INSIGHT INTO THE VALUE OF SYSTEM LEVEL THERMAL VACUUM TESTING

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ABSTRACT

Increasing cost and schedule pressures are leading satellite developers to question the cost/benefit of system level thermal vacuum testing. This study investigates the effectiveness of the thermal vacuum test as a screen to prevent on-orbit failures. The study then delves into the failures found and missed in the thermal vacuum test in an effort for test planners to better understand the value of the test and the risks associated with its deletion. One key finding is the opportunity for better test screening before, during, and after the system level thermal vacuum test, since a large portion of the failures found could have been detected earlier in the test program.

KEY WORDS: Satellite, thermal vacuum test, system test, Integration & Test, thermal cycling, test effectiveness, ground test failure, flight failures.

INTRODUCTION

The second half of the 1990s saw a significantly increasing rate of satellite failures as shown in Figure 1. The bars on this chart reflect an increasing number of launches for commercial, civilian and DoD satellites per year. However, the percentage of mission degrading or catastrophic failures occurring within the first three years of operation was noticeably increasing to a failure rate approaching 30%[1]. This rising failure rate occurred in a period of increasing pressure to decrease the time and cost of building satellites and delivering them to orbit. This failure trend, coupled with program cost and schedule pressures, gives one pause as to whether the recipe for mission success has been lost.

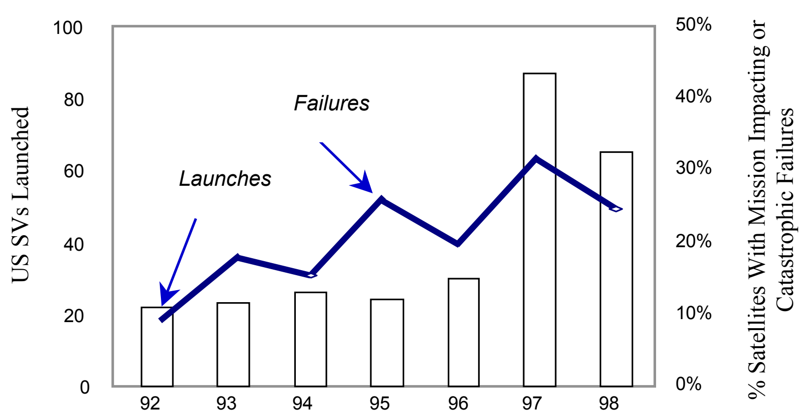

Figure 1: Increased degradation trend, 304 U.S. satellites

One reaction to continuing cost and schedule pressures is a desire to decrease satellite ground testing. The system level thermal vacuum test (TV) sequence represents a prime target for deletion due to its considerable duration and high cost. This reaction led the authors to address the following three fundamental questions: (1) What is the value of the system level TV test sequence as a part of the overall satellite test program? (2) What is the value of the test sequence in detecting failures escaping from pre-TV screens? and, (3) What is the value of the test sequence in terms of failures escaping from the TV test?

By analyzing the value of the test sequence, in terms of the number and nature of failures both detected and undetected, the intention is to support empirical decision-making, both on the issue of potential deletion of this test from future programs, and overall test process improvement.

DEFINITIONS AND METHODOLOGY

A consistent definition of what is, and what is not a mission degrading failure (MDF) is required to count important ground and flight failures in a consistent and defensible manner. The Aerospace Corporation uses the following definition:

A mission degrading failure is any flight failure leading to a change in mission reliability, or a ground test failure that, if undetected and launched, would cause a change in the mission reliability.

Examples of MDFs include:

- Catastrophic failure
- Loss of mission redundancy
- Operations below requirements or specification limits
- Failures causing redesign on this or future satellites
- Failures causing equipment repair in place, or removal, repair, replacement and reverification

The discrepancy reports assessed in this study were prescreened. Excluded were:

- Flight single event upsets
- Operator errors
- Procedural errors
- Test equipment hardware and software failures and inconsistencies
- Flight software changes during ground test
- Test database errors
- Unverified or “ghost list” failures
- Discrepancies resulting in wavered requirements changes
- Nonconforming material
- Insufficiently documented discrepancy reports

The remaining MDFs represent real ground test and flight hardware failures.

The study objectively assessed mission degrading failures during the TV test sequence, post-TV Integration and Test (I&T), and on-orbit across a representative sample of recent government satellites. Escapes are failures that should have been detected in a previous screen. The study tracked escapes from pre-TV screens into the TV test sequence, and escapes from the TV test. Understanding escape rates and their nature provides valuable insight for improving future test programs.

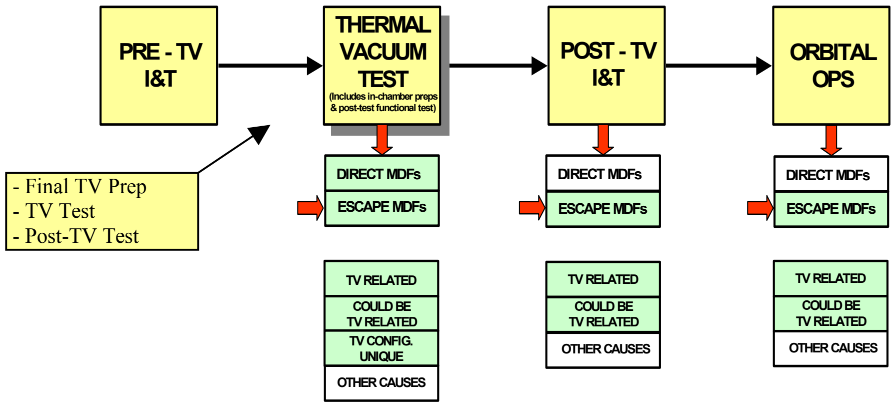

Figure 2: Study Methodology

The TV test sequence process begins when the satellite is first installed in the TV test chamber for final test preparations. MDFs occurring during final TV test preparations, the TV exposure itself, and the immediate post-test and in-place electrical functional testing were scored against the TV test sequence, Figure 2.

MDFs were initially binned into two categories:

- Escapes into the test
- Direct MDFs

Direct MDFs are those detected during TV that are not escapes into that test, and are further binned into categories that would identify which TV MDFs were truly attributable to the TV test screen. The categories are:

- TV-related MDFs
- “Could be” TV-related MDFs
- TV configuration unique MDFs

TV-related MDFs are those requiring the specific vacuum and resulting thermal environment for detection. “Could be” MDFs are where the discrepancy report suggests that the failure is TV-related, but attribution was not conclusive. The study then assessed all MDFs occurring after the TV test, from the time the satellite returned to its I&T location until shipment to the launch site.

The study assessed orbital MDFs that occurred in the initial three months after launch (the infant mortality time frame for determining test effectiveness), and the subsequent 33 months, for a total of 36 months of flight performance. By looking at the three-year failure history, it was hypothesized that better insight into the nature and cause of the failures could provide critical insight for test process improvement.

The primary TV test data set selected for this study included 39 U.S. government satellites. These satellites had optical, RF, or scientific payloads, and were integrated in five different factories. All satellites were fairly mature, complex designs. All are large (>1500 lb launch mass) and were tested using MIL-STD-1540-like approaches. Launch dates range from 1983 through 1997. The cut-off at 1997 allows a full three years of on-orbit performance assessment. Single satellite procurements were excluded from the study. About 30% of the satellites have not been considered in The Aerospace Corporation's previously published studies.

FINDINGS FROM THE TV TEST SEQUENCE

Figure 3 shows a top level summary of the MDFs. The lower portion of each bar represents escape MDFs found in each time period. These are the failures that should have been found in prior test phases. The strikingly large percentage of escapes will be explored later in the study. The upper half of the bars represents the direct MDFs, failures directly attributable to that phase of testing.

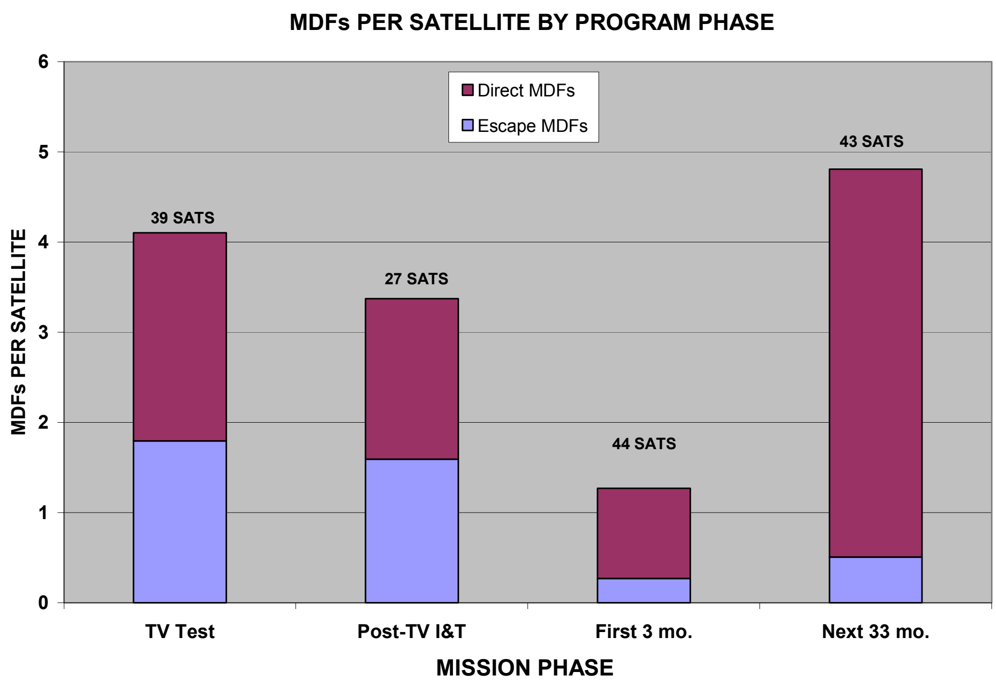

Figure 3: Summary of MDFs by program phase

Analysis of the failure data revealed that the TV test sequence detected an average of 4.1 MDFs per satellite (MDFs/sat). For "First in Block" satellites (7 of 39), the TV test sequence detected 6.0 MDFs/sat. Every satellite in the study had at least one MDF detected during the thermal vacuum portion of the sequence.

Figure 4 shows the percentage of satellites tested as a function of the minimum number of MDFs identified in the TV test sequence. All (100%) satellites showed *at least* one MDF during the TV test sequence. Fifty percent showed *4 or more* MDFs.

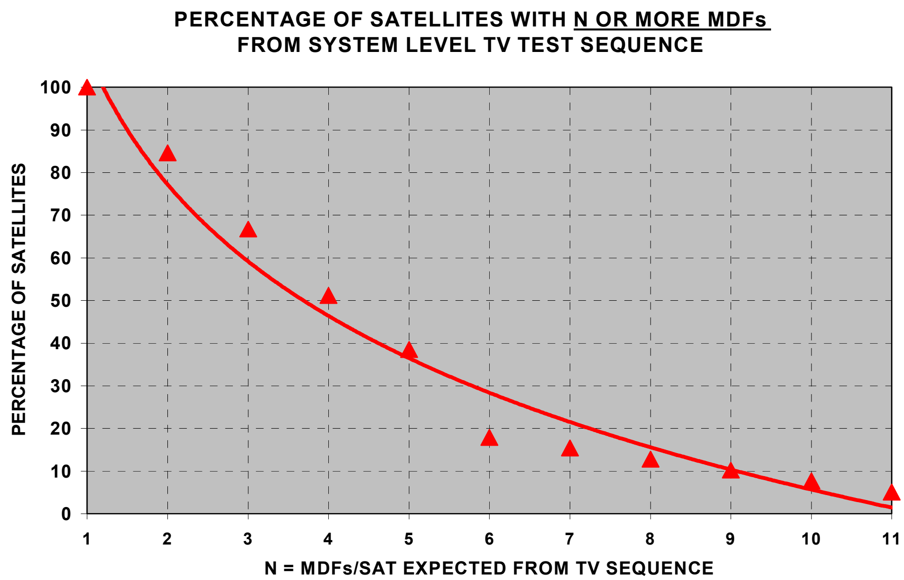

Figure 4: Percentage of satellites with N or more MDFs from TV sequence

The data were then analyzed for the kinds of failures that were detected in the TV sequence. Figure 5 shows the distribution of TV sequence MDFs by satellite subsystem. The lighter, bottom portion of the bars represent escape MDFs coming into the TV test from previous screens, and will be discussed below. The darker portion represents the direct MDFs.

During the TV final preparation phase, steps are often performed that are unique to the TV test phase, such as thermal control subsystem preparation. The study looked into discrepancies that occurred during final preparations and assessed whether these failures could/would be detected later in the I&T process or were TV sequence preparation unique. Approximately half of the MDFs found in final preparations fell into the "configuration unique" category. Examples of these included the misinstallation of multi-layer insulation and flight temperature transducers. Twenty percent of the TV MDFs/sat (0.8 of 4.1) detected for all the satellites were detected in the final TV preparation phase, because this was the first time the satellite was fully configured for the TV test. However, it is inconclusive whether these failures would be detected later in I&T if the TV sequence were deleted. Subsequent installation of solar arrays and final deployables can limit access for visual inspection, and the satellite would see no further thermal environments before launch.

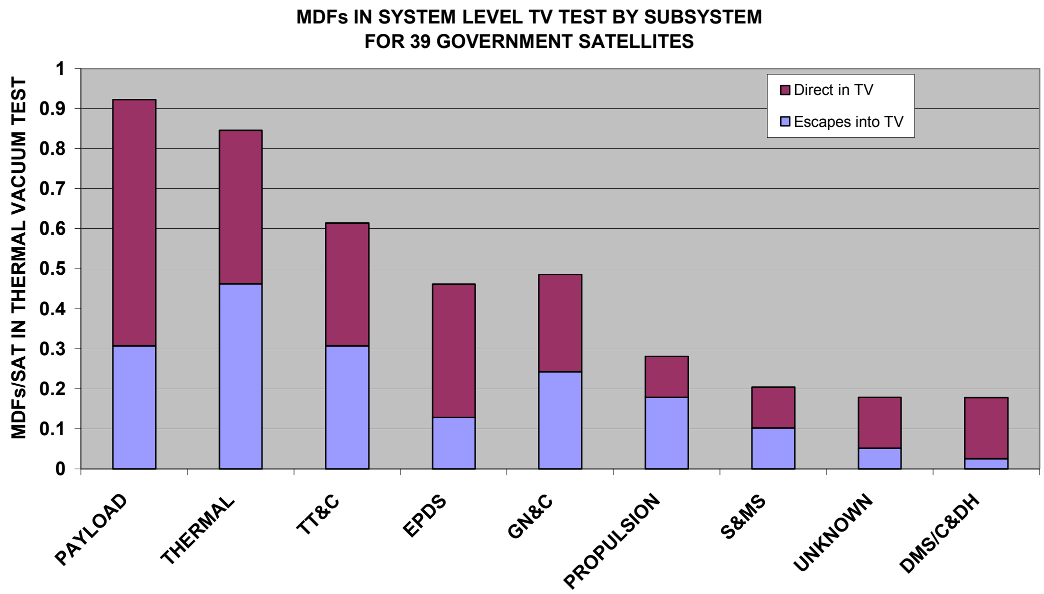

Figure 5: TV sequence MDFs by subsystem

Twenty-five (64%) of the satellites assessed for the TV test sequence had been through an ambient pressure thermal cycling test prior to the thermal vacuum exposure; the remainder had no vehicle thermal exposure prior to test. For vehicles that had seen a previous thermal cycling test, the TV test sequence detected 3.7 MDFs/sat (Table 1). For the remaining 36% of the satellites which saw no ambient pressure thermal cycling prior to the TV test sequence, 4.8 MDFs/sat were experienced from the TV test. The difference suggests that thermal cycling improves the screening process.

Table 1: Effect of previous thermal cycling on MDFs detected in TV test sequence

MDFs/sat Detected in the TV Test Sequence			
TV Sequence MDFs for All Sats in Study (39)		Satellites With Previous Thermal Cycling (25)	Satellites Without Previous Thermal Cycling (14)
4.1 MDF/sat		3.7 MDFs/sat	4.8 MDFs/sat
1st in Block	2nd+ in Block		
6.0	3.7		

As stated earlier, TV-related MDFs occur *only* in the thermal vacuum environment. Typical examples include failures driven by temperature gradients or outgassing realizable only in vacuum. Defects in the thermal control subsystem are the most common. We found that 0.8 of the 4.1 MDFs/sat (20%) to be clearly TV-related (Table 2), a result independently confirmed by thermal experts. Since this type of MDF requires the vacuum environment for detection, they will escape if the TV test is deleted. A further 0.9 of the 4.1 (22%) MDFs/sat were judged to be possibly TV related. In summary, this study has identified that between 0.8 and 1.7 MDFs/sat would escape if the TV test were deleted, causing on-orbit failures.

Table 2: TV-Related and Could-Be TV-Related MDF summary

MDFs/satellite Detected During the TV Test Sequence		
TV Sequence MDFs All Sats in Study	TV-related MDFs	All Potential TV-related MDFs
4.1 MDFs/sat (100%)	0.8 MDFs/sat (20%)	1.7 MDFs/sat (44%)

The Aerospace Corporation has been tracking test effectiveness for decades[2,3,4]. The actual system level TV test effectiveness for this set of satellites, with final TV test prep MDFs included, is 72%. With final TV test preparations excluded (for consistency with previous studies), the TV test effectiveness is 66%. These results are consistent with historically reported values and methodologies[5].

ESCAPES INTO AND OUT OF THE TV TEST SEQUENCE

A key finding of the study was the number of escapes into the thermal vacuum test, because previous screens failed to find these failures. The lower portion of the bars in Figures 3 and 5 show that a strikingly large percentage of escaped MDFs were detected during the TV test sequence. For the 39 satellites, 44% of the TV sequence MDFs were judged to be previous test escapes. Typical examples include previously broken wires, solder splashes on boards, bent connector pins, design and manufacturing defects, and hardware misinstallations during I&T. The TV sequence is very perceptive at discovering this class of escape MDFs. But it would be more desirable to increase the effectiveness of previous screens at lower levels of assembly, especially for the payload, thermal control, and TT&C subsystems.

Figure 6 ranks the causes of MDFs escaping into, and found during, the TV sequence. Approximately one-half of these escape MDFs were caused prior to hardware delivery to System Level I&T. Examples include unit fabrication errors, component/part failures, unit design errors, harness fabrication and design errors, and hardware layout design errors. The other half were caused during I&T. Unfortunately, none of the pre-TV screens, including I&T, identified these defects. They were all detected in the TV test sequence. Unit fabrication and design errors, component/part failures, hardware misinstallations and bonding errors in I&T account for 50% of the total escape MDFs. Eliminating these escape categories would cut the post-TV I&T impact of escapes in half; another opportunity to improve pre-TV screens.

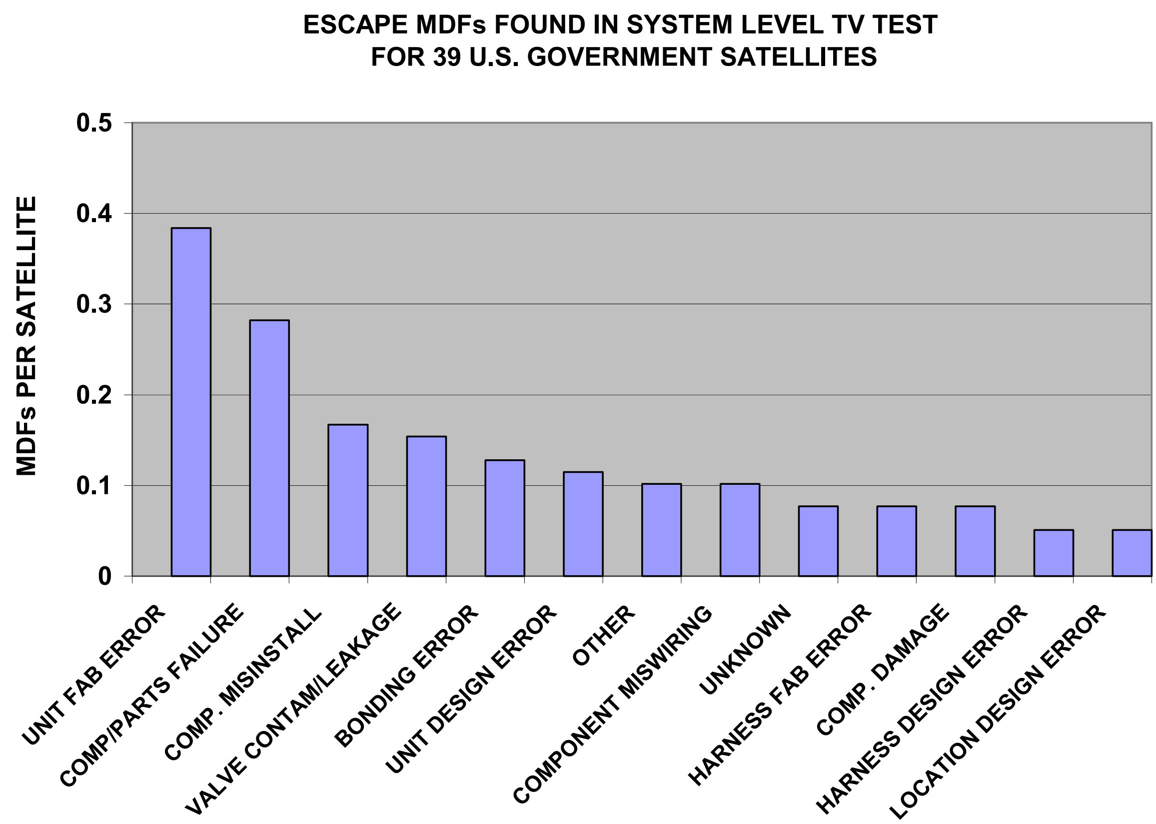

Figure 6: Ranked cause of escapes into the TV test sequence

The above data shows that TV sequence is effective at finding failures that could have been, but were not, found at prior levels of test. But how good is TV at screening for failures? We found that 47% of the 3.4 MDFs/sat detected in I&T, *after the TV test,* were escapes *from* previous screens, including the TV test. In addition to the usual discrepancies one would expect from post-TV I&T, other escape examples included: MLI misinstalled, workmanship error; open circuit, design flaw; resistor bonding, design flaw; and heaters switched, workmanship error. In many cases, failures found at this late level of assembly are reworked without additional system environmental testing. The potential damage incurred from the rework, combined with inadequate system level retest adds to the risk of mission failure. If these failures had been found earlier in the test screening process, less risk would have been incurred as well as less impact to cost and schedule.

Why are satellite developers finding escapes of this nature so late in the I&T process? Previous screens, including the system level TV sequence, should detect these escapes. A second, more fundamental question is how should TV testing be improved so that more escapes are detected? Considering the high escape rate, test planners should consider program-specific risk reduction steps early in the program in order to mitigate downstream failures.

COMPARISON OF THE TV TEST SEQUENCE AND POST-TV MDFs

Finally, the study compared TV and post-TV failures. Figure 7 shows the difference between the MDFs detected in the TV test sequence and those found in post-TV I&T processing by subsystem type. These MDF distributions are different. The grounding assumption for deleting the system level TV test sequence is that MDFs that would have been found in the TV test can be detected in other I&T processing. This assumption is false at a minimum for the thermal subsystem[2], since TV-related MDFs can only be found in a thermal vacuum environment.

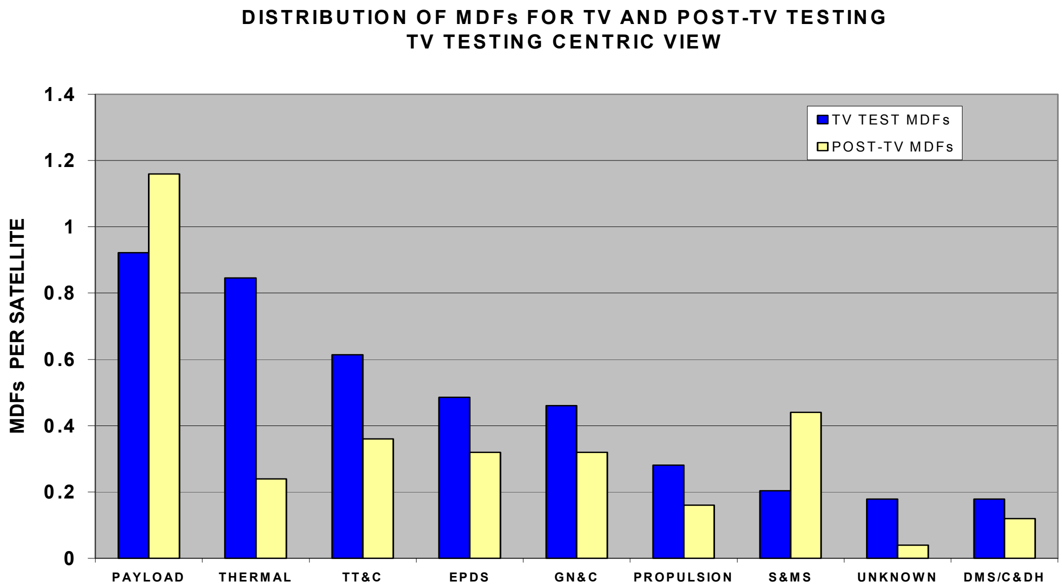

Figure 7: Comparison of MDFs found in TV sequence vs. Post-TV I&T

SUMMARY & CONCLUSIONS

We explored the value of system level TV testing by assessing failures during and after the test. We found that 4.1 mission degrading failures per satellite were attributed to the TV test sequence. Of those, between 0.8 and 1.7 MDFs/sat would not have been detected by other tests. Worse, the first vehicles in a build cycle have a higher failure rate of 6.0 MDFs/sat. Our findings can help test planners assess the risk associated with deleting the TV test.

Further, of the failures that were found in the TV sequence, 44% could likely have been prevented by better test screening prior to TV testing. However, the TV test is not a perfect screen. We found that 47% of the failures detected during post-TV I&T were due to escapes from previous tests, including the TV sequence. These escapes present an opportunity to review and assess test planning, perceptiveness and screening characteristics of all tests, to insure that failures are found at the lowest and least impacting level of the test program. Our findings underscore the fact that although the system level TV test sequence is an effective approach to screening for failures, its effectiveness can be greatly improved.

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BIOGRAPHIES

Mr. Wright works in the Cross Program Research Office for The Aerospace Corporation in the area of test effectiveness and risk management. He recently retired from TRW after a three-decade career providing advanced measurement engineering services for satellite Integration and Test. He founded and for two decades managed TRW's Measurements Engineering Department. In addition, he is the author of *Applied Measurements Engineering* (Prentice Hall, 1995) and teaches nationally on the subject. He holds a BS in Mechanical Engineering and MS in Mechanical Engineering Measurements from Arizona State University, and an MS in Systems Management from the University of Southern California.

Mr. Arnheim is Director of the Cross Program Research Office for The Aerospace Corporation. Mr. Arnheim has over 23 years of experience in aerospace, ranging from RF design, advanced systems design, new business development, systems engineering and systems test. Currently, Mr. Arnheim is responsible for leading cross program studies relating to schedule/cost benefit trades, lessons learned, cross-program failure analysis, and systems effectiveness. He holds a dual BS degree in Engineering from Harvey Mudd College and Economics from Claremont McKenna College, and an MBA from Pepperdine University.