전자 시스템 신뢰도 예측을 위한 217Plus^{TM} 부품모형의 민감도 분석

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Sensitivity Analysis of the 217Plus^{TM} Component Models for Reliability Prediction of Electronic Systems

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Key Words : Reliability Prediction, 217Plus^{TM}, Component Model, Failure Category

Abstract

MIL-HDBK-217 has played a pivotal role in reliability prediction of electronic equipments for more than 30 years. Recently, RIAC developed a new methodology 217Plus^{TM}, which officially replaces MIL-HDBK-217. Sensitivity analysis of the 217Plus component models to various parameters has been performed and meaningful observations have been drawn in this study. We first briefly reviewed the 217Plus^{TM} methodolog and compared it with the conventional model, MIL-HDBK-217. We then performed sensitivity analysis 217Plus^{TM} component models to various parameters. Based on the six parameters and an orthogonal array selected, we have performed indepth analyses concerning parameter effects on the model. Our result indicates that, among various parameters, operating temperature and temperature rise during operation have the most significant impacts on the life of a component, and thus a design robust to high temperature is the most importantly required. Next, year of manufacture, duty cycle, and voltage stress are weaker but may be significant when they are in heavy load conditions. Although our study is restricted to a specific type of diodes, the results are still valid to other cases. The results in this study not only figure out the behavior of the predicted failure rate as a function of parameters but provide meaningful guidelines for practical applications.

1. Introduction

Validated data with systematic approach to secure products reliability becomes a more critical issue and is increasingly demanded by customers. For reliability prediction of electronic systems, MIL-HDBK-217[1] has widely been used and served as a basis for other reliability models for more than 30 years. Recently, DoD RIAC (Reliability Information Analysis Center) developed a new reliability model, 217Plus^{TM}[2,3,4] (hereafter 217- Plus) and announced that it officially replaces MIL-HDBK-217 for reliability prediction of electronic systems. It not only overcomes the traditional component based reliability evaluation with replacing the simple multiplicative form by a multiplicative and additive form of component models but includes additional system level model which incorporates process evaluations concerning non-component failure causes (design, manufacturing, parts, system man-

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agement, induced, wear-out, and cannot duplicate) and software failure rate into the result. 217-Plus further adopts a mechanism which updates the result with empirical experience and field data. It is expected to be widely applied for industry products' reliability predictions. Some researches using PRSIM[5] for real field applications have been made[6,7,8]. However, no specific study applying 217-Plus towards industry products has been performed yet. As known, PRISM is a tentative and limited version of 217-Plus including only 6 of the current 12 component models.

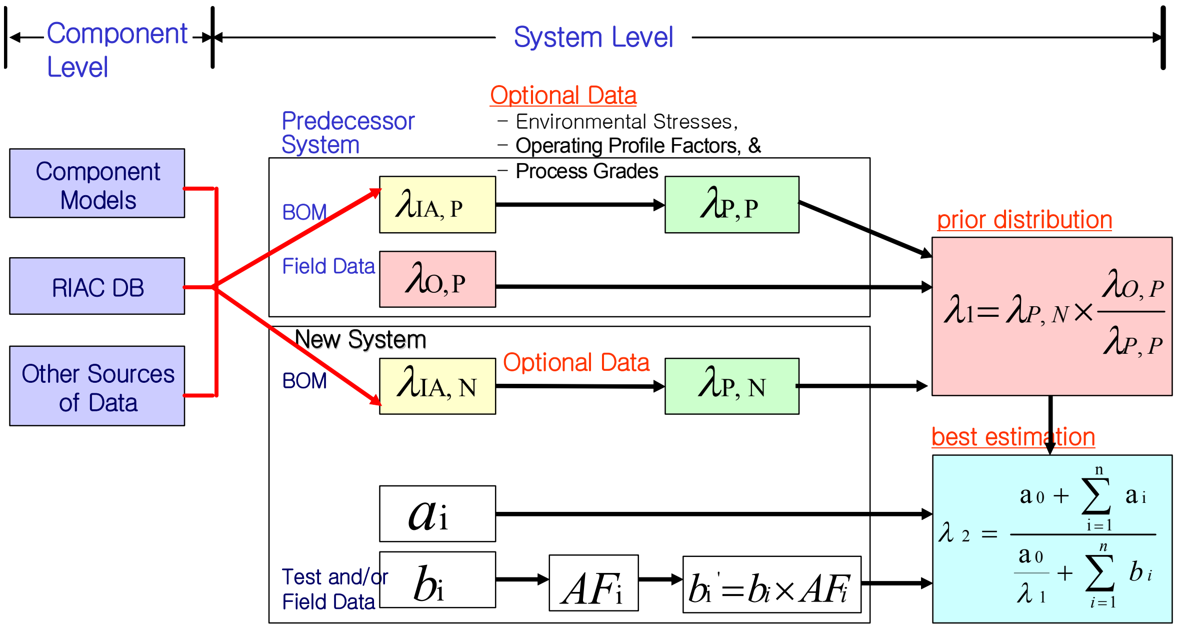
The goal of this research is to examine 217-Plus models for better understanding and applicability of the methodology. We specifically selected the component models within 217-Plus and have performed sensitivity analyses to various parameters. We first briefly overview the 217-Plus methodology and compare it with traditional approach, MIL-HDBK-217. Twelve component models within 217-Plus methodology are summarized and a specific type of component has been selected for analysis. We then extensively examine the sensitivity of the model. Since numerous parameters are involved in the models, systematic experimental design approach were applied for analysis. We examine the parameter effects on the failure rate using Taguchi's orthogonal arrays[9,10]. We further figure out comparative significance of failure categories on total failures. The results in this study not only give explicit answers concerning parameter effects on the models but provide practical guidelines for reliability related decisions.

2. 217-Plus Methodology and Component Models

2.1 217-Plus Methodology Overview

In comparison to conventional prediction models, 217-Plus includes more complicated evaluation procedure for reliability prediction of electronic systems. Figure 1 displays the overall structure of 217-Plus methodology. It consists of component failure rate computation, system level evaluation and update, and field data incorporation.

We first compute each component failure rate using 12 component models (RIACRates) provided in



* Source: Handbook of 217Plus^{TM} Reliability Prediction Models

<Figure 1> Procedure for System Failure Rate Evaluation

217-Plus, RIAC empirical failure rates database (EPRD: Electronic Parts Reliability Data), and/or industry own data or models. The initial assessment or a seed value of the system failure rate, λ_{IA}, is obtained from the above component failure rates. (The second subscripts P and N in λ represent predecessor system and new system, respectively.) BOM (bill of materials) and functional dependency between components may constitute an appropriate approach for system level reliability evaluation. The initial assessment is revised through optional data and is denoted by λ_P. Industry processes concerning various failure causes such as design, manufacturing, parts, system management, induced, wear-out, and cannot duplicate should be evaluated and environmental stresses, operating profiles, and infant mortality are input by the analyst for computation of λ_P. Bayesian approach which incorporates field experience or data into the previously updated failure rate (λ_P) and the prior distribution (λ_1) is another feature of 217-Plus. In the figure, λ_2 represents the final current best estimate of the system failure rate. The reader should refer to 217-Plus handbook for details. As seen, 217-Plus methodology is more comprehensive and

<Table 1> Comparison between MIL-HDBK-217 and 217-Plus

Source: Jeon(2010)

	MIL-HDBK-217	217-Plus
Basic Assumptions	Component-based - system failure is determined from technology & stresses on components Exponential life characteristic No consideration of technology improvement (reliability growth) Failures per 10^6 OH (operating hours)	Failures may depend on components, system level failure causes, and software. Implicitly exponential life characteristic Considers reliability growth - Failures exponentially decrease with time - base year 1993 - unique growth rate by component type Failures per 10^6 CH (calendar hours) * OH = CH/DC
Component Model	Multiplicative functional form (Eq. (1)) - sensitive to factors (π_Q, π_E, etc.) due to direct multiplications Does not consider failure categories	Multiplicative and additive functional form (Table 2) - less sensitive to factors Considers failure categories - operating, non-operating, cycling, solder joint, IND/EOS
System Structure and Model	System failure rate is just the sum of components' - serial structure of components - exponential distribution - components are functionally independent	System failure rate is obtained by RIACRates, EPRD, and/or user own model. System failure rate is further revised by evaluation of system level processes. Bayesian update mechanism is applied.
Environmental stress & Operating profile	Integrated into one factor π_E of the compooent models - 14 qualitative categories with different factor values - incorporate operating profile No consideration of operating profile	Environment and operating profile are separated. Environments environmental stresses - 37 environments - operating temperatures, humidity, vibration Operating profile - DC(duty cycle), Cycling rate
Component Quality	Represented by π_Q in the model - Eq.(1) - directly affects the component failurerate Dependent on the levels of manufacturing environment and quality system - 6-7 level values of π_Q	Considers as a system (not component) level failure cause - evaluated through system level process evaluation
Revision/ update	No update mechanism	Updated by incorporating experience and field data into the current result

complicated than MIL-HDBK-217, reliability evaluation predominantly based on components only.

Table 1 comparatively displays the key characteristics of MIL-HDBK-217 and 217-Plus methodologies. We will not dwell on the details here but the reader may refer to the references[2,3,4,11].

2.2 Component Failure Rate Models

Conventional component reliability (failure rate) models were derived from statistical analysis of empirical failure data. The failure rate of each component type has its own functional form of factors, but may commonly be expressed as a multiplicative form given in Equation (1).

$$\lambda_P = \lambda_b \bullet \Pi_{i=1}^{k} \pi_i \tag{1}$$

where, λ_P - predicted failure rate, failures per 10^6 operating hours.

λ_b - basic failure rate (depending on the component type, category etc.)

π_i - factor of T(temperature), S(electricst ress), Q(quality), E(environment) etc.

In the equation, the factor[1] π_i means the additional effect (over λ_b) expected from the applied conditions of temperature, electric stress, environment, quality etc. and denoted by π_T, π_S, π_Q, and π_E, respectively.

This simple multiplicative form has disadvantages that the predicted values are unrealistically small or large under extreme conditions, where all the factors have their minimum or maximum values[2], and can not explicitly consider the mechanism of each failure category. 217-Plus prefers an additive and multiplicative form considering failure rate by failure category - operating, non-operating, cycling, solder joint, and induced and electronic over stress. 217-Plus includes twelve component models but they may be classified into five groups based on the part types as seen in Table 2 - capacitor, semiconductor, integrated circuit, resistor, and inductor (coil) and others (coil, switch, relay, and connector).

3. Sensitivity of the 217-Plus Component Models

3.1 Experimental Design for Analysis

We now examine the sensitivity of the component models. For our study, we specifically consider a diode of low frequency, general purpose-type, as it is widely applied in many electronic systems. As can be seen later, the results may be generally applied to other component cases. The failure rate formula of 217-Plus for diodes, for convenience, is rewritten in Equation (2).

$$\lambda_P = \pi_G(\lambda_{OB}\pi_{DCO}\pi_{TO}\pi_S + \lambda_{EB}\pi_{DCN}\pi_{TE} + \lambda_{TCB}\pi_{CR}\pi_{DT}) + \lambda_{SJB}\pi_{SJDT} + \lambda_{EOS} \tag{2}$$

where,

λ_P - predicted failure rate, failures per 10^6calendar hours.

λ_{OB} - base failure rate, operating

λ_{EB} - base failure rate, environment

λ_{TCB} - base failure rate, temperature cycling

λ_{SJB} - base failure rate, solder joint

λ_{EOS} - base failure rate, EOS (electrical over stress)

π_G - reliability growth failure rate ultiplier

π_{DCO} - failure rate multiplier for duty cycle

π_{TO} - failure rate multiplier for temperature, operating

π_S - failure rate multiplier, electrical stress

π_{DCN} - failure rate multiplier, nonoperating

π_{TE} - failure rate multiplier, temperature-environment

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[1] In this paper, the term factor is used as the synonyms of multiplier(π) in 217-Plus model and parameter in Section 3.

<Table 2> Classification of 217-Plus Component Models

Category	Failure Rate Formula
Capacitor	$\lambda_P = \pi_G \pi_C(\lambda_{OB}\pi_{DCO}\pi_{TO}\pi_S + \lambda_{EB}\pi_{DCN}\pi_{TE} + \lambda_{TCB}\pi_{CR}\pi_{DT}) + \lambda_{SJB}\pi_{SJDT} + \lambda_{EOS}$
Diode, Thyristor Transistor	$\lambda_P = \pi_G(\lambda_{OB}\pi_{DCO}\pi_{TO}\pi_S + \lambda_{EB}\pi_{DCN}\pi_{TE} + \lambda_{TCB}\pi_{CR}\pi_{DT}) + \lambda_{SJB}\pi_{SJDT} + \lambda_{EOS}$
Integrated Circuit 1) Plastic Encapsulated 2) Hermetic	$\lambda_P = \pi_G(\lambda_{OB}\pi_{DCO}\pi_{TO} + \lambda_{EB}\pi_{DCN}\pi_{RHT} + \lambda_{TCB}\pi_{CR}\pi_{DT}) + \lambda_{SJB}\pi_{SJDT} + \lambda_{EOS}$ $\lambda_P = \pi_G(\lambda_{OB}\pi_{DCO}\pi_{TO} + \lambda_{EB}\pi_{DCN}\pi_{TE} + \lambda_{TCB}\pi_{CR}\pi_{DT}) + \lambda_{SJB}\pi_{SJDT} + \lambda_{EOS}$
Resistor	$\lambda_P = \pi_G(\lambda_{OB}\pi_{DCO}\pi_{TO}\pi_P + \lambda_{EB}\pi_{DCN}\pi_{TE} + \lambda_{TCB}\pi_{CR}\pi_{DT}) + \lambda_{SJB}\pi_{SJDT} + \lambda_{IND}$
Inductor, Transformer Optoelectronic Device Switch, Relay Connector	$\lambda_P = \pi_G(\lambda_{OB}\pi_{DCO}\pi_{TO} + \lambda_{EB}\pi_{DCN}\pi_{TE} + \lambda_{TCB}\pi_{CR}\pi_{DT}) + \lambda_{IND}$

π_{CR} - failure rate multiplier, cycling rate
π_{DT} - failure rate multiplier, delta temperature
π_{SJDT} - failure rate multiplier, solder joint delta temperature

Note that λ_P represents failures per 10^6 calendar hours not operating hours. To evaluate the failure rate given in Equation (2), additional information about other failure rates and parameters are required as input data. Among them, the data provided from 217-Plus for low frequency, general purpose diode are given in Table 3. The other parameters including year of manufacture, temperatures, duty cycle etc. should be input by the analyst. The reader may refer to 217-Plus component models for more details[2,11,12,13].

Among various parameters, we selected year of manufacture, T_{AO} (ambient temperature during operation), T_R(temperature rise during operation), DC (duty cycle), V_S(electrical stress), and CR(cycling rate) as factors for analysis. Year of manufacture is an important variable related to the reliability growth in 217-Plus. Failures in 217-Plus are defined to exponentially decrease through technology improvement as time (year) closes to current date since the base year, 1993. Growth rate, β=0.223 for the selected part type, reflects the growth speed of the reliability, the larger the faster and vice versa. T_{AO} and T_R are ambient temperature and temperature rise during operation, respectively. T_{AE}, ambient temperature during non- operation, may also be important but is set to be constant 25℃ in this study. DC and CR are the time ratio (%) that the part is in operation and the number of power on's during a year, respectively. Finally, V_S is the electrical stress and is defined as the ratio of the applied voltage to the rated voltage. Since the model, Equation (2), has a complicated functional form of many parameters, a systematic approach is needed for proper analysis. We are to apply an experimental design approach and the parameters in the model are considered as factors. That is, we examine diode failure rate in terms of 6 factors above. Some range of each parameter value is considered and two levels for each factor are assumed as given in Table 4.

<Table 3> Parameters for Diode, Low Frequency, General Purpose

Parameter	Value	Parameter	Value
λ_{OB}	0.0000616	Ea_{OP}	0.3
λ_{EB}	0.0000308	$T_{Threshold}$	60
λ_{TCN}	0.000098	$V_{App/Rated}$	0.29
λ_{EOS}	0.00036	DC_{1NonOP}	0.77
λ_{SJB}	0.00021	Ea_{NonOP}	0.4
β	0.223	CR_1	736.84
DC_{1OP}	0.23	DT_1	80

<Table 4> Factors and Their Levels

level	year	T_{AO}	DC	T_R	V_S	CR
1	2000	30	0.30	15	0.3	1000
2	2005	50	0.40	30	0.6	1500

Our final selected design is Taguchi's[9,10] orthogonal array $L_{12}(2^{11})$. As known $L_{12}(2^{11})$ is good for designing and analyzing problems of up to 11 two-level factors with 12 experimental runs (treatment combinations).

3.2 Experimental Results and Analysis

We evaluated Equation (2) and obtained results for 12 treatment combinations. Table 5 shows the overall results. The first column indicates 12 experimental runs. Six columns from 2nd through 7th represent the factors arranged out of 11 columns of $L_{12}(2^{11})$ table. With the assumption that the interactions between factors are negligible, note that five columns are empty. The number 1 or 2 in the table indicates the appropriate factor level. Next six columns summarize the total failure rate from Equation (2) with five category failure rates. For convenience, the results were multiplied by 10,000 indicating failures in 10^{10}calendar hours.

Table 6 and Figure 2 show the average responses of the total failure rate in terms of each factor level. Also Table 7 is the ANOVA results based on the total failure rates in Table 5. Meaningful observations drawn from examination of the results may be summarized as follows:

(1) Of all, T_{AO} and T_R have the most strong and dominant effects on a diode failure rate. As observed from the figure, the failure rate significantly increases with increase in ambient temperature or temperature rise during operation. This indicates that operating temperature is very critical to the life of a diode, and a design robust to high temperature is the most importantly required.

(2) The impacts of V_S, manufacturing year, and DC are much weaker than that of T_{AO} or T_R but may still be significant on the failure rate.

  i) Similar but much less significant influence for V_S may be expected from the results of the tables and the figure. Our experi-

<Table 5> Orthogonal Array and Experimental Results

Run	year	T_{AO}	DC	T_R	V_S	CR	Total failure rate	Operating	Non-operating	Cycling	Solder joint	EOS
1	1	1	1	1	1	1	4.1316	0.1019	0.0588	0.0175	0.3535	3.6
2	1	1	1	2	2	2	5.8906	0.8996	0.0588	0.0802	1.2520	3.6
3	1	1	2	2	1	1	5.1784	0.2226	0.0504	0.0534	1.2520	3.6
4	1	2	2	2	2	2	9.4945	2.1690	0.0504	0.1980	3.4773	3.6
5	1	2	1	1	1	2	5.6514	0.1949	0.0588	0.1047	1.6931	3.6
6	1	2	2	1	2	1	6.8134	1.4001	0.0504	0.0698	1.6931	3.6
7	2	1	2	1	2	2	4.2188	0.2402	0.0165	0.0086	0.3535	3.6
8	2	1	1	2	2	1	5.1838	0.2950	0.0193	0.0175	1.2520	3.6
9	2	1	2	1	1	2	4.0231	0.0446	0.0165	0.0086	0.3535	3.6
10	2	2	1	2	1	2	7.2604	0.0990	0.0193	0.0649	3.4773	3.6
11	2	2	2	2	1	1	7.2690	0.1320	0.0165	0.0433	3.4773	3.6
12	2	2	1	1	2	1	5.6796	0.3443	0.0193	0.0229	1.6931	3.6

ence shows that the results are dependent on the stress range applied, and the strength of diodes is high enough for less than 50% load of the rated voltage. If its load gets higher, say over 60% of the rated voltage, its impact on failures may be very significant.

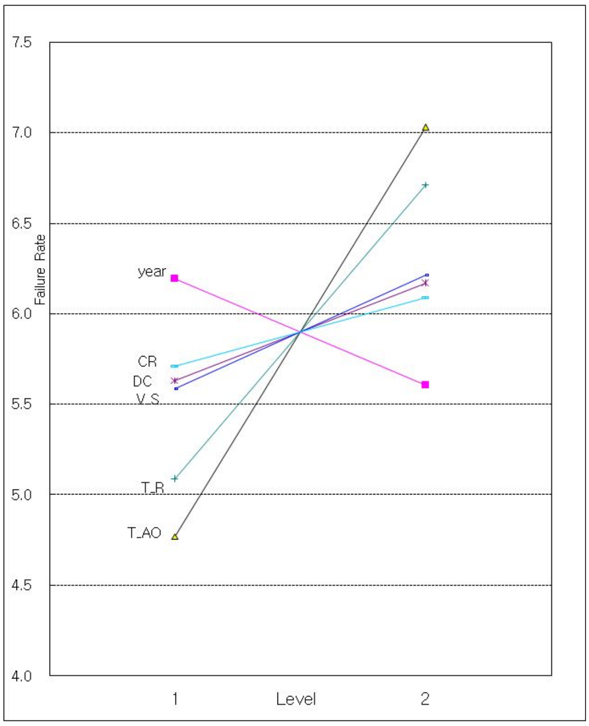
ii) The failure rate is seen to decrease as the manufacturing year increases and its impact may be notable. Failures are generally understood to exponentially decrease as the year of manufacture increases through technology improvement. It should be emphasized, however, that the reduction amount during a given period is dependent upon both growth rate(β) and the time period under consideration. Note that the growth rate of the selected diode type is 0.223 from Table 3. For reference, the growth rates of a hermite IC and inductor are 0.33 and 0, respectively. Larger or smaller reduction in failures may be expected than the selected diode case over a given period. We further note that, even if the failures decrease significantly after the base year 1993, only a limited change is expected during recent years say after 2005. This indicates that the year of manufacture may no longer be an important factor in our study.

iii) DC is also observed to have some significant effect on the failure rate. Since DC is the time ratio that the part is in operation, its level increase indicates increased operating hours and may yield more failures. In this study we considered the range 30-40%, but a significant impact will be expected when DC over 50% is considered.

(3) Within the ranges specified in this study, CR does not show notable significance as compared to other factors. We tentatively conclude that a diode is designed to be robust on switches between operating and non-operating conditions.

<Table 6> Average Failure Rate Response

Level	Year	T_{AO}	DC	T_R	V_S	CR
1	6.19	4.77	5.63	5.09	5.59	5.71
2	5.61	7.03	6.17	6.71	6.21	6.09



<Figure 2> Average Failure Rate Response Graph

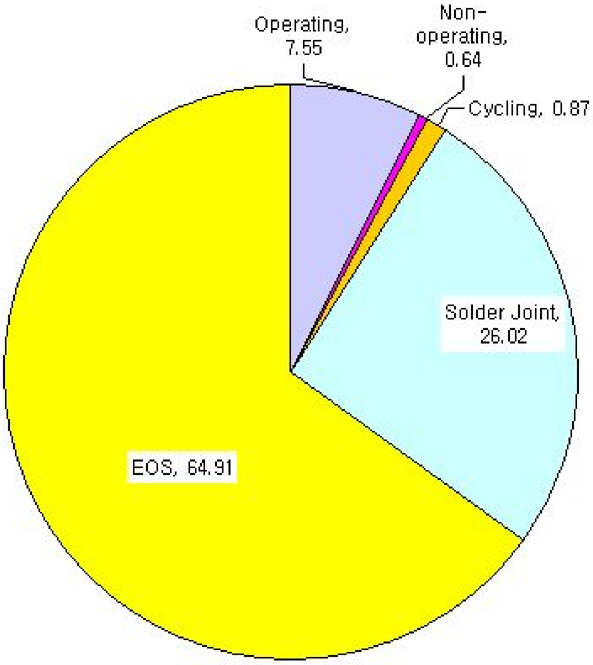
<Table 7> ANOVA for Component Reliability

Source	SS	df	MS	F
Year	1.0356	1	1.0356	3.76^{*}
T_{AO}	15.2820	1	15.2820	55.52^{***}
DC	0.8533	1	0.8533	3.10
T_R	7.9364	1	7.9364	28.83^{***}
V_S	1.1823	1	1.1823	4.29^{*}
CR	0.4343	1	0.4343	1.58
Error	1.3764	5	0.2753	-
Total	28.1002	11	-	-

* : 0.90 significance, *** : 0.99 significance

One important feature of 217-Plus component models lies in that the failure rate may be classified into failure categories. As noted earlier, configuration of failures in terms of failure category is not possible for the conventional model. Rigorous and quantitative examination of category failures is possible through similar analysis above and will provide valuable insights about the factor effects on failure categories and eventually the total failure rate.

Our final consideration is to examine the relative significance between categories. Figure 3 summarizes the relative percentage occupied by each category to the total failure rate. This is based on the average value obtained from percent results of 12 treatment combinations. Note that EOS occupies a significant portion, over 60%, of the total failures. We also see that 26% of total failures may be due to solder joint problems. The failures from other categories may be less than 10% in total. It is clear how we should manage the reliability related decision as well as understand the behavior of the failures as functions of factors. Our results strongly encourage us to put efforts to design a diode to be robust to electrical over stresses. High process or manufacturing quality of solder joint is also critical to diode failure decreases. Finally, rather robust results have been yielded for categories of operating, non-operating, and cycling. This is specifically because that recent industrial level in technology and design of diodes is high and marginal increment expected from improvement in their levels may be very small in comparison to the others. Nevertheless, continuous efforts towards technology and design improvements are strongly encouraged.



<Figure 3> Failure Rate Percentage of Each Category

4. Conclusion

In this research, we have performed indepth analyses for 217-Plus component models. We applied orthogonal experimental designs and examined the effects of parameters on the failure rates. From the results, a design robust to high operating temperature and electrical over stress is observed to be the most important for component reliability improvement. Next, V_S and DC are weaker but may be significant depending upon conditions of the load. Our further analysis of the failures in terms of failure categories indicates that EOS and solder joint are seen to occupy about 90% of the total failures. Improvement in manufacturing process, especially solder joint, is another significant area to direct for component quality. Although our study is restricted to a specific type of diodes, the results may still be valid to other cases. This is easily understood from the formulas given in Table 2. Nevertheless, the same approach taken in this study can be taken towards detailed results of other component cases.

참고문헌

[1] MiL-HDBK-217F Notice 2(1995), *Military Handbook, Reliability Prediction of Electronic Equipment*, Department of Defense.

[2] Denson, W. (2006), *Handbook of 217Plus™ Reliability Prediction Models*, RIAC.

[3] Nicholls, D. (2007), “What is 217Plus™ and Where Did It Come From?”, *IEEE*, pp. 22-27.

[4] Nicholls, D. (2006), “An Overview of the 217Plus™ System Reliability Assessment Methodology”, *RIAC Journal*, 4th Qtr., pp. 20-22.

[5] Dylis, D. D. (2001), “PRISM: A new Approach to Reliability Prediction”; *American Society for Quality Control (ASQC) Reliability Review*; Vol. 2, No. 1.

[6] Brown, L, M. (2003), “Comparing Reliability Predictions to field data for Plastic parts in a Military, Airborne Environment”, *2003 Annual Reliability and Maintainability Symposium*, 27-30 Jan, pp. 207-213.

[7] Kleyner, A. and Bender, M. (2003), “Enhanced Reliability Prediction Method Based on Merging Military Standards Approach with Manufacturer's Warranty Data”, *2003 Proceedings Annual Reliability and Maintainability Symposium, IEEE*, pp. 202-206.

[8] Smith, C. and Womack, J. (2004), “Raytheon Assessment of PRISM as a field failure prediction”, *IEEE Annual Reliability and maintainability Symposium Proceedings*.

[9] Peace, G. S. (1993), *Taguchi Methods*, Addison-Wesley Publishing Company, Inc.

[10] Taguchi, G., Chowdhury, S., Wu, Y. (2005), *Taguchi's Quality Engineering Handbook*, John Wiley & Sons Inc.

[11] Jeon, T. B. (2010), *Reliability Predictions of Electrical and Electronic System*, Kyowoosa.

[12] Nicholls, D. (2007), “An Introduction to the RIAC 217Plus™ Component Failure Rate Models”, *RIAC Journal*, 1st Qtr., pp. 16-21.

[13] Nicholls, D. (2007), “The RIAC 217Plus™ Capacity and Diode Failure Rate Models”, *RIAC Journal*, 2nd Qtr., pp. 16-21.

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