Benefits and efficiency of the environmental robustness testing subsystem of a development and manufacturing project

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Abstract

A system engineering perspective is presented with respect to the testing and evaluation subsystem of a project, with an emphasis on the environmental robustness evaluation sub-system (ERESS). The system called "the development and manufacturing project" with its three sub systems ("development", "manufacturing", and "testing and evaluation") is discussed first. Next the elements of the ERESS are discussed. The "partial testing" and "full testing" models are presented in the following. Examples of their implementation are presented. Next, the importance of concentrating the testing effort in the development stages is discussed, with emphasis on the life-cycle cost improvement by slightly increasing the R&D resources (including testing). The importance of planning the testing resources, bearing in mind the life cycle cost is also discussed. It is also pointed out that the effectiveness and the cost efficiency of the (ERESS) can be increased significantly by transferring testing from the field to the laboratory.

Introduction

A "project", in the authors' opinion which is expressed in Fig. 1, is a system based on three interrelated subsystems: "development", "manufacturing", and "testing and evaluation". The "project system" is designed to fulfill the requirements that specify the features of a product. The "development subsystem" designs the product to meet the specification's requirements. The "manufacturing subsystem" creates the product. In parallel with these two subsystems runs the "testing and evaluation" subsystem that provides at each stage of the project the information required to evaluate the progress of the project, as related to the predefined established goals. Application of the three subsystems leads to the achievement of the product and its required quality, the features of which are presented in Fig. 1 (the required features are defined by the product specifications and contract). In the context of this paper the environmental robustness is of interest. Throughout the project the product quality is evaluated by the environmental robustness testing subsystem, which is part of the testing and evaluation subsystem. This sub-subsystem is applied throughout the project to supply information related to the product's capability to preserve its quality features under the environmental loads of the product's life-cycle (a capability known as environmental robustness). The efficient and effective operation of this sub-subsystem is influenced by the planning and implementation of the management plan that directs the application of the environmental robustness evaluation sub-subsystem (ERESS). The paper elaborates both on aspects that relate to the benefits of applying the ERESS, and on aspects that relate to its efficient operation.

Elements of the environmental robustness evaluation sub-subsystem ERESS

Figure 2 presents the elements of the ERESS. The input to this subsystem is the requirement of information about the product environmental robustness. The output is the required information. This is provided at the different project stages, being used in decision-making and evaluation of the project's specification requirement fulfilling at its different mile-stones. The basic element of the ERESS is the product's life cycle (LC). The ERESS is planned, implemented and operated in order to expose the product to conditions that are an equivalent to the life-cycle's environmental loads, by this enabling the surfacing and correction of the product's environmental robustness weaknesses. Knowledge and understanding of the life-cycle permits the derivation of the environmental conditions matrix (ECM) that correlates between the life-cycle's stages and the appropriate environmental loads. It also enables the identification of the critical testing issues. This means identification of the questions related to the product's environmental robustness that can be answered through laboratory environmental testing. Design criteria on the one hand and testing scenarios on the other hand can be formulated, from the environmental conditions matrix. The environmental engineering management plan (EEMP) is generated to manage all the activities and resources that enable the product's environmental robustness evaluation throughout the project. The EEMP plans and coordinates the testing activities to be performed by computerized simulation, field and laboratory testing. Testing is organized in the project's testing matrix (PTM) that integrates the testing activities at the different hardware levels of the product, starting with the component and ending at the system level. The activities relate both to non-contractual and contractual testing tasks. A test specification can be found behind each square in the testing matrix. The total of all specifications is organized in the project's specification document (SD). Each test requires its own resources.

All the testing resources are organized in the project testing resources matrix (MPTR). Each testing specification defines the test reporting documents, namely the format in which the data accumulated during the testing (the output of the ERESS) is to be presented.

Environmental robustness testing models

The environmental robustness testing and evaluation subsystem operates from the onset of the project throughout the product maturation. One model of the testing mode of operation is described in Fig. 3. Testing starts in the development stages and continues toward the prototype stage, followed by field testing, during which data are accumulated to update the description of the environmental loads, and the testing specifications of the formal testing. Formal testing (qualification), during which the capability of the product to withstand the extreme loads and to survive throughout the life-cycle is demonstrated, follows the updating process.

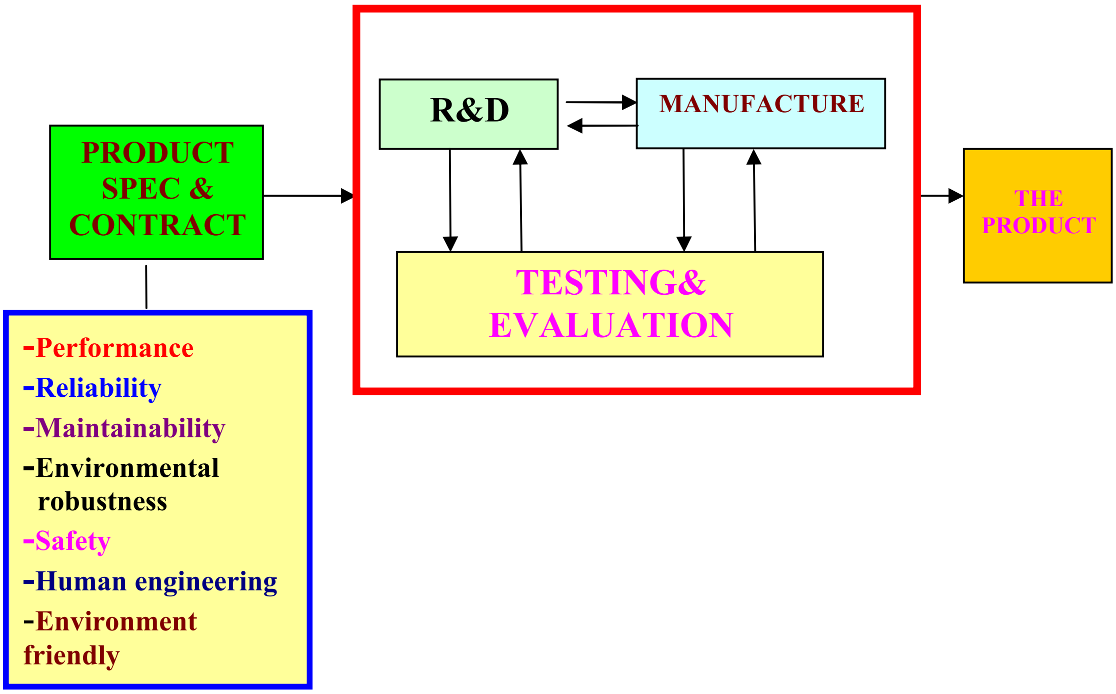


Fig. 1: The "project" - a system for the generation of a product (service)

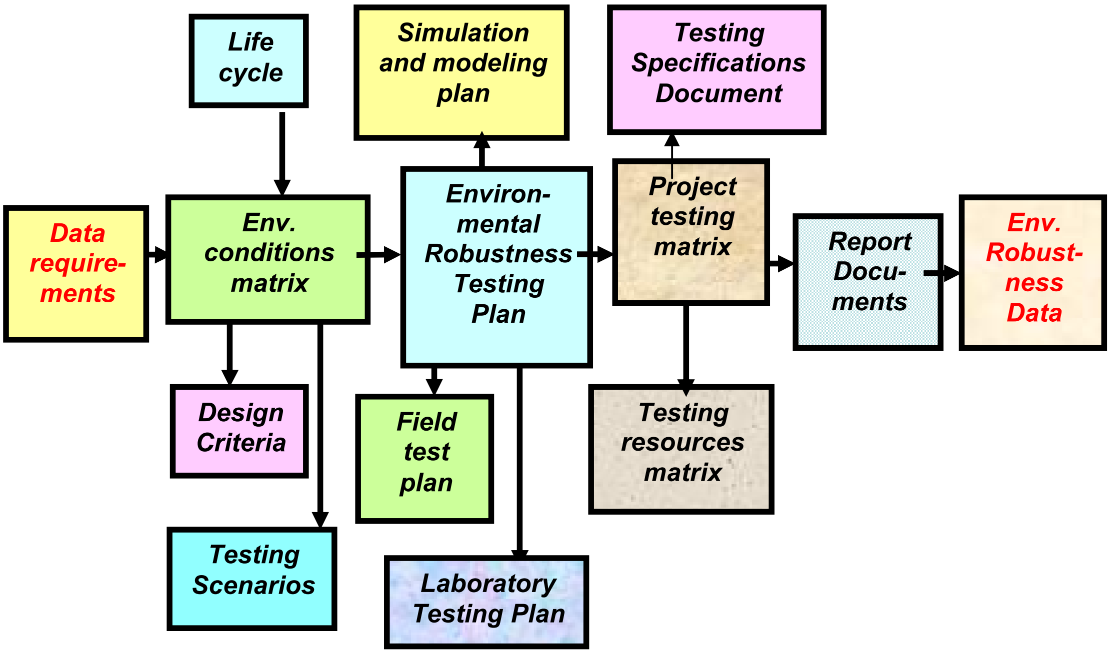


Fig. 2: Elements of the environmental robustness testing system

As can be observed in Fig. 3, at this stage the product has not yet achieved full maturation (has not achieved the product MTBF-Mean-Time-Between-Failure final goal). Mass production starts prior to the achievement of this goal. If design weaknesses surface during the field service of the product, a new development cycle is started to correct and to improve the product and by doing, so to mature the product. The manufacturing line continues to expose the product to laboratory simulated environmental loads, to produce fast surfacing of manufacturing failures (environmental stress screening) on the one hand, and to test the environmental robustness of the product by final acceptance testing, on the other hand. In the frame of this model, the maturation of the product is only partially accomplished by laboratory testing, while exposing the product to simulated environmental conditions. Maturation is completed during field service. This is **the partial testing** model. Two examples are presented in the following. A product to be used in a naval application successfully passed (without failures) the qualification testing (at the stage indicated in Fig. 3). When the customer required testing of the product, for an additional 1750 hours under environmental loads representative of the life cycle's statistics, 30 failures were recorded (a product with 50 hours MTBF). During the first 600 flight hours of an airborne product which was successfully qualified (no failures), 10 failures were recorded. By that time a new customer required a product with an MTBF of 300 hours. The maturation from 60 to 300 hours MTBF requires several thousands of testing hours with exposure to

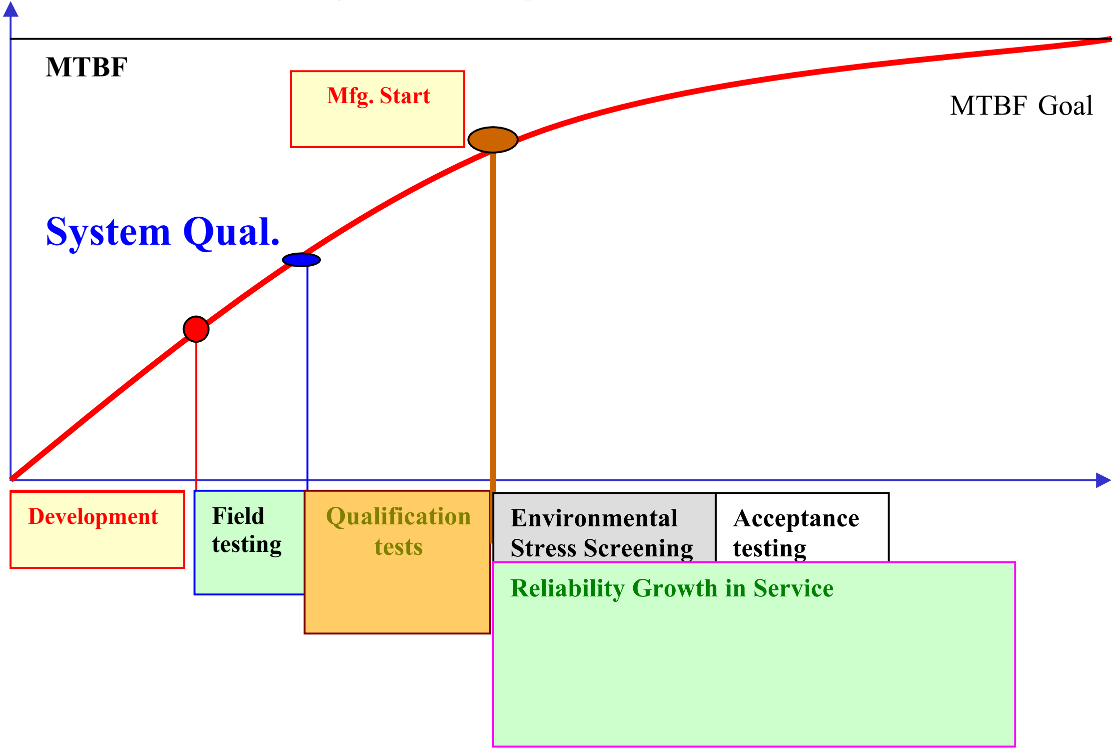


Fig. 3: The partial testing model

environmental loads, when reliability growth is performed as recommended by the appropriate literature [1]. If the testing model presented in Fig. 4 is applied during the development, these testing hours are performed under laboratory simulated environmental loads, prior to the start of the mass manufacturing. The testing hours are accumulated on products manufactured in the pre-series manufacturing stage. The maturation of the product is achieved through the process known as TAFF (Test, Analyze Failure, and Fix). At the end of the maturation process, the product has to be reliability qualified, meaning manufactured according to final manufacturing documentation and processes, and undergoing testing to demonstrate achievement of the final MTBF. The testing model presented in Fig. 4 is the **full testing** model. In the frame of this model use of laboratory simulated environmental loads continues during environmental stress screening and final acceptance testing. The main character that differentiates between the two testing models is that in the frame of the **partial testing** model, the maturation of the product is completed during field service, while in the frame of the **full testing** model the process of maturation is completed before taking the system into the field. An example of the **full testing model** application can be observed in Fig. 5 taken from [8]. The figure describes the reliability growth program for the AMRAAM missile. Testing was performed under laboratory simulated flight conditions using a specially built simulator (Flight Test Simulator –FTS [8]). It can be observed that at 500 testing hours the MTBF was 190 hours and at 8100 testing hours it was 505 hours.

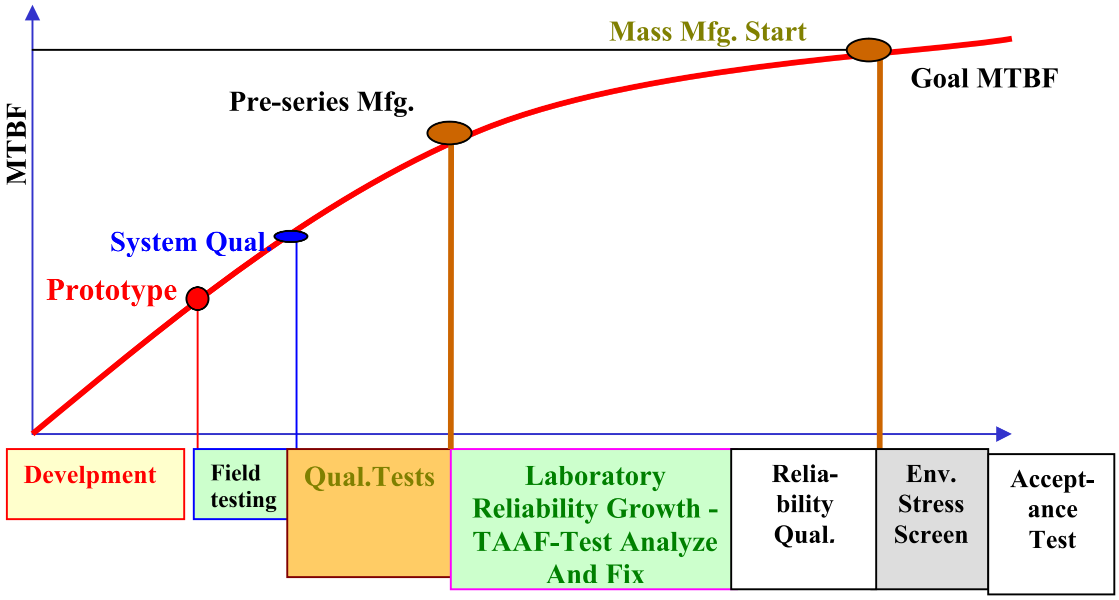


Fig. 4: Full Testing Model

The difference between the two models is elucidated in Fig. 6. The figure which appeared in one of Harvard's Weekly Business issues [2] compares between the development processes in Japanese and American industries during the eighties. The comparison is in terms of engineering changes performed on a product during a development cycle of 24 months. It can be observed that according to the Japanese model 90 percent of the engineering changes are performed approximately 15 months prior to start of manufacturing. According to the American model the engineering changes continue after the start of the manufacturing. The distribution of the engineering changes throughout the project is related to the distribution of the testing efforts. According to the Japanese model these efforts are concentrated in the very early stages of development, while according to the American one, they are invested toward its final stages and even during the product's field service.

Early application of testing efforts - a basis to an efficient and cost effective product development

An early investment in development testing efforts, that enables the early surfacing and correction of development weaknesses, is of high significance in the efficient and cost effective product development. As can be seen from Fig. 7 that originates from [3], the cost of surfacing a product failure increases by a factor of 10 with each development stage. With each project stage the failure surfacing and correction is more complex, complicated and costly. It is quite clear that when the failure is surfaced during field service, the costs caused by loss of reputation add to those required to detect and correct it. The cost of defect removal at different stages can be observed also from Table 1 below.

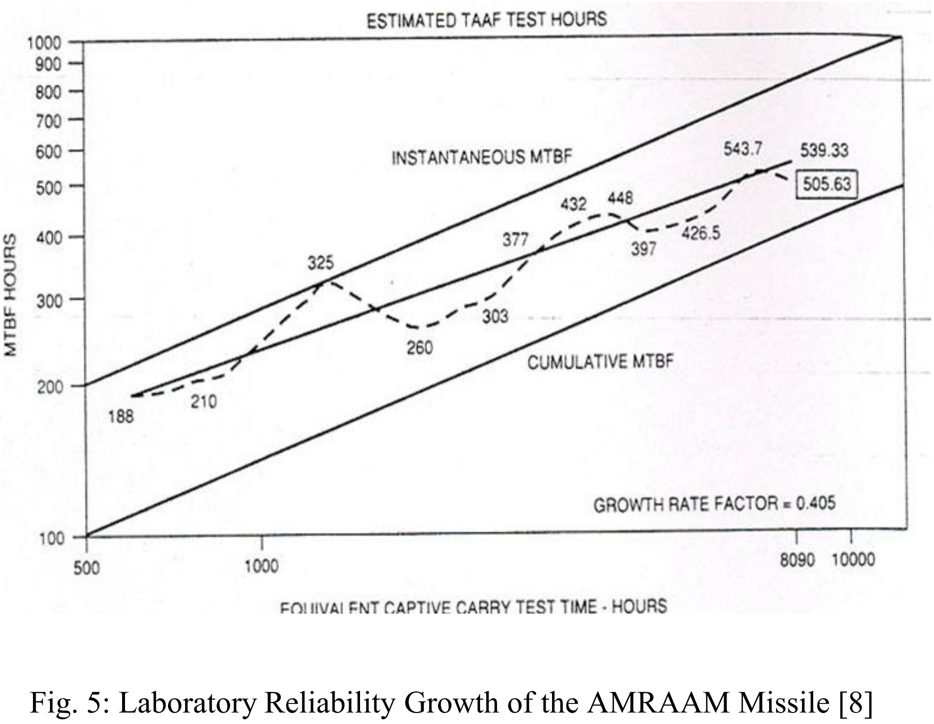


Fig. 5: Laboratory Reliability Growth of the AMRAAM Missile [8]

A small increase of the research and development resources leads to a significant reduction of life cycle costs.

Allocation of appropriate research and development resources (including development testing resources) in the early project stages can significantly affect the product’s life-cycle costs [5]. Results of the research summarized in the paper show that a small increase in the research and development resources, including testing (1 to 2 percent of the life-cycle costs) leads to savings greater than 25 % in the life-cycle costs. This result is demonstrated in the example presented in [6], summarized in Table 2. The example relates to the development program of the Atlas missile guidance system. Two versions were considered, one of nominal reliability and the second of higher reliability. As can be seen from the table, while the development and manufacturing costs of the high reliability system are higher by approximately 10 million dollars, the life-cycle costs are lower by more than 58 million dollars.

Table 1: Cost of defect removal at different stages [4]

Product Market	Cost of defect removal at different stages [U.S. $]			
	Incoming piece parts	Board mount removal	System test	Field use
Commercial	3.00	7.50	7.50	75.00
Industrial	6.00	37.50	67.50	322.00
Military	10.50	75.00	180.00	1500.00
Space	22.50	112.50	450.00	$3\text{x}10^8$

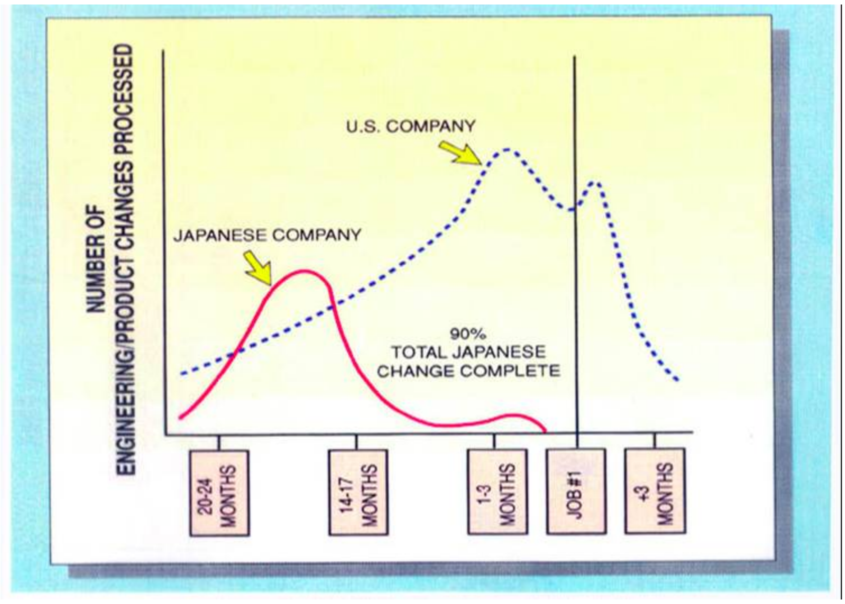


Fig. 6: Comparison of two models of testing effort application [2]

Table 2: Life cycle costs (million dollars) of the Atlas Missile guidance system [6]

Life Cycle Stage	Nominal reliability	High reliability
Research and development	50.00	59.30
Manufacturing	9.40	10.20
Maintenance	99.00	30.50
Total	158.40	100.00

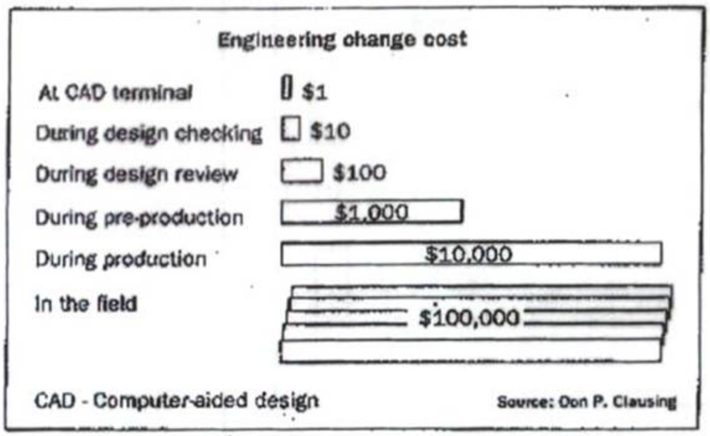
Another example, presented in Fig. 8, also taken from [6] shows that investment of larger development resources leads to a product of higher reliability and higher price, but of much lower use costs. The figure presents data related to an avionic product developed and manufactured by two different suppliers. Supplier A supplies a more expensive product (higher price per unit) and Supplier B produces a less expensive product (lower price per unit). It can also be seen that the initial investments of Supplier A are higher. The product of Supplier A has an MTBF of 941 hours, while that of Supplier B an MTBF of 331 only. It also can be seen that the maintenance costs of Supplier B's product are significantly higher than those of Supplier A. Although the initial resources (development, testing) invested by Supplier A are higher by 2000 K$, the use (life-cycle) cost of the product Supplied by B is higher by 6821 K$.

Effectiveness of the testing and evaluation subsystem in terms of the ratio of benefit to testing cost

As can be learned from the literature [7], “saving” of testing efforts and resources at the appropriate stages of the project can affect the length of the product’s life-cycle. Table 3 presents data related to the way in which non-application of appropriate environmental testing affects the life-cycle of a satellite. Several acceptance tests are performed before the launching of a satellite, including acoustic testing, thermal cycling (a failure screening process) and thermal-vacuum testing. One can learn from the table what percent of the satellite life-cycle is lost by not performing one of the above mentioned tests.

More testing means fewer failures during service - the Test Thoroughness Index

The fact that more testing means fewer failures during service is mentioned also in [9]. The paper describes results of the effectiveness evaluation activities of MIL-STD-1540 (USAF Standard for testing space hardware) during the process of replacing Version B by Version C. A test thoroughness index (TTI) was defined as can be seen in Fig. 9. The TTI defines the percent of test methods of MIL STD 1540 B used during a space project. It can be observed that the GPS project had a TTI of 100 percent. Next the number of the early flight failures for the different space projects was correlated with the TTI, as can be seen in Fig. 10. As expected intuitively, the project with the highest TTI was that with the lowest number of failures per 100,000 parts, as can be seen for GPS project in Fig. 10. A life-cycle gain of 19 dollars was observed for each testing dollar in performing all the above mentioned tests.



The cost of change increases by a factor of 10 through the phases of design, design checking, reviewing, pre-production, production, and, finally, use in the field.

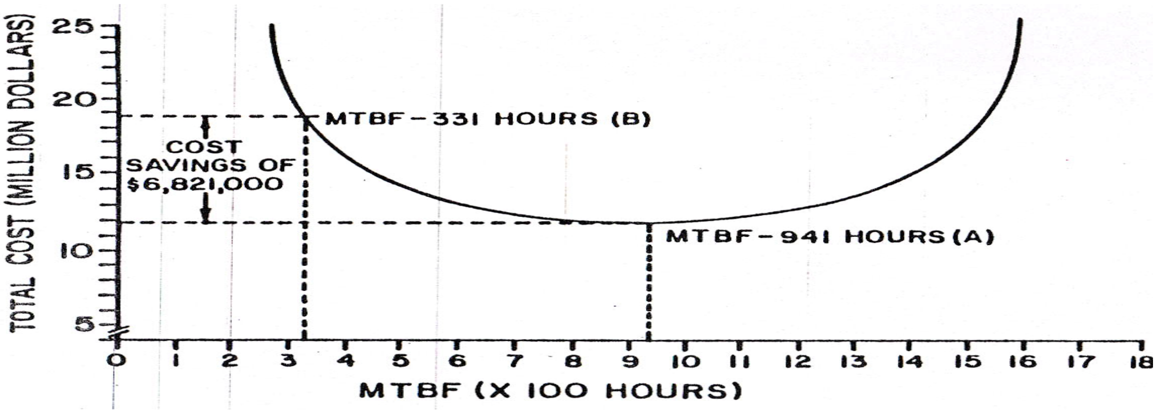
Fig. 7: Early investment of testing efforts makes failure surfacing cheaper [3]

Table 3: Evaluation of the testing contribution in terms of the ratio of benefit to testing cost

Variable	*No acoustic testing*	*No thermal cycling*	*No thermal vacuum*	*No testing at all*
Effect of test cancellation on the mission's average duration(% of the mission's length)	***99***	***72***	***97.1***	***68.1***
Additional satellite cost due to the need of an earlier replacement (K$)	***1.1***	***17.40***	***3.2***	***21.5***
Testing costs (K$)	***0.1***	***0.35***	***0.7***	***1.75***
Ratio of benefit to testing cost	***11:1***	***50:1***	***5:1***	***19:1***

A more efficient product maturation can be achieved by bringing the field into the laboratory

As can be seen in Fig. 5, it took approximately 7600 laboratory testing hours to increase the MTBF of the AMRAM missile from 190 hours to 530. This maturation was a very efficient process due to the fact that it was performed in the laboratory using a special flight conditions simulator. In this facility called the FTS (Flight Test Simulator, Fig. 11) combined thermo-vibro-acoustic loads were applied simultaneously. The simulator consisted of a chamber in which the tested system was installed on a shaker with a thermally insulating and acoustically transparent shroud. Appropriate air conditioning equipment generates the thermal regime in the shroud, and appropriate acoustic noise generating equipment creates the acoustic field. The simulator induces the same type and rate of failures (Fig. 12) as in flight, at an hourly cost several times lower than the cost of a flight hour.



Supplier	*Cost per unit ($)*	*MTBF (hours)*	*Initial cost (K$)*	*Annual maintenance cost* (K$)	*Total cost (K$)*
A	***3227***	***941***	***6454***	***5452***	***11906***
B	***2221***	***331***	***4442***	***14285***	***18727***

Fig. 8: Comparison of reliability and life-cycle cost of the same product developed and manufactured by two different suppliers

Fig. 11 presents on the right the principles of the Flight Test Simulator (FTS), and on the left (upper picture) the interior of a chamber in which a tested system is mounted on a shaker, installed in an acoustic chamber. The acoustic horns and electro-transducers can be seen on the exterior side of the chamber in the lower picture. Figure 12 compares the MTTF (Mean Time To Failure) achieved with the FTS to that achieved during flight (at a confidence level of 80%) [10]. Another example of an efficient maturation of a product is taken from the civil [11] and military automobile industry. According to [11], the Ford Company built a simulator that will save a large part of the field testing needs. The expectation is that by using this simulator, the development cycle will be shortened by 13 months on average. At the Aberdeen Testing Grounds in Maryland testing of vehicles while using the classical testing courses will be replaced with simulators of the course profiles. A schematic description of the profile simulator is presented in Fig. 13.

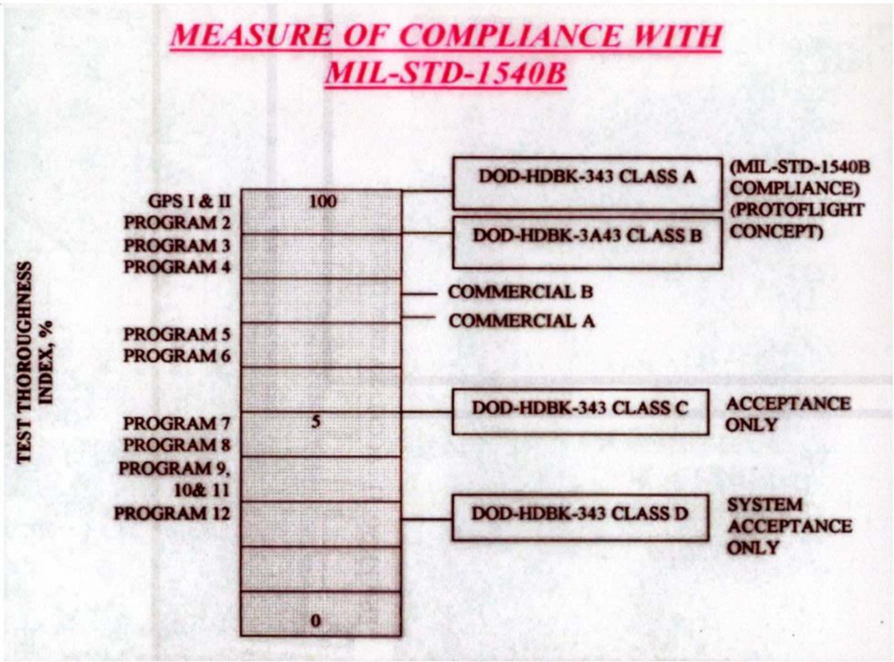


Fig. 9: Test Thoroughness Index, TTI [9]

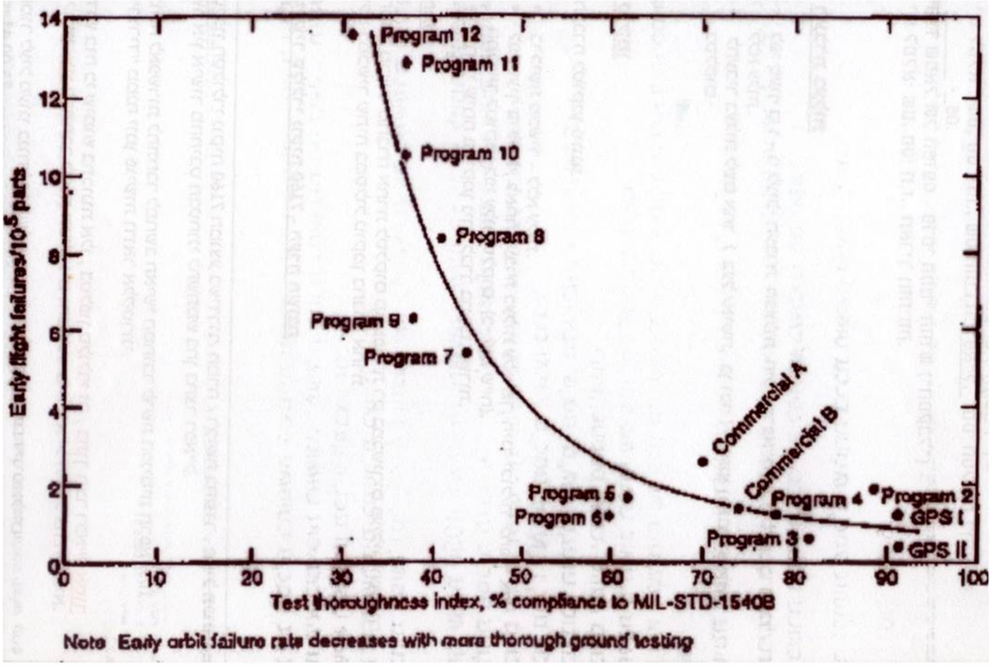


Fig. 10: Early flight failure vs. TTI in space projects [9]

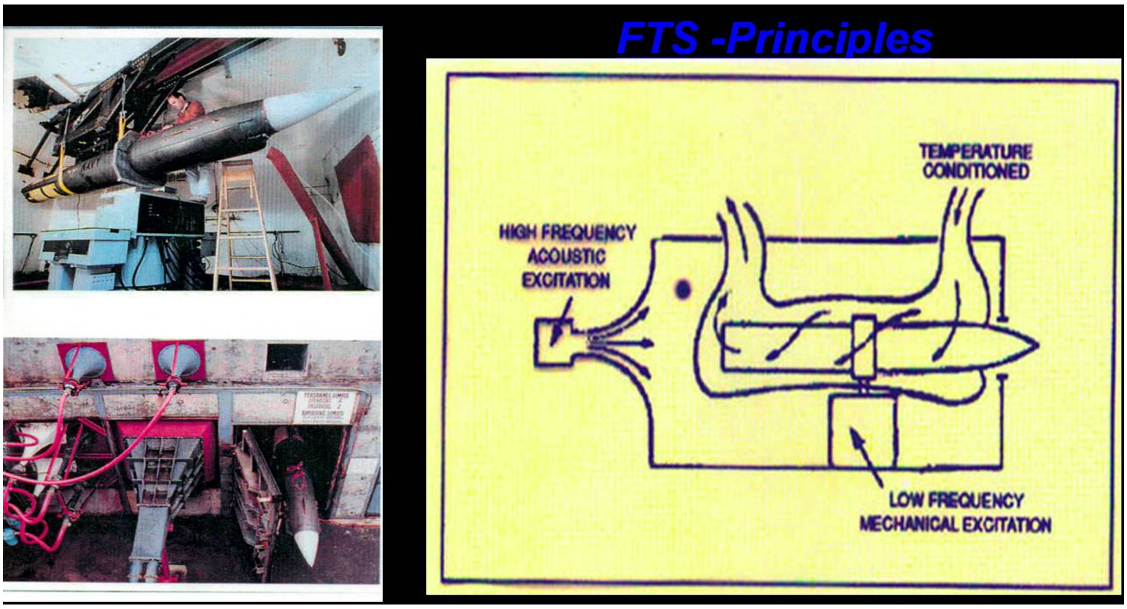


Fig. 11: The FTS principles and examples of use

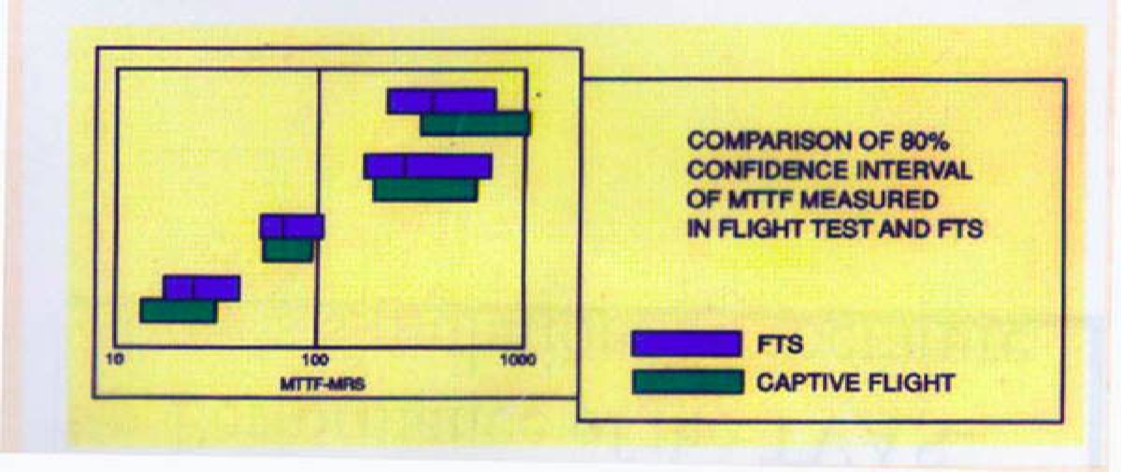


Fig. 12: Comparison of MTBF during flight and during the use of the FTS

Laboratory environmental testing accompanies manufacturing to evaluate the reliability of the products of the line

As pointed out by Reference 8, the FTS accompanies the manufacturing lines when batches of missiles and electronic pods are exposed to simulated flight conditions, to evaluate the reliability of the manufactured equipment. A trend of increasing reliability can be observed generally for various tested systems (Fig. 14). The decrease seen on the curve representing data from the AIM-7E system is related to a relocation of the manufacturing line that detrimentally affected the product's reliability.

Fig. 13: Ground profile simulator at the Aberdeen Proving Ground [12]

Summary

It has been shown that relevant environmental robustness data obtained at appropriate times during project development are critical for the achievement of the product specification required quality. A well-organized Environmental Robustness Evaluation Sub-System (ERESS) can contribute significantly to the efficient and effective achievement of environmental robustness. Early investment of appropriate testing resources permits early surfacing of development weaknesses, and cost-efficient engineering changes. The testing resources are more efficient in the development stages and accordingly, testing should be concentrated in the development stages. It is recommended to plan the project resources including testing, bearing in mind the life-cycle cost. A small increase in the research and development resources can contribute to a significant saving of the product's life-cycle costs. Apparently "costly" testing resources can contribute considerably to the efficient and effective maturation of the product. Efficient use of environmental robustness testing resources in particular, and of the testing resources in general, requires an appropriate system engineering function (Environmental Testing Engineer) at the project management level. It was seen also that the effectiveness and cost efficiency of the ERESS can be increased significantly by transferring the testing from the field to the laboratory.

References

[1] MIL HDBK 189 –Reliability Growth

[2] Harvard Weekly Business- Unknown Issue

[3] S.G. Shinha,"Concurrent Engineering and Design for Manufacture of Electronics Products", Van Nostrand Reinhold, New York, 1992

[4] Unknown

[5] A.M. Patenaude, "Modeling and Simulation Effectiveness in Weapon System Acquisition" ,ITEA Journal March/April 1997

[6] D. Kecegioglu, "Reliability and Maintainability Engineering, Reliability and Life Testing, Environmental Stress Screening in Action at the University of Arizona", The 23rd Annual Relaibility Institute, May 5-9 1997, Tucson Arizona

[7] O. Hamberg, W.F. Tosney, C.A. Brackin, "The Effectiveness and Cost Benefits of Satellite Environmental Acceptance Tests", Proceedings of the Environmental Testing for Space Programs-Test Facilities & Methods, held at ESTEC, Noordwijk, The Netherlands, 26-29 June 1990, ESA SP-304, September 1990

[8] D.B. Meeker, "Reliability Test and Evaluation", in "Test and Evaluation of the Tactical Missile", Vol. 119 Progress in Astronautics and Aeronautics AIIA 1989

[9] C.J. Moening, S. Rubin, "An Overview of DOD Test Requirements for Launch and Space Systems", Presented at the 15th Aerospace Testing Seminar Oct 11-13, 1994, Manhattan Beach, California

[10] Letter to the first author

[11] Nargess Shamanesh, "Driveability Test Facility", Environmental Engineering September 1998

[12] Unknown