# METHODOLOGY FOR PHYSICS & ENGINEERING OF RELIABLE PRODUCTS

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## Abstract

Physics of failure approaches have gained wide spread acceptance by most within the Electronic Reliability Community. These methodologies involve identifying root cause failure mechanisms, developing associated models, and utilizing these models to improve time to market, lower development and build costs and higher reliability. The methodology outlined herein sets forth a process, based on integration of both physics and engineering principles, for achieving the same goals. The proposed methodology is consistent with a "pure" physics of failure methodology, but it has the distinct advantage of not being "dead-in-the-water" if failure physics models do not exist. It also goes a long way to overcoming the age old axiom that "typically the things that fail are not the things that were analyzed, evaluated, etc. but rather the things that were assumed to not to be a problem". It outlines a methodology for integrating all available data, at various data quality levels, to make the best possible decisions, The key components are: 1 ) existing physics and engineering models, 2) utilizing a problem/failure reporting system and other data sources to identify "tall poles" and their root cause for current designs and process and 3) new technology evaluations based on failure physics assessments.

## Objectives

The objectives of the Physics (and Engineering) of Failure based Methodology (PEFM) are: 1 ) to combine the principles of physics and engineering to arrive at a product development and implementation processes that result in cost effective reliable products being developed and fielded, 2) easy to implement and 3) applicable to organizations independent of their size. This methodology should also provide clear guidance for utilization of existing data at all levels, generate road-maps for new information requirements and identify specific areas where study efforts are needed.

## Background/Methodology Description

The PEFM methodology utilizes the root cause/root effect approach. In determining the effectiveness of a particular test or other activity, it is necessary to clearly establish the requirements to be verified or validated and thus the objectives and metrics of each activity. This effectiveness data is needed to assess the value added by these activities as well as to provide a feedback loop to identify opportunities for process improvements. This methodology combines systems engineering principals, product information (test/activity objectives, hardware performance requirements, etc.), behavior/anomaly data (at various levels of integration and in varying levels of data quality/detail), along with failure physics models to assess the root cause and effect of possible defect detection and/or prevention options.

The systems approach (Defect detection and Prevention (DDP)) presented in Reference 1, utilizes a PACT (prevention, analysis, control or test) effectiveness matrix to systematically identify and rate the ability of various PACT's to prevent and/or detect failure mechanisms that have the potential to impact product requirements. This PACT effectiveness matrix is itself a product of two matrices. One matrix rates the criticality and likelihood for the occurrence of individual failure mechanisms on the product requirements to establish weighting factors, while the other matrix ranks the effectiveness of each available PACT at detecting/participating defects on a failure mode by failure mode basis. The "ratings" (or metrics) involved in both matrices are based on a combination of failure physics, engineering principles and analysis of available data. This approach is an integral part of NASA's Test Strategy development efforts (Reference

2) and is described in more detail in Reference 3. This paper briefly summarizes the DDP methodology as applied to the NASA/JPL Test Effectiveness Program and provides a discussion of the approach for using data from a problem/failure reporting system to arrive at these rankings when failure models do not exist.

Standard systems engineering tools and approaches are applied to assessing the impact of various failure modes on the products basic and derived requirements. The PACT Effectiveness Matrix (EM) described above involves rating the effectiveness of the things that can be done to prevent (usually best) or detect failure modes/mechanisms versus the weighted failure modes/mechanisms that were identified in the requirements matrix. These ratings are arrived at by evaluating the effectiveness of the various "knobs" (parameters which can be varied for each PACT (temperature level, electrical and/or mechanical load, etc.), and the individual settings selected for each "knob" (-20C to 75C, etc. ) of a particular PACT.

### Concept Illustrations

Being limited to only using ratings that were derived only from failure physics models would be an extreme handicap because physics and engineering models do not exist for many of the failure modes. Therefore, knowing how to come up with rankings when models do not exist can significantly extend the usefulness of this approach. Work done as part of the physics of failure efforts at the University of Maryland Electronic Packaging Research Center (EPRC) is being integrated and supplemented by other physics of failure data and the engineering data available across NASA and our industry partners through the NASA Test Effectiveness Working Group. The NASA Test Effectiveness Program is integrating the best of commercial and government approaches with currently available data to significantly improve the test and validation process for spaceflight applications, although the results have general applicability. The concept illustrations presented below, show how data from a variety of sources (such as a problem/failure system, SPC charts, research data, technology evaluations, etc. ) can be used in combination with physics/engineering models to arrive at effectiveness ratings. Related data and findings may be found in References 4 - 8.

In the illustrations presented, the following notations have been used: Capital X's are used to denote that a particular PACT (or knob) is thought to be effective, although no specific effectiveness determination has been made. In a similar sense, small x's denote that this PACT is slightly effective but again no specific effectiveness determination has been made. Where the effectiveness is not known, the entry is represented by a question mark and where it is not effective at all, a O (zero) is entered, In the illustrations where numerical ratings are shown, the same interpretations are applied to the zeros and question marks. A 1 (one) is similar in interpretation to the small x, in that it represents the case where data has indicated that the PACT can prevent and/or detect the failure mode/mechanism being evaluated, but not very effectively. In a like manner, a 3 (three) is used to indicate that a PACT is effective at preventing/detecting a failure mode/mechanism but it should not be considered as a primary PACT for this failure mode/mechanism. An entry of a 9 (nine) is used to indicate that a significant number of these failure mode/mechanisms are prevented/detected when this PACT is applied compared to the total number of them present in the hardware/software.

### Phenomenological/Empirical Data Source Examples

Useful PACT effectiveness assessments can still be made when the only information available is phenomenological in nature (i.e. cause and associated effect not determined at the root level). Consider the following example. "Program XYZ was a successful "Class A" program and it implemented the following design, assurance and test program . ...". While this statement implies that the things that were done to prevent and/or detect defects were successful on program XYZ, no cause and effect data was presented to differentiate between various PACTs and thus tailoring is essentially impossible. In the absence of any other data, a PACT effectiveness matrix (based on the PACT's implemented on program XYZ) could still be developed for a new product. However, these entries would have a greater uncertainty associated with them and may not have as much sub-categorization as entries based solely on PEFM evaluations. In this case, the entries in the PACT effectiveness matrix could be represented by either X's or question marks. The completed effectiveness matrix based on these entries would still indicate potential areas of overlap, missing coverage and so on.

For example, consider Table 1 which is a hypothetical partial top level PACT effectiveness matrix from the above XYZ program. Note that both powered and urr-powered random vibration testing were used on this successful program. If we are trying to apply program XYZ's PACT effectiveness matrix to an electronic card on a new program, we would most likely chose to do the powered vibration PACT because Table 1 indicates that it is more effective on the failure modes most likely to be present in electronic cards. On the other hand, if we are testing a piece of spacecraft structure, then the non-powered PACT would be the choice. The trade-off illustrated in Table 1, was so simple that a matrix was not really necessary. However, consider a complete PACT effectiveness matrix for this same simple electronic card. It would not be unreasonable for there to be 25 PACT's listed (inspections, tests design rules, reviews, etc. and their respective knobs and setting ranges) and possibly an equal or greater number of failure modes/mechanisms. Imagine trying to do trade-offs for this set of variables without the aid of the matrix tool.

Now lets look more closely at a particular PACT to see what else can be learned. Table 2 presents a partial high level assessment of a PACT called thermal test. Note that for many of the failure modes it is not known if any of the knobs are effective in detecting them. Also note that the overall effectiveness of some of the knobs is unclear. Table 2, can be read like a "road-map" with respect to areas where new information requirements are needed or where specialized, detailed effectiveness studies are warranted. These studies could be a combination of problem/failure data searches, simple engineering/failure physics models and/or "engineering judgement". These studies would be like removing layers from an onion, one layer at a time. Table 3 represents a hypothetical example of moving one layer deeper than Table 2 because we now have specific PACT levels and thus numerical ratings. At the Table 3 level of detail, we can clearly see that one should not count on this PACT to be the primary mode of problem detection for: application specific integrated circuit (ASIC) parts, solder balls (workmanship) or mechanical design problems/failure modes. Again, we can remove another layer and now look at the effectiveness of the individual knobs and rank the effectiveness of the individual settings. Table 4 illustrates these points. The specific PACT illustrated is a thermal test. The 'environmental' knobs for a thermal test are considered to be temperature levels (hot and cold), dwell times (at hot and cold), rate of temperature transitions, number of thermal cycles and pressure level (i, e. vacuum, ambient or other). By making trade-offs between the various knobs and their settings, one can optimize the cost to benefit ratio of an individual PACT which can then be rolled up for comparisons with other PACTS. To facilitate this illustration Table 4 has an added column which sums the effectiveness of each knob or setting option. Note that, in this illustration, the most effective knob is temperature level. In contrast, the two least effective knobs/settings are unpowered testing and performing many thermal cycles.

One final point to keep in mind is that while a knob or setting may be very effective at preventing or detecting a failure mode or mechanism it is not cost effective to prevent or detect failures that could not occur in the mission life cycle. For example, setting test pressure knob to the vacuum setting is more effective for failure modes/mechanisms that are due to: 1) high temperature and/or gradients (circuit timing, part parameter drift over life, transistor gain, etc.), 2) "pure" vacuum effects (such as corona) and 3) a variety of workmanship failure modes (such as bondlines, etc.). However, it is less effective at detecting cold temperature related failure modes/mechanisms (timing, parameter drift, hot carrier injection, etc. ) because, in general, testing in a vacuum biases device temperatures, board temperatures, etc. upward. Another consideration would be the probability of occurrence in the mission life cycle. Remember that as a result of Requirements matrix the effectiveness rating for the PACTS discussed above would be multiplied by the weights (probability of occurrence and impact on the mission objectives) for each failure mode to arrive at the applicable mission effectiveness of a given PACT and allow tradeoffs and prioritizations within cost and schedule constraints. Therefore, mission life cycles which do not expose the hardware to vacuum conditions would have a zero probability of occurrence for a "pure" vacuum related failure mode/mechanism. While the vacuum pressure setting could be used on hardware where the mission life cycle only involved "ambient office" pressures, this choice probably would not be cost effective.

?-he above illustrations clearly demonstrate that useful PACT effectiveness matrices can be made without necessarily having detailed failure physics models for every entry. These illustrations also show that as one goes into more and more detail, the specific strengths and weaknesses of a given PACT are revealed, allowing cost benefit trade-offs to be made within a given PACT and across collections of PACT s.

## Root Cause Analysis Examples

Next we will look at how an organization's problem/failure reporting system can be used to come up with effectiveness rating for various PACT's/knobs. At the board level and higher, it is routine to establish formal test plans and document hardware anomalies in a problem/failure reporting (P/FR) system or its equivalent. These P/FRs document the "symptom" or failure mode(s) observed or measured and assess the significance of the P/F relative mission risk, should it occur in the mission. The P/FR process also documents the root cause and corrective action for the problem/failure. It is at this point where determination is made of the required fix and the likelihood of the fix eliminating similar future problems and revisions (if required) of the significance of the original failure. In many cases these causes are not always at the physics of failure level. That is, it is not always necessary to establish a model based on physics principles which predicts the anomaly and establishes the point(s) in parameter space where the fix lies. Examples are presented below which illustrate the usefulness of the data contained within typical P/FR's for identifying the types of failure modes detected by various PACT'S.

### Assessment by Inspection Processes

A bondline failure was detected during high temperature testing after random vibration exposure. An inspection of the failure site indicated that only 10% of the bondline area adhered to one surface. A subsequent check of the build checklist indicated the primer application step was skipped. This example clearly illustrates that the root cause could be determined without going down to the physics of failure level. Moreover, the root cause can be considered more in the realm of process control than failure physics.

### Assessment by Inspection & Analysis

A bondline failure was detected during high temperature testing after random vibration exposure. Upon inspection it was noted that the bondline was only half as long as required by the design guidelines. Mechanical analysis confirmed that a one sigma random vibration test load (on this out-of-specification bondline area) would exceed the ultimate strength of this material by 25%. In this case, a "violation" of one of the prevention measures (i.e. the design guideline for bondlines) can be considered as the root cause.

### Assessment by Failure Analysis

A bondline failure was detected during high temperature testing after random vibration exposure. Upon visual inspection, the bondline geometry was found to be within specification. A small sample of the bonding material was removed and placed in a mass spectrometer for analysis. The analysis indicated that the two part adhesive was only 25% mixed. Based on manufacturers data it was determined that this "mixture" would only have 10% of the strength of a fully mixed material. Mechanical analysis confirmed that a one sigma load during random vibration testing would exceed the reduced ultimate strength of this material. This case also presents a process control problem as the root cause.

## Summary and Conclusions

The key benefit of this methodology to management is that it provides a tool for identifying the tall poles within the organization (based on accepted processes), their overall impact on the organization and possible solutions that could result in a better overall optimization of organizational resources. The key benefit to the practitioner is that it provides them a tool to estimate the consequences of the choices they are considering and then measure the impact of the choices they actually made. These metrics are critical to enabling decisions and institutional changes to be made intelligently both within, and across, programs.

This process also enables several key functions within an organization. For example, the PEFM methodology:

1. Can be used as the engine for Reengineering activities,
2. Is capable of identifying the tall pole activities within an organization's operations,
3. Is capable of identifying appropriate metrics to measure the value-added by individual activities

within an organization,
4. Provides the feedback process necessary for achieving continuous process improvement,
5. Recognizes the effects and constraints of the technologies involved, resources available, manufacturing and use environments and existing corporate culture.

Using all of the existing data allows an organization to close the loop with respect to the effectiveness of their PACTS (such as, design guidelines, process controls, analyses, etc.). It can also identify the need for new or updated standards, process controls, etc. The reason that the examples cited above were effective in identifying the root cause was that the these PACTS were based originally on some form of research/modeling activities. In fact, many were the result of new technology evaluations which identified the limits/sensitivity of a new technology and the associated screens as PACTS. Even the PACTS which were the result of "tiger team" findings ( i.e. models developed in quasi-real-time to predict a previously unknown phenomena) for a particular failure mode may now be generalized and provide a data source for evaluating PACT effectiveness on future programs.

Information of the type presented above, can be used to make useful, first-order predictions of the effectiveness and likelihood of "escapes", or problems which were undetected. This historical data can be superseded by either engineering analysis data or data from physics of failure models to arrive at second through "Nth" order reliability expectations, as may be appropriate. The typical physics of failure approaches have ignored these types of engineering problems, primarily because the approach fails if the effect cannot be modeled using physics principles.

These examples have illustrated the approach for getting the root cause of the problem without necessarily going down to the failure physics level. In the cases presented above, the root cause can be considered more in realm of engineering. This combination of engineering and physics of failure provides the most cost effective utilization of all available data.

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## TABLE 1. TOP LEVEL PACT EFFECTIVENESS " DATA"

| PACT | DESIGN IN SPEC. | | | WORKMANSHIP | PARTS |
|---|---|---|---|---|---|
| | ELECTRICAL | MECHANICAL | THERMAL | | |
| T/V | x | ? | x | X | X |
| PART STRESS ANA. | x | 0 | x | 0 | X |
| WORST CASE ANA. | X | o | ? | 0 | X |
| UNPOWERED VIBRATION | 0 | x | 0 | x | 0 |
| POWERED VIBRATION | x | X | x | x | x |
| INSPECTION | o | o | ? | x | 0 |

## TABLE 2. PACT EFFECTIVENESS VS. FAILURE MODE FOR HIGH LEVEL INFORMATION ONLY

| OVERALL PACT/INDIVIDUAL KNOB'S & KNOB SETTINGS | FAILURE MODE/MECHANISM | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | KMA | | | | | | | |
| | ELECTRICAL | MECHANICAL | ITG. INTERFACE | ART TEMPS. | OARD TEMPS. | PACKAGING | COLD SOLDER JOINTS | SOLDER BALLS | SHORTS | WRONG PART | REWORK | ASIC's | TRANSISTORS | MEMORY |
| ROLL-UP OF T/V TEST (SEE FEATURES LISTED BELOW) | x | x | x | ? | ? | ? | x | ? | x | x | x | ? | ? | ? |
| UNKOWN LEVELS, DURATIONS, RAMP RATES & CYCLES | x | x | X | ? | ? | ? | X | ? | X | ? | X | ? | ? | ? |
| UNKOWN PERCENT COVERAGE OF FUNCTIONAL RQMTS. | X | 0 | ? | ? | ? | 0 | ? | 0 | X | X | x | ? | ? | ? |
| VOLT./FREQ./TEMP. MARGINING OF AN UNKOWN AMOUNT | x | o | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? | ? |

TABLE 3. PACT EFFECTIVENESS VS. FAILURE MODE FOR MODERATLY DETAILED DATA

| OVERALL PACT/INDIVIDUAL KNOB'S & KNOB SETTINGS | FAILURE MODE/MECHANISM | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DESIGN | | | | | | WORKMANSHIP | | | | | PARTS | | |
| | | | THERMAL | | | | | | | | | | | |
| | LECTRICAL | MECHANICAL | MTG. INTERFACE | PART TEMPS. | OARD TEMPS. | ACKAGING | OLDSOLDER JOINTS | OLDERBALLS | HORTS | VRONGPART | EWORK | SIC's | RANSISTORS | MEMORY |
| ROLL-UP OF T/V TEST SEE FEATURES LISTED BELOW | 9 | 3 | 1 | 1 | | 3 | 1 | 1 | 9 | m | 3 | 3 | 3 | 3 |
| 70C to -20C, 1 cycle, 144/24 hrs. hot/cold dwell, XXC/hr. 8 CYCLES | 9 | 3 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 9 | 1 | 3 | 3 | 3 |
| FUNCTIONAL TESTING | 9 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 9 | 3 | 1 | 1 | 1 | 1 |
| ELE. TESTING WITH MARGIN (VOLTAGE, FREQUENCY, TEMP.) | 3 | 1 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 3 | 1 | 3 | 3 | 3 |

TABLE 4. PACT EFFECTIVENESS VS. FAILURE MODE FOR DETAILED LEVEL DATA

| OVERALL PACT/INDIVIDUAL KNOB'S & KNOB SETTINGS | FAILURE MODE/MECHANISM | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DESIGN | | | | | | WORKMANSHIP | | | | | PARTS | | | |
| | | | THERMAL | | | | | | | | | | | | |
| | LECTRICAL | MECHANICAL | ATG. INTERFACE | ART TEMPS. | OARD TEMPS. | ACKAGING | OLD SOLDER JOINTS | OLDER BALLS | HORTS | RONG PART | EWORK | SIC's | RANSISTORS | EMORY | TOTAL FM'S DETECTED |
| ROLL-UP OF T/V TEST (SEE FEATURES LISTED BELOW) | 9 | 3 | 9 | 9 | 3 | 3 | 1 | 9 | 9 | 9 | 3 | 3 | 3 | 3 | 73 |
| FUNCTIONAL TESTING | 9 | 0 | 3 | 3 | 1 | 1 | 1 | 9 | 9 | 9 | 1 | 3 | 3 | 1 | 52 |
| TEMPERATURE LEVEL (-20 TO 70c) | 9 | 1 | 3 | 3 | 1 | 3 | 0 | 3 | 3 | 3 | 3 | 3 | 3 | 1 | 38 |
| INTERNAL PART TEMP. VOLTAGE ETC. MEASUREMENTS | 3 | 1 | 9 | 9 | 3 | 0 | 0 | 1 | 1 | 1 | 3 | 3 | 3 | 1 | 37 |
| HOT AND COLD DWELL TIME (144 HRS./24 HRS.) | 3 | 1 | 3 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 3 | 3 | 3 | 18 |
| TEMPERATURE RAMP RATES (20c/ MIN.) | 1 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 3 | 1 | 1 | 3 | 1 | 18 |
| EIGHT THERMAL CYCLES | 1 | 3 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 10 |
| UNPOWERED TESTING | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TOTAL FAILURE MODES/MECHANISMS FOUND BY ALL KNOBS | 26 | 9 | 20 | 17 | 8 | 7 | 3 | 15 | 13 | 18 | 9 | 13 | 15 | 7 | |

**NOTES,** Rankings are to be interpeted as follows:

1) OVERALL RANKINGS ARE BASED ON THE HIGHEST RANKING OF ANY ONE KNOB