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A General Reliability and Safety Methodology and Its Application to Wind Energy Conversion Systems

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A GENERAL RELIABILITY AND SAFETY METHODOLOGY AND ITS APPLICATION TO WIND ENERGY CONVERSION SYSTEMS

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FOREWORD

This report documents work done on SERI Task 3522.10 by members of the Systems Analysis Branch, Research Division.

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SOLAR ENERGY RESEARCH INSTITUTE

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SUMMARY

In conventional system reliability calculations, each component may be in the Operable state or the Under Repair state. These calculations derive system unavailability, or the probability of the system's being down for repairs. By introducing a third component state between Operable and Under Repair--namely, Defective, But Defect Undetected--the methods developed in this report enable system safety projections to be made in addition to availability projections. Also provided is a mechanism for computing the effect of inspection schedules on both safety and availability. A Reliability and Safety Program (RASP) is detailed which performs these computations and also calculates costs for system inspections and repairs. RASP is applied to a simplified wind energy conversion system example.

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SECTION 1.0

INTRODUCTION

In the electric power industry, a standard methodology has been developed for calculating system reliability [1-3]. Under this methodology it is assumed that each component of a system occupies either of two states: Operable or Under Repair. The duration of residence in the Operable state is the "time to failure," and the duration of residence in the Repair state is the "time to repair." This construction assumes that the Operable state lasts until failure and that the Repair state begins immediately thereafter.

In this simple form, the reliability methodology assumes perfect knowledge of the inoperability or "failure" of a component. For many components, however, there is an intermediate state between Operable and Under Repair which is of serious concern. This intermediate state we shall call "Defective, But Defect Undetected." Thus the cycle of performance for each component may be diagrammed as in Figure 1-1.

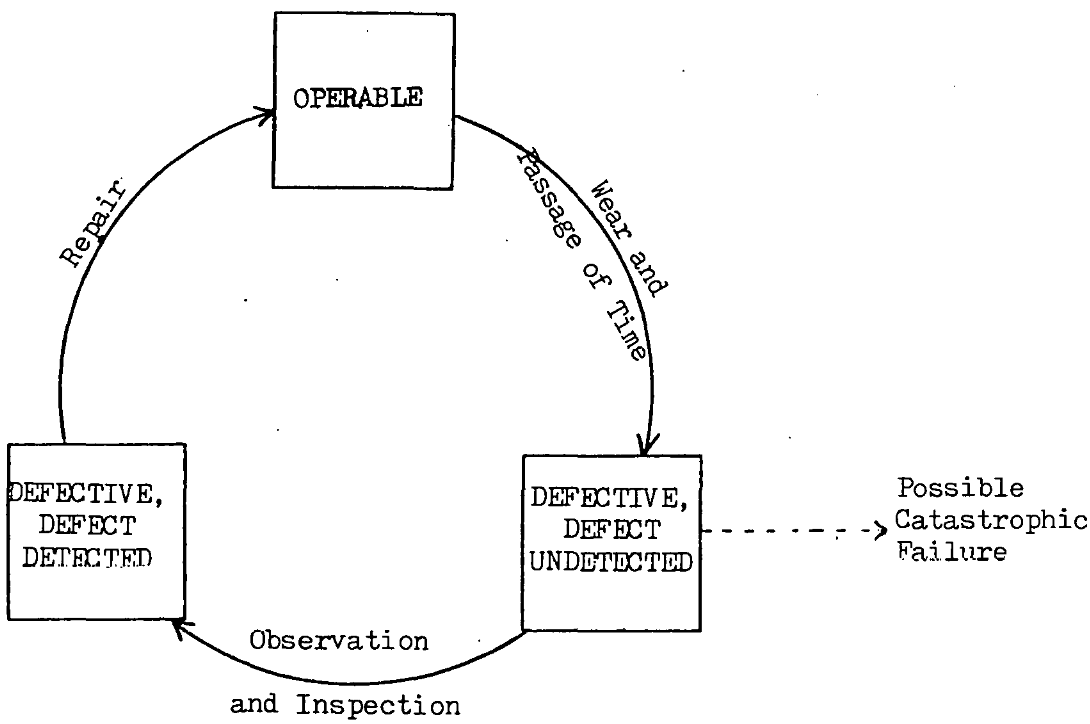

Figure 1-1. Performance Cycle for Each Component

By identifying this intermediate state between Operable and Under Repair, we can calculate not only the system's reliability--i.e., its unavailability, or probability of being down for repairs--but also the probability of catastrophic failure due to undetected defects.

The method so developed will be applied to determining the reliability and safety of a simplified wind energy conversion system. Work on wind energy conversion system reliability is nascent. A failure modes and effects analysis has been performed by Kaman Aerospace Corporation [4], and a systems analysis study has been completed in Canada for a large vertical axis wind turbine [5]. Analysis by General Electric on component failure modes was recently completed for the Mod-1 wind turbine [6]. Boeing has studied reliability and maintainability for the Mod-2 [7]. Calculations of system reliability and safety will surely be required as wind power moves toward commercialization.

SECTION 2.0

THE DEFECTIVE STATE

A component resides in the "Defective, But Defect Undetected" state if it is either

- operating substandardly and thereby degrading system performance (but not enough to occasion immediate detection),
- in danger of experiencing total failure (even if not currently degrading system performance), or
- totally failed, if a standby component.

We shall refer to the "Defective, But Defect Undetected" state as simply the "Defective" state.

There is some arbitrariness about the boundary between the Operable and Defective states. The threshold at which a component has degraded to the point of being called "substandard" is arbitrary. So is the point at which the danger of total failure becomes significant. We shall use as a working definition of the Defective state: a defect which would be identified, if detected during an inspection, as warranting nonroutine maintenance or repair. Crack development beyond a specified size is one example of defect development.

A component in the Defective state might experience total failure before its defectiveness is detected. The possibility of a component's going from defective to failed is a matter of concern only if failure of the component affects system safety. We shall refer to the total failure (as opposed to the defectiveness, or susceptibility to failure) of components affecting system safety as "catastrophic failure." A datum which will be required for such a component is its rate of catastrophic failure, given that it is defective.

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SECTION 3.0

A SIMPLE EXAMPLE

Consider a special automobile braking system, consisting of the usual foot brake and an independent emergency brake. Suppose that the rate of defect development (such as brake fluid leak) is once in five years for both brakes and that the rate of catastrophic failure, given that the brake is defective, is once in ten days. To restate, each brake can be expected to perform an average of five years before becoming defective and, once defective, can be expected to last ten days before failing completely.

The foot brake is used constantly. A defect like a brake fluid leak will be noticed fairly quickly. Assume an average time of one day until detection of this defect in the foot brake. The emergency brake, on the other hand, is used only as backup for the foot brake. A defect in the emergency brake will be discovered only during inspection, which takes place at regular four-month intervals. Thus, the expected time (in a probabilistic sense) until detection of a defect in the emergency brake is equal to the expected time until the next inspection, or two months.

Assume for this example that repair of either brake requires two days, but that inspections take negligible time.

The data for the two components of the braking system are given in Table 3-1.

Table 3-1. BRAKING SYSTEM DATA

Parameter	Foot Brake	Emergency Brake
Expected Time to:		
Defect Development	5 Years	5 Years
Defect Detection	1 Day	2 Months
Repair	2 Days	2 Days
Total Cycle Time	5.0082 Years	5.1721 Years
Catastrophic Failure Rate, Given Defective	1/(10 Days)	1/(10 Days)

It is apparent that the expected time to defect development is identical to the expected residence time in the Operable state. Further, the expected time to defect detection is the expected time in the Defective state and the expected time to repair is the expected time in the Repair state. Table 3-2 gives the state residence probabilities which are normalized to the Total Cycle Time.

Table 3-2. STATE RESIDENCE PROBABILITIES

	Foot Brake	Emergency Brake
Probability of:		
Operable	0.9984	0.9667
Defective	0.0005	0.0322
Under Repair	0.0011	0.0011

Assume that, once defective, each brake is subject to a constant failure rate. This implies that the failure distribution is exponential, so that the probability of a failure of either brake within time t in days after defect development is 1 - exp(-t/10). Therefore, the probability that the foot brake will fail during its expected one day until defect detection is 1 - exp(-1/10) or 0.0952. The probability that the emergency brake will fail during its expected 60 days (two months) until defect detection is 1 - exp(-60/10) or 0.9975.

We shall need to know the probability that each brake resides in the "catastrophically failed" state. If T is the duration of residence in the defective state,* then the expected duration in the failed state is

$$\int_0^T (T-t)\ \Pr\{\text{failure occurs during time } dt\}$$

$$= \int_0^T (T-t)\ \frac{1}{10}\ e^{-(1/10)t}\ dt = T - 10\left[1 - \exp\left(-\frac{1}{10}T\right)\right]$$

For the foot brake, T = one day. Therefore, the expected residence time in the failed state during one cycle is 1 - 10 [1 - exp(-1/10)] = 0.0484 day or 0.00013 year. Since one cycle spans 5.0082 years (from Table 3-1), the probability that the foot brake is in the failed state is 0.00013/5.0082 or 2.6×10^{-5}. Similarly, the probability that the emergency brake is failed is

$$\{60 - 10[1 - \exp(-60/10)]\}/(5.1721 \cdot 365) = 0.0265$$

Table 3-3 shows the state residence probabilities of Table 3-2 expanded to include the probability of residence in the failed state. It also states the

*We have assumed in these calculations that the duration of residence in the Defective state is deterministic, although it is really a random variable. This approximation is warranted since some choice of a probability distribution must be made, and the one-point distribution--while unrealistic--is simplest and likely to produce as good an approximation as any other assumption.

failure rates on a per year basis. These are all the data needed for the reliability and safety calculations.

Table 3-3. STATE RESIDENCE PROBABILITIES EXPANDED TO INCLUDE FAILED STATE

	Foot Brake	Emergency Brake
Probability of:		
Operable	0.9984	0.9667
Defective	0.0005	0.0322
Under Repair	0.0011	0.0011
Failed	2.6×10^{-5}	0.0265
Failure Rate, Given Defective (per year)	36.5	36.5

Catastrophic failure of the two-brake system occurs whenever one brake fails and the other has already failed. (Failure of both brakes at the same instant is an event with a vanishingly small probability.)

The probability that catastrophic failure occurs during the instant Δt is therefore equal to

$$\begin{aligned}
&\Pr\{\text{foot brake failed}\} \cdot \Pr\{\text{emergency brake defective}\} \\
&\cdot (\text{emergency brake failure rate}) \cdot \Delta t \\
&+ \Pr\{\text{emergency brake failed}\} \cdot \Pr\{\text{foot brake defective}\} \\
&\cdot (\text{foot brake failure rate}) \cdot \Delta t \\
&= (2.6 \times 10^{-5} \cdot 0.0322 \cdot 36.5 + 0.0265 \cdot 0.0005 \cdot 36.5) \cdot \Delta t \\
&= 0.0005\ \Delta t
\end{aligned}$$

This implies that the probability of catastrophic failure of the braking system is about 0.0005, or one in 2000, per year.

Note that a figure for unavailability of the system due to repairs may also be obtained from the data. The system is unavailable when either the foot brake or the emergency brake is being repaired. The probability is

$$\begin{aligned}
&\Pr\{\text{foot brake under repair}\} + \Pr\{\text{emergency brake under repair}\} \\
&- \Pr\{\text{foot brake under repair}\} \cdot \Pr\{\text{emergency brake under repair}\} \\
&= 0.0011 + 0.0011 - 0.0011 \cdot 0.0011 = 0.0022
\end{aligned}$$

Therefore the system is available 1 - 0.0022 = 0.9978, or 99.78% of the time. Of course, this is not meaningful in practice since components of the system other than brakes have not been considered. In a realistic example, all components of the system should be included in the availability calculation.

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SECTION 4.0

GENERALIZED COMPONENT CALCULATIONS

We now proceed to the calculations for the general case.

The inputs required for each component of the system are as follows:

- T_o, mean time to defect development (in years)
- T_f, expected time (in days) until catastrophic failure, given that component is operating defectively (required only if component failure affects system safety)
- N_i, frequency of inspections of this component (number per year)
- H, time in man-hours required to inspect this component
- Q, probability of detecting an existing defect during an inspection
- C_i, inspection cost in dollars allocable to this component
- t_d, mean time to defect detection (in days), if less than time until next inspection
- T_r, mean time to repair (in days)
- C_r, average cost in dollars to repair/replace this component

Also required is W, the number of workers on the inspection and maintenance team (this input is system-specific, not component-specific).

The duration of an inspection is

$$\frac{H}{8W} \text{ (days)} = \frac{H}{8W}/365 \text{ (years)} = \frac{H}{2920W} \text{ (years)}$$

assuming an 8-hour work day.

Therefore,

$$\text{time between inspections} = \frac{1}{N_i} - \frac{H}{2920W} \text{ (years)}.$$

If a component is currently in the operating mode (either Operable or Defective), then the expected time until the next inspection is

$$\frac{1}{2}\left(\frac{1}{N_i} - \frac{H}{2920W}\right) .$$

If the component is defective but the defect is not discovered until the (k + 1)'st inspection, then the operating time until detection is

$$\frac{1}{2}\left(\frac{1}{N_i} - \frac{H}{2920W}\right) + k\left(\frac{1}{N_i} - \frac{H}{2920W}\right) = \frac{1}{2}\left(\frac{1}{N_i} - \frac{H}{2920W}\right)(2k + 1).$$

The probability that a defect is discovered during the (k + 1)'st inspection, but not until then, is $Q \cdot (1 - Q)^k$. Therefore, the expected operating time until a defect is discovered by inspection is

$$\frac{1}{2}\left(\frac{1}{N_i} - \frac{H}{2920W}\right) Q \sum_{k=0}^{\infty} (2k + 1)(1-Q)^k$$

which equals

$$\frac{2 - Q}{2Q}\left(\frac{1}{N_i} - \frac{H}{2920W}\right) .$$

The expected time until defect detection, however, may be less than the expected time for a defect to be found through inspections. The input, t_d, is provided to cover this eventuality. For example, the defective foot brake is discovered not through shop inspections but through observation of its behavior in use. To summarize, the expected time T_d in years until defect detection is expressed by

$$T_d = \text{minimum}\left[\frac{2 - Q}{2Q}\left(\frac{1}{N_i} - \frac{H}{2920W}\right), \frac{t_d}{365}\right] .$$

The inspection time as a fraction of the nominal operating time (i.e., all but the time down for repairs) is

$$f = \frac{H}{2920W}\Big/\frac{1}{N_i} = \frac{N_i H}{2920W} .$$

Then the elapsed time which is actually spanned by the first two states of the component's cycle (Operable and Defective), when time down for inspections is included, is $(T_o + T_d)/(1 - f)$.

Letting T_i = inspection and maintenance time during component cycle,

$$T_i = (T_o + T_d)/(1 - f) - (T_o + T_d) = \frac{f}{1 - f}(T_o + T_d).$$

Letting T_c be the time required to complete one component cycle,

$$T_c = T_o + T_d + T_i + T_r.$$

The associated state residence probabilities are

$$P_o \equiv T_o/T_c$$
$$P_d \equiv T_d/T_c$$
$$P_i \equiv T_i/T_c$$
$$P_r \equiv T_r/T_c \quad .$$

The failure rate of the component, given that it is defective, is

$$\lambda = 365/T_f \text{ per year}$$

and the probability of residence in the failed state is

$$P_f = P_d - \frac{1 - e^{-\lambda T_d}}{\lambda T_c} \quad .$$

The expected inspection and maintenance cost per year is

$$C_i N_i \; (T_o + T_d + T_i)/T_c$$

and the expected repair/replacement cost per year is C_r/T_c.

The above calculations assumed that the component is not operating during inspections or repairs. It is easy to adjust the calculations for cases when these assumptions are not true. These adjustments are incorporated as options in the computer program listed in Appendix B.

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SECTION 5.0

GENERALIZED SYSTEM CALCULATIONS

A generalized system is described through its minimal path sets and minimal cut sets. A "path set" of a system is a set of components such that, if all are in working order, then the system is in working order. A minimal path set is a path set such that no proper subset is a path set. Obviously, any component which is not in a specified minimal path set can be labeled redundant. A "cut set" of a system is a set of components such that, if all are not in working order, then the system is not in working order. A minimal cut set is a set of components such that no proper subset is a cut set.

If all the minimal path sets of a system are specified, then the minimal cut sets can be derived and vice versa [8]. Nevertheless, the computer program listed in Appendix B requires both minimal path sets and minimal cut sets as input. An algorithm deriving one from the other could be added easily as a front end to the program. However, it is a useful exercise in qualitative analysis of the system for the program user to list both the system's minimal path sets and minimal cut sets.

The system reliability and safety calculations to be presented are based on the assumption that the performance cycles of the components in the system are independent of one another. For example, the time to defect development of component A is assumed to be independent of the time to defect development of component B, and the time to repair component A is assumed to be independent of the time to repair component B. This is an assumption which may not apply to some systems. Care should be taken to consider the possible invalidity of this assumption before applying the methodology.

We shall describe in detail the calculation of two system statistics: the probability of the system's being down for inspection and maintenance or repairs (i.e., system unavailability), and the probability of catastrophic failure (i.e., system safety). Other statistics--the probabilities of normal and defective system operation and the annual inspection and repair costs--also are computed in the Reliability and Safety Program listed in Appendix B. (See Appendix A for sample output.)

System unavailability, the probability of being down for inspection or repair, is easily calculated. The probability that the system is down due to inspection or repair of some component is the probability of the union over all k of the events {component k is undergoing inspection or repairs}.* Let $r_k = P_I + P_r$ for the k'th component. The probability of a union of events can be computed from the probabilities of the events themselves by means of an elementary law of probability (see, for example, [9], page 27) sometimes called the General Law of Addition. Thus, the probability of system unavailability for a system of m components is

*Assuming the system is shut down whenever any component is undergoing inspection or repair. The program in Appendix B relaxes this requirement.

$$\sum_k r_k - \sum_{j \neq k} r_j r_k + \sum_{i \neq j \neq k} r_i r_j r_k - \cdots + (-1)^{m+1} \prod_k r_k \qquad (5\text{-}1)$$

To compute the rate of system catastrophic failure, we first note that system failure will be determined by some sequence of component failures. Any one of the components may be the last to fail.

Suppose that the k'th component is the last to fail. System failure due to failure of the k'th component will occur during the instant Δt if:

(1) All the other safety-related components in some cut set to which component k belongs have already failed.

(2) Component k is defective (but not failed).

(3) Component k passes from defective to failed in the subsequent instant Δt.

Let the minimal cut sets containing component k be designated $S_1, \ldots, S_N$, and let E_n denote the event {all safety-related components in S_n (except component k) have failed}.

Letting $q_j = P_f(j)$ = the probability that component j is in the failed state (= 1 if component j does not contribute to system safety),

$$Pr(E_n) = \prod_{\substack{j \in S_n \\ j \neq k}} q_j$$

The probability that all of the safety-related components except component k have failed in at least one of the cut sets $S_1, \ldots, S_N$ [i.e., that event (1), above, occurs] is Pr $(E_1 \cup E_2 \cup \ldots \cup E_N)$. But by the General Law of Addition we have

$$\rho_k = Pr\{\text{event (1)}\} = Pr(E_1 \cup E_2 \cup \ldots \cup E_N)$$

$$= \sum_{n=1}^{N} Pr(E_n) - \sum_{m \neq n} Pr(E_m \cap E_n) + \ldots + (-1)^{N+1} Pr(E_1 \cap \ldots \cap E_N)$$

$$= \sum_{n=1}^{N} \prod_{\substack{j \in S_n \\ j \neq k}} q_j - \sum_{m \neq n} \prod_{\substack{j \in S_m \cup S_n \\ j \neq k}} q_j + \ldots + (-1)^{N+1} \prod_{\substack{j \in \cup_{n=1}^{N} S_n \\ j \neq k}} q_j \qquad (5\text{-}2)$$

The probability that events (2) and (3) occur is

$[P_d(k)-P_f(k)]\ \lambda(k)\ \Delta t.$

Hence, the probability that events (1), (2), and (3) occur is

$$\rho_k \left[P_d(k)-P_f(k) \right] \lambda(k) \quad \Delta t.$$

The probability that catastrophic system failure occurs during time Δt is simply the sum of these probabilities over all components k. Letting λ_S be the rate of catastrophic system failure, so that $\lambda_S \Delta t$ is the probability of catastrophic system failure during the instant Δt, we have

$$\lambda_S = \sum_k \rho_k \left[P_d\ (k) - P_f\ (k)\right] \lambda(k) \qquad (5\text{-}3)$$

The mean time to system catastrophic failure is then $1/\lambda_S$, and the probability of catastrophic failure in a single year can be assumed to be $1 - \exp(-\lambda_S)$, or approximately λ_S (if λ_S is small).

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SECTION 6.0

A SIMPLIFIED WIND ENERGY CONVERSION SYSTEM EXAMPLE

The general methodology described in the previous section is capable of treating systems containing many components. One reason for developing the methodology was for use in analyzing the reliability and safety of wind energy conversion systems.

A recently reported wind turbine accident involving the collapse of a 150 ft vertical axis machine was, in fact, closely related to one component, a set of drag brakes, having been in the "Defective, Defect Undetected" state [10]. Similar undetected defects seem to have been responsible for the collapse of several small wind turbines. While many of these problems have been due to lack of quality control in the production of research and demonstration machines, the possibility of wind turbine catastrophic failure is not insignificant. The following examples are fairly realistic but are simplified considerably to illustrate the methodology's application.

Figure 6-1 diagrams a skeleton wind energy conversion system (WECS). Note that this is a highly simplified version of a WECS, including no pitch-control or yaw-control mechanisms. Furthermore, a large or sophisticated WECS will include many auxiliary safety devices such as vibration, loss of line voltage, overspeed, and other critical parameter sensors.

The WECS diagrammed in Fig. 6-1 has only a braking system to control the rotor. The primary brake is the disc brake, which is applied to the shaft of the rotor. The drag brake, which serves as backup, is located near the outer extremities of the rotor and extends to offer air resistance against the rotor's angular momentum. The failure probability of such a system has been analyzed previously using conventional electric power systems reliability methods [5].

Modes of catastrophic failure of this system are:

- both brakes fail, resulting in an uncontrollable rotor; or
- the rotor fails catastrophically of its own accord--i.e., breaks and collapses.

The gear box and generator can become defective also, but we can assume that their defectiveness will not pose a safety hazard. Their defectiveness, however, will have a negative effect on system performance. As a result, the defectiveness of either gear box or generator would probably be discovered simply through observing the system performance over time.

As the above discussion implies, the cut sets of this system are:

- rotor;
- disc brake and drag brake;

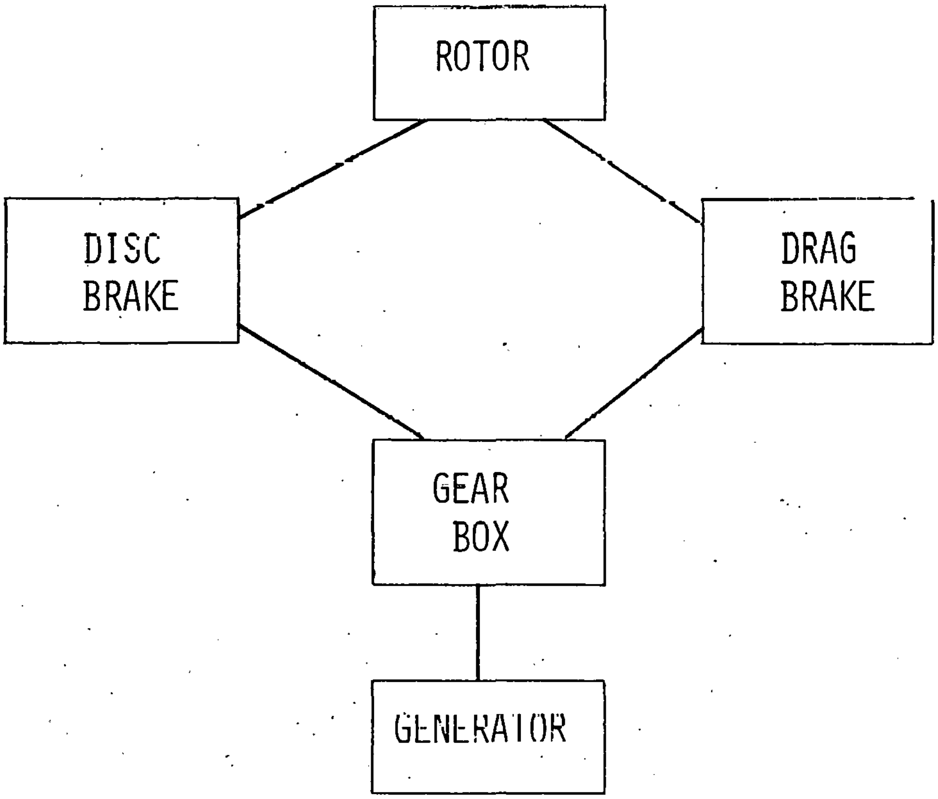

Figure 6-1. SIMPLIFIED WIND ENERGY CONVERSION SYSTEM

- gear box; and
- generator.

That is, the system is operating defectively (or in danger) if all the components in one of these four sets are Defective.

The path sets of the system are:

- rotor, disc brake, gear box, and generator; and
- rotor, drag brake, gear box, and generator.

That is, the system is operating normally (i.e., it is safe and performance is not degraded) as long as all the components in one of these two sets are Operable.

Appendix A shows the output of the Reliability and Safety Program (RASP) for this example. Pages A-2 and A-3 list the component inputs which were used. Page A-4 lists the minimal path sets and minimal cut sets that were input. These inputs were chosen in order to represent as realistically as possible those of a real wind energy conversion system, but they are still illustrative.

Page A-7 gives the system outputs. The probability of a catastrophic failure as calculated by Eqs. 2 and 3 is 0.012 per year in this example, and the mean time to catastrophic failure is 81.4 years. The unavailability due to maintenance or repairs (Eq. 1) is 1.3%. 4.2% of the time the system will be operating but defective. Thus the system is available for normal operation 94.5% of the time. The cost of maintenance and repairs averages about $3900 per year. These numbers are probably reasonable for a wind turbine of intermediate size, but note that other protection devices, such as pitch and yaw controls on a horizontal axis wind turbine, have not been included.

The subsequent tables on pages A-7 and A-8 show the effect of improving each of the components, either by increasing its mean time to defect development, by decreasing the time to defect detection, or by decreasing the time to repair. For example, on page A-7 it is shown that increasing the mean time to rotor defect development by 50% increases the mean time to system failure by 43.5%. On the other hand, increasing the mean time to defect development for either brake has a much smaller impact on system safety. This shows clearly that the rotor is the most safety-critical component. If maintenance and repair costs are a concern, however, improvement of the drag brake will have the most favorable impact (-7.79%). Such sensitivity calculations provide valuable input to a design-to-cost project, in which the systems engineering of a wind energy conversion system is optimized while the system cost is minimized.

As an improvement to the system, let us consider the addition of a crack sensing device which would detect major cracks developing in the rotor blades. Figure 6-2 diagrams the system with this addition. Only system safety is being considered so the gear box and generator are irrelevant and are shown in dashed lines.

The crack sensor will be attached so as to activate the disc brake if a major crack is sensed.

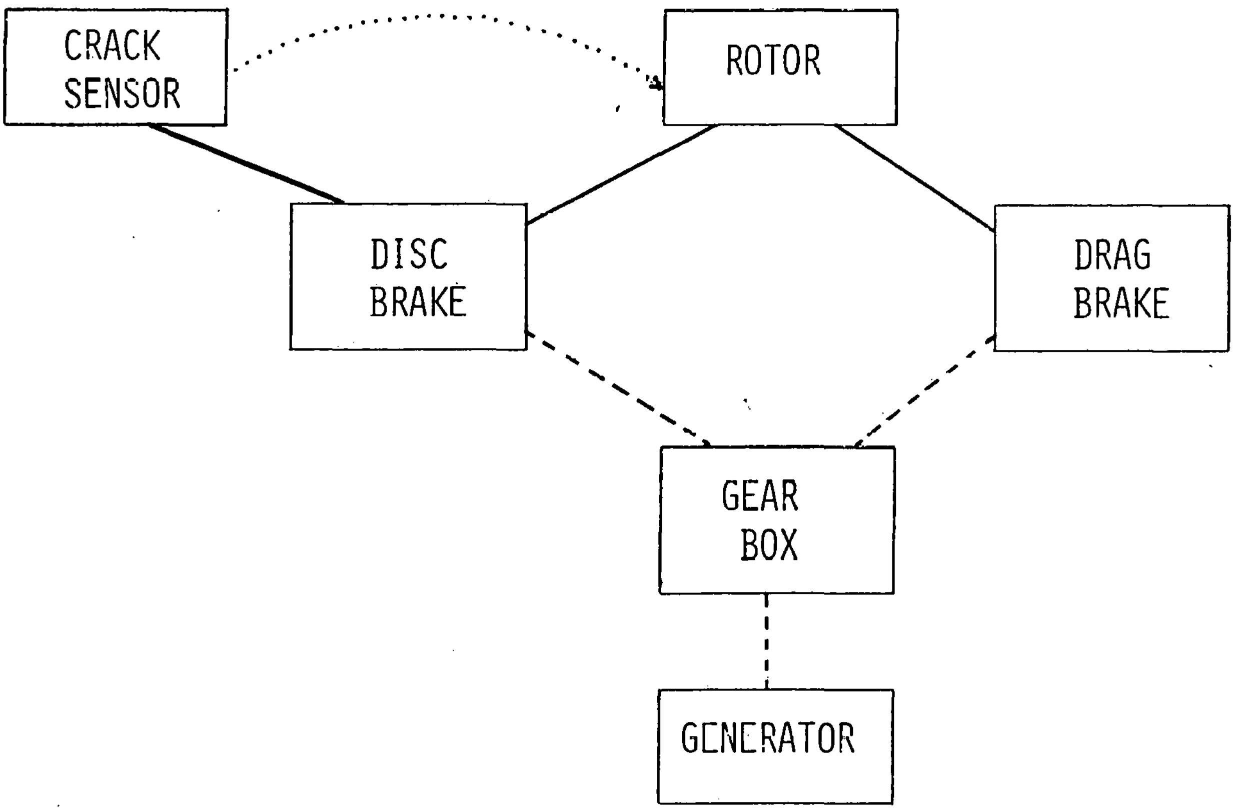

Figure 6-2. SIMPLIFIED WIND ENERGY CONVERSION SYSTEM WITH CRACK SENSOR

For the objective of system safety, the cut sets become:

- rotor and crack sensor (because if the rotor becomes defective and the crack sensor is not working then the system is in danger);
- rotor and disc brake (because if the rotor becomes defective and the disc brake is not working then the crack sensor has no means to stop the rotor); and
- disc brake and drag brake (as above).

The fact that the crack sensor is a rather unreliable device is expressed by its being assigned a one-year mean time to defect development (which we shall assume is followed immediately by or is synonymous with failure). Assume the crack sensor is inspected four times a year, but that the probability of detecting and correcting a defect is only 0.8.

The result of rerunning RASP with the crack sensor included is that the probability of catastrophic system failure becomes 0.0044, about three times less than that of the system without the crack sensor.

The above example shows how system reliability and safety projections can be made when data on component defect development and failure rates are available. It cannot be emphasized enough that component failure rates are often unknown or highly uncertain. This is the case, for example, for the rotor in a large wind turbine. Additional testing and experience will make better component failure rates available, which will improve the meaningfulness of system reliability and safety estimates. Even in the absence of good component failure rate estimates, however, the Reliability and Safety Program can compare different system designs to determine their relative reliability and safety.

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SECTION 7.0

CONCLUSION

The methodology embodied in the Reliability and Safety Program can be used to determine both system availability and the probability of catastrophic system failure. By investigating the sensitivity of these statistics to changes in the reliability of individual components, the methodology can identify critical components, thereby aiding in decisions relating to inspection and maintenance schedules, durability of various components, and system redundancies. Although the program was developed for wind energy conversion systems, it is a general one and would be useful for any system for which reliability and safety are major concerns.

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SECTION 8.0

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APPENDIX A

Output of
Reliability and Safety Program
for
Simplified Wind Energy Conversion System Example

SIMPLIFIED SKELETON WIND ENERGY CONVERSION SYSTEM

FUNCTION: RELIABLE AND SAFE OPERATION

COMPONENT:	1. ROTOR	2. DISC BRAKE	3. DRAG BRAKE
MEAN TIME TO DEFECT DEVELOPMENT (YEARS)	20.00	5.00	5.00
DOES FAILURE AFFECT SYSTEM SAFETY? (1=YES, 0=NO)	1	1	1
EXP. TIME IN DAYS TO CATASTROPHIC FAILURE, GIVEN DEFECTIVE	1000.00	10.00	10.00
DOES FAILURE CAUSE IMMED. SYSTEM FAILURE?	1	0	0
# OF INSPECTIONS OF THIS COMPONENT PER YR.	1.00	1.00	2.00
TIME REQD. TO INSPECT IN MAN-HOURS	16.00	4.00	4.00
PROB. OF DETECTING DE-FECT DURING INSPECTION	.8000	.9000	1.0000
SYSTEM SHUT DOWN DURING INSPECTION?	1	1	1
COMPONENT OPERABLE DURING INSPECTION?	0	0	0
INSPECTION COST IN $	1000.00	250.00	250.00
MEAN TIME TO DEFECT DETECTION (DAYS)	-1.0000	1.0000	-1.0000
MEAN TIME TO REPAIR (DAYS)	7.00	1.00	7.00
AVERAGE COST IN $ TO REPAIR/REPLACE	5000.00	1000.00	5000.00
SYSTEM SHUT DOWN DURING REPAIR?	1	1	1

COMPONENT:	4. GEAR BOX	5. GENERATOR
MEAN TIME TO DEFECT DEVELOPMENT (YEARS)	20.00	25.00
DOES FAILURE AFFECT SYSTEM SAFETY? (1=YES,0=NO)	0	0
EXP. TIME IN DAYS TO CATASTROPHIC FAILURE, GIVEN DEFECTIVE	0.00	0.00
DOES FAILURE CAUSE IMMED. SYSTEM FAILURE?	0	0
# OF INSPECTIONS OF THIS COMPONENT PER YR.	1.00	1.00
TIME REQD. TO INSPECT IN MAN-HOURS	4.00	4.00
PROB. OF DETECTING DE- FECT DURING INSPECTION	.7000	.7000
SYSTEM SHUT DOWN DURING INSPECTION?	1	1
COMPONENT OPERABLE DURING INSPECTION?	0	0
INSPECTION COST IN $	250.00	250.00
MEAN TIME TO DEFECT DETECTION (DAYS)	30.0000	30.0000
MEAN TIME TO REPAIR (DAYS)	7.00	7.00
AVERAGE COST IN $ TO REPAIR/REPLACE	3000.00	3000.00
SYSTEM SHUT DOWN DURING REPAIR?	1	1

MINIMAL PATH SETS

ROTOR
DISC BRAKE
GEAR BOX
GENERATOR

ROTOR
DRAG BRAKE
GEAR BOX
GENERATOR

MINIMAL CUT SETS

ROTOR

DISC BRAKE
DRAG BRAKE

GEAR BOX

GENERATOR

EXPECTED STATE RESIDENCE DURATIONS
FOR INDIVIDUAL COMPONENTS

(IN YEARS)

	NORMAL OPERATION	DEFECTIVE OPERATION	REPAIR	INSPECTION & MAINTENANCE
ROTOR	20.00000	.74795	.01918	.00274
DISC BRAKE	5.00000	.00274	.00274	.00068
DRAG BRAKE	5.00000	.24966	.01918	.00068
GEAR BOX	20.00000	.08219	.01918	.00068
GENERATOR	25.00000	.08219	.01918	.00068

STATE RESIDENCE PROBABILITIES
FOR INDIVIDUAL COMPONENTS

	NORMAL OPERATION	DEFECTIVE OPERATION	REPAIR	INSPECTION & MAINTENANCE
ROTOR	.96042	.03592	.00092	.00274
DISC BRAKE	.99822	.00055	.00055	.00068
DRAG BRAKE	.94768	.04732	.00363	.00136
GEAR BOX	.99428	.00409	.00095	.00068
GENERATOR	.99528	.00327	.00076	.00068

MAINTENANCE AND REPAIR COSTS ($ PER YEAR)

	INSPECTION & MAINTENANCE	REPAIR OR REPLACEMENT	TOTAL
ROTOR	999.08	240.11	1239.19
DISC BRAKE	249.86	199.64	449.51
DRAG BRAKE	498.18	947.68	1445.86
GEAR BOX	249.76	149.14	398.90
GENERATOR	249.81	119.43	369.24
TOTAL SYSTEM COSTS	2246.70	1656.01	3902.70

SIMPLIFIED SKELETON WIND ENERGY CONVERSION SYSTEM

FUNCTION: RELIABLE AND SAFE OPERATION

SYSTEM AVAILABILITY	94.5 PERCENT
UNAVAILABILITY DUE TO MAINTENANCE AND REPAIRS	1.3 PERCENT
PERCENTAGE DEFECTIVE OR SUB-STANDARD OPERATION	4.2 PERCENT
MEAN TIME TO CATASTROPHIC FAILURE	81.4 YEARS
PROBABILITY OF CATASTROPHIC FAILURE	.12E-01 PER YEAR
COST OF MAINTENANCE AND REPAIRS ($)	3902.70 PER YEAR

SENSITIVITIES TO 50 PCT. INCREASE IN MEAN TIME
TO DEFECT DEVELOPMENT, FOR EACH COMPONENT

CHANGE IN:

	SYSTEM AVAILABILITY	MEAN TIME TO CATASTROPHIC FAILURE	MAINTENANCE AND REPAIR COSTS
ROTOR	1.256 PCT	43.50 PCT	-1.99 PCT
DISC BRAKE	.040 PCT	2.23 PCT	-1.70 PCT
DRAG BRAKE	.153 PCT	2.15 PCT	-7.79 PCT
GEAR BOX	.180 PCT	0.00 PCT	-1.27 PCT
GENERATOR	.149 PCT	0.00 PCT	-1.02 PCT

SENSITIVITIES TO 50 PCT. DECREASE IN MEAN TIME
TO DETECT DEFECT, FOR EACH COMPONENT

CHANGE IN:

	SYSTEM AVAILABILITY	MEAN TIME TO CATASTROPHIC FAILURE	MAINTENANCE AND REPAIR COSTS
ROTOR	1.459 PCT	1424.51 PCT	.09 PCT
DISC BRAKE	-.063 PCT	6.54 PCT	-.00 PCT
DRAG BRAKE	-.142 PCT	2.90 PCT	.55 PCT
GEAR BOX	.128 PCT	0.00 PCT	.01 PCT
GENERATOR	.090 PCT	0.00 PCT	.00 PCT

SENSITIVITIES TO 50 PCT. DECREASE IN MEAN TIME
TO REPAIR, FOR EACH COMPONENT

CHANGE IN:

	SYSTEM AVAILABILITY	MEAN TIME TO CATASTROPHIC FAILURE	MAINTENANCE AND REPAIR COSTS
ROTOR	.042 PCT	-.04 PCT	.01 PCT
DISC BRAKE	.026 PCT	-.00 PCT	.00 PCT
DRAG BRAKE	.172 PCT	-.01 PCT	.07 PCT
GEAR BOX	.045 PCT	0.00 PCT	.00 PCT
GENERATOR	.036 PCT	0.00 PCT	.00 PCT

APPENDIX B

Listing of Reliability and Safety Program (RASP)

```
      PROGRAM RASP(INPUT,OUTPUT,TAPE5,TAPE6)
C
C**************************************************************************
C*                                                                        *
C*    R E L I A B I L I T Y   A N D   S A F E T Y   P R O G R A M        *
C*                                                                        *
C*                         ( R A S P )                                    *
C*                                                                        *
C**************************************************************************
C
C
C      THIS PROGRAM COMPUTES, FOR A GIVEN SYSTEM OF COMPONENTS:
C
C         - SYSTEM AVAILABILITY
C         - MEAN TIME TO CATASTROPHIC FAILURE
C         - MAINTENANCE COSTS
C
C--------------------------------------------------------------------------
C
C      INPUTS REQUIRED ARE:
C      --------------------
C
C      FOR EACH COMPONENT
C      -NAME OF COMPONENT (IN 15 CHARACTERS OR LESS)
C      -DOES FAILURE OF THIS COMPONENT AFFECT SYSTEM SAFETY?  IF YES,
C       -EXPECTED TIME IN DAYS UNTIL CATASTROPHIC FAILURE,
C        GIVEN THAT COMPONENT IS OPERATING DEFECTIVELY
C       -DOES FAILURE OF THIS COMPONENT CAUSE IMMEDIATE SYSTEM FAILURE?
C      -FREQUENCY OF INSPECTIONS OF THIS COMPONENT (NUMBER PER YEAR)
C      -TIME REQUIRED TO INSPECT THIS COMPONENT (MAN-HOURS)
C      -PROBABILITY OF DETECTING DEFECT DURING INSPECTION
C      -IS SYSTEM SHUT DOWN DURING INSPECTION OF THIS COMPONENT?  IF NO,
C       -IS COMPONENT OPERABLE DURING INSPECTION?
C      -INSPECTION COST ALLOCABLE TO THIS COMPONENT ($)
C      -MEAN TIME TO DEFECT DETECTION, IF LESS THAN TIME UNTIL
C       NEXT INSPECTION
C      -MEAN TIME TO REPAIR (DAYS)
C      -AVERAGE COST TO REPAIR/REPLACE THIS COMPONENT ($)
C      -IS SYSTEM SHUT DOWN DURING REPAIR OF THIS COMPONENT?
C
C      FOR SYSTEM
C      -SYSTEM STRUCTURE, OR RELIABILITY BLOCK DIAGRAM, AS SPECIFIED BY:
C       (1) ALL MINIMALLY SUFFICIENT SETS OF COMPONENTS FOR
C           NORMAL OPERATION (PATH SETS), AND
C       (2) ALL MINIMALLY SUFFICIENT SETS OF COMPONENTS FOR
C           DEFECTIVE OPERATION (CUT SETS)
C      -NUMBER OF PERSONNEL IN INSPECTION AND MAINTENANCE TEAM
C
C--------------------------------------------------------------------------
C
```

```
C
      COMMON/X/TITLE(8),FNCTN(8),CNAME(2,100),DT(100),FT(100),XNI(100),
     & H(100),Q(100),CI(100),DD(100),RT(100),CR(100),DDT(100),
     & TIM(100),PN(100),PD(100),PR(100),PIM(100),FR(100),PF(100),
     & IS(100),JI(100),KI(100),LR(100),IDP(100,30),NCP(100),
     & IDC(30,100),NCC(30),NP,NC,N,Z(100),IM(100)
      DATA UND/'----------'/
C
C
C   READ IN NAME OF SYSTEM FOR THIS RUN
      READ 10,TITLE
   10 FORMAT(8A10)
C
C   READ IN FUNCTION OF SYSTEM FOR THIS RUN (E.G. RELIABILITY OR
C   SAFETY OR BOTH)
      READ 10,FNCTN
C
C   READ NUMBER OF DIFFERENT COMPONENTS IN SYSTEM (UP TO 100)
      READ 20,N
   20 FORMAT(I3)
C
C   READ COMPONENT INPUTS FOR EACH COMPONENT
C   (COMPONENT I.D. NUMBERS WILL BE ASSIGNED IN INPUT ORDER)
      DO 30 I=1,N
   30 READ 40,CNAME(1,I),CNAME(2,I),DT(I),IS(I),FT(I),IM(I),XNI(I),H(I),
     & Q(I),JI(I),KI(I),CI(I),DD(I),RT(I),CR(I),LR(I)
   40 FORMAT(A10,A5,F10.2,I2,F8.2,I2,F7.2,F6.2,F6.4,2I2,F10.2,F10.4/
     & 2F10.2,I2)
C-----------------------------------------------------------------------
C   CNAME = NAME OF COMPONENT (15 CHARACTERS)
C   DT = MEAN TIME TO DEFECT DEVELOPMENT (YEARS) (F10.2)
C   IS = 1  IF FAILURE OF THIS COMPONENT AFFECTS SYSTEM SAFETY
C      = 0  IF NOT  (I2)
C   FT = EXPECTED TIME IN DAYS UNTIL CATASTROPHIC FAILURE, GIVEN THAT
C        COMPONENT IS OPERATING DEFECTIVELY (BLANK IF IS=0)  (F8.2)
C   IM = 1  IF FAILURE CAUSES IMMEDIATE SYSTEM FAILURE
C      = 0  IF NOT  (I2)
C   XNI = FREQUENCY OF INSPECTIONS OF THIS COMPONENT (#/YR)  (F7.2)
C   H = TIME IN MAN-HOURS REQUIRED TO INSPECT THIS COMPONENT  (F6.2)
C   Q = PROBABILITY OF DETECTING DEFECT DURING INSPECTION  (F6.4)
C   JI = 1  IF SYSTEM IS SHUT DOWN DURING INSPECTION OF THIS COMPONENT
C      = 0  IF NOT  (I2)
C   KI = 1  IF COMPONENT IS OPERABLE DURING INSPECTION
C      = 0  IF NOT, OR IF JI=1  (I2)
C   CI = INSPECTION COST IN $ ALLOCABLE TO THIS COMPONENT  (F10.2)
C   DD = MEAN TIME TO DEFECT DETECTION, IF LESS THAN TIME UNTIL
C        NEXT INSPECTION (DAYS)  (F10.4)
C      = MINUS ONE, IF TIME TO DEFECT DETECTION NOT LESS THAN TIME
C        UNTIL NEXT INSPECTION
C   RT = MEAN TIME TO REPAIR (DAYS)  (F10.2)
C   CR = AVERAGE COST IN $ TO REPAIR/REPLACE THIS COMPONENT  (F10.2)
C   LR = 1  IF SYSTEM IS SHUT DOWN DURING REPAIR OF THIS COMPONENT
C      = 0  IF NOT  (I2)
C-----------------------------------------------------------------------
```

```
C
C    PRINT OUT COMPONENT INPUTS
      PRINT 50,TITLE,FNCTN
   50 FORMAT(10(/),T11,
     & 'R E L I A B I L I T Y   A N D   S A F E T Y   P R O G R A M'
     & /T11,59('-'),5(/),8A10//8A10)
      DO 70 I=1,N,3
      M=I+2
      IF(M.GT.N)M=N
      PRINT 55,(K,K=I,M)
   55 FORMAT(5(/),10X,'COMPONENT:',T15,3(16X,I3,'.'))
      PRINT 60,((CNAME(J,K),J=1,2),K=I,M)
   60 FORMAT(20X,3(5X,A10,A5))
      PRINT 65,(UND,UND,K=I,M)
   65 FORMAT(20X,3(5X,A10,A5))
      PRINT 71,(DT(K),K=I,M)
      PRINT 72,(IS(K),K=I,M)
      PRINT 73,(FT(K),K=I,M)
      PRINT 74,(IM(K),K=I,M)
      PRINT 75,(XNI(K),K=I,M)
      PRINT 76,(H(K),K=I,M)
      PRINT 77,(Q(K),K=I,M)
      PRINT 78,(JI(K),K=I,M)
      PRINT 79,(KI(K),K=I,M)
      PRINT 80,(CI(K),K=I,M)
      PRINT 81,(DD(K),K=I,M)
      PRINT 82,(RT(K),K=I,M)
      PRINT 83,(CR(K),K=I,M)
   70 PRINT 84,(LR(K),K=I,M)
   71 FORMAT(/5X,'MEAN TIME TO DEFECT'/5X,'DEVELOPMENT (YEARS)',
     & T16,3(10X,F10.2))
   72 FORMAT(/5X,'DOES FAILURE AFFECT'/5X,'SYSTEM SAFETY?'/5X,
     & '(1=YES,0=NO)',T14,3(19X,I1))
   73 FORMAT(/5X,'EXP. TIME IN DAYS TO'/5X,'CATASTROPHIC FAILURE,'
     & /5X,'GIVEN DEFECTIVE',T16,3(10X,F10.2))
   74 FORMAT(/5X,'DOES FAILURE CAUSE'/5X,
     & 'IMMED. SYSTEM FAILURE?',T14,3(19X,I1))
   75 FORMAT(/5X,'# OF INSPECTIONS OF'/5X,'THIS COMPONENT PER YR.',
     & T16,3(13X,F7.2))
   76 FORMAT(/5X,'TIME REQD. TO INSPECT'/5X,'IN MAN-HOURS',
     & T16,3(14X,F6.2))
   77 FORMAT(/5X,'PROB. OF DETECTING DE-'/5X,
     & 'FECT DURING INSPECTION',T16,3(14X,F6.4))
   78 FORMAT(/5X,'SYSTEM SHUT DOWN'/5X,'DURING INSPECTION?',
     & T14,3(19X,I1))
   79 FORMAT(/5X,'COMPONENT OPERABLE'/5X,'DURING INSPECTION?',
     & T14,3(19X,I1))
   80 FORMAT(/5X,'INSPECTION COST IN $',T16,3(10X,F10.2))
   81 FORMAT(/5X,'MEAN TIME TO DEFECT'/5X,'DETECTION (DAYS)',
     & T18,3(10X,F10.4))
   82 FORMAT(/5X,'MEAN TIME TO REPAIR'/5X,'(DAYS)',T16,
     & 3(10X,F10.2))
   83 FORMAT(/5X,'AVERAGE COST IN $'/5X,'TO REPAIR/REPLACE',
     & T16,3(10X,F10.2))
   84 FORMAT(/5X,'SYSTEM SHUT DOWN'/5X,'DURING REPAIR?',T14,
     & 3(19X,I1))
C
```

```
C
C   READ SYSTEM INPUTS
C
C   READ NUMBER OF MINIMAL PATH SETS (UP TO 30) AND NUMBER OF
C   MINIMAL CUT SETS
      READ 90,NP,NC
   90 FORMAT(2I3)
C
C   READ NUMBER OF COMPONENTS IN EACH MINIMAL PATH SET, AND I.D.
C   NUMBERS OF COMPONENTS IN IT
      DO 110 J=1,NP
      READ 100,NCOMP,(IDP(I,J),I=1,NCOMP)
  100 FORMAT(20I4)
  110 NCP(J)=NCOMP
C
C   READ NUMBER OF COMPONENTS IN EACH MINIMAL CUT SET,
C   AND I.D. NUMBERS OF COMPONENTS IN IT
      DO 115 J=1,NC
      READ 100,NCOMP,(IDC(I,J),I=1,NCOMP)
  115 NCC(J)=NCOMP
C
C   PRINT PATH SET INFO
      PRINT 120
  120 FORMAT(10(/),T32,'MINIMAL PATH SETS'/T32,17('-'))
      DO 140 J=1,NP
      NCOMP=NCP(J)
      PRINT 130
  130 FORMAT(/)
      DO 140 I=1,NCOMP
  140 PRINT 150,CNAME(1,IDP(I,J)),CNAME(2,IDP(I,J))
  150 FORMAT(T33,A10,A5)
C
C   PRINT CUT SET INFO
      PRINT 160
  160 FORMAT(10(/),T33,'MINIMAL CUT SETS'/T33,17('-'))
      DO 170 J=1,NC
      NCOMP=NCC(J)
      PRINT 130
      DO 170 I=1,NCOMP
  170 PRINT 150,CNAME(1,IDC(I,J)),CNAME(2,IDC(I,J))
C
C   READ NUMBER OF PERSONNEL ON INSPECTION AND MAINTENANCE TEAM
C   (MAY BE FRACTIONAL)
      READ 180,PERS
  180 FORMAT(F6.2)
C
```

```
C
C   COMPUTE STATE RESIDENCE DURATIONS AND PROBABILITIES
C   FOR EACH COMPONENT
      DO 190 I=1,M
C
C   FIND RATIO OF INSPECTION TIME TO NORMAL
C   OR DEFECTIVE OPERATION TIME
      RATIO=XNI(I)*H(I)/(2920.*PERS)
      IF(RATIO.GT..9999)RATIO=.9999
C
C   FIND EXPECTED TIME TO DETECTION OF DEFECT
      DDT(I)=(1./XNI(I)-H(I)/(2920.*PERS))*(2.-Q(I))/(2.*Q(I))
      IF(DD(I).LT.0.)DD(I)=99999999.
      IF(DDT(I).GT.(DD(I)/365.))DDT(I)=DD(I)/365.
C
C   COMPUTE DOWN TIME FOR INSPECTION AND MAINTENANCE DURING CYCLE
      TIM(I)=(DT(I)+DDT(I)-DT(I)*RATIO*(1.-JI(I))*KI(I))
     & *RATIO/(1.-RATIO)
C
C   FIND DOWN TIME FOR COMPONENT REPAIR
      RT(I)=RT(I)*LR(I)/365.
C
C   COMPUTE DEFECTIVE OPERATION TIME, INCLUDING POSSIBLE OPERATION
C   DURING REPAIR OR MAINTENANCE
      DDT(I)=DDT(I)+RT(I)*(1-LR(I))+TIM(I)*(1-JI(I))
C
C   FIND COMPONENT CYCLE TIME
      Z(I)=DT(I)+DDT(I)+RT(I)+TIM(I)
C
C   FIND EXPECTED INSPECTION AND MAINTENANCE COST PER YEAR
      CI(I)=XNI(I)*CI(I)*(DT(I)+DDT(I)+TIM(I))/Z(I)
C
C   FIND EXPECTED REPAIR/REPLACEMENT COST PER YEAR
      CR(I)=CR(I)/Z(I)
C
C   FIND PROBABILITY OF NORMAL OPERATION
      PN(I)=DT(I)/Z(I)
C
C   FIND PROBABILITY OF DEFECTIVE OPERATION
      PD(I)=DDT(I)/Z(I)
C
C   FIND PROBABILITY OF BEING UNDER REPAIR
      PR(I)=RT(I)/Z(I)
C
C   FIND PROBABILITY OF INSPECTION AND MAINTENANCE
      PIM(I)=TIM(I)/Z(I)
C
C   COMPUTE FAILURE RATE, WHEN DEFECTIVE
      IF(IS(I).EQ.0)FR(I)=0.
      IF(IS(I).EQ.0)GO TO 185
      IF(FT(I).EQ.0.)FT(I)=1.E-6
      FR(I)=365./FT(I)
C
C   COMPUTE PROBABILITY COMPONENT IS FAILED
  185 IF(IS(I).EQ.0)PF(I)=0.
      IF(IS(I).EQ.0)GO TO 190
      EXPNT=FR(I)*DDT(I)
      IF(EXPNT.GT.90.)EXPNT=90.
      PF(I)=PD(I)-(1.-EXP(-EXPNT))/(Z(I)*FR(I))
  190 H(I)=H(I)/(2920.*PERS)
C
```

```
C
C   PRINT OUT STATE RESIDENCE DURATIONS AND PROBABILITIES
      PRINT 200
  200 FORMAT(10(/),T24,'EXPECTED STATE RESIDENCE DURATIONS'/T28,
     & 'FOR INDIVIDUAL COMPONENTS'//T36,'(IN YEARS)'//)
      PRINT 210,(CNAME(1,I),CNAME(2,I),DT(I),DDT(I),RT(I),H(I),I=1,N)
  210 FORMAT(T28,'NORMAL',T40,'DEFECTIVE',T55,'REPAIR',T66,
     & 'INSPECTION &'/T26,'OPERATION',T40,'OPERATION',T67,
     & 'MAINTENANCE'/T26,9('-'),T40,9('-'),T55,6('-'),T66,12('-')
     & ,(/5X,A10,A5,4F13.5))
      PRINT 220
  220 FORMAT(5(/),T26,'STATE RESIDENCE PROBABILITIES'/T28,
     & 'FOR INDIVIDUAL COMPONENTS'//)
      PRINT 210,(CNAME(1,I),CNAME(2,I),PN(I),PD(I),PR(I),PIM(I),I=1,N)
C
C
C   PRINT OUT MAINTENANCE AND REPAIR COSTS
      PRINT 230
  230 FORMAT(10(/),T20,'MAINTENANCE AND REPAIR COSTS  ($ PER YEAR)'///
     & T29,'INSPECTION &',T49,'REPAIR OR'/T30,'MAINTENANCE',T48,
     & 'REPLACEMENT',T69,'TOTAL'/T29,12('-'),T48,11('-'),T69,5('-'))
      CIM=0.
      CRR=0.
      DO 250 I=1,N
      CTOT=CI(I)+CR(I)
      PRINT 240,CNAME(1,I),CNAME(2,I),CI(I),CR(I),CTOT
  240 FORMAT(/5X,A10,A5,3F18.2)
      CIM=CIM+CI(I)
  250 CRR=CRR+CR(I)
      CTOT=CIM+CRR
      PRINT 260,CIM,CRR,CTOT
  260 FORMAT(/T21,3(10X,8('-'))//2X,'TOTAL SYSTEM COSTS',T21,3(F18.2))
C
C
C   CALL CRASP TO COMPUTE SYSTEM RELIABILITY AND SAFETY STATISTICS
      CALL CRASP(SA,UMR,DEF,FTIME,FPROB)
C
C   PRINT SYSTEM RELIABILITY AND SAFETY STATISTICS
      PRINT 270,TITLE,FNCTN,SA,UMR,DEF,FTIME,FPROB,CTOT
  270 FORMAT(15(/),8A10//8A10///4X,'SYSTEM AVAILABILITY',T54,2PF15.1,
     & 1X,'PERCENT'//4X,'UNAVAILABILITY DUE TO MAINTENANCE AND REPAIRS',
     & T54,2PF15.1,1X,'PERCENT'//4X,
     & 'PERCENTAGE DEFECTIVE OR SUB-STANDARD OPERATION',T54,2PF15.1,1X,
     & 'PERCENT'//4X,'MEAN TIME TO CATASTROPHIC FAILURE',T51,0PF18.1,
     & 1X,'YEARS'//4X,'PROBABILITY OF CATASTROPHIC FAILURE',T54,E15.2,
     & 1X,'PER YEAR'//4X,'COST OF MAINTENANCE AND REPAIRS ($)',T54,
     & F15.2,1X,'PER YEAR')
C
```

```
C
C   INVESTIGATE SENSITIVITIES TO 50 PCT. INCREASE IN MEAN TIME TO
C   DEFECT DEVELOPMENT, FOR EACH COMPONENT
      PRINT 280
  280 FORMAT(8(/),T18,'SENSITIVITIES TO 50 PCT. INCREASE IN MEAN TIME'/
     & T20,'TO DEFECT DEVELOPMENT, FOR EACH COMPONENT')
      PRINT 290
  290 FORMAT(//T22,'CHANGE IN:'//T27,'SYSTEM',T42,'MEAN TIME TO',T60,
     & 'MAINTENANCE AND'/T24,'AVAILABILITY',T38,'CATASTROPHIC FAILURE',
     & T61,'REPAIR COSTS'/T24,12('-'),T38,20('-'),T60,15('-'))
      DO 300 I=1,N
      ZNEW=1.5*DT(I)+DDT(I)+RT(I)+TIM(I)
      PN(I)=1.5*DT(I)/ZNEW
      PD(I)=DDT(I)/ZNEW
      PR(I)=RT(I)/ZNEW
      PIM(I)=TIM(I)/ZNEW
      FF=PF(I)
      PF(I)=Z(I)*FF/ZNEW
      CALL CRASP(SAN,UMRN,DEFN,FTIMEN,FPROBN)
      CAV=SAN-SA
      CMTTF=FTIMEN/FTIME-1
      PN(I)=DT(I)/Z(I)
      PD(I)=DDT(I)/Z(I)
      PR(I)=RT(I)/Z(I)
      PIM(I)=TIM(I)/Z(I)
      PF(I)=FF
      CINEW=CI(I)*Z(I)*(ZNEW-RT(I))/(ZNEW*(Z(I)-RT(I)))
      CRNEW=CR(I)*Z(I)/ZNEW
      CC=(CTOT-CI(I)-CR(I)+CINEW+CRNEW)/CTOT-1.
  300 PRINT 310,CNAME(1,I),CNAME(2,I),CAV,CMTTF,CC
  310 FORMAT(/5X,A10,A5,2PF10.3,1X,'PCT',2PF14.2,1X,'PCT',2PF14.2,1X,
     & 'PCT')
C
C   INVESTIGATE SENSITIVITIES TO 50 PCT. DECREASE IN MEAN TIME
C   TO DETECT DEFECT
      PRINT 320
  320 FORMAT(8(/),T18,'SENSITIVITIES TO 50 PCT. DECREASE IN MEAN TIME'/
     & T23,'TO DETECT DEFECT, FOR EACH COMPONENT')
      PRINT 290
      DO 330 I=1,N
      ZNEW=DT(I)+.5*DDT(I)+RT(I)+2.*TIM(I)
      PD(I)=.5*DDT(I)/ZNEW
      PIM(I)=2.*TIM(I)/ZNEW
      PN(I)=DT(I)/ZNEW
      PR(I)=RT(I)/ZNEW
      FF=PF(I)
      IF(IS(I).EQ.0)PF(I)=0.
      IF(IS(I).EQ.0)GO TO 325
      EXPNT=.5*FR(I)*DDT(I)
      IF(EXPNT.GT.90.)EXPNT=90.
      PF(I)=PD(I)-(1.-EXP(-EXPNT))/(FR(I)*ZNEW)
  325 CALL CRASP(SAN,UMRN,DEFN,FTIMEN,FPROBN)
```

```
      CAV=SAN-SA
      CMTTF=FTIMEN/FTIME-1.
      PD(I)=DDT(I)/Z(I)
      PIM(I)=TIM(I)/Z(I)
      PN(I)=DT(I)/Z(I)
      PR(I)=RT(I)/Z(I)
      PF(I)=FF
      CINEW=CI(I)*Z(I)*(ZNEW-RT(I))/(ZNEW*(Z(I)-RT(I)))
      CRNEW=CR(I)*Z(I)/ZNEW
      CC=(CTOT-CI(I)-CR(I)+CINEW+CRNEW)/CTOT-1.
  330 PRINT 310,CNAME(1,I),CNAME(2,I),CAV,CMTTF,CC
C
C   INVESTIGATE SENSITIVITIES TO 50 PCT. DECREASE IN MEAN TIME TO REPAIR
      PRINT 340
  340 FORMAT(8(/),T18,'SENSITIVITIES TO 50 PCT. DECREASE IN MEAN TIME'/
     & T26,'TO REPAIR, FOR EACH COMPONENT')
      PRINT 290
      DO 350 I=1,N
      ZNEW=DT(I)+DDT(I)+.5*RT(I)+TIM(I)
      PR(I)=.5*RT(I)/ZNEW
      PN(I)=DT(I)/ZNEW
      PD(I)=DDT(I)/ZNEW
      PIM(I)=TIM(I)/ZNEW
      FF=PF(I)
      PF(I)=Z(I)*FF/ZNEW
      CALL CRASP(SAN,UMRN,DEFN,FTIMEN,FPROBN)
      CAV=SAN-SA
      CMTTF=FTIMEN/FTIME-1.
      PN(I)=DT(I)/Z(I)
      PD(I)=DDT(I)/Z(I)
      PR(I)=RT(I)/Z(I)
      PIM(I)=TIM(I)/Z(I)
      PF(I)=FF
      CINEW=CI(I)*Z(I)*(ZNEW-.5*RT(I))/(ZNEW*(Z(I)-RT(I)))
      CRNEW=CR(I)*Z(I)/ZNEW
      CC=(CTOT-CI(I)-CR(I)+CINEW+CRNEW)/CTOT-1.
  350 PRINT 310,CNAME(1,I),CNAME(2,I),CAV,CMTTF,CC
      STOP
      END
```

Note: Subroutine CRASP is available upon request.

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15. Supplementary Notes

16. Abstract (Limit: 200 words)

In conventional system reliability calculations, each component may be in the Operable state or the Under Repair state. These calculations derive system unavailability, or the probability of the system's being down for repairs. By introducing a third component state between Operable and Under Repair -- namely, Defective, But Defect Undetected -- the methods developed in this report enable system safety projections to be made in addition to availability projections. Also provided is a mechanism for computing the effect of inspection schedules on both safety and availability. A Reliability and Safety Program (RASP) is detailed which performs these computations and also calculates costs for system inspections and repairs. RASP is applied to a simplified wind energy conversion system example.

17. Document Analysis

a. Descriptors Wind Energy Conversion Systems; Reliability; Technology Assessment; Safety; Performance; Performance Testing; Components; Probability; Repair; Maintenance; Replacement; Cost; Rotors; Wind Turbines; Electric Generators; Gears; Brakes; Statistics.

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