Report on Autonomous Systems In Extreme Environments Workshop

Held: 31 August – 2 September 1999

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0.0 Executive Summary.

Antarctica and the Arctic are expensive and difficult places to do research because of their remote nature and harsh environmental conditions. They are the most isolated places on Earth and also experience the most extreme weather conditions. Antarctica and its special challenges is the driver for this workshop; it is the prototype extreme environment. In some regions of Antarctica, temperatures have been recorded as low as -90°C, wind gusts at nearly 90 m/sec, and absolute humidity lower than in the Sahara desert. The polar regions are among the Earth's most sensitive to environmental change and also have exceptionally long natural climate records. Scientists are constantly looking for ways to accomplish research goals at the lowest possible cost and still maintain a high level of scientific value. In 1996, the Committee on Fundamental Science of the National Science and Technology Council (NSTC) recommended that cost savings for the U.S. Antarctic Programs could be achieved by reducing requirements for on-site supporting staff by developing autonomous data gathering systems utilizing advanced computers and micro-electronics and emerging satellite capabilities.

Numerous investigators are conducting experiments in polar or other extreme environments that require the use of autonomous systems and the number of autonomous systems is expected to increase. Examples of programs that currently use autonomous systems in the Antarctic are the Automated Geophysical Observatories (AGO) program, University of Wisconsin remote weather stations, remote GPS stations deployed by JPL and UCSB, and remote seismic stations deployed by Penn State University. The Arctic division of NSF/OPP sponsors autonomous systems development for environmental monitoring. The goal of the Long-term Observations in the Arctic program is to increase the availability of long-term environmental data in the Arctic. Sites are needed due to the scarcity of observations in the Arctic (compared to most places on Earth), the lack of ready access to many parts of the Arctic, or the necessity to collect new samples because no Arctic sample curatorial facility exists except for ice cores. Ocean engineers have a long history of dealing with remote stations on the sea floor. Our emphasis for this workshop will be on sub-aerial systems.

While these systems may vary in size and power requirements, they have similar problems that must be overcome in order for them to function properly. These problems include, but are not limited to, issues related to power, thermal environment, data storage, communications, and packaging. A workshop was convened August 31 - September 2, 1999 at the Jet Propulsion Laboratory in Pasadena, California to discuss these issues.

An integrated systems approach must be used to design a successful autonomous station. For example thermal systems impact power systems and these systems may have feedbacks on themselves. Changes in one aspect of the system may impact another component. The workshop sought to promote discussion between investigators so that lessons learned could be efficiently communicated and successful systems developed that maximize scientific output. Scientists, engineers, and industry partners participated in the workshop. The goals of the workshop are as follows:

1. Promote dialogue between scientists and engineers on autonomous system design.
2. Make recommendations on power, thermal, data, communications, and packaging systems.
3. Discuss whether standardization is recommended for future systems.
4. Discuss and recommend whether design and testing criteria should be met before systems are deployed in polar regions.

1.0 Introduction.

Science has been inexorably tied to the history of exploration of the physical world. Until tamed by the presence of shelter, energy production and sustainable logistics, every frontier has presented an extreme environment in which to conduct research. Today we face three frontiers, the deep ocean, the polar-regions, and space beyond Earth's orbit, into which expeditions have made initial forays. Now, as our experience in those environments matures we seek to move from an exploratory to an observatory approach to science. John Orcutt, who has spent a career at Scripps Institute of Oceanography developing sea floor observatories, eloquently introduced this evolution at the workshop's opening.

> The exploratory approach has a long tradition; it is a rich and old approach to doing this work. Voyages of discovery are well known in each of these frontiers yet it is not an inexpensive way to do research, by any means. But one of the problems with doing research is that by visiting places for short periods of time you have a very limited ability to quantify change. Today, observatories are common on the populated continents and even in earth orbit but in our frontiers, they're rare and our frontiers account for 70% of the total Earth's surface area, 10% of the total land area and most of our solar system and beyond. Two observatory strengths are clear. First, it is the only way to observe transients or changes and second, low signal to noise ratios require long-term observations. The advantage to making these observatories autonomous is cost. The challenge is making them in the extreme environments in which they must operate.

In September 1999 a joint NSF/NASA workshop was convened to discuss the building and deploying of autonomous systems in extreme environments. Autonomous systems were defined as permanent geophysical or astrophysical installations that are self-sustaining over periods of months and years. They acquire data on a regular time interval or upon a triggering event and either store that data or transmit it to a data center. In attendance were representatives from research institutions, government agencies, and private industry, all interested in the development of technology to assist science in extreme environments with a focus on space, the polar-regions, and the deep oceans. They established the following goals for the workshop:

- Promote dialogue between scientists and engineers on autonomous system design.
- Make recommendations on power, thermal, data, communications, and packaging systems.
- Discuss whether standardization is recommended for future systems.
- Discuss and recommend whether design and testing criteria should be met before systems are deployed in the polar-regions.

The publication of this workshop is a first step toward improving dialogue between scientists and engineers across all communities. It is envisioned that periodic conferences supplemented by a frequently updated web site will further information and technology transfer, avoid the duplication of development efforts, and help assure that more robust systems are deployed which will reduce the cost of operating in these environments. The creation and maintenance of such a web site is the first recommendation of the committee.

Action Item: Identify an organization responsible for maintaining an interactive web site for the promulgation and discussion of new ideas, and develop a means for funding it.

Action Item: Prepare and maintain an experimenter's handbook that includes a compilation of proven technologies, lessons learned and other information relevant to designing and deploying autonomous systems to extreme environments.

2.0 Extreme Environments.

In order to make recommendations on system components and integrated design it is necessary to understand the environment in which they are required to operate. What aspects of space, the polar-regions, and the deep ocean make them extreme? Our degree of design success depends in a large part, on our knowledge of the environment, yet because these are new frontiers our knowledge is not complete and not always accurate.

Action Item: Principal Investigators deploying systems to the field should make an effort to include meteorological instruments in their systems and the data obtained from said instruments should be added to a database maintained on-line.

Here are the anticipated environmental characteristics, as they are presently known.

2.1 Temperature.

The deep ocean possesses a relatively stable temperature environment typically in the range of 0-5.6°C (32-42°F). An exception is in the vicinity of active hydrothermal vents where effluent water temperatures can exceed 315°C (600°F). In space, temperature is dependant upon incident solar radiation and areas of direct sunlight and shade can vary by as much as hundreds of degrees, even when such areas are adjacent to one another. In the Antarctic, temperatures vary with season and location. On the coast, summertime temperatures vary from -29°C to +4.5°C (–20°F to +40°F) while winter temperatures are typically –45.5°C to -29°C (-50°F to -20°F). On the Antarctic plateau, where elevations range from 2,500 to 3,500 m (8,000 to 11,000 ft.), the summer temperatures vary from -40°C to –6.7°C (–40°F to +20°F) while winter temperatures may reach as low as -73°C (-100°F).

2.2 Wind and Current.

In the deep ocean, especially near the sea floor, currents are typically low and rarely exceed 2 m/sec (4 knots). Systems are easily anchored in the seabed and may often be buried to avoid damage from vessel anchors, fishing or trawling. Ocean surface observatories (buoys) face real survivability concerns with regard to wind speed and its subsequent effect on wave height. The likelihood of a buoy to sustain damage goes up about the fourth power of the sea height and sea height goes up about the square of wind speed. So roughly a factor of the sixth power applies to wind speed on the oceans and potential for damage to buoys. In space, solar wind is a negligible detrimental effect though attention must be paid to shielding for micrometeorite abrasion and space debris. In Antarctica, wind is a significant factor and varies considerably with location and season. On the Antarctic plateau winds remain steady and relatively calm throughout the year, seldom exceeding 15 m/sec (30 knots) and more typically blowing 4-6 m/sec (8-12 knots). Along the coast, particularly in mountainous regions, winds vary from calm air to sustained speeds in excess of 30 m/sec (60 knots). During winter, these storms may even exceed 66 m/sec (130 knots). Black Island, by no means an unusual coastal location, has recorded winds of 28-31 m/sec (55-60 knots) sustained for the entire month of October. High winds also carry the threat of impact damage from airborne debris (i.e. rocks).

2.3 Pressure.

The most extreme case exists for systems in the deep ocean where pressure increases 44.5 psi for every 100 feet (3069 mb per 30.5 meters) of descent. A maximum depth of

10,927 meters (35,840 feet) is attained at the Challenger Deep location in the Mariana Trench, with a resulting pressure of 15,950 psi. The problem of pressure, however, is well known, predictable, and has been solved with some expense, using pressure vessels or pressure compensation systems. Such solutions, though effective, have become the most expensive component of underwater instruments. Pressure vessel technology works equally well in space applications. In the Antarctic the only pressure concerns involve air-dependant systems (i.e. combustion or wind) operating on the Antarctic plateau at elevations of 2400-3400 meters (8,000 – 11,000 feet).

2.4 Static Discharge.

The ocean is a natural electrical ground and internal components can be easily safeguarded if they are grounded to their pressure vessel casing. In many cases, particularly in submersible design, however, the internal electrical system is maintained isolated to assist in ground isolation procedures. In spacecraft, the build-up of charge can be extremely localized and have catastrophic effects on the micro-powered systems onboard. Although spacecraft have failed in the past due to static discharge, the threat is recognized and its solution is fairly well understood. Careful selection of materials, quality control during production, and attention to static dissipation in design, have proven successful in managing this problem. In Antarctica we have only begun to appreciate the significance of the very prevalent static discharge conditions. Extremely low humidity and the presence of blowing snow seem to precipitate a large static charge build-up. It may occur as a result of piezoelectric charging and transfer on impact and/or the snow particles themselves may carry some charge; it is simply not yet known. The micro sparking that results can damage electronic components or distort data so as to render it unusable for research.

2.5 Radiation.

Radiation is negligible in the deep ocean since the water column attenuates solar and natural earth sources. In Antarctica, the altitude of the polar plateau, depletion of ozone, and the 24-hour summer sunlight exposure can accelerate ultraviolet degradation of some materials such as plastic. Cosmic rays can also cause problems with data storage, particularly when magnetic media is used.

In space, two types of radiation cause problems for semiconductor devices. They are electromagnetic radiation and ionizing radiation. Electromagnetic radiation is comprised of photons of gamma rays, X-rays, ultraviolet or UV radiation, visible light, infrared, microwaves, and radio waves. The source of electromagnetic radiation is primarily the Sun. The relevant types of ionizing radiation are Galactic Cosmic Rays (GCR), and Van Allen Belts. GCR are made up of high-energy protons, helium nuclei, and heavy nuclei. GCR originate in distant stars and are the most penetrating radiation because of the high energy they possess. The total flux for GCR is fairly small, and may or may not cause a problem for electronic devices. The Van Allen Belts are regions around the Earth that comprise high-energy protons and electrons.

Each type of radiation described has an individual effect on electronic devices, making it necessary to know what the device will be exposed in order to know what to protect it against. There are four basic categories of radiation effects relevant to integrated circuit protection. These four effects are Neutron, Total Ionizing Dose, Transient Dose, and Single Event Effect (SEE).

- **Neutron Effects:** When neutrons strike a semiconductor chip, they displace atoms within the crystal lattice structure. The minority carrier lifetime is reduced because of the increased recombination centers created. Silicon devices begin exhibiting changes in their electrical characteristics at levels of 1×10^{10} to 1×10^{11} neutrons/cm^2. Because bipolar components are minority carrier type devices, neutron radiation affects them more than MOS devices. In bipolar integrated circuits, the base transit time and width are the main physical parameters affected. Therefore, neutron radiation significantly reduces gain in bipolar devices. MOS devices aren't normally affected until levels of 1×10^{15} neutrons/cm^2 are reached.
- **Total Ionizing Dose Effects:** Total Ionizing Dose is the accumulation of ionizing radiation over time, typically measured in rads. Slow, steady accumulation of ionization over the life of an integrated circuit causes performance parameters to degrade. Eventually, the device fails. The total dose creates a number of electron-hole pairs in the silicon dioxide layers of MOS devices. As these begin to recombine, they create photocurrents and changes in the threshold voltage that make n-channel devices easier to turn on and p-channel devices more difficult to turn on. Even though some recovery and self-healing takes place in the device, the change is essentially permanent. Some holes created during ionizing pulses are trapped at defect centers near the silicon/silicon oxide interface. Charges induced in the device create a field across the gate oxide sufficiently high to cause the gate oxide to fail, or sufficient carriers are generated in the gate oxide itself to cause failure.

- **Transient Dose Effects:** A Transient Dose is a high-level pulse of radiation, typical in a nuclear burst, which generates photocurrents in all semiconductor regions. This pulse creates sudden, immediate effects such as changes in logic states, corruption of a memory cell's content, or circuit ringing. If the pulse is large enough, permanent damage may occur. Transient doses can also cause junction breakdown or trigger latchup, destroying the device.
- **Single Event Effect (SEE):** Single Event Effects have been studied only recently. They typically only affect digital devices significantly, but SEE's are of primary concern in today's digital age. A SEE occurs when a single high-energy particle strikes a device, leaving behind an ionized track. The ionization along the path of the impinging particle collects at a circuit node. If the charge is high enough, it can create a soft error Single Event Upset (SEU), such as a bit flip, a change in state that causes a momentary glitch in the device output, or corruption of the data in a storage element. A SEE can possibly trigger a device latchup and burnout. Latchup occurs when sufficient current is induced in part of the device that causes the device to latch into a fixed state regardless of circuit input. Burnout occurs when the radiation induces sufficient power dissipation to cause catastrophic device failure. Burnout often occurs as a result of latchup. SEE's can wreak havoc on satellites, spacecraft, and aircraft as well. Therefore, circuits used in aerospace controls systems must be protected from potentially disastrous SEEs.
- **Single Event Upsets (SEU):** These are also known as soft errors that occur due to either the deposition of depletion of charge by a single ion at a circuit node,

causing a change of state in a memory cell. In very sensitive devices, a single ion hit can also cause multiple-bit upsets (MBUs) in adjacent memory cells. This type of event causes no permanent damage and the device can be reprogrammed for correct function after such an event has occurred.

- **Single Event Latchup (SEL):** This can occur in any semiconductor device that has a parasitic n-p-n-p path. A single heavy ion or high-energy proton passing through either the base emitter junction of the parasitic n-p-n transistor, or the emitter-base junction of the p-n-p transistor can initiate regenerative action. This leads to excessive power supply current and loss of device functionality. The device can burnout unless the current is limited or the power to the device is reset. SEL is the most concern in bulk CMOS devices.
- **Single Event Snapback:** This is also a regenerative current mechanism similar to SEL, but a device does not need to have a p-n-p structure. It can be triggered in a n-channel MOS transistor with large currents, such as IC output driver devices, by a single event hit-induced avalanche multiplication near the drain junction of the device.
- **Single Event-Induced Burnout (SEB):** This event may occur in power MOSFETs when the passage of a single heavy ion forward biases the thin body region under the source of the device. If the drain-to-source voltage of the device exceeds the local breakdown voltage of the parasitic bipolar, the device can burn out due to large currents and high local power dissipation.
- **Single Event Gate Rupture (SEGR):** This has been observed due to heavy ion hits in power MOSFETs when a large bias is applied to the gate, leading to

thermal breakdown and destruction of the gate oxide. It can also occur in nonvolatile memories such as EEPROM during write or erase operations, the time when high voltage is applied to the gate.

2.6 Chemical Reaction.

The primary concern is corrosion in a salt-water environment, although reaction between dissimilar metals, leakage of system fluids (i.e. battery electrolytes, refrigeration coolants, hydraulic fluids, lubricants), or the exposure to system exhausts or effluents, such as a hydrazine thruster, could result in adverse chemical interactions and should be considered in system design. Exhausts have proven particularly troublesome since their behavior once vented is not under the control of the system and often not predictable. The condensation and freezing of exhaust vapor in the AGO system is one example that caused numerous problems and demanded detailed re-design. Spacecraft have been known to travel in a cloud of associated effluent particles whose presence may adversely impact the science being performed. Similar problems can be easily envisioned for an earthbound station located downwind or downstream from an undesirable effluent source. In other cases, the impact of effluents on the environment must be minimized to comply with local ordinances, treaties, political policies, or simply popular opinion. One last situation to consider is the reaction a system could experience if exposed to unusual gases while passing through the emissions of a hydrothermal vent or the atmosphere or mass ejections of another planet or moon.

2.7 Inaccessibility.

Although perhaps not conventionally considered as an environmental condition, the reliability and survivability required of autonomous systems is dictated by the degree of difficulty in reaching them for troubleshooting or repair. Inaccessibility may be considered physically, or from the perspective of remote communications ability for monitoring system health and transferring data. Deep spacecraft, by virtue of their distance, speed and trajectory are physically remote yet in continuous communication. Weather, particularly in winter, impedes physical access to Antarctic systems and lack of adequate communications infrastructure makes telemetry access equally difficult. The physical accessibility of ocean sites is most subject to the availability of support ships and submersibles. Whatever the reason, the degree of difficulty associated with reaching each environment drives up the cost per pound to transport items to that environment. Weight and logistical cost must be considered as corollary factors contributing to the inaccessibility of a particular extreme environment.

3.0 System Design.

Measurement needs drive power and communications requirements; environment and measurement needs drive system design. Thus, the first critical step in system design is to identify needs versus wants in data collection, recognizing that the design process will be an iterative one. As outlined by Jack Doolittle, longtime engineer for the Antarctic AGO system,

> Ask why are we going to a site? Science drives us to select the site where we prefer to go to make the observations, such as the highest point on the Antarctic plateau for an infrared cosmic telescope, or the sea floor on the Juan de Fuca plate for a seismic network. Then go through a process of examining the amount of data that needs to be acquired; what options are available for data acquisition systems to accommodate that data volume; how that influences power and whether or not we need to have thermal control on the system; how much of a shelter we need to accommodate it and then, probably key to this entire process, is what the logistics support methods are that puts the system in place. Logistics provides the reality check.

One of the keys to successful design is the close cooperation between scientists, defining their needs and objectives, and engineers, developing solutions that will work in the proposed environments. Scientists at the conference agreed time and again, “get good engineers involved”.

3.1 Power.

The major problem facing autonomous systems in remote extreme environments is power. The challenge of building a reliable power system was echoed by all the participants among all the various disciplines. The lack of real breakthroughs in power generation technology has driven one of the fundamental autonomous system design maximums; keep loads low. The smaller the load, the cheaper and lighter the system, and every watt and pound counts. Technological advancements have continued to move toward micro-powered devices that substantially ease the demand made on remote power generation equipment, however, micro-power carries with it its own complications. Electrostatic discharge poses a greater threat to micro-power systems, and all aspects of construction from component selection to solder joints must be held to higher standards. More thought must be given to shock hardening and thermal control since micro-power devices are likely to be more sensitive to such influences.

In general, systems can be classified according to their power requirements as low (<3 watts), medium (3-50 watts), and high (>50 watts). The first preference for power is to remain on the global power grid, however the majority of the planet is devoid of any power at all, and it is in these remote extreme environments that we desire to place our systems. Several factors, succinctly outlined by Jack Doolittle, may drive the need for science to operate beyond the power grid.

- It may be the best place, or the only place to make such observations.
- It may be a site for conjugate studies.
- It may be a remote portion of a larger distributed network.

It may be possible to select a site that is off the power grid but has its own power generation such as in remote population centers, mining or fishing villages, defense bases or established research bases. Within a limited range of such locations it can be practical and most economical to consider cabling power to an instrument or network of instruments. As range increases, however, I^2R losses become considerable even when a high voltage is used for transmission. Cost of the cable, particularly if it includes an optical fiber, can also become prohibitive as distance increases. Finally, consider that the copper in a cable could represent significant value to remote populations and thus could become a liability to cable deployment.

If one's science goes beyond these established sites then the options available are to either build a new manned facility or deploy an autonomous station to support the science. The primary objection to creating a new manned station is cost, and minimizing cost is the motivator to going into automated stations. An autonomous facility can be built at a fraction of the cost of an attended facility but despite that, a significant expense of any autonomous system will be the power supply.

3.1.1 Fossil Fuels.

The primary advantage to using fossil fuel is its reliability and ease of power regulation. Such systems usually require greater maintenance to set up and keep running. They are not renewable and typically incur greater transport difficulties, particularly considering the fuels, gasoline, diesel, kerosene, propane, etc., are all hazardous materials and hazardous cargo with appreciable weight. Of the possible fuel choices, propane is the most preferred because it is clean burning which is essential for long service intervals. Traditional fossil fuel plants use combustion to turn a generator that produces a regulated electrical output. Another method, used successfully with the U.S. AGO program, is to use a thermoelectric generator. One of its principle advantages it is that it can be constructed with no moving parts. In this type of system, propane gas is flowed into a burner box, which has a bed of platinum coated pellets that serve as catalysts. There, a catalytic conversion occurs, basically a low temperature burning without flame, just a glowing heat generation. The byproducts are essentially carbon dioxide and water vapor.

Although the process is somewhat inefficient (about 20%) the significant waste heat generated can be put to good use in thermal control of the system enclosure.

Two things to consider in the design of a combustible fuel generator are the venting of exhaust and the storage of the fuel. In cold environments the exhaust may freeze to the outlet and the resulting backpressure may shut the system down. In the AGO system this problem was overcome by extending and heating the exhaust shroud. Also, at low temperatures (<10°C), propane and other fuels may not be self-vaporizing and may require the addition of thermal energy to keep it warm or a pressurization charge of dry nitrogen. Another refinement in the burner system, especially in cold environments at high altitude, is to boost the burner temperature by providing some turbo-charging, forcing a fanned aspiration on the generator. The higher burner temperature produces a hotter exhaust which helps avoid some of the problems with exhaust condensation and freezing.

Diesel generators are commonly used on ocean buoys supporting autonomous instruments. The efficiency and reliability of internal combustion under conditions of moderate temperature and low altitude make the diesel generator the power supply of choice. In this application, even the mass of fuel is not a problem, indeed it contributes to the overall system buoyancy, is compatible with the fuel used by buoy servicing vessels and represents a fraction of the fuel carrying capacity of such vessels. At sea, combustion exhaust is conveniently vented and the vibration produced by diesel generators seldom exceeds that caused by the pitch and roll of the ocean surface. Thus instruments designed for the surface ocean environment are unlikely to be adversely affected by the use of a diesel generator for power.

Of course, fossil fuels have little application in space although some have proposed utilizing combustion engines on Mars. Such engines would burn a mixture methane and oxygen to power a generator. Both of these reactants could be produced in situ by combining carbon dioxide from the Martian atmosphere with hydrogen, a process known as a Sabatier reaction. Initially the hydrogen would be transported from Earth but later supplied as a byproduct of reaction.

Combustion Reaction: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

Electrolysis: $2H_2O \rightarrow 2H_2 + O_2$

An autonomous system utilizing such a combustion process would be in the enviable position of being able to draw on virtually inexhaustible, in situ resources, namely the Martian atmosphere, for fuel supply.

3.1.2 Fuel Cells.

A fuel cell is a galvanic cell in which the reactants are continuously supplied. The reaction process is highly reliable, involving no moving parts and providing a stable power output with no noise or vibration and clean emissions. The reaction in a single typical fuel cell produces only about 0.7 Volts. To raise this voltage to a useful level, many separate fuel cells must be combined to form a fuel cell stack. The number of fuel cells in the stack determines the total voltage, and the surface area of each cell determines the total current. Multiplying the voltage by the current yields the total electrical power generated.

Typical reactants are hydrogen and oxygen, although hydrogen may be extracted from many hydrocarbon compounds such as methanol, propane and natural gas to provide the necessary reactant. This extraction is accomplished in three ways: incorporate an endothermic reforming process, utilize enzyme activity of certain algae or employ solar or wind energy to perform electrolysis on water. The addition of these processes decreases fuel cell efficiency but simplifies the fuel purchase, shipping and storage problems associated with hydrogen. Although hydrogen-oxygen PEM cells are probably the best candidates for autonomous systems, a variety of fuel cell technologies are being developed.

- **Phosphoric Acid.** This type of fuel cell is commercially available today. More than 200 fuel cell systems have been installed all over the world; in hospitals, nursing homes, hotels, office buildings, schools, utility power plants, an airport terminal, even a municipal waste dump. Phosphoric acid fuel cells generate electricity at more than 40% efficiency since nearly 85% of the steam this fuel cell produces is used for cogeneration. This compares favorably with the 35% efficiency achieved by the utility power grid in the United States. Operating temperatures for this type of cell are typically about 204°C (400°F).

- **Proton Exchange Membrane.** These cells operate at relatively low temperatures (about 93°C or 200°F), have high power density, can vary their output quickly to meet shifts in power demand, and are suited for applications, such as in automobiles, where quick startup is required. According to the U.S. Department of Energy, "they are the primary candidates for light-duty vehicles, for buildings, and potentially for much smaller applications such as replacements for rechargeable batteries". The proton exchange membrane is a thin plastic sheet that allows hydrogen ions to pass through it. The membrane is coated on both sides with highly dispersed metal alloy particles (mostly platinum) that are active catalysts. Hydrogen is fed to the anode side of the fuel cell where the catalyst encourages the hydrogen atoms to release electrons and become hydrogen ions (protons). The electrons travel in the form of an electric current that can be utilized before it returns to the cathode side of the fuel cell where oxygen has been fed. At the same time, the protons diffuse through the membrane to the cathode, where the hydrogen atom is recombined and reacted with oxygen to produce water, thus completing the overall process.

- **Molten Carbonate.** Molten carbonate fuel cells promise high fuel-to-electricity efficiencies and operate at about 650°C (1,200°F). To date, molten carbonate fuel cells have been operated on hydrogen, carbon monoxide, natural gas, propane, landfill gas, marine diesel, and simulated coal gasification products. 10 kW to 2 MW molten carbonate fuel cells have been tested on a variety of fuels. Carbonate fuel cells for stationary applications have been successfully demonstrated in Japan and Italy.

- **Solid Oxide.** Another highly promising fuel cell, the solid oxide fuel cell (SOFC) could be used in big, high-power applications including industrial and large-scale central electricity generating stations. Some developers also see solid oxide use in motor vehicles and are developing fuel cell auxiliary power units (APUs) with SOFCs. A solid oxide system usually uses a hard ceramic material instead of a liquid electrolyte, allowing operating temperatures to reach 980°C (1,800°F). Power generating efficiencies could reach 60%. One type of SOFC uses an array of meter-long tubes, and other variations include a compressed disc that resembles the top of a soup can. Tubular SOFC designs are closer to commercialization and are being produced by several companies around the world. Demonstrations of tubular SOFC technology have produced as much as 220 kW.

- **Alkaline.** Long used by NASA on space missions, these cells can achieve power generating efficiencies of up to 70%. They use alkaline potassium hydroxide as the electrolyte. Until recently they were too costly for commercial applications, but several companies are examining ways to reduce costs and improve operating flexibility.

- **Direct Methanol Fuel Cells.** These cells are similar to the PEM cells in that they both use a polymer membrane as the electrolyte. However, in the DMFC, the anode catalyst itself draws the hydrogen from the liquid methanol, eliminating the need for a fuel reformer. Efficiencies of about 40% are expected with this type of fuel cell, which would typically operate at a temperature between 50-90°C (120-190°F). Higher efficiencies are achieved at higher temperatures.

- **Regenerative Fuel Cells.** Still a very young member of the fuel cell family, regenerative fuel cells would be attractive as a closed-loop form of power generation. Water is separated into hydrogen and oxygen by a solar-powered electrolyser. The hydrogen and oxygen are fed into the fuel cell, which generates electricity, heat and water. The water is then recirculated back to the solar-powered electrolyser and the process begins again. These types of fuel cells are currently being researched by NASA and others worldwide.

In general, fuel cell technology has still not fully matured and prices remain high (on the order of $3000 per kilowatt). Hydrogen supplies cost more than traditional hydrocarbon fuels and are less conveniently obtained. Many companies are actively involved in developing fuel cell technology for powerplant, transportation, and portable applications. Two companies with specifically portable products are Ballard Power Systems, Inc. and Warsitz Enterprises, Inc. As an example, the latter company has available a product called ROAMPOWER which is a hydrogen fuel cell measuring 47x42x19 cm and weighing 9 kg. It provides 12-14.4 VDC at 30, 60, or 90 watts for 5, 2.5, or 1-hour duration, respectively. Present costs vary from $2500 to $4500.

3.1.3 Batteries.

A battery is an electrochemical device that converts chemical energy into electricity, by use of one or more galvanic cells. A galvanic cell is a fairly simple device consisting of two electrodes (an anode and a cathode) and an electrolyte solution. As chemicals in the battery change, electrical energy is stored or released. In rechargeable batteries this process can be repeated many times, however, batteries are not 100% efficient and some energy is always lost during charging and discharging. Typical efficiency in a lead-acid battery is 85-95%, in alkaline and NiCad battery it is about 65%.

Batteries are categorized in two ways, by application (what they are used for) and construction (how they are built). The major applications are starter (automotive), marine, and deep-cycle. The major construction types are flooded (wet), gelled, and AGM (Absorbed Glass Mat). AGM batteries are also sometimes called "starved electrolyte" or "dry", because the fiberglass mat is only 95% saturated with Sulfuric acid and there is no excess liquid.

- **Starting** (sometimes called SLI, for starting, lighting, ignition) batteries are commonly used to start and run engines. Engine starters need a very large starting current for a very short time. Starting batteries have a large number of thin plates for maximum surface area. The plates are composed of a lead "sponge", similar in appearance to a very fine foam sponge. This gives a very large surface area, but if deep cycled, this sponge will quickly be consumed and fall to the bottom of the cells. If deep cycled, automotive batteries will generally fail after 30-150 cycles, while they may last for thousands of cycles in normal starting use (2-5% discharge). As a general rule, if a true deep cycle battery is to be used also as a starting battery, it should be oversized at least 25% compared to the existing or recommended starting battery group size to get the same cranking amps.

- **Deep cycle** batteries are designed to be discharged down as much as 80% time after time, and have much thicker plates. The major difference between a true deep cycle battery and others is that the plates are solid lead plates - not sponge. Plate thickness (of the positive plate) matters because of a factor called "positive grid corrosion". This ranks among the top 3 reasons for battery failure. The positive (+) plate is what gets eaten away gradually over time, so eventually there is nothing left; it all falls to the bottom as sediment. Thicker plates are directly related to longer life, so other things being equal, the battery with the thickest plates will last the longest. Automotive batteries typically have plates about .040" (40/1000") thick, while forklift batteries may have plates more than 1/4" thick and the typical golf cart battery will have plates that are around .07 to .11" thick. Most industrial deep-cycle batteries use lead-antimony plates rather than the lead-calcium used in AGM or gelled deep-cycle batteries. The antimony increases plate life and strength, but increases gassing and water loss. The self- discharge of batteries with lead-antimony plates can be high, as much as 1% per day on an older battery. A new AGM typically self-discharges at about 1-2% per month, while an old one may be as much as 2% per week.

- **Marine** batteries are usually actually a "hybrid", and fall between the starting and deep-cycle batteries, while a few are true deep cycle. In the hybrid, the plates may be composed of Lead sponge, but it is coarser and heavier than that used in starting batteries. "Hybrid" types should not be discharged more than 50%. Starting batteries are usually rated at "CCA", or cold cranking amps, or "MCA", Marine cranking amps - the same as "CA". Any battery with the capacity shown in CA or MCA may not be a true deep-cycle battery. It is sometimes hard to tell, as the terms marine and deep cycle are sometimes overused. CA and MCA ratings are at 32 degrees F, while CCA is at 0 degree F.

It is important to note that all of the batteries commonly used in deep cycle applications are lead-acid primarily because they offer the best price to power ratio. This includes the standard flooded (wet) batteries, gelled, and AGM. They all use the same chemistry, although the actual construction can vary considerably. A few systems use NiCad**,** which have very good cold temperature performance, however they are expensive to buy, and very expensive to dispose of due the hazardous nature of cadmium. Very limited experience with NiFe (alkaline) batteries has revealed two disadvantages. There is a large voltage difference between the fully charged and discharged state and they are very inefficient, losing from 30-40% in heat just in charging and discharging. Many inverters and charge controls have a hard time with NiFe batteries.

Flooded batteries may be standard, with removable caps, or the so-called "maintenance free". All gelled batteries are sealed and a few are "valve regulated", which means that a tiny valve keeps a slight positive pressure. Nearly all AGM batteries are sealed valve regulated (commonly referred to as "VRLA" - Valve Regulated Lead-Acid). Most valve regulated are under some pressure, typically, 1 to 4 psi at sea level.

- **Gelled electrolyte:** Gelled batteries, or "Gel Cells" contain acid that has been "gelled" by the addition of Silica Gel, turning the acid into a solid mass. The advantage of these batteries is that it is impossible to spill acid even if they are broken. However, there are several disadvantages. One is that they must be charged at a slower rate (C/20) to prevent excess gas from damaging the cells. They cannot be fast charged on a conventional automotive charger or they may be permanently damaged. This is not usually a problem with solar electric systems, but if an auxiliary generator or inverter bulk charger is used, current must be limited to the manufacturers specifications. Most higher quality inverters commonly used in solar electric systems can be set to limit charging current to the batteries. Some other disadvantages of gel cells are that they must be charged at a lower voltage (2/10th's less) than flooded or AGM batteries. If overcharged, voids can develop in the gel that will never heal, causing a loss in battery capacity. In hot climates, water loss can be enough over 2-4 years to cause premature battery death. The newer AGM (absorbed glass mat) batteries have all the advantages of gelled, with none of the disadvantages.
- **Absorbed Glass Mat:** A newer type of sealed battery uses "Absorbed Glass Mats", or AGM between the plates. This is a very fine fiber Boron-Silicate glass mat. These types of batteries have all the advantages of gelled, but can take much more abuse. These are also called "starved electrolyte", as the mat is about 95%

saturated rather than fully soaked. AGM batteries have several advantages over both gelled and flooded, at about the same cost as gelled. Since the electrolyte (acid) is contained in the glass mats, they cannot spill, even if broken. This also means that since they are non-hazardous, the shipping costs are lower. Even under severe overcharge conditions hydrogen emission is far below the 4% max specified for aircraft and enclosed spaces. The plates in AGM's are tightly packed and rigidly mounted, and will withstand shock and vibration better than any standard battery. In addition, since there is no liquid to freeze and expand, they are practically immune from freezing damage. Nearly all AGM batteries are "recombinant", meaning that the oxygen and hydrogen recombine inside the battery. These use gas phase transfer of oxygen to the negative plates to recombine them back into water while charging and prevent the loss of water through electrolysis. The recombining is typically 99+% efficient, so almost no water is lost. The charging voltages are the same as for any standard battery, requiring no special adjustments and posing no problems with incompatible chargers or charge controls. And, since the internal resistance is extremely low, there is almost no heating of the battery even under heavy charge and discharge currents. Most AGM batteries have no charge or discharge current limits. AGM's have a very low self-discharge, typically from 1% to 3% per month. This means that they can sit in storage for much longer periods without charging than standard batteries.

A number of factors affect battery performance characteristics, most significant are temperature and the manner in which the batteries are cycled. Battery capacity is reduced as temperature goes down, and increased as temperature goes up. If batteries spend part of the year in the cold, the reduced capacity must be taken into account when sizing the system batteries. The standard rating for batteries is at room temperature, 25°C (77°F). At approximately -27°C (-22°F), battery capacity drops to 50%. At freezing, capacity is reduced by 20%. Capacity is increased at higher temperatures; at 122°F battery capacity would be about 12% higher.

Battery charging voltage also changes with temperature. It will vary from about 2.74 volts per cell (16.4 volts) at -40°C to 2.3 volts per cell (13.8 volts) at 50°C. If batteries are outside and/or subject to wide temperature variations then their charge controllers should have temperature compensation features. Some charge controls have temperature compensation built in which works if the controller is subject to the same temperatures as the batteries. Another complication is that large battery banks make up a large thermal mass. A large insulated battery bank may vary as little as 10 degrees over 24 hours internally, even though the air temperature varies from 20 to 70 degrees. For this reason, external (add-on) temperature sensors should be attached to one of the positive plate terminals, and protected with some type of insulation on the terminal. The sensor will then read very close to the actual internal battery temperature.

Even though battery capacity at high temperatures is higher, battery life is shortened. Battery capacity is reduced by 50% at -22°F, but battery life increases by about 60%. Battery life is reduced at higher temperatures; for every 15°F over 77°F, battery life is cut in half. This holds true for any type of Lead-Acid battery, whether sealed, gelled, AGM, or industrial.

A battery "cycle" is one complete discharge and recharge cycle. It is usually considered to be discharging from 100% to 20%, and then back to 100%. However, there are often ratings for other depth-of-discharge (DOD) cycles, the most common ones are 10%, 20%, and 50%. Battery life is directly related to how deep the battery is cycled each time. If a battery is discharged to 50% every day, it will last about twice as long as if it is cycled to 80% DOD. If cycled only 10% DOD, it will last about 5 times as long as one cycled to 50%. The most practical number to use is 50% DOD on a regular basis. This does not mean a battery cannot be discharged to 80% once in a while, just that when designing a system with some idea of the loads, figure on an average DOD of around 50% for the best storage versus cost factor. Also, there is an upper limit; a battery that is continually cycled 5% or less will usually not last as long as one cycled down 10%. This happens because at very shallow cycles, the lead dioxide tends to build up in clumps on the positive plates rather in an even film.

All Lead-Acid batteries supply about 2.14 volts per cell (12.6 to 12.8 for a 12 volt battery) when fully charged. Batteries that are stored for long periods will eventually lose all their charge. This "leakage" or self-discharge varies considerably with battery type, age, and temperature. It can range from about 1% to 15% per month. Generally, new AGM batteries have the lowest, and old industrial (ead-antimony plates) are the highest. In systems that are continually connected to some type of charging source, whether it is solar, wind, or an AC powered charger this is seldom a problem. However, one of the biggest killers of batteries is sitting stored in a partly discharged state for a few months. A "float" charge should be maintained on the batteries even if they are not used (or, especially if they are not used). Even the "dry charged" batteries (those sold without electrolyte so they can be shipped more easily, with acid added later) will deteriorate over time. Maximum storage life on those is about 2-3 years.

Batteries self discharge faster at higher temperatures. Lifespan can also be seriously reduced at higher temperatures. Most manufacturers state this as a 50% loss in life for every 15°F over a 77°F cell temperature. Lifespan is increased at the same rate if below 77°F, but capacity is reduced. This tends to even out in most systems since they will spend part of their life at higher temperatures, and part at lower.

State of charge, or conversely, the depth of discharge can be determined by measuring the voltage and/or the specific gravity of the acid with a hydrometer. This will not indicate how good (capacity in amp-hours) the battery condition is; only a sustained load test can do that. Voltage on a fully charged battery will read 2.12 to 2.15 volts per cell, or 12.7 volts for a 12-volt battery. At 50% the reading will be 2.03 VPC (Volts Per Cell), and at 0% will be 1.75 VPC or less. Specific gravity will be about 1.265 for a fully charged cell, and 1.13 or less for a totally discharged cell. This can vary with battery types and brands somewhat. It is recommended to charge new batteries and allow them sit for a while before taking reference measurements. Many batteries are sealed, and hydrometer reading cannot be taken, so voltage must be relied on. Hydrometer readings may not tell the whole story, as it takes a while for the acid to get mixed up in wet cells. If measured right after charging, there might be 1.27 volts at the top of the cell, even though it is much less at the bottom. This does not apply to gelled or AGM batteries.

A battery can meet all the tests for being at full charge, yet be much lower than it's original capacity. If plates are damaged, sulfated, or partially gone from long use, the battery may give the appearance of being fully charged, but in reality acts like a battery of much smaller size. This same thing can occur in gelled cells if they are overcharged and gaps or bubbles occur in the gel. What is left of the plates may be fully functional, but with only 20% of the plates left, capacity is reduced. Batteries usually go bad for other reasons before reaching this point, but it is something to be aware of if batteries seem to test OK but lack capacity and go dead very quickly under load.

When consulting the table below, ensure that voltage measured is not merely the surface charge. To properly check the voltage, the battery should sit at rest for a few hours, or be placed under a load, such as a small automotive bulb, for a few minutes. The voltages below apply to all Lead-Acid batteries, except gelled. For gel cells, subtract 0.2 volts. Voltage measured while the battery is under charge will be quite different and the numbers listed below are not applicable.

State of Charge	**12 Volt battery**	**Volts per Cell**
100%	12.7	2.12
90%	12.5	2.08
80%	12.42	2.07
70%	12.32	2.05
60%	12.20	2.03
50%	12.06	2.01
40%	11.9	1.98
30%	11.75	1.96
20%	11.58	1.93
10%	11.31	1.89
0	10.5	1.75

Note: Voltages are for a 12-volt battery system maintained at 77°F and at rest for at least 3 hours. For 24-volt systems multiply by 2, for 48-volt system, multiply by 4. Equalization is indicated by variations in volts per cell of more than 0.2. Voltage measurements are only an approximate indication of charge, the best determination is to measure the specific gravity.

All deep cycle batteries are rated in amp-hours (amps x hours). The accepted AH rating time period for batteries used in solar electric and backup power systems (and for nearly all deep cycle batteries) is the "20-hour rate". This means that it is discharged down to 10.5 volts over a 20-hour period while the total actual amp-hours it supplies is measured. Sometimes ratings at the 6-hour rate and 100-hour rate are also given for comparison and for different applications. The 6-hour rate is often used for industrial batteries, as that is a typical daily duty cycle. Amp-hours are specified at a particular rate because of something called the Peukert Effect. The Peukert value is directly related to the internal resistance of the battery. The higher the internal resistance’ the higher the losses while charging and discharging’ especially at higher currents. This means that the faster a battery is discharged, the lower the capacity. Conversely, if it is drained slower, the capacity is higher. Nearly all batteries will not reach full capacity until cycled 10-30 times. A brand new battery will have a capacity of about 5-10% less than the rated capacity.

After batteries reach full charge, charging voltage is reduced to a lower level (typically 12.8 to 13.2) to reduce gassing and prolong battery life. This is often referred to as a maintenance or trickle charge, since it's main purpose is to keep an already charged battery from discharging. PWM, or "pulse width modulation" accomplishes the same thing. In PWM, the controller or charger senses tiny voltage drops in the battery and sends very short charging cycles (pulses) to the battery. This may occur several hundred times per minute. It is called "pulse width" because the width of the pulses may vary from a few microseconds to several seconds. Note that for long term float service, such as backup power systems that are seldom discharged, the float voltage should be around 13.02 to 13.20 volts. When using a small solar panel to keep a float (maintenance) charge on a battery (without using a charge controller), choose a panel that will give a maximum output of about 1/300th to 1/1000th of the amp-hour capacity.

Most flooded batteries should be charged at no more than the "C/18" rate for any sustained period. "C/18" is the battery capacity at the 20-hour rate divided by 8. For a 220 AH battery, this would equal 26 Amps. Gelled cells should be charged at no more than the C/20 rate, or 5% of their amp-hour capacity.

Charging at 15.5 volts will give you a 100% charge on Lead-Acid batteries. Once the charging voltage reaches 2.583 volts per cell, charging should stop or be reduced to a trickle charge. Note that flooded batteries must bubble (gas) somewhat to insure a full charge, and to mix the electrolyte. Float voltage for Lead-Acid batteries should be about 2.15 to 2.23 volts per cell, or about 12.9-13.4 volts for a 12-volt battery. At higher temperatures (over 85 degrees F) this should be reduced to about 2.10 volts per cell.

Never add acid to a battery except to replace spilled liquid. Distilled or de-ionized water should be used to top off non-sealed batteries. Float and charging voltages for gelled batteries are usually about 2/10th volt less than for flooded to reduce water loss. Note that many shunt-type charge controllers sold for solar systems will not provide a full charge. To get a full charge it is necessary to continue to apply a current after the battery voltage reaches the cutoff point of most of these types of controllers. Not all shunt type controllers are 100% on or off, but most are.

Flooded battery life can be extended if an equalizing charge is applied every 10 to 40 days. This is a charge that is about 10% higher than normal full charge voltage, and is applied for about 2 to 16 hours. This makes sure that all the cells are equally charged, and the gas bubbles mix the electrolyte. If the liquid in standard wet cells is not mixed, the electrolyte becomes "stratified". A very strong solution may exist at the top with a very weak solution at the bottom of the cell. Stratification can distort battery capacity measurements taken with a hydrometer. If it is not possible to equalize for some reason, allow the battery to sit for at least 24 hours and then use the hydrometer. AGM and gelled should be equalized 2-4 times a year at most; check the manufacturers recommendations, especially with gelled cell batteries.

Given the large variety of batteries from which the researcher may choose to power their autonomous system, the experience of numerous persons over many years suggests that commercially available, standard 12 VDC, Gel-Cell batteries provide good performance at an economical cost. Their ability to retain capacity at low temperatures, resist freezing when carrying a charge, and the fact that they are not considered hazardous cargo for air transport, make them particularly attractive in polar environments. Batteries are particularly well suited to ocean applications where a thermally stable, cool environment exists and weight is not typically a factor (except in submersible vehicle design). The primary challenge is in devising a method of recharging the batteries in situ. For space applications the overwhelming problem with batteries is their considerable weight. Missions to the inner solar system can easily take advantage of solar energy to recharge and those venturing beyond the asteroid belt will typically rely on long term nuclear sources for power, obviating the need for a battery.

3.1.4 Solar Power.

For applications other than deep space or the deep ocean, solar power probably represents the most practical and reliable method for providing power in situ from indigenous sources. The technology is well developed and simple, and although it involves some expense, it avoids the logistical costs of hazardous fuel resupply. Presently there are three types of photovoltaic technologies. Single crystal silicon and multi-crystal silicon cells represent the most prevalent, well developed and energy efficient methods and are the most expensive. To produce them, molten silicon is cast and then sliced into cell sized pieces, which are then assembled on a flat surface. Thin film systems create cells by depositing a thin layer of photovoltaic material onto a substrate such as glass or metal. This process is inherently cheaper but not as efficient. It does have the advantage of being able to produce a cell that contains no glass and is therefore more rugged.

	Typical Efficiency	**Maximum Recorded**	**Laboratory Max**
Mono Crystalline	12 – 15%	22.7%	24.0%
Multi Crystalline	11 – 14%	15.3%	18.6%
Amorphous Silicon	6 – 7 %	10.2%	12.7%

Solar-thermal systems represent another approach to solar power but are not considered practical for autonomous observatory applications. These systems utilize collectors to concentrate solar energy as heat and transfer it to a fluid.

A great deal of experience has been accrued in the use of solar panels in a variety of environments. Typically, the solar panels employed have consisted of multi-crystal silicon cells because they provide the best balance between cost and efficiency. It is worthwhile to consider some of the lessons learned about their use. In the polar-regions panels should be mounted vertically to take advantage of the sun's low elevation at high latitude. Consider using two or three panels, each with a different azimuthal orientation to guarantee full exposure at all hours of the day. Vertical mounting will avoid problems of snow accumulation and all panels should be faced with shatterproof Plexiglas to guard against debris impact. Experience has shown that with such protection, debris strike sufficient to "spiderweb" shatter the Plexiglas has left the array undamaged and still functional. SOLAREX panels are one widely used brand that has produced good results. One unexpected discovery in the Antarctic has been the ability of moonlight to provide some photon incidence, sufficient to power a seismic instrument on Mount Erebus once a month through the winter. Some additional charge can also be generated from the blue sky even when the panel is in shade as well as from scattered light on days when clouds obscure the sun.

In surface marine environments use of solar energy is best achieved if panels can be elevated above the waves and sea spray and, at latitudes closer to the equator, oriented more horizontally. An autonomous system in space, on the ocean or in the polar latitudes should carefully consider and generally avoid the use of a training motor to align the solar panels with the direction of incident radiation; the energy requirement and complexity of the training mechanism, particularly in icing or corrosive environments, makes such devices undesirable and prone to failure.

The following two pages provide a generic worksheet for the sizing of a photovoltaic system and associated battery bank.

Photovoltaic System Sizing Worksheet

Step 1: Determine power consumption demands.

Device	watts **x** qty **x** hrs/day = watthrs/day **x** days/week =	wh/week
___________	____	________
___________	____	________
___________	____	________

1. Total power requirement — Total ________

2. Multiply total by 1.2 to compensate for system losses during battery charge/discharge cycle. ________

3. Enter the voltage of the battery bank ________

4. Divide line 2 by line 3. This is your amp/hr requirement per week. ________

5. Divide line 4 by 7 days. This is your average amp/hr requirement per day that will be used to size the battery bank and PV array. ________

Step 2: Optimize power system demands.

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

Step 3: 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, value should not exceed 0.8. This provides a safety factor so that over-draining the battery can be avoided. (Example: If the discharge limit is 20%, use 0.2) ________

9. Divide line 7 by line 8. ________

10. Select the multiplier below that corresponds to the average wintertime temperature the battery bank will experience. ________

°F	°C	Multiplier	°F	°C	Multiplier
80	26.7	1.00	40	4.4	1.30
70	21.2	1.04	30	-1.1	1.40
60	15.6	1.11	20	-6.7	1.59
50	10.0	1.19			

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. ________

Step 4: Determine the sun hours available per day.

Several factors influence how much sun power the photovoltaic modules will be exposed to including weather conditions, location and angle of PV array, fixed mounting vs. trackers and whether the system will be running in the summer, winter or year-round. Determine an hour per day average for the desired site.

Step 5: Size the photovoltaic array.

16. Average sun hours per day. ________

17. Divide line 5 by line 16. This is the total solar array amps required. ________

18. Optimum or peak amps of solar module used. ________

19. Multiply line 18 by 0.9 for normal loads or by 0.8 for critical loads. ________

20. Divide line 17 by line 19 and round off to the next highest whole number. This is the number of solar modules in parallel required. ________

21. Multiply line 20 by the number of modules required to achieve the DC battery voltage. This is the total number of solar modules required. ________

3.1.5 Wind Power.

Although an undeniably cheap and seemingly simple power source, reliable wind power generation in extreme environments has proven to be the most difficult to master. This is primarily because the characteristics of the wind are temperamental, unpredictable, prone to excess and uncontrollable, but unfortunately during the winter months at high latitudes it is often the only choice. To a much greater degree than with solar energy, wind conditions vary considerably with season, geographic location and meteorological conditions. Complicating the problem is that for much of the polar latitudes, accurate historical wind data is simply not available and must be inferred. In general, the Antarctic plateau sees calmer, steadier wind for which a variety of rugged commercial wind generators may be adequate. Southwest Windpower, Inc. a leading commercial manufacturer of wind generators produces a model called Air Industrial 403 designed for adverse marine conditions (i.e. offshore oil rigs) which has had mixed success in Antarctica.

The coastal, mountainous regions of the continent experience winds of such variation and severity that no commercially available product has been found to be satisfactory. Some of the many problems encountered include, rime icing on blades, uneven ice shedding leading to blade imbalance, debris impact, regulator failure, overspeed and vibration failure. Horizontal axis turbines with both upstream and downstream wood blades seem especially prone to blade breakage. One of the problems complicating the design is that generators built heavy and rugged enough to survive the most severe conditions often produce insufficient power during periods of prevailing light winds. Lubricants, greases and bearings must also be capable of retaining their properties in the extreme cold and under low humidity conditions. In environments of extreme wind speeds, vertical axis turbine designs have had some success since their compact blade arrangement minimizes the amplification of out-of-balance vibration. Models in which the blades were allowed to flex actually compensated for an out-of-balance condition by adjusting the geometry of their revolving body. Such a design successfully withstood wind tunnel testing up to 170 mph and is currently in trial use in three autonomous GPS stations deployed to Marie Byrd Land.

To handle the problem of excess power generated in times of extreme winds, two methods presently exist. The first, extensively used with moderate success, is to provide a dump load, typically a resistor bank, which sheds the power as heat. The unpredictable nature of the wind has made it difficult to incorporate this resistor as part of a thermal control system for the enclosure. Most often the heat is merely discharged to the environment. If sufficient thermal mass existed to act as a buffer, for example a large tank of fuel, then dumping the waste heat within the system might be viable. The second approach is to utilize a charged stator instead of permanent magnets in the generator. When excess energy is being produced the regulator simply removes the charge from the stator and the wind generator stops producing power and spins freely. This method is still undergoing evaluation in the field but does pose two potential drawbacks. 1) The need for a charge on the stator does represent a small but continuous electrical load that could become significant during periods of extended calm and 2) the turbine must be capable of free spinning without the benefit of an electromagnetic brake.

In marine environments, corrosion, particularly of the rotating components is the biggest difficulty with wind generator units. The National Wind Technology Center operated by the National Renewable Energy Laboratory is an excellent resource for information regarding wind power developments. In particular, they maintain an archive of research papers related to wind technology at: http://www.nrel.gov/wind/library.html.

3.1.6 Radioisotope Thermoelectric Generator (RTG).

To create electricity, RTG's convert the heat produced by the decay of a small amount of radioactive material. From an engineering point of view, RTG's characteristics of long life, small size and weight and lack of dependence on refueling or in situ resources make it the ideal solution over a wide range of power in remote extreme environments. Although RTG technology is technically reliable and has been in use for 30 years, its cold reception by the public has ensured that manufacture of such devices is not commercially viable. Thus, each unit must be built for its specific application, a practice that maintains the cost extraordinarily high. Additional expense is incurred maintaining the necessary Quality Assurance Program and obtaining Certificates of Compliance and a license from the Nuclear Regulatory Commission. Even in situations where the high initial cost might be competitive with conventional power sources that require extensive logistics to support their large mass and frequent service intervals, public opinion guarantees they are not the power system of choice. To date, only in extreme environments that permit no other possible power source and are far removed from human presence (i.e. deep space) has it been possible to employ the RTG. The few historical occasions when nuclear power has been utilized in the oceans or in Antarctica have only served to highlight their technical suitability as well as their political liability.

In reality the causes for concern are quite minimal. RTG's do not produce a self-sustaining chain reaction, nor do they contain sufficient material to be able to initiate one.

The radioactive decay that occurs is entirely natural, predictable and requires no control mechanism to maintain that condition. With sufficient shielding they pose little risk to personnel if handled properly and the very nature of the sites envisioned for their use are extremely removed from any human contact, intentional or otherwise. The possibility of a compromise in the integrity of the containment vessel is extraordinarily remote. Federal regulations require that RTG's be constructed and tested to withstand fire and shock forces associated with aircraft, railroad, and vehicle accidents and explosions. Furthermore, during the time that it is deployed, the radioactive material in an RTG is continuously decaying into a stable, safer, form. It is a common belief that this decay period is extremely long based on the historical use of very long-lived material such as plutonium in spacecraft. In environments such as the ocean or the polar regions where RTG's are recoverable, such long-lived material need not be used. It is possible and perhaps preferable to consider shorter-lived material whose half-life for decay is on the same order of magnitude as the expected duration of the research project.

Radioactive Material	**Half-life (years)**	**Watts (thermal) per gram**	**Dollars per watt (thermal)**
Polonium 210	0.378	141	570
Plutonium 238	86.8	0.55	3000
Cesium 144	0.781	25	15
Strontium 90	28.0	0.93	250
Curium 242	0.445	120	495

Note: Current thermal to electric conversion is approximately 10-11% efficient and must plan for end mission outputs because heat and semiconductor efficiency decay over time.

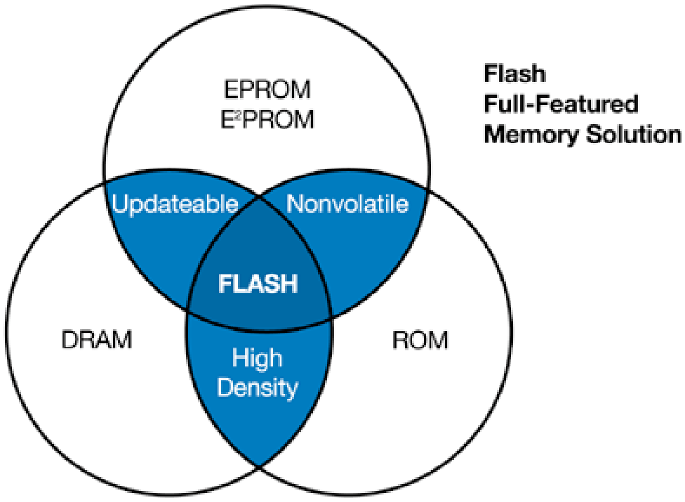
For the time being, the reality is that RTG's are not economically or politically viable unless the government sponsors a program to subsidize RTG power sources and provide them on loan to research groups, while administering a control and monitoring program to regulate their use.

Action Item: Provide federal funding for a study to research the political and economic feasibility of a federally funded and administered RTG power source program for extreme environment research applications.

3.2 Data Management.

Some of the biggest technological advances that have aided autonomous system design in recent years have involved data management. Decreasing costs and increasing handling and storage capabilities make this an encouraging area of autonomous system design. Two factors affecting the volume of data to be stored are the sampling rate and the nature of the information stream. When power or memory technology impose a limit on data storage it is important to distinguish between what information is desired and what is essential. Format is important to consider as well since typical values for an electromagnetic instrument might be 1 or 2 bits per second; a broadband seismometer, 1 kilobyte per second; an array of hydrophones about 25 kilobytes per second; and Mpeg2 video about 1 or 2 megabytes per second. Video data complicates storage possibilities even with current compression techniques. For most other forms of data, Flash memory technology is attaining sufficient capacity (512 MB per cartridge) that its ruggedness and lack of moving parts make it the clear choice. The ideal memory subsystem optimizes density, preserves critical material in a nonvolatile condition, is easy to program and reprogram, can be read fast, and is cost-effective for the application. Some memory technologies meet one or more of these requirements very well, but offsetting limitations can prevent the product from becoming a genuine solution, especially in newer applications.

Memory Type	Features
FLASH	Low-cost, high-density, high-speed architecture; low-power, high reliability
ROM Read-Only Memory	Mature, high-density, reliable, low cost; time-consuming mask required, suitable for high production with stable code
SRAM Static Random-Access Read-Only Memory	Highest speed, high-power, low-density memory; limited density drives up cost
EPROM Electrically Programmable Read-Only Memory	High-density memory; must be exposed to ultraviolet light for erasure
EEPROM or E^2 Electrically Erasable Programmable Read-Only Memory	Electrically byte-erasable; lower reliability, higher cost, lowest density
DRAM Dynamic Random Access Memory	High-density, low-cost, high-speed, high-power



Flash memory is capable of retaining digital information under certain conditions. This retained material might be operational code or data files, or a combination of the two. Flash memory is non-volatile memory using NOR technology, which allows the user to electrically program and erase information. Typical Flash memory uses memory cells similar to an EPROM, but with a much thinner, precisely grown oxide between the floating gate and the source. Flash programming occurs when electrons are placed on the floating gate. The charge is stored on the floating gate, with the oxide layer allowing the cell to be electrically erased through the source. Flash memory is an extremely reliable nonvolatile memory architecture.

Another new emerging technology with promising potential is the microdrive, capable of up to 1 GB of data storage. The large storage capacity coupled with the small size and power requirements of the microdrive may provide a solution for autonomous systems with high data volume requirements. Combining memory technologies may be another means to achieve large data storage and may provide an additional degree of redundancy in system design. At least one project used an additional dual EPROM to store code and found it to be similarly robust. The Flash card and the EPROM used together provided a redundant boot capability, though not redundant data storage.

As the cost for the electronic portion of autonomous systems continues to drop in relation to other components, greater electronic (particularly data) redundancy will be desired and achievable. If the data is not telemetered but instead is retrieved in the field, then whatever device is used should permit simple swap-out rather than require downloading with a computer on-site. In locations where telemetry is possible, it usually imposes a limit on the amount of data that can be returned. In these cases, more advanced autonomy can be selective in the data that is sent. As described by Paul Stolorz, an autonomy expert at the Jet Propulsion Laboratory,

> One major design goal of autonomous systems should be to progress beyond the on/off sample collection and instead permit evaluation and selection of desired data. Nominal limits and abnormal setpoints might be established and continuously refined based on analysis of the accumulated data. In this way, selected significant results might be recognized, avoid compression and be sent with priority. This interpretive and decision making ability is the next generation in autonomous data management.

For now, especially in situations involving large data volume and limited telemetry, compression is one solution to avoid losing valuable data. Two techniques exist, Lossless compression in which every bit of data is captured but sent using more efficient instructions and Lossy compression in which frames of data are skipped and algorithms compare the change in bits and smooth out the differences. Lossy techniques can achieve much higher compression ratios but introduce some distortion and thus are not suitable for data streams consisting of binary or ASCII data.

3.3 Communications.

The ability to remotely communicate with an autonomous station is always desirable whether to ascertain the health of the station, download data, or upload new instructions. Oftentimes it cannot be achieved because of the particular nature of the remote location, the power required, or the availability of suitable infrastructure. Under present conditions in Antarctica for example, no line-of-site to a geosynchronous satellite exists above 81° of latitude. In situations where telemetry is possible, the limiting factor is often bandwidth. Since the available bandwidth is limited at any frequency, and the rate of data transmission (bits/sec) cannot exceed the bandwidth available, a significant problem in telemetry is fitting more information into less bandwidth. Compression techniques, discussed previously, are one useful technique. Another scheme to overcome the limitations imposed by power, transmission time, or available bandwidth is to use a hierarchical approach to the data sent, as outlined by Paul Stolorz.

> At the most minimal level, the system would perform a periodic self-diagnosis and transmit a graduated health signal, a beacon, to the receiver. With additional resources, telemetry could include compressed data in a packet delivery form. A more sophisticated system would be able to evaluate and prioritize the most important or abnormal data to be sent first with the remainder to follow as resources permitted. Subsequent analysis or improved compression algorithms might make it necessary to be able to go back and review data prior to compression so it is important that some archive of original, uncompressed data be maintained.

An ideal system would allow for the eventual transmission of all data without compression to preclude the possibility of losing significant information. John Orcutt quoting from a NSF facilities plan highlighted the importance of moving toward real-time, interactive telemetry with remote stations:

> Increasing the access to data sets in their real time is allowing investigators to respond to natural events and design powerful experiments around natural perturbations occurring in the earth's complex systems. Real time access also provides unique opportunities for communicating

> excitement and mystery of the earth's dynamic environment to the general public. The magnitude of the continuing change in the earth's system is under-appreciated and providing accurate, timely information to the broadest possible audiences is an important goal.

A number of options may exist to accomplish communications and are considered in order of ascending frequency (and data rate).

3.3.1 Acoustic Transmission.

In many underwater applications, a wire connection with submerged instrumentation is either prohibitively expensive or not feasible. The solution is to use the water itself as the medium for the transmission of acoustic signals. However, this solution presents several problems. First, sound travels through water at a much slower speed (approximately 1,500 meters per second) compared to electrical transmissions on a phone line, which travel at the speed of light. Secondly, the water is an open channel into which the acoustic signal is broadcast. Even when the transmission is a narrow beam aimed at its target, the sound wave fans out and generates echoes, which arrive at the target destination shortly after the original signal. These multi-path echoes require additional processing as the signal is received. The open-channel broadcast also results in the need for more processing with each transmission to assure that the target, and only the target, receives the message. Finally, water can be a much more hostile environment. The signal is affected by changes in water temperature, salinity, turbulence, objects in the water, and a host of other factors. Inability to accurately predict these factors makes determining maximum range very difficult as well.

A range estimate can be made based on the known acoustic transmit source level, receive sensitivity, a best guess at noise levels to be encountered, and experience in similar applications. With this in mind, in a vertical channel (transmitting from a deep location to a receiver overhead + or- 45 degrees), one can expect to achieve good performance at any depth, including full ocean depths. In a more horizontal channel, including channels where the desired range is many times depth, the prediction is more difficult. In general, in the lower frequency (9 –14 or 15 – 20 KHz band), ranges of 5 – 7 km can be achieved, falling to 2 – 3 km when using the 30 KHz band. Extended ranges of up to 10 km and higher can be achieved by using repeater modems or by going down into the 3-5 KHz band and using directional transducers.

Directional transducers transmit and receive in a conical radiation pattern typically in the range of 50-60 degrees. Special designs are possible if a broader or more narrow pattern is desired. Omni-directional transducers transmit and receive energy from all directions. When possible, a directional transducer is always preferred for the following reasons: 1) The acoustic source level will be in the range of 10 db higher with a directional transducer. This translates directly into increased range and/or increased signal to noise ratio (SNR), at the receive end. 2) Reduced error rate because the multi-path is greatly reduced. The received in band noise will also be reduced, as the directional transducer will not be responsive to noise coming from directions outside of the transducer beam pattern. 3) Possible reduction in power required. If, for instance, the SNR is high enough, then the transmit power can be reduced, cutting back on current drain. Compared with an omni-directional transducer with 10 db lower source level, the current drain could be reduced to one tenth of the full power current drain. Of course reducing transmit power will result in a lower SNR, so it really depends on the conditions of the application which will dictate the appropriate power setting. Ultimately, one desires to maintain an adequate SNR under all anticipated link conditions. The point is that use of a directional transducer gives one the flexibility of considering additional trade-offs.

In many cases, an omni-directional transducer is necessary because either, or both, the transmitting and receiving platforms cannot be maintained with a fixed orientation. Such is the case with AUV's, moored instruments which can rotate on their mooring lines, or when one wishes to communicate with several modems which are scattered in different directions relative to the data collection modem.

Presently, reliable low-rate (20-100 bits/sec) acoustic data transmission is available in any number of commercial built modems. The range of these devices is dependent on transmitter power and propagation, however they have successfully demonstrated robust communications at ranges of 5-10 km. This low-rate communications is sufficient for simple status information that informs personnel on shore as to the health and basic sensor readings, but higher-rate data uplink is desirable for certain types of information. Although some higher-rate (5-10 kbps) bi-directional communications has been demonstrated with underwater vehicles, in general this requires high source levels and short ranges. Some tests have even achieved compressed video image transmission over very short distances, however the resolution so far, is insufficient for scientific interpretation. High source levels require substantial power, typically unavailable to autonomous underwater stations. To conserve power an efficient messaging system would transmit short data packets most of the time, reserving high-power, high rate transmission for specific items requested from shore.

A better solution to deep ocean communication may be realized by employing a floating surface buoy relay and a hybrid of communications technology. In such a system, instrumentation on the sea floor would transmit telemetry via a shielded wire, fiber optic cable, or acoustic modem to a floating surface buoy. The buoy would act as a relay, transmitting and receiving from shore stations by radio or satellite signals. This technique has already been successfully demonstrated by a German project called DOMEST. That project, near the Canary Islands, utilized an acoustic modem in 3600 meters of water, with communication rates of up to 2400 baud relayed through a surface buoy to ORBCOMM data satellites. The signal was then sent to a ground station in Lario, Italy where the signals were routed via the Internet.

3.3.2 Radio Transmission.

Lower frequencies have the advantage of long propagation allowing for communication with very distant stations. At higher frequencies direct line-of-site or repeater stations are necessary for signal propagation. Generally VHF out performs UHF for communication efficiency with the exception of hand portable applications. VHF modules normally consume less power, offer better temperature stability, lower cost, greater operating distance for a given power, improved penetration of trees and buildings, improved antenna gain and lower attenuation in feeders. The only two negative sides of VHF are the antenna size and the lack of frequency allocations in some countries. RF systems are inexpensive (typically $200.00 – $400.00) and require relatively little power (< 4 watts). They have long been used in the tracking of wildlife and more recently have been applied to vehicles and cargo containers to enable shipment tracking and theft recovery. VHF and UHF transmitters are most often used to relay data from an autonomous station to a local base station (up to 25 km distant) where additional power and equipment permits forwarding the data by satellite, microwave, or fiber optic cable.

Bandwidth limitations on the order of 5 MHz typically limit RF telemetry to only binary or ASCII data, and off-the-shelf units are available with a 19,200 bps transmission rate. Tactical Electronics Corporation and Radio Tech are two companies producing such radio data telemetry transmitters.

3.3.3 Satellite Transmission.

Satellite communications offers the potential to satisfy all the data telemetry and remote control issues of autonomous observatories in extreme environments. At these higher frequencies greater data volume can be accommodated including real time voice and high-resolution video depending on system architecture.

<table>
<tr><th>Usage</th><th>Band Name</th><th>Frequency Range</th></tr>
<tr><td></td><td>HF</td><td>1.8 – 30 MHz</td></tr>
<tr><td rowspan="2">Little LEO systems</td><td>VHF</td><td>50 – 146 MHz</td></tr>
<tr><td>P-Band</td><td>0.023 – 1.000 GHz</td></tr>
<tr><td></td><td>UHF</td><td>0.450 – 1.500 GHz</td></tr>
<tr><td>Big LEO,
Inmarsat</td><td>L-Band</td><td>1.530 – 2.700 GHz</td></tr>
<tr><td></td><td>FCC Digital Radio</td><td>2.310 – 2.360 GHz</td></tr>
<tr><td>Big LEO</td><td>S-Band</td><td>2.700 – 3.500 GHz</td></tr>
<tr><td>FSS,
Inmarsat</td><td>C-Band</td><td>Downlink: 3.700 – 4.200 GHz
Uplink: 5.925 – 6.425 GHz</td></tr>
<tr><td></td><td>X-Band</td><td>Downlink: 7.250 – 7.745 GHz
Uplink: 7.900 – 8.395 GHz</td></tr>
<tr><td>Fixed Satellite Service (FSS)</td><td rowspan="2">Ku-Band
(Europe)</td><td rowspan="2">Downlink: FSS: 10.700 – 11.700 GHz
DBS: 11.700 – 12.500 GHz
Telecom: 12.500 – 12.750 GHz
Uplink: FSS & Telecom: 14.000 – 14.800 GHz
DBS: 17.300 – 18.100 GHz</td></tr>
<tr><td rowspan="3">Broadband GEO systems

Broadband LEO systems</td></tr>
<tr><td>Ku-Band
(America)</td><td>Downlink: FSS: 11.700 – 12.200 GHz
DBS: 12.200 – 12.700 GHz
Uplink: FSS: 14.000 – 14.500 GHz
DBS: 17.300 – 17.800 GHz</td></tr>
<tr><td>Ka -Band</td><td>Approximately 18 – 31 GHz</td></tr>
</table>

To date, however, the promise of a comprehensive satellite network has not been realized. The past five years has seen a dearth of proposals and tumultuous change in the financing, construction and operations of satellite networks. Those few available today and a promising few others on the horizon are discussed below.

GEO Systems: Communication satellite networks which employ satellites in a geosynchronous earth orbit are designated GEO systems. Such systems orbit directly above the equator at an altitude of 35,800 km (22,300 miles) at a rate that matches the speed of the earth's rotation on its axis. By maintaining a stationary position over the earth they can provide continuous coverage over their footprint area which, due to their high altitude, is approximately one third of the earth's circumference. GEO systems therefore require few satellites, no tracking and thus are cheaper and easier to maintain. As a result, such systems were the first to be developed and today, Inmarsat is a commonly used commercial provider.

- **Inmarsat.** Established in 1979 to serve maritime industry by developing satellite communications for ship management and distress and safety applications, Inmarsat currently operates a global satellite system which is used by independent service providers to offer a range of voice and multimedia communications for customers on the move or in remote locations. The satellite constellation is comprised of 9 satellites in geostationary orbit. Four of these satellites, the latest Inmarsat 3 generation, provide overlapping operational coverage of the globe (apart from the extreme polar areas). The others are used as on-orbit spares or for leased capacity. The network offers voice, fax, and messaging services at varying rates of transmission and cost. Usage fees (in 1999) for Inmarsat B, for example, which can handle a maximum data rate of 64 kbps, run about $15.00 per MB.

The position of GEO system satellites also creates drawbacks to their use in autonomous systems. Located over the equator, the satellites can provide little, if any, communications in the polar regions. Furthermore, their high altitude requires a relatively strong transmitter with a higher power requirement and inserts a round-trip delay of 0.24 seconds in real time communications exchange. Fortunately for most science applications signal latency issues have little impact, however, power conservation is a priority in virtually all autonomous system designs.

LEO Systems: By virtue of their low orbital altitude (644 – 2,575 km; 400 – 1600 miles), LEO systems require less transmitter power and incur no detectable signal delay. Since the orbits are not stationary, however, 48 to 66 satellites are required in order for a network footprint (each approximately 6000 km in diameter) to completely cover the earth. The number of satellites and the need to track and pass communication between them complicates LEO system design and greatly increases system development costs. Although many systems have been proposed, mergers or inadequate funding have reduced the systems currently available or projected to be available in the near future to just a handful. Those systems which have skirted the difficulties of financing and building the network required for real-time global communications are known as "little LEO" systems and have instead, focused on messaging and data packet transfer where transmission delay is acceptable but low power is still desired. These systems operate primarily in the VHF and UHF bands and have faced their greatest difficulties in obtaining frequency allocation and sufficient bandwidth.

- **ORBCOMM.** One of the earliest, viable, "little LEO" systems operational, ORBCOMM offers global wireless data and messaging communications.

Presently there are 36 satellites in orbit with plans and approval to increase that total to 48. These satellites provide the link between Subscriber Communicators (SC) and the switching capability at the Network Control Center or a licensee's Gateway Control Center (GCC). Located in a territory that is licensed to use the ORBCOMM system, the GCC provides switching capabilities to link mobile SC's with terrestrial-based customer systems via standard communications modes including X.400, X.25, leased line, dial-up modem, public or private data networks, and e-mail networks including the Internet. ORBCOMM's Gateway Earth Station (GES) link the ground segment with the space segment and will be in multiple locations worldwide. The GES is redundant and has two steerable high-gain antennas that track the satellites as they cross the sky. The GES transmits to a satellite at a frequency centered at 149.61 MHz at 57.6 kbps with a nominal power of 200 watts. The GES receives 3-watt transmissions from the satellite at 137-1138 MHz range. These up and downlink channels have a 50 KHz bandwidth. The Network Control Center (NCC) is responsible for managing the ORBCOMM network elements and the U.S. gateways through telemetry monitoring, system commanding and mission system analysis. It provides network management of ORBCOMM's satellite constellation and is staffed by ORBCOMM controllers. There are several types of Subscriber Communicators (SC). The SC for fixed data applications uses low-cost VHF electronics with a simple antenna design and small packaging. Its low-power electronics (5 watt output) allow for extended operations using batteries or a solar panel.

- **E-SAT:** A joint venture formed in 1994 by DBSI and Echostar Communications Corporation, received a license from the FCC in April 1998 to construct, launch, and operate a network of six satellites in low earth orbit for non-voice communications. The system will operate in the 148 – 148.905 MHz uplink and 137.0725 – 137.9725 MHz downlink frequency bands and provide data messaging services primarily for the Automated Meter Reading market, concentrating on those uses classified as remote and hard-to-access. Although its satellite system will offer global coverage of hard-to-access fixed assets, E-Sat will initially concentrate on the continental United States. Transmitting data from the ground in foreign countries requires permission from their regulating agencies, which must be obtained on a country-by-country basis. E-Sat offers Direct Sequence Code Division Multiple Access (CDMA) transmission technology, which permits the transmission of RF at low power (approximately 1.5 watts) even amidst a crowded field of nearby RF sources.
- **LEO ONE.** Planned to be operational by 2003, LEO ONE promises a more comprehensive and versatile low earth orbit data transmission network. System characteristics as currently planned:
    - 48 Operational satellites in 8 polar orbital planes inclined 50°, with 8 on-orbit spares
    - Coverage from 65°N to 65°S at a 15° elevation mask angle
    - Coverage from 73°N to 73°S at a 5° elevation mask angle
    - 104 minute orbital period with 7-10 minute visibility on each pass
    - Subscriber and gateway downlink band: 137 – 138 MHz
    - Subscriber and gateway uplink band: 148 – 150.05 MHz
    - Subscriber and gateway downlink band: 400.15 – 401 MHz
    - Subscriber downlink data rate: 24,000 bps
    - Subscriber uplink data rate: 2,400 – 9,600 bps

- Gateway uplink and downlink data rate: 50,000 bps
- 10 cubic inch terminal with maximum transmit power of 7 watts.

The most ambitious systems, and thus, the ones most difficult to establish, are the real-time, low earth orbit, or "big LEO" systems. The greatest challenge these companies have had to overcome (as evidenced by the collapse of Iridium LLC) is obtaining the necessary subscribers to finance the satellite constellation and then building the constellation in time to satisfy the subscribers. Out of a myriad of proposals in the 1990's, a few strong contenders have emerged.

- **Globalstar.** Globalstar is a partnership of many of the world's leading telecommunications service providers and equipment manufacturers including co-founders Loral Space and Communications and Qualcomm Inc. The system differs from "true" satellite networks in that the satellites utilize "bent-pipe" architecture to merely relay signals to the appropriate gateway where the call is then routed locally through terrestrial telecommunications systems. This simplifies satellite design and reduces their cost; as a result, Globalstar was the first commercially successful "big LEO" system in operation. Presently the constellation consists of 48 satellites with 4 on-orbit spares placed in polar orbit in eight planes inclined at 52°. Their footprints extend from 70°N to 70°S latitude. Recently, Globalstar developed a Flight Modem that permits a rocket or any other space flight vehicle to communicate to ground controllers via the Globalstar communications network. This modem is a modified version of the Supervisory Control and Data Acquisition modem already available for use in industrial data applications such as wireless remote asset tracking and relaying telemetry information from remote sites.

- **Iridium.** In December 2000, Iridium Satellite LLC acquired the operating assets of bankrupt Iridium LLC, including satellite constellation and terrestrial network. The system is the only currently operating, "true" satellite network providing real-time voice communications with 100% global coverage. The system is comprised of 66 satellites (plus 6 on-orbit spares) orbiting in six polar planes. Each satellite is cross-linked to four other satellites; two satellites in the same orbital plane and two in an adjacent plane. The ground network is comprised of the System Control Segment and telephony gateways used to connect into the terrestrial telephone system. The System Control Segment is the central management component for the Iridium system. It provides global operational support and control services for the satellite constellation, delivers satellite tracking data to the gateways, and performs the termination control function of messaging services. The System Control Segment consists of three main components: four Telemetry Tracking and Control sites, the Operational Support Network, and the Satellite Network Operation Center. The primary linkage between the System Control Segment, the satellites and the gateways is via K-Band feeder links and cross-links throughout the satellite constellation. Gateways are the terrestrial infrastructure that provides telephony services, messaging, and support to network operations. Service for voice communications began in the first quarter of 2001 with data service at 2.4 kbps expected to follow later in the year.

- **Teledesic.** Beyond the data transmission rate required for voice communications lies the broadband spectrum necessary for real-time video, teleconferencing and Internet networking. Of the numerous systems proposed or begun, one has emerged and proposes to begin service in 2005, that company is a merger of New ICO and Teledesic and may incorporate Ellipso in 2001. The network, as planned, will consist of 288 satellites in 12 polar planes and will operate in the Ka-Band. It is anticipated that most users will have 64 Mbps on downlink and up to 2 Mbps on uplink with broadband terminals offering two-way 64 Mbps capacity. These speeds are the first satellite system to approach fiber-optic capacities for data transfer. If realized, worldwide, "fiber optic quality" data transmission will become routine and the selection of a communication system for an autonomous observatory in an extreme environment will be a non-issue.

3.3.4 Optical Transmission.

Fiber optic cables have effectively unlimited (5-20 GB/sec) real-time telemetry which can easily handle high-resolution video. The disadvantage is the high cost of fiber optic cable that rapidly becomes prohibitive as distances increase. Additionally, once in place, cabled observatories have limited portability.

The two major classifications of fiber are: multi-mode and single-mode. In general, multimode fiber is best suited for premises applications where links are less than 2000 meters and there are many connectors. The larger core diameter of multimode fiber allows the use of relatively inexpensive Light Emitting Diode (LED) and Vertical Cavity Surface Emitting Laser (VCSEL) transmitters and low-cost connectors. Single-mode fiber is best suited for long distance applications (greater than 1-2 km), but requires higher cost connectors and transceivers. Typically, the cost for single-mode fiber installations is four times that of multi-mode fiber.

The two primary attributes of optical fiber are attenuation and bandwidth. Attenuation is a reduction of signal magnitude, or loss, as light travels through a fiber. Fiber attenuation is measured in decibels per kilometer (dB/km). A higher attenuation number means more loss and poorer performance. Fiber bandwidth quantifies the information carrying capacity of a fiber. Bandwidth is measured in units of MHz*km. This value refers to the capacity of the fiber, which in turn determines the maximum link distances, depending on the baud rate or application protocol speed. The bandwidth value for a fiber is a constant. As the data rate (measured in MHz) increases to gigabit speeds, the distance (km) decreases.

Multimode fiber uses a graded index to minimize modal dispersion. This design maximizes bandwidth while maintaining low attenuation characteristics. For multimode fibers, bandwidth is the major limiting factor in network design. Single-mode fiber is designed to carry only one mode of light, and thus does not experience modal dispersion like multimode fiber. For this reason, single-mode fiber is not limited by bandwidth, but by attenuation and system cost issues. Although fiber bandwidth is a critical factor in determining link length and data rate, it is not the only one. Transmitter and receiver characteristics are as important as bandwidth in determining possible link length and data rates.

Physically, fiber optic cable of the same diameter maintains the same basic tensile strength and turning radius. From an optical standpoint, bending affects attenuation loss only at very small bend diameters (less than 20mm or approximately 1 inch). Optic fibers are constructed of a GeO_2/SiO_2 core with a SiO_2 cladding. This is then coated with two UV Acrylate layers to protect from external mechanical and environmental damage, maintain strength and handle-ability, and facilitate color-coding. Not all fiber suppliers use the same manufacturing process, a key factor in obtaining consistent fiber geometry and optical performance. For example, Owens Corning uses an advanced outside vapor deposition process (OVD) while most other suppliers use a modified core vapor deposition (MCVD) process. Although various multimode fibers are compatible with each other and often interchangeable, they are not compatible with single-mode fiber.

3.4 Packaging.

The packaging of an autonomous system must serve three functions. 1) It must ensure the survivability of the system in its environment and in some cases (RTG's, for example) protect or isolate the environment from the system. 2) The design of packaging must consider the method of placing the system in the field and should facilitate, or at the very least, not impede, that transportation. 3) It is a part of the system in that it provides the primary means for thermal control of the system.

3.4.1 Survivability.

Packaging to ensure survivability is driven by the adverse conditions present in the intended environment. These may include radiation, pressure or vacuum, moisture, corrosion, debris impact, temperature, vibration or shock. When designing for these factors, knowledge of the environment is useful and therefore collection and accessibility of environmental data is essential for the design process. Consider also whether characteristics of the proposed site can be utilized to assist in system protection. Finally, the desired endurance of the system will impact the level of packaging required.

In deep ocean applications the main concerns are pressure, moisture and corrosion. Pressure vessel design, also intended to exclude moisture, is well understood but costly. In fact, it is often the case that it is a more expensive component than the electronics it protects. Occasionally, pressure compensation systems will be employed. The non-pressure resistant housing is kept filled with oil that is maintained by a spring-loaded compensator at just a few pounds above ambient sea pressure. This permits lightweight construction but requires components be immersed in compensating fluid (typically a light oil). Numerous methods exist to combat corrosion, including sacrificial anodes, special surface coatings, and selection of materials (i.e. titanium versus steel). Surface ocean observatories must maintain buoyancy and be able to tolerate roll, pitch and heave which place significant g loading on the buoy. Lightening strike, impact from hail, or floating surface debris is also a concern. Buoy systems are often powered by diesel generators and possess large tanks filled with fuel. In this case, package design must take steps to protect the ocean from the hazard of a fuel spill.

Space systems require protection from temperature extremes, radiation and micrometeorite abrasion. Thermal control techniques will be discussed later, but the answer to the latter two is shielding. Since reducing weight is always a priority in spacecraft design, the components requiring shielding and the amount of shielding required must be given careful consideration. In many aerospace circuits, radiation survivability cannot be left to chance. Electronic systems are constructed with Radiation Hardness Assured (RHA) devices that are process monitored, designed, and layout controlled to ensure radiation hardness. Manufacturers seek out specific technologies that will perform the job based on the needed application. Four basic ways to harden a device to radiation are with: junction isolation, dielectric isolation, silicon-on-sapphire devices, and silicon-on-insulator devices. All of these methods work on the principle of isolating each device from surrounding components. This eliminates the possibility of latchup and reduces the possibility of an SEU because charged ions cannot travel as far in the components.

- **Junction Isolation (JI):** Junction Isolation is typically used for CMOS, and other unhardened bipolar designs. It consists of reverse biasing the junctions to isolate on-chip components from one another. Because this process is electrical, JI radiation tolerances may not be sufficient for circuits exposed to very high radiation levels. Junction Isolated processes may be susceptible to latchup due to their parasitic PNPN SCR structure.
- **Dielectric Isolation (DI)**: Dielectric Isolation is a step up from JI. A thick layer of silicon dioxide is thermally grown between adjacent devices to provide component isolation. The oxide is constrained to grow only in chosen places on the wafer by using an oxidation mask. Dielectric isolation is a better choice for more demanding radiation hardness applications.
- **Silicon-on-Sapphire (SOS):** SOS is a more complex form of dielectric isolation. A single-crystalline silicon film is grown over a sapphire substrate. The silicon island is doped to make a bipolar or FET transistor. Sapphire is a dielectric that has an inherently high tolerance to radiation. The sapphire protects the device against transient, neutron, and single event effects. Leakage currents cannot flow between devices because the transistors are built on an insulating substrate. Therefore, guard rings that limit leakage current between transistors are

unnecessary in SOS, and active devices can be packaged closer together. Also, there are no parasitic transistors to latch up, and there are no capacitances associated with SOS like there are with JI reverse biased junctions.

- **Silicon-on-Insulator (SOI):** SOI technology is very similar to the process used for SOS devices. SOI and SOS have many of the same advantages. The only basic difference between them is the substrate used in each process. Silicon-on-Insulator devices can take several forms, but we will discuss a technique called SIMOX, or Separation by Implanted Oxygen. In SIMOX, a high-current ion-implantation system is used to deposit a heavy concentration of oxygen molecules in a layer just below the wafer's surface. The wafer is then heated, and the oxygen forms a continuous SiO2 layer beneath the silicon surface. Heating also anneals the damage caused by the implant. Therefore, a thin, high-quality layer of silicon is left on top of an insulating layer of SiO2. This silicon is then used for device fabrication. Between active transistor areas, the silicon is etched away and replaced with oxide, which completely isolates the devices. This dielectric-isolation plane enables increased circuit speeds and radiation hardness.

Space packaging must also contend with the shock and g loading encountered at launch and must ensure the earth is adequately protected from potentially harmful components (e.g. RTG’s) in the case of launch failure.

The polar-regions present the problems of temperature, moisture, debris impact and to a lesser degree, shock and vibration incurred in transport. Mounting solar panels vertically minimizes snow buildup but may increase the potential for debris strike. Maintaining smooth surfaces with minimal projections reduces the likelihood of ice formation. Including a desiccant such as calcium hydride inside the system enclosure may reduce moisture problems and be more effective than a “dry” nitrogen purge, which at South Pole temperatures is not effectively dry. Enclosures should be sealed against melt-water intrusion and blowing snow, and grounded to guard against static discharge. As in the deep ocean, external cables must be shielded and insulated to survive on their own. External cable connections require particular attention. It is recommended that only Mil-Spec connectors, possessing a locking screw collar and o-ring seal, be used. In situ techniques that have proven useful include covering external cables with rocks, burying system components in the snow for thermal stability and protection from impact, and utilizing snow slopes to enhance RF antenna propagation. Packaging for the Antarctic continent must comply with the Antarctic Treaty and its stringent regulations regarding environmental preservation.

3.4.2 Transportability.

The size and weight of the assembled components primarily affect ease and cost of transport. For the purpose of deploying an autonomous system, we will define three categories of size and weight as they relate to the means available to deploy them. Appendix E presents details of some equipment and vehicles that researchers may utilize to deploy their systems to the field.

- **Small Systems.** Those systems able to be moved and deployed by one person. Basically limited to backpack dimensions and weights less than 150 lbs. When designing small systems at the upper limits of this size and weight consider the ergonomics of lifting and carrying the system in the designed packaging. Small systems can be expected to be subjected to drops, inverting, and stacking in the course of their transportation.

- **Medium Systems.** Those systems able to be moved and deployed by manpower alone. As many as four to five individuals may be required, but the components are able to be lifted and transported without motorized equipment. In design, consider the spacing, height and number of handholds necessary to accommodate the individuals required to move it. The packaging may incorporate wheels, jacks or other simple mechanical assists suitable for the most difficult terrain it will encounter. In the polar programs, medium systems should be able to be transported by a Twin Otter aircraft or a Bell 212 helicopter.
- **Large Systems.** Those systems that require the use of motorized mechanical equipment to be moved and deployed. Such systems should have provisions for being handled by forklift or lifted by crane, and being secured to a flatbed truck or the cargo deck of a vessel or aircraft. Designs should conform to the standards set for international shipping containers, as much as practicable, to simplify transport. In the polar regions such systems should be able to be transported by LC-130 aircraft, and be able to withstand combat offloading when delivered to field locations where heavy equipment is not available.

3.4.3 Thermal Control.

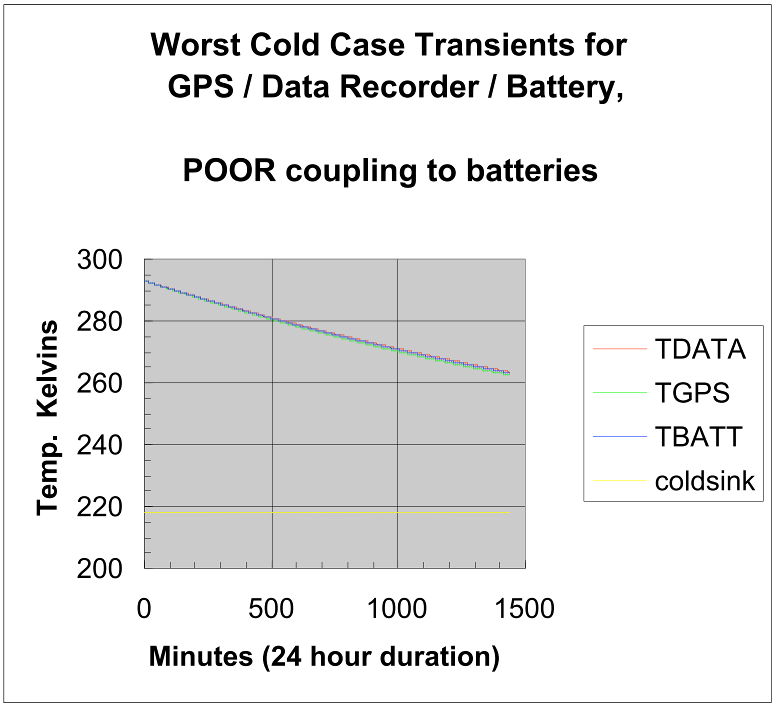
Thermal control is a means of managing the energy in a system so that it will create the desirable thermal state. There are passive and active methods for accomplishing this control. The passive techniques do not require outside force or extra energy to activate them. They include insulation material (foam for earthbound applications or multi-layer insulation blanket for spacecraft), surface color and reflectivity, louvers, which temperature triggers open or shut, and a heat or fluid pipe activated by temperature itself. Other passive systems may include sensible or latent heat storage consisting of one phase or multiple phase materials which can store heat compactly and provide a buffer for heat transport in and out of the system of interest. The great advantage of passive systems is that they are simple, thus fail-safe, and cheaper. Active systems include heaters and fluid refrigeration units. They provide more precise temperature control, but are costlier, more complex, consume power, and generally add extra mass to the system.

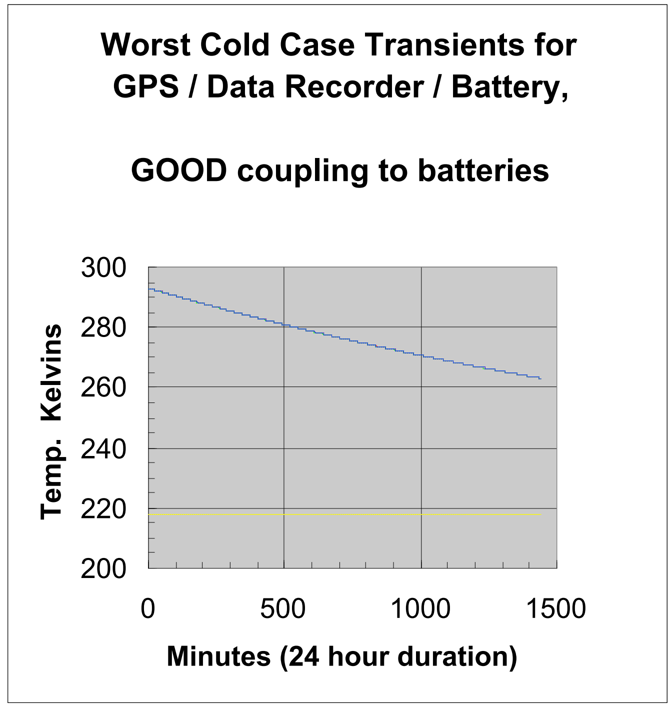
Achieving heat balance within a system requires analyzing the heat sources and heat sinks and either facilitating or restricting the flow from one to the other. Environmental sources, such as the sun, and system sources must be evaluated for their variation, duration, and intensity. With this information a thermal model can be developed that takes into account the different environmental and operating conditions the system is likely to experience. A simple thermal model may only be able to establish the limit of the extremes while more sophisticated models can provide a simulation of the rate of temperature change.

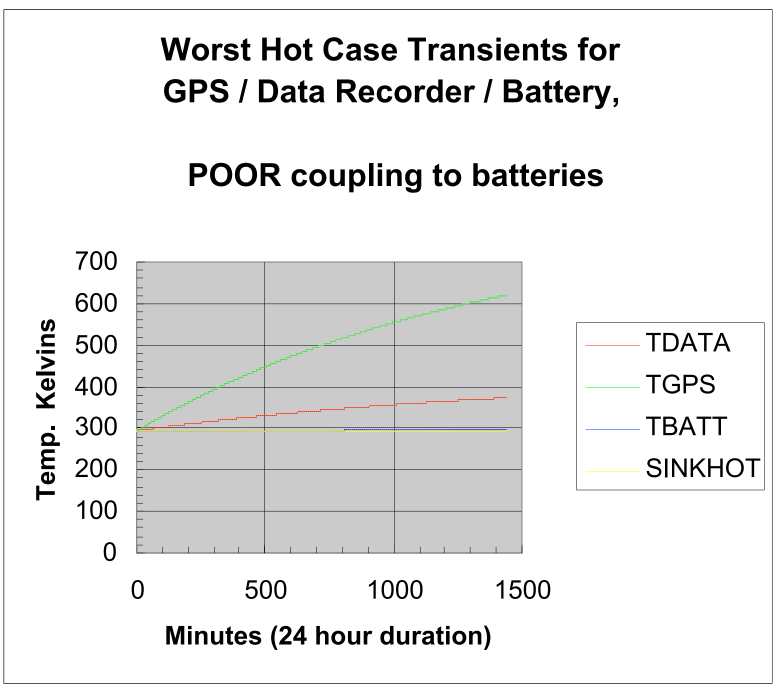
Action Item: Solicit and fund a proposal to develop a simple-to-use, computer based thermal model of the Antarctic environment for system design purposes.

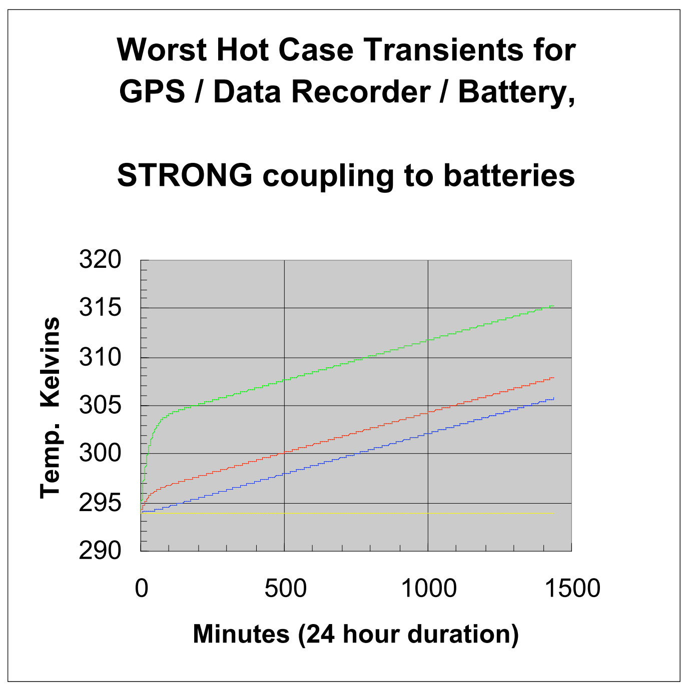
One way to dampen the rate of these temperature changes and mitigate the extremes is to provide the system with inertia in the form of thermal mass. For systems deployed in the deep ocean, the ocean itself serves as an almost infinite, stable thermal mass. As long as temperatures slightly above freezing are acceptable to system performance, little thermal control is required. Heat generated by components within the pressure enclosure can be conducted to the walls of that vessel and use the ocean as a heat sink. In polar environments, the energy storage component of the system can be used to provide thermal mass. This may be the battery bank or liquid fuel storage tanks, which when coupled to the other systems components, can mitigate the speed and extent of temperature variations. Analysis done by Henry Awaya of the Jet Propulsion Laboratory for an autonomous GPS system deployed to Marie Byrd Land clearly illustrates the advantage of coupling to a large thermal mass, in this case, gel-cell batteries:

(See graphs on following page)


Worst Cold Case Transients for
GPS / Data Recorder / Battery,
POOR coupling to batteries
300
280
260
240
220
200
Temp. Kelvins
0
500
1000
1500
Minutes (24 hour duration)
TDATA
TGPS
TBATT
coldsink


Worst Cold Case Transients for
GPS / Data Recorder / Battery,
GOOD coupling to batteries
300
280
260
240
220
200
Temp. Kelvins
0
500
1000
1500
Minutes (24 hour duration)


Worst Hot Case Transients for
GPS / Data Recorder / Battery,
POOR coupling to batteries
700
600
500
400
300
200
100
0
Temp. Kelvins
0
500
1000
1500
Minutes (24 hour duration)
TDATA
TGPS
TBATT
SINKHOT


Worst Hot Case Transients for
GPS / Data Recorder / Battery,
STRONG coupling to batteries
320
315
310
305
300
295
290
Temp. Kelvins
0
500
1000
1500
Minutes (24 hour duration)

Thermal control within a system also depends on the regulation of heat exchange with the environment. Hermetically sealed, vacuum walled enclosures and foam insulation are very effective in restricting heat flow. VACUPANEL is one such box used successfully in the Antarctic. When sealing batteries or fuel sources inside such enclosures take precautions to ensure that they do not trap and allow hydrogen or other dangerous vapors to build up. High internal pressure and/or volatile vapor concentration have led to catastrophic results in the past.

3.5 Instruments and Controls.

Scientific instrumentation represents the reason for building and deploying an autonomous station. A failure of the instrumentation represents an unrecoverable compromise of the system's operation. Despite that, it is often difficult to improve the robustness of the instrumentation. Typically, they must be mounted outside of the system enclosure, exposed to the very elements the packaging is designed to protect against. The need for precision often results in instruments that are sensitive to all the forces and conditions discussed earlier. Instruments are typically expensive and their cost may make it impractical to provide redundancy. These conflicting considerations may place the system instrumentation in the position of being particularly vulnerable, single-point-failure, components.

Ideally, instruments should be tested and selected for being simple, accurate and inexpensive while possessing the ability to function independently, degrade gracefully and operate on low power. It is not uncommon for the desired instruments to be unable to meet these requirements. On a platform with multiple experiments and greater redundancy, a control system may be able to mitigate the impact caused by the loss of one sensor. At the most basic level the control system directs the storage of data and regulates the power supply. In hybrid powered systems this can be accomplished by a simple relay, triggered on the sensing of system voltage, fuel quantity or temperature, for example. The incorporation of a clock or timing chip allows the system to operate on a fixed time schedule rather than in reflexive response to parameters. This may be important for synchronizing telemetry transmission or for providing more precise and predictable data sampling intervals. A system that must perform data compression or decision-making will require some sort of processor and operating code. It may consist of an EPROM with a simple set of coded instructions or may utilize an existing sophisticated operating system such as DOS, WINDOWS, or UNIX. Several researchers reported that DOS was a reliable and relatively “quirk-free” operating system that lent itself to easy adaptation for autonomous system control. It is important to recognize that the level of control provided or the sophistication of the technology used in the control system does not always indicate how easy the system is to design and work with. In fact, the opposite may prove to be true. It may be easier to utilize a commercially available, sophisticated multi-function processor and standard operating system than to create from scratch a much “simpler” custom EPROM code or electrical regulation circuit.

4.0 System Development and Testing.

The paradox of testing is that limited time, money and suitable facilities make it almost impossible to adequately test autonomous systems prior to deployment, yet inadequate testing almost guarantees failure in the field at a cost of even greater expense and time lost. During the design and development of a system, three levels of testing should occur: component testing, system integration testing, and prototype trials. The need for a rigorous and comprehensive test program that incorporates all three levels of testing was a major recommendation of the workshop.

Component testing is done to determine if individual parts of the system meet the necessary specifications. Ideally, the associated manufacturers' specifications should be sufficient to allow economizing on this type of testing, but unfortunately, experience has proven otherwise. As a result, components must be tested both to guarantee accuracy of their stated operation and to evaluate their performance and suitability under the conditions envisioned for their use.

The objective of systems integration testing is to ensure that all components interface correctly and that the system can accomplish its designed task. Troubleshooting efforts at this stage can be simplified if the methods of testing were considered in the original design. Incorporating modularity for example, can permit running and testing parts of the system while other components remain isolated. Systems with more sophisticated control processors may have self-diagnostic routines and testing functions pre-programmed.

After system function is assured under laboratory conditions, prototype trials are conducted under all the conditions the system will experience in the field. Comprehensive testing will encompass static and dynamic stresses to determine a system's vulnerability to shock and vibration, temperature and pressure extremes and variation, radiation, EMI and static discharge, wind, and moisture. Testing must satisfy a higher standard than system performance, it must ensure that the quality of the data recorded is not adversely affected. Large universities and other research institutions may have in-house facilities like wind tunnels, hyperbaric chambers or shake tables. Other possibilities include military or other federal facilities that may be accessible to researchers on federal grants. The AGO program, for example, was able to conduct tests at the Army's Eberding Proving Grounds, utilizing their cold chamber to study system performance at -68°F.

Action Item: Compile and maintain on the web site, a list of government and university test facilities, their capabilities, and a point of contact to discuss their use by researchers funded by NSF grants. Consider the implementation of a national program of shared test facilities in which member institutions would gain mutually enhanced access to other facilities.

There may be natural sites, more easily accessed than the intended field location, that possess similar extreme conditions. The summit of Mount Washington in New Hampshire is one such proposed location for testing in conditions of extreme wind, cold and moisture. In some cases, researchers have been able to have manufacturers conduct more extensive component testing for them, thereby increasing the specification range of their products. The advertising benefit of being selected for use by an extreme environment research program may be sufficient incentive or it may require supplemental funding by the researcher. A manufacturer may very well have resources at their disposal that makes them the most economical choice to accomplish testing.

The answer, then, to the paradox of testing is that time and money spent on testing are resources well spent. Three proposals were discussed that could potentially reduce the burden of testing, thus speeding system design, while still ensuring the quality and probability of success for systems deployed to the field.

4.1 Quality Standards.

Create a quality standard for manufacturers specifications. In effect, a manufacturer could get a "seal of approval" by a review authority that would guarantee their specifications to the standards that engineering for extreme environments demand. In order to be practical, two things would have to occur. First, an appropriate "review authority" would have to be specified or created. It could use the form of the Underwriters Laboratory for electrical appliances or a professional society such as for boiler construction standards, as a model. This type of quality standard exists within many organizations already; "flight hardware" at the Jet Propulsion Laboratory or "subsafe" in the U.S. Navy, to name a couple. If created, a professional society for extreme engineers could provide the quality review and approval. Alternatively it could be assigned to an appropriate government agency much like the USDA is responsible for grading the quality of beef products. Agencies involved in sponsoring extreme environment research, like NASA or the NSF, would be the obvious candidates.

The second thing that must happen in order for quality standards to work in industry is that the market must be sufficiently lucrative to justify the additional expense to manufacturers. It is unlikely that exploration of the frontiers is ever likely to produce the economies of scale to voluntarily coax manufacturers into performing additional testing. It is more likely that superior performance will develop naturally as technologies mature. Going beyond what is required for commercial sales will require inspiring the interests of individuals in the goals of science.

4.2 Standardized System Design.

The development, testing and approval of a standard, field-deployable, autonomous system would relieve the researcher from having to perform any technology development not related to the subject of their particular study. Essentially a generic power and data bus, into which, any number of instruments could be plugged, is desired. But is such a commonality achievable for all environments? The short answer is not yet. The more similar the environments the more likely it is that common design elements will prove suitable. But in most cases where an all-encompassing, single, perfect solution is sought, none is found because each environment imposes different engineering compromises. However, as technologies advance, greater commonality becomes possible because they become less affected by the environment they are in. Data storage, for example is rapidly achieving a level of maturity that for all purposes except video, Flash memory is the technology of choice as it is virtually impervious to the environment in which it is placed. Power generation, on the other hand, remains highly subject to the local conditions. Only RTG's operate essentially independent of environmental conditions and that technology exhibits perhaps the best reliability and autonomy in extreme environments. Communications, particularly data telemetry, is always going to depend to a great extent on infrastructure that is not part of the system design. Presently a variety of schemes are proposed for LEO and GEO broadband data transmission but until these telecommunication systems mature it is difficult to envision a standardized design for earthbound autonomous systems. Packaging represents the most easily achieved standardization in system design. The technology exists to make enclosures that are resistant to all of the conditions that can be encountered in all environments. The drawback to such standardization is increased expense and weight. The fact is, packaging is the one aspect of system design that is minimally engineered to satisfy function while reducing cost, weight and complexity.

4.3 Enforced Testing.

Impose a requirement that all systems funded by federal grants demonstrate satisfactory and applicable test results before deploying to the field. Such a regulation could be self-defeating in that it would encourage spending the limited money and time provided in a grant on technology development, rather than in producing scientific results. Of course its goal would be to prevent the premature deployment of insufficiently tested systems whose failure in the field would produce no science and effectively waste the time and money provided by the grant. Addressing alternative means of achieving this objective leads directly to the heart of a debate on science versus technology and the research infrastructure.

5.0 The Research Infrastructure.

In today's frontiers, science is the motivator that is driving exploration. As science probes deeper into space, the ocean, and the polar regions, there is the discovery that current technology is inadequate to overcome the challenges such environment pose. Science, then, becomes the driver for new technology. In the interim, scientists often have no recourse but to spend their time and limited funding doing the technological development necessary to support their research. That this is less than desirable was an opinion expressed by the majority of the workshop participants.

One alternative that received much discussion was to change the basic grant structure and funding allocation. The three-year period specified in most federal research grants is inadequate when the science proposed requires the development of new technology to accomplish. Proposals which specify the need for technology development should be separately considered and if funded, should be given longer initial periods of support; five or six years for example. By recognizing and funding the need for additional time to accomplish technology development, systems would undergo more extensive testing prior to deployment and likely produce better results during the time they are in the field. In the short term, longer grants would involve greater expense, however, they would reduce the percentage of time a researcher spent preparing proposals and could possibly reduce logistics costs associated with upgrading systems prematurely deployed to the field.

Complementing a lengthened grant period might be a program that provided grants specifically for technology development. Such shorter term funding would encourage and focus technical advancement in areas of particular difficulty to researchers. By focusing strictly on technology, it would attract engineers and manufacturers and apply their superior expertise in solving the technical problems encountered by the scientists. This would be a natural complement to programs, like SBIR, already in existence. The NSF Office of Polar Programs has recently implemented a Polar Instrumentation and Technology Development program, which to a large degree, incorporates the objectives of these recommendations.

Clearly needed, however, is a unifying organization under whose guidance technology transfer can freely occur. Such a forum would avoid the duplication of development programs, could focus funding efforts on the most significant or prevalent problems, and provide a voice for exploratory efforts within industry, the government and to the general public. This organization could take the form of a government agency, a professional society, a lead institution, or an independent steering committee and examples of each exist in other disciplines today.

As a species and a society, we want to explore and learn about our frontiers. We have shown time and again our willingness to support efforts and devote resources to do that. Autonomous systems represent the most efficient use of those resources in performing science, but the harsh nature of our frontiers challenges the technology we employ. This workshop and the recommendations it produced, represent some of the possible ways in which, given limited resources, the focus can be kept on the science.

Appendix A

Workshop Action Items and Recommendations

Action Item #1: Identify an organization responsible for maintaining an interactive web site for the promulgation and discussion of new ideas, and develop a means for funding it.

Action Item #2: Prepare and maintain an experimenter's handbook that includes a compilation of proven technologies, lessons learned and other information relevant to designing and deploying autonomous systems to extreme environments.

Action Item #3: Principal Investigators deploying systems to the field should make an effort to include meteorological instruments in their systems and the data obtained from said instruments should be added to a database maintained on-line.

Action Item #4: Provide federal funding for a study to research the economic feasibility of a federally funded and administered RTG power source program for extreme environment research applications.

Action Item #5: Solicit and fund a proposal to develop a simple-to-use, computer based thermal model of the Antarctic environment for system design purposes.

Action Item #6: Compile and maintain on the web site, a list of government and university test facilities, their capabilities, and a point of contact to discuss their use by researchers funded by NSF grants. Consider the implementation of a national program of shared test facilities in which member institutions would gain mutually enhanced access to other facilities.

System Design Recommendations:

1. Keep system electrical loads as low as possible. Use micro-powered devices whenever available.
2. When selecting batteries for use in cold conditions, use standard 12VDC, Gel-Cell electrolyte type batteries.
3. Take maximum advantage of solar energy sources and utilize multi-crystalline silicone solar cell technology. Select panels with demonstrated robustness such as those produced by Solarex, Inc.
4. Extensively test all wind generator designs prior to deployment to the field.
5. For other than video data, set data sampling rate and retrieval interval to permit the use of commercially available Flash memory cards for data storage.
6. Include some form of telemetered data whenever possible, even if it consists of nothing more than a system health signal. Incorporate a processor and a compression routine into system design if it will permit the telemetry of greater amounts of data.
7. Include provisions for passive thermal regulation and static discharge in packaging design.
8. Ensure that overall design, and particularly the packaging, is compatible with the equipment to be used in transport and deployment of the system to the field.
9. Provide redundancy for critical instruments and data storage.

System Development and Testing Recommendations:

1. Extensively document all system components at all stages of system design, testing and deployment. Implement a method for documenting and tracking revisions and subsequent changes.
2. Modularize system design to permit isolated component testing, replacement repair and upgrading.
3. Test all component manufacturers' specifications that are relevant to the intended field location.
4. Invest in testing to the greatest extent possible and strive to subject integrated system components to combined condition testing in so far as practical.

Recommendations on the Research Infrastructure:

1. Provide longer-term grants to proposals that require the development of new technology. The review of such proposals should ensure adequate provisions for testing are included.
2. Create a grant program for technology development to specifically complement extreme environment research needs.
3. Empower an organization to facilitate technology transfer, focus funding and development efforts, approve quality standards for industry and guide our future efforts to explore our frontiers.

Appendix B

Workshop Attendees

Convenors

	Participant	Affiliation	Area of Expertise
1	Andrea Donnellan	Jet Propulsion Laboratory	GPS
2	Bruce Luyendyk	UCSB	Antarctic geology and tectonics
3	Sridhar Anandakrishnan	University of Alabama	Seismology

Invited Speakers

	Participant	Affiliation	Area of Expertise
4	Henry Awaya	Jet Propulsion Lab	Thermal Systems Engineering
5	Mike Brennan	Northern Power Systems, Inc.	Remote Power Supplies
6	Greg Dace	Acumen Instruments Corporation	Data Systems
7	Ray Dibble	Victoria University	Volcanic seismology
8	Jack Doolittle	Lockheed Martin ATC	Autonomous facility design
9	Ngoc Hoang	NALResearch Corporation	Communications
10	Bill Nesbit	Antarctic Support Associates	Power systems
11	John A. Orcutt	IGPP/Scripps Institution of Oceanography	Ocean Observatories
12	Carol Raymond	JPL	Autonomous GPS
13	Paul Stolorz	JPL	Autonomy

Contributors

	Participant	Affiliation	Area of Expertise
14	Phil Anderson	British Antarctic Survey	Boundary Layer Meteorology
15	Michael Ashley	University of New South	astronomy, software, electronics,

		Wales	optics, mechanical
16	Aris G. Aspiotes	AlliedSignal/USGS	Power Supplies/Communications
17	Davis Atkinson	JPL	Autonomy/artificial intelligence
18	Armen Bahlavouni	Scientific Solutions, Inc.	Met Sensors
19	Scott Borg	National Science Foundation	Antarctic earth sciences
20	Jason E. Box	CIRES/University of CO, Boulder	climatology
21	Frank Carsey	JPL	Glacial in-situ devices
22	Dave Chadwell	Scripps Institution of Oceanography	GPS autonomous buoys/ seafloor systems
23	Andy Chen	Hydrogenics Corporation	power systems
24	Neil Cobbett	British Antarctic Survey	Engineering - AGO programme, Remote low power magnetometers
25	Curt Conquest	UNAVCO	Power, communications, Data retrieval
26	Michael Cousins	SRI International	remote automatic data collecting eqpt & spacecraft
27	Frederick Cruz	SPAWAR System Center (ATS)	Antarctic meteorology
28	Kevin Culin	NSF-Antarctic Support Associates	Power systems
29	Gregory A. Dorais	NASA Ames Research Center	Spacecraft autonomy
30	Richard Doyle	JPL	Artificial intelligence and autonomy
31	Hermann Engelhardt	Caltech	Antarctic glaciology
32	Jill Ferris	ASA Science Support	field science logistics
33	Michael Flynn	Ames/NASA	autonomy
34	Remy Fourre	ASA	power systems
35	Maggi Glasscoe	JPL/UC Davis	GPS
36	Joel Hagen	Acumen Instruments Corporation	data systems
37	Gordon Hamilton	The Ohio State University	Glaciology; Geodesy
38	Ray Highsmith	Universit of Alaska	undersea research
39	Larry Hothem	U.S. Geological Survey	Remote operations in Antarctica, including GPS/GLONASS and tide gage systems.
40	Ken Hurst	JPL	Autonomous GPS

41	Erik Ivins	JPL	General/GPS
42	Bjorn Johns	UNAVCO	GPS Applications
43	John Kelley	Institute of Marine Science, University of Alaska Fairbanks	Marine and Atmospheric Science
44	Steve Kottmeier	Antarctic Support Associates	oceanographic systems
45	Paul Lundgren	JPL	GPS
46	Martin R. Marcin	JPL	Global GPS Network
47	Tim Melbourne	Central Washington University	Low cost telemetry
48	John Militzer	NCAR / ATD	'Weather/flux' stations: data systems, comms, power
49	George "Bub" Mueller	University of Alaska Fairbanks	Arctic Instrumentation
50	Jerry Mullins	USGS	
51	David Murr	Boston University	magnetometers
52	Steve Musko	University of Michigan	Systems & Software
53	Walter Oechel	San Diego State University	Plant physiological and ecosystem ecology; effects of global change and CO2.
54	Ron F. Paetzold	USDA NRCS	Soil moisture & temperature
55	Barb Perin	UNAVCO	General continuous station installation and project planning
56	Stephen Platt	University of Nebraska-Lincoln	Astrophysics, instrument development
57	Ron Rainbow	Independent	remote installations
58	S. D. Rajan	Scientific Solutions, Inc.	Arctic research
59	Jonathan A. R. Rall	NASA Goddard Space Flight Center	autonomous instruments in extreme in environments
60	Tom Rebold	JPL	power systems
61	Spencer Reeder	UNAVCO	GPS permanent station installation and maintenance, L1-network installation, TDMA telemetry
62	Andrew Roach	Applied Physics Lab/University of Washington	Arctic oceanography
63	James Roberson	SPAWAR System Center (ATS)	Automatic weather stations
64	Matthew Rushing	SPAWAR System Center	Antarctic systems

		(ATS)	
65	Larry Sanders	Los Alamos National Laboratory	engineering
66	Mirko Scheinert	Technische Universitaet Dresden	Interest: Autonomous GPS stations in polar regions
67	Michael Sims	NASA/Ames	AI, robotics
68	Mark Smith	JPL	Autonomous GPS station design
69	Patrick Smith	National Science Foundation, Office of Polar Programs	Antarctic communications, instrumentation development
70	John Storey	University of NSW	AGOs, instrumentation
71	James Stowell	Leica GPS	GPS data, communications, and hardware
72	Boyd Taylor	Hydrogenics Corporation	Fuel Cell Power Generators
73	Maya Tolstoy	UCLA/Columbia University	Marine seismology/hydroacoustics
74	Loren Turner	Caltrans	Continuous GPS, remote installations
75	Don Voigt	Penn State University	Geosciences
76	Nick Wynne	VacuPanel, Inc.	Packaging and insulation
77	Efthyia Zesta	UCLA Atmospheric Sciences	Space physics
78	Jim Zumberge	Jet Propulsion Laboratory	Global GPS Network

Appendix C

Workshop Program and Abstracts

General Session:

Invited Talks:

Carol Raymond, Jet Propulsion Laboratory

Past Experiences and Lessons Learned

Many investigators have years of experience with autonomous systems in extreme environments. Careful design and engineering is crucial for a successful system, however, much can be learned from practical experience. Unanticipated feedbacks have occurred within systems, winds and temperatures have proved more extreme than anticipated, and methods for data retrieval or system deployment have changed with time. Accounts of successes and other experiences from current investigators will prove invaluable in formulating recommendations for future autonomous systems within polar regions and other extreme environments.

The most extreme example of systems that survive hostile conditions for long periods is spacecraft. Talks will address experiences investigators have had with spacecraft that could be pertinent to our problems with autonomous systems on Earth. The challenge will be to identify cost-effective solutions that aerospace engineers have identified that can be transferred to terrestrial applications.

Ocean floor observatories are under development for siting in sea floor boreholes and at active spreading centers such as the Juan de Fuca Ridge (under the NSF RIDGE program). The Juan de Fuca Ridge has been selected for focused development of a comprehensive ridge crest Observatory. Two segments within the ridge have been chosen for focused long-term sea floor instrumentation. The Ocean Seismic Network (OSN) Experiment will emplace a broadband borehole seismometer in a cased borehole paired with a sea floor seismograph at the same location. The borehole has been dubbed B3S2 (BroadBand Borehole Seismic System) and the seafloor and buried broadband system is called BBOBS (BroadBand Ocean Bottom Seismograph).

Anandakrishnan, S., D. Voigt, P. Burkett, R. Henry, B. Long
University of Alabama, Penn State University

ANUBiS; Antarctic Network of Unattended Broadband Seismometers

The goal of the Antarctic Network of Unattended Broadband Seismometers Project is to deploy a network of a dozen seismometers that will record data throughout the year. Four stations will be at existing Automated Geophysical Observatory (AGO) sites in East Antarctica and seven will be at sites in West Antarctica that are powered by wind- and solar-energy. These data will fill a huge lacuna in the global seismic dataset and provide valuable new information about the Antarctic crust and mantle structure.

Ashley, M., J. Storey, and M.Burton
University of New South Wales

Lessons learned from running astronomical instruments at the South Pole

In collaboration with the US Center for Astrophysical Research in Antarctica (CARA), we have designed and deployed a number of astronomical instruments at the South Pole since 1995. These have included tip-tilt mirrors driven by piezo transducers, miniature stirling-cycle coolers, small telescopes (0.5-cm, 30-cm and 60-cm aperture), PC/104 computers, web cameras, and sundry rotating gizmos (chopper motors, gearboxes, etc). We have written reliable software that is able to run autonomously or be controlled and updated remotely.

The Antarctic environment is in many ways more difficult to design for than space: there are large temperature extremes, atmospheric pressure changes, convection, and wind-blown ice crystals to contend with. We have had successes and failures in deploying remotely operable and autonomous instruments in Antarctica. This talk will describe our design philosophies and the lessons we have learned.

Box, J.E. and K. Steffen
CIRES/University of CO, Boulder

Automatic weather stations in Greenland

Beginning in 1995 a network of automatic weather stations was installed on the Greenland ice sheet as part of NASA's PARCA program. Each year, between 1 and 5 stations were added to the network. As of the 1999 field season, the Greenland Climate Network (GC-Net) consists of 18 stations distributed widely over Greenland's inland ice. The system samples 27 surface climate parameters on minute time-scales, averages, stores, and transmit the hourly data via GOES and ARGOS satellites to ground stations from which the data are retrieved automatically using the internet and posted on a web page (http://cires.colorado.edu/people/steffen.group/aws/main.html). The stations are powered by large battery packs stored in the snow and recharged by solar panels. So far, our success rate has been over 90% for more than 3.5 million hourly averages.

Chadwell, C.D., J. A. Hildebrand, F. N. Spiess, S. Wiggins
Scripps Institution of Oceanography

Autonomous Sea Floor Geodetic Monitoring using GPS and Acoustic Measurements from an Oceanic Buoy

This is a 3-year project to develop GPS/Acoustic technology that can be operated autonomously from a moored buoy. This technology will monitor continuously undersea crustal deformation in a coastal region where the potential for catastrophic events pose a natural hazard.

From top to bottom, the geodesy buoy is comprised of three main assemblies: electronics platform, flotation/exoskeleton frame, and ballast/transducer stinger. The complete package weighs close to 7000 pounds, is 21 feet from top of GPS radome to bottom of the transducer and has a waterline near the middle of the flotation. At the top of the buoy is the electronics platform. It consists of three GPS antennas, housings for batteries and electronics, solar panels, and a radio antenna. Placed 3-1/2 feet above the deck of the buoy on 20-inch diameter tubes are the GPS antennas, housed in radomes, are spaced 7-1/2 feet apart in an triangle/three-spoke configuration. There are three stainless steel weather-resistant, electronic housings. One is used for battery storage, one for data acquisition, recording, and radio transmission electronics, and one for the GPS receiver electronics. They are cabled together via stainless steel conduit.

We will report on the initial test of this system conducted June 1999.

Cobbett, N.
British Antarctic Survey

I will aim to present a poster on the UK Antarctic AGO program and a new engineering project - Remote Low Power Magnetometers. These experiments operate remotely on the Antarctic plateau between Halley Research Station and the South Pole. We are currently operating 5 AGO sites and 2 LPM sites in Antarctica.

Conquest, C. and B. Johns
UNAVCO

UNAVCO Remote Continuous GPS Station Support - Power, Communication, and Data Management

The UNAVCO facility has supported the installation of over 150 continuously operating GPS stations worldwide and currently monitors the operation of 194 stations. These include stations from the NASA Global GPS Network and various NASA and NSF funded regional networks. From supporting these efforts, UNAVCO offers experience in remote, autonomous GPS site design and support to the GPS science community. Areas of design and field experience include year-round solar powered autonomous GPS sites and data relay stations; data telemetry via radio modem, microwave links, cellular and land line telephone modems to internet sites; low power, low cost L1 autonomous TDMA systems for remote, high density applications; automated GPS download software; and power management strategies. Recent efforts of support include facilitating collocation and integration of various sensors including GPS receivers, seismometers, and MetPaks, in cooperation with JPL, IRIS, NOAA, and individual investigators working in Antarctica and other remote locations. UNAVCO and JPL are collaborating on a VSAT demonstration project to test a low power (~20W), environmentally robust remote satellite data retrieval system.

Donnellan, A., B. Luyendyk, T. Rebold, M. Smith, H. Awaya, B. Nesbit, and G. Dace
Jet Propulsion Laboratory, Antarctic Support Associates, Acumen Instruments Corporation

Autonomous GPS Stations in Marie Byrd Land, Antarctica

During the 1998-1999 Antarctic field season, we installed three autonomous GPS stations in Marie Byrd Land, West Antarctica to measure glacio-isostatic rebound and rates of spreading across the West Antarctic Rift System. The systems collect data throughout the entire year and therefore must function during the warm, relatively mild summer, and cold, harsh winters. They are powered by gel cell batteries that are charged by wind and solar power. The system includes dual data logging capability. We log data at 5-minute intervals within the receiver and at 30-second intervals to a serial data logger. We do not require 365 days of continuous data for well determined crustal velocities, but rather long periods (24 hours) of continuous data distributed throughout the year. Therefore, for simplicity, we designed the system to accept occasional data interruptions. The batteries, in addition to supplying power, act as a thermal capacitive heat storage device to help regulate the temperatures within the system. This storage system absorbs the majority of the 10-15 watts of power from the receiver and 5 watts from the data logger, which helps to maintain temperature for long periods of time. Power is switched off when the temperature within the system enclosure reaches 50 degrees C and is reconnected at 20 degrees C. If battery voltage drops too low the batteries will freeze. Therefore, we cut the power off when the batteries drop to a low voltage of 12.45V. Power is restored at 13.2V. The temperature and power hysteresis allows for a minimum of several days of data to be collected before system shutdowns. A check of all three stations in late January 1999 indicated that the thermal and power control systems are performing as expected. We plan to implement satellite telemetry to the systems during the 2000-2001 season following a year of development.

Flynn, M. and J. Hines
Ames Research Center

The study of life in extreme environments provides and important context from which we can undertake the search for extraterrestrial life. The NASA Astrobiology program is currently working to develop the capability to conduct *in situ* long-duration physical, chemical, and biological investigations of extreme environments. Although these systems are being developed to support generic extreme environment research, the initial target for implementation is deep ocean hydrothermal fields.

Currently, the two most likely targets for the search for extraterrestrial life are Mars and Europa. In both cases, the existence of hydrothermal energy sources is widely considered a prerequisite for life. Developing innovative strategies to explore analogous terrestrial ecologies and the life forms they support will provide insights into how and where to explore these planets/moons.

The objective of this program is to develop an integrated instrumentation platform capable of supporting a wide variety of life in extreme environments research. This activity will focus on both the development of specific instrumentation and the infrastructure required to effectively utilize these instruments. The following tasks are being addressed:

Environmental characterization
Sample Targeting
Sample acquisition

Sample analysis
Data acquisition, storage, and transmission
Power generation
Power distribution and storage
Mobility

Hamilton, G. and I. Whillans
Byrd Polar Research Center, The Ohio State University

We are using remote, autonomous systems to understand important glaciological processes related to the mass balance of the Greenland and Antarctic ice sheets. The work builds on our experience of measuring mass balance using very precise GPS surveys (the coffee-can technique).

The system - RASCAL - has been developed for two purposes. The first purpose is to provide control for measurements obtained by satellite radar altimeters, such as NASA's forthcoming ICESat. Satellite laser altimetry offers one of the best opportunities for measuring the large-scale mass balance of ice sheets. Very precise measurements of ice sheet elevation can be obtained routinely over very large areas. Interpreting elevation changes in terms of mass balance is more problematic, however. Transient variations in processes occurring at and near the snow surface, mainly snow accumulation and firn compaction, complicate interpretation of altimetry data.

RASCAL is designed to make continuous measurements of these processes at sites where we are also measuring long-term mass balance using the coffee-can technique. The study will allow us to link short-term variations in snow surface elevations, as measured by laser altimetry, to the long-term rate of ice thickness change. The second purpose of RASCAL is to study processes responsible for spatial variations in snow accumulation rate. Several studies have described large variations in accumulation rate for sites located a few kilometers apart but on different slope gradients. Differences in katabatic wind speed are hypothesized as being important.

We plan to deploy RASCALs at two sites near Byrd Station in West Antarctica, where large differences in slope and accumulation rate are already known. The systems will make continuous measurements of snow surface elevation (accumulation), firn compaction and wind speed. Results from this study will be important for the interpretation of ice core records. RASCAL is designed using off-the-shelf components. The system is based on, and resembles, an AWS. Mounted above the surface on a tower are ultrasonic ranging sensors, air temperature probes and wind speed/direction sensors. A subsurface box attached the tower contains several linear transducers for studying firn compaction by making continuous measurements of the lengths of wires installed at various depths. Thermocouple wires for measuring firn temperature at several depths are installed in an adjacent hole. Initial field tests of RASCAL were conducted at Siple Dome, Antarctica. One system is currently deployed at Summit, Greenland and several new systems will be deployed during the ITASE (International Transantarctic Science Expedition) traverses, beginning this austral summer.

Rall, J.A.R. and J. B. Abshire
NASA Goddard Space Flight Center, Laser Remote Sensing Branch

We have developed a compact, autonomous, ground-based atmospheric lidar instrument to sense Polar Stratospheric Clouds (PSCs) from an Automated Geophysical Observatory (AGO) situated on the Antarctic polar ice sheet. The AGO program is sponsored be the National Science Foundation and the United States Antarctic Program. Each of the six AGO platforms currently installed in Antarctica provides electric power, data storage and a stable thermal environment for up to seven instruments. One lidar instrument has been installed in AGO Platform P1 at 83 degrees south latitude, 129 degrees east longitude, and at a surface elevation of approximately 9,500 ft. The design constraint for our lidar instrument included high altitude/low pressure (600-700 mBar), extreme temperatures (-80C to +30C), extreme humidity, and severe vibration environments due to aircraft and general handling.

Sanders, L., C. Odom, J. Kelley, D. Dasher, S. Read, F. Levno-Chuthlook, A. Orr, W. Splain, and T. Vargo
Los Alamos National Laboratory, Institute of Marine Science, University of Alaska, Fairbanks, Alaska Department of Environmental Conservation, NEWNET Program, University of Alaska, Fairbanks, Battelle Pacific Northwest National Laboratory

Status of Autonomous Transboundary Radiation Monitoring in Alaska

Storey, J.W.V., M.C.B. Ashley and M.G. Burton
University of NSW

The Automated Astrophysical Site Testing Observatory (AASTO) contains a suite of autonomous instruments designed to fully characterise the astronomical potential of remote antarctic sites. These instruments include infrared sky monitors, an acoustic radar and an optical/UV spectrometer. The instruments typically draw less than 7 watts each. Stirling-cycle cooled detectors and highly efficient electronics systems allow unattended operation throughout the long antarctic winter. This talk will describe the instrument design and performance, and present some preliminary results.

Power and Thermal Systems:

Invited talks:

Bill Nesbit, Antarctic Support Associates

The range of options for powering polar autonomous systems includes both passive sources like solar and wind, and active sources like fuel cells, propane and diesel generators. Environment will be the biggest factor in limiting the design of passive systems. Solar power is not a viable option during the dark polar winters, nor is wind an option in still regions such as the Antarctic polar plateau. Diversified power sources (e.g. wind and propane, or wind and solar) are one way to overcome temporal variations in the source strength of passive systems. Restrictions in weight and size might further limit choices for particular applications. In all cases temperature extremes will determine the key design parameters. Battery freezing points depend on the electrolyte mixture and charge level, thus, both must be carefully controlled. Batteries may also outgas acid vapors if overcharged, which can adversely affect other components within the system. To prevent outgassing, the charging system must be regulated with temperature compensation. Finally, a properly designed system needs a mechanism for safely venting exhaust gasses from active systems and batteries without compromising the thermal insulating barrier.

Ray Dibble, Victoria University

On Ross Island, Antarctica, the Mount Erebus Volcano Observatory (MEVO) group, led by Prof P.R. Kyle of New Mexico Tech, operates a seismic telemetry net on the 3800m volcano, powered by solar panels and auxiliary wind generators. The seismic signals are automatically digitized at McMurdo and FTP'd to NMT and VUW each night. Year round operation is achieved with Gel/cell batteries on the Mountain, which have low self-discharge rates, and excellent tolerance to complete discharge at temperatures as low as -50 deg C. Part time attention by the Science Technician at McMurdo, and yearly servicing of the equipment on the Mountain enables nearly 70% data recovery. All the equipment components are available off the shelf at low prices, and have withstood the environmental conditions and volcanic gases remarkably well. Some of the batteries have been in service for 15 years, and storm damage is rare. Equipment specifications will be provided, including the conversion of DC powered computer fans to auxiliary wind generators.

Similar techniques have been used to operate a television station at the Crater Rim to monitor the activity in the liquid Lava Lake from 1986 to 1990, and to record the infrasonic signals at the Windless Bight Array, powered by a Radioactive Thermoelectric Generator on loan from NSF.

Henry Awaya, Jet Propulsion Laboratory
Yi-Chien Wu, Jet Propulsion Laboratory

The thermal control of an instrument in the Antarctic poses multiple challenges for the instrument designer/implementer. The Antarctic environment is very harsh by Earth's standards and encompasses temperatures ranging from a balmy 0 degrees centigrade all the way down to -60 or -70 degrees centigrade and with wind conditions ranging from still air to velocities of raging windstorms. The sun is either very low to the horizon or below the horizon. One interesting aspect of Antarctic weather (especially at high elevations) is that the temperature ranges resemble those in the fair latitudes of Mars.

The first instinct is to heavily insulate the instrument to protect it from the potential cold, however, heat from power utilizing instruments and support equipment must be removed to avoid an over heat situation. Thus, the problem of thermally controlling an Antarctic instrument becomes one of balancing the changing environment against the variation incurred within the instrument box.

To construct a thermal model, the environment must be characterized first, and the configuration of the instrument/assembly must be thoroughly understood. The power levels generated within the instrument must be known as a function of time. This model can first be used as a predictor of thermal performance. Pre-application tests can help "tweak" the model. Finally, the model is validated/refined and can be correlated with reality when actual instrument data becomes available.

Cargnelli, J., X. Chen, D. Frank, R. Gopal and P. Rivard
Hydrogenics Corporation

PEM fuel cells

Hydrogenics Corporation has concentrated its efforts on the development of air-breathing PEM fuel cell systems which can be operated under extreme conditions ranging from ñ40 to +40 oC, from 0 to 95% relative humidity and from sea level to 2500 meter elevation. The hybrid system incorporates a PEM fuel cell stack and a thermoelectric generator and offers a unique power source that rivals primary and secondary batteries with respect to cost, performance and reliability. The system is ideal for remote applications in the Antarctic and the Arctic regions or specific missions for military. Hydrogenicsí air-breathing 30W PEM fuel cell system is currently being tested in an environmental chamber for deployment in Antarctic next winter. This paper discusses the primary test results and system characteristics.

Data Systems:

Invited Talks:

Gregory Dace, Acumen Instruments Corporation

Autonomous science missions employ data systems to perform many critical tasks. These tasks include data collection, processing, and storage; system monitoring and control; and data retrieval operations. Extreme environments impose unique requirements on data system design that dictate which functions the system must perform and how each function is implemented.

Data requirements vary greatly among experiments being conducted in extreme or polar environments, so data systems should be designed with the expected volume of data in mind. Some systems, such as those for meteorological experiments, collect only a few hundred bytes of data per day (making cost per megabyte only a minor issue), while others (e.g. seismic) collect megabytes per day, requiring the use of low-cost high-capacity storage media.

Deployment in Antarctica can expose systems to extremes in temperature, pressure, and vibration that can adversely affect components. For instance, disk drives are not specified to operate below 0 degrees C, nor do they survive the high altitudes of the polar plateau. Flash memory proves robust in these conditions, but is prohibitively expensive for high capacity systems. Electrostatic discharge (ESD) is another common source of problems in the extremely dry Antarctic conditions. All electrical systems must be built to withstand this harsh environment.

Extreme environments limit data retrieval opportunities. Remote data retrieval is an attractive option, but communications systems are expensive and limited in data bandwidth, making them suitable only for transferring small amounts of data at present. Data compression and/or on-site data reduction can make remote data retrieval practical. Data volume may necessitate archiving data on site for periodic retrieval by field personnel. Systems that archive data for on-site retrieval must provide simple and expedient download mechanisms such as removable media, equipment swapping or high-speed data transfers (e.g. SCSI, Ethernet, FireWire, USB).

Limited development resources (e.g. time and funds) often force compromises in these specifications. As system complexity increases, more failure points are introduced and more resources must be devoted to development and testing. Testing is the most important ingredient for successfully completing a scientific mission in extreme environments, so systems need to be simple enough to provide adequate time for thorough testing and personnel training.

Anandakrishnan, S., D.E. Voigt, P. Burkett, and B. Long
University of Alabama, Penn State University

Results of the Anubis deployment

The Anubis (Antarctic Network of Unattended Broadband Seismometers) network was deployed in 98-99. We report on the results of our design and deployment experiences. We used wind and solar energy sources to heat our systems and to power them. We used a '386 CPU single-board computer running the Linux operating system and custom software as the data logging "engine" of our system. Due to the large volume of data, we used a mechanical hard disk to store the data. We report on the status of the system and the lessons learnt during the design phase and the installation phase.

Communications:

Invited Talks:

Ngoc Hoang, NAL Research Corporation

There is a requirement for a satellite communications system that could supplement, complement or even replace some of the current communications techniques used in polar regions. These include the high data rate NASA Tracking and Data Relay Satellite System (TDRSS), the INMARSAT maritime satellite network, the Argos data relay satellite system, high frequency (HF) radios and some of the old government satellites operating beyond their original design lives. There are shortcomings associated with each of these systems. However, they are the only available options that provide vital voice and data links within the polar regions. For example, HF radios are the best means for on-demand contact between McMurdo and South Pole operations and for communicating with aircraft supporting the station. With these systems, however, blackouts can occur for days due to disturbances in the ionosphere caused by solar activity or due to strong interference from the Earth's magnetic field. Another example is the use of the Argos system for the collections of meteorological data from drifting buoys in the Arctic Ocean or from the Automatic Weather Stations (AWS) and Automated Geophysical Observatories (AGO) in Antarctica. Argos has demonstrated its great potential for the collection of atmospheric data, but it also has many disadvantages including one-way communications, non-continuous temporal coverage, low data transmission rate, long message latency and high cost due to low volume markets. Another example is that a geosynchronous (GEO) satellite will experience orbital inclination over time due to gravitational fields of the sun and the moon if station-keeping corrections are not made. Thus, a GEO satellite at the end of its operating life will tend to drift north-south at an inclination rate of about 0.8 degrees per year allowing direct line-of-sight view of both north and south poles a few hours a day. The National Science Foundation has been taking advantage of these "old" GEO satellites such as ATS-3, LES-9 and GOES-2 to provide a temporarily solution for voice and data communications in the polar regions.

A variety of commercial low-Earth orbit (LEO) satellite communications systems produced by the private sector are now in, or will soon achieve, operational status that may provide solutions for the South Pole Station and other Antarctic and Arctic locations. They will offer considerable research opportunity for autonomous science platforms applications in remote regions including two-way communications, real-time data transmissions, global coverage and reduced costs. They are much closer to Earth; therefore, low-power lightweight transmitters and receivers and omni-antennas can be used. NAL Research Corporation is currently developing a satellite data relay system for remote science platforms utilizing commercial LEO satellite transceivers. The system will allow two-way real-time data collection. In addition, science platforms can be monitored, adjusted and re-calibrated by scientists at their home laboratories or institutions.

Reeder, S., B. Johns, C. Meertens, D. Mencin, B. Perin
UNAVCO

TDMA spread-spectrum communications and low-power VSAT systems for GPS remote networks

A new system of low cost, low power GPS receivers has been developed for deployment in dense arrays to monitor volcano deformation, small-scale crustal deformation, structures, and atmospheric water vapor. The system consists of an L1 GPS receiver, radio modem, solar power, data collection and processing components. System development was funded by NASA and NSF. Networks of two to twelve receivers systems have been deployed along the Hayward Fault, California, on Taal Volcano, Philippine Islands, Popocatepetl Volcano, Mexico, Mauna Loa, Hawaii, in Long Valley, California, and will soon be deployed for tide gauge calibration and for a Department of Energy atmospheric water vapor tomography experiment in Oklahoma. A test deployment on Mt. Erebus, Antarctica is also scheduled for the 1999/2000 field season to evaluate performance of this system in extreme cold environments. The current configuration uses an L1 GPS receiver to continuously transmit carrier phase and pseudorange observations at 10 second to 10 Hz rates through a Time Delay Multiple Access (TDMA) radio data modem/repeater network. The system supports multiple redundant data paths with remote stations also serving as repeaters. Initial tests of the system show mm-level baseline repeatability with 24-hour data. An expanded test of the network capability will occur in the fall when a small L1-network will be co-located with a dual frequency GPS receiver streaming data to the UNAVCO Facility using a new, low-power Very Small Aperture Telemetry (VSAT) satellite system for data telemetry. The VSAT remote uses only 20W of power, which is critical for deployment in remote areas lacking reliable infrastructure. The VSAT system test is a joint JPL and UNAVCO demonstration that will begin in early September with a hub located at the UNAVCO Facility and a remote location at Marshall Field, Colorado.

Packaging and Environment:

Invited Talks:

Brennan, M., Northern Power Systems, Inc.

In finalizing an autonomous system the various sub-systems (communications, data acquisition, power) must be put into a physical framework that meets form and fit requirements. These include size, bulk, weight, operator controls, making the pieces work together, managing the thermal environment for the pieces, etc. Heating, cooling, electromagnetic interference, venting, or other problems may arise when a group of electronics is packed into a tight space. Environmental issues such as shock, vibration, splash, spray, or wind must be taken into account when designing the completely integrated unit. The housing of the system must be able to withstand transport, and temperature extremes and high winds within its local environment.

Anderson, P.S.
British Antarctic Survey

Electrostatic Charge Effects during Polar Blizzards: Effects, Mechanism and Solutions

Running sophisticated equipment in polar regions poses many problems to the engineer and instrument scientist. Some effects such as cold, darkness and snow ingress are well documented and have been a personal hazard since the beginning of polar exploration. With the advancement of modern electronic monitoring systems, both manned and automatic, the electrostatic effects of low temperature blowing snow now give an additional extreme environment.

Electrostatic buildup during blizzards can destroy unshielded electronics, especially modern ultra-low power CMOS based loggers, but there is an additional effect of injected radio frequency interference onto signal lines. This is due to continual "micro-sparking" from plastic coated cables onto the inner shield, which injects wide band current pulses around the Faraday cage. The mechanism for electrostatic charge transfer is not well understood, but measurements of charge magnitude made the British Antarctic Survey's Halley station (76S 26W) imply that the aquired charge is always negative, and the magnitude is highly dependant on the relative humidity of the blizzard, RHice, and not just on the wind speed (that is, snow transfer) alone as might be expected. A mechanism involving RHice dependant quasi-liquid layers of water on the impacting ice crystals may explain this phenomenon.

The dependence of electrostatic charge magnitude on RHice implies that katabatic driven blowing snow, where adiabatic warming maintains the blizzard below saturation, is more prone to static than blizzards driven by coastal synoptic storms. Although shielding is essentially the answer to electrostatic problems, radio communications antennae cannot be protected, and careful attention is needed in the design of such transmitters.

Bahlavouni, A., P. J. Stein, and D. W. Andersen
Scientific Solutions Inc.

Intelligent Sensor Protection System for Polar And Marine Environments

An intelligent sensor protection system has been developed under the U. S. Navy's Small Business Innovation Research Program. Its purpose is to provide a "smart" system to protect sensors during remote unmanned measurements in hostile environments. The first application is to perform solar radiation measurements under Arctic conditions. The sensor protection system consists of an enclosure that houses and protects the sensor. Just before the measurement, the sensor is deployed while clearing of snow and ice build up. After the measurement, the data is stored, and the sensor is brought back within the enclosure for protection. A routine to determine sensor contamination is then executed and the sensor cleaned if necessary. An on-board computer controls all electro-mechanical and logical functions. Eight units were deployed during the yearlong SHEBA experiment and for the first time provided year long radiation measurement from unmanned site in the Arctic. A working model of the instrument will be presented during the talk. Also data from the SHEBA experiment will be presented.

Brennan, M., Northern Power Systems, Inc.

Packaging is where the "system" part of system integration comes into any project. My talk will focus on designing (packaging) environmental enclosures for extreme environments - such as Antarctica and space. While most system designs are fairly consistent in specification, I've found over the years that each system has it's own set of unique attributes (factors) that if overlooked can result in poor performance and even failure. I plan to visit (show slides) several remote autonomous sites and discuss these factors and how they influenced the integration and packaging of each system.

Appendix D

Useful Internet Web Sites

Power:

www.windsun.com
www.nrel.gov
http://216.51.18.233
www.sunwize.com
www.eren.doe.gov/pv
www.ballard.com
www.warsitz-enterprises.com
www.effectivesolar.com
www.tatabpsolar.com
www.solardyne.com

Data Management:

www.dspguide.com
www.storage.ibm.com
www.kingston.com/flash
http://developer.intel.com

Communications:

www.leoone.com
www.iridium.com
www.teledesic.com
www.globalstar.com
www.inmarsat.org
www.orbcomm.com
www.maple-dsp.com
www.link-quest.com
www.radiodata.com
www.aria-glb.com
www.radio-tech.co.uk
www.benthos.com
www.dsbindustries.com

Packaging:

www.vacupanel.com
www.spaceelectronics.com
www.saveinc.com

Other sites:

www.nsf.gov/od/opp
http://geodynamics.jpl.nasa.gov/antarctica
www.asa.org
www.sio.ucsd.edu
www.nosams.whoi.edu

Appendix E

Transportation Equipment

Shipping Containers:

Commercial cargo shipping containers are designed to be compatible with rail, truck and ship transport. They have integral lifting points for cranes and forklifts as well as anchor points to secure them to a cargo deck or to another container. Shipping containers remain sealed throughout their handling and may be tracked by radio transponder. In addition to closed, dry containers, special cargos may be accommodated by flatracks, reefer, liquid, or open-topped containers. A large variety of standard sizes exist, some of which are outlined below.

	Door Opening (mm)		**Internal Dimensions (mm)**			**Weight (kg)**			**Volume (m^3)**	
Container Size	**Width**	**Height**	**Length**	**Width**	**Height**	**Max Gross**	**Tare**	**Max Payload**	**Capacity**	**Material**
20 Std 20'x8'x8.5''	2340	2274	5896	2350	2385	27,000	2150	24,850	33	Steel
40 Std 40'x8'x8.5'	2339	2274	12035	2350	2393	32,500	3700	28,800	67	Steel
40 wide door 40'x8'x8.5'	2343	2278	12056	2347	2379	32,500	2790	29,710	67	Aluminum
40 high 40'x8'x9.5'	2343	2584	12056	2347	2684	32,500	2900	29,600	76	Aluminum
40 high 40'x8'x9.5'	2340	2577	12035	2350	2697	34,000	3800	30,200	76	Steel
40 high 45'x8'x9.5'	2340	2584	13582	2347	2696	32,500	3900	28,600	86	Aluminum
40 high 45'x8'x9.5'	2340	2585	13,556	2352	2697	32,500	4800	27,820	86	Steel

Large Fixed Wing Aircraft:

The transport of cargo on United States Air Force cargo aircraft requires the use of the standard USAF pallet. The 463L pallet is constructed of a corrosion-resistant aluminum surface with a balsa wood core. A lip forming the pallet perimeter provides 22 tie-down rings for securing the cargo nets over the cargo. The tie-down rings are capable of 240 degrees of free movement in a vertical plane that intersects the pallet edge at a right angel. The tie-down ring capacity is 7,500 pounds in any direction. Pallet dimensions are 108 inches by 88 inches, weight is 290 pounds, and it has a maximum load capacity of 10,000 pounds. The pallet permits maximum loads, including wheel loads, of 250 psi up to the maximum capacity. Loads that exceed the psi limit must be shored to reduce psi to the maximum allowable. Pallets may be combined into "pallet trains" to accommodate oversize loads. Maximum height of load and pallet train configuration will vary according to the aircraft utilized and the method employed to load and unload the cargo. Current cargo aircraft in USAF inventory (in order of increasing size and lift capacity) include the C-130 Hercules, C-141 Starlifter, C-17 Globemaster and C-5 Galaxy.

Small Fixed Wing Aircraft

Although a wide variety of small fixed wing aircraft may be employed to transport cargo or small packages, the most popular and successful aircraft specifically designed for cargo transport include the Cessna Caravan and DeHavilland Twin Otter. These aircraft possess large doors for loading cargo and good performance in the field. As a result, they may be found transporting personnel and equipment to field locations that range from Antarctica to Northern Canada. Basic data is provided below, however the addition of auxiliary fuel tanks, cabin fuel tanks or other equipment may significantly alter the values given. Aircraft and helicopter data are intended only to familiarize the researcher with assets that may be available and their limitations; it is not intended to be used for flight/mission planning purposes. The numbers provided do not take into consideration safety reserves or the impact weather, all of which will further constrain aircraft performance.

	DHC-6 series 300 Twin Otter	C-208 Cessna Caravan	C-208B Grand Caravan
Passenger	2+17	10	10
Ceiling (ft/m)	25,000 / 7622	25,000 / 7622	23,700 / 7226
Rate of Climb (ft/min / m/min)	1600 / 488	1225 / 373	975 / 297
Normal Cruise Speed (kts / km/hr)	130 / 240	188 / 348	184 / 341
Empty Weight (lbs / kg)	8,100 / 3681	3993 / 1815	4237 / 1926
Useful Load (lbs / kg)	4400 / 2000	4042 / 1833	4548 / 2063
Fuel Load (lbs / kg)	2500 / 1136	2249 / 1022	2249 / 1022
Cabin Doors (in)	50 x 56	49 x 50	49 x 50
Baggage Door (in)	35.7 x 25.7	N/A	N/A
Cabin Dimensions	18'5"(l) x 59"(h) x 52.5"(floor) 63.2(ceiling)	12.7'(l) x 4.3 (h)x 5.2'(w)	16.7'(l) x 4.3'(h) x 5.2'(w)
Useable Volume (ft^3 / m^3)	384 / 10.8 rear baggage 88/2.5	254 / 7.2	340 / 9.6
Range (nm / km) (standard tanks)	780 / 1444	930 / 1722	1026 / 1900
Wing Span (ft / m)	65 / 19.8	52.1 / 15.9	52.1 / 15.9
Total Length (ft / m)	52 / 15.8	37.6 / 11.5	41.6 / 12.7

Helicopters:

	Bell 212	Bell 412EP	Bell 206B	Astar 350B
Seating	1+14	1+14	1+4	1+5
Max Gross Weight (lbs / kg)	11200 / 5080	11900 / 5398	1451 / 660	4630 / 2105
Useful Load (lbs / kg)	4998 / 2267	5044 / 2880	1498 / 679	1762 / 800
Useable Fuel (gal / l)	216.8 / 820.6	330.5 / 1251	91 / 344	142.8 / 541
Range (nm / km) (standard tanks)	229 / 424	356 / 659	374 / 694	457 / 846
Max Endurance (standard tanks)	2.5 hrs	3.7 hrs	4.5 hrs	
Cabin Floor Area (ft^2 / m^2)	53.9 / 5.0	53.9 / 5.0	12.9 / 1.2	
Baggage Compartment Volume (ft^3 / m^3)	28 / 0.8	28 / 0.8	16 / 0.45	

Manned Submersibles:

To a much greater extent than aircraft or research vessels, manned submersibles are a singular commodity, whose capabilities can vary significantly from vehicle to vehicle. Those with operating depths of 1000 feet or less are more common, but still expensive and difficult to schedule. Less than a dozen submersibles exist worldwide with operating depths in excess of 5000 feet. Obtaining their use typically entails long wait-lists, high cost and may be subject to a review and approval by government agencies or educational institutions.

	Alvin	**Deep Rover**	**Perry**
Length (ft / m)	23.3 / 7.1	13 / 4.0	22 / 6.7
Height (ft / m)	11.8 / 3.6		8 / 2.4
Beam (ft / m)	8.5 / 2.6		8 / 2.4
Gross Weight (lbs / kg)	37,400 / 17,000	11,000 / 5000	8-12 tons
Operating Depth (ft / m)	13,124 / 4000	3300 / 1006	1000 / 304.9
Payload (lbs / kg)	1800 / 818	615 / 280	750 / 340
Speed (kts)	2	2.5	3
Range (nm / km)	6 / 11		8 / 14.8
Dive Duration (hrs)	6-10	6-10	8-10
Life Support Endurance	216 man-hours	240 man-hours	504 man-hours
Crew	3	2	3-5
Manipulators	(2) 75” reach 250 lbs lift	(2) 48” reach	Various

Remotely Operated Submersibles:

New remotely operated vehicles (ROV’s) with differing capabilities are constantly being introduced. It is an area of rapid technological development that has made access to the deep ocean efficient and affordable. These systems are usually truck, air and rail transportable and designed to be temporarily installed on a host surface ship. They consist of the ROV, the winch and deck handling system and some sort of control van. Many companies exist that have ROV systems available for purchase, lease or charter and several research and educational institutions have their own systems that may be available for use by a researcher. As an example of what these systems are capable of and their characteristics, some data is provided on two ROV's below.

	Max Rover	**Scorpio**
Length (ft / m)	7.3 / 2.23	8 / 2.4
Height (ft / m)	3.2 / 0.97	4 / 1.2
Beam (ft / m)	4.0 / 1.22	4 / 1.2
Gross Weight (lbs / kg)	1750 / 795	4500 / 2045
Operating Depth (ft / m)	3300 / 1006	5000 / 1524
Payload (lbs / kg)	200 / 91	250 / 114 each manipulator
Speed (kts)	3 (fwd) 1 (lateral)	4 (fwd) 2 (lateral)
Deck Space Required	300 sqft	400 sqft