TOWARDS COST-EFFECTIVE RELIABILITY VERIFICATION IN DEFENCE ACQUISITION

LEO Ding Yenn, TEO Yew Kheng

ABSTRACT

In defence systems, reliability is an important attribute as it has a profound impact on system availability and ownership cost. During the acquisition of defence systems, reliability verification in the customer's field environment is carried out frequently as part of the acceptance process to ensure that delivered systems meet reliability requirements. While test plans from military handbook *MIL-HDBK-781* are widely used for system reliability verification, there is an uptrend in the cost premium demanded by defence contractors for such verification efforts.

This article explores the reasons for the high cost premium associated with system reliability verification performed using *MIL-HDBK-781* test plans. It also looks at the concerns and objectives of the defence customer and contractor with respect to reliability verification. In addition, the article proposes an alternative approach to manage the cost associated with reliability verification test plans from *MIL-HDBK-781* so as to enhance the cost effectiveness of reliability verification in defence acquisition.

Keywords: availability, reliability, mean time between failure, reliability verification, defence acquisition

INTRODUCTION

System availability and ownership cost are both affected by system reliability design. Adequate system reliability can go a long way in reducing system failures so that system unavailability and maintenance expenditure can be minimised. System reliability is usually expressed as the system Mean Time Between Failure (MTBF).

System availability is an important consideration in the management of defence systems. Major defence systems, such as fighter aircraft, radar systems and weapon systems, require high system availability in order to fulfil their peacetime and wartime roles effectively.

Cost of ownership is another important consideration. Due to their high investment cost, defence systems are usually designed with relatively long service life, typically greater than 10 years, to achieve a reasonable return-on-investment. As a consequence of their long service life, recurring maintenance and support costs contribute significantly to the total ownership cost of defence systems.

MANAGING RELIABILITY IN DEFENCE SYSTEMS ACQUISITION

With respect to the application of systems engineering methods, processes and tools in system acquisition, major defence contractors generally have established in-house systems engineering practices. Nevertheless, during the acquisition of major defence systems, the customer may contractually require the contractor to implement specific systems engineering methods, processes and tools. This is often the case for reliability design and verification.

The systems engineering V-model is applied frequently to manage the system reliability requirement (see Figure 1). During requirements definition, the reliability requirement is determined by considering available technology, operational requirements and support concept. This may be done by the customer independently or in collaboration with the contractor.

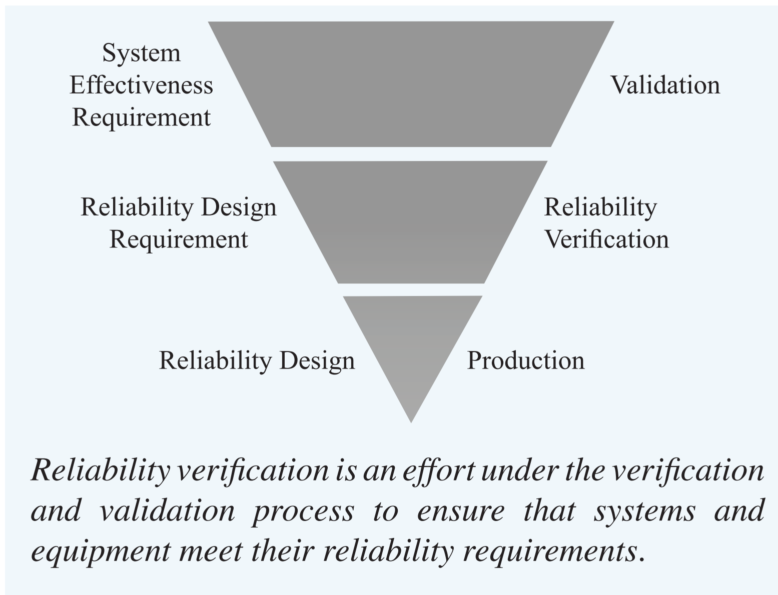


Figure 1. Reliability and the systems engineering V-model

During the design phase, the contractor breaks down the system reliability requirement to derive subsystems and Line Replaceable Units (LRU) reliability requirements for detailed design. The customer may also require the contractor to implement reliability assurance tasks, such as reliability modelling, reliability prediction and Failure Modes, Effects and Criticality Analysis (FMECA), as part of the reliability design effort.

Finally, the contractor verifies the reliability design at various design milestones to ensure compliance with the reliability requirements. In defence acquisition programmes, the customer usually requires a reliability verification to be conducted on the delivered systems in the customer's operating environment, prior to final acceptance of the systems.

RELIABILITY VERIFICATION USING *MIL-HDBK-781* TEST PLANS

The concept of post-delivery reliability verification is not new to the defence industry. The US Department of Defense (DoD, 1996)'s *MIL-HDBK-781* is the de facto guide for reliability verification in defence systems and is widely referenced by international defence contractors. This handbook describes several test plans for reliability verification under the section on MTBF Assurance Tests (DoD, 1996).

Typically, the test plans for reliability verification require the delivered systems to be operated over a period of time, during which the number of failures is recorded and used to compute the interval estimate of the demonstrated MTBF at the specified confidence level. The system reliability is accepted if the lower bound of the interval is equal to or greater than the required MTBF. Otherwise, the delivered systems are rejected for not having met the reliability design requirement. In the event of rejection, the contractor is required to implement reliability design improvements and may also need to compensate the customer in kind by supplying additional spares at the contractor's own cost.

Challenges with Reliability Verification Using *MIL-HDBK-781* Test Plans

In recent years, there has been a worrying trend of defence contractors charging prohibitively high price premiums for post-delivery reliability verification to be conducted per *MIL-HDBK-781* test plans. At times, the application of contracting strategies such as competitive tendering has not been able to control the cost escalation effectively. As such, it has become increasingly challenging to include reliability verification requirements in defence acquisition programmes while ensuring cost effectiveness. Similar observations have been reported by other reliability practitioners (Rogers & Kellner, 2015).

From the customer's perspective, the complete omission of post-delivery reliability verification is unacceptable. Without reliability verification, the risk of accepting a system with latent reliability inadequacies increases significantly. Furthermore, without the failure investigation and remedial action framework provided by the reliability verification process, it would be difficult for the customer to seek redress for reliability inadequacies that surface in delivered systems.

Review of *MIL-HDBK-781* Test Plans and Customer Expectations With Respect To Reliability Verification

Considering the importance of reliability verification in defence acquisition management, efforts have been made to review the reliability verification methodology in *MIL-HDBK-781*, in line with the expectations of both the customer and the contractor. The objective is to understand the reasons for the increasing cost of reliability verification and to identify solutions that can manage the escalating cost.

Findings on Test Plans from *MIL-HDBK-781*

While defence contractors generally concur that reliability verification is relevant in system acquisition programmes, they frequently cite extensive effort and commercial risk as the main reasons for pegging a high price premium to reliability verification.

Extensive Effort Due to Long Test Duration

Reliability verification with *MIL-HDBK-781* test plans frequently require test durations that span a few years. In comparison, the verification process for most other system performance requirements can be completed within a relatively short period of time, usually within weeks or even days.

In general, reliability verification requires a longer test duration because the parameter of interest - the mean time interval between two consecutive failure events or MTBF - is a random variable. The verification of a random variable typically requires the use of statistical acceptance tests founded on data collection and statistical analysis.

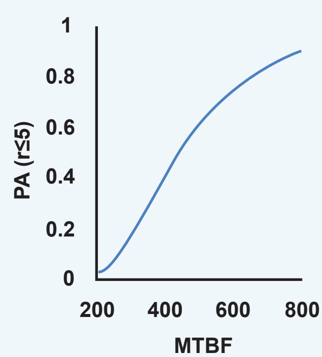
In MIL-HDBK-781 test plans, the test duration is a function of the quantity of systems, their duty cycle and system reliability. In cases where the system MTBF is high and the system quantity and duty cycle are low, a relatively long test duration would be required to observe a statistically significant number of failures for an assessment of the system MTBF.

The statistical test plans, such as those in *MIL-HDBK-781*, contain an inherent producer's risk, in which the test rejects the delivered systems even though they meet the reliability requirement. This is a scenario that is of grave concern to the contractor. In general, the contractor can better manage the producer's risk if the test duration is increased or the level of reliability of the delivered system is significantly higher than that required by the customer. The concept of producer's risk is illustrated in Figure 2 and more information can also be found in *MIL-HDBK-338* (US DoD, 1998).

Suppose a 2500-hour demonstration test with an accept criteria of ≤ 5 failures is used to accept a MTBF requirement of 500 hours. The probability of acceptance, PA, for various values of MTBF of the test unit is shown in the table below and plotted as an Operating Characteristic curve in the figure below

Probability of Acceptance

MTBF	PA (r≤5)
200	0.015
250	0.067
300	0.162
350	0.283
400	0.406
450	0.519
500	0.616
550	0.695
600	0.759
650	0.809
700	0.848
750	0.879
800	0.903



Probability of Acceptance

The test plan, as established by the specified test duration and decision rule, has a 40.6% probability of accepting a MTBF of only 400 hours (i.e. consumer's risk) and about 20% probability of rejecting a MTBF of 650 hours (i.e. producer's risk).

Figure 2. Illustration of producer's risk

However, from the contractor's perspective, a long test duration that spans a few years is generally undesirable as it prevents the redeployment of engineering resources to other projects. This is especially so if reliability verification is the last remaining activity after all other activities related to the acquisition project have been completed. The opportunity cost to retain the engineering team to support reliability verification is often passed on to the customer as a cost premium.

Commercial Risk

Since the *MIL-HDBK-781* test plans for reliability verification are designed to verify the system MTBF, the pass/fail decision is based on total elapsed operating time and total failure quantity recorded within the test period. Delivered systems are considered to have failed the test and are thus rejected as long as the total failure count within the test period exceeds the predefined quantity (i.e. accept criteria). No consideration is given to the reliability assurance tasks performed during the detailed design process to meet reliability requirements.

Furthermore, when the system is rejected by the test plan, the failures may be distributed over a number of LRU types such that the root cause for rejection cannot be readily identified for corrective action. This is because *MIL-HDBK-781* test plans make no distinction between failures from the various LRU types.

In such scenarios, the ability of the contractor to complete its contractual obligations successfully with respect to reliability verification becomes highly uncertain. The contractor may include a price premium for this uncertainty. In extreme cases, the contractor may simply refuse to propose reliability verification in order to avoid this uncertainty completely.

Findings on Customer's Expectations with respect to Reliability Verification

Theoretically, reliability tests such as those in *MIL-HDBK-781* give the customer the contractual right to reject delivered systems that do not meet their system MTBF requirement. However in practice, it is almost never in the best interest of the customer to reject a system solely on the basis of inadequate reliability, when an acquisition programme is close to its end. The preference will always be to improve the system reliability design prior to final acceptance — residual reliability inadequacies can generally be corrected without major redesign efforts if reliability assurance tasks had been implemented during the design phase.

From the perspective of the customer, the primary objective of reliability verification in acquisition management is to assess that the delivered systems have not deviated from their reliability requirement to an extent that the impact on ownership cost and system availability is significant.

In the event that the system reliability is determined to be inadequate, the reliability verification process should aid the identification of the LRU with inadequate reliability for timely remedial actions.

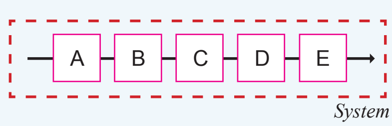
ALTERNATIVE RELIABILITY VERIFICATION APPROACH

An alternative reliability verification approach for defence acquisitions is proposed to address the identified drawbacks of *MIL-HDBK-781* test plans without compromising the fundamental expectations of the customer with respect to reliability verification.

The main differences between the proposed alternative approach and *MIL-HDBK-781* test plans are related to the assessment criteria and definition of test duration. The field reliability data collection process and other administrative processes remain generally similar.

Assessment Criteria

System MTBF and the reliability of LRUs that make up the system are strongly correlated both in terms of reliability engineering and practical application to system supportability (see Figure 3).



In this example, a system comprises five LRUs labelled A thru E as illustrated above. The system failure rate, usually expressed in failures per million hours, given by the sum of the LRU failure rates.

$$\lambda_{system} = \lambda_A + \lambda_B + \lambda_C + \lambda_D + \lambda_E$$

The failure rates are in turn related to MTBF as follows

$$MTBF_{system} = \frac{1}{\lambda_{system}}$$

and

$$MTBF_{A...E} = \frac{1}{\lambda_{A...E}}$$

As such, if each LRU MTBF can be verified, it can be concluded that the System MTBF is also verified.

Figure 3. System MTBF and LRU MTBF in reliability verification

At the start of the development of a new system, the reliability requirement is often specified as the system MTBF figure. This is generally because the system-level reliability requirement correlates directly with the operational requirements, such as expected duty cycle and system availability. In addition, the reliability of the subsystems and LRUs are not fully defined at this juncture since detailed design is still in progress.

As the system design matures, the LRU reliability specifications, determined via reliability prediction, become the primary basis for system reliability specification since the system failure rate is the sum of its LRU failure rates. LRU reliability specifications also form the basis for spares provisioning and maintenance set-up to support the systems post-delivery.

In the alternative reliability verification approach, LRU reliability is used instead of system MTBF to specify the assessment criteria. LRU types with a small failure quantity (i.e. usually not more than two failures) within the test period are deemed to have met their reliability requirements. For LRU types with three failures or more within the test period, the interval estimates of their demonstrated MTBF for a specified confidence interval are computed. The contractor is required to investigate and implement remedial actions if the upper bound of the interval estimate falls below the MTBF specification of the LRU type. The rationale is that while a small quantity of failures over the test period may be expected even for LRU types with high MTBF, a higher failure quantity coupled with an interval estimate below the reliability specification strongly suggests deviation from reliability requirements, warranting further investigations and actions.

In the alternative approach, the assessment criteria is designed to clearly identify LRU types exhibiting systemic failures. As the root causes for systemic failures are generally identifiable and resolvable, the contractor is assured that the reliability verification effort can be completed once corrective actions to address the LRU reliability design inadequacy have been implemented successfully. As such, commercial risk for the contractor is reduced significantly compared to what is expected in *MIL-HDBK-781* test plans.

Test Duration

Since the alternative reliability verification approach does not require the explicit computation of the system MTBF, there is no need to derive the test duration based on the system MTBF figure and the required test confidence interval. Instead, the test period can be mutually agreed upon between the customer and contractor based on administrative considerations and the understanding that a longer test duration reduces the risk of an incorrect assessment.

Experience suggests that for defence systems that are delivered in batches, the end of the test period can be defined to coincide with the end of warranty activities. This usually provides a period of two to three years for reliability verification without requiring the contractor to commit engineering resources beyond that already invested to support outstanding contractual obligations. In this way, the contractor's opportunity cost in retaining engineering resources solely to support reliability verification is mitigated.

A comparison of reliability verification using the alternative approach and test plans from *MIL-HDBK-781* is given in Table 1.

MIL-HDBK-781 **Test Plan (Fixed Duration)**	**Alternative Approach**
• Statistical acceptance test targeting system MTBF. Acceptance criteria linked to total failures cumulated across all LRU types.	• Targets LRU MTBF. Acceptance linked to MTBF interval estimate for individual LRU types.
• Equal emphasis on all failures.	• Greater emphasis on recurring LRU failures that suggests inadequate reliability.
• Minimum consideration of prior reliability design efforts.	• Recognises the reliability design efforts to achieve required MTBF.
• Requires a pre-determined sample size for decision, leading to consumer's risk, producer's risk and rigid tracking period requirement.	• No pre-determined sample size. Decision based on sample collected over existing project timeline. Results in better managed risks and more optimal resource deployment.

Table 1. Comparisons of reliability verification approaches

Potential Drawback of the Alternative Reliability Verification Approach

With LRU reliability as the primary assessment criteria, the alternative reliability verification approach can theoretically lead to the acceptance of a system with system MTBF marginally below the requirement.

In this case, the number of LRU types with one or two failures over the test period would be higher than what is expected based on the system MTBF. However, with an adequate reliability assurance effort implemented during the design phase, the number of affected LRU types would be low. As long as the failure quantity per LRU type remains small, the increase in maintenance demand can generally be absorbed within organisational level support provisions that are already in place to manage normal fluctuations in system duty cycle and maintenance demands. Overall, there would not be significant impact on the availability achievable by the system.

Implementation Experience

The alternative reliability verification approach has been successfully implemented in a number of defence programmes. So far, feedback on the alternative approach has been positive as it addresses the needs and concerns of both the customer and contractor without incurring additional cost premiums often associated with *MIL-HDBK-781* test plans.

Data from two systems are presented in Figure 4. Reliability metrics are calculated at the end of each period and expressed in multiples of the MTBF, denoted by *M*. The calculated MTBF excludes systemic failure modes which have been mitigated via design improvements as part of the verification process.

The instantaneous MTBF figures suggest that with improvements incorporated, both System A and System B meet their reliability requirements. However, if statistical test plans with 10% consumer's risk from *MIL-HDBK-781* had been applied instead, the systems would still have been rejected unless a longer test duration had been used. As discussed, this has the tendency to drive defence contractors to factor in a price premium to deliver a higher than required MTBF or to simply cover commercial risk, resulting in a higher cost proposal.

Separately, our observations also suggest that systemic reliability issues tend to surface in the earlier periods. In System A and System B, a number of systemic LRU failure modes identified during the initial period (i.e. Period I in Figure 4) were mitigated to preclude recurrence. The failure modes in the later periods are predominantly stochastic. This demonstrates the effectiveness of the alternative reliability verification approach in mitigating systemic failures and delivering reliable systems.

System A Reliability Metrics

End of Period[1]	*I*	*II*	*III*
Cumulated Ops Hours	*10.9M*	*18.2M*	*25.0M*
Total Failures (cumulative)	*12*	*16*	*17*
Instantaneous System MTBF	*0.9M*	*1.1M*	*1.5M*
Demonstrated System MTBF for 10% consumer's risk	*0.6M*	*0.8M*	*1.1M*

Legend: M - Required MTBF

System B Reliability Metrics

End of Period[1]	*I*	*II*	*III*
Cumulated Ops Hours	*8.1M*	*15.6M*	*21.3M*
Total Failures (cumulative)	*6*	*12*	*13*
Instantaneous System MTBF	*1.4M*	*1.3M*	*1.6M*
Demonstrated System MTBF for 10% consumer's risk	*0.8M*	*0.9M*	*1.1M*

Legend: M - Required MTBF

Note

[1] *The total test duration is divided into three periods, viz. Periods I, II and III to facilitate discussions.*

Figure 4. Summary data from reliability verification

CONCLUSION

In the application of systems engineering in defence acquisition management, reliability verification is an important process to ensure that delivered systems meet reliability requirements. However, the escalating cost premium levied by defence contractors for reliability verification using *MIL-HDBK-781* test plans made it increasingly challenging to implement reliability verification in defence acquisition.

A review of the existing reliability verification processes was conducted to articulate the verification objectives clearly and to identify the cost drivers. Leveraging the findings of this review, an alternative reliability verification approach for defence acquisition was proposed by DSTA. Having implemented it in a number of defence acquisition programmes, DSTA has found the alternative reliability verification approach to be effective in reducing the cost premium associated with *MIL-HDBK-781* test plans while continuing to deliver reliable systems.

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BIOGRAPHY

LEO Ding Yenn is Head Reliability, Availability and Maintainability (DSTA Masterplanning and Systems Architecting). He leads his team in the development and application of reliability, availability and maintainability (RAM) methods, processes and tools to achieve high availability in defence systems. Ding Yenn graduated with a Bachelor of Engineering (Mechanical) degree from Nanyang Technological University in 1996.

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