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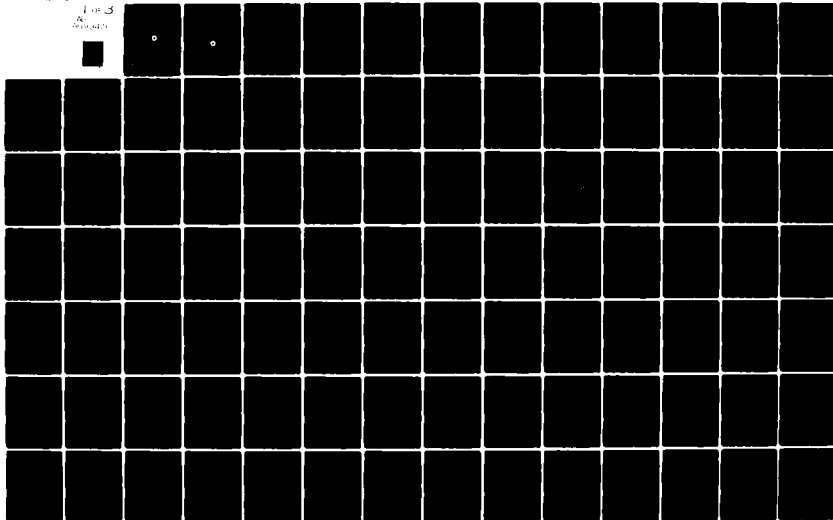
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ALTERNATE HYBRID POWER SOURCES FOR REMOTE SITE APPLICATIONS.(U)
FEB 81 W R POWELL, R J TAYLOR, J L BARON N00024-78-C-5384

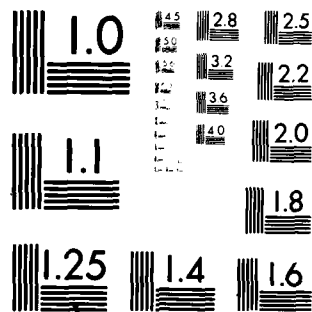
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ALTERNATE HYBRID POWER SOURCES FOR REMOTE SITE APPLICATIONS



February 1981

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Prepared for
U.S. DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
Office of Research and Development
Washington, D.C. 20593

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Report No.

CG-D-06-81

ALTERNATE HYBRID POWER SOURCES FOR REMOTE SITE APPLICATIONS.

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Technical Report Documentation Page

1. Report No. CG-D-06-81		2. Government Accession No. AD-A099471		3. Recipient's Catalog No.	
4. Title and Subtitle Alternate Hybrid Power Sources For Remote Site Applications				5. Report Date February 1981	
				6. Performing Organization Code	
7. Author(s) W. Richard Powell, Robert J. Taylor J. L. Baron, E. E. Mengel, J. C. Ray				8. Performing Organization Report No.	
9. Performing Organization Name and Address The Johns Hopkins University Applied Physics Laboratory Johns Hopkins Road, Laurel Maryland, 20810				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No. DOT-USCG-MIPR No. Z70099	
12. Sponsoring Agency Name and Address Department of Transportation U. S. Coast Guard Office of Research and Development Washington, D.C. 20593				13. Type of Report and Period Covered Final Report February 1980-February 1981	
				14. Sponsoring Agency Code G-DMT-3	
15. Supplementary Notes The COTR (Contracting Officer's Technical Representative) for this project was Dean Scribner. His guidance and assistance in this project are gratefully acknowledged.					
16. Abstract The problems associated with operation of diesel-electric generators at remote Coast Guard sites, typically lighthouses, are discussed. The electric power required by modules and subsystems in a modern lighthouse is investigated. The availability of wind power, solar energy, and other renewable energy sources in the local environment at remote lighthouses and other sites is discussed. Unmanned Coast Guard light-houses currently dependent on diesel generators are classified into six climatic groups and three power classes for generic analysis. Methods for describing both the hourly average and statistical characteristics of the solar energy and wind power available in each of these six climatic regions are developed. The technology currently available or expected during the next five years for collecting energy from the environment and storing it for subsequent generation of electric power is reviewed. A method for computing battery life as a function of the hourly use pattern is developed. A life-cycle-cost analysis methodology applicable to continuously variable life expectancies is developed and illustrated. Diesel generator costs, including service visit expense, are modeled. Other factors relating to the analysis of alternate energy systems as supplements to diesel-electric generators at remote sites are discussed. Simulations show that the use of storage batteries and a DC to AC inverter permits the diesel to be off during periods of low power demand with significant reduction in both annual fuel use and cost. Supplementing this basic diesel-battery hybrid with energy collected from the environment is cost effective and saves additional fuel. Other hourly simulation model results are given and generic systems are recommended for construction and test.					
17. Key Words LAMP Lighthouses Remote Power Systems Remote Coast Guard Sites Energy Storage Technology Battery-Diesel Hybrids			18. Distribution Statement Document is available to the U. S. public through the National Technical Information Service, Springfield, Virginia 22161		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 226	22. Price

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
y	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
sq in	square inches	6.5	square centimeters	cm ²
sq ft	square feet	0.09	square meters	m ²
sq yd	square yards	0.8	square meters	m ²
sq mi	square miles	2.6	square kilometers	km ²
ac	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
teaspoon	teaspoons	5	milliliters	ml
Tablespoon	tablespoons	15	milliliters	ml
fluid ounce	fluid ounces	30	milliliters	ml
cup	cups	0.24	liters	l
pint	pints	0.47	liters	l
quart	quarts	0.96	liters	l
gallon	gallons	3.8	liters	l
cubic foot	cubic feet	0.03	cubic meters	m ³
cubic yard	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in = 2.54 exactly. For other exact conversions and more detailed tables, see NBS Mon. Publ. 286, Units of Weight and Measures, Price \$2.25, SO Catalog No. C13.10-286.

Other Conversion Factors and Assumptions:

Diesel fuel: 1 gallon = 7.3 lbs = 135,000 Btu

3413 Btu = 1 kWh and 746 watts = 1 horsepower

Approximate Conversions from Metric Measures

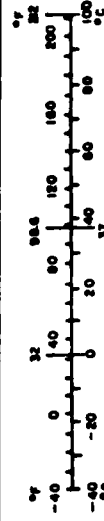
When You Know	Multiply by	To Find	Symbol
LENGTH			
millimeters	0.04	inches	in
centimeters	0.4	inches	in
meters	3.3	feet	ft
meters	1.1	yards	yd
kilometers	0.6	miles	mi
AREA			
square centimeters	0.16	square inches	sq in
square meters	1.2	square yards	sq yd
square kilometers	0.4	square miles	sq mi
hectares (10,000 m ²)	2.5	acres	ac
MASS (weight)			
grams	0.035	ounces	oz
kilograms	2.2	pounds	lb
tonnes (1000 kg)	1.1	short tons	st
VOLUME			
milliliters	0.03	fluid ounces	fl oz
liters	2.1	pints	pt
liters	1.06	quarts	qt
liters	0.26	gallons	gal
cubic meters	35	cubic feet	cu ft
cubic meters	1.3	cubic yards	cu yd
TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature
			



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ALTERNATE HYBRID POWER SOURCES
FOR REMOTE SITE APPLICATIONS

SECTION 1
SUMMARY AND RECOMMENDATIONS

1.1 INTRODUCTION

The Applied Physics Laboratory of The Johns Hopkins University is conducting a program of research and development for the U. S. Coast Guard to conserve diesel fuel at major navigational aids (lighthouses etc.) via the use of alternate power systems. This program consists of four phases. Phase I, Feasibility Research, is an analysis of remote site energy requirements and alternate energy systems culminating in the recommendation of generic components for a prototype system. Phase II, Exploratory Development, consists of the design, development and fabrication of an experimental prototype to verify the design concepts together with the associated test equipment and protocol. Phase III, Advanced Development, is the design, development and fabrication of an advanced development prototype for operational test and its evaluation plan. Phase IV, Engineering Development, is the engineering development of a pilot production prototype for the operational system that can be produced in quantity at reduced costs.

This is the final report to the U. S. Coast Guard for Phase I, the feasibility study of alternate hybrid power systems for remote, diesel-powered Coast Guard stations. The study proceeded under NAVSEA Contract N-00024-78-C-5384 via MIPR No. 270099. The work was divided into 10 Tasks as defined in Appendix A. This report is divided into five major sections. The first section is a summary with recommendations. The second section characterizes the power requirements at remote, diesel-powered Coast Guard stations, recommends energy conservation procedures and classifies these stations into power groups. The third section describes alternate energy resources and technology available for near term application. Section 4 presents the results of a simulation model study of diesel battery power systems supplemented by wind and solar power. The fifth section describes the systems recommended for design, fabrication and testing in Phase II together with some of the considerations that resulted in the recommendation.

1.2 OBJECTIVES

The overall program objective is to develop an alternative power system to replace or supplement the diesel-electric power systems now used at most remote Coast Guard sites. The goals of the alternative power system are to: 1) reduce overall operational costs, 2) reduce diesel fuel consumption, 3) decrease the frequency of maintenance required, and 4) reduce maintenance complexity. These goals may partially conflict. Reduction of cost over the entire life cycle of the power system is the primary goal because it includes the other three goals. It is also mandatory that the alternative power system reduce diesel fuel consumption without degrading station availability (the percentage of time the station is in full operational status).

1.3 PROBLEM STATEMENT

The U. S. Coast Guard, like others, has experienced a sharp increase in the cost of energy. The U. S. Coast Guard currently procures diesel fuel for domestic lighthouses using diesel-electric generators for power from the U. S. Navy at a cost of approximately \$1.30 per gallon. Fuel for remote LORAN-C sites is often acquired at higher costs in foreign spot markets. The effective fuel cost including the expense associated with delivery to the site is considerably higher. Approximately one gallon of fuel is consumed during diesel service visits and resupply operations required by remote lighthouses for every four gallons of fuel used at the sites.¹ The cost of manpower and material resources (ships and helicopters) used for these resupply and maintenance visits is enormous but difficult to quantitatively analyze because site visits are usually combined by field dispatchers with other operational missions or training programs. Typically, fuel resupply visits are now scheduled annually. They could be made less frequent by delivery of larger quantities of fuel with each visit, but diesel service is required approximately every three months because the diesel runs continuously.

The typical remote site now using diesel electric generators for power was formerly a manned lighthouse. In an effort to reduce both the cost and frequency of maintenance visits to the site, the Coast Guard is currently converting manned lighthouses to automatic operation using standardized components in standardized equipment modules. This Lighthouse Automation and Modernization Project, the LAMP program, was initiated in 1968 and will be substantially complete prior to the introduction of alternate energy hybrid power systems. Thus the hybrid power system must be compatible with LAMP modules or require only minor modification of them.

The LAMP diesels are small (12 or 18 horsepower). They develop carbon deposits and frequently require major overhauls if permitted to run under light load conditions for significant periods. Consequently the Coast Guard has recommended that LAMP diesels operate at a minimum of 75% of full load.² Since station power requirements without the light and fog sounder operating are usually much less than 75% of diesel capacity and the light is not likely to burn out,⁺ it is common practice to leave the light on 24 hours per day and run the fog sounder power supply with a ballast load when fog is not present. Under clear day conditions, the typical LAMP station must waste 4.5 kWh per hour to avoid carbon build-up problems in the diesel. (See subsection 2.1.3.1). The electrical energy produced in excess of station requirements at a typical LAMP station to avoid carbon build up problems is approximately

+ Lamps have a life expectancy exceeding the diesel service visit intervals and are routinely replaced during each service. Also an automatic lamp changer can bring a new lamp into service should one burn out prior to the next diesel service visit.

*References

1. Lt. Brad Willis, U.S. Coast Guard G-OP, personal communication 8-28-80.
2. U.S. Coast Guard, "Automatic Technical Guidelines," CG-250-41a, Engine-Generator Size Selection Section 3.D.4 (1980 draft edition).

17 megawatts hours/year. Clearly a significant amount of energy could be saved if a means of turning the diesel off during the day were available.

1.4 SOLUTIONS

Four possible conceptual solutions for the above problem are presented and briefly discussed in the following four subsections.

1.4.1 Diesel and Storage System

The diesel can be turned off during periods of low power demand if energy for station loads can be supplied from an energy storage system. Surplus energy when the diesel is on can be used to recharge the storage system. This system loads the diesel efficiently when it is on and permits the fog sounder and light to be off when not needed. There are losses associated with the storage system but these losses are less than the energy saved by reducing station loads and operating the diesel more efficiently. This system is not dependent upon energy from the environment and is thus universally applicable. It does however, require that the diesel restart reliably.

A variant of this system would use a diesel too small for the peak load that runs continuously. Power required in excess of diesel ratings would be supplied from the energy storage system. The energy storage system would be recharged during periods when the station load was less than the diesel rating. This system is very attractive as it permits the light and fog sounder power supplies to be turned off when these signals are not needed and also avoids both the carbon build-up and diesel restart problems. However, it would not reduce the frequency of diesel service visits required. A continuously running small diesel can not be recommended for Phase II as the Phase II prototype must utilize the existing LAMP diesel.⁺

1.4.2 Alternate Energy System

In principle, energy collected from the environment by an alternate energy system, including energy storage capacity, can supply all of the power needs of a LAMP station without any use of the existing diesel-electric generators. A 100% alternate energy system would eliminate diesel service and fuel expenses as well as all of the problems associated with diesels. However, economic considerations and the Coast Guard's high reliability requirements make a self contained, back-up power system mandatory. It is presumed that the present diesel power system will be retained as the back-up system at least through Phase II. This presumption is not meant to preclude the possibility that alternate energy systems may ultimately eliminate all diesel fuel consumption at some remote sites. It is only practical recognition of the fact that alternate energy systems must first prove their capacity and reliability

⁺ This requirement was being reconsidered just as Phase I was concluding. Some preliminary studies of smaller than standard LAMP diesels are included in Appendix H. Analysis of the continuously running small engine system should be continued in Phase II and efforts to empirically evaluate systems using small engines should be initiated.

under field conditions with routine maintenance by regular Coast Guard personnel before existing diesels of proven reliability will be removed from service.

1.4.3 Alternate Fuel System

The carbon build-up problem and the resulting inefficient station operating mode currently required at LAMP stations can be avoided by replacing the diesel-electric generator with an alternate fuel system designed for efficient operation during periods of reduced load. For example, some fuel cells are more efficient than diesels and have excellent partial load characteristics. This system could be combined with an alternate energy system to further reduce the use of fuel when energy is available from the environment. Some fuel cells, currently under development are reversible and use readily stored fuel.^{3*} Thus it is possible to use alternate energy to regenerate the fuel and avoid periodic delivery of fuel to the site. Such a combined alternate-fuel alternate-energy hybrid holds great promise for the future and should be ready to replace the current LAMP diesels when their economic life is exhausted. Unfortunately these systems are not sufficiently developed and reliable to be considered for use in Phase II.

1.4.4 Hybrid Power System

The existing LAMP diesels and an alternate energy system can be combined to form an attractive hybrid power system, using only current technology. The alternate energy hybrid power system draws power from the environment when it is available and needed. This power is used to recharge the energy storage system and to service station loads. Any surplus power available is used to recharge the energy storage system, if the storage system is not fully charged. When environmental power is not adequate to fully service station loads, the power deficit is taken from the energy storage system, if possible. The LAMP diesels are activated when environmental energy is inadequate and the discharge limit condition of the storage system is imminent. If fog is not a frequent problem the alternate energy system components can be sized to handle all station loads except the fog signal. The LAMP diesel would then be activated whenever peak power conditions exist (fog signal and light both on). This approach avoids part of the initial cost associated with an alternate energy system sized for the peak station load although it is a less efficient design than one that need not utilize the diesel during brief peak power periods.

The hybrid power system uses less fuel than the diesel and storage system discussed in subsection 1.4.1 because part of the station's energy requirements are obtained from the environment. Fortunately, the diesel and storage system is a special case of the hybrid power system, i.e., it is the limiting case when all energy collection components of the alternate energy system are vanishingly small and only the energy

*Reference

3. M. A. Reid, L. H. Thaller, Aug. 1980, "Improvement and Scale-up of the NASA/Redox Storage System," 15th Intersociety Energy Conversion Engineering Conference, Seattle, WA., (Paper No. 809289).

storage system is substantial. Thus we need only construct an analysis methodology for the hybrid power system to evaluate both it and the diesel and storage system.

1.5 ANALYSIS

1.5.1 Simulation Model

Following a general review of electrical storage systems, a lead-acid battery was selected for use in Phase II. The relative merit of various configurations of the alternate hybrid power system as measured by levelized life-cycle cost was investigated by hourly simulation analysis.

The simulation model deals with generic stations and weather rather than site specific conditions. There are three latitude groups (Southern, Northern and Alaskan) and two different wind regimes (coastal and offshore) for each group. The generic model thus considers six representative climatic sites. The Southern group represents 11 remote LAMP stations, all except one lying in a 9° latitude band centered on 33.5°N. The Northern group represents 39 remote LAMP stations in a 10.4° latitude band centered on 43.2°N and the Alaskan group has 6 diesel-powered LAMP stations in a 6° latitude band centered on 57.4°N. Offshore sites are islands or artificial platforms several kilometers from the shore with relatively strong and steady winds. Winds at coastal sites often show significant diurnal variation in strength and direction due to the differential heating rates over land and water along the shoreline. The offshore generic class represents 39 remote LAMP stations and the coastal category includes 17 LAMP stations using diesel-electric generators for primary power.

The station at each generic site can require any one of three different power profiles (high, medium and low). The hourly power requirements for each of these three power classes is automatically constructed for each day within the model using the site latitude and day date to compute the duration of darkness. (Darkness is defined to include one-half hour before sunset and one-half hour after sunrise.) The daily power profiles consist of 24 hourly average power increments. The average power levels required during day-night and night-day transition hours depend upon the exact time of sunset and sunrise, but the other hourly power levels are as shown in Table 1.1.

TABLE 1.1. GENERIC POWER LEVELS (Watts)

	<u>High</u>	<u>Medium</u>	<u>Low</u>
Night	3000	2000	650
Day	500	500	100

1.5.2 Sampling by Time

The average power available each hour from the sun or wind depends strongly upon the time of day and generic site type selected. However, there is only a slow change in the average power available from the environment from week to week. Likewise, the hourly-average station power requirements do not change rapidly as the year progresses. Consequently the simulation model uses analysis days at approximately two week intervals rather than compute results for all 365 days. The model begins each analysis period 24 hours in advance of the sample day with the diesel on and the battery midway between its maximum and minimum permitted state of charge conditions. The initial conditions on the sample day thus reflect the operational conditions prevailing at the end of the prior day rather than arbitrary start-up conditions. The structure of the model forces an equal number of days before or after the solstice to be basically identical (same duration of darkness, same solar power available and same wind conditions). This symmetry is exploited to reduce the cost of computation and to avoid output of essentially identical results when hourly histories of typical days are displayed. For convenience the simulation has 24 sample days uniformly spaced throughout the year so that the 12 uniquely computed days correspond approximately to monthly average results.

It must be noted that the use of sample days and hourly power averages is only an analysis cost control technique. The analysis deals with 18 different generic station types and a vast array of alternate energy system parameters that can significantly effect the results. For example, among the more significant variables explored in Phase I are: 1) wind machine peak power, 2) solar array peak power, 3) battery storage capacity, 4) depth of battery discharge permitted, and 5) year of installation. The model contains a much larger set of variables of lesser significance, for example; inverter efficiency, wind machine start-up speed, battery type, etc. Some variables, for example, the ambient temperature, are not at present contained within the structure of the simulation model. The results of this analysis are intended to identify the more promising systems for each of the different site types. Phase I results are not intended as design data for specific systems at specific sites. That level of detail is part of the Phase II program.

1.5.3 Sampling by Parameter

Several different values of each of the more significant system parameters are typically assumed and the results (annualized cost, or fuel used, etc.) are plotted versus that parameter while the other parameters are held constant. For example, a set of solar array sizes designed to provide 0, 1, 2, 3, or 4 kW when the solar flux is 1000 W/M^2 is typically assumed, if the optimum array size is being sought. Thus with 18 different generic stations and five values for each of the five most significant system parameters, the analysis is potentially dealing with 56,250 different cases, each requiring a full year of simulation for analysis.

Fortunately, it is possible to omit many cases, and certain parameters were fixed at a single value after more limited sampling studies. For example, unless otherwise stated, all results presented in this report have 1985 as the installation year. A second and more fundamental example of sampling with fixed parameters concerns the selection of parameters to control the diesel power level. The diesel power is controlled in response to battery state-of-charge as shown in Figure 1.0 with diesel turn-on when the relative state of charge of the battery drops below 0.8. The diesel is turned off when the relative state of charge reaches 1.0, the nominal battery capacity. Thus only approximately 20% of nominal battery capacity is cycled or used. A deeper depth of discharge range was not significantly more economical in several cases investigated initially with other values for these control parameters. It was judged to be desirable to maintain as much reserve capacity in the battery as was economically feasible, especially since the model deals only with hourly power averages. Thus the diesel control law illustrated in Figure 1.0 was fixed for the remainder of the study while other parameters were varied or sampled.

1.5.4 Loss Mechanisms

Also shown in Figure 1.0 is one of the three loss mechanisms assumed in the model. The battery returns less ampere hours than are used to charge it. This "charge inefficiency" increases rapidly as the nominal fully charged condition is approached. The model assumed prevents the battery state of charge from exceeding 110% of nominal full charge regardless of how long the battery is charged.

The terminal voltage of a battery being charged increases both with the rate of charge and the state of charge and is higher than the terminal voltage when the battery is discharged from the same state at the same rate. Thus energy is also lost because of a "voltage inefficiency". The voltage inefficiency of a lead-acid battery is contained within the model. It is the complex function of two parameters described later in this report (See subsection 4.3).

In addition to the voltage and charge losses of the battery, inverters and dc-to-dc converters producing the required AC or DC voltages for LAMP loads introduce additional "power conditioning" losses. It is typically assumed that all power conditioning is accomplished with 90% efficiency. There are no other losses within the model, except that the efficiency of fuel use by the diesel is dependent upon diesel load. A significant part of the diesel electric power generated at a LAMP station is required for a large air filter fan that runs only when the diesel is operating. This loss and the change in diesel efficiency with load level are combined in the model into a single function that relates the rate of diesel fuel use to the net electric power produced.

1.5.5 Base Case

Although the Coast Guard recommends that LAMP diesels not operate for prolonged periods at load levels less than 75% of capacity, field practice does not always conform to this recommendation. In the

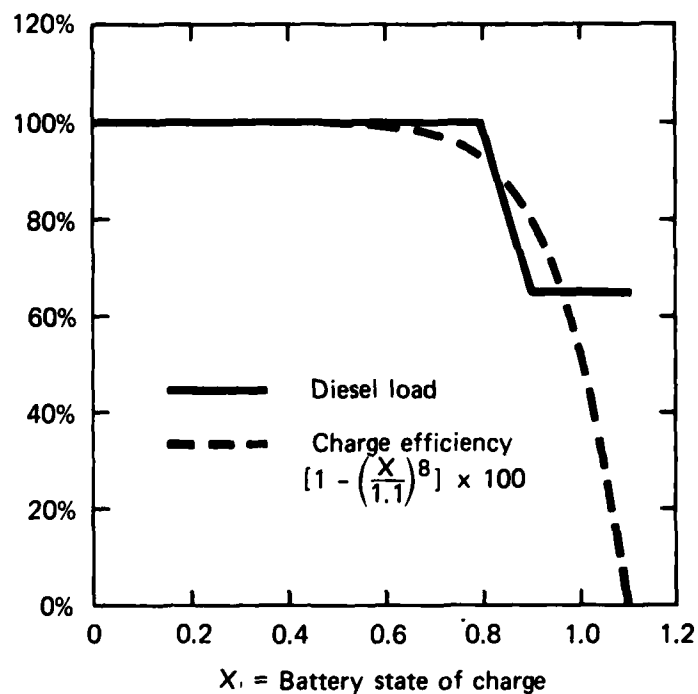


FIGURE 1.0 DIESEL LOAD AND AMPERE-HOUR STORAGE EFFICIENCY VS NORMALIZED STATE OF CHARGE.

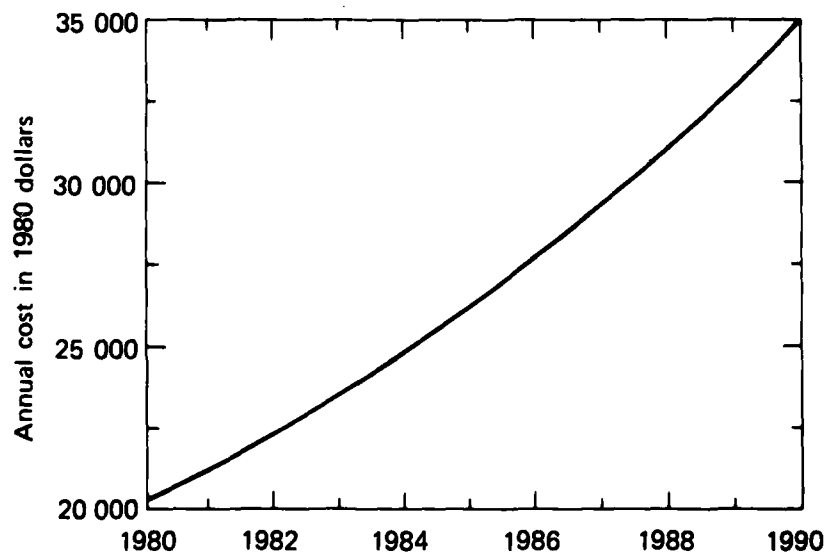


FIGURE 1.1 ANNUALIZED COST OF DIESEL AND FUEL VS INSTALLATION YEAR. (Assumes 8% real fuel cost escalation from \$1.30/gallon in 1980, 15 years of diesel life and 10% discount rate.)

simulation model the diesel is not allowed to run at less than 65% of capacity. At this level, the smallest LAMP diesel generator, a 6.5 kW unit, supplies the 1.2 kW required by the air filter blower and has slightly more than 3 kW net output available for LAMP units. Thus in the base case for all three power groups at all six typical sites, the diesel runs continuously at 65% of full power. At this level, it consumes 4345 gallons of fuel annually. The corresponding annual cost over the 15 year diesel life, with 10% discount rate and fuel escalated at 8% annually from a \$1.30 gallon price in 1980 is given as a function of installation year in Figure 1.1. For example, a diesel installed in a LAMP station in 1985 and serving until 2000 has a life-cycle cost, including fuel and maintenance, equivalent to 15 annual payments of approximately 26 thousand dollars. Alternate energy systems installed in 1985 can be significantly less expensive as is illustrated in Table 1.2.

1.5.6 Model Output Data

The simulation model has two major sections. The "performance section" of the model computes and prints:

- 1) The total number of hours the diesel runs each year.
- 2) The number of diesel starts required during the year.
- 3) The number of gallons of diesel fuel used each year.
- 4) The battery life in years.
- 5) The required inverter size, increased to next larger kilowatt.
- 6) Other variables relating to the details of how energy is lost, but not required for economic analysis.

The "economics section" of the simulation model takes the fuel use data, the battery and diesel life data, and the equipment sizes (battery capacity, solar array rating, etc.) from the performance model and uses additional information (discount rate, installation year, fuel costs, etc.) plus its model of equipment cost versus size and year of purchase to compute the annualized cost. The annualized cost of items that operate identically in both the alternate energy hybrid power system and the standard LAMP station is not included in the economics calculation. The economics model has as routine output a captioned table giving the annualized cost of the diesel (fuel included), the battery, the wind machine, the solar array, the power conditioning or "inverter" and the sum of these separate components.

1.6 RESULTS

The results of the Phase I study are summarized in Table 1.2. The four rows at the top of Table 1.2 correspond to alternate energy hybrid power systems. The two rows at the bottom of the table correspond to the best battery and storage system results. (This special case is obtained in the simulation by setting both the array and wind machine peak power ratings to zero). The battery life and diesel usage are given in the last two rows of the table instead of repeating the zero values for array and wind machine powers. The values of cost and fuel

TABLE 1.2
SUMMARY OF MOST ECONOMICAL SYSTEMS

			ALASKAN SITE		NORTHERN SITE		SOUTHERN SITE	
			DIESEL + BATTERY + ALTERNATE ENERGY HYBRID		DIESEL + BATTERY ONLY			
			HIGH POWER		MEDIUM POWER			
			COASTAL	OFFSHORE	COASTAL	OFFSHORE	HIGH POWER	MEDIUM POWER
	SOUTHERN SITE		NORTHERN SITE		ALASKAN SITE			
	Cost (\$/yr)	20.0K (77%)	Cost (\$/yr)	18.9K (<72%)	Cost (\$/yr)	18.4K (70%)		
	Fuel (gallon)	2568 (59%)	Fuel (gallon)	2099 (48%)	Fuel (gallon)	1815 (42%)		
	Bat. (ampere-hour)	500	Bat. (ampere-hour)	1000	Bat. (ampere-hour)	1500		
	Sun (nominal kW)	1	Sun (nominal kW)	0	Sun (nominal kW)	0		
	Wind (peak kW)	0	Wind (peak kW)	>4	Wind (peak kW)	6		
	Cost (\$/yr)	18.6K (<71%)	Cost (\$/yr)	4.2K (16%)	Cost (\$/yr)	4.0K (<16%)		
	Fuel (gallon)	1959 (45%)	Fuel (gallon)	~ 0 (~0%)	Fuel (gallon)	~ 0 (~0%)		
	Bat. (ampere-hour)	1500	Bat. (ampere-hour)	1500	Bat. (ampere-hour)	2000		
	Sun (nominal kW)	0	Sun (nominal kW)	0	Sun (nominal kW)	0		
	Wind (peak kW)	>4	Wind (peak kW)	6	Wind (peak kW)	>5		
	Cost (\$/yr)	17.1K (65%)	Cost (\$/yr)	15.7K (<60%)	Cost (\$/yr)	14.4K (<55%)		
	Fuel (gallon)	1825 (42%)	Fuel (gallon)	1375 (32%)	Fuel (gallon)	1058 (24%)		
	Bat. (ampere-hour)	1500	Bat. (ampere-hour)	1500	Bat. (ampere-hour)	1500		
	Sun (nominal kW)	2	Sun (nominal kW)	0	Sun (nominal kW)	0		
	Wind (peak kW)	0	Wind (peak kW)	>4	Wind (peak kW)	>6		
	Cost (\$/yr)	15.5K (59%)	Cost (\$/yr)	3.7K (14%)	Cost (\$/yr)	3.6K (14%)		
	Fuel (gallon)	2373 (56%)	Fuel (gallon)	~ 0 (~0%)	Fuel (gallon)	~ 0 (~0%)		
	Bat. (ampere-hour)	1500	Bat. (ampere-hour)	1000	Bat. (ampere-hour)	2000		
	Sun (nominal kW)	0	Sun (nominal kW)	0	Sun (nominal kW)	0		
	Wind (peak kW)	4	Wind (peak kW)	4	Wind (peak kW)	3		
	Cost (\$/yr)	20.8K (80%)	Cost (\$/yr)	20.8K (80%)	Cost (\$/yr)	21.0K (80%)		
	Fuel (gallon)	2836 (65%)	Fuel (gallon)	2842 (65%)	Fuel (gallon)	2879 (66%)		
	Bat. (ampere-hour)	2000	Bat. (ampere-hour)	2000	Bat. (ampere-hour)	2000		
	Battery Life (yr)	8.24	Battery Life (yr)	8.30	Battery Life (yr)	7.73		
	Diesel Use (hours/yr)	5323	Diesel Use (hours/yr)	5353	Diesel Use (hours/yr)	5414		
	Cost (\$/yr)	<18.7K (71%)	Cost (\$/yr)	18.4K (70%)	Cost (\$/yr)	18.4K (70%)		
	Fuel (gallon)	<2420 (56%)	Fuel (gallon)	2309 (53%)	Fuel (gallon)	2290 (53%)		
	Bat. (ampere-hour)	>1500	Bat. (ampere-hour)	2000	Bat. (ampere-hour)	2000		
	Battery Life (yr)	>4.20	Battery Life (yr)	5.26	Battery Life (yr)	5.31		
	Diesel Use (hours/yr)	<4350	Diesel Use (hours/yr)	4198	Diesel Use (hours/yr)	4167		

Cost and fuel usage as percent of current diesel only system are given in parenthesis.

use in parantheses are percentages of the base case (i.e., the present operating system) as described in subsection 1.5.5. Only the on site fuel usage is included in Table 1.2, but the economics includes a 25% allowance for fuel used in logistical support.

Several general conclusions can be drawn from the results obtained:

- 1) Only the Northern and Alaskan offshore sites are dramatically more economical than the simple diesel and storage system when alternate energy is collected from the environment for systems installed in 1985. Later installation dates increase the relative advantage of alternate energy systems because the diesel fuel continues to escalate at 8% annually but the cost in constant value dollars of alternate energy system components is assumed to decrease until 1990.
- 2) Wind systems are more economical than solar systems everywhere except at Southern coastal sites. Solar-wind hybrids were considered but were never more attractive than the better of solar or wind alone. This result may be a consequence of using the average powers expected from the sun and wind each hour computed independently instead of statistically correlated data.
- 3) The savings in fuel use and dollars is greater for the smaller power stations. This is mainly because the smallest LAMP diesel is increasingly over-sized compared to the load as the station load decreases. This conclusion became apparent and quantatively understood during analysis of the high and medium power classes presented in Tables 1.1 and 1.2. Simulation of the low power class was deferred until Phase II when a more appropriately sized diesel can be considered.
- 4) The annual station cost and fuel use of the diesel and storage battery only system do depend slightly upon the site latitude. The duration of darkness varies through a greater range during the year at high latitudes. Thus the station load profile for an Alaskan site is correspondingly more variable and difficult to service. Typically, the diesel and storage battery system for 1985 installation can save approximately 25% of the costs and 45% of the fuel required by the current system.
- 5) The optimum battery size is not a sharply defined value. Large batteries cost more initially but last longer and reduce the number of diesel starts required annually. A battery rated for approximately 20 kWh capacity would be

suitable for all stations.⁺ The model assumes a 12 V battery and gives ratings in ampere hours. Any other combination of voltage and ampere-hour rating with the same product produces the same simulation model results. As is discussed in Section 5, a 120 V battery storage system with one tenth the ampere hour capacity is more practical. The model assumes a 12V battery only to produce ampere-hour numbers familiar to most people.

1.7 RECOMMENDATIONS FOR PHASE II

The following recommendations were developed by the Applied Physics Laboratory in accordance with the requirements of the contract for this Phase of the effort. Acceptance and publication of this report by the Coast Guard does not necessarily imply concurrence with these recommendations.

1) Site Selection and Schedule

A coastal site conveniently accessible from Washington, D.C. that is currently connected to commercial power should be selected as the first application site for the Phase II experimental prototype. The site should be converted to use a standard LAMP diesel for prime power with commercial power being retained for back-up and experimental convenience. The radio beacon on Cape Henlopen is such a site. It is only a mile from the Harbor of Refuge Light and both appear to be on the same electric power distribution circuit. These two sites provide the closest opportunity to test the experimental prototype with radio beacon, light, and fog sounder at operational sites in the marine environment. The Harbor of Refuge Light is on the south end of the break water just off Cape Henlopen. It is a realistic test of installation procedures for an offshore island with limited working space.

It is proposed that APL personnel install the experimental prototype at the radio beacon with the active assistance of Coast Guard personnel. Then, following a brief period of successful operation at the radio beacon, the Coast Guard would relocate the prototype to the Harbor of Refuge Light following procedures mutually developed while APL personnel observe to refine installation procedures and prepare for Phase III. Phase III would begin with the successful installation of the experimental prototype by the Coast Guard at an operational station.

Prior to installing the experimental prototype at any operational site, it would be installed and extensively tested by APL, with the active cooperation of the Coast Guard, at the Alexandria Test Station. Testing at Alexandria should include numerous cold starts of the diesel in subfreezing weather. Thus installation at the Cape Henlopen radio beacon should be scheduled for the spring of 1982 with transfer to the Harbor of Refuge Light scheduled for early summer of 1982.

⁺ The Southern coastal high-power station with 1 kW solar energy and 500 ampere hour battery is insignificantly superior to the diesel and battery only case. The first increment of solar power is the most cost effective. Larger arrays and batteries that could significantly reduce fuel use are not cost effective at this station compared to the diesel and battery only case.

2) Small Diesel (Power Plant) Evaluation

Phase II should include continued evaluation of continuously running small engine and storage system concepts discussed in subsection 1.4.1. An experimental evaluation of any diesels available that appear to be reliable and significantly more economical and efficient in this mode of operation than the standard LAMP diesels should be initiated. This work can proceed at APL and should include the storage system and simulated loads so that the entire system can be evaluated as a functioning unit. Also, alternatives to the internal combustion engine should be considered and evaluated empirically if commercially available and potentially superior power systems can be identified.

3) Development Plan

It is recommended that Phase II proceed initially as two separate but parallel projects. Phase IIa would consist of the design and fabrication of an experimental prototype consisting of a new control system, lead-acid storage batteries and a standard SR-2 LAMP diesel. Sequential testing would be performed as outlined in recommendation (1) above. Phase IIb would consist of the small diesel (or other power plant) evaluation project recommended in (2) above plus the selection and installation of a wind machine for generating electric power for the Harbor of Refuge Light and/or radio beacon on Cape Henlopen. Wind speed measurements at the Harbor of Refuge Light and/or existing available towers near the radio beacon would be initiated early in Phase IIb. The wind machine could be located either on the Harbor of Refuge break water or on the beach near the radio beacon and feed power to either (or both). The primary objective of the wind machine test is to evaluate it in a marine environment. A secondary objective of considerable importance is to develop installation procedures for remote sites. Installation at the Harbor of Refuge Light could serve as a final test of these procedures.

The separate parts of Phase II would merge when wind power was added to the experimental prototype. However, Phase IIb might continue in parallel with Phase III if additional wind machines are to be tested in the marine environment and/or additional testing of the endurance and reliability of small power plants is warranted by initial results. Note that commercial power at the Alexandria Test Station and the Cape Henlopen radio beacon site would be used to simulate wind power for purposes of testing the control system of the experimental prototype in all modes of operation.

4) Additional Recommendations

Early in Phase IIa, one battery of the size and type initially selected for the experimental prototype should be acquired and tested to determine both its charge and voltage efficiency under various conditions and at various points in its life cycle. The purpose of this test is to confirm manufacturers data and provide more specific and accurate modeling of the lead-acid storage system within the simulation model.

The model should be refined to reflect this data and the diesel control scheme should be optimized for the specific station load with the new battery data. Various methods of monitoring the battery state of charge can also be tested and some data, although not statistically significant, will be obtained about the validity of the battery life calculation methods used within the simulation model.

The data collection and recording system now used at the Alexandria Test Station should be used for tests conducted there. However, the system designed and fabricated for use at the Cape Henlopen radio beacon and Harbor of Refuge Light should be tested in Alexandria prior to use at operational stations.

Detailed recommendations for two particular experimental prototypes are presented and discussed in Section 5. These two systems differ primarily in how the fog sounder is energized from the battery. In one case an inverter is used and in the other, the fog sounder power supply's internal 110-120V DC bus is tied directly to the station's main storage battery. The latter case is more efficient if a significant fraction of the fog signal operation is at times when the diesel is off. It also permits a smaller inverter to be selected and reduces adverse reactions between the fog signal power surges and other LAMP modules. However, the depth of discharge of the battery permitted is more limited as the fog signal strength would be noticeably reduced if operated directly from a deeply discharged battery.

The direct connection of the fog signal to the battery appears to be the more economical and efficient choice in spite of the more limited depth of discharge permitted, but detailed analysis is required to definitely resolve this issue. It is recommended that Phase II begin with the concept that the fog signal be directly tied to the main storage battery but other LAMP module loads initially remain on the AC bus. Phase II should thus begin with a system concept somewhat intermediate between the two concepts discussed in Section 5 and proceed toward greater direct use of DC.

The equipment at the LAMP test station in Alexandria should be examined more carefully to permit early selection and test of an inverter. It does not at present appear that a high quality inverter output waveform will be required but early testing of this conclusion is essential to proper inverter selection. Also, if the fog sounder is to be operated directly from a storage battery, this mode of operation must be demonstrated early in Phase II to establish its validity and uncover any associated problems. A small capacity but full voltage battery system of the same basic type planned for subsequent use at the Harbor of Refuge Light can be acquired for this test. It can also be used in a subsequent test of the battery state of charge control method selected.

Small capacity is actually an asset in this latter use as less time is required to complete charge and discharge cycles. Thus it is recommended that the full capacity battery system using new batteries be installed only at the Harbor of Refuge Light. The small capacity battery system acquired would serve as the energy storage system used in the test of small power plants (recommendation 2) after it was no longer needed in Phase IIa.

SECTION 2

ENERGY USE AT MAJOR AIDS-TO-NAVIGATION

The three major subdivisions of this section correspond to Tasks 1, 2, and 3 of Appendix A. This section is concerned with energy use at Coast Guard sites dependent upon diesel-electric generators. Sixty four such installations, typically remote lighthouses, have been identified and listed in Table B-1 of Appendix B. In addition to these 64 sites, 13 diesel-powered LORAN-C stations and two vessel-traffic-system sites with independent power have been identified and listed in Table B-2 of Appendix B.

Task 1 is an investigation of energy use by individual components and aggregate systems in a modern, unmanned diesel-powered lighthouse plus a less detailed investigation of energy use at other diesel-powered, major aids-to-navigation. Task 2 is a review of several methods for reducing energy consumption at modern diesel-powered lighthouses. Task 3 is an investigation and catalogue of power requirements at 79 remote Coast Guard sites. Task 3 results for lighthouses are generalized to define three generic power classes for subsequent analysis in Task 8.

2.1 ENERGY REQUIREMENTS

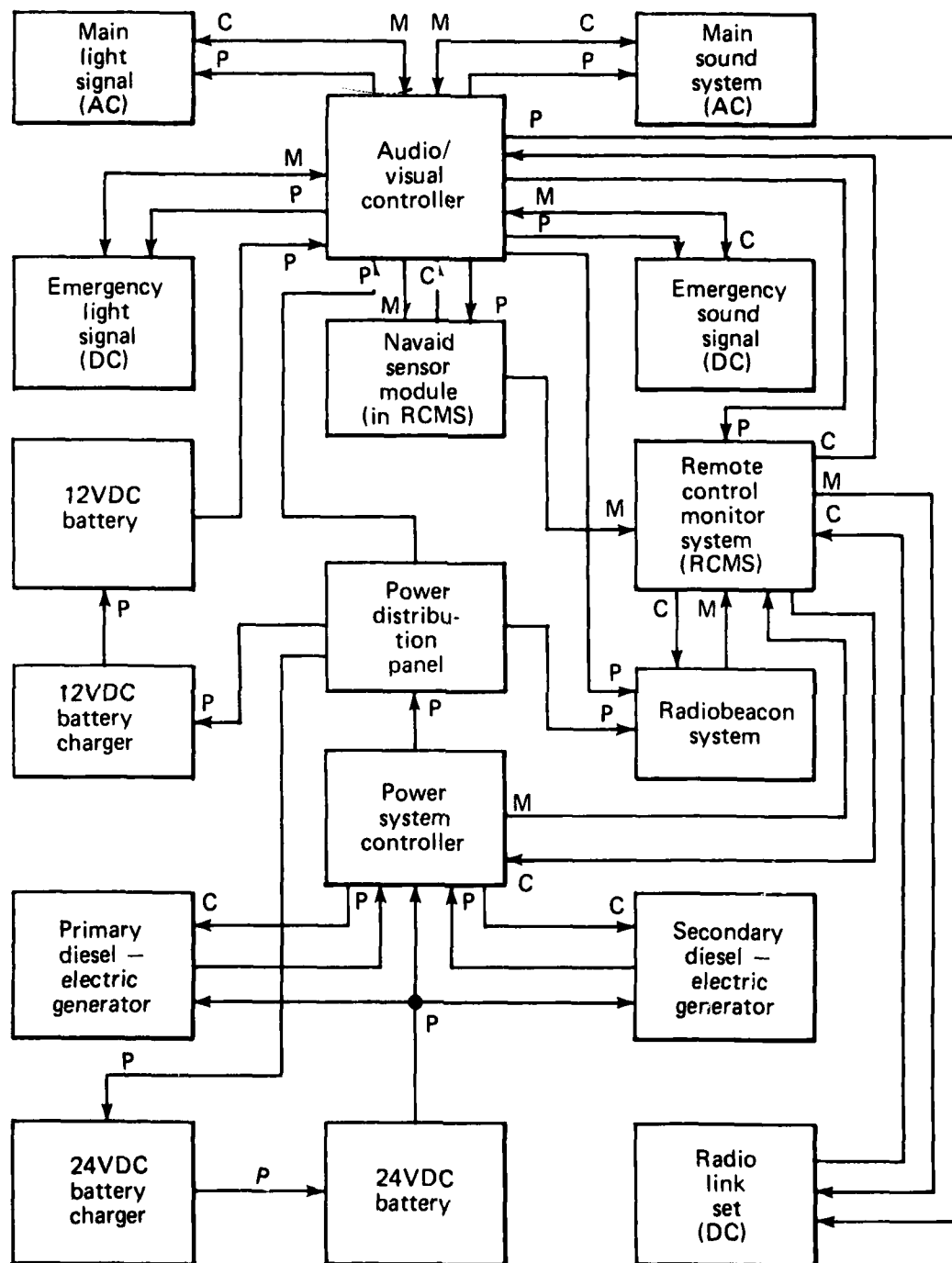
2.1.1 Definition of Lamp Components

LAMP is an acronym for Lighthouse Automation and Modernization Project. The purpose of LAMP is to reduce costs and provide more reliable light, sound and radiobeacon signals as aids-to-navigation.

The three main groups of components which constitute a LAMP installation are the aids-to-navigation, the signal control components, and prime power components. The control components and prime power components are typically placed inside separate standardized containers or huts. The signal emitters and their associated sensors are exposed to the environment and uniquely installed at each site. Not all sites have all components of the LAMP system. Figure 2.0 illustrates how the modules of a fully equipped LAMP station are interconnected. A complete list of these components arranged by signal group or housing hut is given in Appendix C along with their power requirements. A list of the principal components of a typical 1987 LAMP installation with conventional diesel power follows:

2.1.1.1 Aids-to-Navigation

1. A light signal which is either a 10 inch rotating optic, a 24 inch rotating optic or two 24 inch rotating optics,
2. A sound signal rated for 1000 or 2000 watts input power with a 300-Hz audio signal,



Symbols: M = Monitor, P = Power, C = Control

FIGURE 2.0 INTERCONNECTION OF MAJOR REMOTE STATION LAMP COMPONENTS.

3. A solid state radio beacon operating in the 285 kHz to 326 kHz region, and

4. Emergency light and sound signal operated from 12VDC battery.

2.1.1.2 Signal Control Hut

1. A remote control and monitor system (RCMS),
2. A remote station radio link set,
3. An audio-visual controller, and
4. A 12-volt battery and charger.

2.1.1.3 Prime Power Hut

1. Two engine-generator sets,
2. An environmental control unit,
3. An automatic power system controller, and
4. A 24-volt battery and charger.

2.1.2 Power Use by Key Components of Lamp Installations

The power requirements for each of the possible components of a LAMP installation can vary with the operational mode of the component and its site specific use. A discussion of each key component and its variable power requirements follows.

The light signal has two basic parts which draw power: the "lamp" (a light emitting "lamp", not the acronym LAMP), and the motor for rotating the optical device which holds the "lamp". The principal lamps used are 120 VAC tungsten-halogen incandescent filament type lamps. The average power levels drawn by the two major lamps used are 500 and 1000 watts. However, because tungsten has a positive resistance characteristic (the resistance at the operating temperature is much greater than its cold resistance), the initial power requirement of a lamp is much greater than its rated value. Generally, the hot resistance is 12 to 24 times the cold resistance. The low cold resistance of tungsten filaments results in an initial inrush of current which, because of the reactance characteristic of the circuit, does not reach the theoretical value that is indicated by the ratio of the hot to cold resistance. For a 500-watt 120 VAC lamp the normal current is 4.17 amperes while the theoretical inrush current (based on hot-to-cold resistance) is 89.5 amps. The period for this inrush current to fall to the normal value is typically 0.15 seconds. For a 1000-watt 120 VAC lamp the normal current is 8.3 amperes while the theoretical inrush current is 195 amperes. The period for this inrush current to fall to the normal value is typically 0.18 seconds (Ref. 4).*

*Reference

4. John E. Kaufman (ed.) IES Lighting Handbook, Illuminating Engineering Society, Fourth Edition, 1966, page 8-1 to 8-13.

The 500-watt lamp is typically used in the 10-in. rotating optic, while the 1000-watt lamp is used in the 24-in. single and double rotating optic. Reference 5* indicates that the power required to drive the 10-in rotating optic is 100 watts while the power required to drive the 24-in single and double rotating optic with its Class C motor is 470 watts. Reference 5 does not state whether these powers are peak or average. Measurement of the current drawn by the motor for the 24-in. optic under normal conditions indicates 470 watts is the average power drawn. This motor has a speed of 1800 rpm. It is geared down to about 6 rpm for driving the optic. This large reduction in rpm by gearing would indicate that peak loads from wind gusts are probably close to the average load of 470 watts.

The National Electric Code has classified squirrel-cage induction motors in accordance with the ratio of their starting to rated-load currents, and starting to rated-load torques. Design Class C motors have a starting current 5.5 to 6 times rated current and a starting torque 225% of rated torque. (Ref. 6)*. Thus the starting power requirements for the motor driving the rotating optic should not exceed 2800 W (6x470W).

The typical sound signal generator for LAMP is the CG-1000, ELG-300/2. This 300-Hz sound emitter runs on 120 VAC. While emitting maximum sound, the average power requirement is 1632 watts. The surge power at start may be closer to 2400 watts, however. When the sound signal is silent and unballasted, the power drawn by the device is about 240 watts. If two CG-1000 and ELG-300/04 units are used, the previous powers are simply doubled (Ref. 7)*.

The brief but relatively large power surge at the start of the sound signal or required to start the optic rotating and simultaneously turn on the lamp can have significant impact upon the design and/or operational sequence and procedures recommended for an alternate hybrid power system, and are thus included in this description of the optic power requirements in spite of the fact that the energy used during the start-up period is insignificant.

The power required for the new AN/FRN-40 solid state radio beacon depends upon the required range of the beacon, the latitude and frequency of the station and the type of antenna used. The latitude of the station is a very significant factor below 35° because electromagnetic noise from thunderstorms in the frequency band used by the beacons

*References

5. Coast Guard, Aids to Navigation: Technical, COMPTINST. M16500.3, Sept., 1979.
6. T. Baumeister and L. S. Marks (eds.) Standard Handbook for Mechanical Engineers, Seventh Edition, 1967, page 15-64.
7. Pennawalt Corporation, Instruction Booklet for CG-1000, Sound Signal power supply, page 1-1.

(258 kHz to 326 kHz) increases as the equator is approached. This background noise makes the minimum electromagnetic field strength required for reliable detection of the radio signal latitude dependent.

The following table gives the maximum field strength at the edge of the range required for reliable detection at nighttime (the worst time for signal detection because of ionospheric reflections) (Ref. 8)*. Beacons normally operate all day at the power level required by nocturnal conditions.

TABLE 2.1. MINIMUM FIELD STRENGTH VERSUS LATITUDE

<u>Latitude</u>	<u>Minimum Field Strength</u>
> 35°	30 $\mu\text{V/m}$
25° to 35°	70 $\mu\text{V/m}$
15° to 25°	180 $\mu\text{V/m}$
5° to 15°	400 $\mu\text{V/m}$
5°N to 5°S	500 $\mu\text{V/m}$

Note: The contiguous United States ranges in latitude from approximately 25°N to 49°N.

For any given antenna configuration, and for a given direction from the antenna, the required transmitter output power, P , varies as the square of the minimum field strength, E , and approximately as the square of the required range, R . An equation which relates one required transmitter output power to another is therefore the following:

$$P_2 = \left(\frac{E_2}{E_1} \right)^2 \left(\frac{R_2}{R_1} \right)^2 P_1 \quad (2.1)^\dagger$$

The radiated power required decreases with frequency and the efficiency of the fractional wave length antennas used by the Coast Guard increases as the frequency increases, but the frequency is not as significant as the latitude and range in determining the power level required. For analysis of requirements in this feasibility study, all stations will be assumed to radiate at 300 kHz.

A 300 kHz signal from a transmitter with output power of 100 watts using a standing T antenna (60-foot vertical section and a 300-foot horizontal section) has a transmission range over sea-water of 140 miles at 30° latitude (E is 70 $\mu\text{V/meter}$) (Ref. 9)*. From this information and Equation (2.1), one can calculate the required transmission output power as a function of range and latitude for other stations. Then the total transmitter input power requirement can be determined using the

*References

8. Dr. Ray Saterwhite, Southern Avionics, personal communication, April 15, 1980.
9. Chief Warrant Officer Richard A. Lake, III, U. S. Coast Guard (G-EEE), personal communication, April 14, 1980.

† Because of groundwave propagation and skywave ionospheric reflection, the exponent of the range ratio factor is slightly less than two. Thus Equation (2.1) is not exact.

table of required input power versus transmitter output power for the solid state radio beacon given on the first page of Appendix C. For example, the 100 watt output power level discussed above requires 451 watts of input power for the transmitter. Unfortunately, the new solid state radio beacon is not a high efficiency design.+ It requires 173 watts in the quiescent or squelched mode (Ref. 9).

If an 80 ft. whip antenna with a loading coil in the center were used instead of the 60 ft. high top loaded T antenna, approximately 50% more transmitter output power would be required. The reason for this is that the broadcast range from an antenna is proportional to the current in the antenna, and resistive impedance of the T antenna is approximately 8 ohms, while it is 12 ohms for the whip antenna. Other antenna types produce other power demands. Short range beacons often use only a 25 foot whip antenna, because they are economical to install (\$250). The relatively low radiated power requirement of a short range station permits an inefficient antenna to be selected, but major beacons should use the top loaded "T" antenna or a taller whip for greater efficiency. This study will assume that the more efficient T antenna is used at all stations converted to alternate energy sources.

The remote control and monitor system (RCMS) has an estimated power consumption of 27 watts (See Appendix D). The remote station radio link set uses 29 watts in the squelched transmitter mode and 190 watts in the transmit mode (Ref. 10)*. The audio-visual controller was determined to use 36 watts by measurement at the U. S. Coast Guard Electronics Engineering Lab in Alexandria, Virginia and by analysis at APL (See Appendix D).

The 12-volt battery charger can draw a maximum of 850 watts (Ref. 11)*. At the present time, all the DC loads in the signal control hut receive their power through this 12-volt battery charger. Thus the inefficiencies of the AC to DC conversion are added to the DC loads of the RCM, the radio link set, and the audio-visual controller. From Appendix D, this conversion efficiency is estimated to be 77%. Thus 12-volt DC power derived from an alternate energy system and used directly by 12-volt DC loads can avoid losses inherent in the present system. This will be discussed further in subsection 2.2.4.

The 24-volt battery charger in the prime power hut can draw a maximum of 650 watts. The previous assumption and conversion efficiency estimate appear reasonable for this charger.

*References

10. General Electric, Maintenance Manual for Radio Link Set, REM Sta. Type CG-REM-202A, page V.

11. McGraw-Edison, Technical Manual-Battery Chargers, Aug. 1973, page 1-2.

+ As the final version of this report was being prepared, it was learned that the Coast Guard did not exercise its option to proceed with acquisition of more AN/FRN-40 solid state beacons. It is assumed that some new solid state beacon with similar or better efficiency will be acquired to replace the tube-type sets used currently in LAMP stations.

The environmental control unit uses 1200 watts (Ref. 12)*. However, this unit is on only when the diesel engine-generator set is running. The power requirement for any alternate hybrid power source would therefore not include this component load. Reduction in the environmental control unit power use would, however, permit more of the diesel electric power to be used for recharge of the energy storage system and thus conserve diesel fuel. This will be discussed further in subsection 2.2.5.

The automatic power system controller power requirement is approximately 34 watts when the engine-generator set is not operating (Ref. 12), and it is not a significant load when diesel-electric output is available.

The engine-generator set requires power only at start-up. The existing 24-volt battery system supplies this power and the energy required for starting the diesel is negligible compared to the energy dissipated in the 24-volt battery charger and the battery self discharge.

2.1.3 Typical Integrated LAMP System Average Power Requirements

The power requirement for an integrated LAMP system is a function of mission and weather, as indicated by the variability of component power use discussed previously. The variation of power requirements versus mission, weather, and season will be discussed in the next subsection. This subsection will discuss average power use for "typical" LAMP station components in a hybrid power system during four common environmental situations: daytime with and without fog, and nighttime with and without fog (poor visibility). The assumptions used to construct power use during these conditions are:

1. The optic used is a DCB-24.
2. The sound signal is a CG-1000, ELG-300/02.
3. The radio beacon has a range of 60 miles; a 60-ft. vertical, 300-ft. horizontal T antenna is used; and the site is located at 30° North latitude.
4. The light signal is turned off during the day.
5. The sound signal is operated only during periods of low visibility as indicated by Videograph, CDNC-147.122/222.
6. An alternate energy system is supplying power and the engine-generator and environmental control unit are not operating.
7. The alternate energy system supplies 12V DC power to all 12 V loads both day and night. The power for these loads does not pass through the present 77% efficient AC powered battery chargers.
8. The average power requirement is a true average of the peak and base loads based on stated duty cycles.

*Reference

12. Russell Doughty, U. S. Coast Guard, Office of Engineering (G-EOE-3), personal communication May 6, 1980.

Power required by components of the alternate energy system for control, power conditioning, etc., is not included. The alternate energy system must supply its own power requirements as well as the average power listed for LAMP components as follows:

2.1.3.1 Case No. 1, daytime power use (good visibility)

System Component	Average Power (watts)	
	AC	DC
1. RCMS Control		27
2. Radio Link Set		34+
3. Audio Visual Controller		36
4. Radio Beacon	190 ⁺⁺	
5. Automatic Power Controller		34
6. Fog Detector		24
Total	<u>190</u>	<u>155</u>

2.1.3.2 Case No. 2, nighttime power use (good visibility)

System Component	Average Power (watts)	
	AC	DC
1. Light Signal Equipment	1470	
2. Case No. 1 Components	<u>190</u>	<u>155</u>
Total	<u>1660</u>	<u>155</u>

2.1.3.3 Case No. 3, daytime power use (poor visibility)

System Component	Average Power (watts)	
	AC	DC
1. Sound Signal Equipment	426 ⁺⁺⁺	
2. Case No. 1 Components	<u>190</u>	<u>155</u>
Total	<u>616</u>	<u>155</u>

2.1.3.4 Case No. 4, nighttime power use (poor visibility)

System Component	Average Power (watts)	
	AC	DC
1. Sound Signal Equipment	426 ⁺⁺⁺	
2. Case No. 2 Components	<u>1660</u>	<u>155</u>
Total	<u>2086</u>	<u>155</u>

- + Assuming Radio Link Set transmits 10 seconds every 5 minutes
⁺⁺ Assuming the Radio Beacon transmits 1 minute every 6 minutes
⁺⁺⁺ Assuming the sound signal is on for 2 seconds every 15 seconds.

If we assume both that the daytime (light-off) period is 11 hours (and correspondingly the night is 13 hours long) and that fog is present 10% of the time, both day and night, then the 24-hour usage of energy is:

<u>Situation</u>	<u>Time(hours)</u>		<u>Power(watts)</u>		<u>Energy(kWh)</u>
Case No. 1, (day & clear)	9.9	@	245	=	2.426
Case No. 2, (night & clear)	11.7	@	1815	=	21.235
Case No. 3, (day & fog)	1.1	@	771	=	0.848
Case No. 4, (night & fog)	1.3	@	2241	=	2.913
			Total:		27.423 kWh

Thus the 24 hour average power requirements of the modules in a LAMP station operating in an energy efficient mode from an alternate energy system would be only a little more than 1 kW. The annual average power requirement is also only a little more than 1 kW as the 11 hour night and 13 hour day with 10% fog is representative of typical annual average conditions. However, the power requirement of a station vary with its mission, weather and the season of the year.

2.1.4 LAMP Power Requirement as a Function of Mission, Weather and Season

The definition of "mission" in this report not only refers to the aids to navigation required (beacon, yes or no; sound signal, yes or no) at the site but also to the range required for the various signal. Thus the variation of LAMP power requirement as a function of mission is significant.

The percentage of LAMP installations⁺ which have radio beacons is 61%. Assuming that the higher power beacon stations use the T antenna discussed in subsection 2.1.2, the expected peak power requirement for the new solid state radio beacons varies between approximately 200 watts and 385 watts depending upon the required range and the latitude of the station. Some stations with less efficient antennas than the T antenna may now require more power for the radio beacon. Some of the beacons are sequenced (such as one minute transmission every six minutes) while others transmit continuously. Thus the average power requirement for the radio beacon varies from 173 to 385 watts, and details of the signal duty cycle must be examined to determine long term average power.

The percentage of prime powered LAMP installations which have or will by 1987 have a sound signal is 84%. Twenty-seven percent of the LAMP installations have a peak power requirement for the sound signal of 3264 watts while 50% require 1632 watts. An estimated 7% of the LAMP installations will still be using air horns rather than the standard

⁺ LAMP installations which use diesel engine-generator sets for prime power are the ones analyzed for this study. They were identified using the SANDS List, 1979, and LAMP conversion schedules (56 LAMP sites were identified among the 64 diesel-power sites listed in Table B-1 of Appendix B). Some of these installations may have since been converted to commercial power, however.

LAMP sound signal by 1987 and the remainder have no sound signal. Both the station weather and on-time duty cycle of the station fog sounder must be examined to construct long-term average power requirements for the fog sounder.

The percentage of prime powered LAMP installations which use two 1000-watt lamps is 29%; 55% use one 1000-watt lamp and 13% use one 500-watt lamp. Ambrose Light uses a flash tube rather than a standard lamp (8000 watts peak power and 3760 watts average power). Manana Island Fog has no lamp while the light at Monhegan Island (880 feet away) has no fog sounder. Thus the variation in average power required for the light signal (including power for rotating the optic and excluding Ambrose Light) varies from zero to 2470 watts depending upon mission.

A histogram of the peak power used for the radio beacon, if any, and the light at 55 diesel-powered LAMP lighthouses is given in Figure 2.1. Figure 2.1 was constructed from the detailed listing of power requirements for 64 remote aids given in Table B-1 of Appendix B. A similar histogram also constructed from the data of Appendix B giving the peak power used at the 46 diesel-powered LAMP stations equipped with light and electrical sound signal is shown in Figure 2.2.

Figure 2.1 reveals that the peak power requirement for the light and any radio beacon (with the fog sounder off) at LAMP installations is less than 1000 watts for 14% of the sites, 1000 to 2200 watts for 53% of the sites and 2400 to 2800 watts for 33% of the sites. This variation in peak power requirements is a result of different operational requirements at each site. The peak power does not include very brief higher power levels associated with lamp turn-on, etc.

Figure 2.2 reveals that the peak power requirement for the light, radio beacon, if any, and electric sounder at LAMP installations providing both light and fog signals is less than 1000 watts for 2% of the sites (one station), 1000 to 3400 watts for 49% of the sites, 3800 to 5200 watts for 38% of the sites and 5800 to 6000 watts for 11% of the sites. Note that nine of the stations included in Figure 2.1 have no sound signal and are not included in Figure 2.2.

The main variation in power requirements for LAMP installations as a function of weather is between good and poor visibility (absence or presence of fog). The variation in peak power requirement as a function of weather is illustrated by comparing Figures 2.1 and 2.2. Figure 2.1 is for good visibility (no sounder) while Figure 2.2 is for poor visibility. The maximum peak power for navigation aids varies from about 2800 watts for good visibility to a maximum peak power of about 6000 watts for poor visibility. The increased spread in peak power requirements for poor visibility conditions is also illustrated by comparing Figure 2.2 with Figure 2.1.

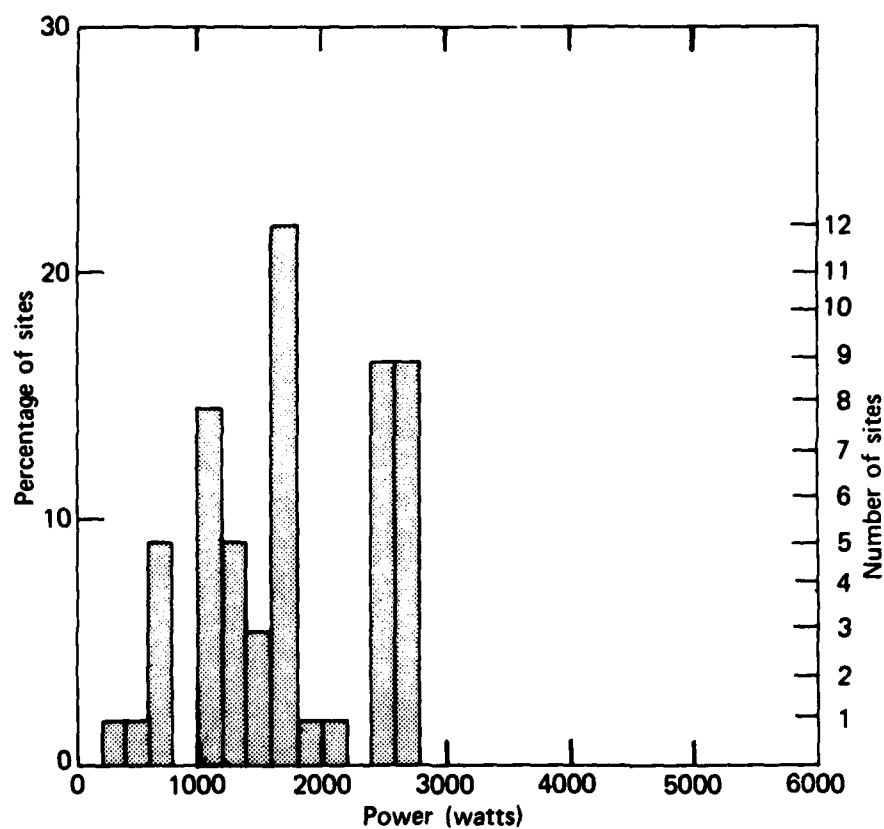


FIGURE 2.1 HISTOGRAM OF PEAK POWER REQUIREMENTS AT 55 PRIME POWERED LAMP INSTALLATIONS DURING CLEAR WEATHER.

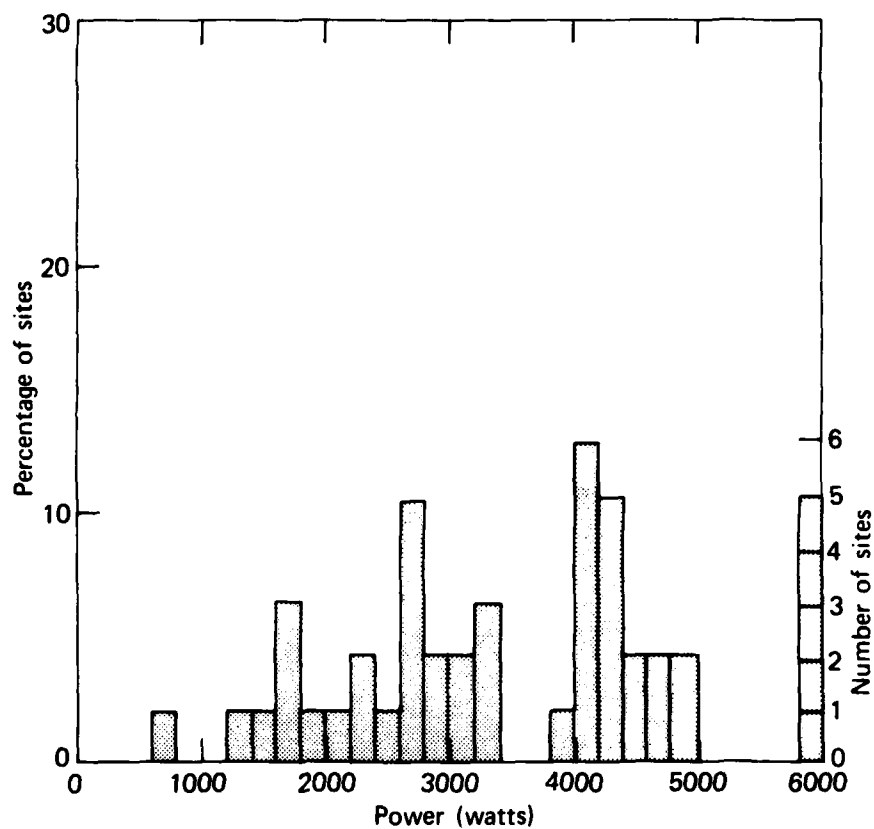


FIGURE 2.2 HISTOGRAM OF PEAK POWER REQUIREMENTS AT 46 PRIME POWERED LAMP INSTALLATIONS WITH FOG SIGNAL ON.

The variation of power requirements for LAMP installations by season results from seasonal variations in low visibility conditions and in the number of hours of nighttime. Sea fog is most common in the fall and winter in the north Atlantic off the New England coast. The warm ocean waters provide moisture that condenses in colder autumn air. Sea fogs are often carried inland with gentle onshore winds. Fogs also develop off the northwest coast but are less common than in New England, perhaps because of the gulf stream. Land fogs originate over both sea and land, but require stagnant air and clear nights. Nocturnal radiation can cool the air near the ground below the dew point producing a temperature inversion and fog in stagnant air. Land fogs typically "burns off" before noon, but sea fogs may persist all day. In general fog is: 1) more common in the fall and early winter, 2) more common on the east coast of the U. S. than the west coast, and 3) more common in the north than the south, but fog is strongly influenced by local conditions, especially land fogs, and site specific records are essential to accurate predictions.

The seasonal variation of nighttime hours as a function of latitude is illustrated in Figure 2.3 (Ref. 13)*. Assuming the light is required to be on one hour plus the number of hours of nighttime each 24 hours, the seasonal variation of the hours of nighttime power use is shown in Table 2.2 as a function of latitude.

TABLE 2.2. SEASONAL VARIATION IN HOURS OF NIGHTTIME

Latitude	Vernal Equinox	Summer Solstice	Autumn Equinox	Winter Solstice
20°N	13	11.8	13	14.2
30°N	13	11.1	13	14.9
40°N	13	10.2	13	15.8
50°N	13	8.8	13	17.2
60°N	13	6.5	13	19.5

Note: Power requirements of both lamp and radio beacon are maximal at night.

2.1.5 Power Required for Lighthouses other than LAMP Installations

In keeping with the power source restriction used in analyzing the power requirements of LAMP installations (only diesel powered sites were analyzed), eight diesel powered lighthouses not scheduled for conversion to LAMP installations have been identified and included in Appendix B. A histogram of the peak power requirement for the radio beacon, if any, and light at diesel powered non-LAMP installations during clear weather is given in Figure 2.4. The difference in the

*Reference

13. W. E. Allen and J. E. Tarr, Final Report on U.S. Coast Guard Solar Powered Aids to Navigation (SPAN) Study, JHU/APL, SDO 5528, February 1980.

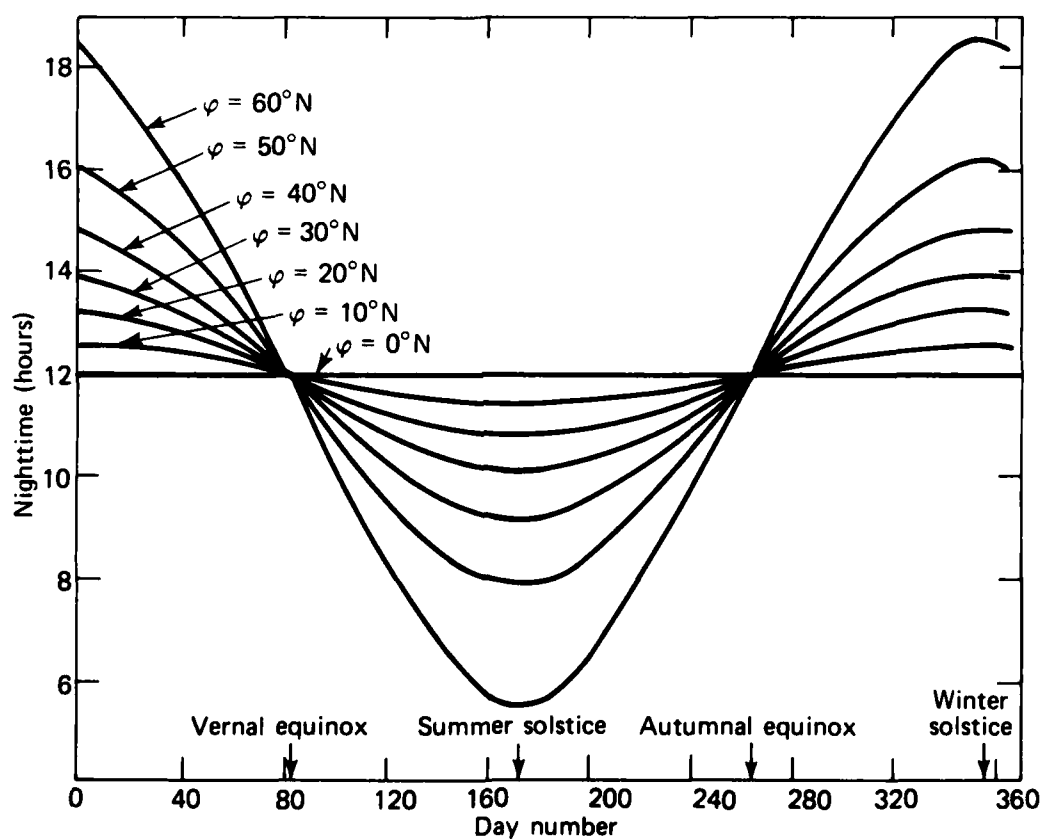


FIGURE 2.3 NIGHTTIME HOURS AS A FUNCTION OF DAY NUMBER AND LATITUDE (ϕ) OF OBSERVER.

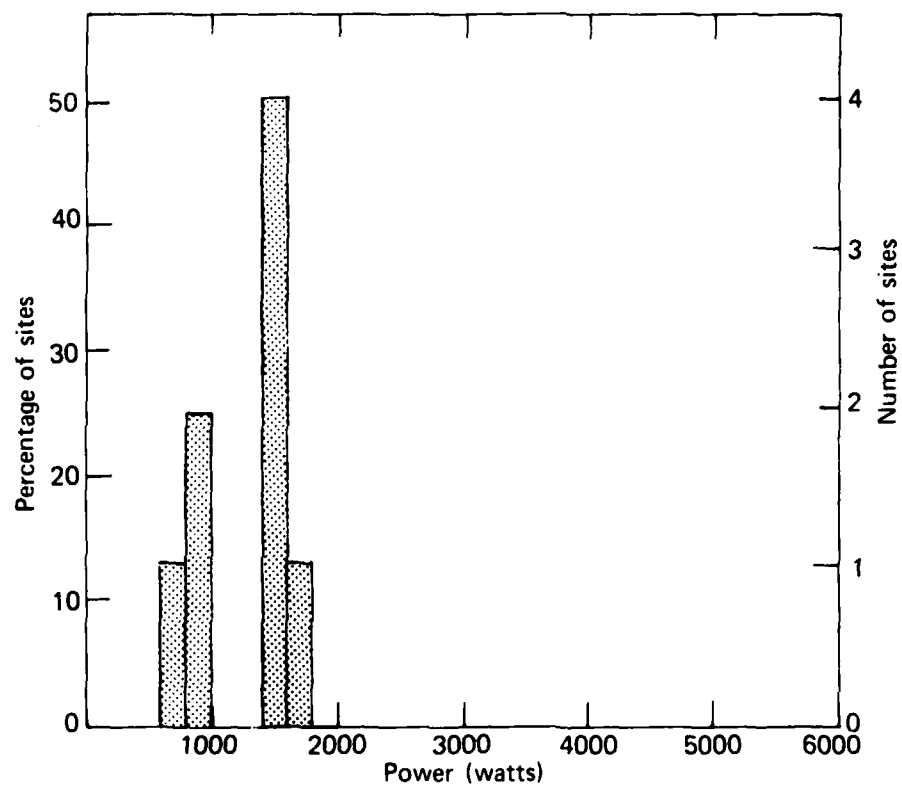


FIGURE 2.4 HISTOGRAM OF PEAK POWER REQUIREMENT FOR THE RADIO BEACON AND LIGHT AT EIGHT PRIME POWERED NON-LAMP INSTALLATIONS.

character of this histogram compared to that of Figure 2.1 is mainly a result of the statistically smaller number of sites. The range of power requirements is very comparable to LAMP installations. The spread in power requirements is actually smaller than that of the LAMP installations.

A histogram of peak power requirements for the light, radio beacon, if any, and sound signal at non-LAMP installations is given in Figure 2.5. Again the range of power requirements is comparable to LAMP installations. (See Figure 2.2.) One main difference between Figures 2.2 and 2.5 is that 75% of the non-LAMP installations have a peak power requirement less than 2400 watts while only about 23% of the LAMP installations have a peak power requirement less than 2400 watts.

2.1.6 Power Required for LORAN-C and Vessel-Traffic-System Transmitters

Thirteen of the 35 LORAN-C stations are prime powered (diesel generators) and listed in Table B-2 of Appendix B. A histogram of the peak input power requirements for transmitters at these 13 LORAN-C stations is shown in Figure 2.6. The transmitted power is typically 2.5 times as large as the generator power rating. (The transmitter stores energy between radio pulses.) The exact relationship between transmitted power and generator power requirements depends upon the antenna efficiency, the number of pulses per group (8 or 9) and the group repetition interval (typical 10 to 15 groups per second), but Figure 2.6 gives an adequate indication of signal power requirements at diesel-powered LORAN-C stations for this study. Note that the power requirement is given in kilowatts and not watts as in previous histograms. Also note that general station power requirements are not included in Figure 2.6 as they vary with the weather and staffing levels at the station. The installed generator capacity given in Table B-2 of Appendix B includes reserve capacity and power requirements for personnel stationed at the site. Automation and demanning of remote LORAN-C stations could reduce power requirements to the levels shown in Figure 2.6.

Only two of the 16 vessel traffic system sites are prime powered. These two are Montague Peak (8 kW) and Potato Point (30 kW). The system at Montague Peak is to be moved to Naked Island; its expected peak power demand will be 15 kW instead of the present 8 kW. Both the vessel traffic system and LORAN-C are 24-hour/day services. Their transmitter power requirements are not significantly dependent upon the weather. Thus the average signal related power requirements are approximately equal to the peak power demand.

Note that the LORAN-C station on Nantucket Island uses commercial power and is thus not technically part of this study, but that power is entirely generated by oil imported to the island. The cost of electricity for the Nantucket LORAN-C station is sufficiently high (10¢/kWh) to make a study of on site wind power generators attractive. Wind generations on Nantucket would not reduce the Coast Guard's oil consumption but may reduce U.S. oil consumption and lower Coast Guard operational expenses.

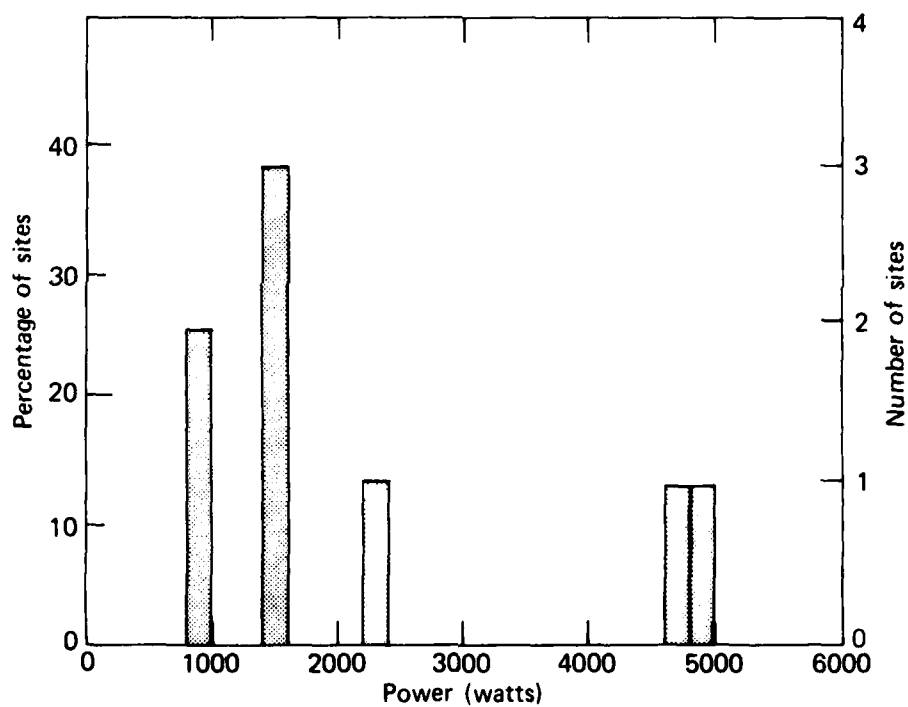


FIGURE 2.5 HISTOGRAM OF PEAK POWER REQUIREMENT FOR THE RADIO BEACON, LIGHT AND SOUND SIGNAL AT EIGHT PRIME POWERED NON-LAMP INSTALLATIONS.

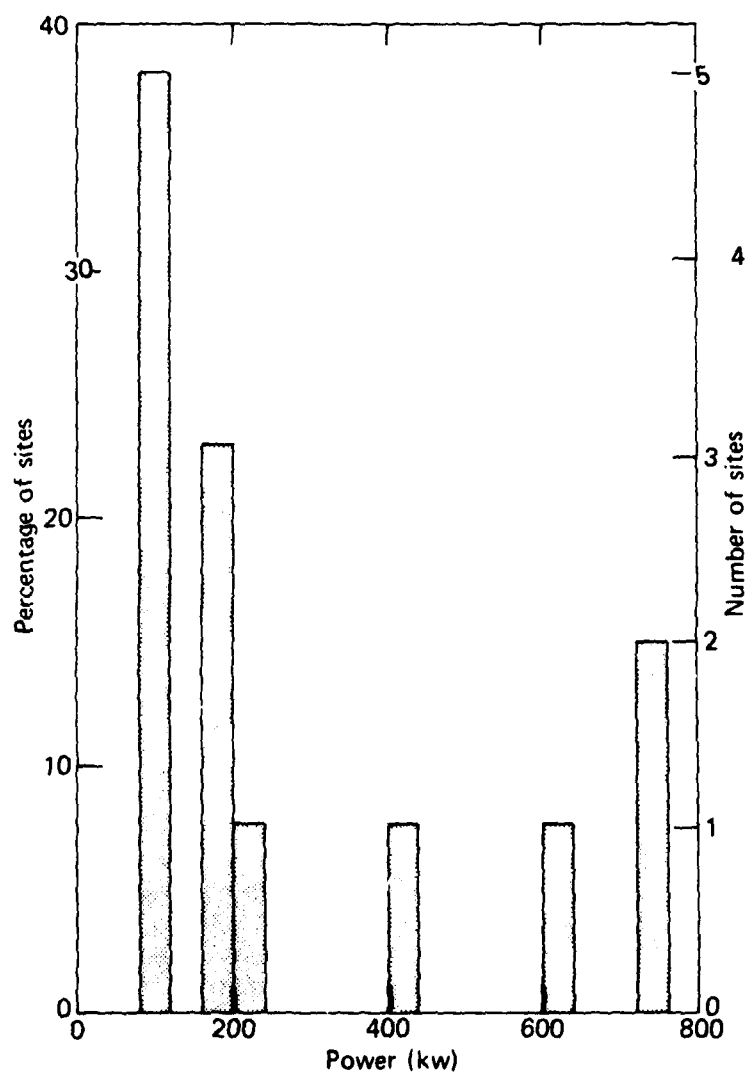


FIGURE 2.6 HISTOGRAM OF PEAK POWER REQUIREMENTS FOR PRIME POWERED LORAN-C TRANSMITTERS, (Note the power is in kilowatts, not watts.)

2.2 ENERGY CONSERVATION

The following methods and techniques for reducing energy and/or fuel were considered: daylight control of the light, the replacement of tungsten lamps with gas discharge lights, more energy efficient electrical equipment, use of DC rather than AC for selected components, operating diesels at their optimum efficiency, recovery and utilization of waste heat, reduction of site visits, and luminance control of light and sound signals. A discussion of each of these follows.

2.2.1 Daylight Control of the Light

Turning off the light signal during daylight hours could save a significant amount of energy, even at high northern latitudes. The effect of latitude upon the number of nighttime hours as a function of day number (Ref. 13) is shown in Figure 2.3. The important thing to observe from Figure 2.3 is that although the number of nighttime hours gets very large at high northern latitudes in the winter, during the summer the number of nighttime hours gets comparably small. The average nighttime hours during the year is 12 hours no matter what the latitude of the observer is. Thus the simple approach of turning off the light signal during the day results in effectively the same annual energy saving independent of latitude.

The light must be on one hour in addition to the nighttime hours to aid navigation during early dawn and dusk periods. Thus the annual average period that the light must be turned on is 13 hours each day. Daylight control can save approximately 16 kWh (11 hrs x 1.47kW) of electrical energy each day or 37% of the total energy used at a typical installation with no daylight control (43.6 kWh). (Care must be taken to insure that sunlight focused by the mirror of a stationary optic can not damage it.)

2.2.2 Gas Discharge Light or Flashtube

Gas discharge lights or flashtubes have been proposed to replace incandescent lamps presently used in the light signal generator. The efficiency of electrical energy conversion to light for flashtubes ranges between 30 and 50 lumens/watt depending upon how hard they are driven. The efficiency of the 1000-watt tungsten-halogen incandescent lamp presently used by the Coast Guard is 17.2 lumens/watt (2.5% efficient). Thus flashtubes are potentially more efficient than incandescent lamps; however, the efficiency of the power supply may decrease the apparent advantage if it is not carefully designed. The short flash duration possible allows the average power required for operation to be very low if the period between flashes is one second or longer. Note also that an omnidirectional array of flashtubes does not require any mechanical rotation to produce the characteristic period used by the mariner to identify the light. Thus, the flashtube lighthouse would not require power for the optic rotation motor. Elimination of the mechanical rotation not only saves energy, but probably increases station reliability.

The problem with using flashtubes for navigation is that although the flash can be seen, its duration is too short for the eye to move and get a fix on its location. To overcome this problem the light can be flashed rapidly several times to simulate a flash of longer duration, but the energy requirement goes up proportionally. Determination of the required flash rate is a complex question involving human factors and station operational performance standards. Another problem associated with most flash lamps is that the spectrum contains little red light. This may limit flashlamps to white light only applications. In LAMP lighthouse applications, flashtubes would appear to have energy conservation advantages over incandescent lamps but this study can not determine how much, if any.

2.2.3 More Energy Efficient Equipment

Much of the equipment presently designed for use at LAMP installations was not designed for energy efficiency. For example, the new solid state radio beacon uses about 173 watts in the squelched transmitter mode. This particular transmitter has triple circuitry for reliability, and significant reduction of its quiescent power requirements was not considered important during its design. However, when one considers the high cost of an alternate energy system to supply 173 watts rather than possibly 20 watts, which might have been the power requirement for the squelched transmitter mode if energy efficiency had had a high priority, the design priority of energy efficiency becomes very clear. A simpler approach to saving energy during the squelched transmitter period other than a total redesign may be possible, however. If the clock section can be isolated from the rest of the transmitter, it might be used to drive a control box which turns off the rest of the transmitter when the transmitter is in the squelched mode. For the sequenced radio beacons which transmit only one minute every six minutes, such an approach would be very useful. Similarly, future redesign of the control and monitor equipment can save energy. For example, the audio-visual controller has a resistor for monitoring the light which consumes 18 watts when the light is on.

Reductions in the power requirements of the RCMS, the audio-visual controller, and the automatic power controller to 10 watts each would reduce the DC power requirements from 155 watts to 88 watts. Also, if the radio beacon quiescent power requirement were reduced from 173 watts to 20 watts this would result in a daily energy savings of 5.8 kWh. This is 21% of the energy (27.4 kWh) expected to be consumed at a typical hybrid energy system LAMP installation with daylight control and a typical 13-hour light-on night.

2.2.4 Use of DC Rather than AC Power for Selected Components

The 12 volt battery chargers convert AC power to DC power at approximately 77% efficiency. At the present time, power for all DC loads goes through the battery chargers. If the alternate energy system produced DC power directly, this power loss in the chargers could be eliminated. This power loss is about 1.1 kWh/day for the DC load at the typical LAMP installation.

The radio beacon converts AC power to DC power which is then used to generate RF power. Assuming the AC to DC conversion is 80% efficient, direct use of DC power for the radio beacon would save approximately 0.9 kWh/day at the typical LAMP installation. Furthermore, the radio beacon is the only AC load on during fog-free days. A great deal of energy is wasted by running a 6.5 kW diesel-electric generator all day to supply an average power of approximately 200 W. The radio beacon should be redesigned for greater efficiency and a 12 volt DC input like all other daytime components in the signal module (except the fog signal). Assuming 75% load minimum is required whenever the diesel runs to avoid carbon build-up problems, then approximately 4.4 kW are wasted each fog-free daylight hour. If the typical day is fog free for 10 hours, 44 kWh/day could be saved by keeping the diesel off and operating the radio beacon directly from 12 volt batteries. Part of this saving would be lost due to battery charge-discharge inefficiency but approximately 30 kWh/day saving should be possible if the diesel were off during fog-free daylight hours.

The sound signal converts 60 Hz AC power to DC power. This power is then converted to 150 Hz AC power which drives the 300 Hz acoustical generator. If DC power were used directly to power the sound signal approximately 2 kWh/day could be saved during those days when the sounder is operating continuously. Assuming the sounder functions about 10% of the time, the average savings would be 0.2 kWh/day. The sounder appears to be designed so that it could operate directly from a 110 VDC supply, but minor modifications may be required.

The total direct savings in power expected at a typical LAMP installation from using DC power rather than AC power for selected components is approximately 2.2 kWh/day. This is 8% of the daily energy used in LAMP modules at a typical hybrid power LAMP installation with daylight control. However, the indirect energy saving is much larger if the diesel can be turned off during the daytime as this avoids wasting energy merely to keep the diesel under sufficient load to avoid carbon build-up problems.

The motors used to drive the rotating optics and the lamps currently operate on AC. If inverters have to be installed to convert DC from an alternate energy system to AC for the motor and lamp(s), the resulting power losses due to inverter inefficiencies may more than offset the direct energy savings expected in LAMP modules as outlined above, but the indirect energy savings achieved when the diesel is off during the day is very significant. Thus either an inverter must be supplied for the radio beacon or preferably it should be designed for a 12 volt DC input power alternative mode of operation.

2.2.5 Operate Diesels at their Optimum Efficiency

An equation for large constant-speed, diesel engine-generator sets that relates the percent of full-load fuel consumption, F , as a

function of the percent of rated full load, X, is given below (Ref. 14)*.

$$F = 0.893X + 10.7 \quad (2.2)$$

It is assumed that this equation also applies to the smaller Lister diesel engines used at LAMP installations.

The net power available from an SR2 diesel generator, P, after subtracting the 1.2 kW required by the environmental control system to furnish filtered air for the diesel enclosure is given in Table 2.3. The diesel-electric generator system, including the fixed 1.2 kW load for the air filter fan becomes increasingly less efficient as the load on the diesel is decreased. At 20% of full-load fuel consumption, the net power produced by this system is nearly zero - i.e., it is just able to power the blower used in the environmental control system. A more efficient fan in the environmental control system could significantly improve the system efficiency, especially under partial load conditions.

TABLE 2.3. DIESEL-GENERATOR PARTIAL LOAD PERFORMANCE
Percent of full-load fuel consumption, F,
versus percent of rated full load, X,
and net power, P, available from model SR2
diesel-generator

X	P(kW)	F
20	0.1	28.6
40	1.4	46.4
60	2.7	64.3
80	4.0	82.1
100	5.3	100.0

For an SR2 Lister diesel operated at 1800 rpm the rated horsepower is 12 and the fuel consumption at full load is 0.44 lb/hp/hr or 0.06 gal/hp/hr (Lister Technical Manual). The rated electrical output from the SR2 engine-generator set is 6.5 kW. The environmental control unit for the diesel generator set (See subsection 2.1.2) requires 1.2 kW and operates whenever the set operates, so the maximum net electrical output actually available for signal loads is 5.3 kW. The amount of diesel fuel required to daily generate all of the 27.4 kWh required for a typical hybrid power LAMP installation with daylight control at the full load diesel-electric efficiency rate would be 3.72 gallons (including the power requirement for the environmental control unit). This amount of electrical energy would be generated in 5.17 hours at the full load rate. At present this energy requirement is generated over a 24-hour period. In a 24-hour period, the environmental control unit requires 28.8 kWh; when added to the 27.4 kWh for a LAMP installation, an average of 36% of the rated full load results. However, because of the potential for carbonization the diesel must be operated at an average of 60 to 75

*Reference

14. Charles L. Segaser, Conventional Alternating-Current Generators and Engine Generating Sets, ANL/CES/TE 78-1, Oak Ridge National Laboratory, April 1978, page 22.

percent of the rated capacity (Refs. 12 and 15)*. Ways that are used to keep the load at 60 or more percent of the capacity are to add flood lights, keep the navigational aids operating even though they are not needed and/or add ballast resistors. If the diesel is operated at 60% of capacity, the fuel required is 64.3% of the full-load fuel consumption rate or 11.1 gal/day (almost a 200% increase in fuel consumption over 3.72 gal/day required for the typical LAMP aid if supplied at the most efficient diesel-electric rate).

In order to operate the diesels at their optimum efficiency and deliver the load when it is needed, an energy storage system is required. If the energy storage system is 70% efficient (returning 70% of the energy supplied to it), then to supply the 27.4 kWh for the navigation aids, the diesel must generate 39.1 kWh for storage. This requires 7.4 hours of optimum running of the diesel. The fuel consumption would be 5.3 gal or 48% of the fuel consumption required for steady operation at 60% of the rated capacity, a significant savings. Note also that the diesel would operate less than one third of the day. The period between overhauls and visits to the station for fuel resupply could be significantly increased.

2.2.6 Utilization of Diesel Engine Waste Heat

Although the diesel engine is the most efficient widely applied prime power mover, the Lister unit used in LAMP stations still converts only about 31% of the fuel energy supplied to it into useful mechanical work. The standard LAMP diesels are air cooled. They discharge approximately 50% of the total fuel energy with the exhaust gas and the balance of the wasted energy heats the air inside the power hut, partially by direct contact with the engine and exhaust system and partially via the lubrication oil and oil sump tank. Some of the heat lost to air inside the power hut is beneficial in a northern climate as it provides the thermal input required by the prime power module environmental control unit. Any hybrid energy system that is successful in eliminating diesel use for many hours must provide an alternate thermal energy source (although significantly less than the diesel provides) for temperature control in northern climates. Thus thermal storage may be required. This thermal storage system could take the form of a closed-loop circulating heat transfer system using engine lubrication oil and the main fuel-oil tank as a storage mass with large thermal inertia. The same closed-loop circulating heat transfer system used to transfer thermal energy into the main fuel tank when the diesel is operating could transfer heat back into the power hut when the diesel is off, although an additional oil-filled radiator in the power hut module may be required. Alternatively, a nonflammable heat transfer fluid and heat exchanger could be used in the hot exhaust gas when the diesel is operating to recover additional thermal energy with smaller heat exchangers.

The high temperature of the exhaust gas makes recovery of mechanical energy from the exhaust gas stream technically possible. Two

*Reference

15. Coast Guard LAMP, CG 250-41a, page 86.

distinct concepts have been applied for energy recovery from waste heat in diesel exhaust gases. The exhaust gases can be expanded through a turbine to develop shaft horsepower or can be used in a "bottoming cycle" heat engine.

The first approach is being actively developed by the automotive industry, but the shaft horsepower developed by the exhaust gas turbine is not employed to drive the wheels of the vehicle or run an electric generator. Instead, an air compressor is driven to "supercharge" the engine with a greater mass flow of air than is possible by natural engine aspiration. Air directly entering an engine from the compressor of the turbocharger is hotter than the air naturally aspirated into the engine and more fuel is consumed with each power stroke. The resulting higher cylinder temperatures and higher power levels can significantly reduce engine life (Ref. 16)*. Consequently, the hot air from the compressor of the turbocharger is usually cooled before entering the engine and part of the thermal energy acquired from the exhaust gas is thus dissipated in the ambient air. Cooling the air also increases its density and allows for a greater injected air mass and more power per stroke without excessive temperatures.

The primary advantage of the turbocharger for the automotive industry is the significant gain in horsepower-to-weight ratio possible with a turbocharged engine. The gains in fuel efficiency, if any, for a stationary turbocharger engine are modest as most of the gains in fuel economy (miles/gallon) achieved in a vehicular application with a turbocharged engine are associated with weight reduction of the vehicle. A lighter vehicle requires a less powerful engine to achieve the same performance (acceleration) and this also contributes to the gains in fuel economy possible in a turbocharged vehicle.

High reliability requirements and the cost of more frequent engine overhauls make the application of turbocharger technology, as developed for vehicular applications, of questionable value for stationary power sources. However, the shaft horsepower developed by the exhaust gas turbine of a turbocharger could be utilized to drive an electrical generator, with potentially significant beneficial effect upon overall fuel efficiency. This technology does not appear as attractive as the second approach to waste heat utilization discussed in the next paragraph.

The organic Rankine engine, or bottoming cycle, is being developed instead of exhaust gas turbines for power recovery from engine exhaust gases. Mechanical Technology, Inc. is developing a bottoming cycle for large (7000 hp) diesels using Freon R-11 and/or R-114 as working fluids (Ref. 17)*. Thermo Electron Corporation is testing

*References

16. B. Haggh, Ernst Holmer, (Volvo Truck Corp.), "Air-to-Air Heat Exchangers Used for Diesel Intercooling," Automotive Engineering 87, No. 7, July 1979, page 30.
17. R. A. Tarkir, "Marine Diesel Bottoming Cycle May Save Fuel," Automotive Engineering 87, No. 7, July 1979, page 35.

Fluorinal-50 and 85 in a bottoming cycle for a diesel truck (275 hp) and reports fuel savings of up to 15% (Ref. 17). Sundstrand Energy Systems is developing several different bottoming engines based on toluene as the working fluid (Ref. 17). Their smallest system is intended for use in a bus with total output (both diesel and bottoming cycle) of 30 hp. The organic bottoming cycles under current development appear to be designed for greater heat fluxes than available from either the 12 or 18 hp standard LAMP model diesels, but larger Coast Guard diesel electric generators at LORAN-C and other sites could use units currently being tested, and small units for LAMP diesel modules appear technically feasible. Fuel savings of approximately 15% should be possible. However, a separate motor generator would be an additional system cost. Large organic Rankine engines are estimated to cost \$800-900/hp developed (Ref. 17) and smaller engines for Coast Guard applications would no doubt cost more per horsepower. The Coast Guard pays only about half this price/hp for its LAMP diesels in spite of the fact that they are much smaller than the large organic Rankine engines considered above. (See Reference 18* for a general discussion of various technical options possible for recovering useful power from diesel engine exhaust heat.)

2.2.7 Reduction of Site Visits

If a highly reliable hybrid alternate power system can be developed, the number of site visits to LAMP installations can be reduced. One reason for this is that a reduction in operating time for the diesel should reduce the required number of inspections and oil samplings. If the diesel operation time is reduced by a factor of two or more the number of required annual visits because of the diesel should likewise be reduced from four to two. (See end of subsection 2.2.5.) Daylight control should likewise increase the lamp life and reduce the required visits for inspection of the lamp.

The potential energy savings arising from reducing the number of annual site visits is estimated using information supplied by the Office of Operations (G-OP) of the U. S. Coast Guard. According to the best information available to G-OP staff, maintenance and resupply missions require approximately 62,000 gallons annually to service 40 LAMP sites with four visits each per year. Thus, each visit consumes approximately 388 gallons of fuel. This seems large but helicopters are often used to deliver maintenance personnel and some stations are quite remote from the supply base. After an alternate energy system is field proven, the more remote sites with great resupply costs would appear to be prime candidates for conversion to alternate energy system hybrids, even if their weather and load profiles are not the most attractive conditions possible for implementation of the alternate energy hybrid.

*Reference

18. C. J. Leising et al., "Using Waste Heat Boosts Diesel Efficiency," Automotive Engineering 86, No. 7, July 1979, page 35.

2.2.8. Luminance Control of Light and Sound Signals

Luminance control of light and sound signals would be based on transmissivity. Transmissivity at LAMP installations is presently detected by a videograph (fog detector). The importance of this device in reducing power required during periods of good visibility is illustrated in subsection 2.1.3 of this report. With the typical sound signal generator installed, the average AC power requirement for a LAMP installation is 2086 watts, as compared to 1660 watts with it excluded. More importantly, the peak power requirement changes significantly as is illustrated by comparing Figures 2.1 (sounder off) and 2.2 (sounder on).

The value of turning off the sound signal when there is no fog is thus obvious. The question of luminance control (variable intensity) for the sound and light signals is not as clear, however. The questions of reliable signals in a variable transmissivity environment versus energy savings cannot easily be resolved. The transmissivity in one direction may be 50% less than in a direction 90° away. The potential requirement for multiple videographs at one installation to ensure that one has determined the worst transmissivity for a given instant in time may negate any advantage from luminance control. Another reason the modulation of the intensity of the sound and light signals was rejected was that in the case of the lamp, even a 30% reduction in luminous intensity would save only approximately 10% energy because of the low efficiency (and other characteristics) of tungsten filaments. Again in the case of the fog sounder, a relatively small fraction of the year's 8760 hours is involved. Intensity modulation control equipment would increase the complexity of the station, the maintenance expense, and probably reduce the reliability of these navigation aids.

2.3 POWER LEVELS AND CLASSES

The power requirements of all known diesel powered Coast Guard installations have been compiled and listed in Tables B-1 and B-2 of Appendix B. Appendix B data is based on References 19, 20, and data supplied by the COTR. There is a concurrent effort within the Coast Guard to verify Appendix B data at the district level. Appendix B reflects the best data currently available, and is adequate for this study even if not entirely error free.

Lighthouses with a 10 inch rotating optic are listed in Appendix B as requiring 100 watts and those with 24 inch and 36 inch rotating optics are listed at 470 watts for the motor rotating the optic. Lighthouses with classical lenses whose speed of rotation are given in the SANDS Major Aid Listing (Ref. 19) are assigned the same power usage as the double 24 inch optic (470 watts) (Ref. 12). Those with classical lenses and lanterns with zero revolutions per minute were assumed stationary with no motor power requirement.

*References

19. Coast Guard, SANDS Major Aid Listing, 1979, LAMP Funding, March 23, 1979 and January 24, 1980.
20. Coast Guard, Light List, Vol. I-IV, 1980.

The power requirement for the sound signal generator (using a CG-1000 power supply) was calculated assuming 1632 watts are used during the blast and 240 watts are used during the silent period. The average power was determined by the duty cycle found in the Light List (Ref. 20). The three duty cycles used were 10%, 13.3% and 20%. For example, a sound signal with one CG-1000 power supply and a 20% duty cycle has an average power of 520 watts $((.20 \times 1632W) + (.80 \times 240W))$. These values were doubled for sound signals with two CG-1000 power supplies.

For a discussion of the power requirements of the rotating optic and radio beacon refer to subsection 2.1.2. It should be noted that the minimum RF output power for the radio beacon transmitter was taken to be 10 watts. Any transmitter calculated with Equation (2.1) to require an RF output power (into the antenna) less than 10 watts was assumed to require an input power of 213 watts $(10 \text{ watts} \times 4 \text{ (25\% efficiency)} + 173 \text{ watts (squelled transmitter mode)})$.

Accurate determination of the average power requirement for the radio beacon and light requires more information than is currently available on their modulation and duty cycle, such as length of various coding (dots, dashes and silences) for the radio beacon signal and how flashed lights are turned on and off or eclipsed (blocked). However, data similar to that given in subsections 2.1.2 and 2.1.3 are judged to be sufficient for this study.

Table 2.4 arranges the data given in Table B-1 in order of increasing peak power requirements during clear weather (fog signal off). Table 2.5 does the same but adds the peak power requirement for the sound signal generator, if any.

The distribution of average power levels for LAMP lighthouses during the night will be greater than peak power without fog shown in Figure 2.1 by the average nocturnal power required for the fog signal. Inspection of Figure 2.1 and Table 2.4 suggest that three nocturnal average power classes be defined for use in Task 8 generic analysis. Based on Figure 2.1, Table 2.4 and 2.5 data, and the recognition that some additional power will be required to manage the storage and use of energy collected from the environment, we define three generic average power classes high, medium, and low as given in Table 2.6 for use in Task 8.

TABLE 2.6. GENERIC POWER CLASSES
Average power (watts) levels

Power Class	High	Medium	Low
Night	3000	2000	650
Day	500	500	100

TABLE 2.4
CLASSIFICATION BY PEAK POWER
(sound signal off)

District	Lat-N (deg,min)	Long-W (deg,min)	Aid Name	Total Peak Power (Beacon & Light) (w)
Less than 500 watts				
1	43,36	69,20	MANANA ISLAND FOG	236
500 - 999 watts				
1	44,02	68,52	HERON NECK	500
12	37,50	122,25	ALCATRAZ	600
*17	58,33	134,55	SENTINEL ISLAND	600
9	44,39	87,54	GREEN BAY HARBOR	713
9	45,35	87,00	MINNEAPOLIS SHOAL	713
17	57,13	133,38	FIVE FINGER	713
*9	44,01	83,32	GRAVELLY SHOAL	813
*5	37,53	76,11	SMITH POINT STANDBY	970
1000 - 1499 watts				
1	44,34	67,22	LIBBY ISLAND	1000
3	38,59	75,07	BRANDYWINE SHOAL	1000
3	39,03	75,11	FOURTEEN FOOT BANK	1000
3	40,32	74,03	WEST BANK (RANGE FRONTY	1000
8	29,22	91,23	POINT AU FER REEF	1000
9	46,58	88,00	HURON ISLAND	1000
1	42,00	70,36	PLYMOUTH	1100
5	37,53	76,11	SMITH POINT	1183
9	42,00	83,08	DETROIT RIVER	1183
3	41,12	72,07	LITTLE GULL ISLAND	1213
5	37,23	76,11	WOLF TRAP	1213
9	45,42	84,22	POE REEF	1213
9	45,46	85,09	GRAYS REEF	1213
9	48,13	88,22	PASSAGE ISLAND	1213
1	43,43	69,46	SEGUIN	1470
1	43,46	69,19	MONHEGAN ISLAND	1470
1	44,22	67,52	PETIT MANAN	1470
1	44,29	67,32	MOOSE PEAK	1470
3	40,59	75,37	GREAT CAPTAINS ISLAND	1470
*7	31,57	80,41	SAVANNAH	1470
*8	29,01	89,10	SOUTH PASS RR	1470
*11	33,43	118,15	LOSA	1470

* Indicates station is not planned for LAMP conversion

TABLE 2.4 (cont'd)

District	Lat-N (deg,min)	Long-W (deg,min)	Aid Name	Total Peak Power (Beacon & Light) (w)
1500 - 1999 watts				
1	44,09	68,15	GREAT DUCK ISLAND	1683
*9	45,30	86,46	ST. MARTIN ISLAND K	1683
9	47,41	90,44	DEVILS ISLAND	1683
9	47,52	89,19	ROCK OF AGES	1683
11	34,01	119,22	ANACAPA ISLAND	1683
12	37,42	123,00	FARALLON	1683
12	41,50	124,23	ST GEORGE REEF	1683
13	48,19	122,51	SMITH ISLAND	1683
9	47,25	87,35	MANITOU ISLAND	1706
17	56,00	134,08	CAPE DECISION	1706
17	60,14	146,39	CAPE HINCHINBROOK	1748
7	24,38	82,55	DRY TORTUGAS	1748
17	59,48	144,36	CAPE ST. ELIAS	1775
17	58,12	136,38	CAPE SPENCER	1846
2000 - 2999 watts				
1	42,58	70,37	ISLE OF SHOALS	2470
1	43,07	70,29	BOON ISLAND	2470
1	43,58	68,08	MOUNT DESERT	2470
3	39,18	75,23	SHIP JOHN SHOAL	2470
9	45,30	84,46	ST. MARTIN ISLAND	2470
9	45,50	85,08	WHITE SHOAL	2470
17	54,24	164,45	SCOTCH CAP	2470
1	41,23	71,02	BUZZARDS BAY	2683
1	43,39	70,02	HALFWAY ROCK	2683
1	43,47	68,51	MATINICUS ROCK	2683
5	33,29	77,35	FRYING PAN SHOALS	2683
5	35,09	75,18	DIAMOND SHOAL	2683
5	36,54	75,43	CHESAPEAKE	2683
9	45,01	85,57	NORTH MANITOU SHOAL	2683
13	48,24	124,44	CAPE FLATTERY	2775
5	34,38	76,32	CAPE LOOKOUT	2775
Greater than 3000 watts				
3	40,28	75,50	AMBROSE	8275
Other				
9	45,54	85,34	LANSING SHOAL	Unknown

* Indicates station is not planned for LAMP conversion.

TABLE 2.5
CLASSIFICATION BY PEAK POWER
(sound signal on)

District	Lat-N (deg,min)	Long-W (deg,min)	Aid Name	Total Peak Power (Sound Signal, Beacon, & Light) (w)
1000 - 1499 watts				
17	57,13	133,38	FIVE FINGER	713
*9	44,01	83,32	GRAVELLY SHOAL	835
*5	37,53	76,11	SMITH POINT STANDBY	970
5	37,23	76,11	WOLF TRAP	1235
1	43,46	69,19	MONHEGAN ISLAND	1470
*8	29,01	89,10	SOUTH PASS RR	1470
*9	43,53	76,27	GALLOO ISLAND	1470
1500 - 1999 watts				
9	47,41	90,44	DEVILS ISLAND	1683
12	37,42	123,00	FARALLON	1683
13	48,19	122,51	SMITH ISLAND	1683
7	24,38	82,55	DRY TORTUGAS	1748
1	43,36	69,20	MANANA ISLAND FOG	1868
2000 - 2999 watts				
1	44,02	68,52	HERON NECK	2132
*17	58,33	134,55	SENTINEL ISLAND	2232
9	44,39	87,54	GREEN BAY HARBOR	2345
17	54,24	164,45	SCOTCH CAP	2470
3	38,59	75,07	BRANDYWINE SHOAL	2632
3	39,03	75,11	FOURTEEN FOOT BANK	2632
3	40,32	74,03	WEST BANK (RANGE FRONT)	2632
8	29,22	91,23	POINT AU FER REEF	2632
1	42,00	70,36	PLYMOUTH	2732
5	34,38	76,32	CAPE LOOKOUT	2775
9	45,46	85,09	GRAYS REEF	2845
9	48,13	88,22	PASSAGE ISLAND	2845
3000 - 3999 watts				
1	43,43	69,46	SEGUIN	3102
3	40,59	75,37	GREAT CAPTAINS ISLAND	3102
1	44,09	68,15	GREAT DUCK ISLAND	3315
9	47,52	89,19	ROCK OF AGES	3315
9	47,25	87,35	MANITOU ISLAND	3338
9	45,35	87,00	MINNEAPOLIS SHOAL	3977

* Indicates station is not planned for LAMP conversion.

TABLE 2.5 (cont'd)

District	Lat-N (deg,min)	Long-W (deg,min)	Aid Name	Total Peak Power (Sound Signal, Beacon, & Light) (w)
4000 - 4999 watts				
1	42,58	70,37	ISLE OF SHOALS	4102
1	43,07	70,29	BOON ISLAND	4102
1	43,58	68,08	MOUNT DESERT	4102
3	39,18	75,23	SHIP JOHN SHOAL	4102
9	45,30	84,46	ST. MARTIN ISLAND	4102
9	45,50	85,08	WHITE SHOAL	4102
1	44,34	67,22	LIBBY ISLAND	4264
9	46,58	88,00	HURON ISLAND	4264
1	41,23	71,02	BUZZARDS BAY	4315
5	35,09	75,18	DIAMOND SHOAL	4315
9	45,01	85,57	NORTH MANITOU SHOAL	4315
9	42,00	83,08	DETROIT RIVER	4447
3	41,12	72,07	LITTLE GULL ISLAND	4477
1	44,22	67,52	PETIT MANAN	4734
1	44,29	67,32	MOOSE PEAK	4734
*7	31,57	80,41	SAVANNAH	4734
*9	45,30	86,46	ST. MARTIN ISLAND K	4947
11	34,01	119,22	ANACAPA ISLAND	4947
17	56,00	134,08	CAPE DECISION	4970
5000 - 5999 watts				
17	59,48	144,36	CAPE ST. ELIAS	5039
17	58,12	136,38	CAPE SPENCER	5110
1	43,39	70,02	HALFWAY ROCK	5947
1	43,47	68,51	MATINICUS ROCK	5947
5	33,29	77,35	FRYING PAN SHOALS	5947
5	36,54	75,43	CHESAPEAKE	5747
13	48,24	124,44	CAPE FLATTERY	5970
Greater than 6000 watts				
3	40,28	75,50	AMBROSE	11539
Power requirement of a component unknown				
5	37,53	76,11	SMITH POINT	
9	45,42	84,22	POE REEF	
9	45,54	85,34	LANSING SHOAL	
*11	33,43	118,15	LOSA	
12	37,50	122,25	ALCATRAZ	
12	41,50	124,23	ST. GEORGE REEF	
17	60,14	146,39	CAPE HINCHINBROOK	

* Indicates station is not planned for LAMP conversion.

SECTION 3
ALTERNATE ENERGY SOURCES AND
TECHNOLOGY FOR COAST GUARD SITES

Section 3 contains major subdivisions corresponding to Tasks 4, 5, 6 and 7 of Appendix A. Task No. 4 is a study of the natural energy resources available at remote diesel-powered Coast Guard sites. Task No. 5 requires a grouping of remote lighthouse sites into a few generic classes that represent typical wind and solar resource categories for use in the simulation model, Task No. 8. Equipment commercially available now or expected in the near term (five years or less) for the production of electric power from environmental energy resources is the subject of Task No. 6. Task No. 7 is a similar investigation of energy storage technology available now or expected in the near term.

3.1 ALTERNATE ENERGY RESOURCES

3.1.1 General Considerations

Energy is available from the environment at remote Coast Guard sites because components of the environment are generally not in hydrostatic, chemical, kinetic, radiative, and thermal equilibrium with each other. Energy of high thermodynamic potential is available in waterfalls, ocean currents, tides, waves, wind, sunlight, and chemical concentration gradients. Lower quality thermal energy is available from thermal gradients. Temperature differences can be natural, e.g., the air-sea interface temperature difference, or artificially enhanced, e.g., by concentrating solar rays onto an absorber. The means used to collect naturally available energy resources will be discussed in subsection 3.3, but certain limits on the collection and conversion efficiency are inherent in the nature of the resource. These features will be discussed here. For example, the intensity and availability of solar energy varies with the season, time-of-day and site location.

This subsection is organized by energy form. Some of the forms are not available at most sites and others have no practical collection and conversion technology currently available. In the former case they are considered briefly to encourage development where possible and in the latter case they are mentioned in the hope that wider recognition of energy potential may encourage technological development. However, the primary emphasis is on wind and solar energy resources.

3.1.1.1 Hydrostatic Energy

Water power developed by dams or naturally occurring waterfalls is not a resource common at most Coast Guard sites in need of independent power. However, it should not be overlooked, because even a

+ Geothermal energy must be developed on an excessively large scale for application at a lighthouse, but may be of interest at LORAN-C stations.

small stream cascading into the sea can provide the station power requirements if harnessed.²¹ There may be environmental constraints^{22,23*} that prevent the construction of a dam and reservoir, but the scale of the construction required to service a typical LAMP station may meet with less opposition than a larger scale project. Development of small scale dams with low head turbines is currently being encouraged by the Department of Energy. Hydrostatic power can be conveniently regulated and controlled to follow the load. That is, more water can be released at night or during periods of fog when station power requirements are greatest. Large hydrostatic power plants have long useful lives and produce power at very low costs. However, manual removal of debris from the turbine inlet screens would occasionally be required at a small hydroelectric power plant, especially after storms. The revitalization and the long term practicality of small scale hydroelectric power in the modern era remains to be demonstrated.

3.1.1.2 Chemical Energy

Natural Gas: Any Coast Guard site located in regions known to produce natural gas may be able to utilize this form of chemical energy from an on-site well even if the natural gas resource is not large enough to permit normal commercial development. Solid forms of chemical energy naturally available in the environment; wood, coal, peat, etc., are all impractical for a remote automated power plant. A chemical energy system based on natural gas and a gas engine could follow the load and may not require separate storage facilities. However, few, if any, Coast Guard stations are located where natural gas is known to be available. Investment in wells and drilling in remote areas may not be economically practical even for an on-site user.

Saline Energy: Almost all oceanic Coast Guard stations have access to abundant natural energy resources in a convenient liquid form because both fresh and saline water are generally available at these sites. In theory, each cubic centimeter of freshwater flowing into the sea is a waste of two joules.²⁴ Thus, in theory, a flow of 475 gallons per hour of fresh water at a sea-side site could supply a continuous 1 kW power requirement. A dam 670 feet high is required to develop 1 kW with this same flow. Thus, there is more energy available in the saline gradient than in the hydrostatic gradient. Unfortunately the technology to capture power from saline gradients is not practical at present.

3.1.1.3 Kinetic Energy

Although ocean and river currents represent large kinetic energy resources, they are not intense enough at most Coast Guard sites

*References

21. Lindsey, E. F., 1977 Water Power for your Home, Popular Science, May 1977, p. 77-93.
22. Taylor, R. J. and Green, L. L., 1979, "Problems of Hydroelectric Development at Existing Dams," JHU/APL - CPE-7901.
23. Jassby, A., D., 1976, "Environmental Effects of Hydroelectric Power Development," Lawrence Berkley Laboratory (Avail. NTIS: LBL-5296).
24. Issacs, J. D., 1979, "Salinity Gradient Power: Utilizing Vapor Pressure Differences," Science 206, 452.

to permit economic utilization. Three forms of natural kinetic energy are broadly available and intense enough in some locations to have attracted significant commercial development efforts. Wave power, tidal power, and wind power are separately discussed below and all other forms of natural kinetic energy will be ignored.

Wave Power: Waves represent a wind-driven propagating gravitational oscillation of the air-water interface. At favorable locations the essentially continuous ocean swells are converted into waves approaching the shore with average power in excess of 10 kW per meter of wave front. Storms hurl megawatt/meter power peaks against the shore. Because the direction of propagation is transverse to interface motion, it is possible in principle to capture and convert all of the incident wave energy. That is, an ideal wave energy extraction machine would create a calm sea between it and the shoreline without reflecting any wave power incident upon it back to sea. This is in contrast to a wind machine, which even in principle can not extract all of the kinetic energy incident upon it as the air passing through the machine must retain part of the initial kinetic energy to avoid zero power output by flow stagnation.

Reliable information relative to the availability of wave power and its short term variation at different sites during different seasons is scarce. For U. S. waters, Professor Carmichael of MIT has constructed an estimate of significant wave height, H_{25} , period, T , and linear power density, $\bar{P}$, averaged over the entire year. His estimate is reproduced in Table 3.1. The linear power density is approximately proportional to the product of the period and the square of the wave height, but depends on waveshape.

TABLE 3.1
SIGNIFICANT WAVE HEIGHT, PERIOD AND AVERAGE LINEAR POWER

Location	Coastal Zone			Open Ocean		
	(H meters)	(T seconds)	($\bar{P}$ kW/m)	(H meters)	(T seconds)	($\bar{P}$ kW/m)
North Atlantic	1.0	8.5	5.2	3.2	6.3	37.1
Mid Atlantic	.8	7.9	3.1	2.7	5.9	25.6
South Atlantic	.7	6.7	2.5	2.4	6.0	22.1
North Pacific	-	-	-	3.4	11.0	81
Mid Pacific	1.0	10.4	5.7	2.6	10.3	52
South Pacific	.9	13.2	4.9	2.1	13.2	25

+ Significant wave height is defined as the average height of the highest one-third of the waves. (U.S. Naval Oceanographic Office, 1966, Glossary of Oceanographic Terms, 2nd Edition, p. 148).

***Reference**

25. Carmichael, A. D., et al. 1978, "An Experimental Study and Engineering Evaluation of the Salter Cam Wave Energy Converter," MIT report 78-22 (Data quoted in NTIS: PB-299851).

More than 70 percent of the time wave heights are less than five feet everywhere in the contiguous United States except off Cape Hatteras during the autumn and winter, off Oregon and Northern California during the summer, and off Oregon and Washington during the autumn.²⁶ Only during summer in the remote parts of the Aleutian Island chain are waves greater than five feet expected more than 30% of the time. The ocean near Hawaii never has waves in excess of five feet more than 30% of the time.²⁶

Certain beaches and coastal formations can greatly enhance smaller ocean swells, and wave power may be practical at some sites in spite of generally poor regional wave resources. Artificial means of enhancing wave power via water lenses are under development.^{27*} The fact that waves are generally periodic not only permits concentration by artificial lenses, but also means that waves can be resonantly coupled to an energy extraction device. Resonate capture permits the effective capture cross section of the wave machine to be larger than its physical cross section. However the period of the waves is neither constant nor sharply defined and resonate coupling enhancement of energy capture is correspondingly limited.

Wave power is attractive at only a few of the Coast Guard lighthouse sites and generally these same sites are also excellent candidates for wind power. Wind power is more broadly applicable at Coast Guard sites and wind power technology is more advanced, with many commercial units available. Consequently wave power resources will be ignored for the present in preference to the more generally useful wind power form of kinetic energy naturally available at many Coast Guard sites. However, it should be noted that because wave power is a more concentrated form of indirect solar energy, it may ultimately prove to be more economical than wind power. The Coast Guard has approximately one month of data collected on the short-term fluctuation in wave power at the Baltimore light (14 miles east of Cape Henry, Va.) in 71 foot deep water.^{28*} The Coast Guard obviously has a continuing interest in waves and wave power, even if no attempt is made to harness this energy source.

Tidal Power. Tidal power is often considered to the long wavelength component of wave power, but this view is fundamentally incorrect. The tides are regular variations in the sea level caused by the gravitational forces of the sun and moon acting on a spinning earth. Waves are unpredictable oscillations of the air-water interface driven by the wind. Wave power is solar energy twice transferred and would cease if the sun did not shine. Tidal power is not dependent upon solar radiation, but

*References

26. U. S. Geological Survey, 1979, National Atlas of the United States of America, (Map Set No. 84).
27. Mehluum, E., Stamnes, 1978, "On the Focusing of Ocean Swells and its Significance in Power Production," NTNF 0411.3248 (avail. from authors at Central Institute for Industrial Research, Forskningsv. 1, Oslo 3, Norway).
28. Hilliker, D. J., Colburn, W. E., 1977, "Coast Guard Evaluation of Wave Activated Turbine Generator," (avail. NTIS: AD AO 076 133).

derives its energy from the 6×10^{15} MW-years of kinetic energy stored in the rotating earth. The continuous tidal dissipation of approximately 3×10^6 MW is lengthening the day (time for ²⁴one rotation of the earth) by approximately 15 microseconds each year.

Because tidal variations are regular, certain coastal inlets reasonably couple to the oceanic variation of the tides and achieve larger amplitude variation in the inlet sea level than would be possible with random low frequency components of the wind driven wave spectrum. However, relatively large bodies of water are required to resonate with the 12-hour period of the tides. A funnel shape for the inlet is also essential to convert large tidal flows at modest amplitude into smaller flows with large amplitude. Consequently, there are relatively few sites available where tidal power can be economically harnessed. The difference between the high and low tide is called the tidal range. The tidal range reaches 50 feet in inlets off the Bay of Fundy during the extreme equinoctial spring tides. At various times, tidal power in these inlets has appeared to be economically attractive. The U. S. Corps of Engineers spent \$7 million during 1935 on tidal power in this area, but the project was dropped during the economic difficulties of the depression.

The simplest plan for harnessing tidal power is to fill an impoundment basin at high tide and release the trapped water at neap tide. This approach results in two power production periods each day with the need to store energy by other means for periods in between. Multi-basin tidal energy systems can produce continuous power, but are more expensive to construct. Tidal power systems rated for less than 100 kW exist in the Peoples Republic of China, but generally only much larger stations are considered to have any prospect for economic viability. The Rance River tidal power plant in Brittany, France is rated for 240 MW and produces power on both the ebb and flood tides by using bidirectional turbines. Small tidal power systems would appear to be more expensive than small hydroelectric power plants because a single dam and reservoir can provide continuous power and the hydrostatic head available at many sites is larger than the tidal ranges. There may be a few Coast Guard sites where the tidal range is both large enough to permit tidal power and greater than the head available from any nearby small stream. Offshore Coast Guard sites have no small streams available and typically have insufficient tidal ranges to make tidal power practical. Shoreline Coast Guard sites on bluffs overlooking the sea may often have some small stream nearby that could be utilized. Thus small scale hydroelectric power should be more generally useful and less expensive than tidal power if dams and impoundment basins are used.

No dams or impoundment basins would be required if tidal currents were employed directly to drive submerged turbines. There are many Coast Guard stations located near gaps in offshore coastal island chains. (Many lights now operated by the Coast Guard were established to assist the ocean-going vessels returning through the gap in the coastal island chain to a bay-side harbor.) The tidal currents through these gaps are often quite large compared to river currents near the

shore. Thus tidal currents are frequently available with greater potential for Coast Guard applications than river currents. Unfortunately free-stream under-water turbines are not commercially available, but something similar to an under-water windmill should be possible. Under-water turbines may not be practical in tidal current channels if these channels must also be used as passage ways for ships.

Thus tidal power using dams and reservoirs appears to be economically attractive in only a few locations and only in a much larger scale than required for typical Coast Guard lighthouse applications. Tidal currents appear to offer some potential for power generation in the power range needed by a lighthouse, but are not commercially available or under active development.

Practical problems related to damage by ship and shifting sand may preclude the use of tidal currents. Consequently, tidal power, like wave power, will not be considered further as it is not close to commercial reality and is restricted to only a few, if any, sites of interest to the Coast Guard.

Wind Power. The power in the wind increases as the cube of the air speed. Thus, modest changes in average wind speed with site location, time of day or season represent much larger variation in available power. However, wind machine characteristics, which are discussed more fully in subsection 3.3, reduce this variation. That is, wind machines are designed to shed the extra power available at wind speeds greater than the minimum necessary for generation of their full rated output.

Unlike solar power, there is significant wind power available during the night when typical LAMP station power requirements are greatest. Thus, wind power can provide a better temporal match to station load requirements and may reduce storage requirements compared to a solar system with the same annual energy production. On a seasonal basis, wind power is also a better match to station load profiles than solar energy. Typically the monthly average wind power increases in the winter when long nights force the average lighthouse power requirements higher. Direct solar energy is obviously less available during winter when the days are short. Thus, wind power availability more nearly matches lighthouse power requirements both diurnally and seasonally.

In windy regions, the average power in one square meter of wind stream is greater than the average power in sunlight striking one square meter of earth. Compare Figures 3.0 and 3.1, but note a factor of $(1000/24)$ difference in scales. However, most solar energy systems are designed to accept the peak solar power available, whereas no wind machine can utilize the full power load available to it during storms. Thus, although the average power density of the wind resource often exceeds the average power density of sunlight it is never possible to collect wind power efficiently when it is most available. For example, a wind machine designed to reach full output and 50% efficiency in a 25 mile per hour wind is at most 6.25% efficient in a 50 mph wind and may be shut down for safety reasons. Wind machines can not exceed approximately 59% efficiency in any wind for the reason mentioned in the prior

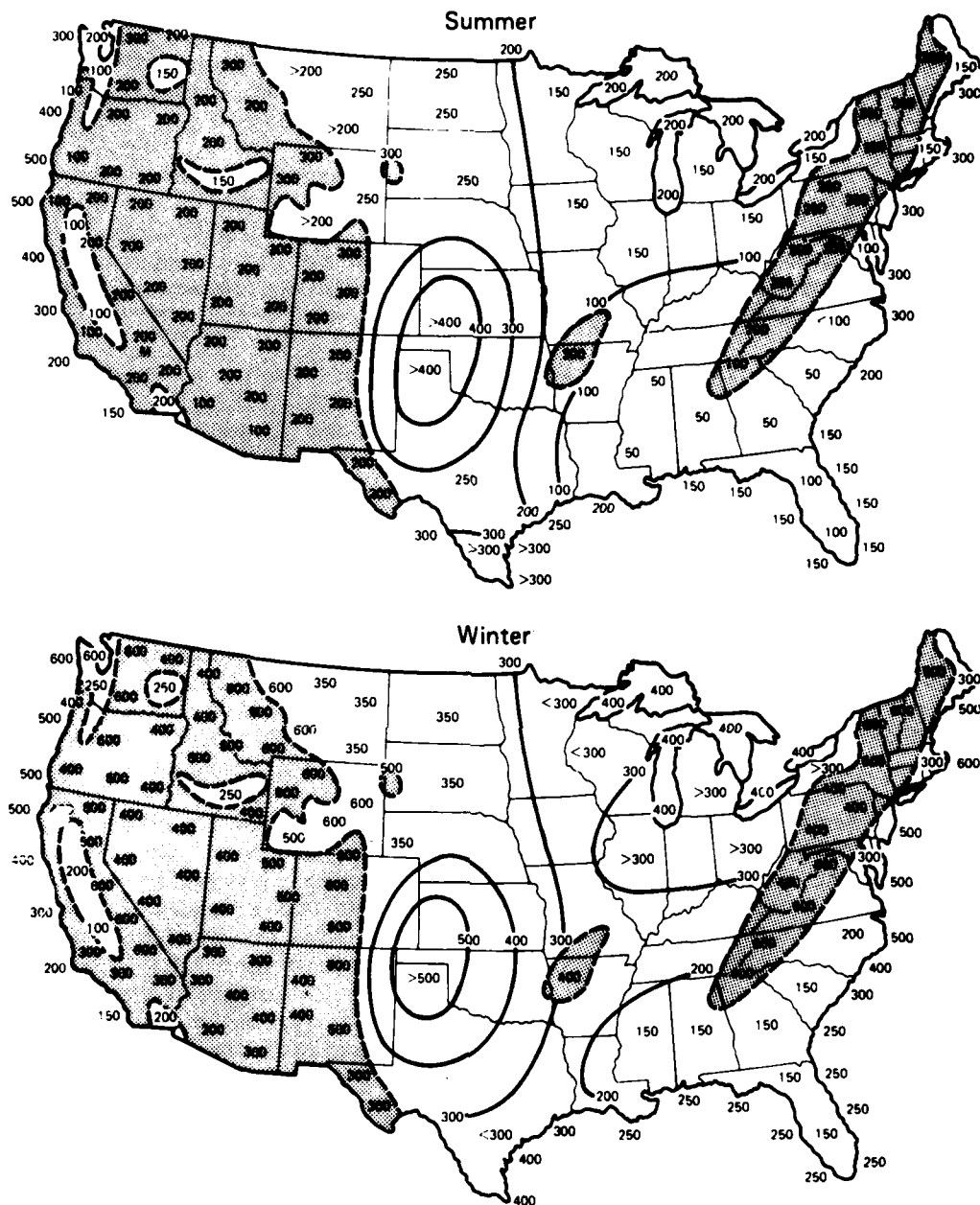


FIGURE 3.0 AVERAGE WIND POWER (W/M^2) ESTIMATED AT 50 M ABOVE EXPOSED AREAS. (Over Mountainous Regions (Shaded Areas), the Estimates are Lower Limits Expected for Exposed Mountain Tops and Ridges.) (Data from Battelle report: BNWL-2220)

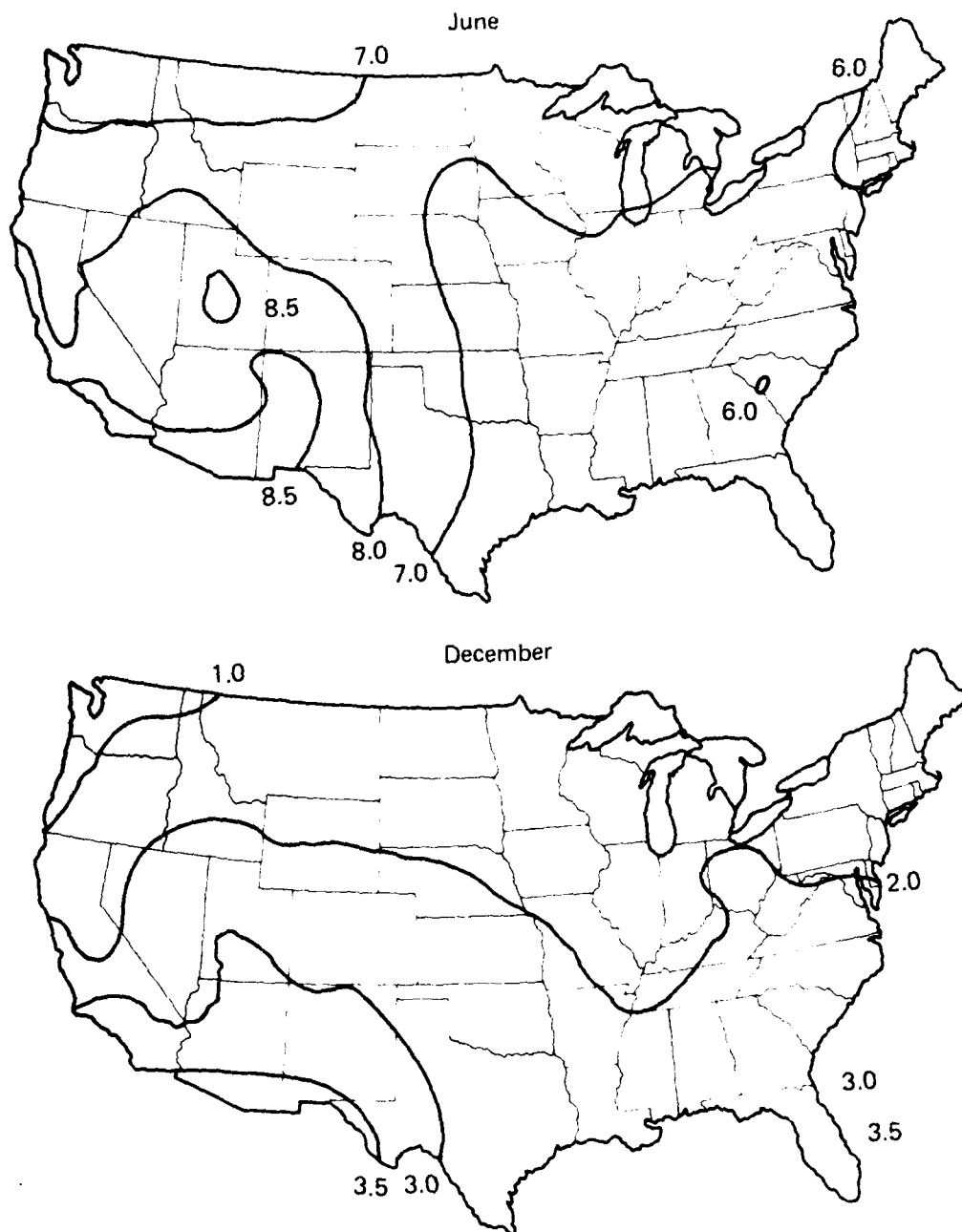


FIGURE 3.1 AVERAGE DAILY TOTAL OF SOLAR RADIATION ON ONE SQUARE METER OF HORIZONTAL SURFACE. (kWh/m²)
(Data from Sandia Laboratory report: SAND-78-0411)

subsection, i.e., 100% would imply stagnant air.

The wind speed increases with height asymptotically to the regional flow field. The wind speed, V , at one height, h , can be related to the wind speed, V_0 , measured at another height, h_0 , by the approximation:

$$V = V_0 (h/h_0)^{1/7} \quad (3.1)$$

Wind speed data is usually measured at 10 meters or corrected to that height prior to publishing it. More accurate estimates of wind speed averages require consideration of the surface roughness features at both the measurement station and the intended application site as is discussed in Reference 30*. Also the atmospheric stability can have influence upon the vertical scaling law especially during unstable conditions as discussed in Reference 31*. In spite of the variation of power density with height, the average wind power available over the area swept by the blades of a wind machine is essentially the same as the power density at the hub height and the $(1/7)^{th}$ power law is accurate enough for the purpose of this study. Thus, the power available for a wind machine increases approximately as the $(3/7)^{th}$ power of the tower height.

The geographical distribution of wind power shown in Figure 3.0 is only an indication of the wind power available at 50 meters on a broad regional scale.^{32*} On a local scale closer to the ground, surface features have great influence on the wind speed. The ocean is devoid of surface features except for the waves raised by the wind. Consequently, the coastal area represents a transition zone from a highly unique, topography dominated wind flow region near ground level to a more general wind structure dominated by regional flow patterns.^{33*} This transition zone is approximately 11 kilometers wide and extends inland sufficiently far to include all lighthouses included in this study except District 9 stations (the Great Lakes). The character of the wind in the coastal area zone has been studied by Garstard et al. at the University of Virginia.³³ Appendix E presents data on the seasonal, diurnal and geographical variation in average wind speed constructed from data found in Reference 33. In addition the geographical and seasonal variations in mean wind speed represented in Figure 3.0, the wind speed shows a large diurnal variation for most coastal wind stations.

*References

29. Peterson, E. W., Hennessey, J. P., 1978, "On the Use of Power Laws for Estimates of Wind Power Potential," Journal of Applied Meteorology, Vol. 17, p. 390-394.
30. Wegley, H. L., et al. 1980, "A Siting Handbook for Small Wind Energy Conversion Systems," Battelle Pacific Northwest Laboratory report PNL-2521 Rev. 1.
31. Sedefian, L., 1980, "On the Vertical Extrapolation of Mean Wind Power Density," Journal of Applied Meteorology, Vol. 19, p. 488-493.
32. Elliot, D. L., 1977, "Synthesis of National Wind Energy Assessments," Battelle Pacific Northwest Laboratory report BNWL-2220 WIND-5.
33. Garstard, M., et al. 1978, "Coastal Zone Wind Energy," (Avail. NTIS: RLO-2344-76/77-5 and -6).

Typically the extremes of the hourly means vary during the day by 40-60 percent of the annual mean wind speed. (See Appendix E.) Marked exceptions to this rule exist. For example, the average of the difference between the extremes of the hourly means expressed as a percent of the annual mean speed for the weather stations at Key West, Fla., New York Shoals, N.Y., Nantucket Shoals, Mass., and George Shoals, Mass. is only 8%. These stations are basically outside the coastal transition zone in a highly exposed region where off-shore winds and regional flow patterns dominate.

In the coastal area, there is usually a diurnal shift in the wind direction with periods of almost calm between. Both on-shore and off-shore winds in the same day are common in the coastal area. Hence, the large diurnal variation in wind speed in the coast area is readily understood. During the day the land surface warms more rapidly than the adjacent ocean, giving rise to afternoon thermals and an on-shore breeze. At night the converse is often true, but the winds speeds usually drop during the night so that the off-shore breeze may be absent. For northern stations, the daily variation associated with diurnal heating of the shore adjacent to the ocean is more pronounced in summer than during winter, and the winter winds are generally stronger as well as more constant. However, even in winter, northern coastal sites exhibit more diurnal variation than an off-shore site. The Texas coast has generally stronger winds than other southern sites adjoining the Gulf of Mexico, but there are no diesel-powered Coast Guard stations in this area.

The mean hourly wind speed of various remote Coast Guard sites can be approximated for a preliminary generic modeling of various sites by the six profiles shown in Figure 3.2. The meaning of the terms "southern" and "northern" will be more specifically defined in subsection 3.2. Analysis based on such gross generalizations as displayed in Figure 3.2 is highly suspect and more site specific data must ultimately be used. Also, days seldom exhibit diurnal patterns closely approximating the hourly means shown in Figure 3.2. Highly exposed sites which are a few kilometers off the mainland shore will be considered offshore but may in fact exhibit more diurnal variation than shown in Figure 3.2. It is desired not to introduce more than six distinct wind profiles and the off-shore class would be rather limited if only sites more than five kilometers from the shore (outside the transition zone) were included in the off-shore category. This division of sites into generic study groups is discussed in subsection 3.2.

A more accurate model of wind power available hourly can be constructed with a probabilistic concept of how the wind speed varies about the hourly mean. Wind speeds are often distributed in accordance with a Weibull distribution function³⁴ of the form:

$$f_w(V) = (c/g)(V/g)^{c-1} \exp(-(V/g)^c) \quad (3.2)$$

*Reference

34. Hennessey, J. P., Jr., 1977, "Some Aspects of Wind Power Statistics," Journal of Applied Meteorology, Vol. 16 No. 2, p. 119-128.

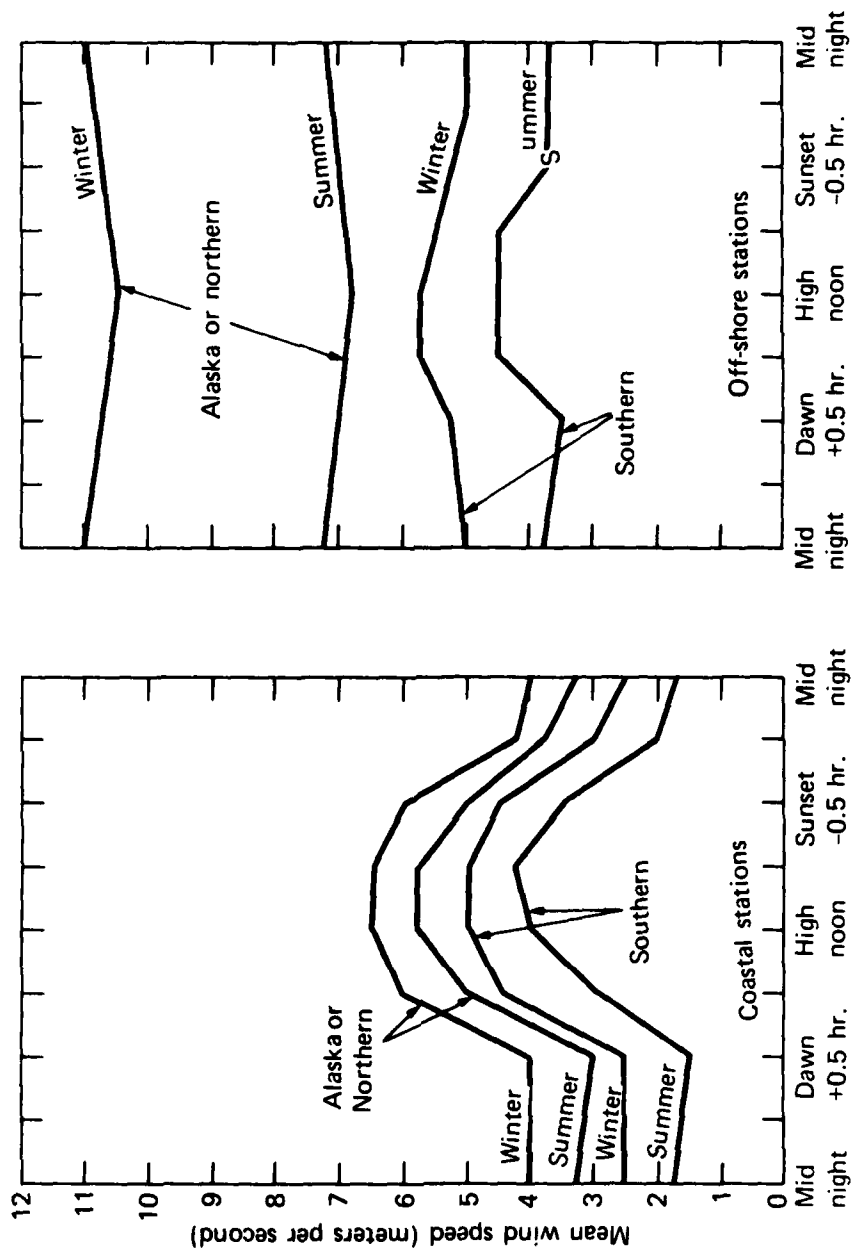


FIGURE 3.2 MEAN WIND SPEED (MODEL) VS LOCAL SOLAR TIME.

where $f(V)$ is the probability of wind speed V , and c is a shape controlling parameter, typically equal to approximately 2, and g is a scale parameter, typically equal to approximately 1.12 times the mean wind speed.

The characteristics of the wind machine utilized must also be included in order to compute the power available hourly. See subsection 3.3.2 for discussion of wind machines and the use of Weibull statistics to analyze the annual energy output of a wind power system.

3.1.1.4 Solar Energy

General Considerations. Solar energy has obvious seasonal and daily periods of reduced availability and total absence. Solar energy at ground level can be divided into two components, direct and diffuse radiation. The direct radiation can be focused and used to produce high temperatures for efficient thermal conversion or directed onto photovoltaic cells rated for use with "multi sun" or concentrated solar fluxes. Some concentration (approximately a factor of three) of both direct and diffuse solar radiation is possible even with stationary collectors because the sun follows a predictable arc through the sky. Higher concentrations can be achieved with seasonally adjusted, but otherwise fixed solar collectors. The diffuse component is primarily utilized by photovoltaic cells rather than thermal engines. Useful power can be obtained from diffuse solar energy even on cloudy days when the direct component is essentially absent. For this reason and others discussed in subsection 3.3.1, it is assumed that photovoltaic cells rather than thermal engines are used to collect solar energy. Consequently primary interest is in the total solar flux available per unit area at ground level.

Specific Considerations. Following the method of Munroe,^{35*} the mean daily total of solar energy on a horizontal surface, E_n , can be approximated as

$$E_n = D + (J-D) \exp\left[-\left(\frac{n-172}{365a}\right)^2\right] \quad (3.3)$$

where D is the average energy available on December 21, J is the average energy available on June 21, n is the day number ($1 \leq n \leq 365$) and

$$a = \frac{A - D}{(J - D)\sqrt{\pi}} \quad (3.4)$$

where A is the annual average of the mean daily radiation.

The annual average, A , and mean daily radiation for each month, E , can be obtained from Reference 36* for many sites in the United States. The values of J and D can be estimated from the June and

*References

35. Munroe, M. M., 1979, "Estimation of Totals of Irradiance on a Horizontal Surface from U.K. Average Meteorological Data, " Solar Energy 24, p. 235-238.
36. Cinquemani, V., et al., 1979, "Input Data for Solar Systems," (Avail. NTIS: DOE/TIC-10 193 Rev. 1).

December values of E_6 and E_{12} and graphically corrected by comparison with the values for E_m for the other months of the year.

The hourly variation in solar intensity, I_s , available on the average can also be estimated as outlined by Munroe³⁸ as follows:

$$I_s(\tau) = \frac{E_n \sqrt{\pi}}{t_d} \left[1 - \exp \left(- \left(\frac{(t_d/2) - |12 - \tau|}{b} \right)^2 \right) \right] \quad (3.5)$$

where τ is the time of day in hours with $\tau = 12.0$ corresponding to local or high noon, t_d is the length of the daylight in hours, and

$$b = (\sqrt{\pi} - 1) t_d / \pi. \quad (3.6)$$

The length of the daylight can be obtained from Figure 2.3 or more accurately computed from:

$$t_d = \frac{2}{15} \cos^{-1} (-\tan \phi \tan S) \quad (3.7)$$

where ϕ is the site latitude and the solar declination, S , is given by

$$S = 23.45^\circ \sin 360^\circ \left(\frac{284 + n}{365} \right) \quad (3.8)$$

Note that τ in Equation (3.5) must be limited to the daylight hours.

For reasons that will be discussed further in subsection 3.2, primary interest is in solar intensity data for coastal weather stations with latitudes near 33.5°N and 43.2°N on the east coast and 57.4°N in Alaska. Data for Cherry Point, N.C., Portland, Maine and Kodiak, Alaska³⁶ are reproduced in Table 3.2. These data represent the average daily total solar radiance, E , in K Joules/ m^2 , incident in coastal areas each month on a horizontal surface. Approximate values for D , J and a of Equation (3.3) are given in Table 3.3 for these same three sites. It should be noted that the average daily solar flux observed at ground level for most sites in Reference 36 tends to reach its maximum a week or two prior to the summer solstice and also is at a minimum prior to the winter solstice. Thus the seasonally varying solar flux predicted by Equation (3.3) tends to be a week or two late but reflects the annual variation well.

It may not be unreasonable to estimate the annual consumption of diesel fuel oil required by a solar powered-diesel hybrid system only with data for the hourly mean solar flux. This is because the increased fuel consumption during days with less solar power available will tend to be offset by the lower fuel consumption required on sunny days. However, more accurate computation requires that the statistical nature of the solar flux availability be considered and actual hourly records for a station near the site would be necessary.

A model of the variation in solar insolation suitable for this feasibility study can be constructed. The variation in insolation

TABLE 3.2 MONTHLY AND ANNUAL MEAN OF DAILY SOLAR
ENERGY FLUX (kJ/m^2)

Month	Cherry Point, N.C.	Portland, ME	Kodiak, AK.
Jan.	8,588	5,110	1,694
Feb	11,635	7,739	4,039
Mar.	15,735	11,004	8,874
April	20,843	14,798	13,707
May	21,843	17,788	15,619
June	22,002	19,425	17,363
July	20,765	18,829	15,981
Aug.	18,547	16,580	13,212
Sept.	16,198	13,140	9,011
Oct.	13,274	9,333	5,552
Nov.	10,290	5,212	2,344
Dec.	8,148	4,118	1,102
Annual	15,615	11,923	9,042

TABLE 3.3 PARAMETERS FOR USE IN EQUATION (3.3)

Parameter	Cherry Point, N.C.	Portland, ME	Kodiak, AK
J	22,100	19,500	17,400
D	7,800	3,900	900
a	0.308	0.290	0.230*

* The value of parameter a for Kodiak, AK was empirically adjusted instead of computed from Equation (3.4).

available at ground level is due to the predictable seasonal variation in solar flux incident upon the upper atmosphere and the statistical variation in the transmission of solar flux through the earth's atmosphere. The solar flux in watts incident upon a square meter of the upper atmosphere's surface parallel to the ground at latitude L is:

$$I(\tau) = 1353 (\sin L \sin S + \cos L \cos S \cos H) \quad (3.9)$$

where the solar hour angle, H , is $15^\circ (\tau - 12)$, S is given by Equation (3.8) and τ is limited to the daylight hours. In Equation (3.9) we neglect the annual variation in the sun-earth separation. Setting $L = \phi$ in Equation (3.9) so that the square meter in the upper atmosphere is parallel to the ground surface below it instead of parallel to the ground at some latitude $L \neq \phi$, then the average transmission factor, $\bar{T}$, is the ratio of Equation (3.5) to Equation (3.9) corrected to common units. The average transmission factor is typically about 0.5 and the maximum possible is unity. If all transmission factors, t , were equally likely the distribution function for solar transmission factors, $f_s(t)$, would simply be unity on the range $0 \leq t \leq 1$ and the average transmission factor, $\bar{T}$, would be exactly 0.5. We will assume a solar transmission distribution function of the form

$$f_s(t) = 1 + m(t - 0.5) \quad 0 \leq t \leq 1. \quad (3.10)$$

If $m = 0$, all transmission factors are equally likely as $f_s(t) = 1$. If $m > 0$, then the average transmission, $\bar{T}$, is greater than 0.5 and $m < 0$ corresponds to less than half of the solar flux reaching ground level. The value of m in Equation (3.10) is computed with Equations (3.8), (3.9) and (3.10) from

$$(I_s/I) = \bar{T} = \int_0^1 t f_s(t) dt \quad (3.11)$$

That is, the value of $\bar{T}$ is computed with Equations (3.8) and (3.9) with $L = \phi$. Then

$$\bar{T} = \int_0^1 [(1 - m/2)t + mt^2] dt \quad (3.12a)$$

$$= 0.5 + m/12 \quad (3.12b)$$

or

$$m = 12\bar{T} - 6. \quad (3.13)$$

In principal $\bar{T}$ has a range $0 \leq \bar{T} \leq 1$ and the corresponding range of m is $-6 \leq m \leq 6$. However, $f_s(t)$ must be non negative everywhere. Thus the range of m is limited to $-2 \leq m \leq 2$. The transmission factors corresponding to this more limited range of m are limited to $(1/3) \leq \bar{T} \leq (2/3)$. In practice $\bar{T}$ defined by Equations (3.5) and (3.9) with $L = \phi$ is outside of this range only near dawn and dusk when sunlight must travel through relatively more atmosphere. Consequently the distribution of transmission factors postulated in Equation (3.10) is usually satisfactory.

In the event that $\bar{T}$ defined by the ratio of Equations (3.5) and (3.9) with $L = \phi$ is not in the range $(1/3) \leq \bar{T} \leq (2/3)$ then one of the following two parameter distribution functions is assumed.

For $\bar{T} < (1/3)$:

$$f_s(t) = 0, \quad a \leq t \leq 1 \quad \text{and} \quad (3.13a)$$

$$f_s(t) = m(t - a), \quad 0 \leq t \leq a \quad (3.13b)$$

For $\bar{T} > (2/3)$:

$$f_s(t) = 0, \quad 0 \leq t \leq a \quad \text{and} \quad (3.13c)$$

$$f_s(t) = m(t - a), \quad a \leq t \leq 1 \quad (3.13d)$$

where the two parameters, a and m , are determined from:

$$\bar{T} = \int_0^1 t f_s(t) dt \quad (3.13e)$$

and

$$1 = \int_0^1 f_s(t) dt. \quad (3.13f)$$

Thus a statistical model for solar insolation on a horizontal surface suitable for this feasibility study consists of the above procedure for computing a distribution function, $f(t)$, for the transmission factor through the atmosphere. Once $f(t)$ is known, statistical methods can be applied to compute a series of random transmission factors, t . The total insolation on a horizontal surface at ground level is t times that present in the upper atmosphere as computed with Equation (3.9). That is

$$I_g(\tau) = t I(\tau) \quad (3.14)$$

However, the ground level radiation consists of two components, the direct insolation, d , and indirect insolation, i . We will assume that the indirect radiation is:

$$i(\tau) = (1 - t) I_g(\tau) \quad (3.15a)$$

or,

$$i(\tau) = (1 - t)t I(\tau). \quad (3.15b)$$

Thus when the transmission, t , is small (cloudy weather) the radiation present at ground level is small but consists primarily of indirect radiation in our model because of the $(1 - t)$ factor in Equation (3.15). The remaining part of the ground level radiation is the direct component given by:

$$d(\tau) = (t) I_g(\tau) \quad (3.16a)$$

$$= t^2 I(\tau). \quad (3.16b)$$

It is assumed that Equation (3.16) applies for direct rays in the case $L \neq \phi$ as well as the case $L = \phi$. That is, the transmission factor t is computed as outlined above assuming $L = \phi$ for a horizontal surface, but

direct rays striking non horizontal surfaces are assumed to pass through the atmosphere equally well. For example, if $L = 0$, the flux incident upon a square meter of upper atmosphere given by Equation (3.9) is the same as the flux incident upon a square meter of horizontal surface above the equator. In Equation (3.16) it is assumed that the factor t^2 is the fraction of this flux that reaches the ground directly. It will strike a surface normally if that surface is inclined towards the equator by the angle ϕ so as to be parallel to a horizontal surface at the equator. If for a second example, at site latitude $\phi = 40^\circ$ a solar collector is tilted toward the equator so that the surface normal makes an angle of 50° with the zenith in an effort to favor wintertime solar collection, then the indirect component of flux on the surface is computed with Equation (3.15) using $L = 40^\circ$ in Equation (3.9) and the direct component is computed with Equation (3.16) using $L = -10^\circ$ in Equation (3.9), but t is computed with $L = 40^\circ$ for both.

3.2 CLIMATIC GROUPINGS

The locations of some of the 56 remote LAMP stations using diesel power listed in Table B-1 of Appendix B are presented in Figure 3.3 with a 5 to 1 emphasis of latitude. (In some areas the stations are too close together to separately illustrate each.) Except for the station in Dry Tortugas off Key West, Florida all of the remote diesel powered stations in Coast Guard districts 5, 7, 8, and 11 lie in a 9° band of latitude centered on 33.5°N . Two stations of district 12 (Farallon and Alcatraz) also lie in this southern band. All of the diesel stations of districts 1, 3, 9, and 13 lie within a 10.4° band centered on 43.2°N latitude. The St. Georges Reef station of district 12 is also included in this northern group. The diesel powered stations of district 17 (Alaska) all lie within a 6° band centered on 57.4°N latitude. Latitude is the primary determination of the seasonal availability of solar energy.

Meteorological conditions (clouds, fog, dust storms, snow storms, etc.) greatly influence the insolation (solar flux) available at ground level. A model for the probability of significant meteorological absorption of solar flux is described in subsection 3.1.1.4 in terms of a distribution function for transmission factors. That model uses weather records for three coastal sites at latitudes near the center of the three bands discussed above. The weather on the east coast and west coast at the same latitude differ, as factors other than latitude have significant influence upon the probability of various meteorological conditions that can obstruct solar insolation. However, there are only three diesel powered stations on the west coast in the northern group centered on 43.2°N and only four west coast stations in the southern group centered on 33.5°N . Consequently, the solar insolation records for east coast stations near 33.5° and 43.2°N were utilized in subsection 3.1.1.4 to characterize solar availability for these two groups. Solar records for Kodiak, Alaska were selected in subsection 3.1.1.4 to model the average insolation available and distribution of transmission factors for district 17 stations.

The wind speed distribution model developed in subsection 3.1 was also divided into three different latitude zones. Each of these

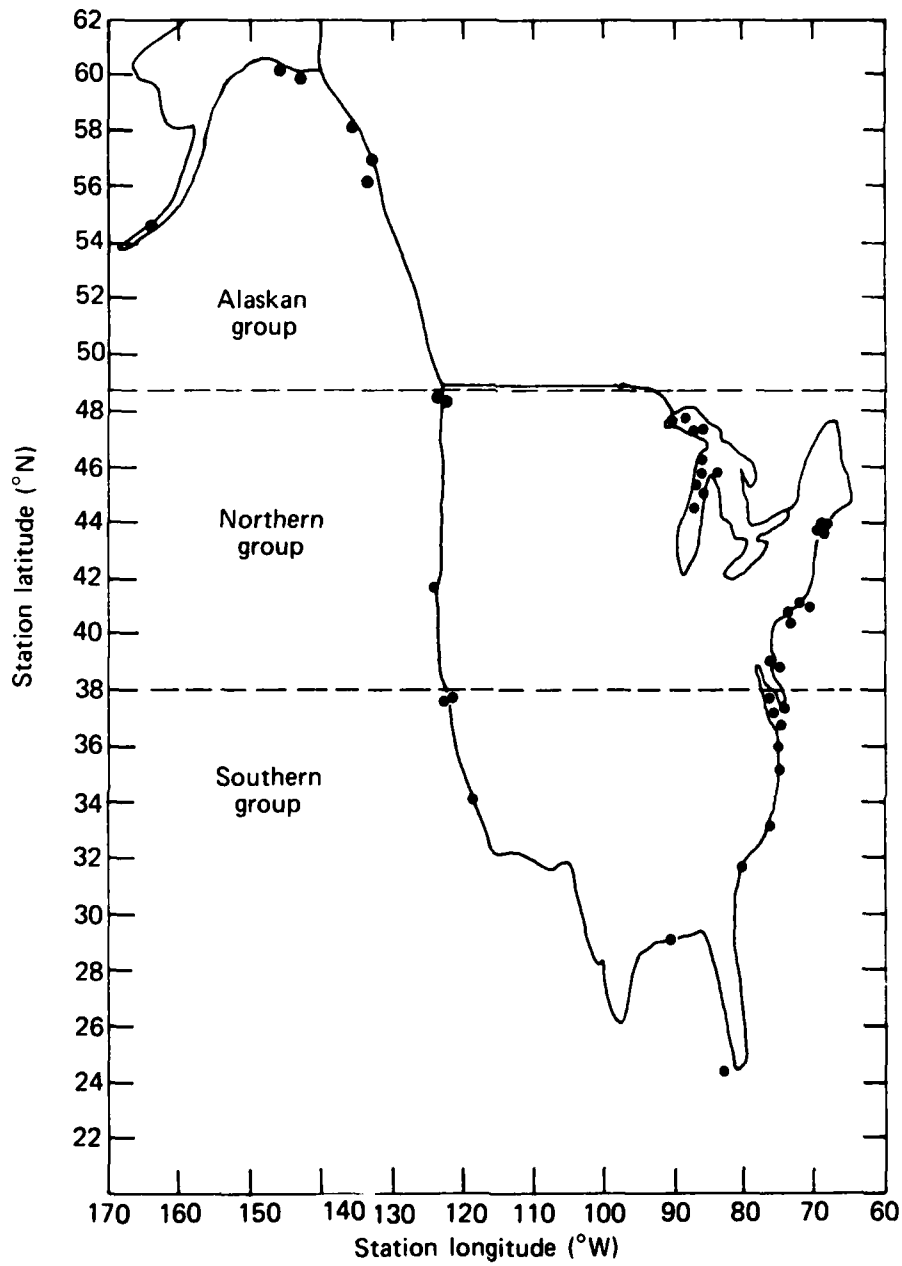


FIGURE 3.3 DIVISION OF REMOTE POWER LAMP STATIONS INTO THREE LATITUDE GROUPS. (Some remote LAMP stations are omitted.)

zones was split into an offshore and coastal subcategory. For convenience it is assumed that the three wind latitude bands utilized in Figure 3.2 are applicable throughout the corresponding latitude bands defined here.

Thus we recognize six district climatic groupings of remote sites for purposes of generic climatic group analysis. The approximate number of remote sites in each group is given in Table 3.4. The classification of the particular stations listed in Table 3.4 is given in Appendix F.

TABLE 3.4 NUMBER OF STATIONS IN EACH CLIMATIC GROUP

	Coastal	Offshore
Alaskan	4	2
Northern	9	30
Southern	4	7

It is assumed that the fog sounder has a duty cycle on time fraction of $2/15$ for both of the High and Medium power stations of Table 2.6. It is also assumed that fog is present with a probability of $(\phi/100)(.3, .2, .3, .4, .3, .2, .1, .2, .3, .4, .5, .4)$ provided that the wind speed is less than 0.05 mps. The factors in the second factor are selected depending upon the month, i.e., the number for January is .3, and ϕ is the site latitude in degrees. In simple simulations using average quantities without statistical variation it is reasonable to assume that there is fog present approximately $(\phi \times 15)$ hours per year. Fog is difficult to model in a generic approach because it is so site specific. When the statistical model indicates that fog is present, it will be assumed that the direct component of solar radiation is absent.

3.3 ENERGY CONVERSION TECHNIQUES

3.3.1 Solar Energy

Of the several energy forms available and discussed in subsection 3.1, only solar energy and wind energy, an indirect form of solar energy, have technically advanced means commercially available for producing electric energy from the environment. Solar energy can be directly converted into electric power via photovoltaic cells or first converted into thermal energy for a heat engine.

The cost of installing either a photovoltaic array or a wind machine at a remote Coast Guard site is estimated to be an additional \$2000 over the installation cost of a conventional site. Thus \$2000 will be added to the cost of these energy collection systems to cover manpower costs. This added installation cost is approximately twice the expense involved in installing a SR2 diesel-electric generator.

3.3.1.1 Thermal Conversion

Solar thermal power requires high temperatures for efficient conversion into electrical power. Consequently a solar tracking optical

system to focus intense solar flux onto an absorber is required. The output available from a solar thermal system decreases rapidly as the transmission of solar flux through the atmosphere decreases. In accordance with the model for solar transmission and division of ground level flux into direct and indirect components presented in subsection 3.1, the indirect and direct components are equally intense when atmospheric haze absorbs half of the extraterrestrial flux. Thus, under 50% transmission conditions the average direct flux is typically only one fourth of the clear day flux and the solar thermal electric power is correspondingly reduced. However, photovoltaic power would be approximately 50% of full output when 50% of the extraterrestrial solar flux reaches the surface.

If the reason for reduced average atmospheric transmission is a general haze instead of broken clouds in an otherwise clear sky, the average power level obtained from a solar thermal electric generator may be less than the direct ray transmission factor times the peak output power. This is because not only is there less direct radiation available during periods of reduced atmospheric transmission, but also the maximum conversion efficiency of the solar thermal power system is reduced as the intensity of the direct flux is reduced. Because it is a thermal process, the maximum theoretical conversion efficiency, η , is limited by the Carnot law

$$\eta = \frac{T_a - T_r}{T_a} \quad (3.17)$$

where T_a is the absolute temperature of the absorber and T_r is the absolute temperature of the waste heat rejected by the heat engine. The absorber temperature, T_a , decreases when the focused direct flux declines, with a corresponding reduction in possible conversion efficiency. To some extent this reduction in efficiency is also present if intermittent shadowing by broken clouds is responsible for the reduced average atmospheric transmission. The thermal mass of the absorber cools when the absorber is in a cloud shadow and does not immediately reach the desired operating temperature when the clouds pass over and the collector is again exposed to the full clear day flux. In practice most heat engines are limited to operating temperatures far less than T_a could be. Thus the actual conversion efficiency is usually much lower than the Carnot limit. High temperature converters, most notably thermionic diodes, are necessary to avoid reducing T_a and the conversion efficiency due to the material limits on the temperature associated with conventional heat engines.

The problem of varying input temperature for the heat engine and problems of energy storage can be solved by operating the thermal engine from heat stored in a thermal mass. The temperature of the thermal storage mass must be significantly less than the clear sky solar absorber temperature in order to permit economical transfer of heat to the storage mass. No solar thermal energy can be collected for the storage mass when the solar absorber temperature is less than that of the storage mass. Consequently, the storage mass temperature must be less than the absorber temperature existing at times of reduced solar flux. In principal, the maximum efficiency of a system using a heat storage mass is less than one operating the heat engine directly from the heat collected by the absorber. In practice, the efficiency of a

system using heat storage may be almost as high as a thermal engine operating directly from the absorber, if the absorber temperature is limited due to material constraints. However, the loss of heat from the storage mass always reduces system efficiency some.

3.3.1.2 Cost and Performance

Compared to solar photovoltaic devices, solar thermal power generators are a mature technology and no significant improvement in efficiency or cost based on technical developments can be expected. Consequently, one of the more commercially successful units^{37*} was examined. The unit uses a metallic thermal storage mass rated for one million Btu thermal storage. Approximately 2% of the energy stored is lost daily from storage. Stored heat can be converted into electric power with approximately 25% conversion efficiency using a steam engine if 70°F water is available for condensing the steam. Thus, the storage unit capacity is equivalent to a battery system storing for cyclic use approximately 75 kWh. Typical Coast Guard applications using a seawater heat exchanger for cooling can expect an overall efficiency of solar energy conversion on clear days of between 15% and 19% with the higher values associated with calm winter days. A complete stand alone solar thermal power system rated for 7.5 kW continuous output, including approximately 10 hours of output at rated power from a fully charged storage system, costs approximately \$70,000 not including site preparation, delivery or installation costs. This is less expensive than current costs for solar photovoltaic collectors and includes major storage facilities. However, on an annual electrical energy collection basis the cost of this approach to solar electric power is essentially the same as current photovoltaic system costs because of the failure of the solar thermal system to utilize the indirect solar flux as discussed above. In applications that can utilize the waste heat rejected by heat engines, the solar thermal approach may result in greater overall economy although the electrical generation efficiency would be less than discussed above if a higher temperature output is required, for example if boiling water is produced.

The cost of photovoltaic power is projected to significantly decline during the next five years. Photovoltaic power appears to be a more economical candidate than solar thermal power if these expectations are realized. Solar thermal power systems require moving large collector mirrors and use of a heat engine with numerous moving parts. Solar thermal power systems consequently are less attractive than stationary photovoltaic arrays from a maintenance point of view. Also, a solar thermal power system is composed of a few massive components instead of numerous small modules. It is much more expensive to install at a remote site as the system is heavy and not broken down into small modules. Solar thermal power systems will not be considered further for this application.

*Reference

37. Dampier, W. P., 1980, Omnium-G, 1815 Organethorpe Park, Anaheim, California (letter of 28 October 1980 and data sheet for model OG-7500S).

3.3.1.3 Photovoltaic Conversion

Certain semiconducting materials, most notably crystalline silicon, can absorb solar photons without immediately degrading all of the photon's energy into heat. Typically a bound electron is liberated as the photon is annihilated. The photon's energy is instantaneously converted into potential energy associated with the breaking of the electron's bonds and kinetic energy associated with the electron's motion. The electron's kinetic energy is converted into heat essentially immediately and only the potential energy of the broken bond remains. Near infrared photons are just energetic enough to liberate electrons in silicon and can be converted efficiently into potential energy but the more energetic visible light photons typically produce more heat than potential energy. For silicon solar cells and a ground-level solar spectrum, at least 78% of the solar energy incident upon the cell is immediately converted into heat. Higher photovoltaic conversion efficiency is possible if photons with different wavelengths are absorbed in separate solar cells made from different materials, but the extra cost is not attractive for most terrestrial applications.

Depending upon the concentration of impurity atoms in the silicon crystal, there may be more free electrons or more "holes" in lattice capable of binding electrons. Silicon with an excess of free electrons is called n-type and that with an excess of holes is called p-type. Solar cells contain some of each type material in mutual contact and separate electrodes for each region. The boundary between the n and p regions is called the p-n junction. If a photon creates an electron-hole pair in n-type silicon, the electron is soon indistinguishable from the other free electrons. If any free electron recombines with the hole, i.e., becomes bound to the lattice site, then all of the photon's energy is converted into heat. Similarly in p-type silicon, holes are numerous and the photon liberated electron may recombine with any hole resulting in the complete conversion of the photon energy into heat. However, if a free electron in p-type silicon or a hole in n-type silicon can migrate across the junction between the n and p-type material without prior recombination, then the potential energy associated with the photons annihilation is available as electrical energy in the outside circuit.

Any defect in the crystal lattice, or on the surface of the crystal creates additional trapping sites for the free electrons and holes and reduces their chance to cross the p-n junction. Thus, solar cells must be constructed from very pure materials and are most efficient if the entire cell is part of a single crystal. The presence of impurities can be carefully controlled to make concentration gradients which assist in the transport of energy across the junction as well as generate the basic n and p regions. Solar cell material is expensive because of the high purity and large crystal requirements, in spite of the fact silicon is readily available (sand is mainly SiO_2). Research efforts are underway at APL and elsewhere to make less expensive polycrystalline systems without excessive recombination at lattice defects.

The number of free electrons present in n-type silicon increases with temperature and the chance of a photon produced hole reaching the junction without recombination is reduced. Likewise, the chance of a photon produced electron being able to migrate across junctions without prior recombination in p-type silicon is reduced with increased temperature. The efficiency of a room temperature silicon solar cell decreases by approximately 0.05% for each degree centigrade that the cell temperature increases.^{38*}

If no external load is connected across the cell electrodes when the cell is exposed to light, the electrodes will become charged to the "open circuit voltage." This subjects the cell to an electric field that prevents collection of additional charge by the electrodes. The typical open circuit voltage in silicon cells is between 0.5 and 0.6 volts depending upon flux intensity and temperature. The temperature coefficient of the open circuit voltage is approximately $-2.2 \text{ mV}/^\circ\text{C}$. (See Figure 3.4).^{39*} The migration of holes and electrons across the p-n junction is effectively stopped and all photon generated minority charge carriers recombine within the photo cell. All of the solar photon energy is degraded into heat with no external load current.

If a very low impedance is connected across the cell, almost all of the photon generated electrons that cross the junction from the p-type region are collected on the electrode attached to the n-type material and flow through the external load to the p-type material's electrode. At this electrode they recombine with one of the numerous holes in the p-type region. However, very little power is delivered to the external load in spite of the current flow because the cell voltage is low. The collection of electrons (and holes) crossing the p-n junction is most efficient as essentially none are driven back or retarded by the weak electric field produced by the low voltage developed on the cell electrodes. Again, almost all of the photon energy is converted to heat within the cell. However, in this case several small inelastic collisions are responsible for the energy loss instead of one larger inelastic event associated with the recombination of the electron and hole. (The recombination of an electron and hole at the p-type electrode is a low energy event compared to the recombination of a free electron in the interior of the p-type material because once the electron has passed through the external load it is at essentially the same energy as the holes.)

As the external circuit impedance is increased, the cell voltage increases and the current declines as is illustrated in Figure 3.4. As is true of all power sources, the maximum power is transferred to the external circuit when the external impedance and internal impedance are equal. However, the internal impedance of the solar cell depends

*References

38. Hovel, H. J., 1975, Solar Cells, (Vol. 11 of Semiconductors and Semimentals, Academic Press) p. 173.
39. Allen, W. E., Tarr, J. E., 1980, "Final Report on U. S. Coast Guard Solar Powered Aids to Navigation (SPAN) Study," Johns Hopkins University Applied Physics Laboratory report SDO 5528, (Figure 3-4).

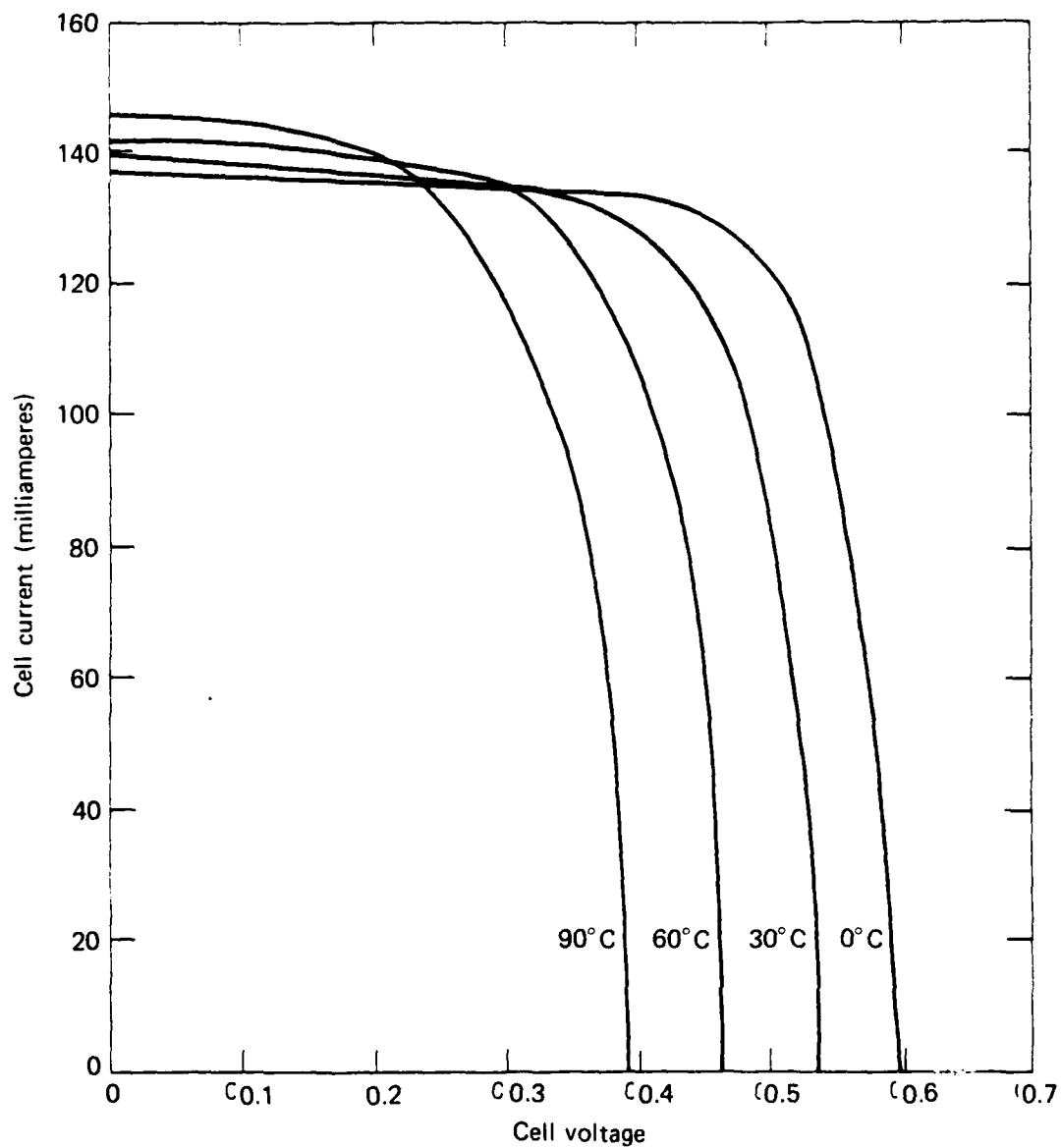


FIGURE 3.4 EFFECTS OF TEMPERATURE UPON SOLAR CELL PERFORMANCE FOR A 2 BY 2 CM, 10 OHM-CM CELL UNDER 1353 W/m² ILLUMINATION (Extraterrestrial Solar Flux at Mean Earth Radius.)

upon the intensity of the light striking it. The number of electron-hole pairs formed increases in direct proportion to the solar flux. The cell voltage also increases slightly with increased flux. Thus the impedance of the external load must decrease as the flux is increased to maintain maximum power transfer. If the optimum external impedance is maintained and the temperature is not allowed to change, the cell efficiency increases with increased illumination. The cell efficiency at constant temperature increases because of the higher cell voltage and because certain leakage or "dark currents" not discussed here become less important. Cells designed for operation in intense flux from a solar concentration typically have a finer metallic grid as the outer electrode to reduce the losses (internal resistance) associated with current collection from the interior of the cell. Typically the efficiency of a room temperature cell may increase by 0.5% if the intensity is doubled and the temperature of the cell is held constant.^{40*} However, it is difficult to prevent the cell temperature from increasing as the flux upon the cell is increased. In practice the cell efficiency tends to decline with increased flux unless a well designed active cooling system is employed. For example, if the cell temperature increases by 10°C when the intensity is doubled, then the thermal decrease in efficiency would offset the gain in efficiency associated with stronger flux. A constant conversion efficiency will be used in this preliminary feasibility analysis to avoid the complexity of modeling the cell temperatures.

3.3.1.4 Cost and Performance

The Department of Energy is coordinating an intensive effort to reduce the cost of photovoltaic power. The National Photovoltaic RD&D Act, passed by Congress in 1979, authorized the expenditure of \$1.5 billion over a ten year period for photovoltaic research, development, and commercialization. The Federal Photovoltaic Utilization Program, FPUP, includes \$98 million during 1980, 1981 and 1982 for purchase of photovoltaic systems for use by U. S. Government agencies. The primary purpose of FPUP is to provide market support for manufacturers of solar cells and systems by encouraging federal agencies to utilize photovoltaic power. The U. S. Coast Guard has already acquired photovoltaic systems under FPUP. It plans to install flash lamp systems on six reefs in the Florida Keys using solar power to recharge storage batteries.

In the private sector, numerous federal and state tax incentive plans exist to encourage utilization of photovoltaic and other solar systems. The existence of FPUP and these incentive programs makes projection of the net cost to the user of a photovoltaic system more difficult. These special considerations will be ignored but it is assumed that DOE's goals for cost reduction will be achieved on schedule. While this last assumption may be optimistic, the existence of FPUP should at least offset any delay or failure to achieve the cost-schedule goal of Figure 3.5. Thus, the proposed cost to the Coast Guard of photovoltaic systems and modules during the period 1980 to 1990 assumed is as portrayed in Figure 3.5.^{41*} for small systems plus the \$2000 extra

*Reference

40. Ref. 38, Figure 101.

41. Ferber, R. R., Forney, R. G., "The DOE Photovoltaic Program," Jet Propulsion Laboratory paper dated 15 May 1980.

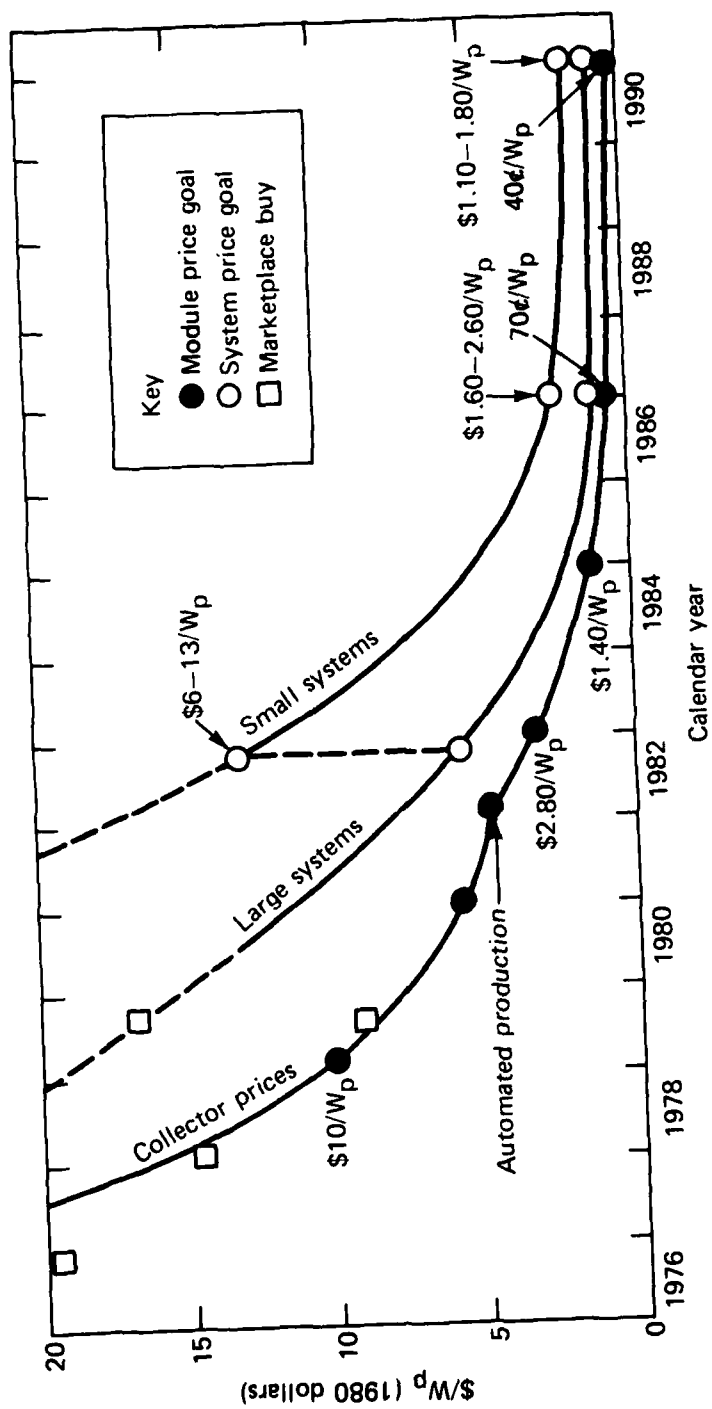


FIGURE 3.5 PHOTOVOLTAICS MODULE AND SYSTEM PROGRAM GOALS.

installation cost mentioned in subsection 3.3.1. It is assumed that by 1990 photovoltaics will be a mature commercial technology and no further decrease in cost in terms of constant value or 1980 dollars can be expected beyond 1990.

The efficiency of modern commercial solar cells for terrestrial use in flat plate arrays exceeds 10%. The efficiency of space type cells typically exceeds 13%, and specially selected laboratory cells in concentrated sunlight (600 suns) have achieved 20% efficiency with active cooling of the cell. But as discussed earlier, separation of the solar flux by wavelength and the use of multiple solar cells of different design are required for any further improvement in efficiency. The cost of delivery to the site, installation, interconnection of panels, land, power conditioning and control equipment usually exceeds the cost of the solar panels and is several times more expensive than the solar cells. (Compare the "system" and "collector" prices in Figure 3.5.) These costs are known as the balance of system costs, BOS. The BOS costs normally also include any storage required, but storage costs will be treated separately in this study. Cells with less than 10% efficiency have little economic value because for a given electrical output, more cell area and larger BOS costs are required.

The DOE goal for flat plate modules is 15% efficiency. The goal for actively cooled cells at the focus of a concentrator, including losses in concentration optics, is 20%. The passively cooled cells in the concentration array developed for the SOLERAS project has achieved 9.9% efficiency with a solar flux of 800 W/M^2 and 28°C ambient temperature. (Cells operate with approximately 30 fold concentration or 25 kW/M^2 flux incident.) The flat plate solar system recently installed at the Natural Bridges National Monument has an average cell efficiency of approximately 11%, but the active cell area occupied only 58% of the panel. Thus, the panel efficiency is only 6%. The cells occupy only 17.7% of the array field. Consequently the array field efficiency of that flat plate system is only 2%. However, solar energy is free and cell efficiency is important only because of its effect on collection costs and land area requirements. The cost data used in the simulation model is given by Figure 3.5 and does not depend upon the efficiency.

An estimate of the land required for the entire array is the only concern related to the efficiency of the cells if one assumes the cost of collecting solar power including efficiency effects is given by Figure 3.5. Based on the DOE goal of 15% efficient panels, the assumptions that panels are arranged in many East-West parallel rows, inclined towards the equator to maximize collection during the winter solstice and spaced to avoid self shadowing, then approximately $[150 \cos(\phi + 23)]^{-1} \text{ M}^2$ of land are required per peak watt if the peak solar intensity is 1000 W/M^2 , and ϕ is the site latitude. The land area required for many parallel rows becomes unreasonably large as the arctic circle is approached. At higher latitudes only a single East-West row of panels with no possibility for shadowing other rows is more efficient in land use. In the case of a single row, the land required under the same

assumptions is $\cos(\phi + 23)/150 M^2$ or less than the panel array area. However, the area on the south side of the panels must be kept clear and land areas less than the panel area are not practical even if the panels are highly inclined at high latitudes. A section of a south facing roof or other elevated structure may, however, accomodate greater solar panel area than the ground projection of the roof area.

The life expectancy of solar cells in terrestrial use at remote Coast Guard sites is not yet certain. Lightning strikes, vandalism, and theft represent catastrophic failure modes of some concern at remote, elevated unmanned sites accessible by boat. For this study, it is assumed that the photovoltaic array is protected from lightning via lightning rods and proper grounding of the panel. The light tower and/or radio beacon antenna serve as "lightning rods". Hail can also produce failure, but most glass covered cells will survive all but the most extreme hail storms, especially if the solar panels are tilted up from horizontal. Silastic and other plastic encapsulation cells are more prone to damage by hail because the impact is more fully transferred to the brittle silicon wafer.

If small stones are available in the immediate vicinity, it would seem to be prudent to shield the photo cells from malicious damage via a wire screen or protective barrier. Because of the large area required and the desire to inform the public of the beneficial use of solar power, it may be impractical to attempt to conceal the photovoltaic array. However, a roof mounted array, hidden behind perimeter screens should be utilized whenever possible. Individual cells in a panel appear to fail at random and can cause excessive heating and further damage related to the initial failure if not suitably interconnected to other cells in the panel. However, by the use of interconnection diodes and careful design of series and parallel circuits in the panel, the propagating loss of panels by random cell failure can be eliminated. The 25 kW array installed at Mead Nebraska is experiencing a random cell failure rate of one cell per 8000 years if initial fabrication and encapsulation faults are ignored. Studies⁴² at the Jet Propulsion Laboratory of various series - parallel interconnection patterns have established that with no cell or module replacement the power loss expected in twenty years due to random cell failures can be reduced to less than 5% of the initial capacity by proper inter-cell connection patterns within each module. Furthermore, the life cycle cost for modules with sufficient interconnections to avoid any replacement is less than for modules that would be more seriously affected by individual cell failures in spite of the greater initial cost of interconnection lines and diodes. Consequently, it is assumed that the photovoltaic panels have a life of 20 years without any maintenance or replacement. This assumption may not be valid for the marine environment. Solar cells may be less economical than assumed. Even with this assumption, solar cells rarely are the system of choice. (See Table 1.2).

*Reference

42. Ross, R. G., Jr., 1979, "Array Engineering" (Proceedings of the U.S. DOE Semi-Annual Program Review of Photovoltaic Development, Applications and Commercialization) p. 236, (Avail. NTIS: CONF 79 1159).

3.3.2 Wind Power

3.3.2.1 Performance Model

As discussed in subsection 3.1, the power of the wind increases as the cube of the wind speed, but the power available from a wind machine as a function of wind speed is typically of the form given in Figure 3.6. Wind machines can be characterized in terms of five parameters for this feasibility analysis: $W\$$, the machine and tower cost; V_1 , the minimum wind speed necessary for any power production, V_r , the lowest speed producing full output in an idealized model similar to Figure 3.6; V_m , the maximum wind speed permitted before mechanical shut down to avoid damage; and P_r , the full output power rating. As discussed in Reference 43*, it is convenient to model that portion of the curve shown in Figure 3.6 between V_1 and V_r with the function of the form.

$$(P(V)/P_r) = a + b V^c \quad (3.18a)$$

$$V_1 \leq V \leq V_r$$

where

$$a = V_1^c / (V_1^c - V_r^c) \quad (3.18b)$$

$$b = 1 / (V_r^c - V_1^c) \quad (3.18c)$$

and c is the same shape parameter used in Equation (3.2). In this feasibility study we will take $c = 2$. This special case is known as the Rayleigh distribution of wind speeds and is commonly accepted as a reasonable approximation when detailed wind speed data are unavailable. More general forms are given in Equations (3.2) and (3.18) for future use with data from specific sites.

The average power of the wind, $\bar{P}$, is not simply the power computed with Equation (3.18) or Figure 3.6 for the average wind speed, $\bar{V}$, because the power-wind speed relationship is nonlinear. However, because of the form of Equations (3.2) and (3.18) it is possible to express the average power as an analytical function of the machine parameters and the wind speed distribution. For the special case considered here ($c=2$),

$$\bar{P} = P_r [\exp(-v_1^2) - \exp(-v_r^2)] / (v_r^2 - v_1^2) - P_r \exp(-v_m^2) \quad (3.19a)$$

where

$$v_1 = (V_1/\bar{V}) (\pi/4)^{1/2} \quad (3.19b)$$

$$v_r = (V_r/\bar{V}) (\pi/4)^{1/2} \quad (3.19c)$$

$$v_m = (V_m/\bar{V}) (\pi/4)^{1/2} \quad (3.19d)$$

*Reference

43. Powell, W. R., 1980, "Output Power of Wind Machines," (Proceedings System Simulation and Economic Analysis) p. 229, (Avail. NTIS: SERI/TP-351-431). (See also Solar Energy, 1981, Vol. 26 p 77-80.)

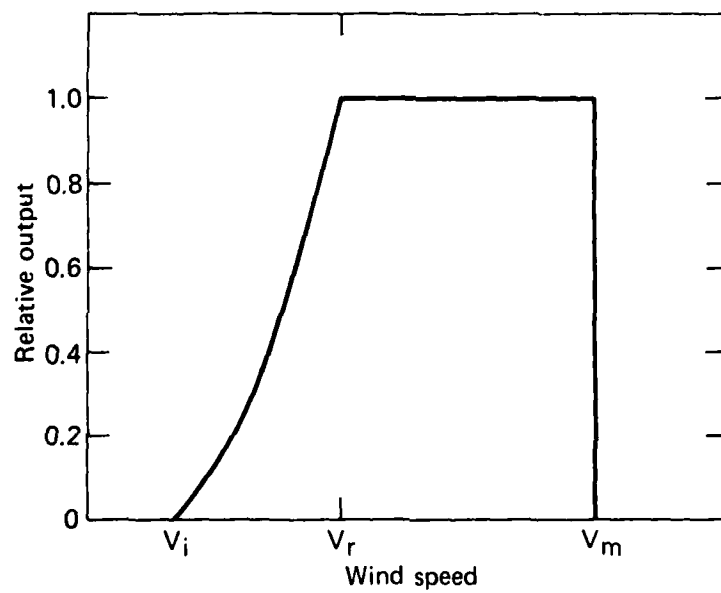


FIGURE 3.6 OUTPUT POWER VERSUS WIND SPEED.

The general (c#2) relationship between $\bar{P}$, P , V_i , V_r , V_m and $\bar{V}$ is given in Reference 43. Thus, when $\bar{V}$ is known and the machine parameters are specified, the average power is simply computed with Equation (3.19).

If the statistical distribution of power is required for more detailed analysis, then Equation (3.2) is used to calculate the statistical distribution of wind speeds. For a time increment with average wind speed V , in the range $V_{i-1} < V < V_i$, the average power during that time increment, P , can be computed conservatively with Equation (3.18). If $V_{i-1} < V < V_i$, then $P = P_i$. If $V < V_{i-1}$ or $V > V_i$, then $P = 0$ is conservative. The smaller the time increments, the more accurate this model of the power distribution becomes. If the wind speed varies significantly during the time interval used for computation, then the power available when the wind speed exceeds the average more than compensates for the lower power levels associated with portions of the time interval when the wind speed is below average.

3.3.2.2 Cost and Performance

The Department of Energy has established a multiyear program to stimulate the manufacture of small wind energy conversion systems, SWECS, and to encourage their utilization. SWECS are defined as wind machines that produce less than 100 kW. Typical Coast Guard applications require far less than 100 kW although LORAN-C Stations might require several SWECS in an array. The goal of the SWECS program is to reduce the cost of wind machines to about one third of present costs and to produce energy at approximately 5¢/kWh. The SWECS program is managed for DOE by Rockwell International with a primary test area at Rocky Flats, near Golden, Colorado. In FY 1979, \$5.2 million was expended in support of the SWECS programs. Thus the SWECS program is small compared to the DOE's photovoltaic program.

The Rocky Flats test center has facilities for concurrent testing of 30 machines with automated data collection. In late 1979, commercially available machines from 18 different manufacturers were being evaluated at Rocky Flats. (See Reference 44* for list.) A total of 59 commercially available SWECS with electric output (water pumpers excluded) have been identified.^{45*} In addition to testing commercially available machines, a set of "high reliability" newly designed machines is being developed with support from DOE via Rocky Flats. Initially three size groups, 1-2 kW, 8 kW, and 40 kW machines were requested, but recently 4 kW and 15 kW power classes have been added to the high reliability machine development program. High reliability machines have a life of at least 25 years, survive 125 mph winds and need routine service no more often than once per year. They have less than a 10%

*References

44. Williams, R., 1979, "An Update on Activities at Rocky Flats," (Fourth Wind Energy Workshop Proceedings), p. 9, (CONF 791097).
45. Rocky Flats Plant Energy Systems Group, 1979, "Commercially Available Small Wind Systems and Equipment - August 20, 1979 Amended." (Original edition: A guide to Commercially Available Wind Machines, 1978, is available NTIS: RFP 2836/3533/78/3.

chance/year of needing non routine service. These machines develop their rated power at only 20 mph (9 mps). The 4 kW machine appears to be the most natural match to the power requirements of a typical LAMP station. It should be able to generate approximately the same amount of energy as the annual total required by the "typical" LAMP station defined in subsection 2.1.3. However, it should be noted that a significant part of this energy will be produced at times when there is no way to use it. A special version of the 4 kW machine designed to tolerate salt water spray, 165 mph (73.8 mps) winds, temperatures between -58°F and 140°F, and 2.5 inches of ice will be available.

The cost of the 4 kW high reliability machine in production quantities is somewhat speculative and no firm goal has been published. The goal is for the 10,000th machine to generate electric power at a cost of 3¢/kWh when the site has a mean wind speed of 10 mph at 30 feet above grade level. A commercially available 4 kW machine^{46*}, designed with operational wind speed parameters similar to those of the high reliability series of wind machines being developed with DOE/Rocky Flats support, costs \$11,900 as a complete system including tower and a 225 amp-hour, 110 volt DC battery. The tower is 60 feet high and guyed and should prove adequate for most lighthouse sites. The battery bank included in this price is estimated to cost about \$2,250 based on \$10 per amp-hour in a 110 volt DC supply (\$90/kWh). The cut-in speed, V_c , of this machine is 7 mph (3.1 mps). The rated speed, V_r , is 22 mph (9.8 mps) and the shutdown speed, V_m , is 60 mph (26.8 mps). The design is expected to survive a 120 mph (53.6 mps) wind.

This machine may not meet all of the high reliability design requirements, but it appears to be similar. The extent to which it would require modification for application at LAMP station sites is unknown. It may not be the best choice of the commercially available machines for applications at Coast Guard sites. However, the cost and wind speed design parameters of this machine will be adopted for the simulation model of wind power.

Larger wind machines with the same wind speed parameters are in principal more economical in energy production costs or initial cost per rated kW capacity ($W\$/P_r$). This is one reason for the DOE emphasis on machines larger than SWECS for central power stations. However, it is difficult to determine how the economy of scale should be modeled using commercially available data. Different machines reach their rated output at different wind speeds and this makes direct comparison of ($W\$/P_r$) difficult. Also the production volume and financial resources available to the manufacturer have considerable influence on machine costs.

The SWECS wind power industry is in a period of rapid growth with most manufacturers being small and recently formed. The emergence

*Reference

46. Hummingbird Remote Power Model 4000/22-Hummingbird Wind Power Corp., Avenger Field Municipal Airport, Sweetwater, TX. (Price List and data sheet dated 6-1-80).

of several particularly strong competitors with higher production volume can be anticipated. Higher reliability and lower cost can also be anticipated.

It is assumed that the price in constant 1980 dollars of a 4 kW machine will be reduced linearly during the decade 1980-1990 to half the current price. The DOE/Rocky Flats goal is for a three fold reduction as production volume and technology are developed. The price schedule assumed here is less optimistic than the DOE/Rocky Flats goal for SWECS only because it will be applied to the price of current commercial units that may not be sufficiently reliable or adequately designed for the typical Coast Guard site. (It should be noted that wind machines for use in district 9 would not need to resist salt spray, but in the interest of logistic and maintenance economy, it is assumed that all Coast Guard units must meet the same standards.)

The economy of scale possible at a mainland site is to a large extent, if not entirely, offset by the greater cost of installing a heavier machine and tower at a remote site. For example, the 4 kW commercially available machine considered above weighs 770 lbs. (approximately half the weight of the 6.5 kW SR-2 diesel-electric generator set). It may be cheaper at a remote site with limited heavy equipment available to install two 4 kW machines than a single 8 kW machine when 8 kW is desired. In view of the difficulty of determining the economy of scale for machines installed at remote sites, we simply assume that the ratio of (W/P_r) is constant for the range of interest ($2 \text{ kW} < P_r < 8 \text{ kW}$). Based on the commercially available 4 kW machine price, we take $(W/P_r) = 2.4 \text{ \$/W}$ in 1980. However, the \$2000 installation cost mentioned in subsection 3.3.1 plus one man-day/year of maintenance expense is also assumed for all wind machines.

It is important to be able to vary the rated capacity of the wind machine in the simulation model to insure that an economical match between wind generated energy and station demand is achieved. There is, however, less flexibility in practice because a wind power system is less modular than a photovoltaic system. The dollars per peak watt for a wind power system are currently significantly less than for a photovoltaic system, but the wind system has only a slight advantage in 1990 in accordance with our assumptions.

3.3.2.3 Summary of Assumptions for Wind Machines and Tower

- 1) $(W/P_r) = 2.4 \text{ \$/W}$ in 1980 with linear decrease to $1.2 \text{ \$/W}$ in 1990 in constant value 1980 dollars with no further decrease thereafter. P_r limited to range $2 \text{ kW} < P_r < 8 \text{ kW}$.
- 2) Cut-in speed, $V_1 = 7 \text{ mph}$ (3.1 mps)
Rated speed, $V_1 = 22 \text{ mph}$ (9.8 mps)
Cut-off speed, $V_m = 60 \text{ mph}$ (26.8 mps)
- 3) Economic life = 20 years with one man-day of service required annually.

- 4) The instantaneous power (as a fraction of P_i) is given by Figure 3.6 when the instantaneous wind speed, V , is specified.
- 5) \$2000 installation cost.
- 6) The average power is given by Equation (3.19) when the average wind speed, V , is specified.

3.3.3 Fuel Cells

It is conceptually possible to replace the diesel-electric generation system with a fuel cell (nonreversible type as discussed in subsection 3.4.2.2). The primary advantage of doing this is the fuel cell's ability to function at low load levels without the carbon build up problems of a lightly loaded diesel. However, its higher conversion efficiency is also attractive. The combination of a continuously operating fuel cell rated for the maximum average power of the station on a foggy night with a small energy storage system rated for the peak power requirements of the station might be an attractive alternative energy system. The storage system would need excellent cycle life characteristics as it would discharge during the ten second continuous radio beacon pulse at the end of each transmission minute. It would also discharge when the fog sounder is on. It would recharge from the fuel cell when these signals were off.

Probably a small modern flywheel would be desired as the energy storage system as no other system currently exists that can repetitively cycle from fully charged to significantly discharged in a fraction of a minute for years.^{47*} APL has been a pioneer in this field^{48*} and holds fundamental patents on this technology. (See also subsection 3.4.2.1.). When alternate energy from the environment is available or the fog signal is not required the average station load is less than the maximum, and fuel consumption is reduced from its maximum rate. However, the fuel cell must remain ready to deliver power and a minimum rate of fuel consumption is required to maintain satisfactory idle conditions.

The Energy Research Corporation, ERC, has developed a series of low power (1 to 5 kW) fuel cell units for the U. S. Army. ERC has developed a computer model to assist in fuel cell design. The portable units designed for the Army utilize high current density to minimize the cell electrode area and associated weight. For the stationary Coast Guard application, weight is not as important, and more efficient cells are possible if lower current densities are assumed for the design.

Using their computer model and a current density more appropriate for stationary operation (50 A/ft²), ERC provided^{49*} a prediction of the performance characteristics of their methanol reforming, phosphoric acid

*References

47. Rabenhorst, D. W. et al., "Low-Cost Flywheel Demonstration Program," (Avail. NTIS DOE/EC/1-5085), April 1980.
48. U. S. Patent No. 3,964,341 and thirty four others including foreign issues.
49. Voyentzie, P. R., Fuel Cell Program Manager for ERC, personal communication (letter dated 10-1-80).

fuel-cell power plant designed for 2.1 kW rated net output. Based on the lower heating value of methanol (8585 Btu/lb - product water not condensed) the unit achieves 45.4% conversion efficiency at rated output capacity. At half the rated output, the fuel consumption is 52.7% of full flow, but idle (zero net output) requires 26.6% of full fuel flow.

This design uses a 58% methanol - 42% water mixture as fuel and requires 0.43 gallons of fuel mixture per hour at full capacity. Thus, in spite of its higher than diesel electric generator efficiency through most of the operating range, the non reversible fuel cell would require significantly more fuel storage and larger periodic deliveries. The cell requires half an hour to come up to operating temperatures. Thus, it would have to remain at idle even when alternate energy is available from the environment if the energy storage system (flywheel) has a small capacity adequate only for the 10 second radio beacon and fog sounder pulses.

A larger energy storage system that could supply the station's energy requirements for the half hour fuel-cell start-up period would permit the fuel cell to be shut down during days when surplus alternate energy is available. However, this does not seem to be a very practical approach from an operational point of view. For example, if the station is on photovoltaic or wind power and clouds arrive or the wind dies, it would be necessary to immediately begin to activate the fuel cell. Twenty minutes later the clouds may have cleared or the wind may have returned. In this circumstance considerable fuel would have been expended during the twenty minute interval to no avail. More importantly the fuel cell would have to be put through a cold start thermal cycle. Numerous daily cold start cycles would significantly reduce the life expectancy of the unit.

No price data are available for ERC's small stationary fuel cell design. However, the manufacturer estimates that it would cost approximately \$2/W. This is somewhat more than the cost projected for wind and/or solar photovoltaic power sources in 1990. These alternate energy systems have zero fuel expense, but would require larger energy storage systems than a fuel cell. Because it does not appear possible to reduce the cost or the volume of fuel delivered to the station via conversion of diesels to fuel cells, and because of their limited commercial availability, fuel cells are not considered to be attractive alternatives for lighthouse applications unless they are the reversible type discussed in subsection 3.4.2.3. It should be noted that fuel cells may be attractive for other Coast Guard applications. The most promising application would appear to be a remote manned station in a cold climate where both heat and electric power are required continuously.

3.4 ENERGY STORAGE

3.4.1 General Considerations

Energy storage is a central feature of any alternate energy hybrid power system that significantly reduces diesel fuel consumption

at remote Coast Guard sites. As discussed in subsection 1.3, it is possible to save a great deal of energy that is currently wasted to avoid carbon build-up problems by adding energy storage facilities and turning off the diesel during periods of light load. By adding alternate energy collection means (wind turbines, photovoltaic cells, etc.), it is possible to further reduce the use of diesel fuel. Alternate energy resources present in the environment are intermittent energy supplies. The larger the capacity of the energy storage system, the more likely it becomes that environmental energy can carry the load instead of diesel power, but the ratio of energy saved to storage system capacity steadily decreases as more storage capacity is added to the system. Thus additional storage capacity is not cost effective beyond an economically optimum storage system size. Very large storage capacity can achieve 100% conservation, i.e., the total elimination of diesel-electric generator fuel requirements. This is unlikely to be a practical case for most Coast Guard applications within the limits of near term (5 years or less) technology availability. The high reliability requirements of Coast Guard applications require that some form of back-up power be retained. For purpose of this study it is assumed that the back-up system is the existing diesel-electric generator. The economically optimum design will conserve less energy than a design with greater energy storage capacity. However, because the funds available for alternate energy hybrid power systems are limited and many potential sites are available, more energy will be saved if the available funds are used to provide economically optimum energy storage facilities at as many sites as possible. Thus it is assumed that an economically optimum hybrid design is desired.

At some future date when all sites have been provided with the most cost effective alternate energy system, the storage capacity can be increased beyond the economic optimum for greater energy conservation, especially if the hybrid power system is basically modular in design. This fact produces a preference for modular designs. This preference is reinforced when the maintenance and logistic costs of a remote site are considered. Also, it is probable that the cost of diesel fuel will escalate relative to alternate energy system costs. Thus the economically optimum sizes for energy storage and alternate energy collection at each site are likely to increase as time passes. Consequently it is assumed that the alternate energy system is capable of modular expansion even if the initial installation is not entirely modular. For example, the initial energy collector may be a wind generator with subsequent additions of photovoltaic panels. Likewise initial storage batteries may be replaced by larger and more efficient storage modules now under development.

Finally it is assumed that the energy storage system can be charged either by the diesel electric generator or by the alternate energy collection system. When the diesel is off, the storage system carries part or all of the load whenever the power supplied by the alternate energy collection system is inadequate and the storage system is not fully discharged. When a fully discharged storage system condition is imminent, the diesel generator is started and operated at the most efficient load level for the system. The output of the diesel generator

in excess of load requirements is used, along with any alternate energy available, to recharge the storage system. At times the diesel may operate at the minimum level permitted to avoid carbon build-up problems even though it is more efficient at full load. That is, it will run at partial load if the energy generated at full load would exceed the energy required for the next diesel off period. Also, power storage systems have a charging rate limit that may prevent operation of the diesel at full output levels. The specific diesel control law assumed for this study is illustrated in Figure 1.0.

Reliable restart of the diesel is fundamental to the concept of saving energy by turning the diesel off during periods of low power demand. The impact this approach may have on station reliability is presently unknown. The station conditions must be monitored to make sure that temperatures in the diesel power hut and other factors are conducive to reliable restart of the diesels. Data must be collected and analyzed to predict the probability of restart failure in both diesels. Assuming that diesels can be reliability restarted, other station failure modes are made less severe. The presence of large quantities of stored energy or energy available from the environmental energy collection system can increase station reliability by deferring the conversion to emergency signal levels in the event that diesel power is unavailable. For example, if a diesel fuel line is damaged by vandals stealing fuel, the stored energy and environmental energy available may be able to carry the station until the repair crew arrives without the need to go to emergency signal levels. The net effect of the alternate energy system upon station reliability is unknown, but a large storage system can be used to reduce the number of diesel restarts required and also provide increased time between diesel failure and the conversion to emergency signal levels. Smaller continuously running diesels or alternate fuel cell power systems are also possible approaches to energy conversion. See Appendix H.

The discussion of energy storage systems thus far has tacitly assumed that only electrical energy is being stored. It is assumed that thermal requirements can be satisfied in extreme climates where they arise by electrical heaters in the diesel oil sump and the "day tank" oil supply. The diesel starter battery bank uses nickel-cadmium batteries and should remain adequately warm because of its proximity to the day tank in a standard LAMP power module. At some northern sites, it may be desirable to store thermal energy if diesels are unused for prolonged periods due to the success of an alternate energy collection and storage system. It is assumed that the main fuel tank has proper insulation to maintain fuel oil temperatures compatible with requirements of the day-tank transfer pump. Waste heat from diesel operations can be transferred to the main fuel tank as needed in a closed loop flow pattern using engine oil or alternate means as discussed in subsection 2.2.6. In some northern locations, this may require diesel operation occasionally to meet thermal demand instead of electrical demand. If this should occur frequently enough to significantly increase fuel-oil use, then electrical heaters can be provided for the main oil storage tank as well as critical points inside the diesel power module. That is, if it will save fuel oil, electrical heating of the main fuel storage tank(s) can be provided

by the alternate energy system. It is anticipated that the thermal inertia of a well insulated main fuel tank will usually be large enough for the diesel waste heat to maintain an adequate temperature with little exercise of the diesel in response to thermal demand. Consequently the remainder of this section will consider only electrical storage requirements. References 50* and 51* provide general reviews of energy storage options.

3.4.2 Storage Types

Electrical energy can be stored and recovered by many different systems. It could be transferred into thermal energy and then recovered via a prime mover, but this approach is very inefficient. In general we will not consider any methods unless approximately 2/3 of the energy delivered to storage can be recovered. Pumped storage systems in which water or compressed air is stored and passed through a turbine to drive an electrical generator can meet this energy recovery criteria. However, pumped storage systems are currently economically practical only on a much larger scale than required by typical Coast Guard applications. Magnetic energy storage via super-conducting magnets also appears practical only on a much larger scale, if it is practical at all. Consequently only three forms of storage warrant further consideration for typical Coast Guard remote-site applications. They are: (1) mechanical energy storage, (2) chemical energy storage, (3) electro-chemical energy storage. The results of this investigation lead to the conclusion that the present state-of-the-art forces one to choose rather conventional electric storage batteries for the Phase II experimental prototype, but some of the salient features of other systems with promise for future application will be described.

3.4.2.1 Mechanical Energy Storage

Recent developments in flywheel energy storage systems suggest that flywheels may be able to replace electrical storage batteries in many applications.⁴⁶ Modern flywheels spin very rapidly, greater than 10,000 rpm, in a vacuum of at least 10^{-2} Torr necessary to reduce aerodynamic dissipation. The energy required to maintain this vacuum represents a serious limit at present to the storage period for flywheels. For example, the 10 kW and 25 kWh systems designed at Lincoln Laboratory^{52,53*} require approximately 160 Watts for the vacuum pumps. Most of this power requirement could be eliminated by improved construction material (lower out gassing rate) and the use of a turbo molecular pump on the flywheel shaft instead of an external diffusion pump. Thus excessive

*References

50. General Electric Co., 1978, "Applied Research for Photovoltaic and Wind Energy Systems," (Avail. NTIS: HCP/T 22221-01, 02 and 03).
51. Electric Power Research Institute, "An Assessment of Energy Storage Systems Suitable for Use by Electric Utilities," Report No. EM-264. 1976.
52. Millner, A. R., 1979, "Scaling Laws for Flywheel System Components," MLI Lincoln Laboratory Report No. COO-4094-63.
53. Hay, R. D., Aug. 1980, "Residential Photovoltaic Flywheel Storage System-Performance and Cost," 15th Intersociety Energy Conversion Engineering Conference, Seattle, WA. (Paper No. 809301).

pump power is not an inherent part of flywheel storage systems, but it is at present a problem without a demonstrated solution. Other fixed losses, i.e., dissipation independent of energy stored, associated primarily with "idling" input and output power-handling electronics that interface the variable speed motor-generator to a 60 Hz line require approximately 200 Watts. Thus fixed losses alone would dissipate the stored energy available in 2.9 days. Consequently flywheels do not appear as attractive as batteries except for storage periods of less than one day. The primary attractive features of a flywheel energy storage system are its ability to repeatedly cycle to deep discharge condition without damage and its long life compared to most battery systems. Its relatively rapid self discharge rate and associated energy loss may not prohibit the use of flywheels in a system using "free" energy from the environment which is usually replenished daily. Also, electronics for a DC load should be much simpler than for the production of 60 Hz from a flywheel with continuously variable rotational speeds. Consequently it should be possible to significantly reduce the 200 W electronic losses estimate with a DC output flywheel.

In addition to fixed losses, about 0.3% of stored energy is lost each hour because of aerodynamic losses, vibrational damping and dissipation in the bearing assembly. Since the Lincoln Laboratory flywheel has 40 kWh when fully charged and 15 kWh of rotational energy remains in the wheel when "fully" discharged, the average power dissipation by aerodynamic and other internal losses associated with a linear discharge schedule is 82.5 W. If the flywheel were discharged linearly for a 24-hour period the internal dissipation would consume about 8% of the rotational energy available.

There are also losses associated with the conversion of electrical power into mechanical energy and back again. These losses depend upon the power transfer level and slightly upon the rotation speed of the flywheel because eddy current and transistor switching losses increase with power level and frequency. This electrical-to-mechanical-to-electrical loss is typically 15% in the Lincoln Laboratory design. Because these losses depend upon the charge and discharge schedules, they can not be stated as clearly as the fixed losses discussed earlier. However, the net effect of these variable losses does not change significantly when different solar energy input profiles are postulated. For a typical solar energy charging schedule, i.e., no input during the night, and a typical 24 hour residential load profile, approximately 61% of the electrical energy supplied to the Lincoln Laboratory system is recovered for load use.

The present state-of-the-art in flywheel energy storage systems probably can not return 2/3 of the energy supplied to storage in a diurnal charge-discharge cycle, but refinements which reduce the outgassing rate of the rotor and motor-generator can be expected to significantly reduce the vacuum pump power. Also some improvements in power transfer equipment, quiescent power requirements and power transfer are expected. For short storage periods as discussed in subsection 3.3.3, modern flywheels can recover approximately 90% of the energy supplied to them.

If 10,000 units were manufactured each year for the residential market with 10 kWh peak power and 25 kWh of usable energy stored in the system as developed at MIT Lincoln Laboratory, then the cost is expected⁵³ to be approximately \$20,000 each (1980 dollars), installed at a typical residence. The Coast Guard installed cost would be greater due to the remote nature of the site. It does not appear likely that such a system will be commercially available during the next five years. Consequently, flywheel storage systems will not be considered further, but the progress of this technology should be monitored as it may someday be economical to replace battery storage systems with flywheel/motor-generator units.

A small flywheel also forms an interesting hybrid with a fuel cell. The fuel cell provides long term energy storage and the flywheel provides high power handling capacity for short periods. Such a hybrid might be attractive in Coast Guard applications to start diesel engines or provide the peak power levels associated with fog sounders and/or the ten second continuous radio beacon transmission generated after fifty seconds of shorter transmissions. Flywheels of appropriate scale may be developed as part of the motor-flywheel hybrid car effort. (See subsection 3.3.3.)

3.4.2.2 Chemical Energy Storage

Chemical energy storage, as distinct from the electro-chemical storage discussed in the next subsection, is associated with the conversion of the stored chemical energy into heat for a prime mover turning a generator. The most important chemical energy storage system at remote Coast Guard sites is the diesel generator and fuel oil tank. It is possible to consider replacing this fuel system with an alternative such as propane, alcohol, or fuel oil derived from coal produced off-site as one means of reducing use of diesel oil derived in part from foreign sources, but this alternate fuel-prime mover concept will not be explored here. It is probably not attractive in any case since diesel fuel is significantly more concentrated in terms of Btu/gallon than any other alternative fuel suitable for delivery by Coast Guard resupply vessels except fuel oil derived from coal. It is, however, possible to generate a chemical fuel on-site from compounds found in the environment or to reprocess on site the oxidation products of a closed fuel system into new fuel using materials delivered to the site only once.

An example of the first or open cycle chemical fuel generation system is the use of alternate energy to electrolyze water. The hydrogen produced can be stored and used as fuel when needed by a prime mover. For a stationary application such as a remote lighthouse, the use of a metal-hydride hydrogen storage system⁵⁴ appears more attractive than compressed gas or cryogenic storage as both these methods require expensive storage containers and energy for refrigeration or gas compression. The electrolyzer portion of this system is commercially available, and metal-hydride hydrogen storage is actively being investigated, but the entire concept as an integrated system does not appear to be under

*Reference

54. Gary, S. C. and A. W. McClaine, 1975, "Metal Hydrides for Energy Storage Applications," (Avail. NTIS: AD AO 141 74).

active commercial development. Several alternative methods of hydrogen storage have been suggested. For example, W. L. Hughes et al. at Oklahoma State University have suggested that the electrolysis be conducted at high pressure to avoid mechanical compression.^{55*} Richard Williams of RCA Laboratories, Princeton, N.J., has suggested that hydrogen can be electrochemically reacted with CO_2 to form formic acid (HCOOH) which can be catalytically decomposed as needed.^{56*} This converts the hydrogen storage problem into a less difficult CO_2 storage problem.

Hydrogen can be converted to ammonia (NH_3) using atmospheric nitrogen for convenient storage of chemically bound hydrogen as suggested in the Applied Physics Laboratory's approach to ocean thermal energy conversion.^{57*} It is interesting to note that one gallon of liquid ammonia contains more hydrogen than one gallon of liquid hydrogen. Ammonia is also much easier to store since it is a liquid at room temperature with a vapor pressure of only 10 atmospheres. However, the synthesis of ammonia in the small scale required by a Coast Guard site may be impractical. The metal hydride approach to hydrogen storage has thermal losses and/or the need for gas compression at various points in the charge-discharge cycle. Unfortunately, there does not appear to be any solution to the hydrogen storage problem which is currently attractive for Coast Guard applications, but several approaches appear promising.

An example of the closed cycle chemical storage system is the SolChem concept^{58*} developed at the U. S. Naval Research Laboratory. In this system, concentrated solar energy is used to disassociate SO_3 gas into SO_2 and oxygen. These product gases are recombined to produce heat for a prime mover turning a generator. While it is relatively easy to store SO_3 and SO_2 as liquids under pressure, there does not seem to be any practical method to store^{59*} the oxygen produced. In the version currently under development, thermal energy is stored rather than the product gases. Other closed fuel generation and use cycles have been suggested^{60*} but small systems including chemical storage are not under active development and may never be commercially available.

The open cycle generation of hydrogen as a synthetic fuel for storage and subsequent combustion appears closer to practical reality than any of the closed cycle artificial fuel systems but even it does

*References

55. Huges, W. L., 1973, "Energy Storage Using High Pressure Electrolysis and Methods for Reconversion," (Avail. NTIS: N74-1675708-3).
56. Williams, R., 1979, "Energy Storage by Electrochemical Reduction of Carbon Dioxide, RCA Engineer 24, #5 p. 29 (Feb./Mar. 79).
57. Dugger, G. et al., 1980, "Projected Costs for Electricity and Products from OTEC Facilities and Plantships," 15th Intersociety Energy Conversion Engineering Conference, Seattle, WA. (Paper No. 809263). 58. U. S.
58. U. S. Patent 3,972,183.
59. Chubb, T. A., 1975, "Analysis of Gas Dissociation Solar Thermal Power," Solar Energy 17, p. 129-136.
60. Cardin, P. O., 1977, "Energy Corradation Using Two Reversible Ammonia Reaction," Solar Energy 19, p. 365-378.

not appear likely to be commercially available as an integrated system during the next five years. It may someday be the most practical way to totally eliminate diesel fuel use at remote stations because energy can be stored economically for long periods of time in chemical form.

3.4.2.3 Electro-chemical Storage

Reversible Fuel Cells. Chemical fuel generated on-site using energy from the alternate energy system need not be converted into heat for a prime mover as discussed in the prior subsection. The chemical fuel can be converted into electrical power more efficiently in a fuel cell. For example, water can be electrolyzed by surplus alternate energy and the hydrogen and oxygen produced can be recombined later in an H_2-O_2 fuel cell for the direct production of electric power. The H_2-O_2 fuel cell^{61*} is well developed and commercially available, but less efficient than others currently under development. A more serious limitation for the H_2-O_2 fuel cell is the difficulty associated with storage of the oxygen produced during water electrolysis. For a stationary application the hydrogen is relatively easy to store by dissolving it in an iron-titanium alloy or one of the other metal-hydride storage systems currently being tested.⁵⁴ The H_2-O_2 electrolyzer/fuel-cell can not achieve a 2/3 energy recovery at practical current densities. The inefficiency of the H_2-O_2 fuel cell is associated with voltage drop (polarization voltage) at the oxygen electrode. Both the oxygen storage problem and low efficiency problem of this fuel cell can be solved by using chlorine instead of oxygen as the oxidizer.

^{62*}The H_2-Cl_2 fuel cell under development by General Electric Company with assistance from Brookhaven National Laboratory^{63*} is particularly attractive because the reaction is efficient and reversible in the same cell. During times of excess electrical power, hydrogen and chlorine are generated. When electric power is desired they are electrochemically reacted to produce HCl again. The HCl is in aqueous solution as hydrochloric acid. The hydrogen is supplied through porous electrodes from a hydride storage system and the chlorine is maintained as a liquid by keeping the entire system under pressure. The electrodes serve only as current collectors and are not chemically transferred as the cell is charged or discharged. Consequently the cell should enjoy a long life even with frequent charge-discharge cycles. At practical current densities which permit compact economical cells, 75% of the electric energy used to charge the cell can be recovered. A system with 10 hours of full power storage is estimated to cost only \$41/kWh when constructed on an electric utility substation scale. Higher costs would be associated

*References

61. General Electric Co./Aircraft Equipment Div. 1978, "Solid Polymer Electrolyte Fuel Cell Technology Program," (Avail. NTIS: N-78-29567).
62. McElroy, J. F., 1978, "Status of Solid Electrolyte Fuel Cell Technology," National Fuel Cell Seminar in San Francisco, (Author at G. E., 50 Fordham Rd., Wilmington, Mass. 01887).
63. Beaufrere, A., et al., 1977, "A Hydrogen-Halogen Energy Storage System for Electric Utility Applications," 12th Intersociety Energy Conversion and Engineering Conference, (Paper No. 779148).

with a system sized for Coast Guard lighthouse applications because smaller storage tanks with a higher cost per gallon stored would be used, but the substation battery consists of many modules. Consequently the modules used in a Coast Guard application may not be smaller or more expensive, only less numerous, provided that individual modules developed for electric utility use can be combined into a battery with suitable voltage and storage capacity ratings for the Coast Guard application.

A similar reversible electro-chemical storage system employing zinc instead of hydrogen to react with chlorine is under development by Energy Development Associates (Gulf Western)^{64*} with support from the Electric Power Research Institute and DOE. Both the Zn-Cl and H-Cl storage systems are intended to be used as an energy storing electrical substation in an electric utility. The zinc chlorine cell has been developed as a completely self contained module with the chlorine stored internally in the module. The chlorine is stored as a refrigerated chlorine hydrate so that it can also have mobile applications. The module stores 45 kWh and has a demonstration efficiency (AC to AC recovered) of 50% which is less than the design value of 63%. The design value should be achieved or exceeded as the performance defects of the first module are understood and correctable. The principal disadvantage of the Zn-Cl cell relative to the H-Cl cell is the use of solid electrodes which develop zinc dendrites during charge and discharge cycles unless the cell is occasionally totally discharged. One cell has more than three years of cycle testings and at least a 10-year life is projected. Based on yearly production of 25,000 modules for use in the electrical industry, a production cost of \$1170 for a 45 kWh module, or \$26/kWh has been estimated.^{65*} Shipment, installation, power conditioning equipment, building, etc. are estimated to cost almost four times as much as the modules used in the energy storage substation.

A cell similar to the Zn-Cl cell, but using bromine instead of chlorine is under development by Exxon Research and Engineering Company.^{66*} The cell uses conductive plastic electrodes and a "protective current shunt" to prevent zinc dendrite growth problems. An 80V - 20 kWh integrated package (22" x 27" x 28") has been designed and 80V stacks of cells have been tested for three months without problems. The Zn-Br cell was previously troubled by a high self discharge rate, but in this design most of the bromine is stored remote from the zinc in a gravity separated chemical complex phase. The bromine cell does not require the use of refrigeration equipment as does the Zn-Cl cell for chlorine hydrate storage.

*Reference

64. Warde, C. J., et al. 1978, "100MWh Zinc-Chloride Peak-Shaving Battery Plants," 13th Intersociety Energy Conversion and Engineering Conference (Paper No. 78962).
65. Electric Power Research Institute, 1979, "Development of Zinc-Chloride Battery for Utility Application," Research Project 226-3, EM-1051 Interim Report.
66. Bellows, R. J., et al. 1980, "Development of a Bipolar Zn/Br₂ Battery," 15th Intersociety Energy Conversion Engineering Conference, Seattle, WA. (Paper No. 809388).

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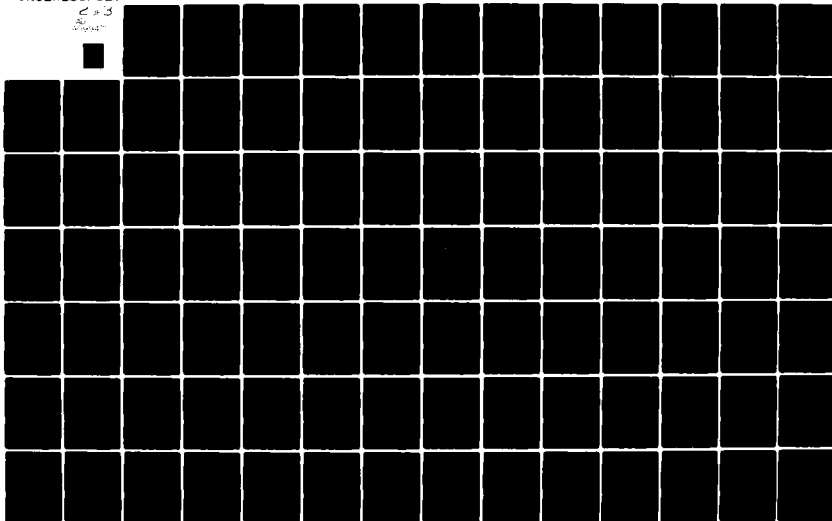
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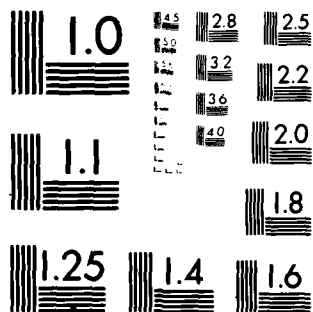
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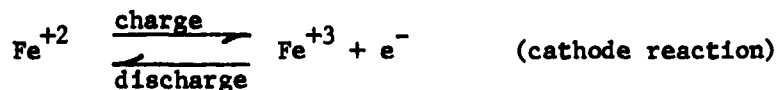
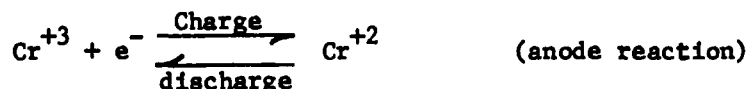


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The Zn-Cl cell is an attractive candidate for use in electric cars because its power density (W/lb) is greater than the lead-acid battery and its energy density (Wh/lb) or "range potential" is more than twice as great as the lead-acid battery. It has been used in a demonstration electric car. Installed in a modified Vega, the unit reportedly gave a range of 152 miles at 50 mph.^{67*} The Zn-Cl cell may be available by 1985 as estimated by the Electric Power Research Institute but the recent announcement by General Motors that GM electric cars will use the zinc-nickel battery reduces the potential market for the Zn-Cl reversible cell and may slow its development. Very recently questions have been raised about the prior claims made for the Zn-Cl battery and its utility for electric car applications.^{68*}

The Zn-Br cell is also suitable for the electric vehicle market and may have less of a problem with safety concerns in the event of a serious accident as the bromine is chemically complexed at room temperature. However the Zn-Br cell does not appear to be as developed as the Zn-Cl cell for this application. The H-Cl cell is not considered suitable for mobile application because its chlorine is stored under pressure as a liquid instead as a refrigerated chlorine hydrate. Neither of the chlorine cells or the bromine cell is likely to be commercially available during the next five years and consequently they are not considered for use in the Phase II experimental prototype. All three permit the long term storage of energy without loss as the energy is in stable chemical form until supplied to the cell electrodes, however, the Zn-Cl cell does require refrigeration power for the chlorine hydrate.

Redox Cell. Another promising reversible electro-chemical storage system is the Redox flow cell being developed by NASA/Lewis Research Center.^{3,69,70*} It is a fuel cell with basically inert electrodes and fully soluble ionic reactants produced on both charge and discharge in separate chambers as follows:



When the cell is fully charged, most of the chromium is in solution as the chromus ion and the iron exist primarily as ferric ions. During discharge, the iron is reduced to ferrous ions and the chromium is oxidized to chromic ions. When the cell is delivering power,

*References

67. Noyes Data Corporation, 1979, Electric and Hybrid Vehicles, p. 183.
68. Energy Today, Vol. VIII No. 1 (Sept. 12, 1980).
69. Thaller, L. H., 1979, "Redox Flow Cell Energy Storage System," NASA TM-79143.
70. Thaller, L. H., 1979, "Recent Advances in Redox Flow Cell Storage Systems," NASA TM-79186.

electrons leave the chromium solution, pass through the outside load and enter the iron solution electrolyte. In order to maintain charge neutrality in both solutions, negative chlorine ions migrate through an ion selective membrane from the iron solution to the chromium solution during discharge and in the opposite direction during charge. Both metallic ions are dissolved in hydrochloric acid and it is the source of chlorine ions. Migration of either chromium or iron ions through the ion selective membrane reduces the cell capacity, but membranes have been demonstrated in the laboratory with a projected loss in cell storage capacity of only 25% in thirty years. Electrode reactions are catalyzed with small quantities of lead and gold on the chromium solution electrode. The gold is a minor component of the cost, but if it should be eroded away by the flowing solutions, the lifetime could be less than the 20 years estimated by NASA.

The cell voltage is low, only 0.9 volts, and decreases as the cell is discharged, but many Redox cells are stacked together for higher output. The total surface area of the electrodes and membrane determine the power level. A 10 kW stack of cells is estimated to require a volume of 2' x 2' x 4' and the 1 kW unit demonstrated by NASA has four modules with a total volume of about two cubic feet. The storage time is determined independently of the power level by the size of the two solution storage tanks. Thus the system is particularly attractive for applications with multiday storage requirements as chemicals and larger tanks are the only cost increments as storage capacity increases. Approximately 1.3 gallons of each solution must be separately stored for each 100 Wh of energy storage desired. A 10 kW - 50 kWh system is estimated to cost \$12,000 and last for decades instead of years as is the case with conventional battery systems. Because the electrodes do not participate in the cell reaction chemistry, they should not be damaged by numerous charge-discharge cycles. That is, unlike conventional lead-acid batteries, the iron-chromium Redox cell can be charged and discharged often without marked reduction in its life.

The Redox cell stack has another interesting feature of considerable significance for Coast Guard application requiring two or more different DC voltages. A stack of Redox cells can function as a DC to DC "transformer". Part of the stack can be generating current (discharging chemicals) while another part is being charged. Thus, it would be possible to charge the system only at 110 volt DC and take power from a 12 volt DC section of the stack without ever charging the system at 12 volt DC. The energy is stored in the chemicals in the tanks. The chemicals can be charged at one DC voltage and discharged at another. A stack of Redox cells can also function as a "max power tracker" for a solar array by switching the output voltage of a series string of solar cells to different voltage points in a Redox stack.

There are still problem areas in the development of the cell. Membranes with lower resistance to chlorine ion transport are required before the cell can be economical in off-peak electric utility storage applications. This problem must be solved and the cost of the membranes must be reduced before the cell will be produced in quantity and be gen-

erally available. During charge, especially at high charge rates, positive hydrogen ions may escape as neutral hydrogen gas from the chromium solution in lieu of an influx of negative chlorine ions. Electrical charge neutrality in the chromium solution is maintained by the loss of positive hydrogen ions instead of the gain of negative ions as is desired. This hydrogen must be replaced to maintain the same state of charge in the chromium and iron solutions. NASA/LeRC has devised a automatic "rebalance cell" for solving this problem. Compensation for the decrease in voltage per cell with discharge has also been demonstrated by the electronic switching of additional cells into the stack as the two solutions become spent. Since the state of charge of all cells is determined only by the concentration of the solutions supplied to them, these less frequently used cells do not differ in chemistry or voltage from cells continuously in use. Another problem relates to the fact that the chemical solutions' flow through the cells is in parallel for all cells in the stack, but the cells are connected in series electrically. Thus conductive solutions join cells with electrodes at different potentials and self discharge current paths exist. However, unlike the zinc dendrite problem in the Zn-Cl and Zn-Br cells this problem can be ignored as all reactants are fully soluble. No information has been published related to this problem and no value for the "shelf life" of a fully charged, open circuit, flowing system is available.

The development of the iron-chromium Redox flow cell at NASA/LeRC is continuing. It will probably replace batteries in the remote stand-alone village power systems designed by NASA/LeRC. It is not likely to be commercially available prior to 1985 and thus will not be included in the current simulation model. It holds considerable promise for remote applications which include sufficient storage to depend 100% upon alternate energy sources because increased storage capacity is relatively inexpensive. So long as long term energy storage is available at Coast Guard sites in the form of diesel fuel, the electrical storage system will not be large enough to supply 100% of load requirements during long periods when alternate energy is not available from the environment. Consequently, the iron-chromium Redox cell should first be demonstrated in remote stand-alone applications not equipped with diesel back-up systems. It may someday find application as a replacement for storage batteries in Coast Guard applications, especially if total elimination of diesel power is desired, or numerous DC voltage levels are required. It would appear to be especially attractive in conjunction with a small modern flywheel energy storage system for peak loads as discussed in subsection 3.3.3, because diesel maintenance and periodic delivery of fuel to the site could be eliminated. However, the small flywheel - rechargeable fuel cell - alternate energy only station is not a sufficiently developed technology to be considered for near term applications.

Secondary Batteries

Batteries are distinguished from fuel cells by the fact that the chemical reagents of the cell can not be physically separated from

the electrodes. That is, a battery has at least one electrode that degrades in form (morphological change) with each charge-discharge cycle. Batteries are usually divided into primary and secondary classes. Primary cells are not designed for recharging and are of little interest in an alternate energy system. Secondary cells are designed for re-charge. Some, like the nickel-cadmium cell, are designed for repeated deep discharge and have minimum morphological change in a charge-discharge cycle. Unfortunately, Ni-Cd cells are relatively expensive. Consequently, the most common secondary battery is made of lead-acid cells. The lead-acid battery can be improved for use in alternate energy storage systems by the addition of calcium to the electrodes. Lead-acid cells are more economical than Ni-Cd cells if the battery is normally fully charged and only occasionally discharged. In an alternate energy system with frequent deep discharges, the Ni-Cd battery may produce a lower life-cycle-cost, especially in a remote site application as the cost of replacement is significantly greater than simply the battery costs. The lead-acid and Ni-Cd batteries are discussed in greater detail in the next subsections. They are the only practical choices for use in the Phase II program.

In addition to the commercially available Ni-Cd and lead-acid batteries, other chemical systems are under active development for electric vehicle applications and may be available commercially by 1985. These systems include:

- 1) Nickel-Iron: This system was one of Edison's many inventions. It has a relatively high self discharge rate and tends to evolve hydrogen gas. It is a modest improvement in both power and energy density over the lead-acid cell and significantly more durable or resistant to permanent damage in charge-discharge cycles. However, it is less efficient than the lead-acid cell. Typically only 50 to 60 percent of the energy supplied to the battery can be recovered.
- 2) Nickel-Zinc: This system is superior to nickel-iron in both power and energy densities but inferior to even lead-acid in number of charge-discharge cycles expected. It would not appear to be useful for stationary Coast Guard applications.
- 3) Sodium-Sulfur: This system requires a high operational temperature, 600°F, and thus is not particularly attractive. It is considered for mobile applications because it could be as economical as a lead-acid battery and yet provide more than twice the energy density or driving range.
- 4) Lithium-Iron Sulfide: This battery has characteristics similar to the sodium-sulphur battery except even higher temperatures are required for operation.

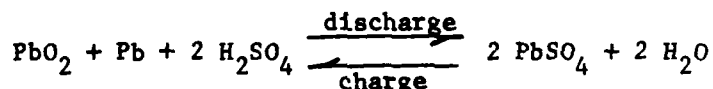
- 5) Zinc-Nickel Oxide: This cell was not generally considered to be especially promising for electric vehicle applications prior to September 25, 1979. On that date General Motors announced it was the GM choice for an electric car. Proprietary data must exist to support this choice.

3.4.3 Lead-Acid Batteries^{*}

3.4.3.1 General Considerations

Since the discovery of the galvanic battery by Volta at the turn of the century the lead-acid battery has evolved as the workhorse of industry. It offers the user a significant cost advantage because of the existing large volume production. If properly used, the lead-acid battery can deliver excellent cycle life, tolerate a wide range of temperatures, and, in general meet the storage requirements of alternate energy systems at relatively low cost.

A fully charged lead-acid battery cell consists of a lead peroxide positive plate and a pure sponge lead negative plate in intimate contact with a sulfuric acid electrolyte. Upon discharge both plates are quantitatively converted to lead sulfate according to the following combined charge-discharge reaction:



The active materials are applied either as a cemented paste to a lattice grid or electrochemically to a highly developed surface used to enhance surface area. The length, width, and thickness of the plates in a cell are determined by the required capacity of the cell. The positive and negative plates are separated by porous sheet forms of wood, rubber, glass, or plastic. The resultant sandwich assembly of plates and separators is physically constrained in a container which holds the sulfuric acid electrolyte. In some cells of the non-flooded type, the electrolyte is entirely absorbed within the porous separator material. The advantage offered by this technique is that the electrolyte cannot spill. Other cells obtain similar advantage by use of a gelled type of electrolyte. Although there are some differences in the electrical performance characteristics of the various types of commercially available lead-acid batteries, they are generally rather similar.

3.4.3.2 Charging Characteristics

A typical voltage characteristic of a flooded six-cell lead-acid battery under charge is provided in Figure 3.7. The battery charge or discharge rate is usually described as a fraction of the nominal name plate capacity "C" (i.e., 0.07 C charge rate for a 100 ampere-hour

^{*} This subsection and the next concerning nickel-cadmium batteries draws heavily upon material developed by W. E. Allen of APL for another Coast Guard project: "Solar Powered Aids to Navigation, SPAN Study," SDO 5528 (February 1980).

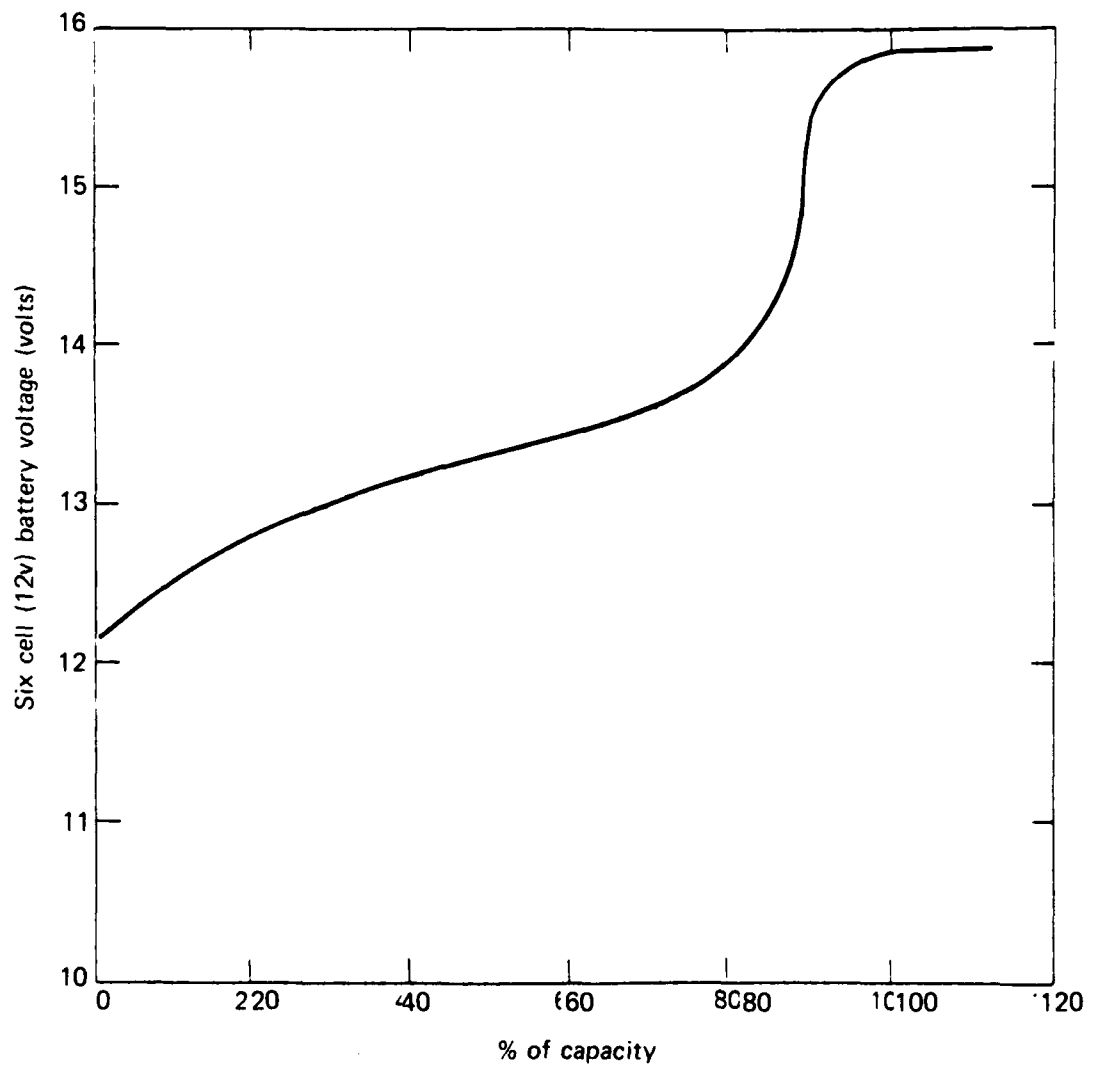


FIGURE 3.7 TYPICAL LEAD-ACID BATTERY CHARGING VOLTAGE AT 0.07C CHARGE RATE AND ROOM TEMPERATURE.

battery denotes a charge current of 0.07×100 or 7.0 amperes). As may be noted in Figure 3.7, the terminal voltage rises slowly in monotonic fashion as the battery is recharged. As full charge is approached the terminal voltage tends to rise markedly until equilibrium is achieved in overcharge. This voltage rise is somewhat dependent upon the rate of charge and is less pronounced at lower rates.

As the charge progresses, the specific gravity of the electrolyte rises. Depending upon the type of battery and the ambient temperature, the specific gravity at full charge will range between 1.2 and 1.3. Most flooded types use a relatively high specific gravity if exposure to freezing conditions is likely. The specific gravity of a stationary flooded cell can become significantly higher on the bottom than the top during repeated charge-discharge cycles with adverse effect on cell life and capacity.

Near the end of charge and during overcharge gases are evolved within the lead-acid battery; the gases liberated are oxygen at the positive plate and hydrogen at the negative plate. Gassing can begin when the terminal voltage is above 2.2 volts per cell. The proportion of hydrogen to oxygen, particularly during the onset of gassing, is not necessarily that resulting from the hydrolysis of water. Gassing can have significant impact upon the requirements for battery water addition. Water loss due to hydrolysis in vented cells, aggravated by evaporation and vapor carry off in the vented gases, can make maintenance requirements rather costly. Excessive gassing can loosen active materials in pasted plates, particularly the positive plates. This tends to limit the useful lifetime of the battery. Gassing can be totally eliminated by limiting the maximum charging voltage to less than 2.2 volts per cell, but higher voltage will occasionally be required to equalize the state of charge in all cells of a battery.

3.4.3.3 Discharge Characteristics

The discharge characteristics of lead-acid battery systems as they relate to applications in alternate energy system may be broadly divided into two distinct categories - (1) self discharge and (2) discharge under load.

Self Discharge. Self discharge is a phenomenon caused by parasitic electrochemical reactions taking place within a charged cell reducing its stored energy with increase in time. Self discharge may be considered, in effect, as an additional external load on the system. Most automotive lead-acid batteries employ lead-antimony alloys for grid strength, but grids using calcium for this purpose are also available. Antimony tends to promote a relatively higher self discharge rate than calcium. With antimony grids, the self discharge rate is a function of temperature and battery age. See Figure 3.8. The lead-calcium grid

*References

71. Vinal, G. W., Storage Batteries, John Wiley, New York, 1955.
72. Becthet National, Inc., 1979, Handbook For Battery Energy Storage in Photovoltaic Power Systems.

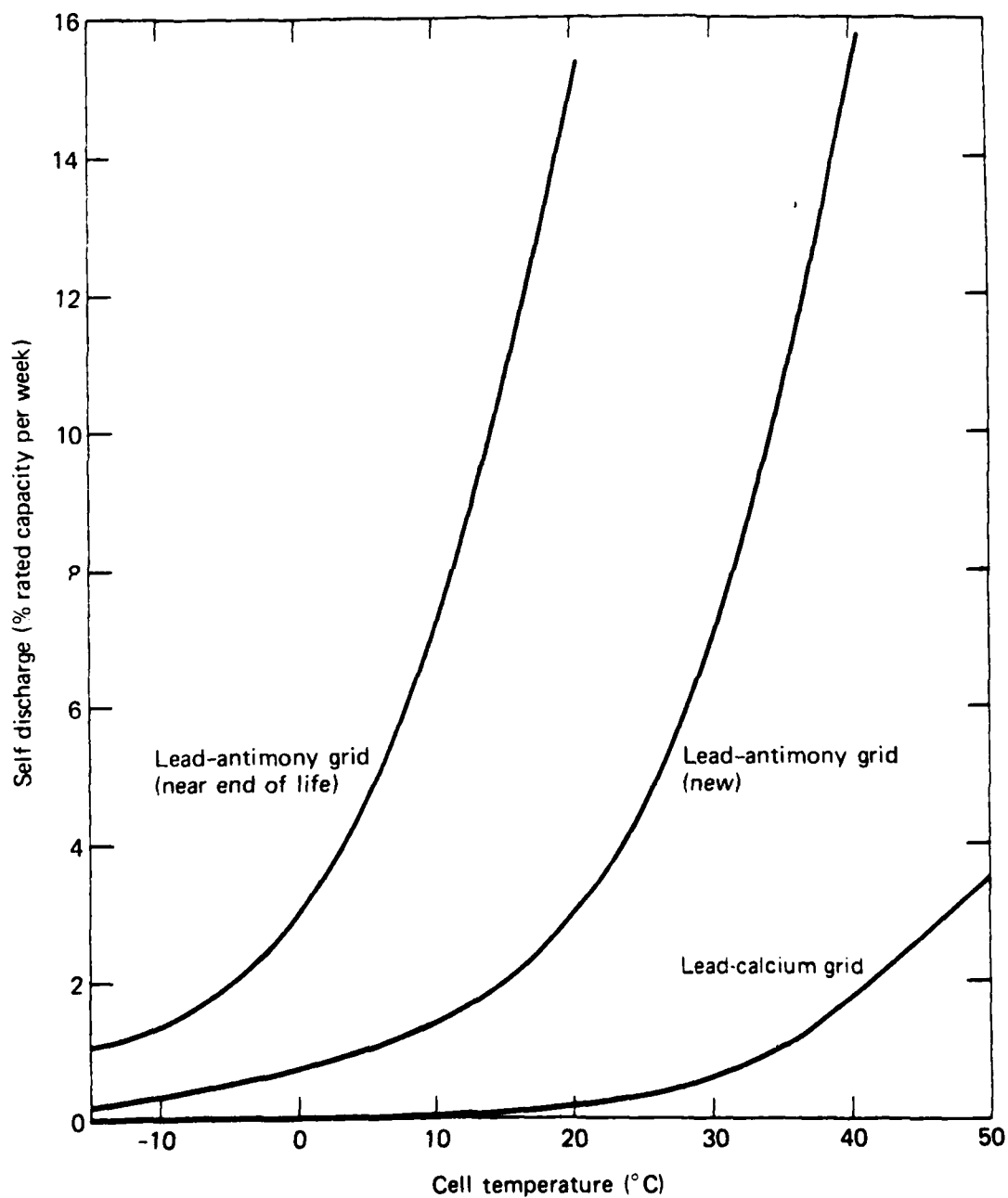


FIGURE 3.8 LEAD-ACID BATTERY SELF DISCHARGE RATE AS A FUNCTION OF TEMPERATURE. (Data from Figure 3-10 of Reference 72)

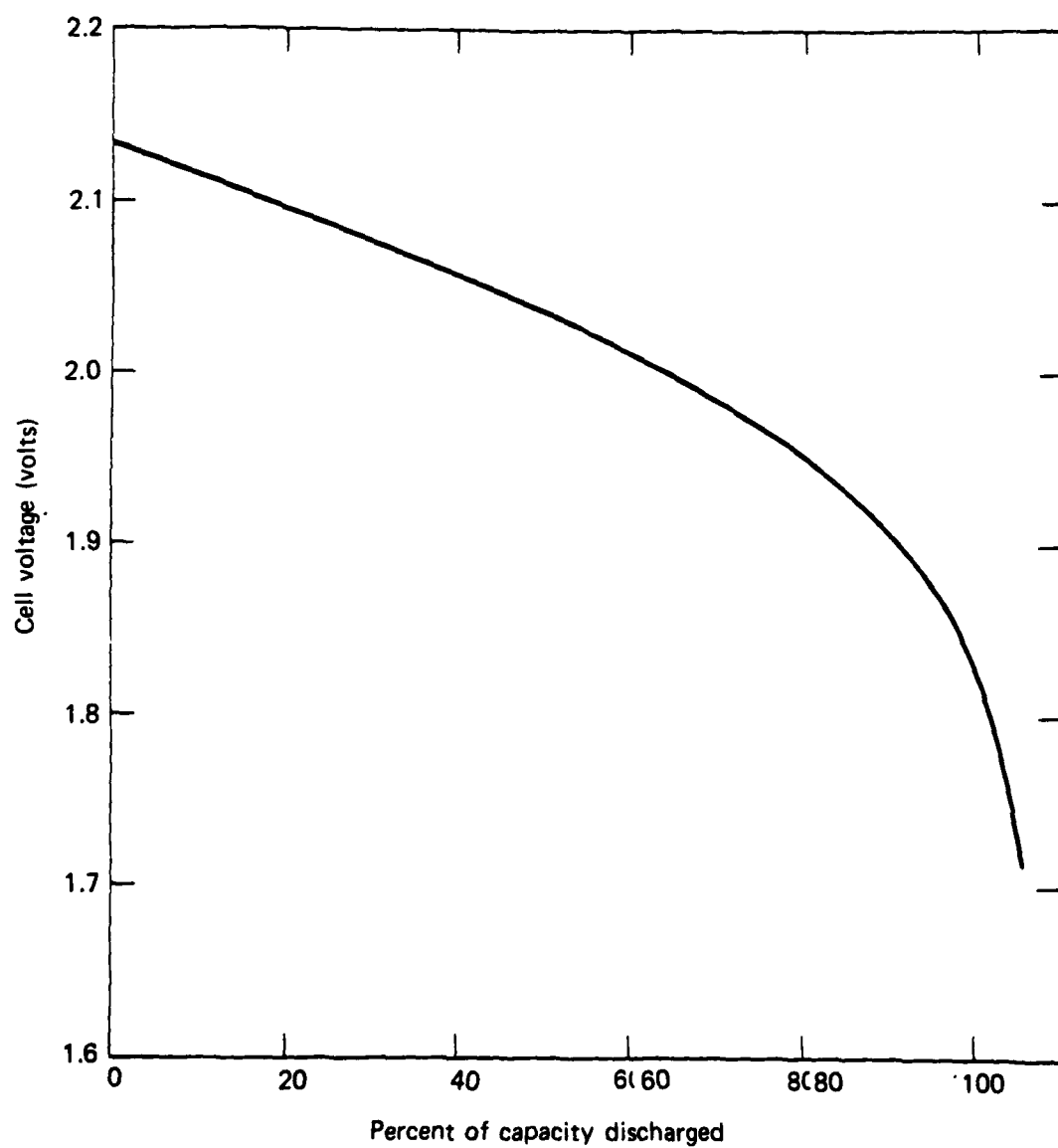


FIGURE 3.9 TYPICAL LEAD-ACID CELL DISCHARGE VOLTAGE UNDER LOAD AT 25° C.

battery and the pure lead battery have almost negligible self discharge characteristics as used in an alternate energy storage system, and antimony grids are acceptable. The choice would depend primarily upon costs and typical storage periods.

Discharge Under Load. The discharge voltage characteristics of lead-acid batteries under a relatively light load are, to a first approximation, independent of cell construction. Cell discharge voltages at room temperature range between about 2.1 volts at the start of discharge to approximately 1.75 volts, the nominal cutoff voltage near cell depletion. A typical discharge voltage characteristic under load is provided in Figure 3.9. As the temperature of a lead-acid cell is reduced, or as the discharge current is increased, the terminal voltage under load and the resultant capacity of the cell decreases. As cell discharge progresses, sulfuric acid electrolyte is consumed as both plates are converted to lead sulfate; this produces a continuing reduction in the specific gravity of the electrolyte. In order to prevent destruction of the battery by freezing when utilizing a flooded lead-acid system, it is necessary to restrict the depth of discharge commensurate with the minimum anticipated operating temperature. A high initial charge rate in a stationary flooded cell in a deep discharge condition may be desirable to promote convective mixing of the stratified electrolyte. The diesel generator would engage when the battery was discharged and the charging current would provide both internal heating of the battery and a stronger acid concentration for freeze protection. Prior to diesel operation, the self heating of the battery due to internal losses is probably adequate to prevent freezing as it is either being charged by the alternate energy system or supplying power to the load.

3.4.3.4 Sulfation

Both the positive and negative plates of lead-acid batteries form lead sulfate when discharged. Crystals of lead sulfate may grow relatively large due to a process known as "Ostwald Ripening" and can insulate active materials thereby inhibiting their further discharge. This process is termed "sulfation" and it often occurs in lead-acid batteries stored in a fully or partially discharged state for an extended time period. Sulfation rate in a lead-acid battery is a function of many variables, including method of cell manufacture. However, this would be mainly a concern for the logistic resupply depot if sealed cells are used. It is a concern only if cells are sealed at the factory, but of no concern if the cells have the electrolyte added at the point of use. At the alternate energy site, sulfation is not likely to be troublesome as the batteries will cycle too frequently, that is, the cycle life will expire before sulfation is serious.

3.4.3.5 Capacity and Cycle Life

The capacity of any battery is typically stated in ampere-hours measured by a constant current discharge until some limiting voltage is reached near battery depletion. For an automotive lead-acid battery the discharge is usually performed at the 6 hour rate ($C=0.17$)

until a voltage of 1.70 volts per cell is reached. A lead-acid battery, all other factors remaining constant, will deliver a higher capacity at lower discharge rates. The nominal capacity of a lead-acid battery will be determined by a number of factors, principally the frequency and extent of use when the alternate energy system is unable to meet the load demands and the battery temperature. During its normal lifetime the capacity of a lead-acid battery is rather dependent upon temperature. Typically the available capacity of a lead-acid battery is diminished as the operating temperature is reduced by about one percent per degree Centigrade.⁷¹ When first placed in cyclic service, a lead-acid battery may show an initial enhancement in capacity reaching a "stabilized" value after plate "formation" has been achieved. As cycle life continues battery capacity is ultimately diminished with ever increasing rapidity until it can no longer perform its mission. In this Coast Guard application, the diesel-electric generator would operate as a back-up supply with increasing frequency, but it would probably not be necessary to visit the site prior to a regularly scheduled diesel service visit because of decreasing battery capacity.

The cycle life of a battery is strongly a function of the exact charge-discharge cycle applied. The lead-acid system has an adequate cycle life and is capable of meeting the technical requirements of the Coast Guard for alternate energy systems. Typically the room temperature cycle lives of flooded lead-acid batteries range from approximately 250 cycles, at a repetitive 90% depth of discharge, to 2,000 cycles at 20% depth of discharge.^{73*} See Figure 3.10. Sealed batteries with gelled electrolyte in the traditional flat plate construction assembly offer substantially lower cycle life than flooded cells but still offer cycle lives of several hundred cycles at 50% depth of discharge. The primary advantage of a traditional construction, sealed battery with gelled electrolyte is its ability to operate in any position. This feature is not required in the alternate energy system.

3.4.3.6 Cost

The lead-acid battery offers a significant cost advantage over other types. Relatively low cost of materials coupled with high volume production to meet an ever growing market has made the lead-acid battery the most inexpensive secondary battery available today. Costs for a 12-volt battery will range from approximately \$1 per ampere-hour for a flooded "charge retaining" battery by Wico (ESB) to approximately \$5 per ampere-hour for a gelled electrolyte system by Globe-Union. Because of the higher cost of sealed flat-plate cells with gelled electrolyte and their lower cycle life, these traditional cells do not appear attractive compared to flooded batteries. Gate's new sealed cell with cylindrical plates costs approximately \$23 per ampere-hour as a 12 volt battery. It has cycle life characteristics similar to a flooded cell. It is available presently only in smaller sizes (25AH), but may be attractive for this application assuming larger and more economical sizes become available. These cells are very tolerant of over-charging and generally require no attention.

*Reference

73. Crisp, J. N. et al., 1979, "Analysis of Remote Site Energy Storage and Generation Systems," (Avail. NTIS: AD A074 869).

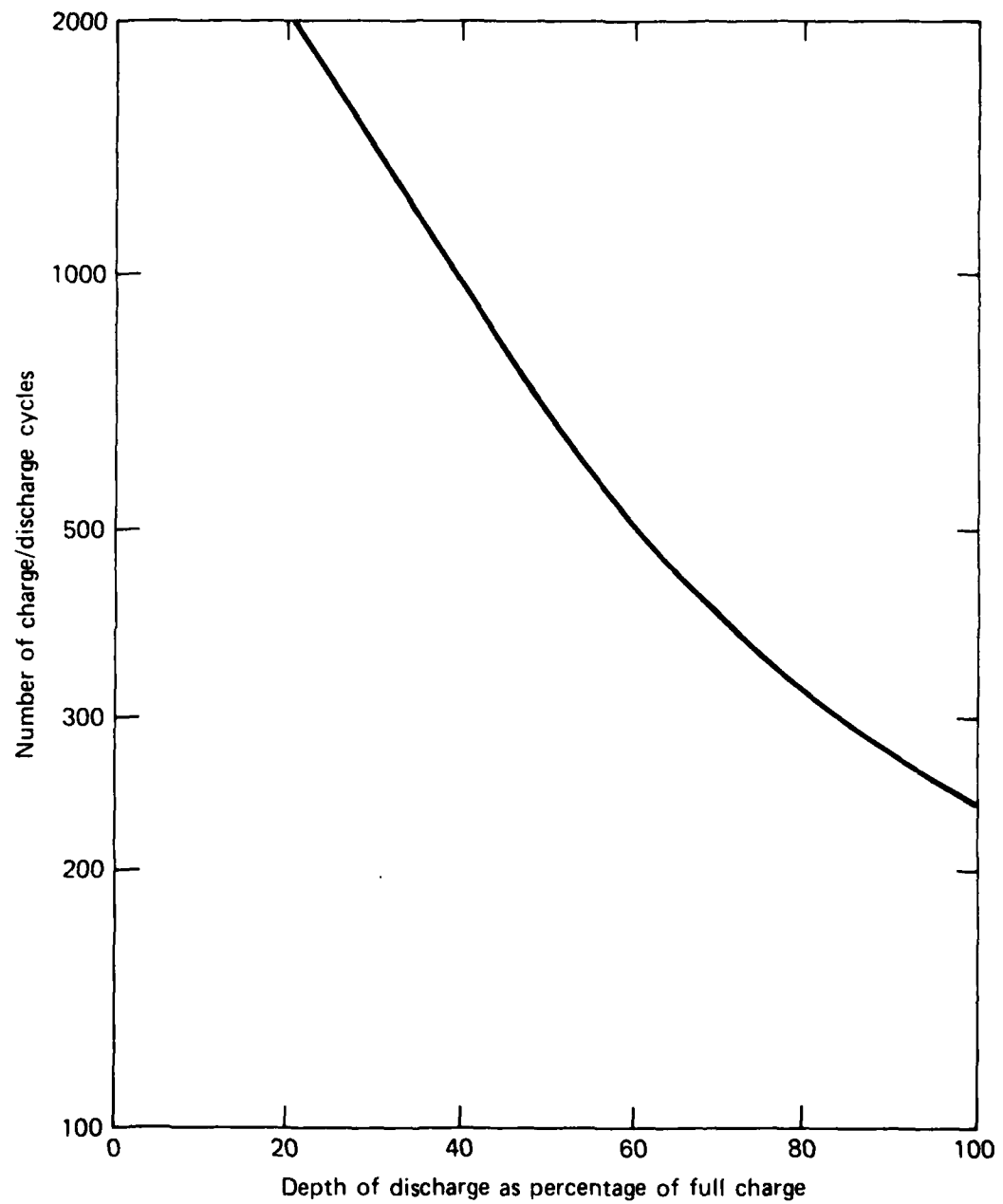


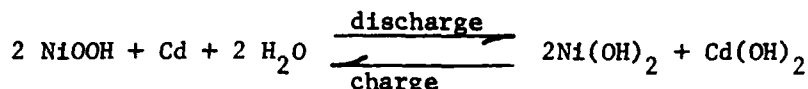
FIGURE 3.10 DEPTH OF DISCHARGE -- LIFETIME CHARACTERISTIC FOR LEAD ACID CELL.

3.4.4 Nickel-Cadmium Batteries

3.4.4.1 General Considerations

The nickel-cadmium battery is a practical and efficient electrochemical storage device which should be considered as a candidate for use in an alternate energy system. It has demonstrated outstanding cycle life over a wide range of operating temperatures. Although first costs are relatively high, it may prove cost competitive when logistical and maintenance costs are considered.

The active material of the charged positive plate is nickel hydrate. The active material of the charged negative plate is pure cadmium sponge. The electrolyte is an aqueous solution of potassium hydroxide. The combined charge-discharge reaction may be written:



Nickel-cadmium cells are manufactured with either sintered or pocket plates. Pocket plates are formed from thin strips of finely perforated nickel-plated steel which are formed to envelop the contained active materials in "pockets". Contact with the electrolyte is maintained through the plate perforations.

Sintered plate construction consists of depositing a slurry of powdered active materials onto a support element or grid, followed by furnace sintering which welds the particles together in a relatively porous structure. The plates are then "formed" by an electrochemical process which deposits the necessary oxides within the pores of the plate.

Positive and negative plates in either type of cell are grouped together and separated from each other by means of porous separators, commonly of nonwoven nylon. Cell containers are usually manufactured of steel or nylon and act to contain the plates and as a reservoir for the potassium hydroxide electrolyte. Pocket plates are invariably flooded with electrolyte while sintered plate cells may be of either the flooded or "starved" electrolyte design. In the starved electrolyte cell the electrolyte used is merely sufficient to moisten the separator. This construction permits rapid recombination of generated gases and therefore allows the cell to be sealed. The electrical characteristics of the nickel-cadmium cell are influenced by the type construction employed. These differences will be discussed in the following subsections.

3.4.4.2 Charging Characteristics

The typical voltage characteristics of nickel-cadmium cells under C/10 charge are provided in Figure 3.11. It should be noted that flooded cells produce a marked rise in terminal voltage near the end of charge. This is associated with gassing which becomes significant near the end of charge. Such cells must be vented since all overcharge is

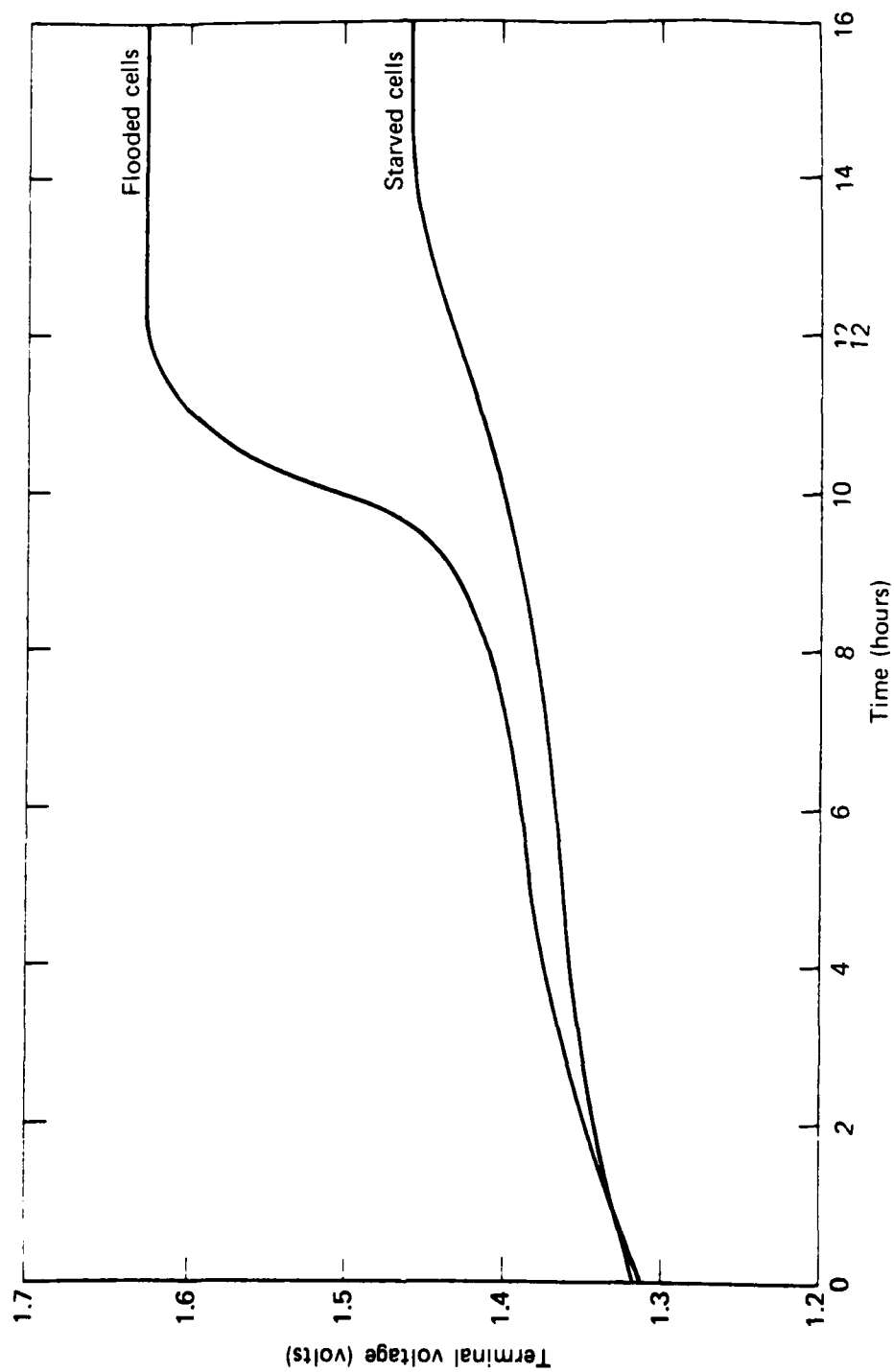


FIGURE 3.11 TYPICAL NICKEL-CADMIUM CELL VOLTAGE UNDER CHARGE
AT C/10 RATE AND 25°C.

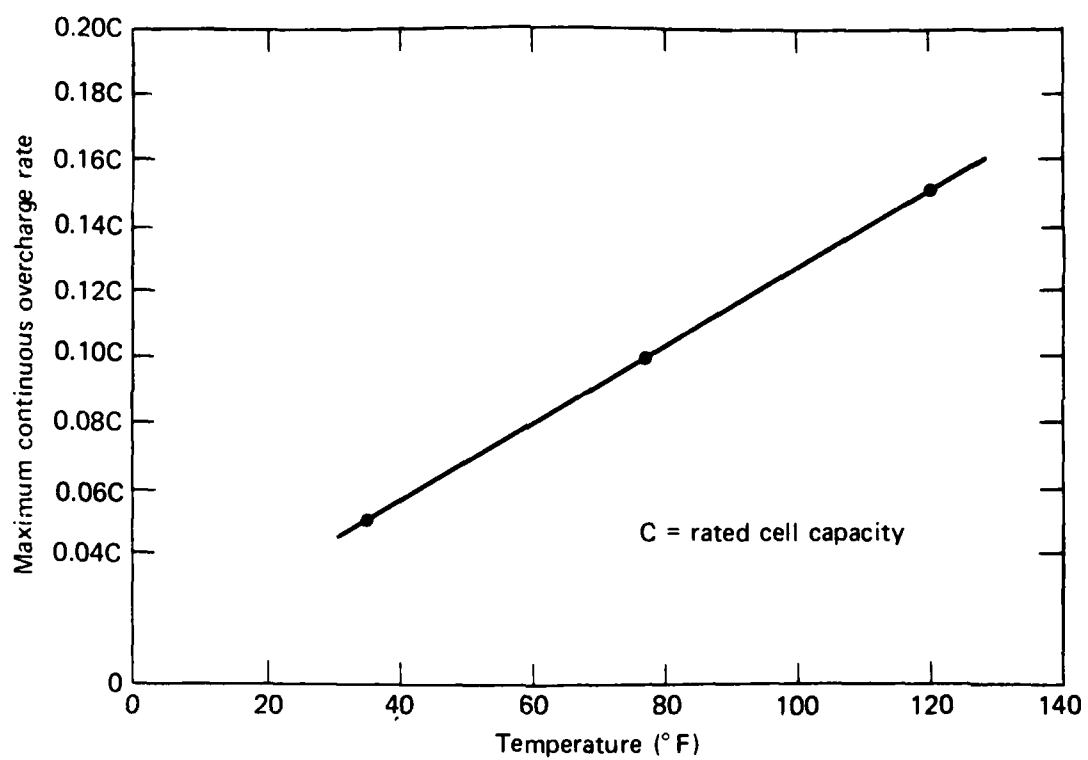


FIGURE 3.12 MAXIMUM CONTINUOUS OVERCHARGE CURRENT FOR A SEALED NICKEL-CADMIUM CELL AS A FUNCTION OF CELL TEMPERATURE.

used for the production of gas which cannot be readily recombined within the cell. As in the case of the flooded lead-acid cell, water loss will occur in direct proportion to the amount of overcharge sustained.

The starved electrolyte cell of Figure 3.11 is typically a sealed cell either with or without a pressure vent. Since the electrolyte does not wet the plates, oxygen evolved within the cell may be more readily recombined at the negative cadmium electrode. By incorporating excess cadmium to act as a "getter" for the oxygen such cells may be safely sealed if charged at reasonable rates. The starved cell characteristic illustrated in Figure 3.11 is typical of all sealed nickel-cadmium cells; a relatively modest voltage rise occurs in overcharge due to the equilibrium recombination of oxygen within the cell. Another characteristic of a sealed sintered plate cell is its tolerance to overcharge. Figure 3.12 provides typical manufacturers' recommendations for allowable overcharge currents as a function of cell temperature.

3.4.4.3 Discharge Characteristics

The discharge characteristics of the nickel-cadmium system, like the lead-acid system, may be broadly divided into two categories - (1) self discharge and (2) discharge under load.

Self Discharge. The self discharge characteristics of nickel-cadmium cells are largely a function of cell manufacture. Impurity ions of tin or nitrate, if present in the electrolyte, will produce a relatively high self discharge rate.^{74*} The rate of self discharge is strongly a function of temperature; at elevated temperatures self discharge is rather pronounced. Considerable variation in self discharge rate has been observed but self discharge is not a very significant consideration when the cells are used in a diurnal charge-discharge cycle as is likely in this remote power system application.

Discharge Under Load. The discharge voltage of a nickel-cadmium cell will be generally above 1.25 volts under a light load. Typical discharge voltage characteristics are provided at various discharge rates in Figure 3.13. These discharge curves are characteristic of both sealed and vented cells. Unlike the lead-acid cell, the electrolyte specific gravity in a nickel-cadmium cell remains relatively constant throughout cell discharge. The potassium hydroxide electrolyte does not enter into any chemical reaction but merely acts as a transport medium for ionic interchange. Since the specific gravity of the nickel-cadmium cell electrolyte typically ranges between 1.24 and 1.32^{75*}, the freezing point is sufficiently depressed to permit safe operation at extremely low temperatures. At the low operating temperatures a reduced terminal voltage under load will be experienced because of an increase in internal cell resistance.

*References

74. Falk, S. U., Salkind, A. J., 1969, Alkaline Storage Batteries John Wiley, New York.
75. Marathon Battery Co., Marathon Battery Instruction Manual, Waco, Texas, Revision 578.

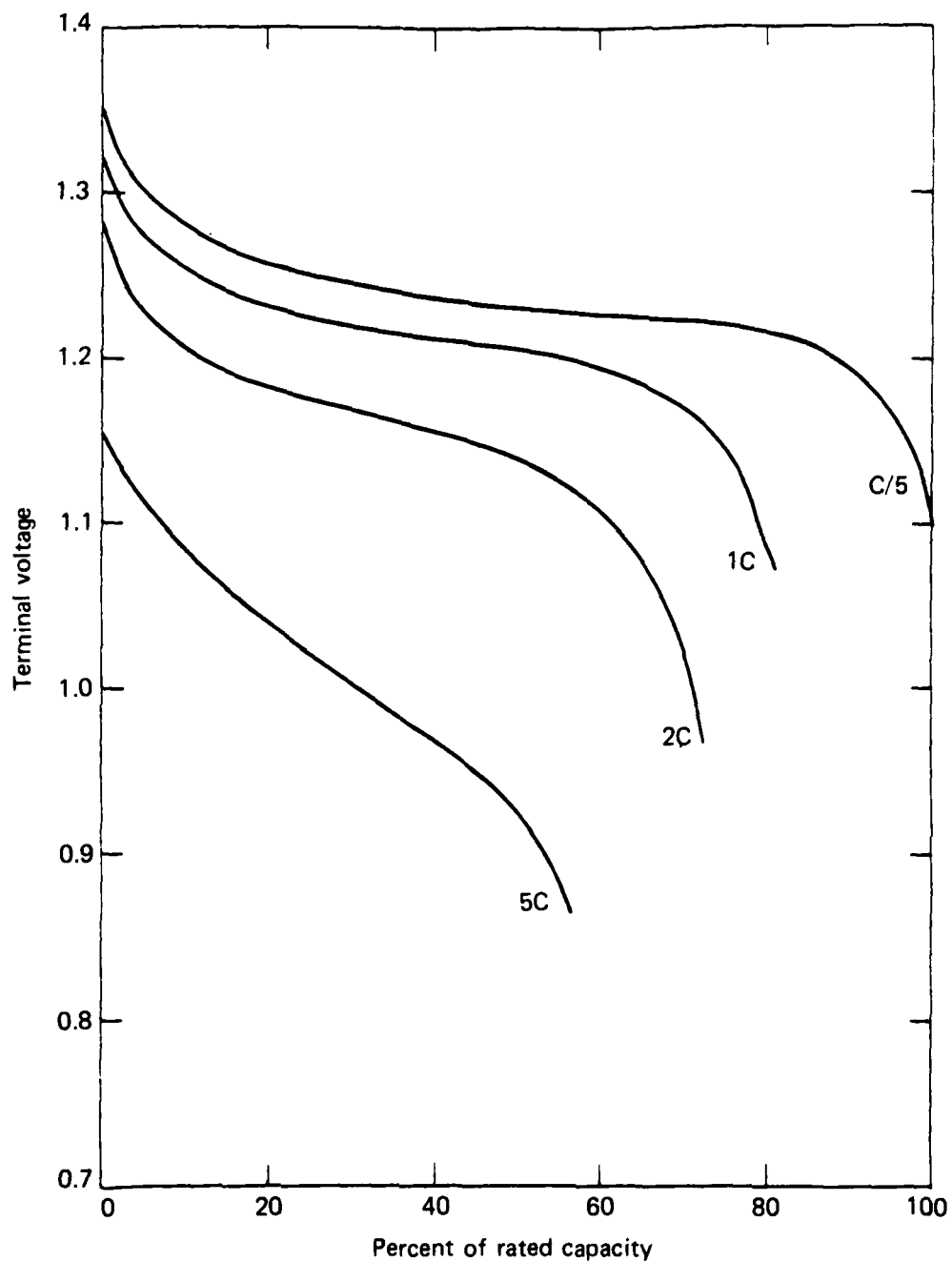


FIGURE 3.13 TYPICAL DISCHARGE CHARACTERISTICS OF A NICKEL-CADMIUM CELL AS A FUNCTION OF LOAD AT 25°C.

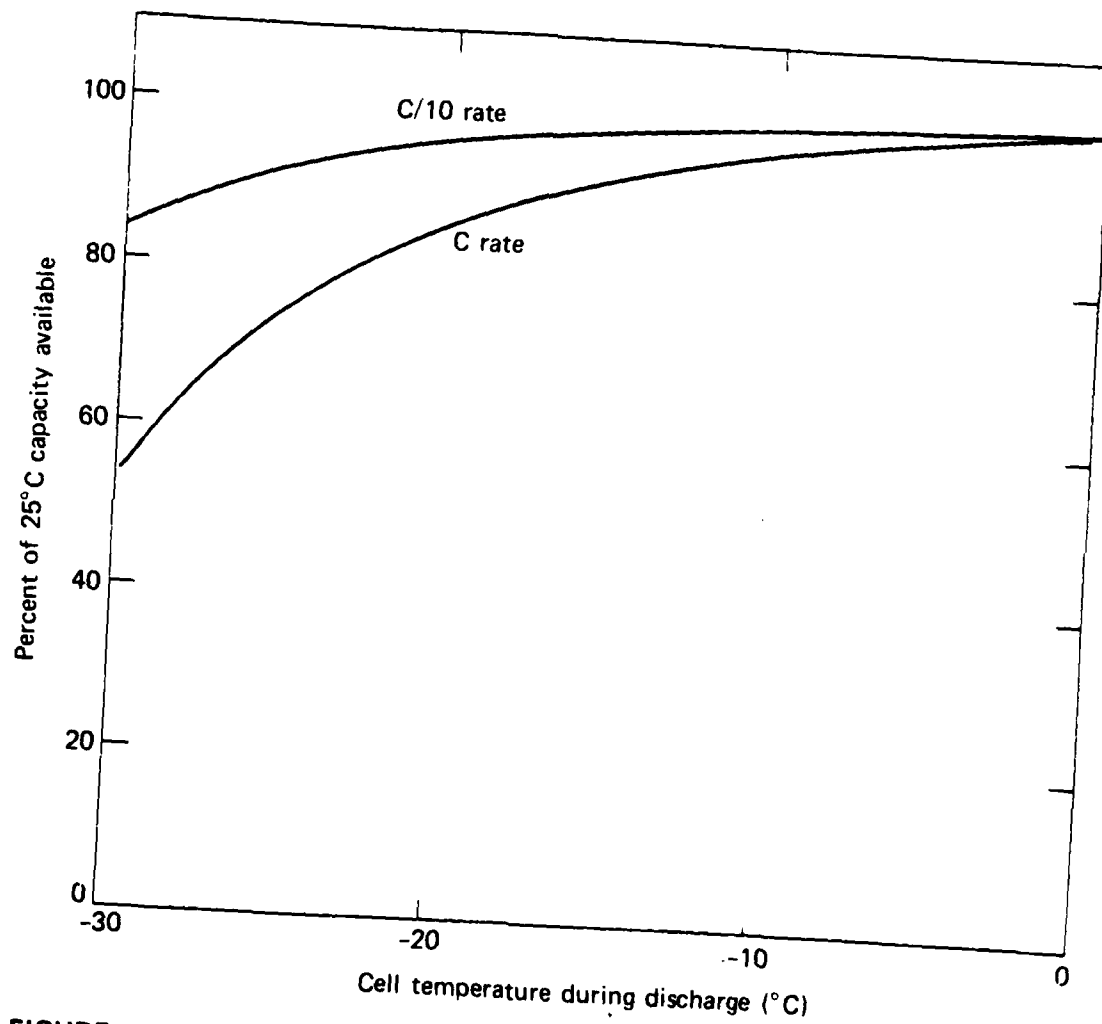


FIGURE 3.14 AVAILABLE CAPACITY FROM A NICKEL-CADMIUM CELL TO 1.0 VOLTS AS A FUNCTION OF TEMPERATURE.

3.4.4.4 Capacity

The capacity of a nickel-cadmium battery is typically measured by applying a constant current load ranging between $C/10$ and C , depending upon battery type and intended use, until reaching a limiting voltage of 1.0 volts per series cell. The ampere-hour capacity attainable is, in very large measure, a function of the temperature of the battery during charge and the charge current-time profile employed. Controlled charge sequences and temperatures are usually employed when making such measurements of capacity. The temperature of the battery during discharge has a relatively minor effect on the available capacity discharged to 1.0 volts per cell. A slight reduction in available capacity results from the increase in cell internal impedance associated with low temperature operation. Figure 3.14 illustrates the effects of below freezing discharge temperature and discharge rate upon the available capacity of a nickel-cadmium cell measured to 1.0 volts. The effect, although undesirable, is considered inconsequential for a nickel-cadmium battery used in the alternate energy system. The Ni-cd battery is less affected by subfreezing temperatures than a lead-acid battery. The heat developed during diurnal charge-discharge cycles is probably sufficient in an insulated enclosure to keep the battery in an acceptable thermal range. Waste heat from the diesel can be supplied if this should not prove to be the case.

3.4.4.5 Memory

Sintered plate nickel-cadmium batteries have been known to exhibit "memory" effects when subjected to highly repetitive cycling as is typical of their use in many spacecraft applications. This phenomenon is defined as an apparent reduction in capacity to some predetermined discharge voltage cutoff point (usually 1.0 volts) resulting from a repetitive use pattern. The exact mechanism producing this effect is uncertain although several theories have emerged which are based upon the observation of significant quantities of exceedingly large particles of charge plate material in cells exhibiting memory effect. The discharge of such a cell appears to proceed uniformly until all of the small particles have been discharged. The larger particles then discharge at a greater current density with an increased polarization that appears as a voltage drop at the terminals of the cell. The net result is a two step voltage plateau under discharge with an attendant loss of available battery energy. This phenomenon is usually observed only in laboratory tests. Flooded cells do not exhibit memory effects nor do starved cells which are cycled randomly. Temperature variation during cycling also appears to inhibit cell memorization. Since any nickel-cadmium battery used in the alternate energy system will be subject to a rather dynamic and variable schedule, cell memorization effects should not occur.

3.4.4.6 Cycle Life

The extended life of a nickel-cadmium battery is perhaps its greatest single virtue; its outstanding cycle life has made it the

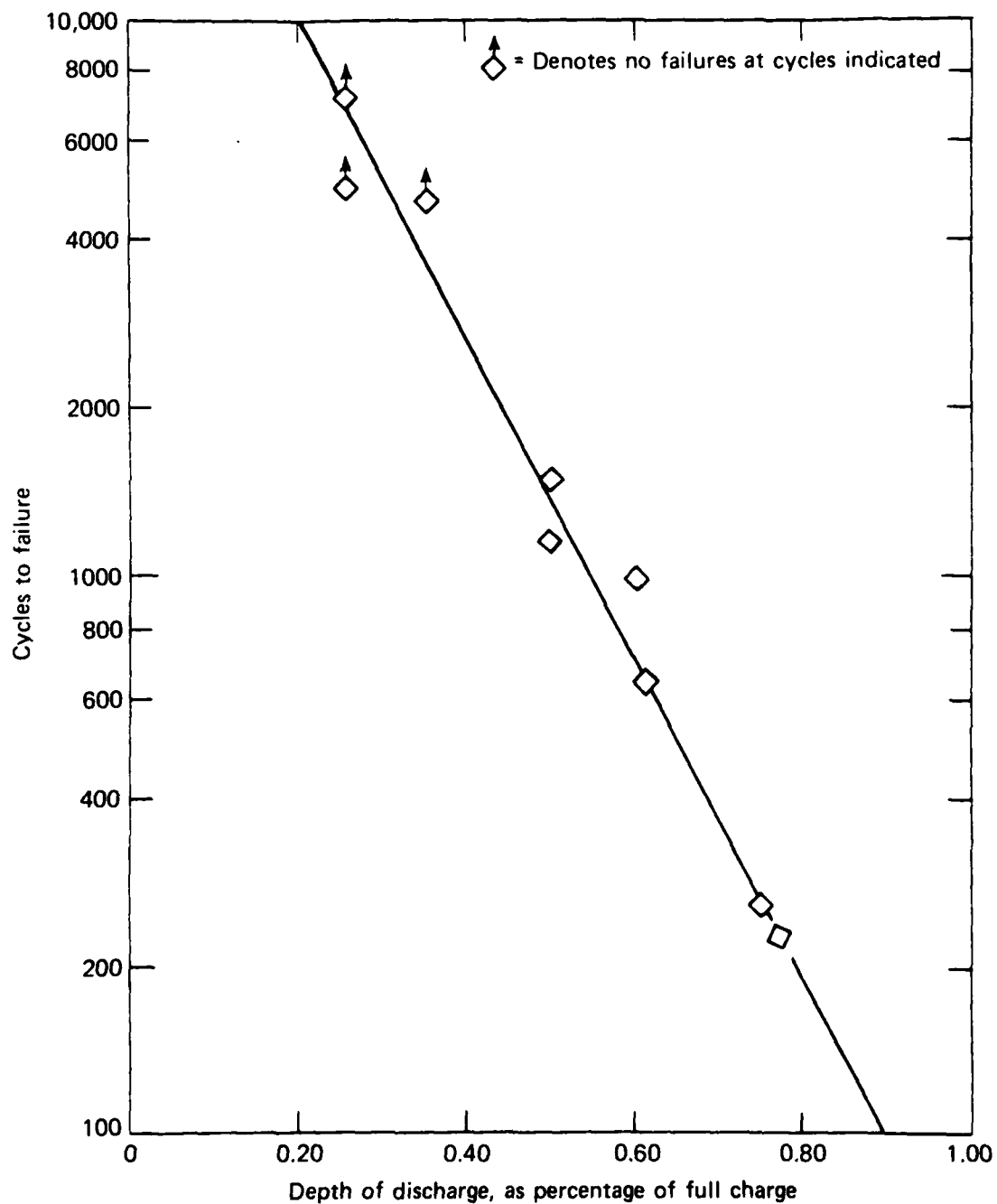


FIGURE 3.15 NICKEL-CADMIUM BATTERY CYCLE LIFE AS A FUNCTION OF DEPTH OF DISCHARGE.

battery type chosen for all spacecraft applications where long life under cycling conditions is essential. Vented cells have also demonstrated exceptional cycle life. Pocket batteries have been used in railroad switchgear control applications for over a decade with no evidence of wear out. Figure 3.15^{76*} illustrates the typical cycle life attainable from nickel-cadmium batteries. The data illustrated were taken on 12 ampere-hour sealed cells operating in the temperature regime between -18°C and 24°C. It should be noted that over one thousand cycles of operation were obtained when cycling to 50% depth of discharge.

Evaluation of cell lifetimes is a statistical problem. Many cells last longer than the lifetimes shown in Figure 3.15. For a more complete discussion of cycle life vs. depth of discharge and temperature effects see Session V of reference^{77*}.

3.4.4.7 Cost

The cost of a nickel-cadmium battery energy storage system will be relatively high. Cell material costs are high, and operating at a voltage of 1.2 volts per cell, 10 series cells will be required for a 12 volt battery compared with only 6 cells for its lead-acid counterpart. The cost of a 12 volt battery of vented cells will range from approximately \$3 to \$7 per ampere-hour over a relatively broad range of available capacities. Commercial cells of the sealed type do not appear to be available in convenient sizes applicable to multikilowatt power requirements. Sealed cells cost in excess of \$20 per ampere-hour for smaller 12 volt batteries.

3.4.5 Battery Selection and Rationale

A modular battery, sized for convenient handling would be ideally suited to the technical needs of the Coast Guard. It would be a sealed battery, requiring no on-site maintenance, and tolerant to overcharge. It would not require a charge regulator. It would have extremely long cycle life. Furthermore, since procurement and storage are potential problems for the Coast Guard, it would readily be obtainable at low cost, have excellent shelf life, and require no maintenance during periods of extended storage in an uncontrolled temperature environment.

The lead-acid battery, although somewhat deficient in a number of desired technical attributes, is the preferred Phase II test program candidate. The relatively low initial cost of an industrial vented lead-acid battery, roughly one third that of a comparable vented nickel-cadmium battery, makes it highly attractive. In addition, considerable testing has been performed by the Coast Guard on a number of commercially available lead-acid batteries to validate their use in minor lighted aids. Wisco, Gates and Globe-Union batteries have been extensively

*References

76. Francis, H. T., 1964, Space Batteries, NASA SP-5004, N64-18052.
77. NASA, 1979, "The 1979 Goddard Space Flight Center Battery Workshop," NASA Conference Publication 2117.

tested for the Coast Guard over a broad range of temperatures by the Naval Weapons Support Center at Crane, Indiana.^{78,79*} Also, considerable experience has been gained from field installations at Miami Beach, Florida where 52 aids employing Wisco DD-3-3 lead-acid batteries were deployed. Although charge regulation in these aids was perhaps less than optimum, they performed adequately.^{80*}

Gates has recently introduced a sealed lead-acid cell of novel construction. It is a "starved electrolyte" type but its plates are rolled up like a jelly roll inside a cylindrical container. The extremely large plate area permits it to charge and discharge at very high rates. It can accept a continuous overcharge at C/3. It requires no attention and has an open circuit shelf life without attention of several years. In float charge service or storage, it should last more than a decade but it is too new to be thoroughly tested. It is currently available only in 25 ampere-hour or smaller sizes but up to four cells can be connected in parallel. It resembles a sealed Ni-Cd except for its higher voltage and potentially cheaper construction materials. Its performance has been demonstrated in various applications and successfully tested as a starter for helicopters at the Naval Weapons Support Center.^{81*} It would appear to be the most attractive storage battery currently available for a small unattended remote station, but larger sizes than currently available would be desired for Coast Guard station application.

In summary, the low cost and acceptable technical characteristics of an industrial type lead-acid battery make it the preferred choice for Phase II use, but it is not unlikely that some other energy storage system now under development will be preferred for Phase III and IV. In the simulation model, we will assume that lead-acid batteries cost \$90/kWh in 1980 and decrease in cost linearly to \$60/kWh by 1990 (in constant 1980 value dollars) because of the current developments related to electric cars and the growing volume of battery sales for photovoltaic, wind, and other deep discharge systems. Vented Ni-Cd batteries will be assumed to cost \$400/kWh with no significant decline in price during the 1980 to 1990 decade. However, it should be noted that Ni-Cd batteries may have lower life cycle costs than lead-acid cells in some Coast Guard applications at present, but the lead-acid

*References

78. Ryba, J. S. et al., 1976, "Laboratory Evaluation of Solar Power Units for Marine Aids to Navigation," Coast Guard Research & Development Center, Groton, Conn.
79. Weapons Quality Engineering Center, 1980, "Evaluation of Lead-Acid Secondary Batteries for Application for U. S. Coast Guard Aid to Navigation," Report WQEC/C 80-32.
80. Nelson, H. D., Tintera, F. J. Jr., 1978, "Seventh District Field Evaluation of Solar Power Units for Marine Aids to Navigation," First Interim Report.
81. Hammel, R., 1980, "Sealed Lead-Acid Battery for Aircraft Applications," 15th Intersociety Energy Conversion Engineering Conference, Seattle, WA. (Paper No. 809432).

battery permits practical experience in system control and installation procedures to be gained in Phase II with the least cost. In view of the extensive development effort currently underway to improve batteries and other storage systems, the choice of storage systems for ultimate deployment in Phase IV should be deferred at least until Phase III.

SECTION 4 COMPUTER SIMULATION

4.1 OVERVIEW

This section describes the computer simulation developed for Task 8 of the Phase I study. The models used for both performance and economics are described in some detail, and representative results are given. A listing of the complete program is included in Appendix I.

4.1.1 Program Description

The simulation includes both performance and economics models, which are normally run sequentially. The performance of a given station can be quantified by time histories of important parameters of its components, such as battery state-of-charge or diesel power. The performance model is essentially a numerical implementation of the dynamic equations for these parameters. By simulating several (typically 12) days sampled from the year, annual mean values of performance parameters are computed. The economics model then uses these performance parameters, as well as independent inputs such as installation year and discount rate, to compute annualized life cycle costs of the major components under study. The total annual cost can be displayed in tabular and/or graphical form to compare relative merits of various parameters, such as battery size or alternate energy systems. These functions are described in more detail below.

The sequence of calculations in the simulation model illustrated in Figure 4.0 is as follows. The main program (YEAR)* is entered, and the user is prompted to enter one or more values of solar array size, rated windmill power, and battery capacity. The function LAMP then computes histories of solar, wind, and load power for all cases and sample days. (The models used in LAMP are described in subsections 4.2 and 4.3.) LAMP then calls BATTERY, which numerically integrates the differential equations of battery state-of-charge (SOC) dynamics for each case. The computed value of SOC is used in the dynamic equations to control diesel output power. Output of LAMP is a multidimensional data array of hourly mean histories of solar, wind, load, and diesel power, SOC, and battery losses, for each solar array, windmill, and battery size. Using this data, YEAR then computes fuel used, number of diesel starts, total diesel run time, battery life, and various loss parameters for each sample day, and then converts these to annual average values. (See subsection 4.4.) Annual values of ERTCY (diesel run time in hours plus number of starts), fuel used, battery size and life, and windmill, solar array, and converter sizes are arranged in a matrix for input to the economics model.

Using the above inputs and other parameters (notably installation year, discount rate, fuel inflation rate and unit equipment costs), the routine TOTALCOST computes the present value and annual cost, levelized over the life cycle of the diesel, of fuel and diesel,

* See Appendix I for details of individual functions.

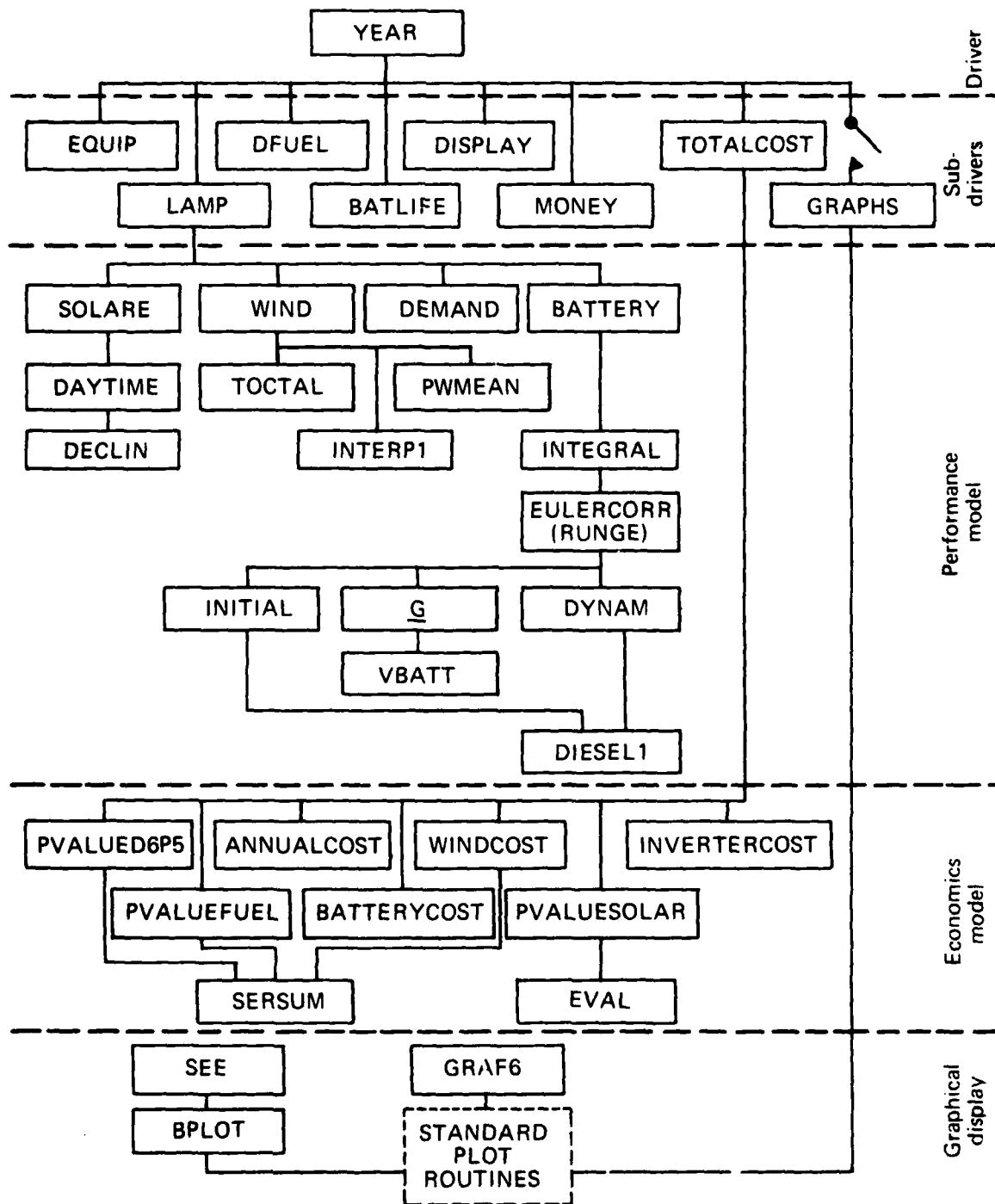


FIGURE 4.0 SIMULATION SOFTWARE ORGANIZATION.

battery, windmill, solar array, and inverter. These are summed to produce total leveled annual cost for each case. Details of the models used by TOTALCOST and its subroutines are described in section 4.5. The outputs of TOTALCOST are stored in an array.

4.1.2 Software Environment

The simulation is written in the APL language, and is run on the APL/MVS interactive timesharing system on the Laboratory's IBM 3033. This approach was chosen because the interactive APL language and operating system provided the quickest way to develop a prototype simulation of this type. The flexibility of programming is especially important when the models being programmed are rapidly evolving. The ease of data manipulation and storage proved very useful for the multidimensional parametric studies done here. The flexible interactive graphics capability is also an asset.

On the minus side, the interpretive nature of the APL language can result in significant penalty in run time, especially for recursive operations. Care must be taken to exploit the array-processing nature of the language wherever possible, and avoid "do-loops". Many of the computations of the simulation are suited for array processing, but the numerical integration ultimately must be looped, since the initial conditions of each time step (one hour in this case) are the results of the previous step and cannot be precomputed. A secondary disadvantage of the language is that its extensive, unique instruction set is unfamiliar to many, and can be intimidating at first exposure. Although this simulation in APL has proven quite useful for model development, it is recognized that any repetitive detailed performance simulation should utilize a standard noninteractive language such as Fortran.

4.1.3 Basic Assumptions

The basic assumptions used in developing all parts of the simulation include:

- a. Absolute accuracy of performance or cost models is not intended. In implementing the models, simplifying assumptions have been made where convenient, provided they preserve fidelity of relative comparisons of results.
- b. Performance calculations are mean values. Specifically, for any given hourly interval the environmental (wind and solar), load, and diesel powers are the mean values expected for that hour, based on the statistical distributions assumed.
- c. Performance calculations assume steady-state, or nearly so. That is, any effects of transients (e.g., warmup) on performance and hence cost are not modeled, except as explicitly stated (e.g., each diesel start is counted as an extra hour of life).

- d. Thermal effects are not included. Battery performance and solar cell characteristics depend upon temperature and occasionally the diesels may need to run to supply heat or part of the energy collected from the environment may be needed for thermal control, but these effects are not included in the model.

4.2 EXTERNAL ENERGY MODELS

External energy is defined as energy which is independent of the dynamic state of the system. It consists of wind, solar, and load, all of which are (modeled as) functions only of time and static station parameters. The station control system has no control over these, thus they are "external" inputs to the dynamic equations. These are precomputed and saved in a multidimensional array by the function LAMP.

4.2.1 Load Power Model

The load power is modeled as two power levels, with switching from low to high 30 minutes before sunset and from high to low 30 minutes after sunrise. (The low and high power levels for generic station classes are given in Table 1.1). Hourly average power is the applicable high or low value, except for the hours during which a switch occurs. The power level for these hours is computed from the actual sunrise/sunset times so that the average value is correct.

In the software, LAMP first uses DAYTIME to compute the duration of daylight for any desired day(s) of the year, which is then used by DEMAND to construct a table of hourly-average load power, according to the above model.

4.2.2 Wind Power Model

The function WIND implements the wind power model described in subsection 3.3.2, which gives average wind power, P , as a function of mean wind speed, V , and the wind machine parameters P_r , V_i , V_r , V_w . The speed parameters (V_i , V_r , V_w) are assumed fixed for a given run. Inspection of Equation (3.19) shows that wind power may be normalized by rated power, P_r . Thus WIND only computes P for $P_r=1$, and P is subsequently scaled to the desired value(s) of P_r in LAMP.

The generic wind speed model of Figure 3.2 (subsection 3.1.1.3) is implemented to compute hourly average wind speed, $\bar{V}$, for given day(s). This model is implemented as tabulated annual mean wind speed versus local octal time., for four groups (combinations of Southern/Northern, Coastal/ Offshore). A corresponding table of deviation from annual mean, assumed sinusoidal over the year, is used to compute $\bar{V}$ for any hour and day, for a given group. Specifically,

$$\bar{V} = V_w(TO) - \Delta V_w \sin \frac{D-81}{365} \quad (4.1)$$

† "Octal time" is the eight generally unequal time periods used in the abscissa of Figure 3.2. It is a unique construct used in this report.

where D is day number, and annual speed $V_w(TO)$ as a function of both the octal hour and site, and the seasonal deviation ΔV_w for the four groups, are given by:

TABLE 4.1
NUMERICAL PARAMETERS OF WIND MODEL

	Octal	Coastal		Offshore	
	Time	Southern	Northern	Southern	Northern
V_w	1	2.055	3.585	4.405	9.03
	2	1.995	3.515	4.365	8.895
	3	3.695	5.525	5.13	8.765
	4	4.455	6.13	5.13	8.67
	5	4.61	6.13	4.995	8.765
	6	3.955	5.485	4.475	8.905
	7	2.455	3.97	4.35	9.015
	8	2.11	3.645	4.36	9.155
ΔV_w	all	0.494	0.399	0.672	1.866

For each hour of a given day, the local octal time (TO) is first computed by the function TOCTAL, and then $V_w(TO)$ and ΔV_w are obtained from the Table 4.1 data by linear interpolation. TOCTAL, uses (previously computed) hours of daylight to compute clock time at (dawn + 30 minutes) and (sunset - 30 minutes). A linear relationship is then assumed such that the following correspondence holds:

<u>Clock Time</u>	<u>Octal Time</u>
0	0
(dawn + 30 min)	2
12	4
(sunset - 30 min)	6
24	8

4.2.3 Solar Power Model

The function SOLARE implements the mean solar power model given in subsection 3.1.1.4 by Equation (3.3) through (3.8). The three necessary parameters (D,J,a) for the generic latitudes are those given in Table 3.3. The average solar intensity given by Equation (3.5) is multiplied by $\cos M$, where M is the angle between the sun-line and local vertical, which effectively produces the transmission ratio, T, given by Equation (3.11). Solar power is assumed zero for $M > 90^\circ$ (i.e., in

darkness). The angle M is found from:

$$\cos M = \sin L \sin S + \cos L \cos S \cos [\pi(t-12)/12] \quad (4.2)$$

where L is the site latitude, S is the solar declination (Equation 3.8) and τ is the local solar time in hours during daylight.

The output of SOLARE is a table of hourly average solar power (in kW) available per square meter of perfectly efficient solar array. We have called this the output power of a solar array rated at 1 kW and obtained solar power for other size arrays in the ratio of their power rating to 1 kW. The actual array size needed to produce the output equivalent to the 1 kW rating would depend on the conversion efficiency of the device, but would be substantially larger than 1 m².

4.3 ENERGY STORAGE AND CONTROL MODELS

System components in this category, notably the battery and diesel-electric generator, respond to external inputs through the system control logic. The significant aspect of this from a simulation viewpoint is that their dynamic models typically involve differential equations, where external energy models are algebraic only. Design flexibility (hence number of parameters to be studied) further increases simulation complexity, since not only sizing parameters but control strategy can be varied.

4.3.1 Battery Model

The battery is an energy storage device. The net power into it determines the rate of change of stored energy. Equivalently, the battery can be considered to store charge (ampere hours). The rate of change of the state-of-charge (SOC) is determined by the net effective⁺ current into the battery. Analytically, this dynamic relationship can be written

$$i = C_0 \frac{dx}{dt}, \quad (4.3a)$$

$$i(nV_c) = P, \quad (4.3b)$$

where

- i = net current into battery (A),
- C_0 = rated battery capacity (A-hr),
- $X = SOC/C_0$ = normalized state-of-charge,
- P = net power into battery (W),
- V_c = single cell voltage (V), and
- n = number of identical cells connected in series.

⁺ The fraction of the actual current that is effective in charging the battery depends upon the state-of-charge. This subsection describes the methodology used to compute the rate of change of the state-of-charge as a function of the applied power, the number of cells, the cell capacity and the present state-of-charge. Subsection 4.3.3 will correct this model to include "charge inefficiency", i.e., the fact that not all of the applied current is utilized to store charge or ampere-hours.

In general the cell voltage, V_c , is a function of current, (i) , and state of charge, (x) . The simulation implements a simplified analytical model of the function $V_c(i, x)$, developed by R. J. Taylor and based on Reference 82*. This model, which is applicable for lead-acid batteries, can be analytically expressed

$$V_c = V_1(x) + b |i|^N. \quad (4.4)$$

Taylor found that an adequate model for the parameters b and N and the function $V_1(x)$ in (4.4) is

$$\begin{aligned} N &= 1, \\ b &= \frac{a_{11}}{C_o} \end{aligned} \quad (4.5)$$

and
$$V_1(x) = a_{10} + a_2 x + a_3 x^2,$$

where the coefficients (a_{10} , a_{11} , a_2 , a_3) are different for charging ($i > 0$) and discharging ($i < 0$). A least-squares fit to data from Reference 82 gives the following values for the coefficients:

	<u>Charging</u>	<u>Discharging</u>
a_{11}	0.5	-0.5
a_{10}	2.004	1.739
a_2	-0.00964	0.6293
a_3	0.5625	-0.679

The rms error of the fit to the independent points used to check the fit was 10 mV for the charging data and 5 mV for the discharging data.

With $N=1$ in Equation (4.4), it is seen that the power equilibrium (Equation 4.2b) gives a quadratic equation for i :

$$ni (V_1 + b |i|) = P, \quad (4.6)$$

which is readily solved for i , given x and P (hence sign of i). The differential equation for normalized SOC immediately follows by substitution of i into Equation (4.3a) (using $b = \pm 1/2C_o$):

$$\frac{dx}{dt} = \frac{-1}{C_o} \left[V_1 \pm \sqrt{V_1^2 + \frac{2P}{nC_o}} \right], \quad (4.7)$$

*Reference

82. Bechtel Corp. 1977, "Battery Storage Performance Requirements for Terrestrial Solar Photovoltaic Power Systems," page 4-23, (Avail. NTIS: ANL/OEPM-77-3).

where V_1 is a function of x and the sign of P . The sign of the square root in Equation (4.7) is chosen to produce the correct sense of dx/dt for charging or discharging.

In the simulation, the function VBAT implements the above model for dx/dt . The function BATTERY numerically integrates the differential Equation (4.6) to obtain time histories of normalized SOC. The net power, diesel and battery loss power, described below. The initial conditions used in the integration of the differential equations are described in subsection 1.5.2.

4.3.2 Diesel-Electric Model

The output power of the diesel-electric generator is controlled directly by the station control logic, subject to certain constraints. The control law governing diesel operation could in principle be chosen to minimize overall cost, by application of optimal control theory. Although this might be done in a later study phase, it was not practical or necessary for the present generic simulation studies. The control law used was developed by engineering judgement, and refined (but not optimized) by trial-and-error. Since it is not optimal, then its performance can be bettered, thus it is conservative.

The control law used assumes the diesel output power depends only on normalized SOC(x), according to Figure 1.0. A form of hysteresis is also included, in that the turn-on and turn-off values for x are usually different. In the simulation the diesel power is computed (by DIESEL1) once each hour, based on x at the end of the previous hour, and held constant during the hour.

4.3.3 Power Loss Models

The net power which enters the SOC differential equation (4.7) is not simply the algebraic sum of external and diesel powers, but must be adjusted to account for power lost due to inefficiency. These losses are either internal to the battery or due to conversion of DC power to AC.

Two types of battery losses are actually included in the simulation model. The first, often called "I-V loss" or "voltage inefficiency" is implicitly accounted for by the use of different battery model coefficients for charge and discharge in Equation (4.7). These losses, which represent the basic fact that all of the energy stored in the battery cannot be retrieved, are not explicitly calculated. A second type of battery losses, referred to as "charging losses" or "Coulombic inefficiency", are explicitly calculated and used to adjust $\frac{dx}{dt}$ in Equation (4.7). Quantitatively, these losses represent the fact that with a constant charging power, the battery SOC will not increase indefinitely but will asymptotically approach a saturated (i.e., "fully charged") limit. The losses are implemented by multiplying (dx/dt) from Equation (4.7) by a Coulombic efficiency factor ϵ_c , which has been modeled as:

$$\epsilon_c = \begin{cases} 1 & \text{(discharging)} \\ 1 - (\frac{x}{1.1})^8 & \text{(charging)} \end{cases}, \quad (4.8)$$

where ($0 < \epsilon < 1$). This functional form, which represents a convenient estimate of the generic form expected for charging losses in lead-acid batteries, is plotted as a broken line in Figure 1.0.

A block diagram of the power flow and overall dynamics of the performance model is shown in Figure 4.1.

4.3.4 Numerical Integration

The solution of the SOC differential equation (4.6) is equivalent to the integration function shown in Figure 4.1. This is accomplished in the simulation by the function INTEGRAL, which implements either a second or fourth order Runge-Kutta integration algorithm. Because all inputs to the integrator (except the integrated variable x itself) are modeled as constant over the integration time step (1 hour), the fourth order algorithm provides very little accuracy improvement over the second order. For a typical case computed both ways, the maximum difference in x (SOC) between second and fourth order integration was less than 0.6%. Accordingly, all results presented were computed with the second order integrator, to save computer time.

4.4 ANNUAL PERFORMANCE

4.4.1 Annual Averaging

The economics model (subsection 4.5) requires performance of a given case expressed as annual totals of specified parameters (e.g., fuel used). It is neither feasible nor necessary to compute performance histories for all 365 days of the year, since the meanvalue assumptions in the models result in only gradual change from one day to the next. Thus performance histories are computed for twelve days of the year (specifically, days 28, 58, 89, 119, 149, 180, 210, 241, 271, 302, 332, 362), and the daily totals of desired quantities computed. The sum of these 12 daily totals is multiplied by 365/12 to produce the estimated annual total. The annual averaging is done by the function YEAR, as described in the next section.

The specific sample days chosen are at approximate monthly intervals, but they are carefully chosen to provide 12 independent samples of the annual sinusoidal variables. The days chosen represent 12 evenly spaced days, starting about one week after the vernal equinox (about day 81).

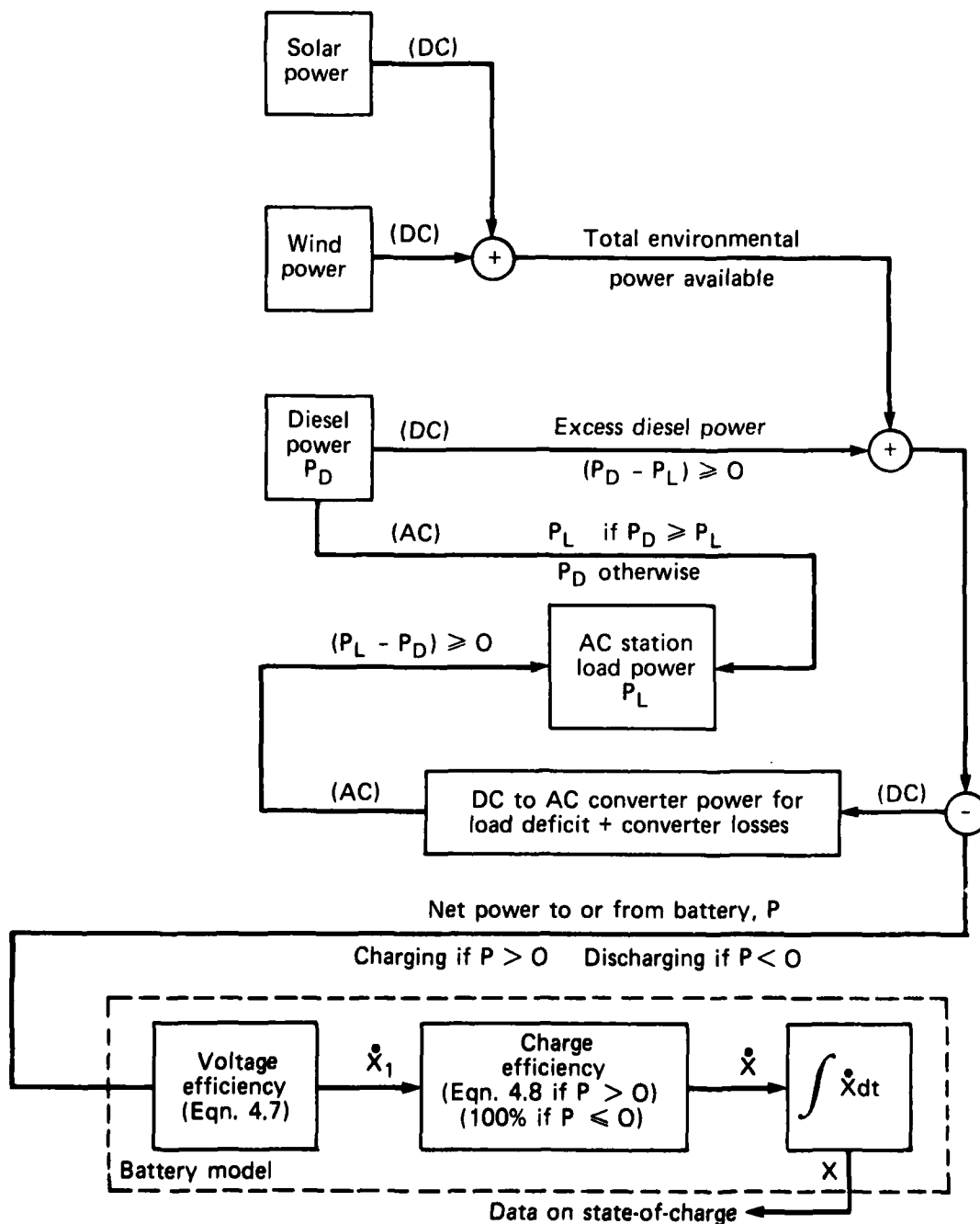


FIGURE 4.1 POWER UTILIZATION MODEL (Note diesel power, P_D , may be zero or less than maximum and depends upon hourly state-of-charge data, X . See Figure 1.0).

Typical hourly results for the diesel power level and battery state-of-charge, for two different windmachine size cases of a given station, are shown in Figures 4.2 and 4.3. The twelve days computed approximate monthly averages and are so labeled in Figures 4.2 and 4.3.

4.4.2 Annual Performance Calculations

The parameters needed by TOTALCOST include ERTCY (total hours of diesel run time plus number of starts), diesel fuel used, battery life, and equipment sizes. The windmill and solar array sizes are inputs to YEAR and are passed to TOTALCOST with only units conversion. The inverter size used for each case is the most negative value of external power in kW as defined in subsection 4.2, negated and rounded up to the next largest integral value in kW. This is based on the assumption that the inverter will be sized to provide at least the largest possible load (AC) by battery power (DC) alone.

The daily total diesel parameters, which directly produce the annual totals, are computed as follows. Total hours run time per day is the sum of all hourly intervals in which diesel power (P_d) is non-zero. The number of starts in a day is the sum of all hourly intervals with $P_d \neq 0$ which immediately follow an interval with $P_d = 0$. The first hour of a day is counted as a start if $P_d \neq 0$ and $P_d = 0$ for the last hour of the day, based on the steady-state assumption that adjacent days are nearly alike. ERTCY is the sum of actual run time in hours plus number of starts each year; i.e., each start is assumed to consume one extra hour of the diesel's life. The smallest value of ERTCY computed in the performance model is 52 hours, equivalent to one start and one hour running time every two weeks. However, the array of data prepared for TOTALCOST by the performance model was manually changed so that ERTCY ≥ 1752 , corresponding to a diesel life of 75 or less years.

Fuel used each hour is computed by DFUEL, which implements the linear fuel consumption versus power model described in subsection 2.2.5. DFUEL uses rated power and blower fan power in conjunction with current output power to correctly account for all the energy which is derived from the fuel.

The fraction of the battery's total life used each day is computed by BATLIFE, which implements the battery life model for lead-acid batteries described in Appendix G, subsection G.7. BATLIFE uses the normalized SOC histories for each day computed by LAMP. The main function YEAR converts these daily totals to an annual total of fractional life consumed as previously described, then inverts the result to obtain expected battery life in years. The maximum battery life allowable is 25 years.

These annual parameters are formatted into an array for input to TOTALCOST by the function MONEY. In addition, YEAR computes annual totals of external power and battery charging loss from the daily histories

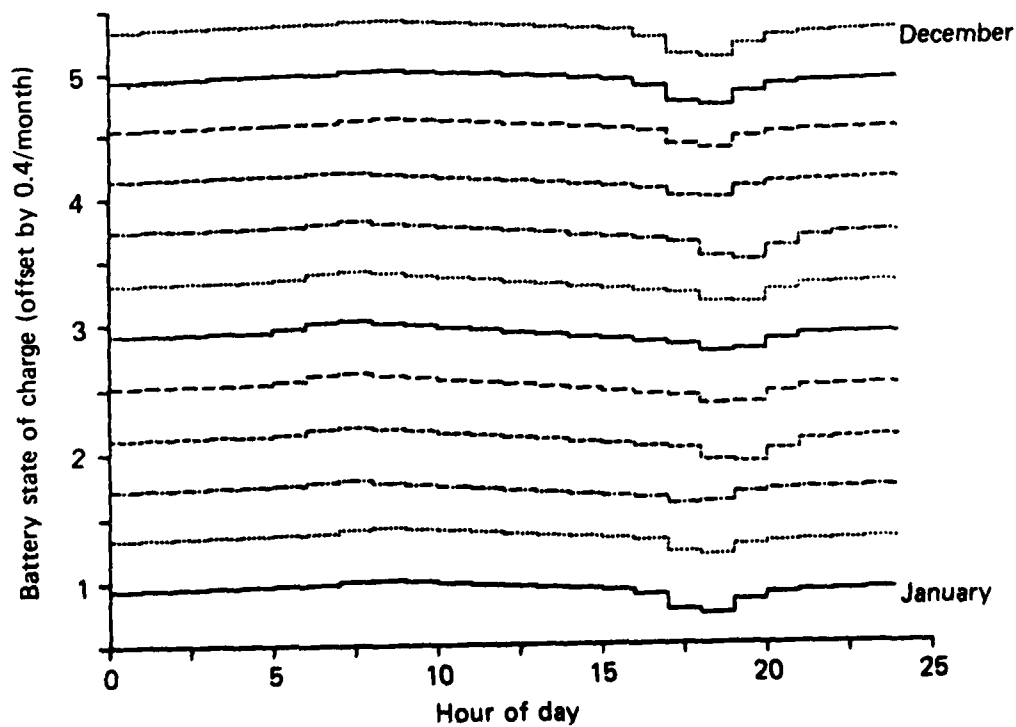
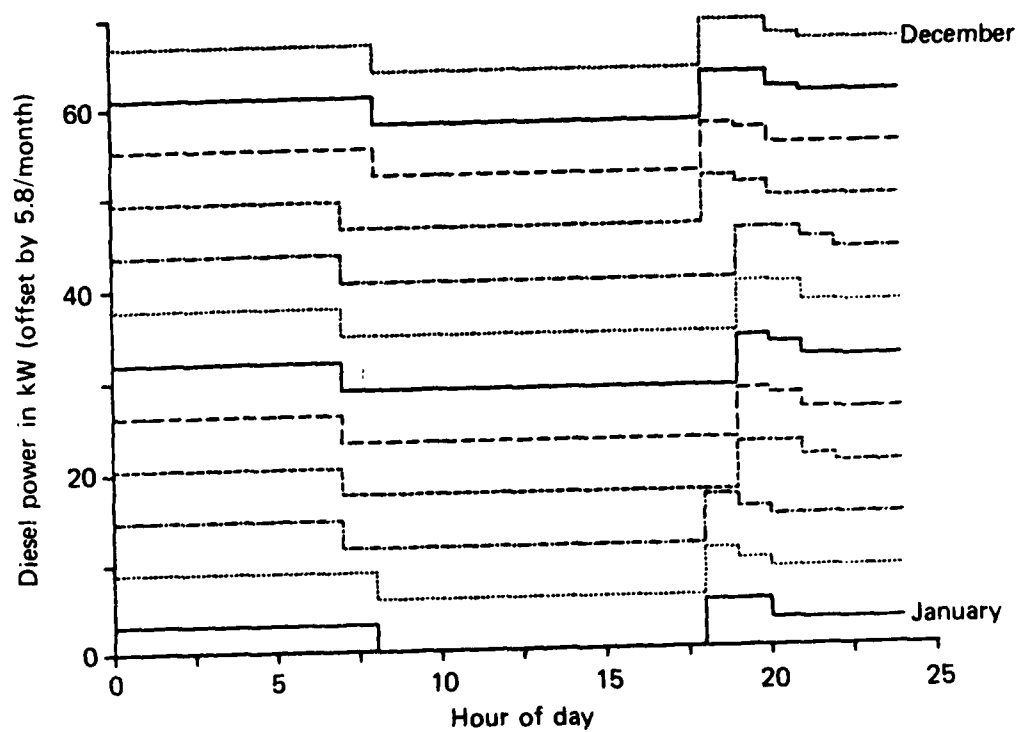


FIGURE 4.2 HOURLY HISTORY OF DIESEL POWER AND BATTERY STATE OF CHARGE. (Southern offshore high-power, code 121, station with 1 kW wind machine and 1500 ampere-hour, 12 volt battery.)

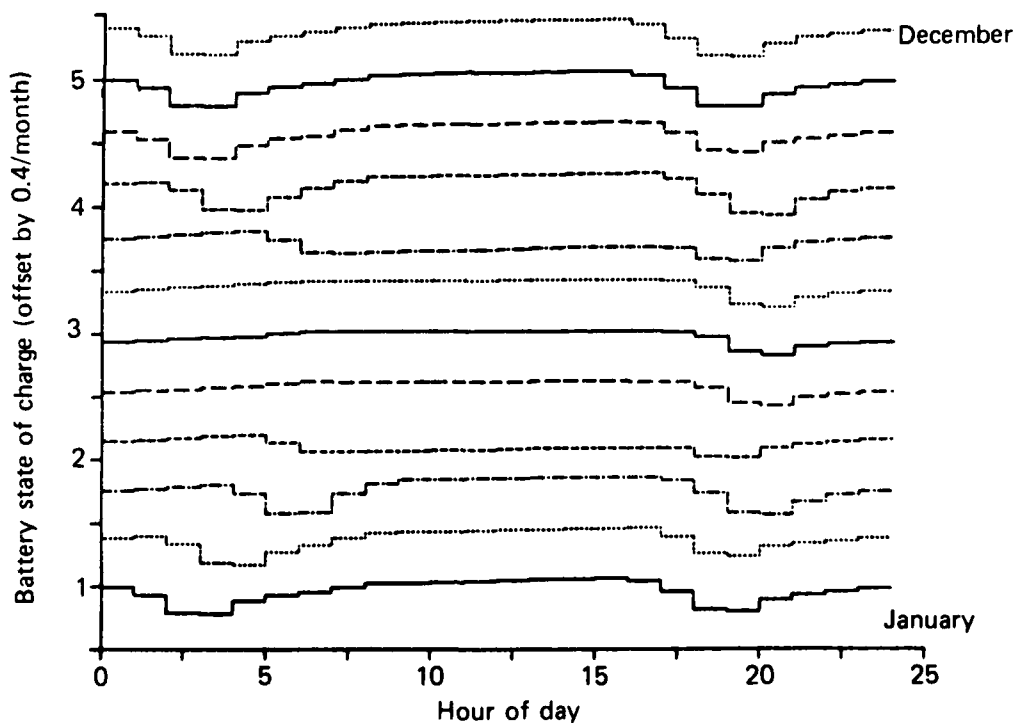
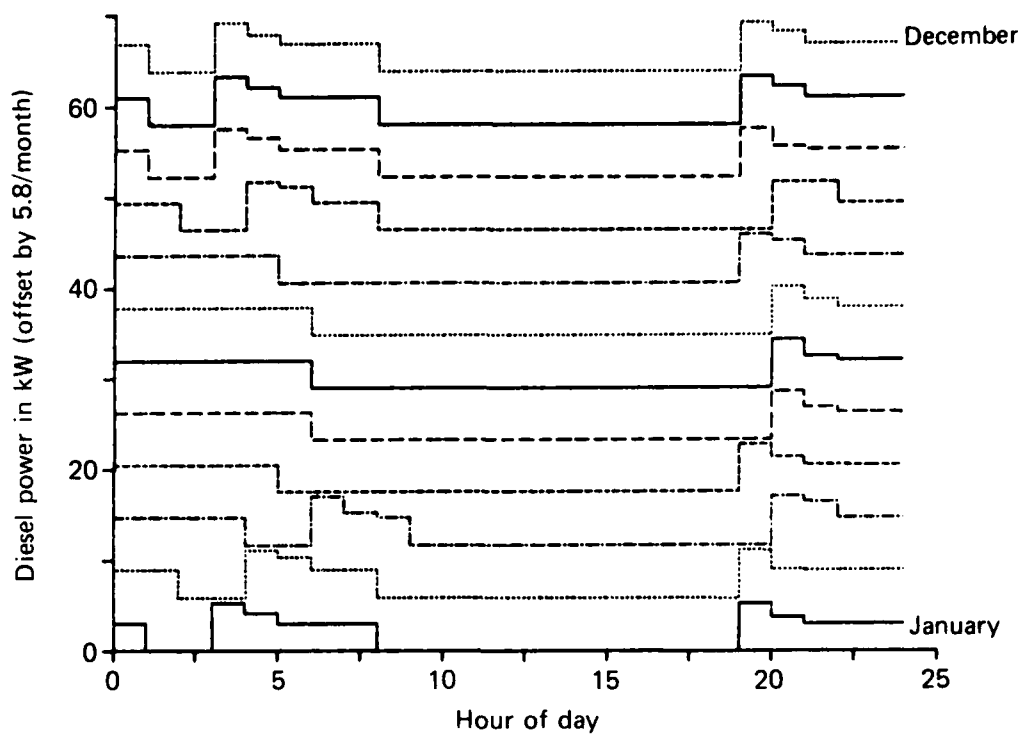


FIGURE 4.3 HOURLY HISTORY OF DIESEL POWER AND BATTERY STATE OF CHARGE. (Southern offshore high-power, code 121, station with 3 kW wind machine and 1500 ampere-hour, 12 volt battery.)

of these computed by LAMP. Total battery losses are also computed, by comparing total diesel output power with external power. This is equivalent to defining total battery losses as the excess energy above the load required from wind, solar, and diesel to keep the battery charged. The assumption of steady-state operation is implicit in this definition.

4.5 ECONOMIC MODEL

4.5.1 General Considerations

In order to effectively compare various energy systems for a given site a life-cycle-cost analysis was utilized. (See Appendix G for a complete discussion of the methodology involved in formulating the economic model.) The life-cycle-cost method enables one to compare alternatives with different capital costs, maintenance schedules, lifetimes, etc. through an annualized cost or annual equivalent amount. All values were calculated using constant value 1980 dollars. A discount rate of 10% was used. Fuel was allowed to inflate, and the battery, solar, and wind systems were permitted to decrease in cost from 1980 to 1990 (in constant value dollars) as technological advances and oil shortages continue.

The economic portion of the simulation receives data input from the performance model for each variation of the alternate energy system. The inputs are:

- 1) The yearly number of hours of diesel operation plus one hour for each start of the diesel, (ERTCY),
- 2) the number of gallons of fuel consumed annually by the diesel, (AFC)
- 3) The kilowatthour capacity of the battery,
- 4). The battery life,
- 5) the rated watt capacity of the wind machine,
- 6) the solar array rating, in watts, and
- 7) the inverter or power conditioning equipment size, in watts.

Cost functions for each energy component (e.g. wind, solar, battery, etc.) contain a model for capital cost versus year of purchase, plus additional costs for installation and maintenance. With the performance model data, the different functions are used to compute the present value of the various component of the energy system (e.g. diesel cost, battery cost, etc.) Utilizing the lifetime of the component, the annualized cost is calculated. These separate component costs are then summed in the function TOTALCOST to give an annual system cost.

4.5.2 Diesel Costs

The present value of the diesel-electric generator, excluding fuel, is computed in the function PVALUED6P5. The ERTCY input from the performance model is used to determine the frequency of maintenance events. The maintenance schedule described in Appendix G, subsection G.5, has been incorporated into PVALUED6P5 utilizing Equation (G.14). The function SERSUM contains the geometric series of Equation (G.8) which is used to sum the cost of the different maintenance events. The final output of PVALUED6P5 is PVD6P5 which is the present value of the diesel, including maintenance and installation. Ancillary output of PVALUED6P5 is YMANHR which is the number of manhours utilized per year for installation and maintenance of the diesel. YMANHR will vary depending on the usage of the diesel and the subsequent maintenance schedule.

The function PVALUEFUEL calculates the present value of the diesel fuel used onsite and for transportation to the site associated with diesel service visits. The annual fuel consumption, AFC, is computed in the performance model. Included in PVALUEFUEL are the variables FUELINFR, DR, and YINSTALL. FUELINFR is the fuel inflation rate, which is presently set at 8%, and DR is the discount rate, set at 10%. Both can easily be changed as desired. The installation year of the alternate energy system is input with the variable YINSTALL. The output of PVALUEFUEL is PVFUEL, the present value of the fuel used for the lifetime of the diesel.

4.5.3 Battery Cost

The battery cost is calculated in the function BATTERYCOST and depends on the year of installation and the kilowatt hour capacity from the performance model. The battery cost model is based on the cost information in subsection 3.4.5. The output of the function is PV, the present value of the battery.

4.5.4 Wind Cost

The present value of the wind machine is computed in the function WINDCOST, with the watt capacity input from the performance model. The model for the capital cost of the wind machine is based on the assumptions outlined in subsection 3.3.2 and the year of the wind system installation. Maintenance costs of one manday of service per year are included in the final output, PVWIND.

4.5.5 Solar Cost

The cost of the solar energy system depending on the year of installation (YR) and the solar array rating from the performance model is computed in the function PVALUESOLAR. The model for the solar cost is derived from subsection 3.3.1 and Figure 3.5. The yearly cost data is contained in the function EVAL. The output of PVALUESOLAR is PVSOLAR, which is the present value of the solar energy system, including installation.

4.5.6 Inverter Equipment Cost

The present value of the inverter or power conditioning equipment is computed in the function INVERTERCOST. This cost is based on an initial cost of \$100 plus \$1 per watt as input from the performance model. The output of this function is PVINVERT.

4.5.7 Annual Cost

The annual cost calculation for each component of the alternate energy system is computed in the function ANNUALCOST. One input to this function is the present value of each component of the energy system (PVD6P5, PVFUEL, PV, PVWIND, PVSOLAR, and PVINVERT) calculated in its respective function. The variable LIFE is the lifetime of the component, i.e. battery life, diesel life, etc. The diesel life is computed by dividing the total number of hours of diesel life (131,400) by ERTCY. However, the diesel life is limited even if it never runs to 75 years. The battery life is computed in the performance model and the wind and solar system lifetimes are constant at 20 years each.

4.5.8 Total Cost

The function TOTALCOST is the main driver for the economics model and the output of TOTALCOST is the annualized cost of the alternate energy system. TOTALCOST calls each function in the economic model and receives its output of present value, annual cost, etc. TOTALCOST then sums each individual annual cost to give a total annual cost for each case being simulated.

4.6 OUTPUTS

Since the simulation operates in the interactive APL/MVS environment, the primary outputs are stored data and graphs. The printed reports will seem sparse compared to the customary "printouts" of a batchmode program. This section describes the content and format of the stored, plotted, and printed outputs of the simulation.

4.6.1 Stored Data

Fundamental to the APL/MVS operating system is the concept of a "workspace", a quantity of (virtual) computer storage in which all relevant program "objects" (functions and data) reside. A workspace may be up to four megabytes (i.e., one million 32 bit words) in size. The entire workspace may be saved on disk at any time by simple interactive command. Details of the storage and/or processing of data are transparent to the user, who may manipulate all objects by name.

The main function YEAR generates the following data objects for each run, which are saved on disk when the user saves the workspace:

DATA-

The output array of the performance simulation function LAMP. This array is always named DATA, and is over-written by the next run, to save storage. The user must assign DATA to an array with unique name if permanent storage is desired. DATA has 6 coordinates (i.e., subscripts) which represent the following:

<u>Coordinate</u>	<u>Parameter</u>
1	Solar array size(s)
2	Windmill size(s)
3	Battery size(s)
4	Month (i.e., 12 sample days)
5	Hour
6	Results

There are 6 results tabulated: array power, wind power, load power, diesel power, normalized SOC, and charging loss. For example, the subscript values (2, 3, 1, 12, 18, 5) would correspond to normalized SOC for 18th hour of 12th month, for 2nd array size, 3rd windmill size, and 1st battery size.

TABxx-

The output array of the economics model TOTALCOST. This array is automatically assigned to a uniquely named object, as indicated by the suffix "xx". The suffix is an arbitrary character string specified as an input to YEAR, and appended to TAB as well as the other output objects described below. TABxx has 5 coordinates, as follows:

<u>Coordinate</u>	<u>Parameter</u>
1	installation year(s)
2,3,4	arrays, windmills, batteries
5	results

The 6 results are annual costs of diesel, battery, windmill, solar array, inverter, and total system.

PARSxx-

The annualized performance totals computed by YEAR. The 4 coordinates represent arrays, windmills, batteries, and results. The 8 results are annual totals for number of starts, fuel used, diesel run time, total battery losses, external energy, charging losses, battery life, and converter size.

- ECONxx- A two-dimensional array of inputs in the form needed by TOTALCOST. The rows represent different cases, and the 7 columns are ERTCY, fuel used, battery life, windmill size, array size, and inverter size.
- STAx- A vector (one-dimensional array) of parameters identifying the run. The vector STAx contains $(7+N_A+N_W+N_B)$ elements, where N_A, N_W, N_B are number of arrays, windmills, and batteries considered, respectively. The contents of STAx are:

<u>Index</u>	<u>Contents</u>
1	latitude; or zero if standard group
2,3,4	station code ijk (see below)
5,6,7	N_A, N_W, N_B
8,...,7+N _A	array sizes
8+N _A ,...,7+N _A +N _W	windmill sizes
8+N _A +N _W ,..., (end)	battery sizes

Although the suffix "xx" can be an arbitrary character string, a naming convention was adopted to facilitate managing the many arrays generated. Specifically, the first three characters of the suffix are numerals ijk which identify the station according to the following code:

Digit	Value:		
	1	2	3
i	Southern	Northern	Alaskan
j	Coastal	Offshore	(not used)
k	High power	Medium power	Low power

The fourth and fifth characters (say, lm) of the suffix indicate the parameters which are varied, as follows:

Digit	Value:	
	'v'	Numeric (=p)
1	array size varies	array size fixed (at p kW)
2	windmill size varies	windmill size fixed (at p kW)

Additional characters can be appended after these five, for special cases.

4.6.2 Printed Output

The functions YEAR and TOTALCOST print a brief summary of their results. Specifically, the values of the objects STAx, PARStx, and TABxx described above are printed, with labels added. An example is shown in Figure 4.4. Note that the suffix for this case would be '1210V',

and the values of (N_A, N_W, N_B) are (1,2,5). The format is largely self-explanatory. The performance data ("HRS RUNTIME" through "CONVERTER SIZE (kW)") are presented as $N_A \times N_W \times N_B$ arrays. In the example, each heading is followed by a 2 by 5 array of numbers (actually $1 \times 2 \times 5$). The rows correspond to the windmill sizes, and the columns to the battery sizes. If more than one solar array had been used, a separate 2×5 matrix would be printed for each $(N_A \text{ in all})$. The cost results are presented as a single matrix, one row per case. The specific case/row correspondence is usually obvious (as in the example), but can be explicitly determined from the rule that array size varies slowest and battery size fastest.

4.6.3 Graphical Output

The primary output mode of the simulation is graphical. Two basic types of graphs are available: parametric display of total cost, and time histories of performance parameters. Examples of the latter are given in Figures 4.2 and 4.3. These were generated by the functions SEE and BPLOT, which are general enough to display any array of hourly data in a family of curves similar to Figures 4.2 or 4.3. These functions are not automatically called.

Parametric cost plots are generated by the function GRAPHS, from the suffixed object TABxx (see section 4.6.2 for discussion of suffixes). GRAPHS may be called automatically by YEAR, or run manually. In either case a family of total cost curves versus two of the four variables (installation year, array size, windmill size, battery size) is plotted. An example is shown in Figure 4.5, which has installation year as independent variable and array size as parameter. The remaining two variables (windmill size and battery size in the example) are held constant at specified values. (Details of use of GRAPHS may be obtained from the comments in the function listing, Appendix I.) Figure 4.5 gives actual cost in dollars, but an optional form of GRAPHS normalizes the cost by the diesel-only base case for the corresponding year. Another optional version (GRAF6) produces 6 plots to a page, and was used for the results shown in subsection 4.7.

In all of these plots, the index of the parameter in a family of curves is indicated by the following line-type code:

<u>Index</u>	<u>Line</u>
1	solid
2	dotted
3	dot-dash
4	short dash
5	long dash

If more than five curves are in the family, this sequence of 5 is repeated (6 = solid, 7 = dotted, etc.).

STATION PARAMETERS:

1 1 2 1

EQUIPMENT:

ARRAY (K*2): 0

WINDMILL (KW): 1 3

BATTERY (A-HR): 500 1000 1500 2000 2500

DIESEL:

HRS RUN TIME:

4775 4928 4745 4830 4806

3772 3863 3833 3853 3833

STARTED:

1339 638 365 365 365

1247 373 577 517 395

FUEL USED (GAL):

2819 2635 2512 2566 2583

2263 2165 2093 2125 2102

ENERGY SUMMARY (KWH):

EXTERNAL:

-1.4377E4 -1.4377E4 -1.4377E4 -1.4377E4 -1.4377E4

-1.0637E4 -1.0637E4 -1.0637E4 -1.0637E4 -1.0637E4

CHARGING LOSS:

5235 2247 1030 1304 1401

4573 3200 1914 2144 1777

TOTAL LOSS:

4617 2464 1593 1940 2179

4736 3570 2902 3168 2879

BATTERY LIFE (YEARS):

1.428 4.666 7.71 9.016 9.081

1.565 4.033 6.047 6.244 8.713

CONVERTER SIZE (KW):

3 3 3 3 3

3 3 3 3 3

FOR INSTALLATION YEAR(S) 1985 :

ANNUAL COSTS OF:

DIESEL	BATTERY	WIND	SOLAR	INVERTER	TOTAL
19775.90	353.63	913.05	.00	364.12	21406.71
19133.54	250.72	913.05	.00	364.12	20661.43
18778.47	259.40	913.05	.00	364.12	20315.05
19006.44	312.20	913.05	.00	364.12	20595.82
19130.10	388.48	913.05	.00	364.12	20795.76
17426.46	324.82	1335.91	.00	364.12	19451.31
16992.92	282.02	1335.91	.00	364.12	18974.97
16923.44	308.17	1335.91	.00	364.12	18931.64
17154.20	401.34	1335.91	.00	364.12	19255.58
17108.78	398.83	1335.91	.00	364.12	19207.65

FIGURE 4.4 ILLUSTRATION OF NUMERICAL DATA FORMAT

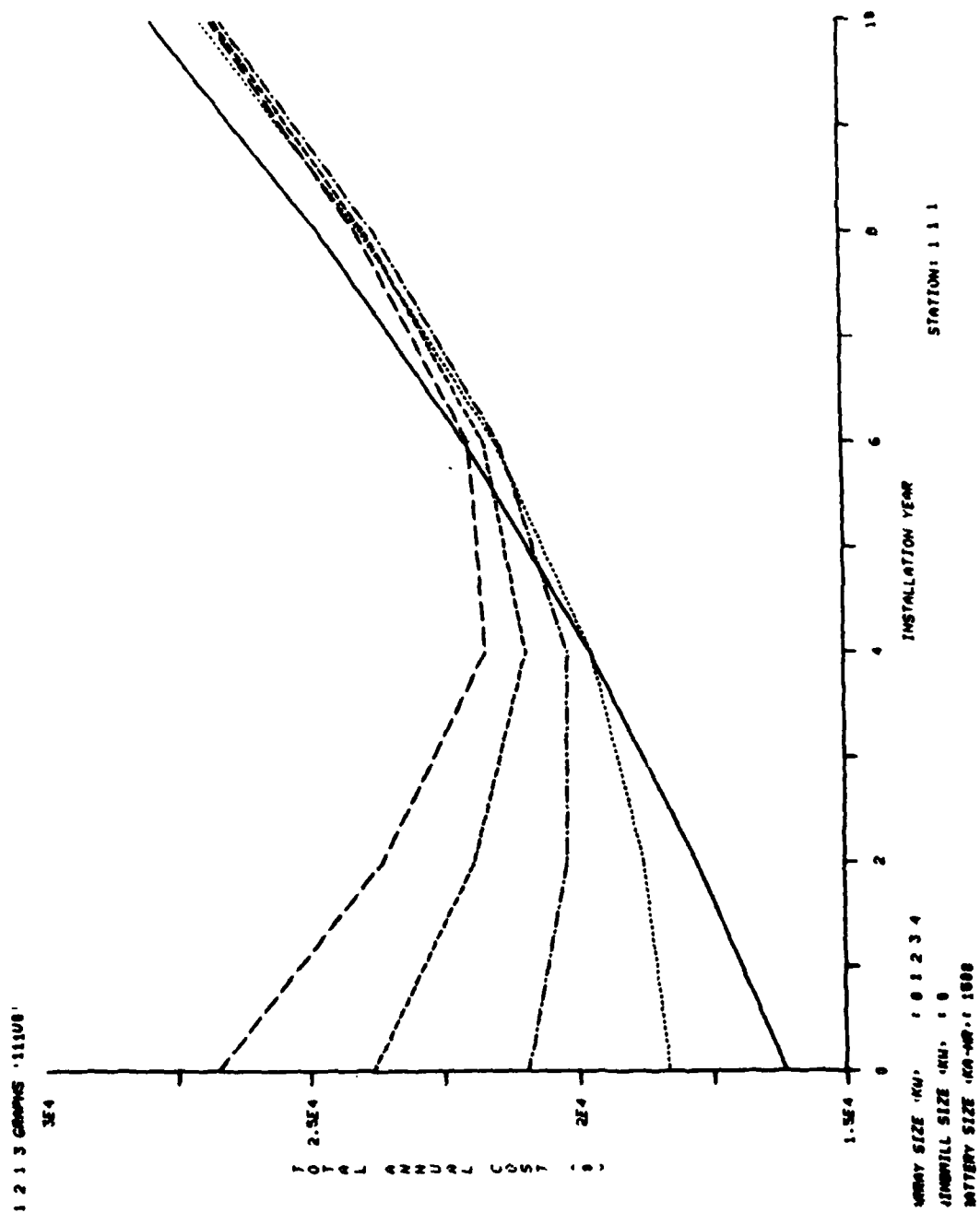
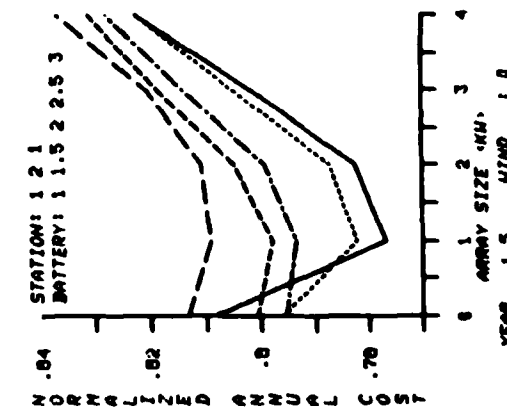
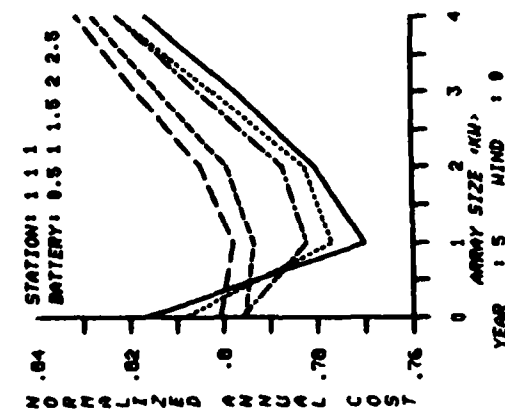
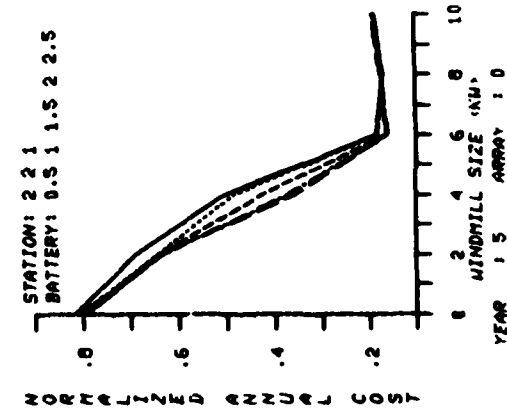
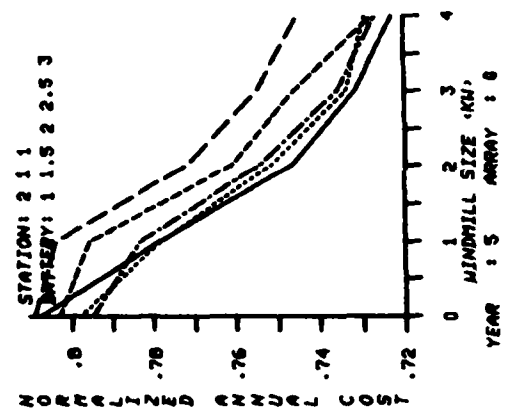
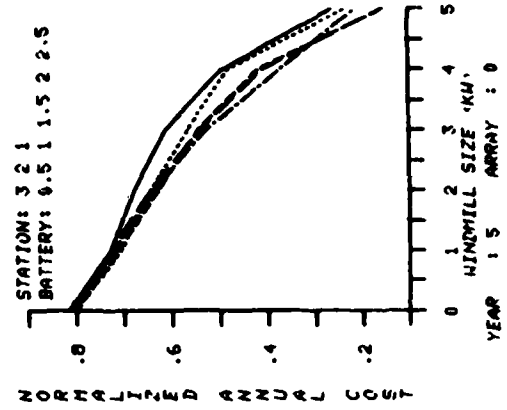
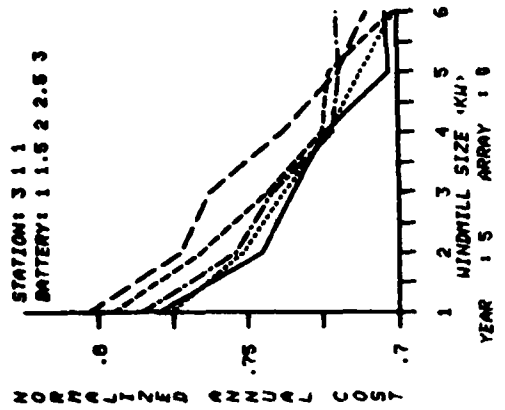
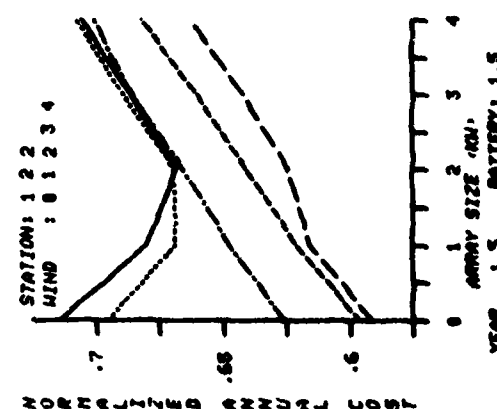
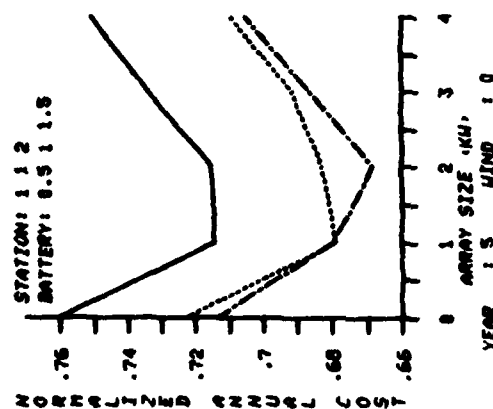
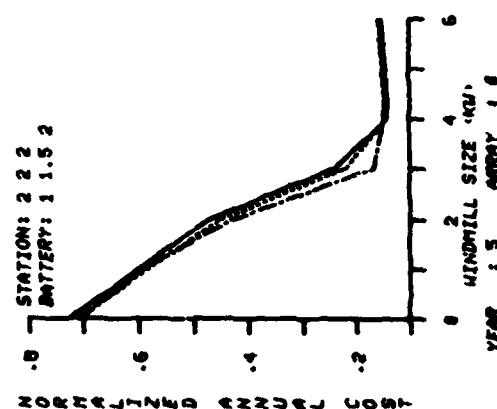
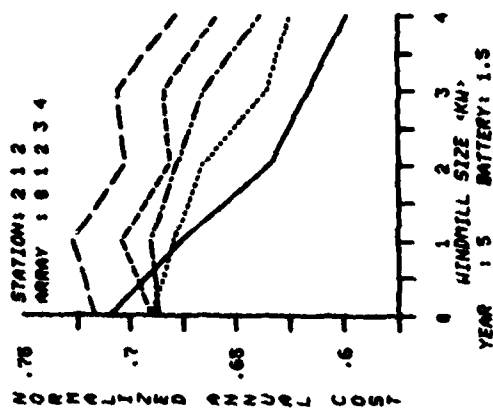
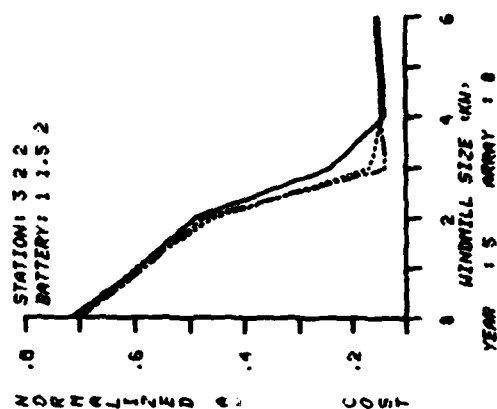
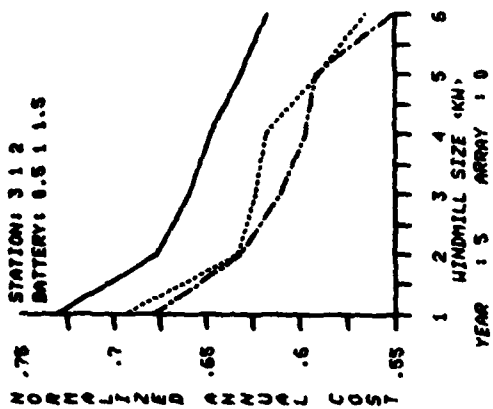


FIGURE 4.5 TYPICAL COMPUTER TERMINAL GRAPH.

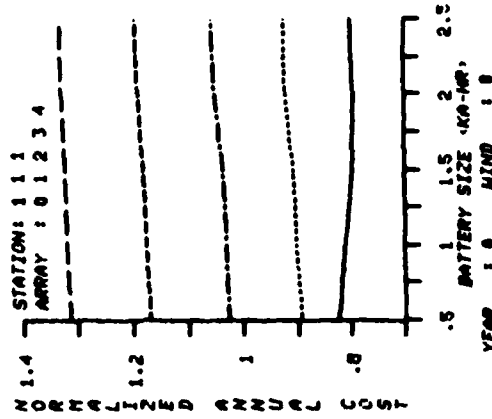
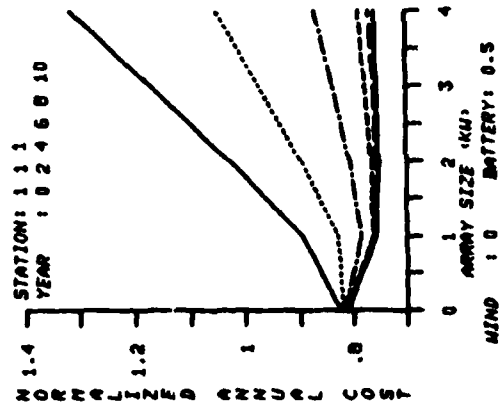
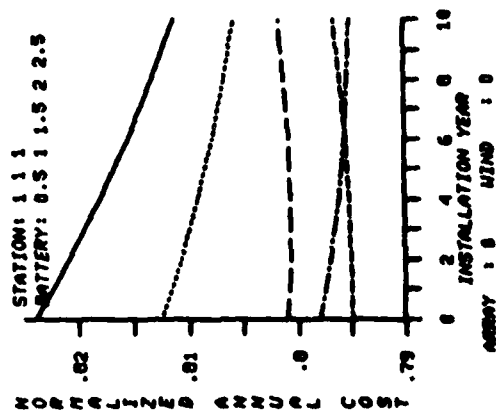
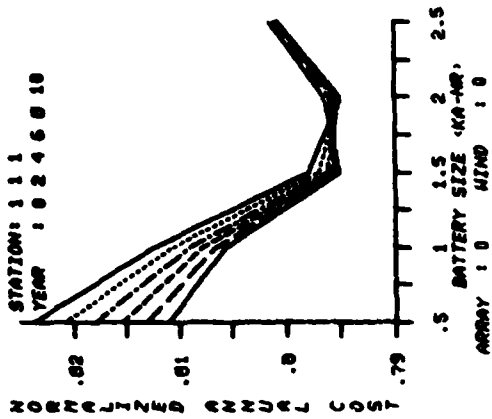
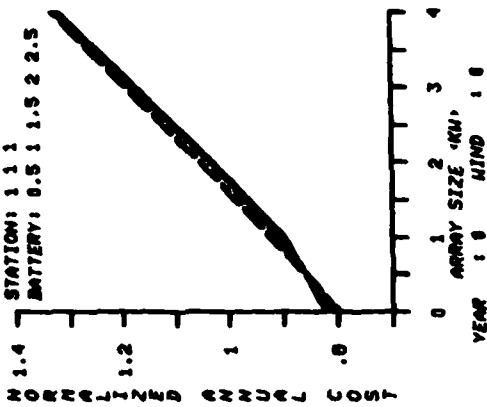
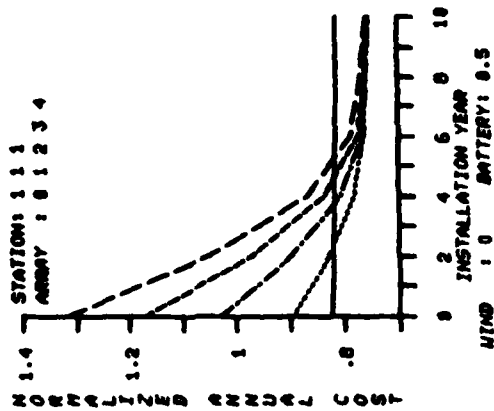
4.7 REPRESENTATIVE RESULTS

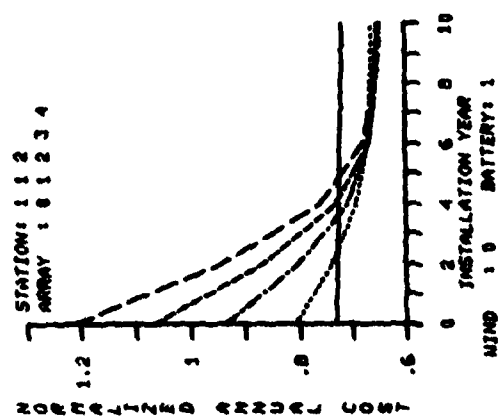
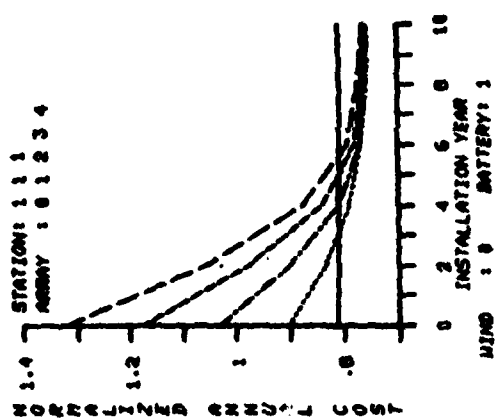
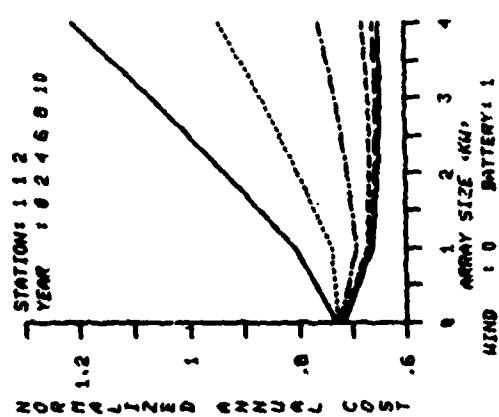
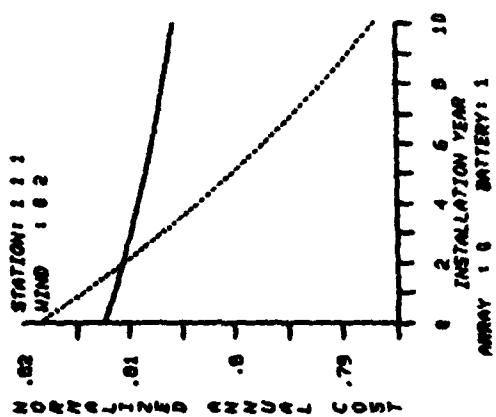
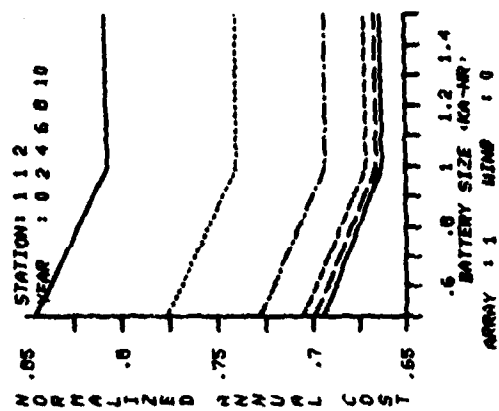
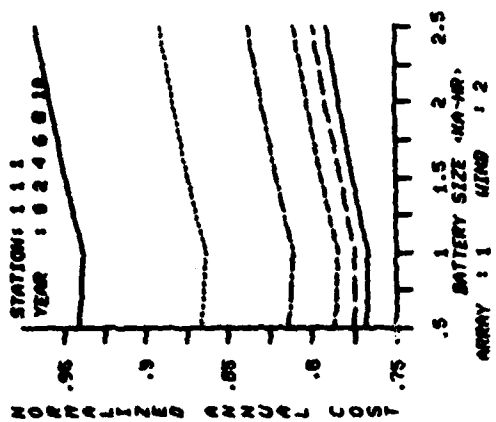
The results for the most economical cases found via simulation analysis are summarized in Table 1.2. This subsection presents these results along with others in graphical form. In the interest of space conservation, the compact six-to-a-page format is used. In the interest of economy, the graphs are directly reproduced from the computer terminal output graphs. The graphs consist of normalized, levelized, annual costs for LAMP stations at different sites, under different conditions as described in the labels and subsection 4.6. The installation year is abbreviated on these plots as years since 1980, i.e., 0=1980, 1=1981,..., 10=1990.

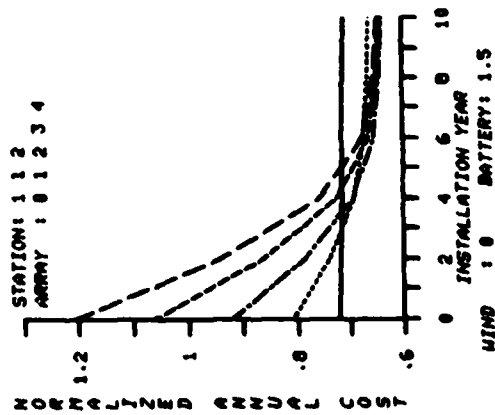
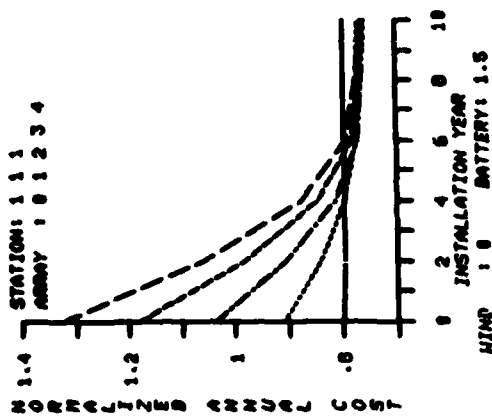
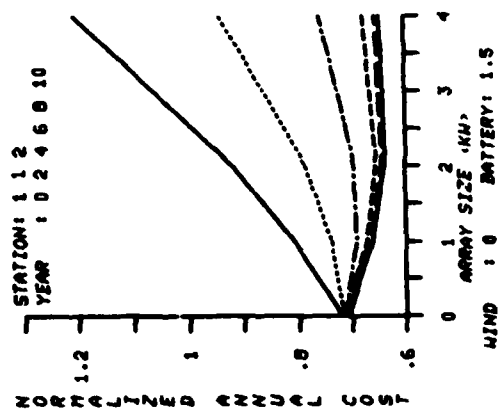
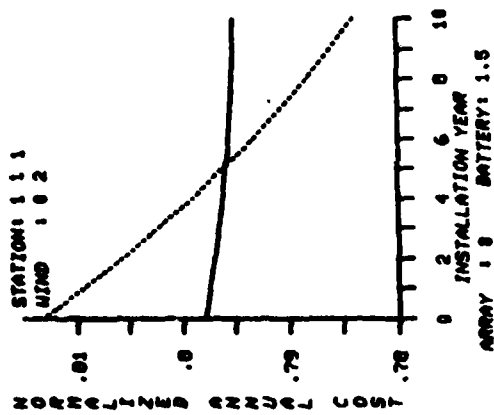
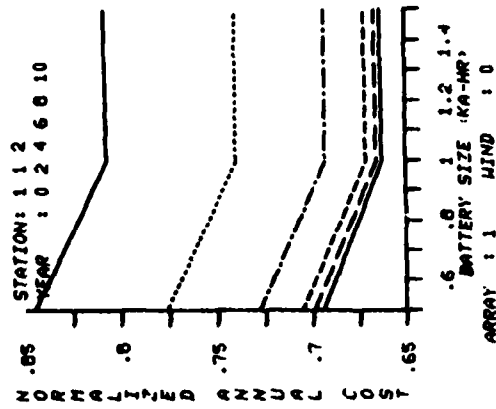
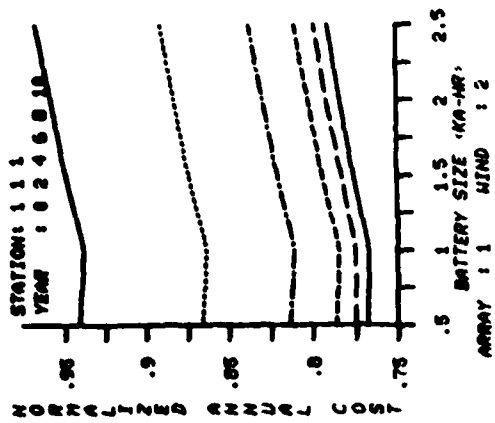


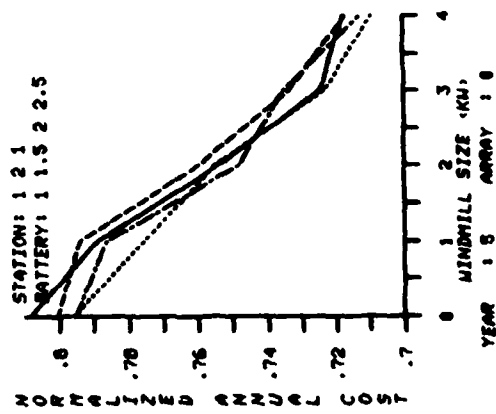
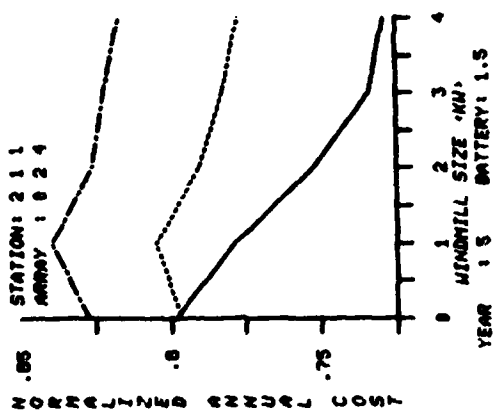
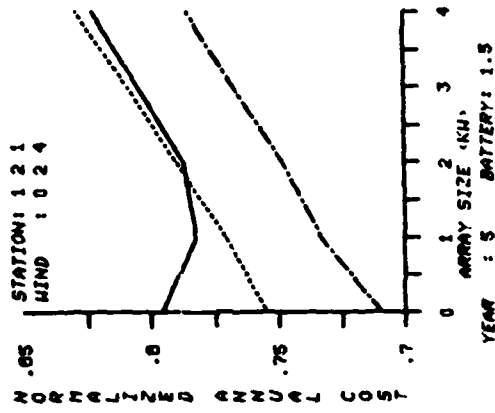
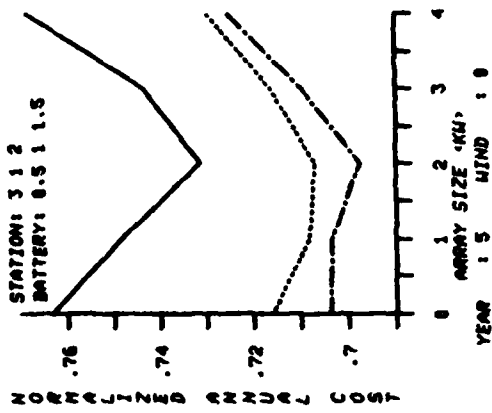
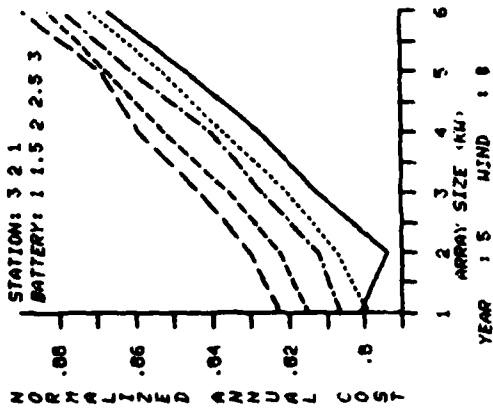
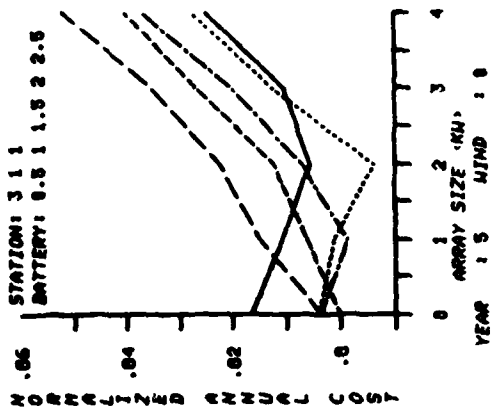


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SECTION 5
PROPOSED CONCEPTUAL DESIGNS FOR PHASE II

5.1 INTRODUCTION

The current remote power LAMP system uses a diesel generator system that runs continuously to power the station. A main storage battery that can power the station during periods of light loading with the diesel off will be added to the LAMP station. This battery will be recharged when the diesel is required to operate during heavy load periods. Environmental energy systems (windmills or solar cells) may also be added. The energy from the environment can also charge the main storage battery and further reduce the use of diesel fuel.

Block diagrams of two systems using this concept are proposed and discussed in this section. Proposal #1, illustrated in Figure 5.0, uses an AC inverter to convert energy from the battery to the 110 volt AC the station currently uses. Proposal #2, shown in Figure 5.1 connects the fog sounder power system directly to the main system battery and can operate the main light filament from battery power via a DC to DC current regulator. The emergency 12 volt battery can also be charged from the main storage battery without using the inverter in Proposal #2. The Proposal #2 system is more efficient than that of Proposal #1, and may be more economical as well, but it requires more extensive changes to the station. Because of the difficulties in changing equipment in operational stations, it may be more effective to start with the inverter only and evolve gradually to equipment operating on DC power from the battery.

The Laboratory proposes that studies of the sounder operation on both DC and AC be investigated early in Phase II to determine the most desirable way to operate the fog sounder. If it is practical to operate the sounder directly off the battery with essentially no change to the station, then this will be the recommended mode of operation for Phase II.

The rest of this section describes the current power system, the AC only proposal, the AC and DC combined proposal, the diesel hut configuration for either new system, and the various components that will be used to implement these changes.

5.2 CURRENT POWER SYSTEM

Figure 5.0 is a simplified diagram of the current power system. It consists of dual diesel generators for routine power requirements and a 12 volt emergency power system.

The dual diesel generator system consists of two diesel generator units and circuitry to control the operation of the diesels. One diesel will normally be supplying power. However, if the voltage or

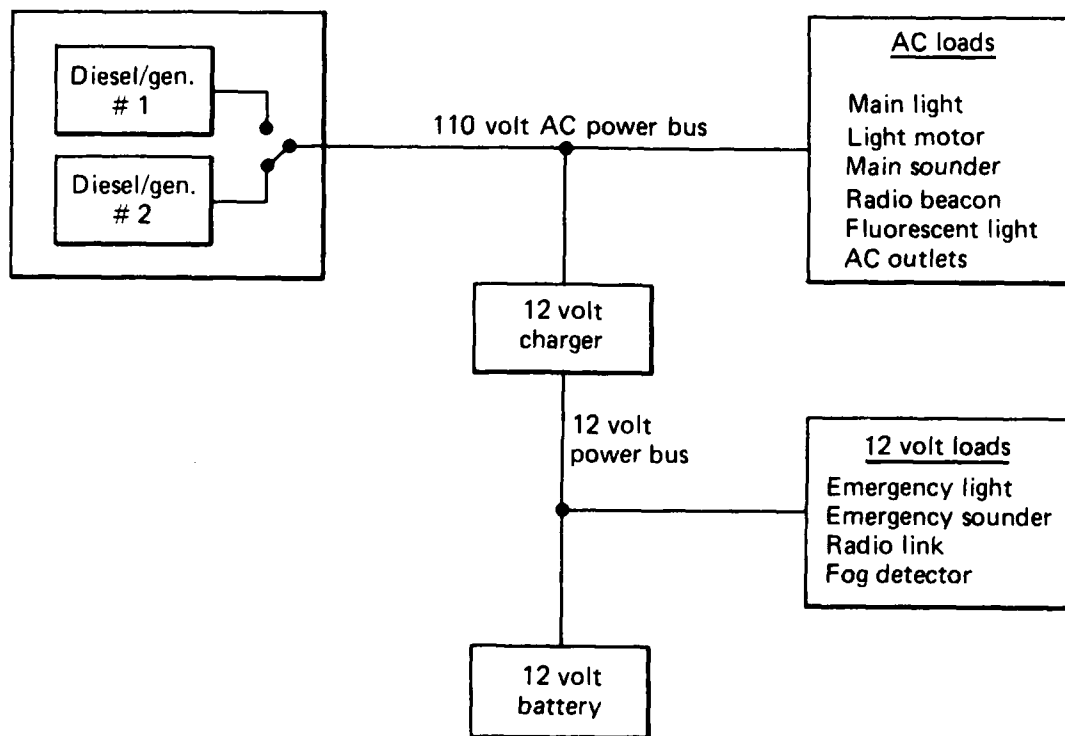


FIGURE 5.0 CURRENT POWER SYSTEM.

frequency deviates from the proper value, the control circuitry will turn on the second diesel and connect it to the station load when it has stabilized correctly. The control circuitry also responds to commands from the Remote Control and Monitor System (RCMS) to turn on the backup diesel.

All of the station loads except the emergency systems operate on 110 volts AC. This includes the main light (filament and motor), main sounder, radio beacon, fluorescent lights, two battery chargers, and AC outlets.

The 12 volt bus powers the radio link, fog detector, and the emergency loads consisting of an emergency light and an emergency sounder. A 12 volt battery charger, operating from the AC line, powers this bus and maintains the battery charge for emergency use.

5.3 MAJOR NEW COMPONENTS

The following new systems are commonly required by both proposals:

- 1) A main storage battery and charger,
- 2) microprocessors for both the signal and diesel huts,
- 3) an AC inverter to supply 110 volts AC power to the system, and
- 4) optionally, a windmill and/or solar cells to recover energy from the environment.

The following paragraphs describe these new systems.

5.3.1 Main Storage Battery

The main storage battery will provide energy to power the station when it is in a low-power mode with the diesels turned off, e.g., during daylight hours. When the diesels are on to handle the heavier load, the main storage battery will be charged up by any excess power available. A lead-acid battery will be used to reduce costs during the experimental development period (Phase II). Other energy storage systems or batteries may be more economical for the final deployed system.

The battery currently recommended will have a nominal voltage of 120 volts. The actual voltage of the battery will be determined during the design phase of the project. This will assure that the minimum voltage of the battery will be sufficient to operate the main light filament when it is operating off of the battery at its lowest point of discharge. The optimum battery size is not a sharply defined value. Large batteries cost more initially but last longer and reduce the number of diesel starts required annually. A battery rated for approximately 20 kWh capacity appears suitable for all station configurations investigated in this study.

5.3.2 Microprocessor Controllers

In order to provide the necessary control and monitoring functions of this system, two microprocessors will be used. One is in

the signal hut and the other is in the diesel hut. It is conceptually possible to utilize a single microprocessor, but for procurement reasons and to permit replacement of individual modules now performing control and monitor functions separately in the signal and diesel huts, it is necessary to use at least two physically separate microprocessor units. It is also intended that each unit should continually check the other. The microprocessor in the signal hut will replace the sensing and logic functions of the RCMS (or supplement these functions in any new replacement for the RCMS),⁺ control the main and emergency Nav aids, monitor and control the environmental systems, and communicate commands and status to the diesel controller.

The microprocessor in the diesel hut will require additional capabilities beyond the current diesel controller. It must communicate status to the signal hut processor, and turn on the diesel in the event of a failure to the main storage battery system or a failure in the signal hut microprocessor. To the extent possible, the diesel hut microprocessor must be designed to have a stand alone mode of operation for use in other engine control situations.

Standard microprocessor modules and backplanes are available commercially that can perform the logic required and have modules that will interface to the various station loads. Selection should be made from several available manufacturers, taking into consideration reliability requirements and the need to acquire a program development system.

Below are listed the various functions that will be performed by each microprocessor. Functions currently performed by the RCMS and existing diesel controller are included, although the replacement for the RCMS may separately perform some of the functions listed.

Function of Microprocessor #1 - Signal Hut

- 1) Receive status requests and commands from the master control center via the radio link.
- 2) Send status information back to the master control station via the radio link.
- 3) Monitor the status of 32 digital inputs now available in a LAMP station.
- 4) Monitor the value of the critical voltages including environmental system parameters.

⁺ Replacement of the RCMS is under study by the Coast Guard at present. This replacement will be designed for independent procurement. However, it will be a microprocessor based system with provision for expansion and flexible adaptation to future needs. It is probable that the new RCMS microprocessor and the signal hut microprocessor can utilize certain common components and possibly be housed in the same module.

- 5) On systems with the old style diesel controllers, send appropriate controlling signals to the diesel controller.
- 6) On systems with new microprocessor diesel controllers, send command information to the diesel hut microprocessor and receive status information from it.
- 7) Monitor the environmental systems and use them to recharge the battery if they have sufficient capacity.
- 8) Turn on the main sounder and the main light when they are required and the power systems are functioning properly.
- 9) Turn off the main light and sounder when they are no longer required, operating improperly, or no power system is capable of supporting them.
- 10) Turn on the emergency systems when they are required.
- 11) Monitor fire and any site security systems.
- 12) Monitor radio beacon transmission.
- 13) Service the local operator monitor and control terminal.
- 14) Monitor and control new energy conversion components.

Function of Microprocessor #2 - Diesel Hut

- 1) Receive commands from the original RCMS, or receive commands from any new RCMS, including microprocessor #1.
- 2) Send status data to microprocessor #1 or any replacement of the current RCMS.
- 3) Start either diesel upon command from RCMS or any replacement for it including microprocessor #1.
- 4) Monitor the operation of the diesel being used to assure that proper operation is attained and maintained.
- 5) Start the backup diesel if the primary diesel does not start properly or fails.
- 6) Connect the diesel generator to the AC power bus when all of the operating parameters are correct.
- 7) Monitor the state of charge of the 24 volt starting battery and turn on the charger when the battery requires charging.

- 8) Monitor fire and any site security systems.
- 9) Service the local operator monitor and control terminal.

5.3.3 AC Inverter

In both proposals an AC inverter operating off of the main system battery is required to operate the station AC loads when the diesels are shut down. In Proposal #1 an efficient inverter that is capable of powering the entire station is required. Inverter tests will be performed to determine if any of the electronic equipment is disturbed by inverter transients or voltage spikes created by the intermittent nature of the fog sounder power surges. In the event that there are incompatibilities, it may be feasible to use two inverters: a ferroresonant type that has no high frequency transients on its waveform for use by the electronic equipment and a more efficient inverter for use with the heavier fog signal load. At the same time during this phase of the project, an investigation of operating the fog sounder directly off the battery will also be made. The results of these investigations will be used to make a final recommendation for the station load configuration and the type(s) of inverter to use in the design of the first experimental prototype.

5.3.4 Environmental Energy Systems

As a means of further displacing diesel fuel, systems may be installed to recover energy from the environment. Current systems being considered include windmills or solar cells depending on the availability of the different forms of energy at the individual station locations. Windmills appear to be the most generally attractive choice at present.

The microprocessor in the signal hut will monitor the outputs of the environmental systems to determine if they have sufficient capacity to recharge the battery and will control their power flow to the main battery. The parameters that must be controlled are typically the field current in a windmill generator or the string configuration and/or load currents for solar cells.

5.4 PROPOSAL #1 (AC INVERTER ONLY)

The first system described retains the present AC power cabling and uses an AC inverter to convert the main system battery voltage to 110 volt AC. Figure 5.1 is a block diagram of this system. All of the system loads operate off of 110 volt AC as they currently do. Whenever the diesels are operating, the system loads are connected directly to the diesel generator output and the battery is charged by the diesel generator as needed. During periods of light station load, the diesels will be shut down and the system loads will be powered by the system battery through the AC inverter. If environmental energy systems are installed, they will be used to recharge batteries when they have adequate capacity. The microprocessor will control the station and any environmental energy systems so that environmental energy can be used to the maximum extent instead of diesel fuel. Power supplies for the microprocessor

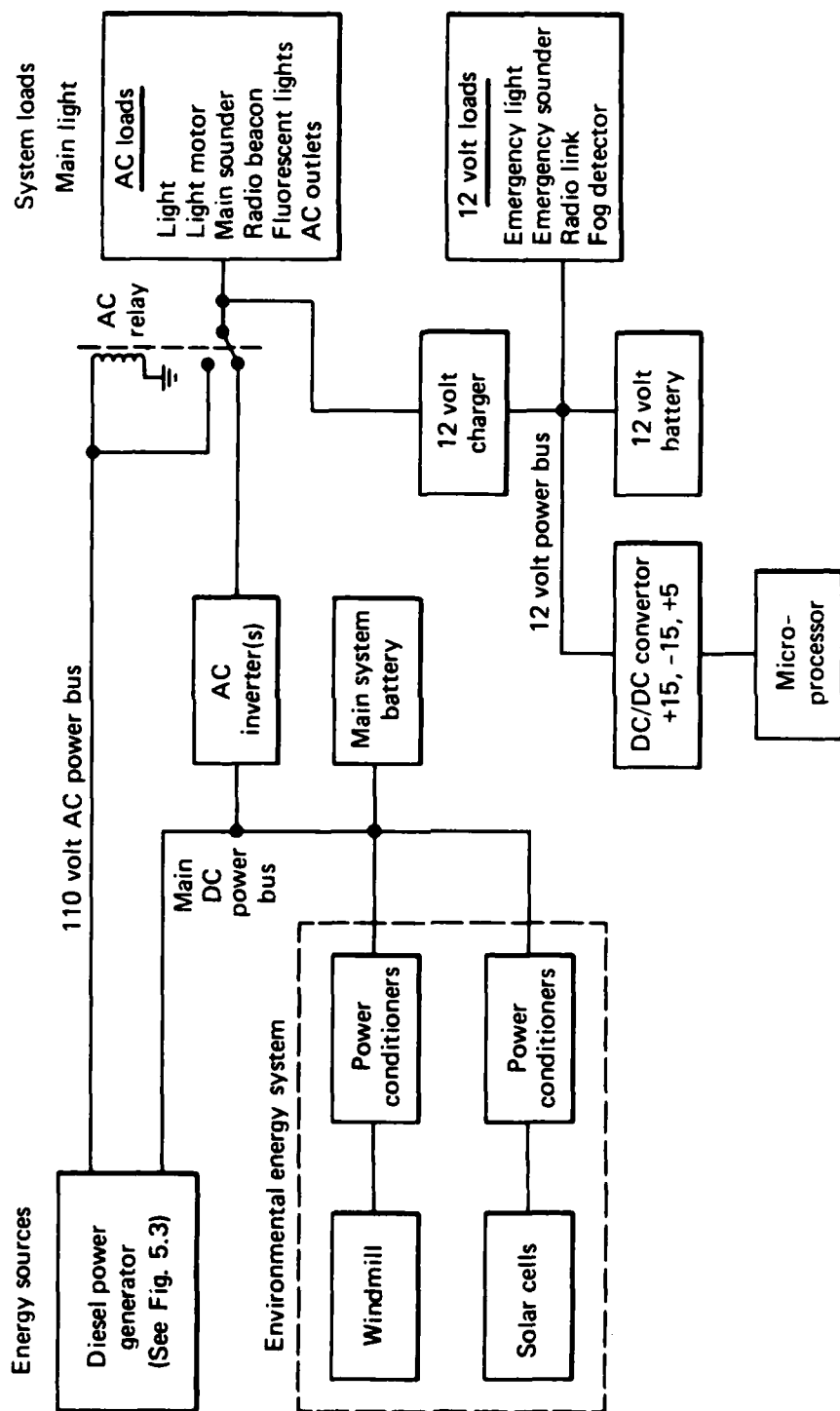


FIGURE 5.1 PROPOSED POWER SYSTEM USING AC INVERTOR.

are connected to the 12 volt emergency power so the microprocessors will function if the primary power fails.

The advantage of the system in Figure 5.1 is that it can be implemented with a minimum of changes to the LAMP modules and power cabling. Inverters are available with efficiencies on the order of 90%, which is comparable to DC/DC converter efficiency. The results of the inverter tests mentioned in subsection 5.3.3 will determine which inverter or combination of inverters should be selected for an efficient power system.

Another reason for selecting the AC only alternative is the uncertainty associated with how the present LAMP modules would respond to DC. For example, the light has automatic lamp changers that utilize the current supplied to the filament. These changers may not work properly if DC is used for the lamp. There are other detailed questions relating to the direct connection of the fog signal power supply to the battery. The continued operation of all LAMP modules on 110 volt AC will surely work, and conversion of some modules to 110 volt DC may be more difficult than it superficially appears.

The fog sounder usually requires more power than other station modules, yet it is not frequently required. Even when it is needed, it is in a low power mode between sound pulses. Thus if fog sounder power must go through an inverter, that inverter will operate most of the time far below its rated capacity. Often this tends to make it inefficient. Another disadvantage of this system is that the AC fog sounder power unit generates a DC voltage internally to operate the fog signal that is at approximately the same voltage as the main system battery. The conversion of energy stored in the battery into AC for the fog sounder power supply followed by its conversion back into DC inside the fog signal power supply is inefficient. It may be possible to operate the fog sounder power unit directly from the main battery supply. (See Proposal #2.)

5.5 PROPOSAL #2 (PARTIAL CONVERSION TO DC)

When the diesel is not operating, the second system proposed utilizes DC/DC converters for the main light, the 12 volt power bus and operates the main sounder directly from the main system battery. When the diesel is operating, the main light, main sounder and 12 volt charger are switched to the 110 volt AC line so they run directly off of the diesel generator. This would also be the default mode in the event of a failure in the main battery system. Figure 5.2 is a block diagram of this system.

The voltage of the main storage battery is sufficiently low even when fully charged to avoid damage to the fog sounder and its supply. The voltage of the main storage battery is sufficiently high even in its lowest state of discharge to provide adequate fog signal and drive the current regulator for the main light.

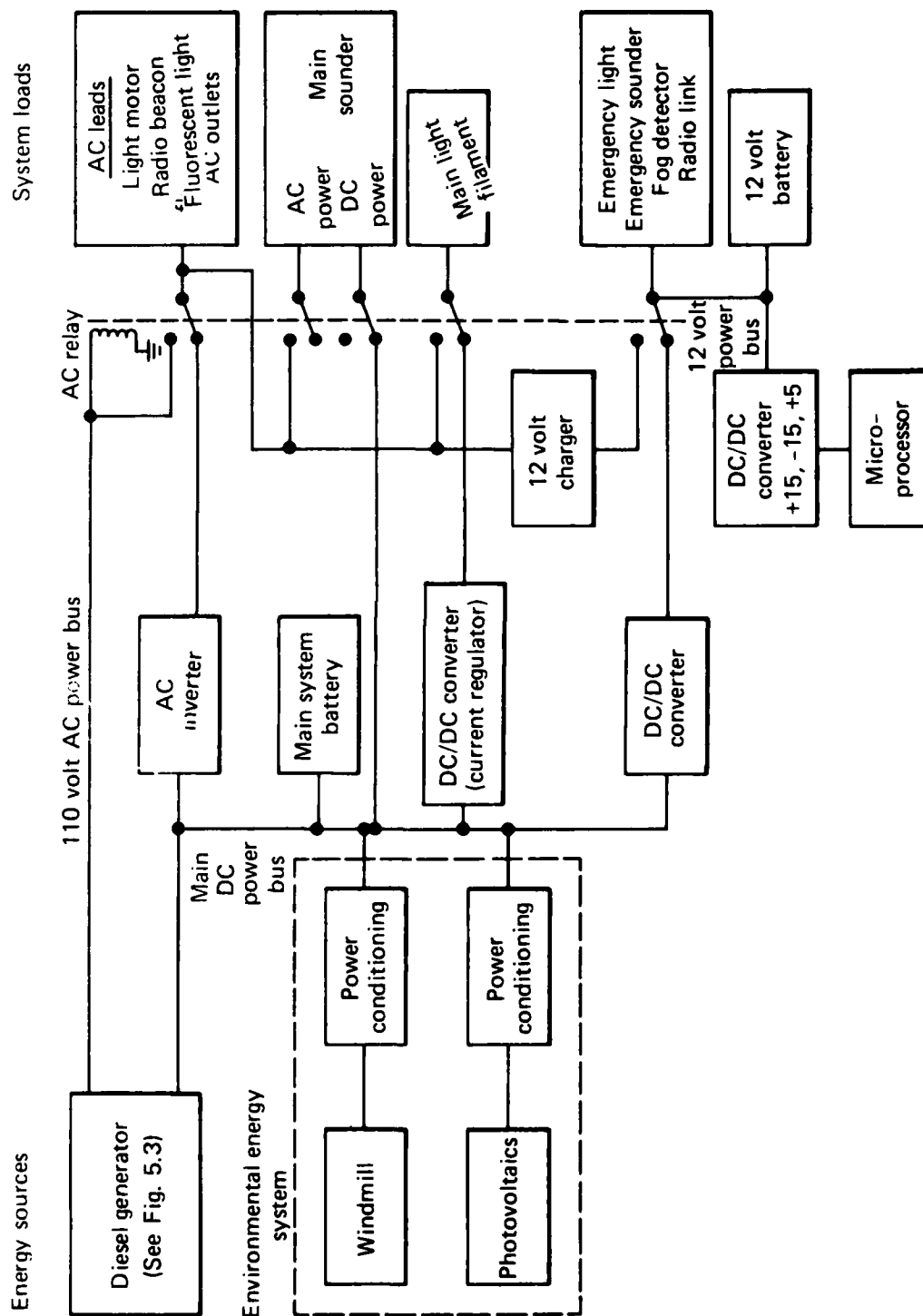


FIGURE 5.2 PROPOSED POWER SYSTEM USING DC/DC CONVERTERS AND AC INVERTER.

The advantages of this system are:

- 1) The largest power user, the fog horn, is connected directly to the main battery, thus losing no energy in converting the battery power to 110 volt AC and then reconverting the 110 volt AC back to DC to operate the horn. There should be essentially no effect of fog signal power surges upon the AC power bus supplying other modules. Also a single relatively small inverter operating efficiently most of the time at near full rating can be utilized for AC loads.
- 2) The main light is operated off of the main storage battery through an efficient DC/DC converter. This converter can also act as a switch (0 volts output) to avoid DC switching transients or arcs.
- 3) Both the fog sounder and the main light can be switched to the diesel generators as a default mode of operation.
- 4) The 12 volt emergency power system uses an efficient DC/DC converter instead of a DC/AC/DC conversion. This converter also serves to isolate the 12 volt emergency supply system from failure in the high voltage DC storage system.

The disadvantages of this system are:

- 1) There are more installation changes to make than the system shown in Figure 5.1.
- 2) An inverter, although a smaller one than required in the all AC system, is still required along with two additional DC/DC converters. All of this tends to add more items for failures and logistical concerns.
- 3) The depth of discharge and maximum voltage of the main storage system are limited by the existing fog sounder and its power system. These limits are not well known at present and may not be optimal for efficient use of the battery and energy sources. An investigation of the fog sounder performance versus applied DC voltage would be required to learn how the radiated audio power decreases as the battery is discharged. If deep discharge of the main storage battery is to be allowed, the Coast Guard must supply guidance as to the acceptable level of radiated audio power. However, the variation in fog signal intensity heard by a mariner at the signal fringe due to battery voltage variation would be much less than that occurring naturally due to variation in atmospheric propagation of sound signal for any reasonable depth of discharge.

5.6 DIESEL GENERATOR

The diesel generator power system consists of two diesel generator sets, a 24 volt starting battery, a battery charger, and a new microprocessor to monitor and control the diesels. The microprocessor also monitors the fire detector and any other units now monitored by the engine controller. Figure 5.3 is a block diagram of this diesel generator power system. This diagram is valid for both proposals, i.e., the AC only and the AC/DC systems. There are only two functions for the diesel-generator system:

- 1) To operate the station and charge the main energy storage battery when the battery is discharged below the desired level if environmental energy systems are not installed or do not have sufficient capacity.
- 2) To provide 110 volt AC to the station for routine, full signal operations in the event of a failure in the main energy storage system. Both proposals permit the station to function normally even if the main storage battery has failed.

When the station loads exceed the energy storage system capabilities, or the main system battery voltage drops below the desired value, the microprocessors will turn on one of the diesels to operate the station and provide energy to recharge both the main battery and the 24 volt starting battery. If the selected diesel does not start properly, then the microprocessor will set the proper error flags and attempt to start the backup diesel. If the situation warrants it, the 24 volt charging battery can be charged from the main system battery to permit extended diesel cranking periods. Also energy from the main storage battery may be used to maintain engine oil temperatures during periods of cold weather. However, this energy should be required primarily for pumps as stored thermal energy can be used for heat. See subsection 2.2.6.

The diesel hut microprocessor controls all of the switches shown in Figure 5.3. Their function is listed below:

- S1 - Starter solenoid for diesel generator #1.
- S2 - Starter solenoid for diesel generator #2.
- S3 - 110 volt AC selector switch for the operating diesel.
- S4 - Switch to connect 110 volt AC to the system when voltage and frequency are stable and correct.
- S5 - Off-on switch for 24 volt battery charger.
- S6 - Disconnect switch for the main system battery charger in the event of a failure in the main DC power system.

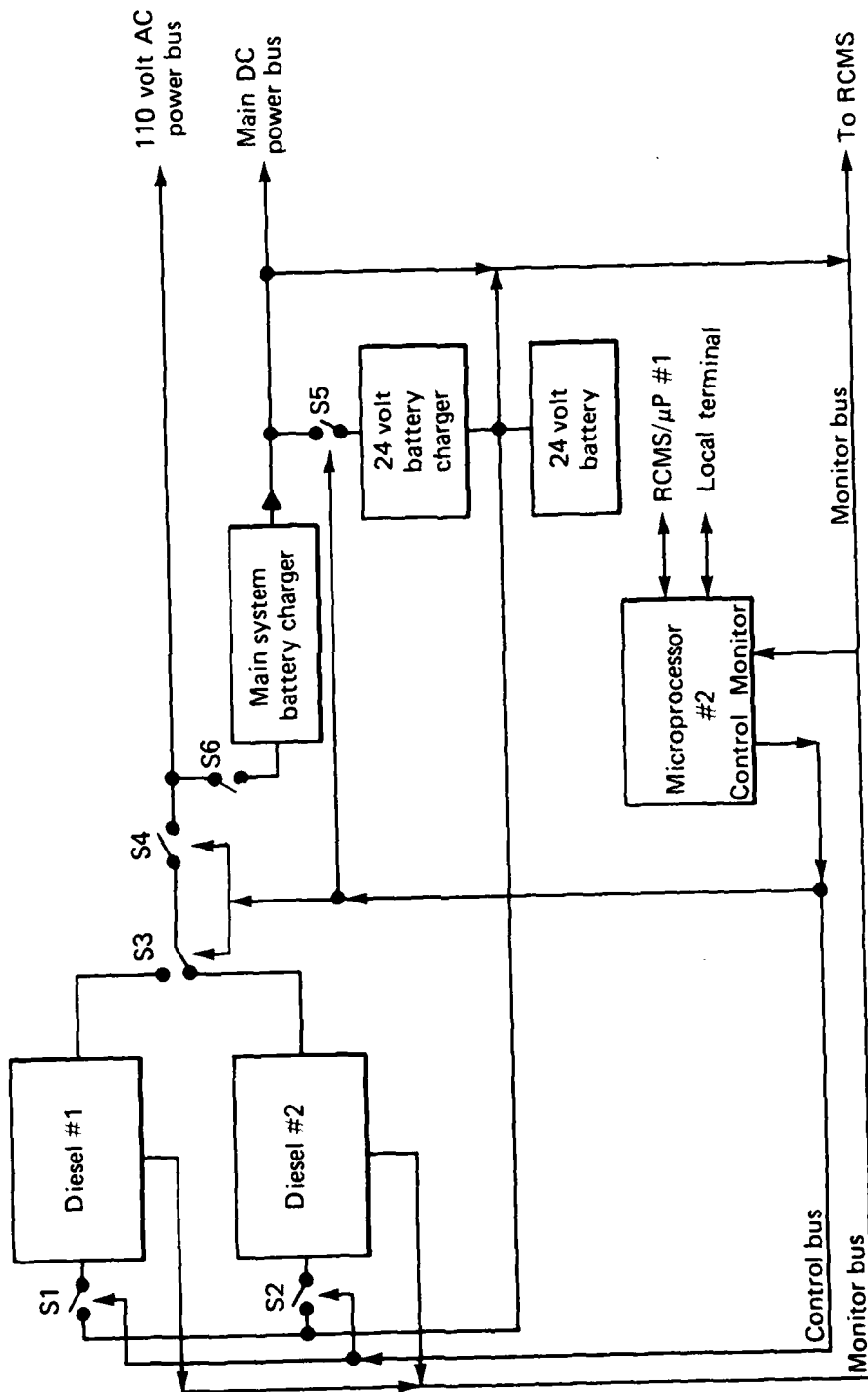


FIGURE 5.3 DIESEL CONTROL MODULE.

5.7 DC/DC CONVERTERS

There are three different DC/DC converters in the two proposed systems. The converter for the microprocessor is common to both systems while converters for the main light and the 12 volt power bus are used only in the second system shown in Figure 5.2.

The +12 volt to +5, +15 volt converters are small, commercially available power supplies commonly used to power microprocessor and controller circuits in mobile equipment.

The converter for the 12 volt power bus is essentially a 12 volt battery charger whose input is a DC voltage instead of an AC voltage. Its controller will sense the battery voltage to keep the battery at the desired state of charge and provide any trickle currents required. The supply will require no filter because of the inherent capacitance characteristics of the battery.

The main light converter is really a current regulator with two functions. The primary function is to maintain a constant current in the lamp. This has the advantages of keeping a constant light output and increasing the life of the lamp⁺ by limiting turn-on currents and high currents which might occur because of surges on the AC line. The controlled current can be optimized to balance lamp life and light output. A second function of this DC to DC converter is to match the voltage required for the lamp to the varying main DC power bus voltage which is determined by other requirements. If the DC power bus voltage variations due to battery management are compatible with the lamp as now used on the AC bus, this converter may not be required. This case may arise in Proposal #2 if only a shallow discharge of the battery is permitted and the lamp and fog signal can both operate in the same narrow battery voltage range.

5.8 DEFAULT MODE

In the event of a failure in the main battery storage system, or a failure in the signal hut microprocessor, the system will default to starting the main diesel and connecting the station loads to the diesel 110 volt AC power bus. This default mode is common to both system proposals and is the logical equivalent of the current system configuration. A fault in the microprocessor in the diesel hut should be less likely than a fault in the present diesel controller. Even if it should occur, it may be possible to operate the station normally using energy stored in the main storage battery and/or energy collected from the environment. Thus conversion to low power emergency signal levels may not be necessary immediately as is the present case when the second diesel or diesel controller fails.

⁺ At present, diesel service requirements force site visits at approximately three month intervals. Lamp life may become more important as the interval between service visits is increased.

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APPENDIX A

STATEMENT OF WORK

The tasks of contract N00024-78-5384 between the U. S. Coast Guard and The Johns Hopkins University Applied Physics Laboratory are listed below.

Task No. 1. Determine Energy Requirements for Major Aids-to-Navigation

a. Determine electrical power requirements for LAMP installations. In particular, power requirements of each LAMP module shall be determined. This should be done using relevant specifications, operating manuals, and engineering drawings supplied by the COTR. When necessary, on-site measurements shall be made of actual modules using the demonstration LAMP installation at the Aids to Navigation Test Facility, U. S. Coast Guard Alexandria Station. The U.S.C.G. Office of Engineering shall directly assist in making any measurements on aids to navigation or at the test facility. After obtaining information on individual modules, the contractor shall determine overall power requirements of LAMP installations as a function of mission, weather and season.

b. Determine the general power requirements for LORAN-C stations and VTS stations. The COTR will supply necessary information.

Task No. 2. Recommend Methods and Techniques for Reducing Energy Consumption at LAMP Installations

a. Recommendations shall be made regarding methods and techniques for reducing energy consumption in LAMP installations in detail and other major aids in general based on the findings of Task No. 1.

b. Questions to be addressed shall be limited to:

- Daylight control of main lights
- Fog detector control of sound signals
- Luminance control of lights or sound signals (based on transmissivity)
- Use of DC current in selected modules of the major aid
- Methods of increasing periods between scheduled overhaul and maintenance
- Using Coast Guard furnished data describing maintenance crew costs, determining methods for saving fuel and reducing costs by modifying present procedures (i.e., using diesels only as a primary power source)
- Other questions suggested by the contractor with the concurrence of the COTR

Task No. 3. Classify LAMP Installations and other Major Aids-to-
Navigation by Power requirements

The COTR will supply necessary information for the contractor
to:

a. Study relevant documents pertaining to major aids-to-
navigation, e.g., Light Lists and Standardized Aids-to-Navigation Data
System (SANOS).

b. Determine a classification scheme which suitably cate-
gorizes remote sites into a small set of power ranges which will allow a
parametric analysis of technical and cost-effective aspects of alternate
power sources.

Prepare Interim Report No. 1 detailing the results of
Tasks 1, 2, and 3 and listing the energy sources projected for evalu-
ation in Task 4.

Task No. 4. Evaluate naturally available energy sources which could be
used to extract power for major aids-to-navigation (i.e.,
evaluate energy sources that are actually available in the
operating environment).

Energy sources shall be selected for evaluation by the contractor
with the concurrence of the COTR. The energy sources selected must be
those which can be converted to electrical energy using experimentally
proven concepts with reasonable assurances that an energy conversion
technique will be commercially available in the next five years. The
energy sources selected of course must be germane to the coastal and
marine locations where the major aids are located. This task shall be
performed primarily by the review and study of existing literature.

Some examples of sources and associated evaluating factors are:

a. Solar energy

- Average annual insolation with regard to applications
areas
- Seasonal and diurnal variation
- Sky cover
- Turbidity
- Precipitable water
- Micro-climate effects (e.g., coastal fog and haze)

b. Wind energy

- Average annual wind energy densities with regard to
application areas
- Seasonal and diurnal variations
- Effects of topography on air flow
- Turbulence
- Micro-climatic effects (e.g., sea breezes)

Task No. 5. Classify LAMP installations and other diesel powered major aids to navigation by climatic regions.

The classification scheme shall be selected in such a manner that it gives a meaningful and quantifiable picture of the energy naturally available in the various U.S.C.G. operating environments.

Based on the results of Task No. 4, determine a classification scheme which suitably categorizes major aids to navigation into a set of climatic regions. This set of climatic regions must be selected in such a manner so as to easily lend itself to a parametric analysis of technical and cost-effective aspects of alternate power sources.

Task No. 6. Investigate alternate energy conversion techniques which can be used to convert natural energy sources into electrical power.

Energy conversion techniques shall be selected for investigation by the contractor with the concurrence of the COTR. The work shall be analytical in nature (i.e., no empirical work shall be performed). The techniques selected must be commercially available or near-term technologies. Furthermore, the techniques selected for study shall be those that have been successfully demonstrated in actual applications or experimental configurations. This task shall be performed primarily by the review and study of existing literature. Some examples of energy conversion techniques and associated evaluating factors are:

a. Photovoltaic Systems

- Rationale for selecting photovoltaics as a candidate alternate energy conversion technique
- Background of photovoltaic cell development
- Theory of the photovoltaic effect from a technological perspective
- Energy conversion efficiencies and life expectancies
- State-of-the-art in present photovoltaic technologies
- Deployment of systems in relevant power ranges
- Cost analysis of photovoltaic cells and ancillary equipment.

b. Wind energy conversion systems (WECS)

- Rationale for selecting WECS systems as a candidate alternate energy conversion technique
- Background of wind energy development
- Theory and performance of WECS system
- State-of-the-art in present WECS development
- Siting requirements
- Cost analysis of WECS system

c. Wave energy systems, fuel cells, solar thermal electric systems.

Task No. 7. Investigate applicable energy storage techniques

Energy storage techniques shall be investigated by the contractor with the concurrence of the COTR. The techniques selected must be commercially available in five years. Furthermore, the techniques selected for study shall be those that have been successfully demonstrated in actual applications or experimental configurations. Prepare Interim Technical Report No. 2 detailing the results of the energy source evaluation of Task 4, the aids to navigation classification of Task 5, the alternate energy conversion techniques investigation of Task 6, and the energy storage techniques investigation of Task 7. Reference to and summarization of the previous interim report shall be included. Include, as preliminary information, any conceptual hybrid power source systems that are a result of work accomplished on Task 8 prior to submittal of this interim report.

Task No. 8. Analyze conceptual hybrid power source systems for use with standardized lighthouses using the results of Task Nos. 1-7 to determine which power sources are best suited to different classifications of installations and climatic regions.

Possible system configurations shall be analyzed. The configurations must be combinations of selected energy conversion techniques (Task No. 6), selected energy storage techniques (Task No. 7), diesel generator sets and necessary power conditioning equipment.

An analysis of each proposed configuration (including the present diesel system) shall be performed. The results of the analysis may be presented in the form of a matrix, wherein the rows correspond to the various classifications of climatic regions. The elements of the matrix contain information describing the most practical hybrid power source(s). The analysis used to determine the most practical hybrid power source shall include (but is not limited to) the following:

- a. Description of the system configuration.
- b. Design considerations based on functions of various classes of major aids (Task Nos. 1-3), energy resources available in various climatic regions Task Nos. 4 & 5, energy conversion systems (Task No. 6) and energy storage (Task No. 7) or combinations of energy storage and diesel back-up. Primary emphasis shall be on sizing methods for various power source modules.
- c. Design considerations based on logistical considerations such as, deployability, reliability, maintainability, supportability, survivalability, life expectancy, acquisition costs and installation costs.

- d. Technical performance characteristics based on available energy resources, energy conversion efficiency, energy storage capability, and energy and diesel fuel expended by major aid. The analysis shall be performed for each proposed configuration which is sized for each class of major aid in each climatic region.
- e. Cost analysis based on parts a, b, c and d above. The analysis shall be done by simulating typical weather patterns for various climatic regions on an hourly basis.

The results of this task shall be summarized as mentioned above and recommendations developed. A task review shall be held at the contractor's facility and be attended by the COTR and other project associated personnel from Coast Guard R&D and Engineering. The results and recommendations of this task shall be presented and reviewed such that the most favorable system may be selected as required by Task 9.

Task No. 9. Prepare a conceptual design for two experimental prototype systems to serve as the basis for the next phase of development.

The two most favorable systems that evolve from the analysis performed in Task No. 8 shall be selected. The systems shall be expanded into a conceptual design (block diagram) which easily lends itself to a modular configuration. Specific generic equipment closely approximating that which could be incorporated into the design shall be identified and recommended for Phase II. The recommendations must be supported by citing previous tests, demonstrations or actual applications in which the equipment has been proven.

The recommendations for developing an experimental prototype system shall include a discussion of selecting a test site with regard to power requirements of the major aid to be powered and its general location. Necessary test equipment for monitoring the system and collecting data will also be described.

Diagrammatical drawings of the system will be prepared. A design review shall be held at the contractors facility and be attended by the COTR and other project-associated personnel. The results of this task shall be presented and the conceptual design drawings reviewed. The drawings shall be revised in accordance with the design review recommendations prior to submittal for approval.

Task No. 10. Prepare final report

A final report shall be prepared including a complete review of the work performed, full description of the findings, conclusions, and recommendations with accompanying rationale. The report shall have an abstract, an introduction, a description of the tasks and the results obtained. Appropriate material shall be placed in appendices. The report shall include final prototype system conceptual drawings.

No release of the information presented in the final report can be made in the form of technical publications, papers, or reports until receipt of Coast Guard approval of the draft final report.

APPENDIX B

TABLE B-1. DIESEL POWER REQUIREMENTS AT REMOTE SITES

DISTRICT	LAT-N (deg,min)	LONG-W (deg,min)	AID NAME	ENGINE-GENERATORS PRESENT PROPOSED #-Size(kw) #-Size(kw) (year)	SOUND SIGNAL PEAK AVERAGE (w) (w)	RADIO BEACON SEQUENCED/ CONTINUOUS PEAK (w)	LIGHT MOTOR PEAK (w)	BEACON & LIGHT PEAK (w)
1	41,24	71,02	BUZZARDS BAY	2-10	1632 425	213 C	470 2000	2683
1	42,00	70,36	PLYMOUTH	2-10	1632 520	-	100 1000	1100
1	42,58	70,37	ISLE OF SHOALS	3-20 2-6.5(83)	1632 380	-	470 2000	2470
1	43,07	70,29	BOON ISLAND	2-6.5	1632 425	-	470 2000	2470
1	43,39	70,02	HALFWAY ROCK	2-10	1632 425	213 C	470 2000	2683
1	43,43	69,46	SEQUIN	3-20 1-6.5(85)	3264 640	-	470 1000	1470
1	43,46	69,20	MANANA ISLAND FOG	- 2-6.5(84)	1632 380	236 S	-	236
1	43,47	68,51	MATINICUS ROCK	2-3/3.5 2-6.5(82)	3264 850	213 C	470 1000	1683
1	43,58	68,08	MOUNT DESERT	2-6.5	1632 425	-	470 1000	1470
1	44,09	68,15	GREAT DUCK ISLAND	3-18 2-6.5(84)	1632 425	213 S	470 1000	1683
1	44,22	67,52	PETIT MANAN	1-12.5	3264 760	-	470 2000	2470
1	44,29	67,32	MOOSE PEAK	1-12.5	1632 425	-	470 1000	1470
1	44,34	67,22	LIBBY ISLAND	1-12.5	3264 850	-	0 2000	2000
3	38,59	75,07	BRANDYWINE SHOAL	2-5	1632 425	-	0 1000	1000
3	39,03	75,11	FOURTEEN FOOT BANK	2-3.5	1632 380	-	0 1000	1000
3	39,08	75,13	MTAH MAUL	2-3.5	1632 163	-	0 1000	1000
3	39,11	75,16	ELBOW OF CROSS	2-3.5	1632 326	-	0 1000	1000
3	39,18	75,23	SHIP JOHN SHOAL	2-3.5	1632 425	-	470 2000	2470
3	40,28	73,50	AMBROSE	3-50 2-10(87)	3264 850	275 S	0 8000	8275
3	40,32	74,03	WEST BANK (RANGE FRONT)	2-10	1632 520	-	0 1000	1000
3	40,59	73,37	GREAT CAPTAINS ISLAND	2-3.5	1632 425	-	0 500	500
3	41,12	72,07	14TH GULL ISLAND	2-6.5	3264 425	213 S	0 1000	1213

TABLE B-1 (cont'd)

DISTRICT	LAT-N (deg.min)	LONG-W (deg.min)	AID NAME	POWER		SOUND SIGNAL		RADIO BEACON SEQUENCED CONTINUOUS	LIGHT		BEACON & LIGHT PEAK (w)
				ENGINE-GENERATORS PRESENT	PROPOSED #-Size(kw) (year)	PEAK (w)	AVERAGE (w)		MOTOR PEAK (w)	LAMP PEAK (w)	
5	33,29	77,35	FRYING PAN SHOALS	2-10		3264	380	213	470	2000	2683
5	34,38	76,32	CAPE LOOKOUT	2-12		-	-	305	470	2000	2775
5	35,09	75,18	DIAMOND SHOAL	2-10		3264	760	213	470	2000	2683
5	36,54	75,43	CHESAPEAKE	2-10		3264	760	213	470	2000	2683
7	24,83	82,55	DRY TORTUGAS	3-40	2-10(84)	-	-	278	470	1000	1748
*7	31,57	80,41	SAVANNAH	2-10		3264	760	-	470	1000	1470
8	28,54	89,26	SOUTH WEST PASS	1-15	2-10(84)	1632	425	278	470	1000	1470
9	42,00	83,08	DETROIT RIVER	2-30	2-6.6(80)	3264	760	213	470	500	1183
*9	43,53	76,27	GALLOO ISLAND	2-other		-	-	-	470	1000	1470
*9	44,01	83,32	GRAVELLY SHOAL	3-20		22	2	213	100	500	813
9	44,39	87,54	GREEN BAY HARBOR	2-6.5		1632	425	213	0	500	713
9	45,01	85,57	NORTH MANITOU SHOAL	2-15	2-6.5(80)	1632	520	213	470	2000	2683
9	43,30	84,46	ST. MARTIN ISLAND	2-6.5		1632	520	-	470	2000	2470
*9	45,30	86,46	ST MARTIN ISLAND K	1-5		3264	1040	213	470	1000	1683
9	45,35	87,00	MINNEAPOLIS SHOAL	2-6.5		3264	760	213	0	500	713
9	45,42	84,22	POE REEF	3-25	1-6.5(82)	DIAPHONE		213	0	1000	1213
9	45,46	85,09	GRAYS REEF	2-10		1632	520	213	0	1000	1213
9	45,50	85,08	WHITE SHOAL	2-10		1632	380	-	470	2000	2470
9	45,54	85,34	LANSING SHOAL	2-10		1632	380	213			
9	46,58	88,00	HURON ISLAND	3-10		3264	850	-	0	1000	1000
9	47,25	87,35	MANITOU ISLAND	2-10		1632	425	236	470	1000	1706
9	47,05	90,44	DEVILS ISLAND	2-15	2-10(80)	-	-	213	470	1000	1683

TABLE B-1 (cont'd)

DISTRICT	LAT-N (deg.min)	LONG-W (deg.min)	AID NAME	POWER		SOUND SIGNAL		RADIO BEACON		LIGHT		BEACON & LIGHT PEAK (w)
				ENGINE-GENERATORS PRESENT	ENGINE-GENERATORS PROPOSED	PEAK (w)	AVERAGE (w)	SEQUENCED CONTINUOUS	PEAK (w)	MOTOR LAMP PEAK (w)	PEAK (w)	
				#-Size(kW)	#-Size(kW) (year)							
9	47,52	89,19	ROCK OF AGES	2-6.5		1632	380	S	213	470	1000	1683
9	48,13	88,22	PASSAGE ISLAND	2-10		1632	380	S	213	0	1000	1213
*11	33,43	118,15	LOSA	2-other		AIR	HORN	-	-	470	1000	1470
11	34,01	119,22	ANACAPA ISLAND	2-6.5		1632	425	C	213	322	1000	1535
12	37,42	123,00	FARALLON	3-15		-	-	C	450	588	1000	2038
12	37,48	122,31	MILE ROCKS	2-6.5	2-10(81)	AIR	HORN	-	-	588	1000	1588
17	56,00	134,08	CAPE DECISION	2-20		3264	760	C	236	470	1000	1706
17	57,13	133,38	FIVE FINGER	2-10		-	-	C	213	0	500	713
17	58,12	136,38	CAPE SPENCER	2-20		3264	760	C	376	470	1000	1846
17	59,48	144,36	CAPE ST. ELIAS	2-10		3264	850	C	305	470	1000	1775
17	60,14	146,39	CAPE HINCHINBROOK	2-10		1632	380	C	236	470	1000	1706

* Indicates station is not planned for LAMP conversion.

Table B-1 was revised prior to printing to reflect best data available April 1981. The count and classification of remote LAMP stations discussed in subsections 2.1.4, 2.3, 3.2 and Appendix F were not correspondingly modified but reflect data available earlier.

TABLE B-2
CLASSIFICATION OF LORAN-C STATIONS AND VESSEL
TRAFFIC SYSTEM STATIONS BY PEAK POWER

District	Station Name	Installed Capacity (#) and (kW)	Radiated Peak Power (kW)
*7	**Montague Peak	-	8
*7	Potato Point	-	30
(Acteur)	Kargabarun	3 x 250	250
(Acteur)	Sellia Marina	3 x 250	250
14	Kure Island	3 x 300	275
17	Attu Island	3 x 300	275
17	St. Paul	3 x 300	275
14	Gesashi	4 x 350	400
17	Narrow Cape	3 x 500	400
(Acteur)	Lampedusa	4 x 250	400
17	Shoal Cove	3 x 500	540
17	Port Clarence	3 x 300	1000
14	Yap	4 x 500	1500
14	Iwo Jima	4 x 500	1800
14	Marcus	4 x 500	1800

* Indicates Vessel Traffic System Stations

** Montague Peak is going to be moved to Naked Island and its peak power demand is expected to be 15kW.

APPENDIX C
LAMP COMPONENT POWER USE

AIDS TO NAVIGATION

Component	Aids to NAV ⁵ Ref.-Page	Voltage AC (Volts)	Voltage DC (Volts)	Current (amps)	Power [*] (watts)	Notes
1. Lamp (NSN 7512) Lamp (NSN 7934)	6-80	120		8.33 4.16	1000 ⁵ 500	Tungsten-halogen incandescent lamps
1a. Optic DCB-24/224	6-85	120		4.9	470 ⁵	Power to rotate both DCB-24 (single optic) and DCB-224 (double optic)
Optic DCB-10	6-82	120		1.04	100 ⁵	Power to rotate DCB-10 (uses 500 W lamp)
2. Emergency Light CG-6P	6-21 6-47		12	0.25- 3.05	36.6 ⁵	Peak (20% duty cycle)
3. Fog Detector Videograph Model B CDNC-147.122	8-26		11-14		24 ⁵	
4. Sound Emitter ELG-300/02 and CG-1000	7-32	120		17 ⁵ 7 2.5	1632 240	During Blast (20% max. duty cycle) Silent, unballasted
5. Emergency Emitter FA-232	7-25		12	1.8	21.6 ⁵	
6. Radio Beacon New Solid State AN/FRN - 40		120		1.8 ⁸ 2.9 3.7 4.7 6.1	173 278 355 451 586	Transmitter power: 0 watts 25 watts 50 watts 100 watts 200 Watts

* AC power factor of 0.8 is assumed (Power = .8 x V x I). Numerical superscripts indicate reference number.

APPENDIX C (cont'd)

SIGNAL CONTROL HUT

Component	Aids to NAV 5 Ref. Page	Voltage AC (volts)	Voltage DC (volts)	Current (amp)	Power (watts)	Notes
1. RCMS Remote Terminal CDHU-6706-R	8-12		12.6		27 ⁸³	RCMS is composed of a decoder and an encoder. The Navaid Sensor module (Ref. 8-22) is part of the encoder.
2. Remote Station Radio Link Set CG-REM-202	8-17		13.6 13.8	10 ¹⁴ 2.1	190 29	Transmit mode (20% max. duty cycle) squelched transmitter. 406 to 420 MHz transmit frequency.
3. Audio-Visual Controller CCF-RWL-2098	8-19		12		36 ⁸³	The many different modes of operation require a detailed investigation for power use in each mode.
4. 12V Battery Charger McGraw-Edison Model 1BC 12-30A	9-31	115/230			850 ¹¹ max.	1BC 12-30A
5. Halon Fire Sup- pressor System			12		84 15 10 ¹⁵	Peak standby power. Average power is about .1 watt.

* AC power factor of 0.8 is assumed (Power = .8 x V x I). Numerical superscripts indicate reference number.

APPENDIX C (cont'd)

PRIME POWER HUT

Component	Aids to NAV ⁵ Ref-Page	Voltage AC (volts)	Voltage DC (volts)	Current (amps)	Power (watts)	Notes
1. Environmental Control Unit	9-27	120			1200 ¹²	Operates only during operation of engine-generators
2. Day Tank Pump Drawing No. 130901 Controls and Indicator Lights	9-28	120		7	662 ¹⁵	Operates only during operation of engine-generators
3. Automatic Power System Controller C-9985/F	9-29		24		34 ⁸³	When the diesel is not operating.
4. 24V Battery Charger TBC 24-20A	9-30	115/230			650 ¹¹	Output voltage is 20 to 32 VOC DC output. Current is 11A nominal 14A max.
5. Halon Fire Suppressor System			24		15 ⁸⁴ 10 ¹⁵	Peak standby power. Average power is about .2 watts

* AC power factor of 0.8 is assumed (Power = .8 x V x I). Numerical superscripts indicate reference number

APPENDIX D
MEASURED POWER USE OF LAMP COMPONENTS

The power consumption levels of components of a test LAMP installation were measured and statistically analyzed by the U. S. Coast Guard Electronic Engineering Laboratory in Alexandria, Virginia. The data were taken on April 23, 1980, and are presented in Table D. The test conditions for these data were as follows:

1. The light, sound generator, radio beacon and environmental control unit were all turned "off".
2. The emergency optic and sound signal were turned "off".
3. The battery chargers were "on".
4. The DC loads on the battery chargers were the following:
 - a. RCMS (including sensor modules)
 - b. CG-REM-202 Radio Link for RCMS
 - c. Audio-Visual Controller, AVC
 - d. Automatic Power Controller, APC

The data in Table D clearly show the increased power requirement for the radio link set during 10 seconds of every 5-minute period. Relying on Reference 10 for the power requirement of the Radio Link Set (29 watts, squelched mode; 190 watts, transmit mode), one can calculate the efficiency of AC to DC conversion through the battery chargers. This efficiency is estimated to be 77%, or $(100 \times (190 - 29) \div (385 - 175))$.

On May 8, 1980 other measurements at the Electronic Engineering Laboratory gave the following results for different combinations of equipment operating:

<u>Equipment Combination</u>	<u>AC Load</u> (volt amperes)	<u>Equipment Power*</u> (watts)
1. AVC and APC	115	71
2. RCMS, Link Set, AVC, APC	203	126
3. RCMS, Link Set, AVC	151	93
4. AVC	58	36

* Equipment power is $.8 \times .767 \times \text{Volt Amps}$ (80% power factor and 76.7% efficiency of the battery charger).

The power for the audio-visual controller is 36 watts (Equipment Combination 4). The power for the automatic power controller (APC) is estimated to be 35 watts (Equipment Combination 1 minus Equipment Combination 4, or 71-36) and 33 watts (Equipment Combination 2 minus Equipment Combination 3, or 126-93). Thus 34 watts will be the power requirement for the APC used in this report. Since the radio link set requires 29 watts, the RCMS requires 27 watts (Equipment Combination 2 minus link set, AVC and APC or, $(126-(29+36+34))$). Another estimate of the RCMS power requirement is 28 watts (Equipment Combination 3 minus link set and AVC, or $(93-(29+36))$).

TABLE D

POWER READINGS IN KILOWATTS FOR
SELECTED LAMP SYSTEM COMPONENTS.

(Data points were taken at five-second intervals.)

DATA				
0.1796	0.1708	0.1764	0.1776	0.1768
0.1768	0.1756	0.1760	0.1744	0.1764
0.1740	0.1700	0.1740	0.1752	0.1744
0.1740	0.1744	0.1752	0.1752	0.1752
0.1724	0.1732	0.1740	0.1732	0.1744
0.1732	0.1712	0.1732	0.1736	0.1736
0.1732	0.1752	0.1672	0.3052	0.2104
0.1792	0.1740	0.1732	0.1712	0.1728
0.1704	0.1728	0.1720	0.1708	0.1704
0.1732	0.1700	0.1712	0.1696	0.1720
0.1720	0.1716	0.1720	0.1704	0.1724
0.1696	0.1732	0.1716	0.1696	0.1720
0.1744	0.1716	0.1732	0.1712	0.1724
0.1720	0.1704	0.1752	0.1720	0.1720
0.1692	0.1700	0.1692	0.1732	0.1704
0.1716	0.1752	0.1712	0.1720	0.1732
0.1704	0.1740	0.1720	0.1716	0.1720
0.1760	0.1716	0.1720	0.1716	0.1724
0.1700	0.1724	0.3756	0.3040	0.1692
0.1732	0.1720	0.1732	0.1752	0.1752
0.1732	0.1728	0.1728	0.1720	0.1720
0.1720	0.1720	0.1752	0.1720	0.1720
0.1920	0.1736	0.1752	0.1748	0.1752
0.1752	0.1752	0.1752	0.1740	0.1752
0.1756	0.1740	0.1752	0.1720	0.1724
0.1724	0.1724	0.1724	0.1728	0.1740
0.1728	0.1728	0.1724	0.1720	0.1724
0.1720	0.1724	0.1724	0.1720	0.1728
0.1724	0.1724	0.1724	0.1720	0.1724
0.1740	0.1724	0.1724	0.1740	0.1724
0.1724	0.1728	0.3044	0.3044	0.1008

APPENDIX E
TABLE E COASTAL WIND STATISTICS

Weather Recording Location	Annual Mean Speed ¹ (MPS) (MPH)		Variation ² of Hourly Means as Percent of Annual Mean	Variation of Seasonal Mean as Percent of Annual Mean	Station Latitude
<u>TEXAS</u>					
Brownsville	5.53	12.37	69	10	25° 55'
Corpus Christi	5.87	13.13	36	05	27° 41'
Galveston	5.47	12.24	22	18	29° 16'
Port Aurther	4.72	10.63	42	38	29° 52'
<u>LOUISIANA</u>					
New Orleans	3.73	8.34	62	42	29° 30'
<u>MISSISSIPPI</u>					
Biloxi	3.34	7.47	60	28	30° 24'
<u>ALABAMA</u>					
Mobile	4.27	9.55	42	21	30° 41'
<u>FLORIDA</u>					
Panama City	3.18	7.11	69	35	30° 04'
Valpariso	3.29	7.36	69	28	30° 29'
Tampa	2.96	6.62	66	43	27° 51'
Fort Myers	3.50	7.83	80	18	26° 35'
Key West	4.83	10.80	16	25	24° 35'
Homestead	3.26	7.29	90	36	25° 29'
Miami	3.99	8.93	68	19	25° 48'
W. Palm Beach	4.60	10.29	61	25	26° 41'
Cape Kennedy	4.06	9.08	58	30	28° 29'
Daytona Beach	4.18	9.35	84	21	29° 11'
Jacksonville	3.67	8.21	52	15	30° 14'
<u>GEORGIA</u>					
Brunswick	2.78	6.22	83	21	31° 15'
Savannah	2.82	6.31	87	32	32° 01'
Charleston	4.16	9.31	60	24	32° 54'
<u>SOUTH CAROLINA</u>					
Myrtle Beach	3.12	6.98	83	15	33° 41'

TABLE E (cont'd)

Weather Recording Location	Annual Mean Speed ¹ (MPS) (MPH)	Variation ² of Hourly Means as Percent of Annual Mean	Variation of Seasonal Mean as Percent of Annual Mean	Station Latitude
<u>NORTH CAROLINA</u>				
Cape Hatteras	5.18 11.59	21	19	35° 16'
<u>VIRGINIA</u>				
Virginia Beach	3.79 8.48	26	33	36° 49'
Norfolk	3.98 8.90	31	22	36° 57'
Hampton	3.87 8.66	43	19	37° 05'
Wallops Island	3.97 8.88	54	20	37° 51'
<u>DELAWARE</u>				
Dover	3.69 8.25	57	34	39° 08'
<u>NEW JERSEY</u>				
Atlantic City	4.98 11.14	46	29	39° 27'
Newark	4.56 10.20	42	23	40° 44'
<u>NEW YORK</u>				
New York Shoals	8.81 19.71	07	60	39° 48'
J.F.K. Airport	5.43 12.15	34	23	40° 39'
La Guardia Airport	5.78 12.93	27	32	40° 46'
<u>RHODE ISLAND</u>				
Quonset Pt.	4.34 9.71	51	26	41° 35'
Providence	6.10 13.65	26	27	41° 50'
<u>MASSACHUSETTS</u>				
Nantucket Shoals	9.16 20.49	05	27	41° 01'
Georges Shoals	9.33 20.87	04	39	41° 41'
Boston	6.06 13.56	26	29	42° 20'
<u>NEW HAMPSHIRE</u>				
Portsmouth	3.48 7.78	60	28	48° 05'
<u>MAINE</u>				
Portland	4.29 9.60	46	22	43° 39'
Brunswick	3.56 7.96	67	24	43° 53'

Notes: 1) The annual mean speed has been adjusted to a standard 10 meter height as described in reference 33.

2) The difference between the extremes of the diurnal variation of the mean for each hour of the day is tabulated as a percent of the annual mean.

**APPENDIX F
CLIMATIC GROUPS**

The 56 remote power Coast Guard stations listed in Appendix B as presently using LAMP modules or scheduled for conversion to LAMP stations were divided into three latitude groups (Southern, Northern and Alaskan) and two wind site types (coastal and offshore) in subsection 3.2. The number of sites in each of these six generic climatic groups was given in Table 3.4.

The purpose of constructing Table 3.4 is to show that there are stations in each of the climatic groups. The identity of the stations is not particularly important in a generic study but specific classification of each of the real sites was required to construct Table 3.4. The district and name of the stations assigned to each of these six groups is given below.

TABLE F TYPE CLASSIFICATION

District	Aid Name	Latitude Group	Site Type
1	Buzzards Bay	Northern	Offshore
1	Plymouth	Northern	Offshore
1	Isle of Shoals	Northern	Offshore
1	Boon Island	Northern	Offshore
1	Halfway Rock	Northern	Offshore
1	Seguin	Northern	Offshore
1	Monhegan Island	Northern	Offshore
1	Manana Island Fog	Northern	Offshore
1	Matinicus Rock	Northern	Offshore
1	Mount Desert	Northern	Offshore
1	Heron Neck	Northern	Offshore
1	Great Duck Island	Northern	Offshore
1	Petit Manan	Northern	Offshore
1	Moose Peak	Northern	Offshore
1	Libby Island	Northern	Offshore
3	Brandywine Shoal	Northern	Offshore
3	Fourteen Foot Bank	Northern	Offshore
3	Ship John Shoal	Northern	Offshore
3	Ambrose	Northern	Offshore
3	West Bank (Range Front)	Northern	Offshore
3	Great Captains Is.	Northern	Coastal
3	Little Gull Is.	Northern	Offshore

TABLE F TYPE CLASSIFICATION (cont'd)

District	Aid Name	Latitude Group	Site Type
5	Frying Pan Shoals	Southern	Offshore
5	Cape Lookout	Southern	Coastal
5	Diamond Shoal	Southern	Offshore
5	Chesapeake	Southern	Offshore
5	Wolf Trap	Southern	Coastal
5	Smith Point	Southern	Coastal
7	Dry Tortugas	Southern	Offshore
8	Point Au Fer Reef	Southern	Offshore
9	Detroit River	Northern	Coastal
9	Green Bay Harbor	Northern	Coastal
9	North Manitou Shoal	Northern	Coastal
9	St. Martin Island	Northern	Coastal
9	Minneapolis Shoal	Northern	Coastal
9	Poe Reef	Northern	Coastal
9	Grays Reef	Northern	Offshore
9	White Shoal	Northern	Offshore
9	Lansing Shoal	Northern	Offshore
9	Huron Island	Northern	Offshore
9	Manitou Island	Northern	Offshore
9	Devils Island	Northern	Offshore
9	Rock of Ages	Northern	Coastal
9	Passage Island	Northern	Offshore
11	Anacapa Island	Southern	Offshore
12	Farallon	Southern	Offshore
12	Alcatraz	Southern	Coastal
12	St. George Reef	Northern	Offshore
13	Smith Island	Northern	Coastal
13	Cape Flattery	Northern	Offshore
17	Scotch Cap	Alaskan	Coastal
17	Cape Decision	Alaskan	Coastal
17	Five Finger	Alaskan	Coastal
17	Cape Spencer	Alaskan	Coastal
17	Cape St. Elias	Alaskan	Offshore
17	Cape Hinchinbrook	Alaskan	Offshore

APPENDIX G
ECONOMIC ANALYSIS

G.1 GENERAL CONSIDERATIONS

Life-cycle-cost analysis methods discount future benefits and expenses to an equivalent present value or cost. If two systems under study have the same useful life and both perform the mission equally well, the system with least present cost is economically preferred. In this study different systems have different life times and consequently their present values are converted to equivalent uniform annual payments to permit economic comparison. The system with the lowest uniform annual cost that satisfactorily performs the task is the most economic choice, regardless of its lifetime.

The Coast Guard approved method of economic analysis is contained in NAVFAC P-442 Economic Analysis Handbook.⁸⁵ The Department of Energy in its Federal Energy Management Program, FEMP, has mandated that all federal agencies use the life cycle cost analysis methods outlined in the Federal Register of 1-23-80 for energy systems serving federal buildings. These procedures are basically similar. Both use a real discount rate of 10% and permit only energy cost to be inflated with time.⁺ All of the economic analysis in this study uses constant value dollars with the parity value approximately equal to the value of a dollar in 1980. The value of fuel and some other items in constant value dollars depends upon a calendar date. The FEMP method assumes that all reoccurring costs occur at the end of the year and thus the discount factor for expenses in the n^{th} year is $(1.1)^{-n}$. The NAVFAC P-442 procedure averages the discount at the start and end of the n^{th} year.

$$\frac{(1.1)^{1-n} + (1.1)^{-n}}{2} = 1.05(1.1)^{-n} \quad (\text{G.1})$$

This method results in a discount factor of $1.05 (1.1)^{-n}$

In this study the time when the expense occurs is known, and neither the annual average nor the year end assumption is required. The exact discount factor is $(1.1)^{-m}$, where m is the time from the start of the project in years. Note n as used by the NAVFAC and FEMP procedures is strictly an integer, but m can have non-integer values. For example an expense of \$1,000 dollars at the middle of the third project year has $m = 2.5$ and corresponds to a present cost of \$787.99. The FEMP method would give it a present cost of \$751.31 and the NAVFAC method would give it a present cost of \$788.88. Both the FEMP and the NAVFAC methods are approximations to the correct value. (Both FEMP and NAVFAC methods are often applied using precalculated tables for discount factors. The values given here may differ slightly from values calculated with tabulated data because of rounding errors in the tabulated data.)

⁺ The FEMP procedure for energy conservation systems has been revised to use a 7% discount factor.⁸⁶ This change can easily be incorporated in the economic analysis because the value of the discount factor is an input parameter in the economic analysis model. The effect of this change, if adopted for Coast Guard analysis, is to make alternate energy system more attractive.

In the above example the NAVFAC method appears to be more accurate than the FEMP method because the expense occurred at mid-year. If the expense occurred nearer the end of the year, the FEMP method would be more nearly correct. However, accuracy is not the only deciding factor. All three methods are sufficiently accurate for a preliminary feasibility analysis. The choice of method is more a matter of convenience than accuracy. In this study it is more convenient to compute accurately because the computer model predicts that energy storage batteries, etc., must be replaced after a non-integer number of years depending upon the details of their use pattern. Also part of the essence of the study would be lost if a fixed life time were assumed for the various system components. For example, the economic analysis must reflect that changing the controls on depth of discharge on a battery storage system to permit it to serve 3.8 years instead of only 3.2 years produces a better control system in spite of the fact that the batteries are replaced in the fourth year of the project in both cases. Only the accurate method used in the analysis method of this report reflects that a battery control system that makes the battery last 3.8 years instead of only 3.2 years is superior. Both the NAVFAC and FEMP methodologies would show no difference because both control systems cause the battery to be replaced during the fourth year of the project.

The NAVFAC procedure for converting a present cost value into a series of equivalent uniform annual payments extending over the life of the system, L years, (i.e., L equal payments, one per year) requires dividing the present value by the cumulative sum factor, CSF.

$$CSF = \sum_{j=1}^{j=L} 1.05(1.1)^{-j} \quad (G.2)$$

In this sum, L is inherently an integer, but this sum is a geometric series equal to:

$$CSF = 10.5 [1 - (1.1)^{-L}]. \quad (G.3)$$

In this form, there is no reason why L must be an integer. The corresponding factor in FEMP analysis is called the uniform present worth, UPW.

$$UPW = \sum_{j=1}^{j=L} (1.1)^{-j} \quad (G.4)$$

and in its continuous analytic form,

$$UPW = 10[1 - (1.1)^{-L}]. \quad (G.5)$$

When the present worth values are calculated for non-integer years with a discount factor given by $(1.1)^{-m}$ as discussed above, then they must be divided by $10[1 - (1.1)^{-L}]$ to obtain the equivalent uniform cost payment.

x is the system lifetime, not necessarily an integer number of years. This extension of integer year concepts to non-integer year lifetime intervals will be illustrated with a specific example. Suppose three different systems all had a present cost of \$10,000 but system A had a useful life of 15 years, system B had a life of 15.5 years and system C had a life of 16 years. The advantages of the extended or generalized concept are clear in Table G.1. The NAVFAC and FEMP methods can not cope with system B or must treat it as a 16 year system. They can not recognize that it is inferior on a uniform payment basis to system C.

Table G.1
COMPUTED UNIFORM COST PAYMENT RATE (\$/Year)

System	Life(years)	NAVFAC	FEMP	GENERALIZED
A	15	1252.12	1314.73	1314.73
B	15.5	N.A.	N.A.	1295.76
C	16	1225.87	1278.17	1278.17

In the above example all three systems have equal present costs (\$10,000). One need not calculate uniform cost payment rates in this case to recognize that the system with the longer useful life is economically superior, but this method is necessary if the present cost of the longer life system is also higher. For example, if system C had a present cost of \$10,250 then system B would be preferred.

The FEMP method includes only 90% of the actual initial investment in the system, but assumes that this reduced sum is paid at the beginning of the first year of the project. NAVFAC's analysis includes the entire investment without any discount associated with payment of initial investment costs over a period of time as construction or installation proceeds. The NAVFAC alternative is adopted for this analysis because the materials and systems required by the Coast Guard for remote site use would be acquired and tested prior to delivery to the site (lighthouse). Installation at the site is assumed to proceed rapidly. The system has no beneficial use until placed into operation at the site. In this situation, the use of less than the full initial cost would be fallacious. One could argue that more than the actual cost of the initial investment should be charged to cover the loss of use of capital while the system components are being assembled and tested prior to useful deployment at the site.

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The NAVFAC procedures recommend that fuel oil cost for the diesel power system at the site be escalated at 8% per year. The FEMP procedures do not consider fuel oil, but give generally lesser escalation rates for heating oil, with different values depending on building type. It is difficult to decide whether a lighthouse, typically unmanned, is a "residential", "commercial" or "industrial" structure owned by the federal government, and fuel oil is not the same as heating oil. Consequently the NAVFAC procedures are adopted for escalating diesel oil prices. Thus the present cost of a quantity of fuel oil currently

valued at one dollar is $(1.08/1.1)^m$, if purchase is scheduled m years from now. However, the program code used in the simulation model, Task No. 8, is structured so that other fuel escalation and discount rates can be considered should the need arise.

The Coast Guard currently pays \$1.30 per gallon for diesel fuel. This value exceeds the FEMP values for heating oil in all regions listed in the FEMP data set regardless of "residential", "commercial" or "industrial" building use class. When actual data are available and the energy costs exceed the values recommended in the FEMP data set, the FEMP procedure recommends that the actual data be used. Thus, the present cost, PC_f , of G gallons of diesel fuel oil acquired by the Coast Guard in year m is

$$PC_f = 1.30 G (1.08/1.1)^m \quad (G.6)$$

Note that m need not be an integer. For example a 1000 gallon shipment of fuel oil could be delivered to a remote lighthouse after $m = 2.7$ years. In this case, the above expression gives a present cost of this fuel oil shipment of \$1237.16 or \$1.24 per gallon. This cost does not include the cost of shipment. Shipment of supplies to the station is a major cost and will be treated separately. Much of the economic advantage expected for the alternate energy systems at remote Coast Guard sites is associated with the decreased frequency of resupply required.

G.2 SPECIFIC CONSIDERATIONS

All physical components in a system have a useful lifetime and an initial cost. During their lifetime they may require service and thus also represent deferred expenses. They must be replaced during the life of the system if their lifetime is less than that of the system or analysis period. The analysis period selected for this study is the life of one diesel electric generator set. The methods used will be illustrated by specifically considering two system components --- the diesel-electric generator, and associated storage batteries with lesser lifetimes.

G.3 SITE VISIT COSTS

The frequency of visits to a typical remote lighthouse equipped with LAMP modules is normally controlled by the need to service the diesel and/or replace lamps in the main light. The standard LAMP diesel used for primary power runs essentially continuously for 2190 hours (three months) between service visits. The automatic lamp changer holds two lamps, each rated for 3000 hours. Thus servicing the diesel is the primary reason for currently scheduling four routine visits to the station each year. Special nonroutine visits to the site may be required; for example, the fog signal may fail. However, it is assumed that failure in a component in the alternate energy system need not be the cause for a special visit to the site because the station with an alternate energy system is designed to revert to the conventional, diesel only, mode of operation when its alternate energy system fails.

We wish only to determine if alternate energy systems can save both diesel fuel and costs. Thus we can ignore special nonroutine visits because the cost of such visits should be approximately the same for both the standard, diesel only, LAMP station and for any of the alternate energy hybrid power systems being considered in this report. An exception to this rule would be a major component failure in the alternate energy system that was not scheduled for routine replacement or service. For example, if a wind machine tower collapses, this is a nonroutine expense that can not be ignored, and may require special service equipment. However, provided that the collapsed wind machine tower does not interfere with station operation in the back-up mode, there is no reason to schedule an extra visit to the site. That is, the station would operate in the back-up mode until the next regular visit but that visit would be more costly because of special equipment needs for tower repair.

The extra cost of routine visits associated with nonroutine repair or replacement of alternate energy system components must be estimated and charged to the alternate energy system during the economic analysis. The extra cost during routine visits for routine service of the alternate energy system components is calculated using the methodology presented in section G.5 of this Appendix for the diesel-electric generator service costs. The alternate energy system service cost, AESSC, is the cost charged to the alternate energy system for service performed during each of the service visits to the site.

G.4 DIESEL LIFETIME

The Coast Guard projects that the diesel lifetime is 15 years (131,400 hours) and that it can run more than 20,000 hours before major (rebuilding) overhaul at the maintenance base. It is assumed for this study that major overhaul is required after 21,900 hours (2.5 years). The Coast Guard assigns zero salvage value at the end of the diesel's life and consequently expends no money to service it at the end of the life for salvage sale.

The sequence of diesel related cost events occurring during the life of the diesel other than fuel resupply is given in Table G.2. Note it is not actually the same diesel continuously at the site for the entire period because the Coast Guard removes one diesel and installs its rebuilt replacement during the same visit to the site for "diesel overhaul". The analysis period is equal to the entire useful life of one diesel even though any particular diesel may see service at several different sites during its lifetime.

The cost of each of these events will be described shortly, but first a discussion of when these same 61 events occur in the alternate energy/diesel hybrid energy system is in order. It is assumed that the alternate energy system supplies power to the LAMP modules part of the time and thus permits the diesel to be turned off for significant periods. Consequently event 11, the first major overhaul and all other cost events are deferred. The economic analysis period is still defined

TABLE G.2 TYPICAL DIESEL HISTORY

Event #	Hours of Operation*	Nature of Event
1	0	Purchase and install diesel generator set
2	2,190(3 months)	Field adjustments and service
3	4,380(6 months)	Field maintenance and service
4	6,570(9 months)	Repeat event 2
5	8,760(1 year)	Repeat event 3
6	10,950(1.25 yr)	Repeat event 2
7	13,140(1.5 yr)	Repeat event 3
8	15,330(1.75 yr)	Repeat event 2
9	17,520(2.00 yr)	Repeat event 3
10	19,710(2.25 yr)	Repeat event 2
11	21,900(2.5 yr)	Exchange diesels (first major overhaul)
12 thru 21	24,090 to 43,800	Repeat events 2 through 11 at same intervals to 2nd overhaul at year 5.0
22 thru 31	45,990 to 65,700	Repeat events 2 through 11 at same intervals to 3rd overhaul at year 7.5
32 thru 41	67,890 to 87,600	Repeat events 2 through 11 at same intervals to 4th overhaul at year 10
42 thru 51	89,790 to 109,500	Repeat events 2 through 11 at same intervals to 5th and last overhaul at year 12.5
52 thru 60	111,690 to 129,210	Repeat events 2 through 10 at same intervals
61	131,400	Discard diesel generator set at year 15.0

* Events do not occur with the precision stated above. Some are earlier and some are later. Precise values are used in the simulation model purely for convenience. All values used in this analysis are therefore approximations.

as the diesel lifetime. Consequently, the economic analysis period for the hybrid system is longer. The extended lifetime or deferral of expenses reduces the present value of these expenses even though all 61 events eventually occur and have the same unescalated cost in the approved economic models. However as noted earlier, systems with different lifetimes can not be compared solely on the basis of their present worth.

The simulation model keeps track of the number of hours each year that the diesel electric set is operated. After the first hour of operation in any given period of continuous diesel operation, each additional hour of operation "consumes" one hour of diesel life. During the first hour after diesel turn-on, however, more than one hour of wear can occur because the initial temperatures are not the equilibrium temperatures, starting motor wear, etc. The simulation model assumes that the initial hour after each turn-on of the diesel consumes two hours of diesel lifetime. This assumption has been checked with the diesel manufacturer and found to be reasonable provided low temperature starts and immediate load are avoided.⁸⁸ Thus we define an equivalent running time, ERT, that exceeds the actual running time, ART, each year by the number of diesel starts in that year. Fuel consumption is computed with ART and the load level each hour, but wear and the need for service are proportional to ERT. That is, when ERT = 2,190 hours the simulation model schedules service event 2 and its associated cost is incurred.

The value of ERT at the end of a calendar year, ERTCY, is less than the number of hours in the year (8760), as frequent stops and starts of the diesel are not allowed. (Typically the diesel will run at full load for several hours and then be off for several hours. It is never operated for less than one hour after being started.) Thus with this model, each of the 61 events will be delayed by the factor (8760/ERTCY). For example if ERTCY = 6,570 hours (total diesel wear equal to 3/4 of a year of continuous operation) then the diesel would be discarded, event 61, at the end of year twenty instead of year fifteen.

We assume that fuel is delivered to the site every 8760 hours of ERT. That is, for the standard diesel-only system, ERTCY = 8760 and fuel is delivered once a year. Thus during the life cycle of the diesel, fuel is delivered 15 times concurrently with service events 1, 5, 9, 13, 17, 21, 25, 29, 33, 37, 41, 45, 49, 53, and 57. Fuel is also delivered with event 61, but that fuel is for the next diesel life cycle and not a cost associated with economic analysis period under study. The timing in calendar years of each of these fuel delivery events is also (8760/ERTCY) times longer than the standard LAMP schedule.

The general method of calculating the present value and uniform cost payment rate developed and discussed in the prior subsection can accurately handle events occurring at fractional year intervals and

*Reference

88. Scribner, D. A., CG-DMT-3, summary of personal communication with Gene Kasel of Fairbanks Morse Diesel in an informal note dated 9/22/80.

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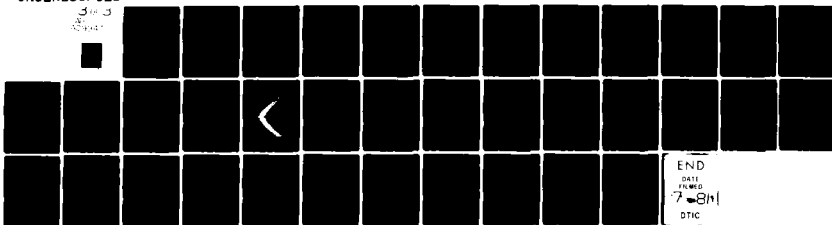
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ALTERNATE HYBRID POWER SOURCES FOR REMOTE SITE APPLICATIONS.(U)
FEB 81 W R POWELL, R J TAYLOR, J L BARON N00024-78-C-5384

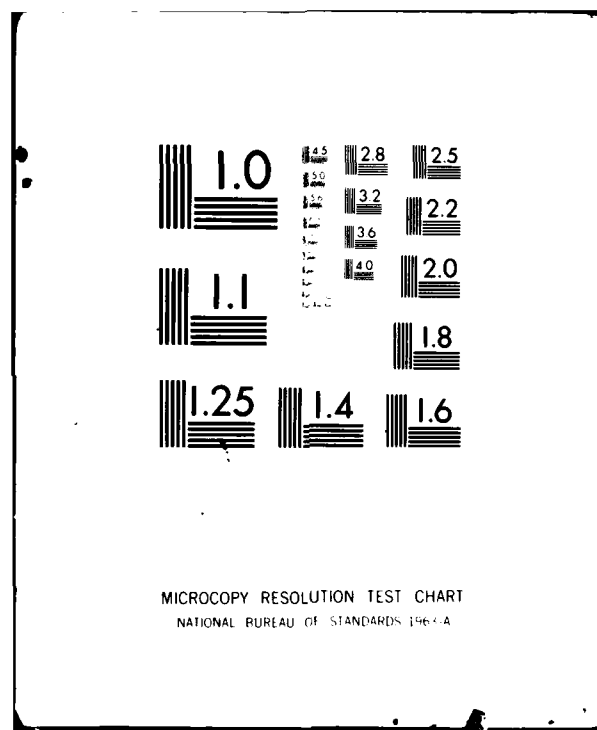
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noninteger year lifetimes. We have now specified precisely (See Table G.2) when each event occurs. Now the analysis is complete except for the current cost of each event.

G.5 DIESEL-ELECTRIC GENERATOR COSTS

The cost of each of the unique events related to the diesel-electric generators, other than the fuel delivery cost events already described, is estimated as follows:

Event 1. Diesel-electric generator sets SR2 and SR3 cost the Coast Guard \$6500 and \$7600 respectively in 1980. They are delivered to the site with the first fuel delivery shipment. Assuming an Aids-to-Navigation Boat is used for eight hours, that the ANB resource cost is \$48/hour, and that two men are used at \$35/hr for each including overhead and all associated expenses, \$944 is the cost of delivery and initial installation. Miscellaneous costs (broken tools and materials consumed at site) result in a total cost of service event 1 of approximately \$7500 for the SR2 generator set and \$8600 for the SR3 diesel generator set. The present value of fuel delivered to the site will be considered separately later.

Event 2. We assume that one man is dropped off at the site and half of an eight-hour ANB resource day is charged to some other mission. Thus the total labor and boat cost for event 2 is half that of event 1. Event 2 also consumes minor cost items, including oil and air filters, etc. Total cost of event 2 is estimated to be \$500.

Event 3. We assume eight ANB resource hours with crew-man and service person (\$944 as in event 1). The "field maintenance parts kit" required for event 2 costs the Coast Guard \$1314 in 1980. Parts in it are used to replace fuel injectors every six months of diesel operation. Other field service is performed with some additional consumables expended. Total cost of event 3 is estimated to be \$2,300.

Event 11. Major overhaul is similar to event 1 in labor and boat costs at the site. In 1980 the overhaul kit for the SR2 costs \$2,630 and that for the SR3 costs \$3,256 (the SR3 kit includes 3 new pistons instead of two, etc.). Labor and machinery operations at the overhaul base are assumed to cost \$970 for the SR2 and \$1144 for the SR3. Thus the total cost of event 11 is \$4600 for SR2 overhaul and replacement and \$5400 for the SR3.

Event 61. The end of the diesel life analysis period coincides with event 1 of the next diesel life time period. No charge is made in the analysis to discard the fully utilized diesel generator set concurrently with the installation of its replacement. That is, all the cost of event 61 is charged to the next life cycle. The old diesel-generator set would have

some salvage value, if only for the copper in the generator and its weight as scrap iron, but the Coast Guard does not consider this small sum available at least 15 years into the future to be significant.

Note that the cost of these events will vary for each site. Different resupply boats are used and the distance from the site to supply and/or maintenance depots is not the same for all LAMP sites. Thus the event cost data are not exact and could not be unless each site were considered separately. These cost values are plausible for a typical site and have been reviewed by Coast Guard personnel.⁸⁹ The same set of values is assumed for diesels in both the alternate energy/ diesel hybrid and the diesel-only power system used as a comparison reference. (It might be possible to utilize a smaller new diesel in a continuously loaded mode with the energy storage system either being charged or assisting the diesel at times of peak power demand. This load leveling option was only briefly considered in Appendix H as it involves an entirely new diesel, has no back-up mode of operation and was outside the original scope of this study.) Minor inaccuracies in the diesel cost data should not have a strong influence on the choice between the standard, diesel only, LAMP power system and a hybrid system using alternate energy sources and/or energy storage.

Each of the delayed cost events after the initial cost could be separately analyzed using the generalized fractional year methods developed and described earlier to compute the present value and corresponding uniform payment rates required. However, it is more convenient to recognize that at least \$500 of expense occurs at regular intervals (every 3 months for the diesel-only case and every 3 x (8760/ERTCY) months for the alternate energy hybrid). This uniformly spaced series of \$500 expenses occurs a total of 59 times. This stream of future costs has a present value (cost) of

$$\$500 \times \sum_{j=1}^{j=59} (1.1)^{-(8760/ERTCY)j/4} \quad (G.7)$$

This is 500 times a geometric series of the form

$$\sum_{j=1}^{j=K} (1.1)^{aj} = \frac{1-1.1^{aK}}{1.1^a-1} \quad (G.8)$$

where K = 59 and a = -(2190/ERTCY).

Thus in the base case or diesel-only system, ERTCY = 8760 and a = -1/4. For this base case a stream of 59 \$500 expenses at three month intervals has a total equivalent present cost of

*Reference

89. Marcoline, R. A., G-EOE-3B/61 personal communication via informal note dated 9-8-80.

$$\$500 \times \left[\frac{1 - 1.1^{-59/4}}{1.1^{1/4} - 1} \right] \quad (G.9)$$

or \$15,651.59

If the alternate energy system is able to provide power for one fourth of the time, i.e., if ERTCY = 6,570 so that these 59 \$500 cost events are spread over 20 years at four month intervals, $a = -1/3$ and K is still 59. Then the total equivalent present cost is

$$\$500 \times \left[\frac{1 - 1.1^{-59/3}}{1.1^{1/3} - 1} \right] \quad (G.10)$$

or \$13,112.69. Thus the present worth of deferring 59 \$500 payments from three month to four month intervals is \$2,538.90. This is only part of the savings associated with less frequent service of the diesel.

Service trips similar to service event 3 occur at $6(8760/ERTCY)$ month intervals. Five hundred dollars of this \$2300 cost has already been included in the 59 \$500 cost events considered above. Also there is no event 3 cost at intervals of $30(8760/ERTCY)$ months when major overhauls occur. However, we can include \$1,800 of the cost of major overhauls along with the remaining \$1,800 expense associated with each service event of type 3 so that 29 \$1,800 expense events occur once every $6(8760/ERTCY)$ months. The present cost equivalent of these 29 \$1,800 events at $6(8760/ERTCY)$ intervals is

$$\$1800 \times \sum_{j=1}^{j=29} (1.1)^{-(8760/ERTCY)/2} \quad (G.11)$$

or with $K = 29$ and $a = -(4380/ERTCY)$ in the general cumulative sum expression given in Equation (3.8), the present equivalent expense is

$$\$1800 \times \left[\frac{1 - 1.1^{-29(4380/ERTCY)}}{1.1^{(4380/ERTCY)} - 1} \right] \quad (G.12)$$

To continue the two numerical examples, i.e., the diesel only case and the hybrid case with ERTCY = 6,570, we find the present cost of these 29 \$1800 expenses is \$27,619.22 for the diesel only case and \$23,092.04 for the hybrid power system that extends the diesel life to twenty years.

Still unaccounted for is most of the expense associated with major overhauls. Five hundred dollars of each overhaul was included with minor tune ups in the field to make an unbroken stream of 59 \$500

expense and \$1800 was included with the 29 events costing \$1800 each just discussed. Thus the cost of each of the five major overhauls not yet accounted for is \$2300 for the SR2 and \$3100 for the SR3 diesel generator set. These five events occur at $2.5(8760/ERTCY)$ year intervals and correspond to a present cost of

$$(\$2300 \text{ or } \$3100) \times \sum_{j=1}^{j=5} (1.1)^{-2.5(8760/ERTCY)j} \quad (G.13)$$

or with $K = 5$ and $a = -21900/ERTCY$ in the general geometric sum form, the present cost in the base case example (diesel only & $ERTCY = 8760$) is \$5,951.32 for the SR2 and \$8,021.34 for the SR3. In the hybrid system numerical example previously considered with 20 year diesel life, the present costs of the 5 \$2300 and \$3100 expenses for the SR2 and SR3 respectively are \$4,894.23 and \$6,596.56.

Summary for Diesel Generator. Thus the present cost of the diesel is:

$$\begin{aligned} PC_d = & (\$7500 \text{ or } \$8600) + \\ & (\$500) \times \left[\frac{1 - 1.1^{-59(2190/ERTCY)}}{1.1^{(2190/ERTCY)} - 1} \right] + \\ & \$1800 \times \left[\frac{1 - 1.1^{-29(4380/ERTCY)}}{1.1^{(4380/ERTCY)} - 1} \right] + \\ & (\$2300 \text{ or } \$3100) \times \left[\frac{1 - 1.1^{-5(21900/ERTCY)}}{1.1^{(21900/ERTCY)} - 1} \right] \quad (G.14) \end{aligned}$$

where $ERTCY$ is the number of wear equivalent running hours in a calendar year and the lower coefficient in the first and last terms is for model SR2 and the higher is for model SR3. The final results for the total present cost of the diesel generators, excluding fuel expenses, for the two previously considered numerical examples (base case with 15 year life and hybrid with 20 year life) is presented in Table G.3.

Table G.3 PRESENT COST OF DIESEL-GENERATORS

Model	Base Case (15yr)	Hybrid (20yr)	Net Savings
SR2	\$56,722	\$48,599	\$8,123
SR3	\$59,892	\$51,401	\$8,491

Thus the saving in reduced use of the diesels provides approximately \$8K of net present worth which can be used to finance the extra cost of the hybrid energy system. Other savings will result when fuel usage and delayed rate of fuel delivery are considered. The hybrid system may be more economical even if the net savings in present value is negative when the present value of all savings and extra costs for the hybrid is computed as the hybrid lasts five years longer. The proper comparison of these two systems with unequal lifetimes can be made only by converting the total present worth of both systems into equivalent uniform payment rate.

G.6 DIESEL FUEL CONSUMPTION

The net power available, NP, in kilowatts from the two standard LAMP diesel-electric generators (models SR2 and SR3) after subtracting the power required for the fan motor in the environmental control unit is

$$NP_{SR2} = 6.5x - 1.2 \quad \text{or} \quad NP_{SR3} = 10x - 1.2 \quad (G.15)$$

where x is the fraction of full load placed on the diesel. The fuel consumption rate, FCR, for these power plants in gallons/hour is

$$FCR_{SR2} = 0.077 + 0.643x \quad \text{or} \quad FCR_{SR3} = 0.115 + 0.865x \quad (G.16)$$

for $x \geq 0.5$. This approximation is based on Equation (2.2) and full load fuel consumption rates of 0.72 and 1.08 gallon/hour for the SR2 and SR3 respectively. This is equivalent to 0.44 lbs/hp hour with a fuel density of 7.3 lbs/gallon. The Coast Guard recommends that $x \geq 0.75$ be maintained at LAMP stations to avoid excessive overhaul expense due primarily to carbon build-up problems when the diesel is lightly loaded.² Currently diesel powered LAMP stations operate the main light during the day and/or run exterior lights and other non-essential loads to maintain load on the diesel. This obviously wastes power. The simulation model assumes only essential loads are powered at both the hybrid power station and the conventional power (diesel only) station used as a base case reference except when nonessential loads are required to load the diesel to the recommended load level.

In reality, some conventional power LAMP stations may not maintain the recommended minimum load on the diesel and others may not be able to shed non-essential loads at times when the diesel is loaded.

In the first case, the actual fuel consumption would be less than that predicted by the simulation model, but overhauls would be required more frequently. In the second case, the simulation model predicts less fuel consumption than would occur in practice because the simulation model assumes that non-essential loads are automatically removed if essential loads maintain the recommended load on the diesel. Typically the simulation model requires that at least 65% of full load be required of the diesel whenever it is running. See Figure 1.0.

Thus for each time step, the simulation model first computes the fractional load, x , imposed on the diesel by the net electrical power demand, NP , assuming no non-essential electrical loads from

$$x_{SR2} = (NP + 1.2)/6.5 \quad \text{or} \quad x_{SR3} = (NP + 1.2)/10 \quad (G.17)$$

and then if $x < .65$, non-essential loads are connected to dissipate power until $x = .65$. That is, x is set equal to .65 unless the essential loads require a greater value. Once the value of x is set, the fuel consumption rate for that time step is computed with Equation (G.16). Then the annual fuel consumption, AFC , in gallons is computed by accumulating the gallons of hourly fuel used for 8760 consecutive hours. However, the fuel resupply ship comes to the site only every (8760/ERTCY) years as fuel resupply is combined with some of the diesel service visits as described earlier. Thus the quantity of fuel supplied with each visit must average $AFC(8760/ERTCY)$. During the life of the diesel, $15(8760/ERTCY)$ years, there will be 15 fuel resupply visits but the last is for use during the next diesel life cycle or accounting period. The initial supply of fuel delivered to the site must be larger than $AFC(8760/ERTCY)$ to be sure that an ample fuel reserve is available immediately prior to each resupply. We will assume that the initial ration of fuel is 50% larger than supplied at regular intervals subsequently.

The present cost of fuel delivered to the site with a current cost of \$1.30/gallon, 8% real fuel price inflation, and a 10% discount rate is

$$PC_f = \$1.5 \times 1.30 \text{ AFC}(8760/ERTCY) + 1.30 \text{ AFC}(8760/ERTCY) \sum_{j=1}^{j=14} \left(\frac{1.08}{1.1} \right)^{(8760/ERTCY)j} \quad (G.18)$$

or

$$PC_f = 1.30 \text{ AFC}(8760/ERTCY) \left[1.5 + \frac{1 - \left(\frac{1.08}{1.1} \right)^{(8760/ERTCY)14}}{\left(\frac{1.08}{1.1} \right) - 1} \right] \quad (G.19)$$

However, the alternate energy diesel power hybrid is not being installed this year. Then it is installed, the cost of fuel during the first year will be $\$1.30(1.08)^t$ per gallon where t is the time in years from the present to the installation date. For example, if installed in 1985, $t=5$, and 1985 fuel cost is projected to be \$1.91 per gallon with an 8% annual inflation of fuel costs. This is equivalent to replacing the 1.30 factor in Equations (G.18) and (G.19) with 1.91. The installation year is important for some other factors, because the capital required for various components of the alternate energy system is a function of purchase year. Other items may cost more or less in constant value dollars in 1985 if inflation continues. We usually assume a 1985 installation date and compute fuel costs in constant value dollars using 1.91 as the coefficient in Equation (G.19). In general, the 1.30 factor in Equations (G.18) and (G.19) must be replaced by $1.30(1.08)^t$ to compute the present cost in an installation year t after year 1980. The effect of installation year upon the levelized costs of the diesel and its fuel was illustrated in Figure 1.1. In order to continue the numerical example we must also assume values for AFC.

The base case (diesel only) would have AFC equal to 5180 gallons if an SR2 is run at 80% load continuously all year and under similar load the SR3 would require 7069 gallons annually according to Equation (G.16). With these values, and a 1985 date for first fuel delivery, the SR2 fuel for 15 years has a present value in constant value dollars of 135,875.87 and the SR3 fuel is presently worth \$185,425.97.* If the hybrid with 20 year diesel life (ERTCY = 6570) runs twice per day for eight hours each time, then the actual running time during a calendar year, ARTCY, equals $16 \times 365 = 5840$. Because each initial hour after starting is counted as equivalent to two hours of wear, $ERTCY = 18 \times 365 = 6570$ as previously assumed for illustration of a hybrid system with 20 year diesel life. If in the hybrid system the diesel is fully loaded when it is on (it is most efficient at full load) then the annual fuel consumption $AFC = 0.72 \text{ gal/hour} \times 5840 \text{ hours} = 4204.8$ gallons for the SR2 and $AFC = 1.08 \times 5840 = 6307.2$ gallons for the SR3. With these assumptions for AFC, and ERTCY = 6570, the present cost of fuel for the 20 year life of the hybrid system used for this illustration is \$141,453.29, for the SR2 and \$212,179.94 for the SR3. The fuel cost over the life of the system for this example is summarized in Table G.4.

TABLE G.4 PRESENT COSTS OF ALL FUEL USED

Model	Base Case(15 yr)	Hybrid(20 yr)
SR2	\$135,876	\$141,453
SR3	\$185,426	\$212,180

* While these numbers appear precise, they obviously are not significant to eight significant figures. In fact, if recent history of oil prices is any guide to the future, even the first digit may be suspect. This relatively meaningless precision is provided only so that the reader can assure himself that he is correctly applying the methodology developed by reproducing the same numbers.

However, the alternate energy diesel power hybrid is not being installed this year. Then it is installed, the cost of fuel during the first year will be $\$1.30(1.08)^t$ per gallon where t is the time in years from the present to the installation date. For example, if installed in 1985, $t=5$, and 1985 fuel cost is projected to be \$1.91 per gallon with an 8% annual inflation of fuel costs. This is equivalent to replacing the 1.30 factor in Equations (G.18) and (G.19) with 1.91. The installation year is important for some other factors, because the capital required for various components of the alternate energy system is a function of purchase year. Other items may cost more or less in constant value dollars in 1985 if inflation continues. We usually assume a 1985 installation date and compute fuel costs in constant value dollars using 1.91 as the coefficient in Equation (G.19). In general, the 1.30 factor in Equations (G.18) and (G.19) must be replaced by $1.30(1.08)^t$ to compute the present cost in an installation year t after year 1980. The effect of installation year upon the levelized costs of the diesel and its fuel was illustrated in Figure 1.1. In order to continue the numerical example we must also assume values for AFC.

The base case (diesel only) would have AFC equal to 5180 gallons if an SR2 is run at 80% load continuously all year and under similar load the SR3 would require 7069 gallons annually according to Equation (G.16). With these values, and a 1985 date for first fuel delivery, the SR2 fuel for 15 years has a present value in constant value dollars of 135,875.87 and the SR3 fuel is presently worth \$185,425.97.* If the hybrid with 20 year diesel life (ERTCY = 6570) runs twice per day for eight hours each time, then the actual running time during a calendar year, ARTCY, equals $16 \times 365 = 5840$. Because each initial hour after starting is counted as equivalent to two hours of wear, $ERTCY = 18 \times 365 = 6570$ as previously assumed for illustration of a hybrid system with 20 year diesel life. If in the hybrid system the diesel is fully loaded when it is on (it is most efficient at full load) then the annual fuel consumption $AFC = 0.72 \text{ gal/hour} \times 5840 \text{ hours} = 4204.8$ gallons for the SR2 and $AFC = 1.08 \times 5840 = 6307.2$ gallons for the SR3. With these assumptions for AFC, and ERTCY = 6570, the present cost of fuel for the 20 year life of the hybrid system used for this illustration is \$141,453.29, for the SR2 and \$212,179.94 for the SR3. The fuel cost over the life of the system for this example is summarized in Table G.4.

TABLE G.4 PRESENT COSTS OF ALL FUEL USED

Model	Base Case(15 yr)	Hybrid(20 yr)
SR2	\$135,876	\$141,453
SR3	\$185,426	\$212,180

* While these numbers appear precise, they obviously are not significant to eight significant figures. In fact, if recent history of oil prices is any guide to the future, even the first digit may be suspect. This relatively meaningless precision is provided only so that the reader can assure himself that he is correctly applying the methodology developed by reproducing the same numbers.

With the larger SR3 diesel, the advantage of turning off the fixed 1.2 kW load of the fan in the environmental control unit for eight hours each day is relatively less important, but for the smaller SR2 diesel this savings and the superior efficiencies at full load makes the 20 year fuel cost only four percent greater than the present cost of 15 years of fuel for the base case.

The present cost of a diesel generator set including maintenance, PC_d , and the present cost of all the fuel it uses during the analysis period or holds as an unused safety reserve, PC_f , can be combined since both cover the same period. That is:

$$PC_{df} = PC_d + PC_f. \quad (G.20)$$

Thus, the results of Tables G.3 and G.4 can be combined to give:

TABLE G. 5 PRESENT SYSTEM COSTS AND SAVINGS

Model	Base Case(15 yr)	Hybrid(20 yr)	Savings
SR2	\$192,598	\$190,052	\$ 2,546
SR3	\$245,318	\$263,581	-\$18,263

The negative "savings" for the larger SR3 generator does not imply that the hybrid is the less attractive alternative in this case, only that the 20 year system will cost more than the 15 year system. The present diesel and fuel cost (PC_{df}) must be converted into an equivalent uniform cost rate, UCR_{df} , (\$/year) extending over the life of the system, $15(8760/ERTCY)$ years, as follows:

$$UCR_{df} = PC_{df} \div 10 [1 - (1.1)^{-15(8760/ERTCY)}] \quad (G.21)$$

The uniform annual cost rates computed with Equation (G.21) for this numerical illustration are given in Table G.6.

TABLE G. 6 ANNUAL COST RATES

Model	Base Case(15 yr)	Hybrid(20 yr)	Saving Rate
SR2	\$25,322/yr	\$22,323/yr	\$2,999/yr
SR3	\$32,253/yr	\$30,960/yr	\$1,293/yr

Thus the hybrid is the preferred alternative for both the SR3 and smaller SR2 diesel systems. Of the two, the smaller is a more attractive investment because not only does it produce a higher yearly savings rate, but according to Table G.5 results, it has less present cost in spite of its longer useful life. However, the cost of the energy storage system and other parts of the alternate energy hybrid system are not included in

Table G.6. Thus, it is premature to conclude that either system is more economical than the diesel only base case. At this point in the illustration all one can conclude is that the uniform annual cost rate corresponding to the cost of the system components needed only in the hybrid system must be less than \$2,999/yr for the SR2 hybrid and less than \$1,293/yr for the SR3 hybrid. Since the energy storage system required for the SR2 hybrid would be smaller and less costly than for the SR3 hybrid and yet greater savings is available to pay for it, one can conclude that the smaller system is more likely to be economically attractive than the SR3 hybrid.

Uniform cost rates can be compared for systems with different lifetimes and the uniform cost rates of various system components can be combined for an integrated or inclusive total system uniform cost rate, even though the various systems components have different lifetimes provided we ignore any salvage value at the end of the overall system life. This point will be illustrated and discussed in the second part of the next section (battery costs).

G.7 BATTERY LIFE

The basic data available for battery life calculations are usually presented as a curve of number of repetitive charge-discharge cycles achievable vs depth of discharge of each cycle such as illustrated in Figure G. The end of the battery's useful life is usually defined as that point in time when it will no longer retain 80% of its nominal capacity (ampere hours). Obviously each battery is different and other things are involved (temperature, rate of charge and discharge, etc.) but it is assumed the simple model given by Figure G is adequate. The curves presented in Figure G are for concept illustration only. The curves used in the simulation model are functionally represented by Equation (G.22a),

$$f(x) = a + bx + cx^2 + dx^3 \quad (G.22a)$$

where $f(x)$ is the number of cycles, x is the fractional state of charge.

For typical lead-acid cells:

$$\begin{aligned} a &= 119 \\ b &= 1722 \\ c &= -4614 \\ d &= 6867 \end{aligned}$$

but the precision given for these constants does not imply that $f(x)$ is equally well known. For Ni-Cd batteries, $f(x)$ is assumed to be the solid line in Figure 3.15. Thus for Ni-Cd batteries,

$$f(x) = 37300 \left[10^{(-x/0.35)} \right] \quad (G.22b)$$

in the simulation model.

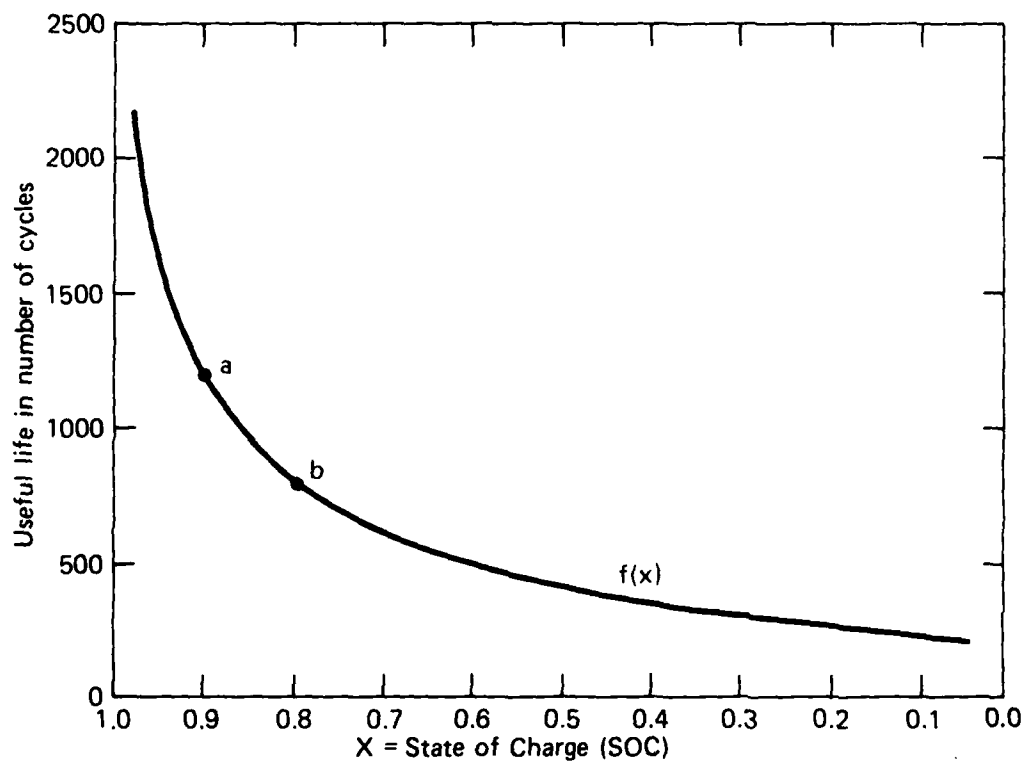


FIGURE G BATTERY LIFE IN NUMBER OF CYCLES VERSUS DEPTH OF DISCHARGE OF EACH CYCLE.

Using Figure G data to illustrate the concept, about 1200 cycles to a state of charge (SOC) = .9 and back to SOC = 1 can be expected (point "a") and only about 750 cycles are expected if the discharge goes from fully charged (nominal) to SOC = .8 and back to SOC = 1. As far as the economics is concerned, neglecting discount with time effects, a discharge from fully charged to point "a" and back (SOC=1→.9→1) uses up $(1/1200)^{th}$ of the value of the battery and a (SOC 1 → 0.8 → 1) discharge cycle uses up $(1/750)$ of the value of the battery. Thus the method of calculating the cost of any cycle which starts and ends at SOC =1 is clear, but what cost is associated with a cycle which starts at SOC = .9 and discharges to SOC =.8 and then recharges to SOC = .9? The answer is found by noting that the (SOC = 1 → .8 → 1) cycle is really the following four step sequence:

Step 1	SOC = 1 → SOC = .9 discharging
Step 2	SOC = .9 → SOC = .8 discharging
Step 3	SOC = .8 → SOC = .9 charging
Step 4	SOC = .9 → SOC = .1 charging

The cost of this four step process is $(1/750)^{th}$ of battery and the cost of step 1 and step 4 is $(1/1200)^{th}$ of battery. Thus the cost of step 2 and step 3 is $(\frac{1}{750} - \frac{1}{1200})^{th}$ of battery.

Now that the method for computing the cost of a closed cycle (SOC=a→b→a) is clear, even though a ≠ 1, we can assume that half of the full cycle cost is due to a→b and half is due to b→a. The 50-50 division of cost is a matter of convenience. It could be 80-20 or anything else as for every (a→b) there is a (b→a) in the long run. Thus the fraction of battery life used by an (a→b) discharge or a (b→a) charge is as follows:

$$\left| \frac{1}{2f(SOC_b)} - \frac{1}{2f(SOC_a)} \right| \text{ or } 1/2 \left| \frac{f(a) - f(b)}{f(a)f(b)} \right| \quad (G.23)$$

Where $f(x)$ is the function represented by the curve in Figure G, and a and b are the two states of charge. It does not matter in this model which is the initial and which is the final state of charge.

Thus at the start of each time step of the simulation we compute and record $f(SOC)$ and then after a new SOC has been computed we compute $f(SOC)$ again. The amount of battery life used by that time step is half the absolute value of the difference between $f(SOC)$ at the beginning and end of the time step divided by the product of $f(SOC)$ at the start and finish. The fraction of the battery life used during 8760 continuous hours of station simulation is inverted to predict how many years, BL, the battery will last.

G.8 BATTERY COST ANALYSIS

The initial cost of the battery and its installation at the site, BC, is equal to the present value of the first battery set because

it is assumed that any service required can be accomplished during regular visits required to service the diesel. Some battery types might require water and all will require some inspection during their normal life, but these activities can take place during regular diesel service visits. The uniform cost rate for batteries, UCR_b , (\$/year) is equivalent to the present cost of the first battery set, BC , divided by the cumulative sum factor.

$$UCR_b = BC/10[1 - (1.1)^{-BL}] \quad (G.24) \text{ In}$$

In Equation (G.24) BL is the battery life.

The second battery set will be required to cover the period between BL and $2BL$. This second battery set represents a cost of BC at BL but the present cost of it is only

$$PC_{b2} = BC (1.1)^{-BL} \quad (G.25)$$

This present cost, PC_{b2} , is exactly equivalent to the present cost of a uniform payment at the rate UCR_b during the period between BL and $2BL$. That is as each new battery set is acquired UCR_b is extended another increment of time of duration BL into the future. Thus all of the battery sets required during the life of the first diesel corresponds to UCR_b , extending over the entire diesel lifetime period $15(8760/ERTCY)$ years. At the end of $15(8760/ERTCY)$ years, it is likely that some physical life and value will remain in the last battery set acquired. The useful life remaining in the last set of batteries would reduce the UCR_b during the next diesel life cycle or if station is closed, would have some salvage value at other sites. It is possible to postulate a model for what fraction of the battery value remains at any point during its life, calculate the salvage value due to the fact that $15(8760/ERTCY)$ is not an exact multiple of BL , and discount this salvage value back to the start of the analysis period. It is then possible to project this present value of the salvage forward as a uniform credit rate over the $15(8760/ERTCY)$ years and then reduce UCR_b by this uniform credit rate. While this is correct in principal the resulting change in UCR_b is sufficiently small that salvage of unused battery life at the end of $15(8760/ERTCY)$ years will be ignored. This omission is conservative in that the hybrid power system would be slightly more attractive if salvage of unused battery life at the end of the diesel life period were considered.

The cost of delivering the batteries to the site has not been specifically included. That cost is added to the purchase price to produce the "initial cost" BL . Delivery of replacement batteries to the site at precisely the battery replacement intervals, would require extra visits to the site in addition to the 59 visits scheduled for diesel maintenance. Extra visits to the site would not appear to be economical. The battery life is not a precise time. Data obtained from the station during its operation would allow one to monitor the capacity of the battery bank. Near the end of the battery life the capacity decreases. End of life is arbitrarily defined, usually as that point in time when the battery capacity is only 80% of its initial nominal value. The batteries can still be used after the "end of life" - they simply can not carry

the station load as long and the diesel would run more frequently than if the system had fresh batteries. Thus we assume that batteries, like fuel, are delivered with a regularly scheduled maintenance boat and no extra trips are required. If the battery capacity does not degrade smoothly, that is if there is an abrupt loss of battery capacity due to a short or cable failure, etc., that can not be automatically bypassed by the system controller, then the system operates as a diesel-only LAMP station until the next "regular" diesel service visit is scheduled. Although the economic model assumes that service visits are at precisely regular intervals, they would in fact be at varying intervals as the dispatcher attempts to service all sites most economically by combining various requirements at different neighboring sites into more economic multipurpose trips. It really makes little difference if the 42nd of 59 regular maintenance visits is a few weeks early or late. In the case of an abrupt loss of battery capacity or a rapid, but smooth decline in battery capacity, one would hope that the next service visit was moved forward to minimize the time that a hybrid station must operate in the diesel-only mode. We assume that a hybrid system would be selected only if it is sufficiently more economical than a diesel-only system to tolerate a few months of operation during its life as a diesel-only station without losing its economic advantage. Thus we do not envision any extra trips to the site solely to service batteries, but presume that the same 59 service trips during the total life span of the diesel are used for all maintenance and resupply. We further presume that the cost of battery maintenance done between battery changes during a diesel service visit is small compared to the cost of battery replacement. That is, the error in battery replacement cost estimates is likely to be larger than battery service costs between replacement intervals provided no special visits to the site to service batteries are allowed. Thus we ignore battery service costs accomplished during a regularly scheduled diesel maintenance visit.

G.9 UNIFORM COST RATES FOR A SYSTEM

The uniform costs rate for a system consisting only of a diesel generator, its fuel supply and storage batteries, UCR_{dfb} , is

$$UCR_{dfb} = UCR_{df} + UCR_b \quad (G.26)$$

even though the diesel generator and batteries have different lifetimes.

There are of course other costs in the battery hybrid system for controls, power conditioning, etc. The initial cost of all these additional components including installation costs must be combined with the initial cost of the battery for a total initial costs of extra components required by the battery hybrid system. There also may be replacement costs and maintenance costs for some of the other components, but the replacement costs of batteries dominate and have been used in this illustration of economic analysis methods. If UCR_{dfb} for a diesel-battery hybrid energy storage system is less than UCR_{df} , the uniform cost rate of the diesel only base case, then the battery hybrid system is more economical.

Other alternate energy hybrid systems might contain energy storage systems other than batteries and/or additional energy sources (photovoltaic cells, wind power, wave power, etc.) The economic analysis methods for them would be similar to those discussed above for the simplest hybrid although it may not be appropriate to ignore salvage values when significant useful life remains at the end of the diesel period 15(8760/ERTCY) years.

G.10 SUMMARY OF ECONOMIC ANALYSIS METHOD

1. Each significant component of the system is modeled to determine its useful life.

2. The initial cost of each component including installation at the site, and any significant maintenance costs are converted to a present value cost.

3. The present cost of each component is converted to uniform cost rate, UCR (\$/year), and extended by component replacement to the life of the diesel, 15(8760/ERTCY) years, at the same UCR.

4. Any salvage value remaining for the last replacement in a series due to the fact that 15(8760/ERTCY) years is not an exact multiple of the component life found in step 1 is ignored if the present value of the salvage value is small compared to the present cost of the initial component and all its subsequent replacements. If salvage values are not small by this standard, the uniform cost rate for that component (see step 3) is reduced by the uniform credit rate obtained by projecting the present value of the salvage value ahead as a uniform credit rate for the 15(8760/ERTCY) year diesel life. (See earlier discussion of this point for batteries.)

5. The uniform cost rates for all system components, including any uniform credits due non-ignorable salvage values, (see step 4) are summed to form the uniform cost rate for the entire system.

6. The system with the smallest uniform cost rate (\$/year) for the entire system is preferred. Note that any system components common to both systems with identical service and maintenance costs and schedules need not be included if the purpose of the analysis is to identify the more economical system.

APPENDIX H SMALL DIESEL SYSTEMS

Although this program may ultimately eliminate diesel power plants at LAMP lighthouses and other remote Coast Guard sites, there is no possibility that existing diesels can be eliminated in Phase II. However, it is not desirable to be forever bound to the existing diesel power system. Consequently, a brief preliminary investigation of the small continuously running diesel concept discussed in subsection 1.4.1 was initiated at the end of Phase I.

The simulation model was modified so that 91 days at four day intervals (one year spanned) were sampled, but unlike previous simulations each new sample day began with the battery in the same condition as at the end of the last hour of the previously computed day. The diesel control law was also changed so that the diesel did not run at 100% of rated capacity until the normalized state-of-charge of the battery dropped below 0.4 instead of 0.8 as illustrated in Figure 1.0. The diesel ran at 65% of rated capacity when the relative state-of-charge was 0.9 or greater. Thus the linear range of diesel output extended between 0.4 and 0.9.

Some preliminary simulations for December 21 were used to select a battery and diesel size. It was assumed that the system should get through the 24 hours of the day with longest night without any net decrease in the state-of-charge provided that SOC was relatively low (0.2 to 0.3 range) initially. A 3000 ampere-hour 12 volt battery and a diesel generator rated for 1.75 kW at full load were selected, but other combinations are likely to be superior as no optimization was attempted. The Northern medium power station (2000 W at night, 500 W during the day) was used as a test application. Ten percent of the diesels output at full load (0.175 W) was assumed to be required continuously for a new air filter blower.

The daily range of the state-of-charge and its seasonal variation are shown in Figure H. The simulation was started on June 21 with a relative state-of-charge of 0.9, but this proved to be too high. The points for June 21, located at the top center of Figure H, are not connected together with the others. The next computed day (June 25) is also too high, but after approximately four computed days, the results settled into the seasonal pattern. During the summer when the nights are short and the average power required each day is correspondingly reduced, the battery tends to become more fully charged and the diesel power control law operates in the linear range between 100% and 65% of rating. During the winter (right and left margins of the curve in Figure H), the diesel must operate most of the day at 100% of its rated value to supply the energy required. The battery is continually in a low state-of-charge during the winter. In actual practice, it would be necessary to occasionally run the diesel continuously at 100% for a few days to equalize the charge in all cells of the battery. This and some other practical considerations were neglected so that an estimate

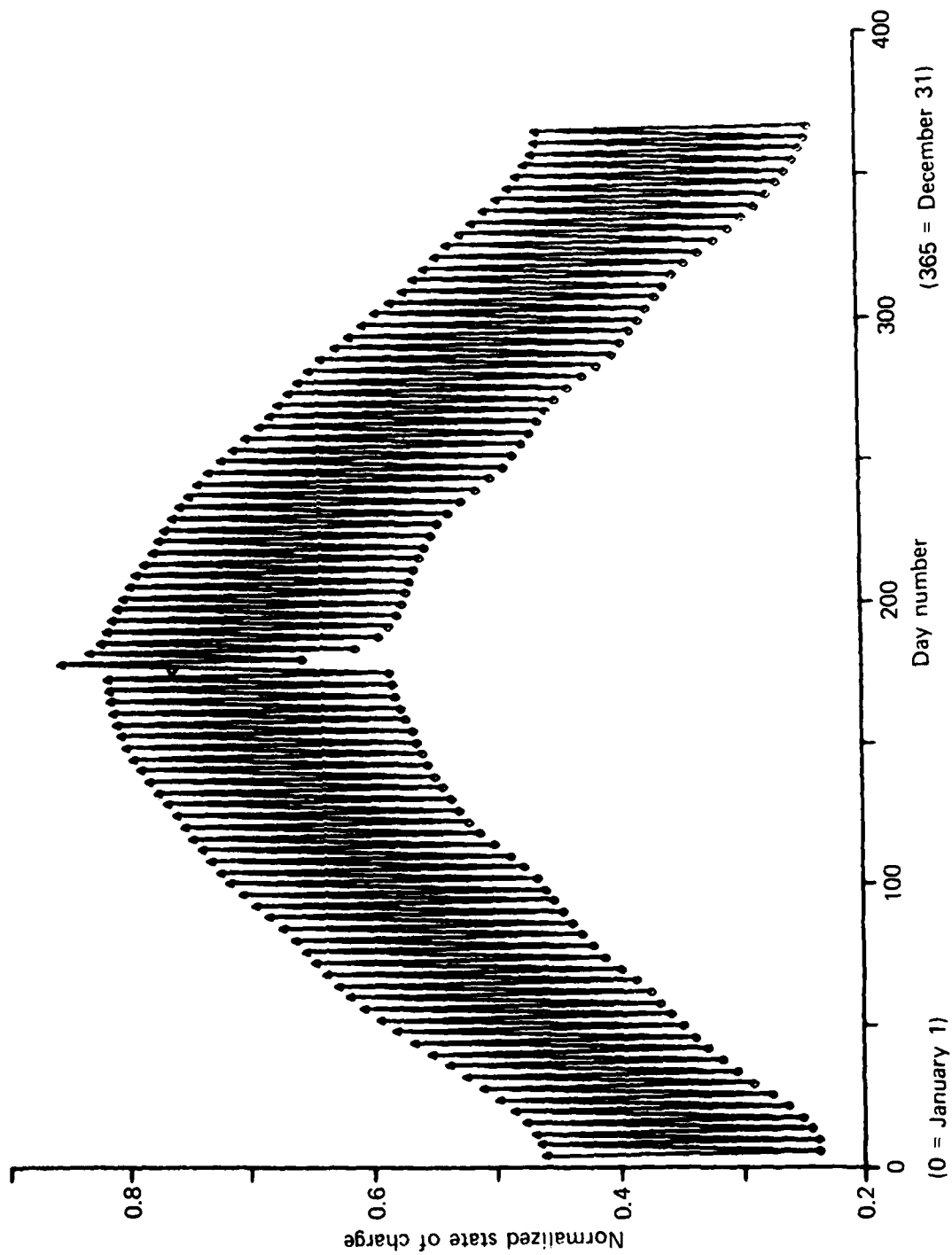


FIGURE H EXTREMES OF DAILY STATE OF CHARGE.

of diesel fuel use could be obtained. The diesel is assumed to have the same fuel use vs load characteristics as previously assumed (Equation 2.2) and be equally efficient at full load. The small diesel as simulated for Figure H-1 required only 1531 gallons of fuel annually instead of the 4345 gallons required by the standard SR-2 LAMP diesel.

The first and last terms of Equation (G.14) were modified to estimate the cost of a 1.75 kW diesel electric generator. These two terms already contain a choice of numerical values for the SR2 and SR3 LAMP diesel generator sets. The higher value corresponds to 10 kW from an SR3 and the smaller value corresponds to 6.5 kW from an SR2. A value for 1.75 kW was created by assuming that the first and last terms in Equation (G.14) depend linearly upon rated power and include the previously assumed values for the SR2 and SR3 units. That is for a 1.75 kW set, the first term is \$6007 and the coefficient in the last term is \$1214. Cost terms associated with manpower and boats required for the service visits were not changed.

With this model for diesel cost and the prediction of 1531 gallons of fuel use, the annualized cost of the small diesel power plant was only 15 thousand dollars for a 15 year system installed in 1985. This compares very favorably with the 26 thousand dollars required currently for the diesel only system and is also less than most alternate energy hybrids constrained to use an SR2 diesel electric generator. Thus unless the site has attractive wind resources, it is potentially more economical and more efficient to replace the existing diesels with a small diesel + battery system as discussed in subsection 1.4.1 than to keep the existing LAMP diesels and add alternate energy collection means. The most efficient and economical course of action may be to do both, i.e., install a smaller diesel + battery system and supplement it with energy collected from the environment. See also recommendation number (2) in subsection 1.7.

DOCUMENTATION OF WORKSPACE 2544 USCG

10:08 AM EST 1/9/81

APL-MVS

APP=10

PIO=1

ACT=1E-13

URL=16007

ALX=

ALC=

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1	2	3	. . .	DIGITS
"				DIERESIS
-				NEGATIVE SIGN
<				LESS
≤				LESS OR EQUAL
=				EQUAL
≥				GREATER OR EQUAL
>				GREATER
*				NOT EQUAL
v				OF
&				AND
-				SUBTRACT
+				ADD
÷				DIVIDE
x				MULTIPLY
?				QUESTION
ω				OMEGA
ε				EPSILON
ρ				RHO
~				TILDE
t				TAKE
d				DROP
i				IOTA
o				CIRCLE
*				POWER
>				RIGHT ARROW
<				LEFT ARROW
α				ALPHA
␣				ANY OTHER (NON-PRINTING) CHARACTER

⌈				CEILING
⌊				FLOOR
_				UNDERSCORE
⌋				DEL
Δ				DELTA
␣				NULL
⌞				QUOTE
⌘				QUAD
(				LEFT PAREN
)				RIGHT PAREN
[				LEFT BRACKET
]				RIGHT BRACKET
(				UC Z (OPEN SHOE)
)				UC X (CLOSE SHOE)
^				UC C (CAP)
u				UC V (CUP)
⌘				DECODE (BASE VALUE)
⌘				ENCODE
⌘				RESIDUE
;				SEMICOLON
:				COLON
,				COMMA
.				PERIOD
⌘				EXPAND, SCAN
⌘				[1] EXPAND
/				COMPRESS
⌘				[1] COMPRESS

⌘				ROTATE
⌘				[1] ROTATE
⌘				TRANSPOSE
⌘				LOG
⌘				NOR
⌘				NAND
⌘				GRADE DOWN
⌘				GRADE UP
⌘				MATRIX DIVIDE
⌘				EXCLAMATION MARK
⌘				EXECUTE
⌘				FORMAT
⌘				QUAD QUOTE
⌘				DELTA UNDERSCORE
⌘				DEL TILDE
⌘				COMMENT
⌘				1 BEAM
⌘				DOLLAR SIGN
⌘				DIMOND
⌘				LEFT BRACE
⌘				RIGHT BRACE
⌘				LEFT TACK
⌘				RIGHT TACK
⌘				SPACE
⌘				BACKSPACE
⌘				LINE FEED

VARIABLES:

ABAT
BLIFTAB
BUCKS
CONVERSE
DAYTAB
DR
DVWTAB
FUELINFR
KDIES
LATTAB
LOADTAB
METHOD
NCELLS
PARWIND
PLABEL
PLOTS
STOP
SUNTAB
SVPTAB
VMBARTAB
XLABEL
YRSO
P
PPP

ABAT NUMERIC RANK=2 FHO=2 3
2.003571429 -0.009042857143 0.5025
1.738571429 0.6292857143 -0.2678571429

BLIFTAB NUMERIC RANK=1 FHO=4
119 1722 -4614 6867

BUCKS NUMERIC RANK=1 FHO=11
20205.80253 21225.6689 22327.12458 23516.69671 24801.43401 26108.95155
27687.46984 29305.86959 31053.74132 32941.44279 34980.16036

CONVERSE NUMERIC RANK=0 FHO=
0.1

DAYTAB NUMERIC RANK=1 FHO=12
28 58 89 119 149 180 210 241 271 302 332 362

0.1	DE	NUMERIC	RANK=0	RHO=
0.49375 0.399375 0.6725 1.86625	DVWTAB	NUMERIC	RANK=1	RHO=4
0.08	FUELINFR	NUMERIC	RANK=0	RHO=
0.8 0.9 1 0.65 1.2 6.5 0.8 0.011877 0.099123	KDIES	NUMERIC	RANK=1	RHO=9
33.5 43.2 57.4	LATTAB	NUMERIC	RANK=1	RHO=3
0.5 2.5 0.5 1.5 0.1 0.55	LOADTAB	NUMERIC	RANK=2	RHO=3 2
EULC	METHOD	CHARACTER	RANK=1	RHO=4
6	NCELLS	NUMERIC	RANK=0	RHO=
3.1 9.8 26.8	PBWIND	NUMERIC	RANK=1	RHO=3
YEAR ARRAY WIND BATTERY	PLABEL	CHARACTER	RANK=2	RHO=4 7
4 3 1 1	PLOTS	NUMERIC	RANK=1	RHO=4
0	STOP	NUMERIC	RANK=0	RHO=

SUNTAB
7800 22100 0.308
3900 19500 0.29
900 17400 0.23

NUMERIC RANK=2 FHO=3 3

SVPTAB
10 48 30 73
40 48 60 73
70 48 90 73
10 10 30 35
40 10 60 35
70 10 90 35

NUMERIC RANK=2 FHO=6 4

VWBARTAB
0 2.11 3.645 4.36 9.155
1 2.055 3.585 4.405 9.03
2 1.995 3.515 4.365 8.895
3 3.695 5.525 5.13 8.765
4 4.455 6.13 5.13 8.67
5 4.61 6.13 4.995 8.765
6 3.955 5.485 4.475 8.905
7 2.455 3.97 4.35 9.015
8 2.11 3.645 4.36 9.155

NUMERIC RANK=2 FHO=9 5

XLABEL
INSTALLATION YEAR
ARRAY SIZE <KW>
WINDMILL SIZE <KW>
BATTERY SIZE <KA-HR>

CHARACTER RANK=2 FHO=4 20

YRSO
0 1 2 3 4 5 6 7 8 9 10

NUMERIC RANK=1 FHO=11

P
3.025

NUMERIC RANK=0 FHO=

PPP
0.0003949105735 -3.925392760 15607.2284 -31026785.13 3.084012242E10 -1.
226178559E13

NUMERIC RANK=1 FHO=6

FUNCTIONS:

ANNUALCOST
BATLIFE
BATTERY
BATTERYCOST
BPLOT
DAYTIME
DECLIN
DEMAND
DFUEL
DIESEL1
DISPLAY
DYNAM
EQUIP
EULERCORR
EVAL
GRAF6
GRAPHS
HOR
HOR1
INITIAL
INTEGRAL
INTERP1
INVERTERCOST
LAMP
MONEY
NOWE
PVALUED6P5
PVALUEFUEL
PVALUESOLAR
PWMEAN
RUNGE
SEE
SERSUM
SOLARE
TOCTAL
TOTALCOST
VBATT
VER1
WIND
WINDCOST
YEAR
G

ANNUALCOST

[0] ACOST<LIFE ANNUALCOST PVALUE

[1] ACOST<PVALUE+(10x(1-(1+DR)*(-LIFE)))

BATLIFE

```
[0] C<BATLIFE X
[1] # X (N BY 24) IS SCC ARRAY, ONE ROW PER DAY
[2] # C IS FRACTION OF BATTERY LIFE USED EACH DAY
[3] # GLOBAL: BLIFTAB=FUNCTION COEFFICIENTS
[4] # 801126 JCR
[5] C<(X°. *0, i3) +. xBLIFTAB
[6] C<0.5x+ / (C-1φC) +Cx1φC
```

BATTERY

```
[0] K<IN BATTERY PNET; IF; IT; PDI; SIZE; BAT; PL; SHP
[1] # STATE OF CHARGE HISTORY
[2] # SOC IS LOAD POWER HERE
[3] # PNET IS WIND + SOLAR
[4] # IN IS NO. OF PARALLEL HISTORIES (MONTHS)
[5] # BCAP IS BATTERY CAPACITY (GLOBAL VECTOR)
[6] # 801230 JCR
[7] SIZE<(3tSHP<rPNET), IN
[8] TF<24xSHP[4]+IN
[9] BAT< 3 1 2 4 5 φ(, BCAP) °. + (SIZE[ 1 2 4 ], 1) t0
[10] SOC<0.5x+ / KDIES[ 3 7 ]
[11] X<(0, 1, TF) INTEGRAL SIZErSOC0
[12] X<SHPPr0.5x((-5t1)dx) + (-5t-1)dx
[13] PLOSS<SHPPr(-5t1)dPL
[14] PD<SHPPr(-5t-1)dPD
[15] # COUNT STARTS:
[16] NSTARTS<(SIZE, NDAYS) r+ / 0 < (1φPL) - PL<xPD
```

BATTERYCOST

```
[0] PV<BATTERYCOST KWH
[1] PV<((( -3) x (YINSTALL) ) + 90) x KWH
```

BPLOT

```
[0] BPLOT X; N; I; αIO
[1] αIO<1
[2] N<1trX<(2t(rX), 1) rX
[3] 'LZ012345' SPLOT(-1αId, φ(2, 1+N) r0, 1), X[, I, [ 1. 1 ] I<IN; ]
```

DAYTIME

```
[0] TD<L DAYTIME D
[1] # L,D ARE LATITUDE (RAD), DAY NUMBER(S)
[2] #TD IS HOURS OF DAYLIGHT
[3] S<L DECLIN D # SOLAR DECLINATION
[4] TD<(24+01)x-20-(30L)x30S
```

DECLIN

```
[0] S<L DECLIN D
[1] # SOLAR DECLINATION (RAD) AT LATITUDE L, FOR DAY(S) D
[2] S<(023.45+180)x10(204+D)x02+365
```

DEMAND

```
[0] P<STA DEMAND D;#IC;T1
[1] # D IS VECTOR OF HOURS OF DAYLIGHT
[2] # LIGHT IS ON FOR AVERAGE OF 30 MIN. AFTER SUNRISE (AND BEFORE SET)
[3] # 801112 JCR
[4] T1<12-0.5xD-#IO<1
[5] P<P, #P<10,T10.--1+112
[6] P<STA[1]+PXSTA[2] # BIAS PLUS LIGHT POWER
```

DFUEL

```
[0] W<PM DFUEL P
[1] # KDIES[ 5 8 9]:
[2] # PFAN A) A1
[3] # KW |<EFF. LINE >|
[4] # W IN GAL/HR ; PM,P IN KW
[5] W<(P#0)x(PMxKDIES[8])+KDIES[9]xKDIES[5]+P
```

DIESEL1

```
[0] P<DIESEL1 X
[1] # KDIES[ 1 2 3 4 5 6 7 ]:
[2] # XL XH ACFF PMIN PFAN PMAX XON
[3] # XL,XH ARE BOUNDS OF LINEAR RANGE
[4] # X IS CURRENT SOC (NORMALIZED)
[5] # XON,XOFF ARE START,STOP VALUES OF X
```

```
[6]  # PMIN,PFAN,PMAX (KW) ARE MINIMUM,FLOWER,PAIED POWER
[7]  # 801222 JCR
[8]  P<1+(KDIES[1]-X)*X*(1-KDIES[4])+-/KDIES[2 1]
[9]  P<0,(KDIES[6]*X*(1+P,KDIES[4])XX<KDIES[3])-KDIES[5]
[10] P<PXDFLAG<(X<KDIES[7])V(X<KDIES[3])&DFLAG # HYSTERESIS
```

DISPLAY

```
[0]  DISPLAY XX;STA;PARS;SH
[1]  @'STA<STA',XX
[2]  @'PARS<PARS',XX
[3]  'STATION PARAMETERS:'
[4]  4tSTA
[5]  SH<3t4dSTA
[6]  'EQUIPMENT:'
[7]  '  ARRAY (M*2):  ',_SH[1]t7dSTA
[8]  '  WINDMILL (KW): ',_SH[2]t(7+3n[1])dSTA
[9]  '  BATTERY (A-HR): ',_SH[3]t(7++/SH[1 2])dSTA
[10] 'DIESEL:'
[11] '  HRS RUN TIME:'
[12] PARS[:::3]
[13] '  STARTS:'
[14] +PARS[:::1]
[15] '  FUEL USED (GAL):'
[16] PARS[:::2]
[17] 'ENERGY SUMMARY (KWH):'
[18] '  EXTERNAL:'
[19] PARS[:::5]
[20] '  CHARGING LOSS:'
[21] PARS[:::6]
[22] '  TOTAL LOSS:'
[23] PARS[:::4]
[24] 'BATTERY LIFE (YEARS):'
[25] PARS[:::7]
[26] 'CONVERTER SIZE (KW):'
[27] PARS[:::8]
```

DYNAM

```
[0]  X DYNAM Y
[1]  IT<IT+1 # TIME INDEX
[2]  # SAVE DIESEL AND LOSS POWER:
[3]  PD<PD,PLI<DIESEL1 Y
[4]  XOLD<Y
[5]  PL<PL,PLOSS
[6]  @ (STOP)/'T[2]<XMAX<X'
```

EQUIP

```
[0]   EQUIP
[1]   # GET EQUIPMENT ARRAYS:
[2]   'ENTER ARRAY SIZE(S) (M*2):'
[3]   ARRAY<,eA
[4]   'ENTER WINDMILL POWER(S) (KW):'
[5]   PWIND<,eA
[6]   'ENTER BATTERY SIZE(S) (A-HR):'
[7]   BCAP<,eA
[8]   SH<(rARRAY), (rPWIND), rBCAP
[9]   'PARS WILL BE DIMENSIONED ', iSH, 8
[10]  'ARRAY, PWIND, BCAP:'
[11]  ARRAY
[12]  PWIND
[13]  BCAP
[14]  'PROCEED?'
```

EULERCORR

```
[0]   M<X1 EULERCORR Y1;X;Y;K;H;XMAX
[1]   M<Y<(((1-rY1)1, rY1) rY1) 0.+, 0
[2]   TIME<X<X1[1]+0xH<X1[2]+0xXMAX<X1[3]
[3]   X INITIAL Y
[4]   L2:M<M, Y<0.5xK+Y+Hx (X<X+H) G K<Y+hxX G Y
[5]   TIME<TIME, X
[6]   X DYNAM Y
[7]   >(X<XMAX)/L2
```

EVAL

```
[0]   YY<EVAL XX
[1]   YY<(((rXX), 1) rXX) ^PPP
```

GRAFO

```
[0]   LI GRAFO X;DAT;STA;SH;ARRAY;BCAP;PWIND;IV;Z;YEAR;NAMES;CV;II;I;X
      X;SVP
[1]   # 810108 JCR
[2]   # XX IS DATA SUFFIX
[3]   # I[1] IS INDEPENDENT VARIABLE: 1,2,3,4 => YEAR,ARRAY,WIND,DATT
[4]   # I[2] IS PARAMETRIC VARIABLE:          DITTO
[5]   # I[3 4] ARE INDICES FOR CONSTANT VARIABLES
[6]   Ii<1
[7]   LOOP:XX<X, II;]
```

```

[8]   SVP<SVPTAB[II;]
[9]   I<LI[II;]
[10]  @'STA<STA',XX
[11]  SH<STA[5 6 7]
[12]  BCAP<((-SH[3])tSTA)+1000
[13]  ARRAY<SH[1]t7dSTA
[14]  PWIND<SH[2]t(7+SH[1])dSTA
[15]  @'YEAR<,YEARS',XX
[16]  IV<,(I[1]=i4)/NAMES< 4 5 r'YEAR ARRAYPWINDBCAP '
[17]  CV<((-i4)eI[1 2])/Z<i4
[18]  Z[(2tI),CV]<Z
[19]  @'DAT<ZTAB',XX,'[:::6]'
[20]  DAT<DAT+Z@,(BUCKS[YRSOIYEAR])%.+Sht0
[21]  @'PLOT ',IV,',DAT[:::','(fI[3]),':','(fI[4]),',''
[22]  HOR1(I[1]=i4)/XLABEL
[23]  VER1 'NORMALIZED ANNUAL COST '
[24]  ((1,0)+SVP[1 4]) WRITE 'SIATION: ',(fSTA[2 3 4])
[25]  ((1,-1.5)+SVP[1 4]) WRITE PLABEL[I[2];],': ',f@NAMES[I[1];]
[26]  ((-2,-6)+SVP[1 2]) WRITE PLABEL[CV[1];],': ',f@NAMES[CV[1];])[I
[3]]
[27]  ((9,-6)+SVP[1 2]) WRITE PLABEL[CV[2];],': ',f@NAMES[CV[2];])[I
[4]]
[28]  >(6>II<II+1)/LOOP
[29]  0 0 WRITE NOWE
[30]  #HDCOPY 1

```

GRAPHS

```

[0]   I GRAPHS XX;DAT;STA;SH;ARRAY;BCAP;PWIND;IV;Z;YEAR;NAMES;CV
[1]   # 810106 JCR
[2]   # XX IS DATA SUFFIX
[3]   # I[1] IS INDEPENDENT VARIABLE: 1,2,3,4 => YEAR,ARRAY,WIND,DATT
[4]   # I[2] IS PARAMETRIC VARIABLE: LITTO
[5]   # I[3 4] ARE INDICES FOR CONSTANT VARIABLES
[6]   @'STA<STA',XX
[7]   SH<STA[5 6 7]
[8]   BCAP<(-SH[3])tSTA
[9]   ARRAY<SH[1]t7dSTA
[10]  PWIND<SH[2]t(7+SH[1])dSTA
[11]  @'YEAR<,YEARS',XX
[12]  IV<,(I[1]=i4)/NAMES< 4 5 r'YEAR ARRAYPWINDBCAP
[13]  CV<((-i4)eI[1 2])/Z<i4
[14]  Z[(2tI),CV]<Z
[15]  @'DAT<ZTAB',XX,'[:::6]'
[16]  DAT<DAT+Z@,(BUCKS[YRSOIYEAR])%.+Sht0
[17]  @'PLOT ',IV,',DAT[:::','(fI[3]),':','(fI[4]),',''
[18]  HOR(I[1]=i4)/XLABEL
[19]  VER 'NORMALIZED ANNUAL COST'
[20]  70 2 WRITE 'SIATION: ',(fSTA[2 3 4])
[21]  70 0 WRITE NOWE

```

```
[22] 0 4 WRITE XLABEL[I[2]:],': ',f(@NAMES[I[2]:])
[23] 0 2 WRITE XLABEL[CV[1]:],': ',f(@NAMES[CV[1]:])[I[3]]
[24] 0 0 WRITE XLABEL[CV[2]:],': ',f(@NAMES[CV[2]:])[I[4]]
[25] HDCOPY 1
```

HOR

```
[0] HOR CHAR:Z;W;Q;A;C;N;D;F;G;I;L;B;M;T;O
[1] NIO<1
[2] A<1 0 ,A, 0 0 0 0 1 ,rZA
[3] PSCALE
[4] Z<0.5x(-/SVP[3 1])-DD[5]xCS[CHARSIZE]x,-1trCHAR<(-2t1,rCHAR)rCHAR
[5] ((2tSVP)+Z,(-2.75-1trCHAR)xDD[6]xCS[CHARSIZE]) WRITE CHAR
```

HOR1

```
[0] HOR1 CHAR:Z;W;Q;A;C;N;D;F;G;I;L;B;M;T;O
[1] NIO<1
[2] A<1 0 ,A, 0 0 0 0 1 ,rZA
[3] PSCALE
[4] Z<0.5x(-/SVP[3 1])-DD[5]xCS[CHARSIZE]x,-1trCHAR<(-2t1,rCHAR)rCHAR
[5] ((2tSVP)+Z,(-2.75-1trCHAR)xDD[6]xCS[CHARSIZE]) WRITE CHAR
```

INITIAL

```
[0] X INITIAL Y
[1] IT<1
[2] PNET<(SIZE,TF)rPNET
[3] SOC<(SIZE,TF)rSOC
[4] DFLAG<1
[5] PL<PD<(SIZE,1)rPD<DIESEL1 Y
[6] XOLD<Y
```

INTEGRAL

```
[0] Y<Q INTEGRAL YI
[1] Q IS INITIAL,STEP,FINAL TIMES
[2] >(E/(METHOD='EULC'))/LAB3
[3] >(E/(METHOD='RUNG'))/LAB4
[4] 'METHOD DEFAULTING TO EULC'
[5] METHOD<'EULC'
[6] LAB3:
[7] Y<Q EULERCORR YI
[8] >0
```

```
[9] LAB4:
[10] Y<Q RUNGE YI
```

INTERP1

```
[0] Z<V INTERP1 T;X;Y;UIC
[1] UIC<1
[2] Z<(1+Z),[1.5] Z<(-1+UIC)[1]^1,r,T[;1]^0.<,V
[3] X<(T[;1])[Z]
[4] Y<(T[;2])[Z]
[5] Z<(rV) rY[;2]+(-/Y)x((,V)-X[;2])+-/X
```

INVERTCOST

```
[0] PVINVERT<INVERTCOST WATTS
[1] PVINVERT<100+(1xWATTS)
```

LAMP

```
[0] DATA<STA LAMP M;D;TD;KW;LAT;SH
[1] # SIMULATES STATE OF A LAMP STATION AS FUNCTION OF TIME
[2] # M IS MONTH NUMBER(S) TO SIMULATE
[3] # 801229 JCH
[4] # STA[ 1 2 3 4 ]:
[5] # LAT S,N,A C,O H,L,Z
[6] # DEG 1,2,3 1,2 1,2,3
[7] # GLOBAL: ARRAY,PWIND,LCAP
[8] D<(-NDAYS+2)+,DAYTAB[M]^0.+ -1+INDAYS
[9] SH<(r,ARRAY),(r,PWIND),(l,BCAP),(rD),24
[10] KW<(2+STA[2])+2xSTA[3]-1
[11] LAT<STA[1]+(0=STA[1])xLATTAB[STA[2]] # LATITUDE
[12] DATA<0 3 d(LAT,SUNTAB[STA[2];]) SOLARE D # SOLAR POWER
[13] DATA<(,ARRAY)^0.x(SH[2]t0)^0.+(SH[3]t0)^0.+DATA
[14] PD<(KW,PARWIND,1) WIND D # WIND POWER
[15] DATA<DATA,[5.1](SH[1]t0)^0.+(,PWIND)^0.x(SH[3]t0)^0.+PD
[16] PD<+/DATA # SOLAR + WIND
[17] DATA<DATA,SOC<SHr-LOADTAB[STA[4];] DEMAND TD # LOAD POWER
[18] SOC<(r,M) BATTERY PD # STATE OF CHARGE
[19] OUT:DATA<DATA,PD,SOC,[5.1] PLOSS
```

MONEY

```
[0] MONEY XX;DATA;N;UIC;STA
[1] # DATA ARRAY FOR ECONOMIC ANALYSIS
```

```
[9] LAB4:
[10] Y<Q RUNGE YI
```

INTERP1

```
[0] Z<V INTERP1 T;X;Y;QIO
[1] QIO<1
[2] Z<(1+Z),[1.5] Z<(-1+PI)[1]41,+T[;1]0.<,V
[3] X<(T[;1])[Z]
[4] Y<(T[;2])[Z]
[5] Z<(rV) rY[;2]+(-/Y)x((,V)-X[;2])+-/X
```

INVERTERCOST

```
[0] PVINVERT<INVERTERCOST WATTS
[1] PVINVERT<100+(1xWATTS)
```

LAMP

```
[0] DATA<STA LAMP M;D;TD;KW;LAT;SH
[1] * SIMULATES STATE OF A LAMP STATION AS FUNCTION OF TIME
[2] * M IS MONTH NUMBER(S) TO SIMULATE
[3] * 801229 JCR
[4] * STA[ 1 2 3 4 ]:
[5] * LAT S,N,A C,O H,L,Z
[6] * DEG 1,2,3 1,2 1,2,3
[7] * GLOBAL: ARRAY,PWIND,BCAP
[8] D<(-NDAYS+2)+,DAYTAB[M]0.+ -1+NDAYS
[9] SH<(r,ARRAY),(r,PWIND),(l,BCAP),(rD),24
[10] KW<(2*STA[2])+2xSTA[3]-1
[11] LAT<STA[1]+(0=STA[1])xLATIAB[STA[2]] * LATITUDE
[12] DATA<0 3 d(LAT,SUNTAB[STA[2];]) SOLARE D * SOLAR POWER
[13] DATA<(,ARRAY)0.x(SH[2]t0)0.+(SH[3]t0)0.+DATA
[14] PD<(KW,PARWIND,1) WIND D * WIND POWER
[15] DATA<DATA,[5.1](SH[1]t0)0.+(,PWIND)0.x(SH[3]t0)0.+PD
[16] PD<+/DATA * SOLAR + WIND
[17] DATA<DATA,SOC<SHr-LOADTAB[STA[4];] DEMAND TD * LOAD POWER
[18] SOC<(r,M) BATTERY PD * STATE OF CHARGE
[19] OUT:DATA<DATA,PD,SOC,[5.1] PLOSS
```

MONEY

```
[0] MONEY XX;DATA;N;QIO;STA
[1] * DATA ARRAY FOR ECONOMIC ANALYSIS
```

```
[2] DATA[; 1 2 3 4 5 6 7]:
[3] ERTCY FUEL BATT BLIFE PWIND ARFAY INVRT
[4] HRS GAL KWH YRS |← WATIS ---->|
[5] nIO←1
[6] e'N←x/3trPARS',XX
[7] e'DATA←((N,d) rPARS',XX,')[: (1 2 3 ),7, 3r8]'
[8] DATA[;1]←+/DATA[; 1 3]
[9] e'STA←4dSTA',XX
[10] DATA[;3]←(NrSTA[3]t(3+/SIA[1 2])dSTA)x2xNCELLS+1000
[11] DATA[;5]←1000x, 1 3 2 rSTA[1 3 2]rSTA[2]t(3+STA[1])dSTA
[12] DATA[;6]←1000x, 2 3 1 rSTA[2 3 1]rSTA[1]t3dSTA
[13] DATA[;7]←1000xDATA[;7]
[14] e'ECON',XX,'<DATA'
```

NOWE

```
[0] R←NOWE;nIO;A;H;L;S;B
[1] RETURN TIME AND DATE FOR EASTERN TIME ZONE
[2] WTR 9/79
[3] nIO←0
[4] L←0=4|1tH←4tA←nTS & LEAP ADJUST
[5] S←A[1]e 1 2 3 4 11 12 & 1=EST, 0=EDT
[6] B←0 12 , (31 31 , (23+L), 31 30 31 30 31 31 30 31 30 31)[A[1]-1=A
[2]],24
[7] A←(0 1 1 0 +B+(B+H- 0 1 1 0)-4+S),4da & ADJUST GREENWICH MEAN TI
ME
[8] R←'DS ET'[2 3 ,S,4], (4 0 fA[1]), '/' , (fA[2]), '/' , ±100|A[0]
[9] R←((3x(0+12|B)xx12-3A[3]+A[4]+60)t' AM PM'),R
[10] R←((5x12=B)t' NOON'),R
[11] R←((9x0=B)t' MIDNIGHT'),R
[12] R←(f1+12|A[3]-1), ':' , (-2t'0', fA[4]),R
```

PVALUED6P5

```
[0] PVALUED6P5;A;B;K;PVD6P51;PVD6P52;PVD6P53;YMANHk
[1] A←-2190+ERTCY
[2] B←1
[3] K←59
[4] PVD6P51←7500+500xSERSUM
[5] K←29
[6] B←2
[7] PVD6P52←1800xSERSUM
[8] K←5
[9] B←10
[10] PVD6P53←2300xSERSUM
[11] PVD6P5←PVD6P51+PVD6P52+PVD6P53
[12] YMANHR←(ERTCY+8760)x48
```

PVALUEFUEL

```

[0] PVPFUEL<PVALUEFUEL AFC;K;B;DRSAVE;EFC
[1] A<8760*ERTCY
[2] DRSAVE<DR
[3] DR<((1+FUELINFR)+(1+DR))-1
[4] K<14
[5] B<1
[6] EFC<(AFC*1.25)
[7] PVPFUEL<EFC*1.3*((1.03)*YINSTALL)*A*(1.5+SERSUM)
[8] DR<DRSAVE

```

PVALUESOLAR

```

[0] PVSOLAR<PVALUESOLAR WATTS
[1] PVSOLAR<((EVAL 1980+YINSTALL)*WATTS)+2000

```

PWMEAN

```

[0] PW<K PWMEAN V;VIC;VIRM
[1] # MEAN WIND POWER; V IS VECTOR OR MATRIX OF SPEEDS
[2] # K[ 1 2 3 4]:
[3] # VI VR VM PR
[4] # UNITS: |< M/SEC >| KW
[5] # 801107 JCR
[6] # MEAN POWER (SEE EQS. 6.3 OF INT. REPT NO 2):
[7] # IO<1
[8] # (2=rrv)/GO
[9] # V<(1,r,v)rv
[10] GO:VIRM<0.25*(K[1 2 3]*V)*2
[11] PW<((-VIRM[1;;])-VIRM[2;;])+VIRM[2 1 ;;]
[12] PW<K[4]*PW--VIRM[3;;]

```

RUNGE

```

[0] M<X1 RUNGE Y1;X;Y;K;H;XMAX;A;N
[1] TIME<X[X1[1]+0*X[X1[2]+0*X[XMAX[X1[3]
[2] M<Y<((-1,rn)t1,N<ry1)ry1)*.,0
[3] N<(-1drM),-1
[4] X INITIAL Y
[5] A<4 1 r 1 2 2 1
[6] LOOP:
[7] M<M,Y<Y+(H+6)*X(K,(X<X+0.5XH) G Y+HXNtK<K,X G Y+0.5XHxNtK<K,(X<X+
0.5XH) G Y+0.5XHxK<X G Y)+.XA

```

```
[8] TIME←TIME,X
[9] X DYNAM Y
[10] >(X<XMAX)/LOOP
```

SEE

```
[0] N SEE DAT;MOVE
[1] # N IS NO. OF MONTHS
[2] # LAST 2 ELEMENTS OF (rDAT) MUST BE (NO. DAYS),24
[3] DAT←(N,24x(1t-2trDAT)+N)rDAT
[4] #←MOVE←10 1 f1.1x(r/,DAT)-L/,DAT
[5] MOVE←MOVEx((1trDAT),N)r-1+in
[6] BPLOT DAT+MOVE
[7] NOWE
```

SERSUM

```
[0] SUM←SERSUM
[1] SUM←(1-(1+DR)*(AxBxK))+((-1)+(1+DR)*(-AxE))
```

SOLARE

```
[0] DAT←STA SOLARE D;L;EN;S;MIO;A;B;TEAR
[1] # 24 HR. SOLAR ENERGY DATA FOR DAY NUMBER(S) D
[2] #OUTPUT: DAT IS N (NO. OF DAYS) BY 24+3
[3] # LAST 24 COLUMNS OF DAT ARE HOURLY SOLAR INTENSITY (KW)
[4] # FIRST 3 COLUMNS OF DAT ARE DAY,MEAN DAILY TOTAL,SOLAR DECL.
[5] # STA IS STATION PARAMETERS: LATITUDE(DEG);D,J,A (FOR EQ. 4.3)
[6] # 801119 JCR
[7] #MIO←1
[8] L←oSTA[1]+180 # LAT IN RADIANS
[9] # A←(-/STA[4 2])+(-/STA[3 2])x(o1)*.5 # (OPTIONAL - EQ. 4.4)
[10] # EQ. 4.3:
[11] EN←STA[2]+(-/STA[3 2])x*-((D-172)+365xSTA[4])*2
[12] B←(-1+(o1)*0.5)x(TD<L DAYTIME D)+o1 # EQ. 4.6
[13] # EQ. 4.5:
[14] DAT←1-*((((TD+2)°. -112.5-124)+B°. +24t0)*2
[15] DAT←DATx((EN+360xTD)x(o1)*0.5)°. +24t0 # HOURLY AVG IN KW
[16] # COS OF ANGLE BETWEEN SUN AND L. V.:
[17] TBAR←((2oL)x(2oS)°. x2oo(12.5-124)+12)+g(24,TD)x(1oL)x1os
[18] DAT←DATxTBAR>0 # ENERGY IN DAYLIGHT ONLY...
[19] # AVG. TRANSMISSION RATIO:
[20] TEAR←(TBAR#0)xDAT+TEARx1.353
[21] DAT←D,EN,S,DAT
```

TOCTAL

```
[0] TO<TD TOCTAL T;X1;X;Y
[1] # TD IS HOURS OF DAYLIGHT (N-VECTOR)
[2] # T IS CLOCK HOURS (M-VECTOR)
[3] # TO IS OCTAL TIME MATRIX (N x M)
[4] # OCTAL TIME IS: (0,2,4) AT (MIDNITE,DAWN+.5,NOON)
[5] # JCR 801107
[6] X1<0.5x-1+TD
[7] Y<((4+TD-1)°.xx)x(x1°.≥|X|T-12)
[8] TO<4+Y+((4+25-TD)°.xxx)x(x1°.<|X|x(13-TD)°.+|X
```

TOTALCOST

```
[0] YINS TOTALCOST DATA;ABATT;ADIESEL;AINVERTER;ASOLAR;ATOTAL;AWIND;
ERTCY;PVD6P5;II
[1] ERTCY<52,DATA[;1]
[2] PVALUED6P5
[3] TABLE<(1,(1trDATA),6) r0xyINS<,YINSxII<1
[4] LOOP:YINSTALL<YINS[II]
[5] ADIESEL<(131+00+ERTCY) ANNUALCOST PVD6P5+PVALUEFUEL DATA[;2]
[6] ABATT<DATA[;4] ANNUALCOST BATTERYCOST DATA[;3]
[7] AWIND<(DATA[;5]*C)x2C ANNUALCOST WINDCOST DATA[;5]
[8] ASOLAR<(DATA[;6]*0)x2C ANNUALCOST PVALUESOLAR DATA[;6]
[9] AINVERTER<(DATA[;7]*0)x2C ANNUALCOST INVERTERCOST DATA[;7]
[10] ATOTAL<ADIESEL+ABATT+AWIND+ASOLAR+AINVERTER
[11] TABLE<TABLE,[1] ADIESEL,ABATT,AWIND,ASOLAR,AINVERTER,[1.1],ATOTA
L
[12] >((II<II+1)≤YINS)/LOOP
[13] TABLE<1 0 0 TABLE
[14] >TERSE/0
[15] 'FOR INSTALLATION YEAR(S) ',(1980+YINS),' : '
[16] ' ANNUAL COSTS OF: '
[17] ' DIESEL BATTERY WIND SOLAR INVERTER TOTAL'
[18] >TERSE/0
[19] 10 2 TABLE
```

VBATT

```
[0] I<X VBATT P;V1;MSK
[1] # BATTERY CHARGING CURRENT (NORMALIZED)
[2] # 801202 JCR; ASSUMES BIO=1
[3] # X,P ARE SOC (NORMALIZED) AND NET POWER (W)
[4] # GLOBAL:NO.CELLS (NCELLS), CAPACITY (BAT),
[5] # CELL VOLTAGE COEFFICIENTS (ABAT)
[6] V1<X°. * 0 1 2
[7] MSK<P≥0
```

```
[8] V1<(MSKxV1+.xABAT[1;])+(~MSK)xV1+.xABAT[2;]
[9] I<(-V1)+((V1*2)+2xP+NCELLSxBAT)*0.5
```

VER1

```
[0] VER1 CHAR;Z;N;WW;Q;A;C;NN;N;D;F;G;I;L;B;M;TM;IO
[1] IO<1
[2] A<1 0 ,A, 0 0 0 0 1 ,rZA
[3] PSCALE
[4] N<DD[9]v2=INC 'CG=3'
[5] Z<0.5x(-/SVP[4 2])-DD[6-N]xCS[CHARSIZE]x-1trCHAR<(-2t1,rCHAR)rCHA
R
[6] Z<((2tSVP)+(-5+DD[5]xCS[CHARSIZE]x1trCHAR),Z),0,N
[7] Z WRITE((~N)/'0'),'CHAR'
```

WIND

```
[0] PW<K WIND D;IO;VW;VIRM
[1] # HOURLY MEAN WIND POWER; D IS VECTOR OF DAYS
[2] # TD IS VECTOR OF HRS OF DAYLIGHT
[3] # K[ 1 2 3 4 5 6]:
[4] # GRP VI VR VM PR
[5] # UNITS: - |< M/SEC >| KW
[6] # GRP (1,2,3,4): CS,CN,OS,ON
[7] # 801119 JCR
[8] IO<1 # TD IS GLOBAL; RUN DAYTIME OR SOLAR FIRST
[9] # MEAN ANNUAL WIND SPEED:
[10] VW<I(rD),24)r(,TD TOCTAL -0.5+124) INTERP1 VWBARIAE[;1,1+K[1]]
[11] # ANNUAL VARIATION:
[12] VW<VW-p(24,rD)rDVMTAB[K[1]]x1002x(D-81)+365
[13] # MEAN POWER:
[14] PW<(1dK) PWMEAN VW
```

WINDCOST

```
[0] PVWIND<WINDCOST WATTS;A;B;K;PINITIAL;PMAINT
[1] PINITIAL<(((0.12)x(YINSTALL))+2.4)xWATTS)+2000
[2] A<-1
[3] B<1
[4] K<19
[5] PMAINT<(475xSERSUM)
[6] PVWIND<PINITIAL+PMAINT
```

YEAR

```

[0] STA YEAR XX;NIO;NDAYS;CPUT;SH
[1] # DATA FOR A STATION AT MONTHLY INTERVALS
[2] # XX IS SUFFIX FOR PARS AND STA
[3] # PARS[ 1      2      3      4      5      6      7 ]:
[4] #      STRTS FUEL  TDIES PLOSS PEXT  PCCUL TBATT
[5] # 810108 JCR
[6] CPUT←NIO[ 1+NIO<1 ]
[7] NOWE
[8] EQUIP
[9] >('Y'≠1tA)/0
[10] NDAYS←L
[11] DATA←((12XNDAYS) r (-NDAYS) t1)/[4] STA LAMPi12
[12] PARS←(-5tNDAYS-1)dnSTARTS # DIESEL STARIS
[13] PARS←PARS,+/KDIES[6] LPUEL DATA[ : : : : 4 ] # DIESEL FUEL
[14] PARS←PARS,+/0<DATA[ : : : : 4 ] # DIESEL RUN TIME
[15] PARS←PARS,+/+/DATA[ : : : : 14 ] # TOTAL LOSS
[16] PARS←PARS,+/+/DATA[ : : : : 1 2 3 ] # EXTERNAL ENERGY
[17] PARS←PARS,+/DATA[ : : : : 6 ] # CHARGING LOSS
[18] PARS←PARS,BATLIFE DATA[ : : : : 5 ] # BATTERY LIFE
[19] @'PARS',XX,'< (+/[4]PARS) x365+12'
[20] @'PARS',XX,'[ : : : 7 ]<+.04, PARS',XX,'[ : : : 7 ]'
[21] # CONVERTER SIZE:
[22] @'PARS',XX,'<PARS',XX,' (0*CONVERSE) x0,-L/L/+/DATA[ : : : : 1 2 3 ]'
[23] @'STA',XX,'<STA,SH,ARRAY,PWIND,BCAP'
[24] DISPLAY XX
[25] MONEY XX
[26] TERSE←0
[27] @'5 TOTALCOST ECON',XX
[28] @'TAB',XX,'<(1,SH,6) rTABLE'
[29] @'YEARS',XX,'<5'
[30] 'CPU TIME: ',(NIO[2]-CPUT),' MSEC'
[31] NOWE
[32] >(0≥rFLOTS)/0
[33] HDCOPY 1
[34] ERASE
[35] PLOTS GRAPHS XX

```

Q

```

[0] D<T'G X;=P
[1] # 801230 JCR
[2] # DIESEL POWER (PDI) IS COMPUTED IN DYNAM
[3] D<PDI+SOC[ : : : ,IT] # DIESEL + LOAD
[4] # ADD WIND AND SOLAR, WITH CONVERTER LOSS:
[5] D<D+PNET[ : : : ,IT]+CONVERSEx0+D,-PNET[ : : : ,IT]
[6] PLOSS<Dx(X+1.1)*8
[7] PLOSS<0,PLOSS+D # CHARGING LOSS
[8] #P<-(D<0)xCONVERSExD # CONVERTER LOSS
[9] D<(X VBATT 1000xD-#P) x1-PLOSS+D
[10] # PLOSS<PLOSS+#P # TOTAL LOSSES

```

