METRICS EVALUATIONS FOR ENVIRONMENTAL AND RELIABILITY TESTING

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BIOGRAPHY

Mr. Mark Gibbel graduated with a B.S. in Mechanical Engineering from California State Polytechnic University at Pomona and has been involved in design and test of advanced electronic packaging since 1977, when he developed the thermal models for Hewlett Packard's flip-chip technology. He has dedicated his professional career to failure physics based test and verification methodology development and implementation, with a particular interest in space flight electronics. Since 1985, he has been a member of the Reliability Technology Group at the Jet Propulsion Laboratory where he has innovated and led several research projects within NASA's Test Effectiveness Program.

Dr. Steve Cornford graduated from UC Berkeley with undergraduate degrees in Mathematics and Physics and received his doctorate in Physics from Texas A&M University in 1992. He has focused his efforts at JPL on establishing a quantitative basis for performing reliability risk assessments including environmental testing and has received the NASA Exceptional Service Medal for his efforts. He is currently the Payload Reliability Assurance Program Manager for a number of NASA-funded research efforts at JPL.

Mr. Alan Hoffman has a B.S. degree in Physics, a M.S. degree in Mathematics and 35 years of experience in analyzing and specifying environmental requirements and associated environmental disciplines at the Jet Propulsion Laboratory, where he is a Member of the Engineering Staff- Principal. He has authored/co-authored 28 papers in his discipline and is recognized as an authority regarding environmental test and analysis requirements and effectiveness and environmental retest guidelines. He served as the Environmental Requirements Engineer for a number of successful JPL projects, including a recent international collaboration. He has received a NASA Exceptional Service Medal and NASA Group Achievement Awards for Ranger VII, Mariner 9, Viking, Voyager, and Galileo flight projects.

Mr. Michael Gross received a B.S. degree in Electrical Engineering from California State University Northridge. He is currently working on several Test Effectiveness research efforts and is the manager of the End of Life Simulation task which focuses on screening for end of life in electronic circuit performance via a combination of analysis and testing. He is also a member of the Electromagnetic Compatibility (EMC) group where he is involved in both EMC testing and design.

KEYWORDS

Test Effectiveness, Environmental Testing, Reliability Testing, Test Evaluations, Metrics Evaluations, Electromagnetic Compatibility, Pyroshock, Risk Management

ABSTRACT

NASA's Code QE Test Effectiveness Program is funding a series of applied research activities focused on utilizing the principles of physics and engineering of failure along with those of engineering economics to assess and improve the value added by various validation and verification activities. Presented here in are the latest metric evaluations for the effectiveness of the tests involved in one of JPL's recent space flight programs.

INTRODUCTION

As NASA's Jet Propulsion Laboratory continues its implementation of Faster, Better and Cheaper it is imperative to be able to quantify the effectiveness of various detection and prevention activities. Traditional approaches of the past have been very successful, and produced highly reliable hardware. However, with the goal of spending less to achieve more, one must find opportunities to reduce, combine and optimize testing programs. Code QE has taken the lead in proactively supporting efforts to improve the efficiency and efficacy of testing.

The rapid evolution of technology, and the one-of-a-kind nature of JPL spacecraft fabrication, results in significant challenges to utilizing the data of the past to improve the future. We have developed and implemented a methodology to meet these challenges[1,2]. This paper presents a sample of the utilities being performed to develop metrics and evaluate which measure the effectiveness of JPL's design, verification and validation processes.

DATA SOURCES

JPL's Problem/Failure Reporting (PFR System) is a paperless Anomaly data entry and analysis system. It has a variety of utilities ranging from programmatic risk management to studies of the effectiveness and efficacy of the Preventative measures, Analyses, process Controls and Tests (PACT's) used in the design, test and integration processes. It is an electronically searchable system that can perform analyses or output data for import into other tools[1]. The use of such a system makes the metric evaluation process fast and efficient.

PFR's are written for all anomalies that occur once power has been applied to the hardware. Two types of PFR's are utilized during the flight hardware or software design, development, integration, test and launch preparation, as follows: Pre-launch "Developmental" PFR's are utilized for reportable incidents involving breadboard activities, engineering model (EM) hardware not dedicated for qualification, EM hardware dedicated for qualification (up to pre-qualification testing), and developmental software. Pre-launch "Formal" PFRs are utilized for all reportable incidents involving flight, proto-flight* and qualification hardware or software (including engineering model hardware used during qualification testing, starting at pre-qualification testing), and associated test and facility equipment.

TOP LEVEL METRIC EVALUATIONS

Below is presented an example of top level (e.g. lumps all project PFR's together by phase) metric evaluations for one spacecraft. It was generated directly from the output of JPL's PFR System, i.e. without further detailed analysis of individual PFR's. These are relatively fast and easy to perform and provide good insight into the flaw distribution for a particular set of hardware. However, as discussed elsewhere[2] care must be taken not to extrapolate too far with this level of data. This is less of a concern if one is applying the results to another product which is implemented within the same corporate culture and for a similar mission.

Table 1 shows that during the developmental phase 967 anomalous observations, problems or failures were documented. For the "formal" PF documentation phase an additional 2,690 PF's were identified. The combination of rigorous testing and a careful and cautious documentation process resulted in over 3,600 pre-flight "anomalies" being documented. Of these, only 21% were deemed to have had a potentially significant consequence, had they not been detected prior to launch**. However, all of these resulted in activities to eliminate their potential occurrence.

During the pre-launch development phase almost 50% of all reported PF's were attributed to software. This is mostly due to the fact that the development period for software extends beyond the developmental period for hardware. Therefore, the introduction of flight software occurs later in the project life cycle and can result in more observed developmental anomalies. The category of "Other/O's" was a distant second at about 16% of the total. These mostly fell into the sub-category of "Unknown's/X's". During the development phase, "Unknown's/X's" are often less of a concern, since the hardware design is still evolving, parts may not of flight quality, etc. The "Design/D's" category made up about 15% of the total, which is surprisingly low for one-of-a-kind spacecraft builds. This can be attributed to the consistent application of appropriate design rules. "Manufacturing/M's and Workmanship/W's" accounted for only about 7% of the total during this phase.

During the pre-launch Formal PFR phase (flight hardware build and test phase), the "Design/D" category had the highest percentage of reported anomalies or PF's. "Support equipment/S's", "Software/C's" and "test induced error/T's" PF's were a close second, third and fourth. Consistent with reported industry trends in the reliability of commercial electronic parts[3], part related PF's were a relatively small percentage (5.7%) of the total. On a similar program, one decade earlier, part related PF's accounted for 11% of the total. Manufacturing/workmanship accounted for about 10% of the total during this phase. This is somewhat surprising for a one-of-a-kind spacecraft fabrication process.

In the first four months of the flight mission, no significant problems or failures have been reported. However, in general, anomalies (significant and/or non-significant) which have occurred during the post-launch flight phase have not been analyzed or reported on in this paper. As funding becomes available for this task, these will be analyzed.

LOWER LEVEL METRIC EVALUATIONS

Lower level (i.e. more detailed or narrower field of view) metric evaluations are presented below. In this case a

* In ultra-low volume applications, it is sometimes necessary to use hardware for both design qualification and as flight hardware. This hardware is referred to as *protoflight* hardware.

** This number would be much less if the possibility of in-flight work-arounds were considered specific type of hardware was selected and its associated PF's were examined from the period of development through the first four months of the post-launch flight phase. This enabled a look at the distribution of PF's by time as well as the specific effectiveness of individual PACT's. As more of these hardware specific studies are done, comparisons between various hardware types will be performed.

Figure 1 shows the PF's reported for a Solid State Recorder (SSR) according to the PACT's that were responsible for their precipitation/detection. The design and testing of 6 flight units and 1 engineering model is represented by this data. Figure 1 also summarizes the number of PF's reported for each PACT. The PACT's are arranged along the horizontal axis according to when these activities took place in the overall project life cycle. For this hardware, three activities [1) bench testing, 2) qualification/acceptance testing (i.e. formal functional testing) and 3) thermal vacuum testing] are significantly more effective than the rest. However, it will be seen later that there are failure modes that would not have been detected unless some of these other PACT's were performed.

Figure 1 presented the overall effectiveness of the PACT's implemented for this hardware. The data presented in Table 2 allows us to view this data in more detail. It presents data for the specific effectiveness of the PACT's implemented versus specific failure modes precipitated/detected. Table 2 shows PACT vs. cause code PF data for the same Solid State Recorder. The PACT's are arranged on the vertical axis by order of implementation. In all there were 9 cause code categories. Table 2 shows the six most significant ones in detail. They account for 90 of the 95 total PF's reported. The three least significant (handling, software and unknown/other) are summarized in a note at the bottom of the table.

Failure Mode Category Distributions

The design failure mode category (i.e. the "D" cause codes) accounted for 31% (29 of 95) of the total PF's reported. However, the non-specific subcategory of "design/D" accounted for 18 of the 29 total. This is a case where a more detailed (i.e. lower level) analysis of these specific PF's is necessary to classify them. The subcategory of "Packaging Design/D2" accounted for an additional 17% (5 of the 29).

PF's attributed to support equipment (i.e. the "S" cause codes) accounted for 20% of the total reported for this particular hardware. However, 16 of the 19 "support equipment" PF's were related support equipment software issues. Testing of this type of hardware requires simulating a significant number of different interfaces and therefore its support equipment is, by nature, very software intensive.

A slightly less significant category was "test induced error". It accounted for 14% of the total PF's reported. The subcategory of "procedure error/T3" accounted for over half (7 of 13) of the PF's reported. The subcategory of "equipment/T2" accounted for almost another quarter. This is what one would typically expect for the initial build of a new system. In a production environment, the number of PF's attributed to both of these categories would be expected to decrease with time. Conversely, if only 1 or 2 units were produced instead of 7, then this category most likely would have represented an even bigger percentage of the total.

All of "Manufacturing/M's" PF's were due to "tooling and machining". All but 1 of the "workmanship/W's" were due to the general subcategory of "Fabrication/Assembly/W1". A lower level analysis of these PF's is required to identify any meaningful trends within this data.

For the "Part/P" category no PF's were reported as a result of electrostatic discharge. A specific piece part level failure mechanism was reported for only 38% (5 of 13) of the part related PF's. Conversely, 62% of the time data was not available to determine a specific failure mechanism without performing a more detailed analysis of the data.

Overall Effectiveness of the PACT Implemented

The PACT labeled "Qual/Acpt Test" (i.e. formal functional testing) was the second most effective PACT overall, but was the single most effective PACT for design-related failure modes. In the same manner, bench testing was the most effective overall PACT, but only precipitated/detected half as many PF's as did "Qual/Acpt Test". Surprisingly, 4 out of 5 "packaging design/D2" related PF's were detected without applying any environmental stresses. Also surprisingly is the fact that none of the 3 PF's belonging to subcategory of "design specification/D1" were detected during bench testing or formal functional qualification/acceptance testing. These two findings suggest that they be should looked at with a larger data set to see if still they hold true.

For the "support equipment" cause code category, most (10 of 19) of the PF's were detected either during the fabrication process or during bench testing (i.e. first power-on). Interestingly, 9 out of the 10 were software related. Another 7 "support equipment software/S4"

PF's were precipitated/detected by the thermal vacuum testing process.

Conclusions/Post Ground Testing Findings for the SSR

Through the first four months of flight, only one in-flight anomaly has been associated with the performance of this piece of hardware and has been deemed "not significant". The reported anomaly was a radiation "hit" that resulted in a "double bit error" but was still in specification for this type of flight exposure and was handled by fault protection procedures.

Table 2 additionally indicates that there were not any PF's which were considered to be escapes from assembly level testing (i.e. PF's which should have been detected during the assembly level test processes). This indicates that the PACT's performed at lower levels were very effective but may also represent an opportunity to cost effectively do less.

The above observed trends will be compared to those for this spacecraft (S/C) as a whole, other hardware types and to other S/C, to assess their statistical significance.

METRICS EVALUATIONS OF PACTs

Above, this metric evaluation methodology was applied by hardware type above. Below, this methodology is applied by PACT type using data from the same project as SSR evaluation. Two specific PACT evaluations are presented. They are: Electromagnetic Compatibility (EMC) and pyroshock testing.

EMC Evaluations

The following tables summarize the Electromagnetic Compatibility (EMC) tests run on the same spacecraft. In each category, the total passes, fails, etc. are cumulatively counted from multiple tests. That is to say, if a developmental test was run more then once, or developmental tests were run on more than one part, then the total passes, fails, etc. are the sum of these tests. A "Suggested Fix" is a fix that the EMC team suggests to the instrument team that is believed will bring the unit into specification. "Implemented in EMC Lab" means that a temporary change was made to the hardware "on the fly" in the lab. "Implemented Fix on Unit" means that the fix was hardwired permanently on the unit by the instrument team after initial suggestion. "Fix=Help" is the sum of in-lab and hardwired fixes which helped the unit move closer to meeting the EMC requirements. "Fix=inspec" is the total number of in lab and hardwired fixes which bring the hardware into specification. "Waiver" is the total number of waivers (or deviations from original specifications) written for hardware in which fixes may or may not have improved EMC performance, however upon inspection it was believed that the overall out of specification condition would not affect mission integrity.

Science requirements drive the EMC program. Much of the testing in Radiated Emissions (Mil-Standard 461C Tests RE02, LFE and LFH) and DC Magnetics is driven by the needs of Magnetometers and other electromagnetic sensors. Taking this into account and looking at the above EMC testing several key results come to light. One readily apparent observation is that more testing and analysis concerning radiated emissions and DC Magnetics testing should be done in the developmental stage so that proposed fixes can be integrated into the EM and Flight Model (FM) designs. It is apparent that this was done in the case of DC Magnetics testing as it only necessitated two (2) waivers to be written during flight-testing (see testing under both the headings of Developmental and Flight Model). However, this appears not to be the case for RE02 and LFE. Developmental testing was virtually nonexistent in the cases of LFE and RE02. During the Engineering model testing 13 PF's were detected and 11 solutions were recommended to be implemented However, only 2 were actually implemented on the EM hardware. When the flight hardware was tested an additional 5 PF's were detected. All together a total of 7 waivers were required to disposition these PF's. Although much of the LFH testing occurred in the developmental stage, it is apparent that more was necessary. This can be seen by noting that 14 PF's were detected during EM and FM testing which resulted in a total of 6 waivers. The costs associated with these fixes would have been much cheaper during the developmental stages compared to having to perform the same fixes at the EM or FM stages of maturity. Many more EMC Metrics have been developed and can be found in various internal JPL documents.

Pyroshock Test Evaluations

Tables 4 and 5 summarize the pyroshock testing performed on the hardware for a recent JPL spacecraft. Pyroshock testing was performed selectively at the assembly level or the subsystem and then at the spacecraft level. For this reason, these tests were considered as "spacecraft level" or "lower level" tests. Typically, functional testing was performed before and after pyroshock testing. Additionally, cognizant personnel examined the data plots and performed visual external inspections after each axis of dynamic exposure. In some cases, where the hardware was designed and tested outside JPL, functional testing was performed before any dynamics testing but not repeated until after completion of all three dynamics tests (sine, random and pyroshock). Three PF's occurred under these conditions but are not included in this pyroshock metrics evaluation.

They were excluded because it was not possible to determine which environment (or combinations of environments) had been responsible for their precipitation. However, these 3 will be incorporated into an overall metrics evaluation currently being performed for dynamics testing as a whole.

seventy-eight ~~78~~ assemblies/subsystems were tested at the "lower level" during 54 different tests. Additionally, 6 re-tests were performed to verify various fixes, reworks, etc. A total of 16 relevant PF's were associated with these tests. Out of these, 12 were for failures of the test equipment or operator error. Three ~~3~~ were considered to be defects that were precipitated by this testing. One of these was a crack initiated in a piece of waveguide. Another was a leak in a pyro device gas by-product containment tube. One other was a bias shift on an accelerometer and was dealt with by widening the bias change specification. One additional defect was indirectly detected by this PACT. It was an "insufficient solder" problem (still fully functional) noted during a post test inspection.

One spacecraft pyroshock test was performed and 1 directly related PF was reported: It was a containment bolt that sheared off as a result of exposure to the pyroshock environment. One additional PF was reported. It was associated with a known problem which was also detectable during this test or any other time a functional test was run.

While these sample sizes may not be statistically significant, one could expect lower level pyroshock testing to precipitate/detect a defect about 5% of the time. Although the consequence of these PF's occurring in flight would have been insignificant, only the insufficient solder problem could have been detected prior to launch by another PACT.

ONGOING EFFORTS

The results of previous evaluations and the process by which project-specific, and generic needs are identified produces a set of desired follow-on evaluations. Some of those, which are of current interest, include the relative effectiveness of specific PACT activities for high reliability commercial products versus those from the aerospace industry, and for high volume and ultra-low volume production.

Another evaluation currently of great interest is the required PACT set when utilizing commercial electronic parts versus the military grade Class S parts (with which most traditional high-reliability spacecraft have been built). Of continuing interest is the relative effectiveness between various detection and prevention approaches (i.e. when can a given set of objectives be better achieved by inspection, or analysis, or vice versa).

SUMMARY

This paper has described the implementation of a methodology for evaluating Environmental Test Effectiveness. This methodology utilizes existing PFR data (and associated back-up material) to identify trends and patterns which can be used to focus improvement and optimization efforts. Examples of metric evaluations have been provided for high-level hardware (e.g. spacecraft), lower-level hardware (e.g. solid state recorder) and a collection of EMC tests. These metric evaluations can, and have been, used at JPL to tailor subsequent test programs.

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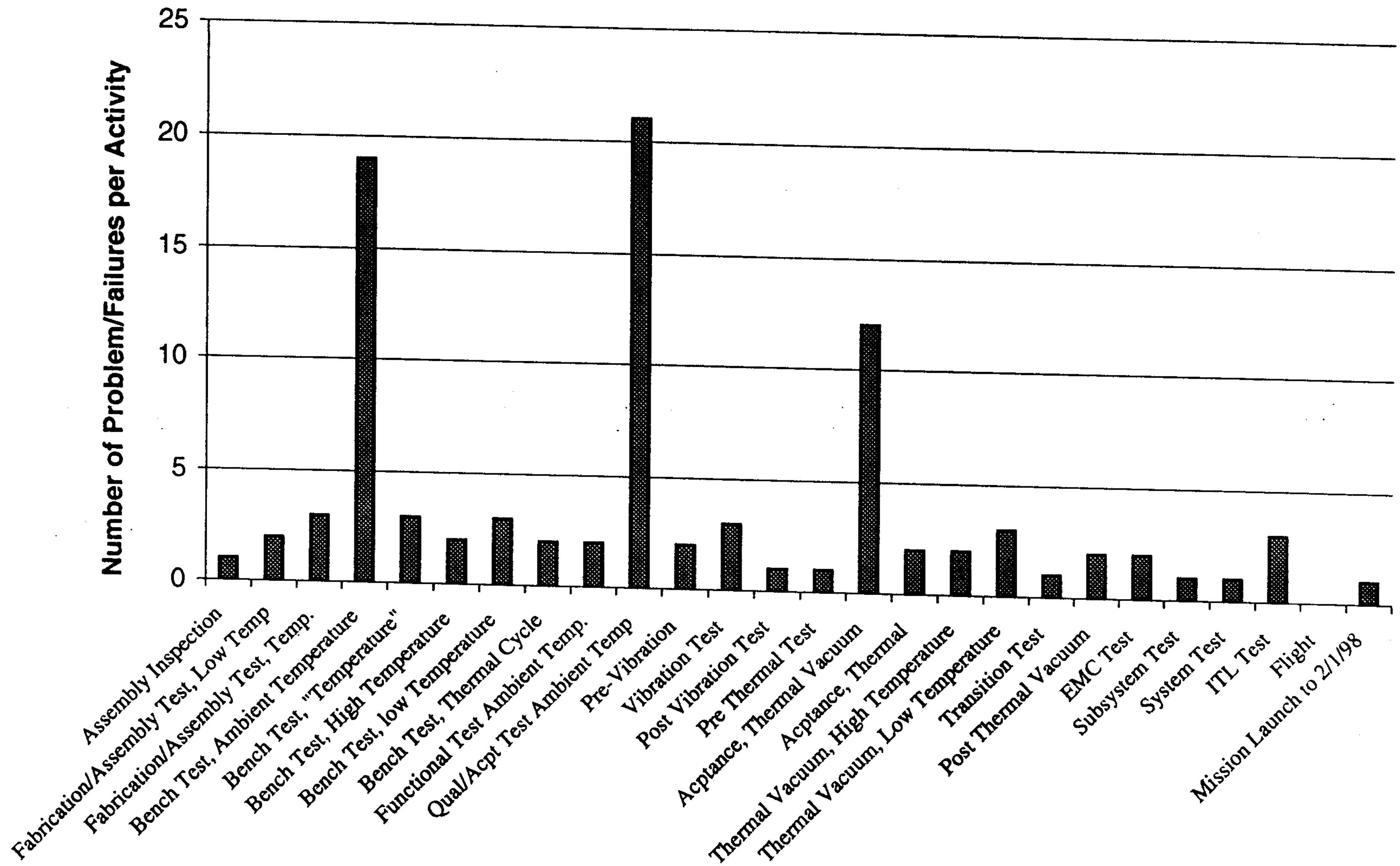

Figure 1: Distribution of Reported Problem/Failures with Time for the Solid State Recorder Assembly for a recent JPL spacecraft. These anomalies include Development up to Launch Pad Operations

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PACT's	Totals	Precents	Adjustment	Software	Design	Handling Damage	Workmanship & Manufacturing	Other	Parts	Support Equipment	Test Induced Error
Code	--	--	A	C	D	H	M, W	O,X	P	S	T
Development Test Program	967	--	4	465	147	6	65	155	40	46	39
	% of Total	100.0	0.4	48.1	15.2	0.6	6.7	16.0	4.1	4.8	4.0
Flight Test Program	2,690.0	--	50	475	509	30	282	368	153	498	325
	% of Total	100.0	1.9	17.7	18.9	1.1	10.5	13.7	5.7	18.5	12.1
Post Shipment	2	--	0	0	0	0	0	2	0	0	0
	% of Total	100.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Totals	3,659	--	54	940	656	36	347	525	193	544	364

Table 1. Distribution of Problem/Failure's by project phase and Cause Code

Units Pyro Shock Tested	Events/Tests	Re-Test	% True PF's/ Acticle Tested	% Test Eq/Op Error Etc.
Asy's/Subsystem's Tested	78	6	5	15
System	1	0	100	0
Totals	79	6	100	0

Table 4. Number of Assemblies, Subsystems & S/C Tested

Level of Integration During Pyroshock Test	Ground Testing						
	True PF's Detected					Test Eq/Op Error Etc.	
	Total PF's	Design	Workmanship		Parts		
		D5	M3	W1	P(x)	PFR's	Damaged Caused
Asy's Tested	4	2	1	1	0	12	0
System	1	1			0	0	0
Totals	5	3	1	1	0	12	0

Table 5. Number of Defects Detected by level of Test (I.e. not previously detected)

Solid State Recorder PFR Data (Covers 6 Flight, 1 Em and Possilby 1 Other)		DESIGN					WORKMANSHIP				MAUNFACTURING			PART				SUPPORT EQUIPMENT				TEST INDUCED ERROR				Flight
SUBTOTAL						29				9			6				13				19				13	1
PERCENTAGE OF TOTAL*						31%				9%			6%				14%				20%				14%	1%
ACTIVITY	Actual Total	DESIGN	SPECIFICATION	PACKAGING/MOUNTING	PRODUCIBILITY	PARTS/MATL MISAPLICATION	WORKMANSHIP	FABRICATION/ ASSEMBLY	REPAIR	TESTING	MANUFACTURING	TOOLING & MACHINING	PRODUCTION SPECIFICATION	PART FAILURE	FAILURE MODE KNOWN	FAILURE MODE UNKNOWN	ESD INDUCED FAILURE	BENCH TEST EQUIPMENT	OPERATIONAL SUPPORT EQUIPMENT	SOFTWARE	COMMERCIAL EQUIPMENT	TEST ERROR	OPERATOR	EQUIPMENT	PROCEDURE	IN-FLIGHT RADIATION HITS - Not out of Spec.
PACT	PRF COUNT	D	D1	D2	D3	D5	W	W1	W2	W5	M	M1	M5	P	P1	P2	P3	S1	S3	S4	S5	T	T1	T2	T3	O1
Design, Test & Integration																										
Assembly Inspection	1			1																						
Fabrication/Assembly Test, Low Temp	2	2																								
Fabrication/Assembly Test, Temp.	3																		1	2						
Bench Test, Ambient Temperature	19	4				1		5	1						3					3	1					
Bench Test, "Temperature"	3																			3						
Bench Test, High Temperature	2															2										
Bench Test, low Temperature	3	1														2										
Bench Test, Thermal Cycle	2														1									1		
Functional Test Ambient Temp.	2																								2	
Qual/Acpt Test Ambient Temp	21	8		2	1			1				6			1											
Pre-Vibration	2			1																					1	
Vibration Test	3			1				1										1								
Post Vibration Test	1																			1						
Pre Thermal Test	1																								1	
Acptance, Thermal Vacuum	12	2						1								2				5				2		
Acptance, Thermal	2		2																							
Thermal Vacuum, High Temperature	2															2										
Thermal Vacuum, Low Temperature	3	1			1																	1				
Transition Test	1																								1	
Post Thermal Vacuum	2																			2						
EMC Test	2		1																			1				
Subsystem Test	1																								1	
System Test	1																									
ITL Test	3																						1		1	
Mission Launch to 2/1/98	1																									1
TOTAL's	95	18	3	5	2	1	0	8	1	0	0	6	0	0	5	8	0	1	1	16	1	2	1	3	7	1

Table 2. Distribution of Problem/Failures Participated and/or Detected during Test and Integration Activities for a Solid State Recorder.

*Note the total reported problems were 95. Ninty are shown in the detailed table entries:not shown are: 1 Handling ,2 Software, 2 Other/Unkown

TOTALS	Development	Pass	Fail	Suggest Fix	Imp in EMC Lab	Imp Fix on unit	Fix = Help	Fix=Inspec	Waiver
	Isolation	0	0	0	0	0	0	0	0
	RE								
	RE02	1	1	1	0	0	0	0	0
	LFE	2	1	2	1	0	1	1	0
	LFH	6	10	11	6	3	6	5	0
	RE SF	0	0	0	0	0	0	0	0
	RS	0	0	0	0	0	0	0	0
	CE								
	PL-Time	1	0	0	0	0	0	0	0
	PL-Freq	1	1	1	1	0	0	0	0
	CM-St.	1	1	1	1	0	1	1	0
	Sig. Lines	0	0	0	0	0	0	0	0
	CS	0	0	0	0	0	0	0	0
	Mag	13	16	18	11	5	12	11	0
	EM								
	Isolation	10	0	0	0	0	0	0	0
	RE								
	RE02	6	6	5	2	1	1	1	0
	LFE	5	7	6	2	1	1	1	0
	LFH	3	8	6	0	1	1	0	0
	RE SF	7	3	2	1	0	0	0	0
	RS	8	3	0	0	0	0	0	0
	CE								
	PL-Time	4	7	0	0	0	0	0	0
	PL-Freq	4	7	1	1	0	1	0	0
	CM-St.	4	7	2	1	1	1	0	0
	Sig. Lines	11	0	0	0	0	0	0	0
	CS	10	1	0	0	0	0	0	0
	Mag	5	8	5	2	1	2	2	0
	FM								
	Isolation	7	1	0	0	0	0	0	0
	RE								
	RE02	5	3	2	1	5	3	1	3
	LFE	8	2	1	0	6	3	2	4
	LFH	7	6	1	0	8	8	6	6
	RE SF	7	1	0	0	1	1	1	1
	RS	7	0	0	0	0	0	0	1
	CE								
	PL-Time	2	6	0	0	0	1	0	7
	PL-Freq	3	6	0	0	2	1	0	7
	CM-St.	6	5	0	0	2	2	0	5
	Sig. Lines	6	1	0	0	0	1	0	0
	CS	7	1	0	0	0	0	0	0
	Mag	10	4	1	3	12	12	11	2

Table 3. Distribution of EMC Anomalies by particular aspect of the EMC test program in which they were found.