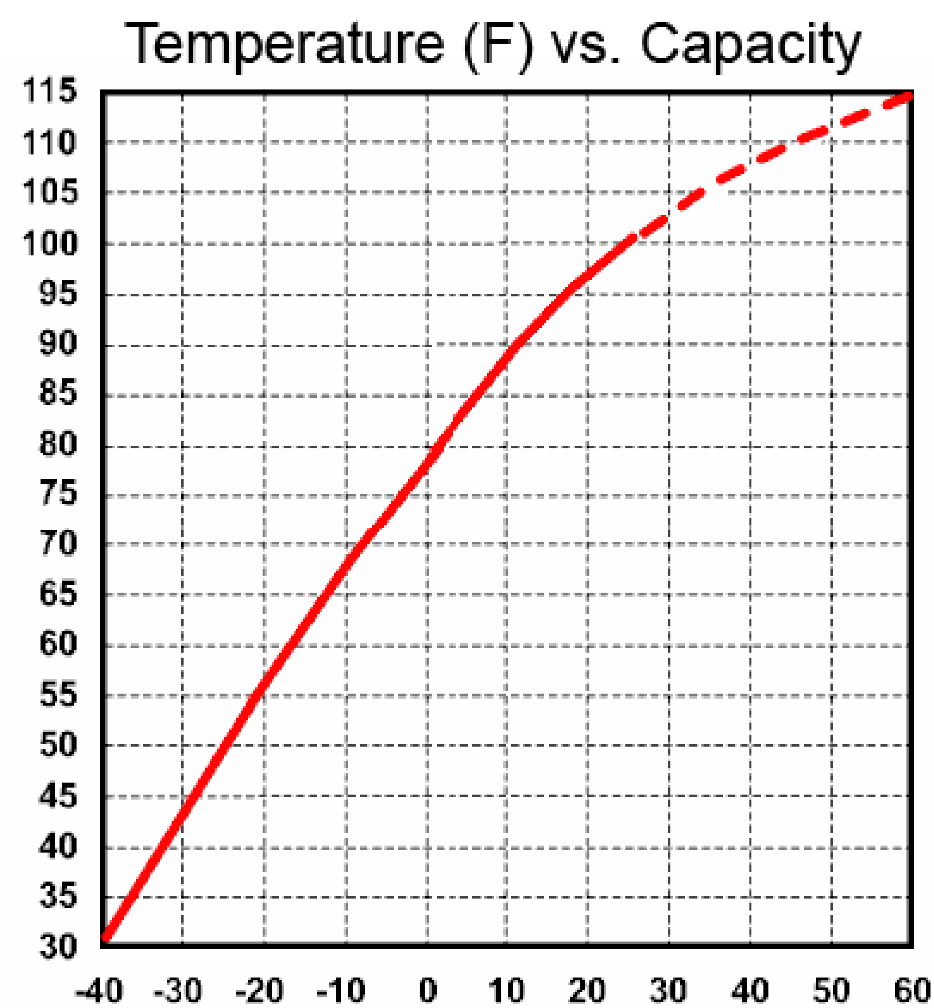
Battery capacity is dramatically affected by the cold. Capacity is reduced by 50% at -10º F, and the risk of freezing becomes much greater. At the same time, battery life is increased by 60% due to a lower rate of self-discharge and generally depressed chemical processes. This applies to all types of lead acid batteries and explains the

Liquid Electrolyte Freeze Points, Specific Gravity, and Voltage

State of Charge	Freeze Point	Specific Gravity	Voltage
100%	-71º F	1.260	12.70
75%	-35º F	1.237	12.50
50%	-10º F	1.200	12.30
25%	3º F	1.150	12.00
0%	17º F	1.100	11.70

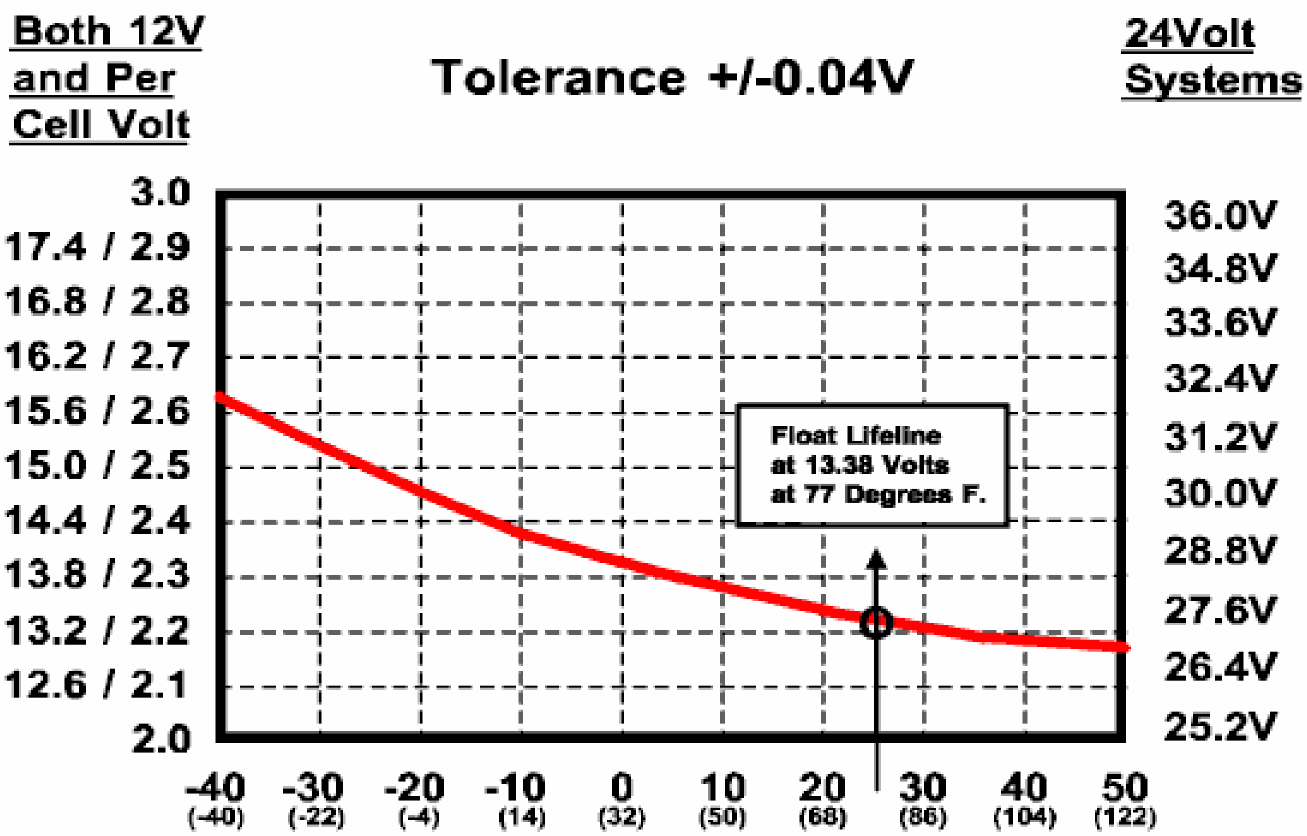
* Adapted from *Photovoltaics Design and Installation Manual* (2004), SEI.

phenomenal service life of some batteries deployed to polar environments. The reduced capacity must be taken into account when determining the battery bank size required for a system.



The *depth of discharge (DOD)* also has a direct bearing on how long a battery will last. A battery discharged to 50% on each cycle will last about twice as long as one discharged to 80% per cycle. Fortunately, this function is entirely controllable for remote power systems incorporating an engine generator.

When diagnosing battery problems, be sure to differentiate between the *surface charge* and the actual *state of charge.* This is particularly important in a system incorporating an alternate charging source such as one using PV. A battery still connected to the PV charging source may appear to have adequate voltage, but this can be very misleading. When analyzing a battery, first ensure that it is fully charged. Run a generator charge cycle if necessary. Next, disconnect it from any charging source as well as the loads. Allow it to sit for an hour before taking a baseline voltage measurement. Next, hook it up to a dummy load, which should be a resistive load. Watch the battery over a period of time and observe the voltage decline. If it drops dramatically right away or maintains voltage for a short time before the bottom drops out, the battery is bad. Generally speaking, it is poor economy to replace only one battery or cell in a battery bank. As with any interconnected system, the performance tends to be reduced to the level of the poorest performing module.



System Monitoring

It is critical that the Researcher can monitor the performance of the system, at least in terms of maintenance. As a bare minimum, system (battery) voltage, generator voltage, and generator frequency provide important indicators of potential problems. A high quality multimeter can provide a means for thoroughly checking the system during an annual maintenance visit. Be sure the meter is capable of measuring frequency, and true RMS (Root Mean Square) voltages. Another option is to utilize an inexpensive meter as shown below, which makes it a bit easier to actually adjust engine governors without an assistant to hold the meter probes.

It is very important to monitor th voltage and frequency output of generators. This inexpensive unit plugs into a 115 volt receptacle for quick and easy on site adjustments, but does not allow for remote monitoring functionality.

In year-round autonomous system applications, satellite communications and other advances in telemetry now allow the Researcher to obtain near real-time system status from afar. This functionality confers a tremendous advantage in monitoring the power system, determining if problems exist, and diagnosing failures prior to heading out into the field. Of course, this ability comes at a price in terms of system complexity, cost, and additional power requirements. Nevertheless, it can often prove critical to the success of a project, and this option should be carefully evaluated during the early stages of system design. This topic goes well beyond the scope of this document. For an example of a system incorporating advanced system monitoring and data transfer capabilities, see: http://polarpower.org . Navigate to Examples > Ivotuk.

Power Consumption (Load)

The strategy for creating a successful battery charging system requires a careful analysis of loads and environmental parameters to determine the appropriate size and type of battery bank, generator, and balance-of-system components. A worksheet follows at the end of this section to help the researcher determine what will work best for their needs.

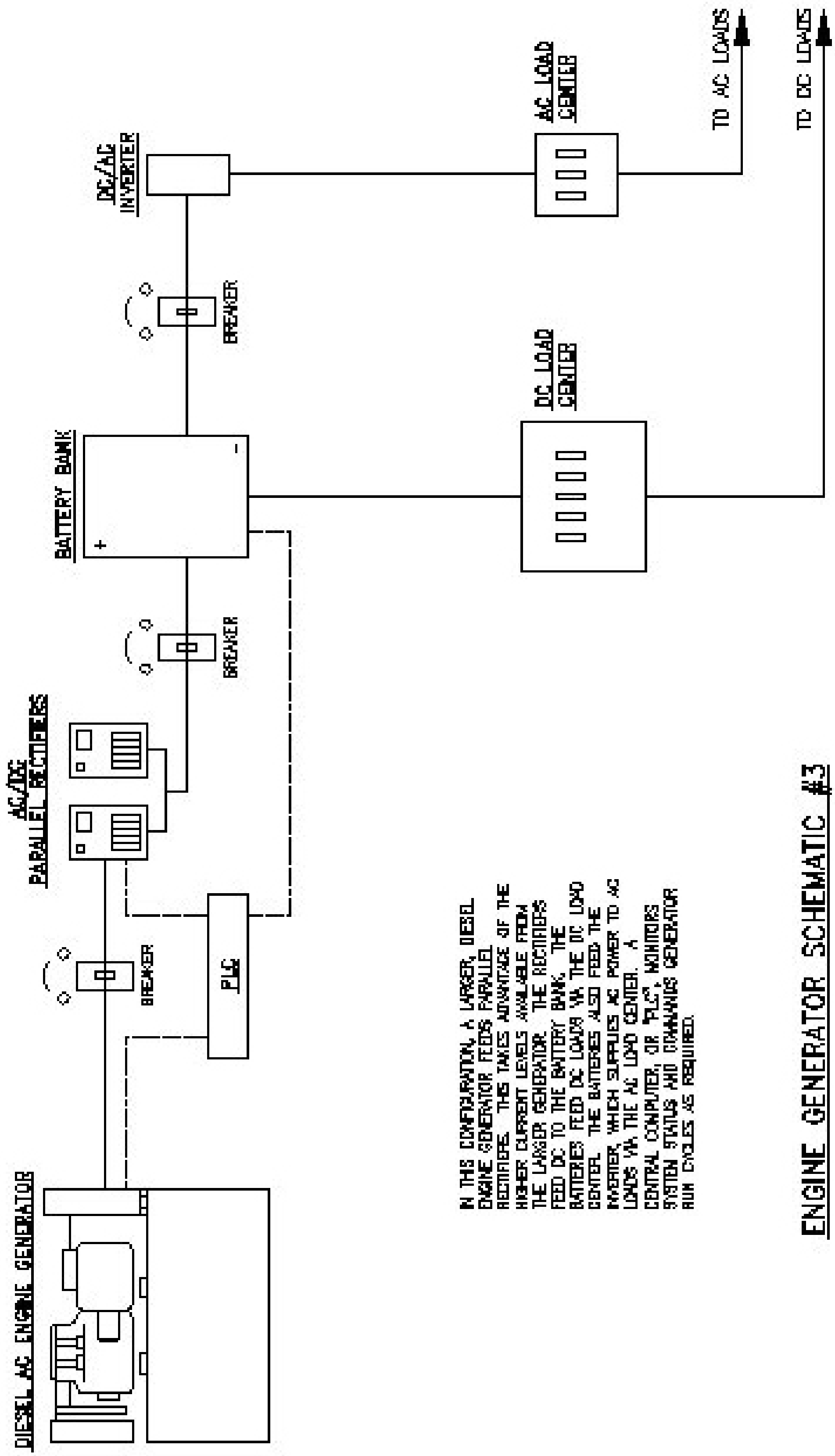
In a well-designed remote power system, there should be a relative balance of power. In other words, there should be enough power input to equal (and slightly exceed) the amount of power going out to instrumentation and other loads. When an engine generator is utilized, this consideration becomes somewhat less critical, although efforts to minimize power requirements are still essential to reduce run time. Essentially, a researcher should always plan on oversizing the system to ensure reliability. A battery bank or battery charger that is too small will lead to excessive generator run time and a subsequent need to increase refueling and maintenance trips. A couple of simple formulas help to define the relationship between the variables in the power balance:

Power consumption = (instrument loads x time) + (system losses x time)

Power available = (power input x time) – (system losses x time)

Power consumption can best be expressed in *watt hours* per day. A watt is the product of amps times volts: A x V = W. (Amps or *current* can also be expressed as *I*.) Watt hours is the product of watts multiplied by hours: watts x time = watt hours. For a more in-depth discussion on electrical concepts, visit http://www.polarpower.org and navigate to Technologies > Power System Fundamentals.

The best way to determine the average watt hours per day that your system requires is to first determine the cumulative amount of power used in a week, then divide by seven. The sum of all instrumentation and other loads should be padded by 25% to compensate for system losses.


DIESEL AC ENGINE GENERATOR
BREAKER
PLC
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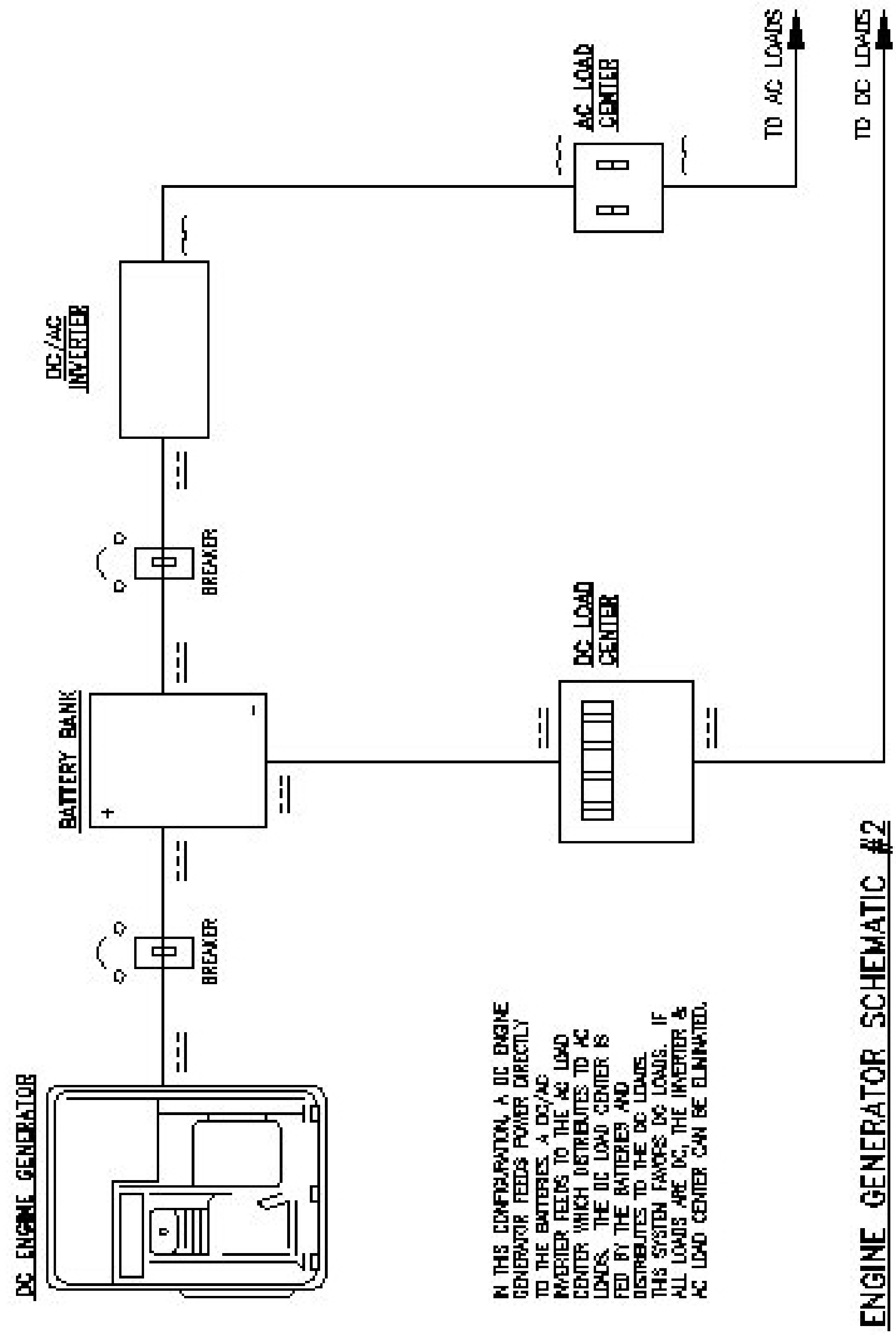
ENGINE GENERATOR SCHEMATIC #3


DC ENGINE GENERATOR
BREAKER
BATTERY BANK
BREAKER
DC/AC INVERTER
AC LOAD CENTER
TO AC LOADS
TO DC LOADS
DC LOAD CENTER
IN THIS CONFIGURATION, A DC ENGINE GENERATOR FEEDS POWER DIRECTLY TO THE BATTERIES. A DC/AC INVERTER FEEDS TO THE AC LOAD CENTER WHICH DISTRIBUTES TO AC LOADS. THE DC LOAD CENTER IS FED BY THE BATTERIES AND DISTRIBUTES TO THE DC LOADS. THIS SYSTEM FAVORS DC LOADS. IF ALL LOADS ARE DC, THE INVERTER & AC LOAD CENTER CAN BE ELIMINATED.
ENGINE GENERATOR SCHEMATIC #2

Efficiency

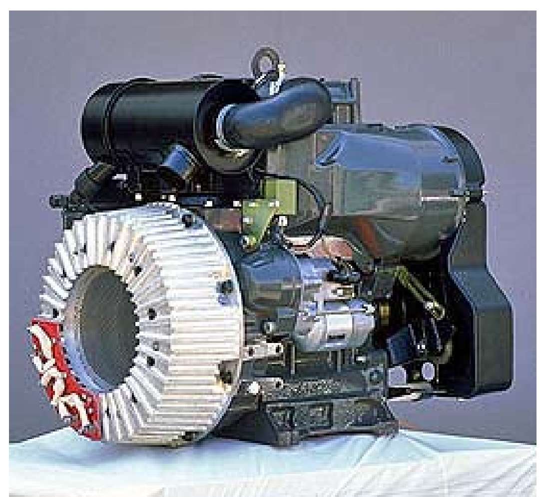
Clearly, the greater the operating efficiency of a system, the lower the overall power requirements will be. This equates to a smaller battery bank, generator, inverter, and balance-of-system components. Moreover, the amount of power used directly relates to the amount of fuel consumed by the engine generator. As mentioned previously, storing a large quantity of fuel on site is problematic for a host of reasons. Small systems are relatively easy and inexpensive to deploy, whereas large systems are costly to build and often expensive and challenging to deploy. ***Note: It is in the researcher's best interest to create systems that approach the problem comprehensively and that emphasize efficiency as one of the prime design criteria.*** Too often, instrumentation is selected based on other criteria such as familiarity, but running an experiment in a laboratory setting and having it run reliably in a polar environment are two dramatically different things. Oftentimes, there is comparable equipment available that can perform the same function at a fraction of the power requirement. Time used in reducing the power requirement is invariably time well spent.

Here are a few things to consider:

1. DC-Dominant Systems (at the load end):

    - Most electronic equipment actually operates on DC power, despite the fact that most of the commercially available equipment is designed to plug in to AC power sources. This is because our electrical infrastructure, or grid, is an AC system due to its better transmission qualities. In essence, AC travels long distances better than DC. In a typical research project, however, distances are typically rather small, and DC may provide a more efficient power supply.

    - Another advantage to a DC-only type of system is that it eliminates the inverter (DC to AC converter), which is one of the more costly and complicated items in a stand-alone power system. Although they are typically very reliable, inverters have certainly been known to fail. Keep it simple. The fewer components there are, the fewer places there are for a failure to occur. Most engine generator/battery systems will still require a battery charger to convert the generator's AC to DC for the battery bank. However, there are a few very efficient DC engine generators available. See http://www.polarpowerinc.com for examples of DC engine generators manufactured by Polar Power, Inc. (note: this manufacturer is in no way affiliated with the http://polarpower.org web site) .



Polar Power's DC Lister generator.

    - It is best to try to match system voltages across the board (e.g., a 12-volt battery bank feeds 12-volt equipment), but this might not always be practical. It is generally easier to convert voltages downward (e.g., 24 volts to 12 volts), although step-up DC/DC converters are also available. Step-down DC/DC converters are very efficient and reliable. Design the system so that the primary system voltage matches or exceeds the highest voltage requirement in the system. System voltages should typically not exceed 48 VDC nominal. Higher DC voltages are suitable for some larger systems but require special equipment and present a much greater shock hazard.

    - The actual DC requirement for a device typically intended for AC service is often listed on the nameplate information. It is often not very difficult to cut a device over to DC operation for dramatically enhanced efficiency. Essentially, the AC circuitry (rectifier and transformer) is bypassed or removed. A DC/DC converter may be required to match the component requirement, but this is still typically much more efficient. ***Note: Familiarity with electronic equipment is a necessity!***

2. Logic Circuits:

   - The use of a programmable logic circuit, or PLC, allows for much greater control of the system. For instance, does every instrument need to be on all the time for sampling, or could some be quiescent for the majority of the time, waking up to take a sample once an hour? The power reduction can be dramatic when this approach is taken.

   - Many pieces of equipment have this functionality built right in.

   - Ladder-logic circuitry can often be employed to control when instrumentation is active. As the name implies, ladder logic simply requires one step to be completed (parameter satisfied) before the next step is initiated. This can often be accomplished with relatively simple circuitry.

3. Thermal Strategies:

   - All electrical equipment performs best within a certain temperature regime, and typically this is not -40º C. (PV panels are the exception: The colder it gets, the more efficiently they work.) Efforts made to control the internal temperature environment can yield great rewards. Batteries have less available power, lower voltages, and accept a charge with greater difficulty at low temperatures. On the positive side, the self-discharge rates are much lower as temperatures decrease. Excessive heat will rapidly deteriorate the performance of a battery bank.

Most electrical components have temperature specifications as well. If they are operated outside of those parameters, reliability and accuracy cannot be assured. Obviously, a system that can maintain a more steady-state temperature—or at least reduce the dramatic swings—will perform better than a system with no thermal strategy employed. Except for medium to large systems of greater complexity, it is typically an acceptable strategy to moderate temperature extremes rather than attempt to hold a system within tight temperature parameters.

To this end, batteries and other equipment should be housed inside enclosures. These enclosures should be well insulated. The inefficiencies discussed elsewhere in this section refer to energy that was not directly utilized to perform a function. The wasted energy is expressed as heat. In most polar environments, heat is a resource that can be used. It should be the objective of every system designer to find ways to harness that otherwise wasted heat to modify the environment of the battery and/or equipment enclosure.

With an engine generator system, controlling the thermal environment of any type of enclosure really relies on just four things:

1. A thermal energy source (engine generator)
2. Insulation to prevent the heat from escaping
3. Thermal mass to moderate temperature swings
4. A means to dump excessive thermal energy, either to the environment or to the thermal mass mentioned above

Methods employed vary widely from simple, passive systems to active systems that control temperature within tight parameters. How this problem is approached will be determined by how closely the temperature needs to be controlled and by the extremes of the environment the experiment is placed in.

The simplest systems rely on waste heat for the thermal energy source, insulation, and the thermal mass of the batteries to moderate the swings. A more comprehensive approach would incorporate water or a glycol-water blend as additional thermal mass by actively heating it whenever the engine generator performs a charge cycle. Engine generator systems can tap into an enormous amount of heat energy that would otherwise be wasted to the environment. Recall that only about 30% of the fuel burned is converted to electrical energy. The remaining 70% is expressed as waste heat. This heat must be dealt with to prevent overheating of the engine and the enclosure. An optimized system will store the heat, typically in a liquid medium, for later use in regulating the temperature of the system. The heated liquid can be circulated through the engine block and radiator to dissipate heat to the enclosure as required via a small, low-power hydronic pump. Another advantage of this approach is that the engine will be preheated to facilitate starting in extreme cold. At least one power system manufacturer offers waste heat recovery strategies as an option.

For more information on thermal strategies, visit http://polarpower.org and navigate to Technologies > Systems Integration.

Cold Weather Operation

A topic related to thermal strategies is how to reliably start and run an engine generator in extremely cold weather. Even running a generator to power loads independent of any other system can be problematic. Lubricating oil is thick and engines crank very slowly. Fuel is difficult to vaporize and exhibits poor combustion characteristics. Once running, air cleaners can become restricted due to snow infiltration. Exhaust systems can plug with ice. Engine breathers can also become ice choked, sometimes resulting in the pressurization of the crankcase and subsequent expulsion of crankshaft seals or gaskets.

For small, air-cooled generators, sometimes utilizing high-quality 0W30 synthetic oil is adequate to ensure reliable operation. Simple enclosures can be constructed of plywood or even a cardboard box to retain some heat from the engine. However, adequate ventilation is essential. The exhaust must be able to escape freely, and a fresh air supply must be allowed to enter.

Cold-soaked engines will always be more difficult to start than engines closer to operating temperature. The best overall strategy is to pre-warm the engine prior to starting. For engines used in portable applications, however, this may not always be practical. Again, consider using what the environment has to offer. Insulate the generator from the ground, and cover it with a dark material to facilitate passive absorption of the sun’s energy. The plywood enclosure mentioned above becomes much more effective when painted black. When combined with an insulated base, the temperature inside the enclosure on a sunny polar day can be 20º or 30º higher than the ambient temperature. For very small portable generators, placing them inside a black plastic garbage bag can raise the temperature significantly. Also, placing the generator in the cargo area of a snowmobile prior to installing the cover can result in a slightly warmer generator.

Do not use starting fluid (ether) on any small engine except as a last resort. Starting fluid is intended for use on heavy-duty diesel engines only. Utilizing this highly volatile and explosive material on a small gasoline engine will very likely damage it.

For larger, more sophisticated systems or autonomous research platforms, active preheating becomes a viable option. Electric block heaters are an option but require a lot of electrical power to operate. Because the engine is likely being started due to a depleted battery bank, this approach is not always viable. Hydronic units are available that utilize the combustion of diesel fuel as the primary heat source. Of course, this requires a liquid-cooled generator, as it is the engine coolant that is being heated and circulated in the engine’s water jacket. Espar and Webasto are two manufacturers that sell high-quality units employing this technology. A small amount of electrical power is still required to circulate the fluid and run a tiny fuel pump, but the draw from the battery bank is modest and relatively brief. A control system, either a PLC or ladder logic circuit, can be utilized for autonomous operation.

Systems utilizing a waste heat recovery system can potentially utilize the reservoir of heated liquid to preheat the engine thus using no additional fuel, only the amount of power required for operating a small hydronic pump (<15 watts). This same methodology can be utilized to keep the enclosure above a predetermined temperature as well.

For liquid medium waste heat recovery systems, one should also consider optimizing generator loading for greater efficiency. When utilizing this strategy, the system controller (PLC) will divert power to resistive water heating elements as the charging load decreases.

System Cycling Frequency

When to run the engine generator can be determined by battery voltage, enclosure temperature, or time between run cycles. The potential strategies for system controls are extensive and go beyond the scope of this paper. A couple of scenarios are listed below but should not be construed as an exhaustive analysis of all the possible methodologies.

Periodic Cycling

The simplest strategy calls for a timed run cycle. In other words, the generator is started at regular intervals and run until the battery bank is topped off. This could be once a day or a couple of times a week depending on the system configuration and requirements. Several inverters offer this generator control functionality and allow for relatively uncomplicated and inexpensive power system development. This frequent cycling also ensures that the temperature will never fall too low for easy starting, and a sophisticated thermal strategy is typically not required. However, because the engine generator is seldom run under a full load for very long, there can be maintenance issues in the long term. Also, it is typically not the most fuel-efficient strategy to pursue. Finally, when used in conjunction with alternative power supplies such as wind and/or PV, there may be unnecessary run cycles, as the battery bank may not actually require a charge.

Battery Status

This strategy calls for continuous monitoring of the battery bank. When voltage falls below a predetermined value (e.g., 23.8 volts on a 24 VDC nominal system), the generator run cycle is initiated. This will typically commence with an engine preheat command prior to actually engaging the starter. This is obviously a more sophisticated control but is still within the capability of several inverters currently on the market.

Putting It All Together

Safety

Working in remote polar environments poses some inherent difficulties. Long hours in extreme cold, wind, and blowing snow can make an already difficult job nearly impossible. It is tempting in these conditions to relax one’s standards and take shortcuts to get the job done more quickly. However, this is exactly the time when one should slow down and move more cautiously. Good work habits are safe work habits thereby reducing the risk of accident and injury and increasing the likelihood of successfully completing a project.

In addition to the environmental hazards, installing engine generator systems bears its own potential hazards. The possibility of electrical shock is quite real. Generators can and have caused electrocution. Moving parts such as fans and belts have the potential to cause mechanical injury. Exhaust emissions are toxic and can lead to asphyxiation in enclosed spaces. Hot exhaust systems and hydronic components can cause burns or even explosions due to steam pressure in poorly designed systems. Batteries contain caustic chemicals and can also represent an additional electrical hazard. Although the shock hazard in a low-voltage system (< 50 volts) is relatively minor, batteries do have a very high short-circuit potential. Arcs can cause collateral damage by making a person jump back in reaction. In severe short-circuit instances, batteries have been known to explode. The acid electrolyte can cause severe burns, and the installer must be prepared to treat immediately with baking soda and water. Charging batteries can release hydrogen gas, which is highly flammable.

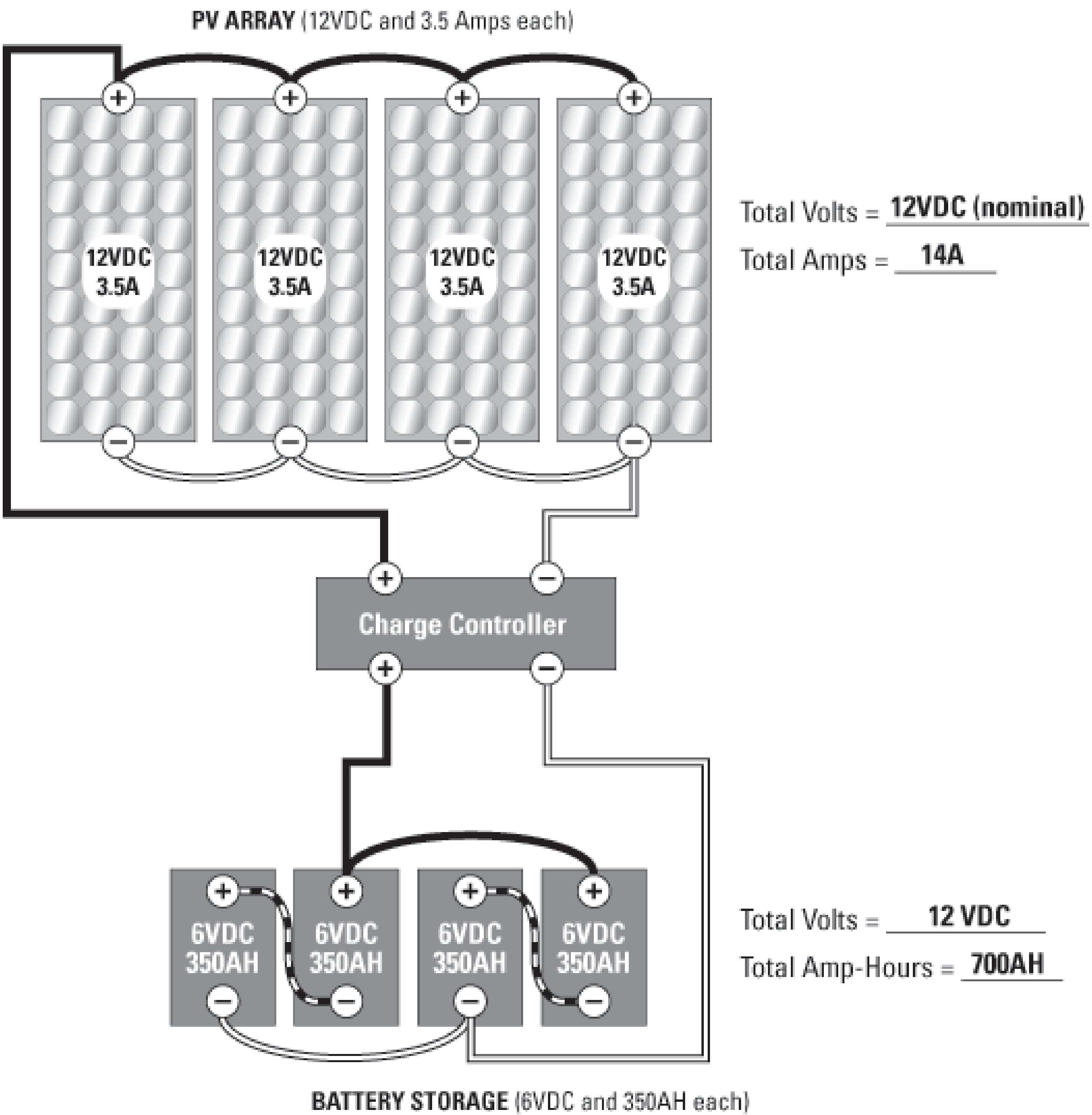
A well-planned and organized work site will dramatically reduce the risks involved with power system installation. Pre-wiring as much as possible and performing a "dry run" while still at the home institution will ensure that everything works properly and will increase familiarity with the system. All of this helps to ensure a safe and successful field deployment. For more on safety, visit http://www.polarpower.org and navigate to Technologies > Power System Fundamentals.

Combustion exhaust gases are poisonous and very hot (>500F). Penetrations in enclosures must be properly designed for safety and reliability. Note the large flange and flexible, high-temperature connector pipe.

System Voltage

Here we are referring to the voltage of the battery bank rather than the output voltage of the generator. For most smaller, autonomous systems, a 12- or 24-volt configuration will be optimal. These lower voltages pose a somewhat lesser electrical hazard and are closer to the operating voltages of equipment typically deployed for purposes of scientific research. Although 12-volt systems have fallen somewhat out of favor in the industry due to the larger gauge cabling required, for many science experiments, this is still the optimal voltage to utilize. When power requirements or longer distances require it, a 24-volt system will usually provide an adequate solution. For only very large systems with high power requirements or systems that need to run DC power for a substantial distance should one ever consider going above 48 volts. High-voltage DC poses significant safety hazards, and even most DC-rated devices are not rated for voltages above 60 VDC.

Batteries are also modular and are typically available in 2-, 6-, or 12-volt ratings. The 2-volt cells are typically *industrial*-type batteries and are often already wired in series within an outer container. The 6- and 12-volt batteries are also composed of 2-volt cells, but they are molded into an integral unit. Most researchers will likely utilize 6- or 12-volt batteries. However, for higher power applications or instances where greater autonomy (periods between generator run cycles) is desired, the 2-volt industrial cells can offer some significant advantages. Battery cabling can be expensive and time consuming, and often the footprint of a battery bank can end up being fairly large. Industrial cells are usually preconfigured in an outer container or a rack and utilize solid bars to interconnect a 12-volt string. Although the cells are typically rather heavy and must be handled individually, the finished bank can end up being much more compact and requires far fewer cable interconnections. Connecting batteries in series results in an increase in voltage while the amp rating remains the same. For instance, four 6-volt/100 amp hour batteries wired in series will produce 24 volts at 100 amp hours (2,400 watt hours). A parallel connection results in an increase in the amperage capacity. Four 6-volt/100 amp hour batteries wired in parallel will produce 6 volts at 400 amp hours (2,400 watt hours). Four 6-volt/100 amp hour batteries wired in a series-parallel configuration will yield 12 volts at 200 amp hours (2,400 watt hours). ***Note: It is very important to deliver and pull power from diagonal corners of the bank, thus ensuring equal loading of the system***.



12 VOLT SYSTEM WITH FOUR 12 VDC PV MODULES

Image courtesy of Solar Energy International.

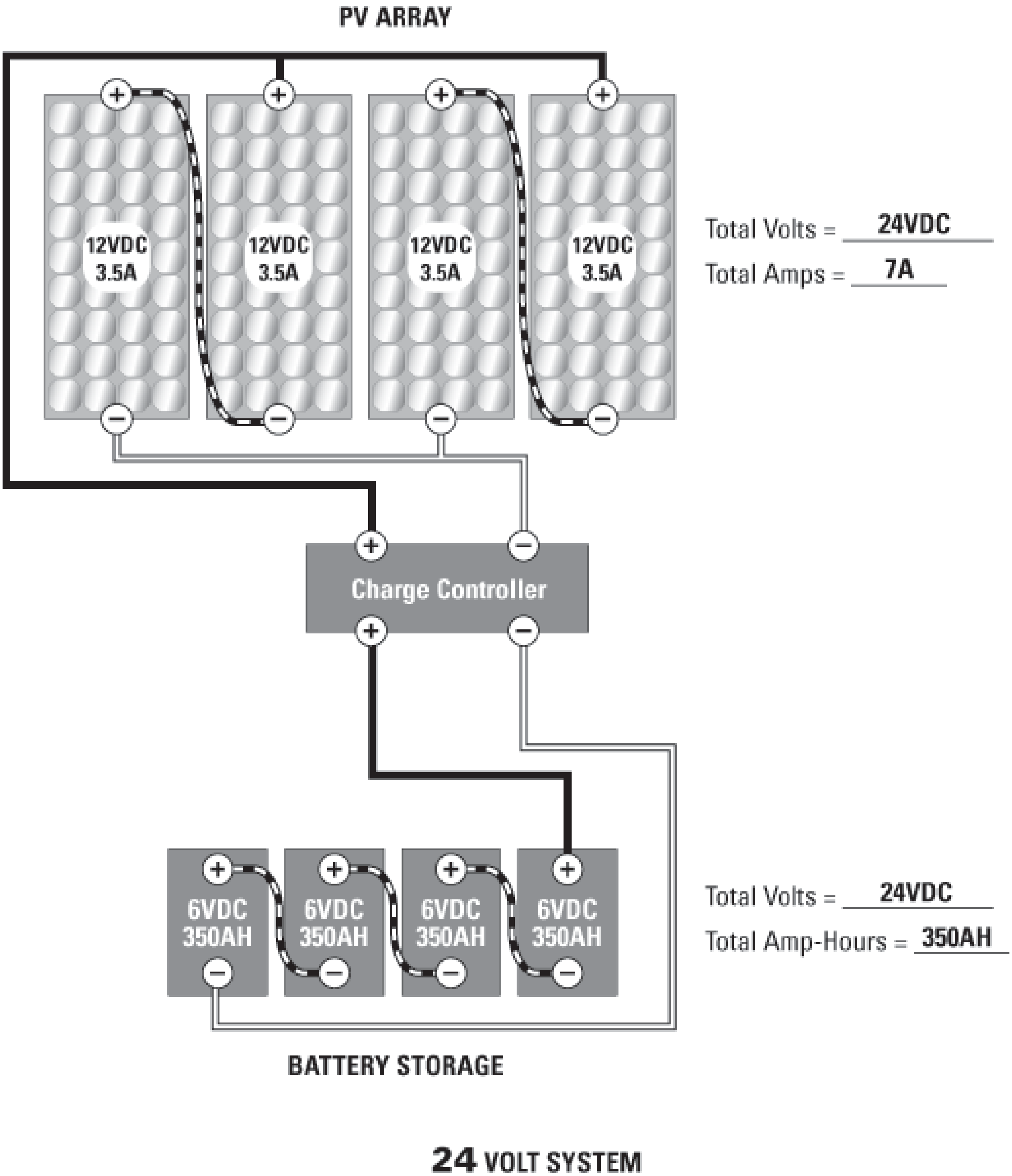


Image courtesy of Solar Energy International.

Conductors

Engine generator systems always incorporate AC systems and usually DC systems whenever a battery bank is employed. AC and DC wiring systems have distinct requirements and should never be mixed in conduit, raceways, or junction boxes. DC systems are typically low voltage (< 48 VDC) and thus require much larger wire sizes than AC systems. Indeed, the wire size required to avoid unacceptable voltage drops across any distance or in high-current applications is often surprisingly large. Many systems have experienced poor performance due to inadequately sized conductors. See the voltage drop charts in the “Basic Electricity” section of this web site.

The polar environment introduces additional challenges in system wiring. Larger cables used for battery connections become incredibly stiff and difficult to work with due to the insulated sheathing. Coarse-stranded wire intended for residential AC-type use exacerbates the difficulty. Pre-assembling as much of the system as possible will reduce field installation woes.

Although conventional wire will often work just fine for the majority of applications, there are a few wire types that are of special interest for remote, cold-weather installations:

- “Arctic Flex” is a product that utilizes a special rubber insulating sheath that stays flexible down to very low temperatures. It is also a fine-stranded wire thus making it quite malleable and easy to work with. It is UL rated and National Electric Code (NEC) compliant. A wide range of sizes and colors is available.

- Welding cable, although not code compliant, offers a perfectly safe and considerably less expensive alternative for high-ampacity cabling requirements.

- For smaller wire sizes, automotive “primary” wire tends to be more flexible and easier to work with in the cold.

- Another favorite wire type of the polar installer is “SO” cord. This type of cord contains three or four insulated conductors inside an outer sheath. This is essentially the same material that extension cords are made out of. It is available in bulk in sizes up to #6 gauge. The outer sheathing varies widely in how flexible it remains in cold environments and seems to be somewhat color coded, with yellow and blue remaining the most flexible. Be sure to check the ratings.

- Armored “liquidtight” cable is heavier and more difficult to work with but offers a higher level of protection for the internal conductors. This is the type of cable to use for long runs in rocky or abrasive terrain or where animals might be a problem.

Remember that if wires are to be left exposed to the environment, they must be rated for exposure including UV radiation. The same energy that is providing power to your experiment can really take a toll on certain types of insulation. UV-resistant sheathing is generally marked as such on the outside. If it does not say “UV rated,” it probably is not.

Remember to include the correct adapters to bring the cables and conduit into the junction boxes and enclosures. Every type of conduit, armored cable, or SO cord requires something a bit different. The devil is in the details, so make sure you have the correct adapters—and plenty of them. Again, pre-assembly at your home institution is an effective way to ensure you have what you need when you arrive at the field site.

Combiner blocks, mechanical lugs, split bolts, and a variety of solderless connectors should have a place in your field tool kit. Rubber splicing tape and low-temperature electrical tape are essential as well. Red electrical tape serves as *code tape* to ensure that you know which of those black cables is the DC positive.

The convention for DC color-coding is as follows:

- Red is for positive—the current-carrying conductor.
- White is for negative. (I code tape mine black.)
- Green or bare is the equipment ground.

The fine-stranded wire recommended above is much easier to work with in cold environments but poses some additional requirements for system installation and maintenance. Mechanical lugs can damage or break the fine strands resulting in a weak connection and reduced ampacity. Take care during installation, and regularly check the tightness on all connections during all maintenance visits.

The positive and negative conductors in a DC system should be kept closely together and in parallel for any long runs to avoid inductive potential.

Grounding

Grounding is a deceptively complicated issue. Although the NEC requires *equipment grounding* on all generator systems regardless of operating voltage, obtaining a true *earth ground* in polar environments can often be difficult or impossible to obtain. In areas of permafrost, rocky soil, or muskeg, grounding plates or grounding rings made of 4/0 bare copper will typically provide a satisfactory earth ground. This earth ground must be bonded to every metal electrical box or component enclosure, receptacle, and bare metal frame. The grounding wire is never fused or switched, and the entire system must be grounded at only one point.

In an ice cap environment, achieving an earth ground is typically not possible. As such, grounding is dealt with in the same way as within the automotive industry. In this method, the frame or chassis becomes the grounding point to which all of the negative conductors are referenced. Most engine generators provide a clearly identified grounding point. Although not as good a system as a true earth ground, it does ensure that overcurrent devices will operate as designed.

For an extensive discussion of system grounding, see the Sandia National Laboratories report, *Photovoltaic Power Systems and the National Electric Code: Suggested Practices* (2001). The PDF version is available at: http://www.re.sandia.gov/en/ti/tu/Copy%20of%20NEC2000.pdf

Overcurrent Protection

Although remote scientific research projects are unlikely to receive a visit from the Electrical Inspector, it is wise to include adequate circuit protection. Breakers and fuses serve to protect the equipment, provide safety, and allow for easier maintenance of the system. Moreover, these devices protect conductors from currents exceeding the rated ampacity. The NEC specifies the maximum overcurrent protection for each conductor size.

When the current exceeds the rated amperage of a breaker or fuse, the circuit opens and the flow of current ceases. Breakers are typically considered preferable, as they can simply be reset, whereas a blown fuse must be replaced. This necessitates having spare fuses on site. It should be noted that not all breakers are rated to handle DC. The arcing inherent in DC-type power systems will quickly burn out the contact points of a non-DC-rated breaker or switch. Specialized DC-rated breakers are available from most suppliers of renewable energy equipment and should be used for main battery disconnects and other high-amperage applications. For smaller DC load protection, Square D “QO” or “QOU” series breakers are rated for up to 48 VDC and are widely available at a significantly lower cost.

Breakers are triggered by unequal expansion of a bi-metal strip as current flows through it and heats it up. In cold climates, the rated ampacity of a breaker can end up significantly lower than the current level at which it actually trips. Fuses are somewhat less affected by temperature extremes. Remember that overcurrent protection is really providing protection for the conductors or wiring in a circuit rather than the electrical device itself. If multiple sizes of wiring exist within a protected circuit, the breaker or fuse must be sized to protect the smallest wire.

Although your project may fall outside the auspices of the NEC, there is still good reason to comply with the provisions it contains to ensure a safe and reliable system. The NEC requires every ungrounded conductor to be protected by an overcurrent device. This is the positive wire in a DC system and the black and red conductors in an AC system.

At a minimum, DC-rated overcurrent protection should be supplied:

- between the battery bank and the DC load center,
- between the battery bank and the inverter (if present), and
- for each DC circuit originating in the DC load center.

At a minimum, AC overcurrent protection should be supplied:

- between the generator and the AC load center and
- for each AC circuit originating from the AC load center.

Fundamental Design Principles

Before moving on to the worksheet, one more area of basic system design should be covered. That is, how does it all physically fit together as a system? Stated simply, there are three basic approaches:

1. *Single unit:* All of the components are housed in a single enclosure with the generator, the batteries, the balance-of-system components, and perhaps even the science equipment integrated into the design

2. *Modular:* Components are set up as modules that can be linked together and added onto as system requirements dictate.

3. *Hybrid:* This is essentially a combination of the first two concepts. There is a single main unit that contains the battery bank, the controls, and so forth but with the engine generator located separately as well as other possible power sources.

Each of these approaches is valid with intrinsic positive and negative features that will determine the suitability for a given project. The single-unit approach can be quite attractive and offers the benefit of being able to keep everything together with minimum field set-up required. It also allows for the easiest integration of a waste heat recovery system. However, how will it be deployed? Typically, this arrangement requires the use of equipment, be it ground based, helicopter, or fixed wing. Unless it is a very small system, this ends up being a rather large and difficult box to move. If the researcher has access to the required equipment, the advantages are hard to beat.

The Northern Power System being offloaded at it's new home in Alaska.

The modular approach is attractive for smaller projects or for areas where deployment will be an issue. There are numerous possible permutations of the basic design. As an example, consider a central unit containing a battery bank, an integral PV array, and balance-of-system components including a place for science equipment. The engine generator, additional PV arrays, wind turbines, battery banks, and so forth can be added on as power requirements dictate. The advantages here are:

- *Ease of deployment:* All of the components can be handled manually without the use of heavy equipment. The individual modules can be transported to the site via small aircraft and moved into position by hand. There are limitations, however.

- *Easy expansion of the system:* Inevitably, project scopes will grow. As additional instrumentation loads are added on, the power requirements go up. Being able to plug in another PV array or battery bank without extensive system modification is a great advantage.

Disadvantages include:

- *More difficult to create effective thermal strategies*.

- *No room for personnel to get out of the weather to work on equipment*. Essentially, plan on working on everything outside, be it fair weather or foul. Setting up a tent adjacent to or even over the top of the system somewhat obviates this drawback.

The hybrid solution offers the option to draw on the best characteristics of both of the previous strategies. This can, however, prove to be a rather costly approach and may not be suitable for all projects.

System Maintenance

For periodic or seasonal use, a small portable generator does not typically require extensive maintenance. Most portable generators require changing engine oil at about a 100 hour interval, with a bit more extensive servicing (air filter, spark plug, etc.) at about every 250 hours of operation. This is all within the capability of the Researcher to perform with only common hand tools and a minimum of time and effort. Items such as engine oil level should be checked daily, or every time the fuel tank is re-filled.

One of the principle disadvantages of utilizing engine generators in an autonomous system is that they require periodic and often fairly extensive maintenance. While the maturity and wide spread nature of internal combustion engine has led to excellent performance and reliability, they remain very complicated pieces of equipment, with numerous potential areas of failure. Maintaining systems such as this may be beyond the capability of most Researchers in terms of the specific tools and knowledge required, as well as the time it takes to perform comprehensive testing and maintenance. The documentation required for system maintenance on sophisticated, autonomous engine generator systems can occupy volumes, and goes well beyond the scope of this introductory paper. Similarly, storing an adequate amount of fuel on site, and minimizing generator run time so as not to exceed allowable service intervals can be very difficult problems to overcome with unmanned systems.

It is prudent to carefully consider all of these factors early on in determining what type of system to use in powering remote scientific investigations. The inherently simpler nature of renewable energy systems (photovoltaic & wind turbines) might make them a more viable option where lower power requirements and/or abundant natural resources allow the utilization of these strategies. Alternatively, combining the simplicity and reliability of renewable energy systems with the high power capability and on-demand nature of engine generators in a "hybrid" system can create a win-win scenario, reducing fuel storage and maintenance issues, while providing an additional level of redundancy for enhanced reliability. These technologies are covered elsewhere in the http://www.polarpower.org web site.

The power module at Ivotuk, Alaska, after installation of PV and wind.

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Engine Generator Sizing Worksheet

I. Load Analysis

DC Loads

Equipment	Qty x volts x amps = watts	x hr/day = watt hr/day	x 7 = watt hr/week	
________	________________ x	________________ x	________ =	________
________	________________ x	________________ x	________ =	________
________	________________ x	________________ x	________ =	________
________	________________ x	________________ x	________ =	________

AC Loads

Equipment	Qty x V x A x 1.2 = watts	x hr/day = watt hr/day	x 7 = watt hr/week	
________	________________ x	________________ x	________ =	________
________	________________ x	________________ x	________ =	________
________	________________ x	________________ x	________ =	________
________	________________ x	________________ x	________ =	________

1. Total power requirement in watt hours per week. ________
2. Multiply total by 1.2 to compensate for system losses during the battery charge/discharge cycle. ________
3. Enter the nominal voltage of the battery bank. ________
4. Divide line 2 by line 3. This is the amp/hr requirement per week. ________
5. Divide line 4 by 7 days. This is the average amp/hr requirement per day that will be used to size the battery bank and PV array. ________

II. Optimize Power System Demands

Examine power consumption and reduce total power requirements as much as possible. Identify any large and/or variable loads and try to eliminate them or find alternatives. Consider the preferential use of DC devices over AC to reduce losses in the conversion process. If there are large loads that cannot be eliminated, consider periodic sampling, use only during peak sun hours, or use only during the summer. Revise the load sizing worksheet with the now optimized results.

III. Size the Battery Bank

6. Enter the maximum number of days of autonomy the system must support. ________
7. Multiply line 5 by line 6. This is the amount of amp/hrs the system must store. ________
8. Enter the depth of discharge for the battery chosen. The value should not exceed 0.5 (50% depth of discharge). This prevents overdischarge and potential freezing of the electrolyte. ________
9. Divide line 7 by line 8. ________
10. Select the multiplier below that corresponds to the average winter temperature the battery bank will experience. ________

º C	º F	Multiplier
10	50	1.19
4.4	40	1.30
-1.1	30	1.40
-6.7	20	1.59
-10	14	1.65
-15	5	1.80
-20	-4	1.95
-25	-13	2.10
-30	-22	2.50
-35	-31	2.75
-40	-40	3.33
-50	-58	Forget it! Use a thermal strategy to keep batteries warmer.

*Note: The multipliers from –10º C/14º F and below are approximate. Information on battery performance in extreme cold is practically non-existent. This chart illustrates the importance of thermal regulation of the battery compartment.

11. Multiply line 9 by line 10. This ensures that the battery bank will have enough capacity to overcome cold weather effects and represents the total battery capacity needed. _______
12. Enter the amp hour rating for the battery chosen. _______
13. Divide line 11 by line 12 and round off to the next higher number. This is the number of batteries wired in parallel required. _______
14. Divide the nominal system voltage by line 3 and round off to the next higher number. This is the number of batteries wired in series required. _______
15. Multiply line 13 by line 14. This is the total number of batteries required. _______

IV. Size the Battery Charger/Inverter

16. Battery bank voltage. _______
    • Charger voltage must match.
17. Battery bank amp hours (from line 11). _______
18. Maximum battery charge rate for battery type. _______
    • 20% of amp hour capacity for flooded or AGM type
    • 5% of amp hour capacity for gel-cell type
19. Multiply line 18 by 1.25. This is the minimum amp rating required for the charger. _______

V. Size the Engine Generator

For utilizing inverter/charger:

20. Total AC instrument loads in amps @ 120 VAC _______
21. Total battery charging load in amps @ 120 VAC _______
22. Add lines 20 & 21 _______
23. Multiply line 22 by 1.25. This is the minimum amp rating the generator must be able to provide. _______
24. Multiply line 23 by 120. This is the minimum watt rating for the generator. Round up to the next suitable size rating available. _______
    • Divide by 1,000 to obtain the kW rating.

For utilizing charger (rectifier) only:

25. Total battery charging load in amps @ 120 VAC _______
26. Multiply line 25 by 1.25. This is the minimum watt rating for the generator. Round up to the next suitable size available. _______
    • Divide by 1,000 to obtain the kW rating.

Note: In either case, if full generator output is not available at 120 VAC, a transformer may be required to convert the 240 VAC output of the generator to 120 VAC output for use by the charger.

* Worksheet adapted from *Autonomous Systems in Extreme Environments*, a white paper resulting from the 1999 event hosted by JPL.