SERI/TR-98073-1A
UC Category: 60

Preliminary Design and Economic Investigations of Diffuser Augmented Wind Turbines (DAWT)

Executive Summary

Final Report

K. M. Foreman

Research Department
Grumman Aerospace Corporation
Bethpage, New York 11714

December 1981

Performance Period: May 15, 1979 to
March 31, 1980

Prepared Under Subcontract No. XH-9-8073-1

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

Technical Monitor: Richard Mitchell

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $3.00
Printed Copy $ 4.50

FOREWORD

The Solar Energy Research Institute (SERI), a Division of the Midwest Research Institute, has been authorized by the U.S. Department of Energy to provide technical management services for the Wind Energy Innovative Systems (WEIS) program. The focus of the WEIS program is to assess the technical and economic feasibility of innovative concepts and systems. A large number of these concepts have potential merit. Therefore, a critical examination of their technical and economic attributes will provide guidance and direction for future WEIS efforts.

This report summarizes work prepared by Grumman Aerospace Corporation, Bethpage, New York, for SERI, Golden, Colorado under Subcontract XH-9-8073-1. The SERI Technical Monitor was Richard Mitchell.

The objective of this research effort was to establish by preliminary design and manufacturing trade-off studies the economic feasibility of the Diffuser Augmented Wind Turbine (DAWT) concept. The results suggest that fiberglass reinforced plastics construction of the diffuser could lead to attractive and competitive cost of electrical generation for the small (5-200 kW) rated output wind energy conversion system range.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION 1.0

INTRODUCTION

This report summarizes an investigation into some system engineering design alternatives and cost and energy output characteristics for the diffuser augmented wind turbine (DAWT). The DAWT innovative wind energy conversion system has been under U.S. Government funded development by Grumman Aerospace since 1975 in its present modern form. Earlier workers (Ref. 1-3) recognized that the mass flow though a wind turbine could be significantly increased beyond the best of bare turbine operational conditions by use of a diffuser to maintain a low pressure downstream of the wind turbine. The suction created by this subatmospheric pressure enhances the air flow and increases the turbine power output well beyond conventional bare turbines. Figure 1-1 shows schematically the DAWT and its flow field boundaries compared to the bare turbine case. However, prior investigators did not address the problem of overcoming the cost penalty incurred by conventional diffuser technology in creating a practical engineered structure. As a result, the diffuser augmentation idea was not accepted as economically competitive with more conventional approaches.

In 1973, (Ref. 4) we began a project to obtain very short length compact diffusers that would be inherently low in cost, while retaining good fluid dynamic performance. Our technical progress through multiphased experimental research, extensively reported in Ref. 5-8, with various sized wind tunnel model systems verified concept feasibility with designs having a 60° included angle and an axial length equal to the diffuser inlet radius. Figure 1-2 shows one DAWT model with a 46 cm (18 in.) in diameter wind turbine mounted in a wind tunnel test section; the air moves from right to left. The demonstrated level of power augmentation with relatively unsophisticated model DAWT configurations (diffuser exit to entrance area ratio of 2.75) exceeded by a factor of four the output of a bare turbine of equal diameter at the same wind speed.

Forecasts of possible DAWT performance for more improved versions of the diffuser and well-matched turbine/diffuser combinations indicated power augmentation factors of between 5 and 8 (Ref. 8). We have assumed an augmentation factor of 5.5 for purposes of this study.

Seven issues directly affect a cost competitive DAWT (Ref. 9). These are:

- Unit system size and rating
- Structural design criteria
- Material selection
- Operational and environmental factors
- Manufacturing approach
- Economics of production and geometric scale
- Siting characteristics.

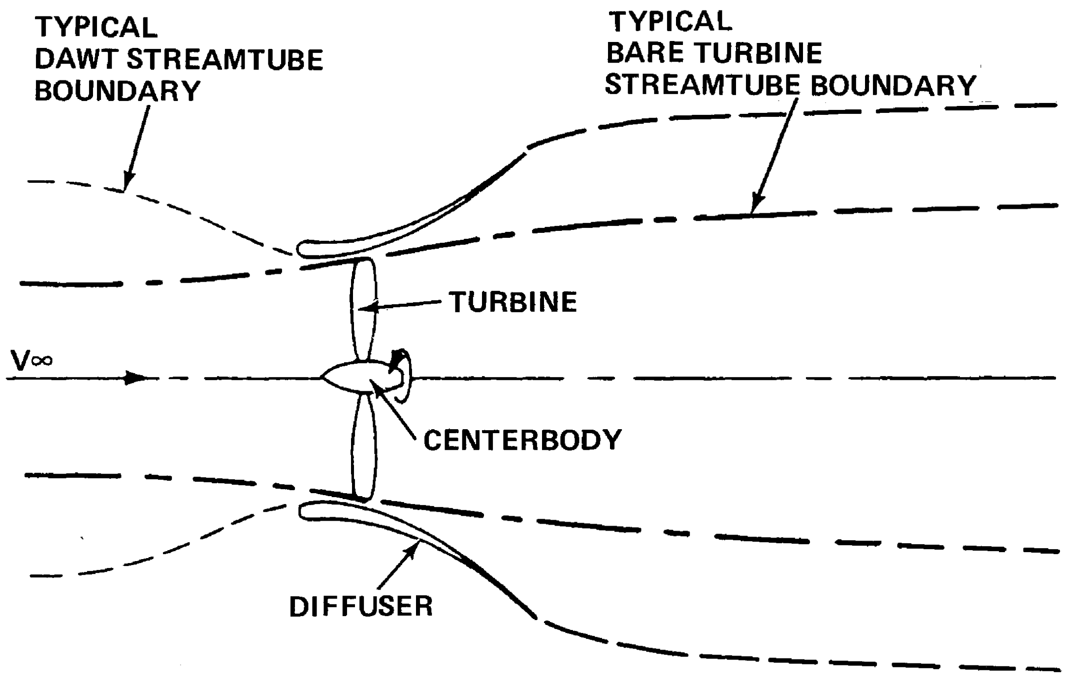


Figure 1-1. BASIC SCHEMATIC OF THE DAWT WITH ITS FLOW FIELD BOUNDARIES COMPARED TO THOSE OF A BARE TURBINE

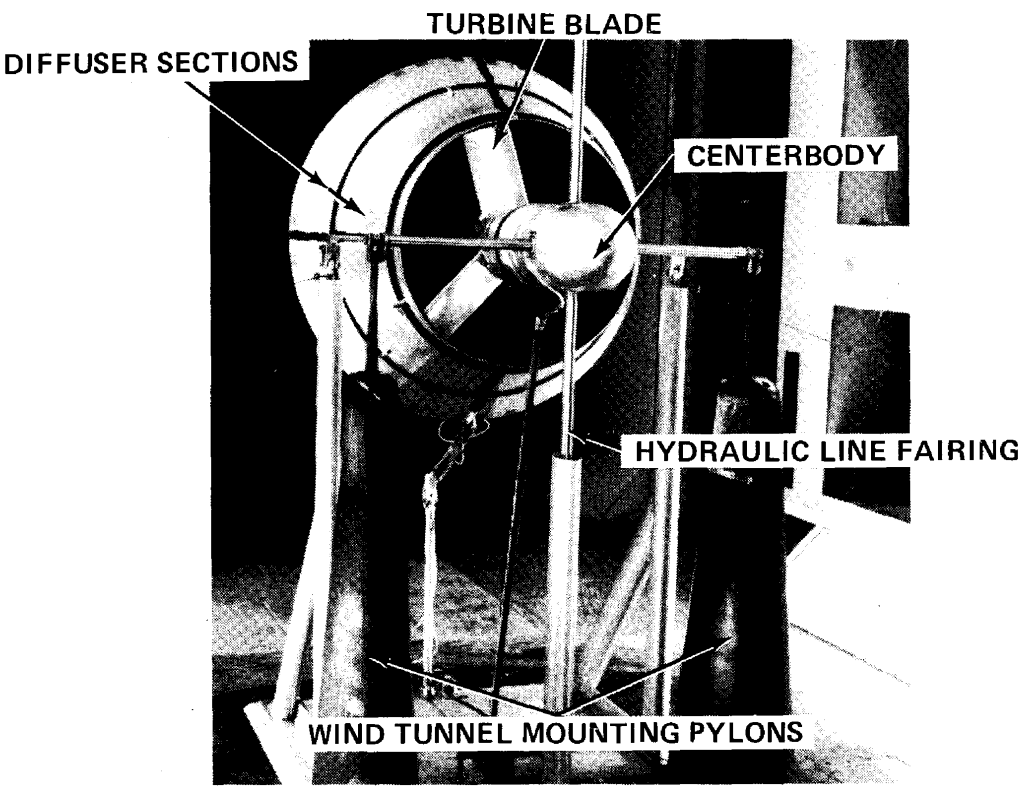


Figure 1-2. DAWT BASELINE MODEL WITH 46 cm (18 in.) DIAMETER TURBINE MOUNTED IN THE 2 x 3 m WIND TUNNEL TEST SECTION

This present reported investigation explores these issues by means of alternative commercially oriented designs. Particular attention is directed to formulate realistic end-user scenarios, and to establish ratings, designs, production approaches and marketing goals that would be compatible with potential customers and the Department of Energy's program objectives concerning cost of energy with wind power conversion systems.

SECTION 2.0

DAWT DESIGN

To provide wide flexibility for application of the results of this DAWT investigation, three baseline sizes (i.e., rotor diameter) were selected as described below. For each size selection, preliminary point designs were made of the baseline diffuser contour in each of three candidate materials of construction. These designs were analyzed by cost estimators for production lots of 100,200 and 500 systems and array installations within 300 - 400 km (185 - 250 miles) of production centers. Considering the preliminary nature of the DAWT designs, an accuracy of about 10 - 15 % was considered reasonable for the costing. Assuming that diffuser cost varies with diffuser surface area, the first order cost estimates for the nine paper designs were modified to provide cost estimate extrapolations for other diffuser configurations than the baseline contours. This procedure is shown schematically in Fig. 2-1.

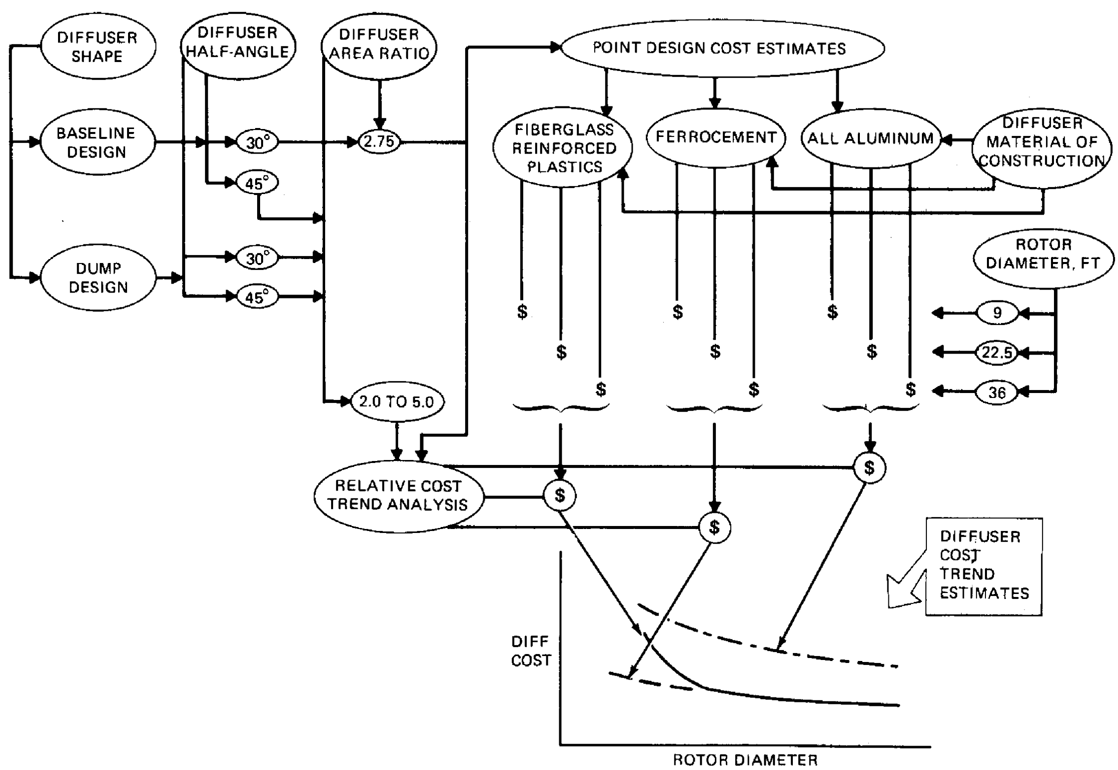


Figure 2-1. DIFFUSER COSTING PROCEDURE

2.1 ROTOR SIZING

The approach assumed for the simple unrefined wind turbine was to use three extruded, 6061-T6 aluminum alloy blades shafted to an 1800 rpm induction generator through a gear box. The blades are untwisted, constant chord, 10 % tip solidity, with NACA 4418 airfoil contours.

Stress considerations limited the maximum blade length for a pure cantilevered span to 5.5 m (18 ft). Centerbody diameter requirements for diffuser compatibility and turbine equipment clearance set the shortest practical blade span to 1.35 m (4.5 ft). A third rotor size, to facilitate trend derivation, was selected arbitrarily at a mid-size span of 3.45 m (11.25 ft). As a result the three rotor diameters of 2.7, 6.9, and 11 m (9, 22.5, and 36 ft) had constant chord lengths of 30.5, 76, and 114 cm (12, 30 and 45 in.) respectively from root to tip. Because the current production extrusion press capacity is 91 cm (36 in.), the largest rotor diameter blade has a trailing edge section made of a separate extrusion and welded spanwise to the front torsion box section along the top and bottom surfaces. If another production approach had been taken for the turbine blades, then larger and more sophisticated rotors, and larger and higher rated DAWTs would have been possible to investigate.

2.2 POWER RATING

Each of the three rotor diameters have been rated on the basis of the 5.5 augmentation ratio assumed for improved DAWT diffuser, a realistic assessment of generator and gear box availability at lowest cost and highest reliability compatible with rating wind speeds and annual distribution spectra of wind speed. As shown by Table 2-1, the three DAWT rotor sizes considered result in ratings between 11 and 150 kW; the available energy is computed from an assumed Rayleigh distribution of wind speed occurrence (Ref. 10), installation site annual average wind speed ($\bar{V}$) of 25.7 km/h (16 mph), and a linear variation of power output from cut-in of 9.6 km/h (6.0 mph) to rated wind speed with cut out at about 64 km/h (40 mph). Ratings of Table 1 are illustrative but do not indicate the ultimate potential of the DAWT beause the rotor considered was relatively simple, as described in the preceding paragraph. Inclusion of rotor improvements such as blade taper, geometric twist along the span, and a blade section of better aerodynamic properties could improve DAWT performance by an estimated 50% with about a 3% increase in rotor cost.

Table 2-1. DAWT RATING AND ROTOR SIZE MODELS

Rotor Diameter		DAWT Rated Performance					
m	(ft)	kW	@ km/h	(mph)	kW h	for $\bar{V}$, km/h	(mph)
2.7	(9.0)	11.2	@ 41.9	(26.0)	47,200	25.7	(16)
6.8	(22.5)	60	@ 39.4	(24.5)	267,000	"	"
11.0	(36.0)	150	@ 38.6	(24.0)	674,000	"	"

2.3 DIFFUSER SIZE

The ratio of diffuser exit area to inlet area (i.e., approximately rotor diameter) has been assumed at 2.75 for the baseline point design. Lower area ratios, to about 2.2, are expected to yield smaller augmentation factors but at relatively lower cost. Conversely, larger ratios (e.g., 4.0) for the diffuser should increase the augmentation factor but at incremental cost increases that we believe result in lower benefit/cost ratio than the baseline conditions of our examination. Fine adjustment of the diffuser area ratio parameter is deferred to more detailed design consideration phases. Table 2-2 establishes the principal dimensions of the baseline diffuser configuration investigated here.

Table 2-2. DIFFUSER DIMENSIONS

Rotor Diam		Inlet Diam		Exit Diam		Axial Length	
m	(ft)	m	(ft)	m	(ft)	m	(ft)
2.75	(9)	3.1	(10)	4.6	(15)	2.0	(6.5)
6.8	(22.5)	7.6	(25)	11.5	(37.5)	4.3	(14.0)
11.0	(36)	12.2	(40)	18.4	(60)	6.6	(21.4)

The turbine axis height above the ground has been assumed to be 3.0 m (10 ft) plus one half the diffuser exit diameter. This height is considered adequate for safety and operational concerns; model test data (in which near-ground wind profiles were simulated) suggest no adverse effects on DAWT performance because of this closeness to the ground or wind velocity gradient. The economic gains in design, installation, and maintenance of DAWT by keeping the rotor axis as low to the ground as possible compensates for the possible power benefits of wind velocity increase at greater heights, according to our preliminary assessment.

2.4 DIFFUSER MATERIAL ALTERNATIVES

Three materials, aluminum, fiberglass reinforced plastic (FRP) sandwich, and ferrocement, were investigated for DAWT construction. Material selection affects the design and production approaches and has considerable impact on the system estimated cost. Aluminum is a widely used construction material in the U.S. with high initial material costs but lower life cycle costs than, for example, steel. It can yield lighter weight and less costly structures than steel of equal yield strength for stresses skin designs.

Fiberglass reinforced plastics (FRP) with balsa core sandwich construction also has relatively high material costs but can be produced with low investment in machinery and tooling and low life cycle costs.

Ferrocement's primary attraction is low raw material cost and low investment requirements for tooling and production equipment.

The design and production analysis responsibility for each diffuser material of construction was assigned to engineering organizations of well known experience and established competence. Subcontracts were awarded to Pearson Yachts for FRP and to David J. Seymour, Ltd for ferrocement studies. Grumman Aerospace conducted the aluminum design study as well as the diffuser support and foundation designs for all three material versions.

2.5 TURBINE SUBSYSTEM

Preliminary designs of the rotor subsystem, and of the transmission generator subsystem and centerbody enclosure were developed by Grumman Energy Systems Inc. on the basis of their prior 8 kW conventional wind turbine generator engineering effort for the DoE Rocky Flats Wind Systems Program. The center spar box of each rotor blade is attached to the low speed drive shaft which is connected through a step-up gear box to a 240 V, 60 Hz, 1800 rpm induction motor. Active pitch control is used for low wind speed start up and to feather the blades for cut-out above 40 mph.

The centerbody bed plate of Cor-Ten steel plate and channel supports all turbine equipment and is enclosed by a cylindrical aluminum shell, incorporating servicing access doors. The centerbody is concentrically mounted within the diffuser by three sets of N-shaped struts connected to the primary ring and longeron network of the diffuser structure.

From wind tunnel data (Ref. 11), the DAWT concept appears insensitive to minor directional changes of the wind (for approximately $\pm$ 30° changes). Therefore, wind yaw-following capability need only respond to major wind/weather system changes with only moderate rates of rotational speed about its vertical axis. This operational characteristic reduces the yaw gust loading for the turbine and relieves blade design stress for fatigue considerations.

SECTION 3.0

OTHER FEATURES

Figure 3-1 is an artist's rendition showing typical DAWT systems installed at the Rocky Flats (Colorado) Test Site. The rotor diameter in this picture is 5.5 m (18 ft). A yaw bearing with active yaw control is located in the cylindrical mounting pedestal just below the attachment webs to the diffuser. The foundation and entire DAWT structure and pedestal has been sized to withstand 193 km/h (120 mph) winds with a gust factor of 1.21; the maximum operational condition is set at 120.7 km/h (75 mph).

The design safety factor of 1.8 applied to the extreme loading condition is the same criterion used in the design of the world's tallest office building, the Sears Tower in Chicago. For the ferrocement version of the DAWT, design was dictated by the DNVR (Norwegian Shipping Board) standards for vessels.

To assure conventional commercial shipment from production centers to installation sites, no DAWT component or subassembly exceeded a width of 3.7 m (12 ft).

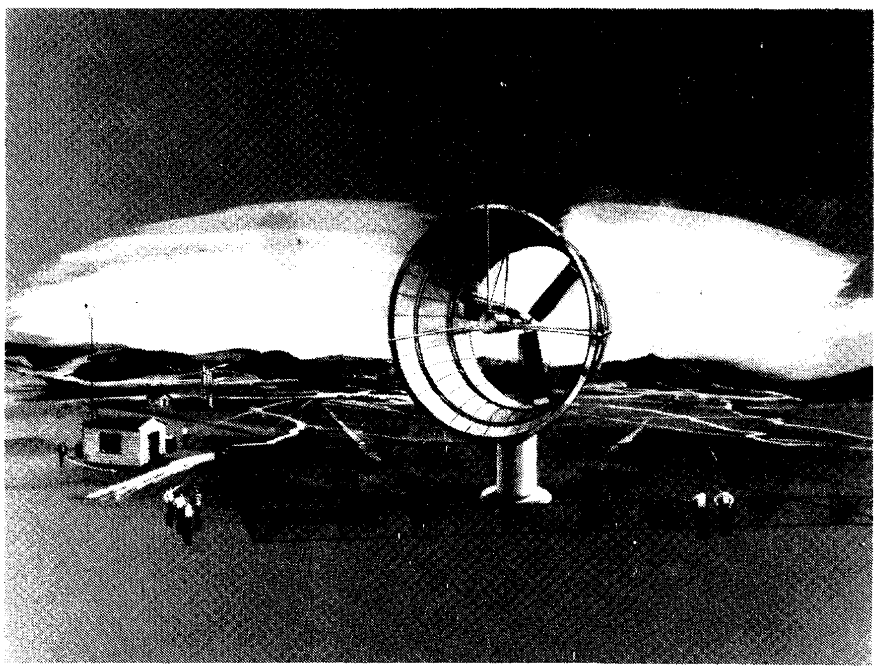


Figure 3-1. CONCEPTUAL INSTALLATION OF TWO DAWTs WITH A 5.5 m (18 ft) DIAMETER TURBINE

SECTION 4.0

MANUFACTURING APPROACH

Primarily because the major marketing areas for wind energy conversion systems are regionally segregated, and long distance shipping of large components is costly, it is assumed that DAWT production centers are located within marketing areas. Another factor in selecting production center locations is the regional cost of labor and materials.

There are two working condition aspects to the manufacturing approach: the controlled environment where factory-made components are produced and the installation site where field conditions and seasonal weather is encountered. In our scenario for the latter aspect, typical multiple unit installation arrays of up to 100 DAWTs are assumed, and the opportunity exists for economies of scale through efficient mobilization of manpower and machines and efficiencies derived from worker cumulative experience.

Factory fabrication assumes the availability of local labor compatible with production requirements of each constructional material. It is also assumed that these materials are available as required.

For the ferrocement diffuser, our subcontractor advised that present knowledge precludes design and fabrication in sizes greater than the 6.8 m (22.5 ft) rotor diameter DAWT. Therefore, this material approach currently is size limited. For aluminum construction, the compound curvature for the front diffuser section creates demands for heavy capacity rolling machinery which may prove a production barrier for the largest DAWT size range because of the need for additional facilities investment or a shortage of available open time at existing plants. Only the FRP sandwich construction diffuser option presented no inherent impediments to fabrication in the sizes and production lots investigated. Tooling for FRP proves to be considerably cheaper than for aluminum. In terms of production lots above 300/year for the DAWT with 11.0 m (36 ft) diameter rotor, it is recommended that more automated, resin injection molded, fabrication may prove cheaper than the assumed manual layup method for this round of cost estimation.

SECTION 5.0

COST ESTIMATES

The practices of general contractors (Ref. 10) have been used in arriving at cost of construction. This is believed a reasonable approach because a substantial effort is required at the field site regardless of the material of construction. Labor rates used for factory production and tooling operations were computed from the averages of appropriate typical mixes of labor categories at Grumman's Stuart, Florida plant during 1979. The Stuart labor market is representative of the regional cost index of Wichita, KA, and Oklahoma City, OK, (Ref. 12) both within the prime wind energy market belt. Production centers serving other candidate wind energy areas would impose cost adjustments associated with their regional indices. Alternatively, shipping costs from prime market belt production centers would have to be added. Prevailing overhead and profit rates of Ref. 12 were applied to direct labor hours and raw material costs supplied by our primary estimating sources. Suitable differentials were considered for field and factory sites of operations. Lot size effects on unit costs (i.e., learning curve adjustments) were applied on an individual basis for each material in accordance with the experience and recommendation of each primary cost estimator. However, these trends have been frozen at the 100th system production lot rate. Only tooling and mold costs have continued to be distributed over each unit for higher (i.e., 200 and 500) production lot sizes. The standard accounting relationships given by Table 5-1 have been used to generate Tables 5-2 to 5-4.

Table 5-1. STANDARD COSTING RELATIONSHIPS

Direct Production Cost	= Variable Production Cost + Fixed Production Cost
Gross Installation Cost	= Direct Production Cost + Indirect Production Cost
Selling Price	= Gross Installation Cost + General & Administrative Cost + Profit

The selling price estimates presented by Tables 5-2, 5-3, and 5-4 are defensible commercial base prices according to general contractor practice. They do not reflect different price-making strategies for the variety of marketing conditions likely to prevail in broad spectrum industrial or commercial merchandising. They do not, further, represent profit margins needed to justify specific investment policies; consideration of the impact of these strategies for pricing is beyond the scope of this paper.

These baseline point design costs indicate that the ferrocement diffuser is the least expensive although limited to the small size range. The aluminum diffuser is somewhat more costly than the FRP sandwich construction, and the former may also require significant early investment for machinery and plant to satisfy fabrication of large size DAWTs in large numbers.

The variation of general contractor selling price with baseline DAWT size appears to vary approximately as the turbine diameter to the 1.50 exponent. Then, the price-to-rated power ratio is inversely proportional to the approximately square root of rotor diameter. Thus, larger geometrically similar DAWT units tend to become more cost effective but we have not yet determined how far this rule can be extrapolated.

5.1 PRODUCT IMPROVEMENT EXTRAPOLATIONS

As is true in virtually all case histories of major innovation, the baseline DAWT point designs represent just the first step in a chain of expected technical improvements arising from continued concept development and design refinement. Already, we are in a position to specify a major cost saving design for the diffuser; preliminary data indicates this proposed change also leads to improved DAWT performance. This modification consists in increasing the diffuser included angle to 90° from the baseline 60° configuration.

On the assumption that fabrication cost is closely correlated to diffuser surface area, the FRP baseline DAWT costs of Table 5-2 have been reduced, as shown by Table 5-5, to the projections for a 90° included angle configuration. Representative installed unit prices for limited production lots of three DAWT ratings are approximately:

- 11 kW - $18,000 to $20,000
- 60 kW - $65,000 to $70,000
- 150 kW - $140,000 to $150,000

for this FRP construction. All aluminum construction of the 90° included angle diffuser yields much higher unit selling prices.

5.2 BUSBAR COST OF ELECTRICITY

Assuming the end use of the DAWT is electricity production, the cost of electricity (COE) has been computed by the standard DoE equation (Ref. 13):

$$\text{COE} = \frac{(\text{Capital Cost}) \times (\text{Annual Fixed Charge})}{\text{Annual Energy, kW h}} + \text{O\&M}$$

The annual energy output has been computed using a Rayleigh wind speed frequency distribution (Ref. 10) and DAWT power rating at the rated wind speed in Table 5-6. A cut-in speed of 9.6 km/h (6.0 mph) and 64.4 km/h (40 mph) cut-out speed has been assumed. Wind values are taken at the DAWT hub height. Because the DAWT's power coefficient varies from a low value at cut-in to its greatest value near rated wind speed, the power variation with wind speed is not just a cubic (i.e., varying with V^3). For simplicity we have assumed a linear variation of power with wind speed between cut-in and rated values. While this may tend to overestimate the power production particularly at low site average wind speeds, the COE inaccuracy introduced in annual energy computations is probably of the same order as the savings not taken in capital cost estimating because of unexamined production engineering improvement possibilities. The actual annual energy resulting from a detailed performance analysis would probably be somewhere between our linear assumption and a cubic relationship.

Table 5-2. ESTIMATED COST ANALYSIS SUMMARY: DAWT-30° HALF ANGLE; FRP ADVANCED DIFFUSER; 2.75 AREA RATIO (1979 DOLLARS)

	36 FT DIAMETER ROTOR	22.5 FT DIAMETER ROTOR	9 FT DIAMETER ROTOR
VAR. PROD. COST $			
DIFFUSER STRUCTURE	62969	14906	5172
FRP PANELS	21944	8041	1421
DIFFUSER SUPPORT	9533	4192	981
ROTOR ASSEMBLY	19325	12485	6103
FOUNDATION	24000	16000	2000
TOTAL VAR. COST, $	137771	55624	15677
TOTAL DIR. PROD. COST, $			
PER UNIT OF 100 UNITS	153368	61270	18642
PER UNIT OF 200 UNITS	147119	59241	17387
PER UNIT OF 500 UNITS	143341	58028	16634
GROSS INST COST, $			
PER UNIT OF 100 UNITS	184554	73757	22436
PER UNIT OF 200 UNITS	177038	71316	20925
PER UNIT OF 500 UNITS	172494	69856	20019
GEN'L CONTRACTOR'S SELL'G PRICE, $			
PER UNIT OF 100 UNITS	212237	84821	25801
PER UNIT OF 200 UNITS	203594	82013	24064
PER UNIT OF 500 UNITS	198368	80335	23022

Table 5-3. ESTIMATED COST ANALYSIS SUMMARY: DAWT BASELINE DIFFUSER: ALUMINUM STRUCTURE; 30° HALF ANGLE; 2.75 AREA RATIO (1979 DOLLARS)

	36 ft Diameter Rotor	22.5 ft Diameter Rotor	9 ft Diameter Rotor
Var Prod Cost, $			
Diffuser Structure *	88803	28806	8923
Rotor Assembly	19325	12485	6103
Foundation	24000	16000	2000
Total Var Cost, $	132128	57291	17026
Total Dir Prod Cost, $			
Per unit of 100 units	148303	63988	20943
Per unit of 200 units	140225	60644	18994
Per unit of 500 units	135361	58630	17815
Gross Inst Cost, $			
Per unit of 100 units	178602	77072	25222
Per unit of 200 units	168872	73051	22877
Per unit of 500 units	163013	70629	21459
Gen'l Contractor's Sell'g Price, $			
Per unit of 100 units	205392	88633	29005
Per unit of 200 units	194203	84009	26309
Per unit of 500 units	187465	81223	24678

* Includes Diffuser Support

Table 5-4. ESTIMATED COST ANALYSIS SUMMARY: DAWT BASELINE DIFFUSER: FERROCEMENT STRUCTURE 30° HALF ANGLE; 2.75 AREA RATIO (1979 DOLLARS)

	36 ft Diameter Rotor	22.5 ft Diameter Rotor	9 ft Diameter Rotor
Var Prod Cost, $			
Diffuser Structure	NOT FEASIBLE	33000	6100
Diffuser Support	WITH	4192	981
Rotor Assembly	CURRENT	12485	6103
Foundation	TECHNOLOGY	16000	2000
Total Var Cost, $		65677	15184
Total Dir Prod Cost,$			
Per unit of 100 units		67252	15686
Per unit of 200 units		66269	15440
Per unit of 500 units		65995	15284
Gross Inst Cost, $			
Per unit of 100 units		74104	17600
Per unit of 200 units		73048	17320
Per unit of 500 units		72728	16980
Gen'l Contractor's Sell'g Price, $			
Per unit of 100 units		85220	20240
Per unit of 200 units		84005	19918
Per unit of 500 units		83638	19527

Table 5-5. ESTIMATED COST ANALYSIS SUMMARY: DAWT-45° HALF ANGLE; FRP ADVANCED DIFFUSER; 2.75 AREA RATIO (1979 DOLLARS)

ROTOR DIAMETER, FT	PRODUCTION LOT SIZE, UNITS	S.P./UNIT, $		REL SURFACE AREA OF DIFF (45°/30°)	PROJECTED S.P./UNIT, $	
		30° BASELINE DIFF COMPONENT ONLY	BALANCE OF DAWT		45° DIFF ONLY	TOTAL 45° DAWT
36.0						
	100	137350	74887	0.518	71147	146034
	200	129527	74067	0.518	67095	141162
	500	124697	73671	0.518	64593	138264
22.5						
	100	33493	51316	0.518	17349	68665
	200	31488	50525	0.518	16311	66836
	500	30297	50038	0.518	15694	65732
9.0						
	100	12710	13091	0.518	6584	19675
	200	11230	12834	0.518	5817	18651
	500	10343	12679	0.518	5358	18037

The annual charge factor for two classes of end users have been applied. For private utilities and industrial applications 0.18 is used, and for farmers, consumers and REA cooperatives a factor 0.10 is used in accordance with recommendations of Ref. 14 and 15. Changes in DAWT ownership conditions that would affect service life, accounting or tax provisions, insurance, or federal grant incentives would alter the applicable annual factor and the resultant COE.

Estimates of the annual allowance for operations and maintenance (O&M) levelized over a 30-year lifetime add about $0.001 to $0.003/kW h for the 150 to 60 kW units, respectively and about 2 to 6 mils/kW h for units rated below 30 kW.

Salvage value of the aluminum DAWT components, technically should be considered in the depreciation allowance making up the annual fixed charge. Aluminum is a high energy consuming metal and reuse of scrap results in considerable savings in energy and cost by the basic metal producer. As a consequence, it is expected that the salvage value of aluminum will increase in the next several decades at a rate exceeding the average general inflation rate from the present approximate of $0.30/lb. In addition to considering salvage at its actual present value (1979 dollars) of $0.30/lb, we have estimated a "high range" for the present value of scrap aluminum. This latter price of about $1.00/lb is obtained by assuming that the scrap appreciates in value at a rate exceeding the general inflation rate by about 4 % compounded over a 30-year period.

As an approximate simplification treating salvage as a negative capital expenditure in the COE equation results in a COE reduction of between 0.1 and 0.75 cents/kW h depending on DAWT size, end user, site wind energy potential, and effective salvage value. Thus, salvage has the potential of offsetting levelized O&M costs.

Table 5-6 indicates busbar costs of $0.04 to $0.06/kW h for 150 kW DAWTs for sites with average annual wind speeds between 16 and 12 mph (25.7 and 19.3 km/h) respectively, and for commercial/industrial users; farm and REA type application would enjoy COEs of between $0.020 and $0.035/kw h over the same site wind characteristics.

At the 60 kW DAWT rating, the corresponding COEs are about $0.045 to $0.070/ kW h for industrial/commercial users, and $0.025 to $0.040/kW h for farmers and co-ops.

Finally, for the 11 kW rated DAWT, the COE for farm applications is estimated between $0.040 and $0.060/kW h.

5.3 COMPARISON TO DoE GOALS

As a means of evaluating these discrete cost estimates for DAWT over a broad range of ratings up to 200 kW, the COE curves of Fig. 5a and 5b have been generated. Further, they are compared against U.S. Dept. of Energy (DoE) goals established in 1978 (Ref. 16) for limited production lots. It is evident, both for farmer and commercial applications, that the DAWT estimates

Table 5-6. ESTIMATED BUSBAR COST OF ELECTRICITY (COE) ADVANCED DAWT - 2.75 AREA RATIO 45° HALF ANGLE; FRP DIFFUSER

ROTOR DIA, FT	PROJ S.P. TOTAL DAWT, $	RATED PWR, kW	RATED WIND SPEED, MPH	FULL POTENTIAL OF OUTPUT ENERGY, kW-h			COE – COE – CENTS/kW-h			
				$\overline{V}$ = 12	14	16 MPH	$\overline{V}$ = 12 ACF = 0.18	16 MPH ACF = 0.18	12 ACF = 0.10	16 MPH ACF = 0.10
36.0										
PER UNIT OF 100	149034 (1)	150	24	466600	579795	674185	5.8	4.0	3.2	2.3
PER UNIT OF 200	144162 (1)	150	24	466600	579795	674185	5.6	3.9	3.1	2.2
PER UNIT OF 500	141264 (1)	150	24	466600	579795	674185	5.5	3.8	3.1	2.1
22.5										
PER UNIT OF 100	68665	60	24.2	185680	230950	267050	6.7	4.6	3.7	2.5
PER UNIT OF 200	66836	60	24.2	185680	230950	267050	6.5	4.5	3.6	2.5
PER UNIT OF 500	65732	60	24.2	185680	230950	267050	6.4	4.4	3.6	2.4
9.0										
PER UNIT OF 100	19675	11.2	26	32350	40510	47170	10.9	7.5	6.1	4.2
PER UNIT OF 200	18651	11.2	26	32350	40510	47170	10.4	7.1	5.8	3.8
PER UNIT OF 500	18037	11.2	26	32350	40510	47170	10.0	6.9	5.6	3.8

Notes:

A) 1979 DOLLARS

B) ACF – ANNUAL CHARGE FACTOR

(1) INCLUDES $3000 ADDED TO TABLE 5 DATA FOR 150 kW UP-RATED GENERATOR AND TRANSMISSION GEARBOX.

in 1979 dollars are lower than the DoE goals in 1978 dollars.*

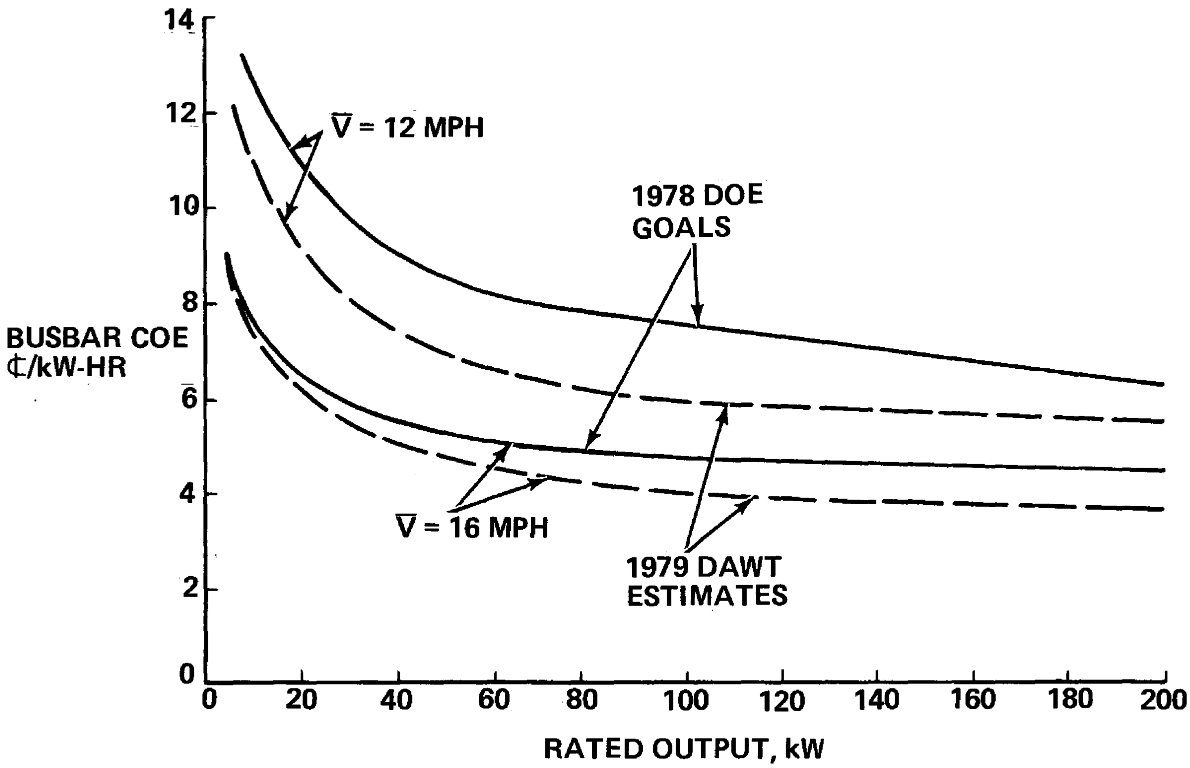
Without further adjustment of the 1978 and 1979 prices to dollar equivalents,* in the high power rating range (e.g., ~ 150 kw) the DAWT offers about 4/5 the COE projected by DoE planners for commercial users.

For the farmer, the smaller DAWT units yield about the same COE for the farmer as desired by DoE, and about 10% lower COE than DoE goals at higher power ratings.

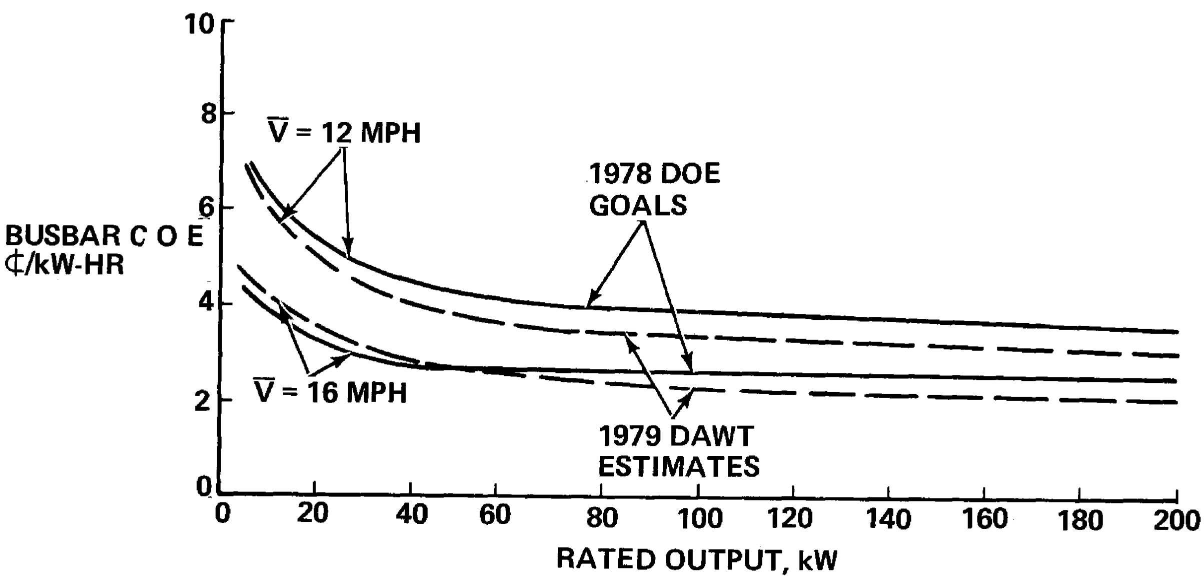
The current differentials between government goals and our first order cost estimates provides ample margin for various pricing strategies as future market development is stimulated and market penetration plans are exercised.

---

*In this one year interval, the U.S. dollar lost 10% of its buying power, while the average cost of energy increased 15% (U.S. Bureau of Labor statistics).



a) Commercial Users



b) Agricultural Users

Figure 5-1. ESTIMATED DAWT COST OF ENERGY (1979) COMPARED TO DoE GOALS (1978), LIMITED PRODUCTION (a) COMMERCIAL USERS AND (b) AGRICULTURAL USERS

SECTION 6.0

CONCLUDING REMARKS

We have provided a preliminary cost assessment for the DAWT approach to wind energy conversion in unit systems to 150 kW power rating. The results demonstrate economic viability of the DAWT with no further design and manufacturing know-how than already exists. Further economic benefits of this form of solar energy are likely through:

- Future refinements in product design and production techniques
- Economies of larger quantity production lots
- Special tax incentives.

Continued cost escalation on non-renewable energy sources and public concern for safeguarding the biosphere environment surely will make wind energy conversion by DAWT-like systems even more attractive to our society. Promotional actions by national policy makers and planners as well as industrialists and entrepreneurs can aid the emergence of the DAWT from its research phase to a practical and commercial product.

SECTION 7.0

ACKNOWLEDGEMENT

This investigation was supported by the Solar Energy Research Institute and Dr. Irwin Vas, under Subcontract XH-9-8073-1.

SECTION 8.0

REFERENCES

1. Betz, A., "Energieumsetzungen in Venturidusen," Naturwissenshaften, Vol 10, No. 3, 1929, pp 160-164.

2. Lilley, G. M. and Rainbird, W. J., "A Preliminary Report on the Design and Performance of Ducted Windmills," Rep. 102, April 1956, College of Aeronautics, Cranfield, England. Also available as Tech. Rep. C/T 119, 1957, the Electrical Research Assoc., Letherhead, England.

3. Kogan, A. and Seginer, A., "Shrouded Aerogenerator Design Study. II, Axisymmetrical Shroud Performance," Israel Journal of Technology Feb 1963, pp 49-56.

4. Oman, R. A. and Foreman, K. M., "Advantages of the Diffuser Augmented Wind Turbine," NSF/NASA Wind Energy Conversion Systems Workshop Proceedings, NSF/RA/W-73-006, Dec 1973, pp 103-106.

5. Oman, R. A. Foreman, K. M. and Gilbert, B.L., "Investigation of Diffuser-Augmented Wind Turbines, Part I and II," ERDA Report COO-2616-2, Jan 1977, Grumman Aerospace Corp, Bethpage, NY.

6. Gilbert, B.L, et al., "Fluid Dynamics of Diffuser-Augmented Wind Turbines," J Energy, Vol 2, No. 6, Nov - Dec 1978, pp 368-374.

7. Gilbert, B.L. and Foreman, K.M., "Experimental Demonstration of the Diffuser-Augmented Turbine Concept," J Energy, Vol 3, No. 4, July - Aug 1979, pp 235-240.

8. Foreman, K. M. and Gilbert, B.L., "Technical Development of the Diffuser Augmented Wind Turbine (DAWT) Concept," Wind Engineering, Vol 3, No. 3, 1979, pp 153-166.

9. Foreman, K.M. and Gilbert, B.L., "Further Investigations of Diffuser Augmented Wind Turbines, Part II - Technical Report," U.S. Dept. of Energy Report COO-2616-2 (Part 2) (Rev 2), July 1979. Grumman Aerospace Corp, Bethpage, NY.

10. Cliff, W.C., "The Effect of Generalized Wind Characteristics on Annual Power Estimates from the Wind Turbine Generators," PNL 2436, Oct 1977, Battelle Pacific Northwest Labs, Richland, WA.

11. Igra, O., "The Shrouded Aerogenerator," Energy, Vol 2, No. 4, 1977 pp 429-439.

12. Godfrey, R. S. (Editor in chief), "Building Construction Cost Data, 1979, 37th Annual Edition," R. S. Means Co, Inc, Duxbury, Mass.

13. Eldridge, F.R. "Wind Machines," MTR-6971, NSF-RA-N-75-051, Oct 1975, The Mitre Corp, McLean, VA.

14. "Wind Energy Mission Analysis," Final Report, Appendix I, ERDA Report COO/2578-1/3, Feb 18, 1977, General Electric Co., Philadelphia, PA.

15. "The 1970 National Power Survey, Part I," Dec 1971, Chapter 19, Federal Power Commission, Washington, DC

16. Divone, L.V. (U.S. Dept. of Energy) private communication to K. Foreman (Grumman Aerospace Corp) Nov 1979.

Document Control Page

1. SERI Report No.: SERI/TR-98073-1A

2. NTIS Accession No.:

3. Recipient's Accession No.:

4. Title and Subtitle:
Preliminary Design & Economic Investigations of Diffuser Augmented Wind Turbines (DAWT) Executive Summary

5. Publication Date: December 1981

6.

7. Author(s):
K. M. Foreman

8. Performing Organization Rept. No.:

9. Performing Organization Name and Address:
Research Department
Grumman Aerospace Corporation
Bethpage, N.Y. 11714

10. Project/Task/Work Unit No.:

11. Contract (C) or Grant (G) No.:
(C) XH-9-8073-1
(G)

12. Sponsoring Organization Name and Address:
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

13. Type of Report & Period Covered: Technical Report

14.

15. Supplementary Notes:

16. Abstract (Limit: 200 words)

This report suggests a preferred design and configuration approach for the DAWT innovative wind energy conversion system. A preliminary economic assessment is made for limited production rates of units between 5 and 150 kW rated output. Nine point designs are used to arrive at the conclusions regarding best construction material for the diffuser and busbar cost of electricity (COE). It is estimated that for farm and REA cooperative end users, the COE can range between 2 and 3.5 cents/kWh for sites with annual average wind speeds of 16 and 12 mph (25.7 and 19.3 km/h respectively, and 150 kW rated units. No tax credits are included in these COE figures. For commercial end users of these 150 kW units, the COE ranges between 4.0 and 6.5 cents/kWh for 16 and 12 mph sites. These estimates in 1971 dollars are lower than DOE goals set in 1978 for the rating size and end applications. Recommendations are made for future activities to maintain steady, systematic progress toward mature development of the DAWT.

17. Document Analysis

a. Descriptors Cost ; Design ; Diffuser Augmented Turbines ; Economics ; Energy Yield ; Manufacturing ; Materials ; Wind Power ; Wind Turbines ;

b. Identifiers/Open-Ended Terms

c. UC Categories
60

18. Availability Statement
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

19. No. of Pages: 36

20. Price: $4.50

Form No. 8200-13 (6-79)

☆U.S. GOVERNMENT PRINTING OFFICE: 1982-0-576-083/214