SANDIA REPORT

SAND87—0792 • UC—60
Unlimited Release
Printed August 1987

RS-8232-2/65974

8232-2//065974

00000001 -

The LIFE Computer Code Fatigue Life Prediction for Vertical Axis Wind Turbine Components

Herbert J. Sutherland, Thomas D. Ashwill, Norman Slack

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

SF2900Q(8-81)

1088662

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors or subcontractors.

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

NTIS price codes
Printed copy: A04
Microfiche copy: A01

Distribution
Category UC-60

SAND87-0792
Unlimited Release
Printed August 1987

The LIFE Computer Code

Fatigue Life Prediction for Vertical Axis Wind Turbine Components*

Herbert J. Sutherland**
Thomas D. Ashwill**
and
Norman Slack***

ABSTRACT

The LIFE computer code was originally written by Veers to analyze the fatigue life of a vertical axis wind turbine (VAWT) blade. The basic assumptions built into this analysis tool are: the fatigue life of a blade component is independent of the mean stress; the frequency distribution of the vibratory stresses may be described adequately by a Rayleigh probability density function; and damage accumulates linearly (Miner's Rule). Further, the yearly distribution of wind is assumed to follow a Rayleigh distribution. The original program has been updated to run in an interactive mode on a personal computer with a BASIC interpreter and 256K RAM. Additional capabilities included in this update include: the generalization of the Rayleigh function for the wind speed distribution to a Weibull function; the addition of two constitutive rules for the evaluation of the effects of mean stress on fatigue life; interactive data input; and the inclusion of a stress concentration factor into the analysis.

*This work is supported by the U.S. Department of Energy under Contract DE-AC04-76DP00789.
**Wind Energy Research Division; Sandia National Laboratories.
***New Mexico Engineering Research Institute.

TABLE OF CONTENTS

	Page
Introduction	1
Analytical Considerations	2
Wind Regime	2
Component Stresses	4
Mean Stress	4
Vibrational Stress Distribution	4
Constitutive Equation	6
S-N Formulation	6
Mean Stress Correction	7
Damage Accumulation	8
Service Lifetime	9
Difference Equations	10
Auxiliary Calculations	13
Altitude Correction	13
Stress Concentration Factors	13
Input Parameters	15
Limitations	19
Example Problem	20
References	28
Appendix A. Printed Output from the Example Problem	30
Appendix B. Program Variables	33
Appendix C. Program Listing for the LIFE Computer Code Version 1.2	36
Appendix D. Stress Cycle Integration Limits	45
Appendix E. Endurance Limit	46
Appendix F. Automated Data Entry for the LIFE Code	47
Appendix G. Program Listing for the LIFEA Computer Code Version 2.1	48

List of Tables

Page

Table I. S-N Properties for 6061-T6 Aluminum and 6063-T6 Aluminum 21

List of Figures

Figure 1. Rotational Bending S-N Diagram for 6061-T6 and 6063-T6 Aluminum 21

Figure 2. Axial S-N Diagram for 6061-T6 and 6063-T6 Aluminum 22

Figure 3. Vibratory Stresses vs. Wind Speed for the DOE 100 kW Vertical Axis Wind Turbine . . 23

Figure 4. Mean Stress Correction for the 6063-T6 Aluminum S-N Diagram 24

Figure 5. Wind Speed and Damage Density Functions for the Example Problem over the Entire Wind Spectrum (0 mph cut-in wind speed and infinite cut-out wind speed) 25

Figure 6. Damage Density Functions for the Example Problem (10 mph cut-in wind speed and 45 mph cut-out wind speed) 26

Figure D1. Effect of the Internal Variables ML and MV on the Predicted Service Lifetime for the Example Problem 45

INTRODUCTION

The production of energy using the Darrieus rotor, vertical axis wind turbine (VAWT) has been shown to be a viable option for using wind energy to meet the national energy production requirements utilizing renewable energy resources. However, to compete economically against conventional, fossil fueled systems, the wind turbine must produce energy for many years. As with all wind turbines, the long service lifetime combines with capital investment considerations to dictate a fatigue critical structure.

Current techniques for the prediction of the service lifetime of a wind turbine are subject to significant errors.[1] This analytical shortcoming has dictated that wind turbine structures be designed with large margins of safety. However, with the loss of the energy credits, the design of wind turbines must become more cost competitive. Highly over designed structures can no longer be tolerated. Moreover, even with large safety margins, the wind turbines located in the high turbulence areas of California have seen fatigue failures. Thus, the inclusion of fatigue analysis into the design of wind turbines has become critical to the wind industry.

For VAWTs, the need for fatigue analysis of critical components has been addressed by Veers,[2-4] Akins,[5] Malcolm,[6] et al. Veers' research lead to the development of a research computer code, entitled the LIFE program, to evaluate the life of VAWT components under a set of simplifying assumptions. That code has now been adapted into an interactive code that can be run on a personal computer with a BASIC interpreter and 256K RAM. This report describes

the new code (LIFE, Version 1.2) and the additional capabilities that have been incorporated into it.

The report starts with a review of the analytical and numerical models used in the code. The input parameters to the code are then discussed in detail. An example problem closes the report. Appendices include the printed output from the code for the example problem, a list of the program variables used in the code, and a listing of the code.

ANALYTICAL CONSIDERATIONS

An analysis of the fatigue characteristics of a VAWT component requires detailed descriptions of the wind regime in which the turbine will be operating, the stresses excited in the component, and an appropriate constitutive equation for the material comprising the component. The following section describes the formulation of the site, machine and material descriptors, and the underlying assumptions that have been incorporated into the analysis to make it tractable.

WIND REGIME

In the initial LIFE code,[3,7] the wind regime is assumed to follow a Rayleigh probability distribution function. In this formulation, the probability density P_V of a wind speed V occurring is given by:

$$P_V = \frac{\pi V}{2 \bar{V}^2} \exp \frac{-\pi V^2}{4 \bar{V}^2}, \qquad (1)$$

where $\bar{V}$ is the annual average wind speed at the site under consideration.

This formulation is a specialized form of the Weibull distribution:[8]

$$P_V = \left(\frac{\alpha}{\beta}\right) \left(\frac{V}{\beta}\right)^{\alpha-1} \exp\left[- \left(\frac{V}{\beta}\right)^{\alpha}\right], \qquad (2)$$

where α and β are the shape factor and the amplitude factor of the Weibull distribution. For α equal to 2, the Weibull distribution is equivalent to the Rayleigh distribution. α and β are related to the average wind speed through the gamma function Γ:[8]

$$\bar{V} = \beta\, \Gamma\left(1 + \frac{1}{\alpha} \right). \qquad (3)$$

For this analysis, the gamma function Γ was evaluated using the following expression:[10]

$$\Gamma(1 + X) = 1 + \sum_{i=1}^{5} G(i)\, X^{i-1}, \qquad (4)$$

where G(i), i = 1 to 5, are constants defined to be -0.5748646, 0.9512363, -0.6998588, 0.4245549, and -0.1010678, respectively. This expansion yields an absolute error that is always less than 5E-5 (5×10^{-5}).

As suggested by several authors, e.g., see Ref. 9, the Weibull distribution is a better description of the wind speed spectrum than the Rayleigh distribution. Therefore, we have incorporated the Weibull distribution into this new version of the LIFE code.

COMPONENT STRESSES

The total stress σ_t in the component under consideration may be divided into two parts: a mean stress S_m and the vibratory stress S. Assuming linearity, these three variables may be related by (here we present only a one-dimensional, scalar, formulation for this problem):

$$\sigma_t = S_m + S \cdot \tag{5}$$

MEAN STRESS: The mean stress S_m can itself be divided into two components: a gravity component σ_g and a rotational component σ_r. Again, assuming linearity permits one to write

$$S_m = \sigma_g + \sigma_r \ . \tag{6}$$

Here, the gravity component is the stress induced into the component by the body force loading on the structure due to its placement in the earth's gravitational field.

The rotational stress may have several interpretations. Here, we define this component to be the stress induced into the component by rotation of the machine under no wind conditions. For constant speed VAWTs, this stress is a constant at a particular location on the blade component.

VIBRATIONAL STRESS DISTRIBUTION: The above definitions for the various stress components imply that the vibrational stress component S is the stress introduced into the component due to aerodynamic loads on the structure. Based on detailed experimental data from the DOE/ALCOA 17-m

Low-Cost VAWT, Veers[3] showed that, for this machine, the amplitude of the vibratory stresses S at any given wind speed follows the distribution of peak values of a Gaussian narrow band random process: namely, a Rayleigh distribution. Akins showed similar results for an Indal 6400 VAWT sited in California.[5] This conditional probability density function $P_{S/V}$ of a stress S occurring at a particular wind speed may be written as

$$P_{S/V} = \left[\frac{S}{\sigma_V^2} \right] \exp \left[\frac{-S^2}{2\ \sigma_V^2} \right], \tag{7}$$

where σ_V is the RMS mean value of vibratory stresses. Here, we assume that the mean stress σ_V is only a function of the wind speed V. Based data taken from the Low-Cost machine,[3] a common form chosen for σ_V is that of a single straight line over the operating range of the machine. The general equation for this formulation is:

$$\sigma_V = m\ V + \sigma_o\ , \tag{8}$$

where σ_o is the zero velocity intercept of the linear approximation of this function over the operating regime under consideration. In this version of the LIFE code, the functional relationship between the wind speed and the mean vibratory stress is not restricted to a single straight line. Rather, the function is input, in tabular form, as a set of ordered pairs of the form $[V_i, (\sigma_V)_i]$. For values of V that lie between the tabulated points, linear interpolation is used to determine the value of σ_V; namely,

$$\sigma_V = m_i\ V + (\sigma_o)_i, \tag{9}$$

where $$V_i \leq V < V_{i+1}, \tag{10}$$

$$m_i = \frac{(\sigma_v)_{i+1} - (\sigma_v)_i}{V_{i+1} - V_i}; \tag{11}$$

and,

$$(\sigma_o)_i = (\sigma_v)_i - m_i (V_i). \tag{12}$$

CONSTITUTIVE EQUATION

<u>S-N FORMULATION</u>: Several constitutive equations have been proposed for the accumulation of damage under cyclic loading (e.g., see Ref. 11). One of the more popular damage rules is called Miner's Rule.[12] This linear rule simply states that the damage accumulation D is independent of the order-of-load application and is the sum of the fraction of the fatigue life exhausted at each stress level. Miner's rule may be written in integral form as

$$D = \int_{-\infty}^{\infty} \int_{0}^{\infty} \frac{n(S_m,S)}{N(S_m,S)} \, dS \, dS_m, \tag{13}$$

where $n(S_m,S)$ is the number of applied cycles at the stress level defined by the mean stress S_m, and the stress amplitude S and $N(S_m,S)$ is the number of stress cycles required to fail the material at the same stress state. The fatigue life is exhausted when D equals one (1.0).

The function $N(S_m,S)$ is a constitutive property of the material under investigation. It is usually formulated as an "S-N" curve at a specific mean stress. For this analysis, the S-N curve is input in tabular form as a set of ordered

pairs of the form (S_i, N_i) at a mean stress of S_m. For values of S that lie between the tabulated points, exponential interpolation is used to determine the value of N. Namely,

$$\log(N) = ms_i \log(S) + (N_o)_i , \tag{14}$$

where

$$S_i \leq S < S_{i+1} , \tag{15}$$

$$ms_i = \frac{\log(N_{i+1}) - \log(N_i)}{\log(S_{i+1}) - \log(S_i)} , \tag{16}$$

and

$$(N_o)_i = \log(N_i) - ms_i \, [\log(S_i)] . \tag{17}$$

<u>MEAN STRESS CORRECTION</u>: If the input S-N curve is for a zero mean stress, it may be corrected by the LIFE code for mean stress. Two rules have been incorporated into the code for this analysis. The first, the Goodman rule,[8] characterizes the effect of mean stress on an S-N material characterization as

$$S = \sigma_e \left\{ 1 - \left[\frac{S_m}{\sigma_u} \right] \right\} , \tag{18}$$

where S is the stress amplitude of the cyclic stress on the component (i.e., the component stress described in Eqs. 5, 7, etc.), σ_e is the effective cyclic stress amplitude on the component at zero mean stress, and σ_u is the ultimate strength of the material.

The second formulation, postulated by Falkenberg for aluminum,[13] is

$$S = 0.6\ \sigma_e - 0.2\ S_m \quad . \tag{19}$$

These formulations have been incorporated directly into the LIFE code and offer the user two formulations for the correction of the mean stress.

Thus, the functions $n(S_m,S)$ and $N(S_m,S)$ are reduced to a function of σ_e alone; i.e.,

$$D = \int_{-\infty}^{\infty} \left(\frac{n(\sigma_e)}{N(\sigma_e)} \right) d\sigma_e \ . \tag{20}$$

Rewriting the limits of integration to encompass the range of stresses encountered in the component yields:

$$D = \int_{\sigma_{min}}^{\sigma_{max}} \left(\frac{n(\sigma_e)}{N(\sigma_e)} \right) d\sigma_e \ , \tag{21}$$

where σ_{min} is the minimum stress encountered and σ_{max} is the maximum. Here, σ_{min} is taken to be the "endurance limit" of the material under consideration, i.e., the stress level below which material damage is assumed to be negligible.

DAMAGE ACCUMULATION

Combining the results of the above three sections permits the determination of the damage in the VAWT component. Starting with Eq. 21, the total damage D_t accumulated over the entire wind regime is given by

$$D_t = \int_0^{\infty} \left(P_v \; P_{s/v} \right) \int_{\sigma_{min}}^{\sigma_{max}} \left(\frac{n(\sigma_e)}{N(\sigma_e)} \right) d\sigma_e \; dV \cdot \tag{22}$$

As this formulation is only for the operating stresses, the integral on wind speed may be reduced to cover only the operating range of the turbine. Thus,

$$D_t = \int_{V_{st}}^{V_{sp}} \left(P_v \;\; P_{s/v} \right) \int_{\sigma_{min}}^{\sigma_{max}} \left(\frac{n(\sigma_e)}{N(\sigma_e)} \right) d\sigma_e \; dV \, , \tag{23}$$

where V_{st} is the cut-in wind speed (starting speed) and V_{sp} is the cut-out wind speed (stopping speed).

SERVICE LIFETIME

To determine the service lifetime of the component under consideration requires that time be incorporated into the damage function D_t (Eq. 23). Namely, we have to determine at what time in the service lifetime of the component we expect failure (i.e., when does D_t equal one).

Veers[2] assumes that damage is accumulated, on the average, at a rate equal to the dominant frequency of blade vibration f_o, then the time rate of damage is given by

$$\frac{D_t}{t} = f_o \;\; D_t \, , \tag{24}$$

where t is the total time the VAWT has been operating. The service lifetime T_f occurs at D_t equal to one; i.e.,

$$\frac{1}{T_f} = f_o \int_{V_{st}}^{V_{sp}} \left(P_v \; P_{s/v} \right) \int_{\sigma_{min}}^{\sigma_{max}} \left(\frac{n(\sigma_e)}{N(\sigma_e)} \right) d\sigma_e \; dV . \tag{25}$$

DIFFERENCE EQUATIONS

To use the above formulation in a numerical computer requires that the above equations be written in discrete form. Here, we will compute the value of an integral by dividing it up to a finite series of intervals, evaluating the kernel at each interval, and then summing the results, using Simpson's rule,[14] over all intervals.

Let us define the start of the ith interval of the wind regime to be V_i and its end to be V_{i+1}. Thus, its width ΔV is given by:

$$\Delta V = V_{i+1} - V_i \cdot \tag{26}$$

In this version of the LIFE code, ΔV is taken to be a constant and equal to one. The mean velocity in this interval is defined to be

$$\begin{aligned} (V_m)_i &= V_i + \Delta V/2 \\ &= \left(V_i + V_{i+1} \right)/2 \cdot \end{aligned} \tag{27}$$

Let the total interval between starting and stopping wind speed be divided into I intervals such that

$$V_{sp} - V_{st} = I \; \Delta V \quad , \tag{28}$$

and,

$$V_i = (i - 1)\,\Delta V + V_{st} \cdot \tag{29}$$

In similar fashion, let the jth interval of the effective stress σ_e in the ith interval of the wind speed start at $(\sigma_e)_{i,j}$ and end at $(\sigma_e)_{i,j+1}$. Thus, its width $\Delta\sigma$ (assumed to be a constant here) is given by

$$\Delta\sigma = (\sigma_e)_{i,j+1} - (\sigma_e)_{i,j} \ , \tag{30}$$

and the mean stress in this interval is defined to be

$$\begin{aligned}(\sigma_{em})_{i,j} &= (\sigma_e)_{i,j} + \Delta\sigma/2 \\ &= \Big((\sigma_e)_{i,j} + (\sigma_e)_{i,j+1}\Big)/2 \ .\end{aligned} \tag{31}$$

Let the total interval on the effective stress integration be divided into J intervals such that

$$\sigma_{max} - \sigma_{min} = J\,\Delta\sigma \ , \tag{32}$$

and

$$\sigma(_e)_{i,j} = (j - 1)\,\Delta\sigma + \sigma_{min} \ . \tag{33}$$

Then Eq. 23 may be written as:

$$D_t = \sum_{i=1}^{I} (P_v \ \ P_{s/v})_i \sum_{j=1}^{J} (n')_{i,j} \tag{34}$$

where,

$$(n')_{i,j} = \int_{(\sigma_e)_{i,j}}^{(\sigma_e)_{i,j+1}} \left(\frac{n(\sigma_e)}{N(\sigma_e)}\right) d\sigma_e \ , \tag{35}$$

$$\approx \left\{ \frac{n\left[(\sigma_e)_{i,j+1}\right]}{N\left[(\sigma_e)_{i,j+1}\right]} + \frac{n\left[(\sigma_e)_{i,j}\right]}{N\left[(\sigma_e)_{i,j}\right]} \right\} \frac{\Delta\sigma}{2} \quad , \qquad (36)$$

and,

$$(P_V \; P_{S/V})_i = \int_{V_i}^{V_{i+1}} \left\{ \frac{\alpha}{\beta} \left(\frac{V'}{\beta} \right)^{\alpha-1} \exp\left[- \left(\frac{V}{\beta} \right)^{\alpha} \right] \right\}$$

$$\cdot \left\{ \left(\frac{S}{\sigma_V^2} \right) \exp\left(\frac{-S^2}{2\,\sigma_V^2} \right) \right\} dV \quad , \qquad (37)$$

$$\approx \left[\left\{ \left(\frac{\alpha}{\beta} \right) \left(\frac{V_{i+1}}{\beta} \right)^{\alpha-1} \exp\left[- \left(\frac{V_{i+1}}{\beta} \right)^{\alpha} \right] \right\} \right.$$

$$\cdot \left\{ \left(\frac{S(V_{i+1})}{\sigma_V^2} \right) \exp\left(\frac{-S^2(V_{i+1})}{2\,\sigma_V^2} \right) \right\}$$

$$+ \left\{ \left(\frac{\alpha}{\beta} \right) \left(\frac{V_i}{\beta} \right)^{\alpha-1} \exp\left[- \left(\frac{V_i}{\beta} \right)^{\alpha} \right] \right\}$$

$$\left. \cdot \left\{ \left(\frac{S(V_i)}{\sigma_V^2} \right) \exp\left(\frac{-S^2(V_i)}{2\,\sigma_V^2} \right) \right\} \right] \frac{\Delta V}{2} \quad . \qquad (38)$$

AUXILIARY CALCULATIONS

The format chosen for input to this code has been designed to minimize input parameters. This approach has one significant drawback: the program's formulations perform only a limited number of internal correction to the input parameters. Thus, specialized corrections must be performed by the user outside the LIFE code. As a guide, some typical corrections are listed below.

ALTITUDE CORRECTION

As the stress amplitude S and the mean RMS vibratory stress σ_V are directly related to the aerodynamic loads on the machine, they are a function of elevation. S and σ_V must be multiplied by the air density correction factor τ_C to correct for elevation changes. The correction is given by[15]

$$\tau_C = 1 + 0.25[(H_O - H)/6100] , \qquad (39)$$

where H is the height of the machine under consideration and H_O is the height of the machine used to determine S (Note: Eq. 39 assumes that the dimensions of H are in feet).

STRESS CONCENTRATION FACTORS

The analysis performed in the LIFE code assumes that the input stress levels are the stresses in the most highly stressed section of the component; i.e., the stress level at

the highest stress concentration (stress riser). If the analysis and/or the experimental data used to evaluate the stress level are away from the stress concentration, the analysis will predict a service lifetime that is nonconservative. To insure that the LIFE code is analyzing the correct stress state, the operator must determine the magnitude of the stress concentration factor. This term is incorporated numerically into the calculations through a stress concentration factor K_t that is defined here to be

$$K_t = \frac{\sigma_{mx}}{\sigma_{nom}} , \tag{40}$$

where σ_{nom} is nominal stress in the component and σ_{mx} is the maximum localized high stress.

Typically, the total stress concentration factor K_t is divided into its contributing factors through the relation[16]

$$K_t = K_1 * K_2 * \ldots * K_n . \tag{41}$$

Each K_n factor is the stress concentration factor due to a particular phenomenon. Typical stress concentration factors that should be considered for VAWT applications include the type of loading, size effects, surface roughness, surface treatment, penetrations, and notch sensitivity. A description of various stress concentration factors is given in Refs. 16 and 17.

INPUT PARAMETERS

To determine the service life of a VAWT component, the following information must be entered into the LIFE code in response to program queries. The program is run using a BASIC interpreter. Each data entry is concluded with the Return (ENTER) button. To document a computational session, selected input and output parameters are automatically printed by the program.

1. TITLE. A title for the calculation may be entered at the first prompt for identification. The title may be up to 34 characters in length. The date of the calculations is automatically added to the printed output.

2. S-N CURVE. The material properties for the analysis are input via a tabular representation of the S-N fatigue curve. The curve is based on standard laboratory tests and may be obtained from several reference books (e.g., see Refs. 18, 19 and 20). The first variable input is the number (integer) of points on the S-N curve you will be entering. A maximum of 20 points is allowed. The program then queries the operator for each S-N data point. The stress level is entered first and then the corresponding cycles to failure are entered. The values must be entered in ascending order of stress level to obtain correct predictions of service lifetime.

3. STRESS CONCENTRATION FACTOR. The stress concentration factor for the section under analysis is the next entry. As discussed earlier, this number is based on the geometry of the component and must be calculated outside of this code.

As noted on the display, the Falkenberg equation (see 4 below) for the mean stress adjustment already contains a

stress concentration factor of 1.67 in its formulation.

A value of 1 disables this feature of the program.

4. MEAN STRESS CORRECTION. Three options for correcting the S-N data for mean stress are available. The choices are

1. The Goodman Rule (see Eq. 18)
2. The Falkenberg Equation (see Eq. 19)
3. No Mean Stress Correction

Options 1-2 will query the operator for the value of the mean stress (see Eq. 6). Additionally, the Goodman rule option will query the operator for the ultimate strength of the material being analyzed. Option 3 disables this feature of the program.

Upon completion of the input, the program automatically prints the adjusted S-N curve. This tabular formulation of the S-N curve has been adjusted for both the stress concentration factor and the mean stress.

5. VIBRATORY STRESS DISTRIBUTION. The mean RMS vibratory stress amplitude, S, is the next input variable (see Eq. 7). As discussed earlier, the stress amplitude is assumed to be a function of the wind speed (Eq. 9). The function is input in tabular form. The query is for the number (integer) of points on the Wind Speed vs. RMS-Stress curve you will be entering. A maximum of 20 is allowed. The program then queries the operator for each point on the curve. The wind

speed is entered first and then the corresponding stress level is entered. The values must be entered in ascending order of wind speed to obtain correct predictions of service lifetime.

The value of S input to the code must contain the machine elevation correction factor τ_c described in Eq. 39.

6. VIBRATIONAL STRESS CYCLE RATE. The next query is for the stress cycle rate in Hz (see Eq. 24). The value chosen for this variable may be obtained using one of several techniques. The first two techniques use experimental data to determine the fundamental (dominant) frequency of vibration. If one frequency clearly dominates the experimental data, then its frequency should be chosen for this variable. If there is no one dominant frequency, the zero crossing rate should be used to determine the cyclic frequency.

If experimental data are not available, then the fundamental blade modes may be used to estimate this variable. For VAWT blade components in spanwise (flatwise) bending, the dominant frequency is of the order of twice the rotational frequency (for two bladed VAWTs). For chordwise (lead-lag) bending, the blade's dominant frequency is of the order of three times the rotational frequency.

Note that the variable must have the units of Hz (cycles per second).

7. OPERATION REGIME. The next set of queries defines the wind regime for the machine. The queries are

Cut-In Wind Speed	-	Wind speed at which the machine starts operation (Eq. 23).
Cut-Out Wind Speed	-	Wind speed at which the machine stops operation in high winds (Eq. 23).
Average Wind Speed	-	Average wind speed at the wind site (see Eq. 2).
Weibull Shape Factor	-	The shape factor in the Weibull distribution of wind speed (Eq. 2).

Note that a value of 2 for the Weibull shape factor ,α, yields a Rayleigh distribution. Values of the last two parameters have been summarized in Ref. 9 for a variety of wind sites.

At this point, the program goes into the main computation loop. After completion, the results of the calculations are printed automatically. The absolute damage (for a time of $1/f_o$ second) the wind speed density (Eq. 1) vs. wind speed table, a short summary of the input data and the predicted service lifetime are included in the output.

8. <u>DATA DUMP OPTION</u>. After completion of the calculations, the operator is queried for a "data dump." If this option is accessed, the operator will be asked for a file name (with the appropriate extension) for a dump of the numbers calculated during the course of this calculational session. The data are put into an ASCII file with appropriate headings. In this form, the data calculated by the code are available for archiving and for manipulation by other software.

9. RESTART OPTION. At the termination of the program, the operator has the following options:

1. Exit to the BASIC interpreter
2. Exit to DOS
3. Restart the LIFE code from the beginning
4. Restart the LIFE code at step 7 above (different wind regime)

LIMITATIONS

As discussed by several authors (e.g., see Refs. 5 and 6), the prediction of the service lifetime for a VAWT component by the LIFE code is subject to several limitations. All predictions should be evaluated in light of these limitations. The limitations include:

1. Miner's rule is a linear rule that is known to over-predict fatigue lifetime by as much as four times.

2. Fatigue damage due to stops, starts, and buffeting while parked is neglected. The importance of these contributions to the the fatigue life depends on the control system used for the machine under study and the site on which it is located.

3. The fatigue life is sensitive to the chosen wind distribution. The choice of a Weibull distribution may or may not be adequate for the particular site under evaluation.

4. The fatigue life is sensitive to the RMS stress distribution chosen. The Rayleigh distribution may or may not be adequate for the particular stress level and wind regime under consideration.

5. The LIFE code assumes that damage is accumulated at a constant rate that is proportional to the frequencey f_o, see Eq. 24. This formulation may or may not be adequate.

6. If the VAWT structure contains an internal flaw (crack), the LIFE code does not analyze its growth.

EXAMPLE PROBLEM

To illustrate the use of this code, we will compute the service lifetime of a VAWT blade joint. The blade will be assumed to be constructed from 6063 aluminum and is to be analyzed using Goodman's rule for correcting the S-N curve for mean stress.

The ultimate strength of the 6063 aluminum is taken to be 35,000 psi.[20] To the authors' knowledge, the only known point on the S-N curve for 6063 aluminum subjected to axial loading is 10 ksi at 5E8 cycles.[20] Therefore, the total S-N curve had to be deduced from other data. In particular, the S-N curve for rotational bending for 6061-T6 aluminum and 6063-T6 aluminum was obtained from Ref. 21 (see Fig. 1 and Table I). As shown in Fig. 1 and tabulated in Table I, the curve for the 6063 aluminum can be inferred from the data for the 6061 aluminum by derating the 6061 curve by the ratio of their ultimate strengths; namely,

$$S(n)\Big|_{6063} = \frac{(\sigma_u)_{6063}}{(\sigma_u)_{6061}} \; S(n)\Big|_{6061} . \tag{42}$$

Here, we have taken the ratio to be 0.7540. Applying this technique to axial loading, the S-N curve for 6061 aluminum[20] may be used to determine the S-N curve for 6063

TABLE I. S-N Properties for 6061-T6 Aluminum and 6063-T6 Aluminum.

Cycles to Failure	Cyclic Stress, ksi				
	Rotational Bending			Axial Loading	
	6061-T6	6063-T6	6063-T6	6061-T6	6063-T6
	Measured	Measured	Calculated	Measured	Calculated
1E4	-	-	-	32.6	24.7
1E5	31.0	23.5	23.5	24.2	18.3
1E6	23.0	16.5	17.4	19.0	14.4
1E7	17.0	13.5	12.9	14.1	10.7
1E8	14.5	11	11.0	-	-
5E8	13.5	9.5	10.2	13.5	10.0

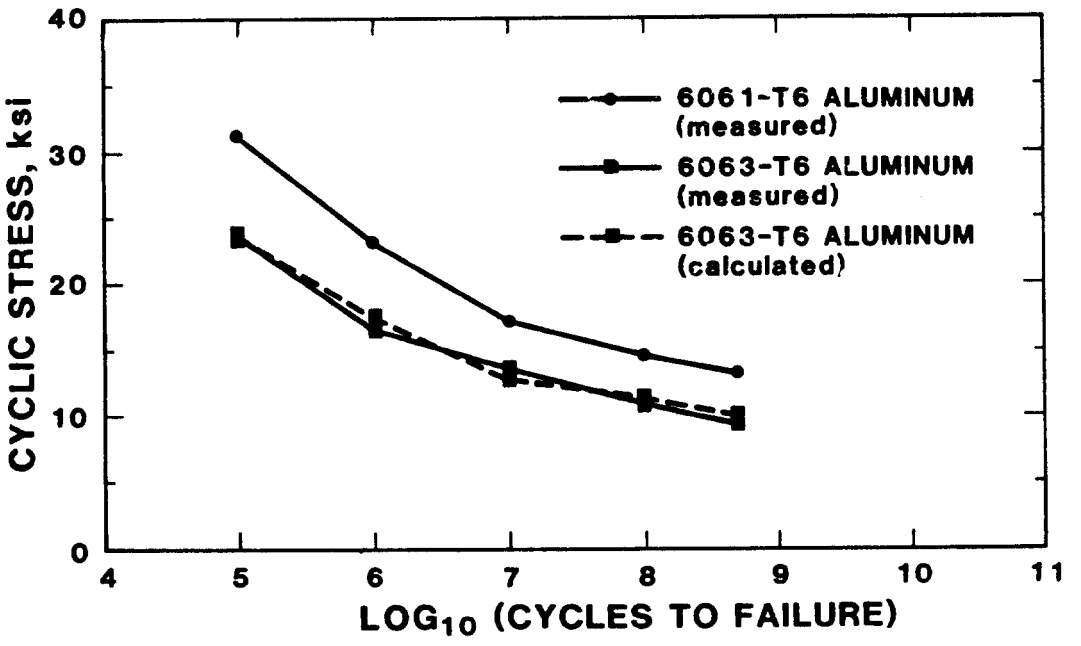

Figure 1. Rotational Bending S-N Diagram for 6061-T6 and 6063-T6 Aluminum

aluminum. The results of this calculation are shown in Fig. 2 and tabulated in Table I. The known data point of 10 ksi at 5E8 cycles cited above is used in this S-N curve.

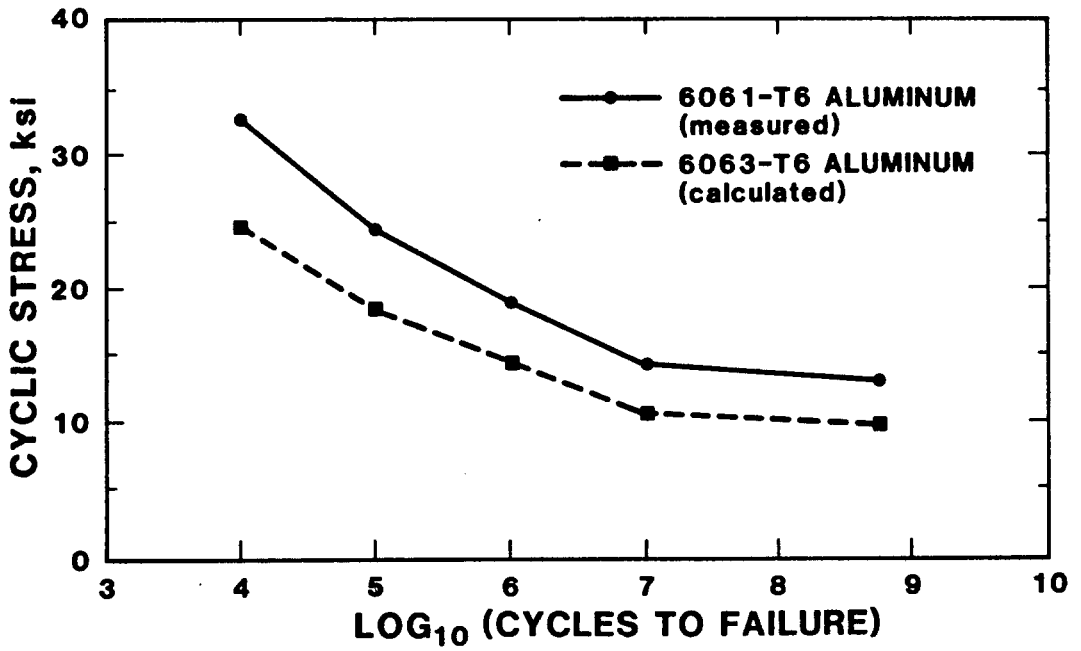

Figure 2. Axial S-N Diagram for 6061-T6 and 6063-T6 Aluminum

The stress state analyzed here will correspond to the lower joint in the DOE/ALCOA Low-Cost VAWT. The mean stress at the joint has a 4000 psi component due to rotation[22] and a gravity component of 3000 psi[23] for a total mean stress of 7000 psi. The vibratory stresses were measured as a function of wind speed in Ref. 24 and are shown in Fig. 3.

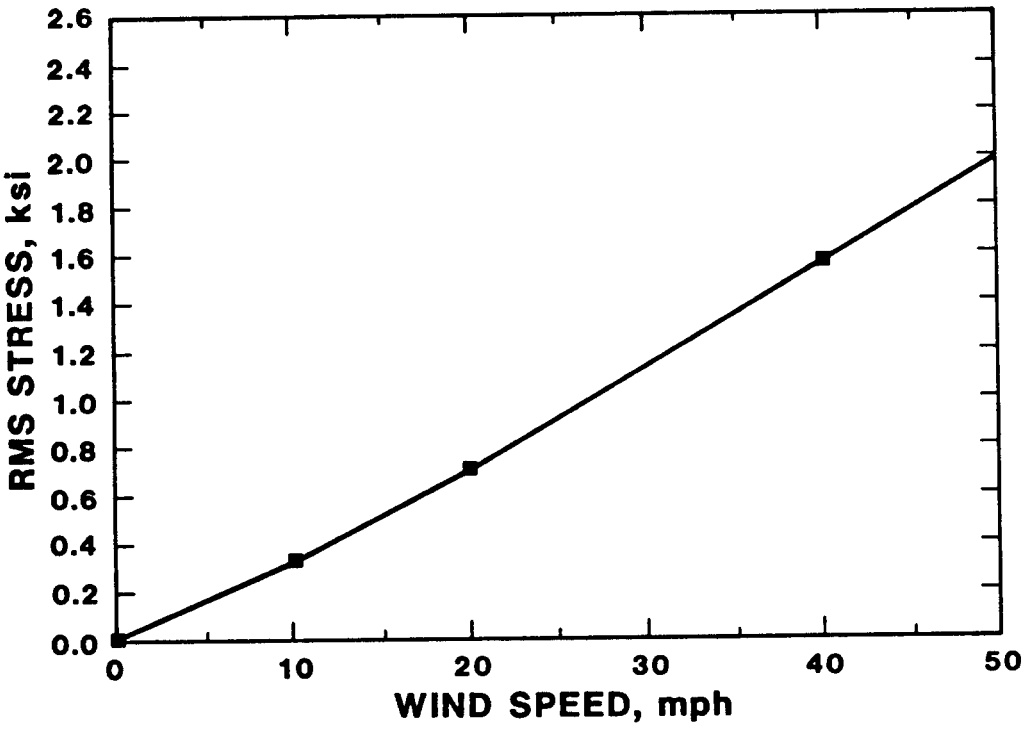

Figure 3. Vibratory Stresses vs. Wind Speed for the DOE 100 kW Vertical Axis Wind Turbine

Assuming that we are analyzing a series of widely spaced holes, the stress concentration factor is 3.0[16]. The data in Fig. 3 were taken at an estimated stress concentration factor of 1.1 to 1.5. We will assume the data have a 1.1 stress concentration factor. Thus, using Eq. 41, the stress

concentration factor entered into the code is 2.73; i.e., 3.0/1.1. The "adjusted" S-N curve for this stress concentration factor and the 7000 psi mean stress are shown in Fig. 4.

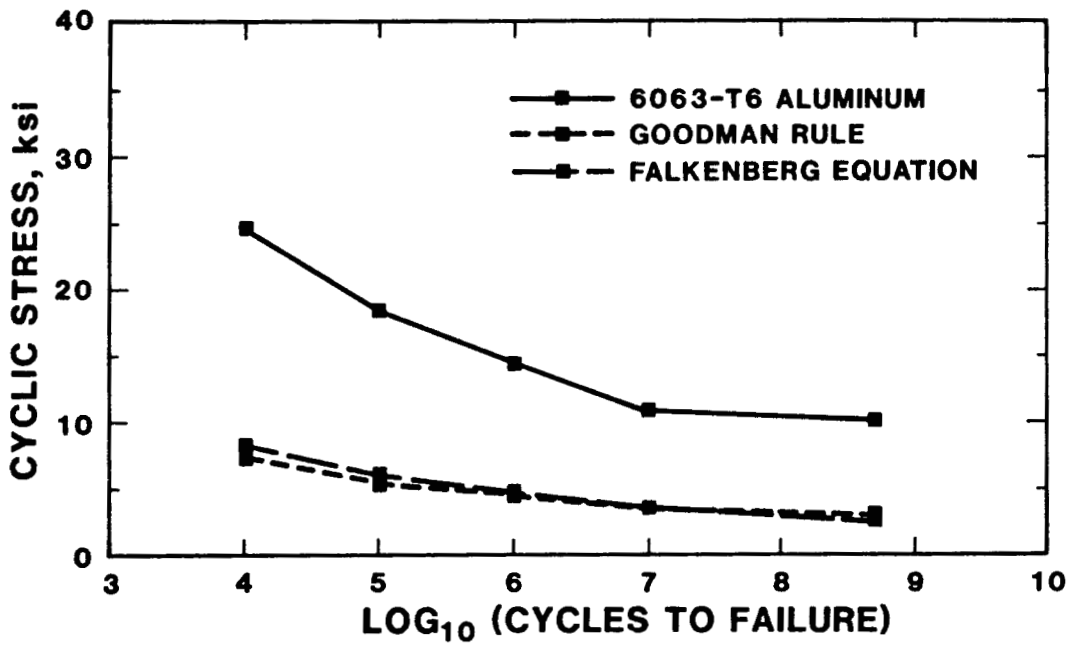

Figure 4. Mean Stress Correction for the 6063-T6 Aluminum S-N Diagram

The wind regime is assumed to have a Rayleigh distribution with a mean velocity of 14 mph. The entire probability density distribution function, Eq. 2, for this wind distribution is shown in Fig. 5.

The primary vibratory stress cycle rate is taken to be 1.6 Hz (the first blade flatwise mode).

The damage density function is the fraction of the damage that occurs in a particular wind speed interval. For an operating range of 0 mph cut-in wind speed and infinite cut-out wind speed, this function takes the form shown in Fig. 5. For an operation regime with a 10 mph cut-in wind speed and a 45 mph high wind speed cut-out velocity, the damage density distribution function becomes the relation shown in Fig. 6.

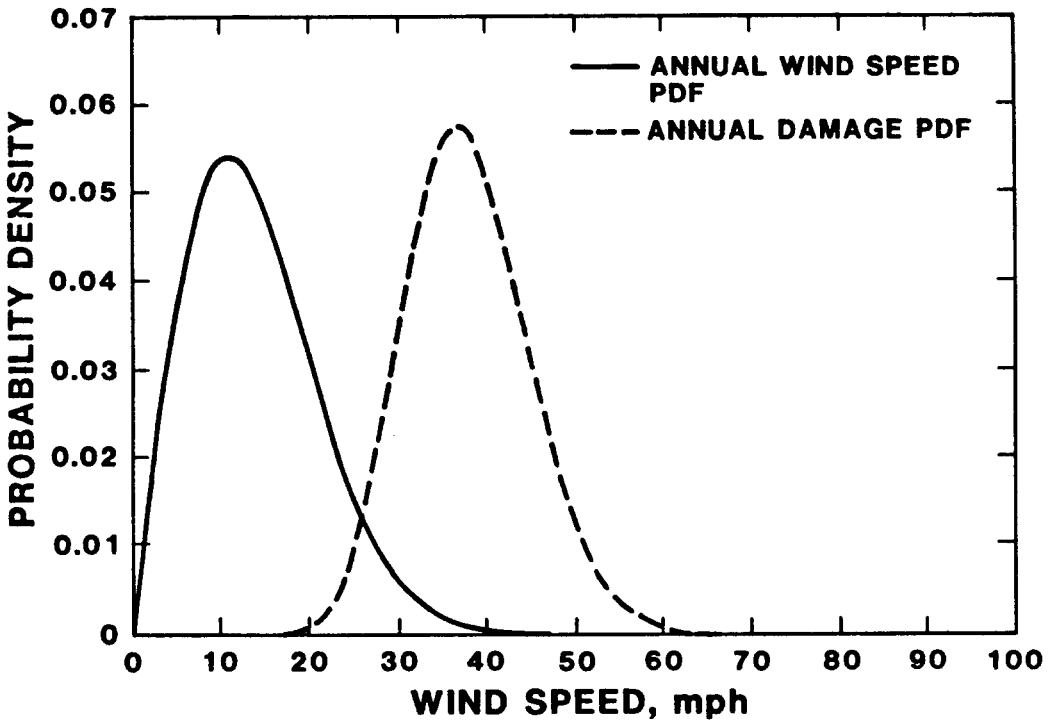

Figure 5. Wind Speed and Damage Density Functions for the Example Problem over the Entire Wind Spectrum

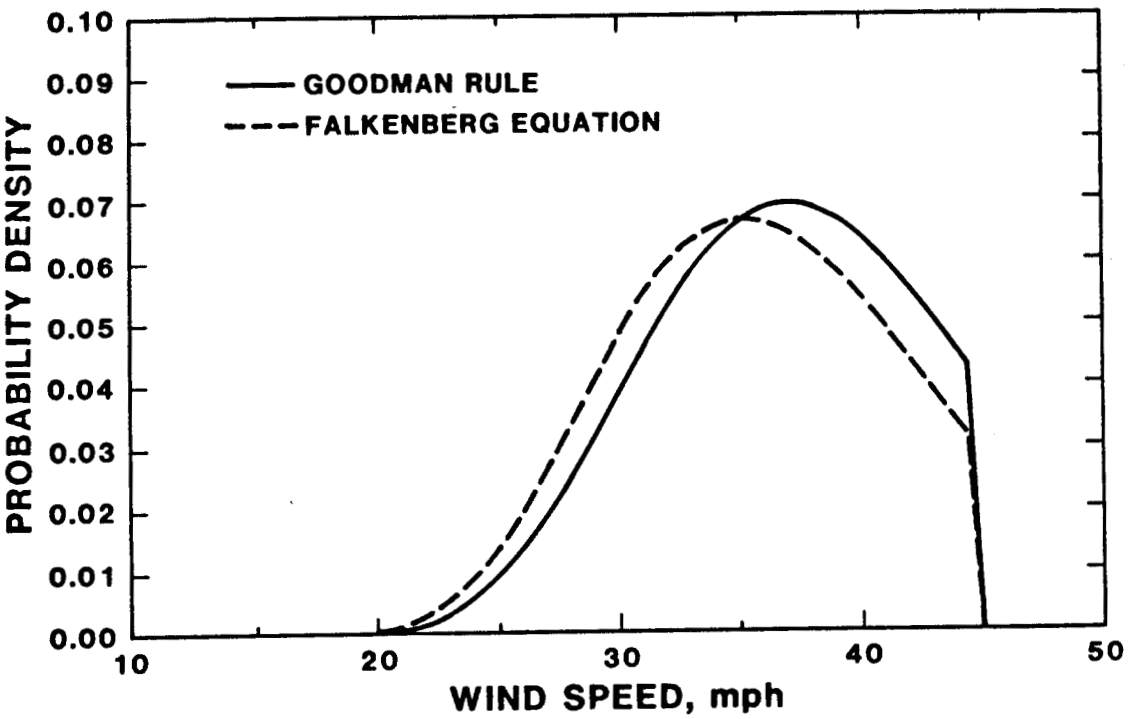

Figure 6. Damage Density Functions for the Example Problem

The prediction of the service lifetime for the component with the operating wind regime between 10 mph and 45 mph is 15.2 years (Fig. 6). Reducing the cut-out velocity to 40 mph increases the service lifetime to 20.6 years. For the 0 mph to infinite wind speed operating regime its life is reduced to 12.6 years (Fig. 5).

A similar calculation using the Falkenberg equation was also conducted. Adjusting the stress concentration factor to 1.63 (the total stress concentration factor of 3.0 must be divided by 1.1 for the input RMS stresses and by 1.67 for the stress concentration factor included in the Falkenberg equation)

yields the S-N curve and the damage density function shown in Figs. 4 and 6, respectively.

The printed output from the computational session using the Goodman rule and a wind regime of 10 to 45 mph is shown in Appendix A. The graphs presented here were obtained using the "Data Dump" files from the LIFE code in coordination with other software.

SUMMARY

This report presents a description of the LIFE computer code. The code is designed to predict the service lifetime of a VAWT component based on a set of assumptions that have been outlined in the report. Within the restrictions placed on the analysis by these assumptions, the LIFE code may be used to predict the service lifetime of a VAWT component using a personal computer with 256K RAM and a BASIC interpreter.

REFERENCES

1. D. E. Berg, "Wind Turbine Fatigue Considerations" (IEA Fatigue Experts' Meeting, Stuttgart, November 1985).

2. P. S. Veers, An Approach to the Fatigue Analysis of Vertical Axis Wind Turbine Blades, SAND81-2130 (Albuquerque: Sandia National Laboratories, September 1981).

3. P. S. Veers, "Blade Fatigue Life Assessment With Application to VAWTs," J. Solar Energy Engineering 104:106, May 1982.

4. P. S. Veers, A General Method for Fatigue Analysis of Vertical Axis Wind Turbine Blades, SAND82-2543 (Albuquerque: Sandia National Laboratories, October 1983).

5. R. E. Akins, "Initial Analysis of Structural Data. DAF 6400 Rotor, Revised Configuration," prepared for Southern California Edison Ltd. (Lexington: Washington and Lee University, June 1985).

6. D. J. Malcom, Fatigue Life Assessment of VAWT Components (Mississauga: Indal Technologies, December 1985).

7. T. D. Ashwill and N. Slack, "Fatigue Life Predeiction for Vertical Axis Wind Turbine Blades Using the LIFE Computer Program" (Albuquerque: Sandia National Laboratories, 1986). Internal memorandum.

8. P. Wirsching, "Reliability Methods in Mechanical and Structural Design," Aerospace and Mechanical Engineering (Tucson: The University of Arizona, 1983).

9. W. R. Barchet, "Wind Energy Data Base," Proceedings of the Fifth Biennial Wind Energy Conference and Workshop II:661-671, ed. I. Vas, SERI/CP-635-1340 (Golden: Solar Energy Research Institute, 1981).

10. M. Abramowitz and L. A. Stegun, Handbook of Mathematical Functions, NBS Applied Math Series, No. 55 (Washington: US Government Printing Office, 1964).

11. C. C. Osgood, Fatigue Design, 2nd Edition (Oxford: Pergamon Press, 1982).

12. A. A. Miner, "Cumulative Damage in Fatigue," Trans. ASME 67:A159, 1945.

13. R. J. Falkenberg, "Operating Stresses in EWEB ALVAWT 1238229-500 (Alcoa Center: Alcoa Technical Center, March 1981). Memorandum.

14. C. Froberg, Introduction to Numerical Analysis (Reading: Addison-Wesley, 1965).

15. A. C. Hansen, Adjustment of SWECS Power Curves for Air Density Variations (Golden: Rockwell International Corp., March 1982).

16. R. E. Peterson, Stress Concentration Factors, Charts, and Relations Useful in Making Strength Calculations for Machine Parts and Structural Elements (New York: John Wiley and Sons, 1974).

17. H. O. Fuchs and R. I. Stephens, Metal Fatigue in Engineering (New York: John Wiley and Sons, 1980).

18. U.S. Department of Defense, Military Standardization Handbook-5C Metallic Materials and Elements for Aerospace Vehicle Structures (Philadelphia: Naval Publications and Forms Center, 1978).

19. T. Baumeister, ed., Mark's Standard Handbook for Mechanical Engineers 8th edition, (New York: McGraw-Hill, 1978).

20. H. E. Boyer and T. L. Gall, eds., Metals Handbook, Desk Edition 8th edition (Metals Park: American Society for Metals, 1985).

21. Military Handbook, MIL-HDBK-694A(MR), December 1966.

22. T. D. Ashwill and T. M. Leonard, Developments in Blade Shape Design for a Darrieus Vertical Axis Wind Turbine, SAND86-1085 (Albuquerque: Sandia National Laboratories, September 1986).

23. T. D. Ashwill, design calculations at Sandia National Laboratories, Albuqueruqe, NM.

24. D. W. Lobitz and W. N. Sullivan, A Comparison of Finite Element Predictions and Experimental Data for the Forced Response of the DOE 100-kW Vertical Axis Wind Turbine, SAND82-2534 (Albuquerque: Sandia National Laboratories, February 1984).

APPENDIX A.

PRINTED OUTPUT FROM THE EXAMPLE PROBLEM

FATIGUE LIFE PROGRAM, VERSION 1.2

****** Low Cost 6063-T6 Example Calc ******

Calculations Performed on : 03-25-1987

THE NUMBER OF INPUT POINTS ON THE SN CURVE IS = 5

THE INPUT S-N DATA ARE:

STRESS LEVEL	CYCLES TO FAILURE
10000	5.00000E+08
10700	1.00000E+07
14400	1.00000E+06
18300	1.00000E+05
24700	1.00000E+04

The Stress Concentration of Factor = 2.73

THE MEAN STRESS AT RATED ROTOR SPEED WITHOUT WIND = 7000

THE GOODMAN RULE FOR MEAN STRESS CORRECTION HAS BEEN SELECTED
THE ULTIMATE STRENGTH = 35000

THE ADJUSTED S-N DATA ARE :

STRESS LEVEL	CYCLES TO FAILURE
2930	5.00000E+08
3136	1.00000E+07
4220	1.00000E+06
5363	1.00000E+05
7238	1.00000E+04

THE NUMBER OF RMS VS WIND SPEED DATA POINTS = 4

THE WIND SPEED AND RMS DATA ARE:

WIND SPEED	RMS STRESS LEVEL
0	0.00
10	320.00
20	700.00
40	1560.00

THE STRESS CYCLE RATE IN HZ = 1.6

THE INTEGER WIND SPEEDS FOR CUT-IN AND CUT-OUT ARE:

CUT-IN WIND SPEED = 10
CUT-OUT WIND SPEED = 45

THE YEARLY AVERAGE WIND SPEED = 14
THE SHAPE FACTOR ON THE WIND DISTRIBUTION = 2

Note: 2.0 implies a Rayleigh Distribution

THE CHOSEN ENDURANCE LIMIT (STRESS) = 2782

The Wind Speed Interval = 1.0

CENTER OF WIND SPEED INTERVAL	WIND SPEED PDF	DAMAGE
10.50	5.3987E-02	4.23474E-25
11.50	5.4148E-02	4.89964E-22
12.50	5.3470E-02	5.81351E-20
13.50	5.2044E-02	2.34628E-18
14.50	4.9977E-02	4.46782E-17
15.50	4.7384E-02	4.83642E-16
16.50	4.4381E-02	3.39308E-15
17.50	4.1086E-02	1.69520E-14
18.50	3.7610E-02	6.46354E-14
19.50	3.4053E-02	1.98139E-13
20.50	3.0507E-02	5.56846E-13
21.50	2.7048E-02	1.35682E-12
22.50	2.3738E-02	2.85610E-12
23.50	2.0627E-02	5.33245E-12
24.50	1.7748E-02	9.01592E-12
25.50	1.5125E-02	1.40350E-11
26.50	1.2766E-02	2.03846E-11
27.50	1.0675E-02	2.79200E-11
28.50	8.8429E-03	3.63738E-11
29.50	7.2582E-03	4.53858E-11
30.50	5.9032E-03	5.45394E-11
31.50	4.7578E-03	6.33968E-11
32.50	3.8003E-03	7.15321E-11
33.50	3.0084E-03	7.85605E-11
34.50	2.3605E-03	8.41630E-11
35.50	1.8358E-03	8.81057E-11
36.50	1.4152E-03	9.02528E-11
37.50	1.0815E-03	9.05715E-11
38.50	8.1929E-04	8.91288E-11
39.50	6.1530E-04	8.60803E-11

40.50	4.5813E-04	8.16521E-11
41.50	3.3818E-04	7.61195E-11
42.50	2.4750E-04	6.97829E-11
43.50	1.7960E-04	6.29457E-11
44.50	1.2922E-04	5.58943E-11

AVERAGE WIND SPEED	=	14	
THE SHAPE FACTOR ON THE WIND DISTRIBUTION	=	2	
CUT-IN WIND SPEED	=	10	
CUT-OUT WIND SPEED	=	45	
COMPONENT LIFE EXPECTANCY IS	=	132910.4	HOURS.
THIS IS EQUIVALENT TO	=	15.16204	YEARS.

APPENDIX B

PROGRAM VARIABLES

The symbols used in this program are defined as follows:

A - Average wind speed.

A1 - Internal variable.

ALP - The shape factor for the Weibull distribution of the wind speed spectrum.

B - Internal plotting variable for stress.

BET - Internal variable for the Weibull distribution.

B1 - Internal variable.

C - The number of data points in the S-N curve, less one. C=N-1.

D - R-1.

E - Flag for ending or restarting the program.

E1 - Stress level at NO cycles.

F - Incremental damage rate (Miner's Rule) in the stress integration loop.

F1 - Reciprocal of the damage T.

F2 - Flag for describing the rule used to adjust the S-N curve for mean stress.

F$ - Output file name for data dump.

H - Life in hours.

G1-G5 - Constants for determining the Gamma Function for the Weibull distribution.

I - Index.

I1 Cut-in wind speed.

J - Segment of the RMS stress curve fit chosen for the current wind speed.

J1 - Index.

K2 - Segment of the S-N curve fit chosen for the current RMS stress level.

K(I) - The intercept of the ith segment in the log-log curve fit of the S-N data.

LB - Internal plotting variable for B.

LD1 - Internal plotting variable for D1(I).

LN1 - Internal plotting variable for N1(I).

LO1 - Internal plotting variable for O1(I).

LS2 - Internal plotting variable for S2.

LT1 - Internal plotting variable for T1(I).

LT2 - Internal plotting variable for T2(I).

LU2 - Internal plotting variable for U2(I).

M - Medium RMS stress level.

ML - Sets M1.

MU - Sets X1.

M1 - Lower bound for integration on the RMS stress.

M2 - Integer value of E1.

M3 - Mean stress for the S-N curve adjustment.

N - Number of data points in the S-N curve.

NO - Log of the number of cycles to the endurance limit for the S-N curve.

NPI - Number of wind speed intervals.

N1(I) - The ith component of the cycles in the S-N curve.

N2 - Incremental stress for the RMS stress integration.

P - Probability density function for the Rayleigh distribution at the current RMS stress.

PLD1 - Damage density function of the wind speed.

Q - Equal to S.

Q1 - Number of cycles in the RMS stress integration loop.

Q2 - Probability distribution for the wind speed distribution at the current wind speed.

R - Number of data points in the RMS stress vs wind speed curve.

R(I) - The ith component of the RMS stress.

S - Stepped wind speed in the wind speed integration loop.

SCF - Stress concentration factor.

S1(I) - The slope of the ith segment in the log-log curve fit of the S-N data.

S2 - Stepped RMS stress level; from M1 to X1.

T - Total accumulated damage.

T1(I) - The ith component of the stress in the S-N curve.

U - Ultimate strength of the material. Used to adjust the S-N curve for mean stress using the Goodman Rule (see Eq. 18).

U1 - Stress integral summation

U2(I) - The ith component of wind speed probability density function.

V1 - Cut-out wind speed.

V2 - V1 minus 1.

W(I) - The ith component of the wind speed.

X1 - Upper bound for integration on the RMS stress.

Y - Stress cycle rate in Hertz.

Y$ - Title of the calculation.

Y1 - Life in years.

APPENDIX C.

PROGRAM LISTING FOR THE
LIFE COMPUTER CODE
VERSION 1.2

```
100 REM  THE LIFE CODE
110 REM
120 REM  VERSION 1.2
130 REM
140 REM  WRITTEN BY T. D. ASHWILL, H. J. SUTHERLAND;
150 REM  SANDIA NATIONAL LABORATORIES AND
160 REM  N. SLACK; NEW MEXICO ENGINEERING RESEARCH INSTITUTE
170 REM
180 REM ************************************************************
190 REM
200 REM  THIS PROGRAM WAS PREPARED AS A PART OF WORK SPONSORED BY AN AGENCY OF
210 REM  THE U. S. GOVERNMENT.  NEITHER THE U.S. GOVERNMENT NOR ANY AGENCY
220 REM  THEREOF, NOR ANY OF THEIR EMPLOYEES, NOR ANY OF THEIR CONTRACTORS,
230 REM  SUBCONTRACTORS, OR THEIR EMPLOYEES, MAKES ANY WARRANTY, EXPRESS OR
240 REM  IMPLIED, OR ASSUMES ANY LEGAL LIABILITY OR RESPONSIBILITY FOR THE
250 REM  ACCURACY, COMPLETENESS, OR USEFULNESS OF THIS PROGRAM, OR REPRESENTS
260 REM  THAT OPINIONS EXPRESSED HEREIN DO NOT NECESSARILY STATE OR REFLECT
270 REM  THOSE OF THE U.S. GOVERNMENT, ANY AGENCY THEREOF OR ANY OF THEIR
280 REM  CONTRACTORS OR SUBCONTRACTORS.
290 REM
300 REM ************************************************************
310 REM SET UP THE DIMENSIONS FOR THE PROGRAM VARIABLES
320 DIM T1(20),T2(20),S1(20),R1(20),W1(20),N1(20),K1(20)
330 DIM U2(100),D1(100),O1(100)
340 CLS
350 REM *************************************************************
360 REM START THE LIFE PROGRAM
370 REM
380 REM USE THIS AREA TO INITIALIZE PROGRAM PARAMETERS
390 PI=3.14159265#
400 REM Set up Parameters for Gamma Function
410 G1=-.5748646
420 G2= .9512363
430 G3=-.6998588
440 G4= .4245549
450 G5=-.1010678
460 REM Set other Parameters
470 U1=0
480 S0=0
490 REM USE THIS AREA TO SET UP PROGRAM CONSTANTS
```

```
500 REM Define the Cycles count at the Endurance Limit
510 N0=LOG(10^10)
520 REM Set Constants for Determining the Limits of Integration on the
530 REM RMS Stress
540 ML=2
550 MV=8
560 REM Set Constant that Determines the Size on the Stress Integration
570 REM Interval
580 Q1=50
590 REM Set Constant for the Number of Intervals in the Data Dump of the
600 REM S-N Curve
610 NP=50
620 REM PUT IN PRINTER CONTROL STATEMENTS HERE TO INITIALIZE YOUR PRINTER
630 REM
640 PRINT "INPUT  --  TITLE FOR THIS CALCULATION OF FATIGUE LIFE (NO COMMAS)"
650 PRINT " |--------------------------------|"
660 INPUT Y$
670 LPRINT "FATIGUE LIFE PROGRAM, VERSION 1.2"
680 PRINT: LPRINT
690 PRINT: LPRINT
700 LPRINT "****** "; Y$; " ******"
710 PRINT: LPRINT
720 LPRINT
730 LPRINT "Calculations Performed on : " ; DATE$
740 PRINT: LPRINT
750 PRINT: LPRINT
760 REM  ************************************************************
770 REM  SET UP THE SN CURVE
780 REM
790 PRINT "FIRST: INPUT THE S-N FATIGUE DATA FOR THE BLADE MATERIAL"
800 PRINT "INPUT THE NUMBER OF DATA POINTS ON THE SN CURVE"
810 PRINT "  The Maximum Number is 20."
820 INPUT N
830 PRINT: LPRINT
840 LPRINT "THE NUMBER OF INPUT POINTS ON THE SN CURVE IS = ";N
850 PRINT: LPRINT
860 C=N-1
870 PRINT "INPUT IN THE DATA IN ASCENDING ORDER,"
880 PRINT "STARTING WITH THE LOWEST STRESS."
890 LPRINT "  THE INPUT S-N DATA ARE:"
900 LPRINT "    STRESS LEVEL        CYCLES TO FAILURE"
910 FOR I=1 TO N
920 PRINT " STRESS LEVEL" SPC(12) I SPC(12) " CYCLES TO FAILURE"
930 INPUT T1(I): PRINT SPC(43) CHR$(30);  : INPUT N1(I)
940 LPRINT USING "       ######          ##.#####^^^^ "; T1(I); N1(I)
941 REM Error Check for Ascending Order of Input Data
942 IF I=1 THEN GOTO 950
943 IF T1(I) > T1(I-1) THEN GOTO 950
944 PRINT "INPUT DATA IS NOT IN PROPER ORDER!"
945 PRINT "PLEASE ENTER DATA AGAIN"
946 GO TO 870
950 T2(I)=T1(I)
960 NEXT I
```

```
970 REM ************************************************************
980 REM  ADJUST THE STRESS LEVELS FOR STRESS CONCENTRATIONS
990 PRINT "ADJUST THE S-N DATA FOR STRESS CONCENTRATIONS"
1000 PRINT "INPUT THE STRESS CONCENTRATION FACTOR"
1010 PRINT "  Use 1 if no Correction is Desired"
1020 PRINT "  Note: FALKENBERG'S EQUATION for the Mean Stress
1030 PRINT "        Correction has a Stress Concentration Factor
1040 PRINT "        of 1.67 INCLUDED in its Formulation.
1050 INPUT SCF
1060 PRINT:LPRINT
1070 LPRINT "  The Stress Concentration of Factor = "; SCF
1080 REM ************************************************************
1090 REM  ADJUST THE STRESS LEVELS FOR MEAN STRESS
1100 PRINT "ADJUST THE S-N DATA FOR MEAN STRESS"
1110 PRINT "SELECT THE FORM OF THE CORRECTION TERM DESIRED"
1120 PRINT " 1 FOR GOODMAN RULE ON THE ULTIMATE STRENGTH"
1130 PRINT " 2 FOR FALKENBERG'S EQUATION"
1140 PRINT " 3 FOR NO ADJUSTMENTS"
1150 INPUT F2
1160 ON F2 GOTO 1180,1180,1240
1170 GOTO 1110
1180 PRINT "INPUT THE MEAN STRESS AT RATED ROTOR SPEED WITHOUT WIND "
1190 INPUT M3 : LET M3 = ABS (M3)
1200 PRINT: LPRINT
1210 LPRINT "  THE MEAN STRESS AT RATED ROTOR SPEED WITHOUT WIND = ";M3
1220 LPRINT
1230 ON F2 GOTO 1300,1410
1240 PRINT: LPRINT
1250 PRINT "NO ADJUSTMENTS FOR MEAN STRESS WERE MADE"
1260 LPRINT "  NO ADJUSTMENTS FOR MEAN STRESS WERE MADE"
1270 GOTO 1460
1280 REM  ***********************************************************
1290 REM  DO THE GOODMAN RULE ADJUSTMENT ON MEAN STRESS
1300 PRINT "THE GOODMAN RULE FOR MEAN STRESS CORRECTION HAS BEEN SELECTED"
1310 LPRINT "  THE GOODMAN RULE FOR MEAN STRESS CORRECTION HAS BEEN SELECTED"
1320 PRINT "INPUT THE ULTIMATE STRENGTH "
1330 INPUT U
1340 LPRINT "  THE ULTIMATE STRENGTH = ";U
1350 FOR I=1 TO N
1360 T1(I) = T1(I) - (M3 * T1(I)) / U
1370 NEXT I
1380 GOTO 1460
1390 REM  ***********************************************************
1400 REM  USE FALKENBERG'S EQUATION TO ADJUST THE MEAN STRESS
1410 PRINT "FALKENBERG'S EQUATION FOR MEAN STRESS CORRECTION HAS BEEN SELECTED"
1420 LPRINT "  FALKENBERG'S EQUATION FOR MEAN STRESS CORRECTION HAS BEEN
SELECTED"
1430 FOR I=1 TO N
1440 T1(I) = .6 * T1(I)  -  .2 * M3
1450 NEXT I
1460 PRINT: LPRINT
1470 PRINT "THE ADJUSTED S-N DATA ARE :"
1480 LPRINT "  THE ADJUSTED S-N DATA ARE :"
1490 PRINT "     STRESS LEVEL      CYCLES TO FAILURE"
```

```
1500 LPRINT "    STRESS LEVEL      CYCLES TO FAILURE"
1510 FOR I=1 TO N
1520 REM Correct the Stress State for the Stress Concentration Factor
1530 T1(I)=T1(I)/SCF
1540 REM Make Sure that the Adjusted Stress Remains Positive
1550 IF T1(I) <.1 THEN T1(I)=I*5
1560 PRINT USING "       ######          ##.#####^^^^ ";  T1(I); N1(I)
1570 LPRINT USING "       ######          ##.#####^^^^ ";  T1(I); N1(I)
1580 NEXT I
1590 REM ************************************************************
1600 REM  THIS PROGRAM USES A LOG-LOG FIT TO THE S-N CURVE CURVE
1610 PRINT: LPRINT
1620 PRINT "CALCULATING THE CURVE FITS FOR THE S-N DATA"
1630 REM LPRINT "  THE CALCULATED CURVE FITS FOR THE S-N DATA ARE:"
1640 PRINT "  INTERCEPT            SLOPE"
1650 REM LPRINT "       INTERCEPT          SLOPE"
1660 FOR I=1 TO C
1670 S1(I)=LOG(N1(I)/N1(I+1))/LOG(T1(I)/T1(I+1))
1680 K1(I)=-S1(I)*LOG(T1(I))+LOG(N1(I))
1690 PRINT USING "    #####.####      #####.####";K1(I); S1(I)
1700 REM LPRINT USING "    #####.####      #####.####"; K1(I); S1(I)
1710 NEXT I
1720 PRINT: REM LPRINT
1730 REM  ***********************************************************
1740 REM   SET UP THE RMS VERSUS WIND SPEED DATA
1750 PRINT "NEXT: INPUT THE DATA THAT DESCRIBES THE WIND REGIME"
1760 PRINT "INPUT THE NUMBER OF RMS VS WIND SPEED DATA POINTS  "
1770 PRINT "  The Maximum Number is 20."
1780 INPUT R
1790 PRINT: LPRINT
1800 LPRINT "THE NUMBER OF RMS VS WIND SPEED DATA POINTS = "; R
1810 D=R-1
1820 PRINT "INPUT THE WIND SPEED VS RMS STRESS IN ASCENDING ORDER,"
1830 PRINT "STARTING WITH THE LOWEST WIND SPEED."
1840 PRINT: LPRINT
1850 LPRINT "  THE WIND SPEED AND RMS DATA ARE: "
1860 LPRINT SPC(4) "WIND SPEED" SPC(9) "RMS STRESS LEVEL"
1870 FOR I=1 TO R
1880 PRINT " WIND SPEED" SPC(14) I SPC(12) " RMS STRESS"
1890 INPUT W1(I)  : PRINT SPC(43) CHR$(30); : INPUT R1(I)
1900 W1(I) = ABS (W1(I)) : R1(I) = ABS (R1(I))
1910 LPRINT USING "     #####             #####.##"; W1(I); R1(I)
1911 REM Error Check for Ascending Order of Input Data
1912 IF I=1 THEN GOTO 1920
1913 IF W1(I) > W1(I-1) THEN GOTO 1920
1914 PRINT "INPUT DATA IS NOT IN PROPER ORDER!"
1915 PRINT "PLEASE ENTER DATA AGAIN"
1916 GO TO 1820
1920 NEXT I
1930 PRINT: LPRINT
1940 REM  ************************************************************
1950 REM  SET UP THE OPERATING CONDITIONS
1960 PRINT "NEXT: INPUT THE OPERATING PARAMETERS FOR THE TURBINE"
```

```
1970 PRINT: LPRINT
1980 PRINT "INPUT THE STRESS CYCLE RATE IN HZ            ";
1990 INPUT Y
2000 LPRINT "THE STRESS CYCLE RATE IN HZ = ";Y
2010 PRINT: LPRINT
2020 PRINT "INPUT THE INTEGER WIND SPEED FOR CUT-IN ";
2030 INPUT I1
2040 PRINT "INPUT THE INTEGER WIND SPEED FOR CUT-OUT";
2050 INPUT V1
2060 LPRINT "THE INTEGER WIND SPEEDS FOR CUT-IN AND CUT-OUT ARE:"
2070 LPRINT
2080 LPRINT "  CUT-IN WIND SPEED            = "; I1
2090 LPRINT "  CUT-OUT WIND SPEED           = "; V1
2100 PRINT: LPRINT
2110 PRINT "WHAT IS THE YEARLY AVERAGE WIND SPEED ";
2120 INPUT A
2130 PRINT "INPUT THE SHAPE FACTOR FOR A WEIBULL DISTRIBUTION "
2140 PRINT "  Note: Input 2.0 for a Rayleigh Distribution "
2150 INPUT ALP
2160 ALR=1/ALP
2170 GAM=1+G1*ALR+G2*ALR^2+G3*ALR^3+G4*ALR^4+G5*ALR^5
2180 BET=A/GAM
2190 LPRINT "THE YEARLY AVERAGE WIND SPEED                  = ";A
2200 LPRINT "THE SHAPE FACTOR ON THE WIND DISTRIBUTION      = ";ALP
2210 LPRINT "  Note: 2.0 implies a Rayleigh Distribution"
2220 REM ************************************************************
2230 REM WIND SPEED INTEGRATION LOOP
2240 REM Set up Constants in Integration Loop
2250 T=0
2260 V2=V1-1
2270 NP1=INT(V2-I1)+1
2280 FOR I=I1 TO V1
2290 O1(I)=I
2300 D1(I)=0
2310 NEXT I
2320 REM Determine the Stress Level at the Endurance Limit
2330 REM This calculation is always based on the first interval
2340 REM in the curve fit.
2350 E1=EXP((N0-K1(1))/S1(1))
2360 REM Only Use Integer Values of Stress
2370 M2=INT(E1)
2380 PRINT: LPRINT
2390 LPRINT "THE CHOSEN ENDURANCE LIMIT (STRESS) = " , M2
2400 PRINT "THE CHOSEN ENDURANCE LIMIT (STRESS) = " , M2
2410 PRINT: LPRINT
2420 PRINT: LPRINT
2430 PRINT "THE FATIGUE LIFE CALCULATION HAS BEGUN"
2440 PRINT "PLEASE WAIT FOR THE CALCULATION TO BE COMPLETED"
2450 PRINT
2460 REM Only Use Integer Values of Velocity
2470 FOR S=I1 TO V1
2480 Q=S
2490 IF S =(INT(NP1*.1)+I1) THEN PRINT "Calculation  5 % Completed"
```

```
2500 IF S =(INT(NP1*.2)+I1) THEN PRINT "Calculation 15 % Completed"
2510 IF S =(INT(NP1*.3)+I1) THEN PRINT "Calculation 25 % Completed"
2520 IF S =(INT(NP1*.4)+I1) THEN PRINT "Calculation 35 % Completed"
2530 IF S =(INT(NP1*.5)+I1) THEN PRINT "Calculation 45 % Completed"
2540 IF S =(INT(NP1*.6)+I1) THEN PRINT "Calculation 55 % Completed"
2550 IF S =(INT(NP1*.7)+I1) THEN PRINT "Calculation 65 % Completed"
2560 IF S =(INT(NP1*.8)+I1) THEN PRINT "Calculation 75 % Completed"
2570 IF S =(INT(NP1*.9)+I1) THEN PRINT "Calculation 85 % Completed"
2580 REM ************************************************************
2590 REM CALCULATE THE RMS STRESS (LINEAR INTERPOLATION)
2600 J=1
2610 REM Chose Segment of RMS-Wind Speed Curve Fit
2620 FOR I=1 TO D
2630 IF Q< W1(I) THEN 2650
2640 J=I
2650 NEXT I
2660 M=R1(J+1)-(R1(J+1)-R1(J))*(W1(J+1)-Q)/(W1(J+1)-W1(J))
2670 REM ************************************************************
2680 REM STRESS INTEGRATION LOOP
2690 REM Set Bounds on Integration
2700 M1=INT(M/ML+1)
2710 X1=INT(MV*M)
2720 REM ************************************************************
2730 REM MAKE SURE THAT INTEGRATION DOES NOT BEGIN AT STRESS
2740 REM LEVELS BELOW THE STRESS THAT PRODUCES INFINITELY LONG
2750 REM LIFE---ie: the Stress at N0 Cycles
2760 IF M2=<M1 THEN 2780
2770 M1 = M2
2780 IF M1=<X1 THEN 2800
2790 X1=M1
2800 N2=INT((X1-M1)/Q1+1)+1
2810 U1=0
2820 FOR J1=1 TO N2
2830 S2=M1+J1*Q1-Q1
2840 REM ************************************************************
2850 REM INTERPOLATE THE S2-N2 CURVE
2860 K2=1
2870 FOR I=1 TO C
2880 IF S2<T1(I) THEN 2900
2890 K2=I
2900 NEXT I
2910 REM ************************************************************
2920 REM EVALUATE THE FUNCTION INSIDE THE STRESS INTEGRAL
2930 REM Check for an Exponential Underflow and Correct if Required
2940 IF -S2*S2/(2*M*M)=>-50 THEN 3010
2950 IF S1(K2)*LOG(S2)+K1(K2)>-50 THEN 3010
2960 B=1
2970 P=0
2980 GOTO 3030
2990 REM Calculate the RMS Stress PDF
```

```
3000 REM Rayleigh Stress Distribution
3010 P=S2/M^2*EXP(-S2*S2/(2*M*M))
3020 B=EXP(S1(K2)*LOG(S2)+K1(K2))
3030 REM Miner's Rule Calculation
3040 F=P/B
3050 REM Corrected Summation for End Points
3060 IF J1=1 THEN F=F/2
3070 IF J1=N2 THEN F=F/2
3080 U1=U1+F*Q1
3090 NEXT J1
3100 REM ************************************************************
3110 REM END STRESS INTEGRATION LOOP
3120 REM Calculate the Wind Speed PDF
3130 REM Weibull Wind Distribution
3140 A1=(Q/BET)
3150 B1=ALP/BET
3160 Q2=B1*(A1^(ALP-1))*EXP(-A1^ALP)
3170 REM PUT THE CALCULATIONS INTO A MATRIX FOR SUMMATION
3180 O1(S)=S
3190 U2(S)=Q2
3200 D1(S)=U1
3210 NEXT S
3220 REM ************************************************************
3230 REM END WIND SPEED INTEGRATION LOOP
3240 REM Print the Damage vs Wind Speed Interval Function
3250 LPRINT "The Wind Speed Interval = 1.0"
3260 LPRINT
3270 LPRINT "CENTER OF WIND" SPC(5) "WIND SPEED" SPC(8) "DAMAGE"
3280 LPRINT "SPEED INTERVAL" SPC(5) "   PDF"
3290 REM ************************************************************
3300 REM USE THE END POINT TO GET AVERAGE IN THE MIDDLE OF THE WIND
3310 REM INTERVAL
3320 PRINT "Calculation 95 % Completed"
3330 FOR I=I1 TO V2
3340 REM Calculate the Average Values over the Summation Interval
3350 REM and Determine the Damage Function
3360 O1(I)=(O1(I)+O1(I+1))/2
3370 U2(I)=(U2(I)+U2(I+1))/2
3380 D1(I)=(D1(I)+D1(I+1))/2 * U2(I)
3390 REM Calculate the Total Damage
3400 T=T+D1(I)
3410 LPRINT USING "  ####.##          ##.####^^^^      ##.#####^^^^"; O1(I);
U2(I); D1(I)
3420 NEXT I
3430 F1=1/T
3440 H=F1/(Y*3600)
3450 Y1=H/(24*365.25)
3460 PRINT "CALCULATIONS ARE NOW COMPLETE"
3470 PRINT: LPRINT: LPRINT: LPRINT: LPRINT
3480 PRINT " A SUMMARY OF RESULTS ARE: "
3490 PRINT
```

```
3500 REM ************************************************************
3510 REM PRINT SUMMARY OF RESULTS
3520 PRINT " AVERAGE WIND SPEED                          = ";A
3530 PRINT " THE SHAPE FACTOR ON THE WIND DISTRIBUTION = ";ALP
3540 PRINT " CUT-IN WIND SPEED                           = ";I1
3550 PRINT " CUT-OUT WIND SPEED                          = ";V1
3560 PRINT " COMPONENT LIFE EXPECTANCY IS                = ";H ,"  HOURS. "
3570 PRINT " THIS IS EQUIVALENT TO                       = ";Y1,"  YEARS."
3580 LPRINT " AVERAGE WIND SPEED                          = ";A
3590 LPRINT " THE SHAPE FACTOR ON THE WIND DISTRIBUTION = ";ALP
3600 LPRINT " CUT-IN WIND SPEED                           = ";I1
3610 LPRINT " CUT-OUT WIND SPEED                          = ";V1
3620 LPRINT " COMPONENT LIFE EXPECTANCY IS                = ";H," HOURS. "
3630 LPRINT " THIS IS EQUIVALENT TO                       = ";Y1," YEARS."
3640 PRINT:LPRINT
3650 PRINT:LPRINT
3660 PRINT:LPRINT
3670 REM ************************************************************
3680 REM DUMP DATA TO A FILE FOR PLOTTING -- USING ANOTHER PROGRAM
3690 PRINT "DO YOU WANT A DATA DUMP FOR PLOTTING THESE RESULTS"
3700 PRINT "     1 - Yes"
3710 PRINT "     2 - No"
3720 PRINT
3730 INPUT P1
3740 ON P1 GOTO 3760,4260
3750 GOTO 3690
3760 PRINT "WHAT FILE DO YOU WANT FOR THE DATA DUMP?"
3770 INPUT F$
3780 PRINT "Opening the Data File "
3790 OPEN F$ FOR OUTPUT AS #1
3800 PRINT#1, Y$
3810 PRINT#1, "Calculations Performed on : " ; DATE$
3820 REM OUTPUT THE WIND SPEED DISTRIBUTION AND DAMAGE FUNCTION
3830 REM Calculate the Number of Points and Print
3840 PRINT#1, USING "######  "; NP1
3850 PRINT#1, "CENTER OF WIND  WIND SPEED      DAMAGE     PERCENT"
3860 PRINT#1, "SPEED INTERVAL     PDF                     DAMAGE"
3870 FOR I=I1 TO V2
3880 LO1=(O1(I))
3890 LU2=(U2(I))
3900 LD1=(D1(I))
3910 PLD1=D1(I)/T
3920 PRINT#1,USING"##.######^^^^  "; LO1; LU2; LD1; PLD1
3930 NEXT I
3940 REM Output the Original and Modified S-N Data
3950 PRINT#1, USING "######  "; N
3960 PRINT#1, "   INPUT        MODIFIED        CYCLES TO"
3970 PRINT#1, "   STRESS       STRESS          FAILURE "
3980 FOR I=1 TO N
3990 LT1=(T1(I))
```

```
4000 LT2=(T2(I))
4010 LN1=(N1(I))
4020 PRINT#1, USING "##.######^^^^  "; LT2; LT1; LN1
4030 NEXT I
4040 REM Output a Plot of the Calculated S-N Curve
4050 PRINT#1, USING "######     "; NP
4060 DELS = (LOG( T1(N)) - LOG( T1(1))) / (NP-1)
4070 PRINT#1, "    STRESS      CYCLES TO "
4080 PRINT#1, "                FAILURE"
4090 FOR J =1 TO NP
4100 S2=EXP((J-1)*DELS+LOG(T1(1)))
4110 REM INTERPOLATE THE S-N CURVE
4120 K2=1
4130 FOR I=1 TO C
4140 IF S2<T1(I) THEN 4200
4150 K2=I
4160 NEXT I
4170 B=(S1(K2)*LOG(S2)+K1(K2))
4180 B=EXP(B)
4190 PRINT#1, USING "##.######^^^^  "; S2; B
4200 NEXT J
4210 CLOSE #1
4220 PRINT
4230 PRINT "  Select from the following options:"
4240 PRINT
4250 PRINT
4260 PRINT "    0  - EXIT PROGRAM to Basic"
4270 PRINT
4280 PRINT "    1  - EXIT PROGRAM to Dos"
4290 PRINT
4300 PRINT "    2  - Start the Program from the Beginning "
4310 PRINT "           and the Same Material Function"
4320 PRINT
4330 PRINT "    3  - Continue Program with a Different Wind Spectrum "
4340 PRINT
4350 INPUT E
4360 IF E=0 THEN 4440
4370 ON E GOTO 4430,340,2020
4380 GOTO 4270
4390 CLS: SYSTEM
4400 CLS
```

APPENDIX D.

STRESS CYCLE INTEGRATION LIMITS

The upper and lower limits of the stress cycle integration (Eq. 21) are set via the ML and the MV parameters (lines 540 and 550 in the code shown in Appendix C). The limits of integration are determined by

$$\sigma_{min} = \sigma_v \ / \ ML \quad , \qquad (D1)$$

and

$$\sigma_{max} = \sigma_v \ (MV) \quad . \qquad (D2)$$

To minimize computational time, ML and MV should be set as small as possible. However, if their value is chosen too small, the prediction of the service lifetime will be too large. In Fig. D1, the influence of ML and MV on the predicted lifetime of a VAWT component (the example problem) is shown. In this figure, the predicted service lifetime is normalized to the predicted lifetime for large values of ML and MV.

As seen in the figures, values of 2 and 8 for ML and MV, respectively, yield consistent predictions, and based on this and other analyses, represent the minimum values of these variables that yield correct results. These values are included in the current LIFE code. However, the operator may want to examine a range of values for these variables to determine if the integration interval is sized properly for the particular problem of interest.

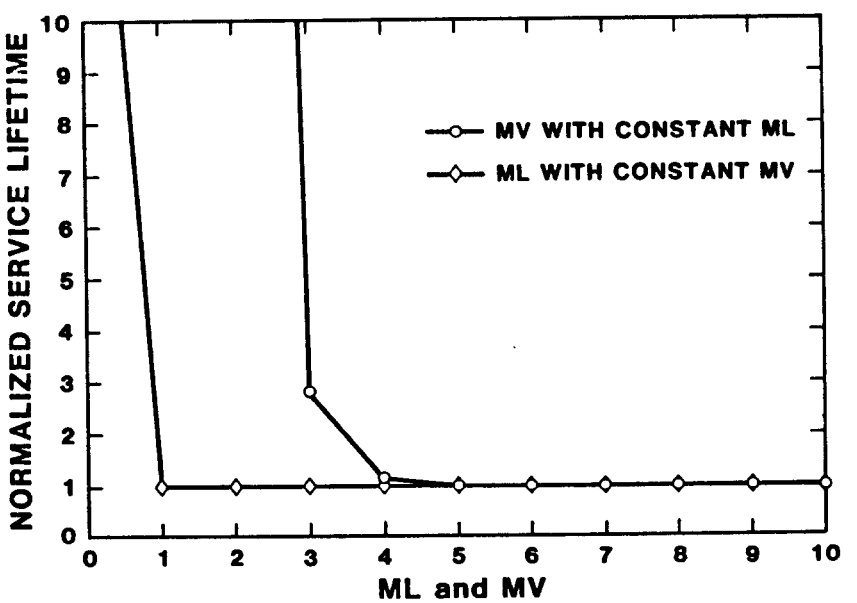

Figure D.1 Effect of the Internal Variables ML and MV on the Predicted Service Lifetime for the Example Problem.

APPENDIX E.

ENDURANCE LIMIT

Again to minimize computational time, the stress integration loop is limited to values above the "endurance limit" as determined by the S-N diagram input into the code.

Here we have defined the endurance limit to be the stress level at which 1E10 cycles will not produce failure in the material. This parameter is set in with the N0 variable (line 510 in the code shown in Appendix C). The program automatically determines the stress level corresponding to this number of cycles (via the adjusted S-N diagram) and outputs its value in the summary printout.

Other values for this variable may be chosen by the operator by editing this line in the program.

APPENDIX F.

AUTOMATED DATA ENTRY FOR THE LIFE CODE

As the process for data input is somewhat cumbersome when parameter studies are being conducted, the LIFEA (automatic data entry) version of the LIFE code is also available (see Appendix G). In this form all of the keyboard inputs have been "remarked" out of the process statements and replaced by data entries. The version of LIFEA listed here is set up to do the example problem shown in Appendix A.

For operation LIFEA is simply executed by running it using a BASIC interpreter. Although the operator is queried by the program, no inputs are required.

To run a parameter study with this version of the code, the operator should edit all of the data inputs to the particular problem of interest. Note that all of the statements requiring editing have been marked with a "*-" pattern remark statement. As the input statements for data entry have not been deleted, keyboard entry for any particular variable (or sets of variables) can be reactivated by removing the "REM" at the beginning of each line of data input.

APPENDIX G.

PROGRAM LISTING FOR THE
LIFEA COMPUTER CODE
VERSION 1.2

```
100 REM  THE LIFE CODE with Automated Input
110 REM
120 REM  VERSION 1.2
130 REM
140 REM  WRITTEN BY T. D. ASHWILL, H. J. SUTHERLAND;
150 REM  SANDIA NATIONAL LABORATORIES AND
160 REM  N. SLACK; NEW MEXICO ENGINEERING RESEARCH INSTITUTE
170 REM
180 REM ************************************************************
190 REM
200 REM  THIS PROGRAM WAS PREPARED AS A PART OF WORK SPONSORED BY AN AGENCY OF
210 REM  THE U. S. GOVERNMENT.  NEITHER THE U.S. GOVERNMENT NOR ANY AGENCY
220 REM  THEREOF, NOR ANY OF THEIR EMPLOYEES, NOR ANY OF THEIR CONTRACTORS,
230 REM  SUBCONTRACTORS, OR THEIR EMPLOYEES, MAKES ANY WARRANTY, EXPRESS OR
240 REM  IMPLIED, OR ASSUMES ANY LEGAL LIABILITY OR RESPONSIBILITY FOR THE
250 REM  ACCURACY, COMPLETENESS, OR USEFULNESS OF THIS PROGRAM, OR REPRESENTS
260 REM  THAT OPINIONS EXPRESSED HEREIN DO NOT NECESSARILY STATE OR REFLECT 270
REM  THOSE OF THE U.S. GOVERNMENT, ANY AGENCY THEREOF OR ANY OF THEIR
280 REM  CONTRACTORS OR SUBCONTRACTORS.
290 REM
300 REM ************************************************************
310 REM SET UP THE DIMENSIONS FOR THE PROGRAM VARIABLES
320 DIM T1(20),T2(20),S1(20),R1(20),W1(20),N1(20),K1(20)
330 DIM U2(100),D1(100),O1(100)
340 CLS
350 REM ************************************************************
360 REM START THE LIFE PROGRAM
370 REM
380 REM USE THIS AREA TO INITIALIZE PROGRAM PARAMETERS
390 PI=3.14159265#
400 REM Set up Parameters for Gamma Function
410    G1=-.5748646
420    G2= .9512363
430    G3=-.6998588
440    G4= .4245549
450    G5=-.1010678
460 REM Set other Parameters
470 U1=0
480 S0=0
490 REM USE THIS AREA TO SET UP PROGRAM CONSTANTS
```

```
500 REM Define the Cycles count at the Endurance Limit
510 N0=LOG(10^10)
520 REM Set Constants for Determining the Limits of Integration on the
530 REM RMS Stress
540 ML=2
550 MV=8
560 REM Set Constant that Determines the Size on the Stress Integration
570 REM Interval
580 Q1=50
590 REM Set Constant for the Number of Intervals in the Data Dump of the
600 REM S-N Curve
610 NP=50
620 REM PUT IN PRINTER CONTROL STATEMENTS HERE TO INITIALIZE YOUR PRINTER
630 REM
640 PRINT "INPUT  --  TITLE FOR THIS CALCULATION OF FATIGUE LIFE (NO COMMAS)"
650 PRINT " |-----------------------------------|"
660 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
670 Y$="Low Cost 6063-T6 Example Calc"
680 REM INPUT Y$
690 LPRINT "FATIGUE LIFE PROGRAM, VERSION 1.2"
700 PRINT: LPRINT
710 PRINT: LPRINT
720 LPRINT "****** "; Y$; " ******"
730 PRINT: LPRINT
740 LPRINT
750 LPRINT "Calculations Performed on : " ; DATE$
760 PRINT: LPRINT
770 PRINT: LPRINT
780 REM  ***************************************************************
790 REM  SET UP THE SN CURVE
800 REM
810 PRINT "FIRST: INPUT THE S-N FATIGUE DATA FOR THE BLADE MATERIAL"
820 PRINT "INPUT THE NUMBER OF DATA POINTS ON THE SN CURVE"
830 PRINT "  The Maximum Number is 20."
840 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
850 N= 5
860 REM INPUT N
870 PRINT: LPRINT
880 LPRINT "THE NUMBER OF INPUT POINTS ON THE SN CURVE IS = ";N
890 PRINT: LPRINT
900 C=N-1
910 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
920 T1(1)= 10000      :N1(1)=5E+08
930 T1(2)= 10700      :N1(2)=1E+07
940 T1(3)= 14400      :N1(3)=1000000!
950 T1(4)= 18300      :N1(4)=100000!
960 T1(5)= 24700      :N1(5)=10000!
970 PRINT "INPUT IN THE DATA IN ASCENDING ORDER,"
980 PRINT "STARTING WITH THE LOWEST STRESS."
990 LPRINT "  THE INPUT S-N DATA ARE:"
```

```
1000 LPRINT "    STRESS LEVEL       CYCLES TO FAILURE"
1010 FOR I=1 TO N
1020 PRINT " STRESS LEVEL" SPC(12) I SPC(12) " CYCLES TO FAILURE"
1030 REM INPUT T1(I): PRINT SPC(43) CHR$(30);  : INPUT N1(I)
1040 LPRINT USING "       ######          ##.#####^^^^ "; T1(I); N1(I)
1041 REM Error Check for Ascending Order of Input Data
1042 IF I=1 THEN GOTO 1050
1043 IF T1(I) > T1(I-1) THEN GOTO 1050
1044 PRINT "INPUT DATA IS NOT IN PROPER ORDER!"
1045 PRINT "PLEASE ENTER DATA AGAIN"
1046 GO TO 970
1050 T2(I)=T1(I)
1060 NEXT I
1070 REM ************************************************************
1080 REM  ADJUST THE STRESS LEVELS FOR STRESS CONCENTRATIONS
1090 PRINT "ADJUST THE S-N DATA FOR STRESS CONCENTRATIONS"
1100 PRINT "INPUT THE STRESS CONCENTRATION FACTOR"
1110 PRINT "  Use 1 if no Correction is Desired"
1120 PRINT "  Note: FALKENBERG'S EQUATION for the Mean Stress
1130 PRINT "        Correction has a Stress Concentration Factor
1140 PRINT "        of 1.67 INCLUDED in its Formulation.
1150 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
1160 SCF=2.73
1170 REM INPUT SCF
1180 PRINT:LPRINT
1190 LPRINT "  The Stress Concentration of Factor     = "; SCF
1200 REM ************************************************************
1210 REM  ADJUST THE STRESS LEVELS FOR MEAN STRESS 1220 PRINT "ADJUST THE S-N
DATA FOR MEAN STRESS"
1230 PRINT "SELECT THE FORM OF THE CORRECTION TERM DESIRED"
1240 PRINT " 1 FOR GOODMAN RULE ON THE ULTIMATE STRENGTH"
1250 PRINT " 2 FOR FALKENBERG'S EQUATION"
1260 PRINT " 3 FOR NO ADJUSTMENTS"
1270 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
1280 F2=1
1290 REM INPUT F2
1300 ON F2 GOTO 1320,1320,1400
1310 GOTO 1230
1320 PRINT "INPUT THE MEAN STRESS AT RATED ROTOR SPEED WITHOUT WIND "
1330 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
1340 M3=7000
1350 REM INPUT M3 : LET M3 = ABS (M3)
1360 PRINT: LPRINT
1370 LPRINT "  THE MEAN STRESS AT RATED ROTOR SPEED WITHOUT WIND = ";M3
1380 LPRINT
1390 ON F2 GOTO 1460,1590
1400 PRINT: LPRINT
1410 PRINT "NO ADJUSTMENTS FOR MEAN STRESS WERE MADE"
1420 LPRINT "  NO ADJUSTMENTS FOR MEAN STRESS WERE MADE"
1430 GOTO 1640
1440 REM  ***********************************************************
1450 REM  DO THE GOODMAN RULE ADJUSTMENT ON MEAN STRESS
1460 PRINT "THE GOODMAN RULE FOR MEAN STRESS CORRECTION HAS BEEN SELECTED"
```

```
1470 LPRINT "  THE GOODMAN RULE FOR MEAN STRESS CORRECTION HAS BEEN SELECTED"
1480 PRINT "INPUT THE ULTIMATE STRENGTH "
1490 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
1500 U=35000!
1510 REM INPUT U
1520 LPRINT "  THE ULTIMATE STRENGTH = ";U
1530 FOR I=1 TO N
1540 T1(I) = T1(I) - (M3 * T1(I)) / U
1550 NEXT I
1560 GOTO 1640
1570 REM  ************************************************************
1580 REM  USE FALKENBERG'S EQUATION TO ADJUST THE MEAN STRESS
1590 PRINT "FALKENBERG'S EQUATION FOR MEAN STRESS CORRECTION HAS BEEN SELECTED"
1600 LPRINT "  FALKENBERG'S EQUATION FOR MEAN STRESS CORRECTION HAS BEEN
SELECTED"
1610 FOR I=1 TO N
1620 T1(I) = .6 * T1(I)  -  .2 * M3
1630 NEXT I
1640 PRINT: LPRINT
1650 PRINT "THE ADJUSTED S-N DATA ARE :"
1660 LPRINT "  THE ADJUSTED S-N DATA ARE :"
1670 PRINT "     STRESS LEVEL      CYCLES TO FAILURE"
1680 LPRINT "    STRESS LEVEL      CYCLES TO FAILURE"
1690 FOR I=1 TO N
1700 REM Correct the Stress State for the Stress Concentration Factor
1710 T1(I)=T1(I)/SCF
1720 REM Make Sure that the Adjusted Stress Remains Positive
1730 IF T1(I) <.1 THEN T1(I)=I*5
1740 PRINT USING "       ######          ##.#####^^^^ ";  T1(I); N1(I)
1750 LPRINT USING "       ######          ##.#####^^^^ ";  T1(I); N1(I)
1760 NEXT I
1770 REM ************************************************************
1780 REM  THIS PROGRAM USES A LOG-LOG FIT TO THE S-N CURVE CURVE
1790 PRINT: LPRINT
1800 PRINT "CALCULATING THE CURVE FITS FOR THE S-N DATA"
1810 REM LPRINT "  THE CALCULATED CURVE FITS FOR THE S-N DATA ARE:"
1820 PRINT "  INTERCEPT           SLOPE"
1830 REM LPRINT "      INTERCEPT         SLOPE"
1840 FOR I=1 TO C
1850 S1(I)=LOG(N1(I)/N1(I+1))/LOG(T1(I)/T1(I+1))
1860 K1(I)=-S1(I)*LOG(T1(I))+LOG(N1(I))
1870 PRINT USING "    #####.####      #####.####";K1(I); S1(I)
1880 REM LPRINT USING "    #####.####      #####.####"; K1(I); S1(I)
1890 NEXT I
1900 PRINT: REM LPRINT
1910 REM  ************************************************************
1920 REM   SET UP THE RMS VERSUS WIND SPEED DATA
1930 PRINT "NEXT: INPUT THE DATA THAT DESCRIBES THE WIND REGIME"
1940 PRINT "INPUT THE NUMBER OF RMS VS WIND SPEED DATA POINTS  "
1950 PRINT "  The Maximum Number is 20."
1960 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
1970 R=4
1980 REM INPUT R
1990 PRINT: LPRINT
```

```
2000 LPRINT "THE NUMBER OF RMS VS WIND SPEED DATA POINTS = "; R
2010 D=R-1
2020 PRINT "INPUT THE WIND SPEED VS RMS STRESS IN ASCENDING ORDER,"
2030 PRINT "STARTING WITH THE LOWEST WIND SPEED."
2040 PRINT: LPRINT
2050 LPRINT "  THE WIND SPEED AND RMS DATA ARE: "
2060 LPRINT SPC(4) "WIND SPEED" SPC(9) "RMS STRESS LEVEL"
2070 FOR I=1 TO R
2080 PRINT " WIND SPEED" SPC(14) I SPC(12) " RMS STRESS"
2090 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
2100 W1(1)=0       :R1(1)=0
2110 W1(2)=10      :R1(2)=320
2120 W1(3)=20      :R1(3)=700
2130 W1(4)=40      :R1(4)=1560
2140 REM INPUT W1(I)  : PRINT SPC(43) CHR$(30); : REM INPUT R1(I)
2150 W1(I) = ABS (W1(I)) : R1(I) = ABS (R1(I))
2160 LPRINT USING "     #####              #####.##"; W1(I); R1(I)
2161 REM Error Check for Ascending Order of Input Data
2162 IF I=1 THEN GOTO 2170
2163 IF T1(I) > T1(I-1) THEN GOTO 2170
2164 PRINT "INPUT DATA IS NOT IN PROPER ORDER!"
2165 PRINT "PLEASE ENTER DATA AGAIN"
2166 GO TO 2020
2170 NEXT I
2180 PRINT: LPRINT
2190 REM  ************************************************************
2200 REM  SET UP THE OPERATING CONDITIONS
2210 PRINT "NEXT: INPUT THE OPERATING PARAMETERS FOR THE TURBINE"
2220 PRINT: LPRINT
2230 PRINT "INPUT THE STRESS CYCLE RATE IN HZ           ";
2240 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
2250 Y=1.6
2260 REM INPUT Y
2270 LPRINT "THE STRESS CYCLE RATE IN HZ = ";Y
2280 PRINT: LPRINT
2290 PRINT "INPUT THE INTEGER WIND SPEED FOR CUT-IN ";
2300 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
2310 I1=10
2320 REM INPUT I1
2330 PRINT "INPUT THE INTEGER WIND SPEED FOR CUT-OUT";
2340 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
2350 V1=45
2360 REM INPUT V1
2370 LPRINT "THE INTEGER WIND SPEEDS FOR CUT-IN AND CUT-OUT ARE:"
2380 LPRINT
2390 LPRINT "  CUT-IN WIND SPEED            = "; I1
2400 LPRINT "  CUT-OUT WIND SPEED           = "; V1
2410 PRINT: LPRINT
2420 PRINT "WHAT IS THE YEARLY AVERAGE WIND SPEED ";
2430 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
2440 A=14
2450 REM INPUT A
2460 PRINT "INPUT THE SHAPE FACTOR FOR A WEIBULL DISTRIBUTION "
```

```
2470 PRINT "  Note: Input 2.0 for a Rayleigh Distribution "
2480 REM *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
2490 ALP=2
2500 REM INPUT ALP
2510 ALR=1/ALP
2520 GAM=1+G1*ALR+G2*ALR^2+G3*ALR^3+G4*ALR^4+G5*ALR^5
2530 BET=A/GAM
2540 LPRINT "THE YEARLY AVERAGE WIND SPEED                    = ";A
2550 LPRINT "THE SHAPE FACTOR ON THE WIND DISTRIBUTION    = ";ALP
2560 LPRINT "  Note: 2.0 implies a Rayleigh Distribution"
2570 REM ************************************************************
2580 REM WIND SPEED INTEGRATION LOOP
2590 REM Set up Constants in Integration Loop
2600 T=0
2610 V2=V1-1
2620 NP1=INT(V2-I1)+1
2630 FOR I=I1 TO V1
2640 O1(I)=I
2650 D1(I)=0
2660 NEXT I
2670 REM Determine the Stress Level at the Endurance Limit
2680 REM This calculation is always based on the first interval
2690 REM in the curve fit.
2700 E1=EXP((NO-K1(1))/S1(1))
2710 REM Only Use Integer Values of Stress
2720 M2=INT(E1)
2730 PRINT: LPRINT
2740 LPRINT "THE CHOSEN ENDURANCE LIMIT (STRESS) = " , M2
2750 PRINT "THE CHOSEN ENDURANCE LIMIT (STRESS) = " , M2
2760 PRINT: LPRINT
2770 PRINT: LPRINT
2780 PRINT "THE FATIGUE LIFE CALCULATION HAS BEGUN"
2790 PRINT "PLEASE WAIT FOR THE CALCULATION TO BE COMPLETED"
2800 PRINT
2810 REM Only Use Integer Values of Velocity
2820 FOR S=I1 TO V1
2830 Q=S
2840 IF S =(INT(NP1*.1)+I1) THEN PRINT "Calculation  5 % Completed"
2850 IF S =(INT(NP1*.2)+I1) THEN PRINT "Calculation 15 % Completed"
2860 IF S =(INT(NP1*.3)+I1) THEN PRINT "Calculation 25 % Completed"
2870 IF S =(INT(NP1*.4)+I1) THEN PRINT "Calculation 35 % Completed"
2880 IF S =(INT(NP1*.5)+I1) THEN PRINT "Calculation 45 % Completed"
2890 IF S =(INT(NP1*.6)+I1) THEN PRINT "Calculation 55 % Completed"
2900 IF S =(INT(NP1*.7)+I1) THEN PRINT "Calculation 65 % Completed"
2910 IF S =(INT(NP1*.8)+I1) THEN PRINT "Calculation 75 % Completed"
2920 IF S =(INT(NP1*.9)+I1) THEN PRINT "Calculation 85 % Completed"
2930 REM ************************************************************
2940 REM CALCULATE THE RMS STRESS (LINEAR INTERPOLATION)
2950 J=1
2960 REM Chose Segment of RMS-Wind Speed Curve Fit
2970 FOR I=1 TO D
2980 IF Q< W1(I) THEN 3000
2990 J=I
```

```
3000 NEXT I
3010 M=R1(J+1)-(R1(J+1)-R1(J))*(W1(J+1)-Q)/(W1(J+1)-W1(J))
3020 REM ************************************************************
3030 REM STRESS INTEGRATION LOOP
3040 REM Set Bounds on Integration
3050 M1=INT(M/ML+1)
3060 X1=INT(MV*M)
3070 REM ************************************************************
3080 REM MAKE SURE THAT INTEGRATION DOES NOT BEGIN AT STRESS
3090 REM LEVELS BELOW THE STRESS THAT PRODUCES INFINITELY LONG
3100 REM LIFE---ie: the Stress at N0 Cycles
3110 IF M2=<M1 THEN 3130
3120 M1 = M2
3130 IF M1=<X1 THEN 3150
3140 X1=M1
3150 N2=INT((X1-M1)/Q1+1)+1
3160 U1=0
3170 FOR J1=1 TO N2
3180 S2=M1+J1*Q1-Q1
3190 REM ************************************************************
3200 REM INTERPOLATE THE S2-N2 CURVE
3210 K2=1
3220 FOR I=1 TO C
3230 IF S2<T1(I) THEN 3250
3240 K2=I
3250 NEXT I
3260 REM ************************************************************
3270 REM EVALUATE THE FUNCTION INSIDE THE STRESS INTEGRAL
3280 REM Check for an Exponential Underflow and Correct if Required
3290 IF -S2*S2/(2*M*M)=>-50 THEN 3360
3300 IF S1(K2)*LOG(S2)+K1(K2)>-50 THEN 3360
3310 B=1
3320 P=0
3330 GOTO 3380
3340 REM Calculate the RMS Stress PDF
3350 REM Rayleigh Stress Distribution
3360 P=S2/M^2*EXP(-S2*S2/(2*M*M))
3370 B=EXP(S1(K2)*LOG(S2)+K1(K2))
3380 REM Miner's Rule Calculation
3390 F=P/B
3400 REM Corrected Summation for End Points
3410 IF J1=1 THEN F=F/2
3420 IF J1=N2 THEN F=F/2
3430 U1=U1+F*Q1
3440 NEXT J1
3450 REM ************************************************************
3460 REM END STRESS INTEGRATION LOOP
3470 REM Calculate the Wind Speed PDF
3480 REM Weibull Wind Distribution
3490 A1=(Q/BET)
```

```
3500 B1=ALP/BET
3510 Q2=B1*(A1^(ALP-1))*EXP(-A1^ALP)
3520 REM PUT THE CALCULATIONS INTO A MATRIX FOR SUMMATION
3530 O1(S)=S
3540 U2(S)=Q2
3550 D1(S)=U1
3560 NEXT S
3570 REM ************************************************************
3580 REM END WIND SPEED INTEGRATION LOOP
3590 REM Print the Damage vs Wind Speed Interval Function
3600 LPRINT "The Wind Speed Interval = 1.0"
3610 LPRINT
3620 LPRINT "CENTER OF WIND" SPC(5) "WIND SPEED" SPC(8) "DAMAGE"
3630 LPRINT "SPEED INTERVAL" SPC(5) "   PDF"
3640 REM ************************************************************
3650 REM USE THE END POINT TO GET AVERAGE IN THE MIDDLE OF THE WIND
3660 REM INTERVAL
3670 PRINT "Calculation 95 % Completed"
3680 FOR I=I1 TO V2
3690 REM Calculate the Average Values over the Summation Interval
3700 REM and Determine the Damage Function
3710 O1(I)=(O1(I)+O1(I+1))/2
3720 U2(I)=(U2(I)+U2(I+1))/2
3730 D1(I)=(D1(I)+D1(I+1))/2 * U2(I)
3740 REM Calculate the Total Damage
3750 T=T+D1(I)
3760 LPRINT USING "  ####.##          ##.####^^^^      ##.#####^^^^"; O1(I);
U2(I); D1(I)
3770 NEXT I
3780 F1=1/T
3790 H=F1/(Y*3600)
3800 Y1=H/(24*365.25)
3810 PRINT "CALCULATIONS ARE NOW COMPLETE"
3820 PRINT: LPRINT: LPRINT: LPRINT: LPRINT
3830 PRINT " A SUMMARY OF RESULTS ARE: "
3840 PRINT
3850 REM ************************************************************
3860 REM PRINT SUMMARY OF RESULTS
3870 PRINT " AVERAGE WIND SPEED                          = ";A
3880 PRINT " THE SHAPE FACTOR ON THE WIND DISTRIBUTION = ";ALP
3890 PRINT " CUT-IN WIND SPEED                           = ";I1
3900 PRINT " CUT-OUT WIND SPEED                          = ";V1
3910 PRINT " COMPONENT LIFE EXPECTANCY IS                = ";H ,"  HOURS. "
3920 PRINT " THIS IS EQUIVALENT TO                       = ";Y1,"  YEARS."
3930 LPRINT " AVERAGE WIND SPEED                          = ";A
3940 LPRINT " THE SHAPE FACTOR ON THE WIND DISTRIBUTION = ";ALP
3950 LPRINT " CUT-IN WIND SPEED                           = ";I1
3960 LPRINT " CUT-OUT WIND SPEED                          = ";V1
3970 LPRINT " COMPONENT LIFE EXPECTANCY IS                = ";H," HOURS. "
3980 LPRINT " THIS IS EQUIVALENT TO                       = ";Y1," YEARS."
3990 PRINT:LPRINT
```

```
4000 PRINT:LPRINT
4010 PRINT:LPRINT
4020 REM ************************************************************
4030 REM DUMP DATA TO A FILE FOR PLOTTING -- USING ANOTHER PROGRAM
4040 PRINT "DO YOU WANT A DATA DUMP FOR PLOTTING THESE RESULTS"
4050 PRINT "     1 - Yes"
4060 PRINT "     2 - No"
4070 PRINT
4080 INPUT P1
4090 ON P1 GOTO 4110,4570
4100 GOTO 4040
4110 PRINT "WHAT FILE DO YOU WANT FOR THE DATA DUMP?"
4120 INPUT F$
4130 PRINT "Opening the Data File "
4140 OPEN F$ FOR OUTPUT AS #1
4150 PRINT#1, Y$
4160 PRINT#1, "Calculations Performed on : " ; DATE$
4170 REM OUTPUT THE WIND SPEED DISTRIBUTION AND DAMAGE FUNCTION
4180 REM Calculate the Number of Points and Print
4190 PRINT#1, USING "######  "; NP1
4200 PRINT#1, "CENTER OF WIND  WIND SPEED      DAMAGE     PERCENT"
4210 PRINT#1, "SPEED INTERVAL     PDF                        DAMAGE"
4220 FOR I=I1 TO V2
4230 LO1=(O1(I))
4240 LU2=(U2(I))
4250 LD1=(D1(I))
4260 PLD1=D1(I)/T
4270 PRINT#1,USING"##.######^^^^  "; LO1; LU2; LD1; PLD1
4280 NEXT I
4290 REM Output the Original and Modified S-N Data
4300 PRINT#1, USING "######  "; N
4310 PRINT#1, "   INPUT        MODIFIED        CYCLES TO"
4320 PRINT#1, "   STRESS       STRESS          FAILURE "
4330 FOR I=1 TO N
4340 LT1=(T1(I))
4350 LT2=(T2(I))
4360 LN1=(N1(I))
4370 PRINT#1, USING "##.######^^^^  "; LT2; LT1; LN1
4380 NEXT I
4390 REM Output a Plot of the Calculated S-N Curve
4400 PRINT#1, USING "######     "; NP
4410 DELS = (LOG( T1(N)) - LOG( T1(1))) / (NP-1)
4420 PRINT#1, "    STRESS      CYCLES TO "
4430 PRINT#1, "                FAILURE"
4440 FOR J =1 TO NP
4450 S2=EXP((J-1)*DELS+LOG(T1(1)))
4460 REM INTERPOLATE THE S-N CURVE
4470 K2=1
4480 FOR I=1 TO C
4490 IF S2<T1(I) THEN 4510
```

```
4500 K2=I
4510 NEXT I
4520 B=(S1(K2)*LOG(S2)+K1(K2))
4530 B=EXP(B)
4540 PRINT#1, USING "##.######^^^^  "; S2; B
4550 NEXT J
4560 CLOSE #1
4570 PRINT
4580 PRINT "  Select from the following options:"
4590 PRINT
4600 PRINT
4610 PRINT "    0  - EXIT PROGRAM to Basic"
4620 PRINT
4630 PRINT "    1  - EXIT PROGRAM to Dos"
4640 PRINT
4650 PRINT "    2  - Start the Program from the Beginning "
4660 PRINT "           and the Same Material Function"
4670 PRINT
4680 PRINT "    3  - Continue Program with a Different Wind Spectrum "
4690 PRINT
4700 INPUT E
4710 IF E=0 THEN 4750
4720 ON E GOTO 4740,340,2290
4730 GOTO 4580
4740 CLS: SYSTEM
4750 CLS
```

DISTRIBUTION:

Alcoa Technical Center (5)
Aluminum Company of America
Alcoa Center, PA 15069
Attn: D. K. Ai
J. T. Huang
J. R. Jombock
M. Klingensmith
J. L. Prohaska

Alternative Sources of Energy
Milaca, MN 56353
Attn: L. Stoiaken

Amarillo College
Amarillo, TX 79100
Attn: E. Gilmore

American Wind Energy Association
1017 King Street
Alexandria, VA 22314

Arizona State University
University Library
Tempe, AZ 85281
Attn: M. E. Beecher

Dr. A. S. Barker
Trinity Western
7600 Glover Road
Langley, BC
CANADA V3A 4R9

Battelle-Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352
Attn: L. Wendell

Bechtel Group, Inc.
P.O. Box 3965
San Francisco, CA 94119
Attn: B. Lessley

Dr. George Bergeles
Dept. of Mechanical Engineering
National Technical University
42, Patission Street
Athens, GREECE

Bonneville Power Administration
P.O. Box 3621
Portland, OR 97208
Attn: N. Butler

Burns & Roe, Inc.
800 Kinderkamack Road
Oradell, NJ 07649
Attn: G. A. Fontana

Canadian Standards Association
178 Rexdale Blvd.
Rexdale, Ontario, M9W 1R3
CANADA
Attn: T. Watson

Monique Carpentier
Energy, Mines and Resources
National Research Council
of Canada
Montreal Road
Ottawa, Ontario
CANADA K1A OR6

Professor V. A. L. Chasteau
School of Engineering
University of Auckland
Private Bag
Auckland, NEW ZEALAND

Colorado State University
Dept. of Civil Engineering
Fort Collins, CO 80521
Attn: R. N. Meroney

Commonwealth Electric Co.
Box 368
Vineyard Haven, MA 02568
Attn: D. W. Dunham

Gale B. Curtis
Curtis Associates
3089 Oro Blanco Drive
Colorado Springs, CO 80917

M. M. Curvin
11169 Loop Road
Soddy Daisy, TN 37379

Department of Economic Planning
and Development
Barrett Building
Cheyenne, WY 82002
Attn: G. N. Monsson

Otto de Vries
National Aerospace Laboratory
Anthony Fokkerweg 2
Amsterdam 1017
THE NETHERLANDS

DOE/ALO
Albuquerque, NM 87115
Attn: G. P. Tennyson

DOE/ALO
Energy Technology Liaison Office
NGD
Albuquerque, NM 87115
Attn: Capt. J. L. Hanson, USAF

DOE Headquarters (20)
Wind/Oceans Technologies Division
1000 Independence Avenue
Washington, DC 20585
Attn: L. J. Rogers
P. R. Goldman

J. B. Dragt
Nederlands Energy Research Foundation
(E.C.N.)
Physics Department
Westerduinweg 3 Petten (nh)
THE NETHERLANDS

Dynergy Systems Corporation
821 West L Street
Los Banos, CA 93635
Attn: C. Fagundes

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304
Attn: E. Demeo
F. Goodman

Dr. Norman E. Farb
10705 Providence Drive
Villa Park, CA 92667

Alcir de Faro Orlando
Pontificia Universidade Catolica-PUC/Rj
Mechanical Engineering Department
R. Marques de S. Vicente 225
Rio de Janeiro, BRAZIL

Fayette Manufacturing Corporation
P.O. Box 1149
Tracy, CA 95378-1149
Attn: W. Thompson

FloWind Corporation (2)
1183 Quarry Lane
Pleasonton, CA 94566
Attn: L. Schienbein
B. Im

A. D. Garrad
Garrad Hasson
10 Northampton Square
London EC1M 5PA
UNITED KINGDOM

Gates Learjet
Mid-Continent Airport
P.O. Box 7707
Wichita, KS 67277
Attn: G. D. Park

H. Gerardin
Mechanical Engineering Department
Faculty of Sciences and Engineering
Universite Laval-Quebec, G1K 7P4
CANADA

Dr. I. J. Graham
Southern University
Department of Mechanical Engineering
P.O. Box 9445
Baton Rouge, LA 70813-9445

R. T. Griffiths
University College of Swansea
Dept. of Mechanical Engineering
Singleton Park
Swansea, SA2 8PP
UNITED KINGDOM

Helion, Inc.
Box 445
Brownsville, CA 95919
Attn: J. Park, President

Indal Technologies, Inc. (2)
3570 Hawkestone Road
Mississauga, Ontario
CANADA L5C 2V8
Attn: D. Malcolm
C. Wood

Institut de Recherche d'Hydro-Quebec
1800, Montee Ste-Julie
Varennes, Quebec, JOL 2P.O.
CANADA
Attn: Bernard Masse

Iowa State University
Agricultural Engineering, Room 213
Ames, IA 50010
Attn: L. H. Soderholm

K. Jackson
West Wind Industries
P.O. Box 1705
Davis, CA 95617

M. Jackson
McAllester Financial
1816 Summit
W. Lafayette, IN 47906

Kaiser Aluminum and Chemical
Sales, Inc.
14200 Cottage Grove Avenue
Dolton, IL 60419
Attn: A. A. Hagman

Kaiser Aluminum and Chemical
Sales, Inc.
6177 Sunol Blvd.
P.O. Box 877
Pleasonton, CA 94566
Attn: D. D. Doerr

Kansas State University
Electrical Engineering Department
Manhattan, KS 66506
Attn: Dr. G. L. Johnson

R. E. Kelland
The College of Trades and Technology
P.O. Box 1693
Prince Philip Drive
St. John's, Newfoundland, A1C 5P7
CANADA

KW Control Systems, Inc.
RD#4, Box 914C
South Plank Road
Middletown, NY 10940
Attn: R. H. Klein

Kalman Nagy Lehoczky
Cort Adelers GT. 30
Oslo 2, NORWAY

L. K. Liljergren
1260 S.E. Walnut #5
Tustin, CA 92680

L. Liljidahl
Building 005, Room 304
Barc-West
Beltsville, MD 20705

Olle Ljungstrom
FFA, The Aeronautical Research
Institute
Box 11021
S-16111 Bromma, SWEDEN

Robert Lynette
R. Lynette & Assoc., Inc.
15042 NE 40th Street
Suite 206
Redmond, WA 98052

Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139
Attn: Professor N. D. Ham
W. L. Harris, Aero/Astro Dept.

H. S. Matsuda
Composite Materials Laboratory
Pioneering R&D Laboratories
Toray Industries, Inc.
Sonoyama, Otsu, Shiga, JAPAN 520

G. M. McNerney
US Wind Power
160 Wheeler Road
Burlington, MA 01803

Michigan State University
Division of Engineering Research
East Lansing, MI 48825
Attn: O. Krauss

Napier College of Commerce and
Technology
Tutor Librarian, Technology Faculty
Colinton Road
Edinburgh, EH10 5DT
ENGLAND

National Rural Electric
Cooperative Assn
1800 Massachusetts Avenue, NW
Washington, DC 20036
Attn: Wilson Prichett, III

Natural Power, Inc.
New Boston, NH 03070
Attn: Leander Nichols

Northwestern University
Dept. of Civil Engineering
Evanston, IL 60201
Attn: R. A. Parmalee

Ohio State University
Aeronautical and Astronautical Dept.
2070 Neil Avenue
Columbus, OH 43210
Attn: Professor G. Gregorek

Oklahoma State University
Mechanical Engineering Dept.
Stillwater, OK 76074
Attn: D. K. McLaughlin

Oregon State University
Mechanical Engineering Dept.
Corvallis, OR 97331
Attn: R. E. Wilson

Pacific Gas & Electric Co.
3400 Crow Canyon Road
San Ramon, CA 94583
Attn: T. Hillesland

Ion Paraschivoiu
Department of Mechanical Engineering
Ecole Polytecnique
CP 6079
Succursale A
Montreal H3C 3A7
CANADA

Jacques Plante
Hydro Quebec
Place Dupuis Ile etage
855 est rue Ste-Catherine
Montreal, Quebec
CANADA H2L 4P5

The Power Company, Inc.
P.O. Box 221
Genesee Depot, WI 53217
Attn: A. A. Nedd

Power Technologies, Inc.
P.O. Box 1058
Schenectady, NY 12301-1058
Attn: Eric N. Hinrichsen

Public Service Co. of New Hampshire
1000 Elm Street
Manchester, NH 03105
Attn: D. L. C. Frederick

Public Service Company of New Mexico
P.O. Box 2267
Albuquerque, NM 87103
Attn: M. Lechner

RANN, Inc.
260 Sheridan Ave., Suite 414
Palo Alto, CA 94306
Attn: A. J. Eggers, Jr.

Dr. R. Ganesh Rajagopalan, Asst. Prof.
Aerospace Engineering Department
Iowa State University
404 Town Engineering Bldg.
Ames, IA 50011

The Resources Agency
Department of Water Resources
Energy Division
P.O. Box 388
Sacramento, CA 95802
Attn: R. G. Ferreira

Reynolds Metals Company
Mill Products Division
6601 West Broad Street
Richmond, VA 23261
Attn: G. E. Lennox

R. G. Richards
Atlantic Wind Test Site
P.O. Box 189
Tignish P.E.I., COB 2BO
CANADA

Riso National Laboratory
Postbox 49
DK-4000 Roskilde
DENMARK
Attn: Troels Friis Pedersen
Helge Petersen

A. Robb
Memorial University of Newfoundland
Faculty of Engineering and Applied Sciences
St. John's Newfoundland, A1C 5S7
CANADA

Dr. Ing. Hans Ruscheweyh
Institut fur Leichbau
Technische Hochschule Aachen
Wullnerstrasse 7
FEDERAL REPUBLIC OF GERMANY

Beatrice de Saint Louvent
Establissement d'Etudes et de Recherches
Meteorologigues
77 Rue de Serves
92106 Boulogne-Billancourt Cedex
FRANCE

Gwen Schreiner
Librarian
National Atomic Museum
Albuquerque, NM 87185

Arnan Seginer
Professor of Aerodynamics
Technion-Israel Institute of Technology
Department of Aeronautical Engineering
Haifa
ISRAEL

Mr. Farrell Smith Seiler, Editor
Wind Energy News Service
P.O. Box 4008
St. Johnsbury, VT 05819

David Sharpe
Dept. of Aeronautical Engineering
Queen Mary College
Mile End Road
London, E1 4NS
UNITED KINGDOM

Kent Smith
Instituto Technologico Costa Rico
Apartado 159 Cartago
COSTA RICA

Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401
Attn: R. W. Thresher

Bent Sorenson
Roskilde University Center
Energy Group, Bldg. 17.2
IMFUFA
P.O. Box 260
DK-400 Roskilde
DENMARK

Peter South
ADECON
32 Rivalda Road
Weston, Ontario, M9M 2M3
CANADA

Southern California Edison
Research & Development Dept., Room 497
P.O. Box 800
Rosemead, CA 91770
Attn: R. L. Scheffler

G. Stacey
The University of Reading
Department of Engineering
Whiteknights, Reading, RG6 2AY
ENGLAND

Stanford University
Dept. of Aeronautics and Astronautics Mechanical Engineering
Stanford, CA 94305
Attn: Holt Ashley

Dr. Derek Taylor
Alternative Energy Group
Walton Hall
Open University
Milton Keynes, MK7 6AA
UNITED KINGDOM

R. J. Templin (3)
Low Speed Aerodynamics Laboratory
NRC-National Aeronautical Establishment
Montreal Road
Ottawa, Ontario, K1A 0R6
CANADA

Texas Tech University (2)
Mechanical Engineering Dept.
P.O. Box 4289
Lubbock, TX 79409
Attn: J. W. Oler

K. J. Touryan
Moriah Research
6200 Plateau Dr.
Englewood, CO 80111

Tulane University
Dept. of Mechanical Engineering
New Orleans, LA 70018
Attn: R. G. Watts

Tumac Industries, Inc.
650 Ford Street
Colorado Springs, CO 80915
Attn: J. R. McConnell

J. M. Turner
Terrestrial Energy Technology
Program Office
Energy Conversion Branch
Aerospace Power Division/
Aero Propulsion Lab
Air Force Systems Command (AFSC)
Wright-Patterson AFB, OH 45433

United Engineers and Constructors, Inc.
P.O. Box 8223
Philadelphia, PA 19101
Attn: A. J. Karalis

Universal Data Systems
5000 Bradford Drive
Huntsville, AL 35805
Attn: C. W. Dodd

University of California
Institute of Geophysics
and Planetary Physics
Riverside, CA 92521
Attn: Dr. P. J. Baum

University of Colorado
Dept. of Aerospace Engineering Sciences
Boulder, CO 80309
Attn: J. D. Fock, Jr.

University of Massachusetts
Mechanical and Aerospace
Engineering Dept.
Amherst, MA 01003
Attn: Dr. D. E. Cromack

University of New Mexico
New Mexico Engineering
Research Institute
Campus P.O. Box 25
Albuquerque, NM 87131
Attn: G. G. Leigh

University of Oklahoma
Aero Engineering Department
Norman, OK 73069
Attn: K. Bergey

University of Sherbrooke
Faculty of Applied Science
Sherbrooke, Quebec, J1K 2R1
CANADA
Attn: A. Laneville
P. Vittecoq

The University of Tennessee
Dept. of Electrical Engineering
Knoxville, TN 37916
Attn: T. W. Reddoch

USDA, Agricultural Research Service
Southwest Great Plains Research Center
Bushland, TX 79012
Attn: Dr. R. N. Clark

Utah Power and Light Co.
51 East Main Street
P.O. Box 277
American Fork, UT 84003
Attn: K. R. Rasmussen

W. A. Vachon
W. A. Vachon & Associates
P.O. Box 149
Manchester, MA 01944

Dirk Vandenberghe
State Univ. of Ghent
St. Pietersniewstraat 41
9000 Ghent
BELGIUM

Washington and Lee University
P.O. Box 735
Lexington, VA 24450
Attn: Dr. R. E. Akins

Washington State University
Dept. of Electrical Engineering
Pullman, WA 99163
Attn: F. K. Bechtel

West Texas State University
Government Depository Library
Number 613
Canyon, TX 79015

West Texas State University
Department of Physics
P.O. Box 248
Canyon, TX 79016
Attn: V. Nelson

West Virginia University
Dept. of Aero Engineering
1062 Kountz Avenue
Morgantown, WV 26505
Attn: R. Walters

D. Westlind
Central Lincoln People's Utility District
2129 North Coast Highway
Newport, OR 97365-1795

Wichita State University
Aero Engineering Department (2)
Wichita, KS 67208
Attn: M. Snyder
W. Wentz

Wind Power Digest
P.O. Box 700
Bascom, OH 44809
Attn: Michael Evans

Wisconsin Division of State Energy
8th Floor
101 South Webster Street
Madison, WI 53702
Attn: Wind Program Manager

1520	C. W. Peterson
1522	R. C. Reuter, Jr.
1523	J. H. Biffle
1524	A. K. Miller
1524	D. W. Lobitz
1550	R. C. Maydew
1552	J. H. Strickland
1556	G. F. Homicz
2525	R. P. Clark
3141	S. A. Landenberger
3151	W. L. Garner (3)
3154-3	C. H. Dalin (28) For DOE/OSTI (Unlimited Release)
3160	J. E. Mitchell (15)
3161	P. S. Wilson
6000	D. L. Hartley
6200	V. L. Dugan
6220	D. G. Schueler
6225	H. M. Dodd (50)
6225	T. D. Ashwill
6225	D. E. Berg
6225	T. C. Bryant
6225	L. R. Gallo
6225	P. C. Klimas
6225	S. D. Nicolaysen
6225	D. S. Oscar
6225	M. E. Ralph
6225	D. C. Reda
6225	M. A. Rumsey
6225	L. L. Schluter
6225	W. A. Stephenson
6225	H. J. Sutherland
7111	J. W. Reed
7544	D. R. Schafer
7544	T. G. Carne
7544	J. Lauffer
8024	P. W. Dean
9100	R. G. Clem
9122	T. M. Leonard