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Developing the Optimized Method of Reliability-Growth Target Setting for Complex and Repairable Products from Business View

Young-Kug So[1†] · Young-Rok Jeon[2] · Byeong-Jin Ryu[3]

[1]Volvo Construction Equipment, [2]Kyungnam University, [3]Volvo Construction Equipment

Purpose : The purpose of this research is to develop the optimized method and process in the reliability-growth target setting, especially for complex and repairable system (or products) such as vehicle and airplane, construction equipment.
Method : A reliability-growth test plan specifies a scenario to achieve the planned reliability value (or reliability target). The major elements in test planning are reliability-growth starting time and reliability level at that time, reliability-growth rate and reliability-growth target. All of them except a reliability target can be referred to the previous development data and reference researches. The reliability target level is directly influencing to test period (or time) which is related to test and warranty cost together. There are a few researches about the reliability target setting method and but showing the limitations to consider the views of engineering, business and customer together. There is no research how to handle the target setting process in detail.
Result : We develop the optimized method and systematic process in reliability target setting with considering such views. This research also establish the new concept as production capability which means company (or supplier) capability to product its products.
Conclusion : In this research result, we apply the new method to a few projects and can set the reasonable test planning. The developing results is showing the good balance between the developing cost and warranty cost at market.

Keywords: Current System, MTBF, New Feature Risk, Reliability Test Target, System Production Capability, Warranty Cost

1. Introduction

The objective of reliability-growth test is to find failure modes during test and incorporate the corrective actions, and then finally increase the reliability of product. This process continues during the planned test time until achieving the set reliability target. It is important that there should be the proper tradeoff between developing budget and reliability level expressed as warranty cost in view of customer.

Burnett (1997) reported the relation between the reliability-growth target level and the developing cost in software development, no considering warranty cost by poor quality. Yadav and Singh (2003) presented the method of subsystem based on their functionality, without touching developing and warranty cost. Chowdhury and Koval (2004) researched the relation of reliability level and customer cost, maintenance cost for electric system and no information about developing cost. Bartholdt *et al*. (2014) suggested the reliability setting method for subsystem which is portioned to warranty cost without considering a developing cost. The suggestion of Crow (2004) and (2010) is the representative one that requires to know all of failure information before starting test. There is no research of the optimized method and systematic process in the reliability-growth target setting considering developing cost and warranty cost, especially for complex and repairable system.

Through this research we find the optimized reliability-growth target setting method based on the balance between development and warranty cost. We also set-up the systematic process to set it which is considering a product developing capability and resources, market situation. The results may be applicable to other product and system development. Chapter 2 treats the previous research results and the concerns in implementing to a general

† Corresponding Author youngkug.so@volvo.com
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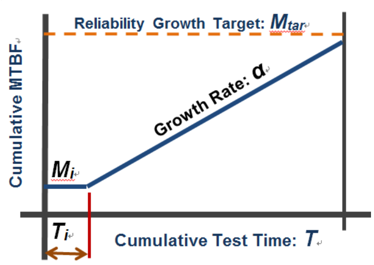
industry. Chapter 3 shows this research finding of optimized reliability-growth target setting method and process, Chapter 4 presents the application case with this research method.

2. Reviewing Previous Researches

Crow (2004) mentioned that an effective reliability-growth test planning and management strategy can contribute greatly to the successful development of new products to meet the desired reliability goals on time and within the developing budget. When the unrealistic value is set as a reliability-growth test target, the result may be painful to company by the high developing cost or customer by the low quality of products. Therefore it is necessary to set it under consiering such situations.

2.1 Concept of Reliability-Growth Test Planning

The reliability-growth test planning should include the reliability target for developing product and reliability-growth schedule as a function of accumulated test time and other resources such as <Figure 1>.



〈Figure 1〉 Reliability-Growth Planning

It is necessary to select the proper reliability-growth model to make a test plan and to assess test data, to project reliability level correctly. Braun and Paine (1977) said that the success of specific model must be judged on how well they allow the prediction of future failures. The interesting system for this research is a complex and repairable system. Dune model (1964) and Crow-AMSAA model (1975) are mainly used for reliability-growth test planning with complex and repairable system according to MIL-HDBK-189C (2009). We mainly apply the Duane model in this research as reliability-growth test planning, MIL-STD-1635 (1978) expressed the Duane model as like below:

$$M_c(T) = M_i\left(\frac{T}{T_i}\right)^{\alpha} \quad (1)$$

Where M_c, M_i, T and T_i are cumulative MTBF, initial MTBF, cumulative test time and reliability-growth starting time. The Equation (1) can be expressed such as:

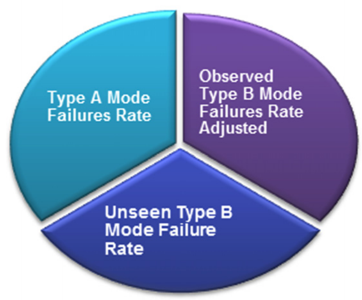
$$T = T_i\left(\frac{M_{tar}}{M_i}\right)^{-\alpha} \quad (2)$$

Where M_c is transferred to M_{tar}. The equation can be plotted such as <Figure 1>. The cumulative test time is increasing as the reliability-growth target increasing.

2.2 Limitations of Crow Suggestion

The conventional researches are mainly focusing how to assess the reliability-growth test result and project the reliability level accurately. The theoretically and commercially representative method in the reliability-growth target setting was introduced and developed by Crow (2010) for complex and repairable system.

According to Crow (2010), all of failure modes detected during testing can be classified into the type A-modes and the type B-modes as like shown in <Figure 2>. The type A-modes are all failure modes happened during test and no corrective actions, but the type B-modes are all of failure modes with the solutions.



〈Figure 2〉 Failure Categories by Crow 19

If all type B failure modes are seen and corrected with an average resolution effectiveness factor which means the ratio of failure mode disappearing with the solutions, then the reliability-growth potential failure rate during test which is also expressed as a reliability-growth target is:

$$\lambda_{tar} = \lambda_A + (1-d)\lambda_B \quad (3)$$

where the λ_{tar}, λ_A, λ_B and d are a target (or potential) failure rate, failure rate coming from the type A mode, failure rate related to the type B mode and the average resolution effectiveness factor which is the ratio of deleting failure mode after implementing solutions. The reliability-growth target (or potential) as MTBF is:

$$M_{tar} = \frac{1}{\lambda_{tar}} \quad (4)$$

He also introduced the concept of reliability-growth design margin, RGDM. It can be considered as a safety margin when setting target MTBF value, M_{tar} for the reliability-growth plan. It is common for systems to degrade in reliability when a proto-type and pilot-type product is going into serial production due to variation in material, processes, human skill etc. The typical value for it is around 1.2. Higher values yield less risk for the program, but require a more rigorous reliability-growth test plan. During the reliability-growth test planning stage, the final reliability-growth target, M_{ftar} , can be expressed as:

$$M_{ftar} = RGDM \cdot M_{tar} \tag{5}$$

It is true that the method of Crow (2004) is the most advanced one for complex and repairable system, but also there are some of concerns in implementation.

The first concern is how to know the information of the type A mode and the type B mode failure modes before starting system test. When companies prepare a reliability-growth test, the main objective is to detect the un-expected failures as many as before starting of serial (or mass) production and solve them before delivering to customers.

The second one is related to the resolution effectiveness. It is necessary to measure it of some solutions after implementing them to test units, so it is impossible to know it before starting test. If a test is for very simple components (or parts) which have the simple (or same) failure mode for every time and same solution, it might be possible to know it before testing. In case of general complex and repairable system, it is impossible to expect the same failure modes and solutions as ones of previous production system. The MIL-STD-1635 (1978) mentioned that the average 75% of all product design problems are not possible to be detected prior to a test. With our experience in construction equipment and vehicle developments, we are facing the average 65% of new failures modes not expected and experienced before.

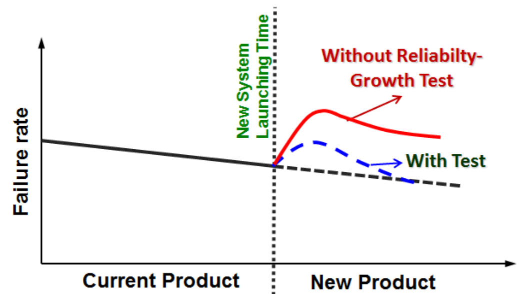
The third concern is no way how to count the business factors into the target setting, a reliability-growth test is just one step in many essential tests for the new system development. There should be limitation in a reliability-growth test time, so it is necessary to set the target with considering company resource and customer requirement in quality expressed as, warranty cost.

3. Optimized Reliability-Growth Target Setting Method and Process

When the project team starts to begins a project to develop a system, the first stage is to set a system specification with VOC (Voice of Customer) and the developing target. In view of reliability-growth methodology, the stage is very important to set the reliability-growth target and establish the reliability-growth planning. It seems very earlier time to set such important key elements, but it is essential activities to calculate a necessary resources including to a developing budget in view of business point. If the resources to develop a system are over the company capability including to budget, then they would give up or reduce the features in devoping system. Therefore it is very important for project team to set the reasonable one in view of engineering and business points.

3.1 Setting Reliability-Growth Test Objective for This Research

During this research, we set up the main objective of reliability-growth test in the new system development, which seem very important to set the method and process of reliability target setting. The most advantage of such approach is to shorten development time and cost compared the fully new system development. With our research result, there are not over the average 50% in designs and technologies from the previous system or product. The interesting system in this research is typically complex and repairable system which failures follow an exponential distribution and HPP.



<Figure 3> General Concept of Reliability-Growth Test Objective

With such background, we set the concept of reliability-growth test object to occupy the matured quality level of previously production system through detecting many unexpected failures and solving them during test as depicted in <Figure 3>. The meaning is that the quality (or failure rate) of previous (or baseline) serial production system may be improved and matured as the production period accumulated. When the quality trend of new system after launching without reliability-growth test would badly jump up and take long time to achieve the matured level which is usually taken a few years. But when applying the quality changing is relatively very small and matured in quality very soon.

3.2 Process of Reliability-Growth Target Setting

The reliability requirements or target should be set with considering developing experience (or competence) and production capability, developing budget in view of company. Then it also needs to consider, the promised delivery time and also warranty cost to customer which can be called as a business points. There were not such method and process in reliability target setting, therefore we develop the new one for complex and repairable system development as like next steps.

(1) Calculating System Production Capability (or Matured Reliability Level)

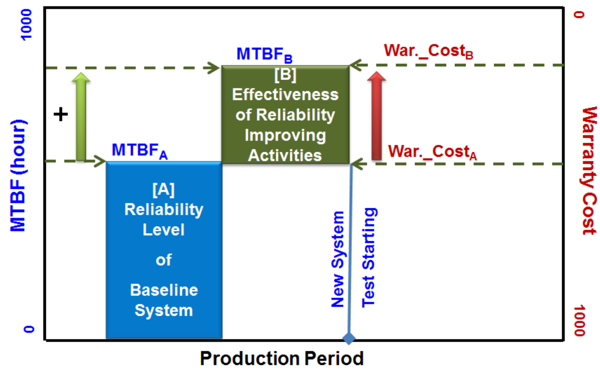
This step is to calculate the system production capability of current production system in view of MTBF and warranty cost at the test time of developing system. The main objective of reliability-growth test in this research is to achieve the same level of matured reliability in the previous (or baseline) model. We developed the new concept of system production capability including to design, manufacturing and process competence in view of quality (or reliability). The important factor is that it is necessary to estimate it of previous serial system at the time of new system testing. The estimated system production capability can be the reliability-growth target depicted at <Figure 4>.

To calculate the system production capability at the time of new system testing requires to know the current system reliability level expressed as current *MTBF* in here and the warranty cost at market. The methods to calculate them may be different according to the company situation. After calculating the current reliability, $MTBF_A$, and warranty cost, $War.\text{-}Cost_A$, of baseline (or current) system, it is necessary to know the effectiveness of reliability improving activities until the test starting time of developing system. Then it is possible to calculate the matured reliability level, $MTBF_B$, in future such as Equation (6).

$$MTBF_B = MTBF_A + \Delta MTBF_1 \qquad (6)$$

where $\triangle MTBF_1$ is an increasing MTBF by the effectiveness of reliability improving activities as shown bellow:

① Six-sigma project to improve a reliability level of quality issued component and parts
② Supplier changing from the quality issued company to quality proven company
③ Design changing of quality issued parts with the quality proven ones



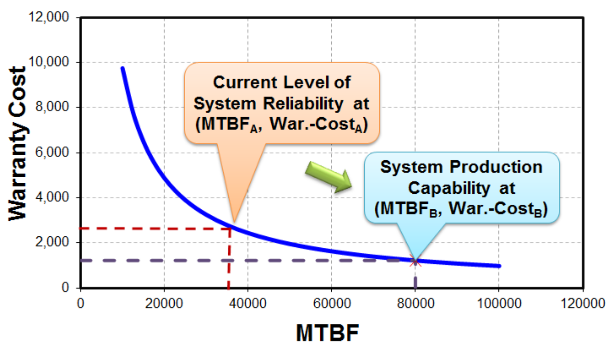
<Figure 4> General Concept of System Production Capability

There are many methods in the previous researches to calculate it with Burnett (2004), Bartholdt and others (2014). The next is to calculate the system production capability in view of warranty cost, $War.\_Cost_B$, it is necessary to know the current warranty cost and the decreasing cost with an increasing MTBF in future. Then the matured warranty cost, $War.\_Cost_B$, is like Equation (7) as:

$$War.\_Cost_B = War.\_Cost_A + \nabla War.\_Cost_1 \qquad (7)$$

where $\nabla War.\_Cost_1$ is a decreasing warranty cost by the effectiveness of reliability improving activities. For such calculation it is necessary to know the relation between a various reliability level and warranty cost of current systems in interesting such as <Figure 5>.

The relation can be made with the market warranty data including to the failure information such as a system production date, failure time and warranty cost and job site.



<Figure 5> Relation Curve of Reliability Level and Warranty Cost

(2) Calculating Drop of System Production Capability by New Features Risk of Newly Developing System

After estimating the system production capability in MTBF and warranty cost, the next step is to put the new feature risk of new one, and then the system production capability will be decreased by such risks as shown in <Figure 6>. With the risk from the new feature will reduce the MTBF from the level of system production capability such as:

$$MTBF_C = MTBF_B + \nabla MTBF_2 \qquad (8)$$

Where $\nabla MTBF_2$ is the decreasing MTBF from the system production capability because of the new feature risks. There are many types of new feature risks in industry as like:

① Component or part design change or modification because of new VOC (Voice of Customer) and regulation, emission

② Load (pressure, stress and vibration, temperature, humidity) increasing even no changing in design

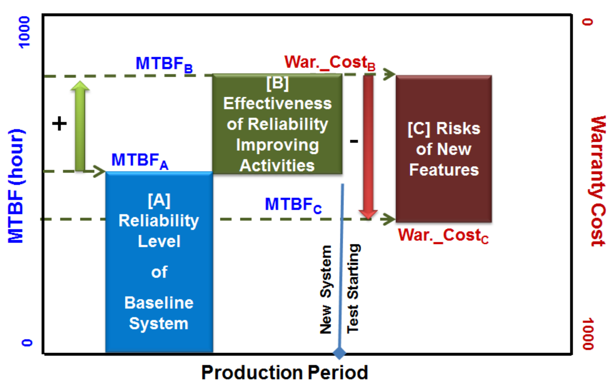
③ Changing of supplier for important component and part who don't have the experience to delivery

④ Implementing the very new technology, especially unproven one before

All of them mentioned at the above may be the representative risks to reduce the quality (reliability) of system. The calculation method of decreasing MTBF may be very different according to company capability, So and others (2012) suggested one of methods for complex and repairable system. When the reliability from system production capability is decreasing, the warranty cost from that is increasing as like Equation (9):

$$War.\_Cost_C = War.\_Cost_B + \triangle War.\_Cost_2 \qquad (9)$$

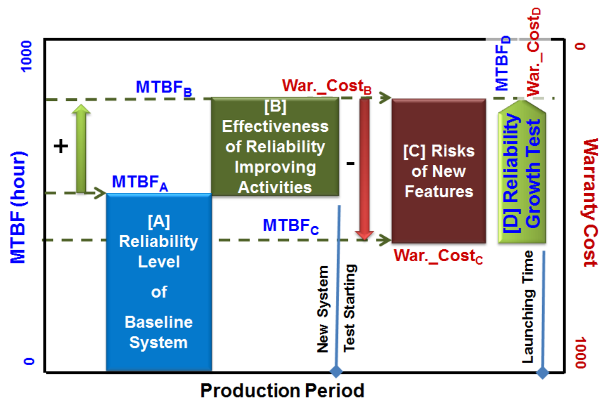
where $\nabla War.\_Cost_2$ is an increasing warranty cost by the new feature risks.



<Figure 6> System Production Capability with Risk of New Features

(3) Setting Various Reliability-Growth Test Targets

In this step, we need to set the level of reliability increasing and warranty cost decreasing by the effectiveness of reliability-growth test, the baseline for such calculation are the calculated value with Equation (8) and (9).



<Figure 7> Recovering System Production Capability with Reliability-Growth Test

With <Figure 7> we can see how to set the reliability-growth target, $MTBF_D$, which can be expressed such as Equation (10):

$$MTBF_D = MTBF_C + \triangle MTBF_3 \qquad (10)$$

where $\triangle MTBF_3$ is the increasing MTBF by the reliability-growth test and failures solving activities as like FRACAS (Failure Reporting, Analysis, and Corrective Action System) process. The project team can set the reliability-growth target with controlling the value of $\triangle MTBF_3$, we set the important disciplines for setting it after many project results as shown below:

① The value of $\triangle MTBF_3$, cannot be over $\nabla MTBF_2$, namely the reliability-growth target should be same as or lower than the value of $MTBF_B$ The most ideal case is to set the target to the system production capability as $MTBF_B$

② If the value of $\triangle MTBF_3$ is lower than $\nabla MTBF_2$, there will be the remained warranty cost even reliability-growth test finished. In that time the total warranty cost will be the sum of $War.\_Cost_A$ and the remained one after test and solving.

The calculation method for warranty-cost changing by the reliability increasing by testing and solving is like Equation (11):

$$War.\_Cost_D = War.\_Cost_C + \nabla War.\_Cost_3 \qquad (11)$$

where $\nabla War.\text{-}Cost_3$ is a decreasing warranty cost by increasing MTBF by reliability-growth test and solving activity.

(4) Calculating Reliability-Growth Test Cost

After setting the reliability (or MTBF) target, a project team needs to calculate the cost of reliability-growth test. The cost is related to all resources to take a test and solving such as man-power, building test-systems, fuel, consuming parts and replacing component, etc. The calculation of reliability-growth test cost, Test-Cost, is such as:

$$Test\_Cost = Test\_System\_Building + Man\_Hour + Other\_Resourcess \quad (12)$$

where the composition of it may be different according to the system specification and company situation, the important factor is that it should include all kinds of cost related to the reliability-growth test performing and failure solving activities.

(5) Choosing the Optimized Reliability Target Considering Warranty Cost and Reliability-Growth Test Cost

Even the higher reliability level will be better to reduce the warranty cost and happier to customer, but it will take much cost for the company to develop such products and also increase the sale price of system. There should be trade-off between the reliability-growth target and test cost.

For such work it is necessary to set the various reliability-growth targets and calculate the remained warranty cost with such various MTBF level. The next is to calculate the test cost for each case. Finally need to compare the various levels of warranty costs and test cost, and then find the similar level in both sides which can be a candidate as the optimized point for reliability-growth target. The more detail information is in the next chapter with the application case.

4. Application Case with New Reliability-Growth Test Setting Method

The case in this chapter is the typical one for complex and repairable system such as construction equipment development and it is possible to see the detail method about how to set the reliability-growth target in this chapter. For this calculation, there are some assumptions such as below:

① Interesting system is a typically complex and repairable system whose failures are following exponential distribution

② The current production system MTBF and warranty cost are 10,000 and 1,000

4.1 Calculating System Production Capability

In this step it is necessary to know the effectiveness of reliability improving activities until the test starting time of new system, we assume 40% increasing in reliability by the activities and get 40% decreasing in warranty cost from the relation between MTBF and warranty cost for the current production system depicted at <Figure 5>. Then with the Equation (6) and (7), the system production capability is as like <Table 1>:

<Table 1> System Production Capability

Baseline System		Changing 1 by Reliability Improving Activities		System Production Capability	
$MTBF_A$	War-$Cost_A$	$MTBF_1$	War-$Cost_1$	$MTBF_B$	War.-$Cost_B$
10,000	20,000	4,000	-8,000	14,000	12,000

4.2 Calculating Drop of System Production Capability by New Feature Risks of Newly Developing System

After estimating the system production capability by all reliability improving activities, the next step is the calculation of reliability dropping and warranty cost increasing from the capability by adding new feature risks.

Here we assume that the new feature risks reduce the MTBF level to 35% from the capability and increase the warranty cost to 60%. The calculation is following to Equation (8) and (9) and the result is at <Table 2>.

<Table 2> MTBF Changing with New Feature Risks

System Production Capability		Changing Value 2 by New Feacture Risk		Reduced System Production Capability	
$MTBF_B$	War-$Cost_B$	$MTBF_2$	War-$Cost_2$	$MTBF_C$	War.-$Cost_C$
14,000	12,000	-4,900	7,200	9,100	19,200

4.3 Setting Various Reliability-Growth Test Targets

Next, it is necessary to set the various steps of reliability-growth increasing, $\triangle MTBF_3$, by reliability-growth test, the maximum value may not be over the $\bigtriangledown MTBF_2$ according to our experience. The total MTBF level with the MTBF increasing effectiveness of testing cannot also be over the system production capability. The warranty-cost decreasing by the various MTBF levels can be estimated by Equation (11) and <Figure 5>. The step numbers of various MTBF target in Equation (10) should be over six points at least and the more is better simulation to choose the optimized point between MTBF, warranty cost and test cost calculated later. The various reliability-growth targets and warranty-costs are listed at <Table 3>.

〈Table 3〉 Various Reliability Targets and Warranty Costs

Reduced System Production Capability		Changing Value 3 by Reliability Growth Test		Target of Reliability-Growth	
$MTBF_C$	War-$Cost_C$	$MTBF_3$	War-$Cost_3$	$MTBF_D$	War.-$Cost_D$
9,100	19,200	4,900	-7,200	14,000	12,000
		4,410	-7,128	13,510	12,072
		3,920	-6,984	13,020	12,216
		3,430	-6,768	12,530	12,432
		3,185	-6,552	12,285	12,648
		2,940	-6,264	12,040	12,936
		2,450	-5,544	11,550	13,656
		2,205	-5,026	11,305	14,174
		2,107	-4,824	11,207	14,376
		1,225	-2,520	10,325	16,680
		735	-360	9,835	18,840

4.4 Calculating Reliability-Growth Test Cost

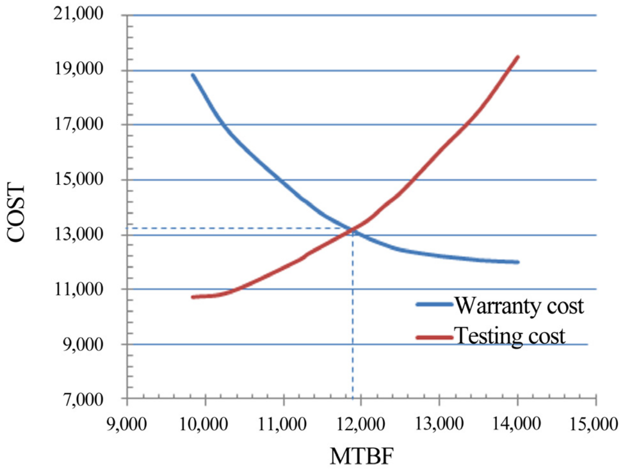
With the various target MTBF levels, it is possible for project team to calculate the reliability-growth test cost with Equation (12). The result is at <Table 4>.

〈Table 4〉 Cost for Reliability-Growth Test

Target of Reliability-Growth		Reliability-Growth Test Cost			
$MTBF_D$	War-$Cost_D$	Yesting System Building	Man Hour Cost	Other Resources	Sum
14,000	12,000	15,000	3,000	1,500	19,500
13,510	12,072	13,500	2,700	1,350	17,550
13,020	12,216	12,390	2,478	1,239	16,107
12,530	12,432	11,250	2,250	1,125	14,625
12,285	12,648	10,800	2,160	1,080	14,040
12,040	12,936	10,350	2,070	1,035	13,455
11,550	13,656	9,750	1,950	975	12,675
11,305	14,174	9,450	1,890	945	12,285
11,207	14,376	9,300	1,860	930	12,090
10,325	16,680	8,400	1,680	840	10,920
9,835	18,840	8,250	1,650	825	10,725

4.5 Choosing the Optimized Reliability Target Considering Warranty Cost and Reliability-Growth Test Cost

Based on <Table 4> which includes all of the calculation results, it is possible to draw <Figure 8>. Then we can see that the point of 12,000 MTBF crosses one of test cost and warranty-cost curves, so such MTBF is the trade-off point in view of company and customer which is one of best selection for company.



〈Figure 8〉 Optimized Curve between Warranty-Cost and Reliability-Growth Test Cost

5. Conclusion

The most important element in reliability-growth management process is a reliability-growth test which is showing the reliability-growth planning and tracking, projecting a reliability level. In the reliability-growth test, the reliability target setting may be most critical factor to influence the length of test period. we developed the practical and optimized reliability-growth target setting method and process. During the this research, we also set up the concepts of system production capability, the kinds of new design risks, the correlation between reliability level and warranty cost of system in market. It may be applicable to any product or system development with the small modification according to its specification.

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