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Final Report on Testing of ACONF Technology for the US Coast Guard National Distress Systems

A Study for the DOE Energy Storage Systems Program

Garth P. Corey, Jerry W. Ginn, Tom M. Byrd, Leanne M. Storey,
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A Study fore the DOE Energy Storage Systems Program

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Abstract

This report documents the results of a six month test program of an Alternative Configuration (ACONF) power management system design for a typical United States Coast Guard (USCG) National Distress System (NDS) site. The USCG/USDOE funded work was performed at Sandia National Laboratories to evaluate the effect of a Sandia developed battery management technology known as ACONF on the performance of energy storage systems at NDS sites. This report demonstrates the savings of propane gas, and the improvement of battery performance when utilizing the new ACONF designs. The fuel savings and battery performance improvements resulting from ACONF use would be applicable to all current NDS sites in the field. The inherent savings realized when using the ACONF battery management design was found to be significant when compared to battery replacement and propane refueling at the remote NDS sites.

Preface

United States Coast Guard, Maintenance and Logistics Command Pacific, Electronics Division maintains the National Distress System (NDS) throughout the coastal waters of Alaska. NDS ensures that mariners in need of assistance can communicate with rescue officials via a VHF-FM network. Due to the nature of the service NDS provides, it is crucial that the system always be online.

NDS consists of several remote VHF-FM communications sites typically located atop mountains in coastal Alaska. The sites are highly susceptible to the unpredictable and harsh winter weather conditions, which make it impossible to perform maintenance or fuel the majority of the sites from mid-October through mid-March.

Because of their remote locations and the critical functions they perform, NDS communications sites are expensive to operate and maintain. The primary costs associated with the continued operation of the VHF-FM sites are propane fuel to run the generators and sealed Valve Regulated Lead Acid (VRLA) batteries to store and discharge energy.

As a result of the study performed at Sandia National Laboratories, documented evidence supports the installation of an ACONF unit at an existing NDS site in the near future. The addition of an ACONF unit is predicted to reduce propane fuel consumption by over 25% and improve battery health (and life) at the site. Pending the sustained successful performance of ACONF at the selected NDS site, ACONF units would be installed at all applicable remote NDS sites. Assuming ACONF performs in the field as expected, propane fuel savings alone would be in the hundreds of thousands of dollars over the first few years after installation. Additionally, the ability to predict when the batteries are at end of life significantly reduces the probability of random battery failures and allows for the optimal replacement of batteries. Overall, the addition of ACONF units at remote hybrid NDS sites would reduce both site downtime and operational costs.

LT Zachary Weiss
United States Coast Guard
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Executive Summary

For the past several years, the DOE and Sandia National Laboratories have been involved in testing a new controller that is specifically designed to improve the efficiency of off-grid hybrid power systems that use renewable energy, battery energy storage, and an engine generator. Since the United States Coast Guard (USCG) National Distress System (NDS) system uses just such a power source, a project was developed with USCG and USDOE funding to compare two identical NDS power systems. One of them operated under the control of the Sandia-developed ACONF system controller while the second operated under the Mechron© controller currently in use at all remote NDS sites. A testing strategy was developed which would put the two systems through their paces in much the same seasonal environment as is experienced at a selected NDS site. Testing was segmented in such a way as to run the systems in a winter, spring/fall, and summer season to get a good comparison of the operations based on the availability of the photovoltaic resource typical of the selected site.

Following a lengthy acquisition and system assembly process, testing of both units commenced on March 19, 2004. Loads and power sources were identical for the two systems. Extreme care was taken to ensure the two systems followed the same load and photovoltaic generation patterns. The primary difference in the way the systems were operated is that the generator start command and battery charge management in one of the systems was controlled exclusively by an ACONF controller. The Mechron field controller was not utilized to make generator start and stop decisions in the ACONF controlled system. Both systems ran smoothly until May 23, 2004 when one of the Mechron generators failed. Both generators were returned to the manufacturer for repair where it was found that a bearing had been improperly aligned in the equipment originally delivered. After the generators were returned to Sandia on September 23, 2004 they were immediately installed and operations reinitiated.

Because at the time of the generator bearing failure the test was very near the halfway point, analyses of the results-to-date were conducted. Details of the analyses are available in this report; however, one very important result was determined. The system operating under the ACONF control strategy consumed approximately 20% less propane fuel for the same amount of power generated by each system at the mid-point of the test program.

After completing the mid-point capacity test, both systems resumed operations for the spring operating environment followed immediately by the summer operating environment. During this second part of the test, an ACONF solar optimization strategy was implemented. This had been available before the first part of the test but had not been implemented then for a variety of reasons. The test project was completed on January 20, 2005 and both systems were capacity tested and final analysis was initiated. As expected, the fuel savings were even better for the spring/summer period with savings noted in the 30% range. This report contains the details of the test work and a performance analysis of both systems for the full six months of testing, together with a discussion of the results.

Introduction

The United States Coast Guard (USCG) and the DOE Energy Storage Systems Program are funding work at Sandia National Laboratories to evaluate the effect of a battery management technology known as ACONF[1] on the performance of energy storage systems at National Distress System (NDS) sites. Two systems were configured to replicate an actual NDS site in Alaska. The two systems were identical except that one included an ACONF controller. This report summarizes the results at the end of six-month test program that simulated a year of actual use, during which the two systems were operated in a way that is similar to an NDS site. The key performance metric is the comparison of fuel consumption for the two NDS propane generators each operating under their respective control philosophies.

Test Setups

The two systems under test are located at the Distributed Energy Technologies Laboratory (DETL) of Sandia National Laboratories in Albuquerque, NM. Both systems are housed in a portable, air-conditioned building. Heat generating components such as the generators and the loads are mounted outside, but adjacent to, the portable building. Several views of the two setups, and of the ancillary equipment, are shown in the photos displayed as Figures 1 to 6.

Figure 1 Reference and ACONF battery systems

Figure 2 ACONF controller and monitor

A Data Acquisition System (DAS) based on National Instruments Lab View™ acquires and stores measurements from both systems. The DAS continuously scans the channels listed in Table 1 at a rate of 1000 samples per second and digitizes them using a 16-bit digitizer. The DAS computes an average for each signal over a one minute time period. It saves these averages, the single-point maximum and minimum values observed during the one-minute period, and a time stamp.

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[1] US Patent 6,353,304 B1; Atcitty et al. March 5, 2002

Figure 3 ACONF controller

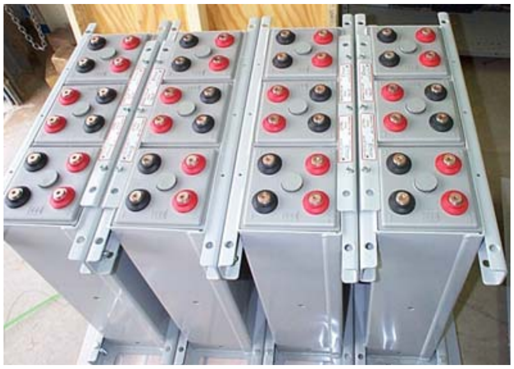

Figure 4 One 24-V nominal battery string

The data files are backed up to a server on a LAN every night. A user-selectable subset of these signals is displayed on a dedicated monitor along with information on the status of the system. The time interval over which the displayed signals are averaged is adjustable so that signals can be displayed graphically much faster than once per minute. The DAS can be viewed and controlled both locally within DETL and over a secure network.

Figure 5 Mechron generators

Figure 6 Mechron controllers

The two setups, described in the next sub-sections, are identical except that in the ACONF system, an ACONF solar hybrid/battery system management controller has been interposed between the battery and the rest of the system.

Channel Name	Channel Type	Description
ACONF Temp	Analog Input	ACONFMOSFET heat sink temperature
Ambient Temp	Analog Input	Ambient temperature at TP384
BAT1 Ias	Analog Input	Battery 1 current in ACONF system
BAT1 Irs	Analog Input	Battery 1 current in Reference system
BAT1 Vas	Analog Input	Battery 1 voltage in ACONF system
BAT1 Vrs	Analog Input	Battery 1 voltage in Reference system
BAT2 Ias	Analog Input	Battery 2 current in ACONF system
BAT2 Irs	Analog Input	Battery 2 current in Reference system
BAT2 Vas	Analog Input	Battery 2 voltage in ACONF system
BAT2 Vrs	Analog Input	Battery 2 voltage in Reference system
Bat1 Tas	Analog Input	Battery 1 temperature in ACONF system
Bat1 Trs	Analog Input	Battery 1 temperature in Reference system
Bat2 Tas	Analog Input	Battery 2 temperature in ACONF system
Bat2 Trs	Analog Input	Battery 2 temperature in Reference system
Gen FRas	Analog Input	Generator fuel mass flow rate in ACONF system
Gen FRrs	Analog Input	Generator fuel mass flow rate in Reference system
Gen Ias	Analog Input	Generator current in ACONF system
Gen Irs	Analog Input	Generator current in Reference System
Gen SRas	Analog Input	Generator start-request in ACONF system
Gen SRrs	Analog Input	Generator start-request in Reference system
Load Ias	Analog Input	Load current in ACONF system
Load Irs	Analog Input	Load current in Reference system
Load Vas	Analog Input	Load voltage in ACONF system
Load Vrs	Analog Input	Load voltage in Reference system
PV CIas	Analog Output	Control current for PV-Simulator in ACONF system
PV CIrs	Analog Output	Control current for PV-Simulator in Reference system
PV CVas	Analog Output	Control voltage for PV-Simulator in ACONF system
PV CVrs	Analog Output	Control voltage for PV-Simulator in Reference system
PV Ias	Analog Input	PV-Simulator current in ACONF system
PV Irs	Analog Input	PV-Simulator current in Reference system
PV Vas	Analog Input	PV-Simulator voltage in ACONF system
PV Vrs	Analog Input	PV-Simulator voltage in Reference system

Table 1 DETL DAS Signal List

Reference System

The Reference System (REF) is meant to represent a mountaintop solar hybrid power system as currently implemented by the USCG. As shown in Figure 7, the REF system consists of:

- A two-string, 24V battery, with 12 GNB 1000Ah VRLA cells in each string
- A Mechron© 7kW generator, with a 160amp, 30VDC battery charger/controller
- A DC power supply and appropriate software to simulate a 2.88-kW solar photovoltaic (PV) array
- A bank of power resistors to represent the load at a typical USCG site. At the nominal battery voltage, these resistors draw a load current of about 20amps.

For clarity Figure 7 does not show circuit protection devices such as switches and disconnects or sensing devices such as current shunts, voltage probes and thermocouples.

Except in case of a malfunction, the load is continuously connected to the battery bus. The voltage of the battery varies throughout each charge and discharge, so the current, and thereby the power delivered to the load varies over time. This variation was judged to be acceptable because the reliability of passive resistive loads was desirable over the long duration of the test and because short-duration time resolution of the load power was not significant in evaluating the effect of the ACONF. The load value was selected based on analyses of average NDS site load data.[2]

Identical solar inputs to each system are provided by programmable power supplies controlled with a sub-routine running on the DAS. The power profile corresponds to the solar power that might be expected from the type of array used at an actual USCG site on a mountaintop close to Sitka, Alaska. Input data for solar irradiance was obtained from publicly available hourly Typical Meteorological Year (TMY) measurements taken at Juneau, Alaska.[3]

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[2] ANALYSIS AND COST OPTIMIZATION OF A USCG REMOTE HYBRID POWER SYSTEM, Zachary A. Weiss, thesis, Naval Postgraduate School, Monterey, CA, June, 2002.

[3] User's Manual for TMY2s, Typical Meteorological Years, Derived from the 1961-1990 National Solar Radiation Data Base http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/reference

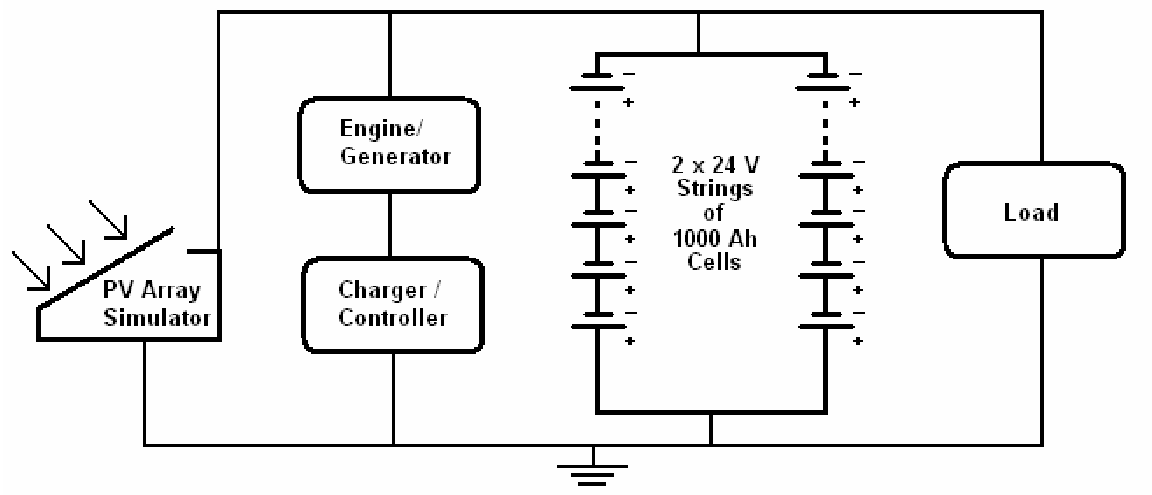


Figure 7 REF System Setup

NDS sites include PV charge controllers that prevent overcharging the batteries. The USCG has different charge controller models at different sites. The effect of the charge controller is simulated in the current test by limiting power supply voltage to no more than 27.6V. The effect of this limit is to reduce the simulated PV current to zero whenever the generator has charged the battery to 27.6V. For these tests the simulated PV was reduced to zero whenever the generator was running to avoid control instabilities that were observed when setting up the systems.

As is the case at the NDS sites, the generator is started and stopped by the Mechron© charge controller. A generator start is initiated if the battery voltage falls below 23.76V (1.98V/cell) at the battery bus. When the battery voltage during charge reaches the control level, the charge current is reduced (tapered) so as to ensure that the battery voltage (measured at the battery bus) does not exceed 28.6V. When the battery current falls below 40amps, the Mechron© controller instructs the generator to stop. The REF system is continuously cycled to simulate NDS site operations.

ACONF System

The ACONF system, shown schematically in Figure 8, is very similar to the REF system, except for the addition of an ACONF controller unit between the positive terminal of each battery string and the positive bus of the power system. Thus, the ACONF systems has two parallel 24V strings of battery cells, an engine/generator and charger controller, a PV simulator, and a resistive load bank, that are identically specified and provided by the same manufacturers as in the case of the REF system.

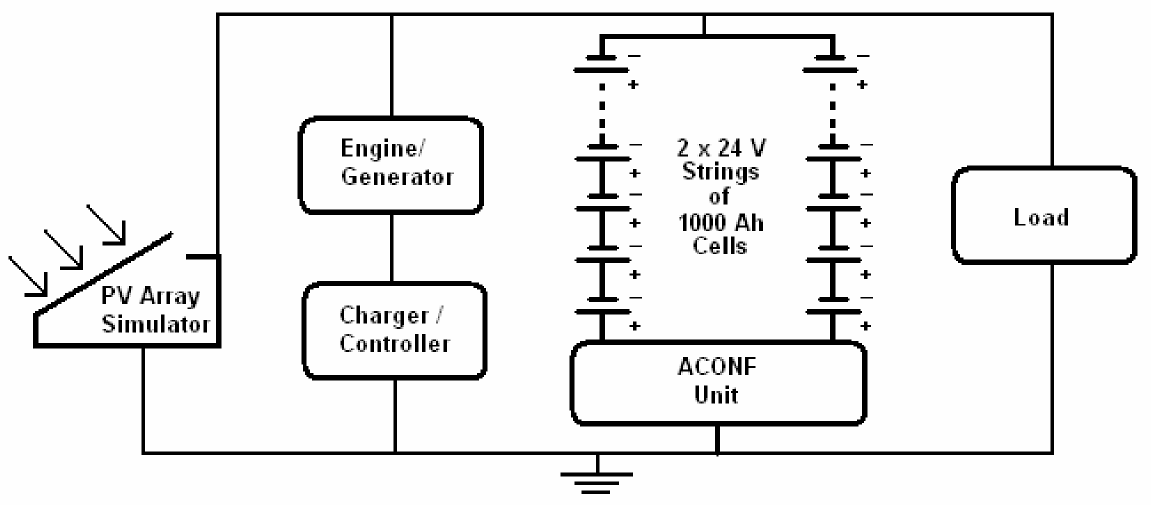


Figure 8 ACONF System Setup

Details of the ACONF unit that is interposed between the battery strings and the positive bus of the power system are shown in Figure 9. The ACONF unit includes both control circuitry and data acquisition. The control circuitry is dispatched on the basis of data acquired, as described in the ACONF Operating section. The data acquisition portion of the ACONF unit consists of a “PC104 stack”, with a PC104 embedded computer, a video card, and a 16-bit, 8 differential channel data acquisition card.

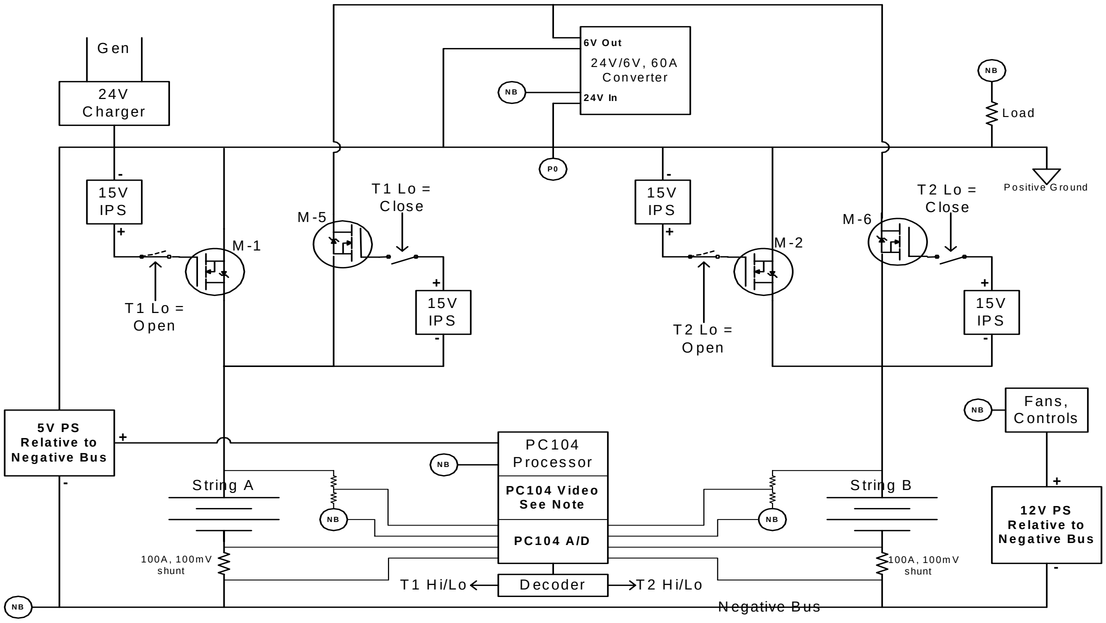


Figure 9 Details of ACONF Unit

Table 2 lists the data acquired by the ACONF DAS. The ACONF needs only five data points in order to accomplish the required control functions, which minimizes costs and data storage requirements. Data is acquired several hundred times per second, averaged over a two second period, displayed on a monitor connected to the video card, further averaged over a one minute period, then stored with a time stamp. Data is stored locally on a Compact Flash “fixed disk” and is downloaded periodically (once or twice a week depending on personnel availability) via a serial port for archiving to a LAN at DETL. Copies of the ACONF data are also sent to Symons/EECI for further analysis.

Data Point	Description
Time	Time Stamp for ACONF system
StrA Volts	Battery 1 voltage for ACONF system
StrB Volts	Battery 2 voltage for ACONF system
StrA Amps	Battery 1 current for ACONF system
StrB Amps	Battery 2 current for ACONF system

Table 2 ACONF DAS Data Points

ACONF Operation

Unlike the REF system, dispatch of the generator is controlled by the ACONF, rather than by the Mechron© charger controller. Using the PC104 based data acquisition subsystem, the ACONF monitors each of the two parallel battery strings individually to optimize system performance. Figures 10 through 14 illustrate the ACONF operation. Figure 10 is a simplified diagram of the ACONF system, showing placement of the ACONF controller with respect to the rest of the system.

In the “Discharge All” operating mode, energy is drawn from the two parallel strings to power the loads (Figure 11). The generator is started and a charge is initiated when the voltage reaches the lower “generator cut-in” point (1.98 V/cell) or when 60% of the nominal amp-hr capacity of the battery (sum of amp-hrs discharged from the two strings) has been discharged, whichever point is reached first. In the subsequent “Charge All” mode (Figure 12) both strings are charged by the generator at a constant current of 140A (70 A/string). This “bulk charge” returns approximately 90% of the capacities of the batteries.

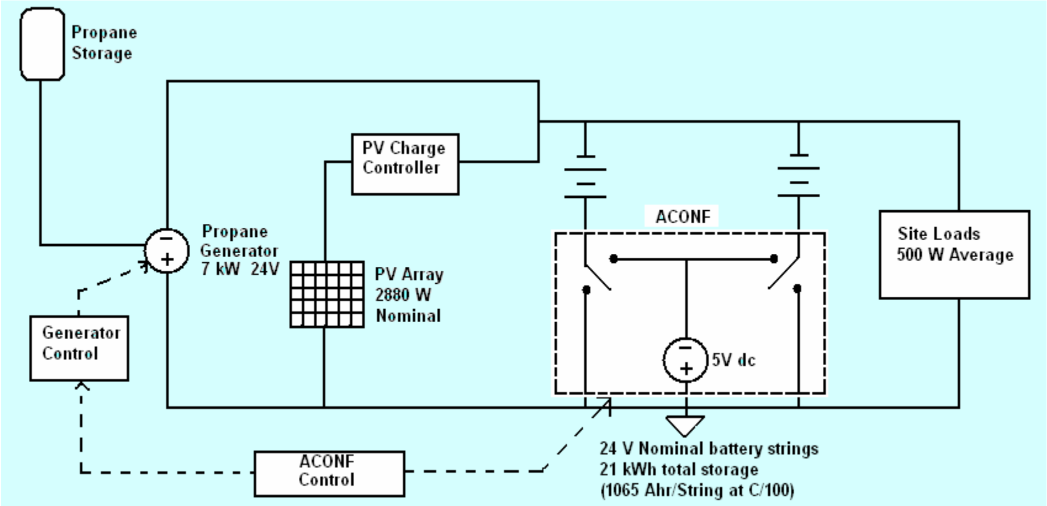
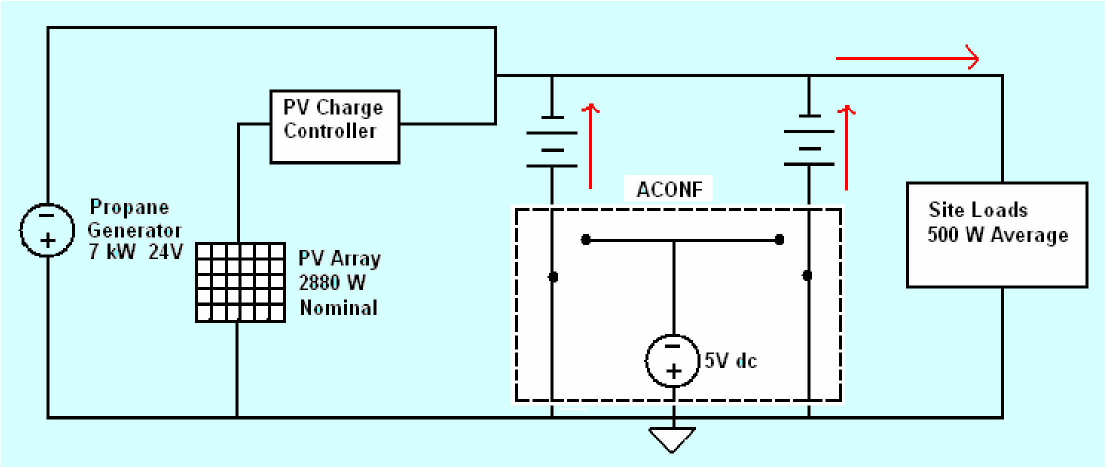
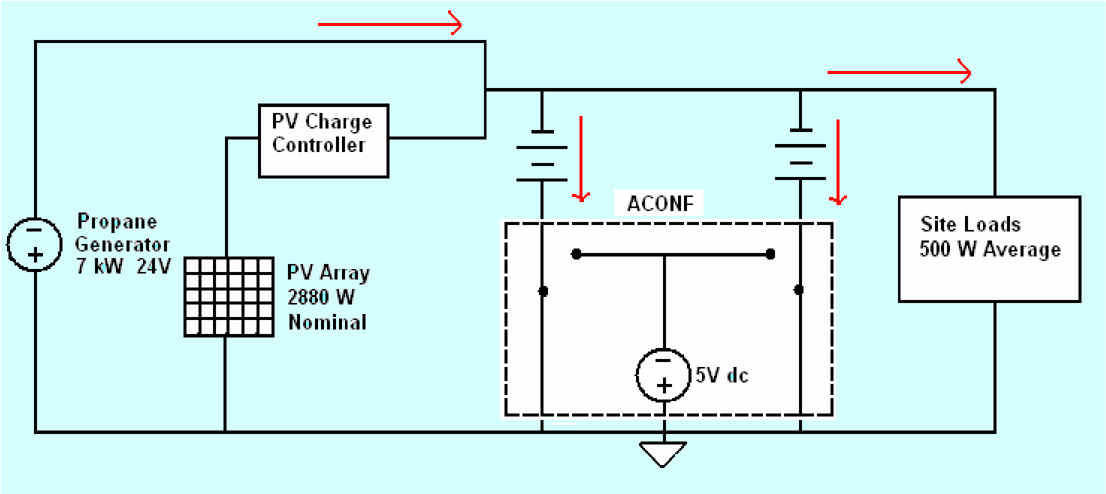


Figure 10 Simplified ACONF System Operation Diagram



State	String A	String B	What ends state
discharge all	discharging	discharging	% Discharge from Ah count (priority) OR low Batt voltage OR time exceeds limit OR if high Batt voltage (lots of PV, no load) go to finish charge

Figure 11 Discharge All



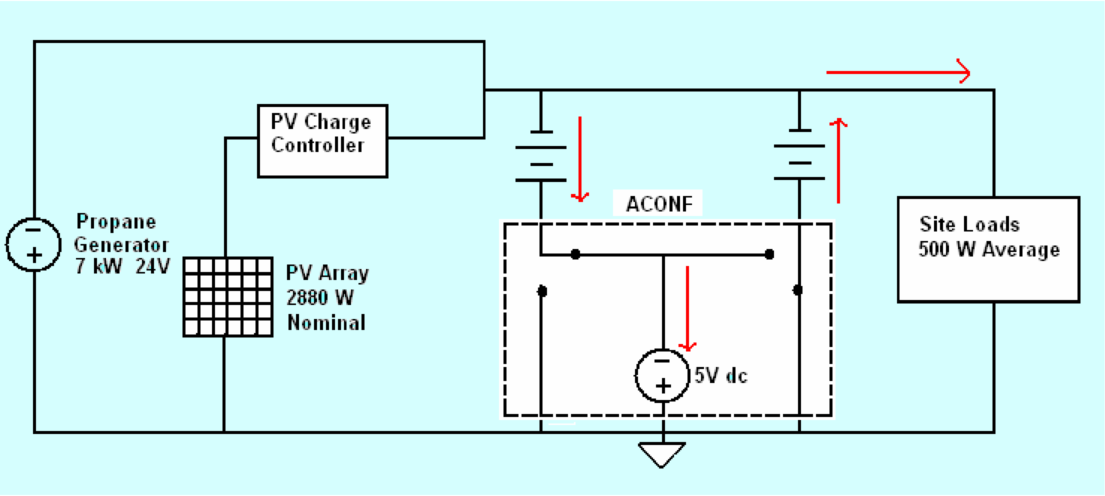
State	String A	String B	What ends state
charge all	bulk charge	bulk charge	String resistance exceeds value (approx 92-95%) OR Ah in exceeds last discharge Ah out by some %

Figure 12 Charge All

The bulk charge continues until the ACONF controller determines, using an internal resistance algorithm, that the battery voltage at the nominal charge current (140 amps) has reached the equivalent of 28.6 V. The word equivalent is used since the Mechron© charger may cause the charge current to taper somewhat before the cut-off voltage is reached. In practice, the amount of tapering that occurs is quite small, so battery charges with the generator are terminated at a much higher current with the ACONF than for the REF system. It is this earlier charge termination and minimal current tapering that leads to the major savings in generator run time and fuel consumption that are predicted for the ACONF and is the primary reason for which the USCG testing is being performed.

In order to ensure the charging of the batteries is completed on a consistent basis, each string of the ACONF system is "finish charged" every other cycle (Figure 13). This is accomplished using the MOSFET switches and the upverter shown in Figure 9, under the control of the ACONF software running on the PC104 computer. Essentially, on completion of a bulk charge with the generator, one of the two strings is disconnected from the positive bus and is reconnected to the ACONF system via the upverter. In this way, the string still connected as normal provides the power for discharge to the load and also, via the upverter, provides power to finish charge the other string. In order to maintain the correct charging voltage on the string being finish charged, the ACONF reduces (tapers) the charge current coming from battery string A to finish charge battery string B. This process continues until the ACONF determines that the string being finish charged has been returned to virtually 100% of its original capacity. At that time, the two strings are again connected in parallel and the system returns to "Discharge All" mode.

On completion of the next bulk charge with the generator (Charge All mode), the ACONF proceeds to finish charge the other string, as shown in Figure 14.



State	String A	String B	What ends state
finish charge	voltage regulated finish charge	discharging	String A current tapers to some value OR Ah exceeds 120% of last disch Ah OR time exceeds some value OR string B can't keep up (string B voltage too low)

Figure 13 Finish Charge String A

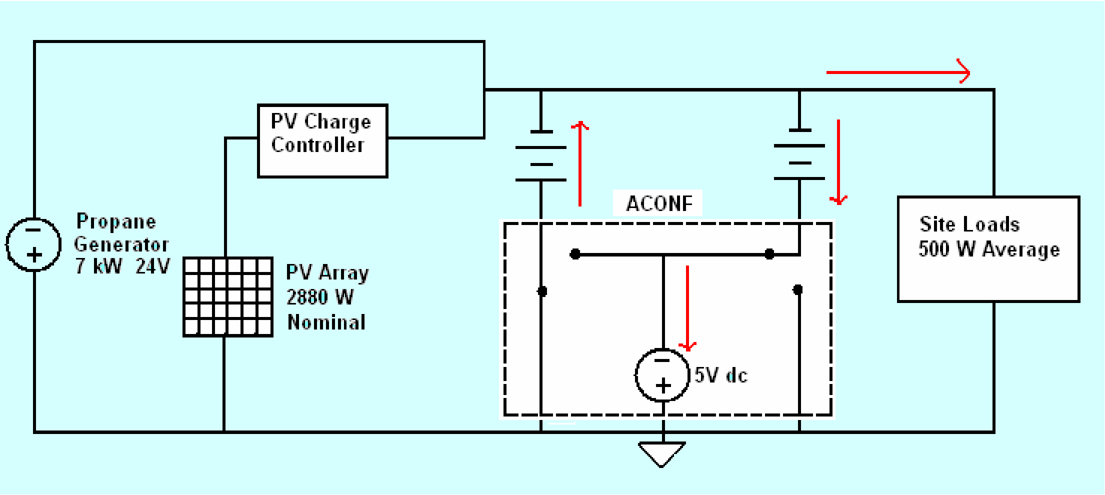


Figure 14 Finish Charge String B

To illustrate the previous discussion, we show in Figure 15 a plot of the voltages and currents for the two strings (identified as String A and String B) of the USCG ACONF system for May 5, 2004, a day on which a charge with the generator and a finish charge took place. Note the charge with the generator started at about 3AM, and that during most the charge the currents in the two strings were approximately the same. It can be seen that the voltage of the battery increased monotonically throughout the charge.

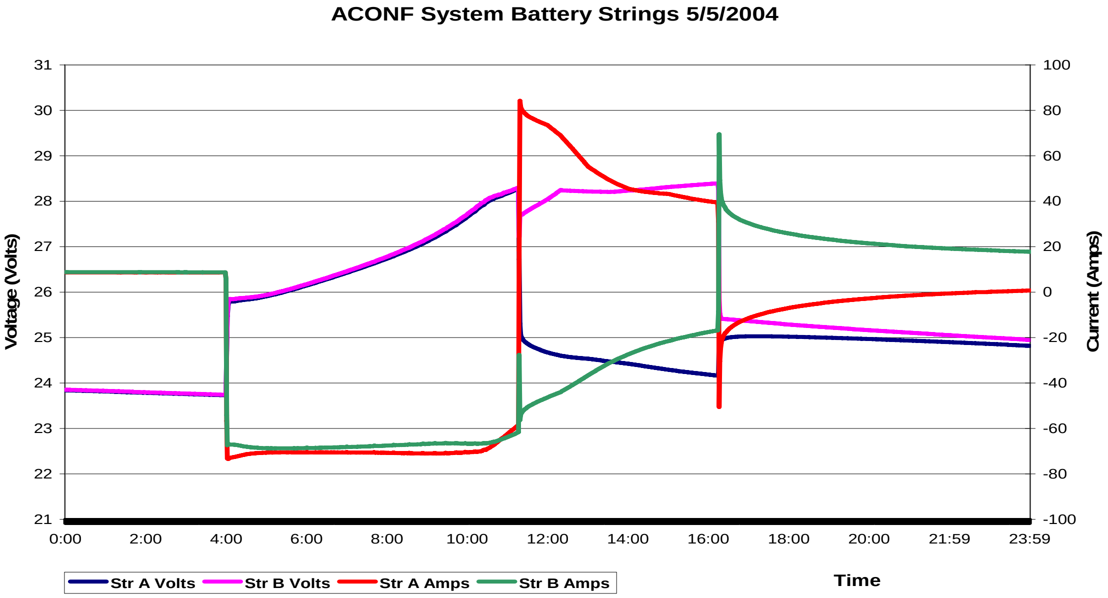


Figure 15 USCG ACONF system string voltages and currents May 5, 2004

There was a small amount of current tapering towards the very end of the charge period, just before the ACONF software determined that the charge should be terminated. After the generator had been turned off at about 10:20, the MOSFET switches in the ACONF Unit were reconfigured so that String A provided the power for discharge and also provided power to finish charge String B. Note that the current for String B continues negative (charge) and tapers throughout the finish charge period, while the current for String B is positive (discharge) and declines in this time as the charging current in String B tapers. The finish charge was terminated at 15:20.

In addition to the basic operation described here, the ACONF provides some more subtle operational capabilities to enhance system performance. The most important of these for the USCG sites, optimization of battery charge scheduling that can lead to further fuel savings, was only tested during the second part of the testing. The results with and without this enhancement will be discussed later in this report.

Results and Discussion

Automated cycling of the REF and the ACONF systems was initiated on March 19 2004. Cycling continued until the generator of the REF system failed totally on May 23. Both generators were returned to Mechron© to be rebuilt shortly after this. Upon their return, cycling recommenced and continued through to completion of the ACONF testing period on January 20, 2005.

The schedule of testing initially planned for the two systems was as follows:

1. Capacity test to establish baseline characteristics of batteries for both systems
2. Eight weeks of cycling with solar inputs corresponding to period from November 23 to January 18, i.e., centered on the shortest day of sunshine, 12/21
3. Four weeks of cycling with solar inputs corresponding to period from February 21 to March 21, i.e., leading up to the Spring equinox
4. Capacity test to determine if cycling had any impact on characteristics of batteries for both systems
5. Four weeks of cycling with solar inputs corresponding to period from March 22 to April 18, i.e., immediately following the Spring equinox
6. Eight weeks of cycling with solar inputs corresponding to period from May 23 to July 19, i.e., centered on the longest day of sunshine, 6/21
7. Final Capacity test to determine if cycling had any impact on characteristics of batteries for both systems

The schedule was designed so that a projection could be reasonably made for entire year of cycling with only 24 weeks of testing.

As mentioned above, the generator for the REF system failed on 5/23/04, i.e., ~10 weeks into the test. Thus, test operations were eleven days into the 56-day Spring total (Item 3 of the test schedule) when testing was forced to be suspended. It was decided, therefore, to complete the second capacity test (Item 4) early so that time could be saved later in the testing, after the repaired generator had been returned.

After the generators were returned in late September, 2004, testing was resumed at the point at which testing had been previously shut-down. At this point, slightly less than 14 weeks remained for the test, which was in fact resumed on the twelfth day of the spring simulation. During this Second Period of testing, the solar optimization function of the ACONF (see above) was invoked, this not having been done during the First Period of testing. Cycling was continued under automated control until the end of the test in early January, except for a two week break for the Holiday Season. In this Second Period of testing, the remainder of item 3 along with items 5 and 6 were completed. The final capacity test (Item 7) was performed after the end of the automated cycle testing.

Two aspects of the results obtained will be described in this section: results related to operation of the generators and results obtained from measurements of the capacity of the batteries in the two systems under test. The results related to operation of the generators will be described and discussed in two parts, corresponding to the First and the Second Periods of testing

Results of Generator Operations for First Period of Testing

Summaries of the results of the cycle testing are shown in Table 3 for the REF system and in Table 4 for the ACONF system. It can be seen from Table 3 for the REF system that a total of 13 charges were completed and one was partially completed during the first period before the generator failed. Thus, 14 discharges were completed after the test sequence was started with a discharge.

First Period Reference Cycle Data

REF	Fuel Consumed (Gallons	Cumulative Gallons Consumed	Generator Run Time (minutes)	Cumulative Generator Run (minutes)
Winter Cycle	13.05	13.05	771	771
	12.1	25.15	737	1508
	12.18	37.33	724	2232
	15.16	52.49	897	3129
	12.31	64.8	712	3841
	12.57	77.37	739	4580
	12.12	89.49	688	5268
	11.54	101.03	684	5952
	11.33	112.36	646	6598
	10.59	122.95	580	7178
	8.58	131.53	445	7623
	12.82	144.35	718	8341
	12.61	156.96	697	9038

Table 3 REF System First Period Data Summary

First Period ACONF Cycle Data

ACONF	Fuel Consumed (Gallons	Cumulative Gallons Consumed	Generator Run Time (minutes)	Cumulative Generator Run (minutes)
Winter Cycle	6.06	6.06	423	423
	9.7	15.76	503	926
	8.13	23.89	426	1352
	8.93	32.82	473	1825
	6.73	39.55	362	2187
	8.14	47.69	417	2604
	7.67	55.36	380	2984
	7.56	62.92	392	3376
	8.8	71.72	456	3832
	8.19	79.91	421	4253
	8.23	88.14	428	4681
	7.61	95.75	405	5086
	8.45	104.2	433	5519
	8.42	112.62	435	5954
	9.19	121.81	475	6429
	9.28	131.09	480	6909
	8.35	139.44	423	7332
Spring Cycle	8.86	148.3	456	7788
	8.47	156.77	434	8222

Table 4 ACONF System First Period Data Summary

For the ACONF system during the first period of testing, see Table 4, a total of 19 discharges and charges were completed before the testing was suspended because of the failure of the REF system generator.

Thus, the generator started somewhat more frequently for the ACONF system as compared to the REF system. However, it should be noted that one of the more subtle features of the ACONF technology, a solar optimization function that automatically schedules generator start times in coordination with sunrise and sunset, was not turned on during the First Period of testing. In order to test the efficacy of the solar optimization function to reduce generator start times, but also to evaluate the possible fuel saving that could result, the solar optimization function was implemented during the Second Period of testing.

In contrast to the frequency of generator starts, Tables 4 and 5 show that, as expected, the generator run-time for the ACONF system is significantly less for the ACONF system than for the REF system. This indicates that for the ACONF system, generator life should be extended somewhat and that generator maintenance requirements should be somewhat lower as compared to the REF system.

The advantage of the ACONF technology becomes even clearer when the fuel consumption measurements made during the first part of the Coast Guard testing are analyzed. This is not apparent directly from the fuel consumption data in Tables 4 and 5, but can be clearly seen when these data are normalized to the energy delivered to the load for the two systems, as shown in Figure 16. The reason for adopting this metric to compare the fuel consumption for the two systems lies in the fact that there were interruptions in the continuous cycling process because of minor component malfunctions.

To construct Figure 16, the energy delivered to the load was computed by summing the integrands of the product of the voltage and the current for each sting from the beginning of the test to the point at which each charge with a generator was completed. Note that the fuel consumption for the last charge on the REF system is omitted since this charge was not completed due to generator failure.

Once the fuel consumption data is normalized as shown in Figure 10, it becomes quite clear that the fuel consumption by the ACONF system is significantly less than that for the REF system. From the data used to construct Figure 10 it can be calculated that the specific fuel consumption for the REF system was 0.28 gallons of propane consumed per kWh of energy delivered to the load over the entire first period, whereas the corresponding value for the ACONF system was 0.22 gallon/kWh. Thus the fuel consumption with the ACONF battery management controller was approximately 20% less than for the REF system.

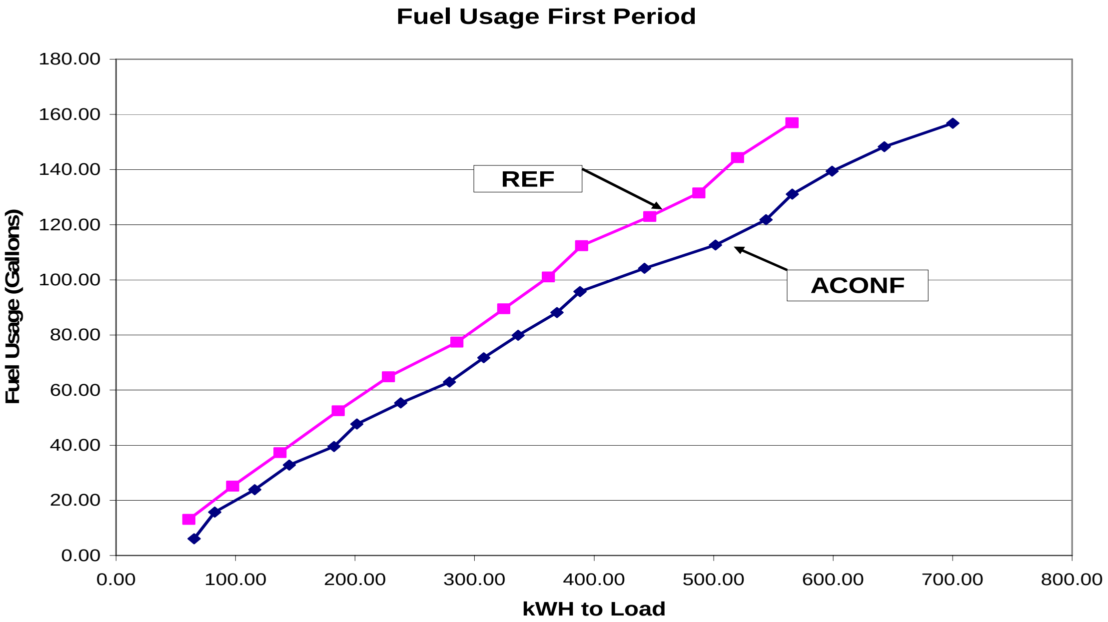


Figure 16 First Period Fuel Usage

Results of Generator Operations for Second Period of Testing

Table 5 shows a summary of the results of the cycle testing of the REF system during the Second Period of testing, i.e., for mid and late spring and for four weeks on each side of Midsummer. Analogous results for the ACONF system are shown in Table 6.

Second Period Reference Cycle Data

REF	Fuel Consumed (Gallons	Cumulative Gallons Consumed	Generator Run Time (minutes)	Cumulative Generator Run (minutes)
Spring Cycle	15.85	15.85	887	887
	17.36	33.21	962	1849
	14.37	47.58	820	2669
	12.47	60.06	648	3317
	12.15	72.21	742	4059
Summer Cycle	12.20	84.41	689	4748
	12.07	96.48	718	5466
	11.49	107.97	664	6130
	11.26	119.23	655	6785

Table 5 REF System Second Period Data Summary

Second Period ACONF Cycle Data

ACONF	Fuel Consumed (Gallons	Cumulative Gallons Consumed	Generator Run Time (minutes)	Cumulative Generator Run (minutes)
Spring Cycle	15.28	15.28	765	765
	10.05	25.33	471	1236
	9.91	35.25	486	1722
	8.99	44.23	436	2158
	8.34	52.57	607	2765
	7.06	59.63	351	3116
Summer Cycle	7.16	66.80	354	3470
	7.66	74.45	562	4032
	6.63	81.08	333	4365

Table 6 ACONF System Second Data Summary

From Tables 5 and 6, it can be seen that the same number of charges (9) were completed for both the REF system and for the ACONF system during the Second Period of testing. However, looking at the tables in more detail shows 5 charges during the spring season for the REF system versus 6 for the ACONF system. Also there were 4 charges for the REF system and 3 for the ACONF system during the summer season. From these results in comparison to those for the Winter and early-Spring periods cited above, it is clear from implementation of the solar optimization function did indeed reduce the number of generator starts for the ACONF system, as expected. In addition, the cumulative generator run time for the ACONF system was less than 2/3rds that for the REF system, offering further to the expectation that generator maintenance should be less costly for an NDS site with an ACONF system than with the current implementation.

In a similar fashion to the First Period of testing, we show in Figure 17 a plot of the propane consumed by the generator as a function of the kWh of electrical energy delivered to the load.

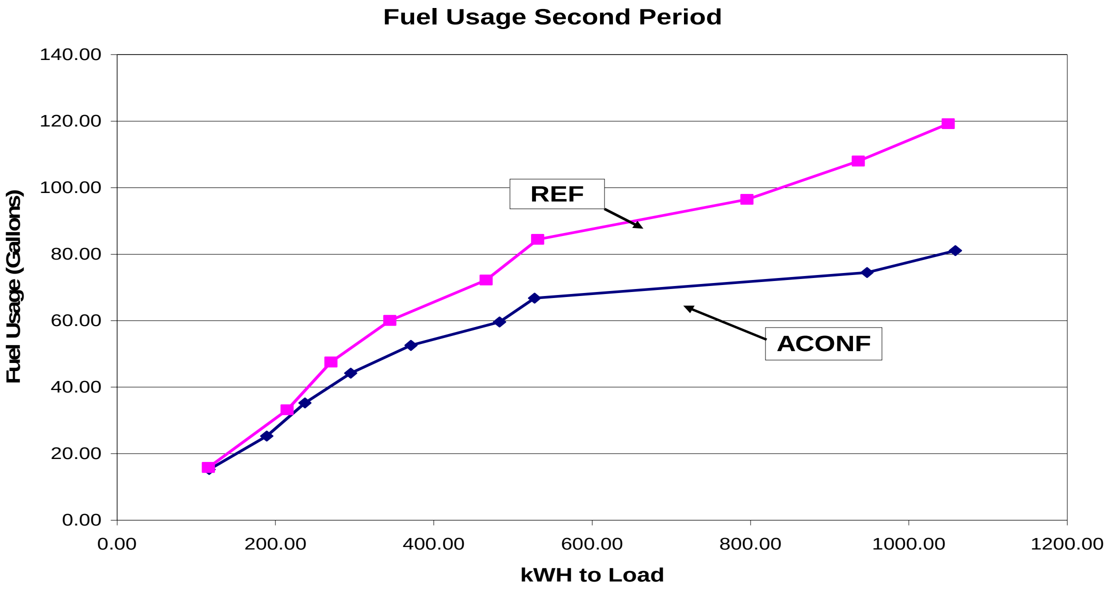


Figure 17 Second Period Fuel Usage

From examination of Figure 17, it is once again apparent that there are significant savings in fuel when using the ACONF in comparison with the REF system. Indeed, at the end of the test, it can be calculated that the ACONF system required 32% less fuel to operate than the REF system for the same amount of energy (kWh) delivered to the load.

Some part of the increased fuel savings in the Second Period compared to the First Period (32% versus 20%) can be attributed to the differing seasons (late Spring and Summer rather than Winter and early Spring) but some part of the increased savings are thought to be due to the implementation of the solar optimization function in the ACONF for the Second Period of testing. The relative importance of these factors can only be determined by further testing.

The slope of the lines in Figure 17 is the specific fuel consumption, i.e., the number of gallons of fuel consumed per kWh of energy delivered to the load. Close examination of Figure 17 indicates a change in the slope of the lines part way through the cycling, this corresponding to increased energy input from the (emulated) PV arrays.

Results of Capacity Tests

The results from the capacity tests that were performed before cycle testing started (Item 1 of Test Schedule), after the REF generator failed (modified Item 4 of Test Schedule), and of two capacity tests performed after the entire six month test had been completed (Item 7 done twice) are shown in Table 7. The average temperatures of all the battery strings being used at the time of the capacity test are also shown in Table 7.

Capacity (Ah to 1.85V/cell at C/20 discharge rate)					
Date	**ACONF 1**	**ACONF 2**	**REF 1**	**REF 2**	**Avg. Battery Temp**
2/4/2004	**897**	**895**	**879**	**902**	**21.9**
6/17/2004	**968**	**974**	**936**	**978**	**31.1**
1/25/2005	**849**	**848**	**791**	**861**	**15.7**
2/21/2005	**933**	**922**	**836**	**930**	**13.4**

Table 7: Capacity Test Results at C/20 Rate

It can be seen from Table 7 that there is an increased capacity for the batteries of both the REF and the ACONF systems from the first to the second tests. This probably results mostly from the higher battery temperature at the time of the second test, but could also result in part from further formation of the plates in the cells. The latter effect might have in turn resulted from the cycling that was performed, since this is an effect that is almost invariably seen in the initial cycling of lead acid batteries.

The apparent drop in capacity from the second to the third test was at first thought to be due to the difference in the temperature of the batteries between the times of the two tests. However, when the test was repeated on 2/21/05, the capacity was significantly higher for all the strings except REF1, as discussed separately below. It is thought that higher capacities were recorded for the last test because all the strings were on a trickle charge for a longer period of time than they were for the test on 1/25. This probably indicates that finish charges to a lower current are desirable for the Absolyte IIP batteries being used, and that perhaps an occasional equalize might be necessary. This could have been managed by the ACONF unit utilized in the test, but this was not done because we wanted to keep the operating conditions for the REF and the ACONF systems as closely alike as possible. We hope to validate this hypothesis in future testing.

As mentioned above, there is a clear indication that one of the cells in the REF1 battery is not performing as well as all the rest of the cells, and that it may in fact have a manufacturing defect. This can be seen by examination of Table 8, which shows the voltages of each of the cells of the REF battery towards the end of the two latest capacity tests. The Item 7 capacity test was repeated, in part, because it was observed that the string with the poorly performing cell did not give the same capacity as any of the rest of the strings. It can be seen from Table 8 that the voltage of Cell 10 of REF String 1 is quite a lot lower than the other cells of the REF battery string towards the end of discharge, this being an indication that the low-voltage cell might have a manufacturing defect. A close watch will be kept on this cell in any future testing that might be performed, and it could be replaced if it shows indications of imminent failure.

REF Cell Voltages				ACONF Cell Voltages			
REF String 1		REF String 2		ACONF String 1		ACONF String 2	
Cell	Voltage	Cell	Voltage	Cell	Voltage	Cell	Voltage
1	1.956	1	1.945	1	1.945	1	1.943
2	1.954	2	1.949	2	1.949	2	1.947
3	1.954	3	1.949	3	1.946	3	1.943
4	1.938	4	1.938	4	1.942	4	1.95
5	1.954	5	1.941	5	1.956	5	1.952
6	1.954	6	1.947	6	1.947	6	1.955
7	1.951	7	1.944	7	1.945	7	1.955
8	1.952	8	1.94	8	1.956	8	1.932
9	1.934	9	1.947	9	1.95	9	1.946
10	1.882	10	1.944	10	1.948	10	1.954
11	1.934	11	1.938	11	1.951	11	1.949
12	1.956	12	1.942	12	1.947	12	1.942

Table 8 Cell Voltages during Capacity Test

At this point in the test program, it is very early in the life of the lead acid (VRLA) batteries being used, and little difference in capacity between the two systems would be expected at this point. To illustrate this point, Table 9 shows the actual amp-hrs of discharge that have been passed from each of the strings of the REF and ACONF batteries during the testing that has been performed.

Total Ah of discharge for each battery string			
ACONF 1	ACONF 2	REF 1	REF 2
25038	24745	20046	21741

Table 9 Capacity Discharged from Batteries during Entire period of Test

The expected life of the Absolyte IIP cells being used in the current tests (currently at NDS sites) is about 1250 cycles at 80% depth of discharge. Since the cells have a capacity of (approximately) 1000 Ah, cycling at less than 80% DOD (as is done at NDS sites) would be expected to yield a total discharge capacity of at least 1250 cycles * 80% DOD * 1000Ah = one million Ah, because cycling at a more shallow depths generally leads to more total Ah of discharge in lead acid cells. Currently, only about 2.5% of expected total Ah have been discharged from the ACONF test strings and only 2% from the REF test strings, so we are only very early in the expected life of the cells. However, it should be noted that given the discharge rate for NDS sites of 10 amps per string, one million Ah of discharge corresponds to 100,000 hours (11 years) of discharge time, so NDS batteries may need to be replaced because of their age before the potential Ah capacity can be discharged from them.

Table 8 also contains some interesting results in the comparison of the operational strategies of the two systems. Note that the total Ah delivered for the ACONF system is approximately 20% higher than the REF system. The reason for this disparity is that one

ACONF string is used to finish charge the other which requires additional Ah beyond that discharged by the REF strings.

Conclusions and Recommendations

A six-month parallel test of two hybrid power systems that imitate those used at USCG NDS sites, one configured similarly to those currently implemented and the other with an ACONF battery management unit, has been successfully conducted. The hybrid power systems that were tested included a propane-fueled generator, a power supply that emulated the solar PV array in eight-week periods around mid-Winter, the Spring Equinox, and mid-Summer, and a 24V battery comprised of two parallel strings each with twelve 1000Ah cells in series. A fixed resistor was used in each of the two systems to emulate the loads at an NDS site.

During testing that emulated solar inputs for the eight weeks around mid-Winter and for three weeks in early-Spring, the test system with the ACONF unit consumed ~20% less fuel than the one without the ACONF. The run time for the generator was significantly less for the ACONF system that for the system configured as currently at NDS sites, but the number of generator starts was somewhat more for the ACONF system for the other, for the Winter and early-Spring testing. For this part of the testing, it would be expected that generator maintenance requirements would perhaps be reduced because of the reduced run time.

For testing with solar inputs that emulated mid-Spring and for the eight weeks around mid-Summer, the hybrid system with the ACONF consumed almost a third less fuel than the other system. This more-favorable reduction in fuel consumption was partly a result of the higher solar inputs for the Spring/Summer period as compared to the Winter/Spring period, but also resulted in part from implementation of a solar optimization function in the ACONF during the later testing. This solar optimization function also contributed to the still lower generator run and to the reduced number of generator starts, as compared to the reference system.

The beneficial results regarding fuel consumption and generator run time obtained in this work have led the USCG to ask that more work be performed on utilizing the ACONF technology for their NDS sites. Although it is early in the life of the batteries being used in the test, it is projected that the ACONF technology can be of further value to the Coast Guard by allowing a deferral of battery replacements at NDS sites. Thus, the ACONF technology is thought to be capable of providing battery life enhancement, and additionally, ACONF units track battery usage thereby allowing a more reliable method for determining when a battery replacement will be required.

We recommend that two related but separate tasks be performed to advance the ACONF technology for the USCG NDS application. First, we recommend that further testing be performed on the reference and the ACONF systems used in the current work, to further evaluate fuel savings and generator run time, and to determine if indications of battery longevity enhancement can be observed at a relatively early stage of battery life. This extended period of testing will also permit extended evaluation of the reliability of the

ACONF units. Second, we recommend that an ACONF unit be deployed at a working NDS site, as selected by the USCG. This will allow the USCG to become more familiar will the technology and with the benefits such units can provide, so that ACONF units might ultimately be deployed at all NDS sites with remote hybrid power supplies.

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