An Investigation into Fan Reliability

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***Abstract*—Common failures in the electronic products can be traced back to thermal-related issues. While the power of electronic components and power densities are rapidly increasing, thermal management of electronic products becomes a challenge. Since the lifespan of electronic components is shortened drastically due to the high temperature, fans are widely used to create airflow in electronic products for cooling purpose. Therefore, fan is a critical part for thermal management in electronic products, and reliability of electronic products is heavily dependent on the fan's reliability. There is a standard IPC-9591 that standardized fan's performance parameters (including reliability). However, it is still difficult to compare the fan reliability directly among different fan manufacturers because they report their fans' reliability using different parameter values in Weibull distribution, acceleration factors, and reliability tests. This paper reviews, compares, and discusses the approach of fan life expectancy calculation. It concludes that IPC-9591 recommends the most conservative values (biggest Weibull shape parameter, lowest test temperature, smallest acceleration factor) for reliability analysis. Since bearing is the most critical component in fan, its life is also discussed in the paper. Considering the very light bearing loads in fan, it is recommended that bearing life should refer to its grease life, not the fatigue life.**

Keywords- fan reliability; life expectancy; Weibull distribution; accelerated life testing

I. INTRODUCTION

Barrel theory [1], also called Law of the minimum, states that the stave in the shortest length limits the capacity of a wooden barrel. This idea can also be used to explain the reliability of electronics and applied to the life of electronic products. That is to say, the life of an electronic product is limited by the weakest link in it. Fan, which has already been widely used for cooling, is one of the weakest links in electronic products, such as telecom system, power supply and computer. Schroeder and Gibson analyzed field failure data collected from large systems, and reported that fan was one of the top ten failure components [2].

Generally, fan life is shorter than the operating life of electronic components in many cases. Multiple fans are configured in parallel to increase the reliability of electronic products; these paralleled fans are designed to operate alternatively. Hence, the operating life of electronic products can be equally distributed into the paralleled fans. Therefore, the operation time of each fan is decreased, and the reliability of fan cooled electronic products is increased accordingly. This idea was presented in one of Dell's patents, named as "Fan Reliability" [3].

Since fan is a critical part of the air cooled electronic products, many famous companies, such as General Electric (GE), International Business Machines (IBM), Hewlett-Packard (HP) and Advanced Micro Devices (AMD), had reported fan reliability issues and tried to propose a robust method for assessing fan reliability [4]-[8]. Hogan [4] developed a model: 1) to predict the reliability of electronic-chassis cooled by fan in terms of electronics and fan reliability, and the fan's cooling performance; 2) to study the reliability and the benefit of the fan's health management in the electronic-chassis. Kim et. al [5][6] reviewed the way used to calculate fan life expectancy and aimed to standardize the way to evaluate fan reliability in industry. They proposed an approach with a life experiment and data analysis. They also suggested a compromised acceleration factor (AF) of 1.5 per 10 ^{o}C for accelerated life test (ALT) based on the analysis. Sidharth and Sundaram [7] compared different AF models with the recommended Arrhenius based model. They recommended to assume Weibull slope value, β, as 3.0 for fan reliability analysis, and studied the effects of sample size and Weibull slope during the test time. Tian [8] reported fan's major failure modes based on the field and laboratory test data. He reviewed the way used to estimate fan life, pointed out the concerns in ALT, and proposed a useful method to quantify fan reliability.

Different fan manufacturers use different reliability metrics, failure criteria and models to report fan reliability issues. It is difficult for users to understand and compare fan reliability among different manufacturers. Similar problems were also raised by famous companies [5]-[8]. To address these problems, an industry standard IPC-9591, named "Performance Parameters (Mechanical, Electrical, Environmental and Quality/Reliability) for Air Moving Devices", was developed in 2006 [9]. This standard standardizes the performance parameters for fan, to improve the fan reliability, and to eliminate the misunderstanding between fan manufacturers and the users. This paper investigated fan reliability and compared the approaches used by fan manufacturers with IPC-9591. Since bearing is the most critical component in fan, its life is also discussed in the paper. The paper is organized as follows. In section 2, fan failure criteria used for reliability test are compared between fan manufacturers and IPC-9591. In section 3, Weibull

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distribution is briefly reviewed. In section 4, the approach of life expectancy calculation, ALT, and reliability test are summarized and discussed. Since fan reliability is heavily dependent on its bearing, the bearing and grease life are discussed in section 5. Finally, the conclusions of the investigation are presented in section 6.

TABLE I. FAN FAILURE CRITERIA

	RPM	Current, I	Noise	Others
IPC-9591	<=0.85 $RPM_{original}$	>1.15 $I_{original}$	+3 dBA	Incorrect or erratic operation of electronic interface; Visible cracking of fan structure; Visible leakage of lubricant.
Company A	<0.9 $RPM_{original}$	> $I_{maximum}$	N/A	N/A
Company B	<0.9 $RPM_{original}$ / >1.1 $RPM_{original}$	> $I_{maximum}$	+3 dBA	Defects in fan components; Cannot operate at the lowest start up voltage in the spec.
Company C	<=0.85 $RPM_{original}$	>1.15 $I_{maximum}$	+3 dBA	N/A
Company D	<0.85 $RPM_{original}$	> $I_{maximum}$	+3 dBA	N/A
Company E	<0.7 $RPM_{original}$	N/A	N/A	N/A
Company F	<0.85 $RPM_{original}$	>1.15 $I_{original}$	+3 dBA	No function.

II. FAN FAILURE CRITERIA

Fan, a mechanical and electrical product, may suffer mechanical and/or electronic failure. Considering the very low failure rate of modern electronic components, it is rare to find electronic failures (such as electronic packaging failures, solder-joint failures, printed circuit board failures and semiconductor failures) during the product's life. Most fans' electronic failures happened in the infant stage. Such electronic failures can be mostly avoided by applying the appropriate derating requirements of electronic components, and can be found out during burn-in test before delivery to customers. Mechanical failures in fans include bearing failure, fan housing crack and rotor failure, etc. Bearing failure is the dominant failure mechanism in fans, which can cause fan to fail, and have symptoms such as abnormal vibration and sound, rotary speed drop, etc. Therefore, it is helpful to differentiate between mechanical and electronic failures when talking about fan reliability. IPC-9591 recommends fan failure criteria, however, different fan manufacturers customized these criteria for their own failure definitions. TABLE I summarizes the failure criteria that IPC-9591 proposed and fan manufacturers used.

III. WEIBULL DISTRIBUTION

Weibull distribution is widely used in reliability engineering and failure analysis. The probability density function (PDF) of the two-parameter Weibull distribution is shown as follows:

$$f(t;\alpha,\beta)=\frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1}e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \tag{1}$$

where, α, is a scale parameter, which is also called the characteristic life; β, is a shape parameter, which is also called slope. Its cumulative density function (CDF) is:

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

The accuracy of the approach to get fan's life expectancy is heavily dependent on the value of shape parameter β, which should know or assume first. Different fan manufacturers, based on their own assumptions and experiences, use different values for β, which are listed in TABLE II. However, the effective way to get an accurate β is to run a meaningful number of fans at its rated input voltage, and at a certain temperature until all of them fail. Then plot these life data in Weibull probability paper to find the accurate β. β<1, means failure rate decreases over time; β=1, represents failure rate is constant over time; β>1, says failure rate increases over time.

IV. LIFE EXPECTANCY

Life expectancy is one specification of fan. For example, L_{10} at 60 °C, is 40000 hours [10]. ALT is usually adopted to get such life expectancy. Since ALT is used to accelerate the degradation process of failure mechanism, it cuts down the test time for the same life expectancy. A number of fan samples will be tested in a predefined time, or the predefined failure number are found to assure that the fan's life equals to, or longer than the claimed life with a certain confidence level (such as 90%). Figure 1 shows the flowchart of the approach widely used to get fan's life expectancy.

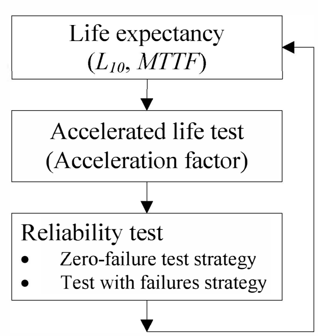

Figure 1. The flowchart of the approach to get the claimed life expectancy

A. Life Expectancy Metrics

L_{10} and mean time to failure *(MTTF)* are two metrics used for life expectancy [11]. L_{10} is the lifetime when ten percent of

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population fails under the specified test conditions. *MTTF* measures the average time to failures with the modeling assumption that the failed system is not repaired.

Based on the Weibull distribution, L_{10} can be calculated using below equation

$$F(t) = 10\% = 1 - e^{-\left(\frac{L_{10}}{\alpha}\right)^{\beta}} \tag{3}$$

Rearrange equation (3):

$$L_{10} = \alpha\left[\ln\frac{1}{1-0.1}\right]^{\frac{1}{\beta}} \tag{4}$$

The *MTTF* calculation is:

$$MTTF = \alpha\Gamma\left[1+\frac{1}{\beta}\right] \tag{5}$$

where, $\Gamma[1+1/\beta]$ is the gamma function in [12]. Equation (6) shows the relationship between *MTTF* and L_{10}.

$$MTTF = L_{10}\bullet\left\{\Gamma\left[1+\frac{1}{\beta}\right]\Big/\left[\ln\frac{1}{1-0.1}\right]^{\frac{1}{\beta}}\right\} \tag{6}$$

However, the ratio of *MTTF* to L_{10} depends on the value of β, which already known or assumed based on IPC-9591 or fan manufacturers' own experiences.

TABLE II. THE RATIO OF *MTTF* TO L_{10} BASED ON DIFFERENT SHAPE PARAMETER VALUE

	Shape parameter value, β	***MTTF/L*₁₀**
IPC-9591 and Company A	3.0	1.89
Company B	2.5	2.18
Company C and Company D	1.1	7.47
Company E	2.0	2.73
Company F	2.9	1.94

B. *Accelerated Test*

The life expectancy of fans under normal operating condition is very long (such as L_{10} at 60 °C, is 40000 hours [10]). It is impossible to test fans until they fail to work in its normal operating condition. Therefore, accelerated test, uses higher level of stress to shorten fan life accordingly, is applied. It is widely used to assess and improve product reliability [13]. It helps to identify and quantify the failure mechanisms that cause fan to fail. It also helps fan manufacturers to save time and cost compared with the tests in normal condition; to meet the increasing competition; to get products available in market in a short time; and to satisfy customer's high expectation on reliability.

Generally, there are two accelerated test models: accelerated life test (ALT), and accelerated degradation test (ADT). ALT is concerned with product life data, and their statistical distribution to quantify products reliability characteristics, while ADT studies the degradation process of product performance over time [14]. Although fans seldom fail during the high temperature reliability test, they do degrade during the test (Weibull shape parameter is bigger than 1). Therefore, ADT will also be valuable to develop the fans' degradation model to estimate their lives. High level of stress test induces fan degradation in a much shorter time, and is useful for getting timely reliability information about the fan. However, any potential pitfalls while implementing accelerated test should be avoided, since such pitfalls could lead to wrong conclusions [15].

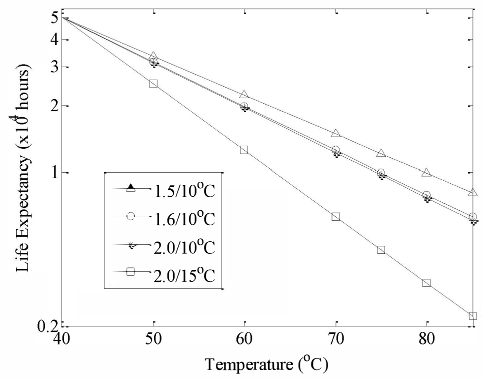

Figure 2. The equivalent life expectancy L_{10} at different temperature

TABLE III. AF AND THE TESTING TEMPERATURE USED BY DIFFERENT FAN MANUFACTURERS

	Acceleration factor	**Test temperature (°C)**
IPC-9591	$AF = 1.5^{\left(\frac{T_{test}-T_{use}}{10}\right)}$	70
Company A	$AF = 2^{\left(\frac{T_{test}-T_{use}}{15}\right)}$	85
Company B	$AF = 1.6^{\left(\frac{T_{test}-T_{use}}{10}\right)}$	75
Company C	$AF = 2^{\left(\frac{T_{test}-T_{use}}{10}\right)}$	80
Company D	$AF = 2^{\left(\frac{T_{test}-T_{use}}{10}\right)}$	70
Company E	$AF = 1.5^{\left(\frac{T_{test}-T_{use}}{10}\right)}$	80
Company F	$AF = 1.5^{\left(\frac{T_{test}-T_{use}}{10}\right)}$	70

The stress types used in accelerated test may include temperature, humidity, voltage, current, pressure, cycling rate, vibration, loading, etc., or combinations of these. In fan industry, temperature is an effective stress that has been widely used in accelerated test. Therefore, the main concern is to find the appropriate value of the AF considering the effect of temperature. The effective way to get the accurate AF is to test a large number of fans fail at different temperatures, and then calculate the effect of temperature. However, this is not always adopted by fan manufacturers considering such test will last a long time, and need many resources to support. Different fan manufacturers based on their own experiences use different values for AF. They also use different testing temperatures in the reliability test that will be discussed later. IPC-9591 recommends that fan life drop by an AF of 1.5 for every 10°C increase in temperature as below.

$$AF = 1.5^{\left(\frac{T_{test} - T_{use}}{10}\right)} \quad (7)$$

where, T_{test} is the testing temperature used in ALT. T_{use} is operating temperature where fan is used.

Some fan manufacturers use the Arrhenius model to calculate the AF with the following equation:

$$AF = e^{\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{test}}\right)} \quad (8)$$

where, E_a is the activation energy, and k is Boltzmann's constant ($8.617 \times 10^{-5}\,\mathrm{eV/K}$). The effect of different activation energies on AF is discussed by Sidharth [7]. Figure 1 shows the equivalent life expectancy L_{10} at different temperatures under the different AF assumptions. The AF recommended by IPC-9591 is the most conservative one. TABLE III summarizes the AF and the testing temperature adopted by different fan manufacturers. The testing temperature suggested by IPC-9591 is the lowest.

C. *Reliability Test*

In fact, it is difficult to get fan failure data, even with those fans tested in high temperature, and it is usually time consuming to test fans until some, or all of them fail. Generally, there are two test strategies used to investigate whether fans have the claimed life expectancy or not. One approach is zero-failure test strategy where obtained data are called time censoring data; another one is to test fans until a certain number of fans fail, these data are called item censoring data.

1) *Zero-failure Test Strategy: Time Censoring Data*

Using the zero-failure test strategy to assure a life expectancy with a certain confidence level (such as 90%), it needs to determine the test time t for each fan. Moreover, the test time t is also dependent on the sample size n. Two methods are widely used to calculate test time t, one approach is to transform the Weibull distribution data into exponential distribution data, then, use methods for the exponential distribution to analyze the transformed data. Another way is to consider the time censoring data as the Binomial distribution data. Since the sample size n is large and the probability for fan to fail at time t or earlier is very small, therefore Poisson distribution could be used to approximate the Binomial distribution with the parameter $\theta = nF(t)$. With some other approximation, the test time t is a function of Chi-square percentile, sample size n and character life α. Details of these two methods are discussed as below.

a) *Method 1: Exponential Distribution*

Since the shape parameter β in Weibull distribution has already been known or assumed, the methodologies of exponential distribution can be applied to the test data from a Weibull distribution by using the below transformation [16].

$$u = t^{\beta} \quad (9)$$

The parameter of the exponential distribution is

$$\lambda = 1 / \alpha^{\beta} \quad (10)$$

therefore,

$$nu = B_{r;c} / \lambda \quad (11)$$

where, $B_{r;c}$ is the Poisson distribution factor, r is the number of failures, and c is the confidence level.

The test time t can be obtained by substituting equation (9), (10) into equation (11).

$$t = \alpha \left[\left(B_{r;c} \right) / n \right]^{1/\beta} \quad (12)$$

when, r equals zero, it means that there is no fan failure during the reliability test, and with 90% confidence; $B_{0;0.9} = 2.303$, the required test time for each fan t is

$$t = \alpha \left[\frac{2.303}{n} \right]^{1/\beta} \quad (13)$$

b) *Method 2: Binominal Distribution*

The reliability test will stop when the test time for each fan reaches at t with a sample size n. Since t is a set of Weibull distribution data, the probability of each fan fail during the test time t is $F(t)$, the number of failures r follows a Binomial distribution.

$$P(i \le r) = \sum_{i=0}^{r} \binom{n}{i} \left[1 - e^{-(t/\alpha)^{\beta}} \right]^{i} \left[e^{-(t/\alpha)^{\beta}} \right]^{n-i} \quad (14)$$

When sample size n is large, and probability of failure $F(t)$ is small, binomial distribution can be approximated by Poisson distribution with the parameter $\theta = nF(t)$

$$\begin{aligned} P(i \le r) &= \sum_{i=0}^{r} \frac{\left\{ n \left[1 - e^{-(t/\alpha)^{\beta}} \right] \right\}^{i}}{i!} e^{-n\left[1 - e^{-(t/\alpha)^{\beta}}\right]} \\ &= \int_{2n\left[1 - e^{-(t/\alpha)^{\beta}}\right]}^{\infty} f(t, 2r+2)\,dt \\ &\cong \int_{2n\left(\frac{t}{\alpha}\right)^{\beta}}^{\infty} f(t, 2r+2)\,dt \end{aligned} \quad (15)$$

$f(t, 2r+2)$ is the PDF of Chi-Square distribution. From equation (15) it is noted that

$$\chi_{\delta}^{2}(2r+2) = 2n \left(\frac{t}{\alpha} \right)^{\beta} \quad (16)$$

δ is the confidence level. Rewrite the equation (16),

$$t = \alpha \left[\frac{\chi_{\delta}^{2}(2r+2)}{2n} \right]^{1/\beta} \quad (17)$$

Since it is a zero failure test strategy, r equals zero. For 90% confidence, the Chi-Square value is $\chi_{0.9}^{2}(2) = 4.605$. Substitute it into equation (17), the test time t for each fan is:

$$t = \alpha \left[\frac{4.605}{2n} \right]^{1/\beta} \quad (18)$$

Two methods described above are used to determine individual test time t that (n) fan samples need to experience using the zero-failure test strategy. Although these two methods are different, the difference between the calculated individual test time t based on these two methods is small.

$$B_{0;0.9} \cong \frac{\chi^2_{0.9}(2)}{2} \tag{19}$$

2) Test with Failures Strategy: Item Censoring Data

This test strategy does not have the complicated calculation to get the test time *t*, but it will last a long test time, and the cost is also high. The test based on this strategy will be stopped when the predefined failure number, such as 5 or 10, has been found in the test. Then, the logged failure data are plotted in Weibull probability paper to get the values of β and characteristic parameter α. Therefore, it is not necessary to assume β beforehand to get the life expectancy using this test strategy. Afterward, equations (4) and (5) are used to obtain fan's life expectancy, either L_{10} or *MTTF*. It is better to have more failure data, since it helps to get parameter values, α and β, more accurately in Weibull distribution. However, it is always difficult to get failure data. It is because to get more failure data means testing the same fan samples for a long time. Compared with zero-failure test strategy, test with failures strategy needs to spend more than a year for each fan to get the same life expectancy with the same ALT, test temperature and sample size. During this fan reliability investigation, only one fan manufacturer adopts this test strategy. TABLE IV summarizes the reliability testing recommended by IPC-9591 and used by different fan manufacturers.

D. Discussion

One example is given below to illustrate the approach recommended by IPC-9591 using zero-failure test strategy for better understanding. Customers expect that fan's life expectancy L_{10} at 40 °C (denote as $L_{10@40^oC}$) should be longer than 50,000 hours. The following equations explore the time each fan should be tested at 70 °C using zero-failure test strategy of a sample size 60 to satisfy customer requirements with 90% confidence.

$$L_{10@70^oC} = \frac{L_{10@40^oC}}{1.5^{(70-40)/10}} = \frac{50000 \text{ hours}}{3.375} = 14815 \text{ hours}$$

The characteristic life α at 70 °C (denote as α_{70^oC}) can be calculated as below using the ALT

$$\alpha_{70^oC} = \frac{L_{10@70^oC}}{[-\ln(1-0.1)]^{1/\beta}} = \frac{14815 \text{ hours}}{[-\ln(1-0.1)]^{1/3}} = 31367 \text{ hours}$$

To satisfy customer requirements, each fan should be tested for a time *t* at 70°C using a sample size of 60 if there is no fan failure during the test.

$$\begin{aligned} t &= \alpha_{70^oC}\left[4.605/(2n)\right]^{1/\beta} \\ &= 31367 \text{ hours} \times \left[4.605/(2\times 60)\right]^{1/3} \\ &= 10580 \text{ hours} \end{aligned}$$

TABLE IV. SUMMARY OF RELIABILITY TEST USED BY DIFFERENT FAN MANUFACTURERS

	Reliability test	Data type
IPC-9591 / Company A / E	Method 2: Binominal distribution	Time censoring data
Company B / C / D	Method 1: Exponential distribution	Time censoring data
Company F	/	Item censoring data

TABLE V. COMPARISON OF THE TEST TIME FOR EACH FAN USING DIFFERENT WEIBULL SHAPE PARAMETER VALUE AND SAME SAMPLE SIZE FOR THE SAME LIFE EXPECTANCY TARGET

	Life expectancy: L_{10} (hours)		Test temperature (°C)	Acceleration factor	Weibull shape parameter (β)	Test time for each fan using zero-failure test strategy (hours)
	40 °C	Test temperature (°C)				
IPC-9591	50000	14815	70	1.5/10°C	3	10580
Company A	50000	6250	85	2.0/15°C	3	4463
Company B	50000	9651	75	1.6/10°C	2.5	6443
Company C	50000	3125	80	2.0/10°C	1.1	1247
Company D	50000	6250	70	2.0/10°C	1.1	2493
Company E	50000	9877	80	1.5/10°C	2.0	5961
Company F	50000	14815	70	1.5/10°C	2.9	10506

TABLE V compares the required test time *t* for each fan based on zero-failure test strategy using the same sample size (n=60); different testing temperature; AF; and Weibull shape parameter β recommended by IPC-9591 and adopted by different fan manufacturers. Company F is assumed to adopt the zero-failure test strategy using the same parameter values obtained from the test with failures strategy. There are large deviations among the test time varying from 1247 hours to 10580 hours. Therefore, the accuracy of the parameters used by different fan manufacturers is questionable. However, the parameters suggested by IPC-9591 are most conservative. It suggested the biggest value of Weibull shape parameter β, smallest AF value, and lowest test temperature. The required test time for each fan based on zero-failure test strategy is the longest (10580 hours). It should be noted that there are two metrics for life expectancy, *MTTF* and L_{10}, their ratio is dependent on Weibull shape parameter β. The bigger shape parameter value is, the smaller the ratio of *MTTF* to L_{10} is.

V. BEARING LIFE

Bearing is a critical component in fans. Most fan failures are caused by the failure of bearing. Therefore, IPC-9591 recommends fan manufacturers to provide the bearing life estimation and grease life calculation. International Standard ISO 281 "Rolling Bearings – Dynamic load ratings and rating life" outlines the method to predict bearing rating life under different operating conditions [17]. For conventional operating conditions, the radial ball bearing's basic rating life is given as follows:

$$L_{10} = \left(\frac{C_r}{P_r} \right)^3 \quad (20)$$

where, C_r, basic dynamic radial load rating (N); P_r, dynamic equivalent radial load (N). Equation (20) is about the calculation of bearing fatigue life. However, the bearing load in fans is low; the fatigue failure of bearing rarely happens. ISO 281 also state that this International Standard does not cover the failure modes which caused by very light loads. Therefore, using ISO 281 to calculate the fan's bearing rating life may be misled.

Several approaches have been reported to estimate the grease life [18]-[23]. The most widely used one is the Booser equation [18]. Booser did many tests to evaluate grease performance in ball bearings and recommended equation (21) for quick grease life estimation.

$$\log L = -2.30 + \frac{2450}{273 + T} - 0.301S \quad (21)$$

where, L is the geometric mean grease life for 50 % bearing failures, hours; T is the bearing temperature, ^{o}C. S is the half-life subtraction factor, it equals to the summation of S_G , S_N and S_W, where S_G is the grease composition half-life subtraction factor; S_N is the speed related half-life subtraction factor; and S_W is the half-life subtraction factor referring to load. However, this equation does not cover all grease, especially for the new developed ones, and should be revised per the accumulated experiences since 1974.

Kawamura et al. [22] reported the methods to predict grease life for both urea and lithium soap greases in sealed ball bearings in 2001. They found that the grease life in bearings with inner ring rotation is longer than those bearings with outer ring rotation. They also generated formulas for these two different rotation conditions respectively. Their formulas based on the following testing conditions: 1) the temperature ranged from 100 to 180 ^{o}C; 2) rotary speed was between 10000-12000 rpm; 3) and the axial loads were from 67-670 N, which is quite different to the fan bearing working conditions. Therefore, their formulas are not applicable either to estimate the grease life in fan bearings.

Bearing companies, such as NSK, developed equation (22) to estimate the grease life by themselves [23].

$$\log L = 6.54 - 2.6\frac{n}{N_{max}} - (0.025 - 0.012\frac{n}{N_{max}})T \quad (22)$$

where, L, is the average grease life (hours); n, is the speed (min^{-1}); N_{max}, is the limiting speed with grease lubrication (min^{-1}); T, is the operating temperature (^{o}C).

It should be noted that the dynamic bearing loads in a fan are very light comparing with its basic dynamic load ratings. Fan's bearing life is heavily dependent on its lubricant system, not its fatigue life. Hence, the reliability of fan mainly depends on grease life. However, it is inappropriate to use it to estimate bearing rating life in fan, since the approach of calculating bearing rating life specified in ISO 281 does not consider the very light loading condition; it is also misleading to use Booser, or Kawamura equation to estimate the grease life in light of new developments in grease and light loading condition,. Therefore, the best way to calculate the grease life in fan bearing is to follow the equations provided by the bearing or grease manufacturers.

VI. CONCLUSION

IPC-9591, a fan industry standard, addresses fan reliability assurance. It proposes the most conservative values for reliability analysis. However, different fan manufacturers use different failure criteria, life expectancy metrics, Weibull shape parameter β, ALT, and reliability test. Since it is difficult to compare the life expectancy among different fan manufacturers, it is critical to understand the specific approaches used by fan manufacturers to analyze fan reliability. The accuracy of the way to estimate fan's life expectancy is heavily dependent on the Weibull shape parameter β.

Due to the technology improvement, it is hard to detect fan failures even during high temperature reliability test. Hence, many fan manufacturers use the zero-failure test strategy. In many cases, mechanical failures, especially the bearing failures, are the dominant failure modes in fan. It should also be noted that bearing loads in fan are very light and fan's bearing life is heavily dependent on grease life. Therefore, it is inappropriate to use the methods based on ISO 281 or proposed in [18]-[22] to estimate the bearing life in fans. Grease life, which considers light loading conditions in bearing, is feasible to be used to estimate fan bearing life.

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