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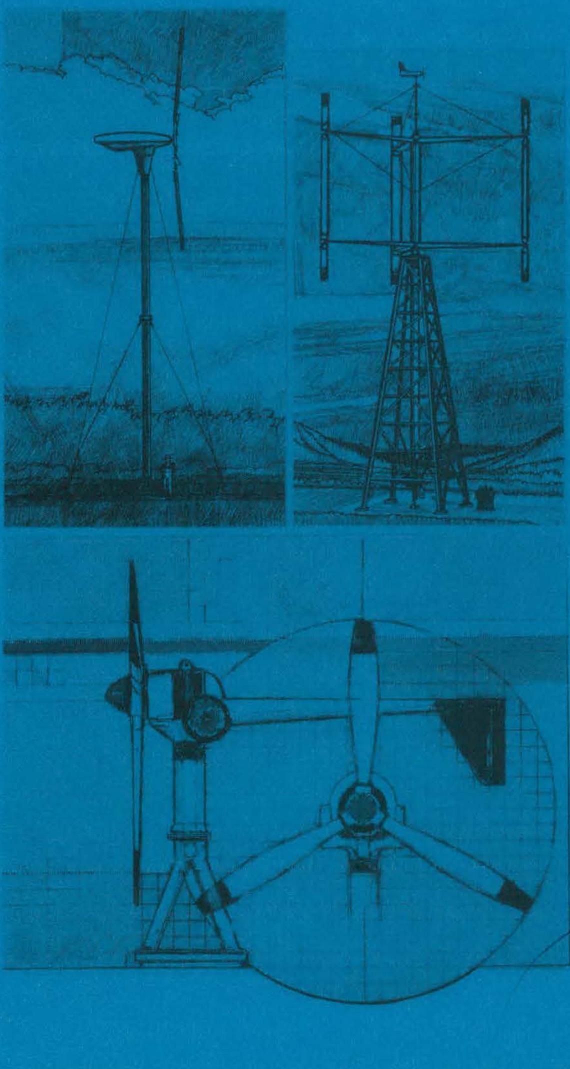
STRUCTURAL COMPOSITES INDUSTRIES 4-KILOWATT WIND-SYSTEM DEVELOPMENT

Phase I - Design and Analysis Executive Summary

May 1981



N. Malkine
G. Bottrell
O. Weingart

Prepared by
STRUCTURAL COMPOSITES INDUSTRIES
6344 North Irwindale Avenue
Azusa, California 91702

For

Rockwell International Corporation
Energy Systems Group
Rocky Flats Plant
Wind Systems Program
P.O. Box 464
Golden, Colorado 80402

Subcontract No. PF07420C

As a Part of the

U.S. DEPARTMENT OF ENERGY
WIND ENERGY TECHNOLOGY DIVISION
FEDERAL WIND ENERGY PROGRAM

Contract No. DE-AC04-76DP03533

ROCKWELL INTERNATIONAL NOTE

The contract awarded to Structural Composite Industries, Inc. by the Rockwell International Energy Systems Group to develop the 4 kilowatt wind system described in this report was terminated after completion of the Phase I Design and Analysis effort. Thus, a prototype of the design was not fabricated or tested under federal funding.

Excess cost required to complete the project was the prime reason for termination. Contributing factors were:

1. The inability of the design to meet contract cost of energy goals

2. The extreme complexity of the system; in particular, the control system

3. The lack of technical advancement over existing wind systems

While the design did have several interesting features--such as a new type of pitch control system--these features only contributed to the complexity of the machine and did not result in lowering the cost of energy, increasing reliability, or advancing the state of the art.

DISCLAIMER

DISCLAIMER

PATENT STATUS

The composite blades and tower described in this report are covered by one or more of the following U.S. Patents issued to Structural Composites Industries, Inc., Azusa, California

U.S. Patent No. 4,260,332

U.S. Patent No. 4,264,278

and other patents pending.

The torque actuated blade pitch control system is covered by the following U.S. Patent issued to Ventus Energy Corporation, Covina, California

U.S. Patent No. 4,219,308

and other patents pending.

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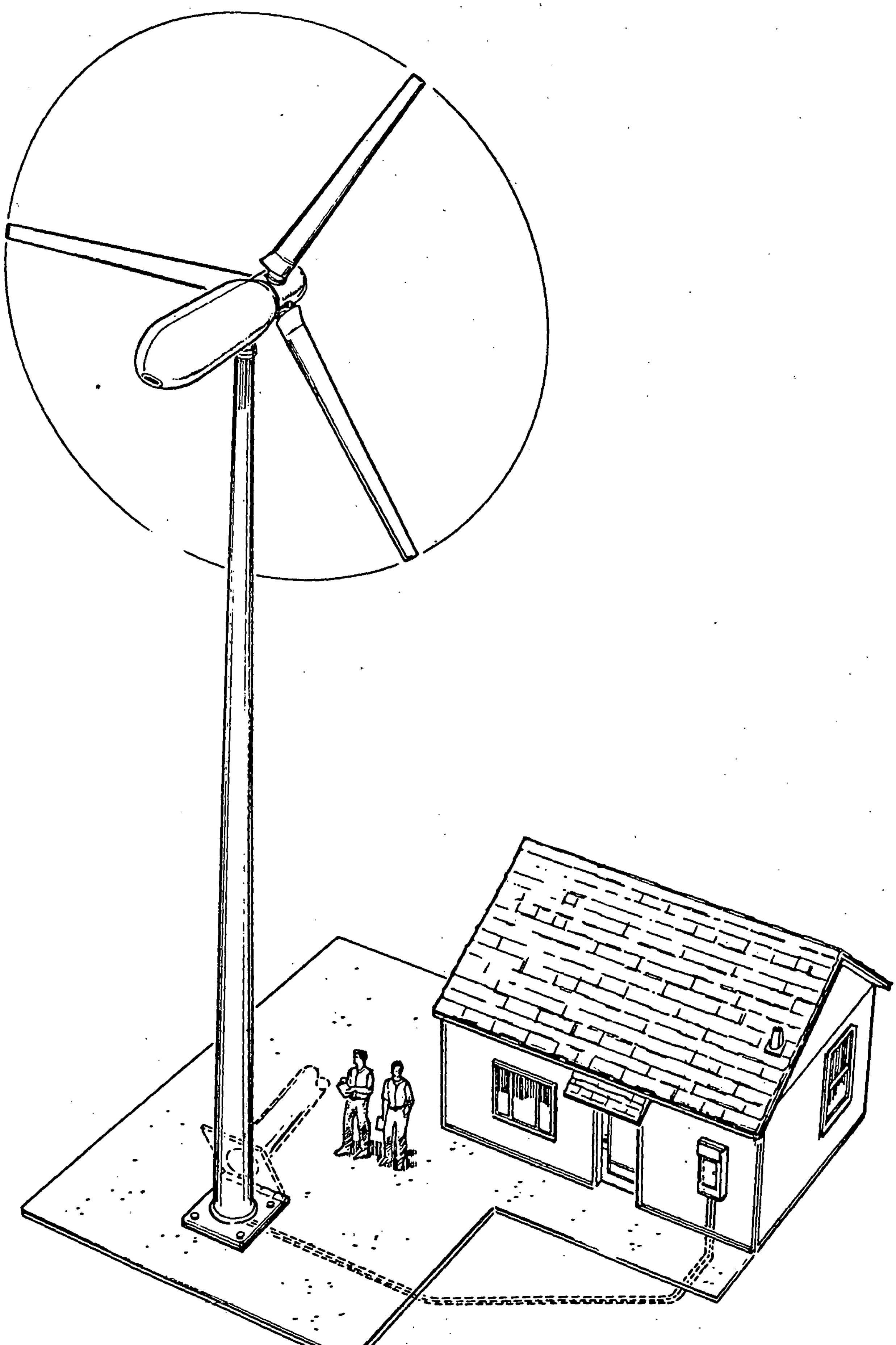


Concept - Structural Composites Industries 4kW Wind System

ABSTRACT

A 4 kW small wind energy conversion system (SWECS) has been designed for residential applications in which relatively low (10 mph) mean annual wind speeds prevail. The objectives were to develop such a machine to produce electrical energy at 6 cents per kWh while operating in parallel with a utility grid or auxiliary generator.

The Phase I effort covered by this report began in November, 1979 and was carried through the Final Design Review in February 1981. During this period extensive trade, optimization and analytical studies were performed in an effort to provide the optimum machine to best meet the objectives. Certain components, systems and manufacturing processes were tested and evaluated and detail design drawings were produced.

The resulting design is a 31-foot diameter horizontal axis downwind machine rated 5.7 kW and incorporating the following unique features:

- Composite Blades
- Free-Standing Composite Tower
- Torque-Actuated Blade Pitch Control

The design meets or exceeds all contract requirements except that for cost of energy. The target 6 cents per kWh will be achieved in a mean wind speed slightly below 12 mph instead of the specified 10 mph.

TABLE OF CONTENTS

FIGURES

TABLES

NOMENCLATURE

A	Area
AAWS	Annual Average Wind Speed
AOM	Annual Operating and Maintenance Cost
ac	Alternating Current
C	Chord
^oC	Degrees Celcius
CDR	Critical Design Review
c.g.	Center of Gravity
COE	Cost of Energy
Cp	Rotor Power Coefficient
Cpr	Rotor Power Coefficient For a Local Blade Station at Radius r
$\frac{C}{P}$	$\frac{\text{Basic Load Rating}}{\text{Load}}$ (For Bearings Life Evaluation)
DIA	Diameter
dc	Direct Current
DC	Decreasing Pitch Angle
DBT	Double Bias Tape
DLO	Direct Labor Overhead
DOE	Department of Energy
E	Young's Modulus
^oF	Degrees Farenheit
FDR	Final Design Review
FMEA	Failure Mode and Effects Analysis
Fx	Force in the Lateral Direction
Fy	Force in the Fore-Aft Direction
Fz	Force in the Vertical Direction
Fr	Force in the Radial (Centrifugal) Direction
ft	Foot
G	Shear Modulus
G & A	General and Administrative Overhead
Hz	Hertz (Cycles Per Second)

NOMENCLATURE

I	Area Moment of Inertia
IC	Increasing Pitch Angle
in.	Inch
J	Torsional Area Moment of Inertia
k	Stiffness
kW	Kilowatt
kWh	Kilowatt Hour
ksi	1000 lb Per Square Inch
L	Pitch Ball Screw Lead
Lf	Feathering Ball Screw Lead
lb	Pound
lb-ft	Pound x Foot (Moment)
$lb\text{-}ft^2$	Pound x $Foot^2$ (Inertia)
LFT	Longitudinal Filament Tape
LTLT	Linear Taper Linear Twist
mph	Miles Per Hour
m/s	Meter Per Second
Mx	Moment About the Lateral Axis
My	Moment About the Fore-Aft Axis
Mz	Moment About the Vertical Axis
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
OPOP	Optimum Taper Optimum Twist
OSHA	Occupational Safety and Health Administration
oz	Ounce
P	Power
PDR	Preliminary Design Review
psi	Pound Per Square Inch
R	Radius of Blade
r	Distance From Centerline of Rotation to Local Blade Station
R_g	Generator Sprocket Number of Teeth
r_s	Pitch Sprocket Number of Teeth
rpm	Revolutions Per Minute

NOMENCLATURE

S	Slip Speed of Center of Contact Area
SCI	Structural Composites Industries
SF	Safety Factor
SM	Safety Margin
SOW	Statement of Work
SWECS	Small Wind Energy Conversion System
t	Thickness
TFT	Transverse Filament Tape (SCI Patented Process)
ULT	Ultimate
UTRC	United Technologies Research Center
v	Wind Velocity
$\bar{v}$	Average Mean Wind Speed
W	Weight
X	Tip Speed Ratio $\frac{\Omega R}{v}$
YR	Year
Zo	Roughness
ZTZT	Zero Taper Zero Twist
β	Blade Pitching Displacement (degrees)
β	Flux Density
ρ	Density (lb/cu ft)
η	Efficiency
ν	Poisson Ratio
σ	Stress (psi)
Ω	Rotor Rotational Speed

1.0 INTRODUCTION

Recent studies have indicated the need for small wind energy conversion systems (SWECS) to meet energy requirements for small residential applications.

In October 1979, Structural Composites Industries (SCI) was awarded a contract by Rockwell International, on behalf of the Department Of Energy (DOE), to develop such a SWECS. This program is managed by the Rockwell International Energy Systems Group, which operates the Rocky Flats SWECS Test Center.

The system is to provide electrical power in conjunction with an auxiliary generator or intertied with a utility and is designed for an average annual wind speed of 10 mph to increase availability of sites. To be marketable, it must be cost competitive with existing energy sources.

The program to accomplish these goals consisted of two phases: I - Design and Component Development, II - Prototype Fabrication and Testing.

In Phase I, SCI conducted the necessary design and analytical studies required to optimize and finalize a SWECS design. Parametric, system and component trade-off studies were performed to select the design concept which showed the most promise of meeting program objectives, for further development. Specific component development, including the generator, was an integral part of Phase I, to insure adequacy and feasibility of the design. A detailed final design was prepared for the optimized system.

During Phase II, SCI was to fabricate one standard configuration prototype system, assemble and erect the complete system at a site, and conduct a preliminary performance/shakedown evaluation. SCI was to then ship the prototype system to Rocky Flats for field testing. There the system was to be subjected to a comprehensive test evaluation. SCI completed the Phase I final design review in February 1981. Phase II has been discontinued (see Rockwell International Note), although certain long leadtime items for Phase II were purchased during Phase I.

This report presents the results of the Phase I studies, including the optimized detail design for the 4 kW SWECS.

2.0 PROGRAM OBJECTIVES

Objectives of the Phase I effort were to develop a complete detailed design of a SWECS capable of generating electrical energy at a cost competetive with alternative energy sources.

The SWECS was required to produce 3 to 6 kW in wind speeds between 15 and 20 miles per hour, when operating in parallel with a utility grid or an auxiliary generator. The target cost of energy, for the 10,000th production unit, was to be 6 cents per kWh, in 1978 dollars, when operating in a 10 mph mean annual wind speed. Other design criteria are summarized in Table 2-1. The "special" design was an alternate machine that would be adequate to withstand more severe environmental conditions.

Table 2-1
BASIC DESIGN CRITERIA

	STANDARD DESIGN	SPECIAL DESIGN
OUTPUT:	* 7,500 TO 15,000 kWh/yr IN A WIND REGIME HAVING A MEAN ANNUAL WIND SPEED OF 4.6 m/s (10 mph) MEASURED AT 9.1 m (30 ft) ABOVE GRADE	SAME
	120/240 ± 5% ac SINGLE PHASE, 60 Hz INTERTIE WITH A UTILITY OR WITH AN INTERCONNECTION WITH AN AUXILIARY GENERATOR (E.G. DIESEL).	SAME
	* DESIGN ENVELOPE: 3 TO 6 kW AT A WIND SPEED BETWEEN 6.7 AND 9.0 m/s (15 AND 20 mph).	SAME
OPERATING WIND RANGE:	CUT-IN: MINIMIZE CUT-OUT: MAXIMIZE	SAME
	SURVIVAL: 56 m/s (125 mph) PEAK GUST	74 m/s (165 mph) PEAK GUST
OPERATION ENVIRONMENT:	-30°C TO 60°C (-22°F TO 140°F)	-50 C TO 60 C (-58 F TO 140 F)
	ICE 1" THICK*	ICE 2½" THICK*
	RAIN, DUST, LIGHTNING	SAME + SALT WATER SPRAY
OPERATION AVAILABILITY:	95% AVAILABILITY FACTOR	SAME
SYSTEM LIFE:	25 YEARS, MINIMUM	SAME
ENERGY COST GOAL:	6¢/kWh FOR 10,000th UNIT (1978 DOLLARS)	SAME
CONTROLS:	AUTOMATIC STARTUP AND SHUTDOWN. ROTOR OVERSPEED PROTECTION. BRAKE FOR LOCKING ROTOR NOT REQUIRED IF BLADES ARE FULLY FEATHERED.	SAME

* NEED NOT OPERATE WHILE ICE COATED

3.0 PHASE I ACTIVITIES

3.1 REPORTING ACTIVITIES

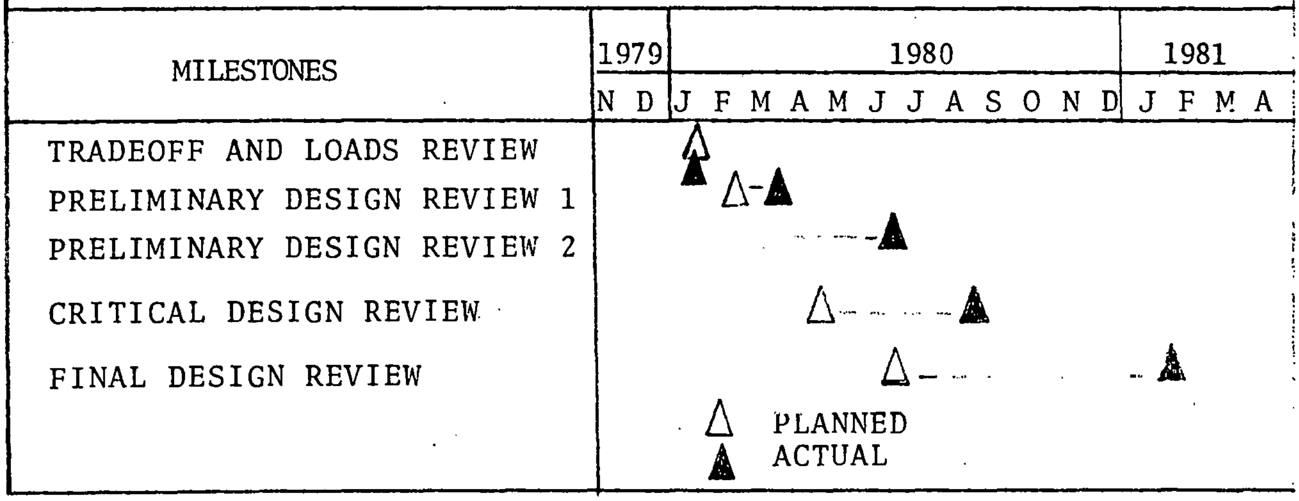
The Phase I effort began in November, 1979 and was carried through the Final Design Review in February, 1981. During this period, five formal design reviews were convened: Tradeoff and Loads Review (TLR), Preliminary Design Review 1 (PDR-1), Preliminary Design Review 2 (PDR-2), Critical Design Review (CDR), and Final Design Review (FDR). These reviews, together with monthly progress reports, provided DOE and Rockwell International the means to effectively monitor program progress and technical adequacy.

3.2 PROGRAM SCHEDULE

As shown in Table 3-1, a 7-month period was originally planned for the Phase I activities. The actual performance required 14 months for this effort due, in part, to the following factors:

- Death of SCI's aerodynamics and structural consultant, Dr. David J. Peery, in November, 1979.
- The need for more extensive optimization and trade studies than those originally planned by SCI. This led to the introduction of PDR-2 which was not originally scheduled.
- The need to document virtually all decisions on an analytical basis.
- Adoption of a more complex design than that originally proposed.

Table 3-1 PHASE I SCHEDULE



The extensive optimization and documentation mentioned above undoubtedly led to a more refined, integrated and optimized design than otherwise would have been possible.

3.3 TRADE STUDIES

Starting from the original proposal concept, trade and optimization studies were performed in order to select that design for further development which showed the most promise for meeting the program objectives. Listed in Table 3-2 are the major trade and optimization studies performed during the Phase I period.

Table 3-2

MAJOR TRADE AND OPTIMIZATION STUDIES

STUDY	SELECTION
ROTOR HUB TYPE	RIGID
BLADE AIRFOIL	NACA 44xx
BLADE GEOMETRY	LTLT (1)
ROTOR DIAMETER	31 ft
ROTOR SPEED	94 rpm
ROTOR STARTUP METHOD	AERODYNAMIC
BLADE PITCH CONTROL	VARIABLE PITCH
PITCH CONTROL SYSTEM	ELECTRO-MECHANICAL
GENERATOR TYPE	1-SPEED, INDUCTION
GEAR BOX TYPE	2-STAGE, SPUR GEAR
TOWER MATERIAL	COMPOSITE
TOWER SUPPORT	FREE-STANDING

(1) Linear Taper, Linear Twist

3.4 DESIGN EVOLUTION

As a result of the trade and optimization studies, the final design differed in some aspects from the original. The design evolution is shown in Table 3-3.

Table 3-3 DESIGN EVOLUTION

FEATURE	SCI PROPOSAL APRIL, 1979	PDR-2 JUNE, 1980	CDR SEPT., 1980	FDR FEBRUARY, 1981
ROTOR SIZE & TYPE				NO CHANGE
NO. BLADES	TWO	THREE	THREE	
TYPE HUB	RIGID	RIGID	RIGID	
ORIENTATION	DOWNWIND	DOWNWIND	DOWNWIND	
DIAMETER (ft)	31	32	31	
CONING (DEGREES)	5	5	5	
HUB HEIGHT (ft)	51.25	51.25	51.25	
ROTOR CONTROL			NO CHANGE	NO CHANGE
TYPE	VARIABLE PITCH	VARIABLE PITCH		
SPEED (rpm)	54/107	94		
START UP	MOTOR	AERODYNAMIC		
SHUT DOWN	FEATHER	FEATHER		
BLADE TYPE		NO CHANGE		NO CHANGE
AIRFOIL (NACA)	23012		44xx	
GEOMETRY	ZTZT		LTLT	
CONSTRUCTION	PULTRUDED FIBERGLASS		FILAMENT WOUND	
TOWER		NO CHANGE	NO CHANGE	
LENGTH (ft)	50			48.5
TYPE	FREE-STANDING			FREE STANDING
CONSTRUCTION	TAPERED DIA. TAPERED WALL			TAPERED DIA. TAPERED WALL
MATERIAL	TFT* E-GLASS POLYESTER			TFT* E GLASS POLYESTER
GENERATOR			NO CHANGE	
TYPE	INDUCTION	INDUCTION		INDUCTION
SPEED (rpm)	1800/900	1850		1862
VOLTAGE (volts)	240, 1 PHASE	240, 1 PHASE		240, 1 PHASE
UTILITY INTERCONNECTION	DIRECT	DIRECT		DIRECT
SYSTEM OUTPUT			NO CHANGE	NO CHANGE
RATED (kW)	5.7 @ 15 mph (1)	5.7 @ 15.7 mph (1)		
PEAK (kW)	6.3 @ 50 mph (1)	6.3 @ 50 mph (1)		
ANNUAL OUTPUT				
@ 100 mph (2) (kWh)	15,000	16,059	15,801	15,676
COST OF ENERGY				
@ 10 mph (2) (¢ per kWh)	6.0	6.8	6.9	8.0
SYSTEM WEIGHT				
NACELLE/TOWER (lb)	1395/1335	1336/1157	1299/1236	1600/1270
CUT-IN WIND SPEED (1) (mph)	6	7.6	8.22	8.84
RATED WIND SPEED (1) (mph)	15	15.7	NO CHANGE	NO CHANGE
CUT-OUT WIND SPEED (1) (mph)	50	NO CHANGE	NO CHANGE	35
SURVIVAL WIND SPEED (1) (mph) STANDARD/SPECIAL DESIGN	125/165	NO CHANGE	NO CHANGE	NO CHANGE

(1) WIND SPEED MEASURED AT 30 ft
(2) MEAN ANNUAL WIND SPEED MEASURED AT 30 ft

ZTZT - ZERO TAPER/ZERO TWIST
LTLT - LINEAR TAPER/LINEAR TWIST
*SCI PATENTED

3.5 DESIGN AND ANALYTICAL STUDIES

Listed below are the major design and analytical studies performed during the Phase I period. Because of the iterative nature of the program, many of these studies were re-done three or four times while others were performed once and merely updated for each design review.

1. Aerodynamics
2. Critical wind loads
3. Pitch control aerodynamic loads
4. Survival wind load dynamic analysis
5. Yaw analysis
6. Blade properties
7. Blade structural and fatigue analysis
8. Tower properties
9. Tower structural and fatigue analysis
10. Structural and fatigue analyses of mechanical components and supporting structures
11. Aeroelastic analysis
12. Rotor/tower dynamic analysis
13. Pitch control system design analysis
14. Pitch control dynamic analysis
15. Availability analysis
16. Failure modes and effects analysis
17. Maintainability analysis
18. Safety analysis
19. Cost of energy
20. Utility interface requirements
21. Life expectancy calculations for mechanical components and major electrical equipment

3.6 COMPONENT DEVELOPMENT

Certain components, systems and processes involved technological advances and, as such, required testing and evaluation before they could be adopted. The following such developmental activities were accomplished during the Phase I effort:

1. Tests of single phase induction generators
2. "Breadboard" testing of electro-mechanical control system
3. Blade fabrication process development (not completed)

3.7 DETAILED DESIGN EFFORT

The detailed design effort consisted primarily of equipment and materials selection and the design and drafting of detail and assembly drawings. A total of 45 drawings were produced. Certain detail drawings were not completed within the Phase I period.

4.0 DESIGN OVERVIEW

4.1 MAIN FEATURES

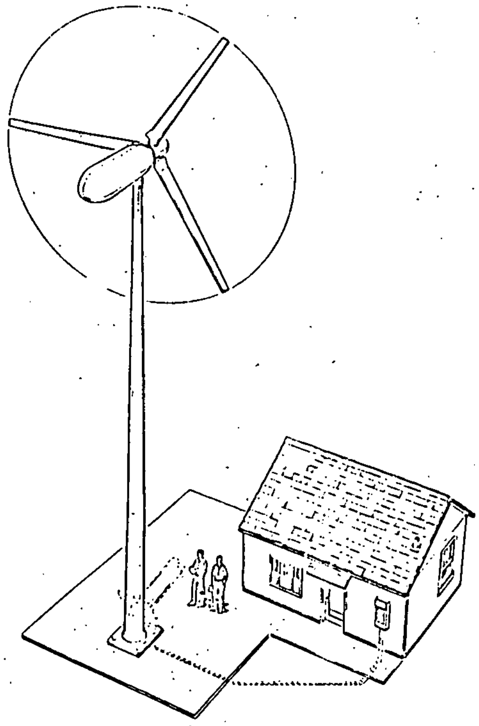
The SCI final design incorporates the following features not available in other SWECS of this size:

- Composite blades with filament-wound composite D-spar.
- Free-standing composite tower with tapered diameter and tapered wall thickness.
- Full-span pitch control responsive to generator torque.

The free-standing tapered tower enhances appearance of the unit as shown in the perspective drawing, Figure 4-1. The unit is a highly versatile machine which can operate in a wide range of wind regimes at near optimum performance.

The SWECS is designed for direct inter-connection with the alternating current utility network or auxiliary generator. Batteries or power conditioning equipment are not required.

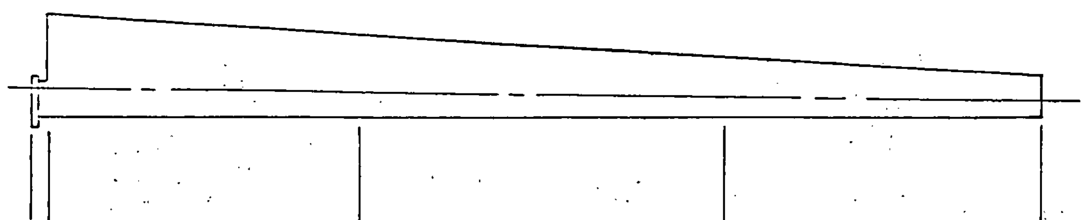
Figure 4-1 PERSPECTIVE VIEW



4.2 ROTOR

The rotor, consisting of three composite blades and a rigid hub, is described in Figures 4-2, 4-3 and 4-4. The rotor is designed for full-span pitch control and emergency shut-down by means of blade feathering.

Figure 4-2 BLADE GEOMETRY



1.55 ft	R	6.2 ft	10.85 ft	15.5 ft
.09 .1	r/R	.4	.7	1.0
--	AIRFOIL	4418	4415	4412
4.48°	TWIST (1)	2.40°	0.33	-1.75°
14.97	CHORD(in)	11.99	9.00	6.0
7.8	THICKNESS(in)	2.16	1.35	.72
196500	EI lb-ft^2	55610	9994	1281
83240	GI lb-ft^2	26140	4702	339

(1) 0° Reference is at 0.75R

Figure 4-3 BLADE CONSTRUCTION

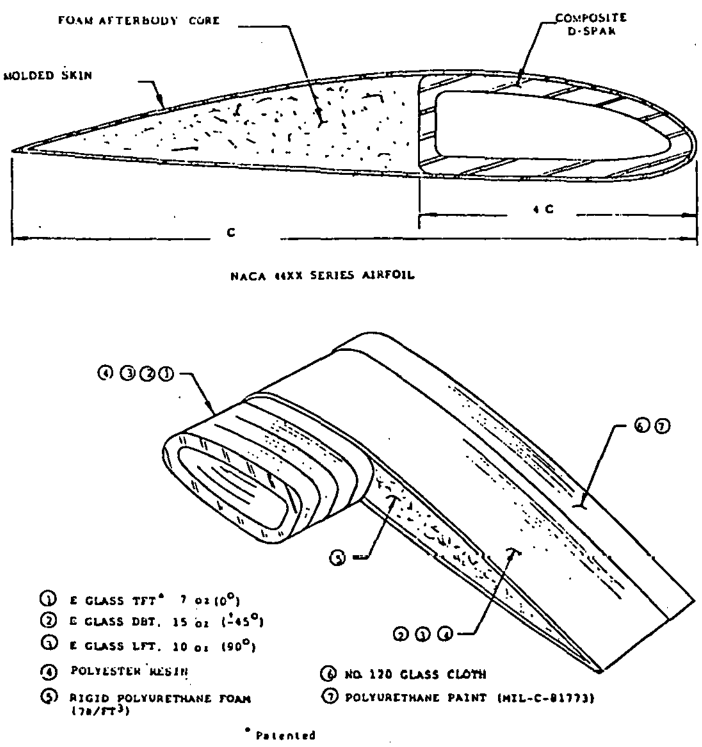
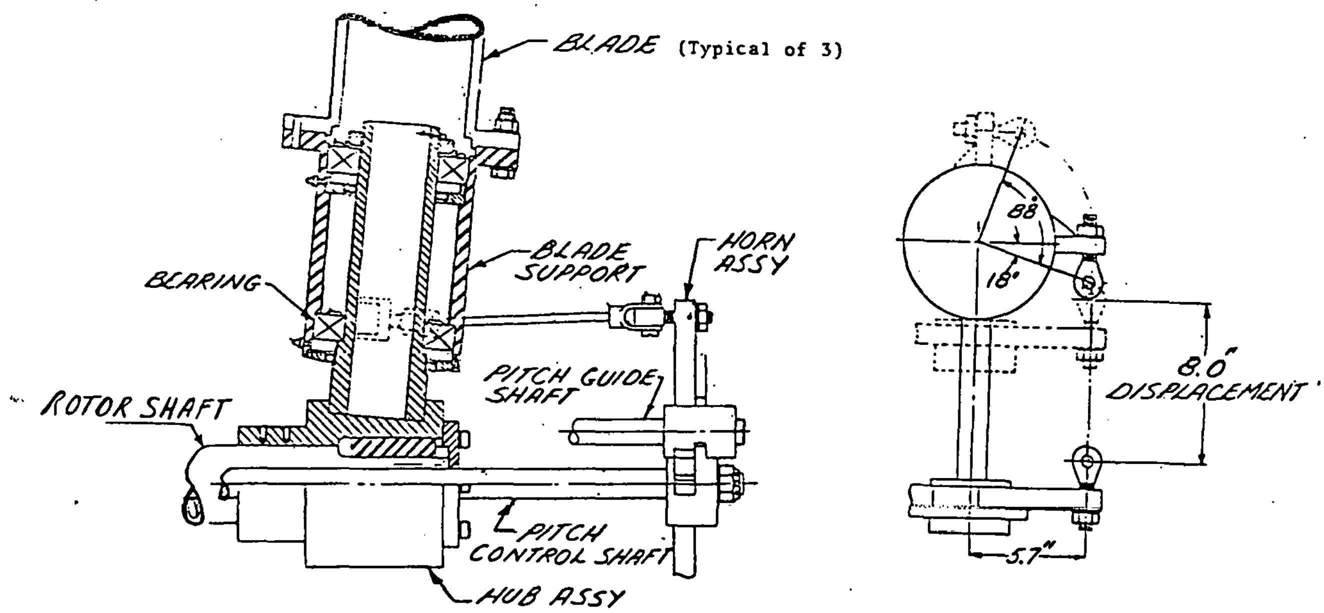


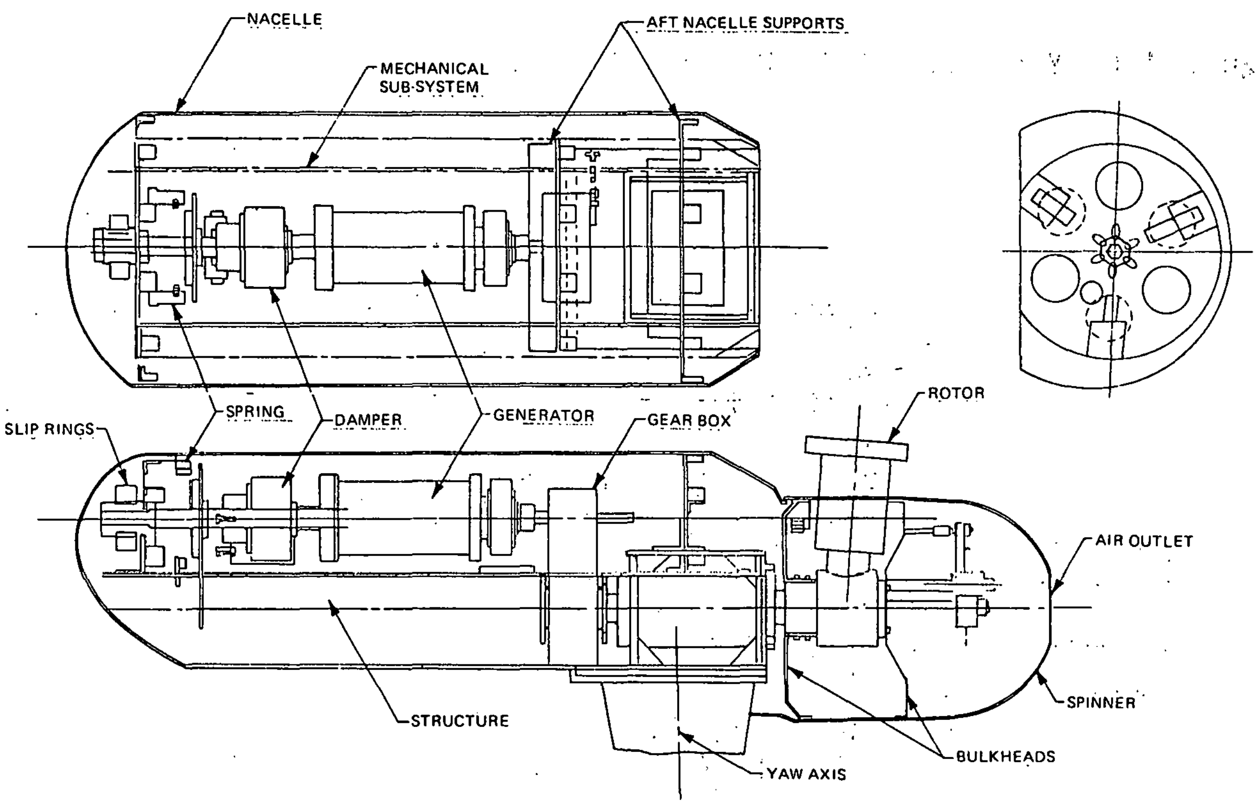
Figure 4-4 ROTOR HUB



4.3 MECHANICAL SUBSYSTEM

As shown in Figure 4-5, the mechanical subsystem consists of a main structure supporting all machinery and mechanisms, and enclosed by a composite nacelle and spinner.

Figure 4-5 NACELLE CONFIGURATION

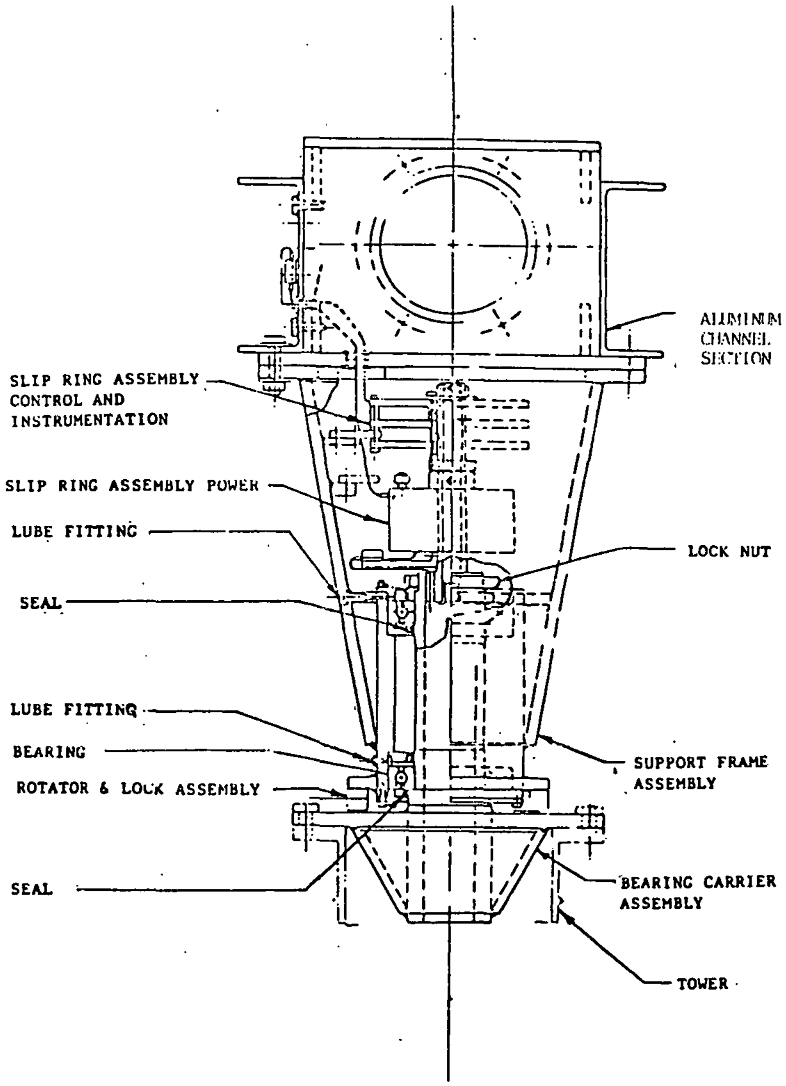


The rotor and rotor shaft are supported by a main bearing assembly which also supports the shaft-mounted gear box. The generator is driven through a flexible coupling from the high-speed shaft of the gear box. The generator frame is mounted in bearings to allow limited rotation to perform pitch control functions described below.

4.4 YAW BEARING ASSEMBLY

The nacelle is connected to the tower through the yaw bearing assembly shown in Figure 4-6. This assembly provides a low-friction rotational axis to allow the rotor to align itself with the wind. The yaw bearing assembly also serves as an enclosure for sliprings which carry power and control circuits between the stationary tower and electrical equipment within the nacelle.

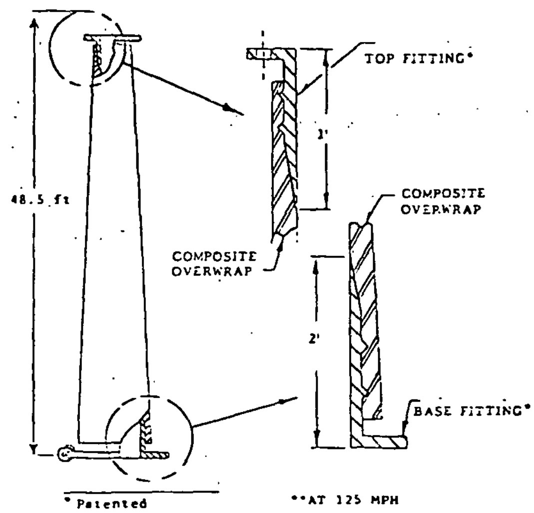
Figure 4-6 YAW BEARING ASSEMBLY



4.5 TOWER AND ERECTION SYSTEM

The nacelle and yaw bearing assemblies are flange-connected to the top of the tapered composite tower. The tower and its steel end fittings are described in Figure 4-7. Figure 4-8 shows the SWECS erection system.

Figure 4-7 TOWER DESCRIPTION



DESCRIPTION	
HEIGHT (ft)	48.5
BASE DIAMETER (in)	24
TOP DIAMETER (in)	12
BASE WALL THICKNESS	0.4
TOP WALL THICKNESS	0.15
TOWER COMPOSITE WEIGHT (lbs)	804
BASE FITTING WEIGHT (lbs)	400
TIP FITTING WEIGHT (lbs)	66
TOTAL WEIGHT (lbs)	1270
TIP DEFLECTION (in)**	19

Figure 6-1 TOWEP DESCRIPTION

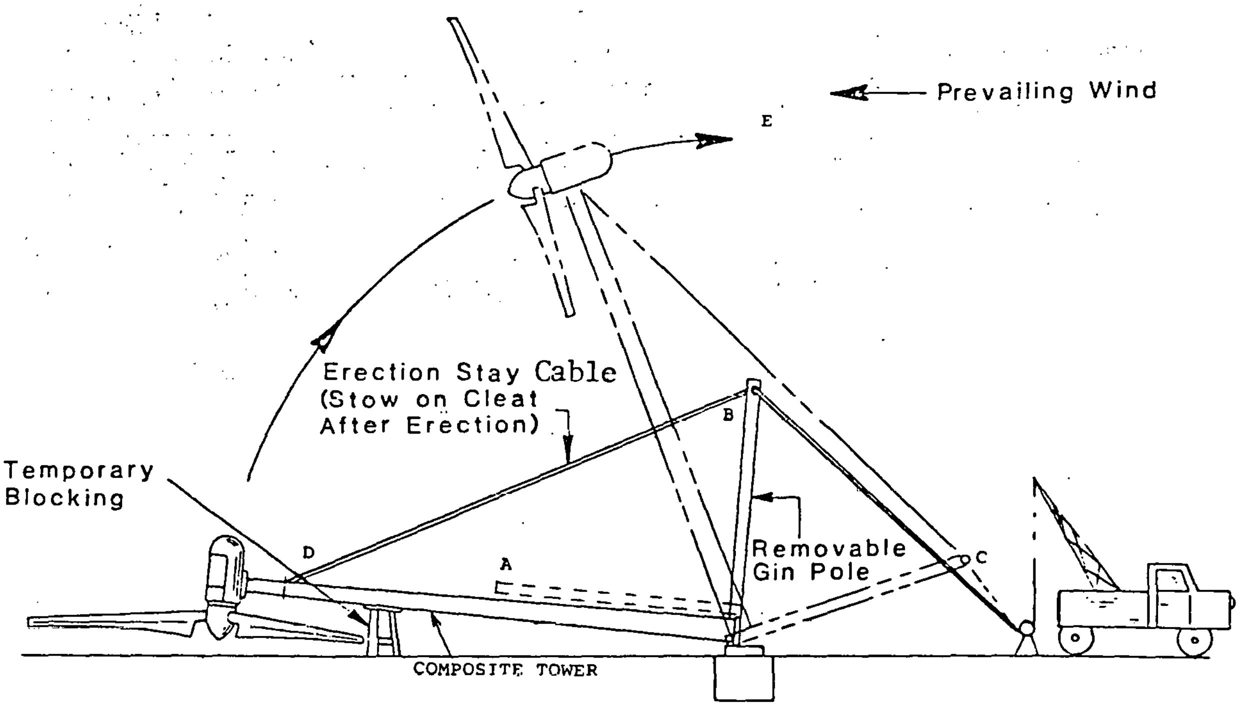
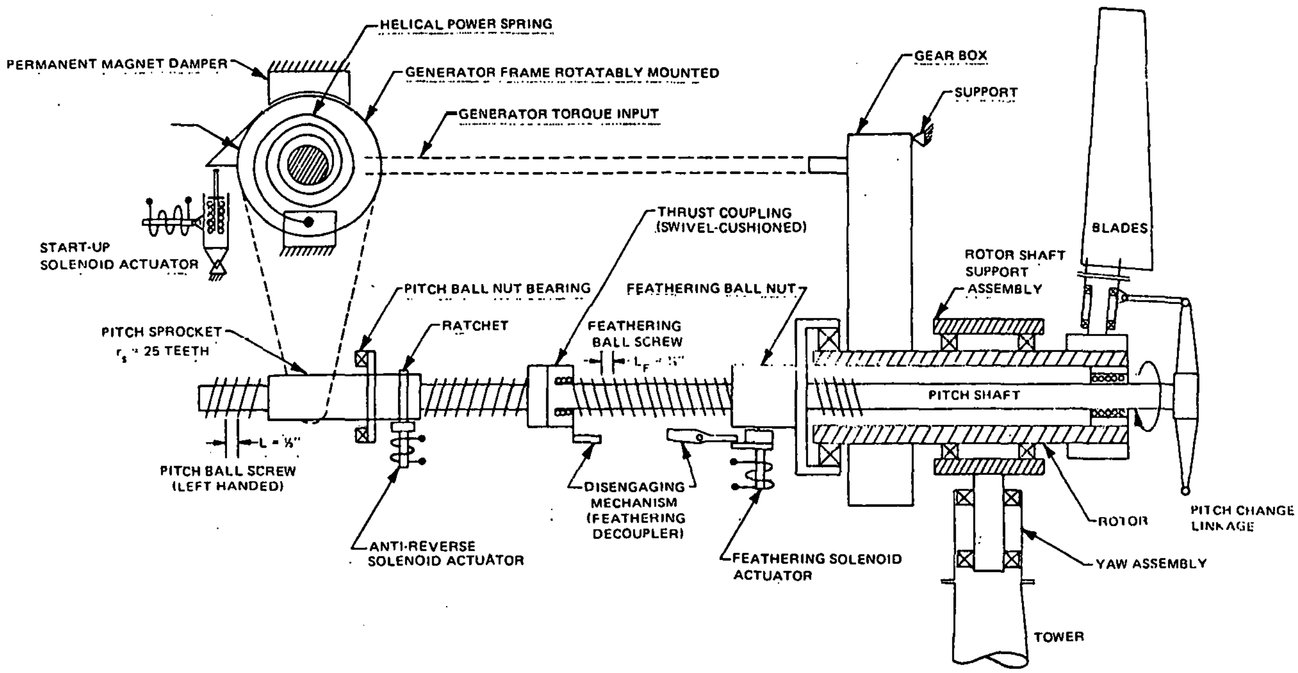


Figure 4-8 TOWER ERECTION SYSTEM

4.6 PITCH CONTROL AND FEATHERING SYSTEM

The rotor pitch control and feathering system is shown schematically in Figure 4-9. The system is fully automatic and essentially passive in that virtually no external power is required to perform the major functions. Kinetic energy in the spinning rotor is used to feather the blades and to charge a spring, thus providing energy to automatically adjust blade pitch for startup.

Figure 4-9 ELECTROMECHANICAL CONTROL SYSTEM - SCHEMATIC DIAGRAM



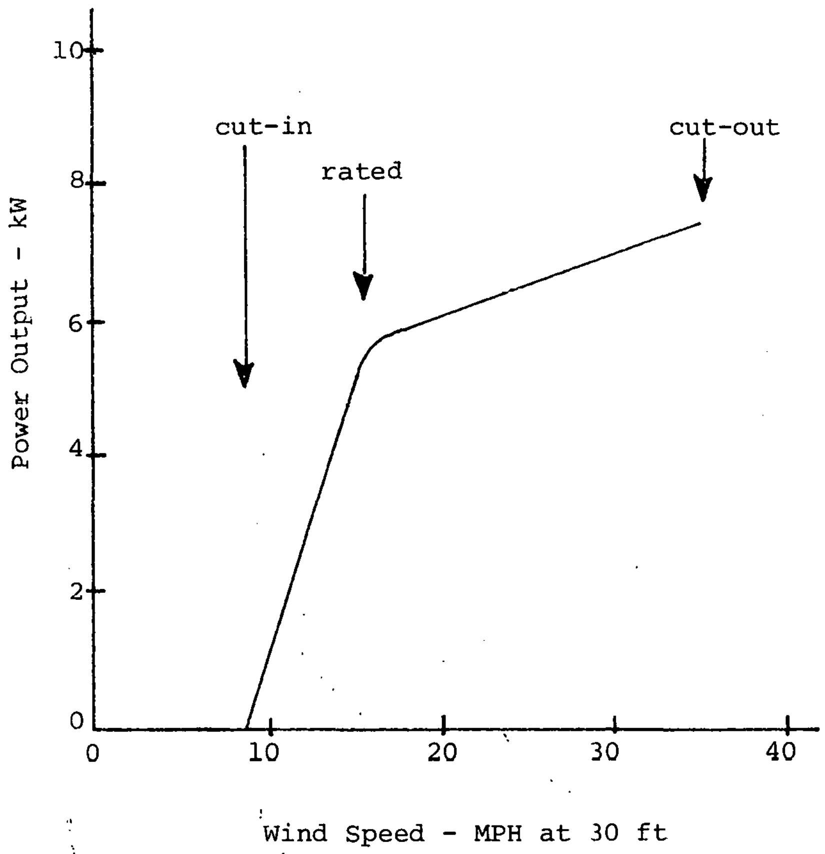
In a similar manner, excess energy in high winds and gusts is used to control pitch of the blades to prevent overloading the generator and to avoid gust-initiated disturbances on the interconnected electric power system. This control is accomplished through reaction torque of the generator frame. Frame torque is utilized to sense torque levels and to drive the blade pitch mechanism to reduce over-torque conditions to acceptable levels.

5.0 SYSTEM PERFORMANCE

5.1 POWER VERSUS WIND SPEED

A plot of generated power output versus wind speed is shown in Figure 5-1.

Figure 5-1 POWER OUTPUT VERSUS WINDSPEED



5.2 ENERGY PRODUCTION

Annual kilowatt-hour production, based on Rayleigh wind speed distribution curves, are summarized in Table 5-1, for a range of mean annual wind speeds.

Table 5-1
ANNUAL KILOWATT HOURS PRODUCTION

$\bar{v}$ (1) mph	AkWh (2)
8	8,732
9	12,207
10	15,676
12	22,041
14	27,156
16	30,740
18	32,801

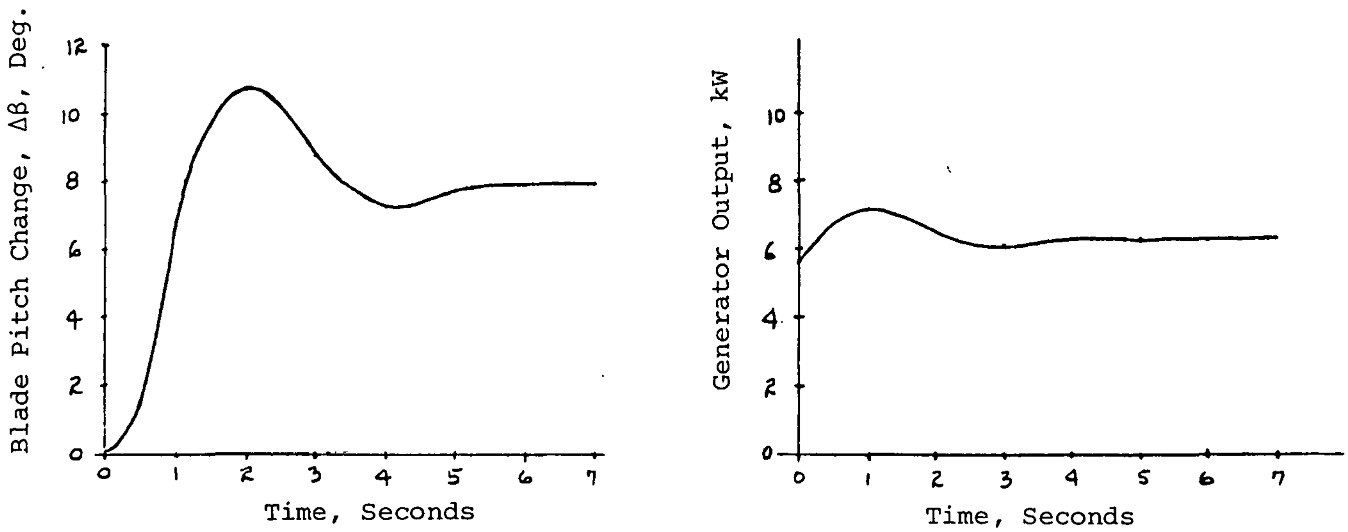
(1) $\bar{v}$ = Mean annual wind speed measured at 30 ft elevation.

(2) Annual kilowatt hours corrected for 95% availability and control system losses.

5.3 CONTROL SYSTEM PERFORMANCE

A dynamic analysis of the control system indicated stable, slightly oscillatory performance. Speed control and gust response were found to be excellent. The curves of Figure 5-2 illustrates calculated system gust response.

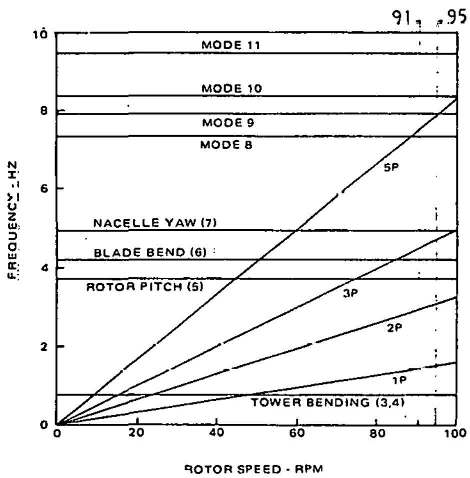
Figure 5-2 RESPONSE TO 3.4 MPH GUST STEP ABOVE RATED WIND SPEED



5.4 ROTOR-TOWER DYNAMICS

A rotor-tower dynamics analysis gave results as summarized in the Campbell diagram, Figure 5-3. This study indicated no serious vibration problems although modes 6 and 7 were found to be rather close to the 3-per-revolution rotor operating frequency.

Figure 5-3 ROTOR-TOWER CAMPBELL DIAGRAM



6.0 COST ANALYSIS

6.1 COST OF ENERGY CALCULATIONS

Cost of energy estimates were based on the following expression:

$$COE = \frac{((1.5 \times HWC) + IC) \times (FCR) + (AOM)}{AkWh}$$

WHERE:

HWC = Hardware cost, dollars. This is the FOB cost multiplied by 1.5 to account for transportation costs, dealer's markup, etc.

IC = Installation costs, dollars, including those for foundations and site preparations.

FCR = Annual fixed charge rate (0.129).

AOM = Uniform annual operation and maintenance costs, dollars.

AkWh = Annual kilowatt hours produced, when operating at 95% availability.

6.2 INSTALLED COST

Tables 6-1 and 6-2 show the development of hardware costs and total installed cost for the 1st, 1000th and 10,000th production unit.

Table 6-1 HARDWARE COST SUMMARY $ (1)			
COMPONENT	1ST UNIT	1,000th UNIT (2)	10,000TH UNIT (2)
MECHANICAL ASSEMBLY & NACELLE	5,747	1,949	1,387
ROTOR, BLADES & SPINNER	4,304	1,163	760
ELECTIRCAL POWER & CONTROL	1,387	638	492
TOWER, YAW ASSEMBLY & ERECTION SYSTEM	3,733	1,063	710
TOTAL PURCHASED MATERIALS	15,171	4,813	3,349
LABOR HOURS (HR)	378.5	94.4	59.4
LABOR COST	1,794	447	282
DLO @ 145%	2,601	648	409
G & A @ 15%	2,935	886	606
TOTAL COST LESS FEE	22,501	6,794	4,646
TOTAL COST (10% FEE)	24,751	7,474	5,111

(1) 1978 Dollars for the "standard" SWECS design.

(2) Costs are based on the following learning curves:
Purchased Parts - 92.5%
Fabricated components and shop labor - 87%
Overall - 89.3%

Table 6-2 INSTALLED COST $ (1)			
	1ST UNIT	1,000TH UNIT	10,000TH UNIT
HARDWARE FOB	24,751	7,474	5,111
x 1.5	37,125	11,211	7,666
INSTALLATION	1,120	916	876
TOTAL INSTALLED COST	38,245	12,127	8,542

(1) 1978 Dollars for the "standard" SWECS design.

6.3 COST OF ENERGY

Results of cost of energy calculations for the "Standard" production unit are given in Table 6-3. Figure 6-1 summarizes these data in graphical form for the 10,000th production unit. It is seen that the target 6 cents per kWh requires a mean annual wind speed of 12 mph.

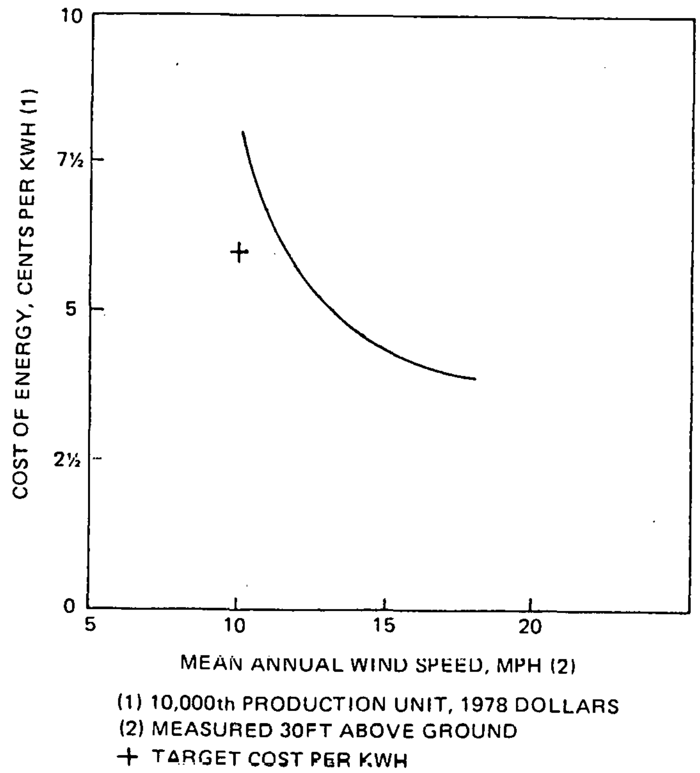
Table 6-3 COST OF ENERGY (1)

	1ST UNIT	1,000TH UNIT	10,000TH UNIT
INSTALLED COST	$38,245	$12,127	$8,542
ANNUAL OPERATING & MAINTENANCE	148	148	148
COST OF ENERGY,			
(2) $\bar{v}$ = 10 mph	0.324	0.109	0.080
$\bar{v}$ = 12 mph	0.230	0.078	0.057
$\bar{v}$ = 14 mph	0.187	0.063	0.046
$\bar{v}$ = 16 mph	0.165	0.056	0.041
$\bar{v}$ = 18 mph	0.15	0.052	0.038

(1) 1978 Dollars for "standard" production unit.

(2) Mean annual wind speed measured at 30 ft elevation.

Figure 6-1 COST OF ENERGY VS MEAN ANNUAL WIND SPEED



6.4 WEIGHT AND COST SUMMARY

A summary of weights and costs, for both the "Standard" and "Special" SWECS designs is given in Table 6-4. Costs are for the first production unit. The "special design" requires a heavier tower and extensive protection for salt water spray environment.

Table 6-4 WEIGHT AND COST SUMMARY

	WEIGHT		LABOR (MHRS)		MATERIAL COST	
	STD	SPECIAL	STD	SPECIAL	STD	SPECIAL
MECHANICAL ASSEMBLY & NACELLE	904	904	117.6	119.6	5,747	6,395
ROTOR, BLADES & SPINNER	660	688	150	151	4,304	4,611
SUB-TOTAL ATOP TOWER (lb,mhr, $)	1564	1592	267.6	270.6	10,051	11,006
ELECTRICAL POWER & CONTROL	75	90	45	48	1,387	1,751
TOWER, YAW & ERECTION SYSTEM	1720	1932	65.9	69.9	3,733	3,945
SWECS TOTAL (lb,mhr, $)	3359	3614	378.5	388.5	15,171	16,702
G & A @ 15%					2,276	2,505
FEE @ 10%					1,745	1,921
TOTAL COST					19,192	21,128

(1) 1978 Dollars, first production unit, FOB Azusa, California

7.0 CONCLUSIONS AND RECOMMENDATIONS

The Phase I design and analysis resulted in a 4 kW SWECS design which met most program objectives. The resulting design had some unique features:

- Composite Tower and Blades
- Torque-Actuated Blade Pitch Control

It is recommended that the Phase II fabrication, testing and evaluation of the SCI final design be continued in order to confirm and debug the Phase I design. This is an essential step toward the final goal of commercialization of this promising SWECS design.