ESA STUDY CONTRACT REPORT

ESA CONTRACT N° 4000105946 /12/NL/RA	**SUBJECT** Analysis of Spacecraft qualification Sequence & Environmental Testing CCN1 (ASSET+)	**CONTRACTOR** **Thales Alenia Space Italia S.p.A.**
* **ESA CR () No**	**No of volumes: 4** **This is Volume No. 3**	**Study Manager:** P. Messidoro

ABSTRACT:

SUMMARY REPORT

This document summarizes the findings of the ESA ASSET (Analysis of Spacecraft qualification Sequence and Environmental Testing) study, in the form of a concise and informative conference or journal paper.

Names of authors: ASSET Study Team

NAME OF ESA STUDY MANAGER: B. Laine	**ESA BUDGET HEADING**

Summary report

DRL/DRD: D3

Written by	Responsibility + handwritten signature if no electronic workflow tool
M. Pasquinelli	Author for ASSET team 17/10/16
Verified by	
V. Basso	Checker 17/10/2016
G. De Logu	Configuration Control 18/10/2016
Approved by	
P. Messidoro	ASSET Study Manager 17/10/16
Released by	
S. Pioli	Documentation Manager Stefania Pioli, 10/11/2016

Approval evidence is kept within the documentation management system.

ThalesAlenia Space

AIRBUS DEFENCE & SPACE

CHANGE RECORDS

ISSUE	DATE	§ CHANGE RECORDS	AUTHORS
01	3/OCT/2016	Document written by M. Pasquinelli on behalf of the ASSET team. First issue.	L. Pace, A. Ferrero, M.Pasquinelli, P.Messidoro, P. Giordano, F. Verges, P. Hugonnot, R. Werner

Acronyms

ASSET	Analysis of Spacecraft qualification Sequence & Environmental Testing
Airbus DS	Airbus Defence & Space
ECSS	European Cooperation for Space Standardization
ESA	European Space Agency
FLA	(in-) Flight Anomaly
FM	Flight Model
ITT	Invitation To Tender
JAXA	Japan Aerospace eXploration Agency
JPL	Jet Propulsion Laboratory
MATED, MAT€D	Model And Test Effectiveness Database
MBSE	Model-Based System Engineering
Mech	Mechanical tests
NASA	National Aeronautics and Space Administration
NCR	Non-Conformance Report (used as alias for on-ground anomaly)
NCTS	Non Conformances Tracking System
PFM	ProtoFlight Model
RFT	Reduced Functional Test
TAS	Thales Alenia Space
TTE	Total Test Effectiveness
TV	Thermal Vacuum
w.r.t.	With Respect To

1. Introduction

The ASSET+ study extension originated by the need to improve several aspects of the Thermal Vacuum test; in order to achieve such task, a deeper knowledge of the phenomena linked to the test had to be assessed in detail, as an outcome of the concluding ASSET study.

The study identified from the companies' historical records and from ASSET cases the relevant Flight Anomalies (FA's), Non-conformance Reports (NCR's) and Thermal Vacuum Test Plans data and analyzed them in detail, w.r.t. the different objectives, with the aim of proposing recommendations aimed to improve test effectiveness, cost saving and correspondence between ECSS standards and practice.

To reach those objectives, the following steps were followed (keeping the methodology defined in the main ASSET study):

- identification of the type of data required to perform the activity, as a subset of the data identified by the ASSET selection criteria

- survey of the available data potentially used in the study (including but not limited to the data already surveyed in ASSET)
- selection of the interesting cases to be analyzed
- analysis of the in-orbit anomalies that provide useful feedback on TVT
- analysis of the on-ground testing anomalies that provide useful feedback on TVT
- analysis of the as-run TVT
- synthesis of the study results including recommendations for TVT improvements and proposal for further activities

2. Methodology

The methodology has been mostly inherited from the preceding ASSET study. *Selection criteria* for the screening of NCRs and FLAs have been tailored for the new study and a new set of *study questions* has been defined, to guide the analysis of selected anomalies.

Selection criteria

To collect cases (NCRs and FLAs) able to bring useful hints for the objectives of the study, a set of selection criteria has been defined, has presented in the following tables.

Nevertheless, according to their sensibility, all the personnel involved in the study may consider including cases that, even if not exactly in line with these criteria, can contribute effectively to the results.

Table 1 : NCR selection criteria

Criterion	ASSET-related	To be discarded*
Affected Item (item failed during test)	Space segment system Space segment element/module Space segment subsystem Space segment equipment Part and Materials	Launch Segment Ground segment Software GSE/TSE
Verification level (at which the test activity is performed)	Space segment system Space segment element(/module)	Space System Space segment Subsystem Space segment Equipment
Severity (potential impact on mission)	Critical (loss of function, loss of mission) Major (switch to redundant, delay to operations)	Minor (no potential impact on mission) *In case of doubt or interesting outcome keep also the minor*
Cause (Process)	Design Workmanship Part and Material Excessive Testing Not Reported	Operator Error* Failure to Follow Procedure Defective GSE

Cause (Nature)	Electrical Mechanical Thermal Others (Optical/Fluidic)	Software (*only* if unrelated to hardware)
Type of test	*Thermal Vacuum Test; if interesting, keep NCR from Thermal Balance, Ambient and Cycling. Include any test (e.g. functional tests) after TVT which could have discovered TVT-related anomalies*	*All other tests*
Verification Stages	- Qualification - Protoqualification - Acceptance	

Table 2 : FLA selection criteria

Criterion	ASSET-related	To be discarded*
Affected Item (item failed during operations)	Space segment system and lower tier	Launch Segment Ground segment Software
Severity (impact on mission)	Critical (loss of function, loss of mission) Major (switch to redundant, delay to operations)	Minor (no potential impact on mission) *In case of doubt or interesting outcome keep also the minor*
Cause (Process)	Design Workmanship Part and Material Excessive Testing Unknown Not Reported	Operator Error* Failure to Follow Procedure
Cause (Nature)	Electrical Mechanical Thermal Others (Optical/Fluidic) Unknown	*Software (if unrelated to hardware)*
Type of test that would have discovered it (preliminary screening)	*TVT or Unknown (but which could be discovered in TVT according to experience)*	*All other tests*

** Operator error as defined during ASSET, i.e. keep anomalies due to operator errors before the test and which have been discovered by TVT (and if it was not pointed out it would become a mission-degrading failure). Discard anomalies due to operator error during the TVT and solved during TVT.*

Study questions

The following detailed objectives and study questions have been defined:

- testing environment:
  - What is the importance of the Vacuum condition? What is the importance of the Vacuum condition?
    1. How critical is the vacuum condition to precipitate flaws? Are the anomalies specifically related to the vacuum condition, or could they be anticipated by tests on the spacecraft before TV without losing in test effectiveness?
  - What is the importance of thermal cycling during thermal vacuum?
    2. Does TV cycling at S/C level precipitate flaws (i.e. anomaly appears because of the temperature cycling)? If yes, what is the impact on test effectiveness of each TV cycle?
  - What is the importance of simulated radiated flux (solar/infrared)?
    3. Are there anomalies that would have been found earlier if sun simulation had been used during TVT? Are there anomalies found thanks to sun/infrared simulation? Are there anomalies which are linked to the use or lack of infrared flux?
  - What is the impact of temperature?
    4. How critical is the temperature level to precipitate flaws? Are the anomalies related to the extreme temperature level?
    5. Is there a relation between failure of functional test and test phase (hot phase/cold phase)?
  - Are intermediate temperatures or transitions important in thermal vacuum?
    6. Do ground and flight anomalies occur also at not extreme temperatures? What type of anomalies appear during transitions? Which type of tests performed during thermal transients would have helped to detect a flight anomaly on ground? Which type/level of test actually found such non conformances on ground?
- testing facilities and operations:
  - What is the impact of facilities and operations?
    7. Are there anomalies that are not related to a spacecraft flaw, but are due to operations/facility?

Anomalies due to operator error during the TVT and solved during TVT are discarded on principle; as a consequence, two kind of TV7 related anomalies can exist:
1) those kept anyway because significant
2) those that reveal to be TV7-related during analysis

3. Selected cases

Applying the selection criteria a total of 59 NCRs and 15 FLAs have been selected.

The selection process has not been completed using only filters, as most databases are not consistent with the selection criteria established for ASSET, with the exception of MATED. Instead, a case by case selection has been carried out as far as possible, especially for the severity; this case by case check has been chosen also for MATED data, so to verify the correctness of inserted information.
The final selection of cases has been completed only with the analyses, where the deeper knowledge of the selected cases has made possible to know in detail what had happened for each anomaly. In this phase, cases found to be not relevant have been kept for track but no longer considered in the analyses.

After the analysis phase, the anomalies still considered to be relevant have been 42 NCRs and 10 FLAs; 8 of the 42 NCRs where found to be linked to facility and/or operations, (i.e. not linked to spacecraft) therefore discarded by principle, yet escaped from the initial filtering because such link was not obvious.

4. Results of the analyses

The logic followed for the assessment of anomalies has been to proceed anomaly by anomaly, considering which study questions were applicable and to which the analysis was able to produce interesting contributions.

At a first glance, it is possible to see that most of the analyzed failures are linked to temperature level, vacuum, functional test in hot/cold.

Such findings confirm the importance to perform the TV test in realistic flight conditions, in vacuum, at the extreme predicted hot and cold temperature limits and to repeat the functional tests both at hot and cold temperature level. The commonly used test practices foresee these conditions and therefore appear adequate.

The following Tables and Charts provide an overall picture of the numerical outcomes which results from the analyses.

As the amount of available cases is not large (52 anomalies in total), these results should not be taken as statistically significant data. Nevertheless, they can be used to draw some conclusions. The considerations and recommendations provided later in this document rely also on a case by case assessment and justification, based on available analyses **Error! Reference source not found.**.

Table 3 - Level of the anomalies

Level detail:	
EQP	14
SYS	32

undetermined	6

Table 4 – Type of anomalies

Type	
NCR	42
FLA	10

Table 5 - Cycle of occurrence.

Cycle of occurrence (NCR)	
1	30
2	0
3	1
undetermined	11

Note: not applicable to FLA; in case NCR is detected at the end of the test, it is not always possible to determine the cycle of occurrence.

Table 6 - Physical phenomena

Phenomenon	
Temperature change	3
Thermal leak	4
Overheating/underheating	5
Thermoelastic	10
Trapped air dilatation	2
Outgassing	3
Leakage	1
Specific (e.g. reasonating frequency)	12
Other (no physical phenomena)	12

Note: heat leak in this study is considered as an unexpected heat path/flux or thermal exchange

Table 7 - Physical phenomena: detail of the thermoelastic anomalies

thermoelastic details:	
- MLI design	2
- Alignment	2
- Broken part	3
- Distorsion with impact on function	3

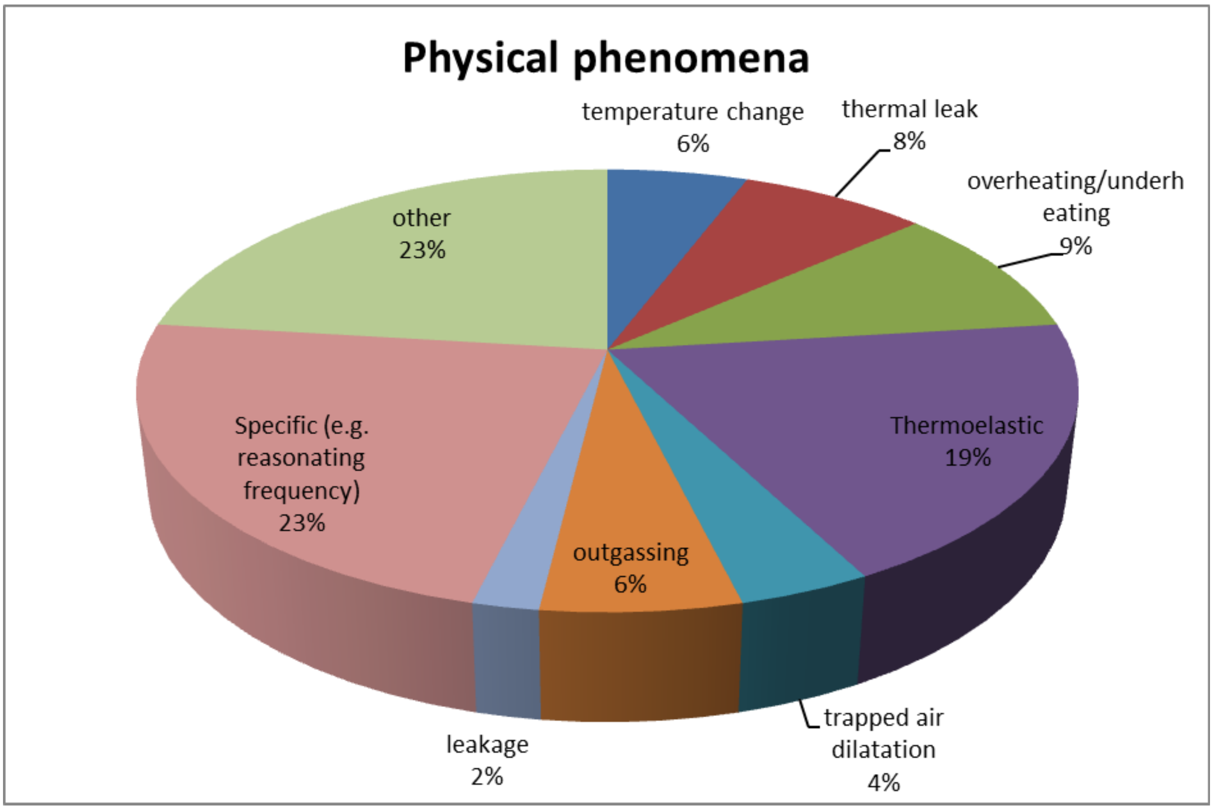

Figure 1 - Pysical phenomena

Table 8 - Phase of occurrence

Phase	
hot	16
cold	15
transient	13
specific range	2
due to cycling	2

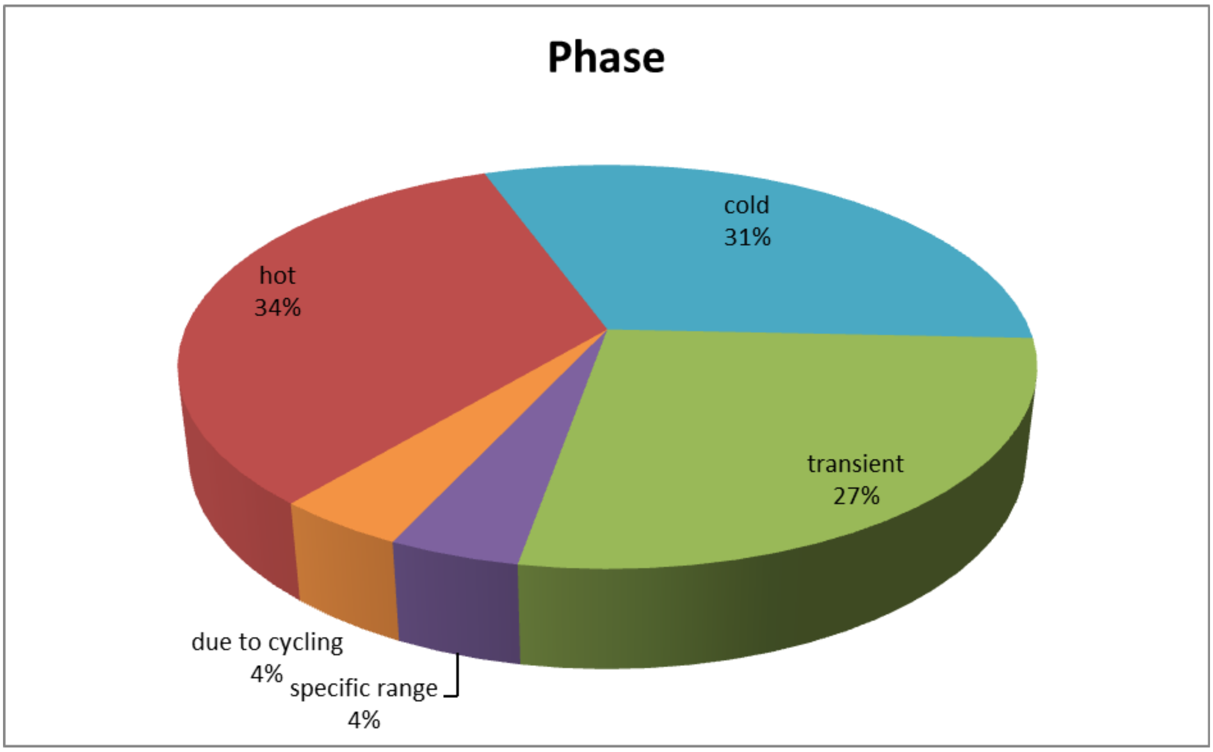

Figure 2 - Phase of occurrence

5. Synthesis and recommendations

General objectives

How to improve effectiveness of TV tests?

The analysis showed that the current practice is able to identify most major issues on ground. Nevertheless, margins of improvement have been found and provided as recommendations in the following.

Why the anomaly are precipitated in TV test, even on already qualified+accepted hardware?

On principle, units should be functionally tested before system TVT, therefore it is not expected to find in the system test anomalies caused by the unit being functionally tested for the first time. However, at least 14 anomalies were Equipment level issues. There are no clear results from the analysis to provide full understanding of this topic. The unit level testing may have been not fully representative of the system level test/flight environment, or the equipment tested at unit level may have been different from the hardware integrated on the system (because of design changes whose impact was not fully considered).

Outcomes related to the study questions

How critical is the vacuum condition to precipitate flaws? Are the anomalies specifically related to the vacuum condition, or could they be anticipated by tests on the spacecraft before TV without losing in test effectiveness?

The vacuum condition shows to be the main driver for a large majority (29 out of 34, not considering FLAs and facility related NCRs) of the selected anomalies. This condition covers different phenomena:

- impact on heat transfer and temperature distribution (lack of convection)
- pressure-related effects: leakage and outgassing
- other vacuum-related phenomena, as corona effects, were not observed among the selected cases.

22 of these 31 anomalies are temperature-related, but can be found only in vacuum, which makes it possible to observe the anomaly (e.g. cold conditions can be reached only in vacuum; specific temperature distributions are linked to absence of convection).

As a conclusion, Thermal Vacuum cannot be replaced with Thermal Ambient.

Does TV cycling at S/C level precipitate flaws (i.e. anomaly appears because of the temperature cycling)? If yes, what is the impact on test effectiveness of each TV cycle?

Of the considered programs, the landscape of the approach is varied: there are testing programs planning for only 1 TV cycle up to 10 cycles. Note that one TV cycle is intended as a succession of hot and cold plateaus, with the needed transitions, and 1,5 is one cycle followed by a cold-to-hot transition and one additional hot plateau.

Scarce evidence of the impact of cycling appears from the analyses: just 3 NCRs/FLAs have thermal cycling among their contributing factors (intended as the need to perform at least one cycle to observe the anomaly). There is no evidence to require to perform 3 cycles (as in current ECSS).

For a majority of cases, the cycle of occurrence was not available; in addition, many aspects of the anomaly reports were not fully clear, and the understanding of what happened was in general obtained through the involvement of project experts who had worked on the considered anomaly.

As a consequence, with the aim of an improvement of the return of experience from past programs, it is suggested to investigate the possibility of an enhancement of reporting, providing a thorough understanding of phenomena and conditions related to the considered nonconformance of flight anomaly.

Considering the test effectiveness of test programs in the ASSET+ perimeter (half TVT with one/two cycles) it is possible to underline that there is no evidence for an increase of FLAs if 1.5 cycles are performed (guaranteeing both types of thermal transient, i.e. from hot to cold and from cold to hot), as opposed to 3 as requested by ECSS.

Are there anomalies that would have been found earlier if sun simulation had been used during TVT? Are there anomalies found thanks to sun/infrared simulation? Are there anomalies which are linked to the use or lack of infrared flux?

5 in 52 cases are linked to solar/infrared flux simulation, and more specifically 4 NCR out of 32 NCR found in TVT where solar/infrared flux simulation was performed and 1 FLA with AIV feedback

indicating that it could not be observed on ground without solar simulation (solar simulation was performed but the anomaly escaped the test anyway). This fact can be seen as a confirmation that solar simulation allows to highlight specific kinds of potential failures, because its impact can be pivotal in the thermal behavior of the spacecraft (e.g. sun trapping effect expected from geometry). Justification should be provided not to use sun simulation. Sun simulation is important to validate the thermo-optical properties (incl. geometry) and to observe possible problems escaped from or not captured by the thermal analysis or workmanship issues.

How critical is extreme temperature required to precipitate flaws?

Extreme temperature (plateau) plays a major role in more than half (28 of 52) anomalies (24 of 34 excluding FLAs and facility related NCRs), in both hot and cold conditions. This means that covering the temperature range during the test is necessary (the hypothesis is that functional testing at ambient should already have captured anomalies not related to environmental conditions). There is not enough evidence to recommend in general that reaching the predicted extreme operating temperatures at the plateaus is important. There is no feedback from flight anomalies to have more extreme temperature testing (i.e. no FLA was missed at ground testing because flight temperatures were more extreme than TVT).

As a conclusion, temperature (both cold and hot) triggers many anomalous behaviors. No evidence indicates that a more severe thermal environment would increase test effectiveness. The overall outcome is that it is important to reach the predicted extreme operating temperatures. No indication emerges that going beyond those levels contributes significantly to detect NCRs; this is not disproven, either, therefore it cannot be excluded that passing those limits would actually increase test effectiveness.

Is there a relation between failure of functional test and test phase (hot phase/cold phase)?

16 of 34 NCRs are linked to the functional test performed at certain TVT phases (more often hot plateau). This can be a confirmation of the importance of having a thorough functional testing at TV predicted temperatures (the hypothesis is that functional testing at ambient should already have captured anomalies not related to environmental conditions).

The functional testing at the temperature plateaus is able to identify issues that cannot be observed during the functional test at ambient.

Do ground and flight anomalies occur also at not extreme temperatures? What type of anomalies appear during transitions? Which type of tests performed during thermal transients would have helped to detect a flight anomaly on ground? Which type/level of test actually found such non conformances on ground?

9 of 52 anomalies occurred at temperatures far from extremes. 13 occurred during transients, but in 8 of these cases the anomaly happened near to the cold or hot plateau; therefore these 7 cases are not included in the list of applicable anomalies. Inside this group of anomalies, it is possible to find anomalies that occur at specific temperature ranges (in some cases this can be already observed at equipment level); this is confirmed for 2 flight anomalies (GOC_SC-56, Anonymous1).

There are also anomalies linked to the effect of thermal gradients created by the transient, and to thermoelastic effects.
The findings are limited by the fact that functional test during the transient is not always performed; it is possible that more anomalies would be found if testing were systematically performed during transients.
Operating temperatures are often not tested (when different from ambient), but can trigger anomalies which, even if few, can be critical. Behaviors linked to specific temperature ranges can usually be identified at equipment level (directly from testing or through system level analyses with validated unit models). It is not affordable to test at system level intermediate plateaus for all possible operative temperature ranges. Functional testing during transitions is able to identify anomalies that are not observed at plateaus.

Are there anomalies that are not related to a spacecraft flaw, but are due to operations/facility?
A large fraction of the anomalies occurring during TVT is not related to the S/C and therefore out of scope for the present study. It is worth mentioning that in several cases (x out of y) the anomaly description was not sufficiently clear and at the beginning of the study the NCR was erroneously interpreted as SC-related. This finding suggests the opportunity to require standardized and detailed NCR reporting. It also shows that there is room for improvement in the preparation/monitoring of the tests, to avoid the issues created by the facility/MGSE.

Recommendations

3 of 7 system level thermoelastic anomalies are due to electrical disconnection.
According to ECSS-E-ST-31C, para 3.2.1.7 and fig. 3-1, the TCS design temperature range, specified for the operating and non-operating mode and the switch-on condition of a unit, is obtained by subtracting acceptance margins from the acceptance temperature range.
Two different aspects emerge from these considerations:
1- functional tests at acceptance temperature (hot and cold) are able to evidence loss of functionality, e.g. due to loss of connection caused by thermoelastic behavior
2- necessity to have a complete cycling to observe behaviors linked to both hot to cold and cold to hot transitions.
It is recommended to perform system functional tests as close as possible to the predicted temperature level (at least) for all units and structural parts, both in cold and in hot phases. Note that this is reflected in ECSS testing (ECSS-E-ST-10-03C).

Several test programs deviate from standards in terms of number of cycles (as low as 1, and commonly 2 or 1.5) and work well in flight (as already seen in ASSET [AD7])
Besides, all screened anomalies related to a functional test have been found the first time such test was performed; as a consequence, there is no evidence that 3 cycles are necessary. On the other hand, the data set is limited as a large number of cases were discarded from this analysis when found in later cycles but it was not clear whether the functionality was tested in an earlier cycle. It is considered that the typical amount of cycles in TVT is insufficient to trigger thermal

fatigue effects. In ECSS, PFM is requested to perform 3 cycles, plus 1 if needed, with no need of functional test at all plateaus.
Since several anomalies have been linked to the extreme predicted temperature level, but no anomaly has been linked specifically to multiple cycling, it seems more important to achieve required temperature levels once and to keep the two different types of transitions than to repeat these plateaus several times. A good compromise with the need to perform outgassing/bakeout phases during the system TV may be to perform 1.5/2 temperature cycles (i.e. hot/cold/hot or cold/hot/cold, or hot/cold/hot/cold).
Considering the limited number of cases it is impossible to derive a strong recommendation. However, ASSET+ findings show no evidence to support the requirement of 3 cycles at system level. **It is recommended to gather more data on this topic and in particular to improve the capture of information during the TV test about the effect of the number of cycles. It is suggested that the ECSS board takes into account the ASSET+ findings as well as other similar data from other sources in evaluating the possibility to relax the 3 cycles requirement.**

5 of 52 anomalies are linked to over/under heating; 4 of 52 anomalies are linked to thermal leaks.
Over/under heating and thermal leak related anomalies are caused by the test environment inducing unexpected temperature levels in some areas of the S/C.
They are linked to the incorrect thermal modeling of the effect of thermal environment on the S/C temperatures, or to an unexpected thermal behavior of the S/C TCS.
Despite all precautions, the thermal model may overlook some effects of the thermal environment on the spacecraft thermal behavior. Therefore it is necessary to reproduce the flight environment, when critical, as closely as possible, in particular as far as external sources of heat are concerned.
Considering the limited number of cases it is impossible to derive a strong recommendation. However, ASSET+ findings show no evidence to support the requirement of 3 cycles at system level.
It is recommended to gather more data on this topic and in particular to improve the capture of information during the TV test about the effect of the number of cycles. It is suggested that the ECSS board takes into account the ASSET+ findings as well as other similar data from other sources in evaluating the possibility to relax the 3 cycles requirement.

5 of 52 anomalies are linked to over/under heating.
Over/under heating and thermal leak related anomalies are caused by the test environment inducing unexpected temperature levels in some areas of the S/C.
They are linked to the incorrect thermal modeling of the effect of thermal environment on the S/C temperatures, or to an unexpected thermal behavior of the S/C TCS.
Despite all precautions, the thermal model may overlook some effects of the thermal environment on the spacecraft thermal behavior. Therefore it is necessary to reproduce the flight environment, when critical, as closely as possible, in particular as far as external sources of heat are concerned.
It is recommended to validate not only the model w.r.t. as built, but also to validate the as built vs. as modeled (which means to make sure, before testing, that what has been built corresponds to what has been designed and modeled).

3 of 52 anomalies are linked to outgassing. One of them led to violated internal pressure requirement.

Outgassing may result in increase of pressure level inside and outside S/C, thus violating the pressure requirement of units and payloads (which in turn are driven by the necessity to avoid Corona effect when RF is on) and leading to delays in the test execution.

The pressure requirements coming from units and payloads can be unclear and withhold large margins that are disclosed only after a lot of negotiation; as a consequence, it is recommended to clarify and justify (i.e. ensure it is necessary) such requirements prior to the test, in order to avoid unnecessary delays.

6. Conclusions

Based on the test and flight data that have been collected, ASSET+ showed that the major anomalies escaped from Thermal Vacuum Testing are few, evidencing that current practice is good overall (this means high test effectiveness).

8 anomalies discovered in TVT would have potentially provoked the loss of mission if not detected; this occurred in 5 out of the 12 considered space programs.

Some margins of improvement have been found and consolidated into recommendations

A deeper understanding of the involved phenomena has been provided, supporting further considerations and developments.