Lessons Learned in Space Life Support System Testing

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The earlier problems can be found and corrected, the easier and cheaper it is to fix them. Doing less testing saves cost and time but doing too little testing increases the risk of operational failures causing large costs and delays. Integrated test is necessary to determine if the subsystems work together and the overall architecture performs as intended.

This report reviews the testing lessons learned from the NASA Systems Engineering Handbook, a National Research Council report, and five reviews of International Space Station (ISS) lessons learned. The five reviews all mention two important points. First, that testing should be performed on the final integrated system, one as close as possible to the intended flight system. Second, "test as you fly," while operating as planned in an environment as close as possible to the expected flight environment. Other lessons are the need for extensive preflight ground testing, the need to establish and defend an adequate budget, the problems using protoflight hardware on ISS, and the benefit of having ISS as a zero gravity test bed.

The major ISS life support systems, carbon dioxide, water recycling, and oxygen recovery, were protoflight systems with little testing before launch to ISS. The failure rates these systems have been much greater than predicted and this has caused dissatisfaction with the protoflight approach. The more costly traditional approach is building qualification and test units in addition to flight units. The test units are used to test, analyze, and fix failure modes. Other work shows that there is an optimum cost-effective intuitive appeal of a human ecosystem in space.

Nomenclature

ConOps	=	Concept of Operations
ECLSS	=	Environmental Control and Life Support System
EMI/EMC	=	Electromagnetic Interference/Electromagnetic Compatibility
ISS	=	International Space Station
NRC	=	National Research Council
PRA	=	Probabilistic Risk Assessment

I. Introduction

The earlier that problems can be found and corrected, the easier and cheaper it is to fix them. The cost to find and fix a failure is thought to increase by a factor of five or ten at each higher level in a system. The amount of testing should depend on the required reliability and the actual failure rate of the system. Doing less testing saves cost and time and avoids the risk of system damage, but not doing enough testing increases the risk of major failure and large costs and delays. (Rechtin, pp. 147-8) Integrated test is necessary to determine if the subsystems work together, the interfaces match, and the overall architecture performs as intended. (Rechtin, p. 149)

This report reviews testing lessons learned from the NASA Systems Engineering Handbook (NASA-SP-6105, 1995, 2007, 2016), (Britton and Schaible, 2003), (Jones, 2007-01-3144), (Jones et al. 2016-105), (2016-250 Messidoro et al., 2016-250), (Henninger 2018-5), (Jernigan 2018-276), (Owens and de Weck 2019-66), and an NRC report (National Research Council, 2015).

II. The NASA Systems Engineering Handbook on Testing

Three editions have been produced of the NASA Systems Engineering Handbook (NASA-SP-6105, 1995), (NASA-SP-6105, 2007), (NASA-SP-6105, 2016). They all discuss component and system testing as methods used in verification and validation. Verification and validation are related but have significant differences.

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A. Testing

Testing is the examination of an intermediate or end product to obtain the detailed data needed to verify its performance directly or through further analysis, or the assessment of the final system for system validation. Verification testing can be conducted on final end products, breadboards, brass boards or prototypes. Verification testing produces data at discrete points in development for each specified requirement under controlled conditions and is the most resource-intensive verification technique. Validation requires operational testing of the flight system in the mission environment. “Test as you fly, and fly as you test.” (NASA-SP-6105, 2007, p. 104)

B. Verification versus Validation

The distinction between verification and validation is important. Verification proves compliance with specifications, and is shown by test, analysis, demonstration, inspection, etc. (Listed below). Validation proves that the system accomplishes its purpose. It is much more important and much more difficult to validate a system than to verify it. Verification is needed at every level of the system but validation can be accomplished only by testing the integrated system. (NASA-SP-6105, 1995, p. 40)

Verification testing is intended to confirm that all the system requirements are met. Verification testing includes: (1) any testing used in the development of products and support processes; and (2) engineering tests used to measure progress, to minimize risk are minimized, and to certify readiness for validation testing. (NASA-SP-6105, 2007, p. 90) (NASA-SP-6105, 2016, p.103)

Validation is based on the Concept of Operations (ConOps) rather than the requirements. Validation testing is conducted under realistic mission environment conditions on the end product to determine how the product works during mission use by typical users. Testing is a method used in both verification and validation. While validation can use many other method, testing is required to validate the final end products. (NASA-SP-6105, 2007, p. 90) (NASA-SP-6105, 2016, p.103)

Basically, verification answers the question, “Was the end product realized correctly?” Validation answers the question, “Was the right end product built?” (NASA-SP-6105, 2007, p. 101) Verify against end product specified requirements, but validate against the ConOps and stakeholder expectations. (NASA-SP-6105, 2007, p. 1018)

C. Verification by Test

Verification methods are used to verify compliance with requirements. The methods are (NASA-SP-6105, 1995, p. 118):

1. Test
2. Analysis
3. Demonstration
4. Similarity
5. Inspection
6. Simulation
7. Validation of records

Verification by test includes functional testing under ambient conditions and environmental testing. The usual verification stages are used for flight systems are (NASA-SP-6105, 1995, p. 119):

1. Development
2. Qualification
3. Acceptance
4. Pre launch

Qualification tests subject the hardware to worst case loads and environmental stresses. The verifications include vibration/acoustic, pressure limits, leak rates, thermal vacuum, thermal cycling, electromagnetic interference and electromagnetic compatibility (EMI/EMC), high and low voltage limits, and life time or number of cycles. Qualification tests can occur at the component, subsystem, or system level. If project eliminates dedicated qualification hardware, and uses the flight hardware for qualification, this protoflight hardware is tested much less rigorously to avoid stress and wear-out. Acceptance tests usual involve a deliverable end item. The end items may be integrated into larger systems and tested end-to-end. Some end item verifications cannot be performed after a flight article has been assembled and integrated and are tested before integration. (NASA-SP-6105, 1995, p. 122-3)

D. Validation by Test

Simply verifying that the components and subsystems meet requirements is not sufficient to show that the integrated system meets requirements. The most important requirements, those that define the purpose of the system, can only be observed and verified at the system level. There are many possible system level problems, such as mistaken requirements, incompatible interfaces, design errors, and mistaken ConOps.

More important, even after the integrated product is verified, it needs to be validated to show that it meets the user expectations documented in the ConOps. "(T) the only way to know that the project has built the "right" integrated product is to perform validation on the integrated product itself." (NASA-SP-6105, 2007, p. 13) "A simplified validation asks the questions: Does the system work? Is the system safe and reliable? Is the system achievable within budget and schedule constraints?" (NASA-SP-6105, 2007, p. 31)

E. Pass Verification But Fail Validation?

Many systems successfully complete verification but are unsuccessful in the validation process, delaying development and causing redesign and reducing stakeholder value. Beginning with communication with stakeholders is needed to identify operational scenarios. Developing a well understood ConOps and refining it during development is necessary for successful validation. If validation fails, a review of the requirements, ConOps, and design, operational scenarios may be necessary. "This can add time and cost to the overall project or, in some cases, cause the project to fail or be cancelled." (NASA-SP-6105, 2007, p. 88) (NASA-SP-6105, 2016, p. 122)

III. Testing of NASA Human-Rated Spacecraft

How much testing should be performed on a human rated space system before it is launched? The development of the Saturn V for Apollo caused a major shift in NASA's approach to rocket testing. Von Braun preferred his original approach of over designing rocket components and thoroughly testing each component, then each subassembly, each system, up to the final complete rocket. In 1963 Director Mueller realized that this approach would not get us to the moon in that decade, and he had NASA adopt an "all-up" approach. The first Saturn V launch included all three stages and the Apollo Command and Service Module. (Shira-Teitel, 2012)

The "all-up" approach was based on optimistic engineering logic, design it right, build it right, and it will work. There was always risk, but once we do everything we can, it's time to go. The spectacular success of Apollo seemed to prove that the "all-up" approach worked. (Boin and Fishbacher, 2011) However, the reliance on excellence in design led to expectations that the shuttle and later the ISS would be much more reliable than they proved to be. The shuttle design was inherently too risky, with safety features removed to save cost, but it seems that ISS equipment such as ECLSS would have benefitted from more testing.

The earlier problems can be found and corrected, the easier and cheaper it is to fix them. The cost to find and fix a failure is thought to increase by a factor of five or ten each time the failure cause is incorporated into the next higher level in the system. The amount of testing should depend on the expected failure rate of the system components. Doing less testing saves cost and time and avoids the risk of system damage, but not doing enough testing increases the risk of major failure and large costs and delays. (Rechtin, pp. 147-8) Integrated test is necessary to determine if the subsystems work together, the interfaces match, and the overall architecture performs as intended. (Rechtin, p. 149)

A. Human-rated Spacecraft Test (Britton and Schaible, 2003) (Jones, 2007-01-3144)

Keith Britton and Dawn Schaible developed a thesis on "Testing in NASA Human-Rated Spacecraft Programs: How much is just enough?" They reviewed the literature available in 2002 and interviewed NASA and other experts to determine the approaches and reasoning used to determine the appropriate amount of testing in human missions. They made several important observations and recommendations that are summarized here. The material in this section is modified from (Jones, 2007-01-3144).

The development of human-rated spacecraft testing requirements is informal, subjective, and inconsistent. They state, "the actual test requirement decision process is not documented as a formal process but relies heavily on the judgment of the decision makers." Since testing proves, but does not <u>im</u>prove, system performance, it "is often regarded as a drain on project resources, rather than a valuable undertaking." System testing occurs late in the development phase, when budget and schedule pressures are most intense, making testing vulnerable to cutbacks.

Britton and Schaible find that, "Contrary to common belief, there is consistency in the decision factors used by the various decision makers. These common decision factors can be divided into technical (safety, risk and confidence building) and non-technical (resource availability, decision process, individual decision-making behavior and political/cultural influences)." (Here "confidence building" means reducing the uncertainty of risk estimates, and resources include budget, schedule, facilities, and personnel.) However, the unexpected consistency is in the "decision factors," and definitely in not in the resulting testing <u>practices</u>. The authors state, "testing practices are not consistent across the aerospace industry." Clearly, the consistent influence of the variable non-technical decision factors -

resources, individual behavior, politics, and culture - leads to inconsistent testing practices. The decision makers can probably articulate convincing rationales for their decisions, but they "are not fully aware of the influences inherent in the decision-making process." The non-technical factors have strong influence because they are immediate, while the technical factors effects are long term.

Cost is a factor in deciding the amount of testing but the overall cost-benefit or life cycle costs are not always considered. Specifically, the cost savings of identifying a problem and fixing it on the ground are not computed. Nor is the expected value of the cost of a risk if it would occur. Surprisingly, "It is often believed that human-tended spacecraft can accept more risk of finding non-critical errors on-orbit due to the ability of repairing."

The authors also find that, "Testing is more of an art than a science: Experience and mentoring are more important than formal training in developing test engineering expertise."

The above observations led Britton and Schaible to develop some specific and very reasonable recommendations. Testing should be planned in the early phases of a project, with the test organization. Software should be tested as "an integral part of the overall system." The costs for testing should be estimated as part of life cycle cost assessment and actual costs (and I would add benefits) should be tracked.

One specific recommendation along the line emphasized in this note is, "Enhance the current risk management practices to include an assessment of all decisions making factors that contribute to the overall level of likelihood (of success)." The decision to perform a test is a decision to spend time and money to reduce risk. Risk is measured by its probability and the severity of impact if it occurs. Since risk assessment is subjective, so is the decision to test. Presumably, better and more consistent decisions will be made on testing practices if risk is treated more formally. Britton and Schaible suggest that a firm recognized process for decision-making in testing will limit the effect of subjective factors. They suggest that the NASA risk matrix, Probabilistic Risk Assessment (PRA), or other familiar methods can be used.

Britton and Schaible suggest the need to understand personal risk tolerance, individual decision making styles and biases including long-term or short-term view and systems savvy, and the influence of agency culture and organizational factors. These are clearly important, and possibly more influential than safety, risk and confidence building in actual testing decisions.

Human-rated spacecraft test planning is judgment-based, informal, subjective, and inconsistent. The decision makers are not fully aware of the non-technical influences on test planning, including resources, individual behavior, politics, and culture. Resources are budget, schedule, facility, and personnel resource availability. Individual behavior includes risk tolerance, decision-making style, long-term or short-term view, and systems orientation. The overall cost-benefit or life cycle cost is not considered in deciding the amount of testing. The cost savings of identifying a problem and fixing it on the ground are not counted, nor is the expected value of the cost of a risk if it could occur.

IV. Lessons Learned

The lessons learned in space systems development have been summarized frequently and they include observations on testing. Several papers will be summarized and their common core and any conflicts will be investigated.

A. Testing Lessons Learned from (Jones et al., 2016-105)

(Jones et al., 2016-105) consider how the lessons learned in the space station program apply to a Mars mission. A long table lists the International Space Station (ISS) lessons learned that have been published. The table is organized in the areas of approach, design, commonality, complexity, reliability, diverse redundancy, testing, test on orbit, operations, maintenance, and lower level repair.

The testing and test on orbit lessons learned are shown below, including the original references. (See 2016-105, not repeated in this paper).

Table 1. Lessons learned from (Jones et al., 2016-105)

Area	Lesson learned	Reason	Reference
Testing			
	Test thoroughly	Discover failure modes and design errors	(Gatens, 2015)
	Perform end-to-end, multi-element, system level testing	Testing identified multiple problems that would have been difficult or impossible to remedy on-orbit.	(Lengyel and Newman, 2014)
	Conduct high fidelity, integrated, system-level, end-to-end testing	Inadequate testing will make the crew rely on potentially flawed spares and risky in-flight repair, potentially endangering the crew	(Lengyel and Newman, 2014)
	The importance of testing must be stressed	Budget issues always end up limiting the scope and duration of test programs	(Lengyel and Newman, 2014)
	Provide budget and schedule for sufficient testing	Testing reduces operational problems and total mission cost	(Gatens, 2015)
	Use the protoflight approach carefully	The protoflight approach can increase schedule and cost risk	(Carrasquillo, 2005-0337)
Test on orbit			
	Mature technology by ground test and in-space operation	The use of protoflight ECLSS on the ISS has resulted in extensive on-orbit repairs	(Hodgson et al., 2012)
	Perform significant testing on the ground and ISS	Testing needed for reliable ECLS systems for multi-year missions	(Guirgis et al., 2014-233)
	Test systems on orbit	Systems on orbit act differently than on the ground	(Parodi et al, 2013-3414)
	Test in operational environment	Many problems seen only in actual environment, e.g., 0 g	(Gatens, 2015)
	Actual on-orbit system use can differ from expected	For example, higher urine calcium levels occurred on-orbit as compared to ground	(Gentry, 2013)

B. Testing Lessons Learned from (Messidoro et al., 2016-250)

(Messidoro et al., 2016-250) studied the effectiveness of system level environmental testing in detecting defects in European science and earth-observing spacecraft. Some general testing lessons were confirmed. "Environmental testing of spacecraft prior to flight provides effective detection of design, process and workmanship defects." The majority of the identified anomalies found in system level testing, 32 out of 57, were caused by system level issues. These included failures in integrated subsystems, wiring harness, and interfaces, along with integration errors and poor workmanship. System level testing has the capability to identify flaws in the complete system that are not detectable in lower level tests. It is important to perform system level tests of protoflight and flight models in realistic flight conditions. It is also recommended that some testing be done in transient environmental conditions since 12 of the anomalies were found during transients.

C. Testing Lessons Learned from (Henninger, 2018-5)

(Henninger, 2018-5) reported on a summary of the key lessons learned from the ISS development and operations including testing. Each lesson learned included its use in future exploration programs. Three notable lessons learned related to integrated testing:

1. Fidelity of Integrated End-to-End Testing

System-level, end-to-end test should include both nominal and off-nominal operational and environmental conditions. Undiscovered problems will lead to on-orbit repair. In future exploration programs, insufficient budget usually limits the scope and duration of test programs. A deep space mission must arguably have a no-compromise, no-shortcut, high fidelity end-to-end system-level test program.

2. Integrated End-to-End Testing is Essential

Integrated end-to-end testing is an absolutely essential requirement. It discovers latent defects in design that are not evident in sub-system and component-level testing. End-to-end testing should be a requirement in any exploration mission. If high risk failure modes are undetected, the crew must rely upon repair using spares, which may not succeed.

3. You Can't Do Too Much Testing

It is necessary to find as many problems as possible on the ground, to prevent their occurring in space. A rigorous verification is needed to find all the ways he system may fail. Exploration missions into deep space will require extensive ground testing.

Henninger recommends high-fidelity, long-term, human-in-the-loop testing. This testing should be carried out in Earth-based, sealed chambers having space based systems intended for flight and human crews to operate within the chamber environment. Ground tests cannot provide 0 g, so flight experiments are also necessary.

Henninger discusses the necessary enabling role of testing in NASA's technology development programs. Early testing from components up to bench prototypes is needed to prepare possible technologies for a range of future missions. Testing is used later during the design, development, integration, and testing of flight hardware selected for an approved mission. Between prototype development and mission selection falls the "Valley of Death" in technology development. Going from a tested prototype to a flight ready system requires extensive testing in a relevant environment. This is often not possible because of the high cost of testing in such environments, especially testing microgravity sensitive components in space.

D. Testing Lessons Learned from (Jernigan et. al. 2018-276)

(Jernigan et al. 2018-276) analyzed ISS life support lessons learned. A fundamental lesson is to test more flight-like hardware in a more flight-like environment. The closer the hardware and environment and configuration are to flight, the more likely that the tests will discover equipment problems. The tests should include flight-like constituent processing, injecting potential contaminants into the system, and operational envelope testing to maximally stress the components. High fidelity and stress testing will help identify and remove more of the failure modes, thus reducing later design iterations caused by the discovery of hidden latent design problems. This testing will not only improve the flight system, it will help plan repair operations and identify the needs for repair equipment. Another suggestion is to develop a high-fidelity ground testbed that can integrate new potential high pay-off technologies or develop long run time proven hardware for possible transition into the flight program.

E. Testing Lessons Learned from (Owens and de Weck 2019-66) (National Research Council, 2015)

(Owens and de Weck 2019-66) has the title, "How Much Testing is Needed to Manage Supportability Risks for Beyond-LEO Missions?" It reports valuable results on reliability growth testing and failure rate estimation testing, concluding, "In the end, there is no simple answer to the question of how much testing is required, but the models described in this paper provide a way to evaluate the potential impacts of testing in order to inform test planning." Previous work (Jones 2020-221) (Jones RAMS 2021) provides a simple answer to, "how much testing is required," in cases where reliability is achieved by redundancy.

(Owens and de Weck 2019-66) summarizes testing lessons learned from an NRC report based on defense contractors' experience. (National Research Council, 2015) They quote (NRC, p. 6)

"High reliability early in system design is better than extensive and expensive system-level developmental testing to correct low initial reliability levels. The former has been the common *successful* strategy in non-DoD commercial acquisition; the latter has been the predominantly *unsuccessful* strategy in DoD acquisition." (NRC, p. 6) Achieving high reliability early in system design has several supporting actions:

1. Reliability is emphasized in initial design.
2. Explicit measurable reliability targets are made system, subsystem, and component requirements.
3. Components and subsystems are tested as soon as possible and repeatedly to identify and repair failure modes.

Further lessons learned include:

1. Reliability should be a major goal considered with cost, risk, and performance during trade studies and design definition.
2. Reliability growth modeling should be used to set realistic goals, establish test plans, and track progress during system development.
3. Initial reliability estimates should not be based on adding the failure rates of the next lower level components, which is invalid, inaccurate, and misleading, and it rejected by major organizations.
4. Failure rate estimates should be validated and updated using test results.
5. Management should allocate specific funding for the testing required to improve and demonstrate reliability.
6. Trying to improve reliability during during full systems testing is typically more expensive, less efficient, and less effective than subsystem and component testing.

System testing can identify system level failure modes involving interface issues and overall system functions, but it is inefficient in identifying problems within subsystems or components. Subsystem or component testing should identify and correct lower level failure modes before system integration, thus helping to avoid costs and schedule delays due to troubleshooting and redesigns. (Owens and de Weck 2019-66) also note that the ISS provides a valuable testbed for long-duration microgravity operations.

V. Conclusion

All the five discussions of lessons learned mentioned two important ones. First, that testing should be performed on the final integrated system, one as close as possible to the intended flight system. Second, "test as you fly," while operating as planned in an environment as close as possible to the expected flight environment. The (NRC) report used in (Owens and de Weck 2019-66) does not state this explicitly but has much discussion of the need to test in the correct operational environments. The need for extensive preliminary ground test is mentioned in all but the (NRC) report, which does not consider space systems. The above summary of (Messidoro et al., 2016-250) does not specifically mention ground testing, but the paper is entirely concerned with ground testing of unmanned scientific satellites. Three sets of lessons learned mention the need to establish and defend an adequate budget. The essential problem is that the recommended high fidelity system level testing may not be done because of budget limitations, increasing the risk of poor reliability.

Some interesting but less frequently mentioned testing ideas include the problems using protoflight hardware on ISS, the benefit of having ISS as a zero gravity test bed, and the advantages of having full system tests with humans on Earth in a closed chamber.

The key but unmentioned fact is that the major ISS life support systems, carbon dioxide, water recycling, and oxygen recovery, were protoflight systems with years of storage but little testing before launch to ISS. The Water Recovery System had about thirty hours of integrated testing for an operational life that started in 2008 and may extend beyond 2025. The failure rates of ISS life support systems have been much greater than predicted and this has caused dissatisfaction with the protoflight approach, which requires gentle handling of the protoflight hardware. Some would prefer the more costly, more difficult, more traditional approach of having qualification and test units in addition to flight units. The test units could be environmentally stressed and accelerated life tested to reveal failure modes. "The traditional DoD process for achieving reliability growth during development is known as test, analyze, and fix." (NRC, p. 47) It may be possible to fund adequate system level testing if it can be shown to be cost-effective. A subsequent report attempts to do this.

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