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# MODELLING OF GENERATOR FAILURES WITHIN A WIND TURBINE

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**ABSTRACT**
Failure modelling is a practical means of assessing and improving the performance of an asset over its life-cycle. Failure characteristic of generators within a particular type of 600 kW wind turbine is assessed and modelled by using Reliasoft Weibull++ 7 software. The shape ($\beta$) and scale ($\eta$) parameters of the generator are estimated. The estimated parameters are used to populate the Reliability Block Diagrams to model the failures of the generator.

**KEY WORDS**
Modelling, simulation, wind turbine, generator failure

## 1. Introduction

Global warming is increasingly becoming a crucial issue in the daily affairs of all living things in the contemporary world. The seriousness of the issue is reflected through the recent commitment of corporate organizations and individuals to combat the effects of global warming. In 1997 the *United Nations* adopted the *Kyoto Protocol* as an amendment to the *Framework Convention on Climate Change (FCCC)*. The Protocol is a legally binding agreement under which industrialised countries are obliged to reduce collective emissions of greenhouse gases [1]. Countries which ratify the protocol commit to reduce their emissions of carbon dioxide and five other greenhouse gases, or engage in emissions trading if they maintain or increase emissions of these gases.

Energy generated from wind is fast becoming one of the most utilised renewable energy sources in the world [2]. As a result, the wind industry is increasingly dominating the renewable energy sector. Improvements in the design of wind turbines [3] and the ready availability of wind resources in most parts of the world are contributing to the rapid development of the industry. Progressively, the world generated wind energy has now increased to about 59,322 MW [4] from 2,000 MW in 1990 [5] with an annual average growth rate of about 26 percent [6]. However, with this huge investment potential and significant increase in generation capacity comes an additional and often overlooked responsibility; the management of wind farms to ensure the lowest total Life Cycle Cost (LCC). Thus, to increase the productivity and profitability of the existing wind farms, and to ensure the lowest total LCC for successful future developments will require modelling and simulation of wind turbines' components and subsystems failures.

## 2. Modelling

### 2.1 Approach and Methodology

Modelling System Failures (MSF) is a quantitative approach to maintenance optimisation which has been recommended as the best technique to assess and optimise the reliability, availability and maintainability of mechanical systems [7]. The MSF technique investigates the operations and failure patterns of equipment by taking into account failure distribution, repair delays, spare-holding, and resource availability to determine optimum maintenance requirements [7]. The first step in the approach is to identify a suitable statistical distribution that will best fit the assessed failure characteristics of the physical asset. Secondly, a suitable parameter estimation method is selected to calculate the parameters of the identified statistical distribution. Then, the calculated parameters are used to build Reliability Block Diagrams (RBD) which permits the use of Monte Carlo simulation to determine the optimal levels of key maintenance variables such as costs, spare holdings as well as the level of reliability and availability required.

#### 2.1.1 Statistical Distributions

Fundamentally, there are three failure patterns that describe failure characteristics of mechanical systems [7]. These include reducing, constant and increasing failures as illustrated in Figure 1. The figure displays a curve usually referred to as a hazard rate or most commonly a bath-tub curve. The reducing failure pattern usually known as the infant mortality denotes failures that occur at the early-life of equipment and the likelihood of occurrence reduces as the age of the equipment increases. The constant failure pattern represents failures that are independent of equipment age, that is, the likelihood of occurrence is invariable through out the life-cycle of the equipment. Lastly, the increasing failure pattern commonly referred to as wear-out symbolises failures that occur at the later life of equipment, that is, the likelihood of occurrence increases with the age of the equipment. The reader is referred to [8] for a more detailed study on types of failure pattern.

A number of statistical distributions exist to fit the failure patterns afore described. Exponential distribution describes a constant hazard rate [7] while Normal and Lognormal describe the increasing hazard rate [7]. However, the most commonly used distribution is the Weibull named after a Swedish engineer Waloddi

Weibull (1887-1979) who formulated and popularised the use of the distribution for reliability analysis. The distribution is very versatile as it fits all the three basic patterns of failure.

### 2.1.2 The Weibull Distribution

This distribution can be represented in 3 different forms; 3-parameter, 2-parameter and 1-parameter. The 2-parameter Weibull distribution denoted by a probability density function (pdf) and cumulative distribution function (cdf) as given in Equations 1 and 2 respectively is considered exclusively.

$$f(T)=\frac{\beta}{\eta}\left(\frac{T}{\eta}\right)^{\beta-1}e^{-\left(\frac{T}{\eta}\right)^{\beta}} \; ; T\geq 0,\ \beta>0,\ \eta>0 \tag{1}$$

$$F(T)=1-e^{-\left(\frac{T}{\eta}\right)^{\beta}} \tag{2}$$

where β and η represent the shape and scale parameter respectively. The value of β describes the failure pattern of the equipment. As a general rule, (β < 1) means a reducing failure pattern, (β =1) signifies a constant failure pattern and (β >1) indicates an increasing failure pattern, as depicted in Figure 1. The scale parameter denotes the characteristic life of the equipment; the time at which there is an approximately 0.632 probability that the equipment will have failed [7]. Estimating the parameters requires a suitable method that will best fit the characteristics of the collated data.

### 2.1.3 Parameter Estimation Methods

Common parameter estimation methods include probability plots, regression analysis and Maximum Likelihood Estimation (MLE). The characteristics of data collated influence the estimation method to be used. Field or life-failure data are seldom complete as they are often subjected to suspensions or censorings. An item could have been temporarily removed from the test during the test-interval or the test-interval could elapse before an item fails. The probability plot and the regression analysis are limited in dealing with data sets containing a relatively large number of suspensions or censorings [9]. The MLE takes into account the times-to-suspension or censoring in the estimation process which makes it a more robust and rigorous estimation method. The process of using the maximum likelihood to estimate the parameters of the Weibull distribution when data are censored is discussed in the next subsection.

### 2.1.4 Maximum Likelihood Estimation in the Weibull Distribution

Consider a random failure sample consisting of multiple censoring or suspension. Suppose that censoring occurs progressively in $k$ stages at times $T_i$ where $T_i > T_{i-1}$, $i=1,2,\ldots k$ and that at the *ith* stage of censoring $r_i$ sample specimens selected randomly from the survivors at time $T_i$ are removed from further observation. If $N$ designates the total sample size and $n$ the number of specimens which fail at times $T_j$ and therefore provide completely determined life spans [9], it follows that

$$N=n+\sum_{i=1}^{k} r_i \tag{3}$$

The likelihood function is

$$L=C\prod_{j=1}^{n} f(T_j)\ \prod_{i=1}^{k}\left[1-F(T_i)\right]^{r_i} \tag{4}$$

where $C$ is a constant, *f(T)* is the pdf, and *F(T)* is the cdf.

Substituting equations 1 and 2 in 4, then taking the natural logarithm and then the partial derivatives with respect to β and η will result in Equations 5 and 6 [10]. These can be used to estimate the values of β and η respectively.

$$\beta(0)=\frac{\sum_{j=1}^{n}(T_j)^{\beta}\ln T_j+\sum_{i=1}^{k}r_i(T)_i^{\beta}\ln T_i}{\sum_{j=1}^{n}(T_j)^{\beta}+\sum_{i=1}^{k}r_i(T)_i^{\beta}}-\frac{1}{n}\sum_{j=1}^{n}\ln T_j+\frac{1}{\ln\left(\frac{\sum_{j=1}^{n}(T_j)^{\beta}+\sum_{i=1}^{k}r_i(T)_i^{\beta}}{n}\right)} \tag{5}$$

$$\eta=\left(\frac{\left[\sum_{j=1}^{n}(T_j)^{\beta}+\sum_{i=1}^{k}r_i(T_i)^{\beta}\right]}{n}\right)^{\frac{1}{\beta}} \tag{6}$$

The estimated values of β and η are used to design Reliability Block Diagrams (RBD). These are employed in modelling failures of the generator.

## 2.2 Data collection

Historical failure data pertinent to generators of a particular type of 600 kW wind turbine were extracted from the Supervisory Control and Data Acquisition (SCADA) system. The SCADA system records failures and the date and time of occurrence; this was used in conjunction with maintenance Work Orders (WOs) of the same period to ascertain the specific type of failure and the components involved. Table 1 shows the failure data of the 600 kW wind turbines' generator over a period of 9 years (1997-2005).

In sorting out the data confidentially, the wind farms were labelled alphabetically. For instance, the 'WF-F' in Table 1, column 1 denotes Wind Farm F. Furthermore, the wind turbines are numbered in each of the wind farms; for example, the 'WF-F-WT-1' in Table 1, column 2 denotes 'Wind Farm F-Wind Turbine 1'. The serial numbers of the generators are recorded in column 3. Also, the manufacturers of the failed components are numbered and recorded in column 4. The fail-date and fail-time from the base-date as well as the causes of failure are recorded in the table.

## 2.3 Field failure data analysis

The shape (β) and scale (η) parameters for the generator and its components are estimated using the ReliaSoft Weibull ++7 software [11] which is based on the fundamental mathematical principles presented in the approach and methodology section. The results are presented in Table 2. The estimated values of β and η for the generator are 1.107 and 17541 respectively. The β value of 1.11 indicates a *random failure pattern*. The Weibull plot is shown in Figure 2. The pdf and failure rate plots are shown in Figures 3 and 4 respectively. The pdf plot of the generator is slightly skewed to the left.

The failure rate plot of the generator in Figure 4 shows a horizontal line which explains the randomness of the failure characteristics of the generator. Note that the estimated mean time between failures of the generator is 16888 days.

## 2.4 Modelling

The estimated values of β and η are used to model the failures of the generator. In the modelling, Reliability Block Diagrams are designed to incorporate the failure characteristics of the components. Figure 5 shows the Reliability Block Diagram of a typical generator in the 600 kW horizontal axis wind turbine. The components are connected in series and the estimated β and η values of each component are incorporated into the RBD. Note that any component which failure data was not available has been set to 'block cannot fail' in the modelling. This is to avoid subjective and illogical assumptions about the component and to ensure the modelling is based solely on field failure data.

The blades of the turbine are connected in parallel as they operate independently. However, all the blades must be in good operating condition before the wind turbine can function. This operating condition is depicted in the 3-out of-3 node (i.e. 3oo3) in figure 5. Similar condition applies to the main bearings which require a 2-out of-2. The operating condition of the mechanical and aerodynamic brakes are however different, one of the brakes is enough to stop the turbine (i.e. 1-out of-2).

## 2.5 Graphs, Tables, and Photographs

Table 1
Failure data of generators

| Farm (*WF*) | Wind Turbine (*WT*) | Serial number | Component Manufacturer | Fail date dd/mm/yyyy | Fail time (days) | Windings | Bearings | Generator catastrophic | Causes of failure |
|---|---|---|---|---|---|---|---|---|---|
| *WF-F* | *WF-F-WT-1* | GSN-1 | 4 | "24/02/1997" | 55 | S | S | F | Fatigue |
| *WF-F* | *WF-F-WT-22* | GSN-2 | 4 | "15/02/1998" | 411 | S | F | S | Fatigue |
| *WF-F* | *WF-F-WT-15* | GSN-2 | 4 | "01/06/2000" | 424 | F | S | F | Fatigue |
| *WF-F* | *WF-F-WT-15* | GSN-3 | 4 | "01/03/1999" | 789 | S | F | S | Fatigue |
| *WF-F* | *WF-F-WT-18* | GSN-4 | 4 | "01/06/1999" | 881 | S | F | S | Other |
| *WF-F* | *WF-F-WT-12* | GSN-5 | 4 | "01/12/2000" | 548 | S | S | F | Other |
| *WF-F* | *WF-F-WT-12* | GSN-6 | 4 | "01/10/1999" | 1003 | F | S | S | Poor Design |
| *WF-F* | *WF-F-WT-17* | GSN-7 | 4 | "15/12/1999" | 1080 | F | S | S | Unknown |
| *WF-F* | *WF-F-WT-15* | GSN-7 | 4 | "01/01/2002" | 746 | F | S | S | Poor Design |
| *WF-F* | *WF-F-WT-15* | GSN-7 | 4 | "01/07/2002" | 181 | F | S | S | Poor Design |
| *WF-F* | *WF-F-WT-5* | GSN-8 | 4 | "08/01/2000" | 1307 | S | F | S | Fatigue |
| *WF-F* | *WF-F-WT-24* | GSN-9 | 4 | "08/01/2000" | 1307 | S | S | F | Poor Design |
| *WF-F* | *WF-F-WT-16* | GSN-10 | 4 | "01/11/2000" | 1399 | S | F | S | Poor Design |
| *WF-F* | *WF-F-WT-7* | GSN-11 | 4 | "01/06/2002" | 1977 | S | F | S | Poor Design |
| *WF-D* | *WF-D-WT-26* | *GSN-12* | 4 | "21/01/2003" | 2211 | S | F | S | Fatigue |
| *WF-A* | *WF-A-WT-29* | *GSN-13* | 4 | "29/01/2003" | 2219 | S | F | S | Fatigue |
| *WF-A* | *WF-A-WT-20* | *GSN-14* | 4 | "09/04/2003" | 2289 | S | F | S | Fatigue |
| *WF-C* | *WF-C-WT-11* | *GSN-15* | 4 | "09/05/2003" | 2319 | S | F | S | Fatigue |
| *WF-A* | *WF-A-WT-18* | *GSN-16* | 4 | "09/06/2003" | 2349 | F | S | S | Fatigue |
| *WF-A* | *WF-A-WT-8* | *GSN-17* | 4 | "24/06/2003" | 2364 | S | F | S | Fatigue |
| *WF-D* | *WF-D-WT-4* | *GSN-18* | 4 | "07/08/2003" | 2409 | S | F | S | Fatigue |
| *WF-D* | *WF-D-WT-2* | *GSN-19* | 4 | "28/08/2003" | 2430 | F | S | S | Fatigue |
| *WF-D* | *WF-D-WT-27* | *GSN-20* | 4 | "15/09/2003" | 2445 | S | F | S | Fatigue |
| *WF-A* | *WF-A-WT-21* | *GSN-21* | 4 | "11/11/2003" | 2535 | F | F | F | Fatigue |
| *WF-H* | *WF-H-WT-11* | *GSN-22* | 4 | "13/11/2003" | 2537 | S | F | S | Fatigue |
| *WF-A* | *WF-A-WT-7* | *GSN-23* | 4 | "29/12/2003" | 2553 | S | F | S | Fatigue |
| *WF-A* | *WF-A-WT-20* | *GSN-24* | 4 | "29/01/2004" | 2584 | S | F | S | Other |
| *WF-C* | *WF-C-WT-8* | *GSN-25* | 4 | "04/03/2004" | 2618 | S | F | S | Other |
| *WF-E* | *WF-E-WT-20* | *GSN-26* | 4 | "25/03/2004" | 2639 | F | S | S | Poor Design |
| *WF-F* | *WF-F-WT-20* | *GSN-27* | 4 | "25/03/2004" | 2639 | S | S | S | Unknown |
| *WF-I* | *WF-I-WT-1* | *GSN-28* | 4 | "20/04/2004" | 2665 | S | F | S | Poor Design |
| *WF-D* | *WF-D-WT-15* | *GSN-29* | 4 | "23/04/2004" | 2668 | S | S | S | Fatigue |
| *WF-A* | *WF-A-WT-1* | *GSN-30* | 4 | "04/05/2004" | 2679 | F | F | F | Poor Design |
| *WF-D* | *WF-D-WT-27* | *GSN-31* | 4 | "07/05/2004" | 2682 | S | F | S | Poor Design |
| *WF-E* | *WF-E-WT-4* | *GSN-32* | 4 | "18/06/2004" | 2724 | S | F | S | Poor Design |
| *WF-I* | *WF-I-WT-6* | *GSN-33* | 4 | "26/06/2004" | 2732 | S | F | S | Poor Design |
| *WF-G* | *WF-G-WT-9* | *GSN-34* | 4 | "08/07/2004" | 2744 | S | S | S | Other |
| *WF-A* | *WF-A-WT-29* | *GSN-35* | 4 | "13/07/2004" | 2749 | S | F | S | Poor Design |
| *WF-A* | *WF-A-WT-17* | *GSN-36* | 4 | "16/07/2004" | 2752 | S | F | F | Poor Design |
| *WF-C* | *WF-C-WT-19* | *GSN-37* | 4 | "30/07/2004" | 2766 | S | S | S | Poor Design |
| *WF-C* | *WF-C-WT-10* | *GSN-38* | 4 | "12/08/2004" | 2779 | S | S | F | Poor Design |
| *WF-E* | *WF-E-WT-11* | *GSN-39* | 4 | "17/09/2004" | 2815 | S | F | S | Poor Design |
| *WF-D* | *WF-D-WT-28* | *GSN-40* | 4 | "21/09/2004" | 2819 | S | F | S | Poor Design |
| *WF-E* | *WF-E-WT-16* | *GSN-41* | 4 | "25/10/2004" | 2853 | F | S | S | Fatigue |
| *WF-E* | *WF-E-WT-13* | *GSN-42* | 4 | "07/11/2004" | 2866 | F | S | S | Fatigue |
| *WF-I* | *WF-I-WT-7* | *GSN-43* | 4 | "29/12/2004" | 2918 | F | S | S | Poor Design |
| *WF-A* | *WF-A-WT-24* | *GSN-44* | 4 | "02/01/2005" | 2922 | F | S | S | Poor Design |
| *WF-A* | *WF-A-WT-6* | *GSN-45* | 4 | "28/02/2005" | 2969 | F | F | F | Poor Design |
| *WF-I* | *WF-I-WT-13* | *GSN-46* | 4 | "07/04/2005" | 3007 | S | F | S | Poor Design |
| *WF-A* | *WF-A-WT-19* | *GSN-47* | 4 | "26/04/2005" | 3026 | S | F | S | Poor Design |
| *WF-J* | *WF-J-WT-9* | *GSN-48* | 4 | "12/09/2005" | 3165 | S | F | S | Poor Design |

Table 2
Shape and scale parameters of components of generator within a 600 kW wind turbine

| Sub-system | Components | Distribution | Analysis | Shape (β) | Scale (η) | Likeli-hood | Failed | Suspended | Mean Life |
|---|---|---|---|---|---|---|---|---|---|
| Generator | — | Weibull-2P | MLE | 1.11 | 17541 | -98.70 | 9 | 68 | 16888 |
| | Bearings | Weibull-2P | MLE | 3.35 | 3599 | -283.98 | 31 | 46 | 3231 |
| | Windings | Weibull-2P | MLE | 1.78 | 6574 | -154.62 | 15 | 62 | 5850 |

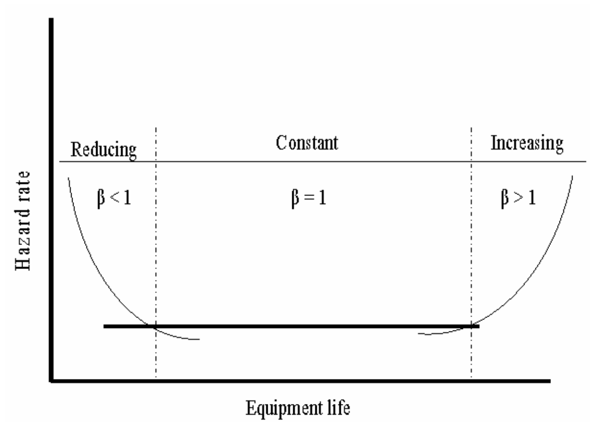

Figure 1 'Bath-Tub' curve showing failure patterns

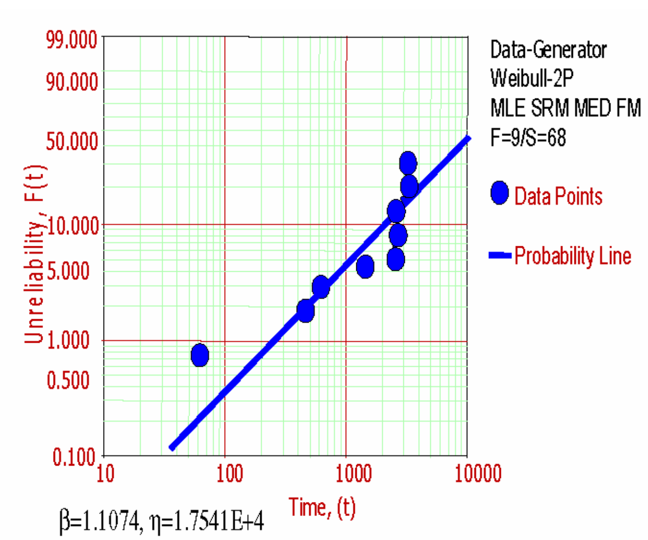

Figure 2 Generator Weibull Plot

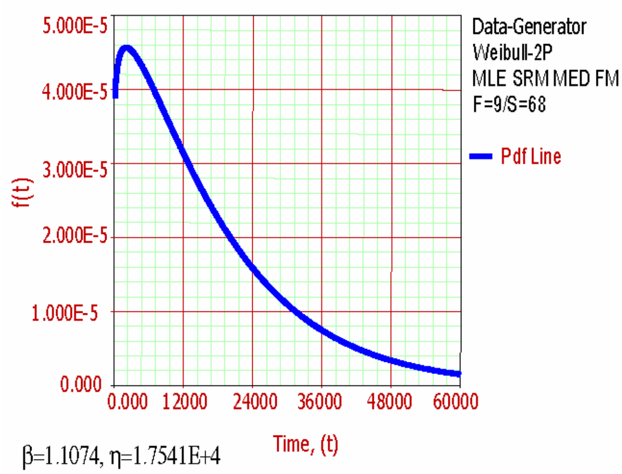

Figure 3 Generator pdf plot

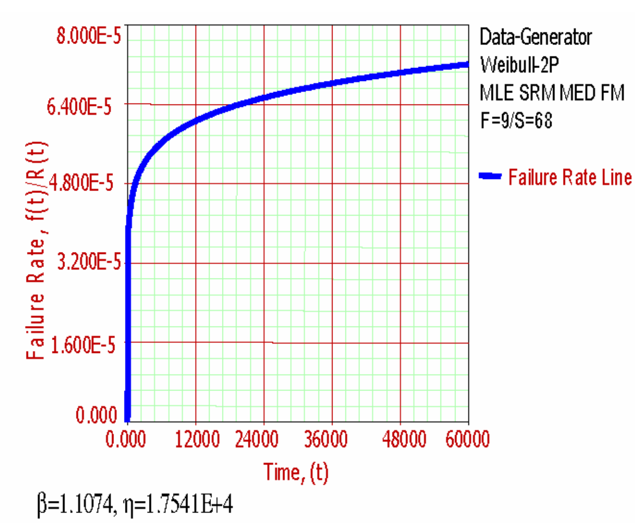

Figure 4 Generator failure rate plot

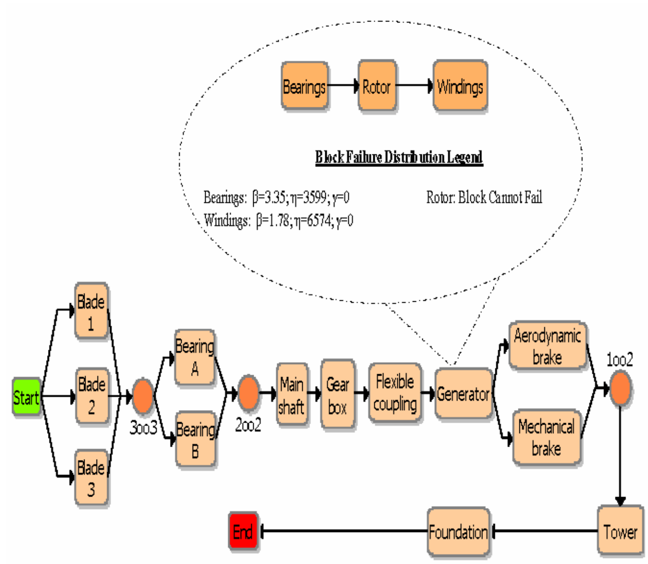

Figure 5 Modelling Failure of a Generator

## 3. Conclusion

This paper has discussed the concept and relevance of Modelling System Failures, and has used the approach to assess the failure characteristics of generators within a particular type of 600 kW wind turbine. Field failure data of the generators have been collated from collaborating wind farm operators. The data have been analysed using MLE in the Weibull distribution. The $\beta$ and $\eta$ parameters of the generator and its components were estimated. The estimated $\beta$ and $\eta$ parameters were used to design RBD to model the failures of the generator.

Further research work is currently under taken to assess the other critical subsystems of the wind turbine using the MSF approach. The results will be incorporated into the turbines failure model presented in figure 5 and the resultant effects on a selected wind farm will be assessed under three common maintenance regime.

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