OPTIMUM DESIGN OF EXPERIMENTS FOR ACCELERATED RELIABILITY TESTING

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Abstract: *In this paper is presented a case study that demonstrates how design to experiments (DOE) information can be used to design better accelerated reliability tests. In the case study described in this paper, will be done a comparison and optimization between main accelerated reliability test plans (3 Level Best Standard Plan, 3 Level Best Compromise Plan, 3 Level Best Equal Expected Number Failing Plan, 3 Level 4:2:1 Allocation Plan). Before starting an accelerated reliability test, it is advisable to have a plan that helps in accurately estimating reliability at operating conditions while minimizing test time and costs. A test plan should be used to decide on the appropriate stress levels that should be used (for each stress type) and the amount of the test units that need to be allocated to the different stress levels (for each combination of the different stress types' levels). For the case study it used ALTA 7 software what provides a complete analysis for data from accelerated reliability tests.*

Keywords: reliability, design of experiment, plan, accelerated reliability testing.

1. INTRODUCTION

Product reliability is a prime contributor to quality and competitiveness. Manufacturers spend millions of dollars improving product reliability every year with much effort going into evaluating reliability through testing and data collection. Major design and production decisions are based on life test data, often from only a few units. For some products, the test time necessary to provide adequate reliability assurance under normal operating conditions might be inordinately long and very expensive. Reliability-data gathering should not hold up development, and should be as economical as practicable, so it is important to be able to conduct reliability tests as quickly as possible consistent with obtaining meaningful results.

The strategies for various reliability tests are primarily determined by the stage of product development during which the testing is performed. During early development of a new product no units are available; therefore no reliability testing can be performed. Reliability tests with a strategy to estimate the failure rate or MTBF of the product can begin once production units become available. These tests, referred to as life tests, accumulate test time on several units while recording failures. These tests are required to run for a period of time [1].

Planning for an integrated reliability test program must begin at the beginning of the project. Planning must be thorough and timely if all the necessary elements are to be in place when they are needed.

Planning must be done to assure that the number of units to be tested, the test facilities including any special equipment, and the necessary time are available when the tests are to be performed. Scheduling of the various reliability tests is necessary so that the results can be used in a timely manner based on the strategy of the test. It is much more efficient to make a design change before the product is released to production.

A test plan needs to include the following (figure 1):

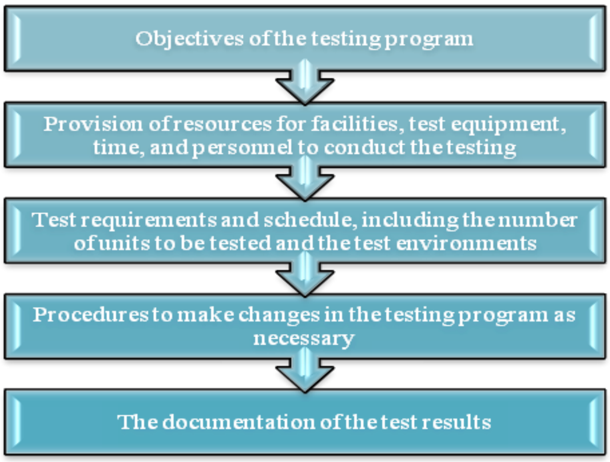


Fig. 1. *Flow chart of reliability test plan*

Reliability accelerated testing are statistically based sampling tests performed to approximate the long term reliability of a product before products are mass produced in manufacturing. The testing is performed under a controlled test environment over specific time and temperature durations. These tests also provide acceleration factors that are used to estimate the mean time to failure, (MTTF), life expectancies of a product under test. There are different types of accelerated experiments plans in use, which include subjective, traditional, best traditional, and statistically optimum and compromise plans [2].

Accelerated reliability testing models relate the failure rate or the life of an product to a given stress such that measurements taken during accelerated testing can then be extrapolated back to the expected performance under normal operating conditions. The implicit working assumption here is that the stress will not change the shape of the failure distribution. The most significant acceleration models is: Arrhenius, Eyring, Inverse Power Law; Life - Thermal Cycling, Life - Voltage, Life - Vibration, Life - Humidity, Life - Temperature – Humidity [3].

Accelerated reliability testing is used in electronics (resistors, lasers, liquid crystal displays, electronic bounds, switches, relays, cells and batteries) in the study of metals and composite materials, but also for certain components and mechanical assemblies (hydraulic components, tools, bearings).

The degree of interdisciplinary of research in the field of accelerated experiments is complex and can include the following industries: manufacturing engineering, the aerospace industry, the nuclear industry, the electronic industry, the dental industry, the pharmaceutical industry and the industry of renewable energy resources [4].

2. DESIGN OF EXPERIMENTS

Design of experiments (DOE), then, is the tool to develop an experimentation strategy that maximizes learning using a minimum of resources. DOE is widely used in many fields with broad application across all the natural and social sciences. It is extensively used by engineers and scientists involved in the improvement of manufacturing processes to maximize yield and decrease variability. Often engineers also work on products or processes where no scientific theories or principles are directly applicable. Experimental design techniques become extremely important in such studies to develop new products and processes in a cost effective and confident manner [5].

The design and analysis of experiments revolves around the understanding of the effects of different variables on another variable. In technical terms, the objective is to establish a cause-and-effect relationship between a number of independent variables and a dependent variable of interest. The dependent variable, in the context of DOE, is called the response, and the independent variables are called factors. Experiments are run at different factor values, called levels. Each run of an experiment involves a combination of the levels of the investigated factors, and each of the combinations is referred to as a treatment. When the same number of response observations is taken for each of the treatments of an experiment, the design of the experiment is said to be balanced. Repeated observations at a given treatment are called replicates [6].

The number of treatments of an experiment is determined on the basis of the number of factor levels being investigated. For example, if an experiment involving two factors is to be performed, with the first factor having m levels and the second having n levels, then m x n treatment combinations can possibly be run, and the experiment is an m x n factorial design. If all m x n combinations are run, then the experiment is a full factorial. If only some of the m x n treatment combinations is run, then the experiment is a fractional factorial. In full factorial experiments, all the factors and their interactions can be investigated, whereas in fractional factorial experiments, at least some interactions are not considered because some treatments are not run.

The flow chart below (figure 1) illustrates the experiment design process:

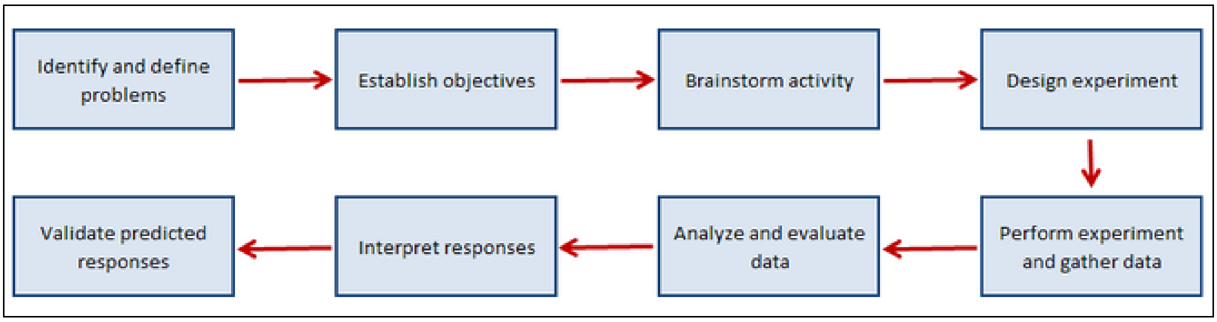


Fig.2. *Experiment Design Process*

3. DESIGN OF ACCELERATED RELIABILITY TESTING PLAN

The scope of accelerated reliability testing plan (ARTP) is to minimize the uncertainty of the life and reliability extrapolations to normal use conditions by determining the optimum stress levels to be used in the test as well as the optimum allocation of test units at each level. ARTP can be performed using simulation or analytical methods. In either case, a minimum amount of information needs to be provided in order to determine the optimum settings for the test. All ARTP techniques begin with the assumptions that

a) the underlying physics of failure are understood;

b) the test will consider only the significant factors;

c) the maximum stress levels are known for all stresses.

For analytical methods in ALTA 7 software, the minimum input requirements are:

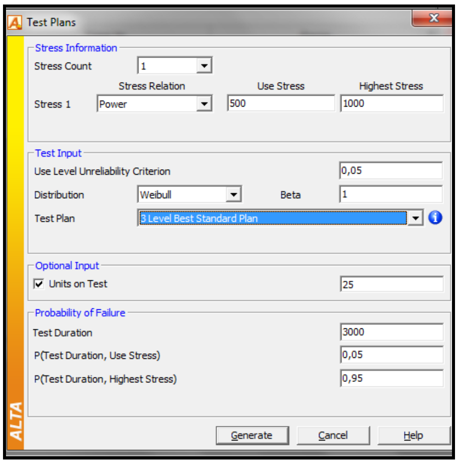
- Number of stresses under consideration. This is the total number of factors that will be included in the test;
- Life-stress relationship. This is the physics-based model that relates life with stress. This relationship is determined by the underlying physics of failure and allows us to compute the reliability of the product at different stress conditions. For example, the use of the power law equation on S-N curves (or Wohler curves) in fatigue is such a relationship. The Arrhenius model for thermal stressing is another. The relationship needs to be specified for every stress under consideration.
- Use stress level. This is the stress level at which the design is expected to operate under normal use conditions.
- Highest (or maximum) stress level. This is the maximum stress level that the design can withstand without introducing foolish failure modes.
- Use level unreliability criterion. This represents the percentile of the distribution at use conditions that needs to be estimated from the QALT data analysis. In other words, this is the objective point of the use level distribution where extrapolations will be performed. This is needed in order to have a criterion such that, using the failure data obtained from the test, we can make predictions with a relatively small uncertainty.

- Test duration. This is the length of time for which the units will be tested.
- Probability of failure for the specified test duration at the specified use stress level. This is an estimate of the percentage of the units that would fail if the test were performed at the normal use conditions for the specified test duration.
- Probability of failure for the specified test duration at the specified highest stress level. This is an estimate of the percentage of the units that would fail if the test were performed at the maximum stress level conditions for the specified test duration.

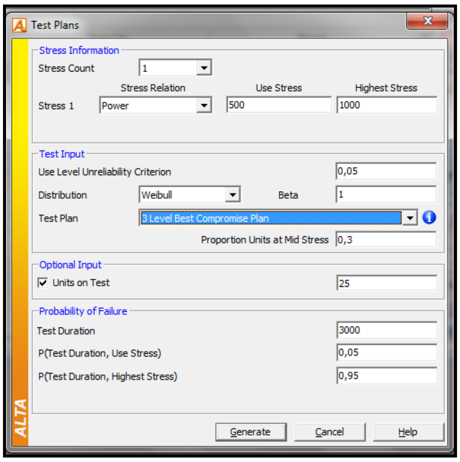
The last two inputs are needed in order to determine the optimum stress levels at which to run the test. These levels are determined by ensuring that a) enough failures are observed within the specified test duration and b) the test stress levels are not too far from the use conditions, thus reducing the extrapolation error. The extrapolation error is computed in conjunction with the use level unreliability criterion.

4. CASE STUDY

A typical ARTP is characterized by the stress levels, the number of test units allocated to each level, and their censoring times. The most commonly used ART in modern manufacturing industry is the constant-stress ART (CSART) where stress applied to a sample of units is constant. A typical parametric model of CSART consists of two components: (1) a lifetime distribution that models the time-to-failure at a constant-stress level; and (2) a stress-life model that quantifies the manner in which the lifetime distribution changes a cross different stress levels. There are different types of ART plans in use, which include subjective, traditional, best traditional, statistically optimum and compromise plans [4, 10].



a)



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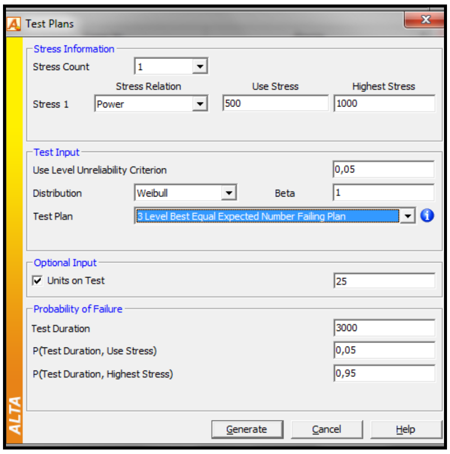
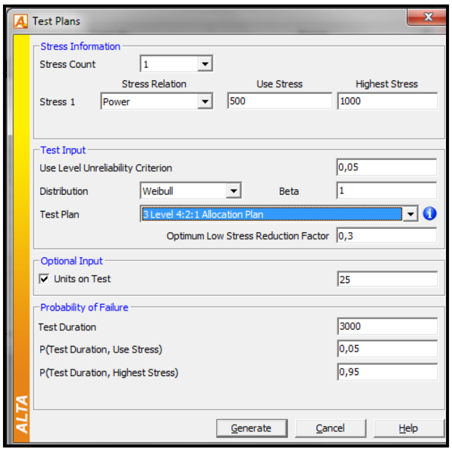


c)



d)

Fig.3. *Test plans*

The case study is directed to design a plan of experiments for a mechanical product that has the following parameters set: use stress: 1 stress: force; 500 daN; maximum stress: 1000 daN; acceleration model: IPL - Inverse Power Law Relationship; distribution: Weibull; β=1; Units on test: 25.

The test plan was realised using the ALTA software, introducing the aforementioned parameters. This case study presents a comparative analysis between accelerated reliability testing plans used by ALTA 7 software (3 Level Best Standard Plan – figure 3.a, 3 Level Best Compromise Plan figure 3.b, 3 Level Best Equal Expected Number Failing Plan - figure 3.c, 3 Level 4:2:1 Allocation Plan - figure 3.d).

The ALTA 7 software generates an optimum testing report, where the levels of accelerated life testing and the number of specimens tested at every accelerated stress level are specified for 4 plans of accelerated reliability testing (table 1-4).

Table 1. *Report regarding 3 level best standard plans*

Results	Stress Level [daN]	Portion Units	Units on Test	Probability of Failure
Low Stress Level	548,286	0,333	8,333	0,084
Middle Stress Level	740,463	0,333	8,333	0,402
High Stress Level	1000	0,333	8,333	0,95

Table 2. *Report regarding 3 level best compromise plans*

Results	Stress Level	Portion Units	Units on Test	Probability of Failure
Low Stress Level	551,717	0,591	14,775	0,087
Middle Stress Level	742,776	0,3	7,5	0,407
High Stress Level	1000	0,109	2,725	0,95

Table 3. *Report regarding 3 level best equal expected number failing plan*

Results	Stress Level	Portion Units	Units on Test	Probability of Failure
Low Stress Level	564,482	0,748	18,712	0,099
Middle Stress Level	751,32	0,173	4,333	0,429
High Stress Level	1000	0,078	1,955	0,95

Table 4. *Report regarding 3 level 4:2:1 allocation plan*

Results	Stress Level	Portion Units	Units on Test	Probability of Failure
Low Stress Level	517,991	0,571	14,286	0,061
Middle Stress Level	719,716	0,286	7,143	0,353
High Stress Level	1000	0,143	3,571	0,95

5. CONCLUSION

Accelerated reliability testing analysis can be conducted on data collected from carefully designed quantitative accelerated life tests. Well-designed accelerated reliability tests will apply stresses at levels that exceed the stress level the product will encounter under normal use conditions in order to accelerate the failure modes that would occur under use conditions. With the DOE methodology, the significant factors affecting the life of the product can be determined. This will assist in designing more efficient accelerated life tests that do not waste time or resources by including unnecessary factors.

A good plan should be multi propose and robust and provide accurate estimates. Such a plan consists of three or four equally spaced test levels with unequal allocation. Such unequal allocation puts more items at the extremes of the test range and fewer in the middle. Also, allocation more items to the lowest level; this is especially effective if the design stress is close to the test range. Of course, more specimens at the lowest test level results a longer test time until the items fail. In conclusion, 3 level best compromise plans represents the optimum plan for this case study and it meets all aforementioned conditions.

6. REFERENCES

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