

Risk Assessment of Small Satellites for TVAC Test Exclusion in Rapid AIT Technique

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Abstract

The Satellite Assembly, Integration and Testing (AIT) is a logical and interrelated set of qualification and verification tests during satellite assembly and integration. Space Agencies around the globe are moving towards time reduction in this phase. For that purpose, a modified form of the standard AIT, called Rapid AIT (RAIT) is being introduced and evaluated for small satellites. In RAIT, some major tests are excluded at the system level. One of those tests is the Thermal Vacuum Chamber (TVAC) Test. There exists risk associated with the success of satellite missions given that tests and verifications of important functions are not realized either due to (1) failure of TVAC or (2) exclusion of TVAC test at the system level. This paper focuses on the risk assessment of mission failure when the TVAC test is not considered at the system level. Expert judgment-based risk assessment of RAIT is provided, given that the TVAC is excluded. Risk assessment of the satellite system considers component failures, loss of performance, delay in project schedule, and associated costs. Risk assessment is made about applicable standards.

Keywords: Plug and Play Satellite; Rapid Assembly, Integration & Testing of the satellite; Thermal Vacuum Chamber Test, Risk Assessment of the satellite.

Nomenclature

<i>AFRL</i>	Air Force Research Laboratory	<i>PEO</i>	Program Executive Officer
<i>AIT</i>	Assembly, Integration and Testing	<i>PMBOK</i>	Project Management Body of Knowledge
<i>APB</i>	Acquisition Program Baseline	<i>PnP</i>	Plug AND Play
<i>APUC</i>	Average Procurement Unit Cost	<i>RAIT</i>	Rapid AIT
<i>BI</i>	Burn-In test	<i>RDT&E</i>	Research, Development Test & Evaluation
<i>ConOps</i>	Concept of Operations	<i>SAC</i>	Solar Array Controller
<i>CTP</i>	Critical Technical Parameter	<i>SADA</i>	Solar Array Drive Assembly
<i>EMC</i>	Electromagnetic Compatibility	<i>TPM</i>	Technical Performance Measure
<i>EMI</i>	Electromagnetic Interference	<i>TVAC</i>	Thermal Vacuum Chamber
<i>EPS</i>	Electrical Power Subsystem		
<i>ETTI</i>	Environment Tests Thorough Index		
<i>KPP</i>	Key Performance Parameter		
<i>KSA</i>	Key System Attribute		
<i>MST</i>	Mission Scenario Test		
<i>OMS</i>	Operational Mode Summary		
<i>MP</i>	Mission Profile		
<i>PAUC</i>	Program Acquisition Unit Cost		

1. Introduction

Designing and developing a small satellite mainly includes four phases: 1) the Feasibility phase, 2) the Design phase, 3) the Manufacturing phase, and 4) the AIT phase. In this paper, only the AIT phase of a PnP satellite is discussed. PnP satellites represent an approach to satellite design and deployment that emphasizes standardized interfaces, modularity and cost-

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effectiveness in the context of satellite communications and space missions. AIT involves three levels of tests. Unit level test: During the design and manufacturing of individual units, all satellite equipment and modules are individually tested and qualified [1, 2]. System level test: Individual units, modules, and equipment are assembled and integrated into the AIT phase. All standard tests required for a successful operation mission of a satellite are performed during the assembly and integration of individual units, modules, and equipment. *Validation level test*: After the whole system development in the AIT phase, the satellite is transported to the Launch center where major validation tests are performed before launching the satellite [1, 3, 4].

A successful mission of a satellite system depends upon the successful performance of the satellite in space. Later, it involves a high cost associated with a series of tests and their performance schedule during the AIT phase. With technological advancement, satellite manufacturers are moving towards the time reduction of the AIT phase. In December 2009, a modified AIT technique, called RAIT was introduced in which seven trials of small satellites whose weights were 100 to 200 kg were carried out at AFRL USA, in which some major tests were excluded at the *system level test* [1]. The excluded tests were 1) the TVAC test, 2) the 3-axis Vibration test, 3) the Burn-in test, 4) the EMC/EMI test, and 5) the Mission Scenario test. TVAC is a major test whose exclusion at the *system level test* can affect system performance, design and development schedule, and associated costs.

There exists a probability of not finding an anomaly related to the equipment failures of a satellite system during unit-level and system-level tests [1]. In a recent satellite operation, failure in the Solar Array Drive Assembly was not found even during the validation test. A satellite named EUTELSAT 5 West B suffered a Solar array-related failure on 17th January 2020 during its real-time operation in space. This failure completely jeopardized the mission of the program [2]. Similarly Chinese-based platform (DFH-4) satellite VENESAT-1 faced both Solar Array Assembly failures on 13th March 2020 during its real-time operation resulting in the whole mission failure. Consequently, VENESAT-1 had to be moved at once to slant orbit (graveyard) [3]. Likewise, NIGCOMSAT-1 which was also a Chinese-based platform satellite had also Solar Array anomaly, failing to achieve its mission [5].

In this paper, a semi-quantitative risk assessment of excluding the TVAC test of a small satellite at the *system level test* is provided. Risk assessment is based on the judgment of senior experts from the satellite industry worldwide. It is investigated whether the risks of excluding the TVAC test are acceptable according to the applicable industry standards such as the MIL standard [6]. Here expert judgment and Monte Carlo-based decision trees for the integration of expert judgment are used. The risk evaluation follows PMBOK-based risk assessment criteria [7]. We have gathered expert judgment on the likelihood of the root causes of the failures. Degraded performance, delay in schedule and increased costs are the possible consequences of failure in the absence of a TVAC test. Calculated risks will then be compared with the given risk acceptance criteria.

2. Introduction to AIT Phase

In this phase, equipment and components of the satellite are assembled, integrated and tested according to given standards and procedures. There are three sections in AIT [8]:

- 1) Assembly (includes mechanical activities and equipment installation);
- 2) Integration (involves functional realization at subsystem, and system foundation levels); and
- 3) Test (to achieve performance validation of design and implementation).

To accomplish the AIT phase, one has to complete three major types of testing. The flow chart in Figure1 shows all tests which are performed during the AIT phase [5]. The flow of activities during a Generic AIT is shown in Figure 2 [5]. In the AIT phase, all modules and subsystems are integrated and tested and all system-level tests are performed. In the beginning of the satellite era, the main focus was to launch the satellite successfully and cost and time were not part of the main focus. Today, the main focus is to reduce the time duration of the AIT phase with improved quality and make the satellite ready to launch as early as possible. For this purpose, in 2009, the Rapid AIT Technique in small satellites was introduced and successfully carried out by the Operationally Responsive Space Office (ORS Office) of the USA. The main focus of this rapid RAIT technique was to minimize and reduce the timeline to accommodate the urgent need for space-based capability [6, 9].

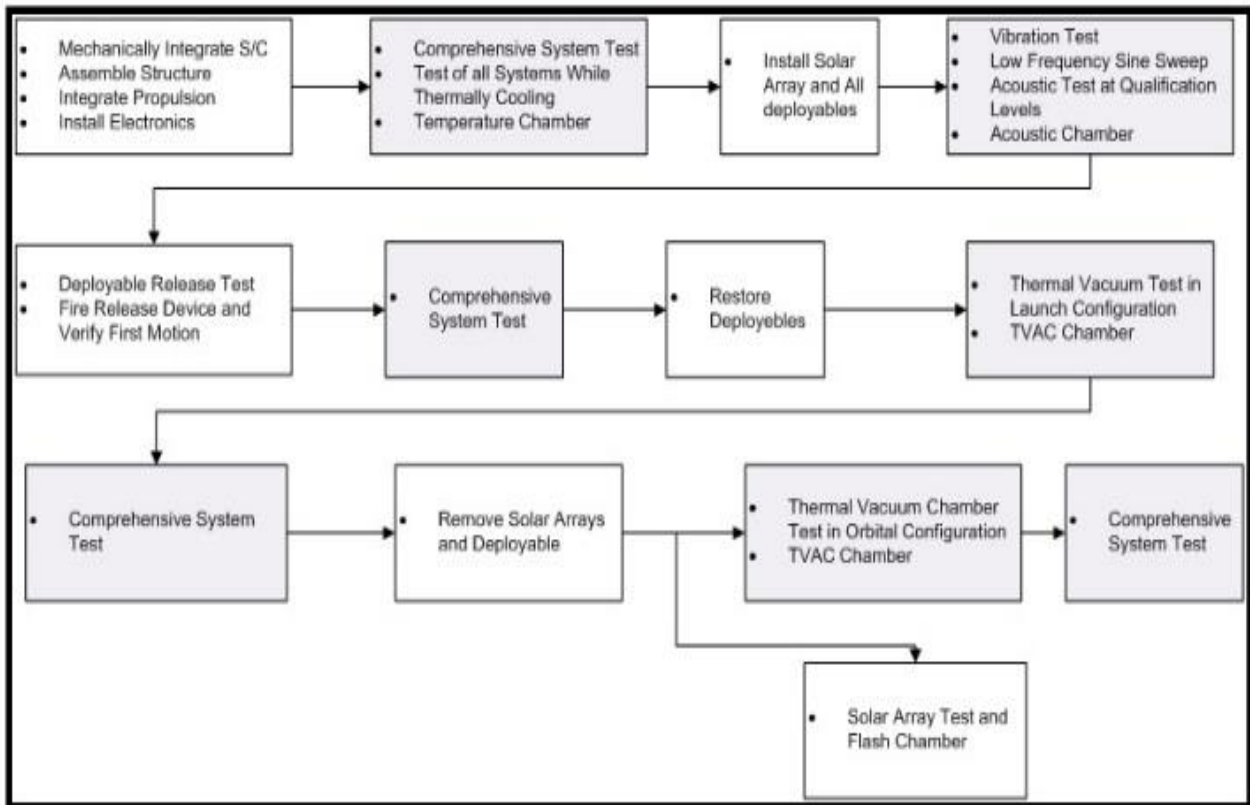


Figure 1. Flow Diagram of Generic AIT [5]

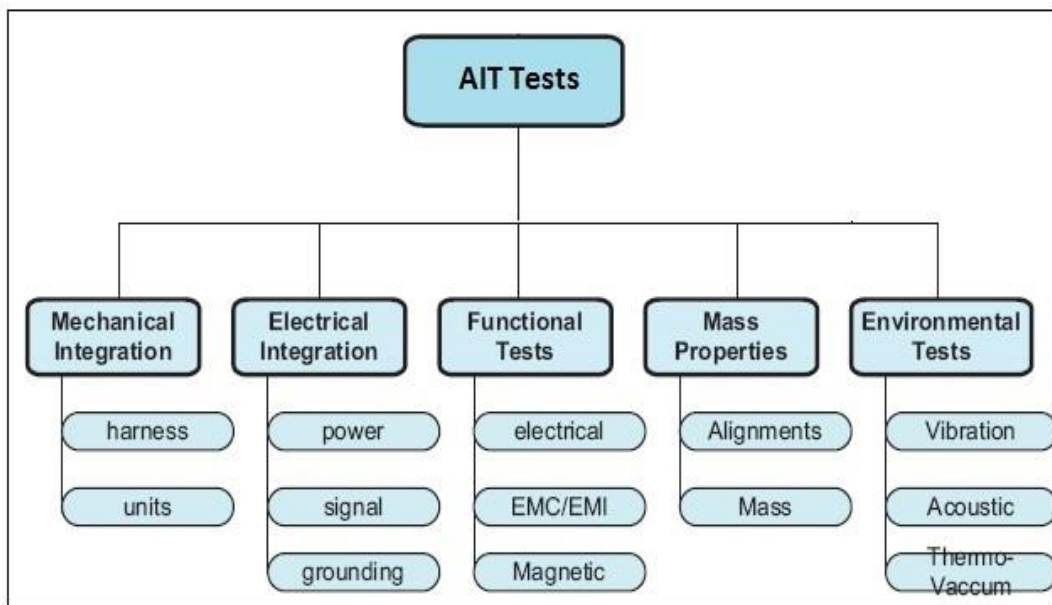


Figure 2. Flow Chart of Generic AIT [5]

2.1 Rapid AIT Method

The rapid AIT Technique is being used for PnP satellites (shown in Figure 3) whose weights are about 100 to 500 Kg. Seven Rapid AIT tests were completed between April to December 2009, at Kirtland Air Force Base, USA. The

baseline Trial, called Trial 0 was conducted at AFRL in 2009, to set a benchmark for such kind of trials at the system level [1].

By adopting RAIT, the time duration of a standard base AIT phase at the system level is reduced from six months to 1 week. Based on the input of domain experts

from some leading space agencies, the following five tests were excluded (at system level test) [1].

1. Thermal Vacuum Chamber Test
2. Vibration Test in Three-axis

3. Electromagnetic Interference Test
4. Mission Scenario Test
5. Burn-In

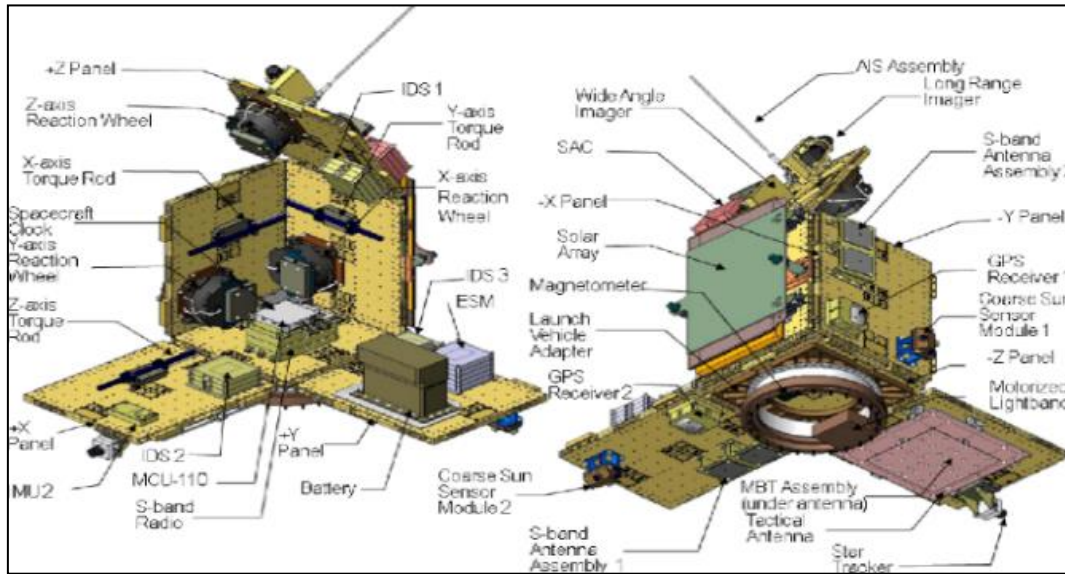


Figure 3. Overall Configuration of PnP Satellite [1]

By excluding the above five tests at the system level, one achieves a rapid AIT method, which is shown in Figure 4. TVAC is regarded as one of the major tests at

the system level and is no longer available during the RAIT flow process in Fig. 4. This paper focuses on the risk assessment of the TVAC exclusion in RAIT.

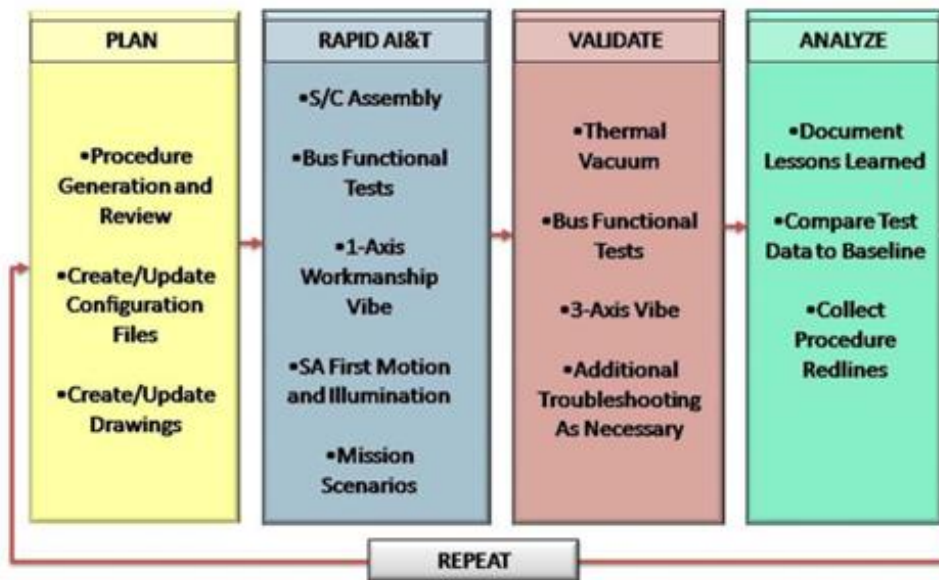


Figure 4. Rapid AIT (RAIT) as part of project planning of a satellite [1]

2.2 Brief Description of Thermal Vacuum Chamber (TVAC)

TVAC, also called “The Chamber of Horrors” is the most important test facility which is used to verify the qualification of a satellite mission. It is required because a satellite has to face the following severe conditions [3, 10, 11, 12]:

- i. The trauma of the launch
- ii. The high temperature of space
- iii. The vacuum of space
- iv. The electromagnetism torques

Performance is tested against all severe conditions for the functions and operations of a satellite in a Thermal Vacuum chamber (Fig. 5). TVAC includes the following set of tests and verifications of functions.

- a. Evaluations of materials for extreme environment and operational conditions
- b. Accelerated electrical and electronic component burn-in and life-cycle testing
- c. Environmental cycling (thermal & humidity) for materials survivability
- d. Verification of the following design factors
 - Rated temperatures
 - Combined thermal and pressure-load distortions of critical structural elements
 - Fluid and gas leakage at low or high temperature
 - Changes in absorptive or emissive properties of thermal coating
 - Evolution of harmful off-gassing products
 - Presence of conditions conducive to electrical-arc or corona discharge

Specification of the TVAC under study is provided in Table 1 and is adopted from [5, 13].



Figure 5. A Thermal Vacuum Chamber [1]

Table 1. Specification of TVAC Chamber [1]

Specifications	Specs Dimensions
Chamber Size	Length: 7 inches & Diameter: 11 inches
Pressure	3.0 x10 ⁻⁵ Pa
Pump (Capacity)	2000 l/s
Temperature	-50 °C to +50 °C
Temperature Rate	1K/min

Standard thermal vacuum testing is an imperative aspect of qualification testing for a wide variety of space-proven components, equipment, sub-assemblies, and mission-critical equipment. The satellite is placed in the TVAC chamber during the AIT phase in defined sections and durations according to missions. After that, the environment is created as per TVAC specifications and then satellite operations, equipment functions, their stability as well as reliability are tested for a successful satellite mission in space. In standard procedures, the TVAC test is performed at all three level tests. At the system level, the TVAC test is performed at different sections during the assembly and integration of the satellite system according to mission complexity and criticality [3, 12, 14, 15]. There exist risks associated with the success of satellite missions given that tests and verifications of important functions are not realized either

due to (1) failure of TVAC or (2) exclusion of TVAC test at the system level. The next sections focus on the risk assessment of the mission due to the non-provision of the TVAC test at the system level.

3. Risk Analysis and Model

Based on PMBOK standards, the procedure of risk assessment includes risk identification, risk analysis and risk evaluation. Risk identification is the process of identifying all possible causes of failures leading to hazardous situations, which can lead to unwanted consequences [16, 17]. In this paper, the risks associated with the TVAC exclusion are identified. Risk Analysis includes systematic structuring of related information of the risk problem. Here, expert judgment and Monte Carlo-based decision trees for the integration of expert judgment are used. The question related to “How big the risk is?” is answered in the risk evaluation, which follows PMBOK-based risk assessment criteria. We have gathered expert judgment on the likelihood of the root causes of the failures. Possible consequences in terms of performance, schedule and costs are evaluated in case of no TVAC test. Calculated risks will then be compared with the given risk acceptance criteria [18-20]. For details on the definitions and application of engineering risk, readers are referred to [21, 20, 22-26] and references in these research documents. The risk of excluding the TVAC test is mathematically defined as the multiplication of the probability of failure occurrence (P) and consequences (C) of the failure. It is based on the Risk, Issue, and Opportunity Management Guide for Defense Acquisition Programs (Jan 2017), which is used for Risk Analysis of Space Programs. Mathematically, it is written as:

$$Risk (R) = Probability (P) \times Consequence (C) \quad (1)$$

Consequences of the exclusion of TVAC include (1) unscheduled delay due to unexpected repair and maintenance (2) degraded performance of the mission and (3) exceeded costs due to consequences mentioned in (1) and (2). To calculate the consequences associated with the scheduling, it is important to note that the time of an event x violates the timeline of project T , and affects or increases the timeline T_E for the whole project is calculated as follows:

$$T_E = \sum_{k=1}^n x_k + T \quad (2)$$

For cost, it is important to note that the cost of an event c increases the budget of the project. The average cost of the project increases as well. It can be calculated as:

$$P_j = \frac{\sum_{j=1}^n c_j}{C_T} \quad (3)$$

Where P_j is the average cost increment of the project and C_T is the total cost. c_j is the increment in the cost due to failure occurrence.

3.1 Probability of failure occurrence by excluding TVAC Test

According to the Risk, Issue, and Opportunity Management Guide for Defense Acquisition Programs of Jan. 2017, levels of probability of failure occurrences and their consequences are defined in Table 2 and Table 3 [6].

Table 2. Level and likelihood of Probability of Failure Occurrence [6]

Level	Likelihood	Probability of Occurrence
5	Near Certainty	>80% to 99%
4	Highly Likely	>60% to 80%
3	Likely	>40% to 60%
2	Low Likelihood	>20% to 40%
1	Not Likely	>1% to 20%

Table 3. Levels of three factors of consequences [6]

Level	Cost	Schedule	Performance
5 Critical Impact	10% or greater increase over APB objective values for RDT&E, PAUC, or APUC Cost increase causes program to exceed affordability caps	Schedule slip will require a major schedule rebase lining Precludes program from meeting its APB schedule threshold dates	Degradation precludes the system from meeting a KPP or key technical/supportability threshold; will jeopardize program success. Unable to meet mission objectives (defined in mission threads ConOps, OMS/MP).
4 Significant Impact	5% - <10% increase over APB objective values for RDT&E, PAUC, or APUC Costs exceed life cycle ownership cost KSA	Schedule deviations will slip the program to within 2 months of the approved APB threshold schedule date. Schedule slip puts funding at risk. Fielding of capability to operational units delayed by more than 6 months	Degradation impairs the ability to meet a KSA. Technical design or supportability margin exhausted in key areas. Significant performance impact affecting System-of-system interdependencies. Workarounds required to meet mission objectives.
3 Moderate Impact	1% - <5% increase over APB objective values for RDT&E, PAUC, or APUC Manageable with PEO or Service Assistance	Can meet APB objective schedule dates, but other non-APB key events (e.g., SETRs or other Tier 1 Schedule events) may slip.	Unable to meet lower-tier attributes, TPMs, or CTPs. Design or supportability margins reduced. Minor performance impact affecting System-of-system interdependencies. Workarounds required to achieve mission tasks.

Level	Cost	Schedule	Performance
		Schedule slip impacts synchronization with interdependent programs by greater than 2 months.	
2 Minor Impact	Costs that drive unit production costs (e.g., APUC) increase of <1% over budget Cost increases, but can be managed internally.	Some schedule slips, but can meet APB objective dates and non-APB key event dates.	Reduced performance or supportability; can be tolerated with little impact on program objectives. Design margins reduced, within trade space 2.
1 Minimal Impact	Minimal impact. Costs expected to meet approved funding levels	Minimal schedule impact	Minimal consequences to meeting performance or supportability requirements. Design margins will be met; margin to planned tripwires.

An expert survey has been performed in which 10 Senior AIT engineers were contacted. The experience of these experts ranges from 20 to 35 years from different space agencies around the globe. A comprehensive expert assessment form of all excluded tests was developed. The objective of the assessment form was to gather the probability of failure occurrences of a variety of equipment of a satellite system in case of exclusion of TVAC and other tests. The results of the expert assessment are provided in Table 4.

The breakdown structure of a PnP satellite is represented through a Tree diagram shown in Fig.6. This tree diagram follows the Top-Down approach. This is required to allocate the probabilities at assemblies and sub-system levels to calculate the satellite-level probability of failure. Mathematical representations of these allocations and calculations are given below.

Probability of Satellite System Failure: $P(S) = \text{Sum of Cumulative Probability of Subsystem Failures}$

Table 4. Probability of Failure Occurrence of a variety of satellite systems by excluding TVAC, based on expert survey

Equipment	Probability of Failure occurrence without TVAC test (%)	Systems of equipment
Electronics	40	Solar Array Drive Electronics, UHF Radio, S-Band Radio, Automated information system, Intelligent Data Storage, Real Time Clock, UPSE, Sun Sensor, TMU, TCU
Electro-mechanical	37	Reaction Wheel Assembly, Torque Rod, Magnetometer, Inertial Measurement Unit, UHF and S-Band Antenna Assembly
Spacecraft Structure	15.3	Bottom Deck, Top Deck, Thru Side Panels, Common Side Panels

Equipment	Probability of Failure occurrence without TVAC test (%)	Systems of equipment
Payload	36	Long Range and Wide Range Imager, Star Tracker
Electrical Equipment	39	Solar Panel, Battery
Propulsion	30	Thrusters, Tank
Thermal	25	Thermal sheet
Antenna/TTC	38	S-band and X-band antennae

$$\sum_{k=1}^8 P(A) \tag{4}$$

Cumulative Probability of Subsystem Failures: P (A) = Probability of Subsystem Failure: P (L1) · [Sum of its cumulative Probability failure: $\sum_{k=1}^n P(B)$ /number of outcomes].

Cumulative Probability of Equipment Level Failure: P (B) = Probability of Equipment Failure: P (L2) · [Sum of its component level failure: $\sum_{k=1}^n P(L3)$ /number of outcomes].

These formulas are implemented onto the tree Diagram in Fig. 6. using the Monte Carlo Method. For an introduction to Monte Carlo Integration, readers are referred to [27]. The Overall Probability of Failure occurrence, excluding the TVAC test, is **0.3314** as shown in Table 5.

How the system level probability of 0.3314, using Monte Carlo-based decision trees for the integration of expert judgment is obtained, is explained below.

3.1.1 Component Level:

Probability of failure occurrence by Expert opinions:

- Solar Array Controller = 0.40
- Energy Storage Module = 0.40
- Bus Bar = 0.40

Probability contribution of components for power control unit in EPS Subsystem:

- Solar Array Controller = 1/3
- Energy Storage Module = 1/3
- Bus Bar = 1/3

Actual Probability of failure Occurrence for power control unit in EPS Subsystem:

- Solar Array Controller = 0.40 x 1/3 = 0.133
- Energy Storage Module = 0.40 x 1/3 = 0.133
- Bus Bar = 0.40 x 1/3 = 0.133

Total Probability of failure occurrence for power control unit:

$$0.133+0.133+0.133 = 0.399$$

3.1.2 Equipment Level:

Probability of failure occurrence by Expert opinions:

- Power Control Unit = 0.399
- Solar Panel = 0.39
- Battery = 0.39

Probability contribution of equipment in EPS subsystem:

- Power Control Unit = 1/3
- Solar Panel = 1/3
- Battery = 1/3

Actual Probability of failure occurrence for equipment in EPS Subsystem:

- Power Control Unit = 0.399 x 1/3 = 0.133
- Solar Panel = 0.39 x 1/3 = 0.130

$$\text{Battery} = 0.39 \times 1/3 = 0.130$$

$$\text{Total failure probability of EPS subsystem} = 0.130 + 0.130 + 0.133 = 0.393$$

3.1.3 Subsystem Levels:

Probability of failure occurrence for the EPS subsystem = 0.393. Similarly, for all other subsystems:

- Probability of failure of AOCs = 0.384
- Probability of failure of OBDH = 0.40
- Probability of failure of TCR = 0.387
- Probability of failure of UPS = 0.310
- Probability of failure of Payload = 0.374
- Probability of failure of Thermal = 0.250
- Probability of failure occurrence of = 0.153

3.1.4 System Level:

Probability Contribution of all subsystems = 1/8 = 0.1250. The total Probability of failure occurrence for the Satellite system is by adding all probabilities and multiplying by 1/8 =

$$(0.393+0.378+0.4+0.388+0.310+0.360+0.250+0.153) \times 1/8 = \mathbf{0.3314}$$

According to Table 2, this probability value lies in the range of 20% to 40%, corresponding to level 2 likelihood [5].

3.2 Consequence of Excluding the TVAC Test

As mentioned earlier, three main factors of consequences of the component failure are relevant here. Please refer to Table 3 for the levels of three factors of consequences. These three parameters are described in this section.

The accomplishment of the function of the satellite system that is measured against standards of accuracy, completeness, results and measurements is referred to as the performance of the test during TVAC [6, 28]. There were seven trials of PnP Satellites on which Rapid AIT had been implemented during six of these seven tests and trials to establish the performance of each type of system [1].

As a consequence, due to the exclusion of the TVAC at the system level, one major anomaly related to the SAC problem occurred. This anomaly was identified by the TVAC test during the validation tests. This anomaly had to be resolved within a 01-day time frame and validation tests were repeated. Please refer to Fig. 4 for details on the validation phase. As a consequence, a delay in the project schedule and extra costs on additional TVAC validation tests occurred. How the delays and extra costs in the project were incorporated into the risk assessment are presented in the next sections.

3.3 Consequences of anomaly detection

As shown in Table 3, there are three factors associated with the consequences: (1) failure of the whole satellite leads to the complete failure of the *performance* and is regarded as a level 05 consequence (2) delay in the defined *schedule* of a satellite program is regarded as level 02 consequence and (3) *costs* occurred due to delay in schedule and repeated validation are level 02 consequences, according to the Table 3 [6].

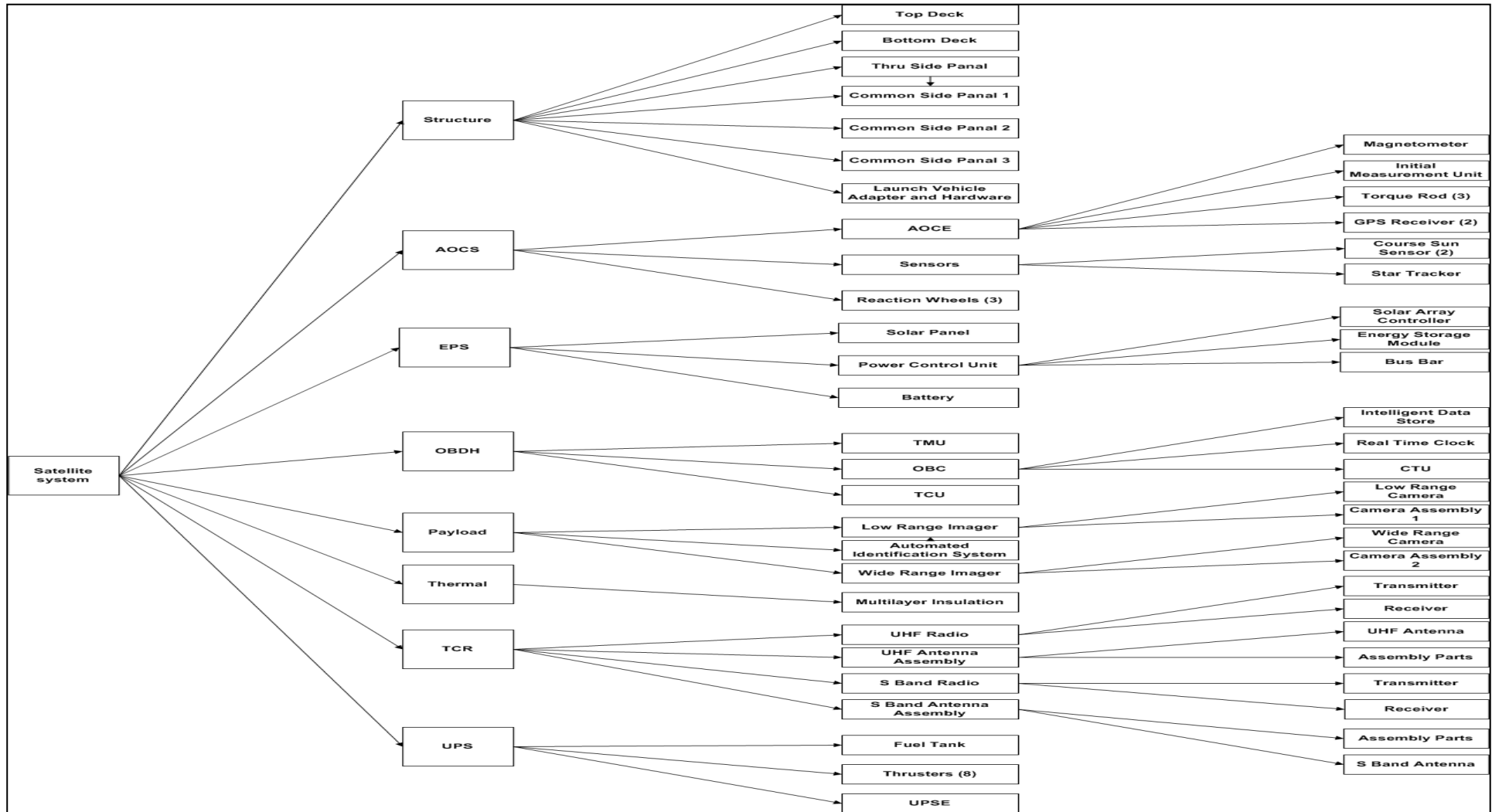


Figure 6. Breakdown structure of a PnP satellite system used for the risk assessment of TVAC exclusion

Table 5. Probability of failure occurrences of a PnP satellite system up to its component level

System	Cumulative Probability of failure P(S)	Subsystem Level	Probability P(L1)	Cumulative Probability P(A)	Equipment Level	Probability P(L2)	Cumulative Probability P(B)	Component Level	Probability P(L3)
Satellite System	0.3314	Structure	0.1250	0.0191	Top Deck	0.1530			
					Bottom Deck	0.1530			
					Thru Side Panel	0.1530			
					Common Side Panel 1	0.1530			
					Common Side Panel 2	0.1530			
					Common Side Panel 3	0.1530			
		AOCS	0.1250	0.0480	Sensors (3)	0.4286	0.1714	Course Sun Sensor (2)	0.2667
						Star Tracker		0.3333	
					AOCE	0.1429	0.0541	Magnetometer	0.0529
								Initial Measurement Unit	0.0529
								Torque Rod (3)	0.1586
					GPS Receiver (2)	0.1143			
		Reaction Wheels (3)	0.4286	0.1586					
		EPS	0.1250	0.0492	Solar Panel	0.3333	0.1300		
					Power Control Unit	0.3333	0.1333	Solar Array Controller	0.1333
								Energy Storage Module	0.1333
								Bus Bar	0.1333
		Battery	0.3333	0.1300					
		OBDH	0.1250	0.0500	Telemetry Unit (TMU)	0.3333	0.1333		
					On Board Computer (OBC)	0.3333	0.1333	Intelligent Data Store	0.1333
								Real Time Clock	0.1333
Tele command Unit (TCU)	0.3333				0.1333				
CTU	0.1333								

System	Cumulative Probability of failure P(S)	Subsystem Level	Probability P(L1)	Cumulative Probability P(A)	Equipment Level	Probability P(L2)	Cumulative Probability P(B)	Component Level	Probability P(L3)
		Payload	0.1250	0.0457	Low Range Imager	0.1200	0.1200		
					Automated Identification System	0.1333	0.1333		
					Wide Range Imager	0.1200	0.1200		
		Thermal	0.1250	0.0313	Multilayer Insulation	0.2500			
		TCR	0.1250	0.0454	UHF Radio	0.2500	0.1000	Transmitter	0.2000
								Receiver	0.2000
					UHF Antenna Assembly	0.2500	0.0938	UHF Antenna	0.1500
								Assembly Parts	0.1850
					S Band Radio	0.2500	0.1000	Transmitter	0.2000
								Receiver	0.2000
		UPS	0.1250	0.0388	S Band Radio Antenna Assembly	0.2500	0.0938	S Band Antenna	0.1500
								Assembly Parts	0.1850
					Fuel Tank	0.0300	0.0300		
					UPSE	0.0400	0.0400		
					Thrusters	0.2400	0.2400		

3.3.1 Consequences of performance

Anomaly related to the SAC was avoidable in case a regular TVAC test was conducted earlier at the system level. The rectification of the anomaly during the design phase, if any, will not affect the overall performance of the PnP satellite in orbit because the satellite has not entered orbit. However, due to the repetition of the validation test, after anomaly identification and rectification, a delay of one day (24 hours) in the finalization of the development of the PnP satellite occurred. This affected the schedule and costs of the overall program. The satellite under discussion here has no redundant SAC. An anomaly related to the SAC is regarded as “Severe degradation in performance; cannot meet KPP or key technical/support threshold (refer to Table 3); will jeopardize program success (level 5 consequence)” as per level and types of consequences criteria given in Table 3 [6]. This level 5-related consequence was sure in case the PnP satellite was sent into orbit without the rectification of the SAC-related anomaly. This is due to the reason that the SAC-related anomaly was not found during the validation test. There exists the probability of not finding an anomaly related to the SAC even during the validation test. That is why solar array controller-related level 05 consequences associated with the performance continue to occur. Recently, a satellite named Eutelsat 5 West B suffered a solar array-related failure with one of its two solar arrays during its real-time operation in space. [2] This loss in performance is regarded as a level 4 consequence due to the redundant solar array in the satellite. Similarly, a Chinese-designed satellite VENESAT-1 has faced both Solar Arrays Assemblies failures during its real-time operation. Due to this, the power has been supplied by batteries of one-day backup. It has to be moved at once to a slant orbit (graveyard) above 300 to 500 km from geostationary orbit [3]. Likewise, NIGCOMSAT-1 which was also a Chinese-based platform satellite had also Solar Array anomaly and consequently mission failed [4].

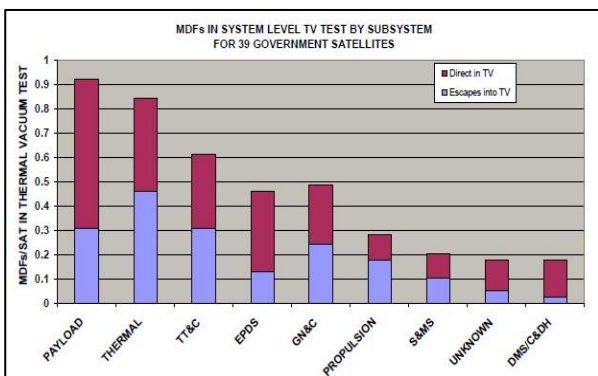


Figure 7. Mission degrading failure of satellites after system-level TVAC test [29]

Research shows that the average probability of anomaly occurrence after performing a single TVAC is

0.18 for electronics (DMS/C&DH) related equipment in Figure 7 [29].

Expert judgment conducted by our research gives an average probability of 0.14 for electronics-related failure in case a TVAC is conducted. These probabilities of electronic failures (after one TVAC test) are independent of the system level or validation level. It implies that electronic components in the satellite system can still fail with the probability of 0.18 (data-based) and 0.14 (expert judgment-based) after the TVAC validation test, given that there was a Rapid AIT at the system level. Here, one can easily conclude that there exists a significant probability of component failure in a satellite in case of no TVAC at the system level.

Expert judgment carried out by this research gives the total failure probability of a satellite as 0.3314, given that there was no TVAC test conducted at the system level shown in Fig.7. This expert judgment-based probability value can be compared with the data of 224 satellites-based failure probability as 0.36 in the case of no TVAC test at the system level [9]. In other words, this database research shows that a TVAC test identifies around 36% of anomalies in an overall satellite system, refer to Figure 8.

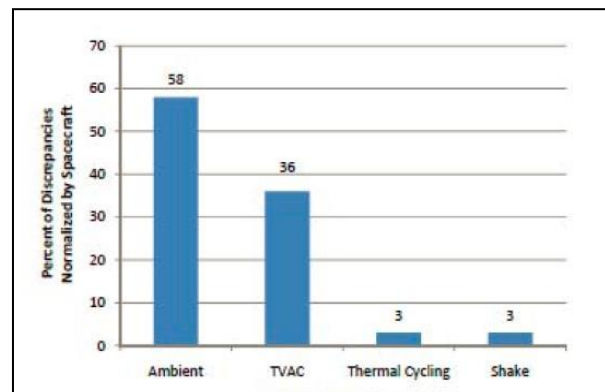


Figure 8. Percentage of Discrepancies of 224 satellites at system level [9]

It implies that the failure probability of the satellite system (due to the absence of TVAC) is 0.36 and that is equal to the probability of anomaly found during the TVAC. Our focus of analysis is to use an expert judgment-based failure probability of 0.3314 (refer to Table 5) for the risk assessment of the satellite mission.

3.3.2 Consequences of delay in project schedule

In the TVAC Test, one of the most affected factors in consequence is the schedule. The delay in the development of a satellite would be larger than 04 weeks to multiple months, depending upon the complexity of the satellite that has to undergo repetition of the TVAC test. Here, as per the Rapid AIT test plan, TVAC is performed for 24 hours (One cycle). The time for satellite design by Rapid AIT technique is Six Days [1]. After the validation test, if there is an anomaly, then one day is required for anomaly rectification. The time taken during these anomalies is the extra time of the whole project. We had one anomaly identification by TVAC test during the

validation test in trial 3 i.e. SAC error. So extra time and costs for the anomaly rectification are calculated in the following way.

The timeline for Rapid AIT is 6 Days. After fault or failure in satellite:

- Time required for fault correction: $T = 1$ day
- Average Timeline increment: $T_E = \sum_{k=1}^n x_k + T$
- Timeline increment: $T_E = 7$ days
- Timeline increment: $1/6 = 0.167$

3.3.3 Consequences of costs of anomaly detection due to TVAC exclusion

There is only one major cost and that is an extra TVAC test required to perform.

The cost of the TVAC test: $c_j = 5k$ \$ (Average) [10]

The cost of the satellite project: $C_T = 13M$ \$ [1]

Average cost increment: $P_j = \frac{\sum_{j=1}^n c_j}{C_T}$

Average cost increment: $5K/13M = 0.00038$

The cost increment in the project budget: 0.038 % which is less than 1 % (Minimal or no impact)

According to Table 3, taken from [1] the consequences of all three factors are summarized below.

1. Performance degradation of the whole satellite lies at level 05 according to Table 3.
2. The delay in the satellite program schedule lies in level 02 as per Table 3
3. Extra costs occurred due to delays and extra TVAC lies in level 02 from same Table 3

The Risk Reporting Matrix is typically used to determine the level of risks identified within a Satellite program. The risk associated with the exclusion of the TVAC test in RAIT is calculated by using the following results:

Level of Probability of failure of occurrence = 2 and Level of consequence = 5

These values are shown in the risk matrix of Figure 9 as per the technique explained in the DoD Risk Guideline [6]. The risk reporting matrix shows that for the stated PnP satellite system, the risk for exclusion of the TVAC test at the system level corresponds to the yellow zone and is approaching the red zone.

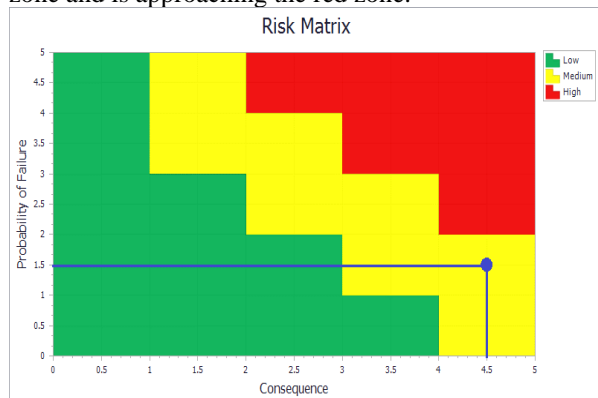


Figure 9. Risk Level of Exclusion of TVAC Test in Rapid AIT [6]

4. Verification And Validation of Risk Results and Control Measures

Multiple studies have been carried out for the distinct correlation of environment tests, especially TVAC test for predicting mission failures. Tosney, Arnheim and Clark have explored the effect on percentage of failure by ETTI in their research. ETTI is a technique of assigning a measure of adequacy to the satellite test programs by ranking the test thoroughness [11]. In Fig. 10 it is shown that the percentage of satellite failure will decrease with the increase in the ETTI number. It means if standard tests including TVAC test are performed at all levels (Component, System, Validation level) then risk of mission failure would be decreased.

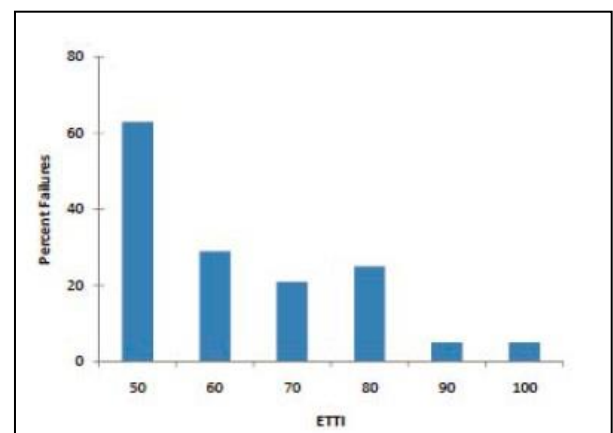


Figure 10. ETTI of TVAC Test [29]

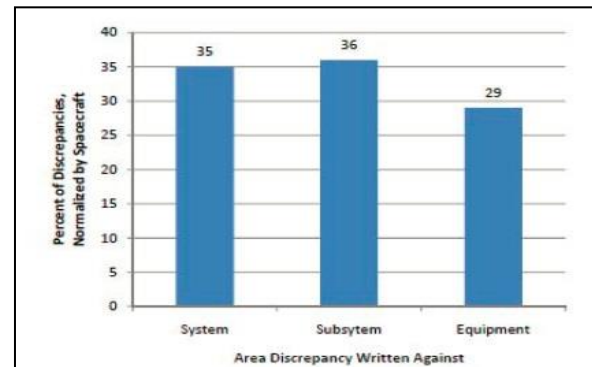


Figure 11. Percentage of discrepancies by excluding TVAC test at different levels [9]

According to Weigel's research on 224 satellites of different platforms and from different vendors, 23,000 discrepancies (Anomaly reports) have been evaluated due to the exclusion of different tests, also including the exclusion of the TVAC test at the system level (Fig. 9). This study calculated discrepancies as 36% if TVAC test was excluded at system level [9]. Moreover, Weigel predicted 35% of anomalies at system level test, 36% anomalies at subsystem levels and 29% anomalies at equipment level, refer to Fig. 11 [9]. It is important to mention that 35% anomaly detection at system-level testing, given that the TVAC test would be excluded

poses a significant level of risk, which can directly affect a satellite mission.

An analysis of failure data revealed that the TVAC test if conducted, can detect 4.1 MDFs (Mission Degrading Failure) per satellite [9]. (Figure 12 and Figure 13 indicate MDF detection during the TVAC test and Post post-TVAC test, after 3 months and after 33 months.

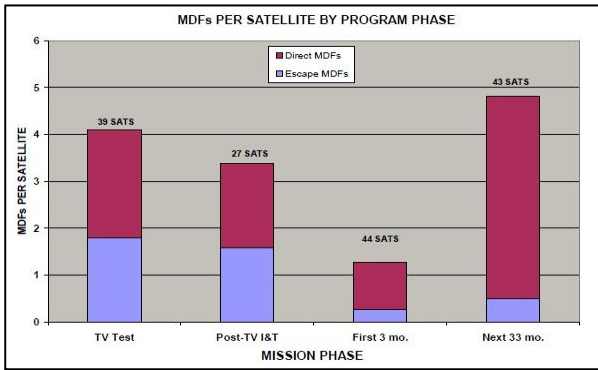


Figure 12. MDFs of satellites by including TVAC test [9]

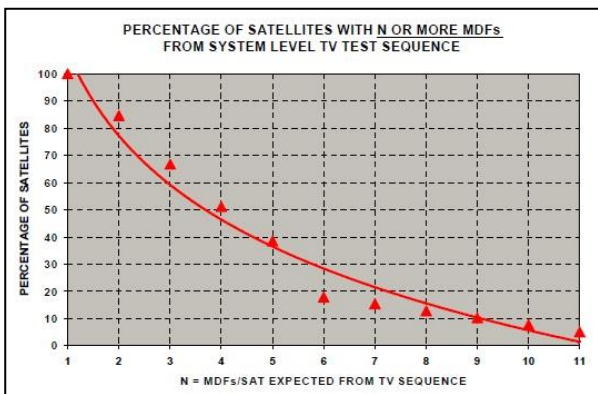


Figure 13. MDFs detection trend by TVAC test [9]

In Figure 13 percentage of satellites tested as a function of the minimum number of MDFs identified during the TVAC test at the system level is presented. In the risk assessment of TVAC test exclusion, it is observed that the risk is closer to the red zone. This result leads to the recommendation of not excluding the TVAC test for complex and commercial satellites. To keep the mission failures-related risks in further control, the following measures are appropriate suggestions:

- **RAIT for matured technology**

Rapid AIT technique should be taken into account only for matured technologies used in a satellite program. It should be applied only on a platform where a large number of satellites have been designed and developed.

- **Customized rapid AIT technique**

Rapid AIT cannot be a standard technique; it would be customized for every satellite design project based on satellite importance, concerning mission requirements and costs. In the Rapid AIT discussed in this paper, the

TVAC test is recommended to be added for small satellites. The TVAC has significant importance regarding the space environment. The inclusion of TVAC will bring mission failure-related risks in the green region of the Risk Matrix.

- **Low budget satellite**

The Rapid AIT Method should be used only for low-budget satellites or small satellites up to the maturity of this RAIT technique. RAIT can be used for big or commercial satellites once the RAIT technique has matured.

- **Experts discussion**

There should be an expert discussion after every major test i.e. TVAC, vibration, and bus functional test to reduce the risk. These discussions, together with test data, will be helpful in the adoption of the RAIT technique for different satellite programs.

- **Schedule margin**

Time margins for every major test will reduce risks as well. There should be a margin in every major test. Fault, anomaly or failure can be detected and handled within the scheduled time margins.

5. Conclusion

This research focuses on the significance of the TVAC test at the system level for small and complex satellites. Expert surveys have been performed with the help of different space agencies around the globe. The probability of failure in satellite equipment is predicted given that TVAC and other tests are excluded during the AIT phase. The risk associated with the exclusion of the TVAC test in a Rapid AIT phase was calculated by combining expert judgment and the Monte Carlo Integration technique. The risk of excluding the TVAC test at the system level corresponds to the yellow zone (not desirable zone) and is approaching the red zone (unwanted zone). The risk assessment results lead to the recommendation of not excluding the TVAC test for complex and commercial satellites. To keep the mission failure-related risks under control, several suitable measures were suggested.

Conflict of Interests

No conflict of interest has been expressed by the authors.

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