CONS/0385-1
NASA CR-135283
BCS 40180-1

A SIMULATION MODEL FOR WIND ENERGY STORAGE SYSTEMS

Volume I: Technical Report

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A Division of The Boeing Company

August 1977

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Cleveland, Ohio 44135

Contract NAS 3-20385

As a part of the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Energy Storage Systems

1. Report No. NASA CR-135283	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Simulation Model for Wind Energy Storage Systems Volume I: Technical Report		5. Report Date August, 1977
		6. Performing Organization Code
7. Author(s) R. W. Edsinger, Y. K. Chan, A. W. Warren		8. Performing Organization Report No.
9. Performing Organization Name and Address Energy Technology Applications Division of Boeing Computer Services Company Seattle, Washington 98124		10. Work Unit No.
		11. Contract or Grant No. NAS3-20385
12. Sponsoring Agency Name and Address Energy Research and Development Administration Divison of Energy Storage Systems Washington, D.C. 20545		13. Type of Report and Period Covered Contractor Report
		14. Sponsoring Agency Report No. CONS/0385-1

15. Supplementary Notes

Final report. Prepared under Interagency Agreement E(49-28)-1026. Project Manager, Larry H. Gordon, Power Generation and Storage Division, NASA Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

The effort developed a comprehensive computer program for the modeling of wind energy/storage systems utilizing any combination of five types of storage (pumped hydro, battery, thermal, flywheel and pneumatic). An acronym for the program is SIMWEST (Simulation Model for Wind Energy Storage). The level of detail of SIMWEST is consistent with a role of evaluating the economic feasibility as well as the general performance of wind energy systems.

The software package consists of two basic programs and a library of system, environmental, and load components. The first program is a precompiler which generates computer models (in Fortran) of complex wind source/storage/application systems, from user specifications using the respective library components. The second program provides the techno-economic system analysis with the respective I/O, the integration of system dynamics, and the iteration for conveyance of variables. This SIMWEST program, as described, runs on the UNIVAC 1100 series computers.

This technical report contains three volumes. Volume I gives a brief overview of the SIMWEST program and describes the two NASA defined simulation studies. Volume II, the SIMWEST operations manual, describes the usage of the SIMWEST program, the design of the library components, and a number of simple example simulations intended to familiarize the user with the program's operation. Volume II also contains a listing of each SIMWEST library subroutine. Volume III, the SIMWEST program description contains program descriptions, flow charts and program listings for the SIMWEST Model Generation Program, the Simulation program, the File Maintenance program and the Printer Plotter program. Volume III generally would not be required by SIMWEST user.

17. Key Words (Suggested by Author(s)) Energy Storage, Computer Programs, System Simulation, Wind Energy		18. Distribution Statement Unclassified - unlimited STAR Category 61 ERDA Category UC-94b	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 104	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161

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FOREWORD

This report presents results of work conducted by Boeing Computer Services Company under NASA Contract NAS3-20385, "Wind Energy Storage Model Development." This program was conducted under the sponsorship of the Advanced Physical Methods Branch, Office of Conservation, ERDA, under the direction of Dr. G. C. Chang, and was administered by the NASA-Lewis Research Center Thermal and Mechanical Storage Section with Mr. L. H. Gordon as Project Manager. This report is in three volumes.

I. Technical Report
II. Operation Manual
III. Program Descriptions

The Boeing Program Manager for this work was R. W. Edsinger, and A. W. Warren was the principal investigator.

For completeness, the summary sections 1.1 and 1.2 of Volume I have been repeated in the Operation Manual, Volume II.

1.0 INTRODUCTION

The need for energy storage for solar energy systems (wind, thermal, heating and cooling, and photovoltaic) is generally recognized. However, until recently a comprehensive computer model for evaluating the type and quantity of storage for a given application did not exist. In November of 1976 NASA-Lewis, as project manager for ERDA, awarded a contract to Boeing Computer Services (BCS), to develop such a model. It is called SIMWEST (Simulation Model for Wind Energy Storage). SIMWEST was required to have the capability of modeling wind energy/storage systems utilizing any combination of five types of storage (pumped hydro, battery, thermal, flywheel and pneumatic). The level of detail of SIMWEST was to be consistent with a role of evaluating the economic feasibility and general performance of wind energy systems. The SIMWEST design was to facilitate its adaptation to other solar applications and other levels of detail.

To meet these requirements BCS developed the SIMWEST based upon an existing dynamic simulation model (EASY). It consists of a library of system components and a precompiler program which allows these components to be put together in building block form. The SIMWEST program, as described here runs on the UNIVAC 1100 series of computers.

Other computer programs exist for the simulation of wind systems and various forms of energy storage. However, SIMWEST is the only publicly available program capable of simulating total wind systems containing any one or combination of the above types of storage and at the same time having the flexibility and depth required to perform thorough and meaningful parametric studies.

Volume I of this report gives a brief overview of the SIMWEST program and describes the two, NASA defined simulation studies including a definition of the systems simulated, the data cards used and a summary of the simulation results. Volume II, the SIMWEST operations manual, describes the usage of the SIMWEST program, the design of the library components, and a number of simple example simulations intended to familiarize the user with the program's operation. Volume II also contains a listing of each SIMWEST library subroutine. Volume III, the SIMWEST program description contains program descriptions, flow charts, and program listings for the SIMWEST Model Generation Program, the Simulation program, the File Maintenance program and the Printer Plotter program. Volume III generally would not be required by a SIMWEST user.

1.1 SIMWEST OVERVIEW

SIMWEST consists of two basic programs, and a library of system, environmental, and load components. The first program, the Model Generation Program, is a precompiler which generates computer models (in FORTRAN) of complex wind energy generator/storage/application systems, from user specifications using SIMWEST library components. The second program exercises the resulting computer model to perform cost and potential utilization analysis. It handles input, output, integration of system dynamics, and iterates to obtain convergence of variables involved in implicit loops. The combination of these two programs provides a powerful tool for analyzing alternate storage system designs.

Figure 1.1-1 shows the general organization of the SIMWEST program. In addition to the two programs described above, there is a third which performs file maintenance. It is used to incorporate user supplied data for new subsystem models. Although the program is shown to be made up of a number of subprograms, it can be executed as a single batch program by supplying the model description control cards and the control cards describing the desired analysis to be performed and the desired tabular and/or plotted output.

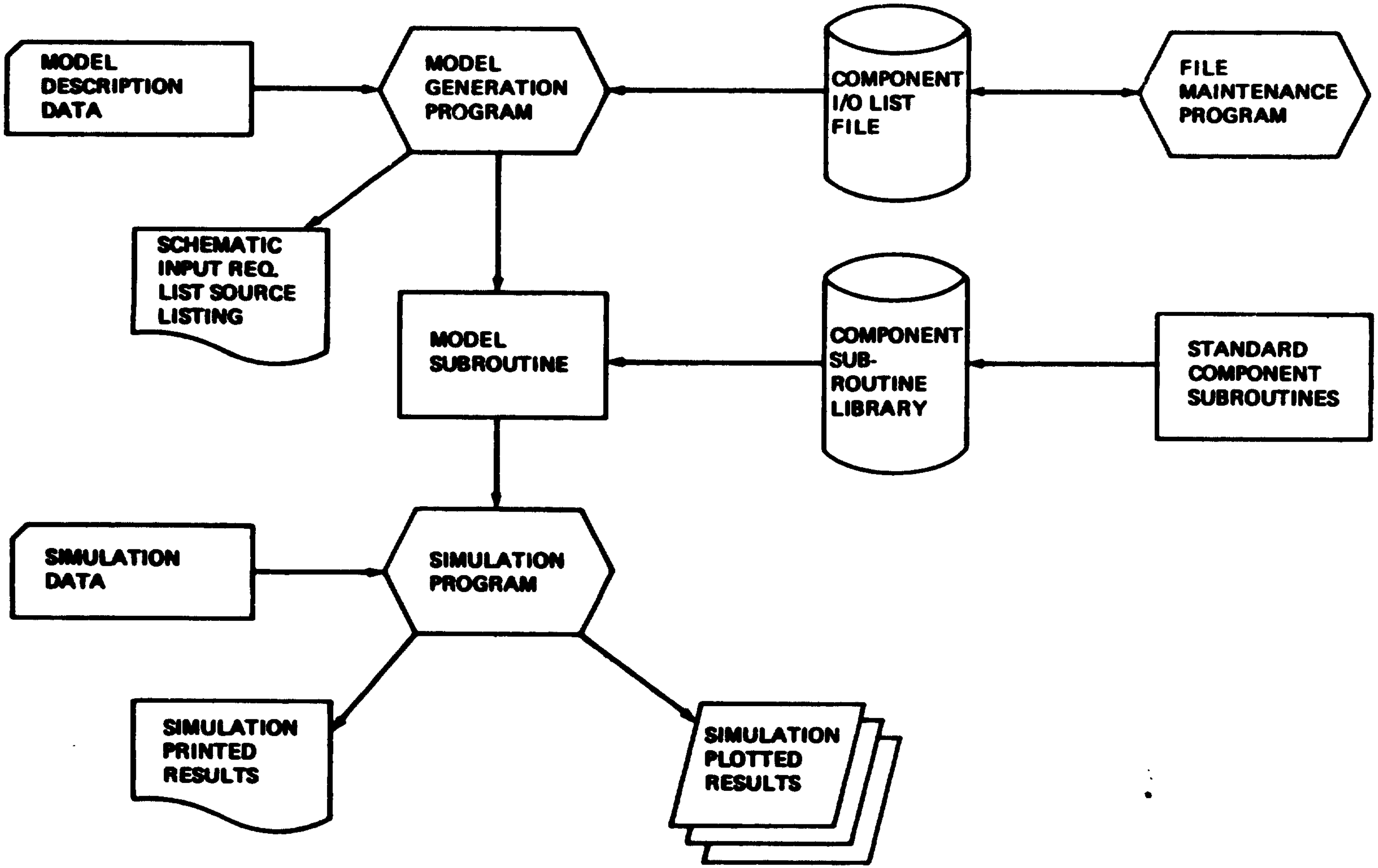

FIGURE 1.1-1 SIMWEST PROGRAM ORGANIZATION

1.2 SIMWEST LIBRARY

The SIMWEST library is listed in Table 1.2-1. It is made up of five types of components: physical, environmental, load, logical, and utility.

Physical components encompass such things as motors, generators, transmissions, flywheels, etc. These components model actual physical hardware which might be used in a wind energy system. The selection of the particular SIMWEST library set of physical components was based on the requirement that it be capable of modeling the five types of energy storage systems mentioned previously: thermal, flywheel, battery, pumped hydro and pneumatic.

The degree of detail in the component models is based upon two design criteria. First, all models should contain sufficient detail to simulate all physical characteristics and constraints having significant impact on the systems overall cost effectiveness. Second, the models should be designed to minimize computer time and required user specification. It is assumed that a typical SIMWEST simulation might cover a time span of one year. Thus, from a computer run time and economic impact point of view a simulation step size of between 15 minutes and one hour seemed reasonable.

As a result of the above two design criteria, many physical components, such as the electrical components, were modeled mainly in terms of power flow and steady state response. This lack of detail is consistent with the 15 minute time step and with the concept that the important transients are on the time scale of demand curves or weather patterns, i.e., an hour or more, rather than on the time scale of electric motor transients of a few seconds. If short electric transients were to be modeled, much detail would need to be added to the component models which would greatly increase the user's task of specifying the model. Further, the simulation time step would have to be reduced to a fraction of a second so the model would not only be much larger but computer runs would be much costlier.

TABLE 1.2-1 SIMWEST LIBRARY COMPONENTS

PHYSICAL		ENVIRONMENTAL	
WIND TURBINE	WT	WIND	WD
TURBINE/GENERATOR	WP	AMBIENT TEMP	TP
AC INDUCTION GEN.	GE		
FIXED RATIO TRANSMISSION	GR	LOAD	
RECTIFIER	RE	ELECTRICAL LOAD	LO
BATTERY	BA	THERMAL LOAD	TL
INVERTER	IV		
ADMITTANCE	AD	LOGIC	
COMPRESSOR (PNEUMATIC)	CO	POWER DIVIDER	PD
ADIABATIC HEAT EXCHANGER		POWER ACCUMULATOR	PA
(INPUT CYCLE)	HX	PRIORITY INTERRUPT	PI
ADIABATIC HEAT EXCHANGER		SWITCH	SW,SX,SY,SZ
(OUTPUT CYCLE)	HY		
PNEUMATIC STORAGE VESSEL	CS	UTILITY	
BURNER	BN	COST MONITOR	CM
TURBINE (PNEUMATIC)	TU	SATURATION	SA
INDUCTION MOTOR	MO	RANDOM NUMBER GENERATOR	RN
VARIABLE RATIO TRANSMISSION	TR	TEST FUNCTIONS	AF
FLYWHEEL/CLUTCH	FL	TABLE LOOKUP	FU,FV
PUMP (HYDRO)	PU	TRANSFER FUNCTION	IT,LA,LL,TF
TURBINE (HYDRO)	HT	ARITHMETIC ELEMENT	MA,MB,MC
HYDRO STORAGE	HS	HISTOGRAM	HG
THERMAL STORAGE	TS	TAPE READ	TA
UTILITY	UT	TIME CONVERSION	TI

Environmental components are those which simulate environmental conditions. In the present SIMWEST library these conditions are wind speed and ambient temperature. These variables are generally used as inputs to physical components. Environmental component output can either be computed from measurement data provided by the user on a data tape, or from randomly generated data, based on user furnished profiles.

The load components in the SIMWEST library are used to simulate various types of power demand. They also monitor how well the system meets the simulated demand and compute the value of the energy delivered by the wind energy system to the load. Like the environmental components these components may be computed from actual measurement data or from randomly generated data based on user furnished load profiles.

The library's logical components are the power dividers, power accumulators, switches and priority interrupts. Although physical hardware could generally be built to serve the function of the logical components, they are not meant to represent any particular piece of existing hardware. Instead, they are idealized components that allow the user the flexibility of modeling the wide variety of control logic which is required for a thorough evaluation of wind energy storage systems. In practice, the control function might be performed by a control room operator using a predefined control strategy or by use of a minicomputer.

Finally, the utility components include such things as the tape read, the histogram and the cost monitor. These components serve only to help the user run the simulation and analyze its results.

1.2.1 Storage Subsystems

Figures 1.2-1 through 1.2-5 give possible configurations of the five types of storage subsystems which can be modeled with the present SIMWEST library. For illustrative purposes the number of variables shown passed between components is limited. A description of the variables being passed is given in Table 1.2-2.

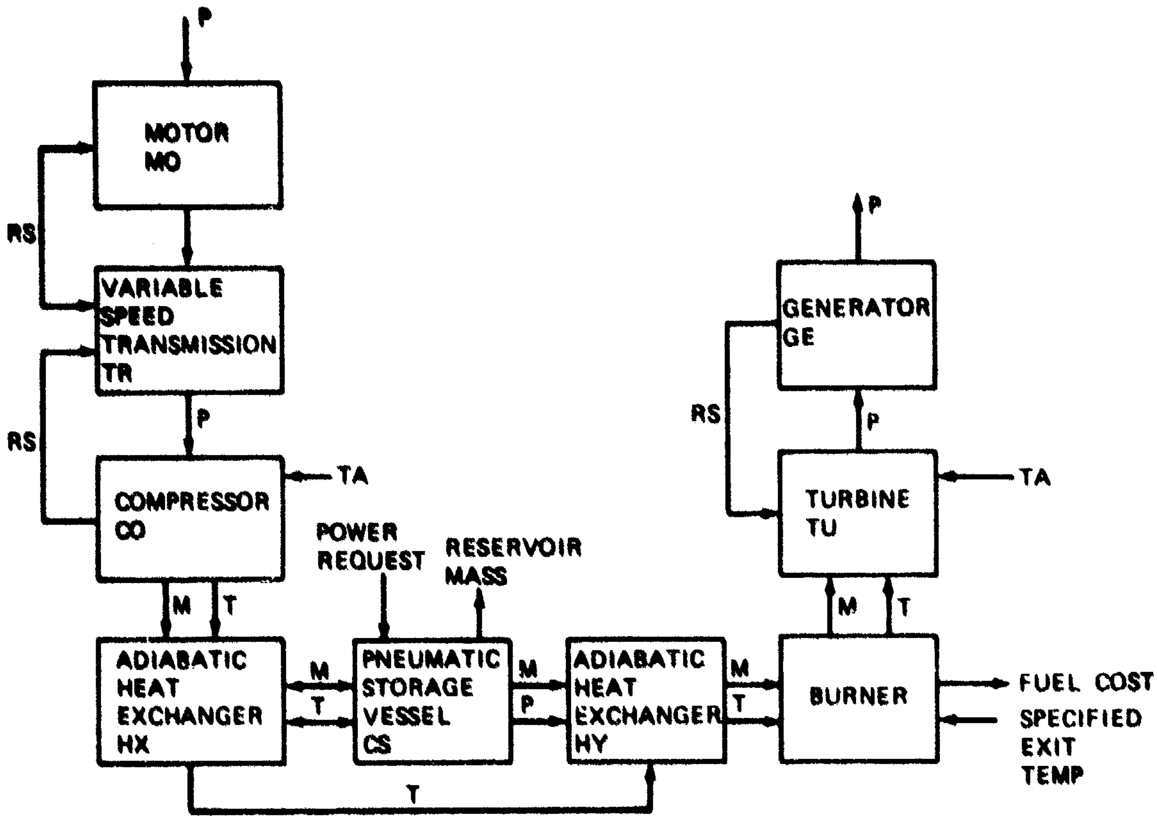

FIGURE 1.2-1 PNEUMATIC STORAGE SUBSYSTEM

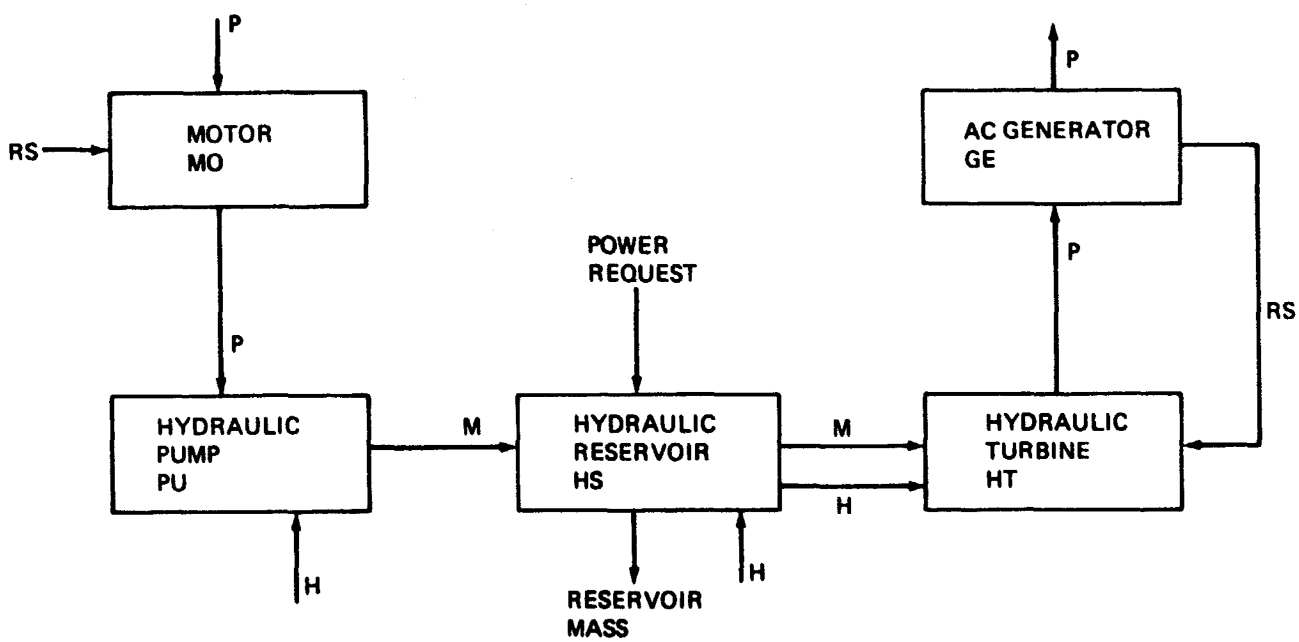

FIGURE 1.2-2 PUMPED HYDRO STORAGE SUBSYSTEM

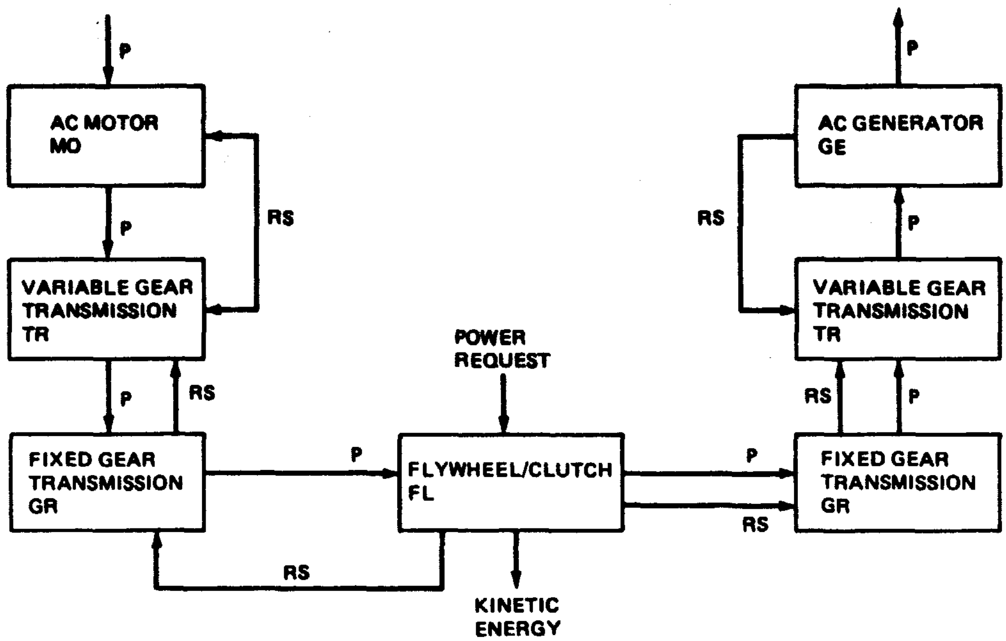

FIGURE 1.2-3 FLYWHEEL STORAGE

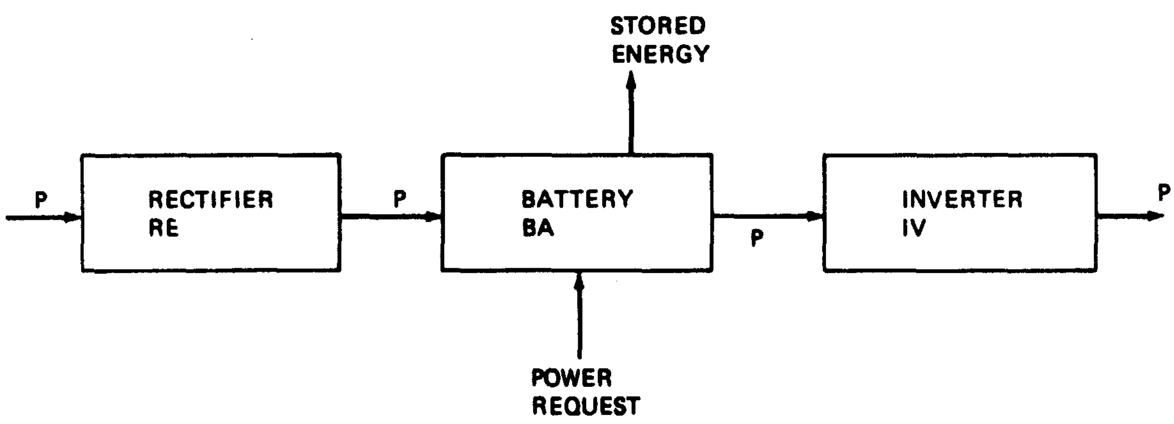

FIGURE 1.2-4 BATTERY STORAGE

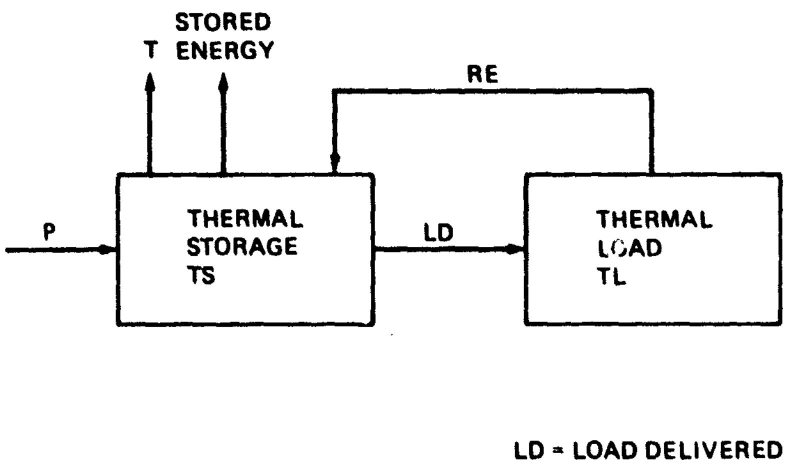

FIGURE 1.2-5 THERMAL STORAGE

TABLE 1.2-2 PARTIAL LIST OF COMPONENT INPUTS AND OUTPUTS

	SYMBOLS
P	POWER
RE	POWER REQUEST
MP	MAXIMUM POWER
RS	ROTOR SPEED
T	TEMPERATURE
TA	AMBIENT TEMPERATURE
M	MASS FLOW RATE
H	RESERVOIR HEIGHT
LD	THERMAL LOAD DELIVERED
WV	WIND VELOCITY
GR	GEAR RATIO
EF	EFFICIENCY
INT	INTERRUPT FLAG
TSO	MINIMUM AIR TEMPERATURE
PR	PRESSURE
PS	PRIORITY SEQUENCE
WY	WEEK OF YEAR
DW	DAY OF WEEK
TD	TIME OF DAY
SP	SURPLUS POWER
VAR	FILE READ VARIABLE

A total wind energy system will generally be made up of elements from a number of different subsystems (see Figure 2.1-1). In addition, the SIMWEST program can be used for models which include networks of storage subsystems of the same type or a network of wind generators.

1.2.2 Logic Components

The capability for modeling complex system control logic is provided by the power divider, power accumulator and priority interrupt components. Both the divider and accumulator operate on a priority basis. The priority interrupt is used by other system components to change the priority setting of the divider and accumulator.

The power divider has one input power port and four output power ports (not all output ports need be used for a given simulation). The divider also has an input request associated with each of its output power ports. These power requests generally come from a component with which the output power port is directly or indirectly connected. The user specifies priorities of either 0, 1, 2, 3, or 4 to be associated with each of the output ports. If the input power to the power divider exceeds that requested of the port with highest priority (priority 1) then the excess power goes to the port with the next lower priority. This process continues until either all power is distributed or all requests of non-zero priority ports are met. A port with zero (0) priority will never receive power. Such ports are included so that the port may be connected to a component but transmit power only in critical situations, say, when a battery has been in discharge state for a critical amount of time. In these situations, the connected component would have to change the zero priority setting of the power divider by use of a priority interrupt.

Two or more ports may be assigned the same priority in which case the user may specify weights to be associated with each port. Then, if there is not enough power available to satisfy all requests of equal priority, the power is divided between them in proportion to the user specified weights.

The power accumulator is similar to the divider except that instead of distributing power from a single input port between four output ports, it accumulates power from four input ports and sends it out through a single output port. The power accumulator also accepts output power requests from the component connected to its single output power port and it outputs requests for each of its input ports in order to service the output power request.

In addition to the actual power delivered to each input port, the power accumulator also accepts information as to the maximum power that can be delivered to that port. These values are used by the accumulator to determine how to distribute its power request between its four input ports. If the input power request exceeds the maximum deliverable power for the port of highest priority, then the remainder is shifted to the port with the next lower priority. This process continues until either the power request has been completely distributed between the highest priority input ports or all input ports have requests equal to their maximum deliverable power. An example illustration of the use of power dividers and power accumulators is given in Figure 1.2-6. It is seen that power from the turbine/generator is distributed with highest priority (priority 1) going to the power accumulator that services load 1. Since the power accumulator servicing load 1 has its priority 1 input port connected to the power divider, it will try first to satisfy load 1 from the turbine/generator and then from the utility. Thus, if power from the turbine/generator does not exceed that required by load 1, all power will flow to load 1. If there is power left over, it will be used to satisfy the request from the battery. Finally, if the battery is full or if its charging rate is met, then the excess power goes to the flywheel. The battery is connected (through the rectifier) to the wind turbine and also has a priority zero connection to the utility. Thus, if the battery remains in a discharge state for more than a specified amount of time, it can change the utility priority (from 0 to 1) to receive the needed power.

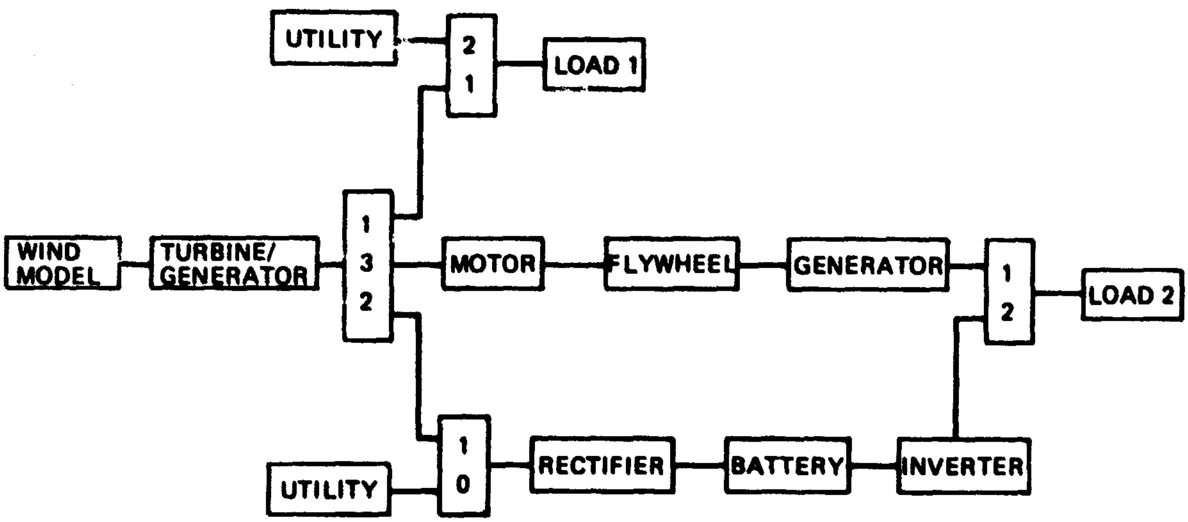

FIGURE 1.2-6 EXAMPLE OF POWER DIVIDER & ACCUMULATOR USE

Also in Figure 1.2-6, we see that load 2 prefers to draw power from the flywheel before turning to the battery. This configuration tends to keep the flywheel as discharged as possible, using it primarily as a means to absorb large influxes of power.

Figure 1.2-6 is a rather simple configuration used for illustrative purposes. A more complex configuration is shown in Figure 2.1-1.

1.2.3 SIMWEST Output

There are three basic forms of SIMWEST output to facilitate the analysis of wind energy storage systems; line printer plots, histograms of system variables and time sequenced output of variable values. To enhance the usefulness of these outputs, each SIMWEST library component is associated with a number of output variables. Prior to simulating a given system the user may select to have the independent variable be time or any of the other variables. For example, he may want to plot the energy of pneumatic storage as a function of time and/or as a function of temperature. If the user wants a time sequenced listing of all variable values, he just specifies the time step between printouts. The listing of all variables has proven to be a useful tool in understanding the performance of the storage system under consideration and a valuable aid in validating the system design.

1.3 TESTING

Sections 2 and 3 describe two simulation studies which were defined by NASA-Lewis to test the SIMWEST program. They provide an excellent test of its ability to model complex systems and in particular complex control logic. The simulation studies also test the usefulness of the program for doing in depth parameter studies and provide a means for checking the accuracy of the program by comparing simulation results with available empirical data and with the results of other studies.

Prior to performing the simulation studies and throughout its development the SIMWEST program was systematically tested. First components were grouped into simple systems and simulations were performed. During these simulations various system parameters were driven so as to force the individual components through every normal program path and to assure that all component outputs assume a wide range of values. The number of components and the number of ways they can be connected makes it impossible to exercise every combination, however, the subsystem groupings that were used were representative of the expected program usage.

Before the testing, the biggest unknown in the SIMWEST definition was the impact of the logic components (power dividers, power accumulators, etc.) on system convergence. Use of these logic components gives the user considerable flexibility in specifying system logic and every effort was made to minimize their effect on system convergence. All physical components output special information variables which have the sole purpose of speeding the convergence of control logic variables. However, it was still extremely difficult to estimate, apriori what the results of such components would be, particularly with regard to complex systems. Thus, it was particularly reassuring to find that even on very complex systems, such as represented by the NASA-Lewis test case, convergence of logic variables was quite rapid. Convergence generally took place in less than six iterations per simulation time step.

A key requirement of the SIMWEST program was that the amount of training required for its use be minimal. Considerable effort has been made to ensure this is the case. That this is indeed the case is evident by the fact that the two NASA defined simulation tests were performed by an analyst who had just joined the SIMWEST development team and who had no previous experience with SIMWEST or the original EASY program.

In terms of computer efficiency, it was found during the testing that the program exceeded original expectations. As an example, the year simulations used in the NASA defined parameter study took less than 420 CPU seconds on the CDC 6600. The very complex NASA defined test case involved simulating only a one week period of time. It took less than 50 CPU seconds on the 6600. If this time is used to predict the CPU time for a year simulation and account is taken of the fact that most of the CPU associated with I/O is independent of run length, then one would expect the CPU time required to simulate one year for the test case to be 1680 CPU seconds on the 6600. It is estimated that CPU time on the UNIVAC 1100/40 will be approximately two to three times as great as that on the 6600.

1.4 OBSERVATIONS

During the testing it became obvious that while the user need not be a SIMWEST expert or software specialist to make efficient use of the program, he should thoroughly think through and be familiar with the characteristics of the system he wants to simulate. Component models, if not carefully specified, may perform in unexpected ways. They will perform as they were intended but the user must be careful that what he actually specifies is what he really wants. Further, if the systems logic is not well thought out, the resulting system can become severely out of balance and all subsystems may not be fully utilized. (An example of this is given in the test case described in Section 2.)

A number of useful procedures were developed during the simulation studies. First it was found that when simulating a complex system, it is best to develop and test one storage subsystem at a time. This allows problems or unexpected results to be isolated and understood prior to the introduction of the more complex characteristics associated with the total system.

Further, when making a year simulation run, it is best to break it into twelve monthly simulations. Thus, measures of performance such as plots, histograms and performance statistics are available on a monthly basis. In addition to giving better visibility of the systems actual performance, this helps limit the job core size. The twelve monthly simulation can be submitted as a single run with the results of a given month acting as initial conditions for the next month. The user only needs to submit new data cards for data which changes from one month to the next.

It was also found during the simulations that the use of FORTRAN Statements in the model definition is very useful for creating special input to system components and for defining parameters to be plotted or statistics to be printed. The use of FORTRAN statements is simple and should be encountered early in SIMWEST applications.

1.5 FUTURE APPLICATION

Although the present application of the SIMWEST program is to wind energy systems, it could be just as advantageously applied to other applications where energy storage might be utilized. Such areas include solar heating and cooling and photovoltaic systems. For these applications additional components representing the photocell, thermal collector, etc. would have to be written, or adapted from existing software and added to the SIMWEST library.

However, most of the required components modeling the total system are presently available in the SIMWEST library. Incorporating solar heating and cooling models and/or photovoltaic models into the SIMWEST program would also allow the analysis of hybrid systems containing different combinations of all three solar energy sources.

The present SIMWEST program has a level of detail consistent with a fifteen minute step size. This is ideal for performing analyses which span time intervals on the order of one year. However, this means that many system components, such as the electrical components, are modeled in terms of their steady state response. The SIMWEST program could also be used to analyze such things as the response of the wind turbine to wind gusts, the impact of large wind turbines on the frequency and voltage control required by small electric utilities and other highly transient effects. However, to do so would require the addition to the SIMWEST library of more detailed component models, particularly for the electrical components.

2.0 TEST CASE

The first of the two NASA defined simulation studies is described below. It is a "test case" of a relatively complex wind energy system containing five different storage subsystems and three separate loads. It was defined to demonstrate SIMWEST's flexibility and ease of handling complex systems. The other NASA defined simulation study is described in Section 3.

2.1 SYSTEMS OVERVIEW

A schematic diagram of the test case is given in Figure 2.1-1. It contains all five types of storage subsystems available in the SIMWEST library and three separate load components. The wind turbine being modeled has a blade diameter of 48.76 meters (160 feet). It is designed for a mean wind speed of 9.39 meters/sec. (21 mph). The cut in speed and rated speed are 2.68 m/s (6 mph) and 12.67 m/s (28.35 mph) respectively. Rated power of the turbine generator is 790 kw. Wind speeds were randomly generated during the simulation using the random component density function shown in Figure 2.1-2 and a mean daily component profile shown in Figure 2.1-3. The average total load on the system is 264 kw. It is made up of controls, domestic, and thermal loads. The control load is assumed to be constant while the domestic load varies stochastically with the average daily and weekly profiles shown in Figure 2.1-4. The average domestic load is 186 kw. The thermal load varies as a function of ambient temperature and time of day. Its average value is 62 kw. One utility shown in Figure 2.1-1 is labeled as a load but actually it serves only as a place to dump surplus wind energy (when all storage is full) and a means of keeping track of the amount of energy dumped.

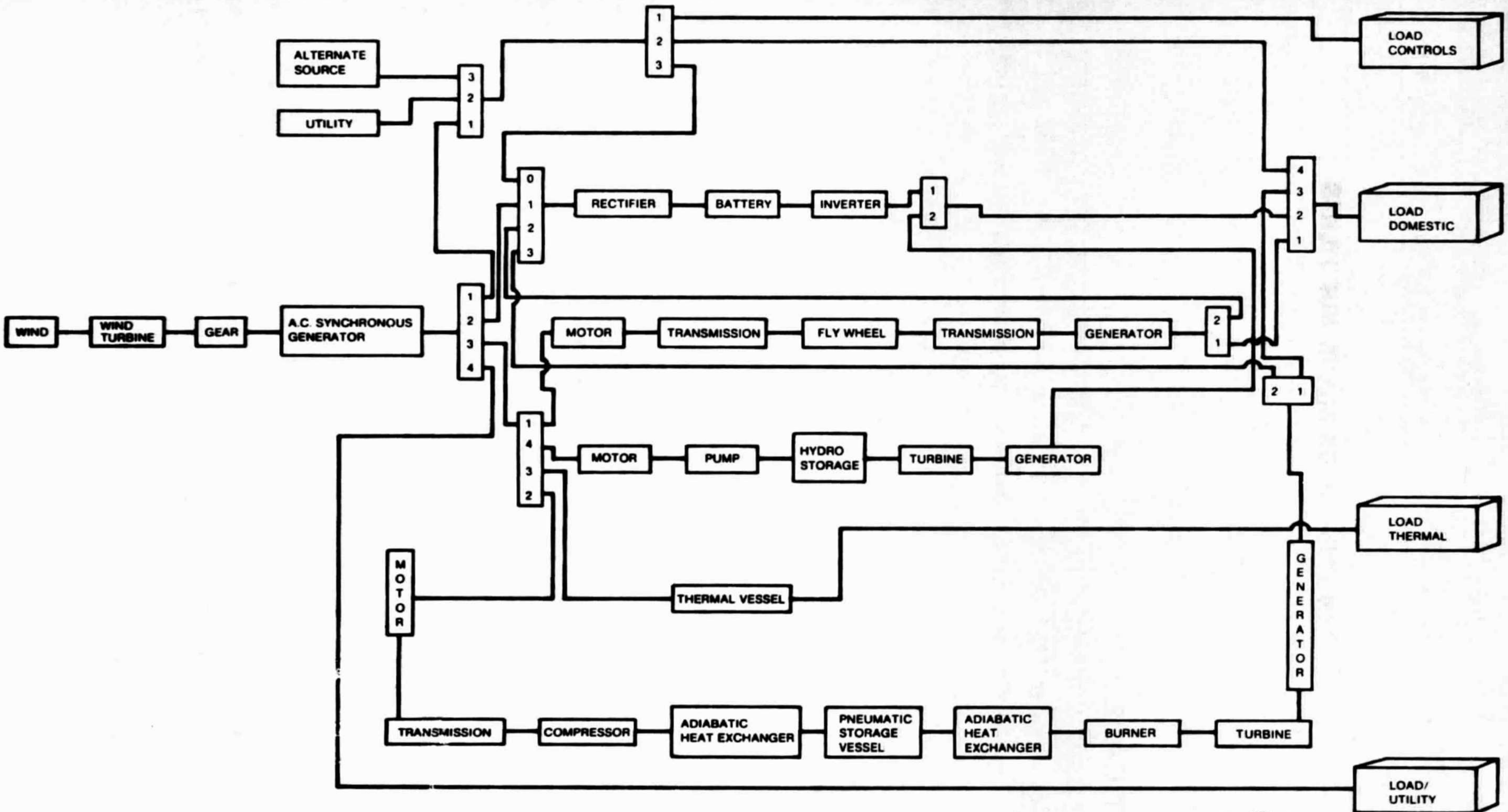

FIGURE 2.1-1 SIMWEST TEST CARE

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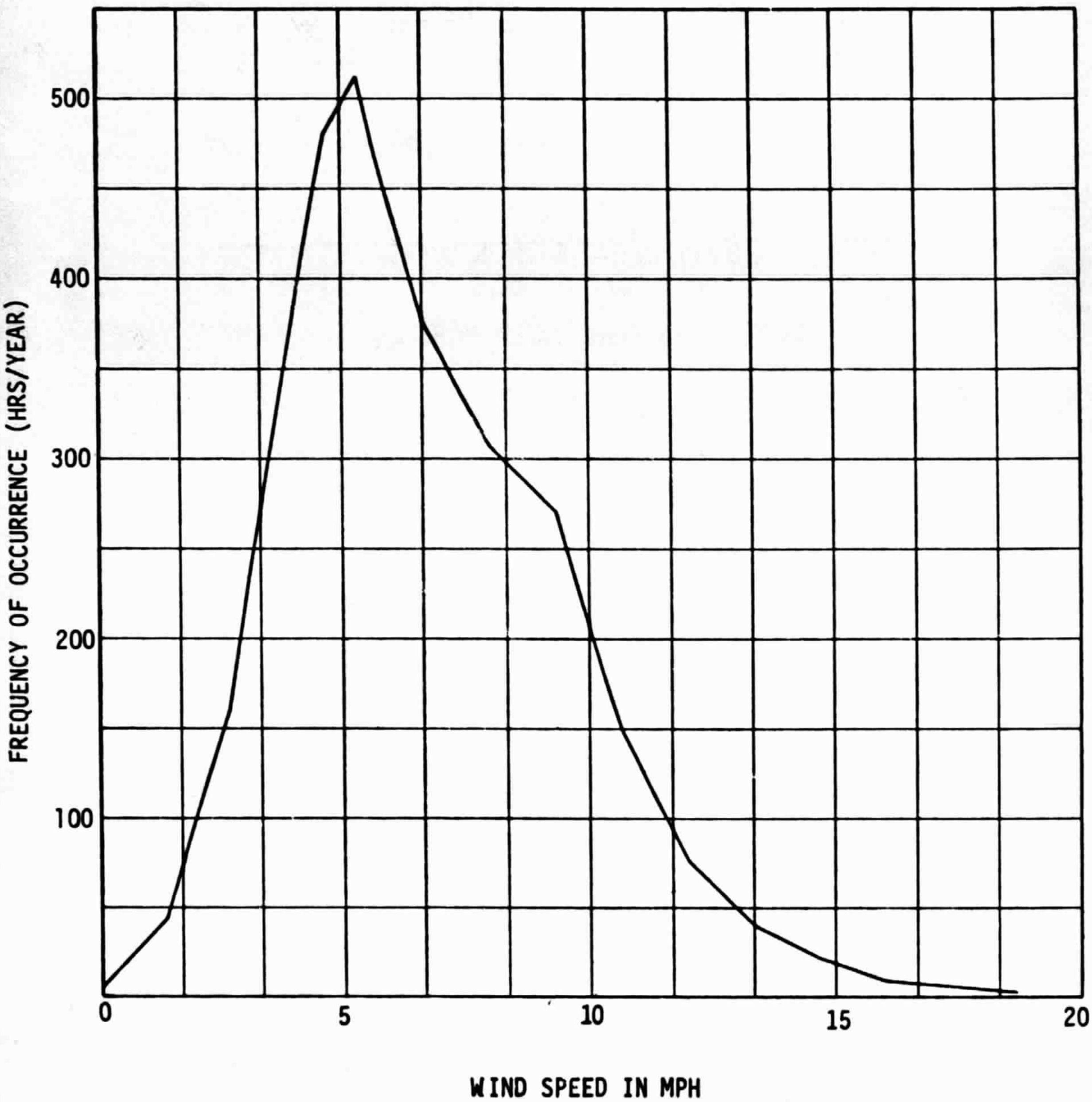


FIGURE 2.1-2 RANDOM WIND COMPONENT DENSITY FUNCTION

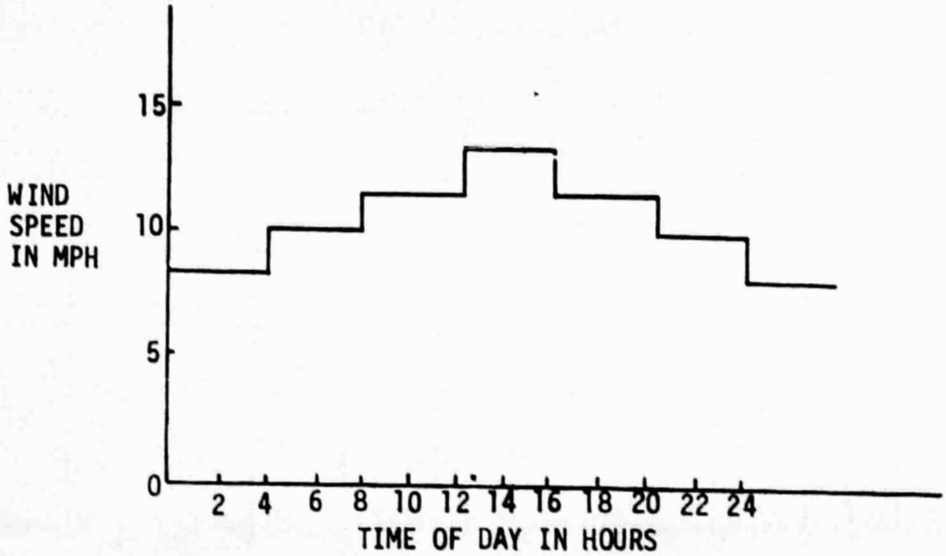
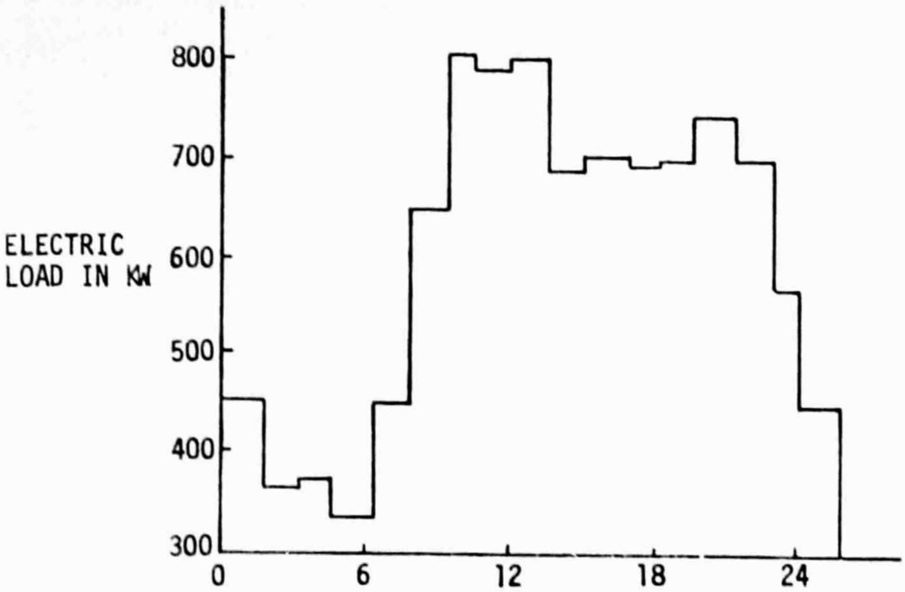


FIGURE 2.1-3 WIND DAILY PROFILE



DAILY DOMESTIC LOAD PROFILE

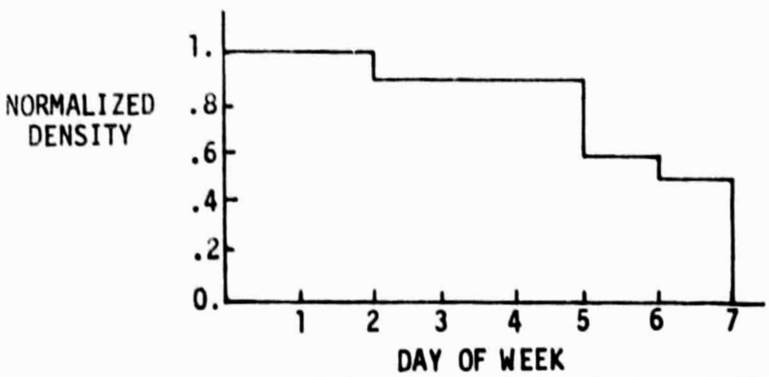


FIGURE 2.1-4 WEEKLY DOMESTIC LOAD PROFILE

The total of all five storage systems has a storage capacity of 11240 kwh. The battery provides 1000 kwh of this, and thus can supply the electrical load for up to 5.37 hours. It can accept energy from the wind turbine at a rate of 80 kw. The storage capacity and power rating of the five storage subsystems is given in Table 2.1-1.

The untitled rectangular components in Figure 2.1-1 represent power dividers and power accumulators. They perform the system control logic and are discussed in detail in Volume II. The power accumulators and dividers are arranged in such a way that the controls load always obtains power from either wind system or from the utility. It has first priority on power from the wind. When power output from the wind exceeds that required by the controls load, excess power goes first to the domestic load and then to the battery. If excess power exceeds the charge rate of the battery, the remainder goes to the flywheel, pneumatic storage, thermal storage and pumped hydro storage, in that order of priority. When all storage systems are full, excess power goes to the utility.

The above described set of storage priorities are established by specifying priority number for each port of the power divider and power accumulator. However, any storage device has the capability of temporarily changing these priorities if it deems it necessary to keep it in the proper operating state. For example, after the battery has been in a discharged state for a specified interval of time, it must obtain power to avoid internal damage.

2.2 TEST CASE SPECIFICATION

The input data for the SIMWEST model generation program is given in Figure 2.2-1. These cards set up the topology of the system to be simulated, and specify the connections between the model components. They do not specify individual component characteristics such as capacities, maximum charging rates, etc. The data creates a Fortran model which contains 50 components, uses 20 lookup tables, and has over 800 input and output variables.

TABLE 2.1-1 CHARACTERISTICS OF STORAGE SUBSYSTEMS

Storage Subsystems	Rated Power (kw)	Capacity (kwh)
battery	80	1000
flywheel	400	400
pneumatic	94	3820
thermal	200	2880
hydro	188	3140

```
MODEL DESCRIPTION        INTEGRATED TEST CASE
LOCATION=31       TI
LOCATION=2        WD      INPUTS=TI
LOCATION=32       WT      INPUTS=WD
LOCATION=52       GR      INPUTS=WT
LOCATION=46       GE      INPUTS=GR
FORTRAN STATEMENTS
      INTPI5=AMAX1(INTFL,INTTS,INTCS,INTHS)
LOCATION=4        PI5
LOCATION=16       PD1     INPUTS=GE(P,2=MP),GE(2,0),PA1(1,1),PA2(1,2),
                                 PD5(RE,0=RE,3),PIA(2,2),PI5(2,3)
LOCATION=38       UT2     INPUTS=PA1(2,2)
LOCATION=7        UTC     INPUTS=PD1(SP=P,0)
LOCATION=48       UT1     INPUTS=PA1(3,2)
LOCATION=19       PA1     INPUTS=PD2(0,0)
LOCATION=70       PD2     INPUTS=LOC(1,1),PA4(4,2),PA2(4,3)
LOCATION=71       LOC     INPUTS=TI
LOCATION=130      LOD     INPUTS=TI
LOCATION=311      PD5     INPUTS=TS(RE,2=RE,3),PIT(2,3),FL(RE,2=RE,1)
                                 HS(RE,2=RE,4),PIH(2,4),CS(RE,2=RE,2)
                                 PIC(2,2),PD1(P,3=P,0),PIF(2,1)
LOCATION=262      MO1     INPUTS=PD5(1,1)
LOCATION=212      TRI     INPUTS=MO1,FL(RS=RS,2)
LOCATION=215      FL      INPUTS=TRI,PD4(RE,0=RE)
LOCATION=218      TRO     INPUTS=FL,GE2(RS=RS,2)
LOCATION=268      GE2     INPUTS=TRO
LOCATION=101      PD4     INPUTS=GE2,PIF(4,1),PIG(4,2)
LOCATION=234      PIF     INPUTS=FL
LOCATION=254      PIG     INPUTS=FL
LOCATION=315      TS      INPUTS=TL,PD5(3,1)
LOCATION=333      PIT     INPUTS=TS
LOCATION=319      TP      INPUTS=TI
LOCATION=317      TL      INPUTS=TP(TA,2=TA),TI
LOCATION=431      PU      INPUTS=PD5(4,1)
LOCATION=433      HS      INPUTS=PU,PA3(2,1)
LOCATION=463      PIH     INPUTS=HS
LOCATION=435      HT      INPUTS=HS
LOCATION=459      GE4     INPUTS=HT
LOCATION=501      MO2     INPUTS=PD5(2,1)
LOCATION=503      TR3     INPUTS=MO2,CO(RS=RS,2)
LOCATION=505      CO      INPUTS=TR3,TP
LOCATION=507      HX      INPUTS=CO,TP,CS
LOCATION=528      CS      INPUTS=HX,PD3(RE,0=RE,1)
LOCATION=509      HY      INPUTS=CS,HX
LOCATION=545      PIC     INPUTS=CS
LOCATION=559      BN      INPUTS=HY(2,1)
LOCATION=555      TU      INPUTS=BN,CS(PR,2=PS),TP
LOCATION=576      GE3     INPUTS=TU
LOCATION=123      PD3     INPUTS=GE3,PIA(2,2),PA2(RE,3=RE,2),PA4(RE,3=RE,1)
LOCATION=121      PA2     INPUTS=PD4(2,2),PD3(P,2=P,3),BA(RE,2=RE,0)
                                 PIC(4,3),PIA(2,2),PIB(2,4)
LOCATION=171      RE      INPUTS=PA2
LOCATION=168      BA      INPUTS=RE,PA3(RE,1=RE,1)
LOCATION=154      PIB     INPUTS=BA
LOCATION=143      PIA     INPUTS=BA
LOCATION=156      IV      INPUTS=BA
LOCATION=136      PA3     INPUTS=IV,GE4,PIB(4,1),PIH(4,2)
LOCATION=128      PA4     INPUTS=PD3(P,1=P,3),PD4(1,1),PA3(0,2)
                                 LOD(1,0),PIC(4,3),GE3(P,2=MP,3)
LOCATION=371      HGW     INPUTS=GE(P,2=FIN)
LOCATION=372      HGB     INPUTS=BA(PE=FIN)
LOCATION=374      HGT     INPUTS=TL(PC=FIN)
FORTRAN STATEMENTS
      FINHGD=100.*(P2 IV+1.E-6)/(PU PA4+1.E-8)
LOCATION=373      HGD
LOCATION=9        CM
END OF MODEL
PRINT
```

FIGURE 2.2-1 MODEL GENERATION INPUT DATA

As an aid to the user in validating his topology description, the SIMWEST program generates line printer schematics from the description of Figure 2.2-1. An example of the schematic for one section of the test case is given in Figure 2.2-2.

After the user satisfies himself that the model topology is correct, he specifies the parameters establishing the characteristics of the individual components using simulation data cards. The data cards for the test case are given in Figures 2.2-3 through 2.2-5. In addition to specifying the parameters describing the individual components these cards specify the length and step size of the simulation, the variables to be plotted, and the time points at which all variables will be printed. Since the test case is only intended to demonstrate the flexibility of SIMWEST and its ease of modeling complex systems, the period of time selected for the simulation was one week and the simulation step size was set at one hour. Further, output variables were selected for plotting on the basis of illustrating the different capabilities and the general potential of the plotted output for use in system evaluation.

2.3 SUMMARY OF RESULTS

This section gives a summary of the results obtained from the simulation of the test case shown in Figure 2.1-1. One should be cautioned about drawing conclusions from these results. The test case was selected to demonstrate the use of the program and is not necessarily a realistic or rational design from the standpoint of making optimal use of storage subsystems. Furthermore, the simulation covers only a one week period, and therefore the resulting statistics may not be representative.

2.3.1 Wind Power

Figure 2.3-1 gives the histogram of the wind speed that was generated during the simulation. It is seen that the average wind speed is 8.61 meters/sec. (19.25 mph). This is .78 m/s (1.75 mph) lower than that for which the rotor

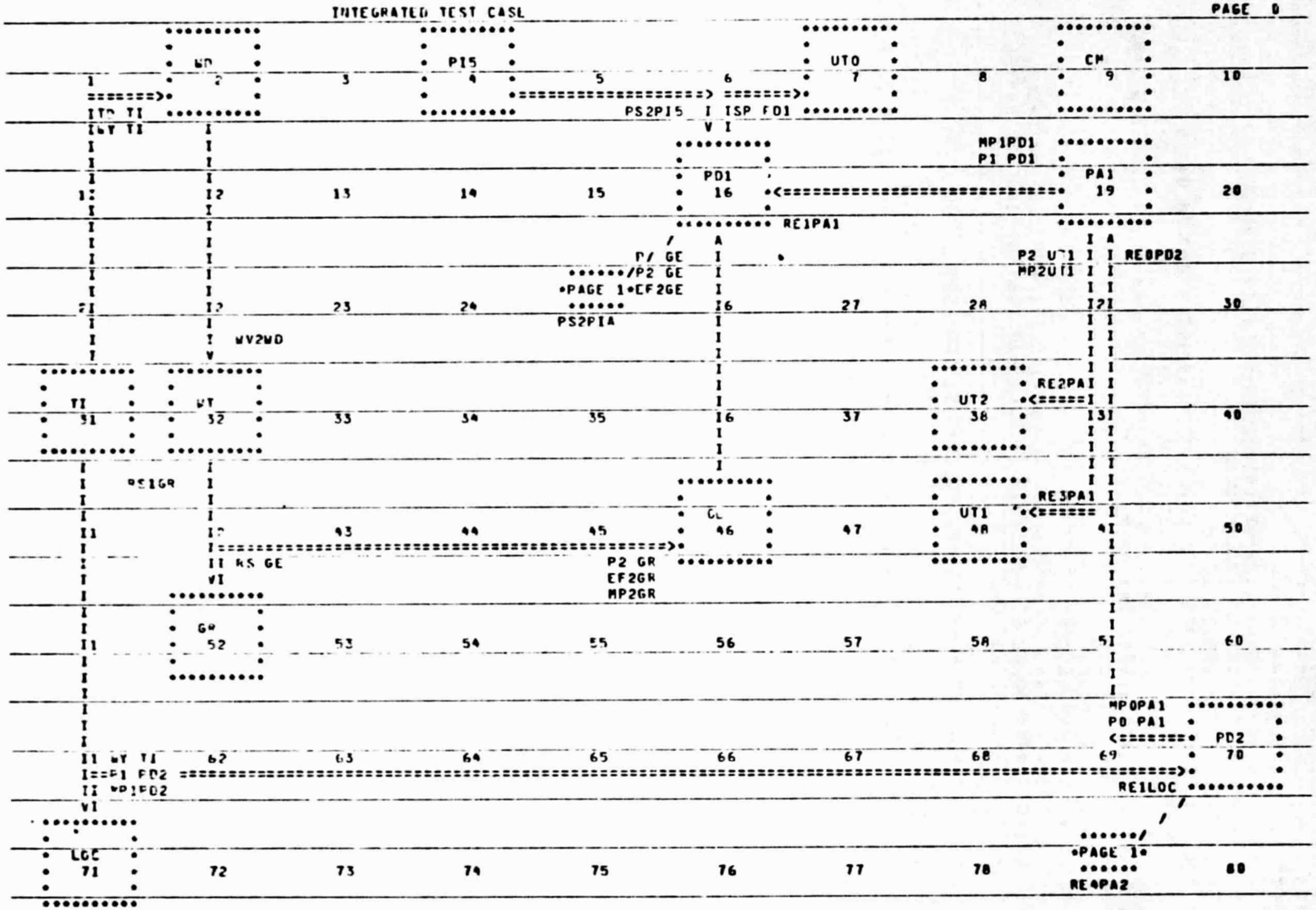


FIGURE 2.2-2 LINE PRINTER SCHEMATICS (PAGE 0 ONLY)

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```
PARAMETER VALUES
MP3PA3=0,MP4PA3=0,MP PD5=1.E8,EF PD5=1
CR CM=18.,LE CM=20.
PS1PI5=3
CYCLES=6.01,DLINES=-10.
VO WT=21,BR WT=80,EC WT=1,CPMWT=.41,CC WT=16000,CM WT=500
MP1GR=1.E3,EF1GR=1,CC GR=100,CM GR=0
RAPGE=2000,CC GE=1000,CM GE=50
BS UT2=0,CB UT2=.016,MP1UT2=1.E8,CP UT2=.032,CC UT2=0,CM UT2=0
BS UT0=0,CB UT0=.016,MP1UT0=1.E8,CP UT0=0.032,CC UT0=0,CM UT0=0
BS UT1=0,CB UT1=0,MP1UT1=1.E4,PC UT1=0,CP UT1=.03,CC UT1=200,CM UT1=50
EF1PA1=1,EF2PA1=1,EF3PA1=1,EF1PA4=1
RAPRE=200,CC RE=200
LO1LOC=15.,VE LOC=0.
FLOHGW=.01,FUPHGW=640.01
FLOHG3=100.,FUPHG3=1060.,FLOHGT=0.,FUPHGT=100.,FLOHGD=0.,FUPHGD=100.
VO BA=100,RAPBA=80,E1 BA=1000,EDEBA=100,DT BA=10,CC BA=2000,CM BA=100
PS1PIA=2,PS1PIB=0,PS3PIB=1
RAPIV=200,CC IV=0
NC LOD=.0016,CT LOD=4,MN LOD=0,STDLOD=7,VE LOD=.023
RS MO1=1750,RAPMO1=1000,CC MO1=500,CM MO1=0
RS1TR1=1750,CC TR1=100,CM TR1=0
PR FL=.02,HM FL=3372,RF FL=3.4,SR FL=.4,WT FL=24000,KF FL=1.3E-5,ZE FL=.1
C2 FL=0
RAPFL=400,E0 FL=40,E1 FL=400,EDEFL=20,CM FL=300,CC FL=2000
CC TR0=100,CM TR0=0
RAPGE2=2000,CC GE2=1000,CM GE2=50
PS1PIF=1.,PS3PIG=2.
TS TS=10,VO TS=110,PD TS=100,MFMTS=10000,LE TS=30,DH TS=.05
TO1TS=200,TO2TS=100,TM1TS=800,TDETS=40
PS1PIT=3.
VE TL=.023,NC TL=40
CT TP=12,MN TP=0,STDTP=5
H1 PU=200
AS HS=3600,MDRHS=80,MO HS=4.E5,H1 HS=200,MDEHS=4.E5,,LE HS=30
CM HS=1000
PS1PIH=4.,PS3PIH=2.
RAPGE4=2000,CC GE4=1000,CM GE4=50
RS MO2=1750,RAPMO2=1000,CC MO2=500,CM MO2=0
RS1TR3=1750,CC TR3=100,CM TR3=0
ST HX=32,BE HX=.001,PD HX=150,TEMHX=350,H  HX=0,TMTHX=700,L  HX=12,LE HX=30
LE CS=30,NU CS=.003,MDECS=1.E4,MD CS=4500,TM CS=125,TEMCS=350,CM CS=100
PS1PIC=2.,PS3PIC=3.
T3 BN=600,LE BN=30
RAPGE3=2000,CC GE3=1000,CM GE3=50
TABLE,PLOTRI=5,4
0.5,1,1.5,1.72
0,400,900,1100,1300
0,15,18,18.5,20
0,10,11,11.5,12
0,10,10,10.5,11
0,6,5.5,7,10
TABLE,PLOTRO=5,4
.5,1,1.5,1.72
0,400,900,1100,1300
0,16,18,18.5,20
0,10,11,11.5,12
0,10,10,10.5,11
0,6,6.5,7,10
TABLE,CLOFL=3,3
-1000,  0,  1000
```

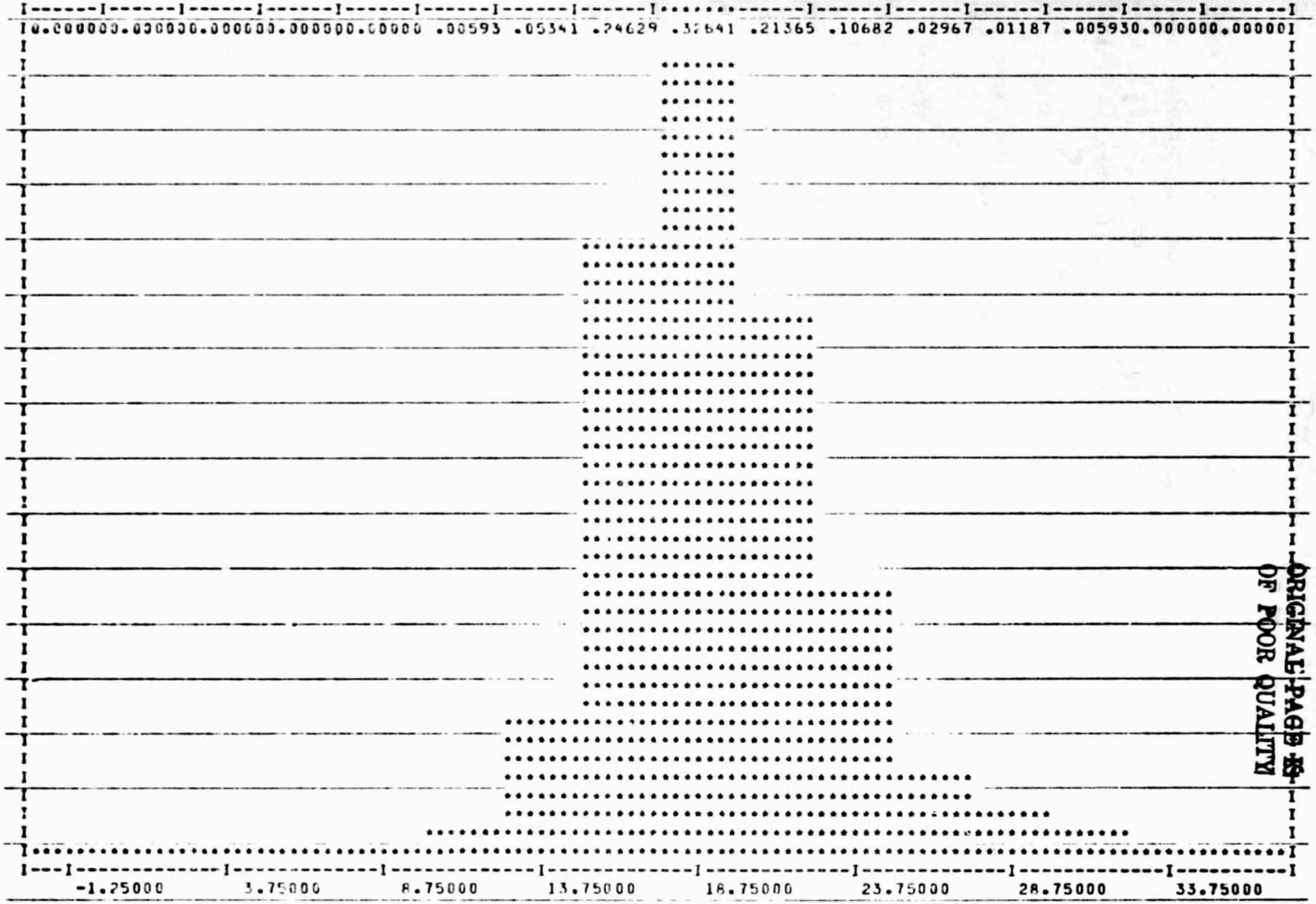
FIGURE 2.2-3 TEST CASE DATA CARDS (PART 1)

```
2000,4000,7000
2.8,     7.4,    15
 .9,     2.5,     5
2.6,     7.2,    15
TABLE,CL1FL=3
1000,4000,7000
 .167,     2.4,     4
TABLE,PY WD=13
0.,4.33,8.67,13.,17.33,21.67,26.,30.33,34.67,39.,43.33,47.67,52.
65,67,68,65,61,56,51,49,49,52,56,61,65
TABLE,PD WD=7
0,4,8,12,16,20,24
8.33,10,11.67,13.33,11.67,10,8.33
TABLE,DF WD=16
0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15
5,44,150,380,490,512,440,375,307,270,148,76,40,22,9,3
TABLE,PD LOD=17
0,1.5,3,4.5,6,7.5,9,10.5,12
13.5,15,16.5,18,19.5,21,22.5,24
450,360,372,330,450,660,810,798,804
690,708,699,702,750,708,570,450
TABLE,PW LOD=7
1,2,3,4,5,6,7
1,1,.9,.9,.9,.6,.5
TABLE,PY LOD=6
0,10,20,30,40,52
226,194,180,174,194,226
TABLE,PLOGR=3
10,50,130
.15,.6,1.3
TABLE,HT TS=6
.0147,.0645,.0821,.0909,.1115,.1525
200,565,555,610,610,850
TABLE,PD LOC=17
0,1.5,3,4.5,6,7.5,9,10.5,12
13.5,15,16.5,18,19.5,21,22.5,24
450,360,372,330,450,660,810,798,804
690,708,699,702,750,708,570,450
TABLE,PW LOC=7
1,2,3,4,5,6,7
1,1,.9,.9,.9,.6,.5
TABLE,PY LOC=6
0,10,20,30,40,52
226,194,180,174,194,226
TABLE,PLOTR3=5,4
0.5,1,1.5,1.72
0,400,900,1100,1300
0,16,18,18.5,20
0,10,11,11.5,12
0,10,10,10.5,11
0,6,6.5,7,10
TABLE,TLOTL=4
0,32,60,100
4.,2.,1.5,1.
TABLE,TWTTL=4
0,6,18,24
.4,1.,1.,.4
TABLE,PD TP=9
0,3,6,9,12,15,18,21,24
46,45,48,55,62,64,56,48,46
TABLE,PY TP=5
```

FIGURE 2.2-4 TEST CASE DATA CARDS (PART 2)

```
0,13,26,39,52
40,59,75,65,40
INITIAL CONDITIONS, KE FL=380,E  CS=370,MS CS=3.3E5,EC1HX=2600,EC2HX=1700
                  MA HS=1.6E6,E  TS=400,PE BA=950
PRINTER PLOTS,PLOT ON
DISPLAY1
PE BA,VS,TIME
E  TS,VS,TIME
MA HS,VS,TIME
E  CS,VS,TIME
KE FL,VS,TIME
PLOT OFF
DISPLAY2
T2 CS,VS,TIME
INTCS,VS,TIME,YRANGE=-5,5
P2 GE,VS,TIME
P1 PD5,VS,P2 GE
P1 PD5,VS,PE BA
DISPLAY3
FD BN,VS,TIME
T2 HX,VS,M2 HX
RE1LOD,VS,TIME
RE TL,VS,TIME
P2 GE,VS,WV2WD
DISPLAY4
LO2LOD,VS,TIME
RE TL,VS,TIME
WV2WD,VS,TIME
TINC=1.,TMAX=168.,PRATE=16,PRINT CONTROL=3,INT MODE=3,OUTRATE=2
TITLE=INTEGRATED SYSTEM MODEL TEST
SIMULATE
```

FIGURE 2.2-5 TEST CASE DATA CARDS (PART 3)



HISTOGRAM FOR 337 SAMPLES MEAN= 19.24398 STANDARD DEV.= 3.17734

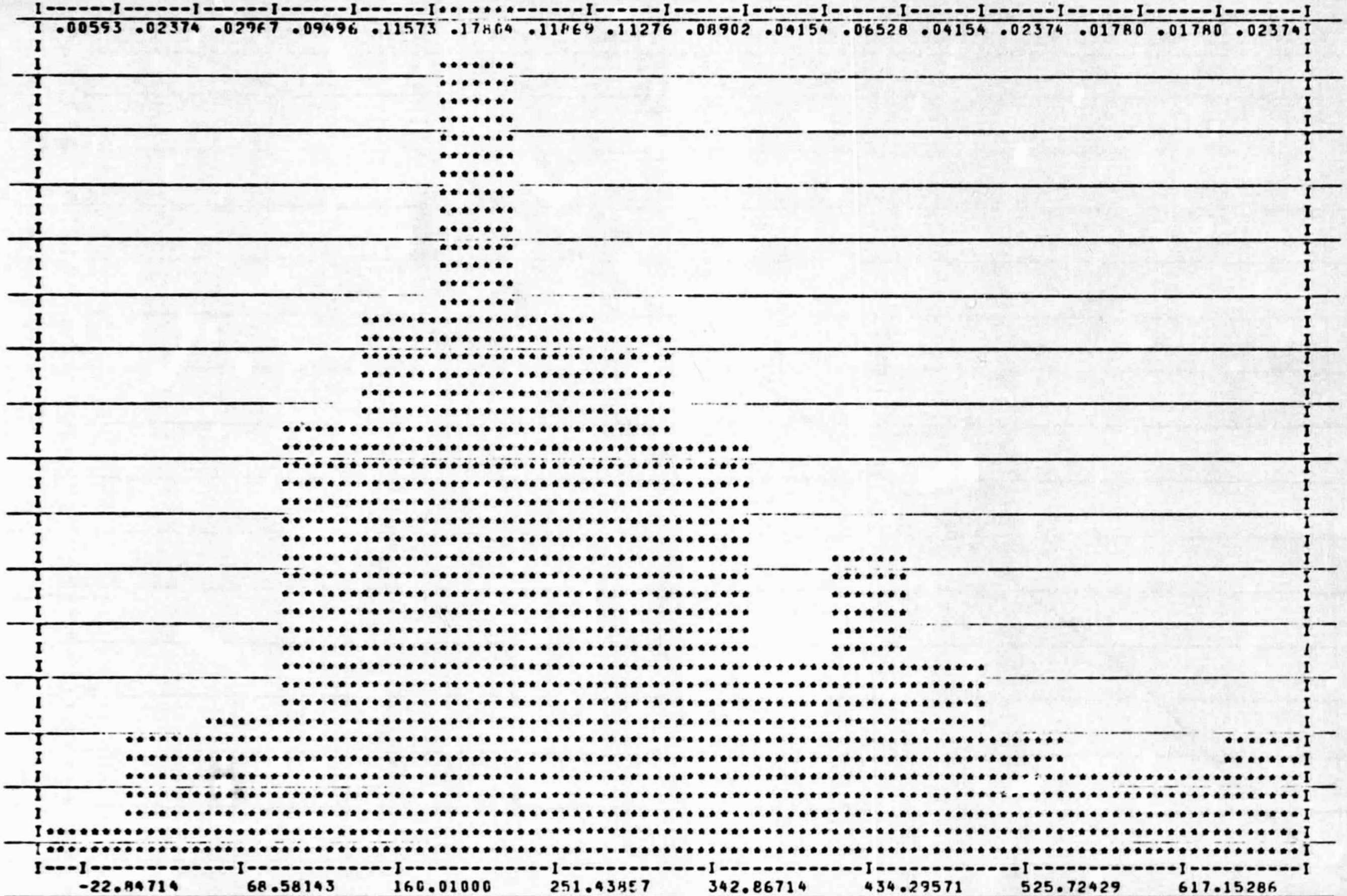
FIGURE 2.3-1 WIND SPEED HISTOGRAM (MPH)

was designed. Figure 2.3-2 is a histogram of the power that resulted from the wind. The mean power is 277 kw. This compares with an average total load of 264 kw. Figure 2.3-3 plots the power generated vs. wind speed. It is seen that at times the power reaches the rated value of 790 kw (when the wind is in excess of 28 mph).

2.3.2 Storage Subsystems

The one week time histories of the five storage subsystems are given in Figure 2.3-4. Notice that the scale on the abscissa should be multiplied by ten to get hours. On the other hand, the scales on the ordinates each have their own multiplicative factor. Thus, for example, the scale for the battery has a maximum of 1000 kwh. From Figure 2.3-4 it is seen that, in general, storage is drained during mid week and builds back up on the weekend. As one would expect, the flywheel shows large fluctuations. This is due to its ability to absorb energy at a high rate and to being the first priority energy source for the domestic load. The battery on the other hand has a lower charge rate but is a second priority source for the domestic load. Thus it remains pretty much in a discharged state during the week. This seems to indicate that the overall control philosophy should be adjusted. The hydro storage tends to discharge its initial charge the first day of operation and is never able to build back up even on the weekend. This can be attributed to the fact that it has the lowest priority of all storage subsystems for charging but has a relatively high priority for discharging.

Figures 2.3-5 through 2.3-7 gives the temperature of the pneumatic storage vessel, the fuel consumption rate of the burner and the outlet temperature of the heat exchanger. Plots such as these are not only useful in monitoring system performance but are also valuable in validating the system definition. It is also useful to make cross plots between different output variables. A cross plot of the power into the flywheel versus the power output by the wind and the battery state of charge is given in Figure 2.3-8 and Figure 2.3-9, respectively. As one would expect, there is good correlation between the wind



HISTOGRAM FOR 337 SAMPLES MEAN= 277.13942 STANDARD DEV.= 150.07442

FIGURE 2.3-2 WIND POWER HISTOGRAM (KW)

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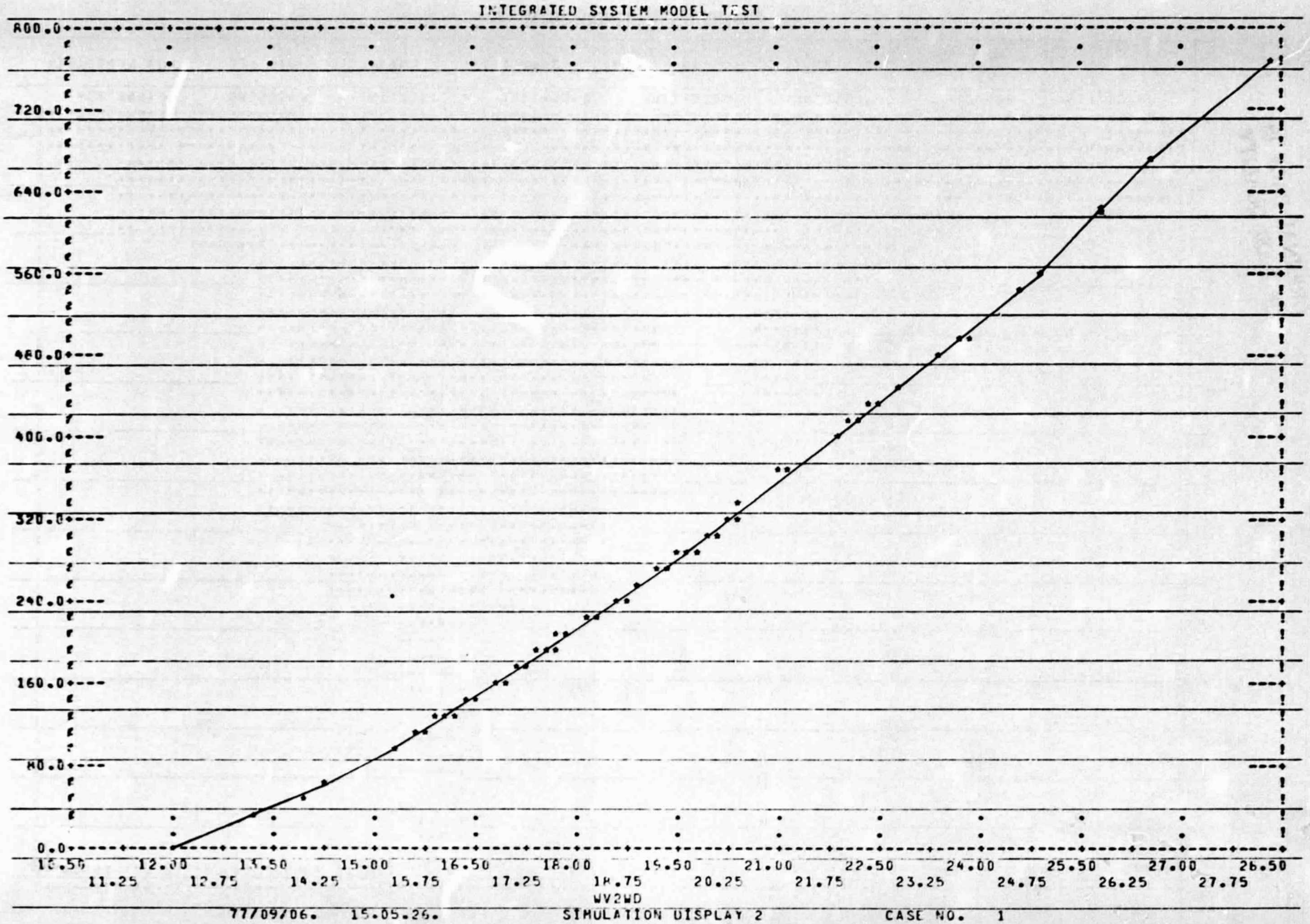

FIGURE 2.3-3 GENERATOR POWER (KW) VS WIND SPEED (MPH)

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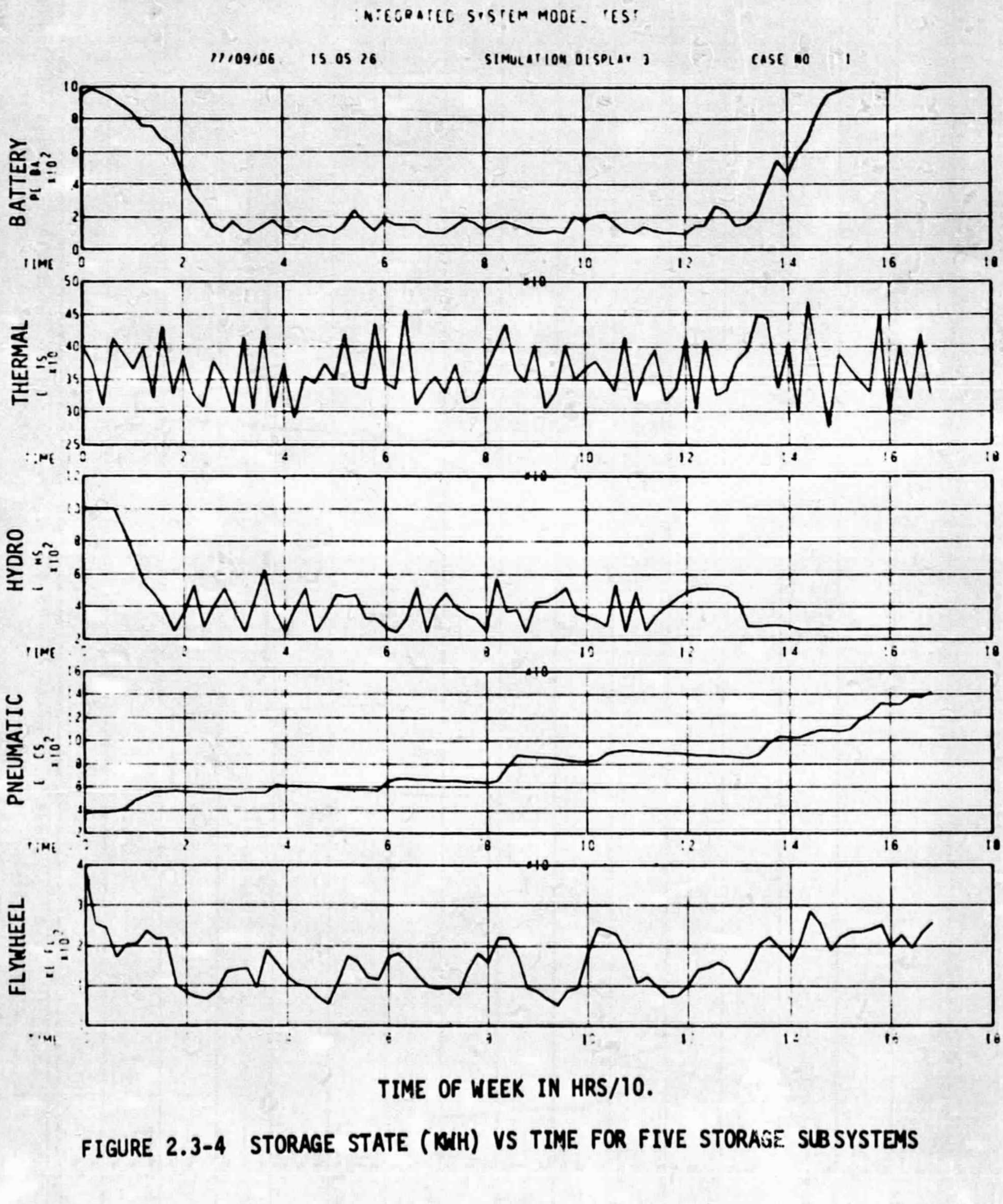
OF POOR QUALITY



TIME OF WEEK IN HRS/10.

FIGURE 2.3-4 STORAGE STATE (KWH) VS TIME FOR FIVE STORAGE SUBSYSTEMS

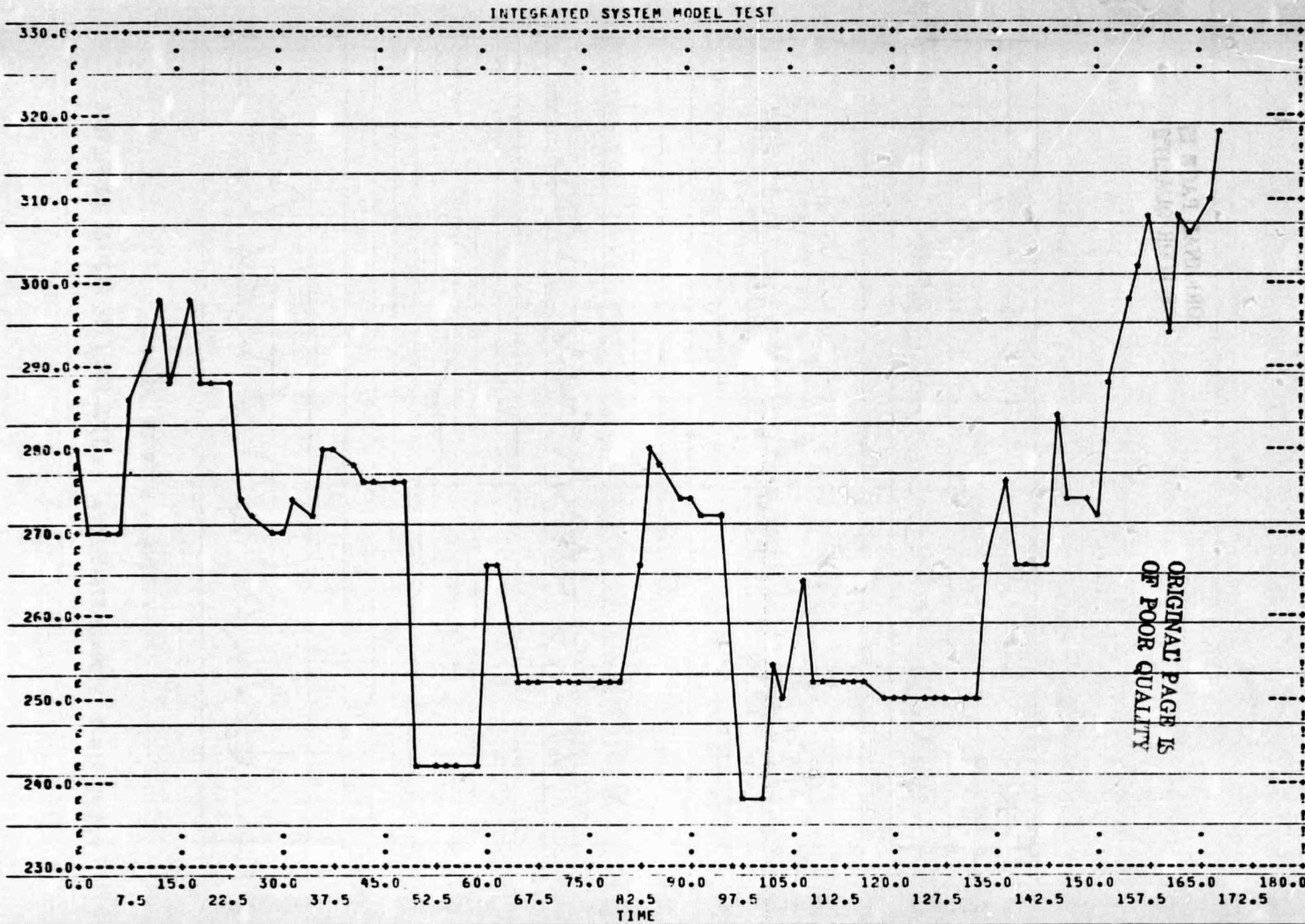


FIGURE 2.3-5 TEMPERATURE OF HEAT EXCHANGER OUTLET

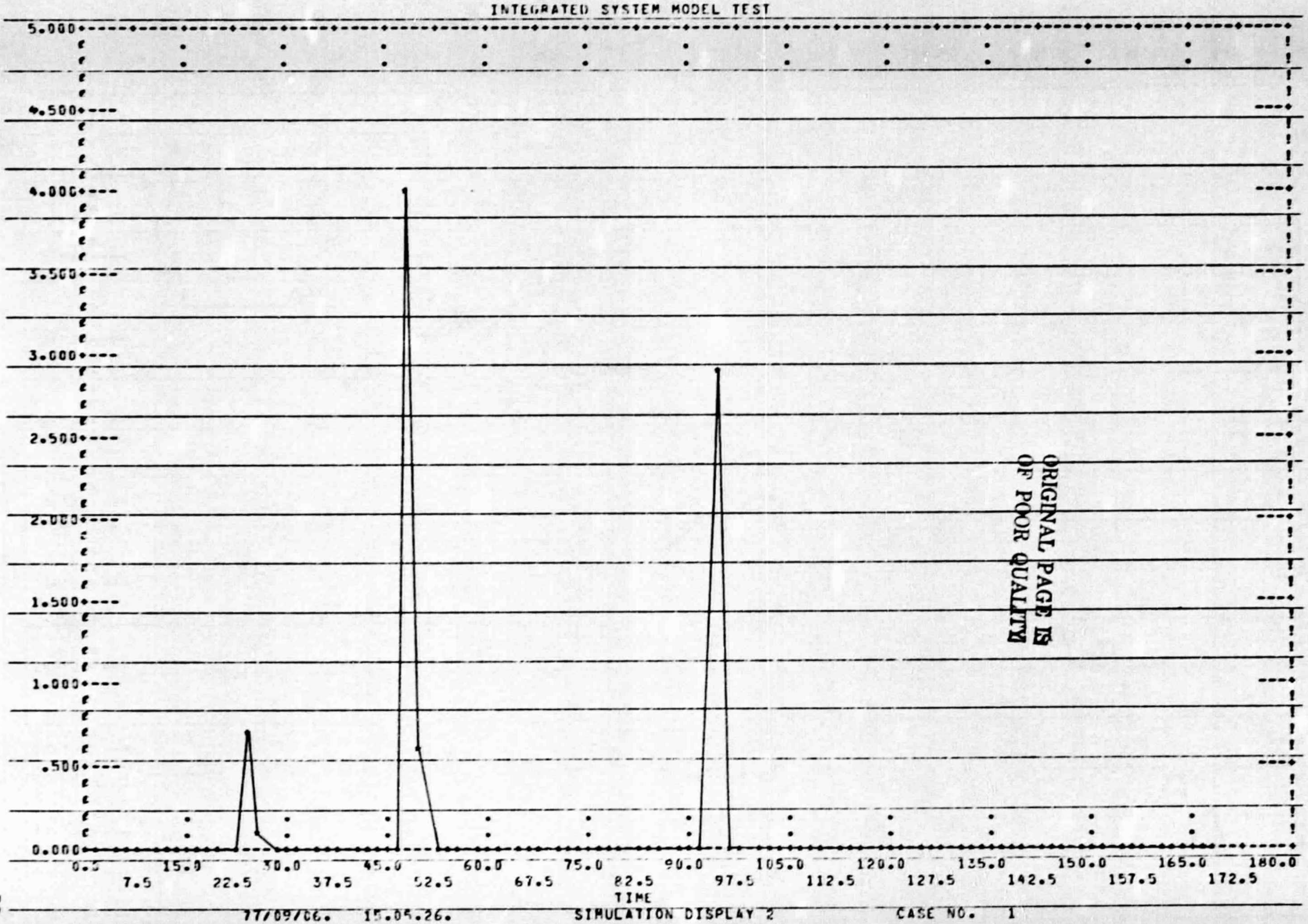


FIGURE 2.3-6 BURNER FUEL CONSUMPTION RATE (LB/HR)

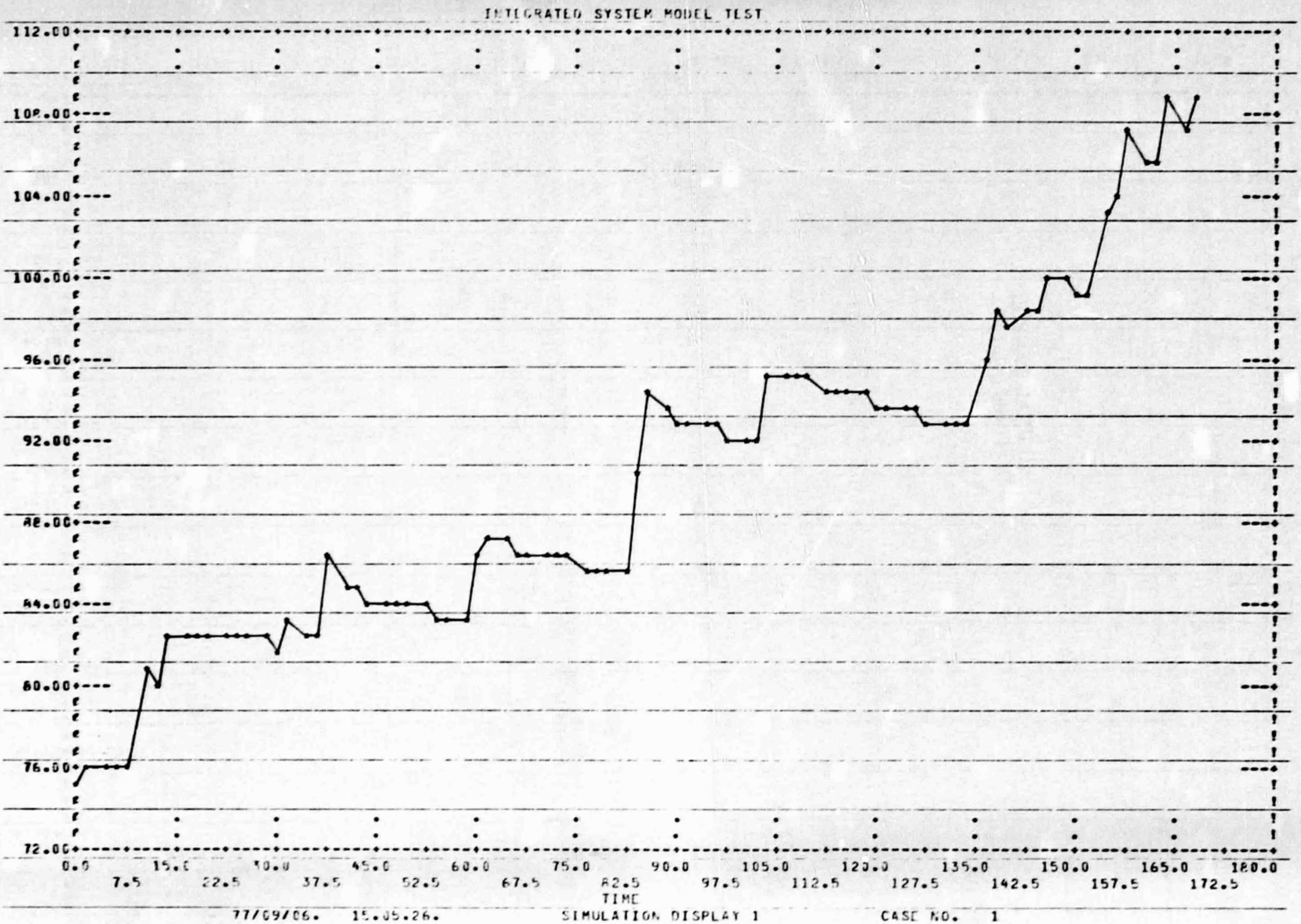


FIGURE 2.3-7 TEMPERATURE (^{O}F) OF PNEUMATIC STORAGE

BCS 40180-1

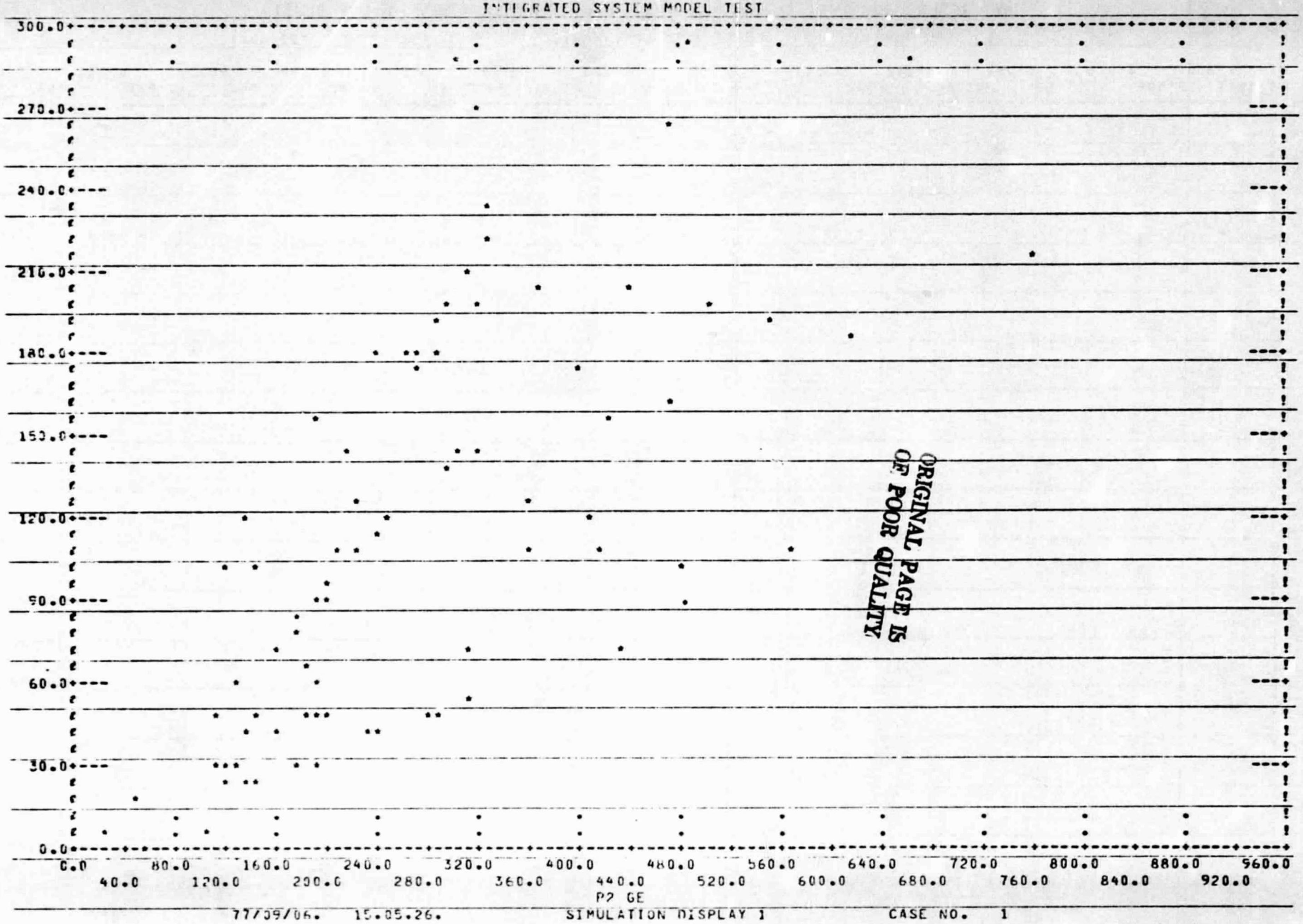


FIGURE 2.3-8 POWER INTO FLYWHEEL (KW) VS POWER GENERATED BY WIND

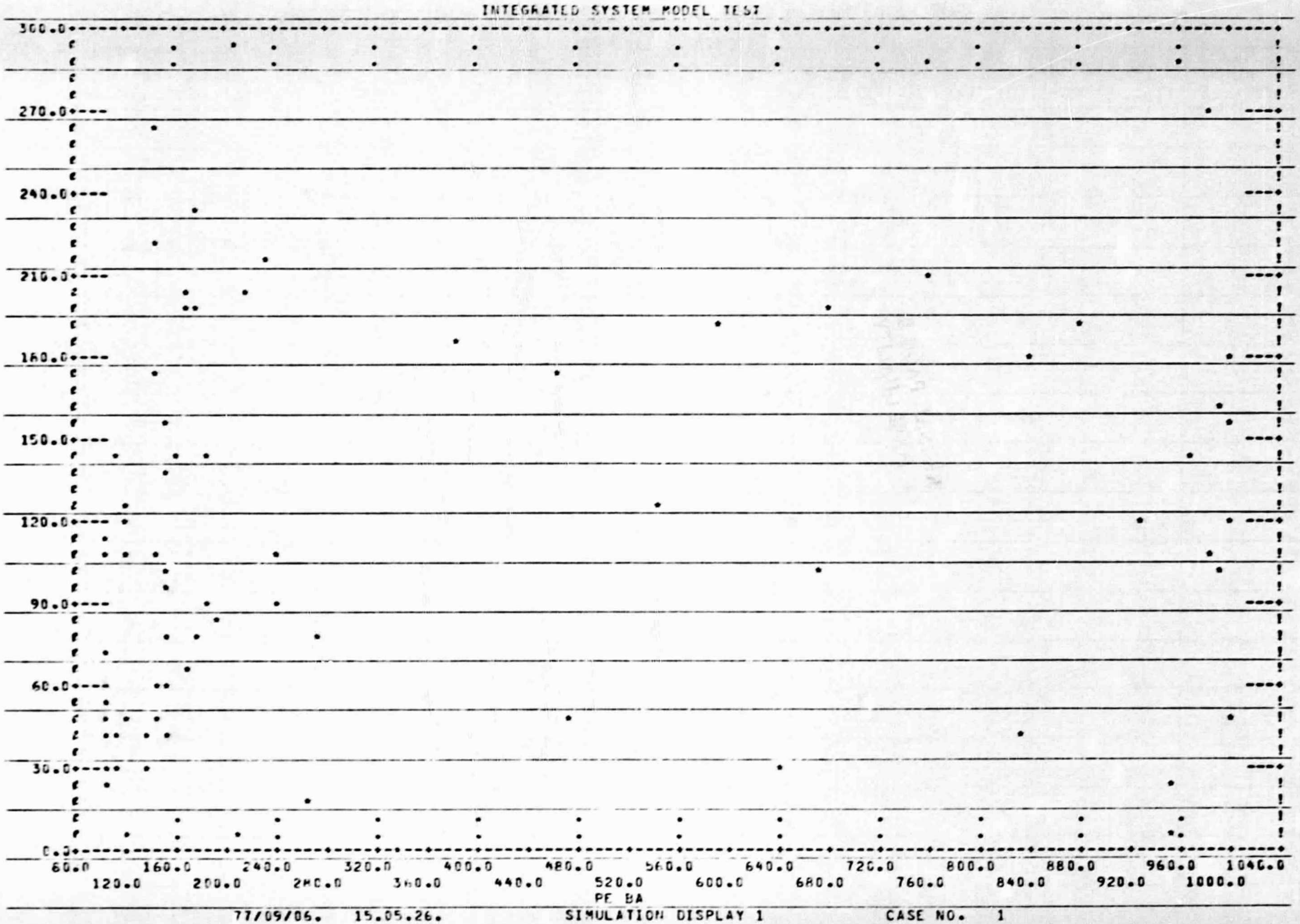


FIGURE 2.3-9 POWER INTO FLYWHEEL (KW) VS BATTERY STATE OF CHARGE (KWH)

output power and input to the flywheel. However, there seems to be less correlation between the battery state and power into the flywheel. This is primarily due to the fact that the battery was fully charged only a small amount of the time and only in the nearly charged state would one expect to find good correlation.

2.3.3 Load Service

Table 2.3-1 gives the percent of each load met by the various storage subsystems and by the wind directly. In summary, 84 percent of the total load is met by wind generated power. In considering Table 2.3-1, it should be remembered that the domestic load is by far the larger of the three (see Section 2.2-1). About 91 percent of this load is met by wind generated power and nearly 50 percent of this is supplied by the flywheel alone while only 15 percent is met by the battery. When one considers that the flywheel obtains power only when the charge rate of the battery is exceeded, this tends to substantiate the results of the last section which indicate the battery charging rate might be too small. Figures 2.3-10 and 2.3-11 give the frequency histograms of the percentage of the domestic load met by the battery and the flywheel respectively. It is seen that 53.7 percent of the time the battery supplies no power at all to the domestic load. On the other hand the flywheel supplies over 96 percent of the domestic load 18 percent of the time.

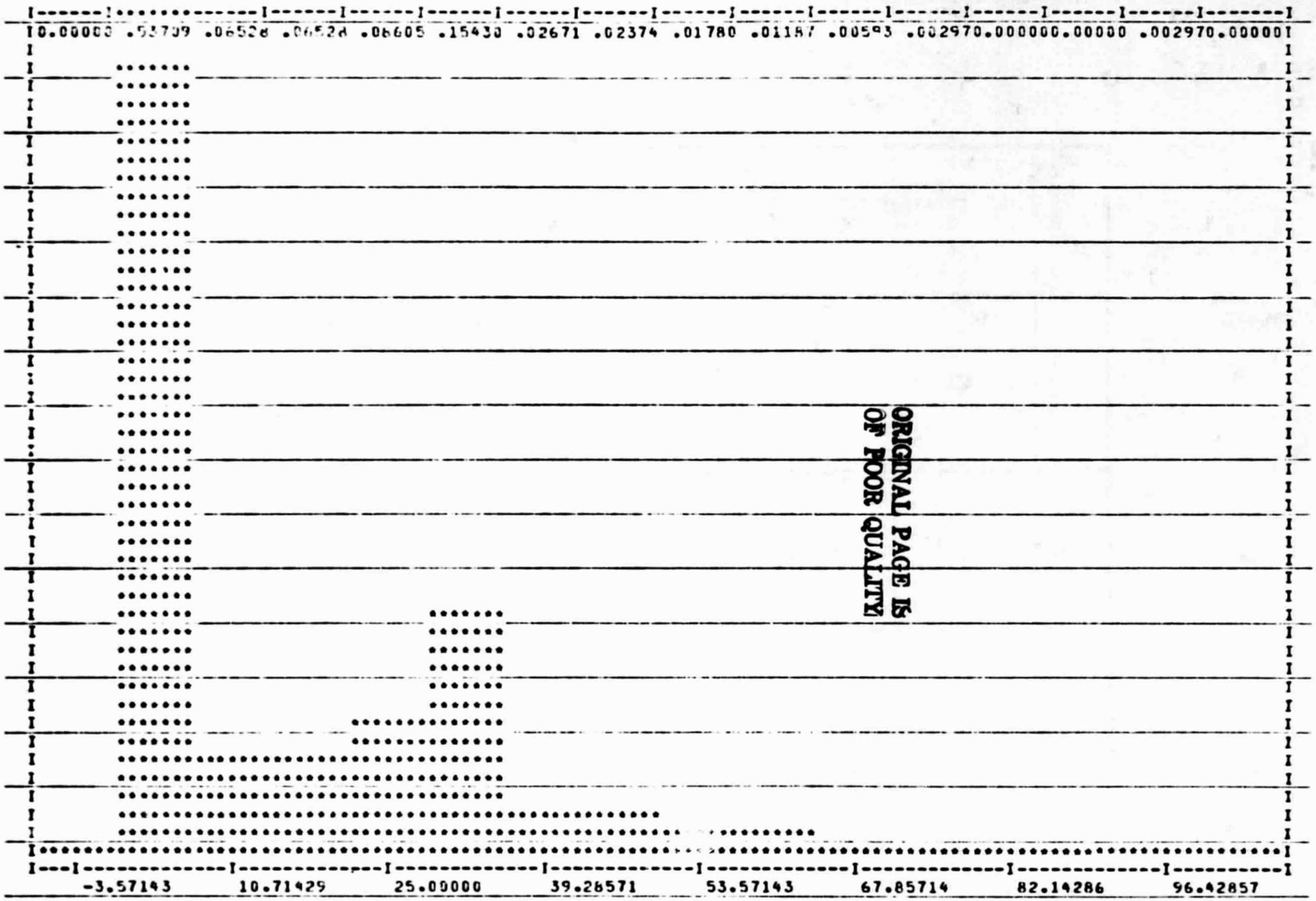
Table 2.3-1 also points out that only a small amount of the domestic load was met directly by the wind turbine without going through storage. This is due to the fact that direct wind power is given the lowest priority on the power accumulator supplying the domestic load. This control strategy was mainly selected to exercise the storage subsystems without a great deal of priority given to overall system efficiency.

The actual storage subsystem efficiencies which were obtained during this one week simulation are given in Table 2.3-2. Again the reader should be cautioned about drawing conclusions from these results. In particular, pneumatic storage, which has one of the lower efficiencies, supplied only 1.5 percent of the total domestic load, and since the simulation only ran for one week, there was not enough data to obtain accurate statistics.

TABLE 2.3-1 LOAD SERVICE BREAKDOWN

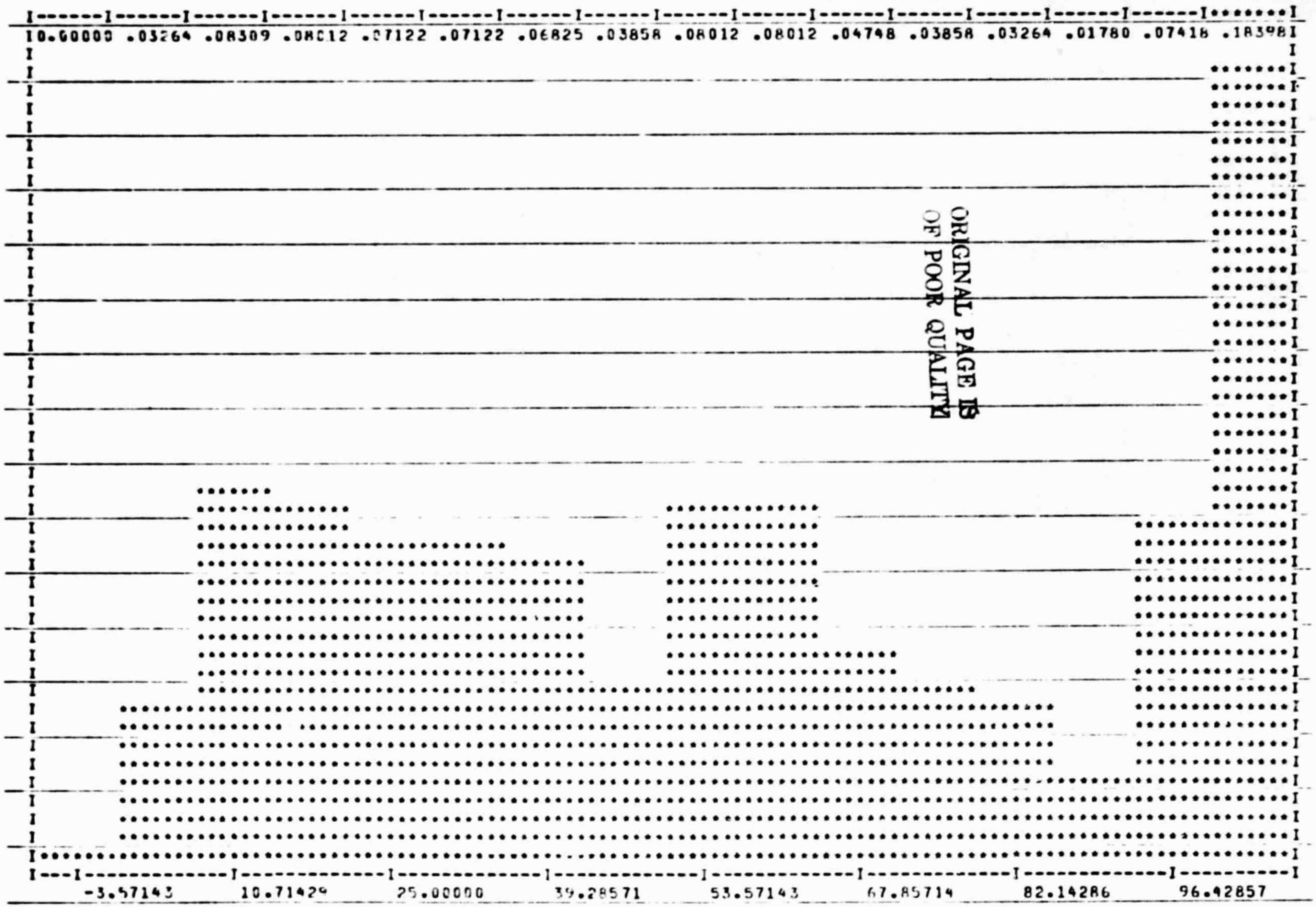
Storage Subsystem	Control	Domestic	Thermal
battery	0	15.1	0
flywheel	0	49.1	0
pneumatic	0	1.5	0
thermal	0	0	58.4
pumped hydro	0	9.7	0
direct wind	74.5	18.3	0
utility	25.5	6.3	0
Total	100%	100%	58.4%

84 percent of total load met by wind generated power.



HISTOGRAM FOR 337 SAMPLES MEAN= 13.85617 STANDARD DEV.= 17.26306

FIGURE 2.3-10 PERCENTAGE OF DOMESTIC LOAD MET BY BATTERY



HISTOGRAM FOR 337 SAMPLES MEAN= 56.15402 STANDARD DEV.= 32.76732

FIGURE 2.3-11 PERCENTAGE OF DOMESTIC LOAD MET BY FLYWHEEL

TABLE 2.3-2 STORAGE SUBSYSTEM EFFICIENCY

Storage Subsystem	Round Trip* Efficiency
battery	.94
flywheel	.79
pneumatic	.70
thermal	.86
hydro	.66

* $\frac{\text{total energy in}}{\text{total energy out}}$

3.0 PARAMETRIC STUDY

The parametric study described in this section is the second simulation study defined by NASA-Lewis as a test for the SIMWEST program. It is based upon an energy storage system planned for the NASA-Lewis Plumbrook wind turbine facility. Specifically, this study was intended to assess the accuracy of the SIMWEST program and its usefulness in performing parameter investigations. The Plumbrook facility was felt to be appropriate since empirical performance and cost data is available, and because it has been the subject of other studies with which the results of this study could be compared.

3.1 STUDY OVERVIEW

A schematic diagram of the system to be studied is given in Figure 3.1-1. The wind turbine shown there has a blade radius of 19.05 meters (62.5 ft.) with a cut in wind speed of 4.02 meter/sec (9 mph). The rated wind speed is 8.05 meters/sec (18 mph) beyond which the turbine power output is a constant 100 kw (the rated power). (Wind turbine data from references [1] and [2] were used in this study.)

Unlike the test case described previously, the parametric study used actual wind data. This was hourly data measured at the Plumbrook site during the 1972 calendar year.

The nominal load for the parametric study is 10 kw with lighting making up 70 percent of this and thermal making up 30 percent. In addition, there is a control load of .5 kw which is supplied only when the turbine is operating.

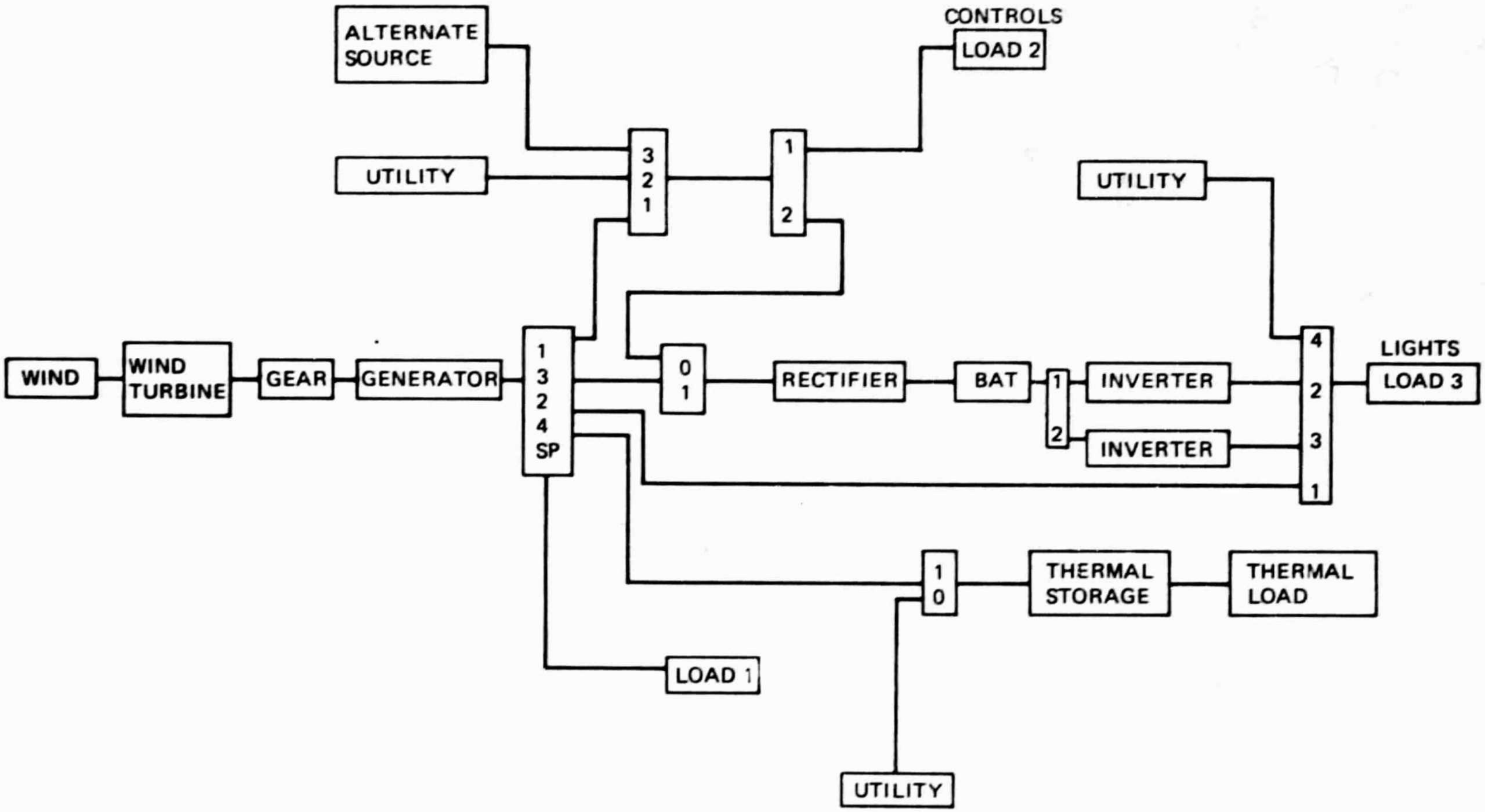


FIGURE 3.1-1 PLUMBROOK CONFIGURATION FOR PARAMETRIC STUDY

Supplying these loads are two storage subsystems, a battery and a thermal unit with the battery accounting for 82 percent of the total storage capacity.

The logic components of Figure 3.1-1 (power dividers and power accumulators) are configured in such a way that the control load gets first priority of the wind generated power. The lighting load has second priority and after that excess power goes to the battery and to the thermal vessel, in that order of priority. If there is still excess power, the surplus power is sold to the utility.

The lighting load requests power first directly from the turbine. If the turbine cannot completely satisfy the load, it turns next to the battery, and finally if the load is still not met it receives power from the utility network. Similarly the controls load first requests power from the wind turbine, and if it is not met it next turns to the utility network. The thermal load is supplied only by the thermal storage unit.

The primary system parameters to be varied in this study are the size of the lighting and thermal loads (their sum taking the values of 10, 20, and 30 kw), the total system storage capacity (2 hours, 4 day and 15 day supply of the load), the wind cut in speed (9 and 10 mph), the initial state of charge of the storage subsystems, and the inverter configuration. It is known that inverters function most efficiently near their rated capacity. The study will determine whether using two inverters is more efficient than using one inverter of twice the size.

A single case having a 10 kw load, 4 days of storage, 9 mph cut in speed, and one inverter is used as nominal and each of the parameters are sequentially varied keeping the remainder of the parameters at their nominal values. It should be pointed out that every separate set of parameters requires a separate simulation (although a number of simulations can be made in one computer run). A summary description of critical parameters is given in Section 3.6.

3.2 BATTERY SUBSYSTEM

The subsystem consists of a rectifier, an inverter (or two) and a number of battery cell banks. The charge-discharge characteristic of each cell bank is given in Figure 3.2-1.* Each cell bank has an average terminal voltage of 120 volts and a storage capacity of 20 kwh. The study assumes as many cell banks, in parallel, as needed to give the desired total storage capacity. Using the SIMWEST battery component each battery cell bank is modeled mathematically as a capacitance, a terminal resistance, and an internal voltage. See Figure 3.2-2.

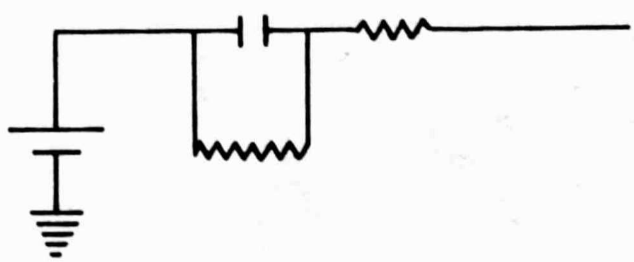


FIGURE 3.2-2 BATTERY MODEL

The capacitance and internal voltage for a single bank are 49505 Farads and 115.2 volts respectively. The terminal resistance varies with current and state of charge, resulting in the characteristic curves in Figure 3.2-1. Likewise, the internal resistance varies so as to reduce by 4.8 percent the charging current. This models a 95.2% amp-hr. charging efficiency. When the battery is not charging, the internal resistance reduces to a constant leakage resistance which allows leakage of half of the storage in one month. The terminal resistance is modeled by a table lookup while the internal resistance is computed using a FORTRAN statement.

* Characteristic curves obtained from Reference [3].

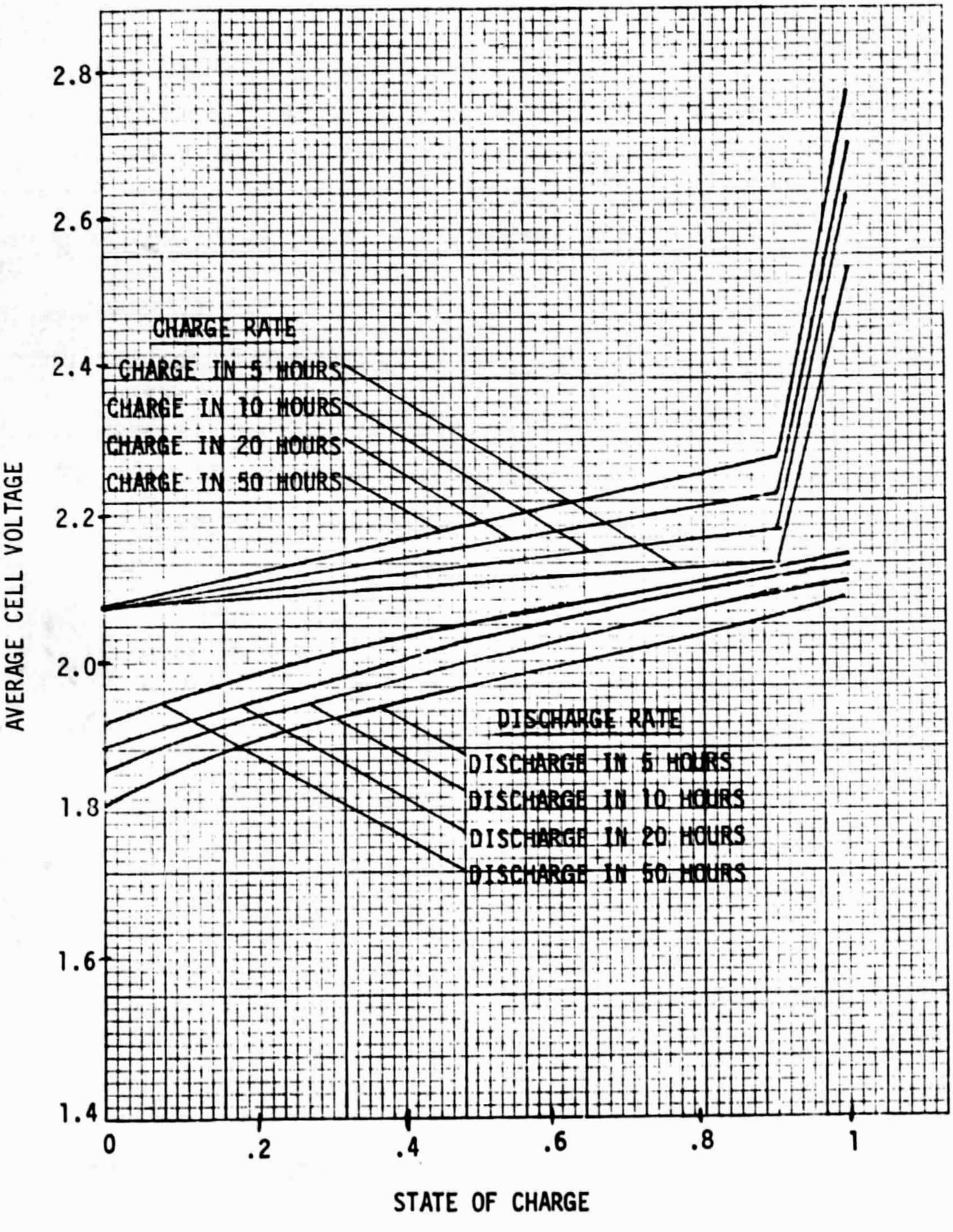


FIGURE 3.2-1 BATTERY CELL VOLTAGE CHARACTERISTICS

For the nominal case of a 10 kw load and a four day storage supply, the battery can store 10X4X24X.82 = 787.2 kwh. Thus about 39 banks (of 60 cells each) were used in the simulation. The rated input and output power for all battery sizes studied are 30 kw. However, the rated input power to the inverter is 10 kw. Thus the effective discharge rate of the battery is 10 kw.

When the battery remains in a discharged state in excess of twelve hours, it will cause the system logic to change priorities so that it purchases power from the utility until its storage level reaches 50 kwh. The model's rectifier and inverter efficiencies varies with the load. Their efficiencies as a function of percent load are shown in Figure 3.2-3.* The rectifier and inverter for the nominal case have rated power = 30 kw and 10 kw respectively.

3.3 THE THERMAL SUBSYSTEM

Anhydrous sodium hydroxide is used as a heat storage medium, with phase changes occurring at 296.11^{o} C (565^{o} F) and 321.11^{o} C (610^{o} F). Maximum and minimum storage temperatures are 454.44^{o} C (850^{o} F) and 232.22^{o} C (450^{o} F) respectively. Whenever the temperature falls below 500^{o} F, the thermal vessel will change the system's logic so that power can be purchased from the utility until the temperature rises to 510^{o}. The storage media mass is chosen in such a way that the maximum stored energy corresponds to a temperature of 343.33^{o} C (650^{o} F). Thus in the nominal case where 172.8 kwh storage capacity is desired, it is found from the enthalpy-temperature curve (see Figure 3.3-1) of sodium hydroxide that 662.24 kg (1460 lb) are needed. This design point enthalpy is .088 kwh/lb, corresponding to a design point temperature of 313^{o} C (595^{o} F). Thus 1460 x .088 = 128 kwh are stored at the design point. This corresponds to a rated storage time of 4.28 hours assuming a rated (design point) power of 30 kw. The rated storage time is the only parameter which needs be changed to give different storage capacities from simulation to simulation.

* See Reference [4].

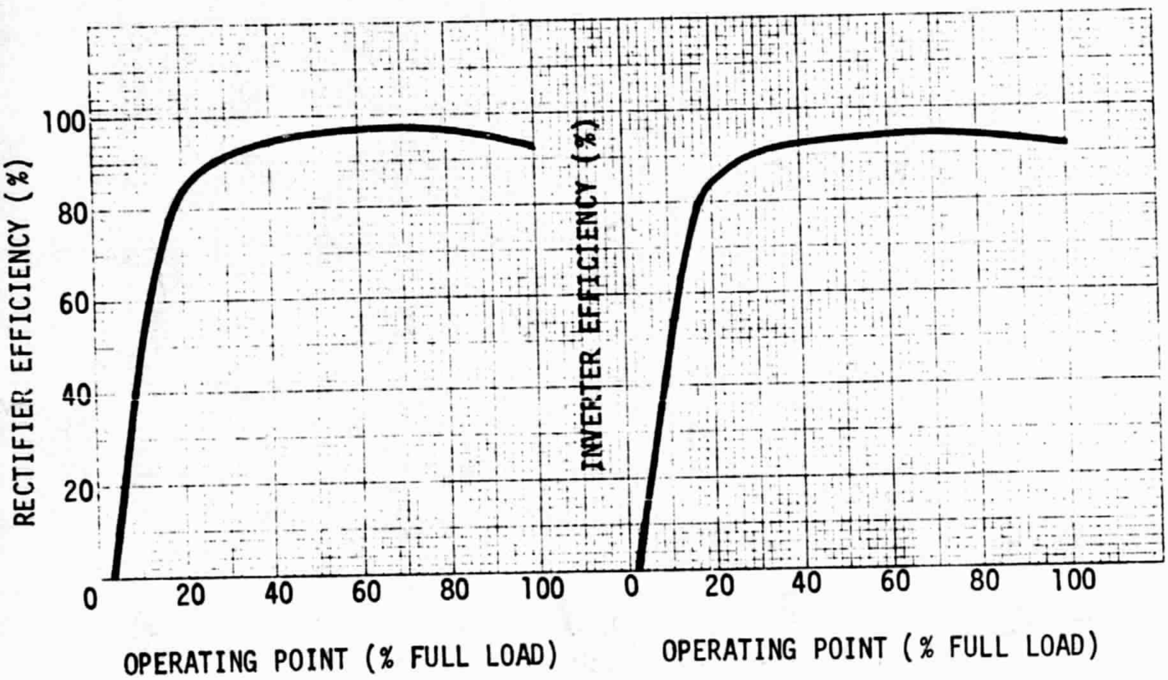


FIGURE 3.2-3 RECTIFIER AND INVERTER EFFICIENCIES

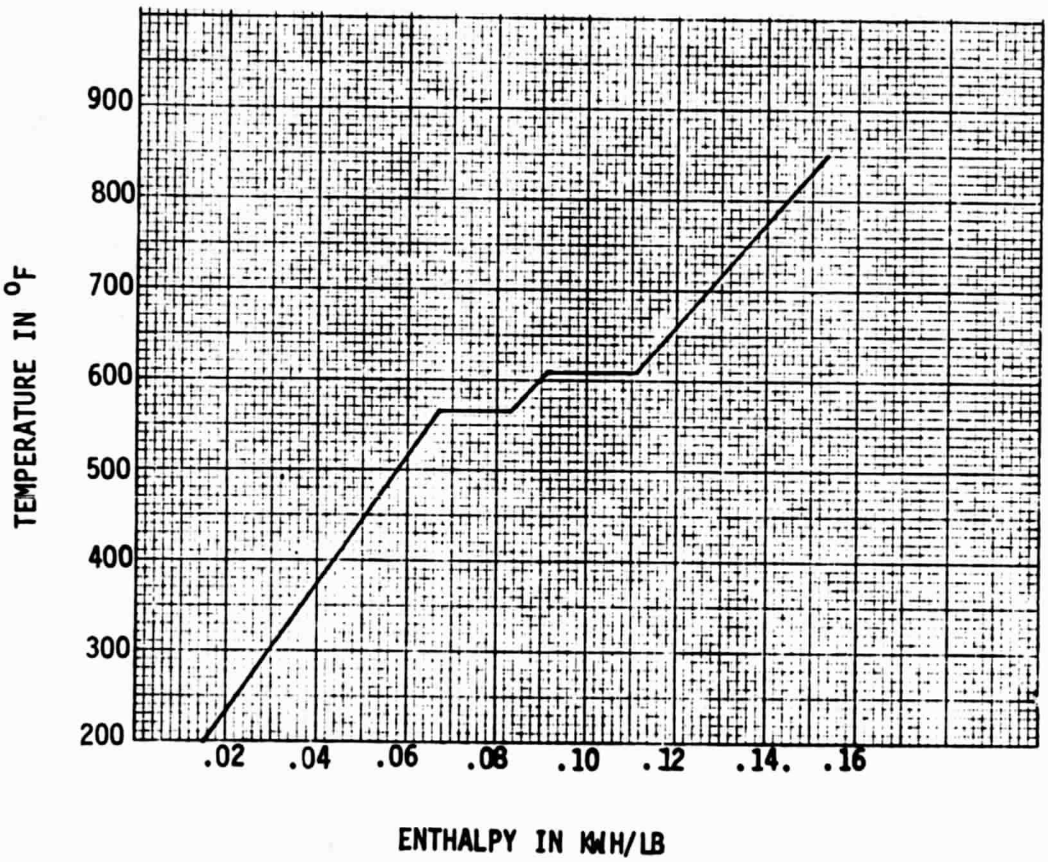


FIGURE 3.3-1 TEMPERATURE-ENTHALPY CURVE FOR THERMAL VESSEL HEAT STORAGE MEDIA

3.4 PARAMETRIC STUDY SPECIFICATION

The input cards for the SIMWEST model generation program used for the parametric study are given in Figure 3.4-1. These cards define the general topology of the system shown in Figure 3.1-1. The schematic printout of the resulting system is shown in Figures 3.4-2 through 3.4-4. Figure 3.4-2 shows the portion of the system which contains the wind turbine and the utilities. Figure 3.4-3 shows the battery subsystem. Figure 3.4-4 depicts the thermal subsystem as well as the cost monitor and the histogram components. In Figure 3.4-2, the wind turbine WT drives the generator GE through the gear GR according to time TI and wind data WD. The power is then distributed by the power divider PD1. Note that PD1 receives requests from the power accumulator PA3 in the thermal system shown in Figure 3.4-4. Likewise, the power divider PD2 receives requests from, and supplies, the power accumulator PA2 in Figure 3.4-3. Communication with a component printed on a different page is depicted by the input name and page number of the component. Thus, the request RE2PA2 together with PAGE 1 is printed at the lower left of PD2 in Figure 3.4-2.

Each simulation of the parametric study required a slightly different set of simulation data cards. The set of data cards used for the nominal system is given in Figure 3.4-5. In the parametric study wind data was also input through simulation data cards. For brevity these are not included in Figure 3.4-5. A summary description of the more important parameters is given in the appendix.

3.5 SUMMARY OF RESULTS

Figure 3.5-1 gives the average output power from the wind turbine generator which would be generated by the 1972 Plumbrook wind data. It is seen that the power drops off significantly during the summer months. The average output power over the twelve month period is 20 kw. During the simulations this energy attempts to satisfy combined lighting and electrical loads of 10, 20, and 30 kw. Excess power goes to a battery unit with a charging rate of 58.6 kw.

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```
MODEL DESCRIPTION          PARAMETER STUDY
ADD PARAMETERS=                      CB60,CCBA60,ROBA60,ANBAT,CFACT,CUSTO,COST1
ADD VARIABLES=OPCOST,PCWITL
ADD TABLES=WIND,802
FORTRAN STATEMENTS
      COMMON/CSIMUL/ADUM(6),TINC
LOCATION=41        TI
FORTRAN STATEMENTS
C              READ WIND VELOCITY DATA
      WV1WD=TBLU2(TD TI,DY TI,WIND(35),WIND(4),WIND(59),
     1  0,0,24,-31,24,31)
LOCATION=71        WD       INPUTS=TI
LOCATION=62        FUW      INPUTS=WD(WV,2=FIN)
LOCATION=53        WT       INPUTS=WD,FUW(FO=CP)
FORTRAN STATEMENTS
C              SET GEAR RATIO
      GR WT=45.
LOCATION=65        GR       INPUTS=WT
LOCATION=45        GE       INPUTS=GR
LOCATION=23        PIW      INPUTS=GE(P,2=INT)
LOCATION=25        PD1      INPUTS=GE(P,2=MP),GE,PA1(1,1),PA2(1,3),PA3(1,4),
                                   PA4(1,2)
LOCATION=48        UT1      INPUTS=PA1(3,2)
LOCATION=17        UT2      INPUTS=PA1(2,2),PD1(SP=P),FUU(FO=CP)
LOCATION=172       UT3      INPUTS=PA4(4,2),FUU(FO=CP)
LOCATION=28        PA1
LOCATION=10        PD2       INPUTS=PIW(2,1),PA1(0,0),PA2(2,3)
LOCATION=1         LOC      INPUTS=TI,PD2(1,1)
LOCATION=107       PA2      INPUTS=BA(RE,2=RE,0),PIC(2,2)
LOCATION=125       FUR      INPUTS=PA2(P,0=FIN)
LOCATION=133       RE       INPUTS=PA2(0,1),FUR(FO=RR)
FORTRAN STATEMENTS
C     ANBAT IS NUMBER OF 60 CELL STRINGS IN PARALLEL IN BATTERY
C     FVB IS TABLE LOOKUP FOR TERMINAL RESISITANCE OF SINGLE STRING
      CC BA=CCBA60*ANBAT
      CM BA=CC BA*.04
      FNAFVB=I  BA/ANBAT
LOCATION=171       FVB      INPUTS=BA(VC=FNB)
FORTRAN STATEMENTS
      CB BA=CB60*ANBAT
      RT BA=FO FVB/ANBAT
LOCATION=141       BA       INPUTS=RE,PD3(RE,0=RE,1)
LOCATION=147       PIC      INPUTS=BA
LOCATION=153       PD3      INPUTS=BA(2,0),PA4(RE,2=RE,1),PA4(RE,3=RE,2),
FORTRAN STATEMENTS
C     INTERNAL RESISTANCE TO ACCOUNT FOR BATTERY AMP-HR CHARGING EFFICIENCY
      RL BA=ROBA60*(VC BA + 1.E-8)/
     X  (VC BA + 1.E-8 - .048*AMIN1(I  BA,0.)*ROBA60)
LOCATION=166       FUI      INPUTS=PD3(P,1=FIN)
LOCATION=164       IV1      INPUTS=PD3(1,1),FUI(FO=RI)
LOCATION=169       FUJ      INPUTS=PD3(P,2=FIN)
LOCATION=167       IV2      INPUTS=PD3(2,1),FUJ(FO=RI)
```

FIGURE 3.4-1 MODEL GENERATION INPUT DATA

```
FORTRAN STATEMENTS
      MP2PD1=P2 GE - P1 PD1
      MP3PD1=MP2PD1 - P2 PD1
      MP4PD1=MP3PD1 - P3 PD1
LOCATION=175       PA4      INPUTS=IV1(2,2),IV2(2,3),LOD(1,0)
LOCATION=258       FUU      INPUTS=TI(TD=FIN)
LOCATION=180       LOD      INPUTS=TI,FUU(FO=VE)
LOCATION=212       PA3      INPUTS=UT4(2,2),TS(2,0)
LOCATION=242       UT4      INPUTS=FUU(FO=CP)
LOCATION=215       TS       INPUTS=TL
LOCATION=218       TL       INPUTS=FUU(FO=VE)
FORTRAN STATEMENTS
C     RESET PRIORITY FOR POWER PURCHASE WHEN THERMAL VESSEL LOW
      PS2PA3=0.
      IF(T  TS.LE.TO1TS)PS2PA3=2.
C                   HISTOGRAM OF POWER PURCHASE FROM UTILITIES.
C                   STORAGE SYSTEM IN OPERATION WHEN PURCHASE IS 0
      FINHG=P2 UT1  +  P2 UT2  +  P2 UT3 + P2 UT4
LOCATION=262       HG
FORTRAN STATEMENTS
C     COMPUTE PERCENT OF THERMAL LOAD SUPPLIED BY WIND
      PCWITL=100.*PC1PA3/(PC1PA3 + PC2PA3 + 1.E-8)
C         HISTOGRAMS OF POWER SURPLUS AND POWER PURCHASE COST
C         IF NO STORAGE SYSTEM WERE USED
      PWSP=P2 GE  -  (RE1LOC + RE1LOD + RE TL*CFACT)
      PWPC=AMAX1(-PWSP,0.)
      PWSP=AMAX1(PWSP,0.)
      FINHGS=PWSP*TINC
      FINHGP=PWPC*TINC*FO FUU
      IF(IMPL.EQ.0)COST1=0.
      IF(IMPL.LE.1)GO TO 10
      COST1=COST1 + .5*FINHGP - .5*FINHGS*CB UT2
C     COSTO  IS PER HOUR COST (CAPITAL AND MAINTENANCE) OF
C     WIND SYSTEM WITHOUT STORAGE
      COSTO=(CC WT + CC GR + CC GE + CC UT1 +CCATS*.4*PD TS)*LE CM *
     X  CR CM*.01/8760. +  (CM WT + CM GR + CM GE + CM UT1 )/8760.
      OPCOST=(COSTO*TIME + COST1)/(SRELOD + SRETL +1.E-8)
   10 CONTINUE
LOCATION=263       HGS
LOCATION=264       HGP
LOCATION=265       CM
END OF MODEL
PRINT
```

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FIGURE 3.4-1 MODEL GENERATION INPUT DATA (Cont.)

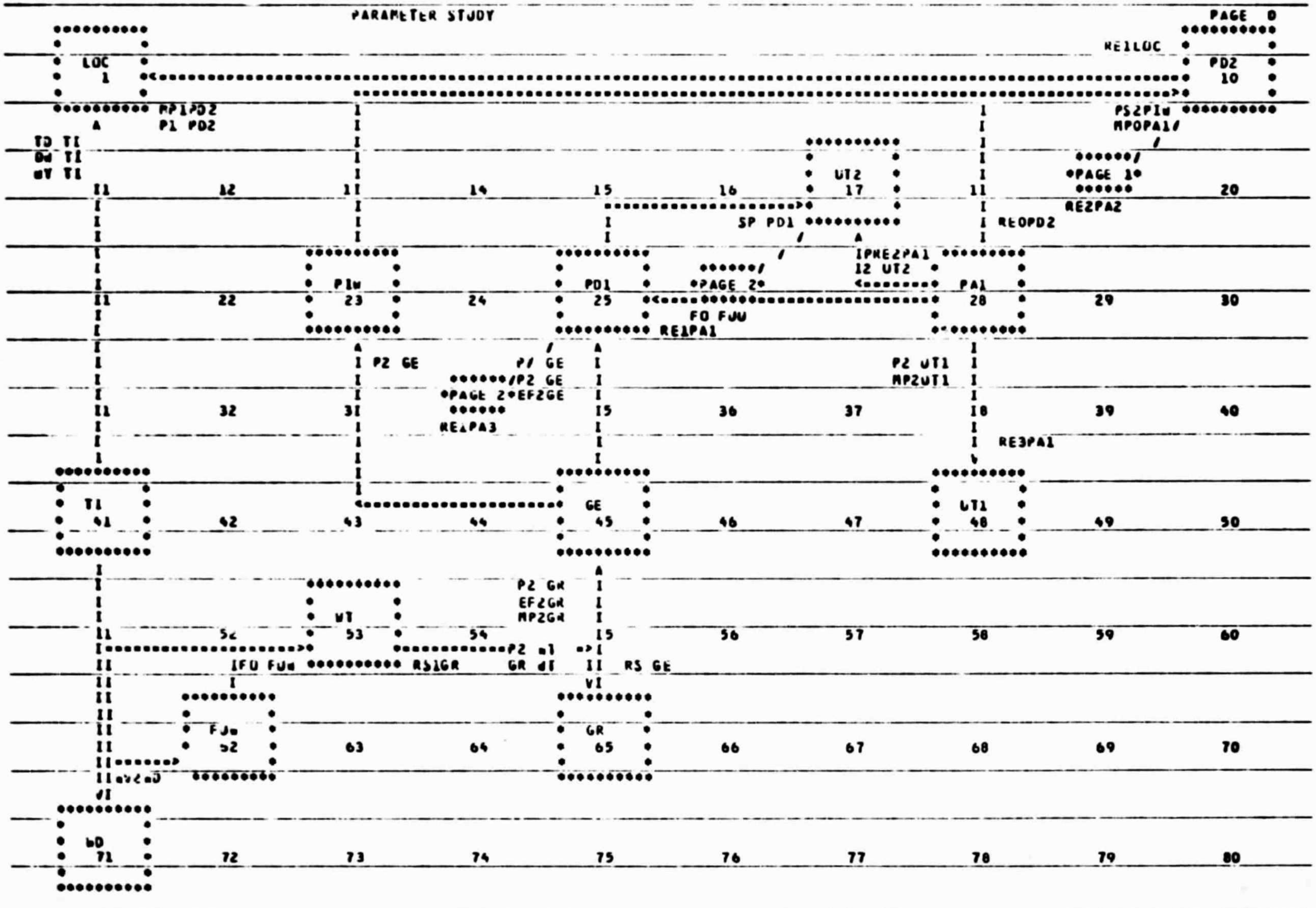

FIGURE 3.4-2 SCHEMATIC PRINTOUT (PAGE 0)

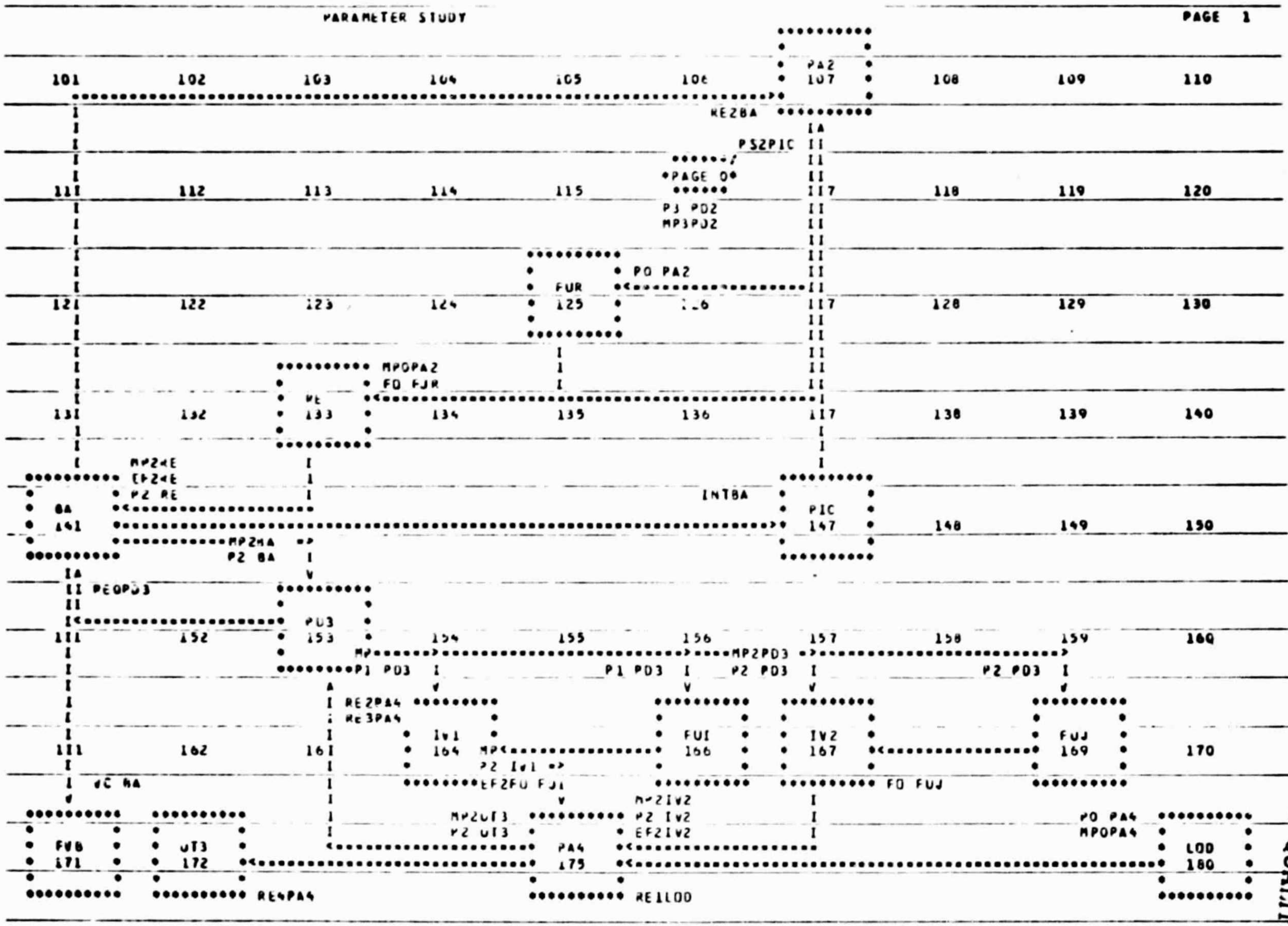

FIGURE 3.4-3 SCHEMATIC PRINTOUT (PAGE 1)

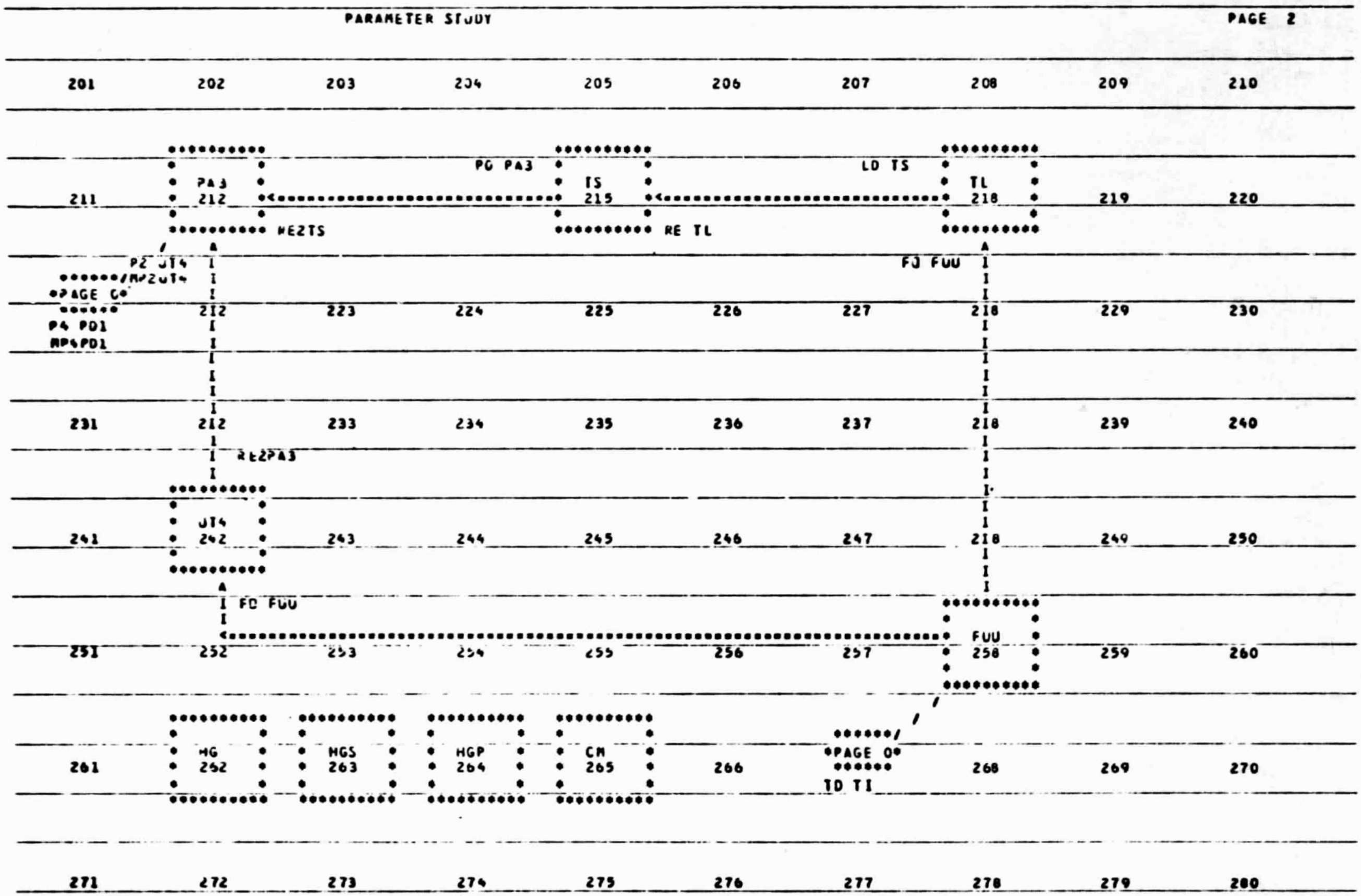

FIGURE 3.4-4 SCHEMATIC PRINTOUT (PAGE 2)

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```
PARAMETER VALUES
CR CM=18.,LF CM=10
CFACT=1.
CYCLES=4.01,DLINES=-10.,RESET=-1.
TO TI=0.
VO WT=12.,VR WT=18.,PSGWT=1800.,RP WT=62.5,EC WT=0.,AD WT=.0023,LAMWT=10,
CPMWT=.45,CC WT=66000.,CM WT=2640.
EF1GP=.95,MP1GP=1.E8,CC GR=1500.,CM GR=64
RAPGE=100.,PSYGE=1800.,RASGE=.005,DA GE=0.,SP GE=.0842,VD GE=400.
CC GE=6800.,CM GE=272
CB UT3=.008,CC UT3=0.,CM UT3=0.
CB UT1=0.,MP1UT1=10.,CP UT1=.008,CC UT1=180.,CM UT1=7.2
CB UT2=0.,CC UT2=0.,CM UT2=0.
PS1PIW=0.
VE LOC=0.,LO1LOC=.5,EF1LOC=1
VACRE=400.,RAPRE=70.,CC RE=1400.
VO BA=115.2,RAPBA=30.,E1 BA=787.,EDEBA=50.,DT BA=12,CCBA60=150
CB60=49505,PDBA60=4.462,ANBAT=39.
PS1PIC=0.,PS3PIC=2.
VDCIV1=100,RAPIV1=10,CC IV1=1000
VDCIV2=100,RAPIV2=0.,CC IV2=0.
LO1LOD=7,EF1LOD=1
CC UT4=0.,CM UT4=0.
NU TS=.002,TS TS=4.283,VO TS=490,TM1TS=700,TO1TS=500,DH TS=.087989,PD TS=30,
PM TS=58.6,MFMTS=640,TOETS=30,CP2TS=9.49E-4,TO2TS=50,TM2TS=190
R  TS=3.08E-4,CM TS=2.667,CSATS=666.7,CSBTS=0.,LE TS=10
NC TL=3.,AN FUU=-1.,AN FV9=-1.,BN FVB=-1.,AN FUI=-1.,AN FUJ=-1.
AN FUR=-1,AN FUW=-1
FLOHG=.001,FUPHG=140.001
FLOHGS=.001,FUPHGS=56.001
FLOHGP=.001,FUPHGP=.701
TABLE,FTAFUW=10
8.999,9,10,11,12,15,18,25,30,50
0,.28,.34,.375,.4,.47,.45,.32,.25,.095
TABLE,PLOGR=3
0,12.32,138.44
0,12.32,53.44
TABLE,HT TS=6
.0147,.0645,.0821,.0909,.1115,.1525
200,565,565,610,610,850
TABLE,FTAFUU=4
6.999,7,22,22.001
.023,.026,.026,.023
TABLE,FTAFUT=12
.5,1,1.5,2,3,4,5,6,7,8,9,10
16.6,4.9,1.63,.775,.317,.2,.13,.1,.079,.075,.078,.08
TABLE,FTAFUJ=12
.5,1,1.5,2,3,4,5,6,7,8,9,10
16.6,4.9,1.63,.775,.317,.2,.13,.1,.079,.075,.078,.08
TABLE,FTAFUP=9
.075,1.75,3.51,5.26,7.02,10.52,14,17.54,70.16
521,12.5,4.85,2.59,1.59,.785,.519,.344,.0831
TABLE,TLOTL=2
0.,1.
1.,1.
TABLE,TWTTL=2
0.,1.
1.,1.
TABLE,FTAFVB=16,4
1.2, 6, 10.8,   12
-280   ,-140   ,-70    ,-34.6 ,-17.3 ,-8.67 ,-3.48 ,-1.74 ,
0      ,3.3    ,8.25   ,16.5  ,33    ,66    ,132   ,264   ,
.32    ,.64    ,.128   ,.255  ,.495  ,.90   ,2.24  ,4.48  ,
1.E-8  ,1.E-8  ,.145   ,.192  ,.154  ,.082  ,.041  ,.02   ,
.0325  ,.065   ,.13    ,.26   ,.416  ,.69   ,1.2   ,2.4   ,
1.E-8  ,1.E-8  ,.073   ,.145  ,.109  ,.055  ,.020  ,.014  ,
.035   ,.07    ,.14    ,.277  ,.364  ,.415  ,.172  ,.344  ,
1.E-8  ,1.E-8  ,.073   ,.145  ,.109  ,.055  ,.028  ,.014  ,
.13    ,.26    ,.53    ,1.075 ,1.9   ,3.32  ,6.55  ,13.1  ,
1.E-8  ,1.E-8  ,.073   ,.145  ,.109  ,.055  ,.028  ,.014
INITIAL CONDITIONS,PE BA=750,E  TS=100
PRINTER PLOTS
DISPLAY1
PF BA,VS,TIME
E  TS,VS,TIME
INTBA,VS,TIME,YRANGE=-5,5
INTTS,VS,TIME,YRANGE=-5,5
VT BA,VS,VC BA
DISPLAY2
P2 GE,VS,WV2WD
RL BA,VS,VC BA
WV2WD,VS,TIME
T  TS,VS,E  TS
EF2IV1,VS,P1 PD3
DISPLAY3
PC2PA4,VS,TIME
PCWITL,VS,TIME
SP PD1,VS,TIME
TINC=1.,TMAX=744.,PRATE=49,PRINT CONTROL=3,INT MODE=3,OUTRATE=3
TITLE=      PARAMETER STUDY OF STORAGE SYSTEM
SIMULATE =
```

FIGURE 3.4-5 PARAMETRIC STUDY INPUT DATA

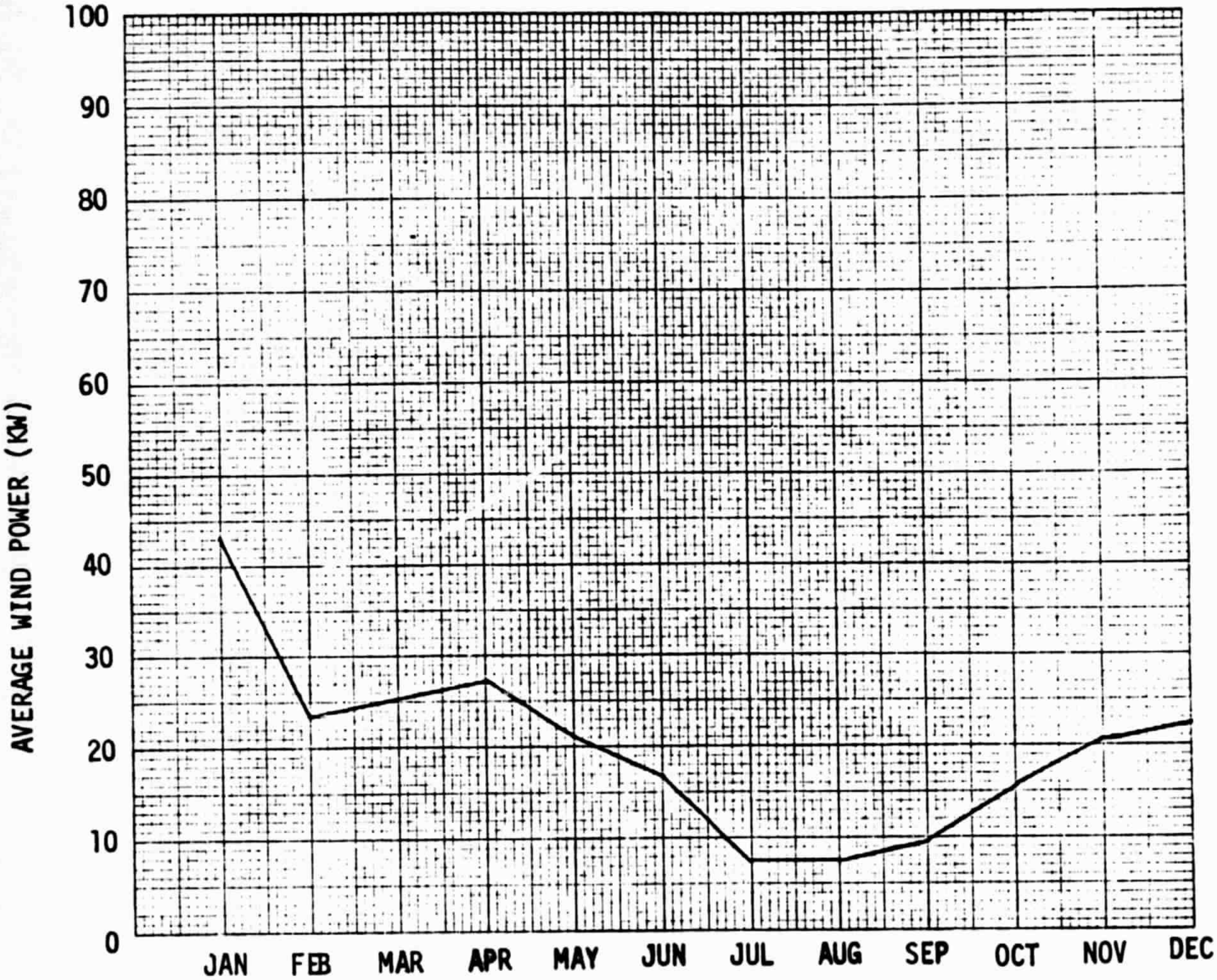

FIGURE 3.5-1 AVERAGE WIND TURBINE OUTPUT POWER (KW)

3.5.1 Effect of Load On Cost of Operation

Figure 3.5-2 shows the effect of 3 different load sizes (10, 20, and 30 kw) on the montly cost of usable energy (whether supplied to the load or sold to the utility); the cost of energy is the sum of all costs (capital, maintenance, and operating) divided by the total amount of wind generated energy that was actually supplied to a load or surplused to the utility. Capital costs are amortized based on a ten year life expectancy. It is seen in Figure 3.5-2 that the cost rises with the size of the load. This is because a four day storage capacity is assumed in each case. Thus, for example, the capital cost for supplying four days of storage for a 30 kw load is greater than that required to supply four days of storage for a 20 kw load.

Returning to Figure 3.5-2, the January energy cost of under 50¢/kwh corresponds to a monthly average wind speed of 6.7 m/s (15 mph) while the cost of above $3/kwh in July and August results from the fact that the average wind speed for these two months are below 3.67 m/s (8.2 mph).

Another way of looking at the cost of energy is to assume, as is shown in Figure 3.1-1, that the loads must purchase energy from the utility when not supplied by the wind system. If this purchased energy is added to the total energy delivered and the added cost of this energy is added to the total cost of energy, then the resulting cost curves are as shown in Figure 3.5-3. In this study energy was purchased from the utility at 2.6¢/kwh during the peak time from 7 AM to 10 PM and 2.3¢/kwh at off peak times.

In Figure 3.5-3, it is seen that now energy is most expensive in the 10 kw load case. This is because the incremental energy added by the utility in the 30 kw case is larger than that of the 10 kw case, and the added cost in either case is small compared to the total system cost. The situation in Figure 3.5-4 is the same as in 3.5-3 except that the simulation was run without storage.

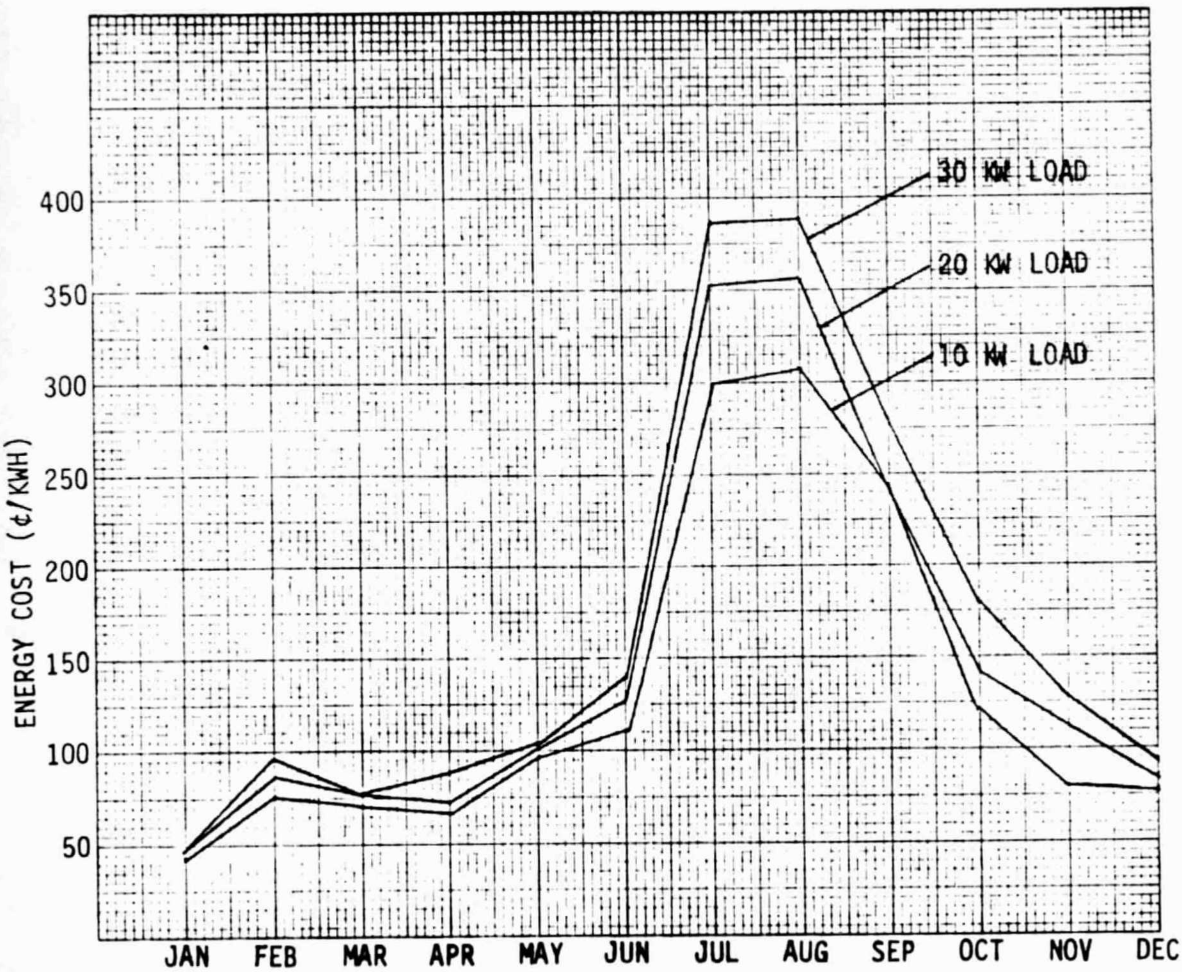

FIGURE 3.5-2 MONTHLY COST OF WIND GENERATED ENERGY

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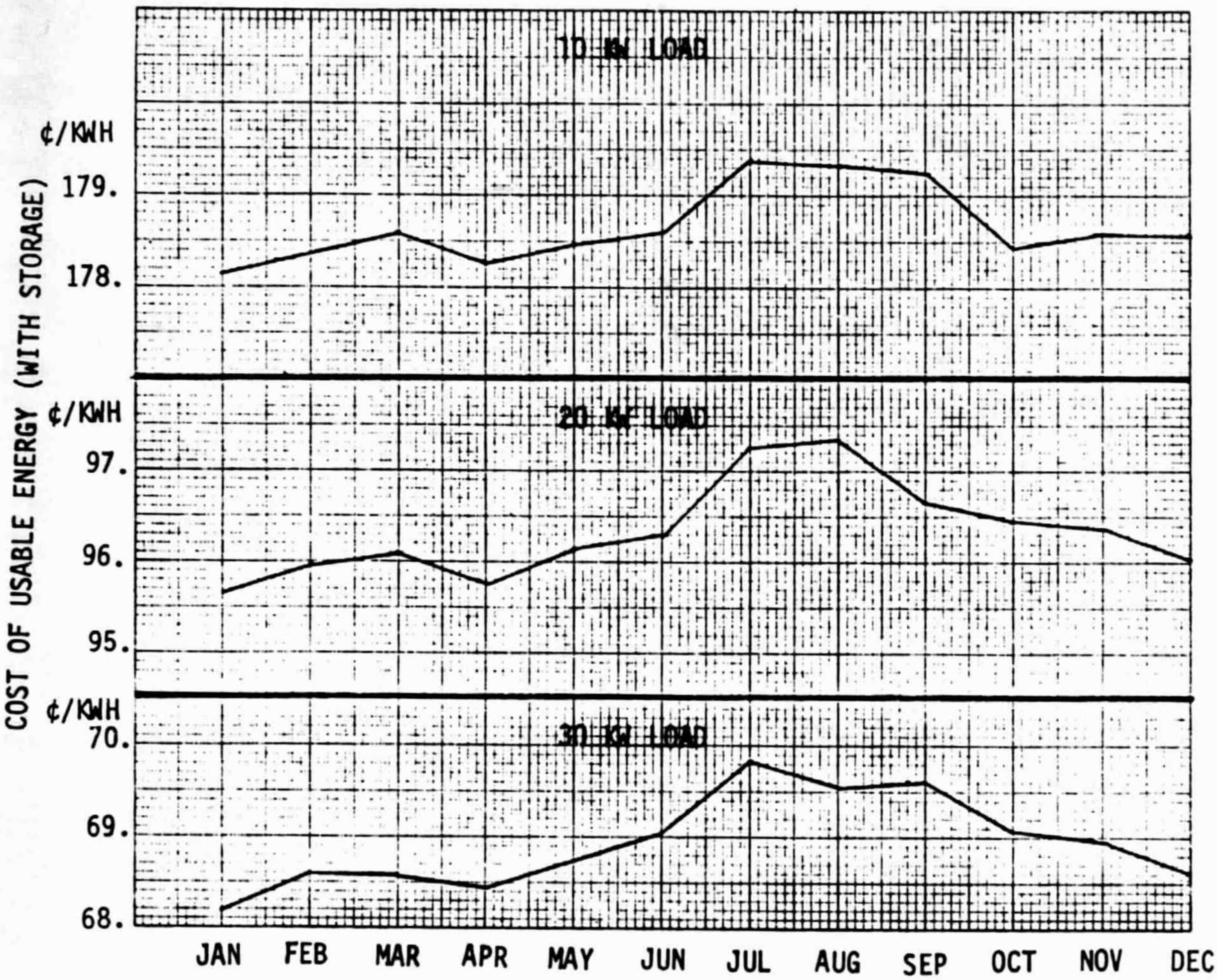

FIGURE 3.5-3 MONTHLY ENERGY COST TO SATISFY THE LOAD

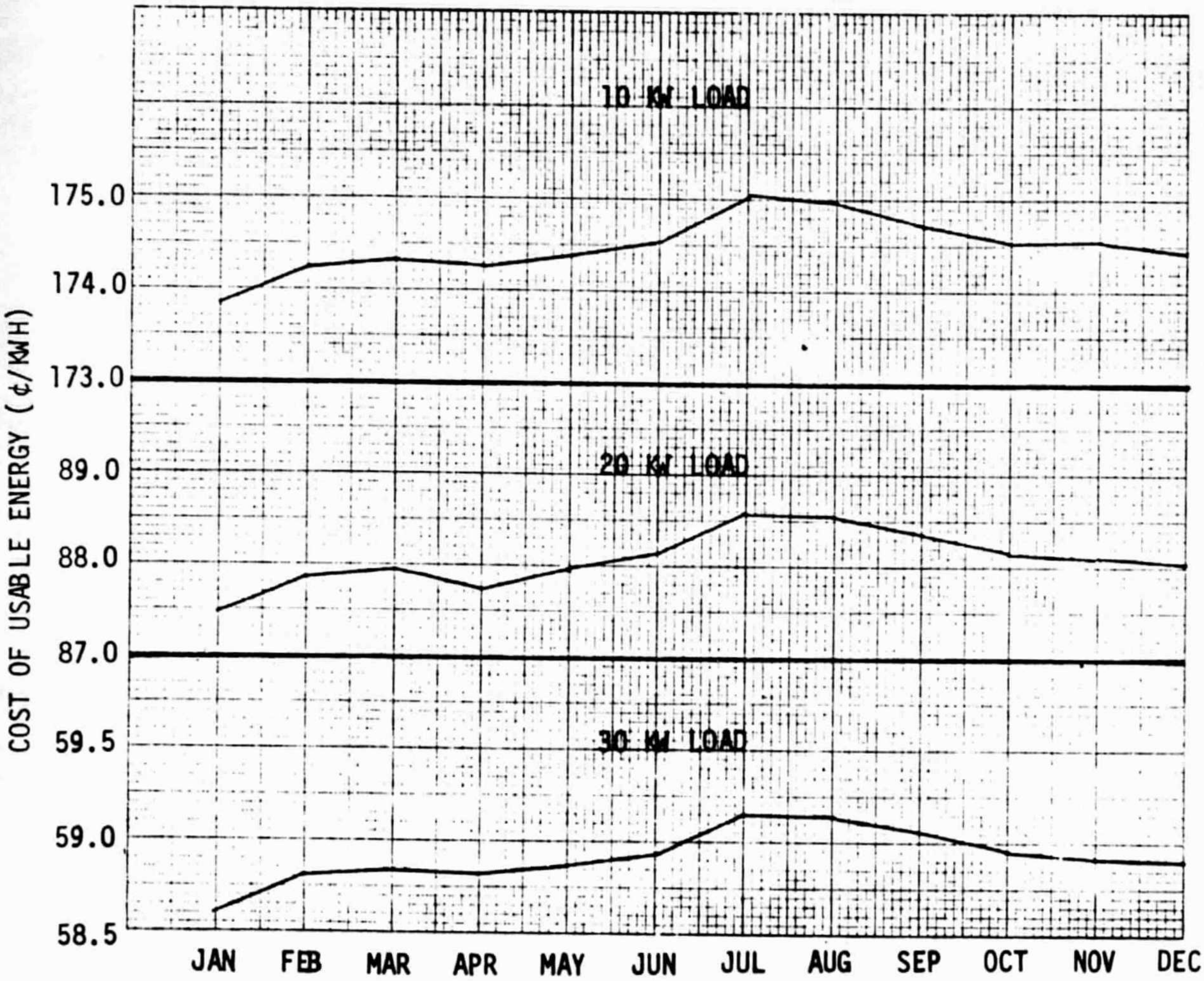

FIGURE 3.5-4 MONTHLY COST OF ENERGY (WITHOUT STORAGE)

One further observation before leaving the subject of energy cost. For the above two computed costs (with and without buying energy from the utility), it was assumed that the system gets credit for surplus wind power. Thus, the total amount of energy in the cost calculation includes not only energy that was delivered to the load but also energy that was surplused to the utility. If it is assumed that the system does not get credit for this surplused energy and also does not buy power from the utility, then the energy costs should go up. Figure 3.5-5 shows the result of this situation. Again, the order of the curves have reversed themselves from Figure 3.5-2. It is seen that if one does not get credit for surplus energy, the system with the larger load and larger storage capacity produces the cheapest power. Figure 3.5-6 gives the energy cost for the same situation if no energy storage is used. It is seen that in the summer months when the average wind speed is low, cost of energy without storage is roughly twice as high as with storage. While during the winter months the cost without storage is approximately 50% higher.

3.5.2 Effect of Load Size on Frequency of Operation

Figure 3.5-7 exhibits the effect of the three different load sizes on the frequency of operation. The frequency of operation is defined to be the percent of time the wind energy system supplies 100 percent of the load. As before, there are different systems supplying the loads so that for each load the system contains the nominal four days of storage. From Figure 3.5-7, it is seen that during the less windy months the frequency of operation drops. Furthermore, even though the 30 kw load utilizes three times as much storage, the 10 kw load case has a much higher frequency of operation (90% in the winter, 60% in summer). Figure 3.5-8 illustrates the situation when no storage is used. It is seen that for the nominal 10 kw case storage (4 day) increases the frequency of operation by roughly 50 percent in the winter months and 200 percent in the summer months. Furthermore, in each of the twelve months the system with storage fully supplies a 20 kw load more often than the wind turbine alone will supply a 10 kw load, i.e., in terms of frequency of operation adding 4 days storage doubles the effectiveness of the wind turbine.

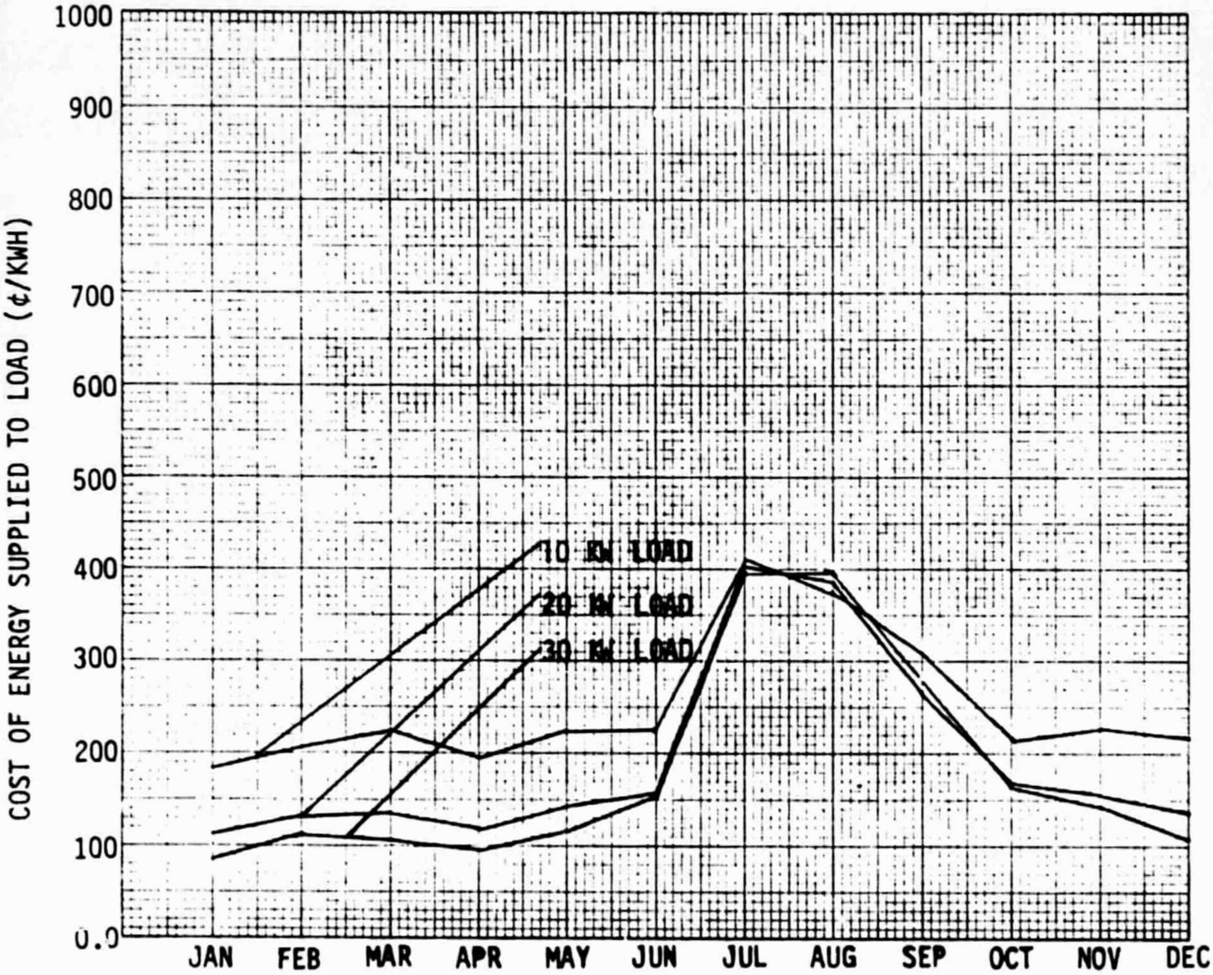

FIGURE 3.5-5 ENERGY COST WITH NO PURCHASE FROM UTILITY AND NO CREDIT FOR SURPLUS POWER

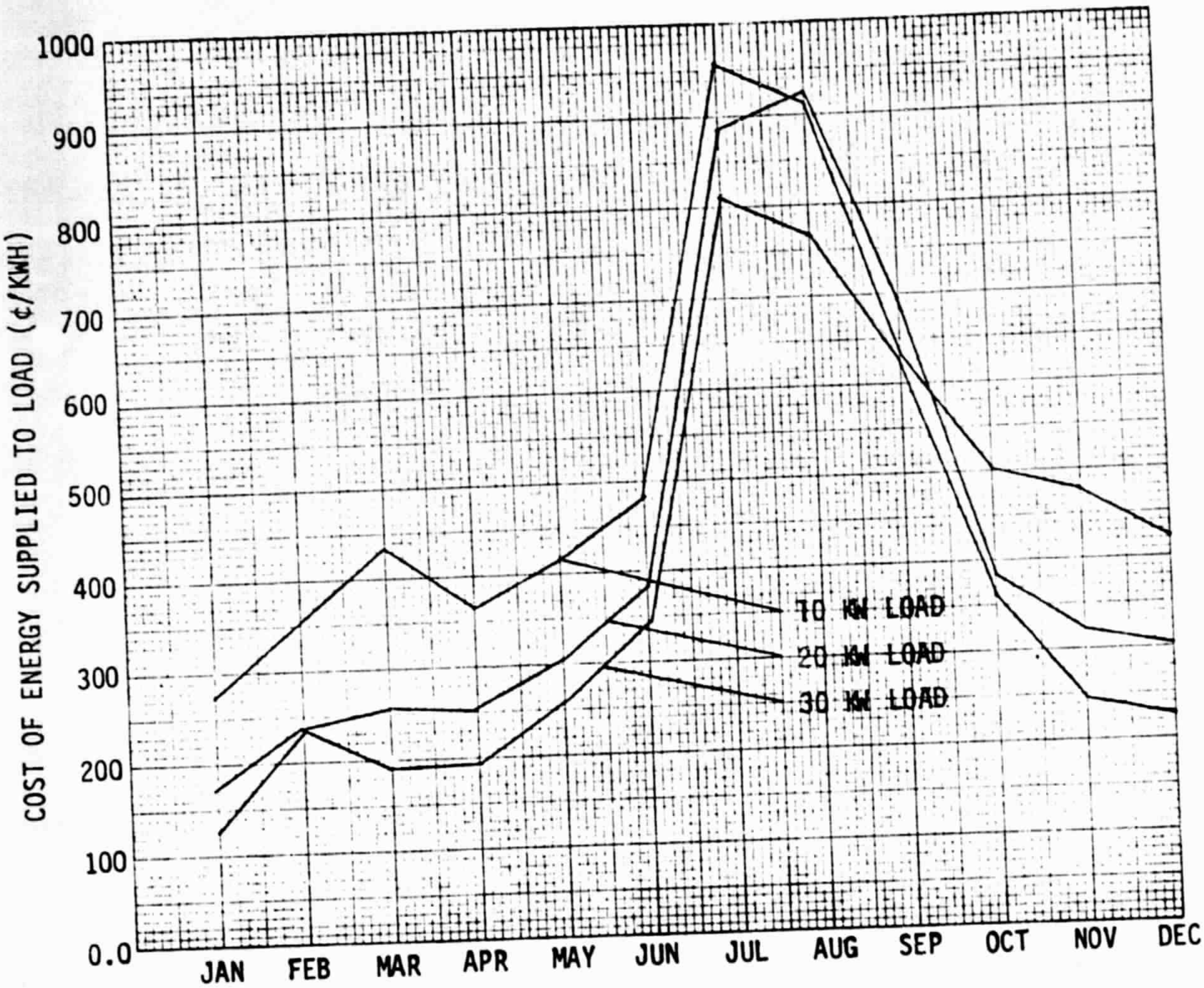

FIGURE 3.5-6 ENERGY COST WITH NO PURCHASE FROM UTILITY, NO CREDIT FOR SURPLUS AND NO STORAGE

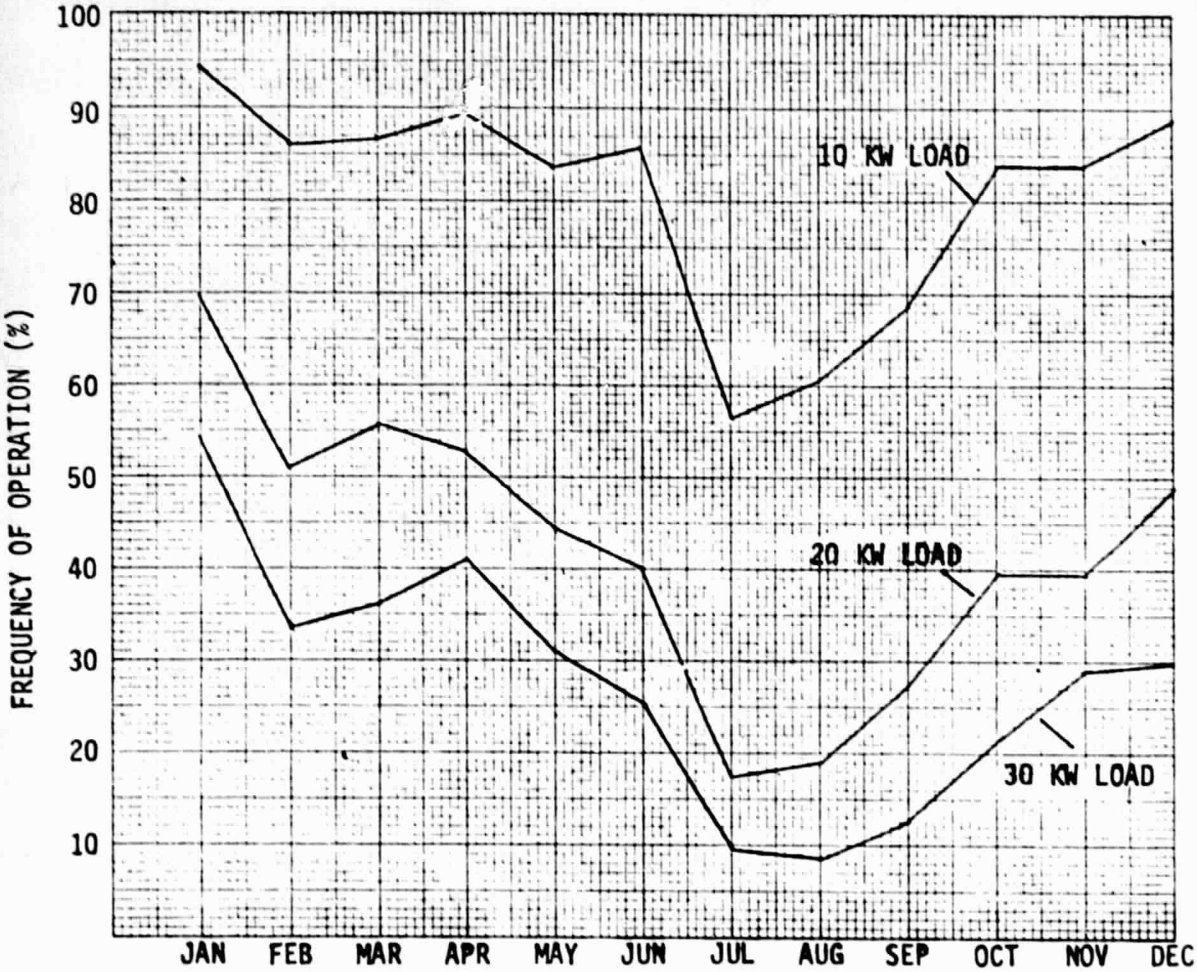

FIGURE 3.5-7 EFFECT OF LOAD SIZE ON FREQUENCY OF OPERATION (WITH STORAGE)

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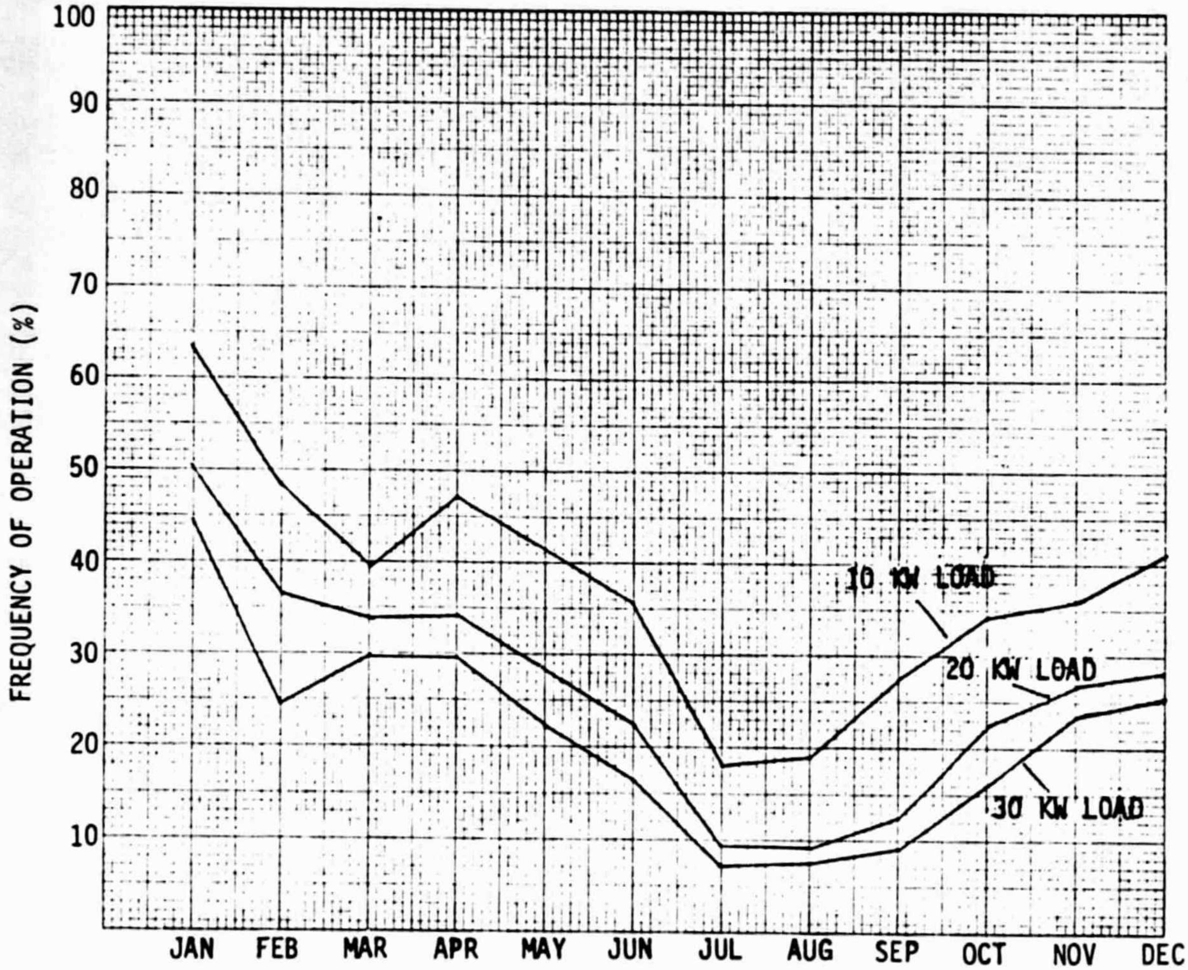

FIGURE 3.5-8 EFFECT OF LOAD SIZE ON FREQUENCY OF OPERATION (WITHOUT STORAGE)

3.5.3 Effect of Cut In Speed On Frequency of Operation

The effect of cut in speed on frequency of operation was studied by assuming the transmission generation efficiency was such that the turbine power at cut in speed was just equal to power needed to overcome friction and inertia in the gear/generator drive train and start generating power. Thus, the turbine/generator for the 9 mph cut in speed is assumed to be more efficient than that for the 10 mph cut in speed. This difference in efficiencies decreases with increasing wind velocity until the generator hits rated power. Figure 3.5-9 gives the frequency of operation of two wind turbines with different cut in speeds, 4.02 meters/sec. (9 mph) and 4.47 m/sec. (10 mph). As one might expect, the design with the lower cut in speed generally produces more power. Two exceptions, however, are noted in Figure 3.5.9. In the months of February and April, because 4.02 m/s (9 m/h) winds occur much more frequently than 4.47 m/sec (10 mph) winds, the wind turbine with the lower cut in speed has more marginal operations. During this time the power generated is sufficient to activate the turbine but not sufficient to supply the control load so that a nominal amount of energy is purchased from the utility. As a result, the lower cut in speed actually resulted in a lower frequency of operation.

3.5.4 Effect of Initial State of Storage on Frequency of Operation

Simulations were conducted to determine the sensitivity of the study results to initial state of the storage subsystems. Since the simulations span a years time and the nominal storage capacity is only four days, one would expect the initial condition to have little effect on the overall performance. This was indeed the case. During the first month of the simulation (January), the difference in the frequency of operation between the two cases was negligible. However, there was a 1.76 percent difference in the total amount of energy purchases from the utility. The difference for the following months was even less significant. It might be pointed out that January is a month of relatively high winds. One would expect somewhat greater difference in the

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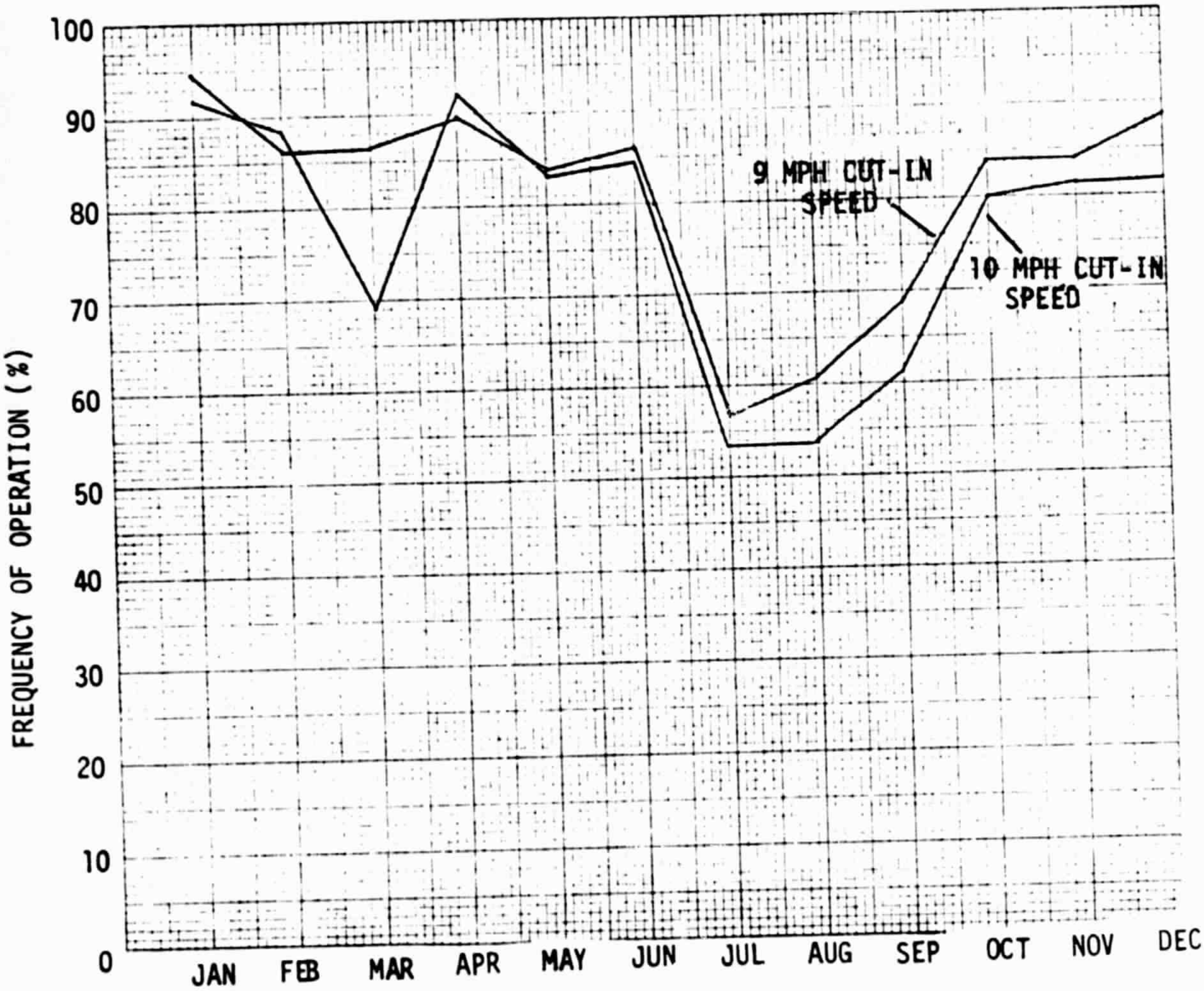

FIGURE 3.5-9 FREQUENCY OF OPERATION FOR DIFFERENT TURBINE CUT-IN SPEEDS

first month performance if the simulation had been started in July rather than January. However, even then these results indicate the effect would be negligible.

3.5.5 Effect of Storage Capacity on Frequency and Cost of Operation

In order to determine the effect of storage capacity on frequency and cost of operation, simulations of three different storage capacities were conducted for each of the three load levels (10, 20, and 30 kw) and also for a time varying load. The three storage capacities were two hours, four days, and fifteen days. The effect of storage on the frequency of operation is summarized in Figure 3.5-10. The percent of operation is computed for the full year. It is seen that for the 10 kw load, increased storage resulted in improved frequency of operation but for a 30 kw load little improvement was achieved. This is due to the fact that the average power from the wind is only 20 kw (see Figure 3.5-1) thus for a constant 30 kw load very little energy goes into storage.

The time varying load of Figure 3.5-10 was produced using the electrical and thermal load profiles shown in Figure 3.5-11. The loads were scaled so that the total average load was 20 kw and 70 percent of the load was electrical. It is interesting to note that for constant loads the percent of operation is generally greater than for time varying loads of equal average value.

The effect of storage on the yearly cost of energy delivered to the load is summarized in Figure 3.5-12. It is seen that by increasing storage size beyond four days supply, one increases capital cost without a commensurate increase in frequency of operation. Figure 3.5-13 gives the yearly costs of energy delivered to the load assuming no utility tie-in. In this case less energy is delivered, resulting in a higher cost per kwh than for 3.5-12.

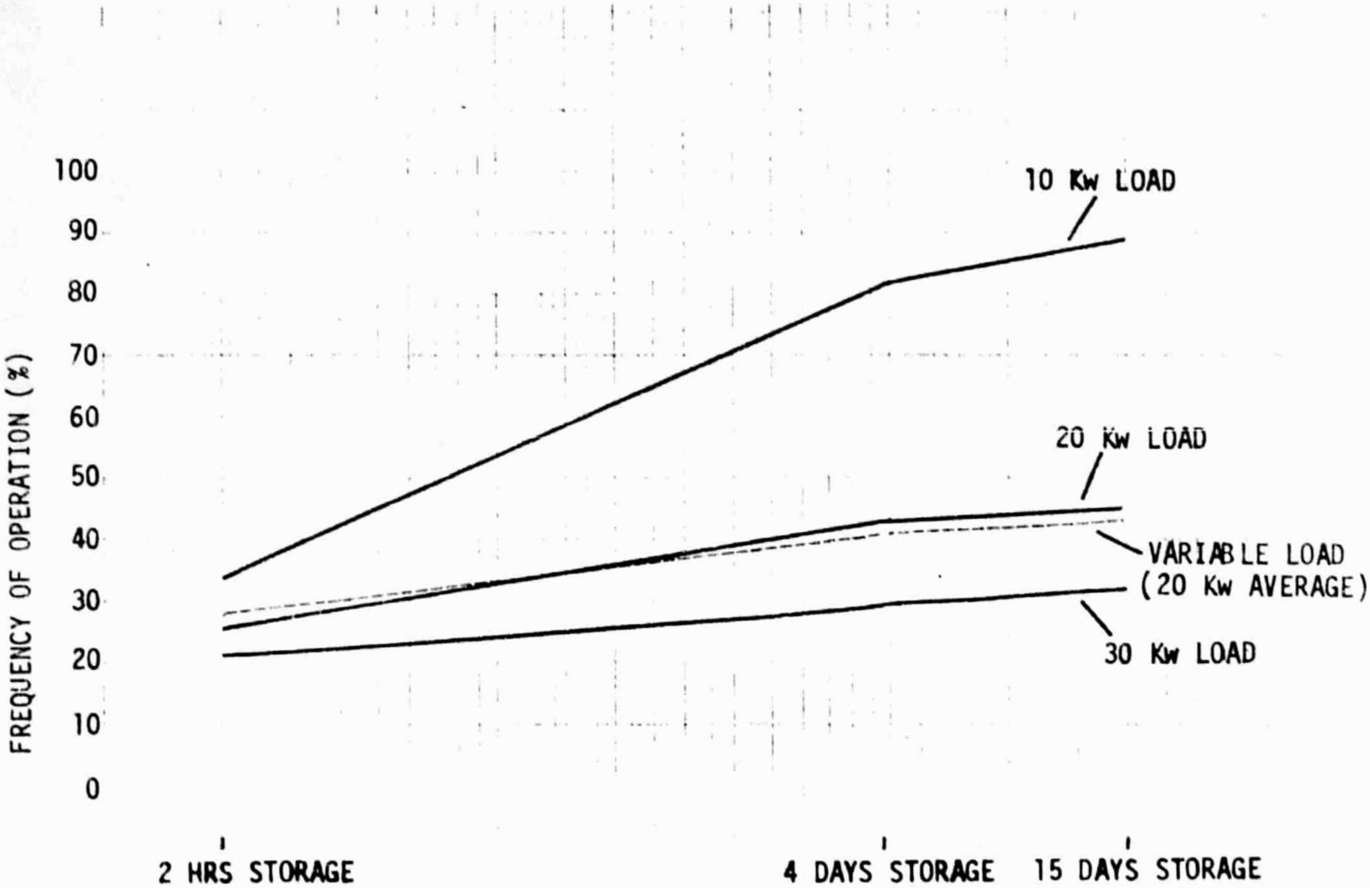

FIGURE 3.5-10 EFFECT OF STORAGE SIZE ON FREQUENCY OF OPERATION

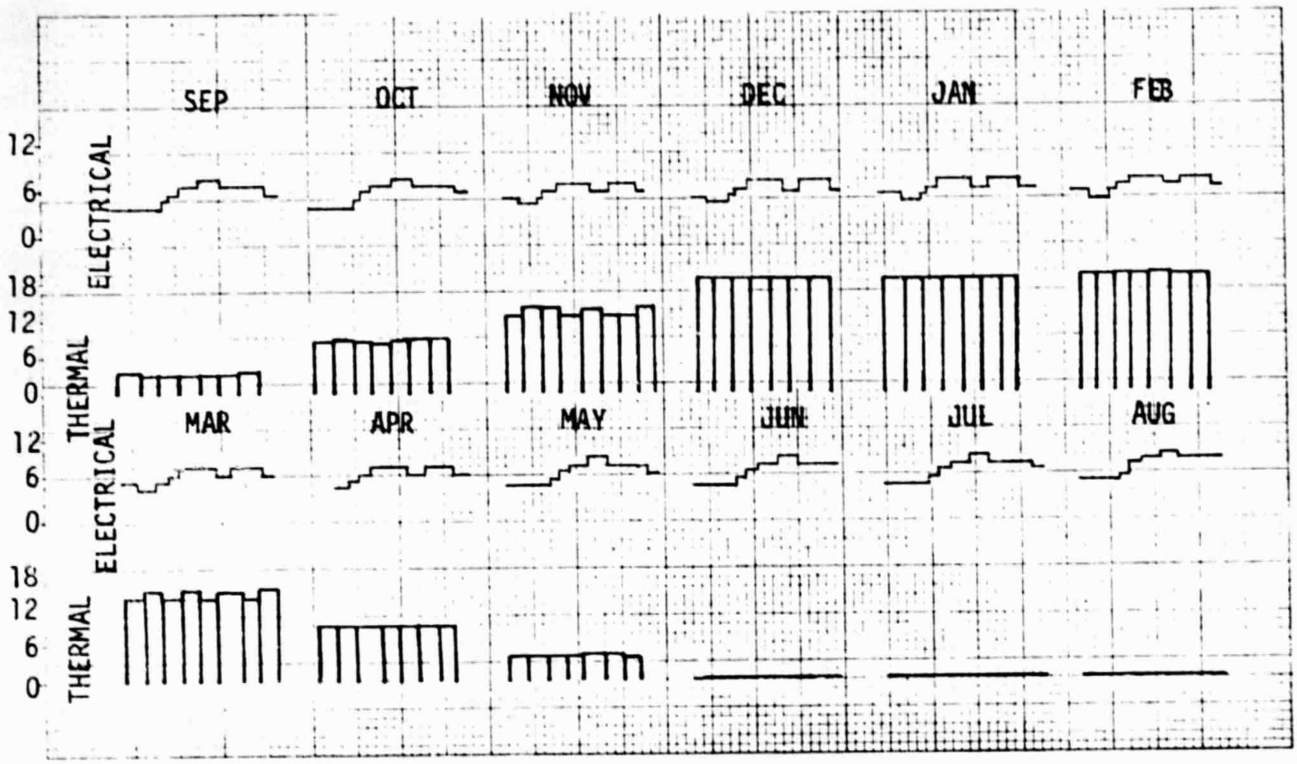

FIGURE 3.5-11 DAILY LOAD PROFILES

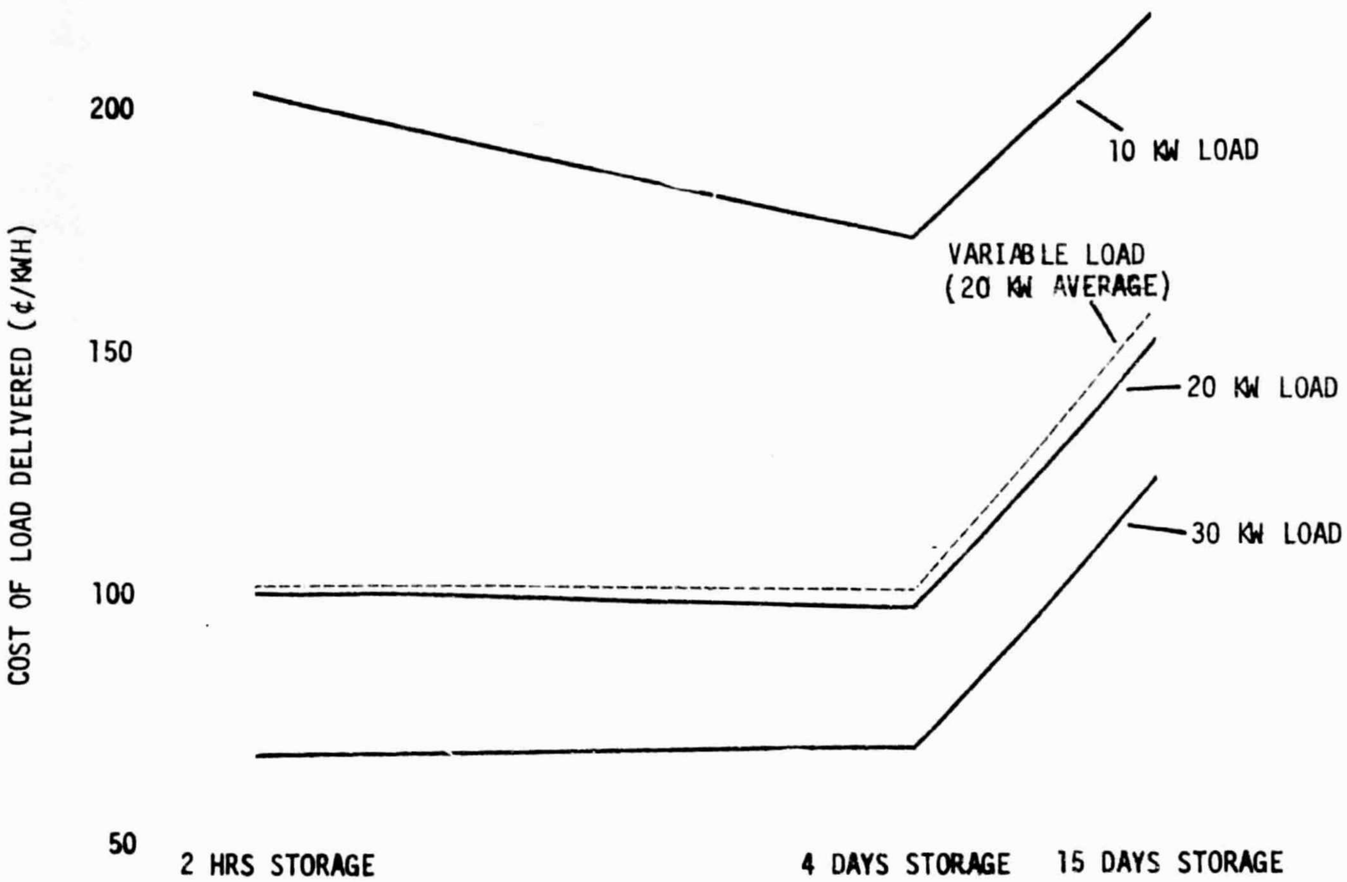

FIGURE 3.5-12 EFFECT OF STORAGE SIZE ON COST OF ENERGY TO LOAD

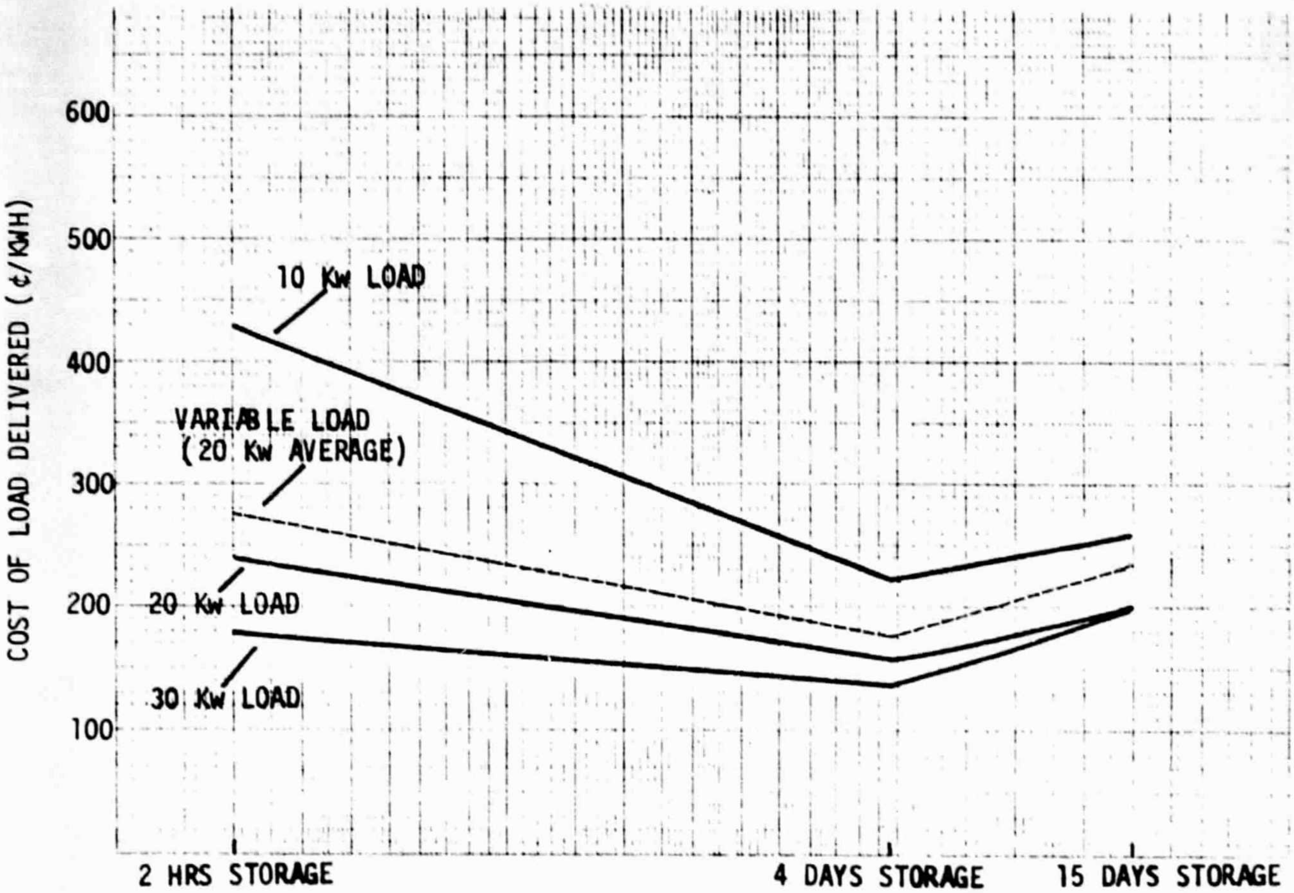

FIGURE 3.5-13 EFFECT OF STORAGE SIZE ON COST OF ENERGY TO LOAD
(NO UTILITY AVAILABLE)

3.5.6 Study of Inverter Efficiency

A study was performed with two 5 kw inverters replacing the one 10 kw inverter used for the nominal case. It is known that inverter efficiencies improve with the degree of utilization (see Figure 3.2-3). Thus one might expect that, for situations where full utilization of inverter capacity is not common, the use of the two inverters would increase the efficiency of the storage system. To perform this study, it was necessary to change the simulation step size away from the one hour step size used for the rest of the study. This is because the wind data is given only at discrete levels which result in requests to the battery not representative of a spectrum of values. The step size was thus set at 1.9 hours. This required interpolation between wind speed data so that a representative spectrum of power requests were made to the battery.

The frequency of operation using two inverters is compared with that using one in Figure 3.5-14. The results were unexpected in that one full size inverter outperforms the two half size inverters. By calculating the composite efficiency of two inverters, one can understand why this is the case. Figure 3.5-15 compares the two efficiency functions. It is seen that the average efficiency of the two inverter system is the same as that of one inverter. However, the latter has a higher efficiency than the former in the region of high power flow (40% of capacity and higher), where efficiency counts more. Thus, in the long run the one inverter system allows a greater fraction of the input power to flow through. This conclusion is made under the assumption that the input power is uniformly distributed over the capacity range of the inverter, as is the case in this parameter study. If some other distribution is valid, the two inverter system may indeed have better performance.

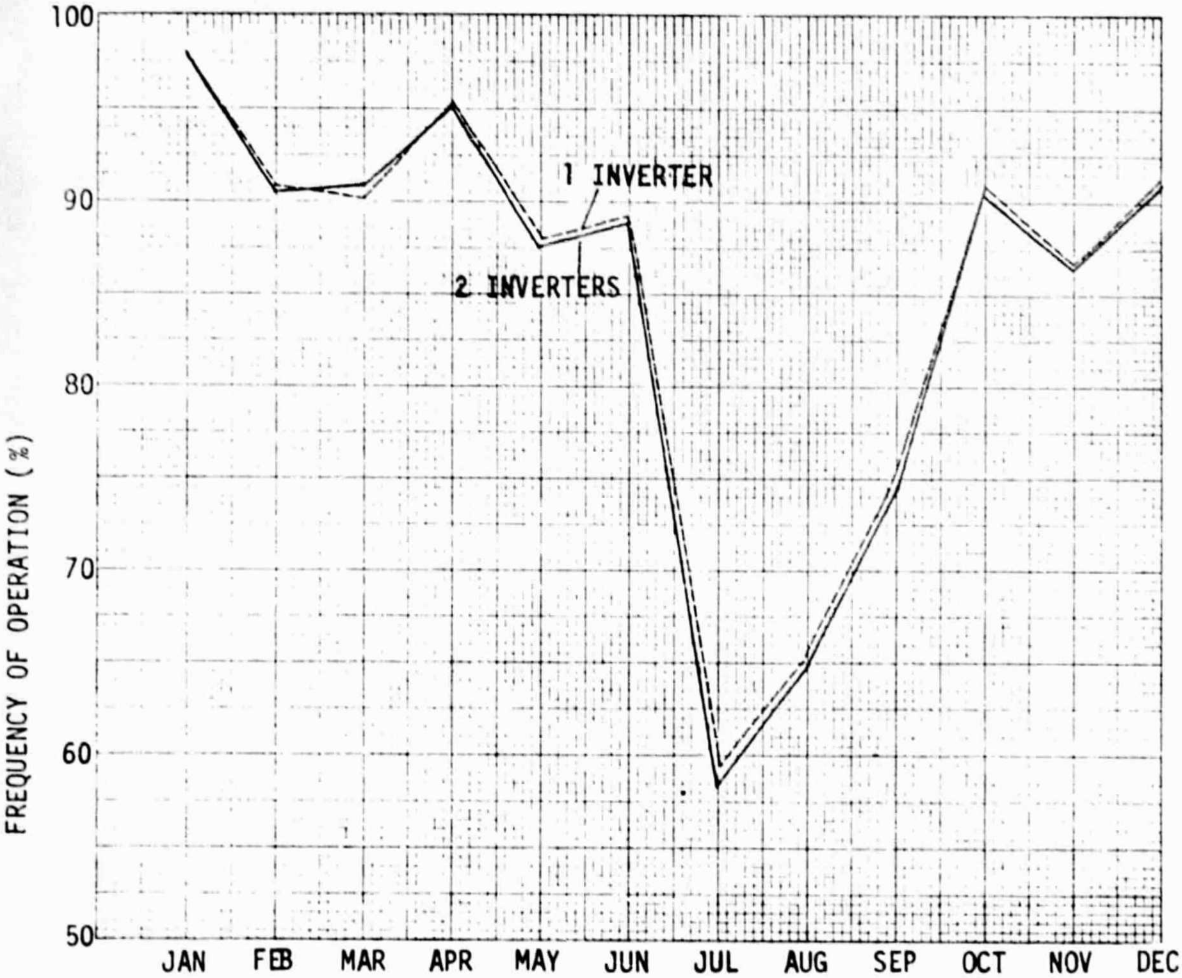

FIGURE 3.5-14 COMPARISON OF FREQUENCY OF OPERATION FOR TWO INVERTER SYSTEMS

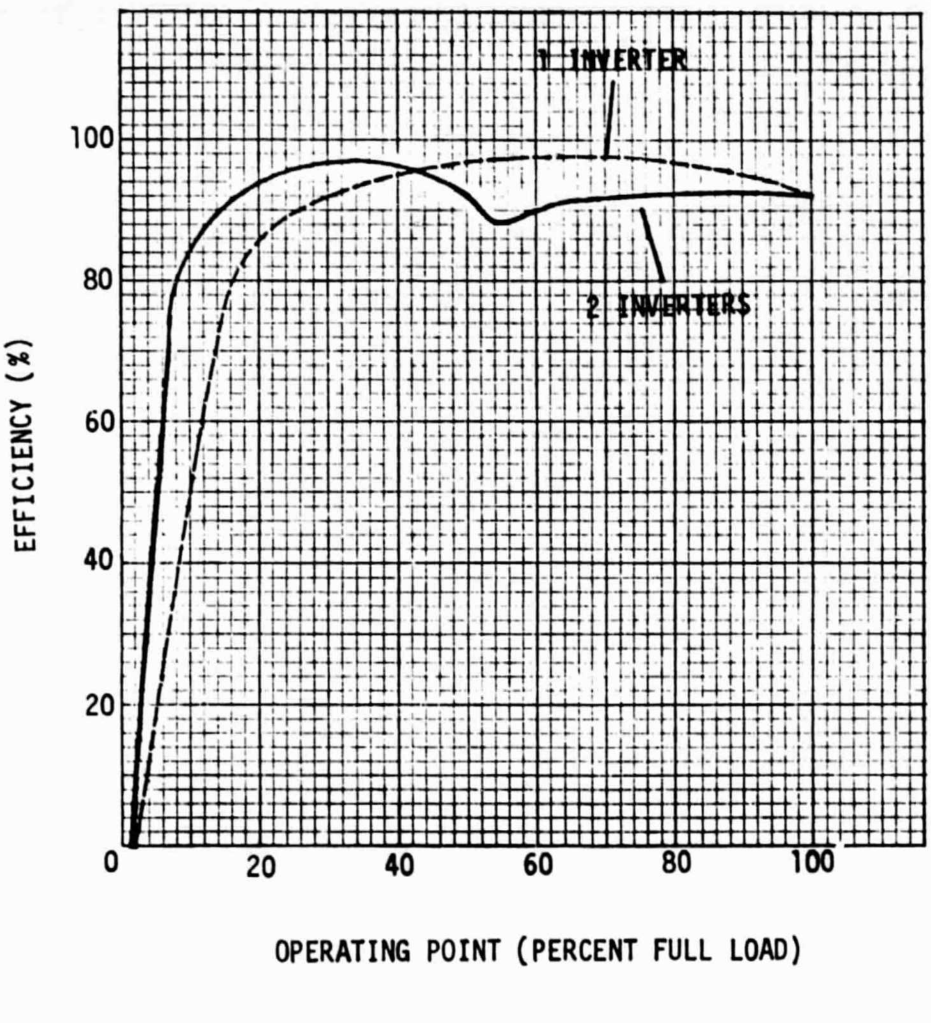

FIGURE 3.5-15 COMPARISON OF INVERTER EFFICIENCIES

3.6 SUMMARY OF CRITICAL SYSTEM PARAMETERS

In this section, critical parameters are summarized in tabular form. The same parameter names are used as in the analysis command cards.

3.6.1 Wind Turbine-Gear-Generator

VO WT	Design point mean wind speed = 5.37 (12 mph)
VR WT	Rated wind speed = 8.05 (18 mph)
BR WT	Blade radius of turbine = 19.05 meter (62.5 ft.)
LAMWT	Design tip speed ratio = 10
FTAFUW	Wind power coefficient curve (Figure 3.6-1)
CC WT	Capital cost of wind turbine = $66000 per year
CM WT	Maintenance cost of wind turbine = $2640 per year
PLOGR	Power loss curve for gear (Figure 3.6-2), designed so that all power below cut-in is lost.
RAPGE	Rated output of generator = 100 kw
DA GE	Generator mechanical damping = 0
SR GE	Generator rotor resistance = .0842 ohm (so that generator has .95 internal efficiency at rated power)

3.6.2 Rectifier-Battery-Inverter

FTAFUR	Rectifier resistance curve (Figure 3.6-3), designed so that rectifier efficiency curve in Figure 19 results.
RAPRE	Rectifier rated input power = 70 kw
CCBA60	Capital cost of one 60 cell bank = $150
CB60	Capacitance of one 60 cell bank = 49505 farad
FTAFVB	Terminal resistance of one 60 cell bank as function of charge-discharge current and state of charge, designed to produce the charge-discharge characteristics as shown in Figure 3.2-1.

ANBAT	Number of 60 cell banks	varies from simulation to simulation
EI BA	Battery capacity	
GDEBA	Minimum allowable battery storage	
RAPBA	Rated battery input power = 30 kw	
RAPIV1	Rated inverter input power = 10 kw	
FTAFUI	Inverter resistance curve (Figure 3.6-4) designed so that inverter efficiency curve in Figure 19 results.	

3.6.3 Thermal Vessel

TM1TS	Maximum storage temperature = 454.44^o C (850^o F)
TO1TS	Minimum storage temperature = 232.22^o C (450^o F)
PD TS	Rated storage thermal power = 30 kw
PM TS	Maximum charge rate = 58.6 kw
TS TS	Rated storage time (varies with storage capacity)
HT TS	Enthalpy - temperature curve for storage media (Figure 3.2-4)

3.6.4 Loads

LO1LOD	Domestic load constants varying from simulation to simulation
NC TL	thermal load

In three of the simulations, the loads vary with time and are supplied by a daily profile (Figure 3.5-11).

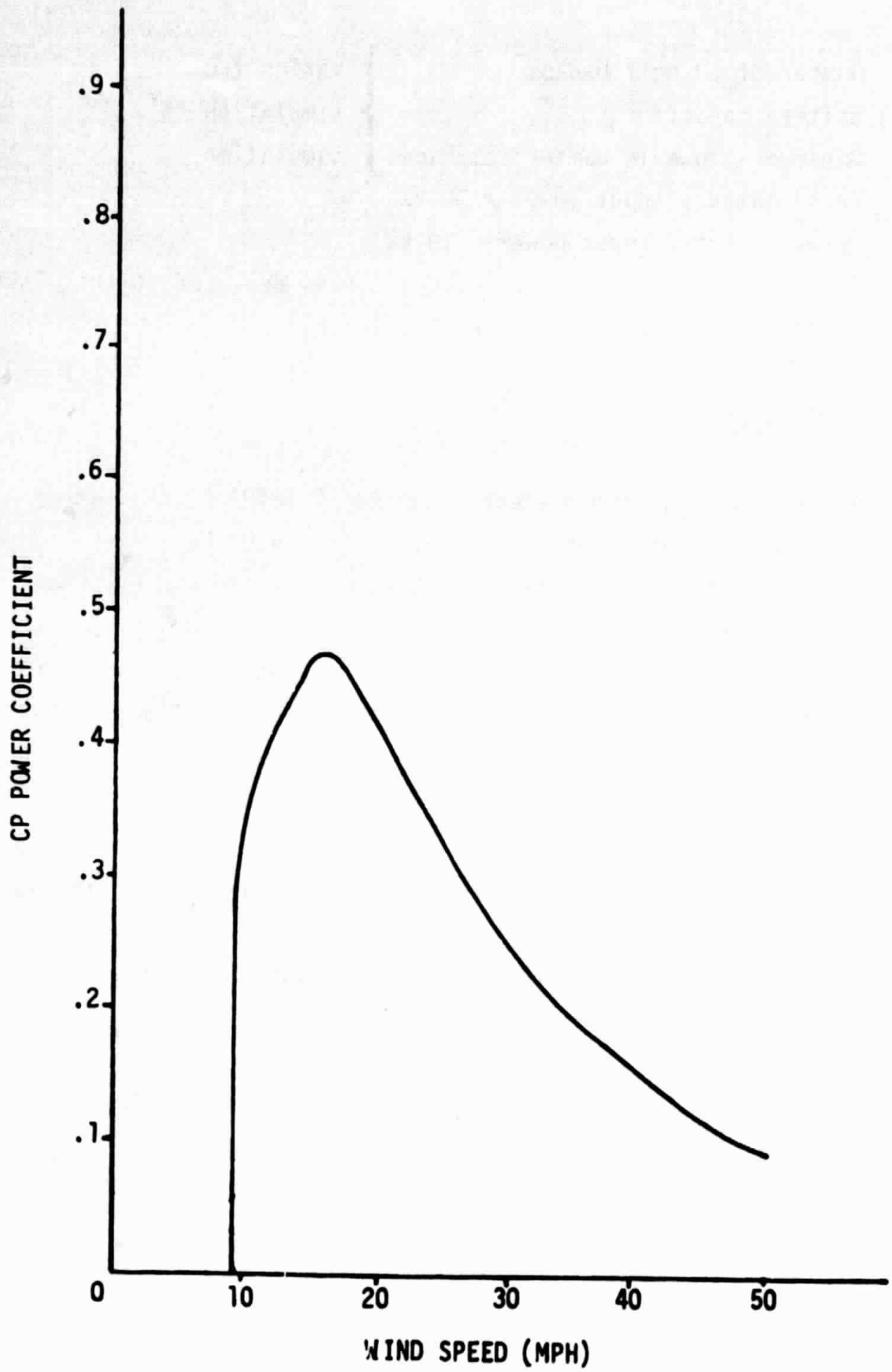

FIGURE 3.6-1 TURBINE POWER COEFFICIENT VS. WIND SPEED

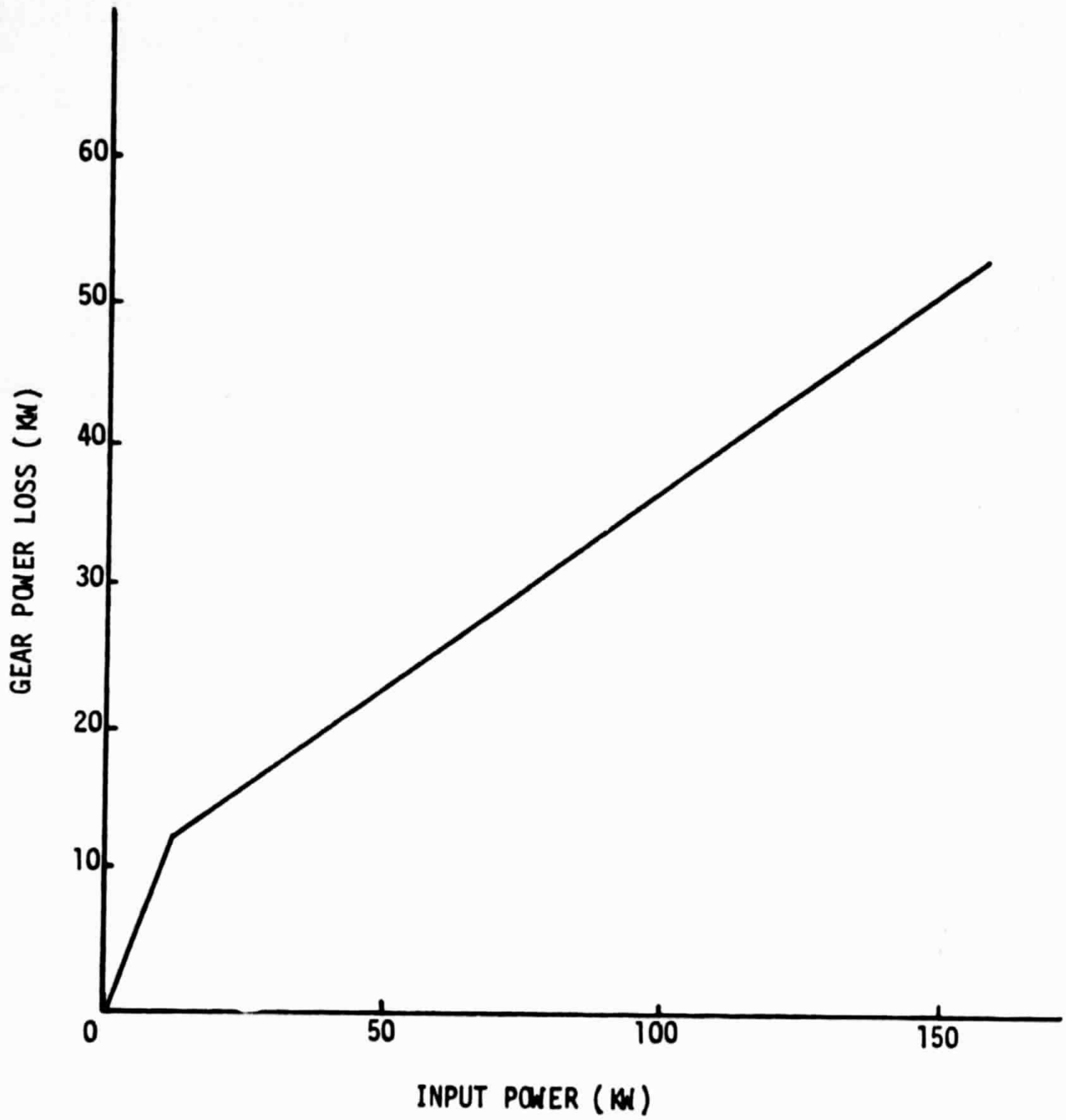

FIGURE 3.6-2 GEAR LOSS (KW) VS. INPUT POWER (KW)

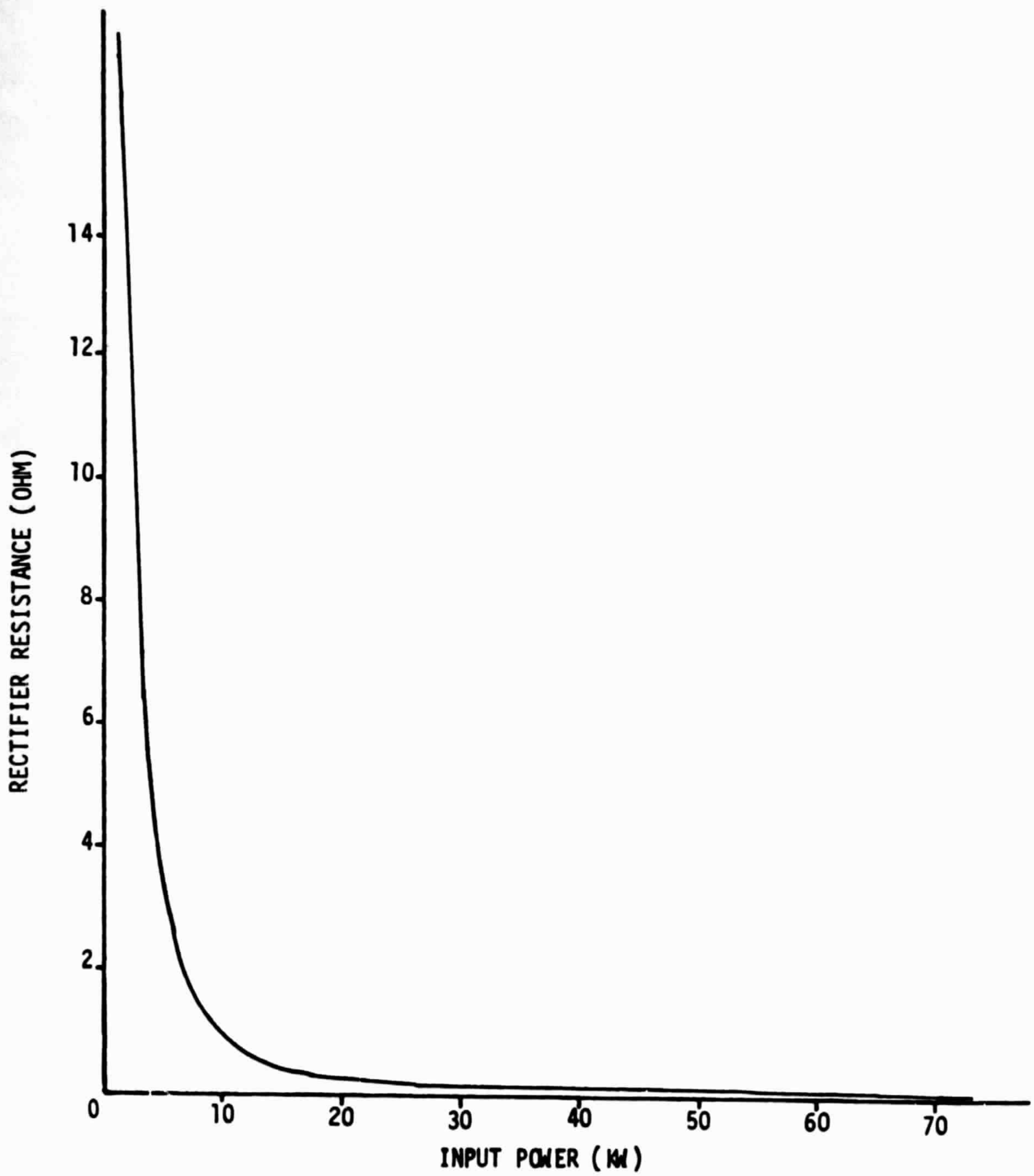

FIGURE 3.6-3 CURVE USED FOR RECTIFIER EFFICIENCY

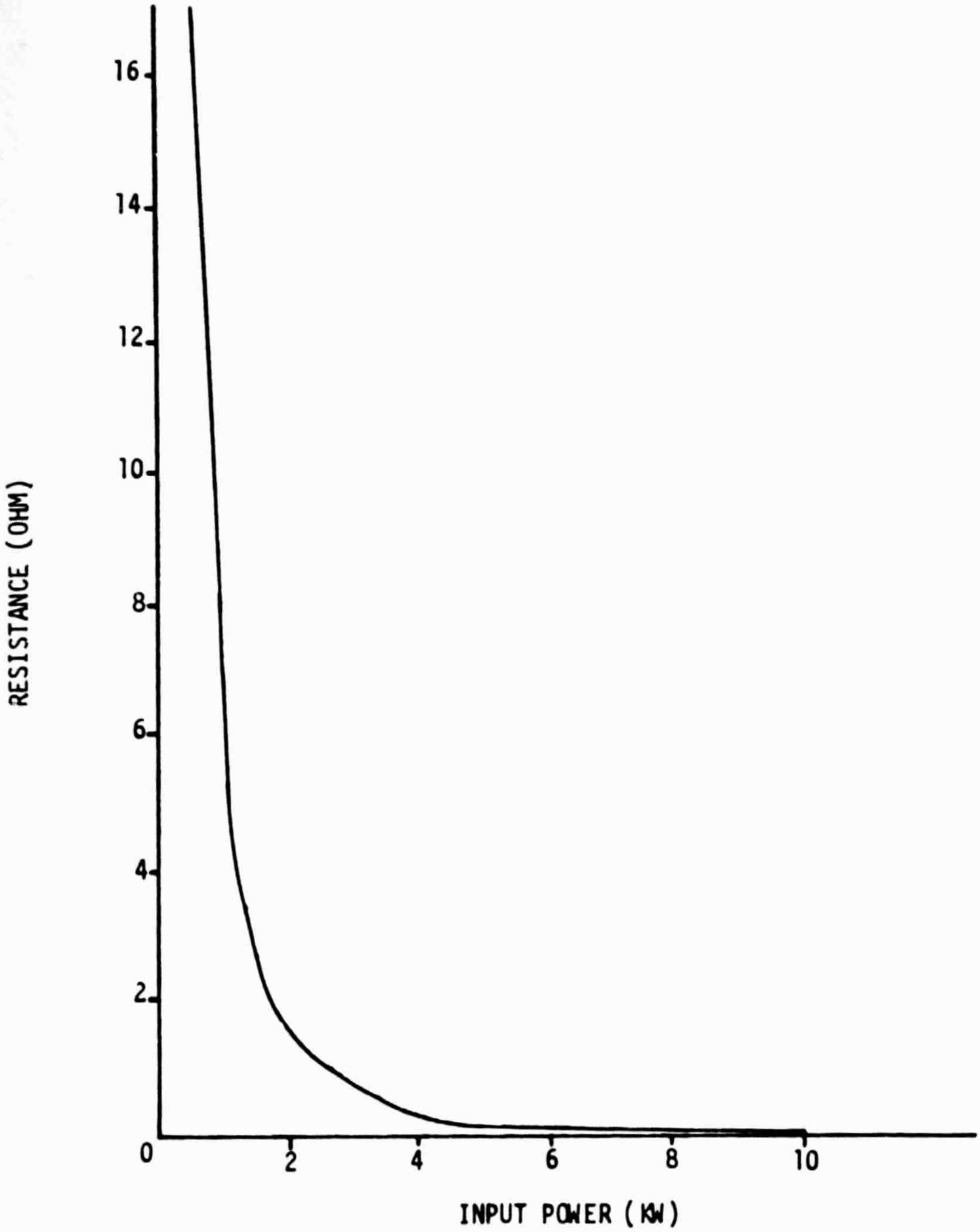

FIGURE 3.6-4 CURVE USED FOR INVERTER EFFICIENCY

4.0 LIST OF REFERENCES

[1] R. Puthoff, "Fabrication and Assembly of the ERDA-NASA 100 KW Experimental Wind Turbine", NASA TMX-3390, April 1976.

[2] R. Thomas, "Large Experimental Wind Turbine - Where We Are Now", NASA TMX71890, March 1977.

[3] G. Vinal, Storage Batteries, Wiley & Sons, 1963.

[4] N. Shepard, "Definition Study for Photovoltaic Residential Prototype Systems", ERDA-NASA 19769-76-1 NASA CR135039.

[5] NASA CR134937 "Design Study of Wind Turbines - 50 KW to 3000 KW - For Electric Utility Applications", Kaman Aerospace Corp., February 1976.