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Preliminary Systems Engineering Evaluations for the National Ecological Observatory Network

Thor D. Osborn, Bernard Zak, Richard Kottenstette, Robert Brocato, Jeffrey Zirzow, Perry Robertson, Karl Gass, Mark Ivey, Edwin Heller, Shannon Crouch, J. Larry Dishman and W. Kent Schubert

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Preliminary Systems Engineering Evaluations for the National Ecological Observatory Network

Produced on behalf of the National Ecological Observatory Network, Inc., under contract to the American Institute of Biological Sciences, Sandia agreement number FI017080104

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ABSTRACT

The National Ecological Observatory Network (NEON) is an ambitious National Science Foundation sponsored project intended to accumulate and disseminate ecologically informative sensor data from sites among 20 distinct biomes found within the United States and Puerto Rico over a period of at least 30 years. These data are expected to provide valuable insights into the ecological impacts of climate change, land-use change, and invasive species in these various biomes, and thereby provide a scientific foundation for the decisions of future national, regional, and local policy makers. NEON's objectives are of substantial national and international importance, yet they must be achieved with limited resources. Sandia National Laboratories was therefore contracted to examine four areas of significant systems engineering concern; specifically, alternatives to commercial electrical utility power for remote operations, approaches to data acquisition and local data handling, protocols for secure long-distance data transmission, and processes and procedures for the introduction of new instruments and continuous improvement of the sensor network. The results of these preliminary systems engineering evaluations are presented, with a series of recommendations intended to optimize the efficiency and probability of long-term success for the NEON enterprise.

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CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

The National Ecological Observatory Network (NEON) is an ambitious National Science Foundation sponsored project intended to accumulate and disseminate ecologically informative sensor data from sites among 20 distinct biomes found within the United States and Puerto Rico over a period of at least 30 years. These data are expected to provide valuable insights into the ecological impacts of climate change, land-use change, and invasive species in those various biomes, and thereby provide a scientific foundation for the decisions of future national, regional, and local policy makers. NEON's objectives are of substantial national and international importance, yet they must be achieved with limited resources. Sandia National Laboratories was therefore contracted to examine four areas of significant systems engineering concern; specifically, alternatives to commercial electrical utility power for remote operations, approaches to data acquisition and local data handling, protocols for secure long-distance data transmission, and processes and procedures for the introduction of new instruments and continuous improvement of the sensor network.

Sandia has determined that several promising commercially available technologies are suitable for providing alternatives to utility line electrical power at NEON sites. The benefits and liabilities of these technologies are presented along with modeled results for the more promising photovoltaic and photovoltaic-hybrid approaches. These analyses are focused on the relatively remote NEON aquatic arrays as they have modest requirements but are stationed at a distance from main focus of site activities.

Data acquisition and communications for each NEON site may be handled in a cost-effective and secure manner using commercially available technologies and tested methods including Zigbee, Wi-Fi, and WiMAX wireless communications, public communications networks, secure hash algorithms, and data encryption. Alternative technologies and methods are discussed for those exceptional cases where standard approaches would be prohibitive. Recommendations include incorporation of self-organizing wireless networks for efficient and adaptive data acquisition, and provision for the use of cellular technology where possible as a data communications pathway as well as for operational efficiency and personnel safety.

NEON must employ highly efficient operational approaches if it is to achieve its goals and objectives. In order to do so, we must firmly recommend that NEON leverage the experiences of the Department of Energy's Atmospheric Radiation Measurement (ARM) program sites and network. While striving to surpass existing multi-site data collection networks, NEON would do well to learn from the successes and failures of similar past undertakings. Among these, ARM is perhaps the most comparable in scope and best organized, and ARM management is supportive of NEON's goals.

The results of Sandia's preliminary systems engineering evaluations are presented in greater detail herein. An effort has been made to provide supportive background and contextual guidance to enable NEON personnel to make informed decisions regarding future pathways for the development of NEON site installations and operational processes. The most pointed recommendation that Sandia can make at this stage of NEON's development is that an extremely *thorough and cohesive* systems engineering analysis be conducted forthwith, fully exploring both infrastructure implementation and operational principles of the network in tandem. Note that this recommendation should not be construed as supporting a rapid-response "Tiger Team" activity, but rather, an ongoing and foundational core effort. This analysis should be commensurate with the complexity of the NEON network, missions, and diversity of its stakeholders. Sandia also strongly recommends that a prototype fundamental instrumentation unit be built and instrumented at a convenient location as soon as possible, and that it be linked to a prototype central database. There is no substitute for testing real hardware, networks, and communication protocols to refine the recommendations of even the most complete analysis.

Recommendations based on the preliminary analyses presented in the following sections are intended to optimize the efficiency and probability of long-term success for the NEON enterprise, yet with the caveat that myriad implicit and explicit assumptions have been made due to the lack of an encompassing framework, and therefore these assumptions and any conclusions drawn from them should be revisited in time as that framework is developed.

Acronyms and Abbreviations

ACRF	Atmospheric Radiation Measurement Program Climate Research Facility
ADC	analog to digital converter
ADSL	analog digital subscriber line
AES	Advanced Encryption Standard
AGM	absorbed glass mat
AH	Ampere-Hour
AMF	Atmospheric Radiation Measurement Program Mobile Facility
ARM	Atmospheric Radiation Measurement (DOE program)
BCR	Baseline Change Request
BOS	balance of system
DMCII	domain modular cyber infrastructure interface
DOD	depth of discharge
DOE	Department of Energy
DRAM	dynamic random access memory
DSL	digital subscriber line
DSLAM	digital subscriber line access multiplexer
ECO	Engineering Change Order
ECR	Engineering Change Request
EIA	Electronic Industries Alliance
EPA	(U.S.) Environmental Protection Agency
FIU	fundamental instrument unit
FSU	fundamental sentinel unit
FCC	Federal Communications Commission
GEO	geosynchronous earth orbit

GMD	(NOAA) Global Monitoring Division
HIPERMAN	High-Performance Radio Metropolitan Area Network
HP	horsepower
HSA	hybrid stand-alone
IEEE	Institute of Electrical and Electronics Engineers
IMB	Infrastructure Management Board
IP	Internet Protocol
LAN	local area network
LEO	low earth orbit
LOS	line of sight
LR-WPAN	low rate wireless personal area network
LTER	Long Term Environmental Research (program)
LVD	low-voltage disconnect
MB-OFDB	Multi-band Orthogonal Frequency Division Multiplexing
MPPT	maximum power point tracker
MRS	mobile relocatable system
NASA	National Aeronautics and Space Administration
NEON	National Ecological Observatory Network
NEPA	National Environmental Policy Act
NOAA	National Oceanic and Atmospheric Administration
NSA	North Slope of Alaska
NSA/AAO	North Slope of Alaska / Adjacent Arctic Ocean
PAN	Personal Area Network
PSTN	public switched telephone network
PV	photovoltaic
QA	quality assurance

QC	quality control
RAM	random access memory
SA	stand-alone
SHA	Secure Hash Algorithm
SISC	Science and Infrastructure Steering Committee
SOC	state of charge
SRAM	static random access memory
SSD	solid state drive
SSH	Secure Shell / Secure Sockets Host
TCP	Transmission Control Protocol
TEG	thermoelectric generator
TWP	Tropical Western Pacific (ARM Climate Research Facility)
UCAR	University Corporation for Atmospheric Research
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunications System
UPS	uninterruptible power supply
UTM	Universal Transverse Mercator
USB	universal serial bus
VAH	Volt-Ampere-Hour
VAP	(ARM) Value Added Product
VPN	Virtual Private Network
WMANS	Wireless Metropolitan Area Networks
WPANS	Wireless Personal Area Networks
WSN	Wireless Sensor Network
Gbyte	gigabyte

kbps	kilobits per second
Mbps	megabits per second
Gbps	gigabits per second
km	kilometer
m	meter

BACKGROUND AND MOTIVATION

NEON Fundamental Designated Missions

The National Ecological Observation Network mission is to address at least three Grand Challenge areas that were identified by the National Research Council (NRC) for the National Science Foundation (NSF) regarding the most important environmental research challenges of the next generation[1]. Among others, the following challenges are the purview of NEON:

Biological Diversity and Ecosystem Functioning

> **Recommendation: Develop a comprehensive understanding of the relationship between ecosystem structure and functioning and biological diversity.**

Hydrologic Forecasting

> **Recommendation: Establish the capacity for detailed, comprehensive hydrologic forecasting, including the ecological consequences of changing water regimes, in each of the primary U.S. climatological and hydrologic regions.**

Land-Use Dynamics

> **Recommendation: Develop a spatially explicit understanding of changes in land uses and land covers and their consequences.**

Gaps in Existing Ecological and Meteorological Data Collection Networks

Background

In the early 1970s the term ecology was popularized and since that time environmental studies have developed into a full fledged science. Most academic institutions as well as government agencies have performed scientific research relating to ecological subjects including forestry, agriculture, air and water pollution and species diversity. In addition a number of academic institutions and government agencies have fielded large scale climate change experiments. The NEON program is composed of both ecological as well as climatological experiments that will be fielded throughout the United States. Predecessors to the NEON project include the Long Term Ecological Research (LTER) program, the Ameriflux Program and a host of other environmental monitoring programs sponsored by NASA, DOE, USGS, NOAA and others. Sandia National Laboratories has participated in the Atmospheric Radiation Measurement (ARM) program since its inception as part of the DOE climate change initiative. A summary of existing ecologically relevant data collection networks and their missions is provided in Appendix A: Existing Measurement Networks for Ecological Informatics.

Limitations of Existing Networks

Long Term Ecological Research (LTER)

A historical look at the LTER program shows a rich diversity of studies that were based on the field sites identified for local ecological processes. These studies were usually confined to site specific investigations that enhanced the understanding of local ecological biomes, but were loosely tied to national trends if at all. Therefore NEON has the opportunity to systematize and link very important ecological information on a national scale.

Atmospheric Radiation Measurement (ARM)

The ARM mission primarily looks at atmospheric radiation flows and the influence of clouds on those flows, and therefore represents only the climate related part of the NEON mission. The ARM program is exemplary for the quality of data and the systematization of processes that lead to maximum sensor on-line operation. The NEON project will do well to emulate ARM in this regard since it will lead to high quality data and carefully orchestrated operations management conducive to the corresponding and required levels of instrument maintenance, calibration and repair.

Ameriflux

The Ameriflux program resembles the NEON program most closely in that it uses largely the same core measurement approach to estimate CO_2, energy and moisture flux. Ameriflux coordinates regional analysis of observations from micrometeorological tower sites. The flux tower sites use Eddy covariance methods to measure the exchanges of carbon dioxide (CO_2), water vapor, and energy between terrestrial ecosystems and the atmosphere. Soil respiration measurements are also made with CO_2 soil chambers. This approach is very similar to that of NEON and indeed Ameriflux can be seen as a predecessor to NEON. The Ameriflux website appears to have much less QA/QC than does the ARM website and does not appear to have the same level of process control (instrument mentors, internal calibration laboratory and web-based QA/QC processes) as does ARM.

Other Ecological Networks

The USA National Phenology Network (USA-NPN) is an attempt to integrate spatially-extensive phenological data and models with both short and long-term climatic forecasts. This proposed network will incorporate phenology studies which look at the times of recurring natural phenomena. Some of these studies look at organism dynamics such as the date of emergence of leaves and flowers, the first flight of butterflies, or the first appearance of migratory birds. This network should be highly complementary to NEON providing species level information related to climate change and land use dynamics such as urban encroachment.

Unique Roles and Opportunities for NEON

NEON may be able to play a unique role to serve the earth science and ecological community in the following areas.

- **NEON will be truly national, taking ecological measurements and incorporating them into a truly nationwide, integrated system that will mesh regional information into a national database.**
- **NEON can ensure that the data quality of the meteorological, soil, water and air analyses is maintained at a high standard. The Eddy Covariance approach for CO_2 fluxes is an industry standard that NEON should apply in a systematic fashion.**
- **NEON is unique in that it uses various advanced chemical sensing platforms including water quality sondes, soil CO_2 chambers and advanced spectroscopies. These spectroscopies include chemiluminescent, ultraviolet, infra-red and cavity ringdown techniques. These methods not only advance**

ecological sciences; they also stimulate research into new long-term environmental sensing instrumentation.

- **NEON may have a unique opportunity to play a lead role in integrating its data into existing meta-databases including the UCAR Community Data Portal (CDP), the NASA Distributed Active Archive Centers (DAAC's) as well as the EPA Storet database. NEON can make a systematic investment into an informatics based research approach that can take the large number of measurements and make them easy to access, use, and maintain.**

Value of Preliminary Systems Engineering Evaluation

NEON is an exciting, ambitious, and timely undertaking of national and international importance aimed at lofty and desirable goals. In moving beyond lofty goals, however, toward the less lofty, yet critically important, process of implementing the NEON site infrastructure, many concerns arise. NEON is envisioned to have an operational life of at least 30 years. The implementation budget is not firmly determined at present, but an expectation has been set for an ongoing annual operations budget of $60M, adjusted for inflation. This constitutes an average annual operating budget of $3M each for the envisioned 20 NEON sites, including the common infrastructure that supports all sites. The DOE ARM Program sites, while admittedly oriented toward different measurement objectives, are nevertheless similar in many respects, yet every ARM site costs over $3M per year to operate, exclusive of the common infrastructure that supports all sites. If NEON is to achieve its goals, it is imperative that NEON's infrastructure and operational processes be developed with both end-to-end technical effectiveness and cost efficiency in mind. This is the crux of a systems engineering approach.

The present project and object of this report does not address the NEON network as a whole. Rather, it is aimed at investigating four areas of significant concern:

- **Alternative electrical power sources for NEON sites or sub-sites where utility line power will be unavailable or prohibitively costly**
- **Acquisition and local handling of sensor data**
- **Secure long-distance transmission of data to a central database**
- **Processes for incorporating new technologies and handling NEON evolution over its 30+ year lifespan**

These four aspects comprise an initial examination of some key system issues. It is our hope that the material presented in the following sections will prove useful and constructive toward the success of the NEON network and program. But it is also important to underscore the limited nature of these findings, and that they do not remotely represent a thorough and holistic systems engineering evaluation of the NEON enterprise. We do wholeheartedly recommend that a more thorough evaluation be vigorously prosecuted in the near future.

ALTERNATIVE POWER SOURCES AND IMPACTS (SOW TASK 1)

Given the relatively remote locations of several NEON sites and sensor array installations, the potential use of electrical power sourcing alternatives to utility line power is worthy of consideration. NEON network site loads comprise sensor suites on towers, in soil arrays, and in aquatic arrays. The soil arrays are closely associated with the towers and the combined loads of a tower and soil array range from about 2.2 to 3.6 kW depending on classification. The load size of the tower sites is therefore high enough that alternative energy technologies are not expected to be cost effective options. The power to run an entire NEON core site is an order of magnitude higher and would be commensurately more awkward to handle with an alternative energy approach. For most sites, this implies diesel generator power if commercial power is not available. The Toolik Lake site will require a diesel or some other type of internal combustion engine (ICE) generator power for its tower facilities since there are no commercial power options. The Guanica site is the next most likely to require this form of power.

Respecting commercial utility power sources, some sites may have limitations on allowed disruptions to the local environment. For example, within certain conservation areas power poles may not be allowed due to expected impacts on the ecological system. In addition, there may be limitations on digging to emplace commercial power lines underground. Within the context of such legal or policy based limitations, alternative power sources can be attractive despite a substantial magnification of costs in terms of price per Watt. Even in the absence of limitations, new overhead and/or underground power lines would increase the environmental impact of NEON.

The case of the aquatic sensor arrays merits thorough evaluation of alternative energy options regardless of obstacles to the availability of commercial line power. The estimated loads for the aquatic arrays are 192W, a power level that is well within reach of modest alternative energy installations, and where the up-front installation costs and higher ongoing price per Watt of alternative energies may not outweigh the financial and environmental impacts of utility line power installation. For these reasons the support of the aquatic arrays is the primary focus of the following analysis. The technical approaches considered herein are:

- **Solar photovoltaic (PV) with storage batteries**
- **Wind turbine with storage batteries**
- **Natural gas fueled thermoelectric generator (TEG)**
- **Hybrid systems combining PV with TEG or a diesel generator**
- **Fuel cells**

Since power storage and controls comprise an essential element of the PV, PV hybrid, and wind turbine based systems, storage batteries and related technologies such as power conditioning electronics are presented in greater detail in a following section.

Solar Photovoltaic Systems

Solar photovoltaic (PV) systems used for NEON aquatic sites would be classified as stand-alone (SA) systems, and for some sites like Toolik, an additional generator or other power source would be needed. The reason for an additional generator is that solar energy cannot provide all the power, due to low solar resources at times of the year. When a system has an additional generator it would be classified as a hybrid stand-alone (HSA) system. Typical components of these systems include PV panels, batteries, charge controllers, battery enclosures, system mounting hardware (pole or ground mounted), foundation materials, wiring materials, and optionally an additional generation source, among others to be considered.

PV System Elements and Design Considerations

A brief introduction to the main component areas of a PV system is presented to provide the reader with a basic understanding of such systems. PV panels, battery systems, and the balance of systems (BOS) will be touched on briefly.

Load Assessment

When considering PV for powering any load one of the most cost effective measures is to actually measure the loads and not make assumptions. Manufacturers' specifications generally represent maximum usage conditions and may also be padded with a safety factor, and are thus insufficient to determine an accurate load. It is much better to have an actual load system running and measure average and peak loads so the power requirements can be sized correctly. Many times the actual load is much less than what is listed in the specifications, and if measured can lead to significant savings in the PV system design. How a load is operated can also have a great impact on the amount of energy needed to run it. For example, if a sensor does not need to be on continuously but has a short warm up time, then it is reasonable to consider reducing the loads by employing conservation measures. Multiplexing power supplies to turn them on and off when needed can be another means of saving power.

Voltage Selection

A 48V system for the PV and battery side is suggested for two reasons; the charging current would fall 75% relative to a 12V system, which saves on copper wiring costs, and yet this is a low enough voltage to make it safe even for relatively untrained personnel to perform repair and maintenance work. In order to reduce cabling size, and save on voltage drop losses and copper cabling costs, assuming the loads are 12V based, the battery bank will have a 48V to 12V DC to DC converter to feed the nominal 12V load. The converter has the effect of raising the effective load by dividing by the efficiency of the converter, which is typically 90%. These loads are presented for the case of the aquatic array in Table I, assessed on a daily usage basis. For comparison, this load is equivalent to running a typical household toaster for five hours per day.

Table I. Aquatic Array Electrical Loads.

Aquatic System Base Load (W)	**Daily Load (kWHrs/Day)**	**Adjusted Daily Load* (kWHrs/Day)**
192	4.6	5.12

*** Assumes 90% DC-DC conversion efficiency.**

PV Panels

PV panels (or modules) are made up of PV cells, usually within an aluminum frame with a protective covering such as glass or other transparent material. The cells in a panel are connected in series to create the voltage needed for a panel. Panels have current and voltage characteristics within well-defined specifications. Panels can be found in 12V, 24V and other voltage configurations. For systems in hot climates, there are panels with a few more cells in a series string, as per cell voltage falls with rising temperature. Using a combination of series (string) and parallel connections essentially provides the system with the level of current and voltage desired. Some benefits and liabilities associated with PV panels are:

Benefits

- **Panels are normally warranted for 20 years, with expected lifetimes to exceed 25 years**
- **No noise or hydrocarbon emission**
- **They are resistant to hail up to 60 mph wind speed, depending on manufacturer and model**
- **Very reliable source of power, with essentially no maintenance for the power source itself**
- **Good choice when costs for fuel access or transportation on other types of power systems present extra or prohibitive costs**

Liabilities

- **PV panels can typically be valued between $500-1000 each and may be targets for theft**
- **Vandalism may need to be considered – a large rock thrown at a panel or bullets shot at them could ruin a panel and bring the system down**
- **Power generation costs must be paid for in advance**
- **PV panels *are very sensitive to shading* from trees or other vegetation; their installation may require clearing installation areas initially and regularly thereafter, or elevating panels on raised mounts or poles to allow unshaded access to the sun without such maintenance**

Energy Storage System

A PV system needs to provide all of the load energy to a storage system plus extra energy for the following:

- **Storage for days when sunshine is limited**
- **Battery charging losses**
- **Battery self-discharge losses**

If capacity is added to run for a time beyond the lowest state of charge normally anticipated, a run-time margin can be incorporated to enable maintenance and repair efforts even at relatively remote locations without interruption of power. This approach adds additional expense to the system, mostly in terms of batteries to cover such times. The advantage of such a system is there is no additional need to include an uninterruptible power supply (UPS).

Balance of System

The BOS comprises those elements beyond the PV panels and storage batteries that are necessary to a fully functioning power system. It includes items such as charge controllers, inverters, module mounting hardware, disconnects, enclosures, mounting poles, trackers, *etc*. It is beyond the scope of this document to provide a thorough presentation of these aspects.

Reliability

Solar PV and PV-hybrid systems can be very reliable if they are designed correctly and implemented according to plan, without cutting corners. For example, storage batteries are expensive and have lifetimes measured in years, not decades, so there is a temptation to under-size the energy storage system. This sort of corner-cutting measure leads to deeper battery cycling, more rapid degradation of the batteries, and significant reductions in power availability (up time) due to more frequent full depletion in cloudy weather. Finding a reputable design and installation vendor is one of the key elements to getting a good system. Due to the complexity of efficient modern installations it is not recommended for a non-expert end-user to finalize the design without the assistance of a qualified vendor, as it is relatively easy to achieve good initial performance in a suboptimal design destined to reliability problems and early failure.

Siting Considerations

The sun shines on every portion of the earth, but with wide variations in power and consistency depending on latitude and local weather patterns. The greater the inconsistency of the solar resource, the larger the PV system and especially the energy storage aspect must be. Whereas virtually any above-ground location can be served by PV power, the economics of PV are highly sensitive to location, and the available resource should be assessed in considering the tradeoffs between power sourcing options. Fortunately, computer software packages are available that incorporate long term resource availability and commercial PV component data to enable estimations of system cost and performance. One such software package is PV Design Pro, produced by Maui Software (Maui, Hawaii, USA).

Installation and Maintenance

Because of the various locations for these systems, installation costs would be hard to estimate at this time, without significant effort, and is not included. Once a design concept is selected, putting out a design RFP would be a good way to get an accurate estimate of an installation and actual system costs. The reason for this approach is that many sites have logistics issues that are beyond the scope of this document, and that are most readily estimated by experienced vendors familiar with these issues. Maintenance costs for the SA systems are mostly battery related. If a hybrid system is considered, the fuel for this system become part of the regular operating cost. A simple example would be a fossil fuel generator that needs fuel on a planned schedule.

Estimated PV Systems for Support of NEON Aquatic Arrays

PV Design Pro, by Maui Software, was used to estimate options for a PV powered system. This software creates hour by hour simulations throughout the year and allows the user to add backup capacity and specify parameters for turn on and turn off. Available resources are estimated within this program using data collected over a 30 year time span. Because most sites are not actually in the database, the next closest city was used that had such data. An assumption was made for these aquatic array sites, that no power would be used in January, February, November and December. The results presented here in Table II should be considered a starting point to define a systems cost. From this basis, adjustments could be made for the different battery configurations, which would add or subtract from the battery cost of the systems and also create an adjustment for the battery replacement costs.

Table II. Estimated PV System Costs to Support Aquatic Arrays at NEON Core Sites.

System Components	CRC	Guanica	Pawnee	Joaquin	Toolik*
Panels ($ 955 Each)	$ 9,550	$ 7,640	$ 9,550	$ 7,640	$ 7,640
Batteries ($255 Each)	$ 6,792	$ 6,792	$ 5,660	$ 5,660	$ 6,792
BOS, Estimated at 30% of Above	$ 4,903	$ 4,330	$ 4,563	$ 3,990	$ 4,330
Generator System Cost	$ -	$ -	$ -	$ -	$ 5,000
Installation Costs	TBD	TBD	TBD	TBD	TBD
Purchase Price (Excl. Installation)	**$ 21,245**	**$ 18,762**	**$ 19,773**	**$ 17,290**	**$ 23,762**
Annual Misc. Maintenance 5% Price	$ 1,062	$ 938	$ 989	$ 865	$ 1,188
Battery Replacements @ 5 yrs	$ 6,792	$ 6,792	$ 5,660	$ 5,660	$ 6,792
Average Annual Maintenance	**$ 2,420**	**$ 2,296**	**$ 2,121**	**$ 1,997**	**$ 2,546**

For the purposes of the simulations, the batteries used were 105AH, 12V units, which create up to six (6) parallel sets of four (4) battery strings. This approach enables ready comparison of the systems and is reasonable with respect to guiding system sizing estimations, but is not how a configuration would normally be implemented in the field. When too many batteries are arranged in parallel, there is a tendency to get uneven charging and discharging of batteries, even within a series string. A three-string configuration will not take down a system if one string is being changed out or evaluated, providing good system reliability. Configuration for the total capacity listed should be achieved in no more than three battery strings. This may require using 2V or 6V cells to keep the unit weight within the range of tolerance for transportation by on-site personnel. As shown in Table III, the weight of systems estimated to support the aquatic arrays is substantial.

Sizing of components in these systems were set to allow battery capacity to go no lower than 50%, so in the event of a catastrophic failure in the panels or charging electronics, or a long span of unsuitable weather, they should provide power for a minimum of 48 hours. For the more remote systems, additional capacity was given to allow for more time before a repair person would be able to reach the site and correct a problem.

Table III. Weight Estimates for Core Site Aquatic Array PV Systems.

System Weight Estimation	CRC	Guanica	Pawnee	Joaquin	Toolik*
Panel Weight	331	264.8	331	264.8	264.8
Battery Weight	1584	1584	1320	1320	1584
BOS Weight Estimated at 30% of	575	555	495	475	555
Generator System Estimated Weight	-	-	-	-	1000
Total Estimated Weight, lbs.	**2490**	**2403**	**2146**	**2060**	**3403**

Operational and Environmental Impacts

The five NEON core sites discussed in the NEON Fundamental Instrument Unit Baseline Document[2] (Draft, Version 1.0) were as follows: Smithsonian Institute Conservation Research Center (CRC), Guanica Forest, Central Plains Experimental Range, San Joaquin Experimental Range, and Toolik Lake. All of them can be considered remote, in terms of being away from heavily populated areas. Two of them would be considered especially difficult in terms of logistics: namely Toolik, which is approximately 280 miles north of Fairbanks, Alaska; and the Guanica, Puerto Rico site. The major impacts on all of these sites would be similar. If vehicles are used in the installation and/or maintenance processes, the resulting vehicular traffic may create a change in the environment that could affect measurements, depending on the specific measurement objectives. PV systems could impact areas on a minimal level as these could be carried in on foot and set up, and they produce no carbon emissions and essentially no noise in comparison to a generator based system. The avoidance of generator emissions would be another area that may be a plus, with limited run time on a generator for the Toolik site. Given the sensitivity of the PV panel output to shading, one key environmental issue with PV in the NEON context is the need for a large swath of open-sky access. This could require substantial local modification of the environment.

Several issues specific to PV systems are linked to the battery requirements. Battery specifications should seriously take into consideration the logistics available at each site for installation. Will people have to carry something for miles or is there some form of transportation? The maximum weight on a per load basis should match the transportation options considered for this to be reasonable. Maximum acceptable weight may be limited by local health and safety laws as well as by common sense expectations of staff personnel. If sealed lead acid batteries are used (those without liquid electrolyte), the issues of spills are avoided. A means of recycling them after use would be required. Proper design choices will reduce the need for expensive infrastructure to install a system. Utilization of equipment that can be carried on foot or using modest vehicles such as ATVs or small carts without the need to create a road for larger vehicles will be a definite advantage. Legal constraints on use of off road vehicles need to be considered on a site by site basis.

Critical note for Toolik site: There is a period of time when all machine traffic is not allowed on the tundra areas, since this area is on State of Alaska or U.S. Department of the Interior Bureau of Land Management (BLM) land. This typically means that starting in May through sometime in later fall, no off-road vehicle traffic is allowed on the tundra. This should be a driving consideration in choosing the types and sizing of the system components. Startup and operational items such as installation, maintenance, and re-fueling need to be taken into account, not only for the Aquatic sites, but also for the Advance and Basic Tower sites as well.

Wind Power Systems

Wind energy may be a possible resource to supply power to remote NEON sites. Small wind generators, such as the Air-X Wind Turbine (Southwest Windpower, Flagstaff, AZ), are inexpensive, can be mounted on a variety of structures such as the top or side of a tower or the ridge of a pitched roof, and can supply a few hundred Watts under favorable wind conditions. Small wind generators such as this are frequently used on remote residential sites, telecommunications sites and in the developing regions of the world for modest amounts of power. Modern small wind generators can start in very low winds (5 to 10 mph) and have internal mechanical and electrical speed governing for control in high-wind conditions such as thunderstorms. Wind is a variable resource at best, and therefore should probably be considered a supplemental rather than a primary energy source for

NEON sites. Wind power is frequently used to supplement solar energy at remote sites where the wind resource may be more favorable on cloudy days or during night-time hours.

System Elements

The elements of a wind power system are similar to those of a PV system in that each has a variable and intermittent electrical power source electrically connected to a storage battery array. These elements are supported by an appropriate Balance of System comprising a support structure, electronic control and power conversion circuitry, cabling, *et cetera.*

Siting Considerations

There are several resources available to assess the suitability of wind energy at any particular NEON site. The National Renewable Energy Laboratory (NREL) and the United States DOE have produced extensive wind resource maps for broad areas of the continental United States as well as Alaska, Hawaii and Puerto Rico. A map showing the general distribution of the wind resource across the United States is provided in Figure 1. These maps can provide an initial notion of whether wind power is a reasonable approach to alternative energy for a particular location. In many areas, however, the wind resource may be much more localized than suggested by such maps. For example, an area shielded by a hill may have very poor wind resources while a hilltop, canyon or prairie just few tens of meters away may have abundant wind. The available wind resource data have predominantly been charted on coarse grids ranging from as low resolution as $\frac{1}{3}$° of latitude by $\frac{1}{4}$° of longitude, to higher resolution data on a grid as fine as 200m, all referenced to an altitude of 50m, which may or may not represent a practical turbine placement. Even the relatively high resolution 200m grid is still coarse compared to the variability of the wind resource. In addition, the effectiveness of the wind can be extremely seasonally dependent. These effects cannot be easily evaluated using such coarse resolution large area maps. It is likely, therefore, that if wind power is to be used, individual sites would need to be evaluated for local wind resources after system energy requirements at a particular NEON site or location have been determined.

Wind sites are classified using a system that depends upon the local wind speed and the energy density (W/m^2) in the wind (which is affected by elevation). This classification scale is summarized in Table IV. The first two levels represent poor or extremely poor wind resources for power generation and are indicated by the tan or white colored areas, respectively, in Figure 1. In practice, the usable power produced by a turbine tends to be about one-third of the available wind power density[3]. Thus, while the Air-X turbine sweeps an area of approximately 0.75 m^2, and is capable of generating 400 Watts in a 28 mph wind, a realistic expectation of the average power output at a Level 4 ("Good") wind power classification NEON site would be about 110W.

The power output from an Air-X Wind Turbine as a function of instantaneous wind speed is shown in Figure 2. The upper curve shows the output in a smooth, steady wind while the lower curve shows the output power in a more turbulent wind. It is clear from this plot that wind turbulence near NEON sites will have an impact on energy production if wind turbines are used as an energy source. Wind turbulence may be influenced by local terrain, NEON site buildings, and perhaps even the tower that the wind generator is mounted upon. Small wind generators are typically mounted 30 to 50 ft (9 to 15m) above the surrounding terrain to reduce these effects. The output of the Air-X Wind Turbine decreases rapidly with decreasing wind speed. In variable or light wind conditions, energy production from such a turbine may be significantly reduced. The speed of the turbine is also mechanically and electrically governed to protect the turbine in wind speeds above 30 mph; such governing mechanisms are typical of small wind turbines. With this kind of protection, most small wind turbines can survive wind speeds slightly in excess of about 100 mph.

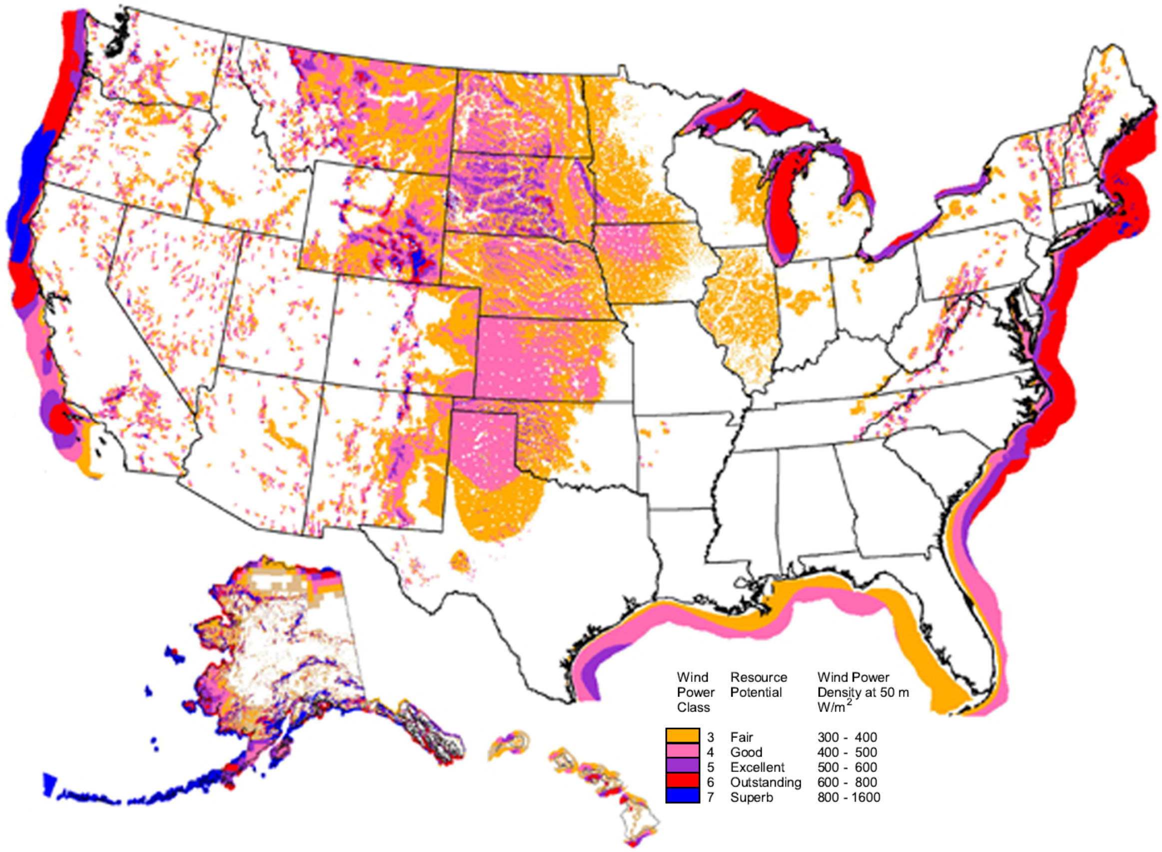

Figure 1. Wind resource availability within the United States. Adapted from graphics provided at the United States Department of Energy Office of Energy Efficiency and Renewable Energy web site www.windpoweringamerica.com.

Table IV. Wind Resource Energy Availability Classifications.

Site Classification	Energy Density (W/m^2)
Level 1	0 - 200
Level 2	200 - 300
Level 3	300 - 400
Level 4	400 - 500
Level 5	500 - 600
Level 6	600 - 800
Level 7	> 800

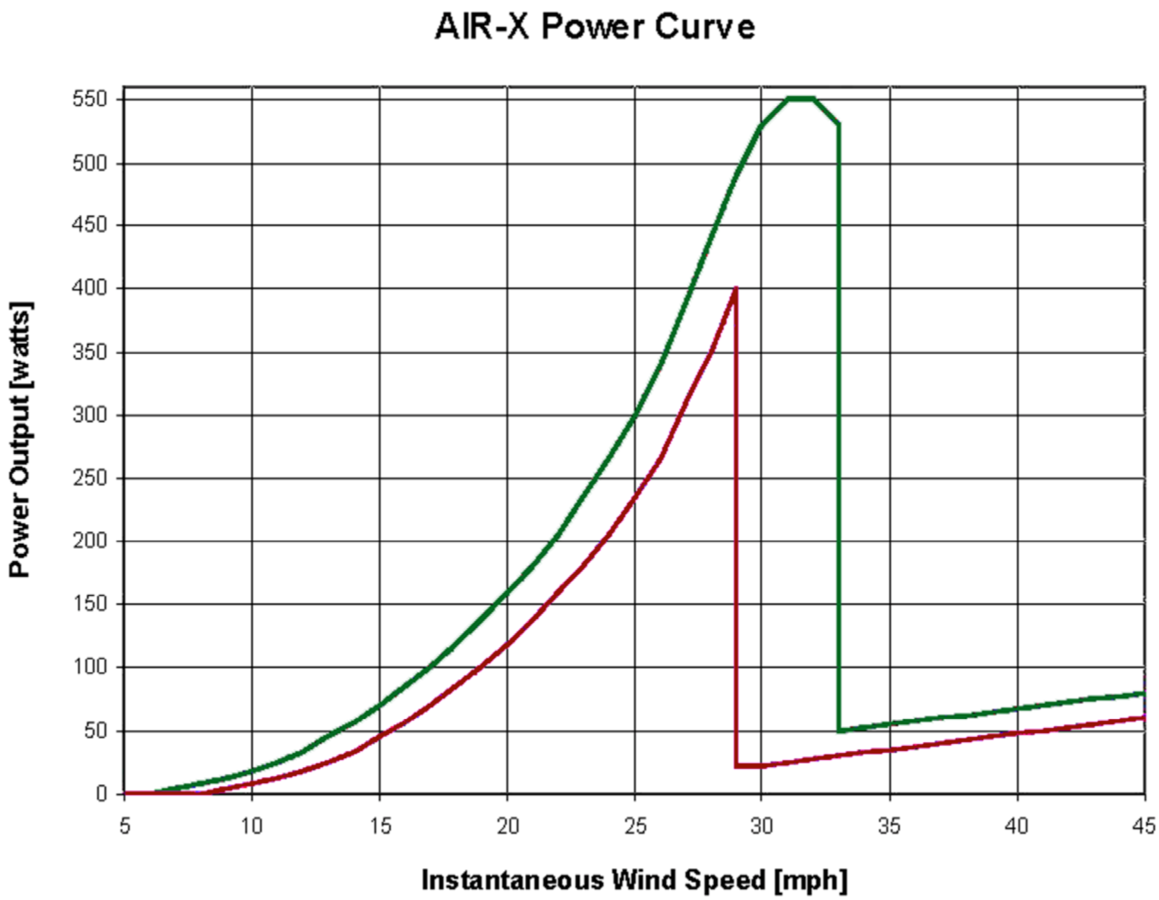

Figure 2. Power output vs. wind speed for the Air-X model turbine. The upper curve represents the power generated by a steady wind. The lower curve represents the power generated by a turbulent wind. Adapted from Air-X wind turbine owner's manual with permission of Southwest Windpower, Flagstaff, Arizona, USA.

Installation and Maintenance

The wind is an intermittent and variable resource and the cost of small wind generating systems can vary greatly depending on system requirements. Small wind turbines, capable of producing 400 to 600 Watts, can cost between $600 and $1000. A small wind-powered system would further require batteries for energy storage and other balance-of-system infrastructure, similar to that required for solar energy of similar capacity, which has been extensively evaluated for NEON sites.

Wind turbines of all sizes are mechanical machines, and as such require some periodic maintenance. However, most modern turbines are very reliable. Damage can include wear to rotating bearings on the turbine housing as well as the yaw shaft that allows the turbine to align to the direction of the wind. Bearings typically need replacement in 3 to 5 year intervals under most conditions. In addition, high winds speeds can result in damage to blades due to flying debris. Blades typically need to be replaced in 5 year intervals. Finally, lightning strikes can result in damage to electronics housed within turbines typically mounted at the top of 30 to 50 foot tall metal towers.

Operational and Environmental Impacts

Wind power systems have similar maintenance requirements to those of PV systems respecting the energy storage battery and BOS. Due to the mechanical moving parts, the labor and materials necessary to supporting the upkeep of the turbine is expected to be somewhat greater than for the PV systems. Wind turbines also have been reported to have negative impacts on bird populations and can be expected to alter local airflow patterns.

Thermo-Electric Generators

System Elements

The main elements of a thermo-electric generator (TEG) system are the TEG unit *per se*, the mounting platform, and the fuel supply, typically a propane tank. Within the internal workings of the TEG unit, thermopile modules (*e.g.*, Lead Tin Telluride or PbSnTe) generate low-voltage DC power. Each module consists of a stack of thermocouple junctions and these modules are in turn stacked to provide DC voltages up to 48V in commercially available units. The thermopiles require a heat source to operate and this is provided by burning the propane fuel, so burners and ignitors are included. Additionally, since a substantial thermal gradient is required for effective operation, the cold side of the thermopile is typically air-cooled via cooling fins. Piped liquid cooling has also been used. Since TEGs can operate continuously there is no need for a storage battery as with PV or wind power.

Siting Considerations

Thermoelectric generators are commonly used for systems in remote places where a clean, extremely reliable source of power is needed and any other sources of power are not practical. Examples might include sites where only a few 10s of Watts are needed, and the solar resource is not reliable. In these situations, a hybrid solar/TEG is commonly used. The electrical power produced from one of these units is normally small compared to the amount of thermal energy used to generate the electricity, with efficiency of such units being around 5%, although technology development work is underway to substantially improve efficiencies and future systems may demonstrate much higher performance. By comparison, a diesel generator set typically operates at 25+% efficiency, generating approximately five times the electrical output per unit of fuel than a TEG. In continuous use, TEGs can reach their 10 year or so expected lifetimes. If they are operated in an intermittent fashion they should be turned on for long times and not just switched on and off frequently as repetitive on-off cycling tends to degrade their output performance.

One company, Global Thermoelectric, has units that produce power in the range of 20+ to nearly 500 Watts, and fuel consumption ranges from 0.8 to over 20.1 gallons of propane per day. One unit, that produces power in the 220W range, just meets the load requirement, and burns over 7 gallons of propane per day to feed such a load. At a price of $2.25 per gallon, this unit would burn approximately $472 of propane per 30 day month or roughly 210 gallons per month. However, this TEG unit would have little reserve capacity and with modest degradation of output due to thermal cycling and aging could drop below requirements. A 480W TEG unit costs in the range of $23,000 and burns commensurately more fuel.

In addition to employing TEGs as a stand-alone power system, TEGs can optionally be hybridized with other power sources. This option may hold promise as a smaller amount of TEG power might be able to supplement a PV powered system to keep it operational during periods of low sun and battery levels. All core sites except Toolik should easily run on solar only. Calculations for this hybrid option are presented in the Photovoltaic Hybrid Systems section.

Installation and Maintenance

Installation consists of mounting the aforementioned system elements. If an appropriate DC voltage is chosen to operate the sensor array, no power conversion circuitry will be required, but if AC power is needed then a power inverter would have to be incorporated in the system. However, the addition of a heated enclosure for the propane tank may be required for arctic or high alpine sites to ensure that the propane fuel be above its -42°C vaporization point so it can provide gaseous fuel to the TEG. A large propane tank in excess of 1500 gallons as a minimum would be needed to cover the fuel needs during the typical May –October and possibly November time when no heavy traffic would be allowed on the Tundra. The fuel delivery means would have to have the capacity to deliver such quantity as well. Such a large tank may affect the enclosure aspect of the system to keep the propane warm enough unless small volumes could be transferred and warmed as needed

Operational and Environmental Impacts

The two largest operational impacts for a TEG only system would be fuel cost and delivery. For an aquatic site, this may prove difficult if not nearly impossible for all but the most accessible locations. The propane needed to supply a site for a month is probably unsuitable for foot transport by staff personnel. The use of other delivery mechanisms such as ground vehicles, necessitating a large path or road, or possibly helicopter transport, would need to be considered.

TEGS running continuously could affect measurements in the local area if the TEG were close enough to the sensor arrays. Two obvious impacts would be in terms of temperature and CO_2 levels. The development of roads and use of ground vehicles to deliver fuel would be counterproductive to studying an area considered pristine.

TEGs do make little noise and would be a good choice if that were the only consideration.

Photovoltaic Hybrid Systems

Estimated Hybrid Systems for Support of NEON Aquatic Arrays

Two types of support for the PV panels were considered, TEG and diesel generator. It should be noted that an approximately $30,000 worth of modules, or 30 additional modules, would not be enough to cover the load by PV alone based on simulations. Several battery bank sizes were modeled; two for the TEG and four for the diesel. As mentioned before, a TEG has an efficiency around 5% and a diesel generator set something greater than 25%. There are two other distinctions that bear mentioning; the TEG has a charge current to the battery of roughly 2.25A while the diesel would provide up to 62A to the same battery bank. As a battery bank ages, the 2.25A may not be sufficient over the long term to compensate for internal battery losses. In addition, the TEG would be fired up on a periodic basis and not left to run continuously, and such cycling is detrimental to its lifetime.

An example of the output derived from modeling software is shown below (Figure 3). For these models, the back up generator is given the following ranges: 50-95%, 60-95 % and 70-95%. The lower number is the point where a generator would be turned on and the higher number a point where the generator would be turned off. For all, the generator would be turned off at 95% of battery capacity to allow maximum energy transfer to the chemical process of the battery. The upper data shows the swings of the battery state of charge (SOC) as a function of time. Details on these simulations can be seen in Appendix B.

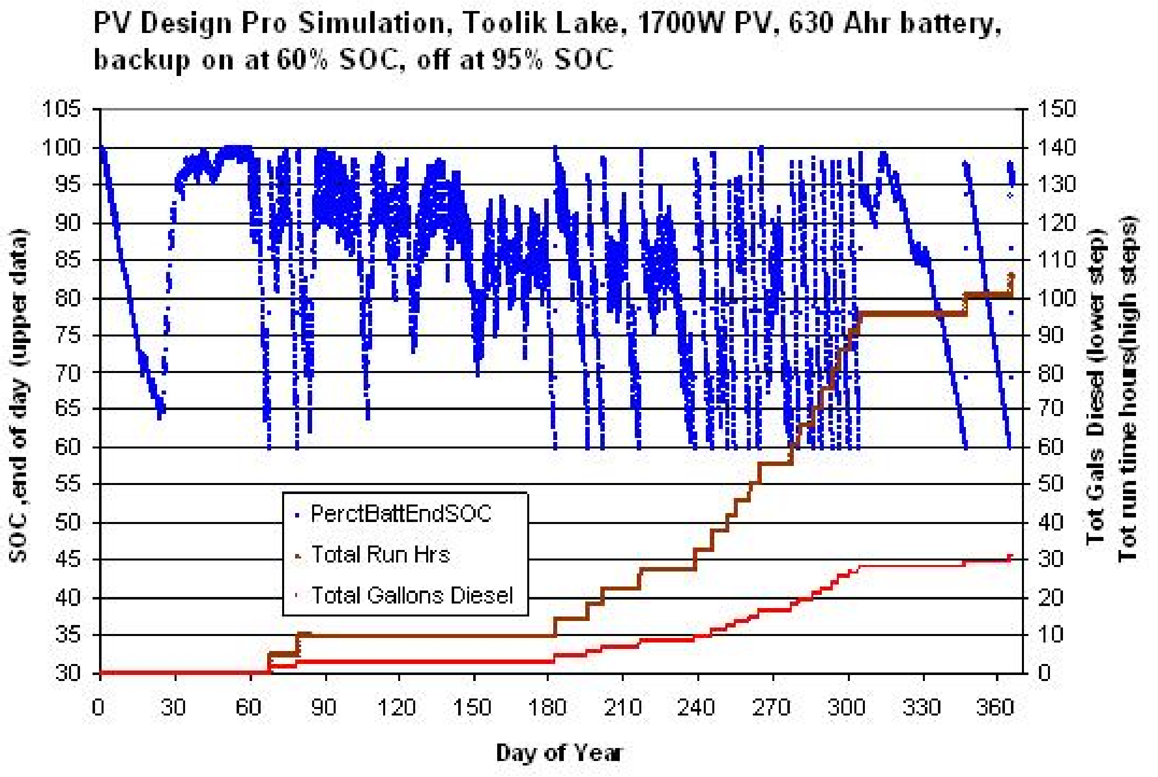

Figure 3. Example of simulated PV-diesel hybrid power source performance.

For brevity, a simplified chart derived from the 42 scenarios evaluated is shown in Table V. This Table illustrates the effects of different battery sizing choices, SOC setpoints, and supplemental power source on fuel consumption. As can be seen in Table V, the diesel generator will end up using far less fuel and would be the recommended choice for the Toolik installation. An enclosure is recommended to mitigate engine noise and provide secondary containment of fuel (required).

It should be noted that the diesel engine envisioned for this backup generator application is somewhat unusual. It is a low-speed, low-power, high-efficiency, and high-reliability type of diesel termed a “Listeroid Diesel” after the engines first produced by the R. A. Lister company in 1929. An image of this type of engine is shown in Figure 4. The base unit is a single cylinder unit, rated at 5 HP, weighs 700 lbs and runs at 650 rpm. These units are extremely reliable yet simple, and can be disassembled for transport. They can run on biodiesel, vegetable oil and regular diesel fuel. Some engines have been reported running almost continuously for 40 years.

Table V. Simulated Fuel Usage and Battery Status for PV Hybrid Systems.

	Backup 50-95%		Backup 60-95%		Backup 70-95%	
TEG 108W Propane Fuel	**Yearly Avg SOC**	*Yearly Fuel Gallons*	**Yearly Avg SOC**	*Yearly Fuel Gallons*	**Yearly Avg SOC**	*Yearly Fuel Gallons*
420 AHrs (4 Months)	**81.5**	*121.6*	**84.8**	*133.9*	**87.6**	*152.5*
630 AHrs (4 Months)	**82.7**	*85.9*	**84.7**	*108.9*	**87.7**	*141.4*
420 AHrs (12 Months)	**78.9**	*285.4*	**82.7**	*308.9*	**86.1**	*331.5*
Listeroid Diesel 3000W / 650 rpm Diesel or Bio-Fuel	**Yearly Avg SOC**	*Yearly Fuel Gallons*	**Yearly Avg SOC**	*Yearly Fuel Gallons*	**Yearly Avg SOC**	*Yearly Fuel Gallons*
420 AHrs (4 Months)	**81.9**	*33.2*	**84.4**	*32.0*	**88.0**	*43.5*
630 AHrs (4 Months)	**82.2**	*27.8*	**84.3**	*31.4*	**88.3**	*40.8*
945 AHrs (4 Months)	**82.5**	*26.0*	**85.3**	*30.2*	**86.9**	*32.6*
1260 AHrs (4 Months)	**81.2**	*23.4*	**84.3**	*24.0*	**87.5**	*32.3*

Figure 4. Listeroid Diesel engine. Reprinted from web site www.listeroid.com with permission of Aelto Systems, Monico, Wisconsin, USA.

Fuel Cell Technologies

One other alternative power technology was considered for use by NEON – fuel cells. A key benefit of fuel cell technology is that while hydrogen-bearing (typically hydrocarbon) fuels are employed, as with internal combustion engine based generator sets, the electrical power is generated directly through the catalytic decomposition of the fuel, generally to carbon dioxide and water. Due to the sensitivity of the catalysts to fouling, fuel cells must be engineered and operated to minimize formation of by-products such as carbon monoxide, and by operating near room temperature they do not tend toward formation of oxides of nitrogen as internal combustion engines do. Efficiencies of 50% or more are readily achievable. Fuel cells are a clean and quiet technological approach to power generation. However, in the context of NEON's operations this technology raises several concerns:

- **Systems start in the 5 kW range at a price around $50,000**
- **Systems require a continuous source of fuel such as propane, natural gas, JP8, or other fuel, and a means of fuel transport to the location**
- **Historical performance data for installations of this size are minimal**
- **Power availability in the 95 – 98% range (2 – 5% downtime) would compromise NEON's data collection goals**
- **Extreme cold weather creates difficulties with system startup**
- **Repairs are frequently needed, and the remoteness of NEON sites would be likely to exacerbate downtime issues**
- **Frequent adjustments by trained staff are necessary to keep these systems operating near top efficiency**

In summary, fuel cells comprise an interesting and exciting alternative power technology, but are not considered sufficiently mature to be appropriate for NEON's remote site operations.

Energy Storage and Control Technologies

Power Control System Considerations

Maximum Power Point Tracking

PV panels have a power curve that allows for maximum power at certain voltage and current points. An example of this behavior is shown in Figure 5. It is paramount to keep the panels at this operating point if maximum energy is to be extracted. For this reason, a maximum power point tracker (MPPT) charge controller is required. This is an effective and reliable way to optimize available power to charge the storage batteries. Viewed simply, the MPPT functions as a smart DC-DC converter, matching PV panel voltage to the necessary battery charging voltage. An equivalent function must be incorporated in wind power systems for similar reasons.

Equalization Charging

On a regular basis, probably yearly or twice yearly, the batteries should be allowed to equalize, which typically means holding them at a charging point higher than normal for a period of time to let those that may be lower in charge due to small differences in each battery come up to charge while those at high levels of charge remain fully charged. This is an excellent practice to ensure the health of the battery.

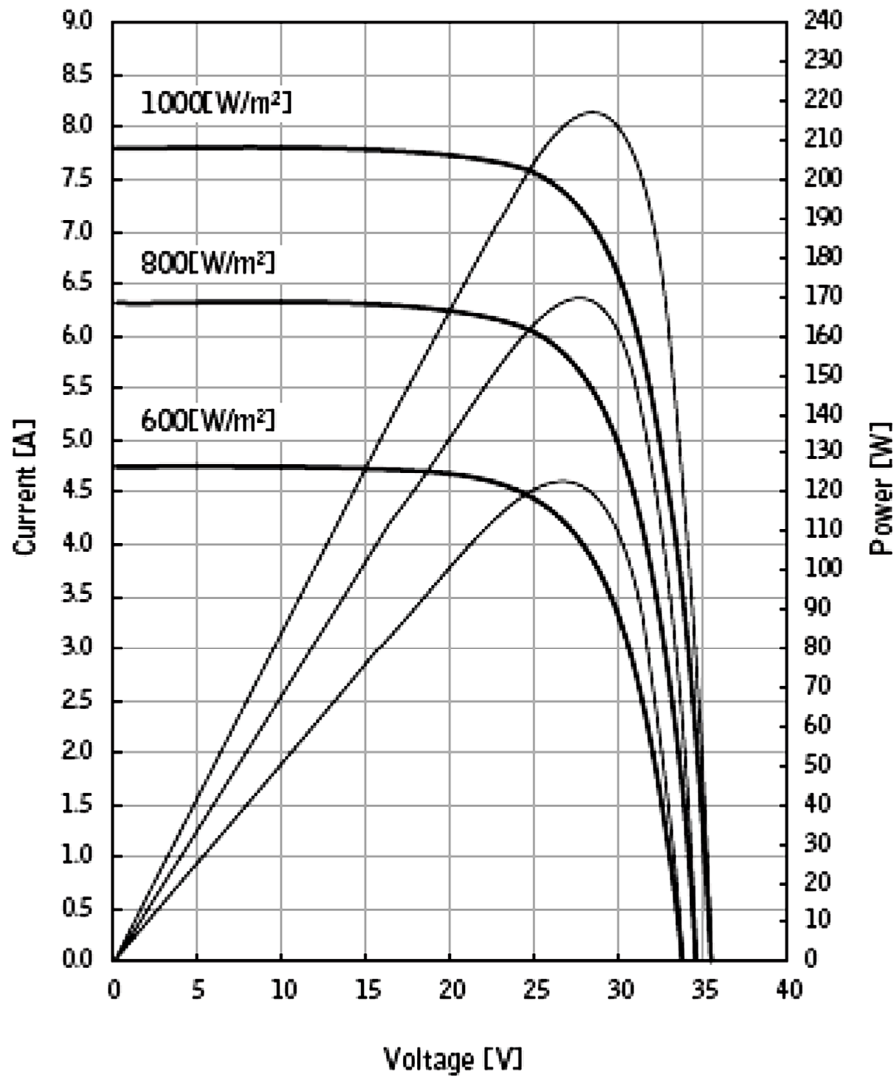

Figure 5. PV panel power output vs. incident solar energy. Peak power and the operating voltage where peak power is achieved both depend on solar energy density. MPPT charge conrollers seek the optimal operating voltage for maximum power extraction from available solar energy. Reprinted from web site www.affordable-solar.com with permission of Affordable Solar Group, LLC, Albuquerque, New Mexico, USA.

Charge Controllers

Charge controllers are commonly used in off-grid (stand-alone) PV systems. A charge controller (or regulator) is used to maintain a battery system at the highest possible State of Charge (SOC). It can protect batteries against extended overcharge by the PV array. It can also be commonly used to protect the battery from excessively deep discharge by the loads through having a low voltage disconnect (LVD) function. Most charge controllers operate on voltage regulation set points. This can be a problem, as voltage is not representative of the true SOC, so new algorithms are being developed to evaluate the state of the battery, based on Ampere-Hour (AH) or combined Volt-Ampere-Hour (VAH) monitoring. Additional features such as battery temperature or wire compensation, meters and alarms can enhance the ability of the charge controller to meet the load demand and extend battery lifetime. Other functions such as MPPT, DC-to-DC conversion, and data logging can be built into the charge controller.

Enclosures

Enclosures are a critical item no matter what systems are chosen. For the battery specifically, they can provide a means to moderate the temperature. For warm or hot climates there are passive cooling enclosures that reduce the temperature swings seen by batteries to extend their lifetimes. For a location such as Toolik, some sort of insulated enclosure would be needed to keep the batteries from getting too cold. Deeply discharged lead-acid batteries are much more susceptible to permanent damage from freezing. A small heater may be required that shunts excess unneeded energy from the solar system if available. Heat from a diesel or TEG exhaust would also be a good way to heat a battery area. Good insulation is a must, but some sort of automatic ventilation will most certainly required to prevent overheating and reduced battery lifetime in warmer months. Even in the Arctic, 24 hours of summer sun can be equally troublesome for temperature control as the 24 hours of darkness seen in winter. Shortened lifetimes from poor temperature control translate into more operational replacement costs on a regular basis. Avoiding such situations could be mitigated by utilizing passive temperature controlled systems such as those manufactured by Zomeworks, which are mostly aimed at keeping batteries cooler.

Periodic Inspections

For the systems that are PV only (all but Toolik), a regular visit should be scheduled every several months or more frequently, to monitor performance. As an alternative to on-site inspection, there are control systems that could allow remote monitoring, so a measure of system performance could be remotely tracked. As a bare minimum the loads to these aquatic arrays would need to be shut off in late October or near the beginning of November and then turned back on at the end of February in areas where freezing temperatures occur. At these times, they should be checked for proper operation.

Battery Options and Considerations

A sensible choice of batteries and system design will result in a longer-lived system and one that will need minimal maintenance throughout its life, and have less impact on operational costs in the long term.

The most common type of battery for PV systems is the lead-acid type. For the purposes of this document, we have focused on the sealed types and those typically called absorbed glass mat or AGM batteries. These types of batteries do not have any electrolyte to spill and are mountable in almost any position. The lack of liquid electrolyte is also a key benefit during transport and installation. They have a good performance history in many systems. As compared to flooded batteries, there is not a need to water them or perform any kind of regular maintenance on them, however, they are not as tolerant of abuse as flooded electrolyte or wet cells, and require a more sophisticated charging system.

Batteries are heavy, with lead being the largest contributor to its weight. When considering the type of battery to use, it is important to envision how it will be transported to its destination. It may be important for remote sites to preserve the option of hand carrying the batteries to the installation. Otherwise, the impacts of using ground vehicles or helicopters must be considered. This is very important for the Aquatic sites, where batteries may need to be transported miles from a place where a truck may be parked. As a result, it makes good sense to limit a size to what 1-2 people could safely and easily carry, as many sites will only be able to rely on human power to get them to their destination. In some cases like Toolik, ATVs and snow machines with sleds might be viable options in winter and spring.

Challenges in Battery Lifetime Estimation

Given that batteries constitute a substantial fraction of the cost of alternative power sources utilizing intermittent energy resources such as PV or wind power (see Table II), it would be highly desirable to minimize battery costs. Battery in-service lifetime is a key variable of interest in this context, since for a given type of battery the replacement costs are inversely proportional to lifetime. However, the operational durability of batteries is sensitive to environmental conditions and usage patterns in a complex fashion. We are not aware of an openly available model or multivariate data set for diverse usage conditions that would enable straightforward prediction of battery lifetime under arbitrary circumstances.

Battery lifetimes depend on several factors including fundamental chemistry and manner of construction, as well as usage conditions such as depth of discharge (DOD) and average temperature. Given the importance of lifetime to the economics of battery applications, manufacturers perform and publish test results obtained according to prescribed patterns of discharge and recharge. The problem with using these data to estimate lifetimes for systems in the field is that they are not subjected to the same cycling conditions used to create laboratory-generated lifetime curves. By analogy, automotive manufacturers' fuel mileage performance or powertrain lifetime expectations, determined under carefully constrained circumstances, offer drivers only a very approximate expectation of actual performance on the road, and do not make allowances for abuse, chance accidents or unexpected patterns of use. With the differences between laboratory and operational performance in mind, Figure 6 and Figure 7 below illustrate laboratory longevity performance for several types of lead-acid batteries. While exact duplication of the indicated lifetime performance in the field is unlikely, these illustrations should give the reader a sense of the relative lifetimes of the various battery designs.

In addition to battery discharge cycling effects, operating temperatures can substantially impact battery longevity. As a rule of thumb, the longevity of a battery system will be reduced by a factor of two for every 10°C rise in average temperature above 25°C (77°F). For example, a battery system capable of six years of operation at 25°C would be expected to last only three years at 35°C (95°F). Operating average battery temperatures at a tropical site such as Guanica could readily reach problematic levels unless moderating steps were taken. Since batteries generate substantial self-heating during both discharge and recharge, protection beyond simply shading from sunlight may be required (*e.g.*, underground emplacement).

Batteries are also sensitive to cold temperatures, but in a different fashion. They will give their best performance in an environment that has a near constant temperature, preferably around 25°C. If subjected to very low states of charge the acid content of the electrolyte will be reduced, raising its freezing point. At temperatures well below the freezing point of water the batteries can then be permanently damaged. Moreover, at lower temperatures the capability of a battery to store and deliver power is reduced, and at sufficiently cold temperatures that capability is nil. The decline in storage capacity with decreasing temperature is depicted in Figure 8.

In addition to the severe reduction in capacity at low temperatures, Figure 8 also shows that excessively rapid charging should generally be avoided at all temperatures for best efficiency. A C/20 rate or a rate that would charge a battery in 20 hours is a good level to aim for. More rapid charging tends to lead to inefficiencies in the form of heat and electrolysis of the electrolyte, accelerating battery wearout. Conversely, if the charging rate is too low, around C/40 or 50, the battery may not fully charge as it gets older.

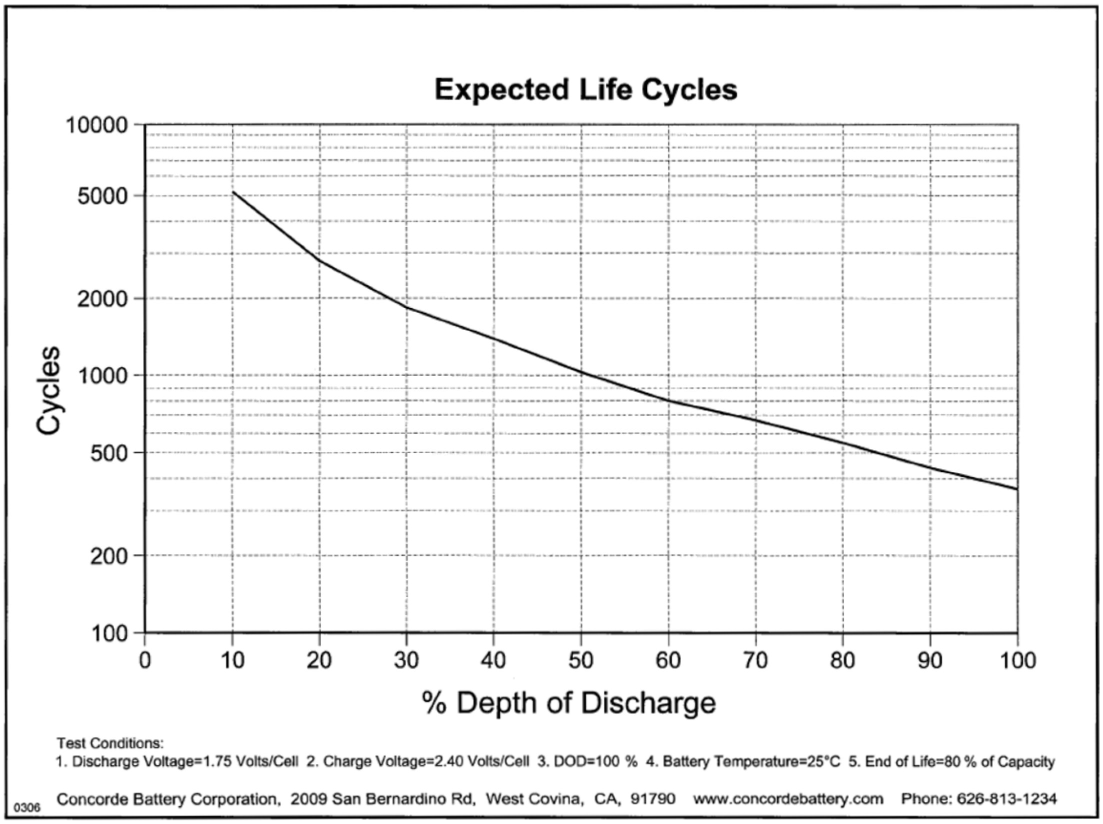

Figure 6. Cycle life vs. depth of discharge for an absorbent glass mat battery. Reprinted from "Technical Manual for Sun Xtender® Batteries" with permission from Concorde Battery Corporation, West Covina, California, USA.

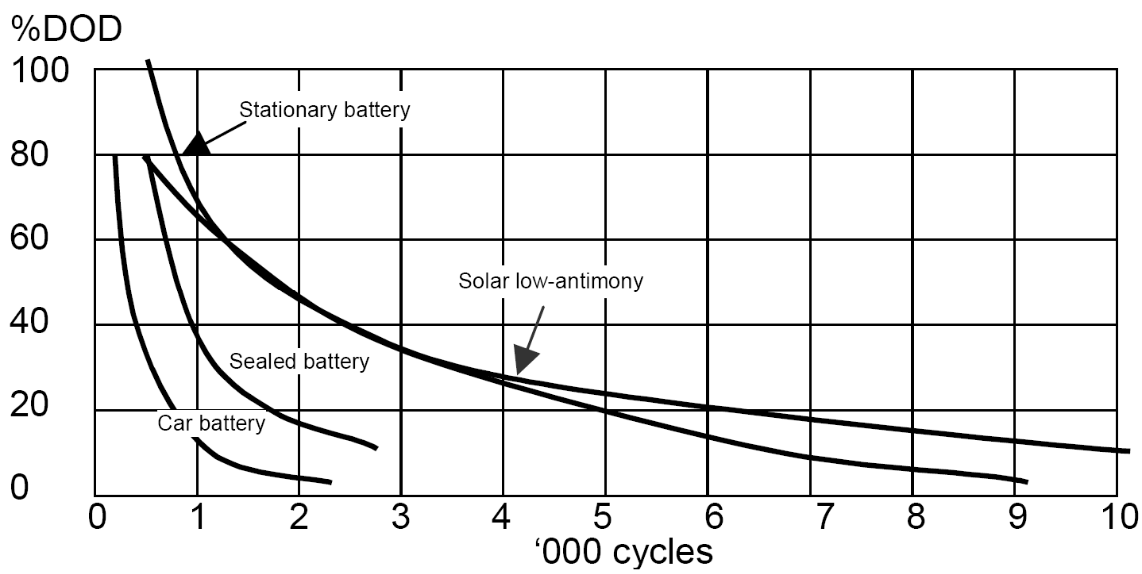

Figure 7. Cycle life vs. depth of discharge for various lead-acid battery types. Reprinted from Appropriate Technology magazine Vol. 21(2), September 1994 (ATBrief No. 9), by permission of Research Information Ltd., Grenville Court, Britwell Road, Burnham, United Kingdom (www.researchinformation.co.uk).

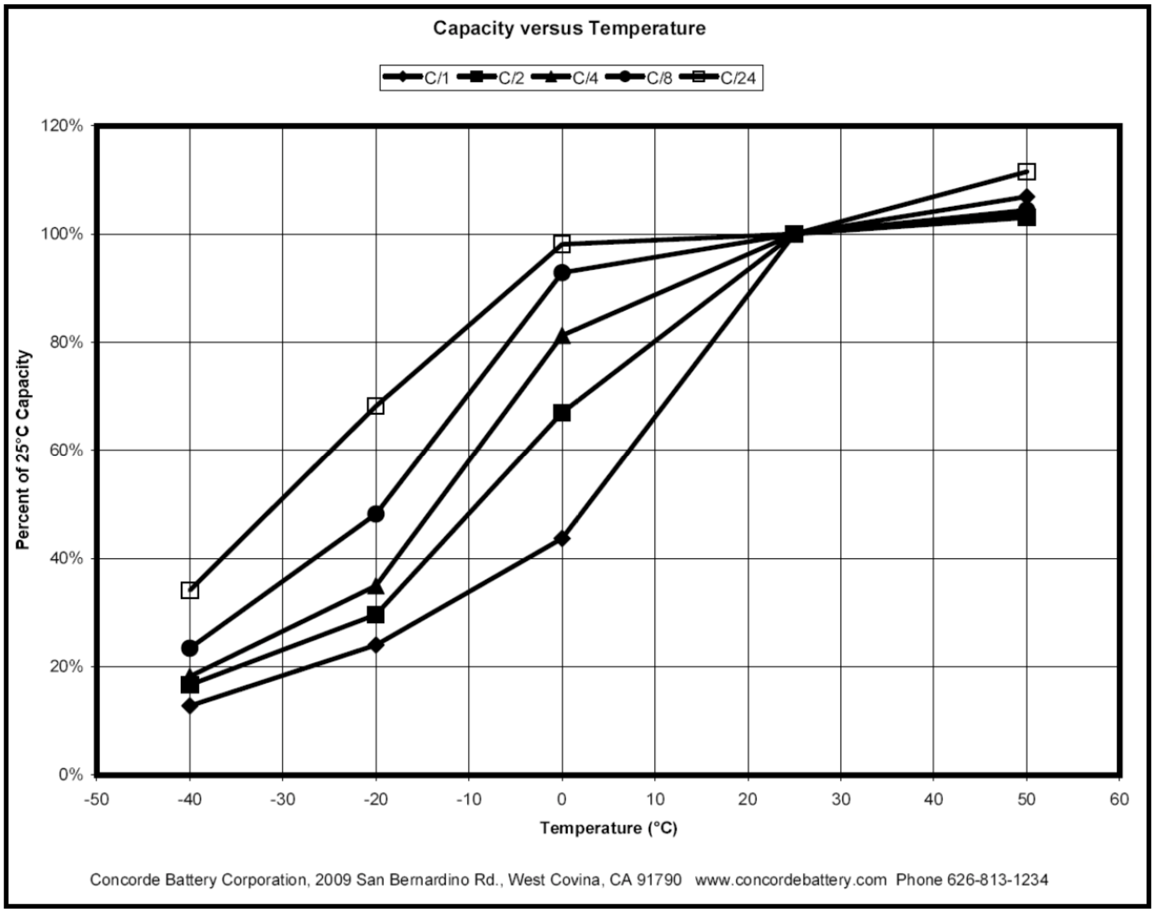

Figure 8. Battery charge retention capacity as a function of temperature. Battery capacities vs. temperature for a range of nominal charging times from one to 24 hours as determined at 25°C. Reprinted from "Technical Manual for Sun Xtender® Batteries" with permission from Concorde Battery Corporation, West Covina, California, USA.

Maintaining a battery near the ideal ambient temperature would be preferred. If that is not practicable, then a charge controller that can maintain the ideal charge voltage as a function of temperature will be critical to battery performance. The effect of temperature on the charging voltage set points for lead-acid batteries is presented in Figure 9. Two voltage levels are indicated. The Absorption voltage is intended to rapidly, but efficiently charge the battery. The Float voltage is intended to maintain battery charge while minimizing decomposition of the electrolyte. This issue is important for all lead-acid batteries because the decomposition products include highly flammable hydrogen gas, but it is especially important for the AGM or gel type batteries because the electrolyte cannot be replaced.

In summary, a variety of factors are known to affect battery lifetime and working capacity. Careful consideration of these factors in the design of NEON infrastructure should enhance system reliability while reducing operating costs. But a cohesive all-encompassing model that would predict battery longevity under all conditions does not appear to exist. Therefore, realistic estimations of battery longevity in the context of NEON's applications are beyond the scope of the present project, and we are left with the intuitive guideline that lead-acid batteries suitable for deep-cycle applications will last about five to seven years if treated well, and will have much shorter lifetimes if subjected to harsh conditions. Assuming reliable data from a highly comparable installation are unavailable for a given site, an empirical preliminary evaluation is recommended prior to permanent implementation, to be achieved by prototyping both the stand-alone power source and instrument load in tandem and then measuring system longevity performance under representative operating circumstances.

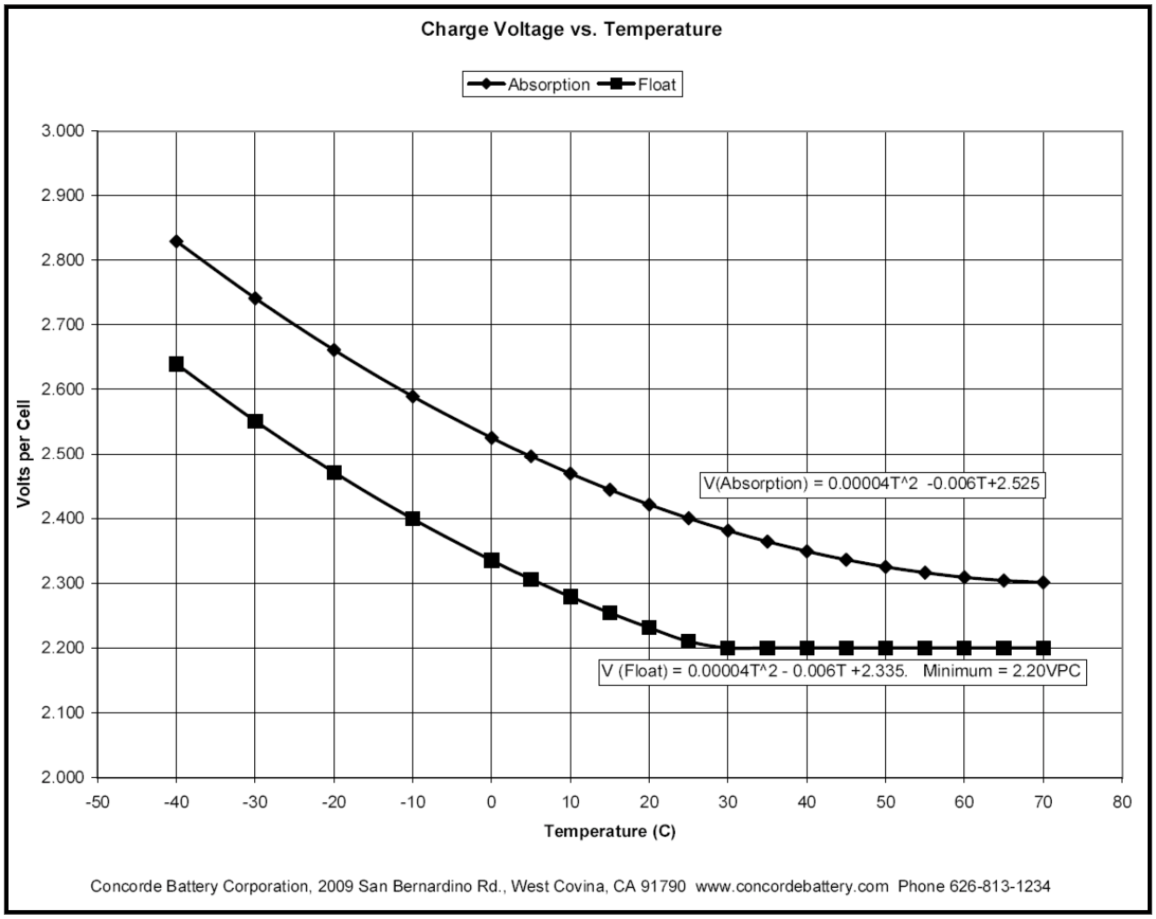

Figure 9. Battery charging voltage as a function of ambient temperature. Recommended rapid-charging (Absorption) and charge-maintenance (Float) voltages vs. battery temperature. Reprinted from "Technical Manual for Sun Xtender® Batteries" with permission from Concorde Battery Corporation, West Covina, California, USA.

Conclusions and Recommendations

Alternative power sources, especially PV or PV/Diesel hybrids, may be suitable for powering NEON installations, especially the aquatic arrays, where power consumption is expected to be modest and the system will be placed in storage during the winter months. All of the power technologies are expected to impact the local environment in some fashion, and NEON implementers will have to weigh these impacts in comparison with the costs and environmental impacts of installing utility line power at remote locations, as well as with respect to the disruption of the site. Respecting PV and wind power, the storage batteries constitute a significant operations cost and logistical burden that will require optimization for each site. Due to the complexities and challenges in optimizing energy storage for these technologies, the engagement of reputable vendors capable of aiding in systems design is highly recommended. Vendor selection on the sole basis of lowest bid is discouraged.

DATA ACQUISITION, TRANSMISSION, INTEGRITY, AND SECURITY (SOW TASKS 2 & 3)

On a very fundamental level, NEON comprises a vast multi-site sensor data collection network. Therefore, the acquisition and reliable transmission of data to a central repository is central to NEON's missions and objectives. Approaches to implementing these capabilities are described in the following, including data retrieval from sensors in the field, local on-site communications, off-site transmission of data to a central database, and data preservation and security. Finally, the concept of a domain control unit for managing the linkages between sensor data streams and the internet is touched upon briefly.

Data Acquisition and Local Communications

Consideration of all National Ecological Observatory Network communications can be broken down into three general categories. In the first category, communication is between the central tower of the fundamental instrument unit (FIU) or the fundamental sentinel unit (FSU) and the sensor suite. The central tower may include wired communication between tower-based antennas and a site-based data logger. The communications in this category are referred to as local communications. Local communications within a site served by a mobile relocatable system (MRS) will be handled in a similar manner for those of an FIU or FSU. In the second category, communication is from the site-specific FIU or FSU to the central data storage facility using standard commercial telephony communications networks, such as the wired or wireless telephone network. The communications in this category are referred to as standard commercial communications. The wired portion of this communication mode is commonly known as the public switched telephone network (PSTN). The wireless portion of this communication mode is referred to generally as Wireless Metropolitan Area Networks (WMANs) which consist of the traditional digital cellular telephone networks along with their extensions for data services, such as the Universal Mobile Telecommunications System (UMTS). The third communication category arises when a remote FIU or FSU communicates to the central data storage facility using commercial satellite communications capability or handcarry of data storage media. This communications category is referred to as non-standard commercial communications.

Local Communications

Local communication in and around the data-collection site should be approached as a fundamentally separate issue from non-local communications. The motivations for separating local communications from commercial communications are several. The first motivation is cost. All communications involving commercial networks to send information off-site include a cost for transmission, while the only cost required to communicate locally is for the power used. Second, all local communications specific to a given NEON site should be stored locally at that site before being forwarded to the central NEON data repository. Many sensors may possess some form of data storage. This can aid in data recovery in the event that site operations or communications are temporarily disrupted. However, each NEON site should have a central data storage facility for all sensor data collected within the environs of that site. The action of storing the data at the local site should also include some data compression and backup archiving to prevent data loss. A final reason for separating local from non-local communications is that local sensor communication devices may be incapable of interfacing with commercial data communications networks due to range or interface limitations.

Site-specific data collection further breaks down into wired and wireless communications. For sensors that operate directly from the site tower, wired or optical fiber communication using local area network (LAN) communication hardware is preferable. Sensors will come with a variety of different communication interfaces, including such venerable types as RS-232, RS-485, and newer Ethernet and universal serial bus (USB) links. These may all need to be accommodated. The recommended approach is to provide a standard network interface to allow conversion of older, wired communication protocols to the standard wired network protocol. The currently accepted standard for moderate performance wired LAN data communications is Ethernet, standardized as IEEE 802.3.

Ethernet, a predominantly open standard, has long ago eliminated the competing token ring and Arcnet standards, which were both primarily proprietary. As an aside, a lesson can be gleaned from this to guide future NEON technology choices, and that is that open standards generally win out over time over proprietary approaches. Ethernet, originally routed via coaxial cable (10BASE2), is now almost universally routed with unshielded twisted pair wires (10BASE-T, 100BASE-T, or 1000BASE-T) and operates as a full duplex system. It is a packet switched system ideally suited to the eclectic suite of devices that a NEON site might well require. The recommended approach for NEON is to use an Ethernet hub[*] to increase reliability, and enable point-to-point management and trouble shooting. Using this approach, a user wishing to connect, say, an RS-232 instrument to the wired data collection network would use an RS-232 to Ethernet adapter to first convert to the Ethernet standard. The data would then be routed through the Ethernet hub and into the data storage system.

Some instruments may exist in a cluster using a data logger such as one of the Campbell data loggers. These are data collection devices with moderate amounts of battery-backed random access memory (RAM). They typically include an analog-to-digital converter (ADC) with a number of analog input pins that can be directly wired to a sensor. The data logger can be programmed for variable data collection intervals directly from the outputs of the suite of sensors that are connected to it. Communications out of the data logger make use of RS-232. RS-232 is an Electronic Industries Alliance (EIA) standard first established in 1969. It is widely used with many variants and will likely be around for a long time yet, but it will eventually be replaced. For this reason, it is recommended that RS-232 to Ethernet converters be used to tie into the wired LAN. This will enable more robust communications that will be both standardized and more easily debugged.

Communications not closely tied to the site tower and central facility should be handled wirelessly. A conceptual diagram of NEON local communications showing the variety of wired and wireless local communications methods is provided in Figure 10. The standard of greatest interest for defining wireless communication at the local level is the IEEE 802.15.4, Low-Rate Wireless Personal Area Network (LR-WPAN). This standard defines the attributes of the communication hardware for executing low power long term communication over moderate distances. Further, the Zigbee specification is an extension of IEEE 802.15.4 and provides a set of protocol layers and application profiles that have been implemented by a number of different commercial manufacturers. The IEEE 802.15.4 standard provides for operation at 868 MHz, 915 MHz, and 2.4 GHz. The operation at 2.4 GHz is accepted worldwide, has a higher data rate and more channels, and is more likely to be widely supported commercially. For these reasons, it should be advantageous to focus LR-WPAN operations on 2.4 GHz. At 2.4 GHz, the IEEE 802.15.4 standard supports 16 channels with a data rate of 250 kbps. The addressing space defined by the standard supports over 1.8×10^{19} devices on 65,535

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[*] Network technicians often make distinctions between hubs, switches, and routers. In this report we use the term “hub” in the colloquial sense. The fine points of distinction among these devices are delineated in http://www.webopedia.com/DidYouKnow/Hardware_Software/2006/router_switch_hub.asp

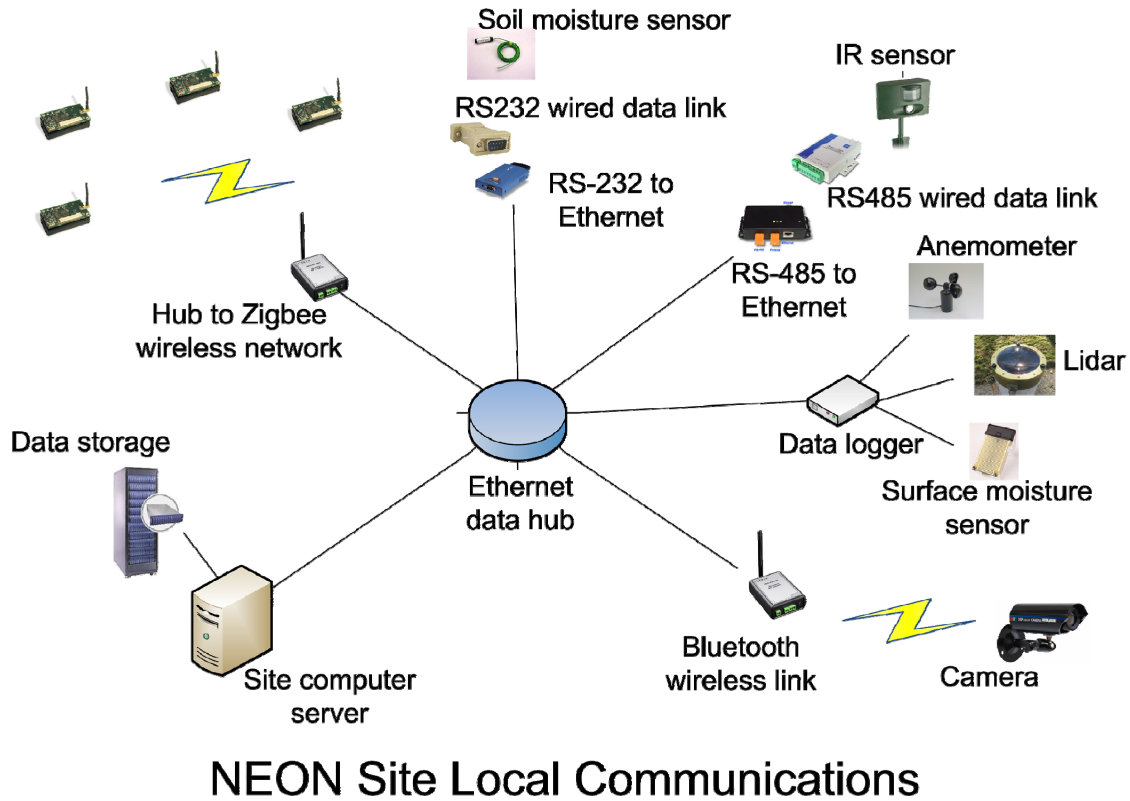


Figure 10. Ethernet hub provides unified interface to data storage and control modules.

networks[4]. For practical purposes, overall network size at a given NEON site will be limited by physical barriers rather than communication limitations.

There are a number of other standards that compete with IEEE 802.15.4 for establishing Wireless Sensor Networks (WSNs), most notably Bluetooth and IEEE 802.11. These other standards lack the power- conserving features designed into the IEEE 802.15.4 standard, and so are not optimal for the construction of sensor networks in which the devices must operate for months or years on a single battery. However, there will most likely be high data-rate sensors at some of the NEON sites for which IEEE 802.15.4 communication links are not adequate. For example, it may be desirable to emplace video cameras in some locations that are remote from the site towers. The fastest Zigbee radios have data rates of 1 Mbps, an inadequate speed to handle video communications. Bluetooth devices currently have maximum speeds of 3 Mbps, and data rates of 53-480Mbps proposed by the WiMedia Alliance. The WiMedia Bluetooth devices, referred to as Bluetooth 3.0, will make use of ultra-wideband multi-band orthogonal frequency division multiplexing (MB-OFDM) to achieve high data rates at modest power consumption levels.

The IEEE 802.15.4 standard supports three types of network devices in a Personal Area Network (PAN). These are the PAN coordinator, coordinators, and devices. The PAN coordinator, of which there is exactly one in each PAN, initiates the network and operates as a gateway to other devices (see Figure 11).

Short Range Network Topologies

The IEEE 802.15.4 (Zigbee) standard lends itself particularly well to the creation of wireless sensor networks. This is because wireless sensors often don't need a great deal of bandwidth to transmit lots of data, but they do need low node latency and very low node power. The low node latency requirement allows the creation of very large sensor networks, since each node rapidly and efficiently forwards on any data that it is tasked with handling. The low node power requirement enables the use of battery-operated devices with long battery lifetimes.

The Zigbee standard permits a variety of different sensor network topologies. The advantage of using devices that adhere to the standard is interoperability. A variety of proprietary wireless devices were created in prior years, but the lack of interoperability of these devices limited their ability to support a long term system. The Zigbee standard should provide a set of unchanging definitions that will enable advanced technology to still communicate with legacy NEON hardware in the future.

The network can grow spatially without requiring the use of high power transmitters. There are two general categories of wireless nodes in the IEEE 802.15.4 standard, the reduced function device and the full function device. Reduced function devices can only be configured in a star configuration with a single full function device talking to a set of reduced function devices. In the star configuration, at least one full function device is required to act as the network coordinator, at the center of the star pattern, illustrated in Figure 12. The network coordinator handles communications with all of the reduced function devices, each of which can talk only to the coordinator. The star topology is the most limited of the possible Zigbee configurations, but it does allow the use of very low cost reduced function devices in locations where many sensor nodes are needed.

The network configuration is determined by the physical placement of the wireless sensor devices. The network coordinator then sets up the network communication by transmitting network beacons. Each network therefore needs exactly one network coordinator, referred to as the PAN coordinator. If a new device enters the network, or an existing device leaves the network, the coordinator updates the network layer to enable uninterrupted communications to and from all devices in the network.

If a network with more than one full function device is to be established, these can be configured in either a peer-to-peer or a cluster tree topology. A cluster tree topology is formed from a set of interconnected star configurations. Each cluster tree network must have just one PAN coordinator, but it can have a number of different cluster trees, each with a single full function device in its center.

A peer-to-peer topology is the most flexible network configuration, as it enables communications to be conducted between many devices without a centrally coordinated scheme. The disadvantages of using a peer-to-peer topology are that each node must be a full function device and nodes will tend to remain in an active, powered state for longer and will consequently have shorter battery lives.

The different types of network topologies can be combined and mixed together, provided that the rules previously stated are adhered to. That is, each network must have exactly one PAN coordinator and partial function devices can only serve as network end devices. The resulting network topologies can be the most efficient to optimize both data throughput and long battery life.

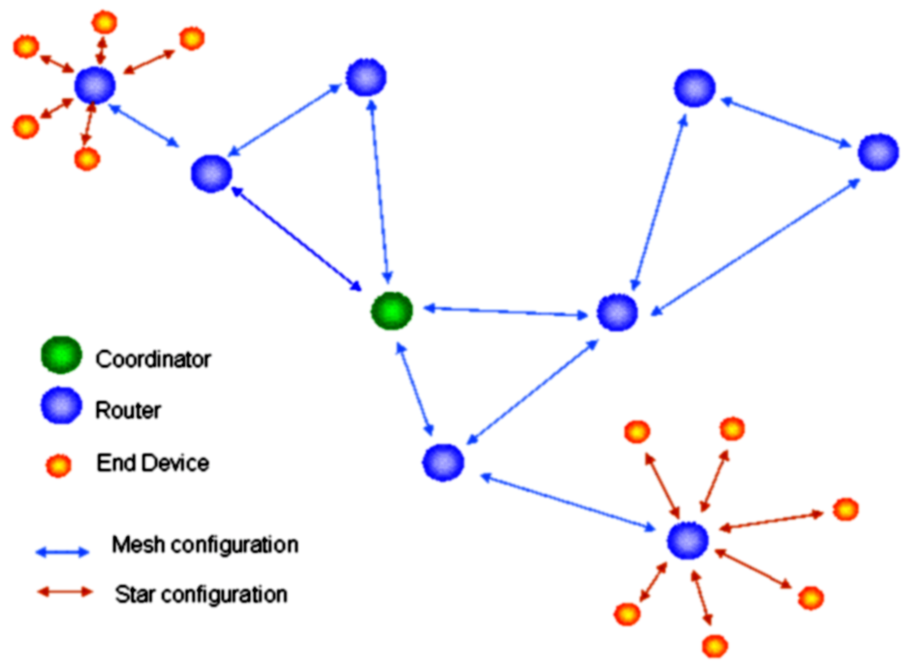


Figure 11. Zigbee network architecture combinations.

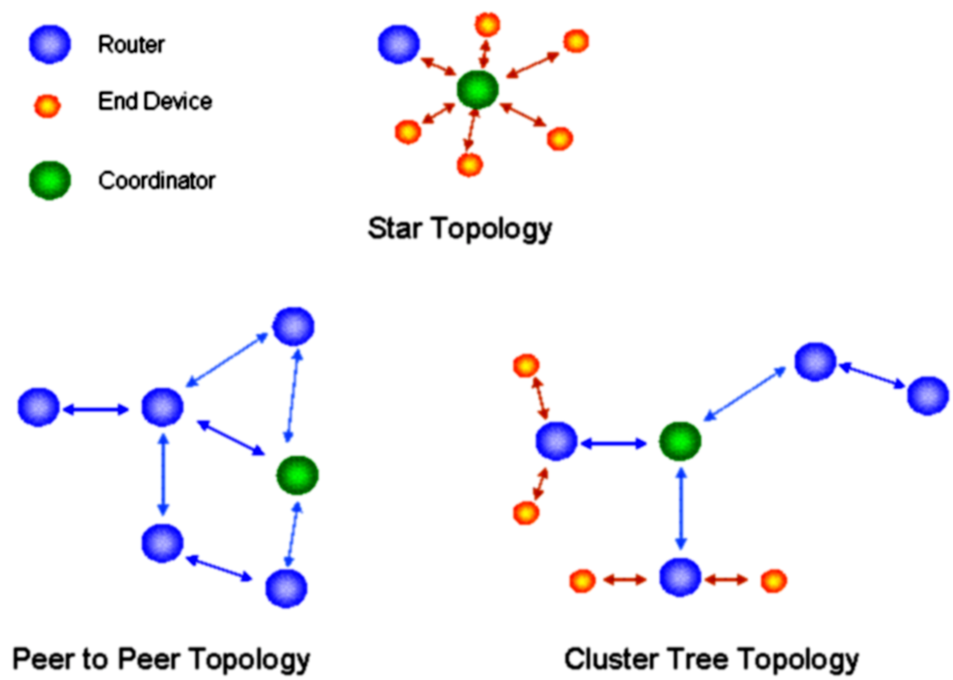
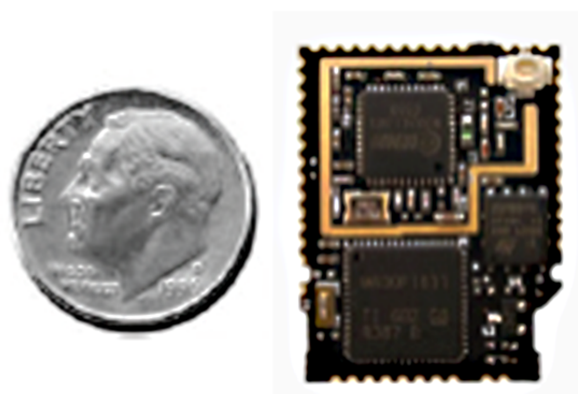


Figure 12. Zigbee network topologies.

Wireless Sensor Network Implementation Using Motes

Field data for NEON sites can be collected by a variety of means. For sensors close to a central data hub, wired connections will suffice. For sensors located in the field, wireless communication networks will be an increasingly attractive option that cannot be overlooked. The IEEE 802.15.4 (Zigbee) standard for wireless data communications has spawned a wide range of data collection devices often referred to as “motes”. Several such motes are depicted in Figure 13 through Figure 18 below. A wireless mote may include a variety of different components and capabilities. Nearly all will contain a wireless transceiver, a control microprocessor, and a battery pack. Most will also have an onboard antenna or antenna port, an expansion port, and an onboard analog-to-digital converter. The TinyOS operating system, created at the University of California at Berkeley, is widely used to implement the software driven protocols of the IEEE 802.15.4 standard. Implementation of a sensor node using one of these commercial devices is primarily an exercise in high level programming. The TinyOS handles most of the difficult operational tasks involved in data collection, storage, and transmission of data as well as network communications. Motes are ideal for many aspects of NEON field data collection. They are capable of directly interfacing to both a sensor and a wireless network to collect data and relay that data back to the local hub of the NEON site. A tremendous amount of sophistication in data conversion and networking has already been incorporated into both the Zigbee standard and the TinyOS operation system. Were NEON system designers to ignore this capability and fail to include it into most NEON sites, it is likely that site users would force a retrofit at some future date.

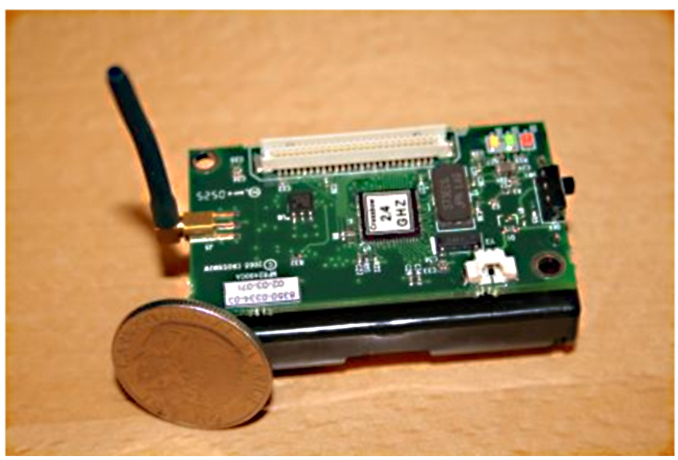


Sentilla Mini: Mote with MSP430 and transceiver, no antenna
no apparent I/O, and no immediate availability

Figure 13. Sentilla Mote.

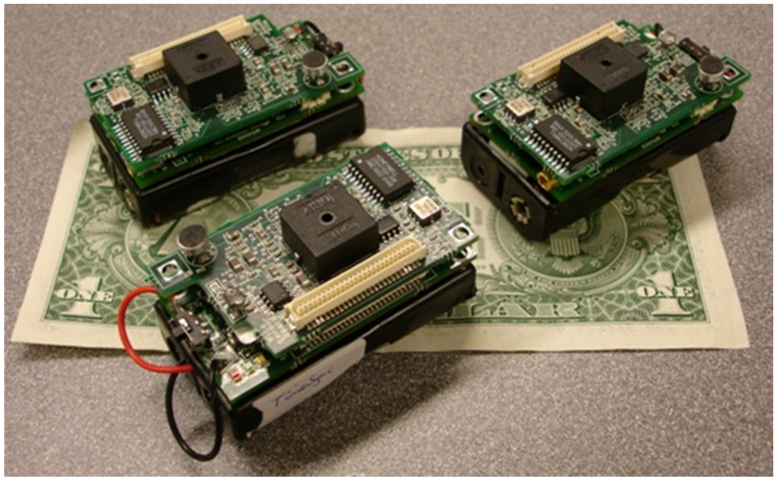
TelosB TPR2420: MSP430, 2.4GHz transceiver, Moteworks/TinyOS operating system, 6 and 10 pin expansion connectors, USB port

Figure 14. TelosB Mote.



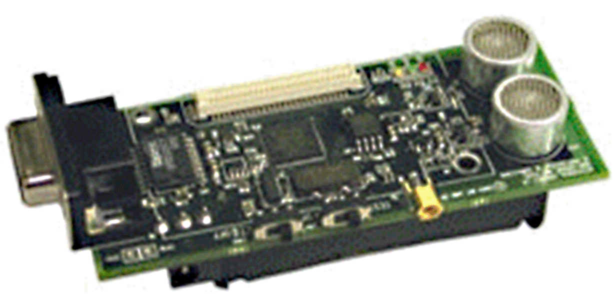
MicaZ: ATmega128L processor, 2.4GHz transceiver, no onboard antenna, 51 pin expansion connector, Moteworks/TinyOS operating system

Figure 15. MicaZ Mote.



Mica2: ATmega128L processor, 868/915MHz transceiver,
51 pin expansion port, Moteworks/TinyOS operating system

Figure 16. Mica2 Mote.



Cricket MCS410CA (version of Mica2): location finding
mote, 434MHz, with RS232 port, 51 pin expansion connector

Figure 17. Cricket Mote.

IRIS: ATmega128L processor, 2.4GHz transceiver, no onboard antenna,
51 pin expansion connector, 250kbps, Moteworks/TinyOS operating system

Figure 18. IRIS Mote.

All of the motes pictured above are commercially produced. Despite increasing production of the essential ZigBee transceiver chips[5], estimated to reach 150 million in 2009, commercial mote availability is somewhat tenuous, as they are all produced by small companies that may drop production with little advance notice. For example, the Sentilla Mini replaces the Tmote Sky, since Sentilla took over production rights from Moteiv, producers of the Tmote Sky. Sentilla has dropped production of the Tmote Sky, and the Mini appears to be not yet available and possessing different capabilities than the Sky. The WeC, Rene, Dot, Mica, Mica2, and Telos all belong to a sequential family of motes designed at the University of California at Berkeley. The last additions to this family, the TelosB and MicaZ are currently produced and marketed by the commercial company, Crossbow. These motes will almost certainly be superseded by more advanced versions which may or may not support a specific desired function extant in a current mote.

The diagram in Figure 19 below shows a cross comparison of eight different mote specifications for five different motes. With these stark differences in mote specifications it should be clear that selection of the most appropriate mote capabilities for NEON applications would necessitate a thorough evaluation of the suite of sensors that might sensibly be linked to motes and the specifications that would best address that sensor suite. Given the variety of NEON sensors it is possible that more than one mote design would be required to adequately address the need.

While one or more of the commercially available wireless motes will certainly be adequate for most sensing tasks at NEON sites, it may still be advantageous to develop a customized variant specifically for NEON applications. The primary reason for this is the tendency for motes to be dropped from production with little notice. Another reason may be the ability to maintain backward compatibility with key mote functions as future capabilities become available and necessary. Developing a standard NEON mote should not be overly difficult. The standard UC Berkeley TinyOS should be operational on the mote, since this is already a *de facto* standard of the wireless mote world and replacing and supporting an operating system is a large effort. Hardware could be an enhanced variant of the Tmote Sky, a UC Berkeley mote with readily available technical documentation that is no longer sold.

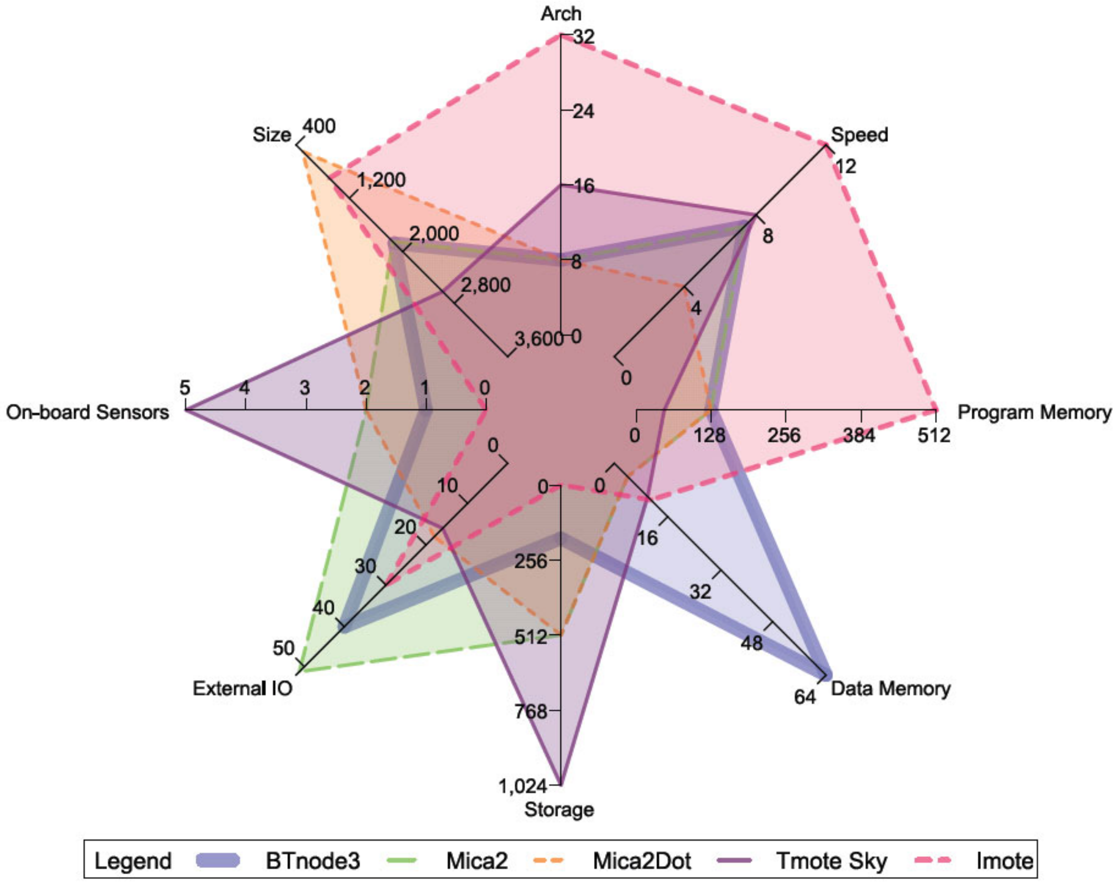


Figure 19. Mote specifications engineering tradeoff diagram. This diagram was produced by and is shown courtesy of the Sensor Network Museum by BTnodes: http://www.btnode.ethz.ch/Projects/SensorNetworkMuseum.

There are certain key elements that should exist in any mote, whether commercial or custom. First, the mote must contain a Zigbee compatible transmitter/receiver. Several appropriate RF transceiver chips produced by reputable manufacturers are presently available on the market. A listing of these transceiver chips is given in Appendix C: RF Communications Hardware Data. In addition to the transceiver, the mote must contain a control microprocessor, a power source, and at least one general purpose data port. It should also contain an integral antenna with an additional antenna port to enable adding a high gain, directional antenna to increase network range. The power source for the mote must include a battery. It might also include a supplemental battery charger via a small solar cell. A conceptual sketch design for a possible NEON mote is provided in Figure 20.

Power consumption in a battery operated sensor application is always a key concern. The field of wireless motes has gone through several generations to optimize this and other specifications. It is currently possible to create a network of motes that achieve battery lifetimes of 2-3 years from a pair of AA batteries[6].

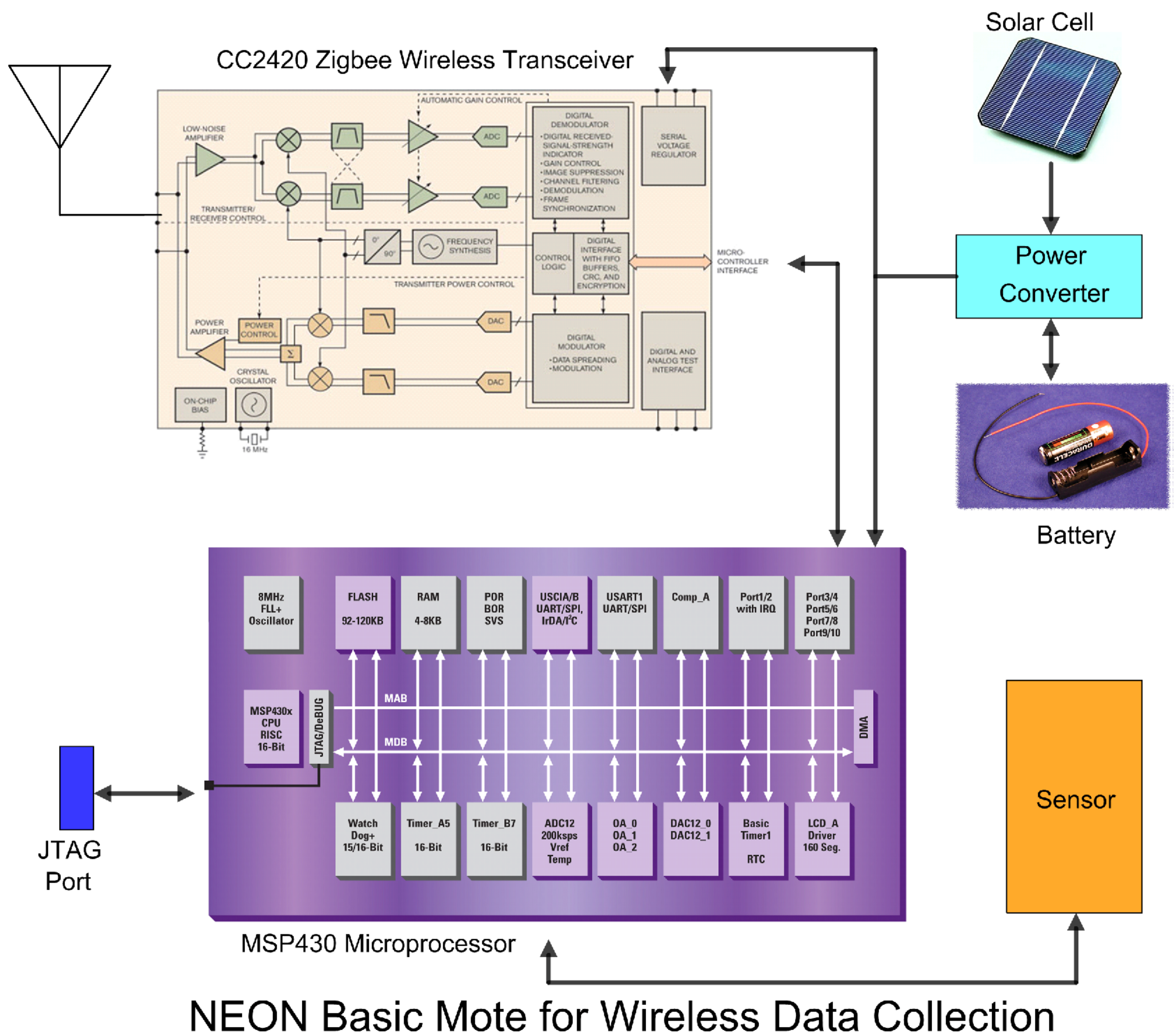


Figure 20. Scheme for a standard NEON mote.

Long Distance Data Transmission

Excepting hand-carry of data storage media, long distance data transmission between the NEON sites and the central database is expected to utilize the internet. A notional diagram illustrating one mode of long-distance data transmission between a NEON site and the internet is provided in Figure 21. Each of the available long-distance communication methods has strengths and weaknesses. The choice of preferred method for a specific NEON site will depend on various factors, and more than one method may be implemented to provide a collateral data path in the event that the primary choice is disabled.

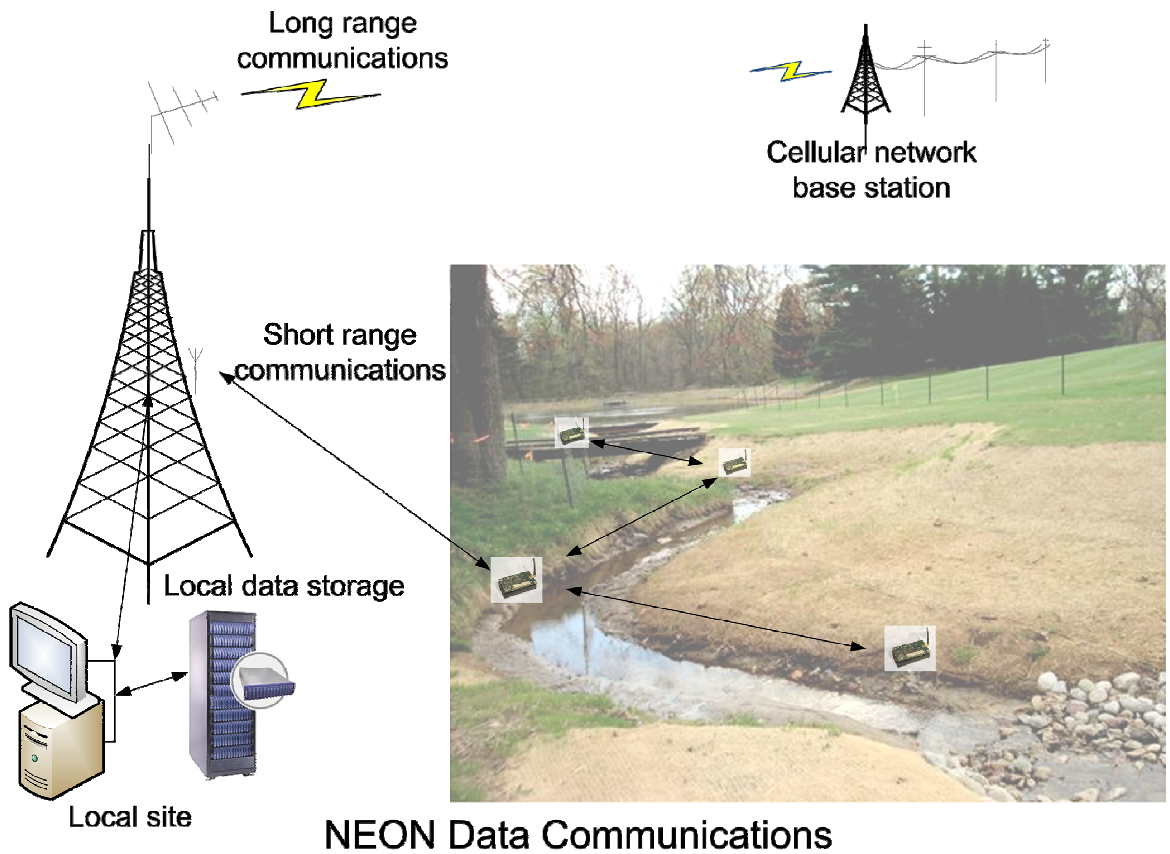


Figure 21. Conceptual NEON data communications framework.

There are multiple options for connecting sites to the Internet. These are listed below:

Standard Commercial Communications –

- **Telephone Land Lines (DSL/ADSL)**
- **Cellular Telecom Networks**
- **Dedicated Wireless / Land Line Hybrid**

Non-Standard Communications –

- **Direct Satellite Communication**
- **Hand-Carry of Modular Data Storage Devices**

Each option has its particular strengths and weakness, described in the following sections.

Standard Commercial Communications

Communications from each NEON site, whether mobile or fixed, to the central NEON data storage site, will primarily be conducted using land-line wired telephone service, more commonly known as public switched telephone network (PSTN), or its wireless equivalent, the Universal Mobile

Telecommunications System (UMTS). Where a wired connection is available, a digital subscriber line (DSL) service is preferred for high data rate communication.

Current DSL equipment can deliver 8.0 Mbps (24 Mbps with ADSL2+) over up to 2 km of standard twisted pair telephone line (or up to 4 km at lower data rates). To communicate over greater distances over the PSTN local loop, an asymmetric digital subscriber line (ADSL) loop extender can be used at a fairly low cost. The ADSL loop extender is essentially an amplifier that boosts the high frequency DSL signal along with any accompanying noise. For somewhat greater cost, a series of signal regenerators can be used to greatly extend the distance between the telephone subscriber, the NEON site, and the digital subscriber line access multiplexer (DSLAM) that defines the starting point of the truly high speed portion of the telephone network. If truly high speed fixed-line communications are needed, a fiber connection can be brought to the NEON site, essentially eliminating the DSLAM and DSL portion of the PSTN communication scheme. The cost for this is typically the incremental increase from that of DSL service (about $40 per month) to that of dedicated T1 service (about $800 per month), so it would be best to make use of DSL service, if possible.

It is worth noting that DSL connections are asymmetric, and normally in a home or small business internet access application are arranged with the larger (downstream) portion of the bandwidth transmitting to the subscriber, and the smaller (upstream) portion of the bandwidth configured for data upload from the subscriber. Thus, a DSL service with 8Mbps downstream feed also has a 1Mbps upstream feed. But the asymmetry could also be arranged in the opposite direction for NEON's applications to expedite data extraction from NEON's sites.

Long range data communications that cannot make use of the PSTN can use the public wireless network (UMTS) as a second option. This option is available for all NEON sites that have a line-of-site access from the NEON tower to a public cellular tower. Range is not an issue for this communication option, as the fixed nature of the data communications permits the use of a very high gain antenna. Even a mobile NEON site can make use of this option for data communications, as long as the site supports a radio tower and remains stationary long enough to establish the communications link. UMTS service providers (ATT/Cingular and Sprint/Nextel) offer 7.2 Mbps data transfer rates in many areas, with 1 Mbps available in most places.

For NEON sites without line-of-sight access to a public cellular tower, a third data communication option exists. It is possible to create a local wireless network between the NEON tower and a local point-of-presence link located at a wired portion of the PSTN. The primary requirement to make use of this option is that a line-of-sight access must exist to a suitable location adjacent to an access point of the wired telephone network. This location may be either on the NEON site or on land that is made available to NEON by agreement. The local wireless network will be capable of carrying data at rates supported by the PSTN, so costs and data rates will be essentially the same as for a direct wired telephone connection, excepting the cost to purchase, install, and maintain the wireless network equipment.

The use of commercially available network equipment will provide a low cost path to system deployment. There are several options available for short distance wireless communications including Wi-Fi, Zigbee and Wi-MAX. Wi-Fi networks are based on two standards; IEEE Std. 802.11b and 802.11g. Both standards have limited range – usually around 100 meters line-of-site using vendor supplied omni-directional antennae[†]. Range can be improved to about 1 km LOS with a

[†] http://en.wikipedia.org/wiki/Wi-Fi

directional antenna. The 802.11b standard has a maximum bit rate of 11 Mbps while the 802.11g standard improves the data rate to 54 Mbps. Capacity should not be an issue, and for local on-site data communications these technologies may prove useful. Considering NEON site communications to the central database, however, it seems likely that extension of the land line would be preferred if a PSTN connection were available within 1 km. Wi-MAX (802.16d, 802.16e), by contrast, has a range of up to 50 km with directional antennae. Bandwidth can exceed 70 Mbps, although there is a range-bandwidth tradeoff, and 10Mbps at 10 km is considered a reasonable expectation. As with any RF communications, the distance that the link can traverse will depend upon the path and what stands between the transmitter and receiver. Foliage will play a big part in signal absorption and needs to be taken into account in any specific installation.

Non-Standard Communications

All long distance communication that is unable to make use of public communications networks falls into the category of non-standard communications. These solutions can consist of several different possibilities, including use of satellite-based data communications systems and physically transporting the data by means of carrying disks, drives, or data tapes. Satellite-based data communication systems are dominated by Hughes/Comsys. Other services are available, including Iridium, Qualcomm, Inmarsat, and Echostar. Hughes, Inmarsat, and Echostar use Geosynchronous Earth Orbit (GEO) satellites at a range of 35,786 km above mean sea level, while Iridium and Qualcomm use fleets of 66 and 44 Low Earth Orbit (LEO) satellites, respectively. The satellite orbits affect how these systems may be used. The GEO satellites appear to be stationary, enabling the use of a fixed-orientation dish, tend to provide upload bandwidth at hundreds of kbps, but line-of-sight may be blocked in valleys or north of mountain ranges, especially at higher latitudes. The LEO satellites appear to be constantly moving, and their orbital paths take them over the polar regions, but data rates tend to be much lower, and unsuitable for applications requiring GBytes per day. Thus, GEO satellite based services are more suitable to the data rates required by NEON, but accessibility would have to be assessed on a site by site basis.

There are several significant limitations to using any satellite-based system for NEON data communications. First, the maximum upload rates are much slower than those available for terrestrial communications. On Hughes satellites, the upload speed for a standard commercial terminal is limited to a maximum of 300 kbps, and slower speeds of 165-180 kbps are to be expected during peak usage periods. Dish Network (and others such as WildBlue) provides a “small dish” high speed internet service via the Echostar geosynchronous satellite network which can provide from 128 kbps upload speeds to 256 kbps. On an Iridium satellite, the data rate is limited to 2.4 kbps. Second, the cost is considerably higher for all satellite-based communications. Hughes lists the cost of their premium data service plan at $349.95 per month, but this service will not support the amounts of data that will need to be communicated out of a NEON site. Rates to support a NEON site will need to be negotiated with the service provider, should that be the preferred solution. A third potential problem with satellite communications from a NEON site is the limited coverage footprint of geosynchronous satellites. The NEON sites which are most likely to be candidates in need of satellite communications are the ones which will have the most down time due to marginal link performance. Satellite communications, particularly to geosynchronous satellites operating in high latitudes or in places with snow or high precipitation levels, have significant amounts of time during which the link is unavailable[7]. Rain margin can be improved at the expense of using larger dishes, but at additional expense.

Hand-carry of modular data storage devices can be used at the most remote sites, or at locations where telecommunications systems have failed, to collect data and return it for analysis. This option would make use of hot swappable data modules that would contain high capacity storage such as removable hard drives or solid state drives. The remote site would need to be visited to collect the modules. They would then be connected to the internet at another location for download of the data. While simple in concept, and requiring no special equipment, hand-carry does have some liabilities. A system for logging and tracking data movements would be required. Also, direct human intervention increases the likelihood of data loss, theft, and unsanctioned modification. Finally, hand-carry cannot be performed on a continuous basis, and data latency time would be increased. But it does provide a clear alternative to electronic means.

Accessibility of Commercial Cellular Communications

The use of cellular communications as an alternative to standard wired telephone services is especially attractive for two reasons. First, the cost of cellular telecommunications is not unreasonable compared to land lines, and has been rapidly dropping over time. The costs of installation and maintenance are borne by a large population of users, ensuring a high probability of continued availability into the foreseeable future. Second, some form of communications between NEON site personnel will be highly advantageous in any event for operational efficiency and safety reasons, and cellular telephones are ubiquitous, reliable, inexpensive, and generally user-owned. The addition of cellular telephony relays employing highly directional antennas for data and voice communications is proven technology, at least out to a range of 30 miles (50 km) from the target cellular tower. A notional illustration of transmission of data from a NEON site to the central database using cellular telecommunications is provided in Figure 21.

In order to communicate with the cellular infrastructure, one must make a connection to it. A radio and /or TV tower cannot do this unless it also has cellular equipment mounted onto the tower. Due to the electromagnetic field propagation characteristics at these wavelengths the need for line of sight (LOS) between the directional relay and the commercial cellular service is crucial. For these reasons we set out to assess the accessibility of commercial cellular services at each of the proposed NEON sites.

A request to NEON for data describing the site characteristics in greater detail yielded 20 ESRI[‡] shape file data sets which, when used with GIS mapping software, outlined the proposed NEON site areas. Location data for each of the 20 core sites was also provided in the Universal Transverse Mercator (UTM, also referred to as Northing and Easting) coordinate system. Within the core sites there were a total of 43 separate NEON Tower locations, five (5) of which are still to be decided. Unfortunately some of the NEON tower locations were inconsistent with the corresponding ESRI shape files. These inconsistencies are detailed in Appendix D: Cellular Telecommunications Site Access Viewsheds. The FCC provided a shape file data set which contained the location and height information of cellular towers throughout the United States. Detailed elevation data were also obtained for each site. The Global Mapper Version 9 software package (Global Mapper Software, LLC) was used to analyze the data. The Global Mapper software allowed us to map the location of NEON's towers, site elevation, and nearby cellular tower positions as well as the outlines of the different site areas. With this data we were able to use Global Mapper's viewshed software tool to analyze communication possibilities.

Viewshed diagrams show the areas within a defined radius that have a clear line of sight to the cellular tower. These areas are shaded and defined with a black outline as shown in Figure 22. To

[‡] Originally known as Environmental Systems Research Institute, Inc.

generate viewsheds the location and height of the transmitter, the height of the receiver, a communication range/radius, and elevation data are required. The viewshed tool assumes a bald earth when analyzing the elevation, meaning that it does not take into account vegetation and man-made structures. However the tool offers an optional canopy feature where an overall vegetation or structure height can be incorporated into the model. This feature was used for the five (5) core sites described in the NEON-provided FIU Baseline document, which listed the canopy height[2].

Using the viewshed tool we were able to roughly determine whether the NEON towers of a particular site could reach nearby cellular towers in order to transmit data. When towers are just out of the range, a viewshed can help determine the location where a tower might be moved to establish contact, or locations of possible relay towers that could serve as an intermediary for the cellular tower and the NEON tower. An example of a situation where a relay tower could be used is provided in Figure 23.

A listing of the NEON sites and their suitability for interfacing with the cellular communications networks is provided in Appendix D.

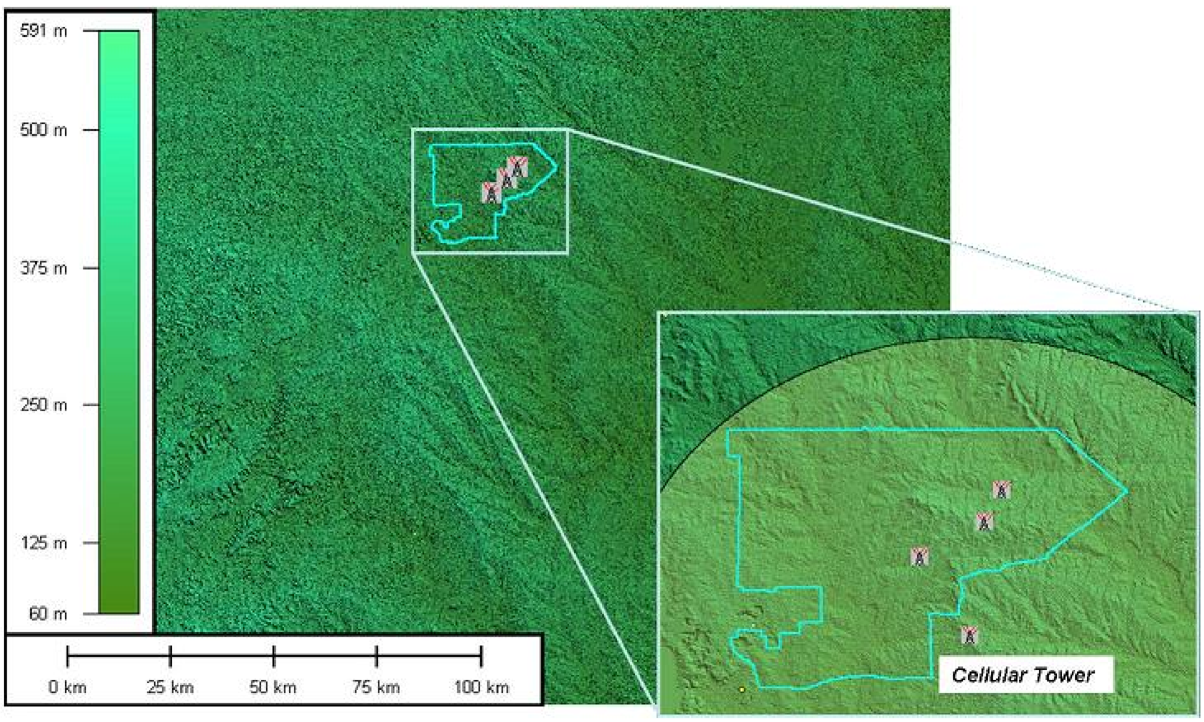


Figure 22. Caddo LBJ Grassland viewshed diagram showing full cellular coverage.

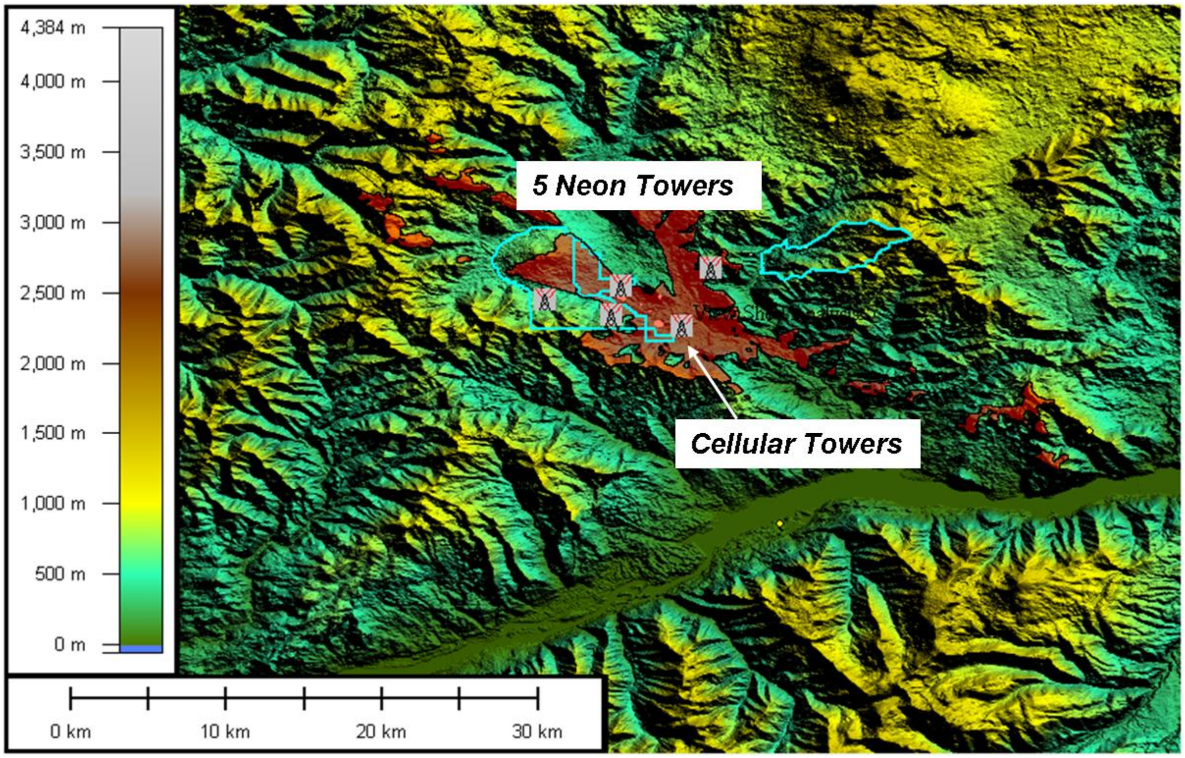


Figure 23. Wind River Experimental Forest viewshed showing need for relay tower.

Data Integrity and Security

The amount of data to be transmitted from the NEON end points to the central database has been estimated to be over 1 TeraByte per year. Data must be transferred from sensors to site collection points and on to the central database via a number of different network media types. All along the way, data must be protected from loss and corruption. Local non-volatile storage is needed to prevent data loss during network outages. The network bandwidth requirement must be greater than 254 kbps in order to permit "catch up" data transmission following network outages. The amount of data that must be stored will exceed 100 MByte per hour. Therefore, some sort of local non-volatile storage is needed on site. Two options have been identified for local storage; traditional hard drives and solid state drives (SSDs). A study of the tradeoffs points to SSDs as a good solution in the anticipated harsh environments.

Straw Man Data Flow

In Figure 24 we can trace the data flow from remote sensors to the NEON data user in this straw man configuration. Data is generated at the remote sensors and transmitted wirelessly to the Remote Data Collection CPU. Wi-Fi is the technology of choice for this link. Wi-Fi is much lower cost when compared to other options being commercially available and is a good option for the relatively short distances to be covered. The use of Wi-Fi reduces installation costs because it requires less infrastructure, is unlicensed and utilizes open standards. Options are available for using Wi-Fi

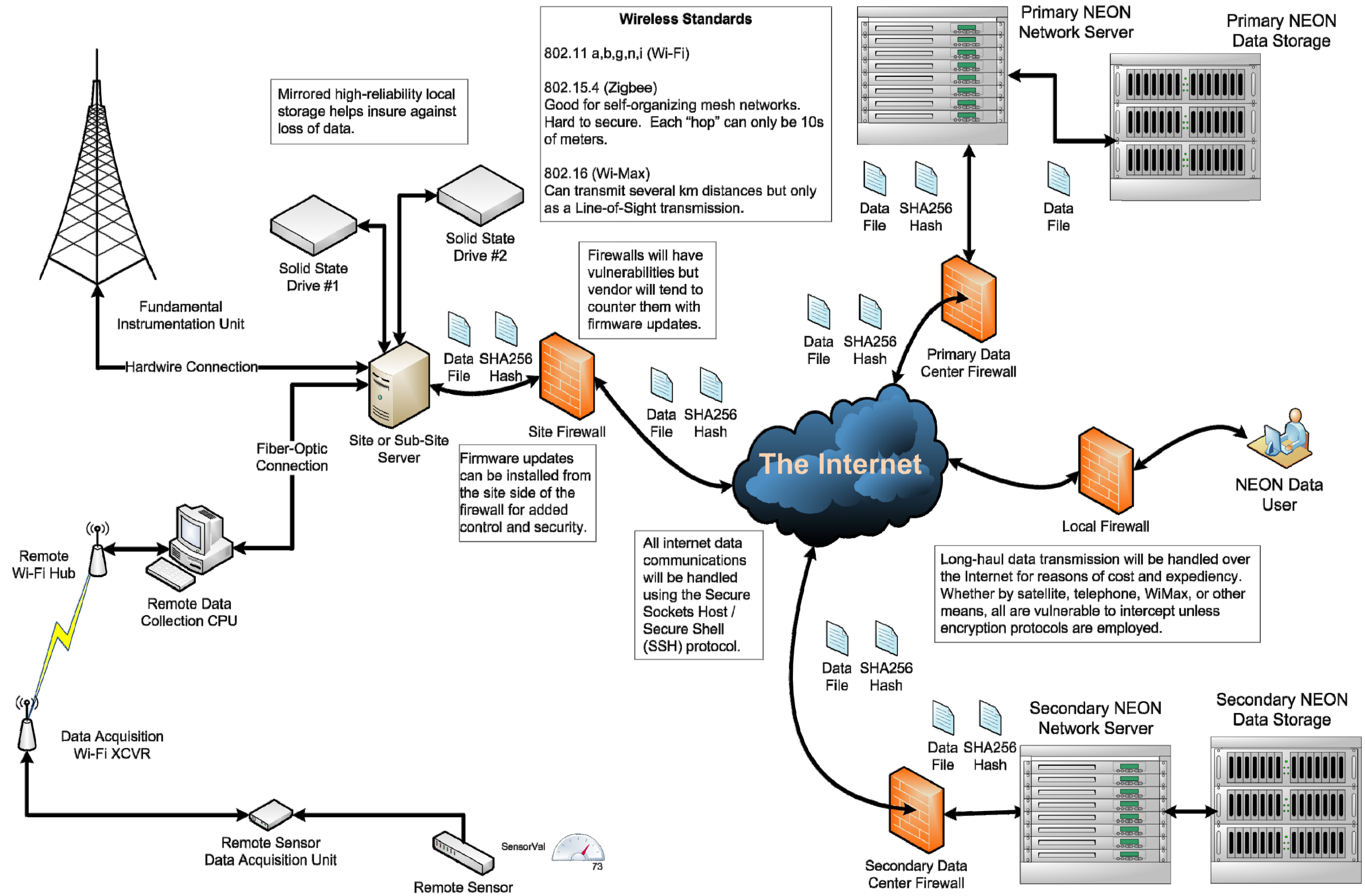


Figure 24. Straw-man data collection, transmission, storage, and retrieval diagram.

protocols and equipment to cover much longer distances point-to-point. Reports of over 100 miles have been found in the literature[§] although this should be considered an extreme demonstration. The Wi-Fi protocols provide for security via data encryption. Specifically, the wireless links can be protected against interception using Wi-Fi Protected Access (WPA) and WPA2 (IEEE 802.11i) standards. WPA2 makes use of Advanced Encryption Standard (AES) block cipher. The 802.11i standard provides for authentication, confidentiality and integrity.

Protection of Data in Transmission to Central Database

For the purposes of this straw man, it has been assumed that the link between the Remote Data Collection CPU and the Site Server is a fiber link. However, for short distances (<100 meters) it might be equally acceptable to use copper. The protocol is Internet Protocol (IP) over Ethernet. The normal IP communications protocols such as Transmission Control Protocol (TCP) or User Datagram Protocol (UDP) will be acceptable for these purposes. This link can be protected with encryption either by encryption of the data files, encryption of the data connection using Secure Shell (SSH) protocol and/or link encryption (Virtual Private Network, or VPN). From this point onward, the underlying protocol is assumed to be standards based.

Encryption of data between nodes is suggested as a way to protect the data from disclosure, corruption and tampering. It would be best to insure that all data is sent through the Internet using Secure Sockets Host/Secure Shell protocol to protect data from interception. The servers must be protected using network firewalls to prevent hijacking of these computers. It would be best to deploy hardware firewalls since they are less susceptible to exploit. The VPN is used to provide protected access to the remote sites and authentication. Since the delivery network (the Internet) cannot be trusted the VPN will enforce security with authentication mechanisms. The VPN uses cryptographic tunneling protocols providing confidentiality, sender authentication and message integrity[**]. Optionally, there are several software VPNs. An example of a standards based, software VPN service is OpenVPN[††]. OpenVPN is free and has an open source code base. There are multiple options available for the VPN and these will need to be studied in detail before a final choice can be made.

The security framework should work with any transmission method and storage medium. Therefore, the suggested format is a data file. Data must be protected from corruption using a hash algorithm. Such algorithms generate a specific sequence from any given data set that may be considered unique to that data set for most practical purposes. Regeneration of the hash code at the receiving end of a data transmission should yield an identical sequence as the pre-transmission original. Any difference is indicative of data corruption, whether due to transmission errors or interception and malfeasance. In the event of data corruption, the data can be discarded and a signal sent to re-transmit the damaged data. The Secure Hash Algorithm SHA-256 is recommended for NEON. It is suggested that the data, any additional meta data and the hash can be provided in one file. The decision on the form that the data takes is up to the system implementation. It should be noted here that the SHA-256 algorithm generates a 256-bit hash, a very modest transmission overhead for data files comprising hundreds of kilobytes of data or more.

[§] http://eslared.org.ve/

[**] http://en.wikipedia.org/wiki/Virtual_private_network

[††] http://en.wikipedia.org/wiki/OpenVPN

It is also possible to encrypt the data file. Encryption would protect the data from disclosure and provide some degree of authentication. The decision to encrypt or not is really a system decision. Authentication and integrity can be achieved without encrypting the data. If encryption is an option, it is suggested that 256-bit Advanced Encryption Standard (AES) would be the best solution.

Software based encryption would be suitable given the data rates associated with this project. But if technology advancement or changes in NEON objectives were to dramatically increase the required data rates, hardware-based encryption could be used.

Finally, it is important to protect the data from premature disclosure or unsanctioned modification in case the hardware is stolen from the remote site. If past experience is any measure, one should expect that the equipment will be stolen at some point. In that case, full disk encryption, such as PGP Whole Disk Encryption or TrueCrypt can be used to protect the data.

Central Database

The central database is the place where all data from the remote sites is collected and maintained. It is suggested that there be both primary and secondary data centers. The data centers will serve as alternative storage sites, providing real time back-up in case of equipment outage, power outage, and/or network outage. These data centers will utilize Intrusion Detection System (IDS), Storage Area network (SAN) and tape backup subsystem LT04 standard. The sites should be located in geographically separated locations to prevent data loss from natural disaster, vandalism, or acts of terrorism. These sites should be connected to different physical networks in order to protect against single point of failure. Sync software is used to keep the data replicated between the two sites. For security reasons, users should only have access to one site. If the budget allows, a third site would offer even greater diversity and protection. It is possible that the use of a third site could offer faster access to a larger group of users.

Local Non-Volatile Data Storage

The remoteness of the sites will mean that there will be extended periods of time when communications with the central server will be lost. It is a requirement that data collected during these network outages must be stored locally for transmission to the central database at a later time. There are two promising options for local storage of this quantity of data; traditional hard drive technology and solid state (FLASH ROM) technology. Most people are familiar with the tried and true rotating disk hard drive. The newest generation of SSD devices provide some advantages over rotating disk drives, however, they suffer from lower storage capacity and higher cost per Gigabyte. Table VI below provides a comparison of specifications for two representative storage devices.

The operating temperature range of the SSD is superior to the hard disk. The SSD operating range is extended at both low and high temperatures. This is important for the harsh environments expected at the remote locations. Temperature extremes are also an issue for the other electronics in the system and may require environmental controls which can moderate those extremes. The SSD are significantly more resistant to vibration and shock since these devices have no moving parts. This feature also plays a part in the greater mean time between failure numbers for the SSD which is over 2 million hours. The cost of storage using SSDs is significantly higher at the current time. The traditional hard drive has the advantage of being a mature technology with $0.69 per GByte compared to $12.34 per GByte for the SSD technology. However, SSDs are relatively new and the cost can be expected to drop dramatically over the next few years.

Table VI. Feature Comparison of Typical Computer Hard Drive and Solid State Drive.

Specifications	Fujitsu MHZ2080BK 80 GB Extended Duty 7200 RPM Hard Drive	Samsung MCCOE64G5MPP 64GB Solid State Drive
Interface, Phy Rate	SATA, 3Gbps	SATA, 3Gbps
Operating Temperature	5°C to 55°C	0°C to 70°C*
Non-Operating Temperature	-40°C to 65°C	-55°C to 95°C
Relative Humidity	8-90% RH	0-55°C / 90-98% RH
Vibration	1G, 5 to 500 Hz	1500G
Shock	5G, 5 to 500 Hz	1500G
Operating Altitude	-1000 ft to 10,000 ft	
Non-Operating Altitude	-1000 ft to 40,000 ft	
Power Requirements	5V 2.30 W Read/Write 0.80 W Idle	5V 0.41 W Read/Write 0.32 W Idle
MTBF	300,000 hrs	2,000,000 hrs
Price (Retail)	$55.00	$790.00

Equipment Reliability and Protection

Commercial network equipment cannot be expected to operate much outside of the 0 – 70°C temperature range (non-condensing humidity levels). However, the cost of hardened equipment can dramatically impact the cost of this equipment. The best, low cost solution is to provide environmental protection (insulation, heaters) from the harsh environments expected at the remote sites. Security of the local sites against theft or tampering is also important. There are numerous accounts of equipment being stolen from remote research sites. Therefore, security at the remote site requires communications with local alarms directed to the attention of on-site staff. This can be achieved over the same data links. It is important to protect the site security information (alarms, sensor data) with the same encryption and authentication techniques used for the site sensor data.

Domain Modular Cyber Infrastructure Interface

The NEON domain modular cyber infrastructure interface (DMCII) is a concept that includes the hardware and software for local and long range communications as well as site data storage and security. The DMCII contains the following elements: local wired (Ethernet) communications, local wireless network (Zigbee) communications, local high-speed wireless (Bluetooth) communications, long range communications (wired or wireless), computational control, data storage, data and communications security, environmental protection, and power source. The necessary elements of the DMCII are diagrammed notionally in Figure 25.

The local and long distance communications systems have already been described in previous sections. The other electronic elements of the DMCII form the control and storage components. The data storage includes both volatile and nonvolatile memories. The volatile memory includes both dynamic random access memory (DRAM) and static random access memory (SRAM). DRAM is available in gigabyte quantities for the control computer but requires a regular refresh cycle to maintain its contents. SRAM is available throughout the wireless networks, but typically only in sufficient amounts to permit temporary storage of local node sensor output data. The local wireless sensor nodes operating under the Zigbee protocol function under power cycled conditions to greatly reduce power consumption at that node. This means that each node must temporarily store its sensor data while the wireless transmitter is in its power cycled "off" condition. The data can then be relayed out while the wireless transmitter of the node is in its "on" state. Once the network has relayed back to the node an acknowledgement that the data has been correctly received and stored, the node SRAM can be freed up to collect the next round of sensor data.

Several approaches to the hardware and software implementation of the full DMCII concept could be taken but these should be carefully examined. While SCADA technology has been mentioned as one option, for example, provisions for data security and integrity in that traditionally open framework are still in the developmental stages[8]. A thorough comparative evaluation of rational implementation approaches is strongly encouraged but beyond the scope of this report.

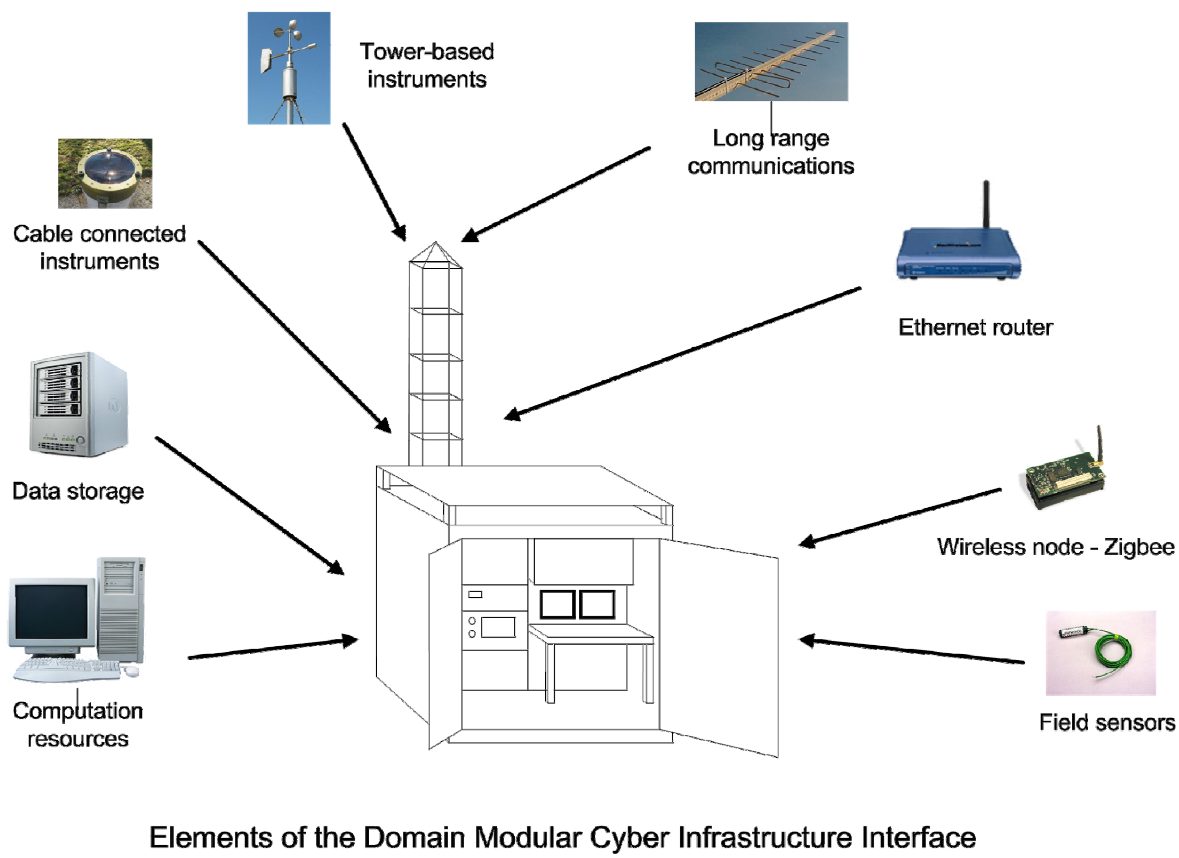


Figure 25. DMCII notional diagram.

Conclusions and Recommendations

In summary, there are several options available to NEON at each stage of the process of data acquisition, local handling, and off-site transmission to NEON's central database. Among these options, we strongly encourage:

Data Acquisition and Local Communications –

- **Adoption of Ethernet as the on-site data communications standard**
- **Selection and periodic updating of an approved set of hardware for conversion of other standards to Ethernet to accommodate existing sensors**
- **Incorporation of adaptive wireless motes as a foundational element of the NEON data acquisition and site communications approach**

Long Distance Data Transmission –

- **In order of preference depending on site conditions use: (1) the land-line telephone system; (2) the cellular telecommunications system; (3) the land-line system with a dedicated wireless link; (4) satellite data communications; or (5) hand-carry of modular data storage devices**
- **Consider incorporation of cellular telecommunications access at all possible sites as a primary or secondary data transmission channel as well as for the safety of site personnel**

Data Integrity and Security –

- **Use hash algorithms for all data file transmissions to the central database**
- **Design all NEON on-site temporary data storage to utilize hot-swap solid state drives in a redundant array configuration in order to facilitate hand-carry of data when needed while preserving data integrity**
- **Develop an accountable system for managing data hand-carries and the deletion of site data following incorporation into the central database**
- **Use software encryption to securely store all data temporarily stored on-site, and for data files transmitted to the central database**

General –

- **Perform a thorough systems analysis examining the data communications accessibility and cost tradeoffs for all NEON sites and sub-site local networks in detail**
- **Consider development of a complete sensor-to-database hardware and software testbed, with *in situ* assessment of options and challenges, prior to full implementation of the NEON network**

NETWORK SYSTEMS DEVELOPMENT AND OPERATIONS MANAGEMENT (SOW TASK 4)

System Models for NEON Infrastructure and Operations Management

Systems engineering should play an important role in the design, implementation, and operation of any large complex system where efficiency and effectiveness are critical for success. Thus NEON should seek to benefit from a holistic systems approach wherever possible. Part of that approach should be to examine existing systems of similar types to learn what one can from them. Here we consider a number of existing systems which have similarities to NEON. However, we focus primarily upon the US Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program, a component of which appears to have much in common with NEON.

ACRF as a Model: Overview and Comparison with NEON

The ARM Program was created in 1989 with funding from DOE's Office of Science, and is managed by the Office of Biological and Environmental Research. ARM is a multi-laboratory, interagency program, and is a key contributor to national and international research efforts related to global climate change. A primary objective of the program is improved scientific understanding of the fundamental physics related to interactions between clouds and radiative feedback processes in the atmosphere. ARM focuses on obtaining continuous field measurements and providing data products that promote the advancement of climate models.

During the early years of the program, efforts were primarily devoted to establishment of field research sites, development and procurement of measurement instruments, and development of techniques for both atmospheric retrievals and model evaluation. An approximate time line for the development of ARM is shown in Figure 26. It is included so that one can see how long the various elements of ARM took to develop. NEON, of course, may proceed either more rapidly or more slowly, depending in part upon the funding available.

In order that ARM obtain the most useful climate data, three main sites were chosen that represent a broad range of climatic conditions. The Southern Great Plains (SGP) site in Oklahoma provides many different cloud and surface types, and large seasonal variation in temperature and specific humidity. The Tropical Western Pacific (TWP) locale plays a large role in the interannual variability observed in the global climate system, due to the consistently warmest sea surface temperatures on the planet (referred to as the Pacific "warm pool"). The North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) site provides data about cloud and radiative processes at high latitudes and low temperatures. The Arctic has been identified as one of the most sensitive regions to climate change. In addition, a Mobile Facility completed in 2004 contains most of the same instruments as the permanent sites. Because of its portability and flexibility, the Mobile Facility can support short-term (up to one year) experiments in climate regions not hosting fixed sites.

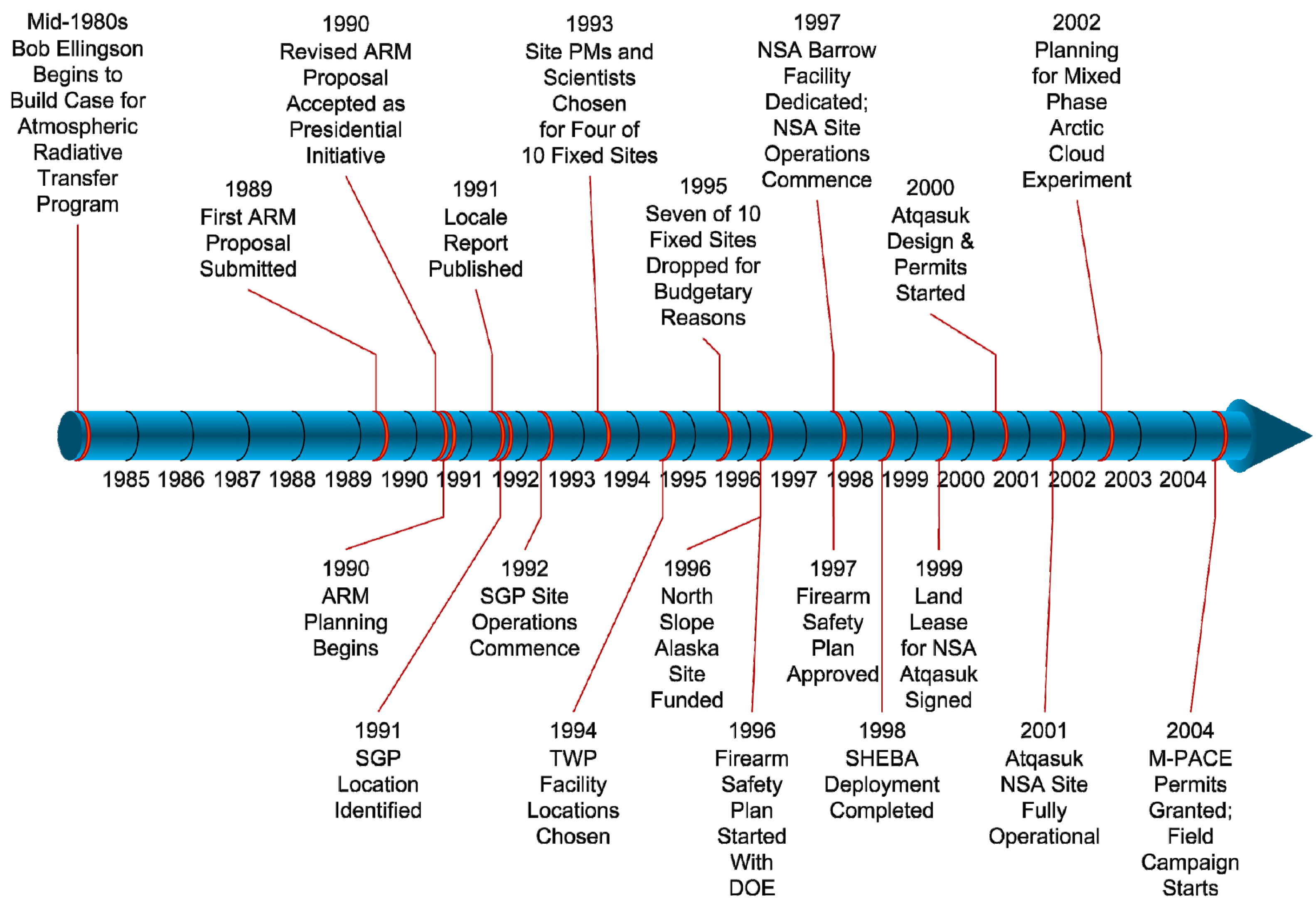


Figure 26. ARM Development Timeline. Milestones in the development of the ARM network from conception through 2005.

The specific component of ARM that resembles NEON is what is now called the ARM Climate Research Facility (ACRF), which includes the ARM field research sites and supporting infrastructure. The ACRF has been designated a national user facility for the purpose of making this asset available to the broader national and international research community. Research at this facility includes the study of alterations in climate, land productivity, oceans or other water resources, atmospheric chemistry, and ecological systems that may alter the capacity of the earth to sustain life. Global change research also includes study, monitoring, assessment, prediction, and information management activities to describe and understand: the interactive physical, chemical, and biological processes that regulate the total earth system; the unique environment that the earth provides for life; changes that are occurring in the earth system; and the manner in which such systems, environments, and changes are influenced by human actions. So by becoming a national user facility. the ACRF now supports much broader research than could be funded by the ARM program alone. It is more cost-effective because it shares its infrastructure with other users.

The permanent ACRF field sites are shown in Figure 27. The first fixed ACRF site was created in the Southern Great Plains of the US; the second, in the Tropical Western Pacific; the third, on the North Slope of Alaska, adjacent to the Arctic Ocean. The ARM Mobile Facility (AMF) has been deployed to the Coast of Northern California, to Sub-Saharan Africa, to Germany, and now to China. Sandia is specifically responsible for the continued development and operation of the North Slope of Alaska ACRF site. Other DOE laboratories are responsible for the other sites.

Figure 27. Permanent ACRF field sites.

The ACRF Southern Great Plains site is depicted in schematic fashion in Figure 28. Note that it involves a central facility and outlying facilities, just as NEON sites will. The same is true of the other ACRF fixed sites.

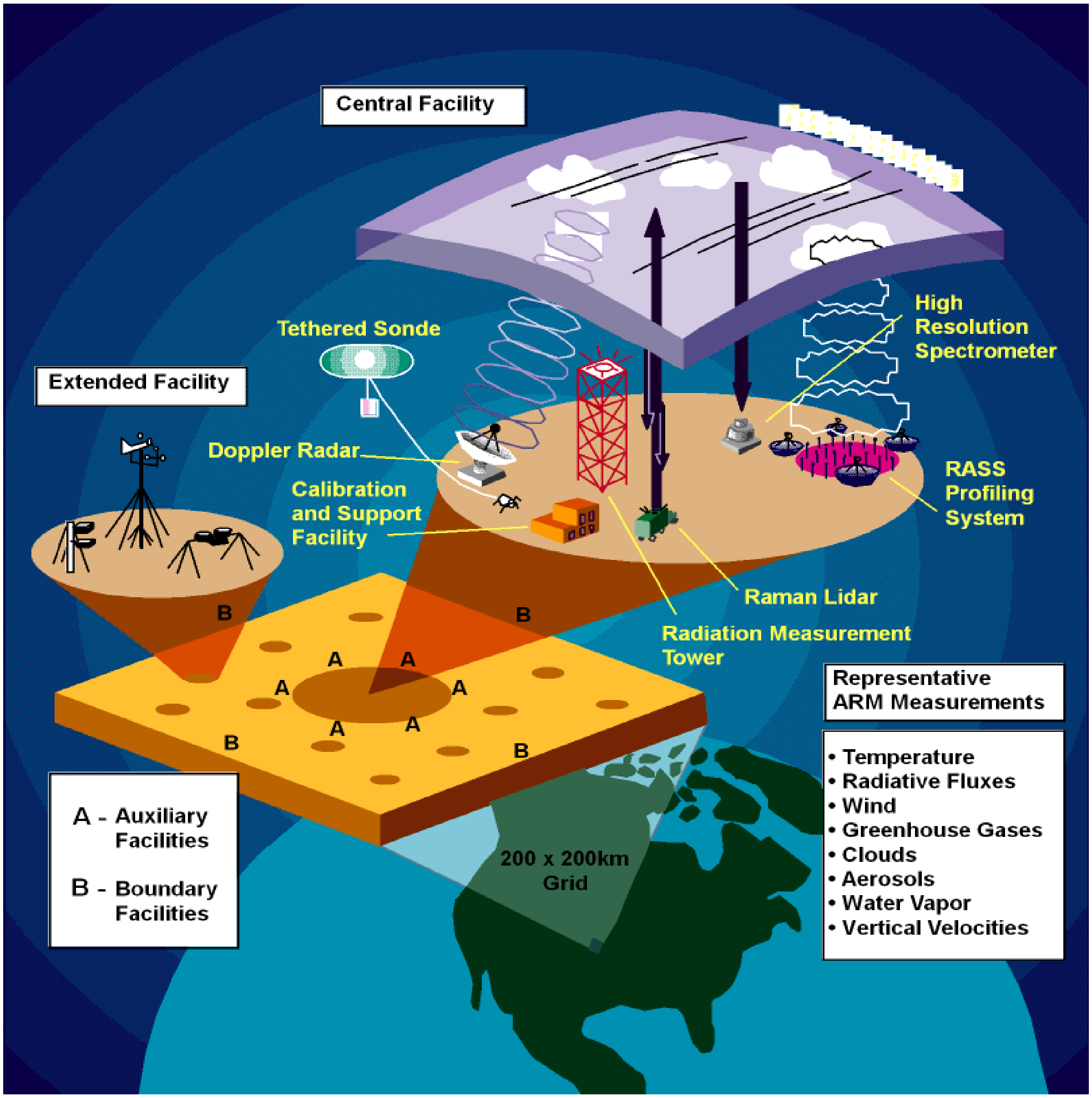


Figure 28. High level schematic diagram of the ACRF Southern Great Plains site.

In comparing NEON with the ACRF, it is clear that NEON proposes to incorporate more measurement sites than ACRF (20 *vs*. 3 fixed plus one mobile). But it may be noteworthy that ACRF originally proposed 10 fixed plus one mobile site before budgetary reality intruded. A complicating factor for ACRF is that it has a fixed site outside the US, and that it has deployed its mobile facility predominantly overseas. On the other hand, a complicating factor for NEON is that, while all of its proposed sites are within the US, typically the NEON sites are in more remote locations than the ACRF sites. Another complicating factor for NEON is that it proposes to field many more, and more diverse sensors than ACRF. A comparison between the sensor suites of the ARM SGP site and the proposed NEON Pawnee site is given in Appendix E: Comparison of ARM SGP and NEON Pawnee Site Sensor Suites. Despite the differences, it would appear that NEON and ARM are similar in many ways, and of roughly the same order of complexity. Hence, the experience of ACRF is relevant to NEON systems engineering.

Other Multi-Site Data Collection Networks with Similarities to NEON and ACRF

The "grand daddy" of all multi-site instrumented data collection networks is the network operated by the US and other National Weather Services around the world. This network has hundreds of stations, and is highly reliable. It is not, however, all that similar to NEON. The reliability is obtained by focusing on a very limited set of proven, robust instruments, and for important stations, manning those stations 24 hours a day, 365 days a year. This is not the NEON model.

The NOAA Global Monitoring Division (GMD) operates a set of five stations primarily for monitoring the concentrations of greenhouse gases in selected clean air locations. The Barrow element of the NSA ACRF site is co-located with the NOAA GMD Barrow Station. These NOAA stations are closer to the NEON model, but not as close as ACRF. Each NOAA station consists of a single location – frequently a single building – housing a concentration of instrumentation. There are no outlying facilities other than sensors some tens of meters from the main building or shelter. Typically, each facility is attended 40 hours per week by technicians who keep a continual eye on their instrumentation.

NASA and NSF each maintain other special purpose networks, as do some other agencies. But, to our knowledge, they differ even more dramatically from the NEON and ACRF models.

The ACRF Operations Management Approach

ACRF Management Structure

In systems engineering, it is not unusual to inadvertently put too little emphasis on the human components of the system – which we'll call the management system. That system performs all of the tasks that must be carried out by human beings, rather than by stand-alone hardware and software. Of course, the management system uses hardware and software to accomplish the purposes for which the entire integrated system was designed. For ACRF, the workings of the current management system are shown at a high level in Figure 29.

In the absence of science proposals for the use of specific ACRF facilities, DOE Program Management, with the advice of the ACRF Science Board and the ACRF Infrastructure Management Board, manages the ACRF infrastructure, which includes Operations at and in support of the field research sites (which function continuously), Engineering for the sites (both hardware and software), and the Data Archive. Each infrastructure element has its own management and staff.

Science proposals for field campaigns and instrument deployments are submitted both in response to annual solicitations, and independent of the solicitation process. They may range in cost from under $10K, to well over $1M. Different evaluations procedures, supported by web-based software, have been set up for evaluating science proposals falling in different cost ranges. Major science proposals are usually formally submitted only after having been vetted and recommended by one of a number of ACRF science working groups, each of which focuses upon a specific scientific area [Aerosol, Cloud Modeling, Cloud Properties, Clouds with Low Optical (Water) Depths, Radiative Processes]. More detail on the composition and function of the respective ACRF elements depicted in Figure 29 is given in Appendix F: Functions of the Various ACRF Elements.

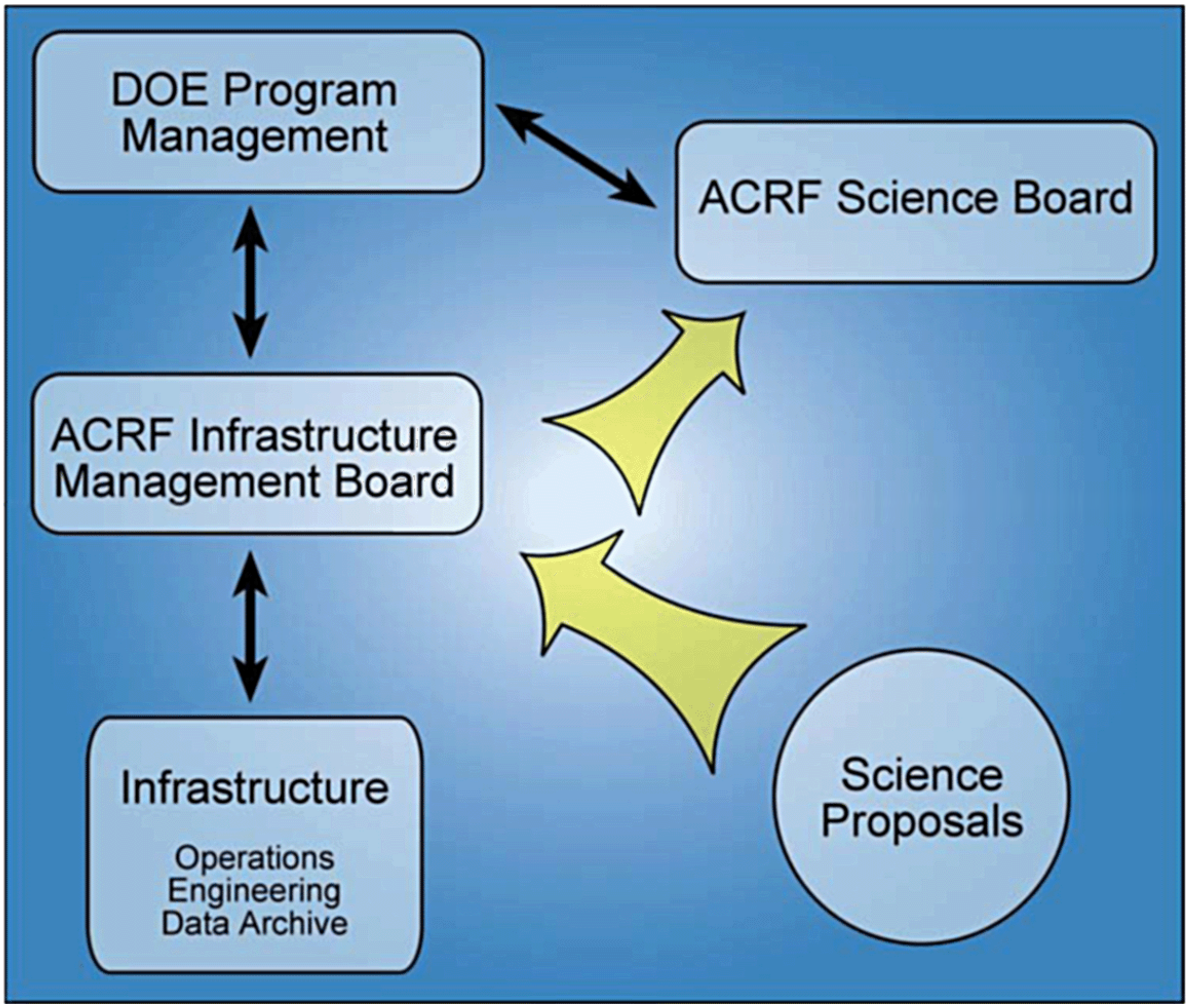


Figure 29. Diagram of the ACRF management structure.

ACRF Change Control and Associated Record-Keeping

For systems of the complexity of NEON and ACRF with anticipated lives measured in decades or longer, the mechanisms for orderly evolution must be designed in from the beginning. New sensors will become available that are either superior to those initially used, that measure important additional parameters that had not previously been measureable, or that replace sensors that are no longer commercially available. A similar situation exists with regard to the data acquisition, transmission, archiving and distribution hardware and software. The same holds true for the organizational elements that comprise the management system. One must anticipate that over the long life of the system, virtually everything will need to change.

The general ACRF process for starting a request for a new capability, functionality or data product is as follows. Any member of the ARM Science Team (the group of all funded and/or approved but unfunded ARM investigators) or of the ACRF Infrastructure can identify a need by initiating an **Engineering Change Request (ECR).** An ECR is based on a science, engineering, or operational need that can result in a new product, capability, or functionality, or in a modification to an instrument, computer system, data stream or facility. Choosing the right path to communicate this need to the ACRF Engineering Group depends upon whether it is a recognized problem, a new functionality, or an immediate operational concern. An ECR can lead to the installation of a new instrrument, or redesign of an existing instrument, data system, data product, value-added product (VAP), or some other physical aspect of the infrastructure. The ECR management process is outlined below and diagrammed in Figure 30. ECRs are accepted and managed through web-based software (Figure 31), which keeps the records.

The generic steps in the change process are:

- **Identify a design or development need (via ECR)**
- **Review and approve request (ECR Review Team, IMB) – changes ECR into an Engineering Change Order (ECO)**
- **Assign accepted request to a developer (relevant infrastructure manager)**
- **Plan, design, and implement request (assigned developer)**
- **Conduct readiness review of completed request through submission of a Baseline Change Request (BCR)**
- **Deploy solution**

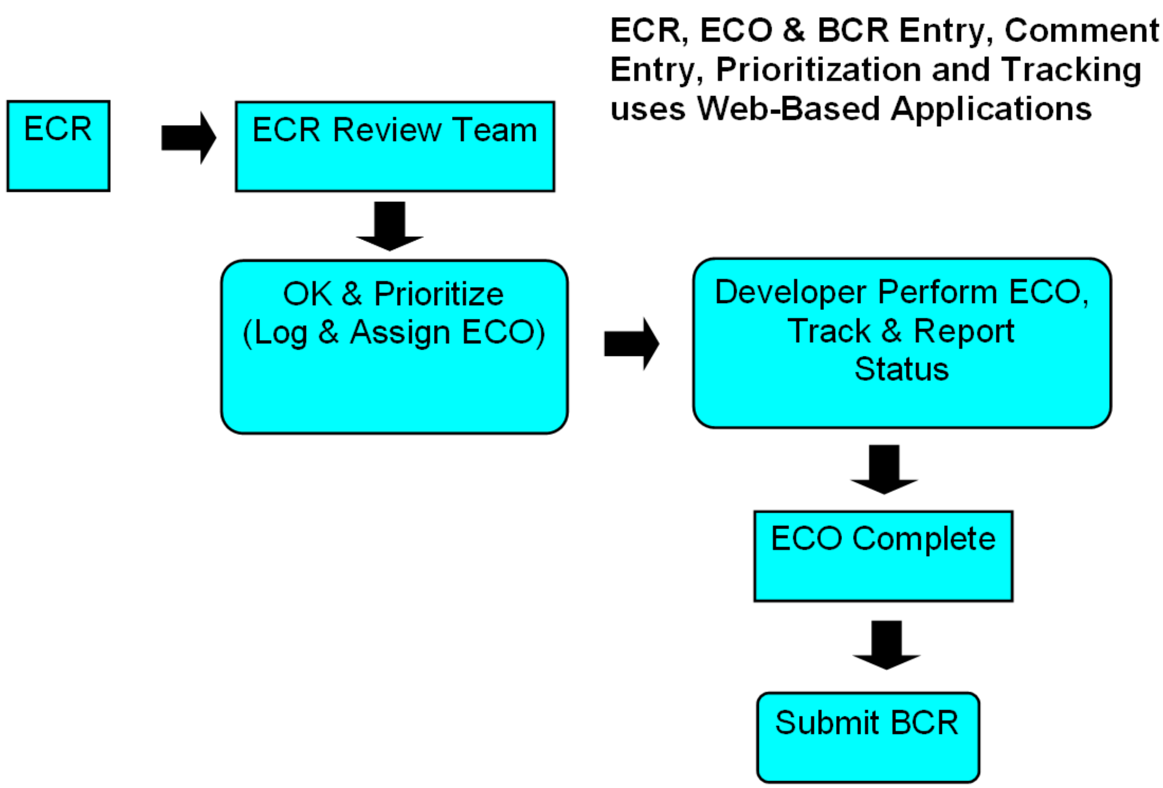
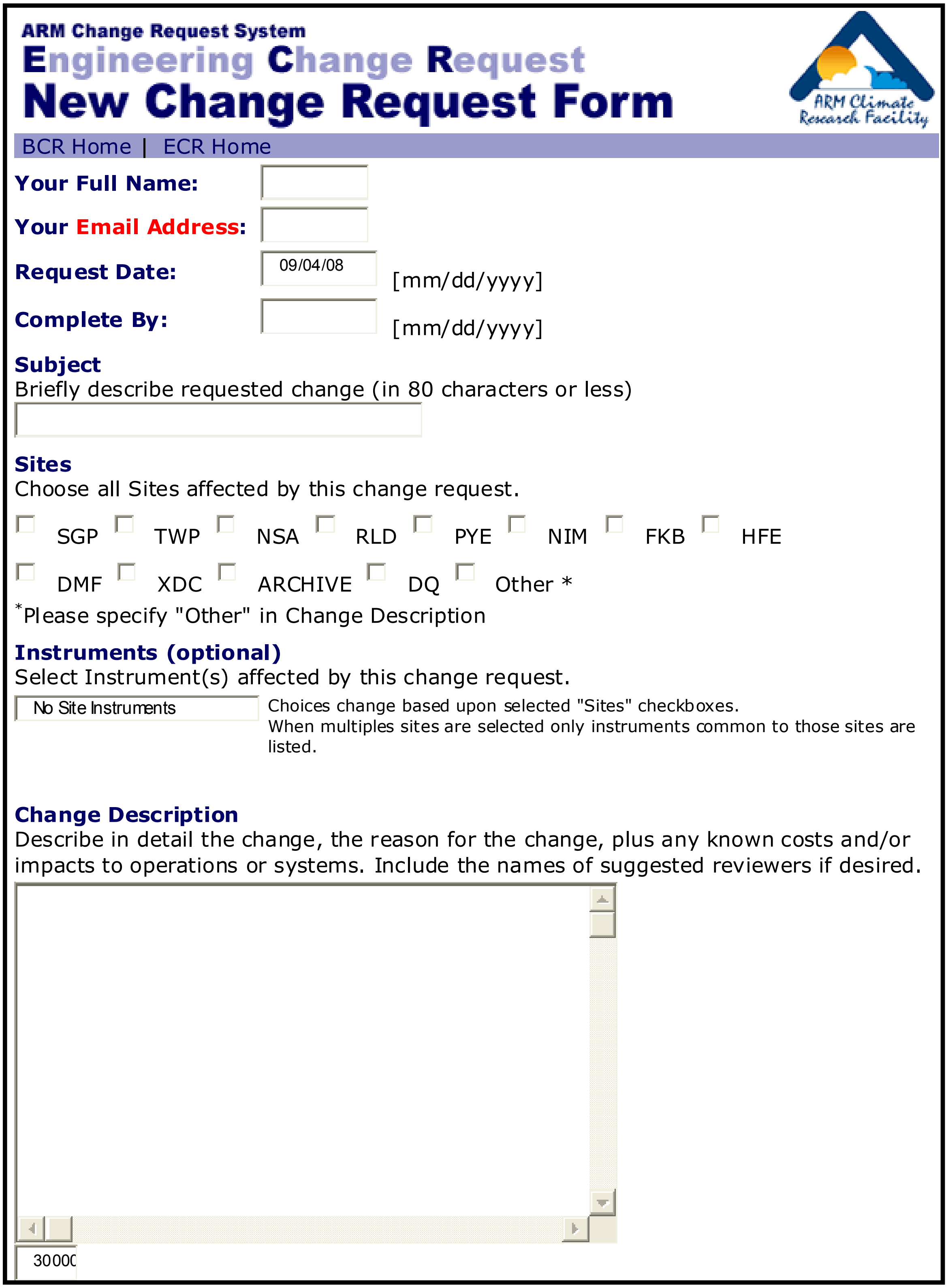


Figure 30. ACRF Engineering Change Request (ECR) high-level process flow diagram.



ARM Change Request System

Engineering Change Request

New Change Request Form

ARM Climate Research Facility

BCR Home | ECR Home

Your Full Name:

Your Email Address:

Request Date: 09/04/08 [mm/dd/yyyy]

Complete By: [mm/dd/yyyy]

Subject

Briefly describe requested change (in 80 characters or less)

Sites

Choose all Sites affected by this change request.

☐ SGP ☐ TWP ☐ NSA ☐ RLD ☐ PYE ☐ NIM ☐ FKB ☐ HFE

☐ DMF ☐ XDC ☐ ARCHIVE ☐ DQ ☐ Other *

*Please specify "Other" in Change Description

Instruments (optional)

Select Instrument(s) affected by this change request.

No Site Instruments

Choices change based upon selected "Sites" checkboxes.
When multiples sites are selected only instruments common to those sites are listed.

Change Description

Describe in detail the change, the reason for the change, plus any known costs and/or impacts to operations or systems. Include the names of suggested reviewers if desired.

3000C

Figure 31. ARM Engineering Change Request web-based form.

The web-based **BCR** system is similar to the **ECR** system**.** Once the BCR is submitted, it is processed as shown in Figure 32 below:

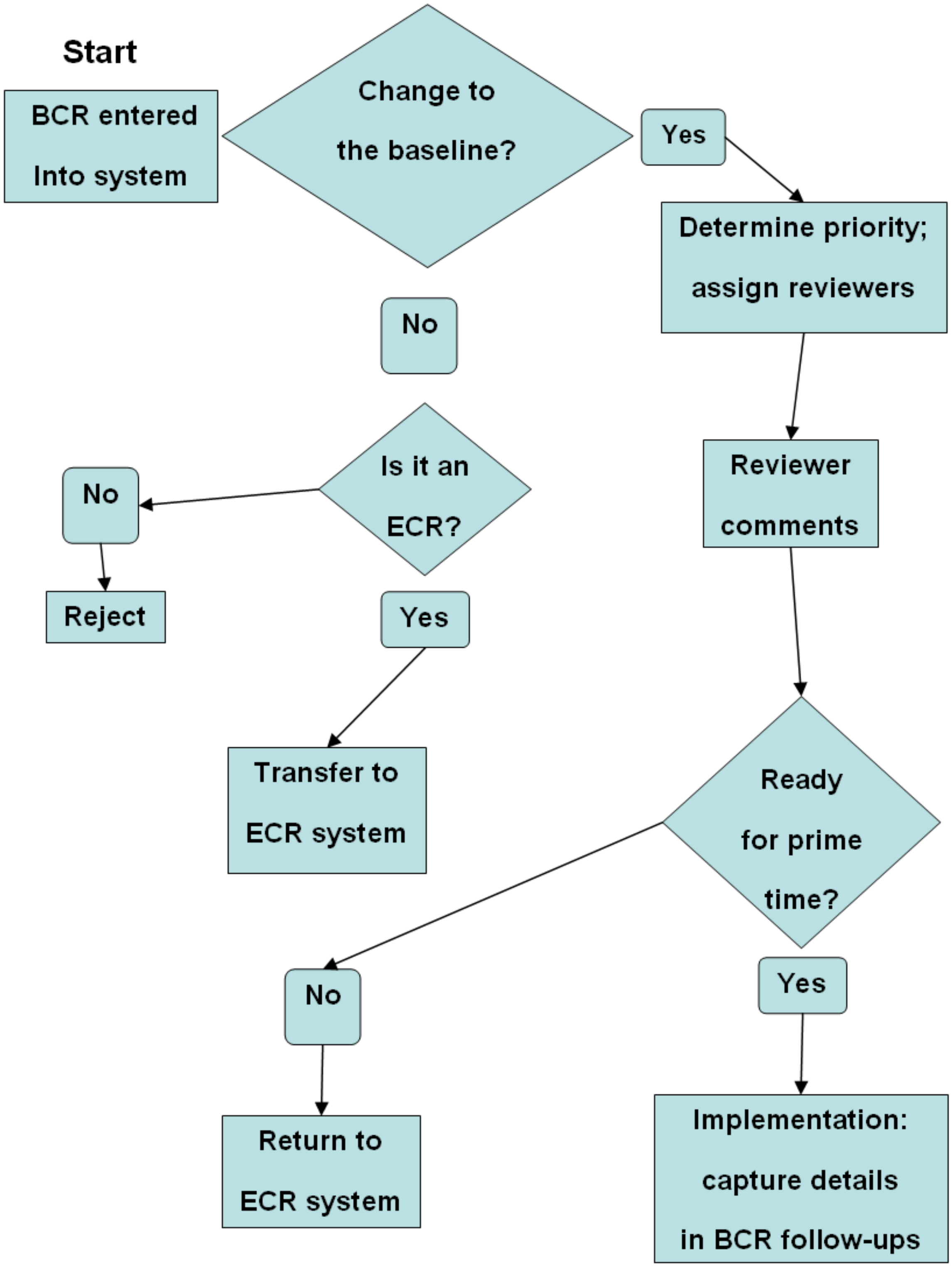


Figure 32. ACRF Baseline Change Request (BCR) high-level process flow diagram.

Specifically for new instruments, since the ARM Climate Research Facility is a National User Facility, ACRF responds to user needs, including new instruments. The ARM Science Team is the largest and most influential group of users. They are divided into 5 Working Groups (Aerosol, Cloud Modeling, Cloud Properties, Clouds with Low Optical (Water) Depths, Radiative Processes). The Working Groups have scheduled meetings. Non-ARM users are invited to attend. One of the activities of the Working Group is to address measurement needs.

Individual members of the Working Groups are invited to make presentations at Working Group meetings, and the Working Group evaluates and provides prioritized recommendations of new instrument needs. The Working Group reports are provided to the ACRF Infrastructure Management Board and to the Science and Infrastructure Steering Committee (SISC). The IMB has the primary responsibility to find instrument vendors and solicit costs and estimate support costs in the deployment and operation of new instruments. At the same time, the SISC evaluates new instrument requests and provides an overall recommendation and priority to the DOE Program Manager. The prioritized list of requests is added to the ACRF Infrastructure budget pending annual budget reviews and scheduling.

Once a specific instrument which meets a need is identified, an Engineering Change Request (ECR) is submitted to the ECR Review Board. If approved, the ECR becomes an ECO, an Instrument Mentor[‡‡] is assigned, and funds are allocated for purchase. The ECO process is structured (checklists) and is intended to gather instrument purchase requirements; data format, collection and processing requirements; formal design reviews (if needed); data bandwidth and storage requirements; quality assurance requirements; deployment and operational requirements; documentation and training, requirements; etc. The ECO process is documented on the ARM web site at www.arm.gov.

Once procured, the instrument is deployed at one of the ACRF sites for a testing and evaluation period that could last several months to a year. This is still part of the ECO process. All software are tested on a Development System, an identical system to the Operations System. The Instrument Mentor must be satisfied that the data provided from the instrument are good. The data are maintained in a blind side of the ACRF Archive during testing.

When the ECO process has been completed and the Operations Team has accepted the operational responsibility for the instrument (operation, calibration, maintenance, etc.), a **Baseline Change Request (BCR)** is submitted, which is used to assure that the instrument is officially ready to be brought on line. The BCR handles configuration management. All elements of bringing the new instrument on line are coordinated through the BCR. Once the BCR is approved, an announcement is made to the ACRF community that a new data product is available.

What Would the ACRF Staff Do Differently If They Started Over Today?

The answer is to get to the now-existing ACRF system described above more rapidly than they in fact did. In spite of a strenuous systems engineering effort at the beginning of the ARM program, it took

[‡‡]An Instrument Mentor is the technical and scientific expert for a specific instrument, who participates in a variety of operational activities including instrument upgrades. Each ACRF instrument has an assigned Instrument Mentor. Individuals within the ACRF infrastructure may serve as mentor for more than one instrument.

quite a few years to arrive at where ARM/ACRF is today. Even with sensible feedback mechanisms and a learning-oriented organizational culture, learning what works and what doesn't takes time. Nor is the present state "the ultimate." Change will continue as new needs become apparent. The NEON project has the opportunity to shortcut the learning process that ARM went through. The management of the DOE ARM program has been informed of the NEON effort at Sandia, and is highly supportive. The June trip by Osborn, Kottenstette and Zak to the Southern Great Plains ACRF site, hosted by the ACRF SGP Onsite Facility Manager (Dan Rusk), provided many insights regarding the orderly upgrading and controlled evolution of sensors and other network elements described above. One other insight regards the value of employing local personnel to operate the sites. This practice makes it much more likely that the local community will be supportive. A supportive relationship tends to discourage theft and vandalism. Other insights are outlined in the trip report provided in Appendix G: ARM SGP Site Visit. DOE/ARM would be pleased to continue to support NEON in any way it reasonably can. The present project has been a good beginning, but if NEON so wishes, it will be just the beginning.

Additional Noteworthy Operations Management Challenges

Change management is just one of many challenges in the operation of multi site instrumented data collection networks that have been confronted by the ACRF, and for which solutions have been developed. Environment, Health and Safety, as well as regulatory compliance, are also noteworthy challenges. To begin, creation of a facility by a federal agency falls under the National Environmental Policy Act (NEPA). NEPA specifies a process that must be followed prior to the commitment of funds for construction. For NEON, this may mean the development of 20 Environmental Impact Assessments, or even one or more Environmental Impact Statements. Typically, these documents are site-specific, and take months to complete and be approved. Facility development will also involve various federal, state and local regulatory agencies, each with their own set of processes and regulations. Obtaining the necessary permits and approvals will likely be a protracted process. If regulatory compliance is not addressed early in the planning process, lack of compliance could halt program development in its tracks. Typically, the applicable regulations have the force of law.

Another particularly important challenge, and one in which the ACRF has invested heavily[9], is data quality assurance. From time to time, instruments either outright fail, or produce incorrect data for a great variety of reasons. Rapidly detecting the failure or incorrect data, and rapidly fixing the problem is by no means easy when there are thousands of different data streams. The ACRF "duty factor" goals for the ACRF sites are 95% for the SGP, 90% for the NSA; and 85% for the TWP: by definition, the goal is the percent of the expected data that would be collected if everything were functioning perfectly that actually reaches the Data Archive and that, on examination according to criteria specified by the Instrument Mentors, are judged to be satisfactory. The reason for the differences among the sites is that if a sensor or any other infrastructure element fails at one of the more remote ACRF sites, it takes longer for the repair action to be completed. Through aggressive action, ACRF routinely exceeds its goals. It has been stated that the comparable system-wide goal for NEON is 99%. Based on ARM experience, it is fair to say that 99% is a very challenging goal indeed.

Rather than go into more detail on other challenges here, we cite the paper by Ivey[10], *et al.*, reproduced in the Appendix. It addresses many of the challenges faced in operating the ACRF Tropical Western Pacific site. Most of the concerns identified in that paper are ubiquitous in nature and should be considered for the proposed NEON sites.

Conclusions and Recommendations

The principal recommendations are to benefit as much as possible from the ACRF systems design experience, and to the extent appropriate to the differences in purpose, to benefit from the ACRF experience with specific sensors, as well as data acquisition, data transmission, data QA, and data distribution hardware and software. It has cost ARM hundreds of person-years and many million dollars to acquire that experience. There is no need to independently re-acquire that experience.

CONCLUSIONS AND SUMMARY RECOMMENDATIONS

The key findings, summary highlights, and recommendations embodied in this report, parsed by area of concern, are as follows:

Alternative Power Sources and Impacts –

- **NEON should give serious consideration to the use of alternative power sourcing at small arrays remote to the tower locations (*e.g.,* aquatic arrays)**
- **Photovoltaic or Photovoltaic Hybrid power sources appear most promising**
- **Energy storage batteries and controls carry significant logistics issues and ongoing operational expenses, and should be right-sized with the assistance of a reputable vendor**

Data Acquisition, Transmission, Integrity, and Security –

- **Standardize NEON's local data acquisition networks on Ethernet, with the use of suitable adapters for legacy equipment, and establish an approved list of acceptable hardware for such purposes**
- **Incorporate adaptive self-organizing wireless mote technology as a foundational aspect of NEON's data acquisition system and approach**
- **In order of preference depending on site conditions use: (1) the land-line telephone system; (2) the cellular telecommunications system; (3) the land-line system with a dedicated wireless link; (4) satellite data communications; or (5) hand-carry of modular data storage devices**
- **Consider incorporation of cellular telecommunications access at all possible sites as a primary or secondary data transmission channel as well as for the safety of site personnel**
- **Use hash algorithms for all data file transmissions to the central database**
- **Use software encryption to securely store all data temporarily stored on-site, and for data files transmitted to the central database**
- **Design all NEON on-site temporary data storage to utilize hot-swap solid state drives in a redundant array configuration in order to facilitate hand-carry of data when needed while preserving data integrity, and establish procedures for tracking and accountability of data hand-carries**

Network Systems Development and Operations Management –

- **Data quality assurance and sensor calibration schedules and procedures should be established early**
- **NEON should leverage the learnings of ARM in the realms of sensor selection, data acquisition, data transmission, quality assurance, data product distribution, site safety, etc.**
- **Change management systems should incorporate transparency and "buy-in" by affected personnel, management decision points to avoid endless activity loops, and the assignment of a specific responsible party when further action is required to collect information for a decision or to implement a change**

In addition to the above findings directly aimed in response to the statement of work, the following general findings and recommendations have come to light:

General Findings and Recommendations –

- **Perform a thorough systems analysis examining the data communications accessibility and cost tradeoffs for all NEON sites and sub-site local networks in detail**
- **Consider development of a complete sensor-to-database hardware and software testbed, with *in situ* assessment of options and challenges, prior to full implementation of the NEON network**
- **Investigate the benefits of developing a meta-level ecological data tool to encompass and leverage the data products provided by other agencies as well as NEON, and to mitigate the need for fully comprehensive data at all NEON sites**

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APPENDIX A: EXISTING MEASUREMENT NETWORKS FOR ECOLOGICAL INFORMATICS

There appears to be a solid rationale for employing a large scale informatics approach to earth science and ecological data. Table A - I below lists a select group of agencies and databases that have national monitoring programs related to environmental science and climate change. The task of measuring ecological change on a national basis and addressing the Grand Challenges in Environmental Science will be enabled by synthesis and cohesion of the large number of existing measurement programs and data sets. This list of sites is far from exhaustive highlighting the need and opportunity for an informational approach toward predictive ecological science. The bullets below present websites that have attempted to aggregate or synthesize larger databases into living interactive archives.

- The UCAR Community Data Portal (CDP) is a collection of earth science datasets from NCAR, UCAR, UOP, and participating organizations that reflects an attempt to start this process.
- NASA has also attempted to collect a set of databases for the earth sciences in the Distributed Active Archive Centers (DAAC's).
- The NSF/DOE sponsored Storage Resource Broker is a Data Grid Management System (DGMS) is a logical distributed file system based on a client-server architecture.
- The Department of Energy: Earth Systems Grid (ESG).
- Science Environment for Ecological Knowledge (SEEK), developed by the University of California, University of New Mexico and the University of Kansas.

Table A - I. Existing Large-Scale Data Collection Networks.

Agency or NGO	Mission	Web Address
DOE-ARM	CO_2 , Climate	http://www.arm.gov/
DOE-FACE	FACE (Free Air CO_2 Enhancement)	http://public.ornl.gov/face/global_face.shtml
Ameriflux	CO_2 Climate Ecosystem	http://www.fluxnet.ornl.gov/fluxnet/index.cfm
NOAA	Ozone, CO_2, Climate	http://www.oar.noaa.gov/organization/backgrounders06/esrl_monitoring.html
NOAA	Satellite –weather	http://www.nesdis.noaa.gov/
LTER	Long Term Ecological	http://www.lternet.edu/
UCAR	Community Data Portal -Climate	http://cdp.ucar.edu/home/home.htm
USGS	Water Quality	http://water.usgs.gov/waterwatch/wqwatch/#
NASA	Distributed Active Archive	http://nasadaacs.eos.nasa.gov/about.html
NASA	Atmospheric Measurement	http://modis-atmos.gsfc.nasa.gov/
EPA	Air Quality/Water Quality Interactive and Legacy	http://www.epa.gov/storet/ http://www.epa.gov/storpubl/legacy/gateway.htm
USDA	Soil -Climate	http://www.wcc.nrcs.usda.gov/scan/
USDA	CO_2 Agricultural Sequestration	http://www.ars.usda.gov/SP2UserFiles/Program/204/GRACEnetpage/GRACENET_Brochure_May_2008.pdf http://gracenet.usda.gov/

Agency or NGO	Mission	Web Address
EPA/ NOAA	Ozone - UV	http://www.epa.gov/uvnet/
USDA	Ecology-Air Quality-UV	http://www.forestry.umt.edu/primenet/
National Phenology Network	Ecosystem - Phenology	http://www.usanpn.org/
Earthscope	Seismic	http://www.earthscope.org/
USDA	Plant taxonomy	http://www.ars-grin.gov/cgi-bin/npgs/html/taxweed.pl
U of New Mexico U of California U of Kansas	Science Environment for Ecological Knowledge (SEEK)-informatics	http://seek.ecoinformatics.org/Wiki.jsp?page=WelcomeToSEEK
DOE	Earth System Grid (ESG)	http://www.earthsystemgrid.org/about/explainPage.do
NSF/DOE	Storage Resource Broker (SRB)/DICE-informatics	http://www.sdsc.edu/srb/index.php/Main_Page http://diceresearch.org/DICE_Site/Home/Home.html
Natural Environ-ment Research Council (UK)	eScience – web based data	http://www.niees.ac.uk/

APPENDIX B: ALTERNATIVE POWER SYSTEM SIMULATIONS

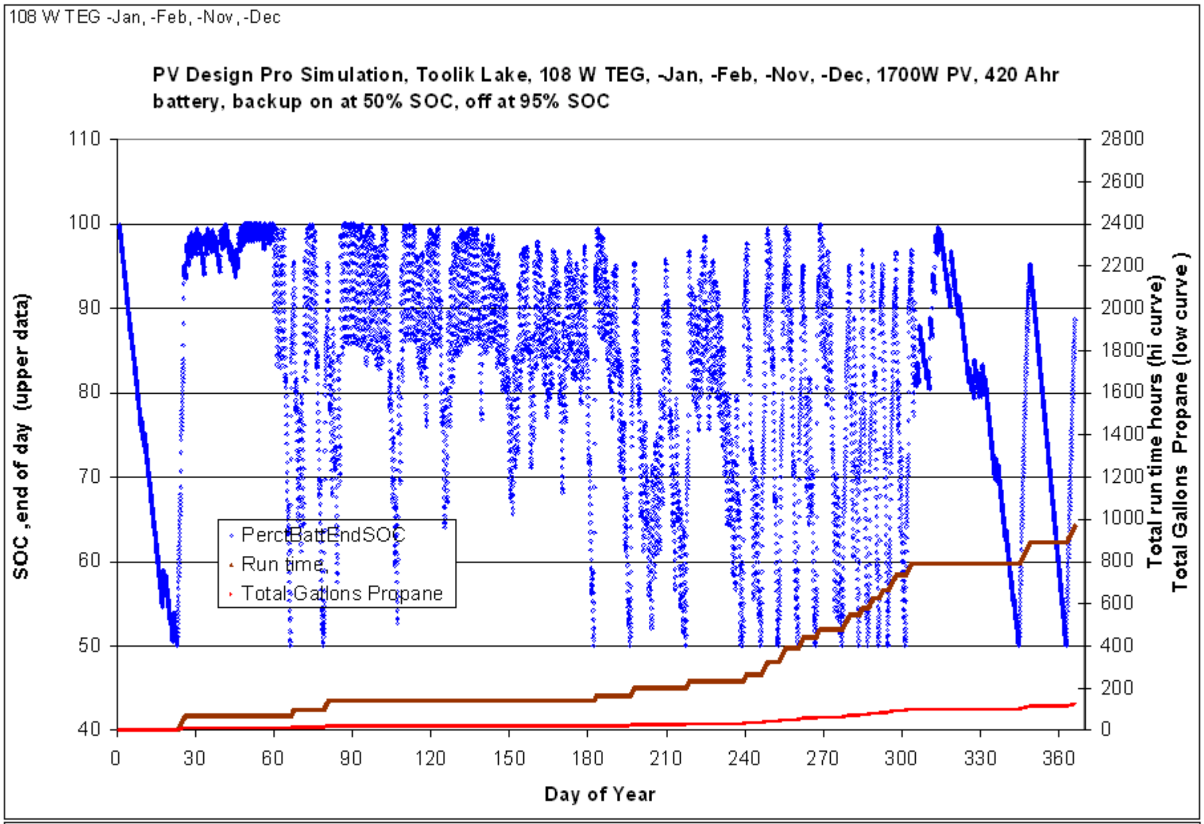
Several of the configuration assumptions regarding the performance simulations of the PV systems designed to support aquatic arrays at the five sites discussed in the FIU Baseline document are provided in Table B - I. Additional constraints and the assumptions used to estimate PV system pricing are presented in Table B - II. PV DesignPro simulation results for a series of PV/TEG and PV/Diesel hybrid systems are given in Figure B - 1 through Figure B - 21. While these figures are voluminous, they provide visualization of trends that compacted tabular data cannot. For example, one can see (Figure B - 4) that a PV hybrid 108W TEG system backing a 630AH storage battery could probably be fueled once in Spring and ignored until October with a relaxed 50% minimum state of charge requirement. Conversely, a system supporting a 420AH battery with a 70% minimum state of charge would operate on a highly intermittent, monthly (or more frequent) basis (Figure B - 3). This mode of operation would put greatly more wear and tear on the TEG, while using only somewhat more fuel.

Table B - I. Assumptions for Aquatic Array PV System Performance Simulations.

System Estimation Assumptions	CRC	Guanica	Pawnee	Joaquin	Toolik*
Climate File	Sterling, VA	San Juan	Sheridan, WY	Fresno, CA	Bettles, AK
Panels in Parallel	7	5	5	4	5
Panels in Series	2	2	2	2	2
Imp, Panel, (A)	4.8	4.8	4.8	4.8	4.8
Number of Panels	10	8	10	8	8
Mounting Angle, Elevation, Degrees	40	25	50	50	80
Batteries in Series	4	4	4	4	4
Batteries in Parallel	6	6	5	5	6
Number of Batteries	24	24	20	20	24
Nominal AHrs @ 48 V	630	630	525	525	630
Calculated Max Charge Rate Hrs	21.6	32.3	26.9	35.7	32.3
Generator, 3000W, 48V ~60 A	-	-	-	-	10.5
Normal Load Draw (A)	4.5	4.5	4.5	4.5	4.5
Min Battery SOC Simulated	65%	65%	60%	70%	70% *
Hrs Load at Min SOC to 15% SOC *	70	70	53	64	77

Table B - II. Assumptions for Aquatic Array PV System Price Estimations.

Item	Details
Batteries	Model: Concorde PVX-1040, Voltage: 12 V, AH: 104 Series: 12-Volt Batteries Weight: 66 Lbs Length: 12.01 Width: 6.6 Height: 8.93 Price$ 284 N.B. Chosen as representative of an appropriate type of battery – many vendors supply similar batteries.
Photovoltaic Panel Modules	Model: BP solar SX170B; Weight: 33.1 lbs; Length: 62.8"; Width: 31.1"; Depth: 1.97"; Price: $955 N.B. Chosen as representative of an appropriate type of module – many vendors supply similar modules.
Voltage Configuration	48-volt nominal, allows for wire sizing 1/16 the size of a 12V system.
BOS Prices	Estimated at 30% of battery and panel costs
Shipping	TBD
Price Dates	September 1, 2008
Toolik	*Toolik needs extra energy beyond PV in Aug, Sept, and Oct. Therefore, a generator is a requirement. Cost is an estimate.
Installation	Not included, would need to be quoted, with detailed specs.
Backup Time	Systems sized to allow at least 48 hours of power without PV or generator under normal worst conditions, recommend longer in more remote sites.
Lowest Battery SOC	Systems sized so battery storage never gets below 50% except in case for Toolik, which would have backup generator set.
Annual Maintenance	Estimated at 5% of Total Cost
Load	Base load 192 W, converts to 214 watts, when converting from 48V to 12V at 90% assumed efficiency.
Availability	100% Availability except for Jan, Feb, Nov, Dec
Simulation Software	PV-DesignPro v6.0 Photovoltaic Energy System Design and Analysis Tool



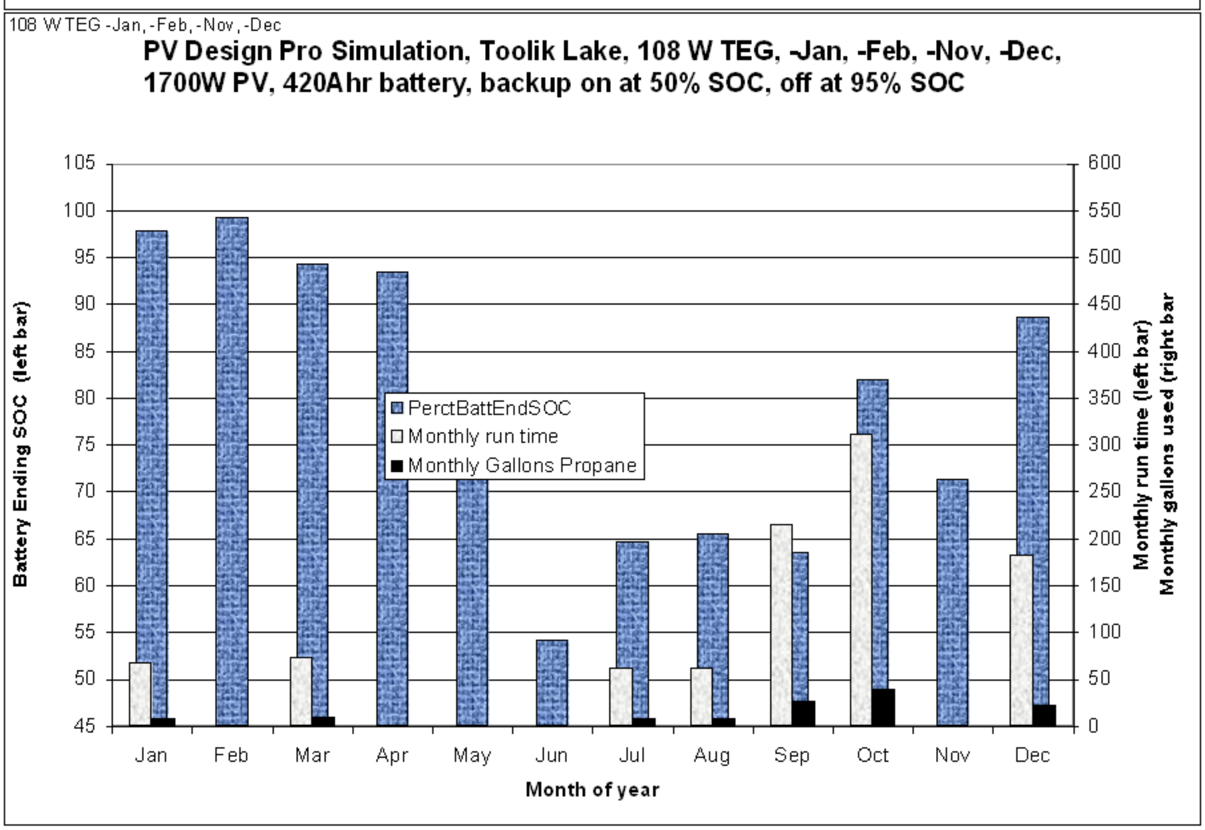
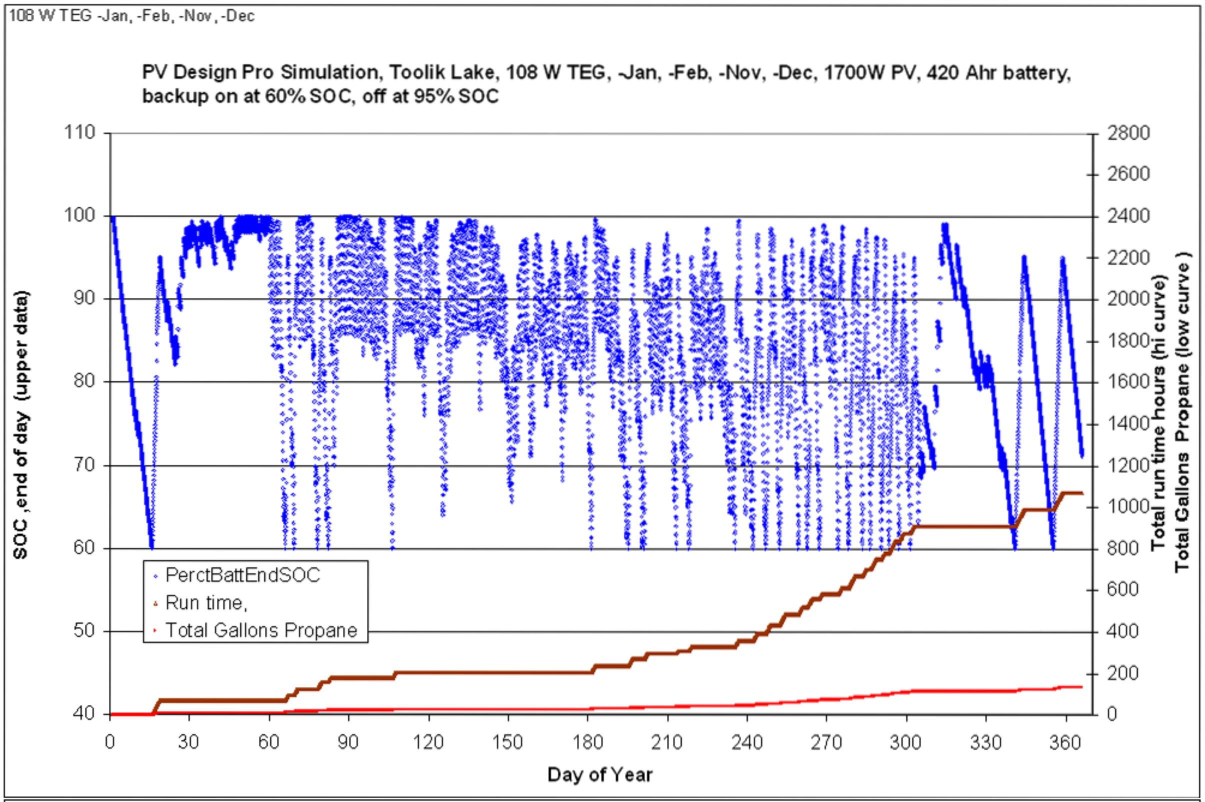


Figure B - 1. Simulation of 108W TEG 420 AH Bat, at 50 to 95% SOC.



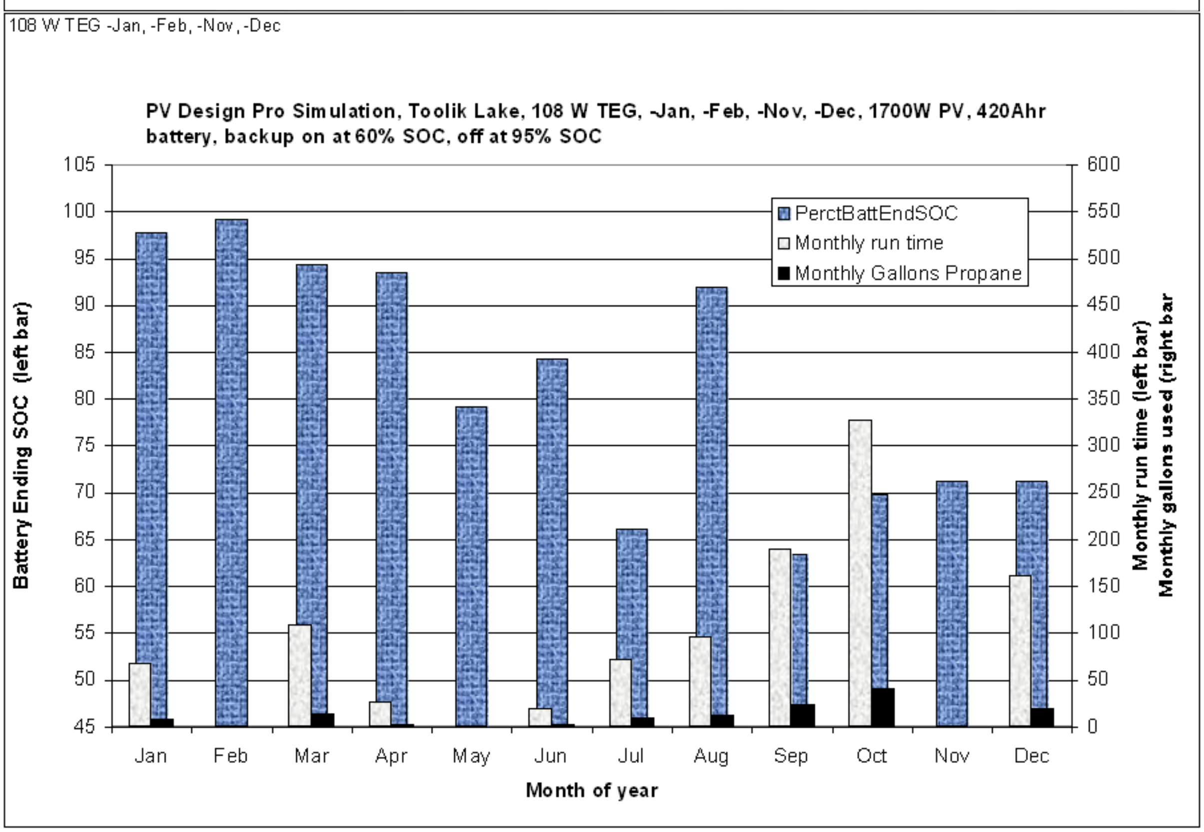
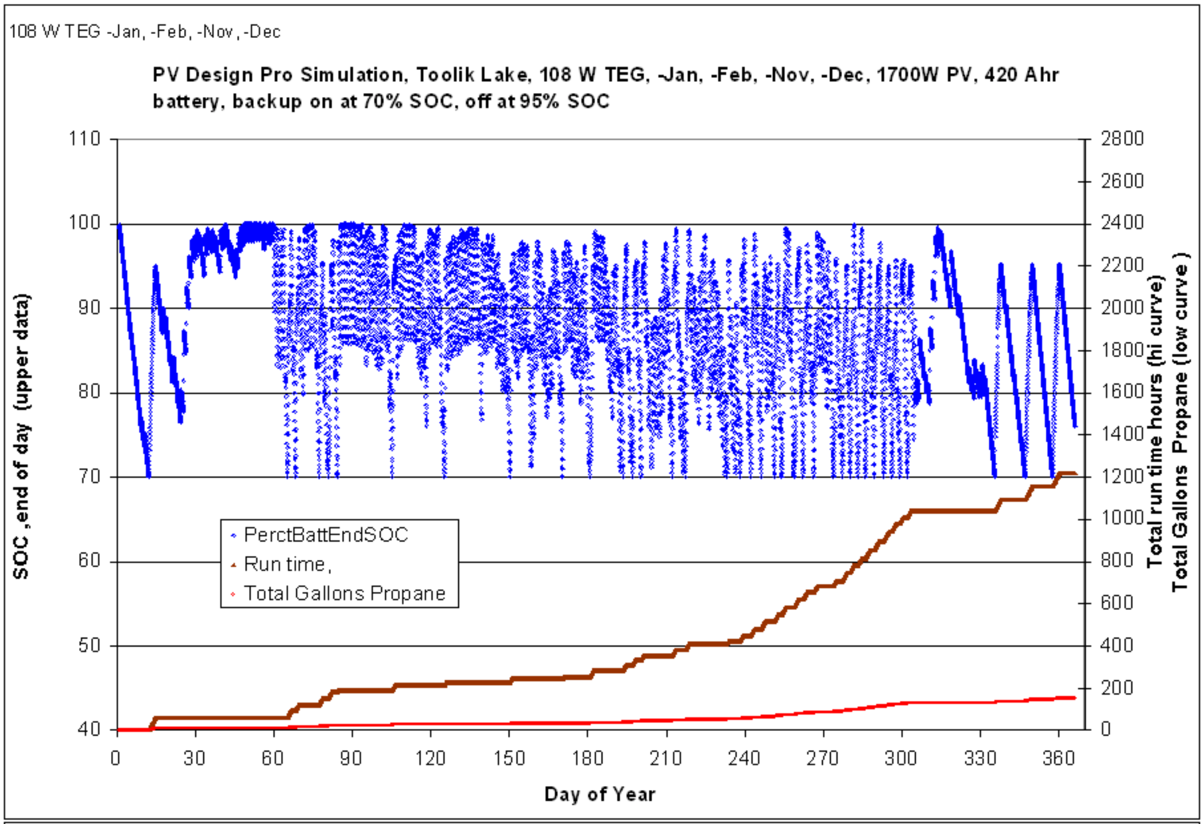


Figure B - 2. Simulation of 108W TEG 420 AH Bat, at 60 to 95% SOC.



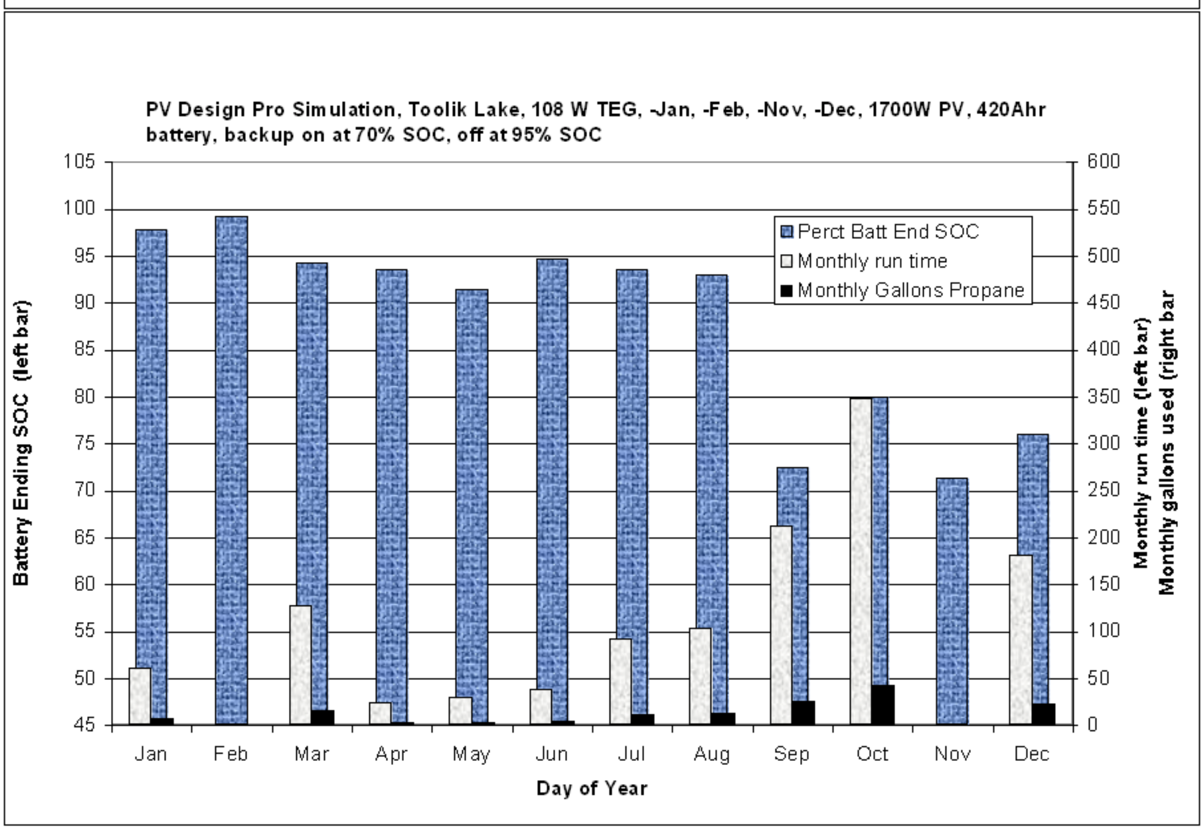
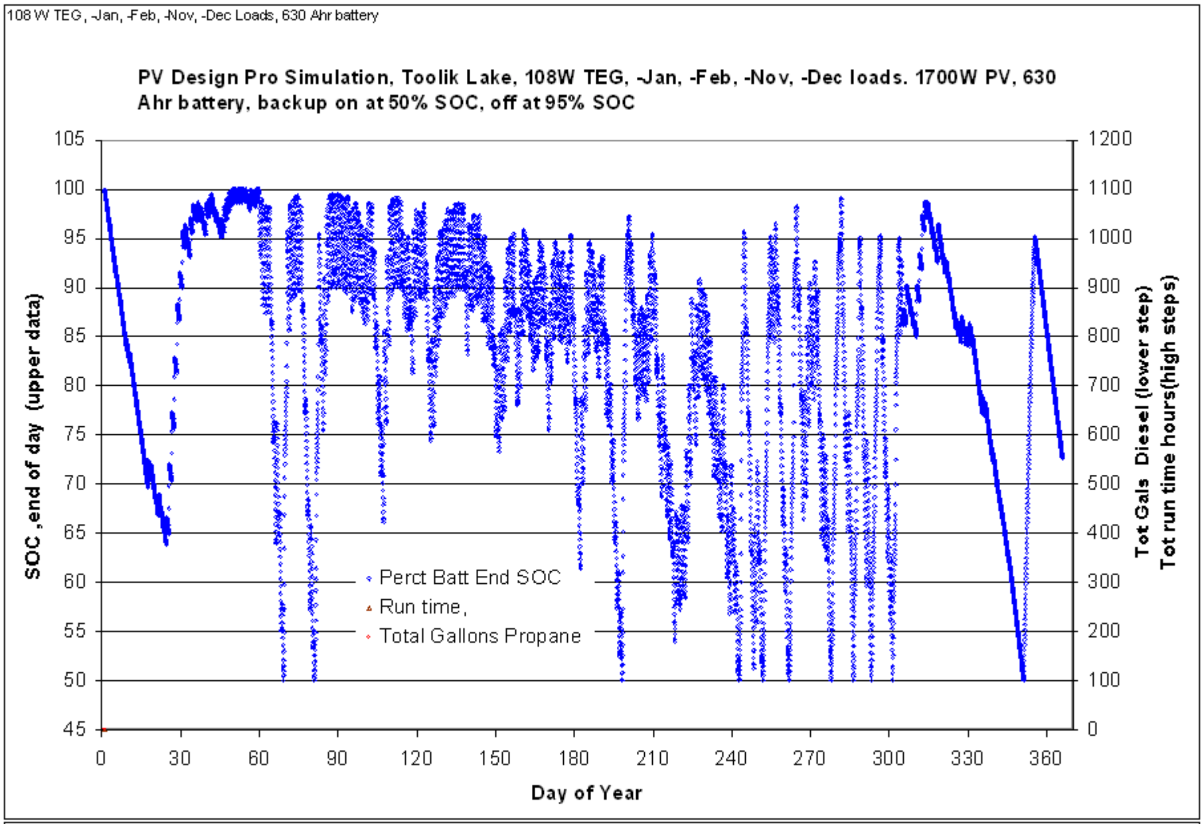


Figure B - 3. Simulation of 108W TEG 420 AH Bat, at 70 to 95% SOC.



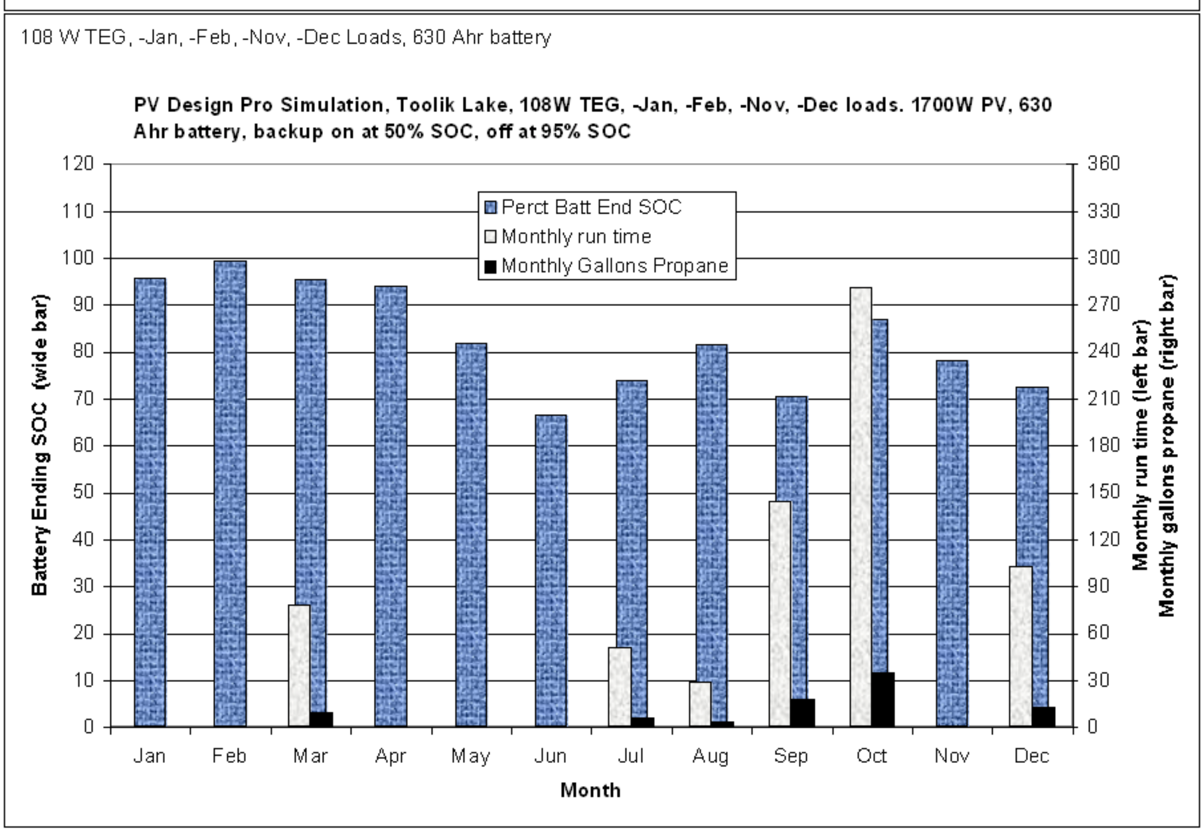
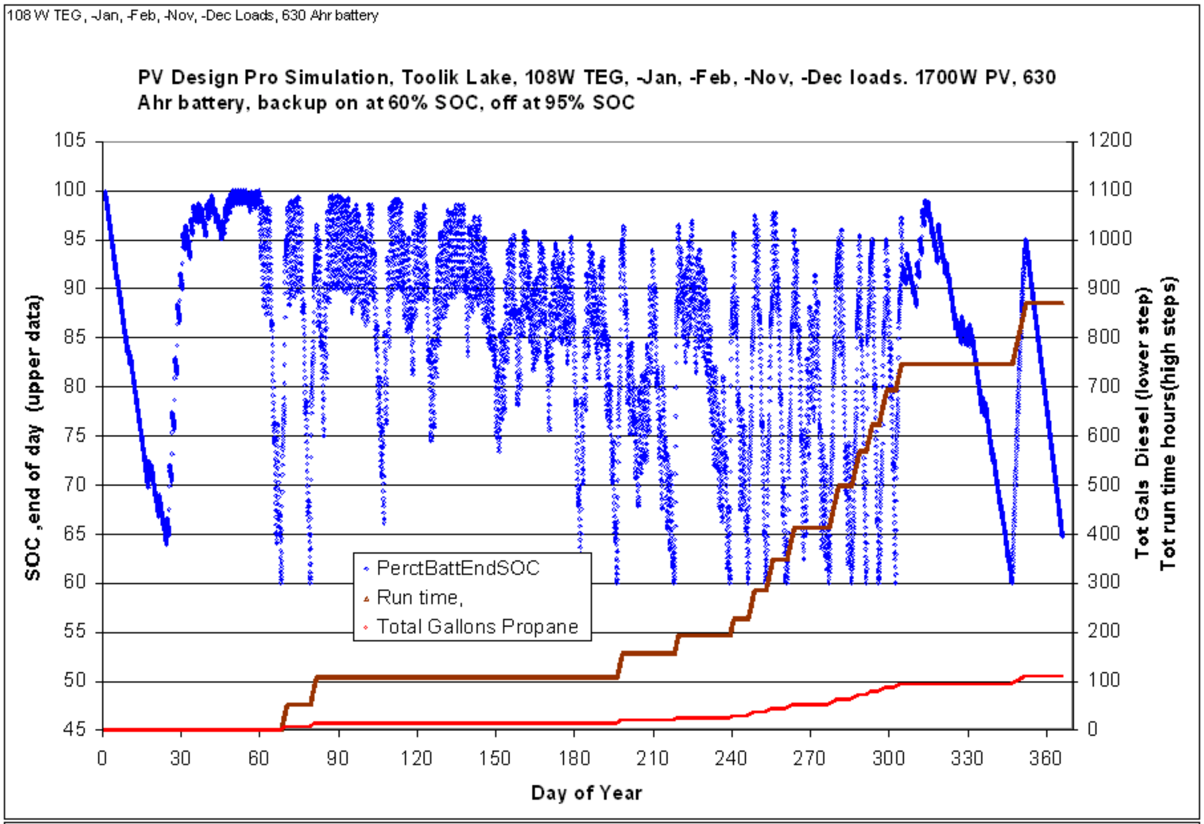


Figure B - 4. Simulation of 108W TEG 630 AH Bat, at 50 to 95% SOC.



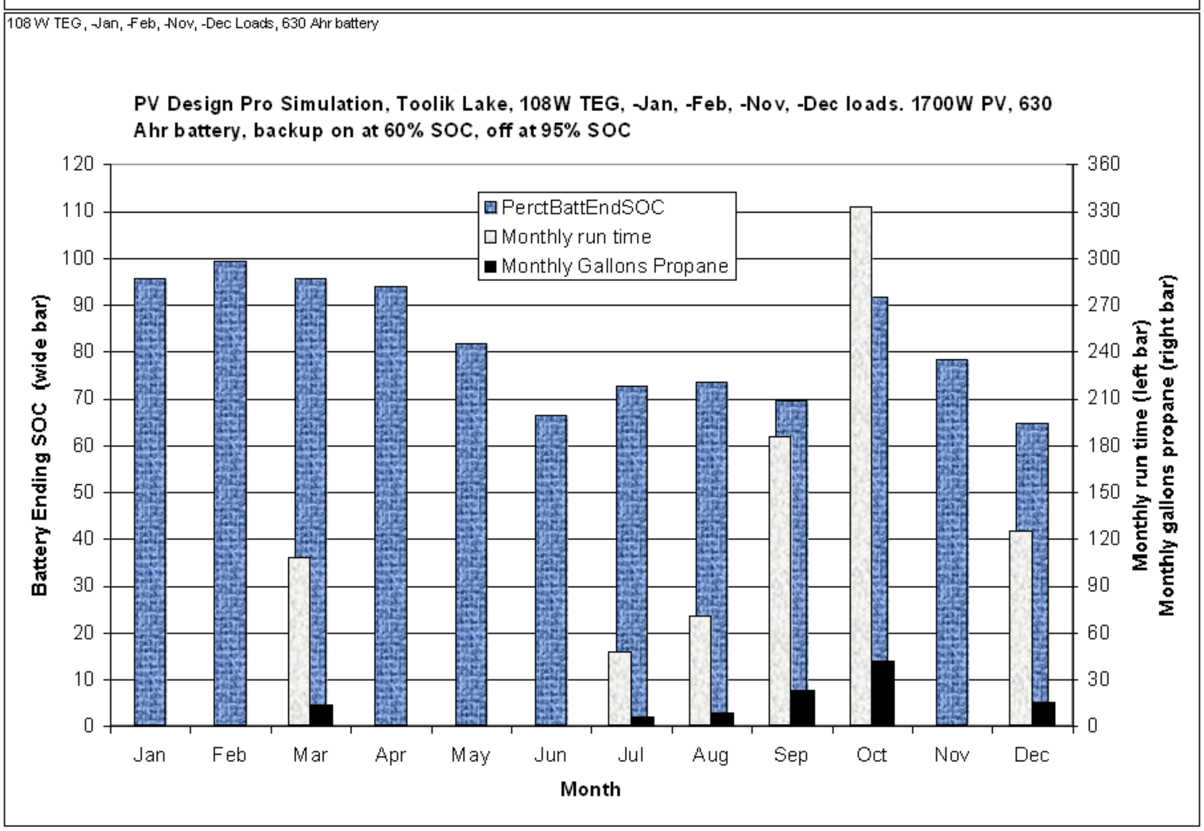
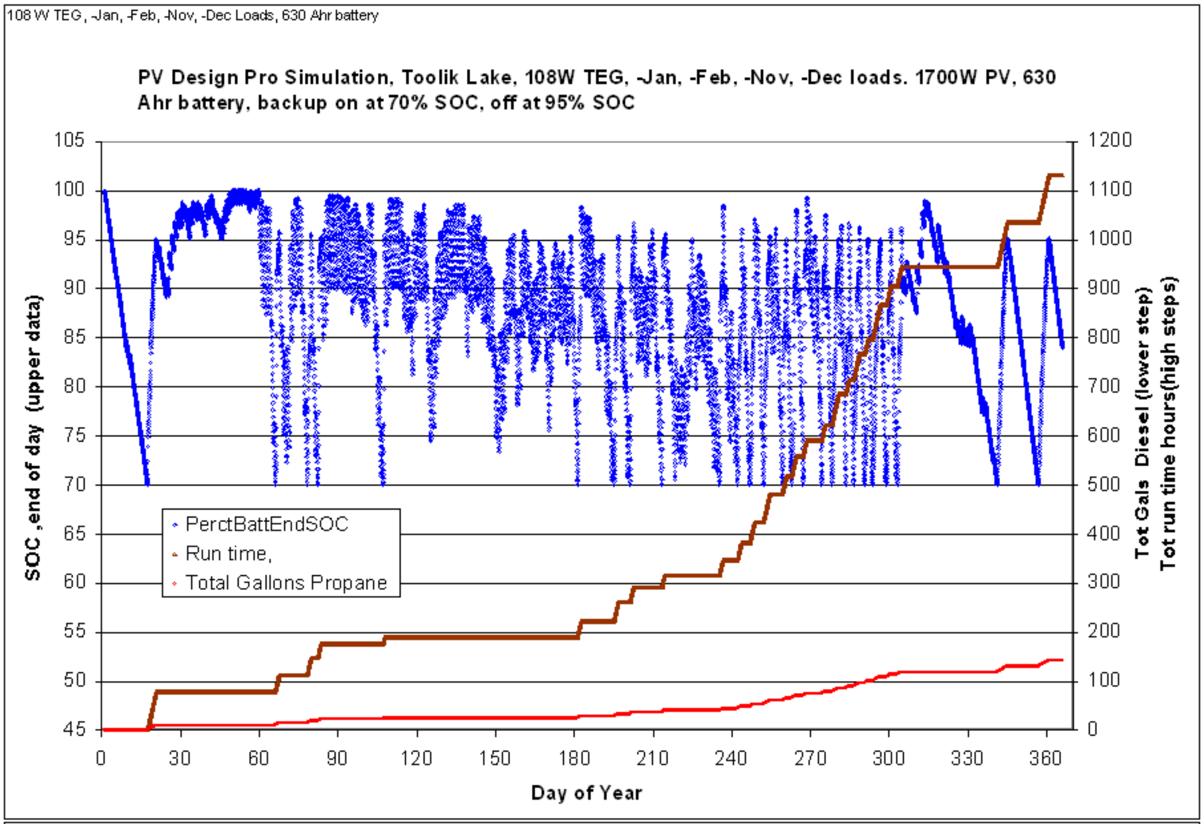


Figure B - 5. Simulation of 108W TEG 630 AH Bat, at 60 to 95% SOC.



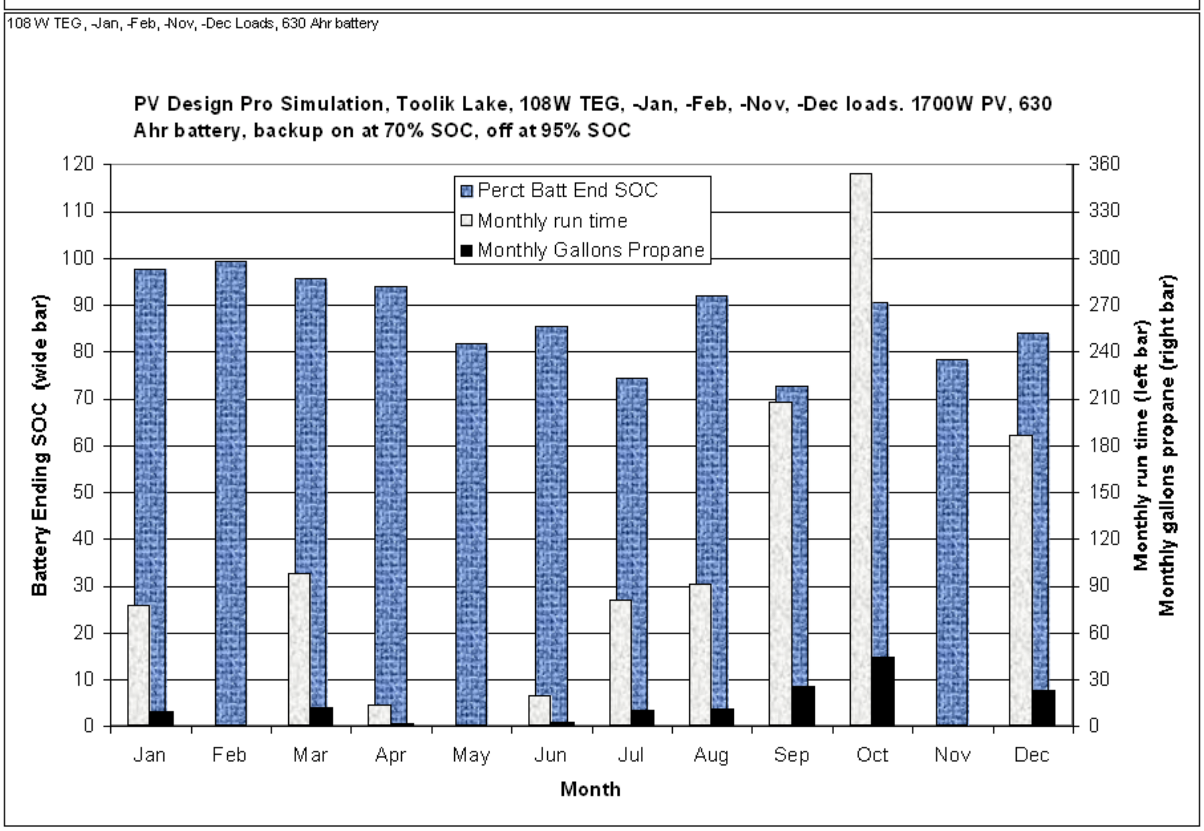
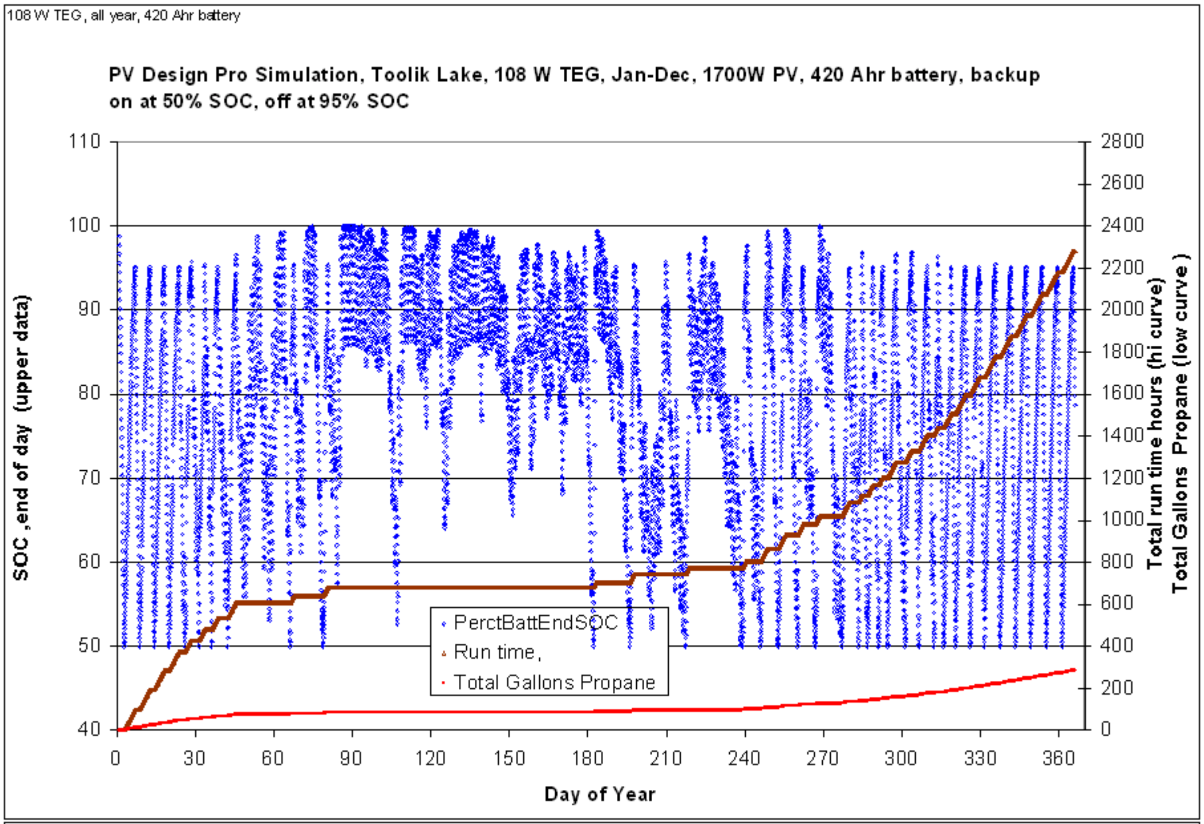


Figure B - 6. Simulation of 108W TEG 630 AH Bat, at 70 to 95% SOC.



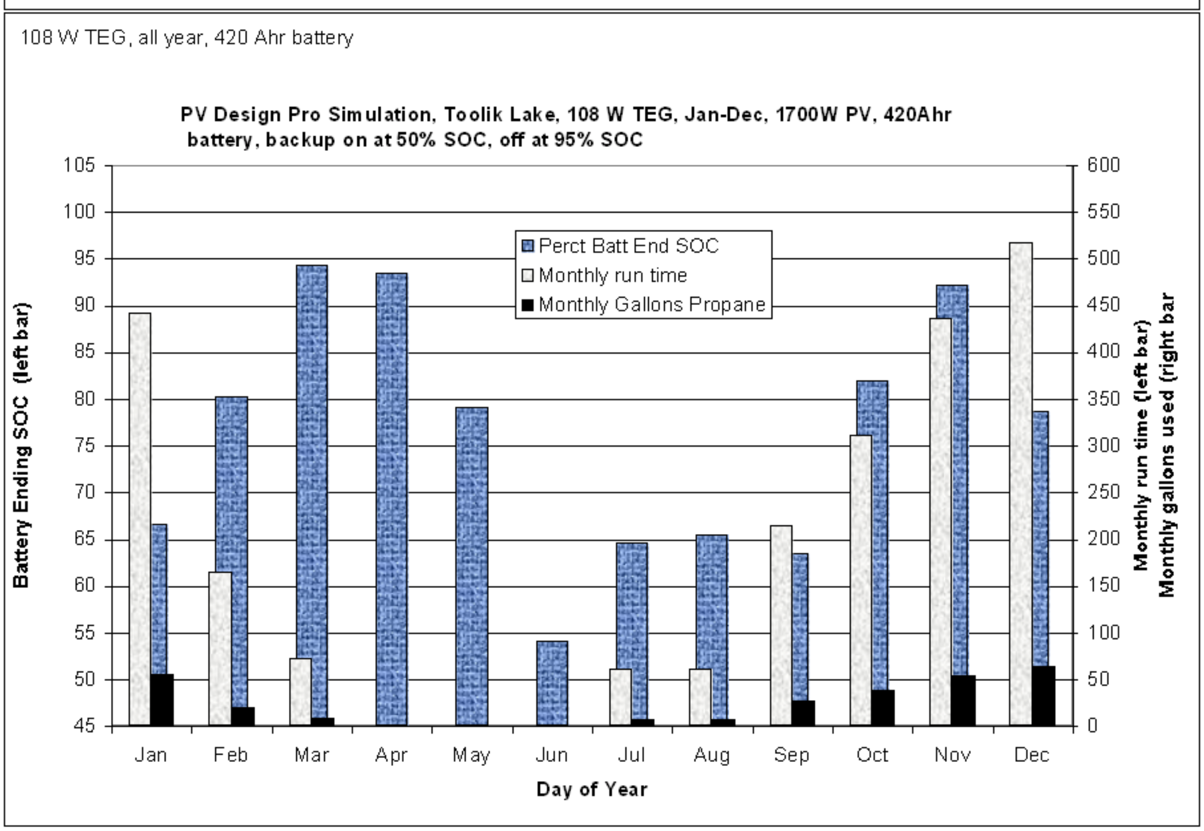
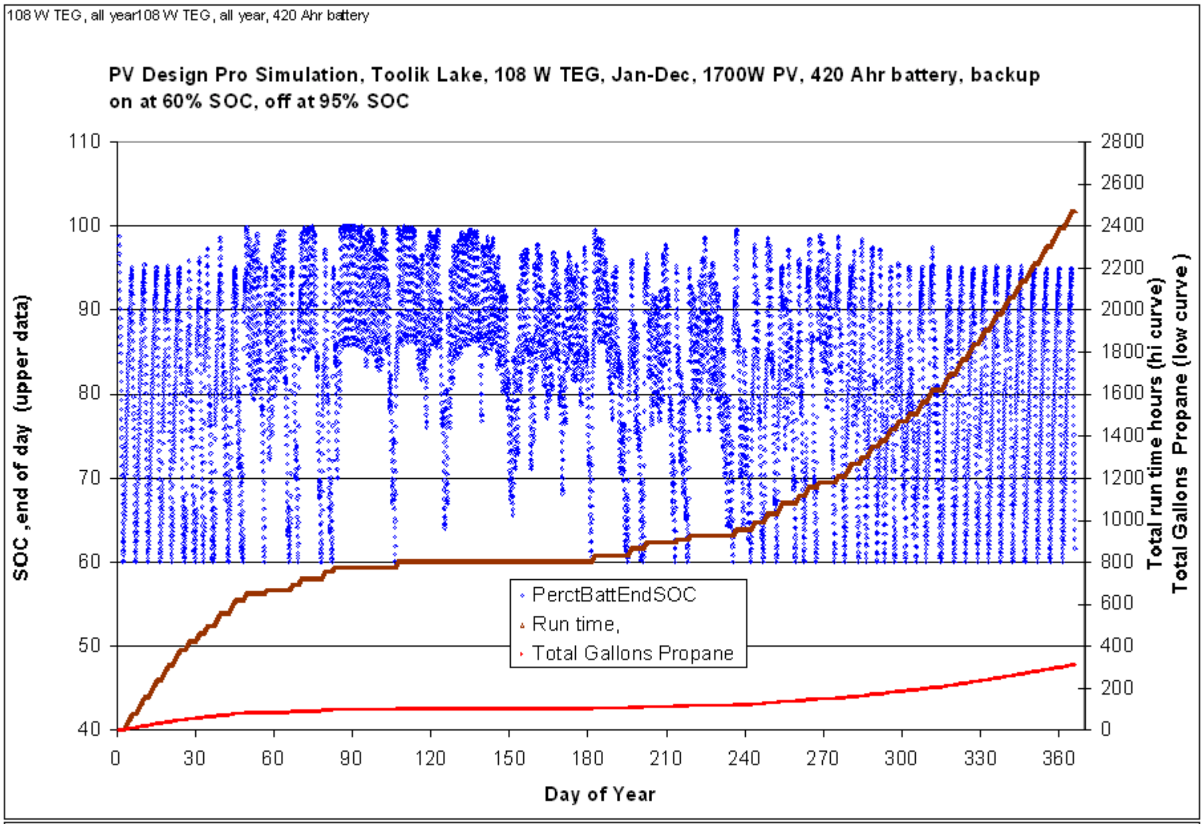


Figure B - 7. Simulation of 108W TEG 630 AH Bat, at 50 to 95% SOC.



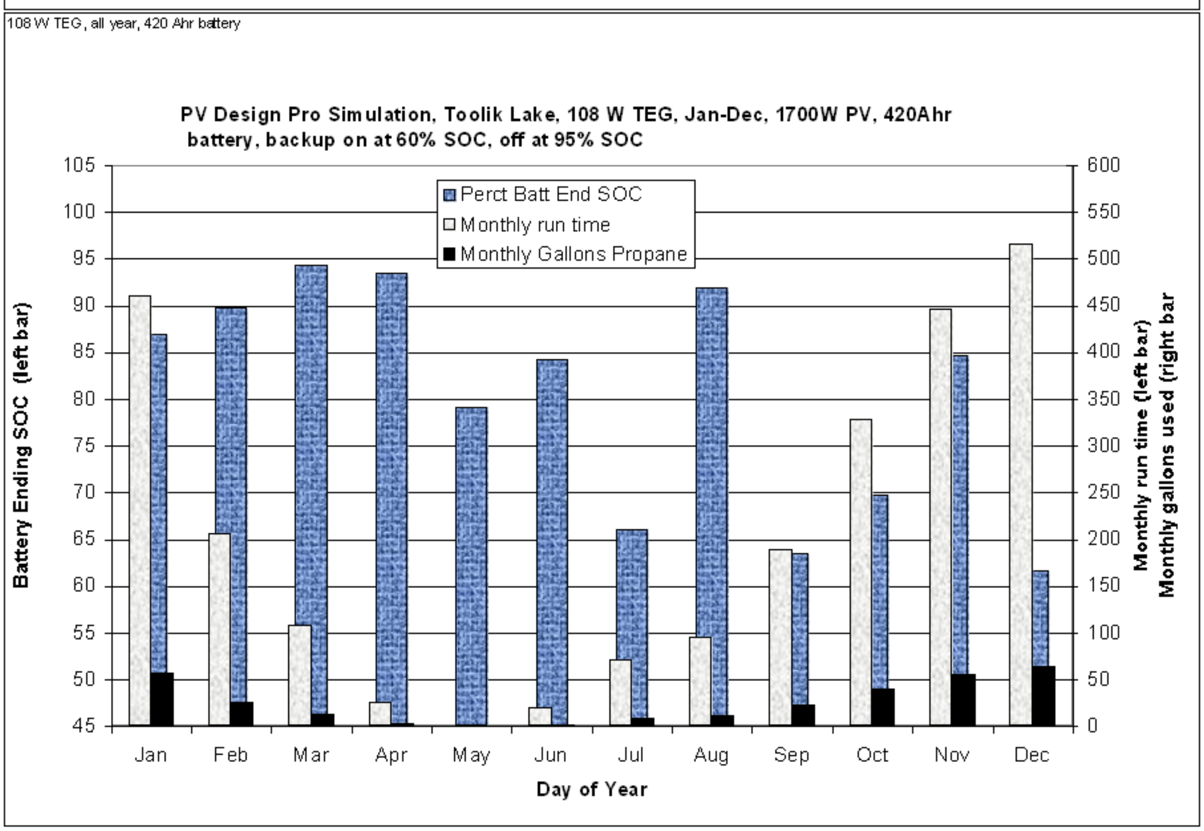
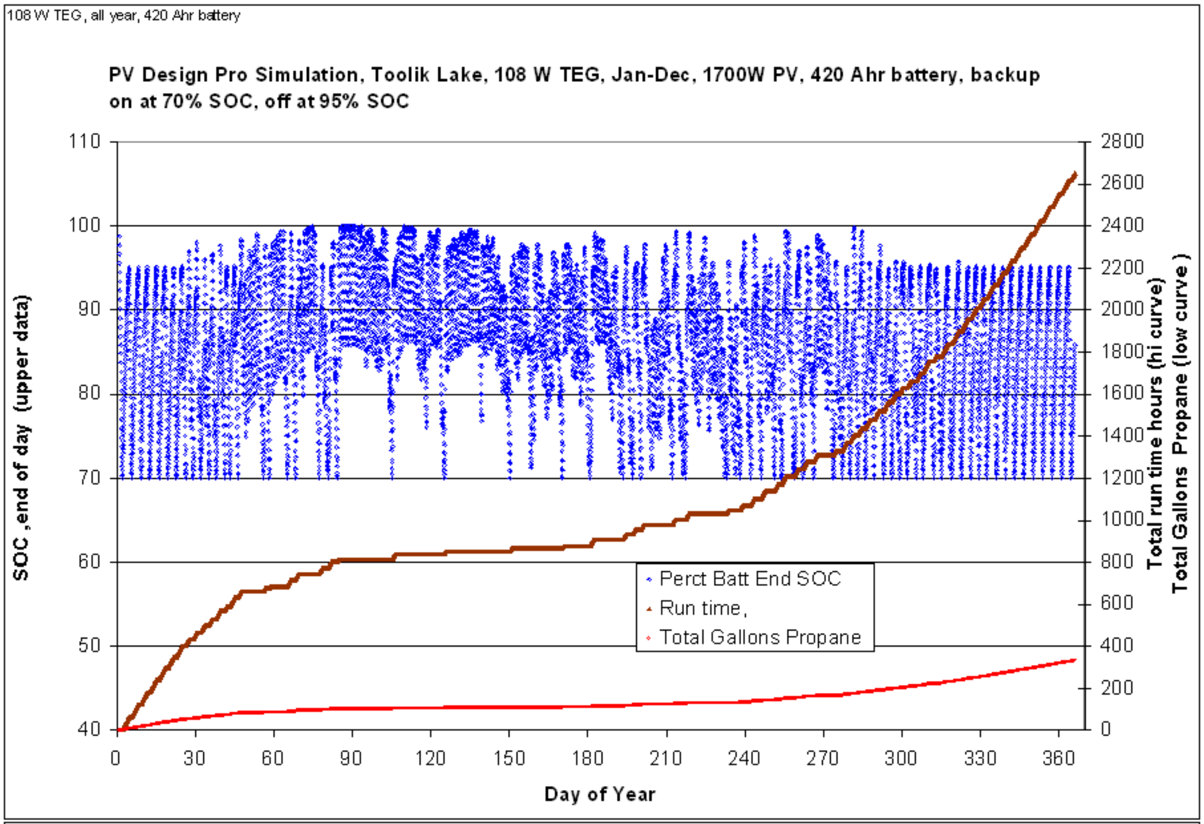


Figure B - 8. Simulation of 108W TEG 630 AH Bat, at 60 to 95% SOC.



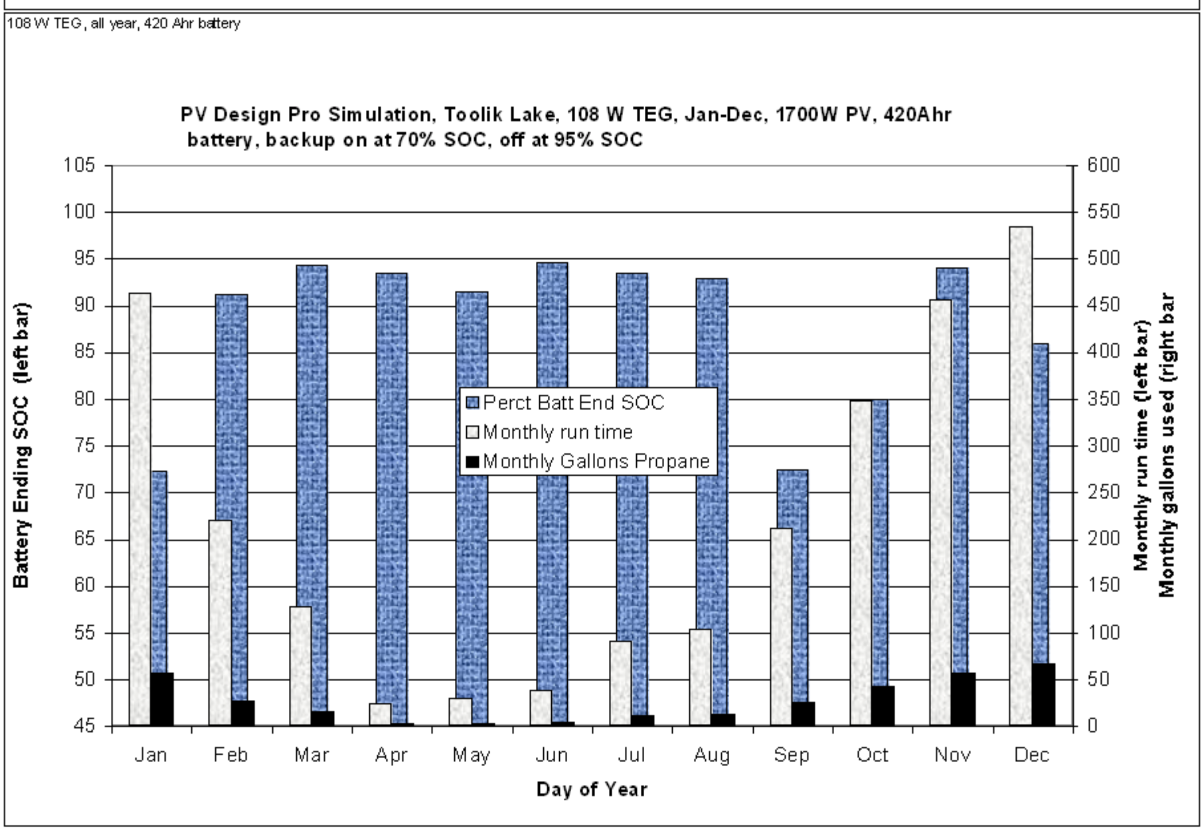
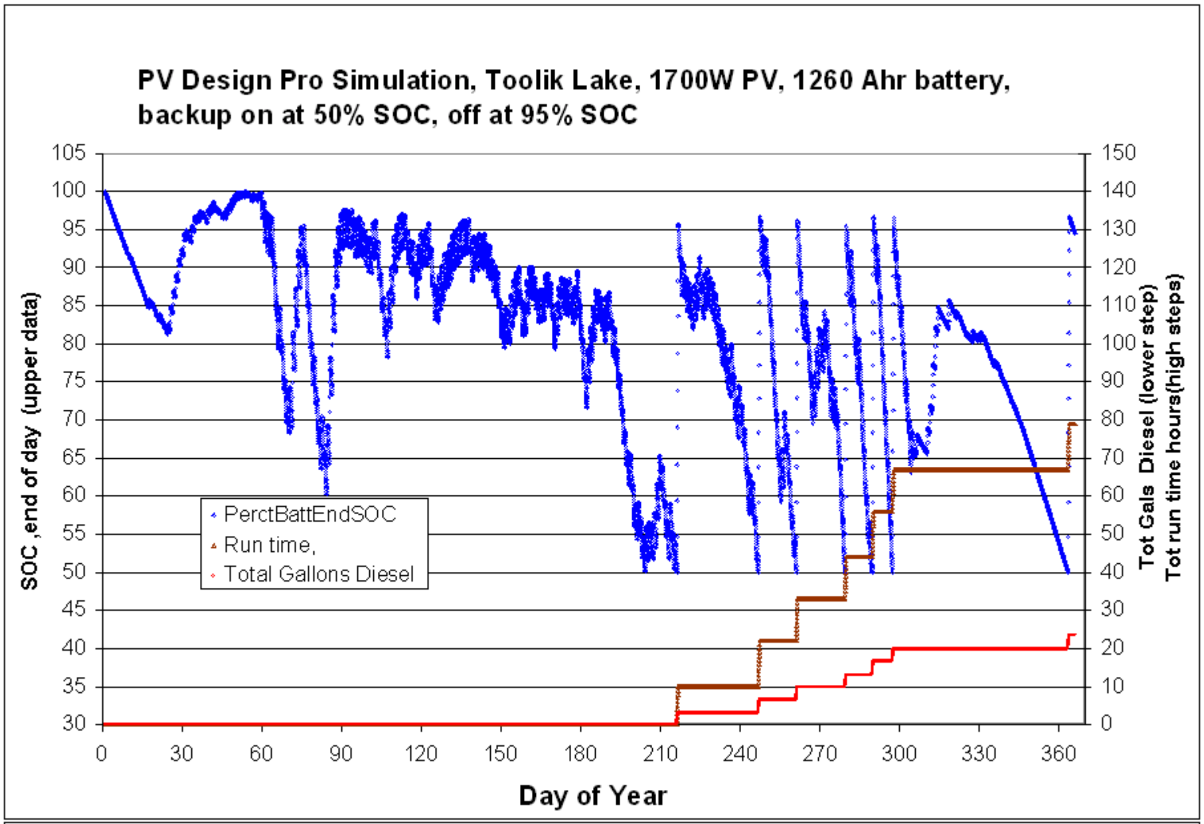


Figure B - 9. Simulation of 108W TEG 630 AH Bat, at 70 to 95% SOC.



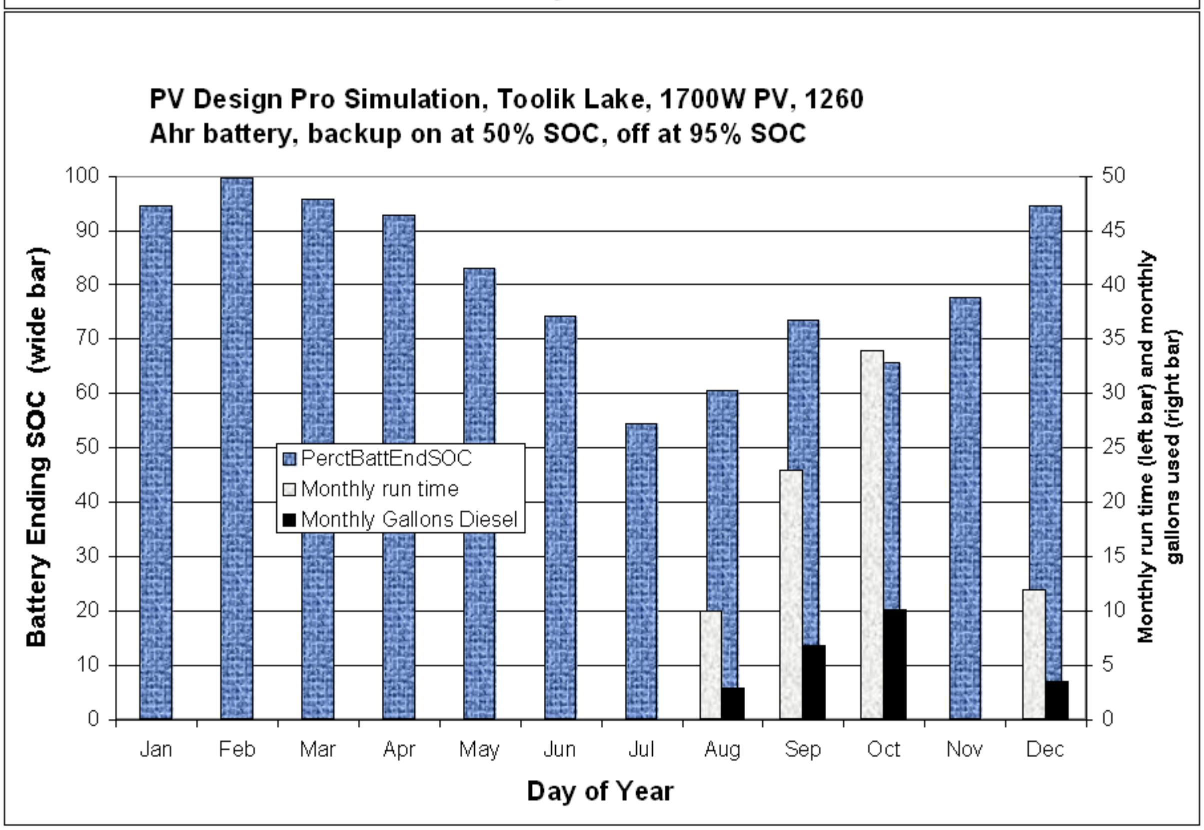
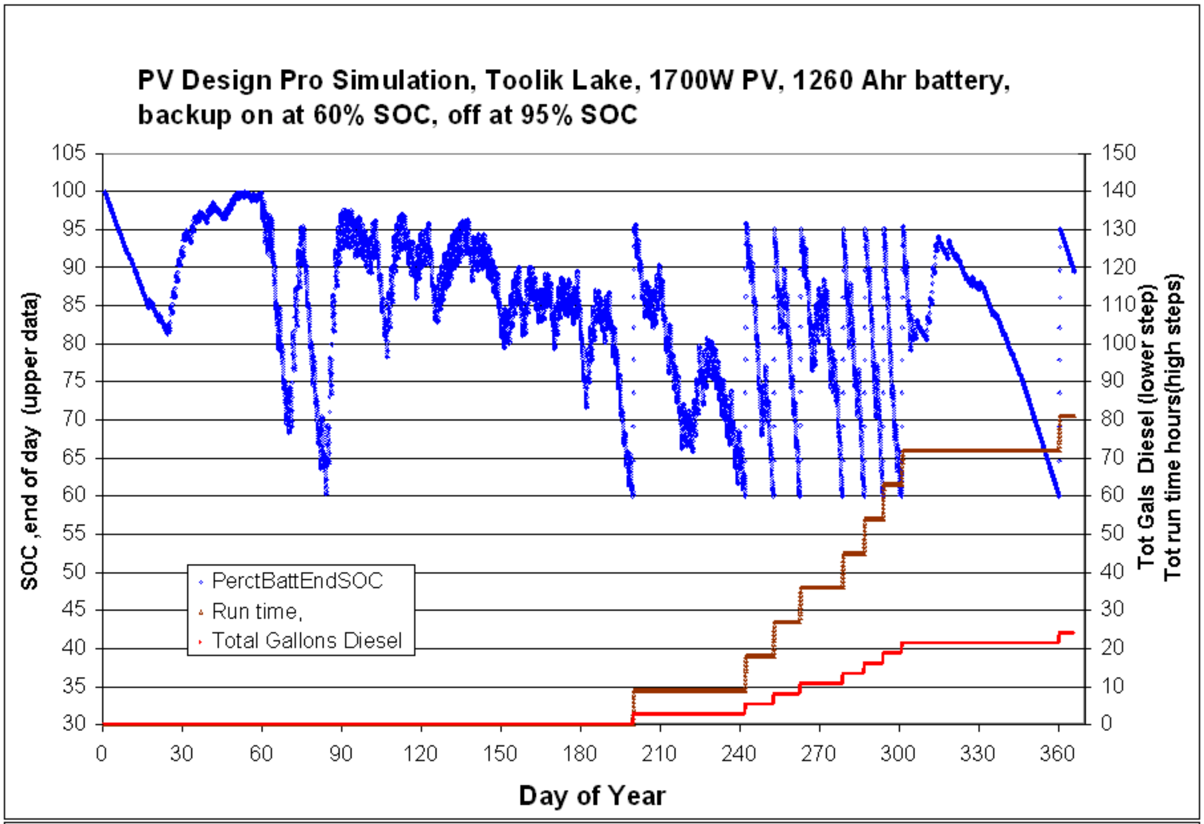


Figure B - 10. Simulation of 3kW Listeroid Diesel 1260 AH Bat, at 50 to 95% SOC.



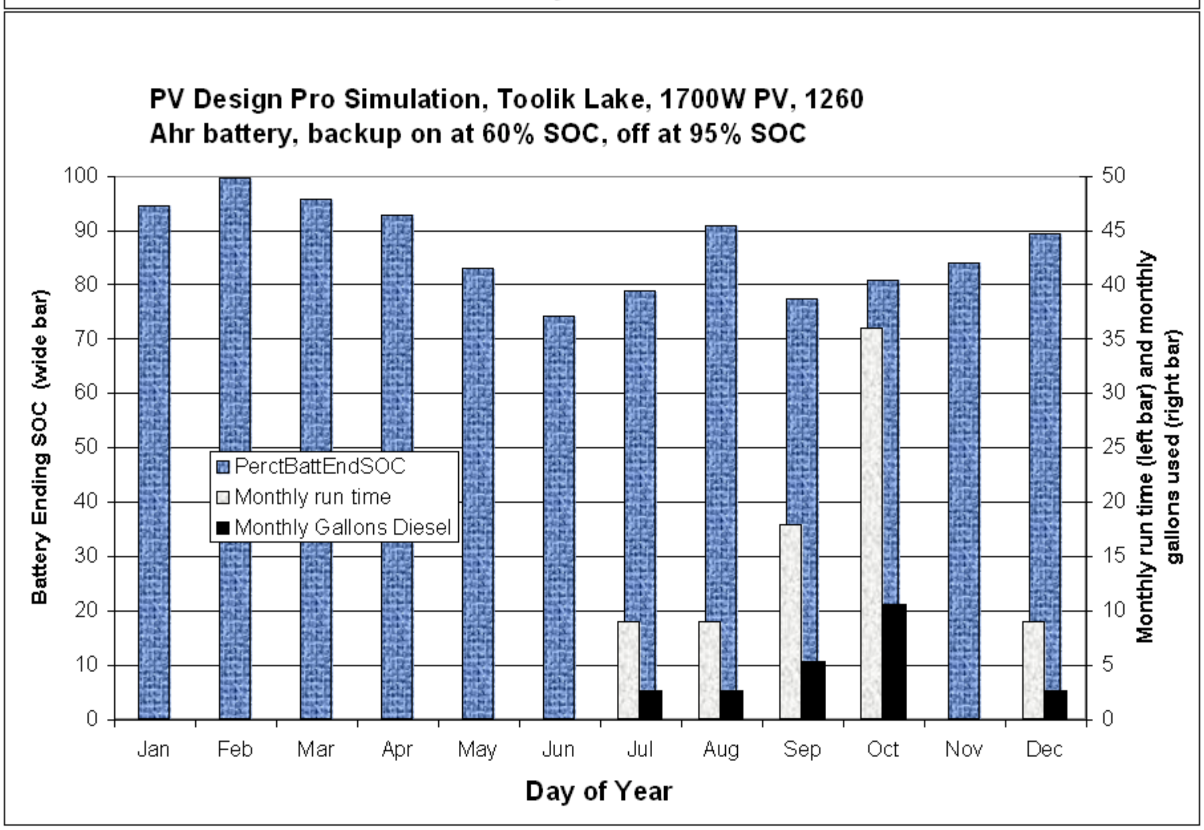
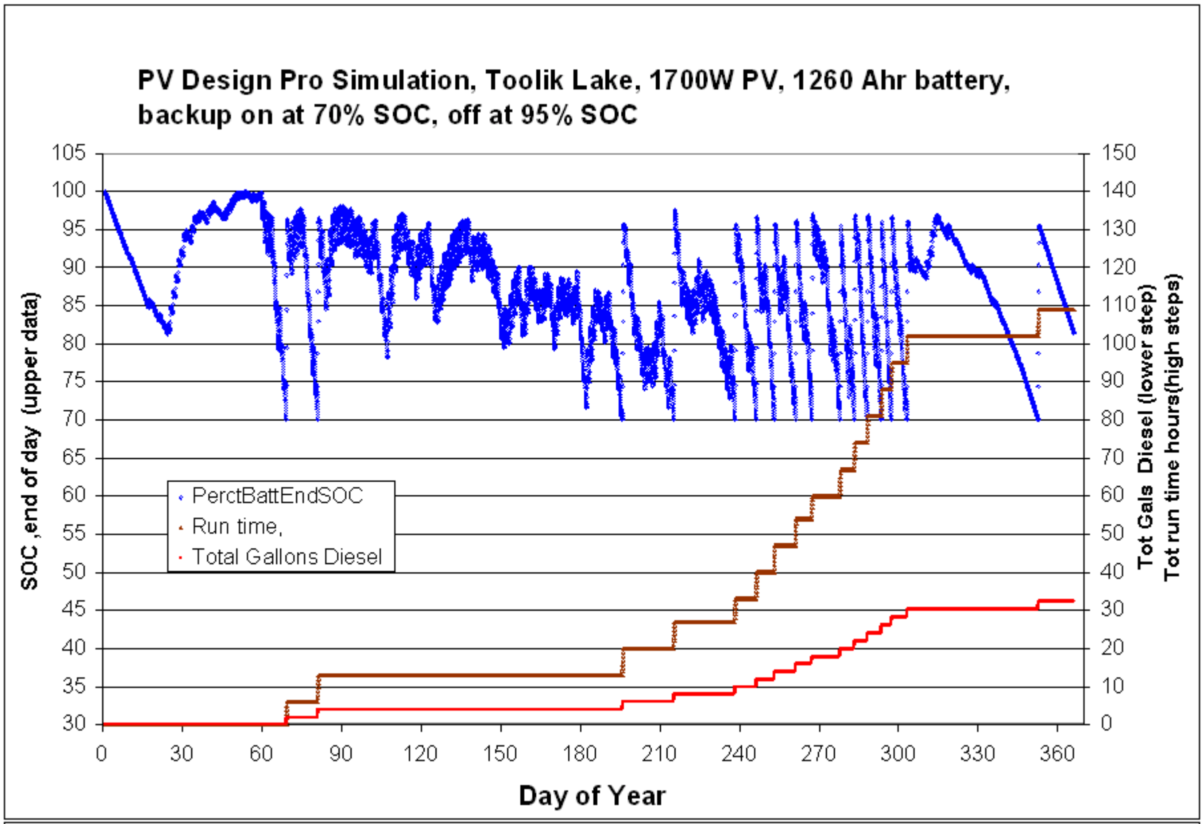


Figure B - 11. Simulation of 3kW Listeroid Diesel 1260 AH Bat, at 60 to 95% SOC.



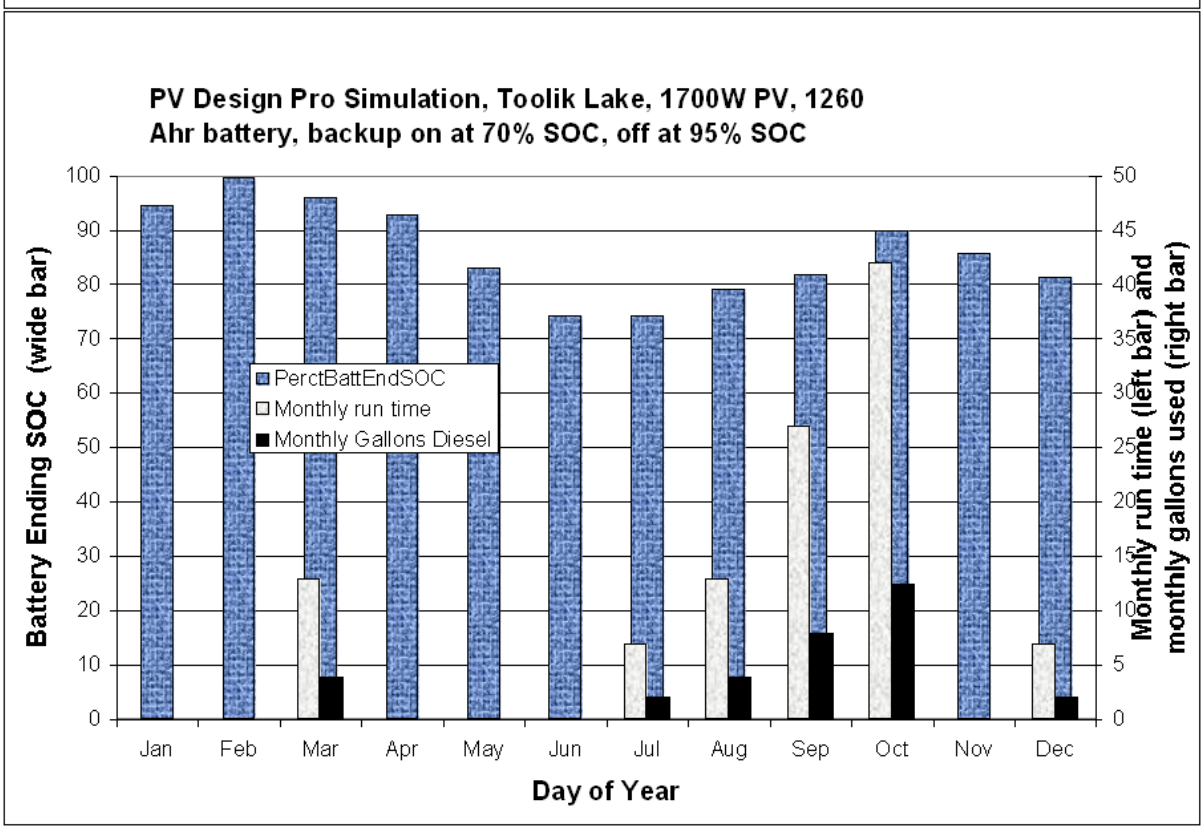
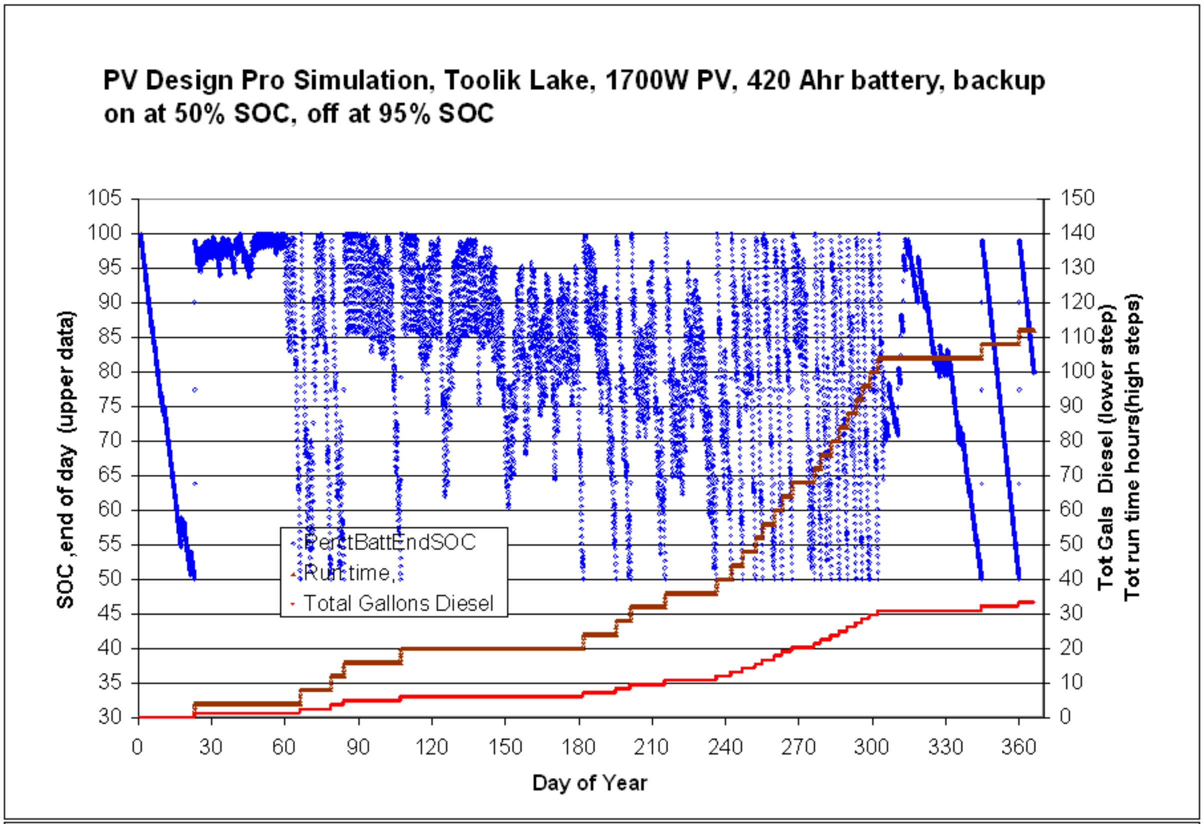


Figure B - 12. Simulation of 3kW Listeroid Diesel 1260 AH Bat, at 70 to 95% SOC.



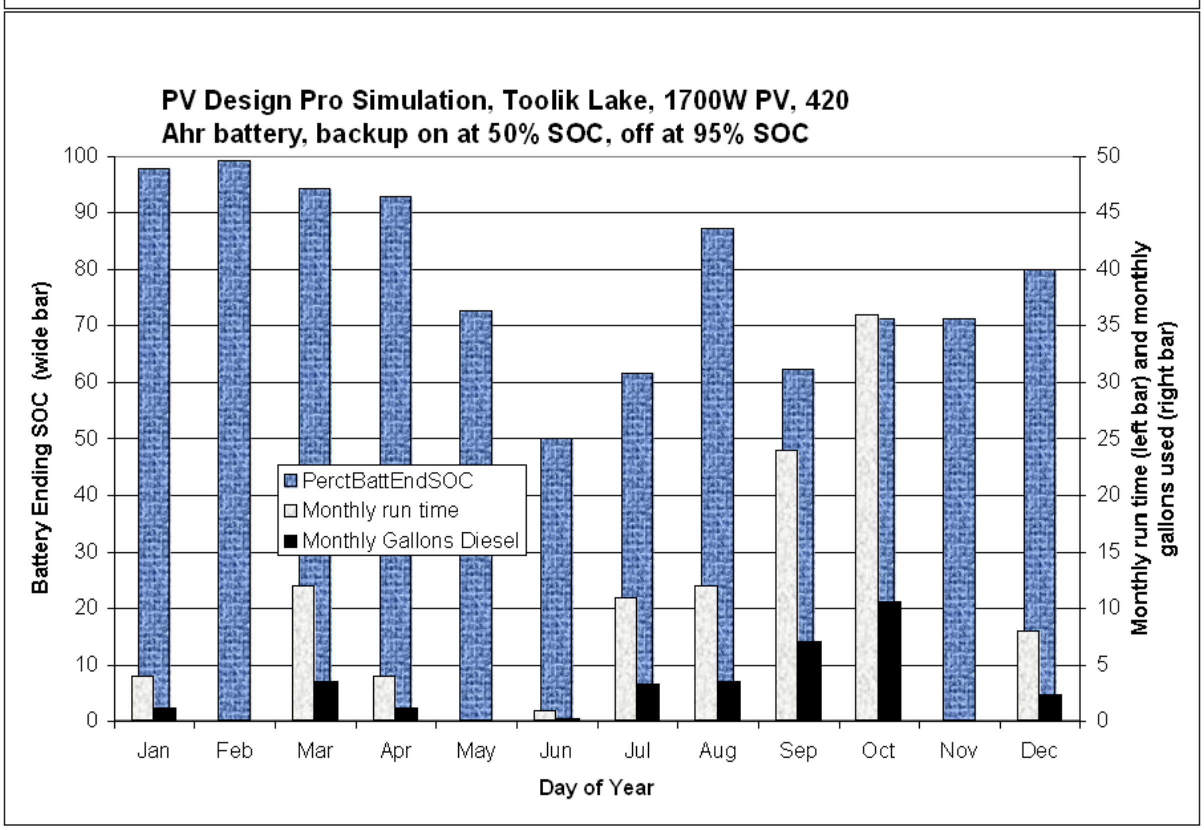
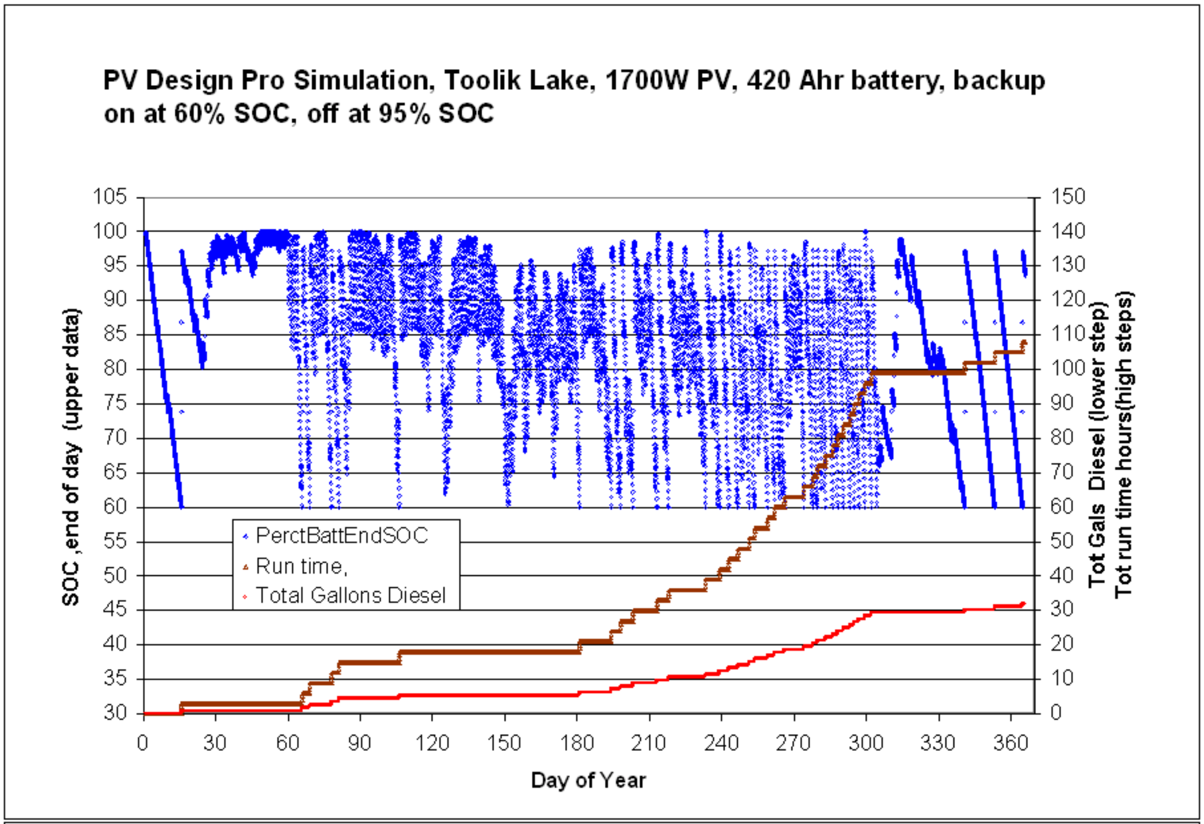


Figure B - 13. Simulation of 3kW Listeroid Diesel 420 AH Bat, at 50 to 95% SOC.



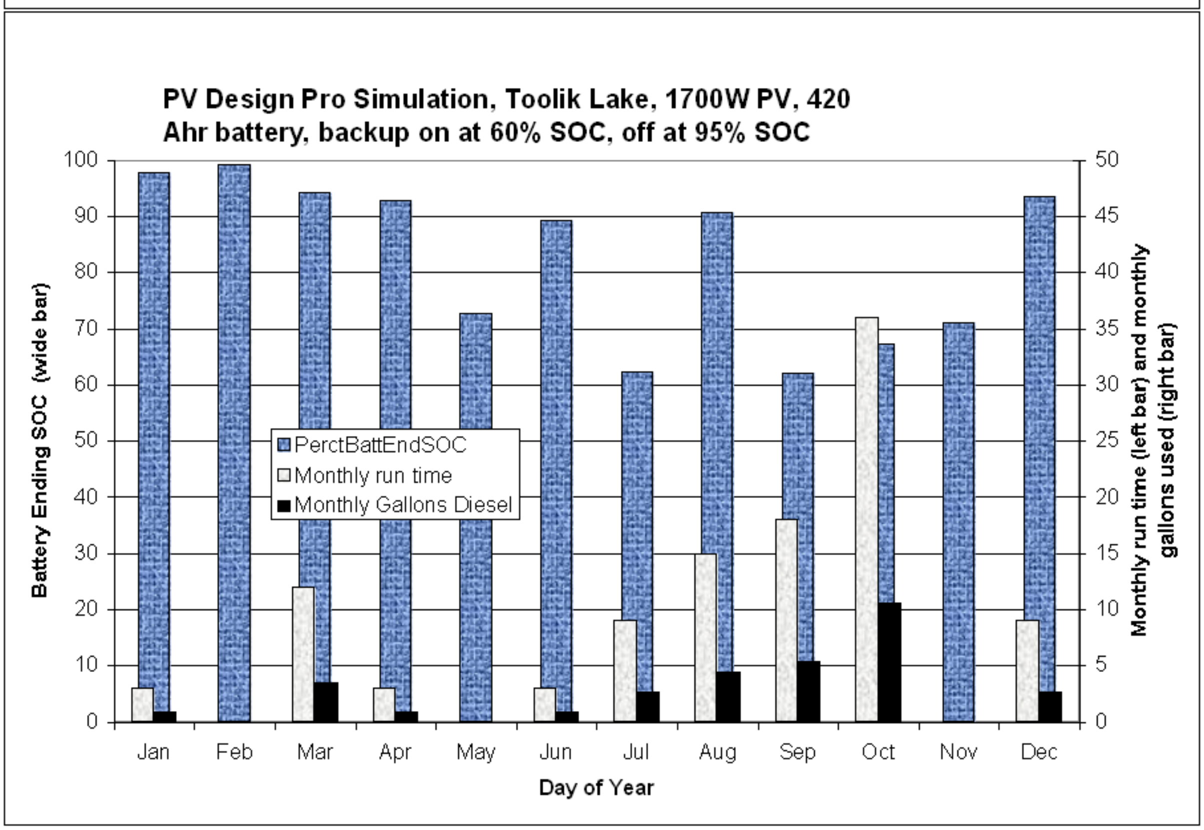
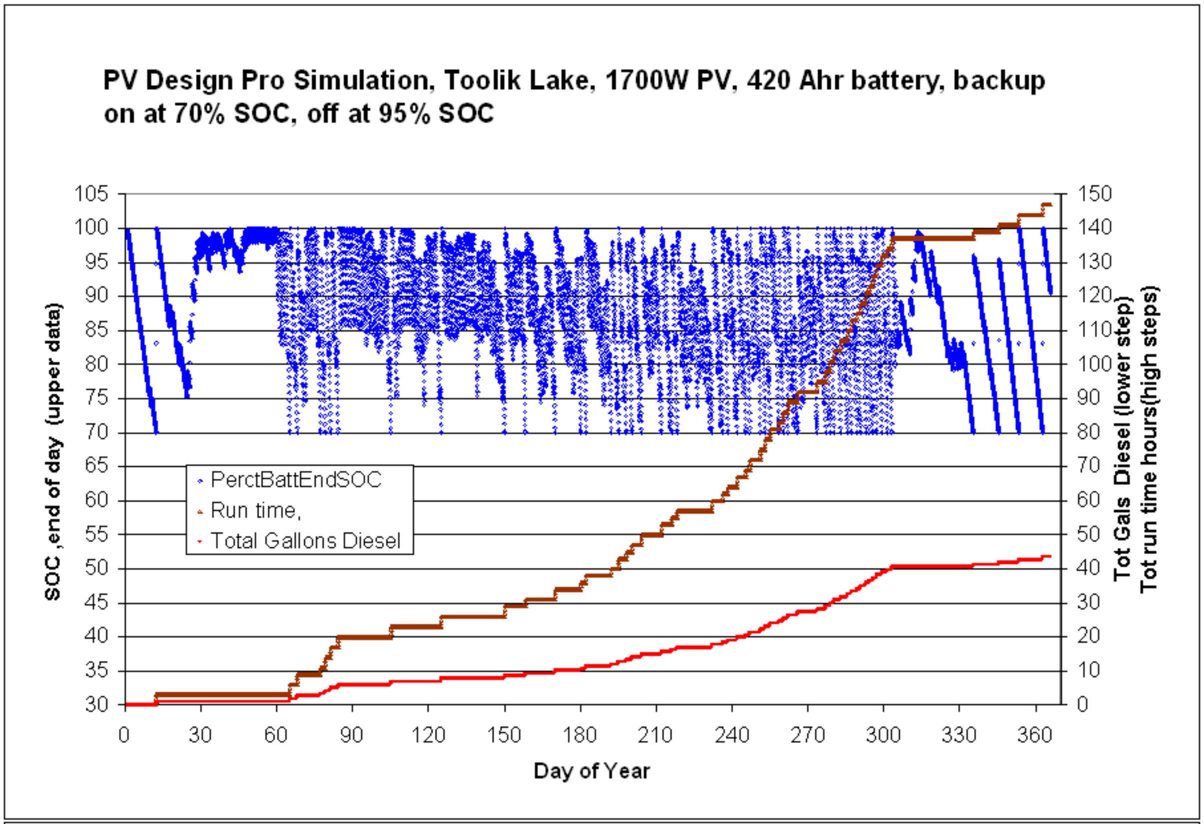


Figure B - 14. Simulation of 3kW Listeroid Diesel 420 AH Bat, at 60 to 95% SOC.



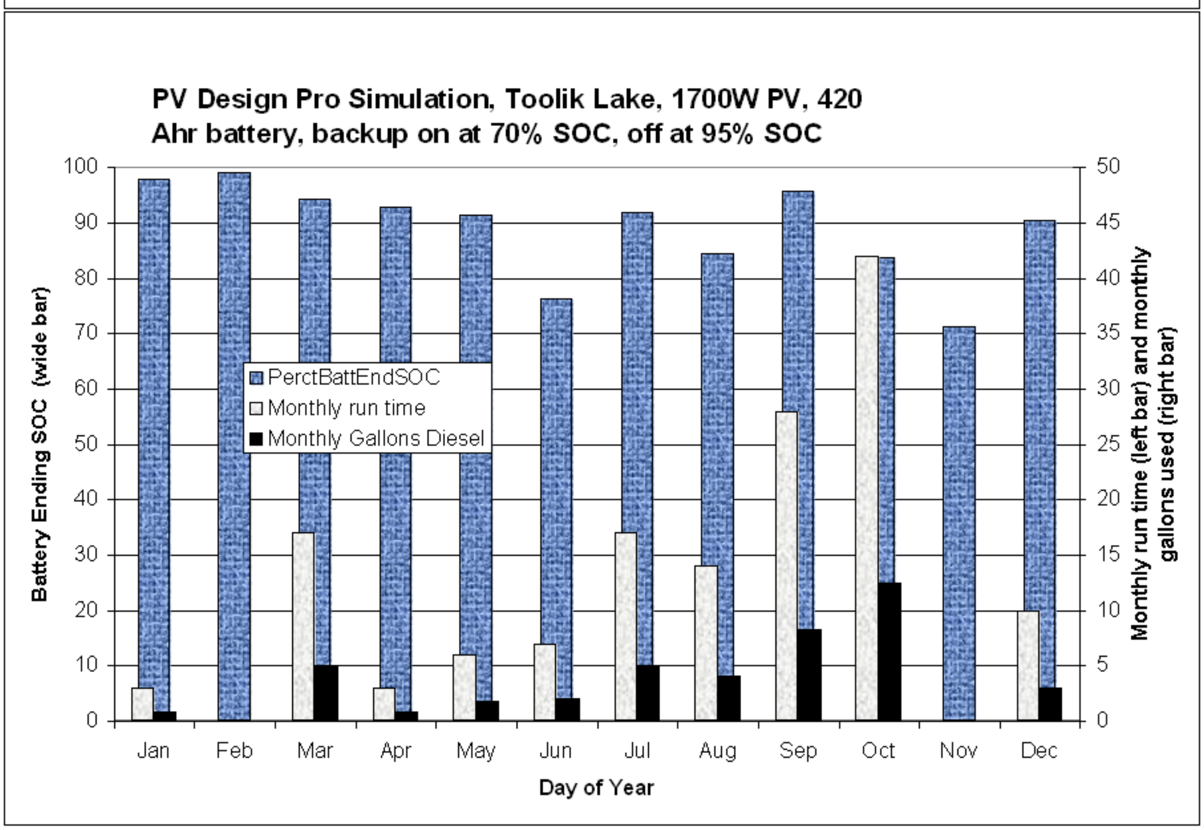
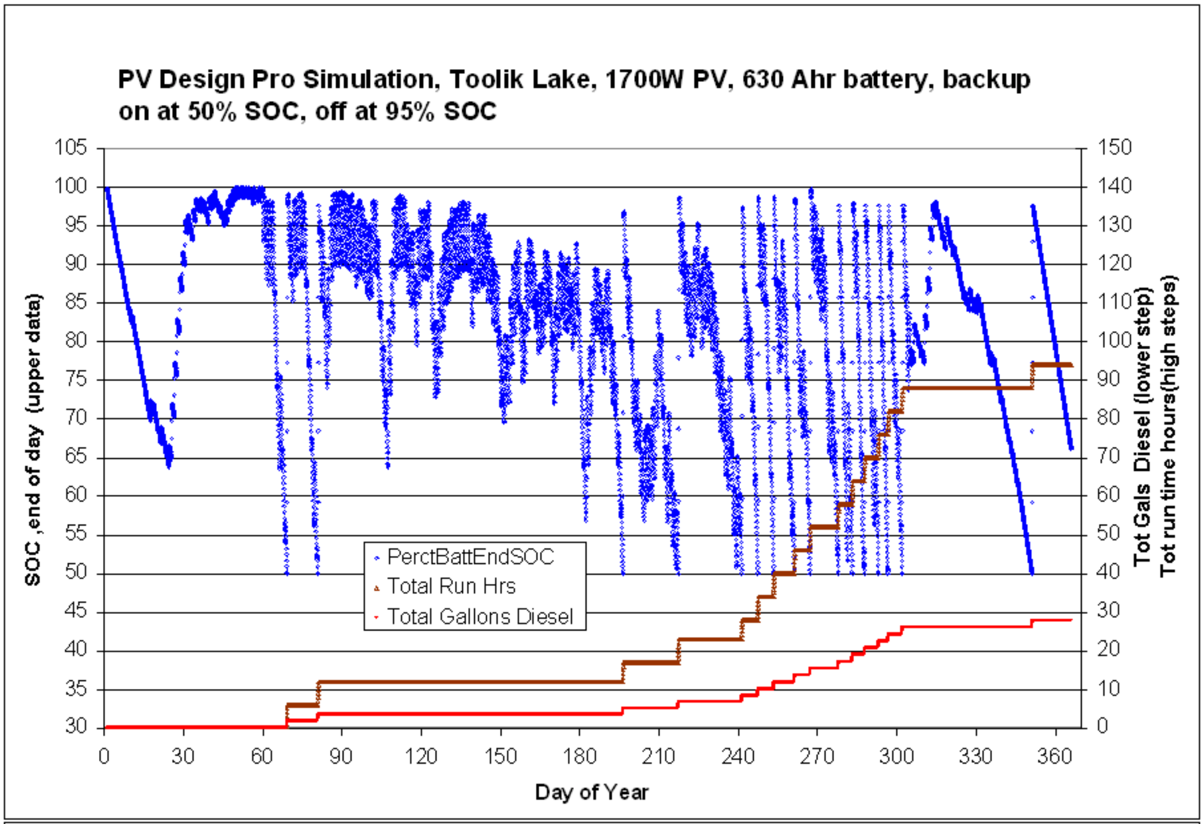


Figure B - 15. Simulation of 3kW Listeroid Diesel 420 AH Bat, at 70 to 95% SOC.



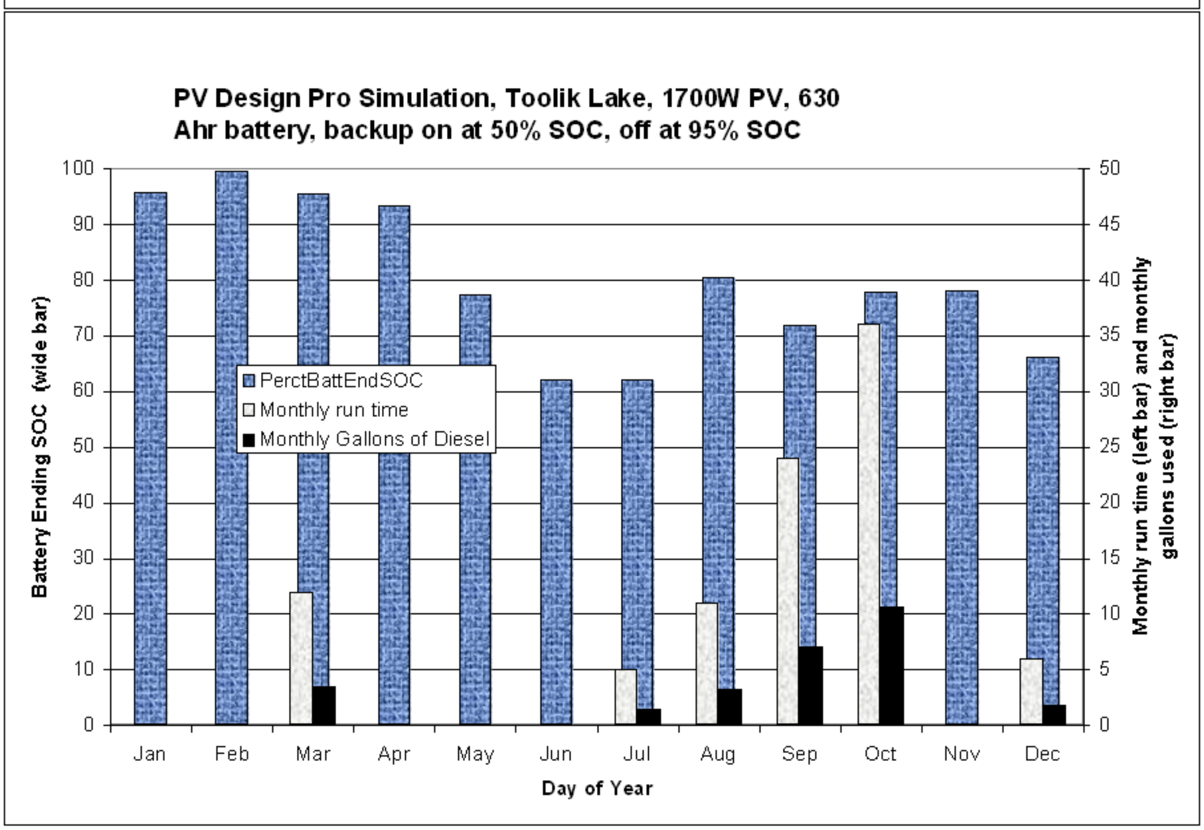
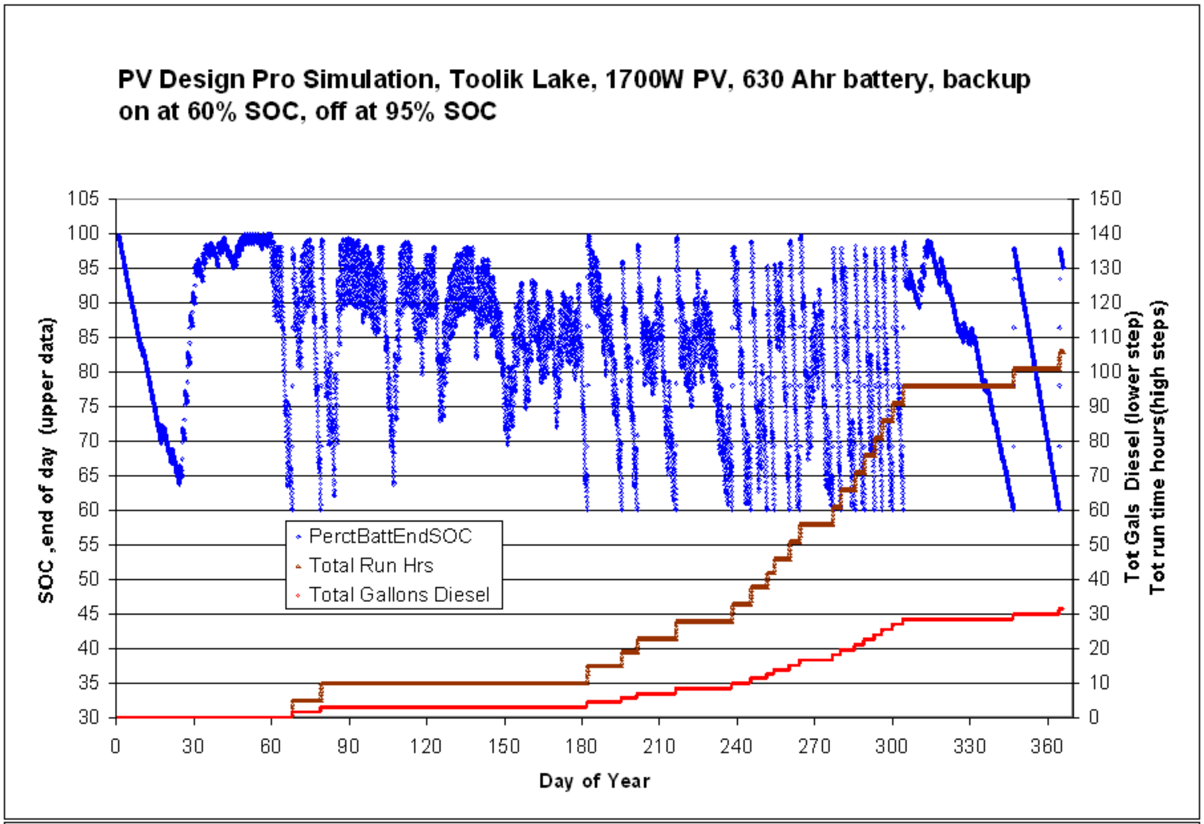


Figure B - 16. Simulation of 3kW Listeroid Diesel 630 AH Bat, at 50 to 95% SOC.



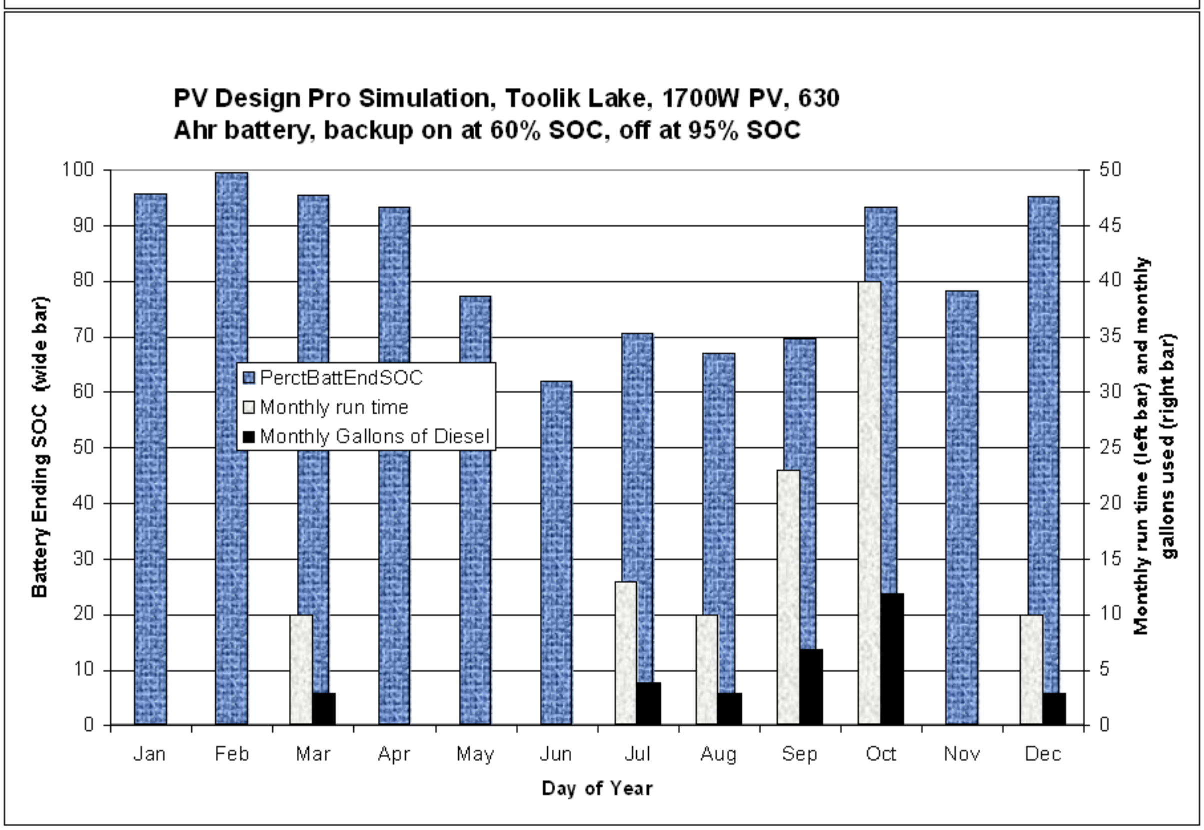
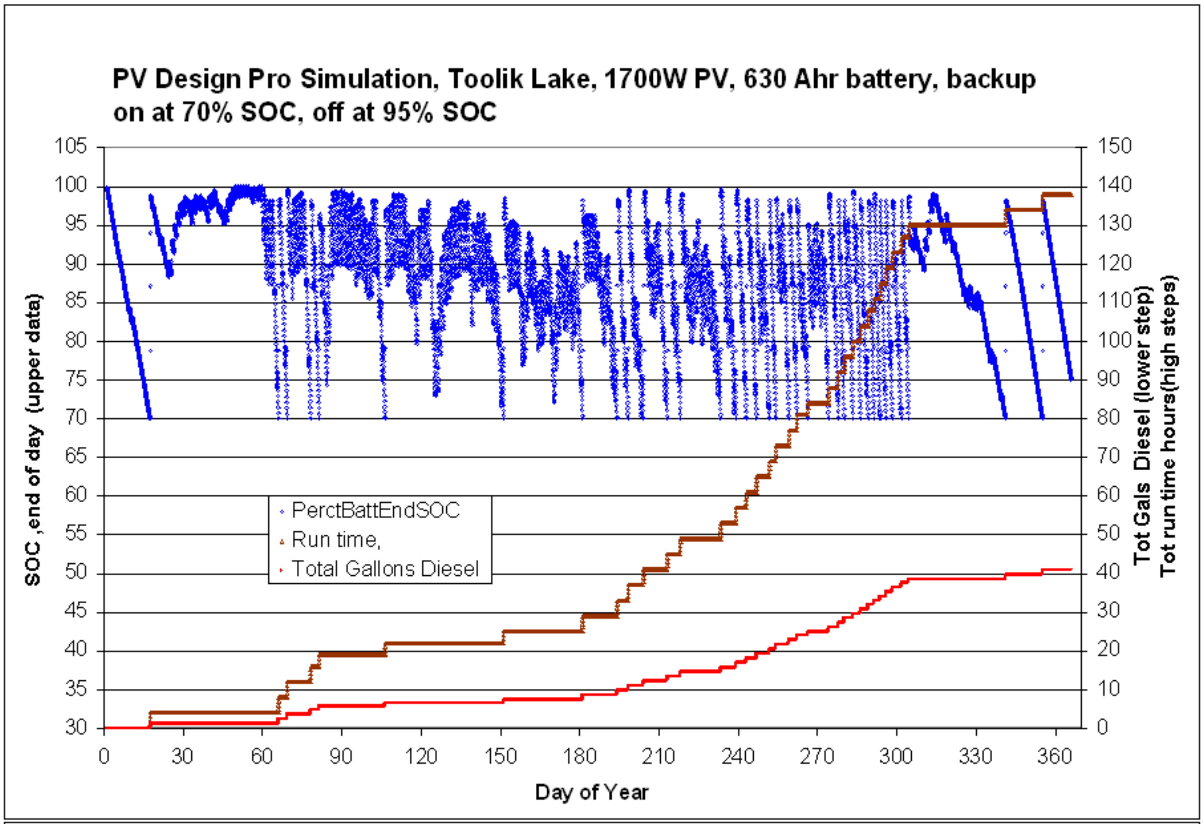


Figure B - 17. Simulation of 3kW Listeroid Diesel 630 AH Bat, at 60 to 95% SOC.



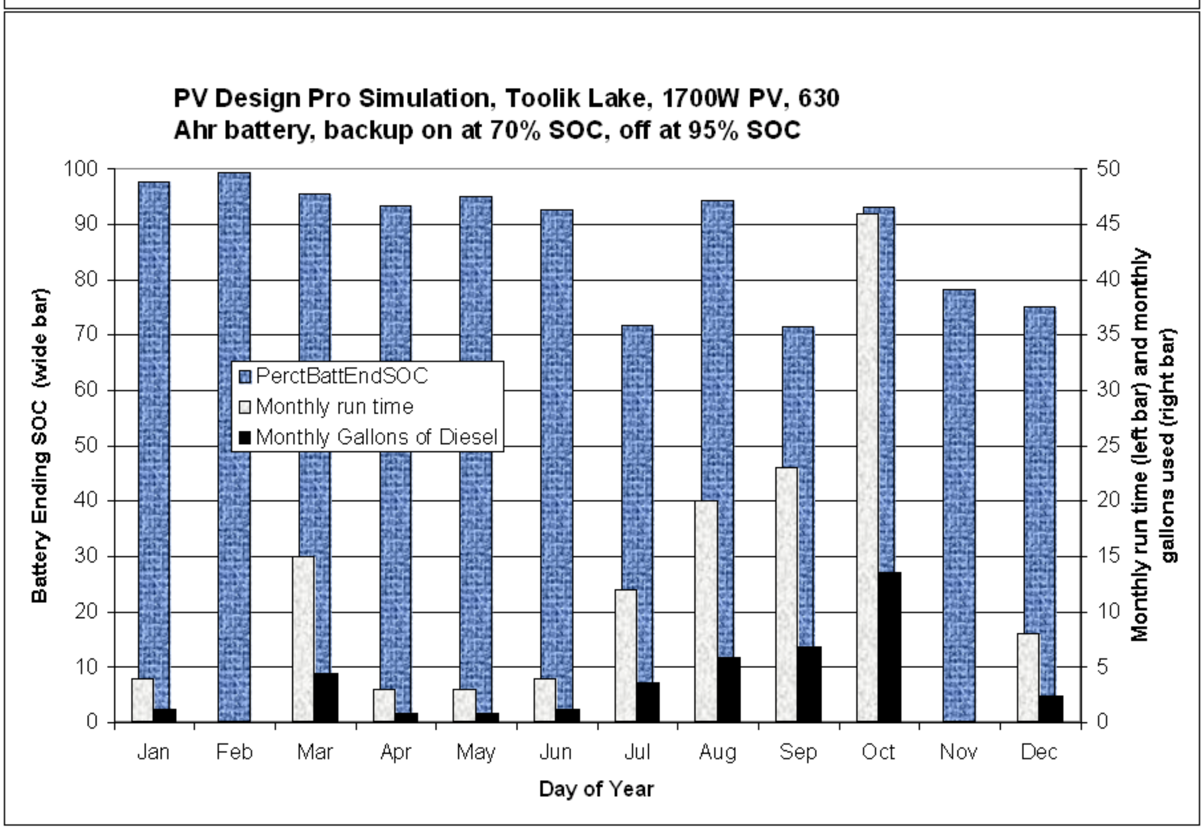


Figure B - 18. Simulation of 3kW Listeroid Diesel 630 AH Bat, at 70 to 95% SOC.

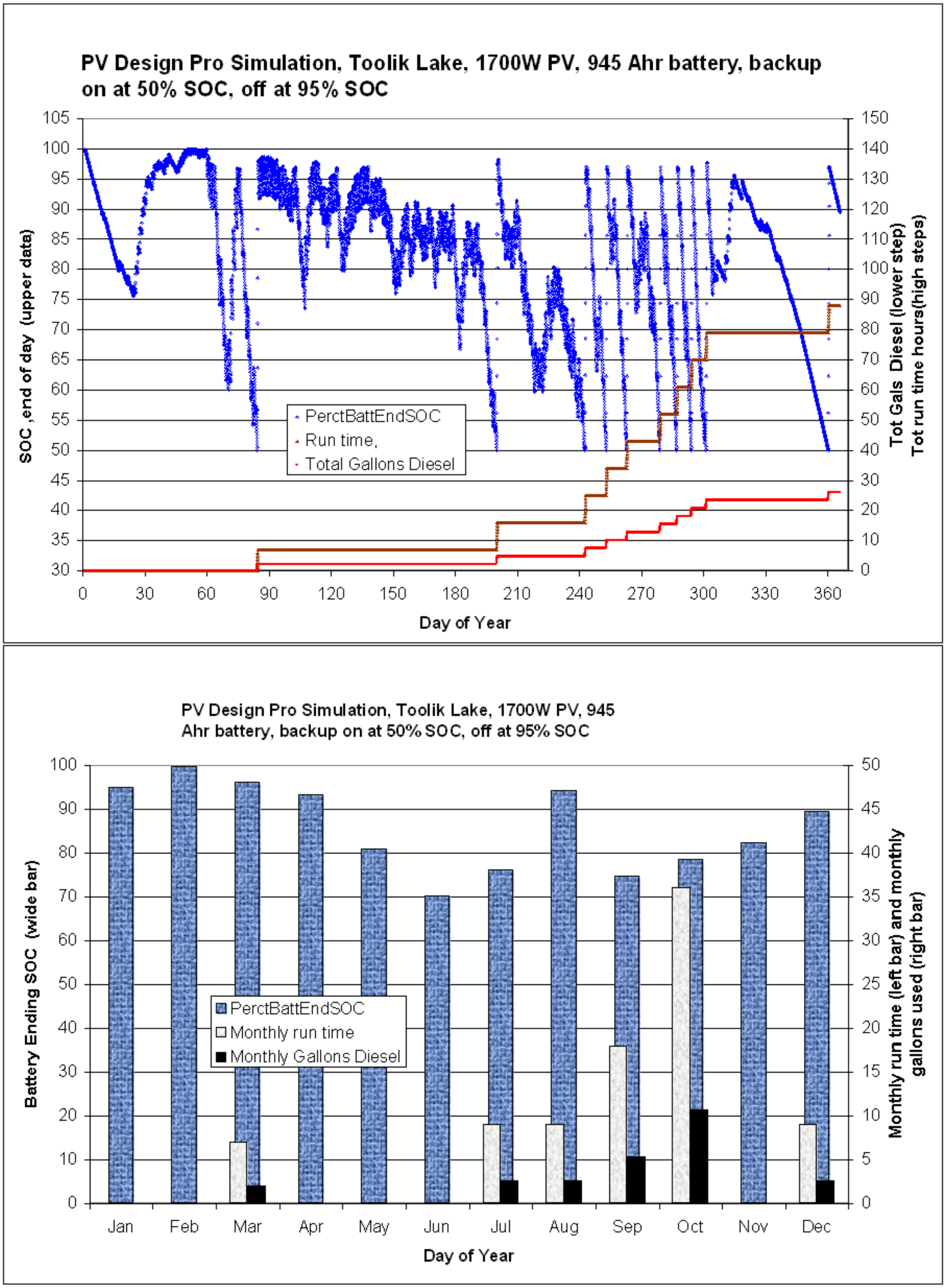
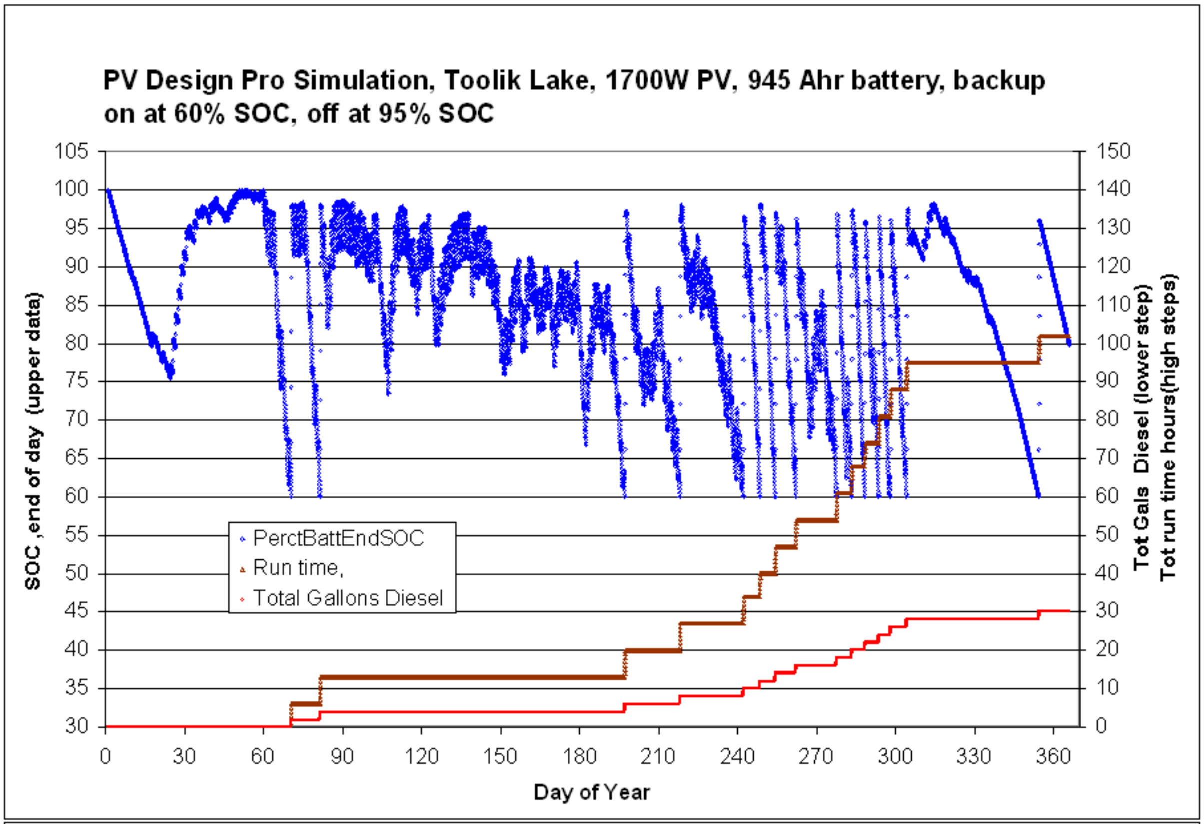


Figure B - 19. Simulation of 3kW Listeroid Diesel 945 AH Bat, at 50 to 95% SOC.



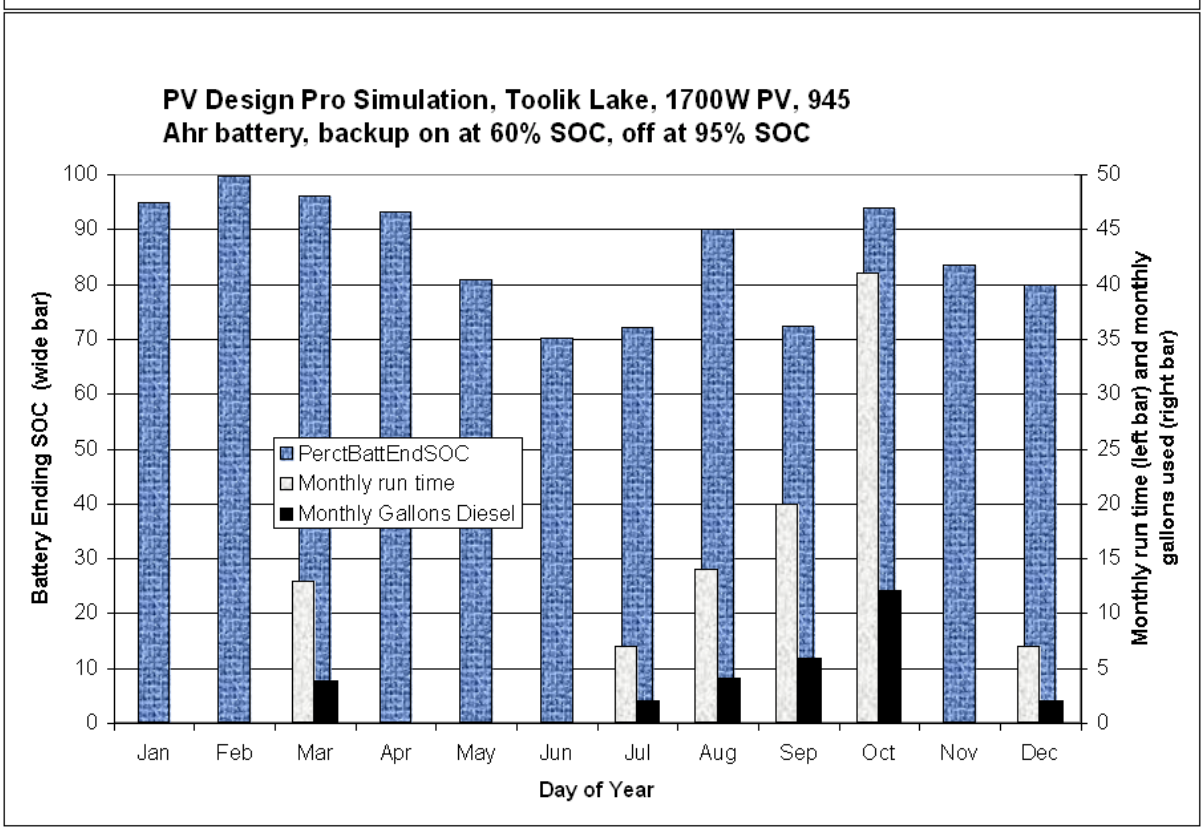
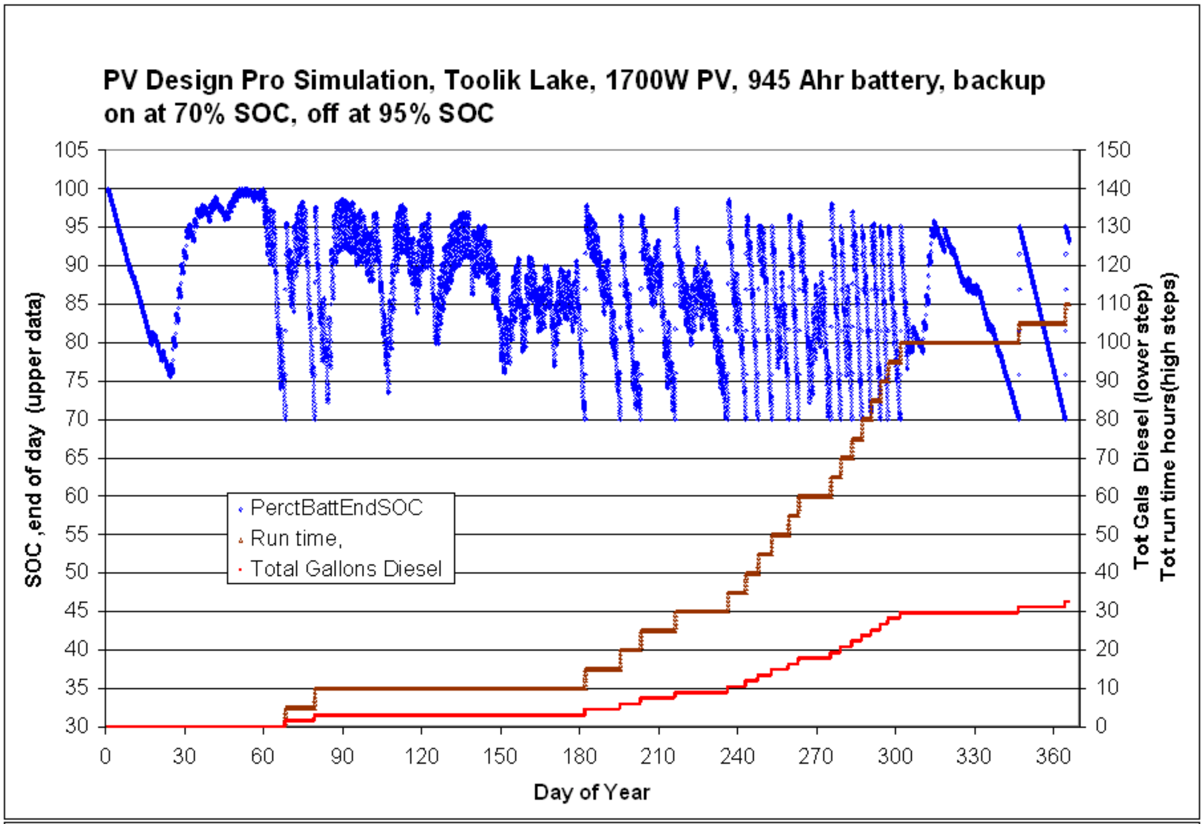


Figure B - 20. Simulation of 3kW Listeroid Diesel 945 AH Bat, at 60 to 95% SOC.



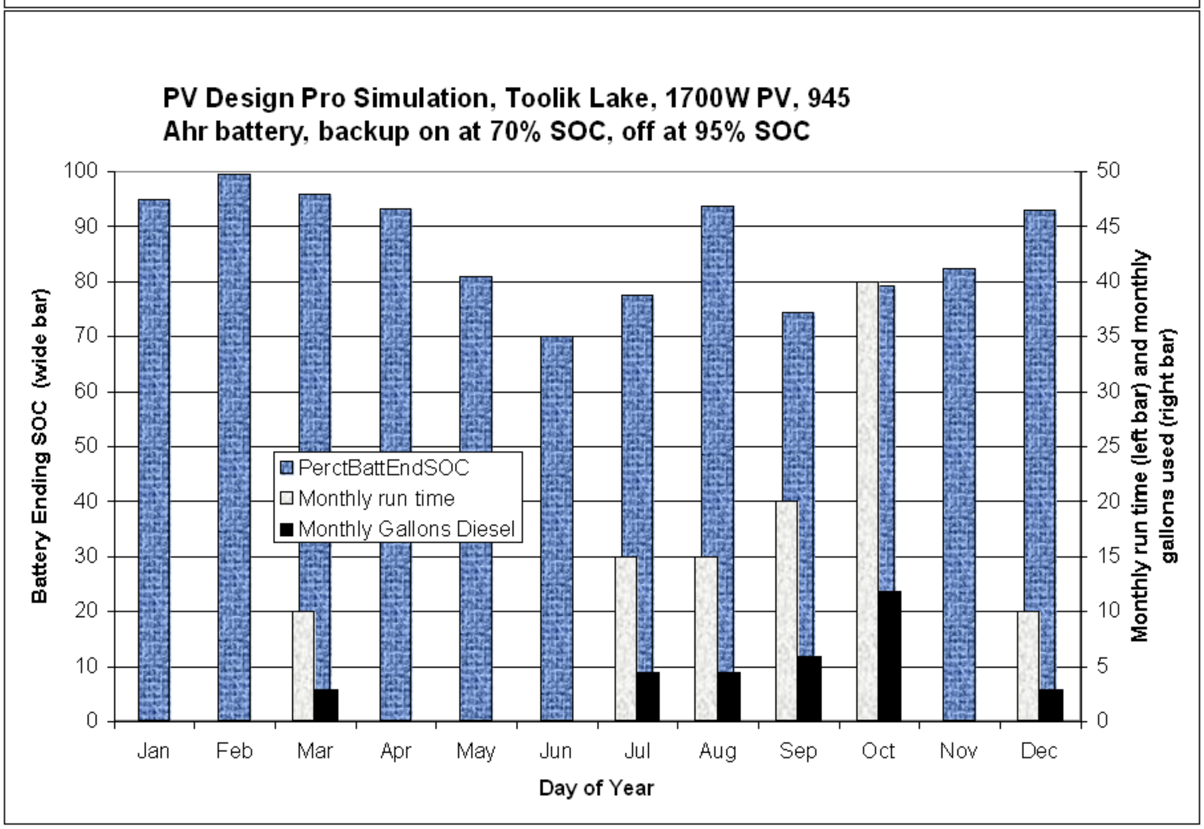


Figure B - 21. Simulation of 3kW Listeroid Diesel 945 AH Bat, at 70 to 95% SOC.

APPENDIX C: RF COMMUNICATIONS HARDWARE DATA

Table C - I. Available Tranceiver Chips

Manufacturer	Model	Band (MHz)	Data Rate (kbps)	Voltage (V)	Transmit Power (dBm)	Receiver Sensivity (dBm)	Receive Current	Xmit Current	Standby Current	Modulation	External Components
RF Monolithics	TR1001	868	115.2	2.2 - 3.7	+1.5dBm	-91dBm@868MHz	3.8mA	12mA	0.7µA	OOK, ASK	moderate
RF Monolithics	TR3100	433	576	2.2 - 3.7	+1.5dBm	-90dBm@434MHz	5.8mA	7mA	0.7µA	OOK, ASK	moderate
Semtech	XE1201A	433 (300-500)	64	3.6	+5dBm	-102dBm@434MHz	6mA	13.5mA	55µA	CP-BFSK	moderate
Semtech	XE1203F	915/868/433	153	3.6	+15dBm @915MHz	-89dBm@915MHz	14mA	62mA	850µA	CP-BFSK	moderate - few
Texas Instruments	CC1000	915/868/433/315	76.8	2.1 - 3.6	+5.0dBm @868 MHz	-98dBm@868MHz	96µA	25.4mA	0.2µA	BFSK	moderate
Texas Instruments	CC1020	915/868/402-470	153.6	2.3 - 3.6	+5.0dBm @915MHz	-87dBm@868MHz	19.9mA	27.1mA	0.2µA	BFKS, GFKS	moderate
Texas Instruments	CC1100	915/868/433/315	500	1.8 - 3.6	+10dBm @915MHz	-87dBm@915MHz	16.4mA	31.1mA	0.4µA	GFKS, MSK	moderate
Nordic Semiconductor	nRF905	915/868/433	50								
Texas Instruments	CC2400	2400	1000, 250, 10	1.8 & 3.6	0dBm @2.4GHz	-87(1Mbps), -91(250kbps), -101dBm(10kbps)	24mA	19mA	1.5µA	FSK, GFKS	few
Texas Instruments	CC2420	2400	250	1.8 & 3.6	0dBm @2.4GHz	-95 dBm	18.8mA	17.4mA	30µA	O-QPSK	few
Texas Instruments	CC2500	2400	500, 250, 10, 2.4	1.8 & 3.6	+1dBm @2.4GHz	-83(500kbps), -99(10kbps), -104dBm(2.4kbps)	19.6mA	21.5mA	1.4µA	OOK, BFSK, GFSK, MSK	few
Microchip	MRF24J40	2400	250	2.4 - 3.6	0dBm @2.4GHz	-91dBm (250kbps)	18mA	22mA	2µA	O-QPSK	moderate
Nordic Semiconductor	nRF2401A	2400	1000	1.9 - 3.6	+4dBm @2.4GHz	-80dBm (1Mbps)	19mA	13mA	12µA	GFSK	moderate
Nordic Semiconductor	nRF24AP1	2400	1000	1.9 - 3.6	+4dBm @2.4GHz	-80dBm (1Mbps)	22mA (600µs)	13.5mA (350µs)	2µA	GFSK	moderate

APPENDIX D: CELLULAR TELECOMMUNICATIONS SITE ACCESS VIEWSHEDS

The NEON site feature locations provided that can be confirmed[§§] to fall within cellular tower viewsheds are presented in Table D - I. All of those sites can either directly access the cellular telecommunications network or could readily do so by using a fixed-orientation high-gain directional antenna. The full site feature location data are presented in Table D - II, with conversions from the UTM data that were provided to the more familiar Latitude and Longitude coordinates. Unfortunately, several of these feature location data were found to be inconsistent either with commonsense placement of features, or with the ESRI shape file data characterizing the outline borders of each site. Given that it is easier to mischaracterize an isolated number than to mischaracterize the outlines of an entire region, the ESRI data have been assumed to be correct. These problematic data are identified in Table D - III.

Table D - I. NEON Site Features Confirmed Within Cellular Tower Viewsheds.

Core Site Name	(zone) Easting	Northing	Conversion to Latitude	Conversion to Longitude
CRC	(175) E 0748090	N 4308787	38.89295	-78.13951
Ordway-Swisher Reserve	(17R) E 0403877	N 3284847	29.68999	-81.99353
Ordway-Swisher Reserve	(17R) E 0403794	N 3284642	29.68813	-81.99437
Ordway-Swisher Reserve	(17R) E 0401545	N 3283391	29.67666	-82.01750
UNDERC	tbd	tbd		
UNDERC	tbd	tbd		
Konza Praire Biological Station	(14S) E 0710739	N 4330771	39.10060	-96.56299
Oak Ridge	(16S) E 0745246	N 3983457	35.96469	-84.28043
Central Plains Experimental Range	(13T) E 0521167	N 4518402	40.81636	-104.74901
Central Plains Experimental Range	(13T) E 0523496	N 4520237	40.83283	-104.72133
Central Plains Experimental Range	(13T) E 0519321	N 4517224	40.80579	-104.77094
Caddo-LBJ National Grassland	(14S) E 626746	N 3688732	33.33029	-97.63816
Caddo-LBJ National Grassland	(14S) E 0631619	N 3691953	33.35875	-97.58535
Santa Rita Experimental Range	(12R) E 0515554	N 3530551	31.91072	-110.83549
Santa Rita Experimental Range	(12R) E 0516119	N 3516793	31.78658	-110.82974
Onaqui-Benmore	(12T) E 0376588	N 4450964	40.20000	-112.45000
San Joaquin Experimental Range	(11S) E 0257388	N 4109454	37.09995	-119.73001
Laupahoehoe	(05Q) E 0261165	N 2207316	19.94767	-155.28198

[§§] All conclusions herein are based on the assumption of correct NEON feature location data and an ability to reach above the vegetation canopy. In addition, all elevation data used were on a 10 meter grid, except for Alaska data, which were on a 90 meter grid. As such, all conclusions must be treated as tentative and in need of verification prior to implementation of a cellular telecommunication link.

Table D - II. NEON Feature Locations Converted from UTM to Latitude and Longitude.

Core Site Name	(zone) Easting	Northing	Converted to Latitude (Dec. Deg)	Converted to Longitude (Dec. Deg)	Converted to Latitude (DMS)			Converted to Longitude (DMS)		
Harvard Forest	(18T) E 4712016	N 321809	2.13433	-39.58123	2	8	3.602	39	34	52.413
CRC	(175) E 0748090	N 4308787	38.89295	-78.13951	38	53	34.607	78	8	22.223
Ordway-Swisher Reserve	(17R) E 0403877	N 3284847	29.68999	-81.99353	29	41	23.949	81	59	36.724
Ordway-Swisher Reserve	(17R) E 0403794	N 3284642	29.68813	-81.99437	29	41	17.267	81	59	39.746
Ordway-Swisher Reserve	(17R) E 0401545	N 3283391	29.67666	-82.01750	29	40	35.992	82	1	3.010
Guanica Forest	(19Q) E 0727439	N 1988820	17.97576	-66.85227	17	58	32.745	66	51	8.165
Guanica Forest	(19Q) E 0713383	N 2003298	18.10796	-66.98345	18	6	28.640	66	59	0.412
UNDERC	(16T) E 0304876	N 5121603	46.21997	-89.53001	46	13	11.874	89	31	48.035
UNDERC	tbd	tbd								
UNDERC	tbd	tbd								
Konza Praire Biological Station	(14S) E 0710739	N 4330771	39.10060	-96.56299	39	6	2.145	96	33	46.759
Konza Praire Biological Station	(14S) E 0707215	N 4331115	39.10454	-96.60360	39	6	16.342	96	36	12.967
Oak Ridge	(16S) E 0745246	N 3983457	35.96469	-84.28043	35	57	52.874	84	16	49.558
Oak Ridge	(16S) E 0249313	N 3982221	35.95217	-89.77945	35	57	7.812	89	46	46.019
Talladega National Forest	(16S) E 0458200	N 3645929	32.95087	-87.44721	32	57	3.127	87	26	49.963
Woodworth	(14T) E 0481658	N 5221017	47.14240	-99.24190	47	8	32.637	99	14	30.856
Central Plains Experimental Range	(13T) E 0521167	N 4518402	40.81636	-104.74901	40	48	58.899	104	44	56.442
Central Plains Experimental Range	(13T) E 0523496	N 4520237	40.83283	-104.72133	40	49	58.180	104	43	16.775
Central Plains Experimental Range	(13T) E 0519321	N 4517224	40.80579	-104.77094	40	48	20.860	104	46	15.373
Caddo-LBJ National Grassland	(14S) E 626746	N 3688732	33.33029	-97.63816	33	19	49.045	97	38	17.378
Caddo-LBJ National Grassland	(14S) E 0631619	N 3691953	33.35875	-97.58535	33	21	31.496	97	35	7.246
Caddo-LBJ National Grassland	(14S) E 0632913	N 3694848	33.38469	-97.57101	33	23	4.897	97	34	15.654
Yellowstone Northern Range	(12T) E 535276.6	N 4977833	44.95306	-110.55278	44	57	11.008	110	33	10.006
Niwot	(13T) E 0448312	N 4483433	40.50000	-105.61000	40	29	59.986	105	36	36.008

Core Site Name	(zone) Easting	Northing	Converted to Latitude (Dec. Deg)	Converted to Longitude (Dec. Deg)	Converted to Latitude (DMS)			Converted to Longitude (DMS)		
Santa Rita Experimental Range	(12R) E 0515554	N 3530551	31.91072	-110.83549	31	54	38.574	110	50	7.760
Santa Rita Experimental Range	(12R) E 0516119	N 3516793	31.78658	-110.82974	31	47	11.697	110	49	47.068
Onaqui-Benmore	(12T) E 0376588	N 4450964	40.20000	-112.45000	40	11	59.995	112	27	0.003
Wind River Experimental Forest	(10T) E 0581417	N 5074490	45.81917	-121.95195	45	49	8.995	121	57	7.010
Wind River Experimental Forest	(10T) E 0585436	N 5075748	45.83000	-121.90000	45	49	47.999	121	53	59.994
Wind River Experimental Forest	(10T) E 0581011	N 5072628	45.80246	-121.95749	45	48	8.844	121	57	26.947
Wind River Experimental Forest	(10T) E 0578055	N 5073616	45.81169	-121.99536	45	48	42.080	121	59	43.294
San Joaquin Experimental Range	(11S) E 0257388	N 4109454	37.09995	-119.73001	37	5	59.824	119	43	48.024
San Joaquin Experimental Range	tbd	tbd								
San Joaquin Experimental Range	tbd	tbd								
San Joaquin Experimental Range	tbd	tbd								
Toolik Lake	(06W) E 403515	N 7618378	68.66055	-149.37638	68	39	37.964	149	22	34.970
Toolik Lake	(06W) E 393142	N 7619296	68.66498	-149.63251	68	39	53.915	149	37	57.037
Toolik Lake	(06W) E 408113	N 7621242	68.68777	-149.26584	68	41	15.969	149	15	57.039
Caribou Flats-Poker Creeks Watershed	(06W) E 476318.5	N 7225142.5	65.14889	-147.50500	65	8	55.990	147	30	18.016
Laupahoehoe	(05Q) E 0260399	N 2250416	20.33674	-155.29498	20	20	12.261	155	17	41.933
Laupahoehoe	(05Q) E 0261165	N 2207316	19.94767	-155.28198	19	56	51.620	155	15	55.143
Laupahoehoe	(05Q) E 0265867	N 2203677	19.91539	-155.23662	19	54	55.388	155	14	11.837
Laupahoehoe	(05Q) E 0220685	N 220685	1.99467	-155.51084	1	59	40.801	155	30	39.015

Table D - III. Problematic NEON Site Feature Coordinates.

Core Site Name	(zone) Easting	Northing	Conversion to Latitude	Conversion to Longitude	Suggestions/Notes
Harvard Forest	(18T) E 4712016	N 321809	2.13433	-39.58123	Not within the boundary area.
CRC	(175) E 0748090	N 4308787	38.89295	-78.13951	
Ordway-Swisher Reserve	(17R) E 0403877	N 3284847	29.68999	-81.99353	
Ordway-Swisher Reserve	(17R) E 0403794	N 3284642	29.68813	-81.99437	
Ordway-Swisher Reserve	(17R) E 0401545	N 3283391	29.67666	-82.01750	
Guanica Forest	(19Q) E 0727439	N 1988820	17.97576	-66.85227	
Guanica Forest	(19Q) E 0713383	N 2003298	18.10796	-66.98345	Site is not in water.
UNDERC	(16T) E 0304876	N 5121603	46.21997	-89.53001	Not within the boundary area.
UNDERC	tbd	tbd			
UNDERC	tbd	tbd			
Konza Praire Biological Station	(14S) E 0710739	N 4330771	39.10060	-96.56299	
Konza Praire Biological Station	(14S) E 0707215	N 4331115	39.10454	-96.60360	This is not Aquatic, so this is labled as Basic Tower 1
Oak Ridge	(16S) E 0745246	N 3983457	35.96469	-84.28043	
Oak Ridge	(16S) E 0249313	N 3982221	35.95217	-89.77945	Tried changing Easting from 0249313 to 0749313, very close to boundary, but now located in water.
Talladega National Forest	(16S) E 0458200	N 3645929	32.95087	-87.44721	Not within boundary.
Woodworth	(14T) E 0481658	N 5221017	47.14240	-99.24190	Is this supposed to be an "Advanced Site" rather than "Basic Tower 2"?
Central Plains Experimental Range	(13T) E 0521167	N 4518402	40.81636	-104.74901	
Central Plains Experimental Range	(13T) E 0523496	N 4520237	40.83283	-104.72133	
Central Plains Experimental Range	(13T) E 0519321	N 4517224	40.80579	-104.77094	
Caddo-LBJ National Grassland	(14S) E 626746	N 3688732	33.33029	-97.63816	
Caddo-LBJ National Grassland	(14S) E 0631619	N 3691953	33.35875	-97.58535	

Core Site Name	(zone) Easting	Northing	Conversion to Latitude	Conversion to Longitude	Suggestions/Notes
Caddo-LBJ National Grassland	(14S) E 0632913	N 3694848	33.38469	-97.57101	Close to water but not located in it.
Yellowstone Northern Range	(12T) E 535276.6	N 4977833	44.95306	-110.55278	Not within the boundary area.
Niwot	(13T) E 0448312	N 4483433	40.50000	-105.61000	Not within the boundry area.
Santa Rita Experimental Range	(12R) E 0515554	N 3530551	31.91072	-110.83549	
Santa Rita Experimental Range	(12R) E 0516119	N 3516793	31.78658	-110.82974	
Onaqui-Benmore	(12T) E 0376588	N 4450964	40.20000	-112.45000	
Wind River Experimental Forest	(10T) E 0581417	N 5074490	45.81917	-121.95195	
Wind River Experimental Forest	(10T) E 0585436	N 5075748	45.83000	-121.90000	Not within the boundry area, but in the middle of two.
Wind River Experimental Forest	(10T) E 0581011	N 5072628	45.80246	-121.95749	
Wind River Experimental Forest	(10T) E 0578055	N 5073616	45.81169	-121.99536	Not within water.
San Joaquin Experimental Range	(11S) E 0257388	N 4109454	37.09995	-119.73001	
San Joaquin Experimental Range	tbd	tbd			
San Joaquin Experimental Range	tbd	tbd			
San Joaquin Experimental Range	tbd	tbd			
Toolik Lake	(06W) E 403515	N 7618378	68.66055	-149.37638	
Toolik Lake	(06W) E 393142	N 7619296	68.66498	-149.63251	
Toolik Lake	(06W) E 408113	N 7621242	68.68777	-149.26584	Not within boundary, but close.
Caribou Flats-Poker Creeks Watershed	(06W) E 476318.5	N 7225142.5	65.14889	-147.50500	Not within boundary, but close.
Laupahoehoe	(05Q) E 0260399	N 2250416	20.33674	-155.29498	Located in water.
Laupahoehoe	(05Q) E 0261165	N 2207316	19.94767	-155.28198	
Laupahoehoe	(05Q) E 0265867	N 2203677	19.91539	-155.23662	Not within the boundary area.
Laupahoehoe	(05Q) E 0220685	N 220685	1.99467	-155.51084	Not within boundary

#1 Harvard Forest Site

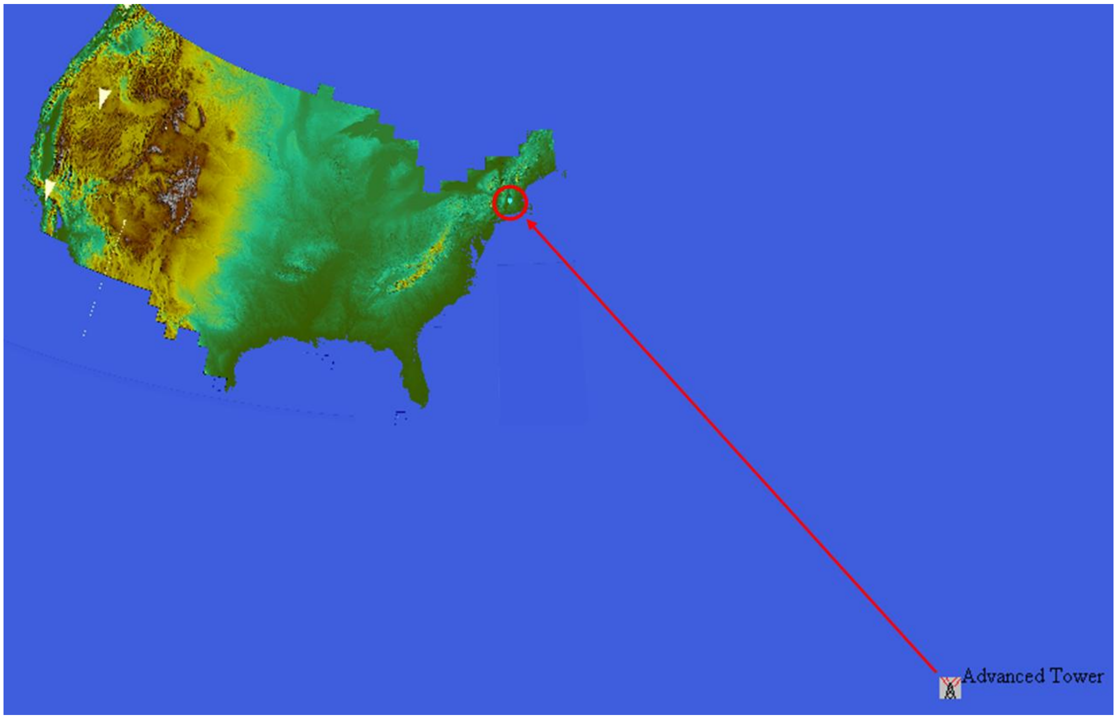


Figure D - 1. Harvard Forest site Advanced tower location (problematic). The advanced tower location given to us is approximately 3,428 miles away from the shape file of the site.

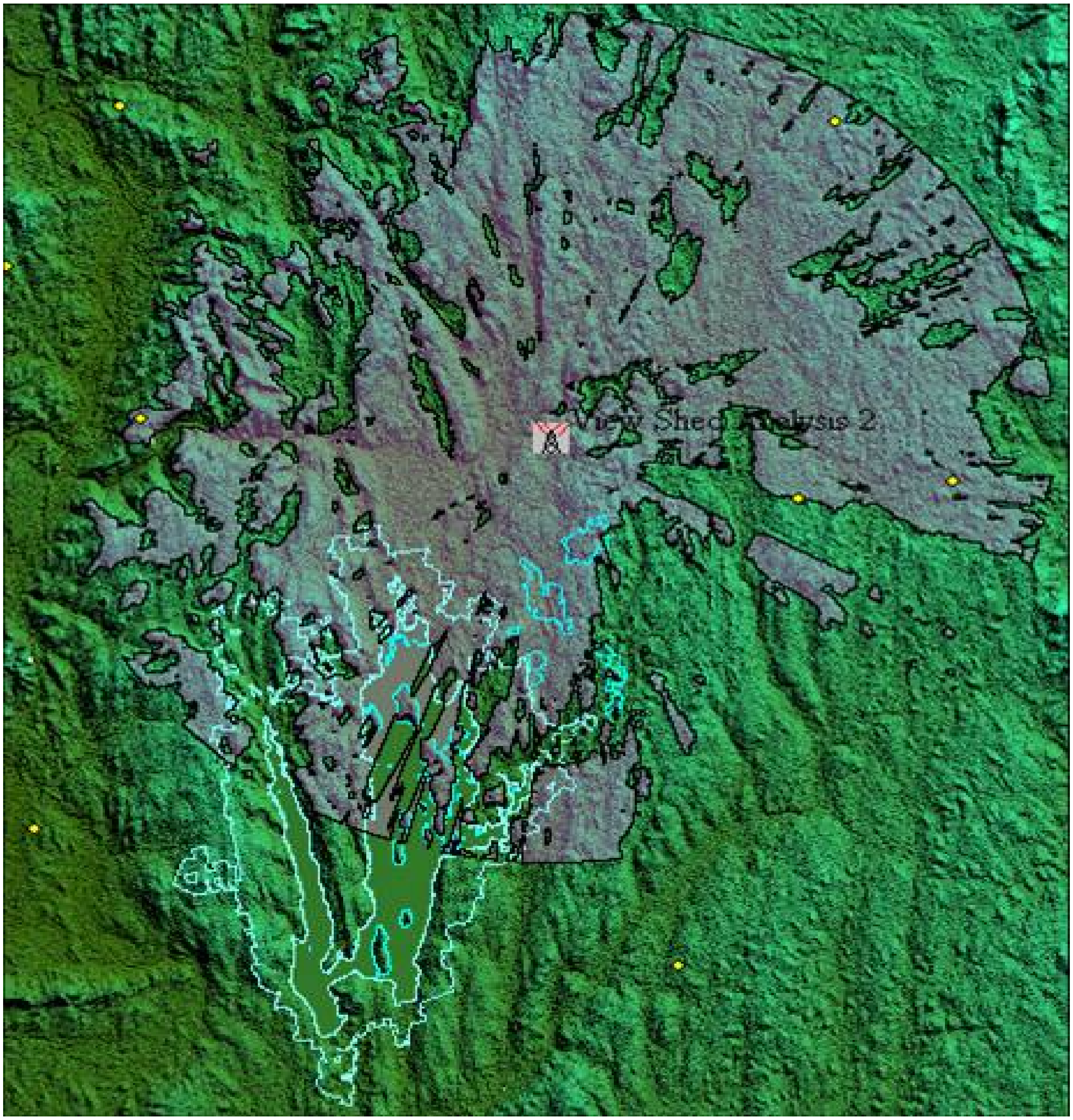


Figure D - 2. Viewshed for Harvard Forest. A tower height of 50 meters was assumed based on nearby cellular towers ranging from 51 to 70 meters. Assuming the tower were placed within the blue outlines indicating the site boundaries, cellular access is possible.

2 Smithsonian Institution Conservation Research Center (CRC Site)

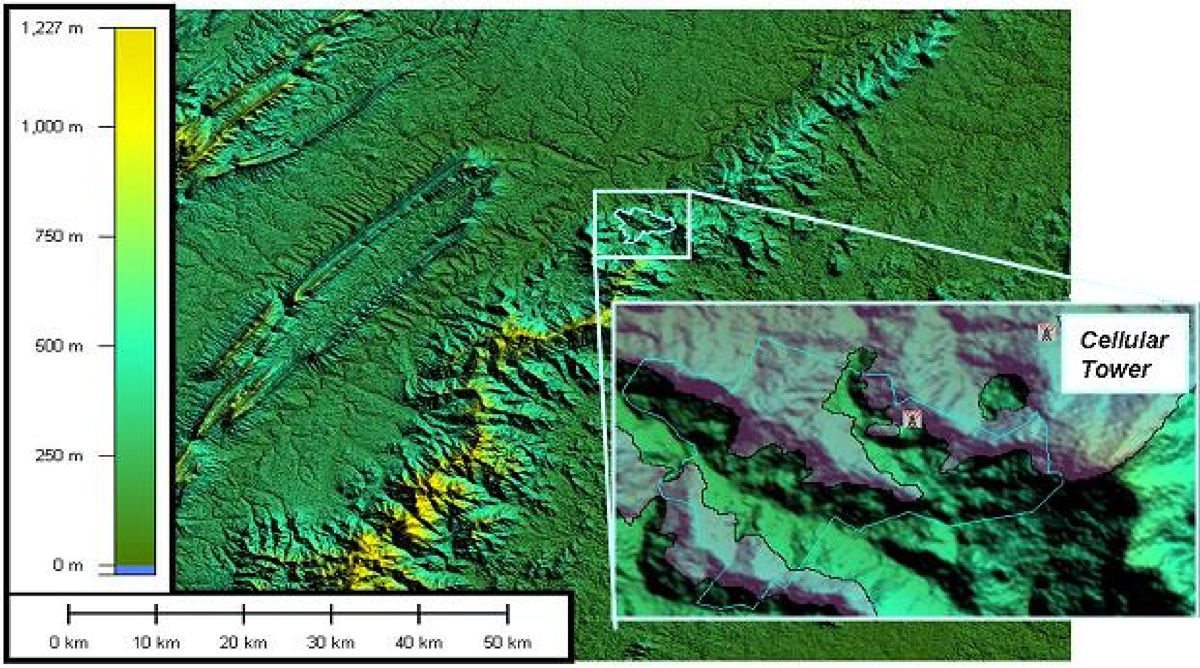


Figure D - 3. Smithsonian Institution CRC site viewshed showing no obstructions. The given tower height of 12 meters was used, whereas neighboring cellular towers ranged from 71 to 210 meters. The Advanced tower is located on the edge of the cellular tower range but there are no obstructions that might hinder communications.

3 Ordway-Swisher Reserve Site

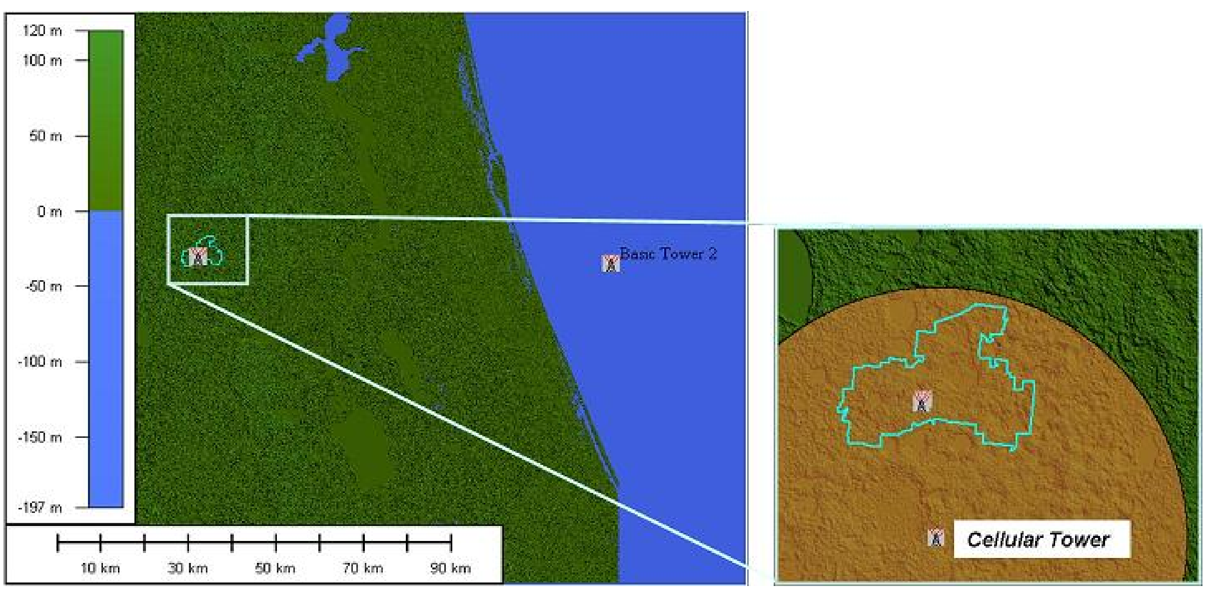
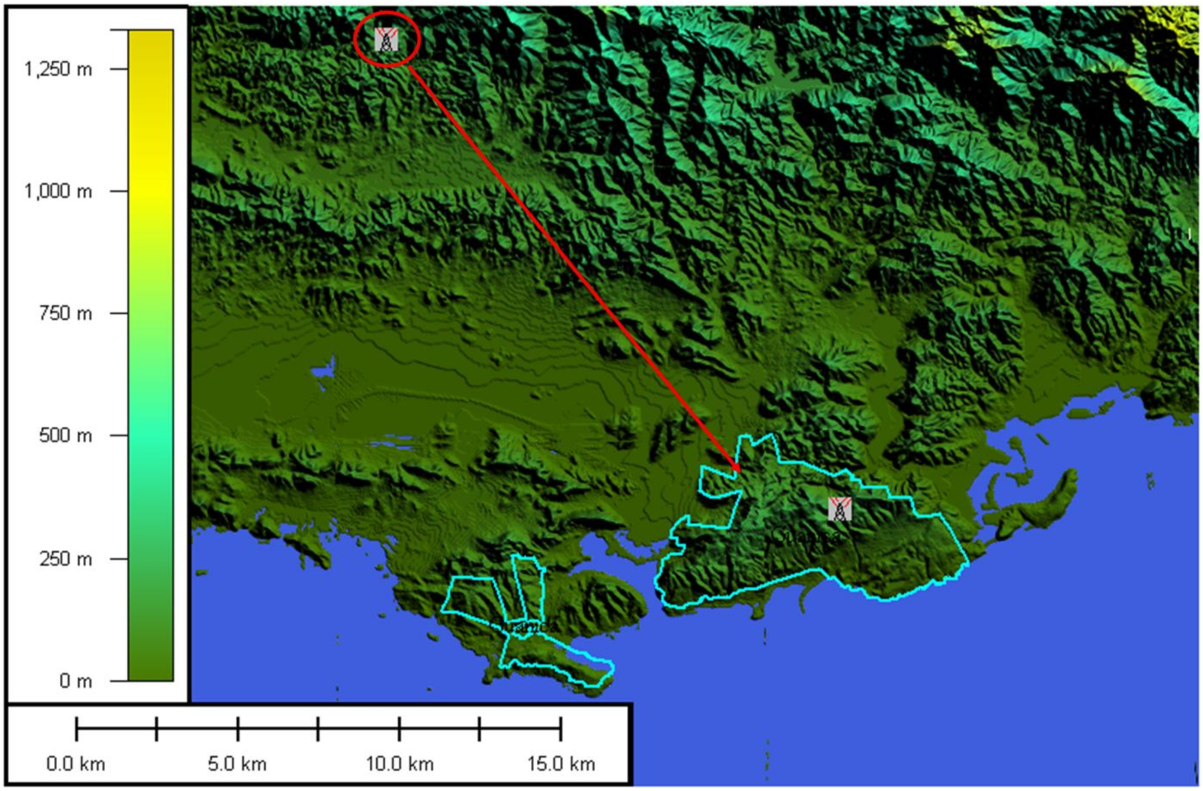


Figure D - 4. Ordway-Swisher Reserve site viewshed. Excepting the item located offshore, all NEON installations at this site should have cellular network access.

4 Guanica Forest Site



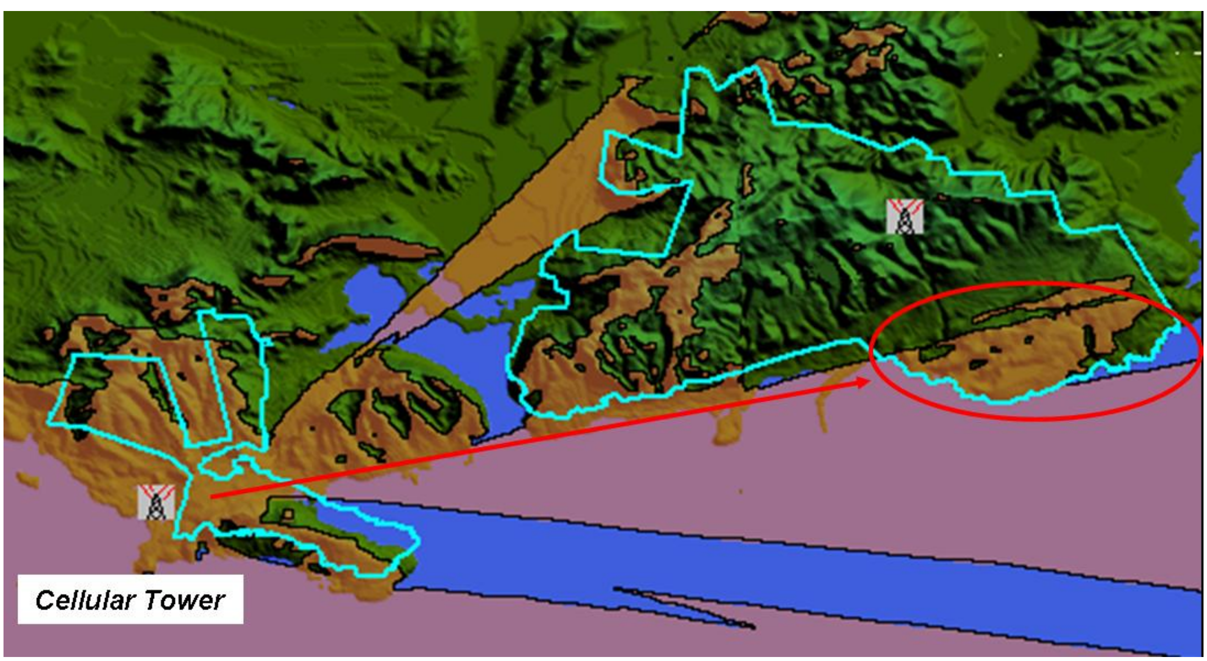


Figure D - 5. Guanica site viewshed. Some of the location data appear to be inconsistent. The NEON features do not have a clear transmission path to the nearest cellular towers.

5 UNDERC Site

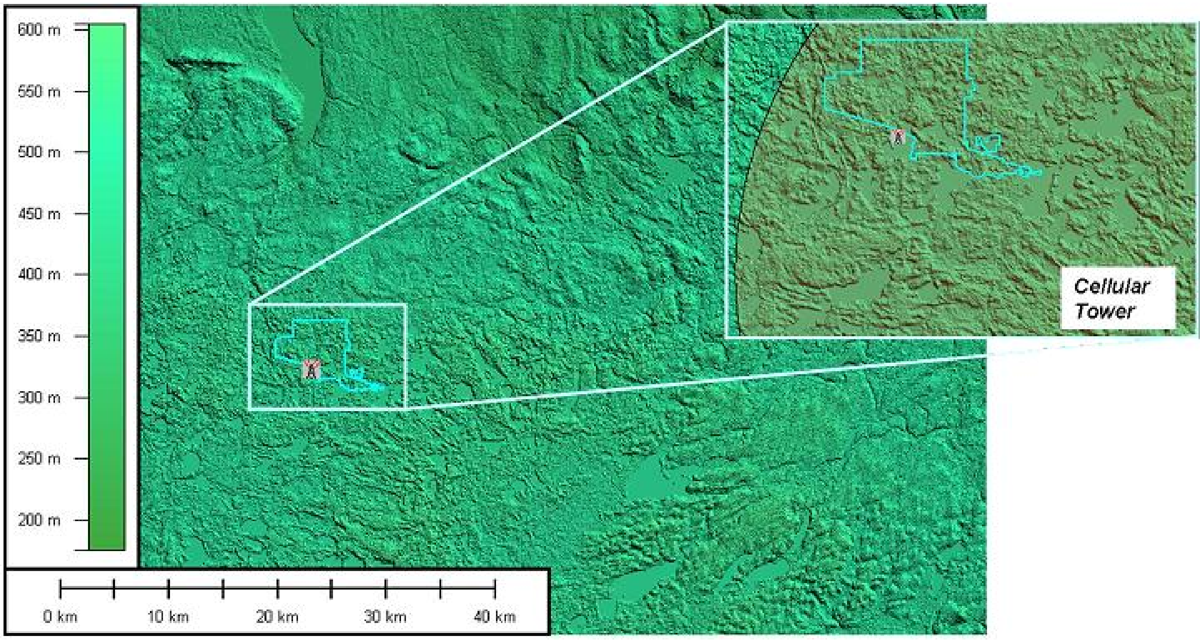


Figure D - 6. UNDERC site viewshed. The NEON tower data are inconsistent with the site boundary data. All areas within the identified boundaries should have cellular access.

6 Konza Prairie Biological Site

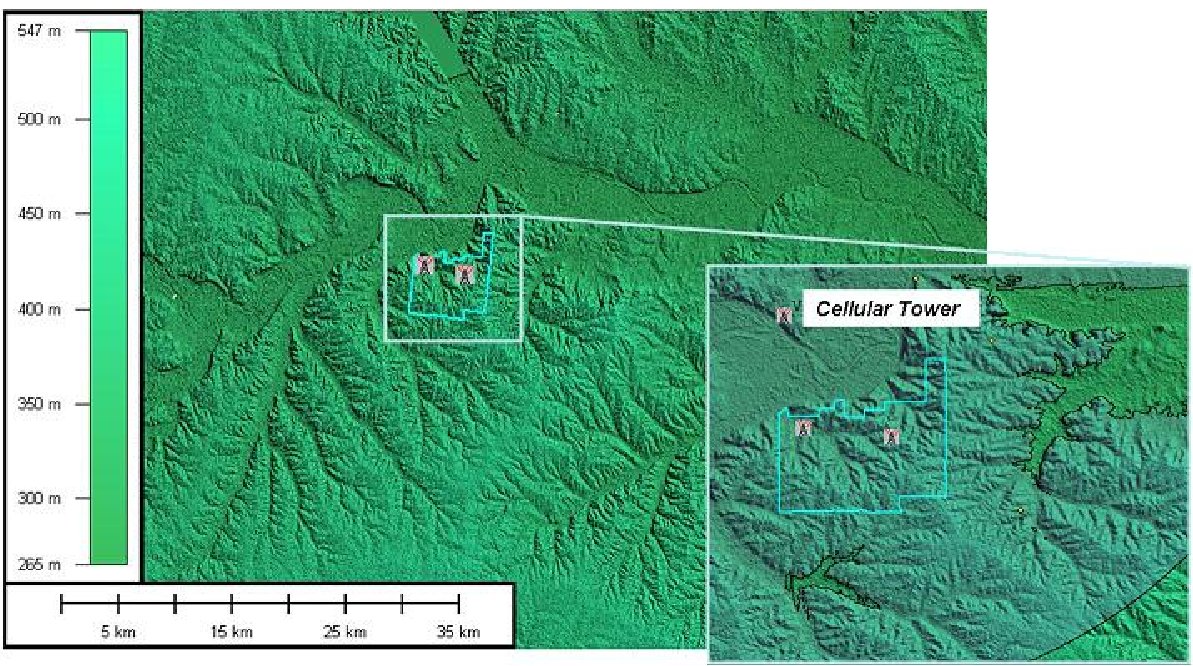


Figure D - 7. Konza Prairie site viewshed. The NEON site locations appear to be within the cellular access viewshed.

7 Oak Ridge Site

Figure D - 8. Oak Ridge Basic tower placement (problematic). Location 490 km from site.

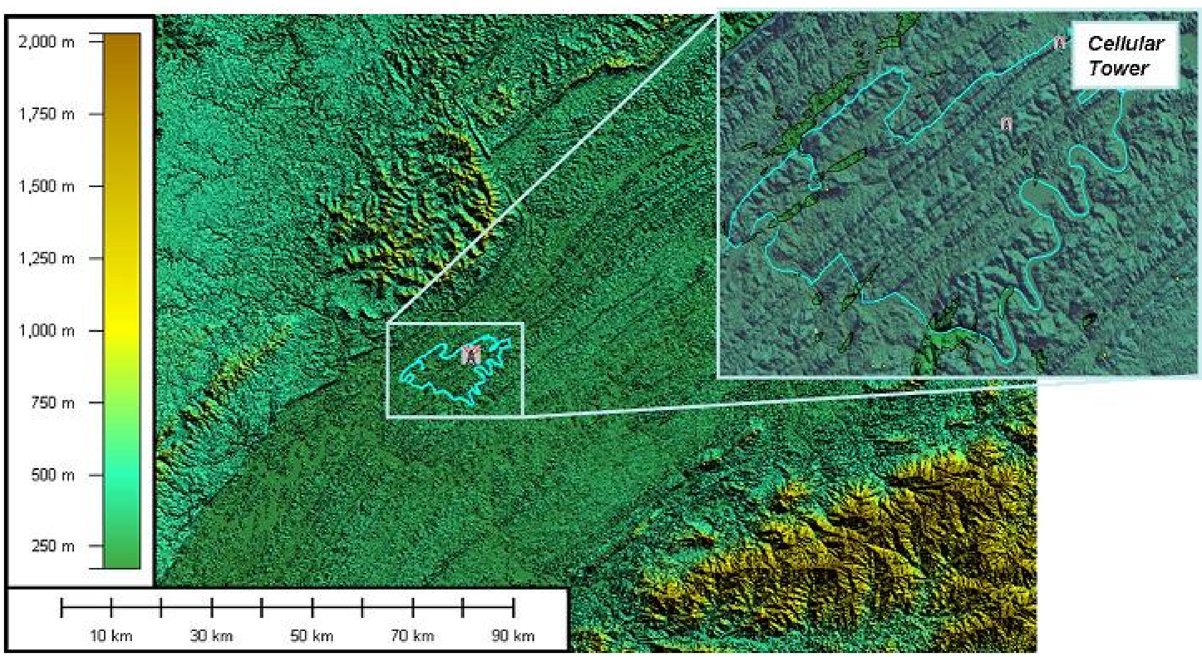


Figure D - 9. Oak Ridge site viewshed. Advanced tower is within range of cell tower.

8 Talladega National Forest Site

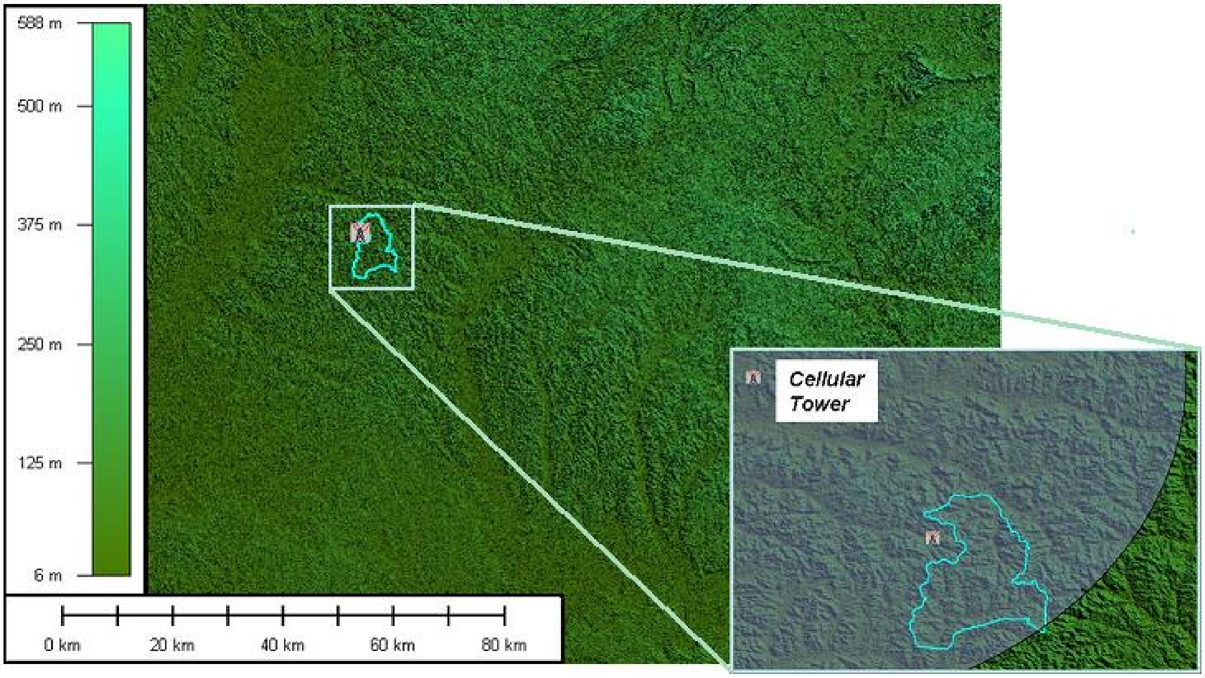


Figure D - 10. Talladega National Forest site viewshed. Virtually entire NEON site is within cellular access range. Advanced tower location inconsistent with site boundaries.

9 Woodworth Site

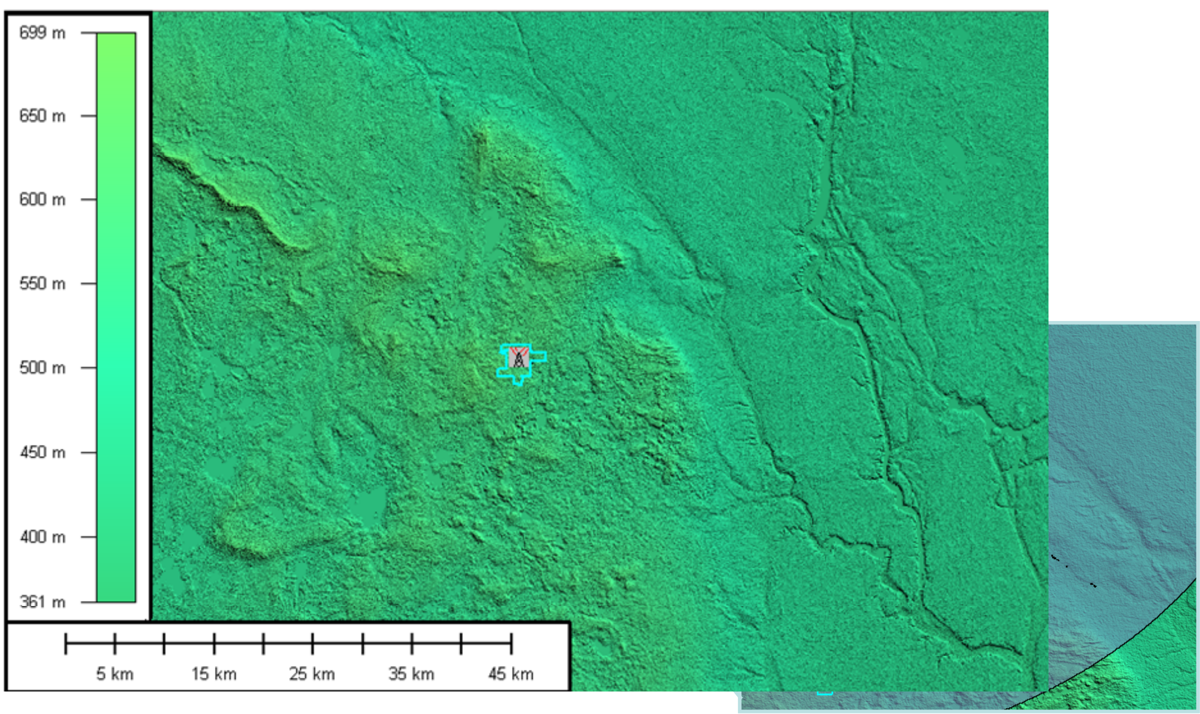


Figure D - 11. Woodworth site viewshed. Advanced tower is within access range.

10 Central Plains Experimental Range Site

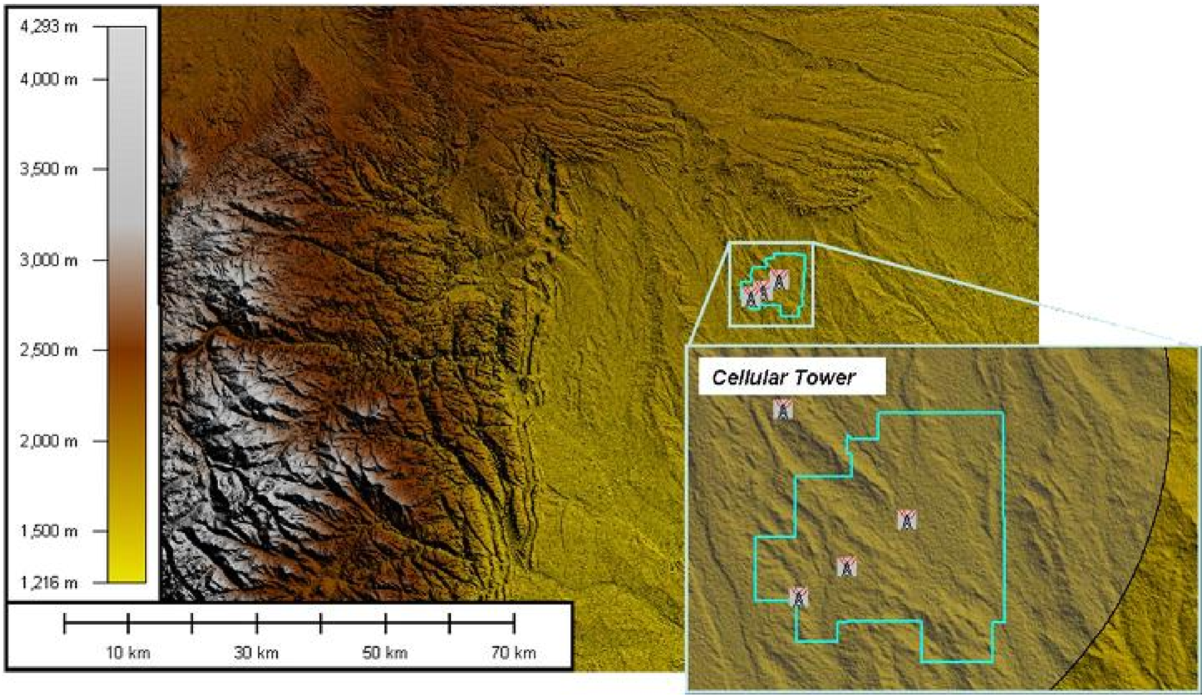


Figure D - 12. **Central Plains Experimental Range site viewshed.** All towers in range.

11 Caddo - LBJ National Grassland Site

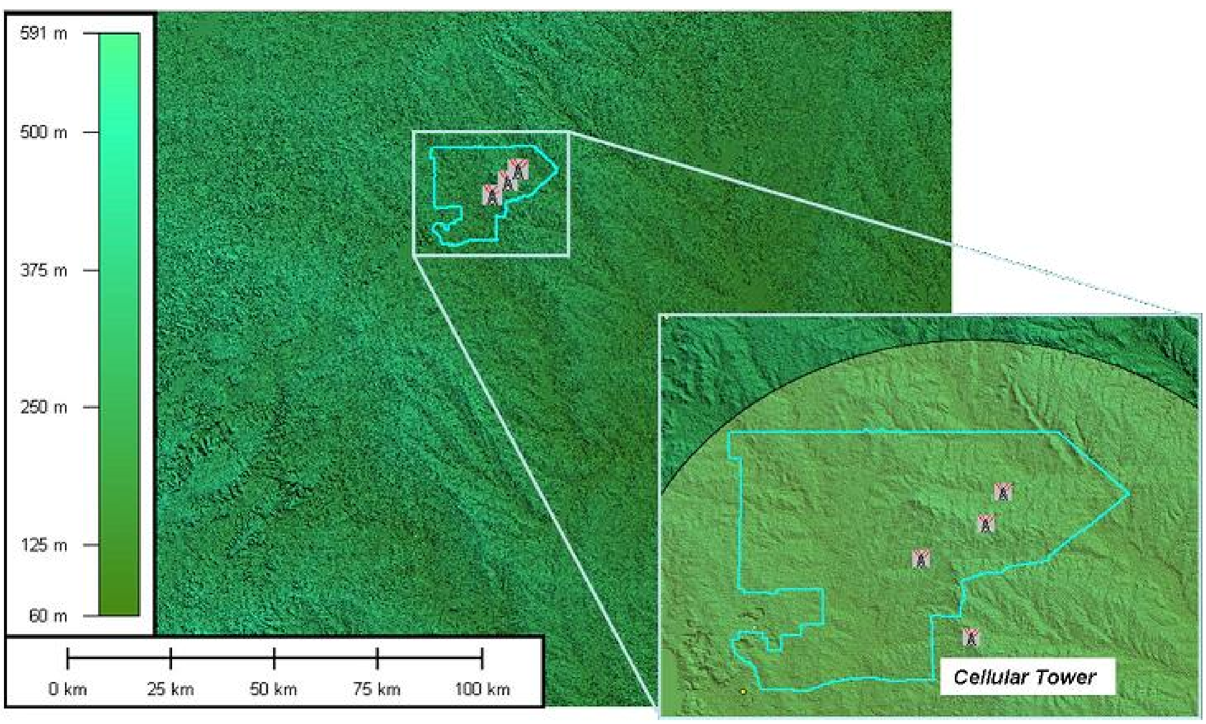


Figure D - 13. **Caddo-LBJ National Grassland site viewshed.** All towers in range.

12 Yellowstone Northern Range Site

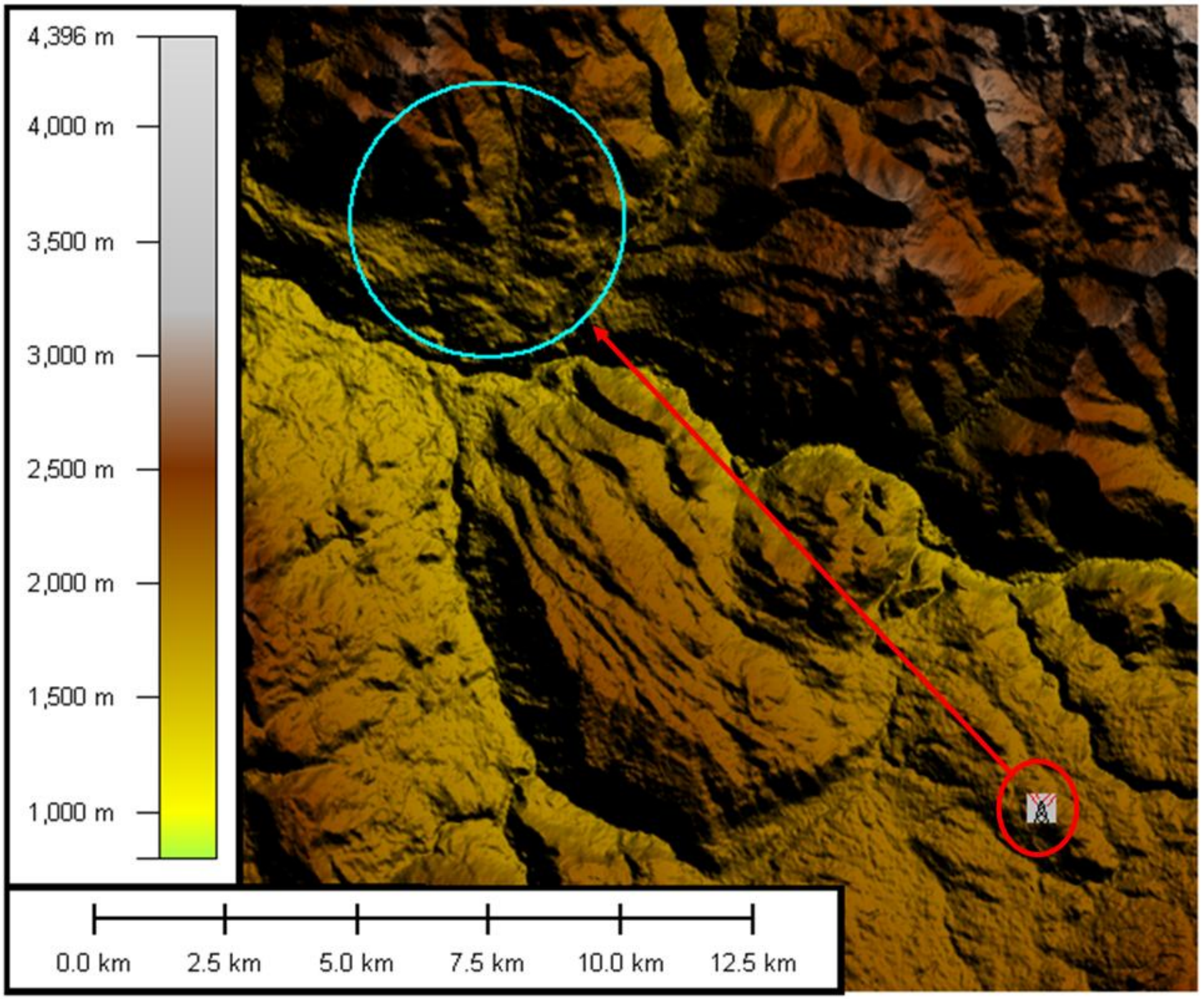


Figure D - 14. Yellowstone Northern Range site Advanced tower placement (problematic). NEON tower is about 13 km from site boundary.

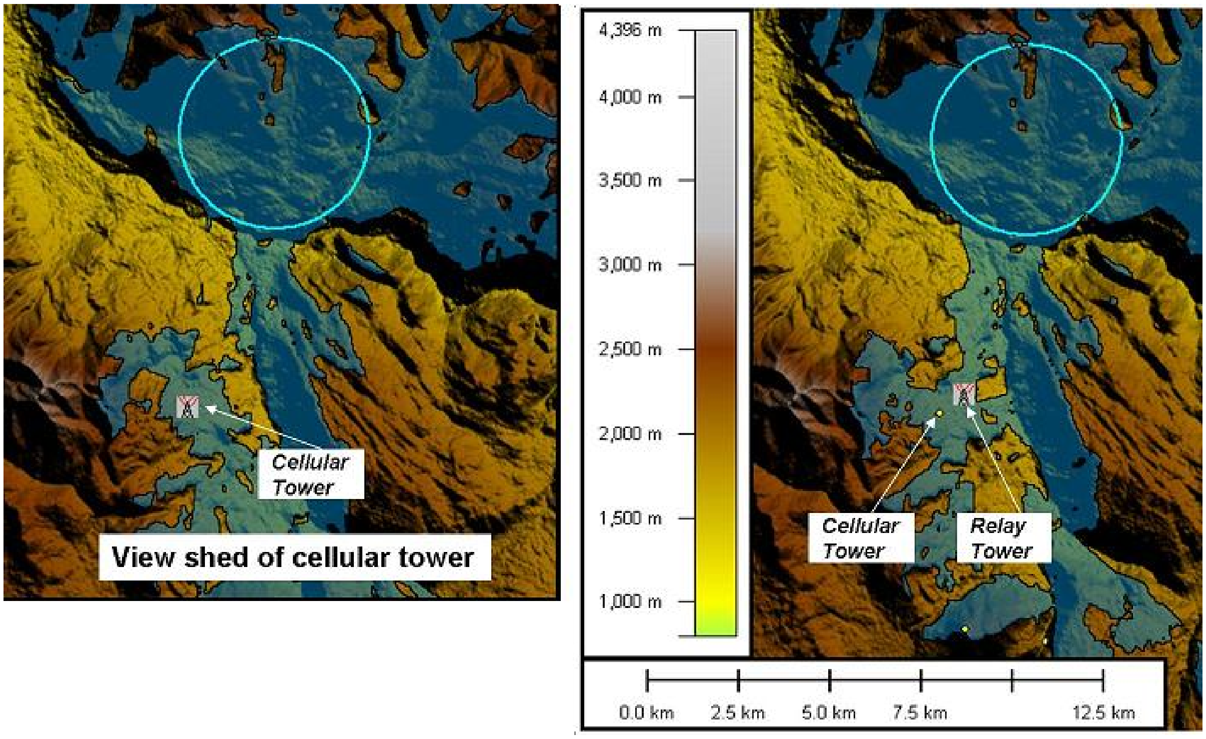


Figure D - 15. Yellowstone Northern Range site viewshed. Cellular access might be possible with a relay tower.

13 Niwot Site

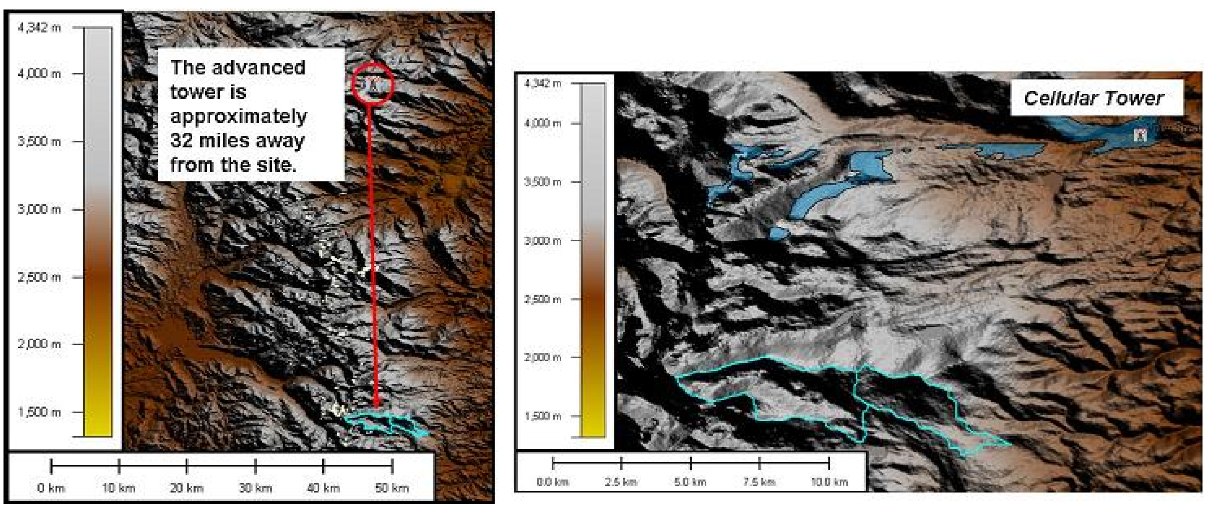


Figure D - 16. Niwot site Advanced tower placement (problematic). Advanced tower placement data suggest it is 51 km from site boundary. Cellular access is difficult in this region regardless due to mountain range.

14 Santa Rita Experimental Site

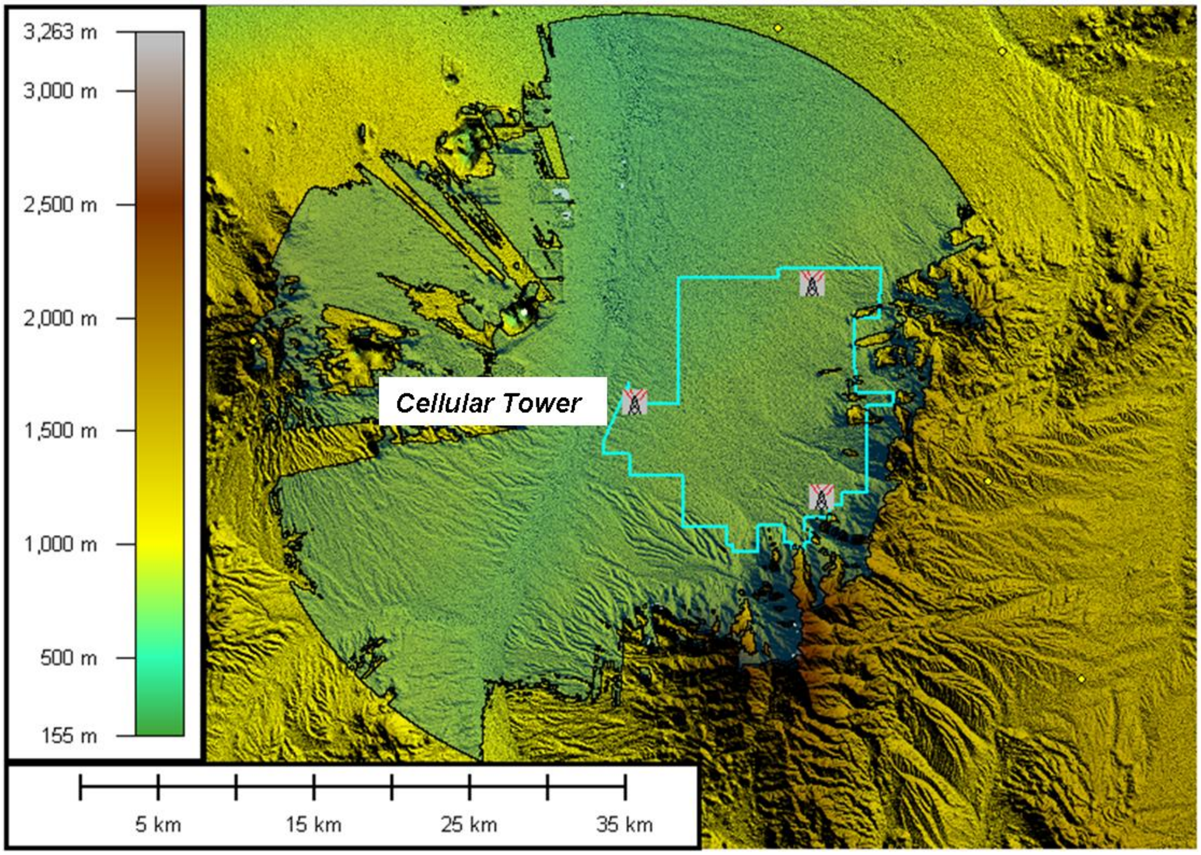


Figure D - 17. Santa Rita site viewshed. All towers within range.

15 Onaqui-Benmore Site

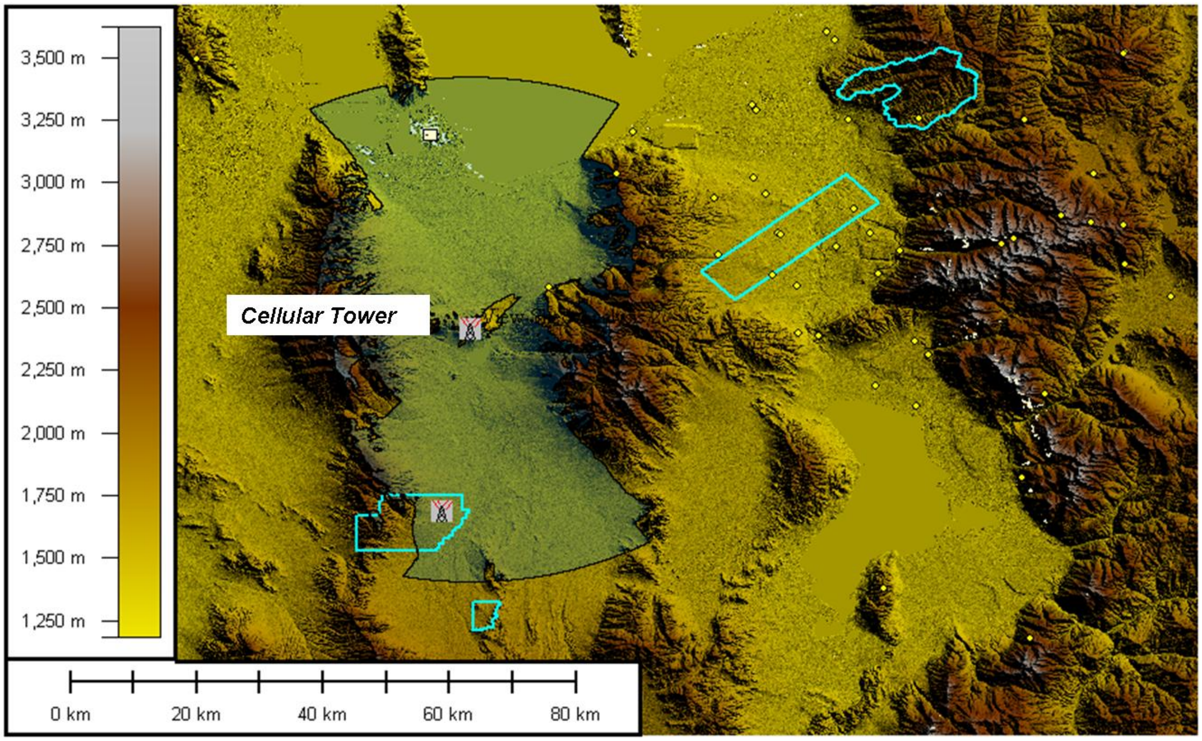


Figure D - 18. Onaqui-Benmore site viewshed. NEON tower is within range.

16 Wind River Experimental Forest Site

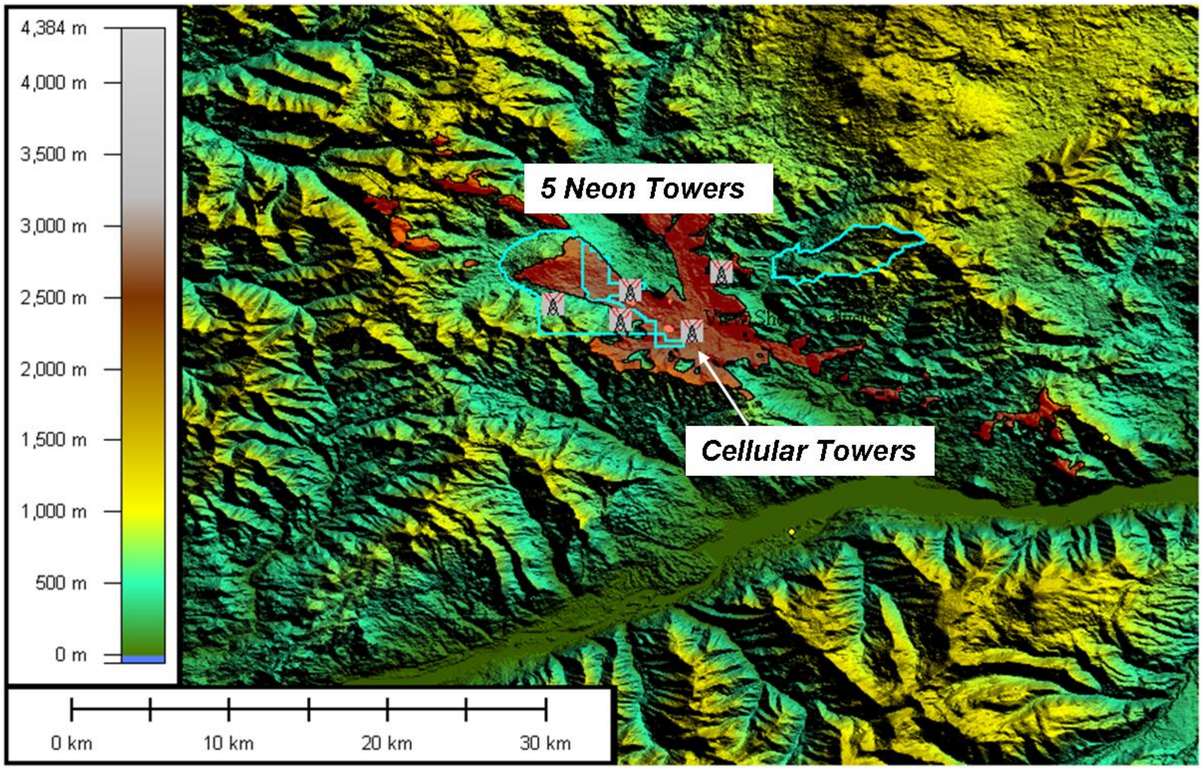


Figure D - 19. Wind River Experimental Forest site viewshed. Mountainous terrain renders cellular access difficult.

17 San Joaquin Experimental Site

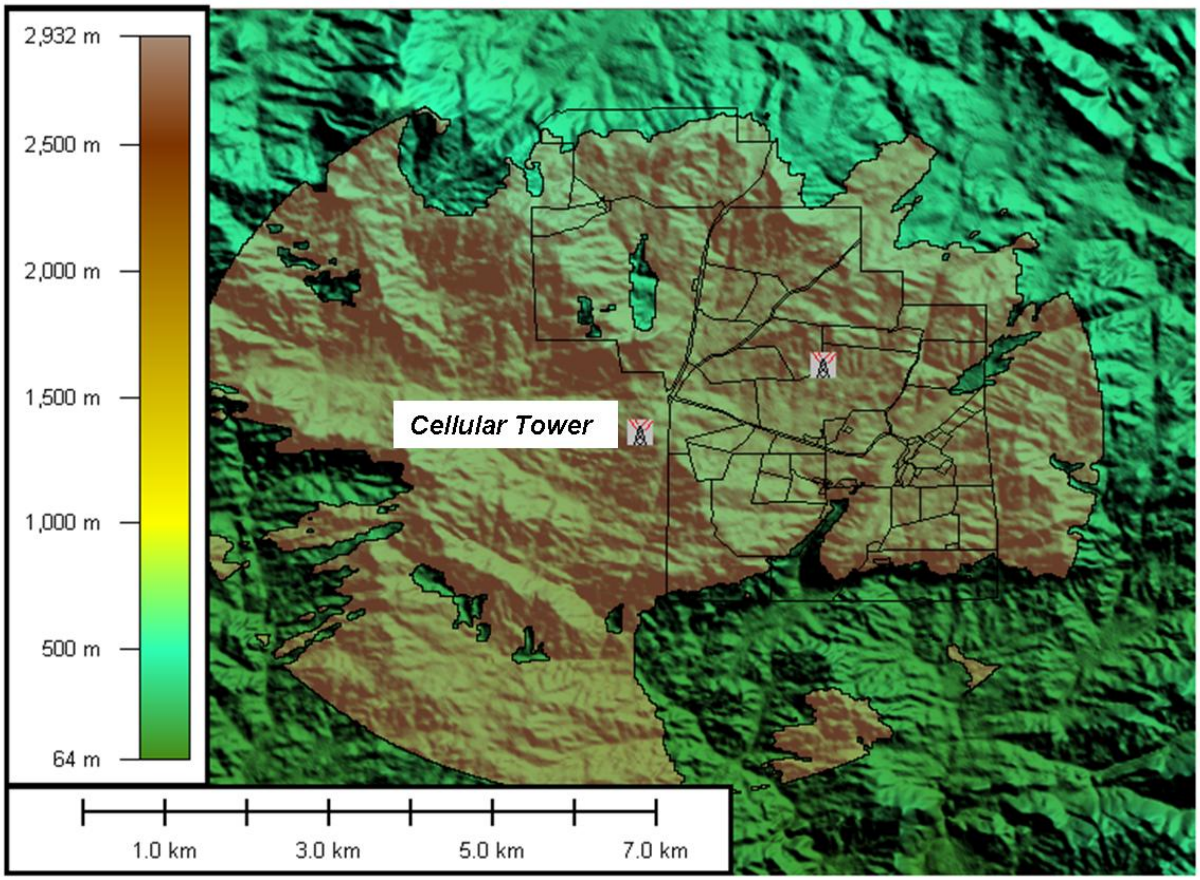


Figure D - 20. San Joaquin Experimental site viewshed. NEON tower is within range.

18 Toolik Lake Site

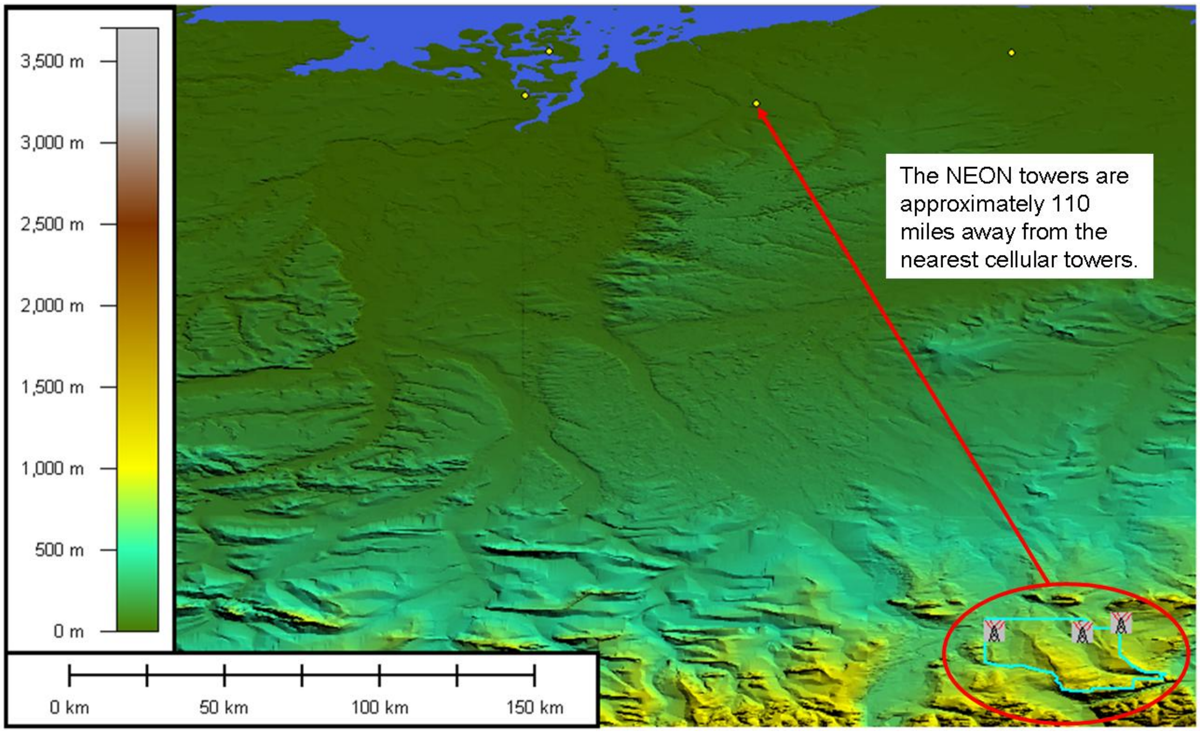


Figure D - 21. Toolik Lake site placement. Nearest cellular towers at prohibitive distance.

19 Caribou Flats-Poker Creeks Site

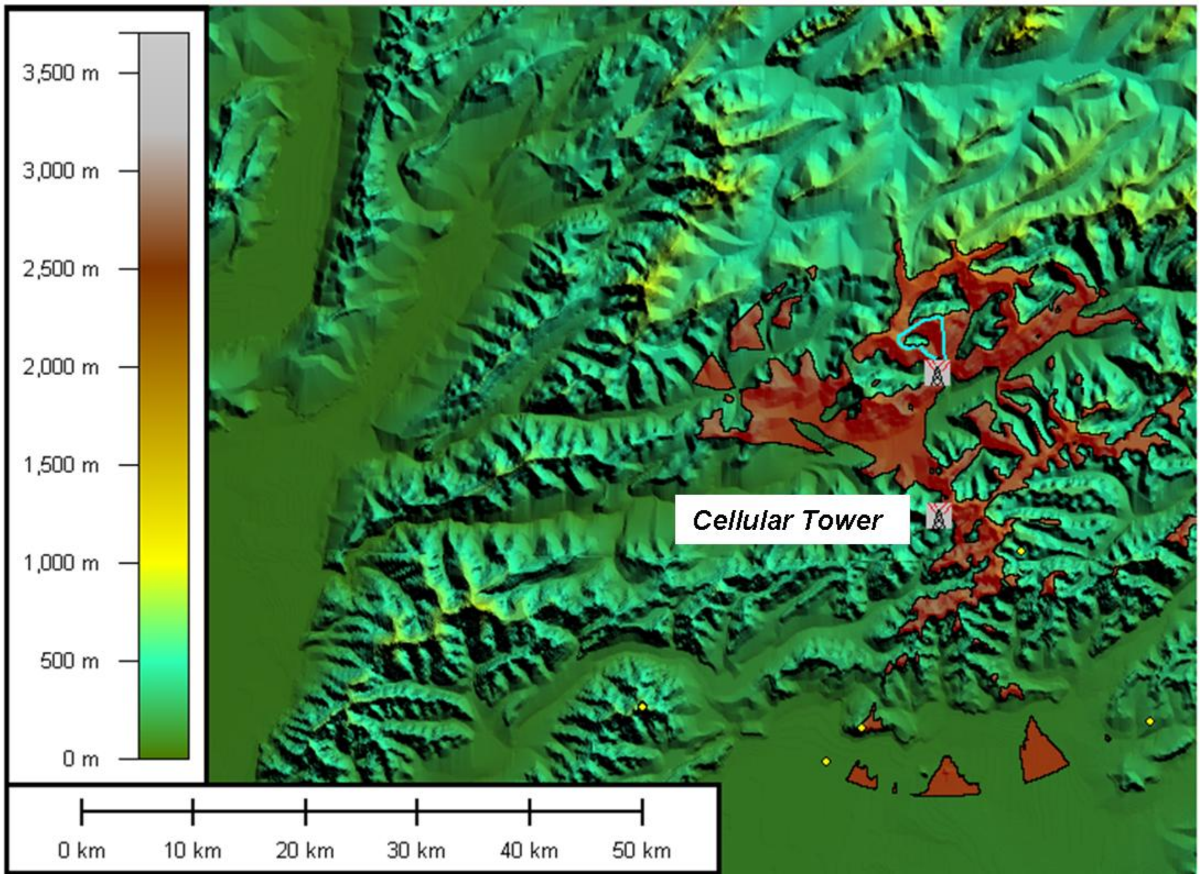


Figure D - 22. Caribou Flats – Poker Creeks site viewshed. NEON site within range but mountainous terrain obstructs LOS access.

20 Laupahoehoe Site

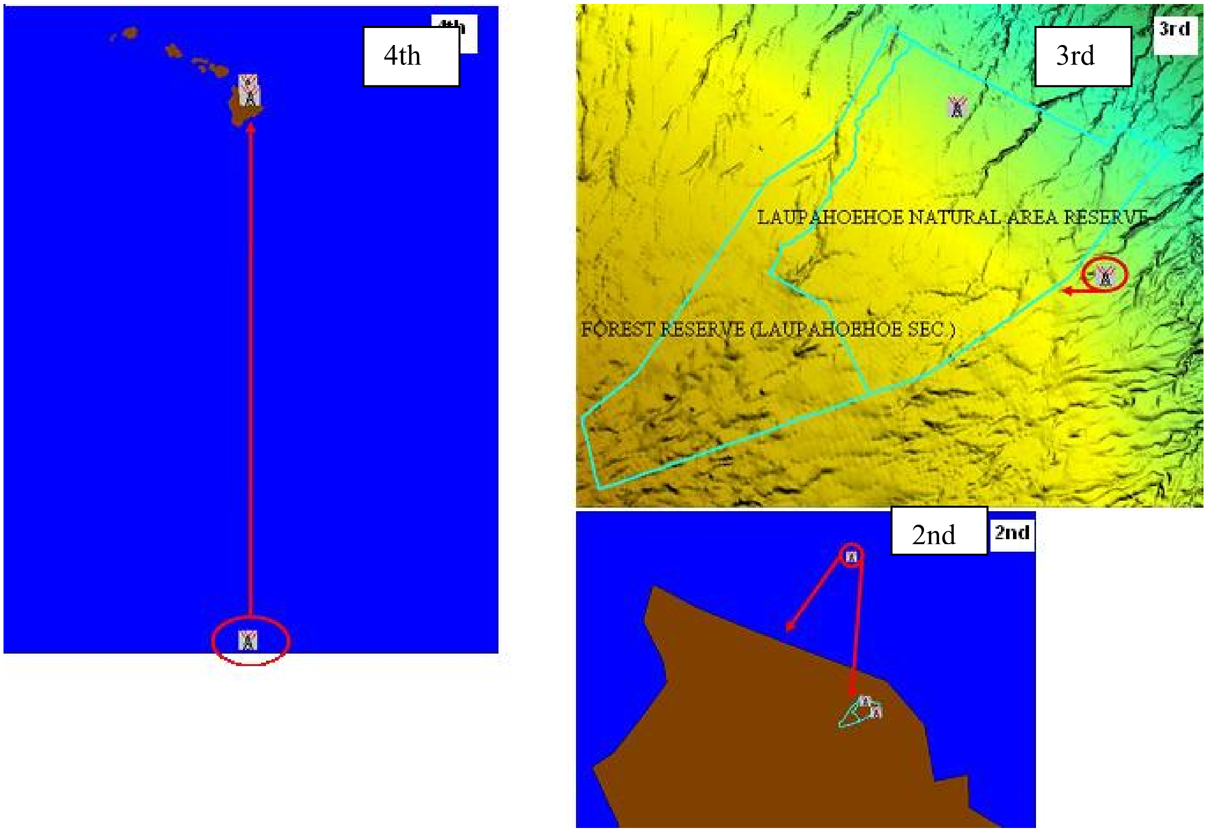


Figure D - 23. Laupahoehoe site inconsistent feature placements. Location #2 is approximately 31 km from land and 42 km from the shape file of the site. Location #3 is approximately 0.6 km outside the shape file of the site. Location #4 is approximately 1,920 km away from the shape file of the site.

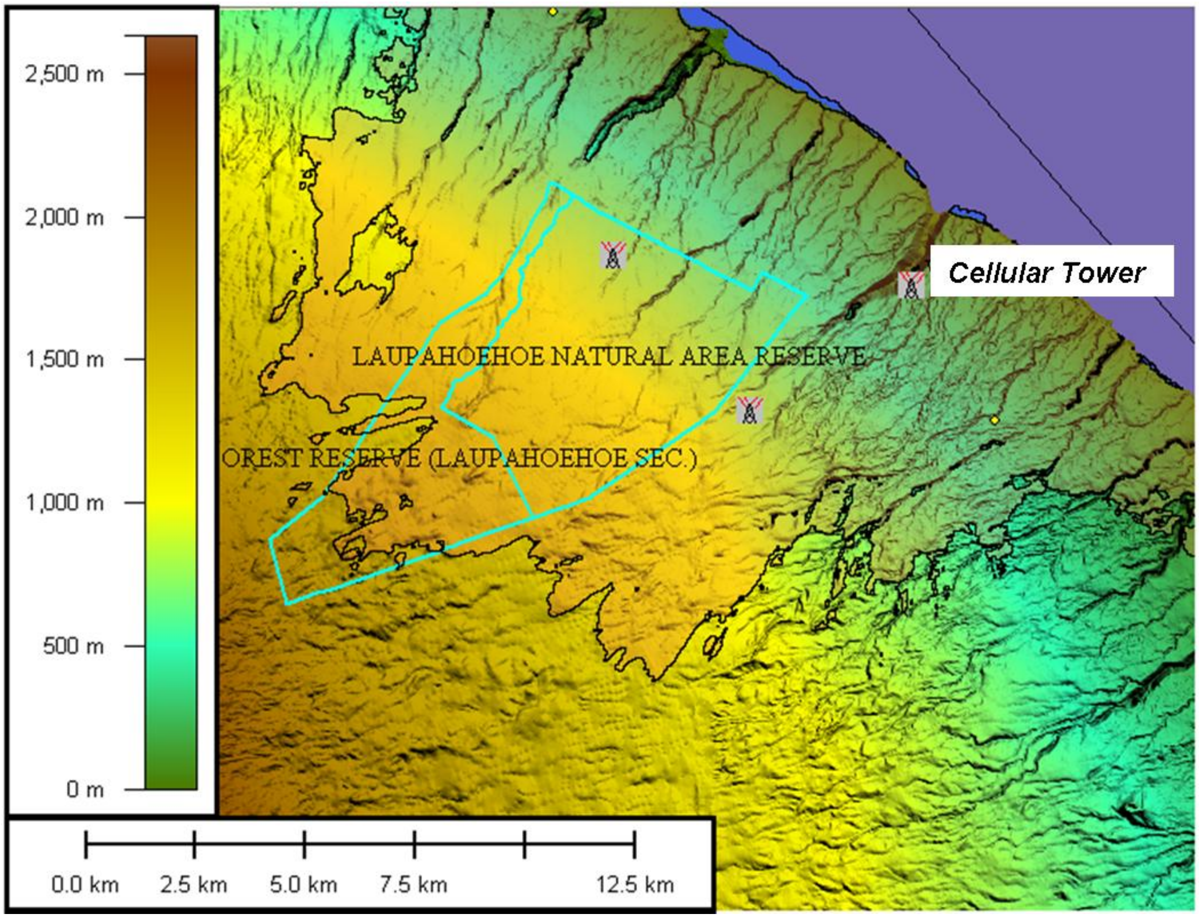


Figure D - 24. Laupahoehoe site viewshed. NEON towers are within cellular range.

APPENDIX E: COMPARISON OF ARM SGP AND NEON PAWNEE SITE SENSOR SUITES

In order to attain a sense of the order of magnitude of activities at NEON sites, and how those activities would compare with the level of effort at proposed ARM sites, an assessment of the sensor suites at the ARM SGP and NEON Pawnee sites was performed. The ARM SGP Central and Extended site sensor suites are provided in Table E - I and Table E - II, respectively. The ARM SGP Boundary and Intermediate site sensor suites are pooled together in Table E - III. In total, the ARM SGP site comprises about 108 separate sensor units. The NEON Pawnee Advanced Tower (Table E - IV) alone has 124 sensor units. Each of the two NEON Pawnee site Basic Towers (Table E - V) has 54 sensor units. The NEON Pawnee Relocatable Tower Number One (Table E - VI) has 121 sensor units, and the Relocatable Tower Number Two (Table E - VII) has 65 sensor units. In total, the NEON Pawnee site will have 418 sensor units vs. 108 sensor units for the ARM SGP site.

While total sensor counts are not a rigidly accurate measure for comparison, the fundamental point of this assessment is that the NEON sites are expected to have both many more sensors and a greater variety of sensors to support. Thus, while the two networks are roughly comparable in a general sense, NEON certainly entertains a more ambitious scope of activities.

Table E - I. ARM SGP Central Facility Sensor Suite.

Quantity	Description	Measurement Objectives
1	Balloon Borne Sondes	Wind Speed Direction ,RH,Temp (4-8 Times/Day)
1	Surface Meteorology (THWAPS)	Wind Speed Direction ,RH,Temp,Pressure, Precip. (Reference for BBS)
1	Aerosol Observation System	68 Measurements
1	Surface Meteorology	Wind Speed Direction ,RH,Temp,Pressure, Precip.
1	Energy Balance Bowen Ratio	Sensiible and Latent Heat
2	Solar Radiometry (SIRS)*	• Direct Normal Shortwave (Solar Beam)
		• Diffuse Horizontal Shortwave (Sky)
		• Global Horizontal Shortwave (Total Hemispheric)
		• Upwelling Shortwave (Reflected)
		• Downwelling Longwave (Atmospheric Infrared)
		• Upwelling Longwave (Surface Infrared)
2	Solar Radiometry (MFRSR)	Normal, Diffuse Horizontal and Total Horizontal Solar Irradiances (Multiwavelength)
3	Eddy Covariance	CO_2 Flux (4m,25m,60m on Tower)
1	Soil Moisture & Temp	8 Depths (5cm to 175 Cm)
1	915 Mhz	Wind Profile/ Virtual Temperature
1	Raman Lidar	Cloud-Vapor Properties
1	MM Cloud Radar	Cloud Properties
1	Wide Band Cloud Radar	Cloud Properties
2	Water Vapor Radiomater	Cloud-Vapor Properties
1	Ceilometer	Cloud Base
1	Shortwave Water Spectrometer	Cloud-Vapor Properties

Table E - II. ARM SGP Extended Facilities Sensor Suite.

Quantity	Description	Measurement Objectives
13	Energy Balance Bowen Ratio	Sensiible And Latent Heat
14	Surface Meteorology	Wind Speed Direction ,RH,Temp,Pressure, Precip
20	Solar Radiometry (SIRS)*	•Direct Normal Shortwave (Solar Beam)
		• Diffuse Horizontal Shortwave (Sky)
		• Global Horizontal Shortwave (Total Hemispheric)
		• Upwelling Shortwave (Reflected)
		• Downwelling Longwave (Atmospheric Infrared)
		• Upwelling Longwave (Surface Infrared)
20	Soil Moisture & Temp	8 Depths (5cm to 175 Cm)
20	Solar Radiometry (MFRSR)	Normal, Diffuse Horizontal and Total Horizontal Solar Irradiances (Multiwavelength)

Table E - III. ARM SGP Boundary and Intermediate Facilities Sensor Suite.

Quantity	Description	Measurement Objectives
4	Balloon borne sondes	wind speed direction ,RH,Temp (4-8 times/day) for IOP only
4	Surface Meteorology (THWAPS)	wind speed direction ,RH,temp,pressure, precip
4	Water Vapor Radiometer	cloud-vapor properties
4	Ceilometer	Cloud Base
3	915 MHz	Wind Profile/ virtual temperature

* SIRS consists of 6 radiometric measurements

Table E - IV. NEON Pawnee Site Advanced Tower Sensor Suite.

Quantity	Description	Measurement Objectives
		Tower
1	Eddy Covariance	CO_2 Flux (at 0.05, 0.75, 2.0, 4.0 m)
1	IR Gas Analyzer (Part of EC)	CO_2 And H_20
1	Solar Radiometry	Incident and Reflected
2	IR Temperature	
3	Surface Meteorology	Wind Speed Direction ,RH,Temp,Pressure, Precip
3	Quanta	Photosynthetic Photon Flux Density (PPFD)
2	Leaf Wetness	
1	Soil Profile (Moisture & Temp)	Temp, Moisture
1	Soil Profile (CO_2 & CH_4)	Cavity Ringdown
3	Cameras	
		Atmospheric Chemistry Array
1	Gas Analysis	NO
1	Gas Analysis	O_3
1	Gas Analysis	C_{13}
1	Gas Analysis	O_{18}
1	Scanning Spectral Radiometer	
1	LIDAR	
1	Dust & Particulates	
		Aquatic Array
10	Groundwater Pressure	Pressure
10	Water Temp	Temp

Quantity	Description	Measurement Objectives
10	Water Quanta	Photosynthetic Photon Flux Density (PPFD)
2	Water Sondes	DO,Ph,ORP, Turbidity,Conductivity, Temp,Chlorophyll
1	UVa-UVb-UVc	Light Meters
2	Soil Heat Flux	
2	Surface Meteorology	Wind Speed Direction ,RH,Temp,Pressure
	Soil Array	
16	Surface Flux	CO_2- Respiration-Chamber
16	Soil (Moisture & Temp)	Chamber Moisture & Temp
5	Soil Profile (Moisture & Temp)	Profile-3 Horizons-Probe-15 Meas
5	Soil Profile CO_2	Profile-3 Horizons-Probe-15 Meas
5	Rain Guage - Throughfall	Precipitation
4	IR Temp (Biological)	Temperature-Surface Radiometer
3	Soil Heat Flux	
5	Micro-Rhizae Phenology	
3	Quanta	Photosynthetic Photon Flux Density (PPFD)

Table E - V. NEON Pawnee Site Basic Towers Number One and Two Sensor Suites.*

Quantity	Description	Measurement Objectives
		Tower
1	Solar Radiometry	Incident and Reflected
3	Surface Meteorology	Wind Speed Direction ,RH,Temp,Pressure, Precip
3	Quanta	Photosynthetic Photon Flux Density (PPFD)
2	Leaf Wetness	
1	Camera	
		Soil Array
8	Surface Flux	CO_2- Respiration-Chamber
8	Soil (Moisture & Temp)	Chamber Moisture & Temp
5	Soil Profile (Moisture & Temp)	Profile-3 Horizons-Probe-15 Meas
5	Soil Profile CO_2	Profile-3 Horizons-Probe-15 Meas
3	Rain Guage - Throughfall	Precipitation
4	IR Temp (Biological)	Temperature-Surface Radiometer
3	Soil Heat Flux	
5	Micro-Rhizae Phenology	
3	Quanta	Photosynthetic Photon Flux Density (PPFD)

* Each of the two Basic Towers has this identical complement of sensors.

Table E - VI. NEON Pawnee Site Relocatable Tower Number One Sensor Suite.

Quantity	Description	Measurement Objectives
		Tower
1	Eddy Covariance	CO_2 Flux (at 0.05, 0.75, 2.0, 4.0 m)
1	IR Gas Analyzer (Part of EC)	CO_2 And H_20
1	Solar Radiometry	Incident and Reflected
3	Surface Meteorology	Wind Speed Direction ,RH,Temp,Pressure, Precip
3	Quanta	Photosynthetic Photon Flux Density (PPFD)
2	Leaf Wetness	
1	Soil Profile (Moisture & Temp)	Temp, Moisture
1	Soil Profile (CO_2 & CH_4)	Cavity Ringdown
2	Cameras	
		Atmospheric Chemistry Array
1	Gas Analysis	NO
1	Gas Analysis	O_3
1	Gas Analysis	C_{13}
1	Gas Analysis	O_{18}
1	Scanning Spectral Radiometer	
1	LIDAR	
1	Dust & Particulates	
		Aquatic Array
10	Groundwater Pressure	Pressure
10	Water Temp	Temp

Quantity	Description	Measurement Objectives
10	Water Quanta	Photosynthetic Photon Flux Density (PPFD)
2	Water Sondes	DO,pH,ORP, Turbidity,Conductivity, Temp,Chlorophyll
1	UVa-UVb-UVc	Light Meters
2	Soil Heat Flux	
2	Surface Meteorology	Wind Speed Direction ,RH,Temp,Pressure
		Soil Array
16	Surface Flux	CO_2- Respiration-Chamber
16	Soil (Moisture & Temp)	Chamber Moisture & Temp
5	Soil Profile (Moisture & Temp)	Profile-3 Horizons-Probe-15 Meas
5	Soil Profile CO_2	Profile-3 Horizons-Probe-15 Meas
5	Rain Guage - Throughfall	Precipitation
4	IR Temp (Biological)	Temperature-Surface Radiometer
3	Soil Heat Flux	
5	Micro-Rhizae Phenology	
3	Quanta	Photosynthetic Photon Flux Density (PPFD)

Table E - VII. NEON Pawnee Site Relocatable Tower Number Two Sensor Suite.

Quantity	Description	Measurement Objectives
		Tower
1	IR Temperature	
1	Solar Radiometry	Incident and Reflected
3	Surface Meteorology	Wind Speed Direction ,RH,Temp,Pressure, Precip
3	Quanta	Photosynthetic Photon Flux Density (PPFD)
2	Leaf Wetness	
1	Soil Profile (Moisture & Temp)	Temp, Moisture
1	Soil Profile (CO_2 & CH_4)	Cavity Ringdown
2	Cameras	
		Atmospheric Chemistry Array
1	Gas Analysis	NO
1	Gas Analysis	O_3
1	Gas Analysis	C_{13}
1	Gas Analysis	O_{18}
1	Scanning Spectral Radiometer	
1	LIDAR	
1	Dust & Particulates	
		Soil Array
8	Surface Flux	CO_2- Respiration-Chamber
8	Soil (Moisture & Temp)	Chamber Moisture & Temp
5	Soil Profile (Moisture & Temp)	Profile-3 Horizons-Probe-15 Meas

Quantity	Description	Measurement Objectives
5	Soil Profile CO_2	Profile-3 Horizons-Probe-15 Meas
3	Rain Guage - Throughfall	Precipitation
4	IR Temp (Biological)	Temperature-Surface Radiometer
3	Soil Heat Flux	
5	Micro-Rhizae Phenology	
3	Quanta	Photosynthetic Photon Flux Density (PPFD)

APPENDIX F: FUNCTIONS OF THE VARIOUS ACRF ELEMENTS

The DOE ACRF **Program Manager** directs and empowers the ACRF budgeting, planning, coordination, and management of activities within the ACRF structure.

The objective of the ARM **Science Board** is to promote the Nation's scientific enterprise by ensuring that the best quality science is conducted at the U.S. Department of Energy (DOE) user facility known as the Atmospheric Radiation Measurement (ARM) Climate Research Facility (ACRF). The goal of the ACRF is to serve scientific researchers by providing unique data and tools to facilitate scientific applications for improving understanding of climate science. The function of the Science Board is to review proposals for use of the ACRF. These proposals may be submitted by the ARM Science Team or by any other interested users of the Facility, including U.S. government agencies engaged in scientific research, colleges and universities, and other interested international scientific and educational bodies. The Science Board will coordinate with the ACRF Infrastructure Management Board to assess the availability and resource requirements of the proposed facility usage. While the ACRF does not provide direct funding for scientific research, small amounts of funding might be provided to allow the facility to assist with logistics, the development of data streams and archiving, and other activities associated with the facility usage. The Science Board will consider facility usage proposals in a timely manner to assist the scientific investigators with their proposals for funding from their prospective funding agencies.

The **Infrastructure Management Board (IMB)** is responsible for the overall ACRF budget that is proposed to the DOE Program Manager for review and approval. Budgets are determined based on the expected allocation of funds from the DOE Program Manager's office and the proposed costs of operating the user facility infrastructure and the proposed costs associated with science requests. The IMB assesses the impacts of all requests for use of the ACRF. The IMB and the ARM Chief Scientist coordinate the screening of science requests for use of the ACRF before consideration by the Science Board and provide information regarding the feasibility and costs associated with the requests. Once a request has been sent to the Science Board for evaluation, the IMB provides to the Science Board detailed information regarding costs and resource use and potential impact on the ARM Program needs at the ACRF. The IMB determines budget allocations for AMF development and deployment, Intensive Operating Periods (IOPs, that is, field campaigns) at the fixed sites, and individual user requests. Budgets are tracked and maintained by the ACRF Administration Office.

The function of the ARM Science and Infrastructure Steering Committee (SISC) is to assist ARM Science and Infrastructure Program Managers to:

- **Develop an overall ARM Program science vision and strategy for implementation**
- **Develop strategies to produce or decommission value-added products (VAPs) that are based on ARM data**
- **Develop strategies for ARM measurement systems**
- **Identify parameters that need to be measured or diagnosed to meet the needs of cloud, aerosol, and radiative processes parameterization development or improvement**

ACRF **Technical Coordinator** is the Chair of the IMB and is the primary point of contact for the ACRF. The Technical Coordinator is responsible for coordinating the evaluation of the costs, logistics, and other requirements associated with full proposals for IOPs at the ACRF before they are brought before the Science Board for discussion. The Technical Coordinator works with the ACRF Science Liaison on discussions regarding projects that are under consideration by the Science Board. The Technical Coordinator provides the engineering services required for the operation and enhancement of the facility. The Technical Coordinator is responsible for overseeing the implementation of user requirements with the Operations Manager, the Archive Managers, and the ACRF Science Liaison. The Technical Coordinator is also responsible for making sure that DOE user facility policies are followed. http://www.sc.doe.gov/ober/facilities.html

The ACRF **Operations Manager** is responsible for ensuring efficient, effective, and continuous operation of instruments and data systems. The Operations Manager helps to develop cooperative relationships with international, regional, and local governments to develop and operate sites, both fixed and mobile. The Operations Manager ensures that field operations are conducted in accordance with DOE and laboratory applicable safety and security policies. The Operations Manager is responsible for maintaining the User Reporting system.

The ACRF **Data Archive Manager** is responsible for the proper storage and access of all user facility data.

The ACRF **Science Liaison** is responsible for coordinating the overall IOP screening process within the IMB. The Science Liaison serves as the communication link between the ACRF IMB and the ACRF Science Board. The Science Liaison works with the IMB to promote the use of the ACRF by the external scientific community and to resolve user issues that might arise regarding external science projects conducted at the ACRF.

The ACRF **Support Administrator** assists with the processing of preproposals and proposals for use of the ACRF. The ACRF Support Administrator is also responsible for assisting with administrative issues related to the DOE requirements for national user facilities. This includes such tasks as preparing facility statistics and processing foreign visitor requests. The ACRF Support Administrator attends the annual DOE user facility Administrator's meeting along with a member of the ACRF IMB to keep abreast of new policies for DOE user facilities.

The ACRF **Financial Administrator** is responsible for working with the IMB to formalize and track the integrated ACRF budget plan.

APPENDIX G: ARM SGP SITE VISIT

Agenda & Attendees

ARM Staff

Dan Rusk — Site Operations Manager (Brad Orr -not present- is the DOE ARM SGP Manager)

Dan Nelson — Facilities (includes roads, new facilities and sensors)

John Schatz — Site Safety

Others in the other room- Trent Doyle (IT), Victor Morris, Tim Grove

SNL Visitors

Bernie Zak

Thor Osborn

Richard Kottenstette

Approximate Flow of Events

9:00 Reprise of NEON Kickoff Meeting Presentation by Thor Osborn

10:00 Presentation of slides originally from James Liljegren by Dan Rusk, with Q&A (Liljegren is a former SGP Site Manager)

12:00 Lunch

1:00 Continued discussion of ARM

3:00 Tour of ARM SGP Central Facilities

5:00 Depart

Key Findings & Items of Interest

ARM Basics

- The SGP approximately 55,000 square miles in area.

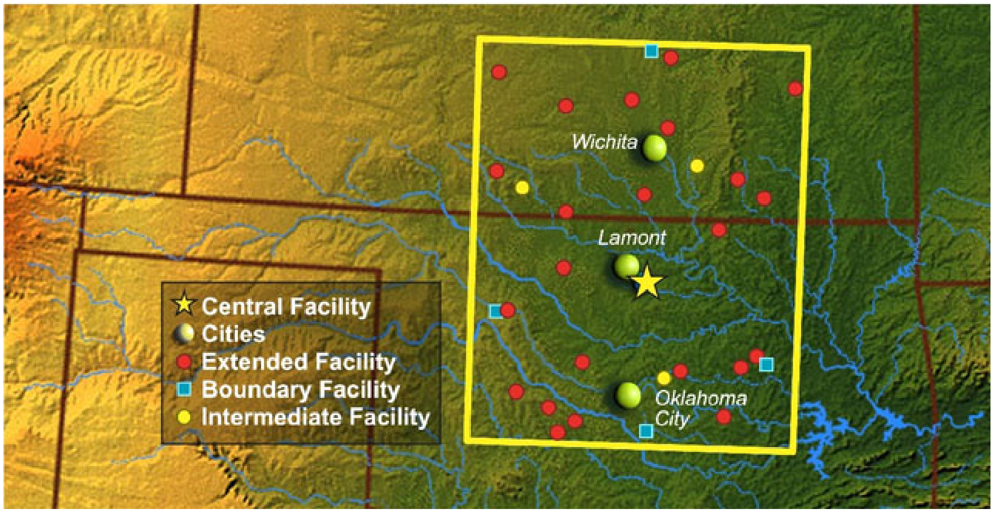


Figure G - 1. Map of Atmospheric Radiation Measurement Program Southern Great Plains site.

- ARM SGP has a Central Facility (which we visited), 23 extended facilities, 4 boundary facilities, 3 intermediate facilities and a radiometer calibration facility. ARM SGP (as well as the other ARM sites) also supports field campaigns.

- The ARM SGP Central Facility is within the Vance AFB Military Operating Area (MOA), used primarily for pilot training. Vance is notified when ARM will have instrumented aircraft in the area. For that period, Vance assigns the sector of its MOA above the Central Facility to ARM.

- The Central Facility has a Guest Instrument Facility (GIF) including a deck for fielding experiments.

- ARM consists of Atmospheric Experimental Scientists, Engineers, Technicians, Software Developers, Data Processing Specialists, Quality Assurance Specialists, Data Storage and Distribution Specialists, Environment, Safety and Health Specialists, Theoretical Atmospheric Scientists, and Managers.

- No NEON sites were chosen to co-locate with ARM sites.

Data Acquisition, Handling, Access, & Security

- Dial-up computer connections are especially prone to interference

- DSL connections are more stable

- ARM data are available to all freely and can be viewed on thumbnails. A new browser has been developed by ARM Archive operations to facilitate the browsing and selection of ARM archive data. The Thumbnail Browser user interface provides users with a graphical view of the ARM data files before they request them or download them for additional use. Data is not just warehoused. More ARM data is distributed to users than new ARM data is acquired each month. Data distribution volume is tracked and continues to rise.

- To combat cyber security threats the staff is continually trained by the SANS institute (http://www.sans.org)

- Remote diagnostics of instruments requires near-real time access to selected data streams

- Raymond McCord from Oak Ridge has been a very strong resource for computer systems

- An issue for the data is a scheduled and budgeted process to transfer data to new storage media. It is believed that over the course of 30 years, technology changes lead to significant effort and expense.

- Sometimes data backup actually uses "sneaker-net." The data loggers usually hold up to 2 weeks of data locally.   ARM now uses Campbell data loggers.

- The Data Quality Office is the "policeman" for the data. The SGP takes data and pumps it out. However, since the techs at SGP are intimately familiar with the instrumentation, they frequently are first to notice anomalies. The DQ office is typically a few days behind at vetting the data.

- University of Alaska Fairbanks looks at North Slope of Alaska ARM data every 24 hours. At all ARM sites, there is a time lag between noticing a problem, identifying a problem, and addressing that problem. If the sites routinely checked all data themselves it would slow the work at the site down and become a choke point. It would also require a higher level of technical expertise than is typically available at the relatively remote ARM sites. The ARM Data Quality Office is at the University of Oklahoma.

- The ARM servers are under constant threat from hackers

Facilities & Instrumentation Maintenance

- The SGP field crews have a two (2) week rotation for service of instruments away from the Central Facility. Their trucks travel over 50,000 miles per year on average.

- ARM has performed a radiometer dome cleaning study to establish the optimum servicing frequency (Tom Stoffel –NREL).

- ARM has also performed a "touch" study to investigate tradeoffs for maintenance of sensors.

- An example was given for low technology being sometimes preferable to high technology. One type of Eddy Correlation instrument was seen as a lemon from the beginning and was replaced with a COTS instrument.

- Dan Nelson mentions that internal metrology is extremely important. This is because you need to have the ability to have control over calibration (cradle to grave pedigree information traceable to the primary solar radiation standard in Davos Switzerland, and to NBS for non-radiometric standards)

- Spare parts replacement strategy is extremely important and budget dependent. It is an effort to consider likely failure and effective ways of using budget to avoid down time.

- Radiometers on shelf at SGP = 50%. These are calibrated and rotated according to a set schedule.

- Radiometers at the North Slope site have a 100% spare parts policy due to remoteness and logistics.

Power Sourcing & Contingencies

- Uninterruptible power supplies (UPS) are essential since rural power systems can be knocked out for extended periods. Some of the UPS's at remote locations are also backed with solar power.

Instrumentation Notes

- ARM developed a method of launching radiosonde (weather) balloons in windy weather. Radiosondea are expensive operations due to the required staffing, the cost of the sondes themselves, and the cost of helium to fill the balloons.

- Total Sky Imager (TSI) - The total sky imager (TSI) provides time series of hemispheric sky images during daylight hours and retrievals of fractional sky cover for periods when the solar elevation is greater than 10 degrees. It is essentially a CCD camera pointed downward onto a domed mirror. This is a low tech solution that has paid great benefits**.** It replaced a much higher tech means of sky imaging which cost an order of magnitude more and was a maintenance nightmare.

- The Raman Lidar (RL) is an active, ground-based laser remote sensing instrument that measures vertical profiles of water-vapor mixing ratio and several cloud- and aerosol-related quantities. Lidar (light detection and ranging) is the optical analog of radar, using pulses of laser radiation to probe the atmosphere. This system is fully computer automated, and runs unattended for many days following a brief (~5-minute) startup period. The self-contained system (requiring only external electrical power) is housed in a climate-controlled 8'x8'x20' standard shipping container.

- The Physikalisch-Meteorologisches Observatorium Davos / the World Radiation Centre of WMO (PMOD/WRC)are working on a new instrument to measure total solar irradiance (TSI) in order to improve the accuracy of the current standard by a factor of 10.

- Millimeter wave cloud radar (MMCR) **-** The main purpose of the millimeter wavelength cloud radar (MMCR) is to measure cloud boundaries (i.e., cloud tops and bottoms), and to record the reflectivity profile of the atmosphere up to 20 km. Unfortunately, for a portion of the year at the ACRF Southern Great Plains (SGP) site, data from the MMCR are often contaminated by "atmospheric plankton" (tiny bugs) at altitudes up to 5 km. Researchers analyzing MMCR data from several experiments concluded that trying to differentiate between the clouds and atmospheric plankton with the current set of instruments was extremely time consuming and inexact. To solve this dilemma, a new W-band ARM cloud radar (WACR) was designed and built during the past year, and was installed in the MMCR instrument shelter at the SGP Central Facility in early July.

Site Security & Personnel Safety

- Site security is also a concern. Copper wires were stripped from one remote site and another was shot at with a shotgun. Local involvement can keep vandalism to a minimum.

- Bernie related an anecdote where two nearby facilities on the North Slope of Alaska experienced widely different impacts from vandalism. One site operated by NOAA has a close relationship with the community and has few problems. The other (an Air Force facility) was more self-contained, had little community involvement and experienced many more problems. Monthly newsletters are useful to inform nearby communities at ARM sites.

- SGP employees do not climb towers due to DOE regulations so they have employed standard tower systems for lowering equipment to the ground for service. These include pulley systems for lowering booms and tippable towers.

- Ice hazard on tower guidelines. Falling icicles can be lethal.

Site & Network Operations Management

- ARM has a process for sensor upgrades that may be leveraged to NEON benefit.

- Working groups of ARM data users help the instrument team decide what additional sensors are needed, and what existing sensors need to be replaced upgraded or changed in some way. Two committees mentioned were the Cloud Working Group and the Aerosol Working Group. These committees recommend new instruments or changes in data processing. They are used to make recommendations to ARM management (the DOE ARM program manager) who either approves or disapproves. Only ARM management can commit funds beyond those already budgeted.

- ARM uses a mentor (0.25 FTE) -technician paradigm. Mentors, usually at Labs or Universities, have expertise in the use of a particular instrument. They coach the onsite technicians by phone and email who service all of the instruments.

- There must be a realistic balance between

    - Manpower ($)

    - Travel requirements- instrument needs

    - Data quality

    - Data continuity

Requirements placed on the rapidity of response to data quality or instrument dropout problems at normally unattended sites directly affect costs. Hence, the proposed requirements must be evaluated in light of estimated costs, and re-evaluated when the actual costs are known.

- The people factor

    - Dan presented the case that hiring local people helps with costs and quality. Typically, these people are high quality (but low tech) who are motivated and tend to adhere strictly to the instructions that are given to them. They provide essential credibility to the project in the local community. All aspects of operations are improved by using them. They also provide a longer term and continuous support, whereas students always have the goal of moving on.

  - Examples were given of farmers, farmers' wives and other tradesmen in Oklahoma as well as local people in Alaska. Ex-military and other local people tend to have a very good work ethic. In Alaska, it was found that having allies in the local community who know the people is essential for identifying and hiring suitable local staff.

- One approach to reducing cost might be to create a mega-data set between ARM and NEON, or some other means of NEON taking advantage of ARM data handling resources. ARM has several other agreements like this already in place

  - Oklahoma Mesonet (http://www.mesonet.org/)

  - NOAA baseline solar radiation (BSRN) net CDF self enfolding data set

  - West Texas Mesonet – Texas Tech

  - NASA AERONET (AErosol RObotic NETwork) project is an international network composed of more than a hundred of sunphotometers that covers a big part of Earth. This network is among others used to study the aerosols and to validate satellite data. (Cimel- photometers)

  - SuomiNet is an international network of GPS receivers, configured and managed to generate near real-time estimates of precipitable water vapor in the atmosphere, total electron content in the ionosphere, and other meteorological and geodetic information. (crustal movement, slant path water vapor).

    (http://www.suominet.ucar.edu/support/)

- A key ARM operating principle is that Field Campaigns must come with funding through ARM management – they are not simply "tacked on" to the duties of operations personnel as unfunded mandates

- ARM processes have already been tested which is a large hurdle for a new program. They could be adopted in the NEON project, with whatever modifications are deemed to be desirable, at low expense.

  - Items that have been tested are flowcharts, procedures, safety and job processes.

  - Other items such as purchasing and routine maintenance

ARM Lessons Learned & Opportunities for NEON

- At one point, Procurement forced the SGP site to purchase a different data-logger to reduce direct costs. The complexity of dealing with two similar but different pieces of equipment cost a great deal of time and money during and post-installation. This is why Southwest Airlines uses only one model of airplane and it is a worthy consideration to examine the system-level impact of such tactical decisions.

- NEON could partner with ARM and build an Alpha site in the field North of the SGP Central Facility, which ARM controls. This approach would enable NEON personnel to rapidly generate and adapt their operating procedures under the mentorship of ARM staff.

- NEON could leverage the ARM calibration facility either on a short-term initial basis or as a long-term strategy. However, this may require facility augmentation, depending upon the size of the additional load.

- NEON could leverage ARM MTTF data on instruments under practical in-service conditions as ARM has a long history and accumulated data set.

- NEON could leverage the ARM database either directly by merging data (if ARM approved) or by adapting the ARM software, hardware and interfaces for NEON use.

- NEON should consider a maintenance cycle study to better understand instrument field behaviors. This could be done in partnership with ARM.

- It is critical to retain the power to make local decisions regarding repairs. Often, sending an instrument back to the manufacturer results in unacceptable delays. Experienced local technicians may be able to analyze the problem and repair with commonly available components. If local site repair efforts do not succeed, a central repair facility can serve as a cost-effective backup (there is such a facility at ARM/ SGP which serves all of the ARM sites worldwide). Return to the manufacturer for repair is a last resort.

- While ARM provides direct access to its data, it also provides what are termed “value-added products” through its Data Processing Center

- Job Safety Analysis and training are key responsibilities that must be addressed to avoid long-term negative consequences. Within DOE, serious safety problems, even “near misses”, threaten the continuation of programs.

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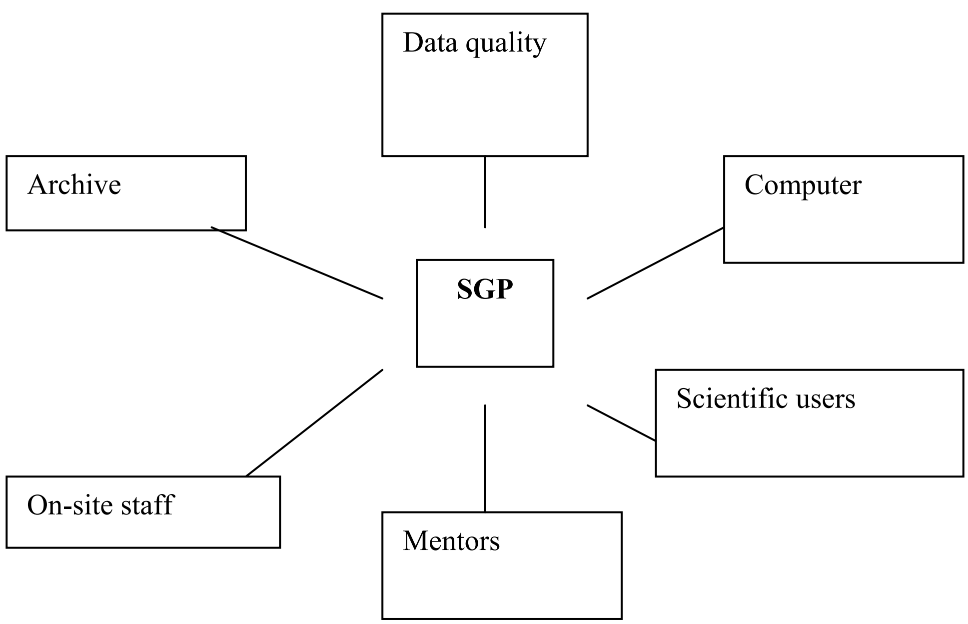

Figure G - 2. Linkages to ARM SGP include site personnel, off-site support personnel, data management, and the data user community.

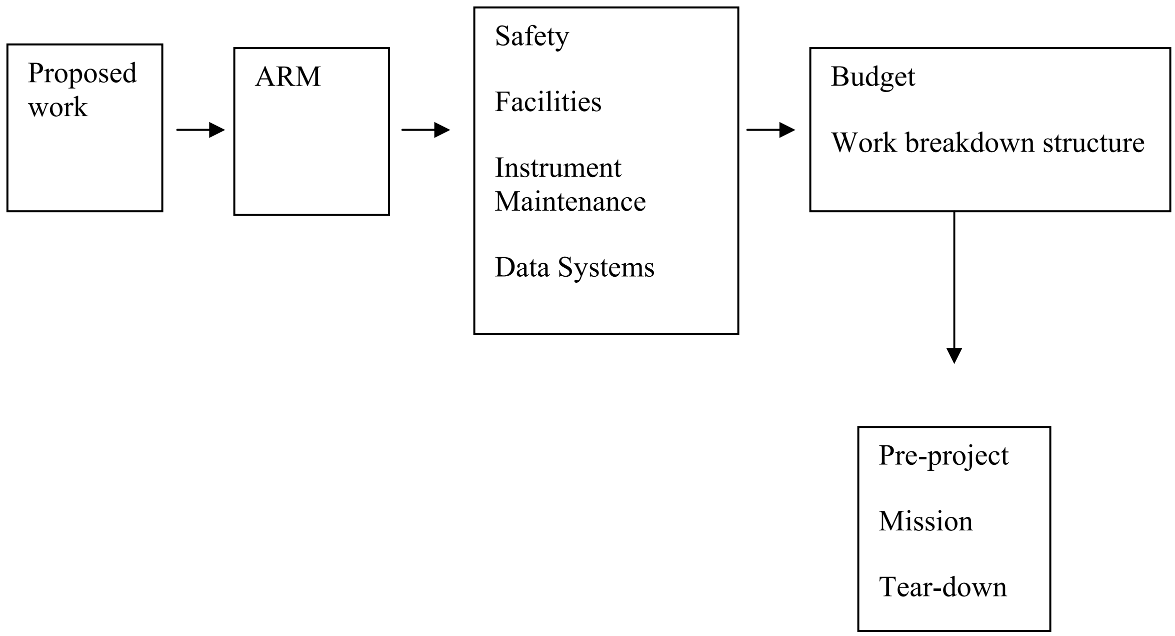

Figure G - 3. Field Campaign approval process employed to ensure match between proposed efforts and allocated funding and resources.

APPENDIX H: ACRF TWP SITE OPERATIONAL CHALLENGES

Long-Term Operation Of Ground-Based Atmospheric Sensing Systems In The Tropical Western Pacific

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ABSTRACT

Three semi-autonomous atmospheric sensing systems were installed in the tropical western Pacific region. The first of these Atmospheric Radiation and Cloud Stations (ARCS) began operation in 1996. Each ARCS is configured as a system-of-systems since it comprises an ensemble of independent instrument systems. The ARCS collect, process, and transmit large volumes of cloud, solar and thermal radiation, and meteorological data to support climate studies and climate-modeling improvements as part of the U.S. Department of Energy's Atmospheric and Radiation Measurement (ARM) Program. Data from these tropical ARCS stations have been used for satellite ground-truth data comparisons and validations, including comparisons for MTI and AQUA satellite data. Our experiences with these systems in the tropics led to modifications in their design. An ongoing international logistics effort is required to keep gigabytes per day of quality-assured data flowing to the ARM program's archives. Design criteria, performance, communications methods, and the day-to-day logistics required to support long-term operations of ground-based remote atmospheric sensing systems are discussed. End-to-end data flow from the ARCS systems to the ARM Program archives is discussed.

Keywords: atmospheric and meteorological sensing, semi-autonomous remote systems, DOE ARM Program, Tropical Western Pacific, remote system diagnostics

1. INTRODUCTION

For many decades, satellites have been used for atmospheric remote sensing. These highly reliable systems operate for years at a time, controlled from a ground station and with no hands-on maintenance. Starting in 1993, an effort began to design ground-based atmospheric sensing systems that would emulate earth-orbiting satellites in their reliability and autonomy. Using "satellite-on-the-ground" as a guiding design metaphor, a set of Atmospheric Radiation and Cloud Stations were designed and built for use in the tropical western Pacific region. A second design and development effort led to Cloud Stations for arctic regions, including a year-long shipboard deployment on an icebreaker. Work is underway to complete the design and begin development of the next generation of ARCS, a fast-deployment, mobile Cloud Station.

This paper describes the original design motivations, design criteria, performance, and operating challenges for remote, semi-autonomous atmospheric measurement systems used in the tropics. The first of these systems to be deployed has been in operation since 1996. Lessons learned over the last decade of design and field operations may be useful to others planning multi-year operation of ground-based remote sensing systems in harsh environments. A performance assessment for the first as-built systems also serves to complete the systems engineering process, providing feedback for successive system designs.

A brief description of the scientific mission for which these systems were designed is presented in the next section. The initial design targets along with later modifications are discussed. This paper concludes with an overview of the logistics, diagnostics, and communications required to maintain these remote systems.

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1.1 The Atmospheric Radiation Measurement (ARM) Program

In the late 1980s, a growing interest in predicting the climatic response to measured and anticipated future changes in earth's atmosphere (increases in atmospheric carbon dioxide for example) led to inter-comparisons among climate models. The substantial disagreement observed among the models' predictions was largely attributed to differences in the ways these models accounted for clouds and their interactions with solar and thermal radiation [1].

In 1990, the United States Global Change Research Program made the treatment of clouds in climate models its highest-priority research topic. The U.S. Department of Energy (DOE) addressed this challenge by creating a peer-reviewed research program, the Atmospheric Radiation Measurement (ARM) Program . The ARM Program provides funding and supporting infrastructure for research and field measurements of clouds and cloud properties as they relate to climate models and atmospheric radiation.

The ARM Program has established three primary field measurement sites. The three locales, shown in Fig. 1, are the Southern Great Plains of the United States (SGP), the Tropical Western Pacific (TWP), and the North Slope of Alaska and Adjacent Arctic Ocean (NSA/AAO). At each of these sites, long-term, precise, and detailed measurements of radiation and optical properties, meteorological parameters, and other atmospheric properties are made and recorded. The ARM Program gathers and archives about 4 gigabytes of raw and processed data each day [1]. Since its inception, the ARM Program has produced a detailed and unique observational record for these three climate regimes that spans years in duration instead of the few months that is typical of previous field measurement campaigns.

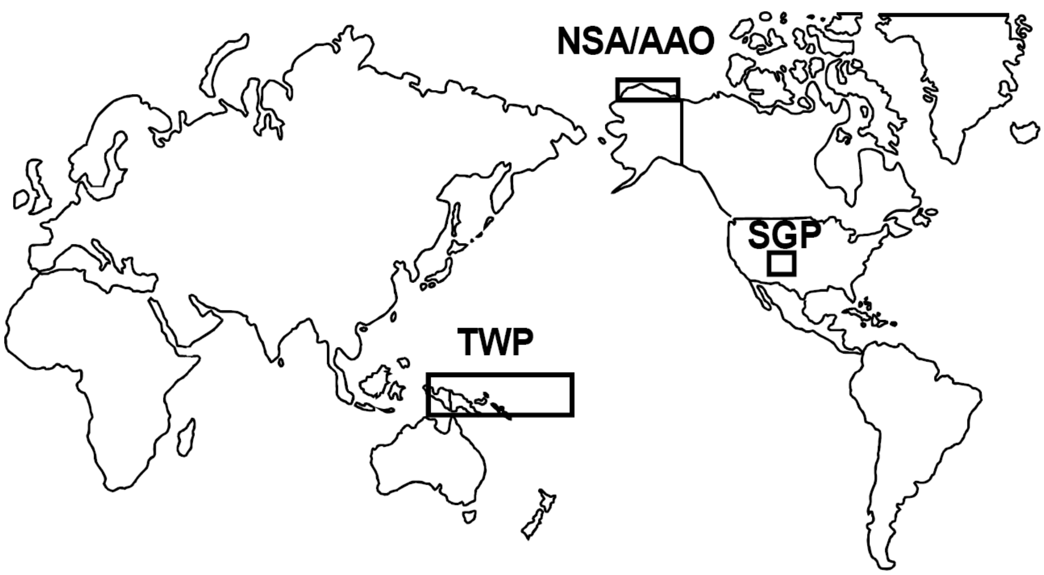


Figure 1: The three primary ARM Locales

These three sites gather continuous data from suites of instruments at Cloud and Radiation Testbeds located at each site. Each instrument at an ARM site is characterized, calibrated, and monitored to ensure that data quality is maintained at all times. Instrument data is collected by a centralized data acquisition and communications system. Since many of the ARM instruments are configured as stand-alone systems, the ensemble of instruments at any one ARM site can be viewed as a system-of-systems. The high degree of measurement precision demanded from state-of-the-art instrumentation combined with exposure to extreme environmental conditions result in unique challenges for the teams that manage and operate these sites.

In July 2003, the DOE Office of Biological and Environmental Research announced that the ARM sites were designated a national user facility and renamed the Atmospheric Radiation Measurement (ARM) Climate Research Facility (ACRF). As a result, the former ARM CART Sites are now known as Climate Research Sites. [2]

1.2 The Tropical Western Pacific Locale

The Tropical Western Pacific locale extends roughly between 10^{O} S and 10^{O}N latitude and from 135^{O}E to 150^{O}W longitude (Fig. 2). The maritime continent area is largely in the southwest and the open ocean area in the northeast of the locale. Climatologically, warm sea surface temperatures, deep and frequent atmospheric convection, high rain rates, strong coupling between the atmosphere and ocean, and substantial variability associated with El Niño - Southern Oscillation (ENSO) phenomenon characterize the locale. The relationship between climatic variability in this region and variability in other areas of the planet is well known.

Ideally, a large number of measurement sites would be spread across the entire tropical western Pacific region. However, the number of sites where an ARM-related atmospheric measurement station could be installed in the region was limited by practical considerations. The ability of a candidate site to provide data that would address the science goals was one important element of this location strategy. The science goals of the tropical western Pacific component of the ARM Program include the following [3]:
1. Determine the magnitude of the surface radiation budget terms and determine their spatial and temporal variability;
2. Identify bulk and optical properties of clouds in the TWP and how these properties affect the radiation budget;
3. Understand the linkages among sea surface temperature, ocean-atmosphere coupling, surface radiation budget, and tropical convection;
4. Determine vertical transports of water vapor, energy, and momentum in convective cloud systems.

The concept of an autonomous or semi-autonomous ARM measurement station developed early in planning for placement of ARM instruments in the tropical western Pacific. The integration of state-of-the-art remote and in-situ atmospheric sensors into a single facility that was easily transportable worked well for the National Center for Atmospheric Research (NCAR) and the Aeronomy Laboratory of the National Oceanic and Atmospheric Administration (NOAA/AL). This concept was demonstrated for measurements in the tropical western Pacific as part of the Coupled Ocean-Atmosphere Response Experiment (COARE) of the Tropical Ocean and Global Atmosphere (TOGA) program [4]. A 20-foot ocean cargo container was used as a portable laboratory shelter during the PROBE experiment on Kavieng [3]. From these early examples, the concept of an Atmospheric Radiation and Cloud Station (ARCS) for ARM tropical sites was developed.

Locating an ARCS on a small-to-medium sized island offered the potential for atmospheric measurements that were more typical or closer to those of an open ocean site. Based on previous experiences during scientific measurement campaigns in the Pacific region, a set of candidate islands in the region were identified. These islands, on average, had the following characteristics [3]:

- a unique set of strengths and problems related to an ARCS installation,
- a well defined local government,
- a local infrastructure available to support basic needs,
- airline service with cargo capacity,
- one or two hotels,
- water, electricity, and phone services that varied in quality and reliability,
- an elementary and high school,
- a medical facility of some sort,
- a harbor, dock, and ability to handle 20 foot sea-containers,
- a Weather Service office with local observers to assist with ARCS operations and balloon launches.

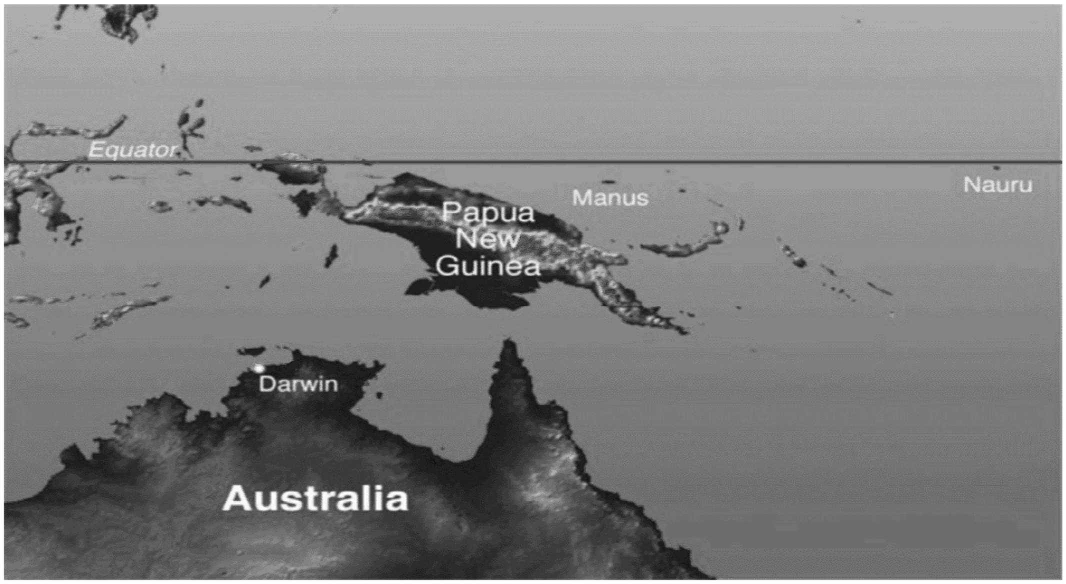


Figure 2. Map of the Tropical Western Pacific sites

1.3 The Three Tropical Western Pacific Sites of the ARM Program

Three sites in the tropical western Pacific region were chosen for an ARCS installation.

Manus Site (2.006° S, 147.425° E, 6 m MSL), *Papua New Guinea*

Operational since October 1996, the Manus Site is located on Los Negros Island in Manus Province, Papua New Guinea (PNG), in the heart of the tropical western Pacific warm pool. The warm pool is an important source of heat, water vapor, and high clouds in the Tropics. The site is operated in collaboration with the PNG National Weather Service (NWS), which provides personnel to serve as on-site Observers conducting daily operations.

Nauru Site (0.521° S, 166.916° E, 7.1 m MSL), *Republic of Nauru*

Operational since November 1998 in collaboration with the Republic of Nauru government, the second ARM/TWP research station is located on Nauru Island, Republic of Nauru. The Nauru Site is positioned at the transition zone between the tropical western Pacific warm pool and the Central Pacific, a location sensitive to meteorological changes caused by the El Niño-Southern Oscillation events. A team of four Naruan government personnel serves as on-site Observers performing daily operations. In addition to the standard set of instruments, the Nauru Site is equipped with an Atmospheric Emitted Radiance Interferometer (AERI).

Darwin Site (12.425° S, 130.891° E, 29.9 m MSL), *Northern Territory, Australia*

The Darwin Site is the third ARM/TWP research station, located adjacent to the Australian Bureau of Meteorology's (BOM) MET office near the Darwin Airport. Operational since April 2002 in collaboration with the BOM, the Darwin Site also serves as a maintenance center for all three TWP stations. This allows rapid response and real-time troubleshooting by the BOM technicians stationed at Darwin. The data collected at the Darwin Site are unique because of the annual monsoon, convective clouds produced during the transitional period, as well as periodic aerosols caused by grassfires.

2. The ARCS Cloud Stations: Satellites on the Ground

The ARCS were designed to be semi-autonomous systems that would require little intervention from local operators in normal operations. The design metaphor of "a satellite on the ground" served to guide early design efforts. Although the ARCS were not expected to be fully autonomous to the extent a satellite must be, that goal was pursued within practical bounds. At the beginning of the project, the ARCS were envisioned as

1. an integrated set of instruments, data systems, and support facilities that were compact, easily shipped and deployed;
2. shelters with conditioned and monitored power for the associated instruments, data and communications systems, and reliable air conditioning systems that are essential for operations in the tropics;
3. robust systems that could operate semi-autonomously in marine environments with a high level of reliability for ten years or more.

The typical instrument suite at an ARCS site is listed in Table 1. In addition to these instruments, an ARCS includes data acquisition systems, communications systems, electrical power generation systems, and specialized sub-systems for ARCS operations including hydrogen generators for balloon sounding. A functional block diagram of ARCS sub-systems is shown in Figure 3.

Measurement	Instrument
Surface Radiation Balance	• Up- and down-looking pyranometers and pyrgeometers • Sun-shaded pyranometer and pyrgeometer using solar tracker • Normal incidence pyrheliometer • Up- and down-looking 9-11μm narrow-field-of-view radiometers • UV-B hemispheric radiometer
Surface Meteorology	• Temperature and relative humidity sensor • Barometer • Optical rain gauge • Propeller vane anemometer
Cloud Properties	• Cloud lidar (523 nm) • Ceilometer (7.5 km maximum range) • 35 GHz cloud radar • Whole Sky Imager • Total Sky Imager
Aerosol Optical Depth	• Multi-filter rotating shadow band radiometer (total, direct, and diffuse irradiance in six 10-nm channels)
Column Water	• Dual channel (23.8 and 31.4 GHz) microwave radiometer
Vertical Structure of Atmosphere	• Rawinsonde (Manus and Nauru)
Atmospheric Emitted Radiation	• Atmospheric Emitted Radiance Interferometer (Nauru only)

Table 1. Typical Instrument Suite at a TWP ARCS Site

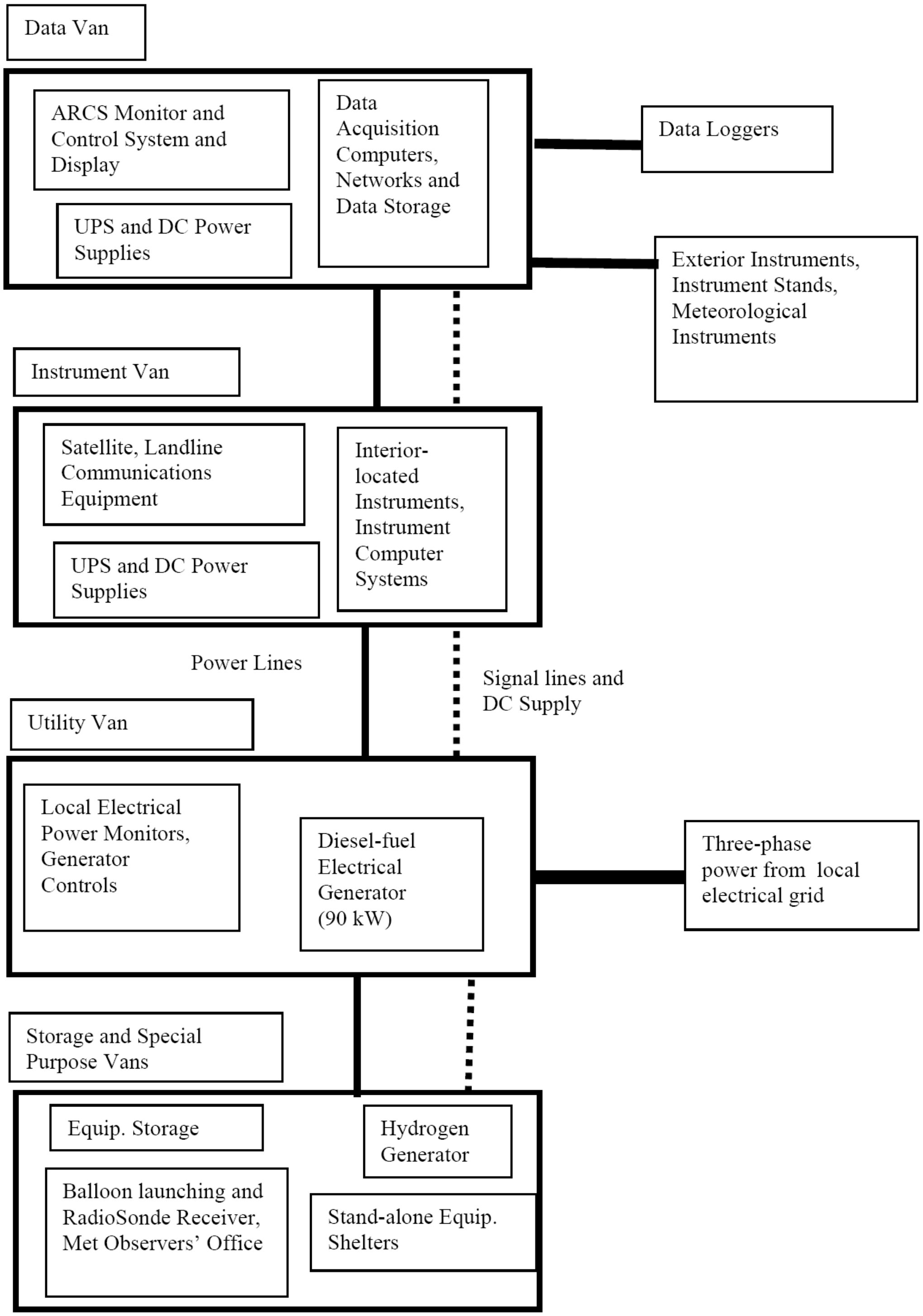


Figure 3: ARCS Block Diagram

These general design objectives were transformed into specific requirements through a series of intensive design sessions. The resulting ARCS design requirements specification included:
1. provision for a physical footprint consistent with a standard 20-foot ISO ocean cargo container;
2. requirement for a ten-year minimum operating life in marine environments;
3. Mil-spec or near mil-spec performance requirements for
   - Operating and storage temperature, humidity
   - Salt fog, sunshine, rain, wind, icing, fungal resistance
   - Mechanical shock
4. adherence to US National Electrical Code or other applicable national electrical codes;
5. adherence to DOE Requirements for fire protection;
6. standard physical design for ports, doors, and through-wall penetrations.

2.1 System Design, Performance, and Evolution

The ARCS was designed to be a system-of-systems comprising six major sub-systems. These six are:
a. a data management system,
b. the set (or suite of instruments),
c. a set of shelters (also called "enclosures" or "vans"),
d. the communications systems,
e. a monitor-and-control system,
f. the power system.

a. The Data Management System
The Data Management System collects, processes, and records instrument data and provides a time stamp for data records. In the first generation of ARCS, data were stored on removable media (swappable hard drives) that were exchanged with empty media units when filled. Full media were then shipped to the U.S. In the current ARCS implementation in the tropics, data from a majority of instruments are transferred to facilities in the U.S. via satellite or internet connections. Some image data and meteorological data from external sources is shipped on Hard Disks or DVDs.

b. The ARCS Instruments
Each ARCS instrument operates independently of other instruments. The instruments can restart and resume operation following loss of power. Diagnostic, calibration, and testing commands from the Data System cause each instrument or instrument interface computer to return health and status information or a requested data stream to the Data System. The ARCS instruments have the capability to buffer or store data independently.

c. Communications System
The Communications System provides communications links between the Data System and external users. In the initial design, landline telephone, one-way GOES data channels, and satellite communications were considered. Over time, the primary communications channels became satellite channels or internet connections.

d. ARCS Shelters
The ARCS Shelters ("enclosures" or "vans") provide a temperature and humidity-controlled environment for certain instruments, the Data Management System, and the Communications System. These shelters provide stable, conditioned AC and DC power to instruments and sub-systems. The exterior finish of the shelters was designed for a minimum of ten years life in tropical marine environments with minimum maintenance requirements.

e. ARCS Monitor and Control System
The ARCS Monitor and Control System measures environmental and power parameters such as internal humidity and temperature, then formats and transmits these to the Data Management and Communications systems. The monitored ARCS parameters are listed in Table 2. The first version of the ARCS Monitor and Control System allowed remote

control of selected power supplies to the enclosure and to air conditioning units. A second generation of the ARCS Monitor and Control System was based on commercially-available programmable logic controllers and power monitors. Health and Status reports for the instrument data streams are monitored with a web-based software tool known as DS View.

f. Power Systems

The ARCS include a diesel-fueled generator and power monitoring system. When incoming grid AC power exceeds preset limits, the generator set starts automatically and the ARCS power load is transferred to the generator. The generator powers the ARCS until the external source returns to expected values. Uninterruptible power supplies and battery systems in the ARCS vans provide stable power to instruments during the time between an external grid power failure and the generator start and transfer.

Measured Parameter	Number of Sensors per Enclosure
Three phase AC voltage	3
Three phase AC current	3
Entry door status	1
Smoke alarm	1
Uninterruptible Power Supply Alarms	1
Uninterruptible Power Supply Battery and AC Output	1
Status of Main Power Contractors	1
Enclosure Temperature and Relative Humidity	1 each
Voltage and Current of External Power Supply (Grid)	1 set for site
Diesel Generator set alarms and status	1 for U-van
Fuel Levels	1 set for each tank

Table 2. Monitored ARCS Enclosure and Power Parameters

Table 3 below summarizes the first generation of ARCS subsystems, problems encountered, and actions taken or lessons learned. A view of the first ARCS to be installed in the tropics is shown in Figure 4.

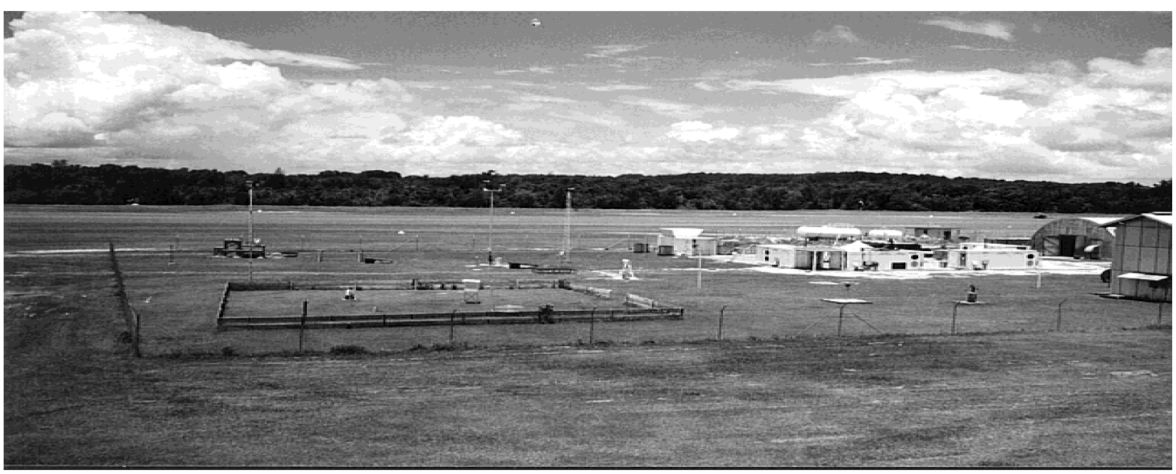


Figure 4. The ARCS Installation at Manus Island, Papua New Guinea

SYSTEM	EVENT OR PROBLEM	DESIGN MODIFICATION OR LESSON LEARNED
Data System		
Dual Workstations	First generation became obsolete, parts unavailable, no support	Expect limited computer system lifecycles and support
Digital-audio tapes used for data collection and transfer	Trouble with reliability, read/write by different drives	Swappable hard drives used to record and transfer data to U.S.
Instrument Systems		
Personal Computers used for instrument systems, interfaces	Variations in models, types, obsolescence	Type and model standardized across the program (CorePC)
Instrument mounting hardware	Corrosion in tropical environment	Changed to synthetics (nylon, delrin); sealants and coatings.
Hardwire instrument lines	Lightning event at test site	Switched to optical fiber wherever possible
Shelters		
Steel ISO containers with marine-grade coating used	Too heavy for some deployments	Second generation shelters built from aluminum
Communications		
GOES (~100 baud) Inmarsat C (~2 kbps) and Landlines used initially	Landline phones not reliable; GOES good for brief data snapshots	Need high-bandwidth data for data system admin and diagnostics
Inmarsat B (~60 kbps)	Unplanned transceiver operations resulted in large expense	Need inexpensive high-bandwidth data for data system admin and diagnostics
New satellite comms	Required custom installation	Improved access and diagnostics TWP Sites use Hughes Global Services VSAT
Frequent communications required with observers	Training and written procedures were a good start but frequent one-on-one conversations required	Email access with capability for digital photo and FAX transmission is important
Monitor and Control System		
Initial system was custom	Hard to expand, modify, maintain	Switched to commercial, off-the-shelf components where possible
Power System		
Backup AC power system in initial design	More power outages than expected	Added fuel reserves and fuel monitoring
UPS systems provided 50-to-60 Hz conversion	Newer ARCS subsystems accept 50/60 Hz power	Replacing original UPS systems with newer units
Photovoltaic panels for backup system	PV panels popular, prone to disappear	Switched to AC-charger and battery bank

Table 3. First Generation Design and Modifications

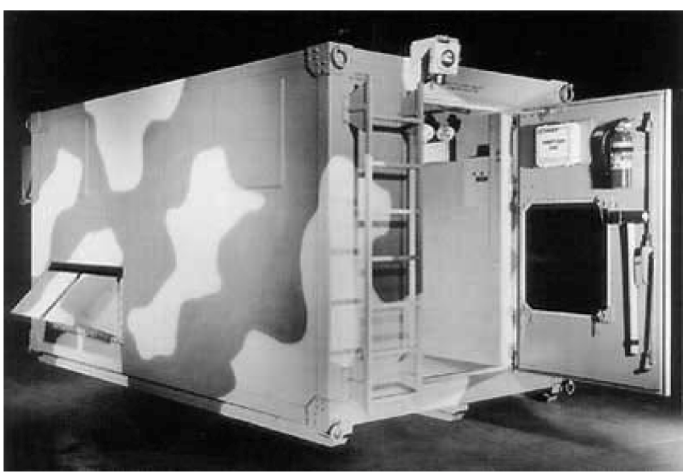
2.2 The Next Generation of ARCS: the ARM Mobile Facility

The first generation of ARCS instrumentation systems were envisioned to be installed and operated at a particular site for multi-year periods. However, the scientific needs of the ARM Program required a Mobile Facility that could be deployed quickly for scientific measurement campaigns lasting up to 18 months. To meet that need, the ARM Mobile Facility (AMF) was designed and is being integrated. One of the authors (K.W.) is lead engineer for the Mobile Facility Design.

This next generation of ARCS incorporates key improvements. Table 4 below lists changes in sub-system design in comparison to the earlier versions of ARCS. The lightweight shelter that will be used for the AMF is shown in Figure 5.

Data System	• Based on other ARM data systems and protocols • Flexible instrument data collection scheme • On-site data storage and media transfer • Data Quick Looks for quality assurance
Instruments	• AMF will support full list of ARM instruments • Instrument interfaces via 10/100BaseT • Instrument Health and Status Collection • Future and Guest Instrument provisions
Shelters	• Small, lightweight, MIL-SPEC
Communications	• Voice and Data Via Satellite
Monitor and Control System	• Shelter and Instrument Monitoring with Local displays and Remote Monitoring via Satellite communications.
Power	• Universal Input Power Design

Table 4. Sub-system Characteristics and Design Evolution for the ARM Mobile Facility



Potential Deployment Sites for the ARM Mobile Facility:

- Amazonia
- Arctic/Antarctic
- Africa
- Australia
- Continental North America
- Europe
- Islands

Figure 5. Lightweight MIL-SPEC Mobile Shelter and Potential Deployment Sites

3. ARCS Operations, Communications, and Data Flow

The high volumes of quality-assured data produced by the ARCS (and the other ARM facilities) requires quick identification and response to instrument malfunctions or failures. This response as well as regularly-scheduled activities, such as instrument calibrations, require an unusual and effective collaboration among international teams.

3.1 An International ARCS Team

An international team is responsible for operating the ARCS, This team operates under the direction of the TWP Office at Los Alamos National Laboratory. ARCS operations in New Guinea are performed by staff from the Papua New Guinea National Weather Service. In Nauru, contracted staff under the administration of the Nauru Department of Economic Development (DED) operate the ARCS. The Darwin ARCS is operated by staff from the Australian Bureau of Meteorology. The Australian BOM also provides a team that provides repair, replacement, and calibration services at all three TWP sites. The South Pacific Regional Environment Programme (SPREP) works with the TWP Office in coordinating regional activities. Active participants in TWP ARCS operations include the following:

- Argonne National Laboratory, Argonne, IL
- Brookhaven National Laboratory, Upton, NY
- Los Alamos National Laboratory, Los Alamos, NM
- National Renewable Energy Laboratory, Golden, CO
- Oak Ridge National Laboratory, Oak Ridge, TN
- Pacific Northwest National Laboratory, Richland, WA
- Sandia National Laboratories, Albuquerque, NM
- Airborne Research Australia, Flinders University, Adelaide, South Australia
- CSIRO, Division of Atmospheric Research, Victoria, Australia
- Bureau of Meteorology, Melbourne, Victoria, Australia
- National Weather Service, Papua New Guinea
- Nauru Department of Economic Development, Republic of Nauru
- The South Pacific Regional Environment Programme, Samoa
- NASA, various divisions
- NOAA, various divisions

Table 5 below lists formal contact reports and shipments required to support operations at the three TWP sites in calendar year 2002. Table 6 summarizes communications required to maintain operations at the TWP sites.

	Manus Island	Nauru Island	Darwin, Australia
Contact Reports	214	260	135
Shipments, total	72	82	47
Shipments, hand-carried	10	10	6
Helium cylinders (as supplements to hydrogen sources)	20	10	

Table 5. Shipments in calendar year 2002 that were required for ARCS operations.

Daily	As required (longer than monthly on average)
♦ Observer daily rounds reports ♦ Site Health and Status reports ♦ Contact sheets (reports) ♦ Technical maintenance reports (during site visits) ♦ System Event logs	♦ Consumable supplies inventory ♦ Maintenance scheduling ♦ Site visit requests ♦ Site visit reports ♦ BCR – ARM Baseline Change Requests
Weekly ♦ Weekly TWP Telephone conference ♦ Weekly Rounds reports	♦ ECR - ARM Engineering Change Requests ♦ TTR – TWP Task Tracking System ♦ DOE export/import documentation
Monthly ♦ Personnel tasking lists ♦ Shipping and receiving forms ♦ Inventory tracking and data base ♦ Monthly Rounds reports ♦ Data Media Changeout reports	♦ USA Customs documentation ♦ Papua New Guinea, Nauru, and Australian Customs documentation ♦ Operations Procedures, Site Safety Manuals ♦ Local Observer Safety and Technical Training ♦ ARCS Operation and Calibration manuals

Table 6. Operations-related communication and information collection sorted by typical time scale.

3.2 Challenges to continuous site operations in the tropics

In early planning sessions, program managers identified problems that were expected to occur during a multi-year site operation in the tropics. Since 1996, that list has grown to include challenges that were not originally anticipated. Factors that site operators must contend with include the following:

- Sudden and unexpected changes in available transportation to the sites;
- Frequent backlogs of air cargo, air shipment delays up to six weeks or more,
- Size limitations on air cargo;
- Cultural differences (confusion in understanding and communication of priorities and practices);
- Language barriers;
- Communication lines (problems with phone or satellite channels);
- Lack of reliable transportation for observers;
- PC upgrades and other problems with on remote computers;
- Fuel shortages, water shortages at the sites and local hotels;
- Frequent and prolonged power outages at the hotel and sites;
- Malaria, dengue fever, and other health issues for local observers and ARM staff;
- Problems associated with transfers of funds for local operations and repairs;
- Time zone differences: TWP observers are just getting to work when the US Operations team's day is ending;
- Reliable and competent local maintenance.

3.3 Daily Rounds, Remote Diagnostics

Local observers follow well-documented procedures for operations at the ARCS sites. On a daily basis, observers perform instrument inspections called "the Daily Rounds." Instrument problems or performance outside of established limits are reported back to the TWP Program office using the communications mechanisms in Table 6.

In addition to local observations, a Health and Status report for each site is compiled at the sites and transmitted by satellite to Pacific Northwest National Lab, where these reports are posted on the web [10]. Instrument "mentors" and other team members check these status reports as well as web sites for individual instruments. When a problem is detected, the TWP Office coordinates troubleshooting using a team that can include local observers, BOM technicians, and ARM Instrument Specialists.

Figure 6 shows a typical cycle for problem identification, diagnosis, and corrective action. Each step of this process is documented with reports available on the web, which allows the international team to easily access current information and problem status.

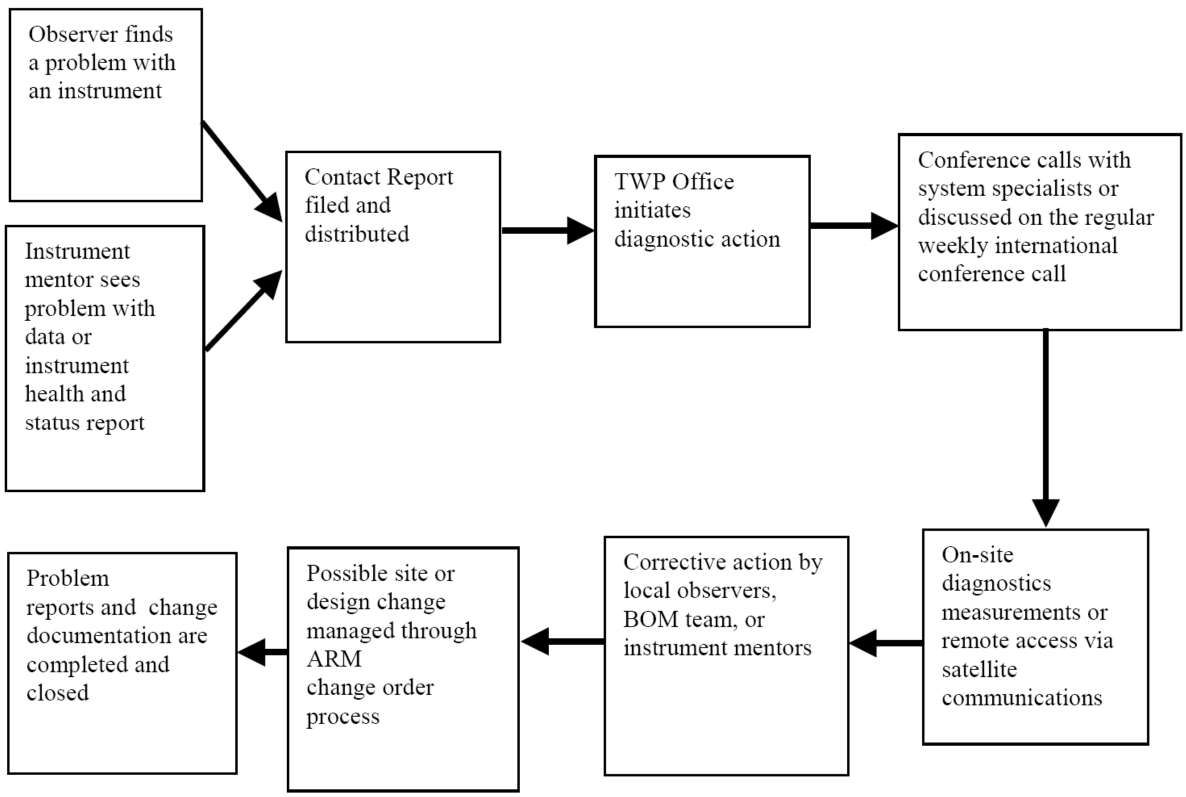


Figure 6. Problem Identification and Corrective Action Cycle

3.5 End-to-End Data Flow

The path that data take from measurement to use by the scientific community is summarized in Figure 7. Once in the ARM data system, atmospheric measurements from the various ARM sites follow a similar path to archive and use. In Figure 7, "DMF" refers to the Data Management Facility, "XDC" to the External Data Center of the ARM Program.

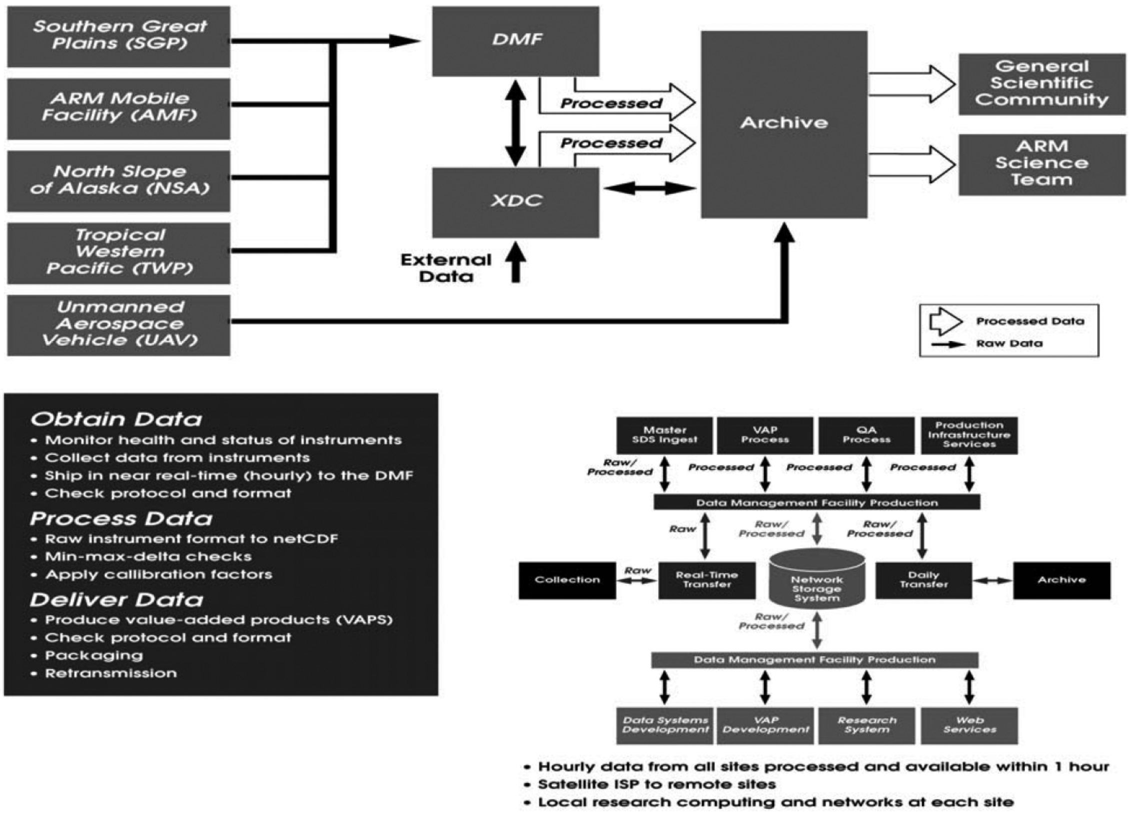


Figure 7: The End-to-End Data Flow for ARM Data

3.6 Use of ARCS Data for Satellite Ground-Truth Verifications

The ARCS site in Nauru has been used to provide data for ground-truth data verifications for two satellite systems. The systems are the DOE Multi-spectral Thermal Imager (MTI) and the MODIS/AQUA satellite. The Japanese geostationary satellite (GMS) data over Nauru has been very useful in the study of the island cloud trail observed downwind of the island (http://www-pm.larc.nasa.gov/). The MTI satellite was launched in Spring 2000. Visible and thermal images of Nauru began to be taken in June 2000 and continued into early 2002. These data have been used to understand the early development of the Nauru island cloud trail as well as sea surface temperature variation up and down-wind of the island. The visible channels of the satellite have been used to compare aerosol scattering observed by MTI and aerosol extinction observed by the sun-photometer and the multi-filter rotating shadow-band radiometer. Water vapor that is remotely sensed by the NASA MODIS/AQUA satellite is compared to balloon-borne sounding measurements made from special launches of rawinsondes from Nauru and the integrated water vapor measurements made with the Micro-Wave Radiometer at the ARCS site. The MODIS (Moderate Resolution Imaging Spectro-radiometer) instrument aboard the EOS/AQUA satellite provides terrestrial images over 36 spectral bands. This work began in August 2002 and is continuing.

4. Conclusions

The lessons learned from long-term operations of ARCS in the tropical western Pacific have driven changes in the configuration of these systems. Our experiences in operating complex instrumentation in the tropics have similarly led to changes in operations management and communication methods over the methods we had originally envisioned. We have found that reliable ARCS operations in the tropics rely heavily on

- reliable, timely, and effective communications with the sites and ARM program participants,
- a complete set of ready hardware spares,
- the daily contributions of dedicated personnel,
- a flexible and patient management approach,
- a requirement for careful, long-lead planning.

A need for careful configuration management and strict quality-assurance requirement of the data results in an emphasis on careful documentation of all communications and actions taken. Changes in equipment or software configurations follow strict process definitions for control. The use of internet-based communications has simplified the task of time-critical communications among an international team.

The ARCS design and operations has evolved over time to accommodate changes we had not anticipated at the project onset. Successful operation of the ARCS facilities in the tropical western Pacific region continues to rely on the close and effective interaction among members of a diverse international team. The ARM Mobile Facility represents the next generation of ARCS, and it incorporates design improvements that resulted from lessons learned in tropical operations.

Acknowledgements

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10. For an example, see http://c1.dmf.arm.gov/ds/dsview/

APPENDIX I: STATEMENT OF WORK

STATEMENT OF WORK

Sandia National Laboratories

Proposal: 017080104-0

HIGH LEVEL DESIGN RECOMMENDATIONS FOR CYBER INFRASTRUCTURE

Sandia National Laboratories, for and in consideration of the funding provided by the Sponsor, shall perform the following work for the Sponsor:

I PROJECT SCOPE:

On behalf of the NEON Project and in close association with NEON Inc., AIBS is requesting that Sandiaconduct a high level design study to provide recommendations that will guide an eventual full system design exercise for the NEON project. This study will assess the current state-of-the-art, identify risks, and articulate trade-offs that should be considered. Such information will contribute to the development of models supporting the civil and cyber infrastructure at instrumented domain sites that will be used to collect long-term, key scientific data on ecological responses of the biosphere to changes in land use and climate, and interactions between the geosphere, hydrosphere, and atmosphere. The fundamental instrument units (FIUs) used to collect this data are comprised of sensor arrays mounted on a collection of fixed and moveable towers, and deployed in the soil and/or streams and lakes.

In particular in this initial study, AIBS has requested that Sandia make recommendations to the NEONimplemenation team that address issues of:

1. Power: adequate, sustainable power to support the needs at each domain.
2. Data acquisition strategies: collect and aggregate data from domain sensors in best form for transmission to a Sponsor-central facility outside the domain.
3. Data Transmission: accurate, reliable communication of aggregated data to Sponsor's central facility.

In the ideal case, the FIU will have direct access to utility power, high-speed Internet connectivity via cabling, and direct line-of-sight between all sensor arrays and the central tower. The sensor arrays will be within 10 km of the central tower. In the worst case, utility power may not be available even for the central tower, terrain is such that line-of-sight is not possible between any of the arrays and the central tower; the sensor arrays may be as much as 240 km from the central tower, and wired Internet connection is not possible. Most of the domains will be some intermediate combination of the ideal and worst cases. It is SNL's current understanding that distributed among the various towers and arrays of an individual FIU there will be over a thousand sensors of various types, requiring more than 10,000 maintenance activities, calibrations, and installations per year per site, some of which must be done by hand. Estimated power requirements rang from 2 kW for basic towers to 17 kW for advanced towers, and up to 45 kW for the whole FIU made up of these components. Data storage and communication requirements have been estimated 2-3 GB/day/domain representing approximately 10^9 discrete measurements. The implications of these estimates for a system concept will be the focus of the proposed study.

The following is a list of requirements and desired characteristics:
- modularity for ease of scaling and adaptation to local conditions, and upgrades as new technology (both hardware and software) becomes available.
- robustness to harsh environmental conditions, power outages, etc.
- ease of maintenance (hardware and software).

- remote diagnostics and control from a central facility.
- potential inaccessibility for extended periods at some domain sites.
- minimal data loss from sensor to data logger, logger to the particular domain's central tower (point of presence/communication device), and between the domain and Sponsor's central facilities.

This research platform presents complex technical and reliability challenges. Sandia will execute an independent trade-off study of the current concepts with respect to the overarching Sponsor goals. This study will address the trade-offs against the ideal and worst case scenarios: (1) available power/comm utilities and line-of-sight links, (2) provide own power and problematic comm paths. The first scenario will allow the researchers to see the maximum that can be affordably achieved in the best of circumstances, and the second will quantify the advantages of developing lower power, maintenance, and data rate options to achieve their goals. This study will allow the Sponsor to better focus their efforts on the most important trade-offs. SNL will focus on issues that impact energy usage, data rate demand, and maintenance schedules. This report will make recommendation on further development that would alleviate problems that have no existing trade-off solution.

II TECHNICAL CONTENT:

Task 1 - Power: Based on SNL experience with long term remote measurements we will:
A) Investigate the commercial options to local power generation including the use of biofuels, photovoltaics, and other technologies, as well as battery backup.
B) Provide rough cost estimates, footprint, installation, and maintenance requirements.
C) Based on the estimated power requirements, provide data that will allow researchers to evaluate trade-offs between power requirements and the potential impact of the power generating equipment on the environment under study.

Task 2 - Data Acquisition and Integrity within an FIU:
A) Minimize maintenance costs and signal degradation.
- Determine hardware standards.
- Recommend standard cabling from data hub to a plug-in interface to the commercial sensor.
- Evaluate standard commercially available analog-to-digital conversion for the analog sensors.
- Investigate methods for automatic continual calibration or verification of sensors.
- Propose methods to detect and accommodate sensor failure.
- Configuration management.
- Propose wireless links for sensors not on the central tower.
B) Minimize data degradation and transmission bandwidth requirements.
- Establish communication protocols.
- Recommend best standard data packed labeling, error correction, and retransmission request protocols.
- Describe fall back low energy data acquisition modes.
- Recommend protocol to multiplex many low data rate measurements into a high data rate stream for transmission.
C) Data integrity.
- Provide trade-off information for local data storage for burst transmission of similar information.
- Evaluate redundant data storage methodologies including hardware (flash memory vs. disks, centralized vs. distributed) and protocols.
- Evaluate data handling risks associated with transmission.

Task 3 - Transmission of Data to Sponsor's Central Facility:
A) Investigate trade-offs in final stage data transmission methods.
B) Recommend cyber security methods to ensure data is not compromised in transmission from FIU to Sponsor's central facility.
C) Recommend RF hardware based on high-efficiency and reliability.

Task 4 - Identifying System Engineering Issues: SNL will draw on experience with other long-lived, complex systems to anticipate and highlight some additional systems engineering issues that will likely become important in this project.
A) Sensor deployment readiness - What is the process for qualifying and deploying a sensor, especially new, unproven technologies?
B) System upgrades and evolution - What is the process for evolving design and hardware? This will become increasingly important with time in a system expected to last decades or more.

Task 5 - Final Report. See Deliverables for more information.

III DELIVERABLES:

Conclusions and recommendations from this study will be documented in a final report. This report should be in the form of oral presentations and associated materials or a written report. This study will allow the Sponsor to better focus their efforts on the most important trade-offs. SNL will provide feedback on issues that impact energy usage, data rate demand, and maintenance schedules. This report will make recommendations on further developments that would alleviate identified problems that presently have no trade-off solution.

This project and the work being proposed are unclassified.

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