Deep Impact Delta II Launch Vehicle Cracked Thick Film Coating on Electronic Packages Technical Consultation Report

Performed by

The NASA Engineering and Safety Center (NESC)

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VOLUME I: Technical Consultation Report

1.0 Authorization and Notification

Bryan O'Connor, Office of Safety and Mission Assurance (OS&MA), requested that the NESC provide a materials expert to evaluate two differing risk assessments regarding the start and propogation of cracks associated with thick film coatings on electronic packages (E-packages) on the Delta II Launch Vehicle.

Mr. Ralph Roe, Director of the NESC, initiated the request for consultation on December 23, 2004.

The NESC approved the white paper at the NESC Review Board (NRB) on January 6, 2005.

2.0 Signature Sheet

NESC Technical Consultation Team

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4.0 Executive Summary

The Deep Impact spacecraft was launched on a Boeing Delta II rocket from Cape Canaveral Air Force Station (CCAFS) on January 12, 2005. Prior to the launch, the Director of the OS&MA, Mr. Bryan O'Connor, requested the NESC to lead a team to render an independent opinion on the rationale for flight and the risk code assignments for the hazard of cracked Thick Film Assemblies (TFAs) in the E-packages of the Delta II launch vehicle for the Deep Impact Mission. The concern was with the possibility of cracks and crack growth in the TFA in the servo-control electrical packages on the Delta II launch vehicle. This issue surfaced during the System Mission Assurance Readiness Review (SMARR). The KSC Launch Services Program (LSP) and the Boeing Launch Services Contractor (LSC) presented this item as no risk, and Kennedy Space Center (KSC) Safety and Mission Assurance (S&MA) presented it as a medium residual risk item.

The NESC team concluded that the KSC S&MA, Boeing and the LSP all agreed on the nature and cause of the TFA cracking hazard, and on the existing rationale for flight. However, they used different rationales in assigning risk codes when using a common assessment tool. The NESC team concluded that the TFA crack risk should be considered to be in the range of medium-to-low risk, and represented an acceptable risk for flight. The NESC team concurred with KSC S&MA that "5x2" more accurately characterized this risk. Boeing and the LSP acknowledged the probability of failure to be "less than 1 percent", but not zero, as assessed by their subjective methods. KSC's S&MA and the NESC team agreed that the TFA cracking hazard represented a reportable risk for the Flight Readiness Review (FRR). The possible cause, excessive conformal coating under the TFA assemblies due to manufacturing changes, was identified, but was not verified by testing. An enhanced component-level screening test, which reviewed parametric data from box-level testing while looking for changes, has proven effective to-date. However, there is some risk that this technique may not be 100 percent effective because it is an indirect method of detection. Due to the potential for undetected micro-cracks to propagate with time or with the launch environment, a residual risk remained to trigger failure of an assembly with micro-cracks that are under stress.

The NESC team concluded that Boeing and the LSP should continue to pursue other design approaches to further reduce the risk to TFA circuits in the future.

Figure 4.0-1. Deep Impact lifts off from pad 17-B at Cape Canaveral Air Force Station, Florida January 12, 2005
(NASA photo)

5.0 Consultation Plan

The NESC approved the white paper at the NRB on January 6, 2005. The mission of this effort was to investigate the possibility of cracks and crack growth in the TFA in the servo-control electrical packages on the Delta vehicle. After evaluation of the risks by the KSC assessment team and Boeing, it was realized that the means for rating risks varied between the organizations, making it difficult to confirm a rating assignment for the FRR.

6.0 Description of the Problem, Proposed Solutions, and Risk Assessment

6.1 Mission Background

The Deep Impact mission is a partnership with the University of Maryland (UMD), the California Institute of Technology's (CIT) Jet Propulsion Laboratory (JPL), and Ball Aerospace and Technology Corporation (BATC). The scientific leadership of the mission is based at UMD. Engineers at BATC designed and built the spacecraft under JPL's management. Engineers at JPL control the spacecraft after launch and send data to scientists for analysis. The mission is implemented with a two-part spacecraft. The larger "flyby" spacecraft carries a smaller "impactor" spacecraft to the comet *Tempel 1*, and releases it into the comet's path for a planned collision.

In January 2005, a Delta II rocket (configuration shown in Figure 6.1-1) launched the combined Deep Impact spacecraft which, after leaving Earth's orbit, was directed toward the comet. The combined spacecraft approached the comet and collected images before the impact. In early July 2005, 24 hours before impact, the flyby spacecraft pointed high-precision tracking telescopes at the comet and released the impactor on a course to hit the comet's sunlit side.

After release of the impactor, the flyby spacecraft maneuvered to a new path that, at closest approach, passed 500 kilometers (km) (300 miles) from the comet. The flyby spacecraft observed and recorded the impact data, the ejected material blasted from the crater, and the structure and composition of the crater's interior. After its shields protected it from the comet's dust tail passing overhead, the flyby spacecraft turned to re-look at the comet. The flyby spacecraft took additional data from the other side of the nucleus and observed changes in the comet's activity. While the flyby spacecraft and impactor performed, professional and amateur astronomers at large, and small telescopes on Earth, observed the impact and its aftermath. Results were broadcast over the Internet.

Vehicle Configuration

- Vehicle configuration: 7925-9.5
- Launch site: SLC-17B at CCAFS
- Launch period: 30 Dec 2004 - 28 Jan 2005
- Unique mission requirements:
  - 3712C payload attach fitting
  - Third stage motor dome blanket (with metal Velcro)
  - Nutation control system (37 lbf reaction engine assembly)
  - De-spin system
  - Third-stage ballast (10 ± 10 lb)
  - 2 mission-specific access doors
  - Two 37-pin PAF umbilicals

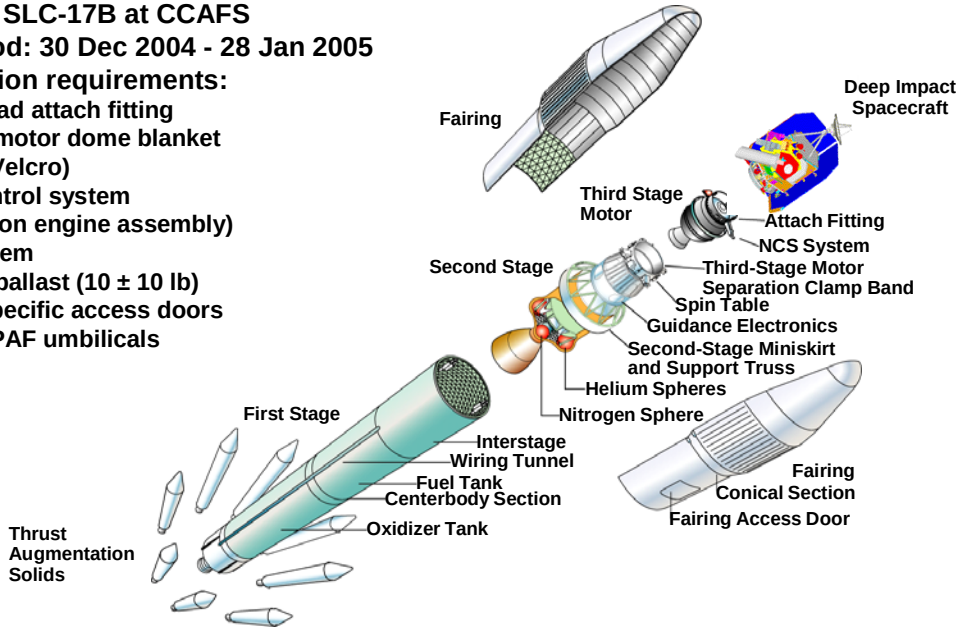

Figure 6.1-1. Deep Impact Launch Configuration

6.2 Technical Issue Description

At the S&MA FRR, the issue of electronic package (E-package) cracked TFAs was assessed by the KSC S&MA organization as a "5x2" residual risk. Note that the Boeing and the LSP did not list this item as a reportable risk. The issue involved a number of E-packages that contained TFAs that were manufactured at an El Paso, Texas facility following a supplier change from Monrovia, California (this supplier change resulted in process changes). Cracks were found in some TFAs in El Paso during 2002. An enhanced screening technique was put in place to perform an enhanced review of box-level acceptance test data to look for parametric changes of greater than 5 percent as an indicator of possible TFA cracks. Appendix C shows the formula and the plot of DeltaR/R versus Crack Size[1]. This issue also was previously addressed for the Swift and Messenger missions' launch vehicles. Two of these potentially "suspect" E-packages, containing a total of twelve TFAs, were used in the Deep Impact Launch Vehicle: one E-package

[1] Extraction from Henning Leidecker's Cutbar Essay.

with one circuit board with two TFAs in the first stage, and one E-package with two circuit cards with a total of eight TFAs in the second stage. These E-packages are part of the vehicle's guidance navigation & control (GNC) system. TFA failure during launch can be catastrophic. The chart from the S&MA FRR is shown in Figure 6.2.-1, which summarizes their assessment of the issue.

E-Package Cracked Thick Film Assemblies

RISK TYPE: Mission Success
HAZARD REPORT: N/A
CRITICALITY: N/A
RISK CATEGORY: Technical
ORGANIZATION: Safety and Mission Assurance
ASSIGNED TO: Raoul Caimi, KSC
INDEPENDENT ASSESSORS: SA-G

X: SMA Risk Assessment

RISK DESCRIPTION:
A cracked TFA has been detected in a first stage E-pkg at the HY1 location. This is the first such departure from the HY3 location for this issue, as seen previously. The existing enhanced screening technique's ability to detect the presence of such a crack was evaluated for applicability to the first stage E-pkg. This screen has been previously used for 2nd stage E-pkgs on MESSENGER and Swift. Both primary and secondary circuits can be affected by a TFA crack leading to loss of mission.

CAUSE:
Not determined. Boeing is attributing the cracks to conformal coating shrinkage during cure.

RISK EFFECTS:
Loss of mission.

RISK REDUCTION ACTIONS:
An enhanced screening technique has been developed to detect TFA cracks for second stage E-pkg's. Boeing and LSP used the same technique to detect TFA cracks in first stage E-pkg's. The Deep Impact 1st stage E-pkg passed the screening with no indication of a cracked TFA.

CONSTRAINTS TO FLIGHT:
None.

RECOMMENDATION / RATIONALE:
The screening technique detects the presence of existing detrimental cracks; therefore, this presents a risk that can be accepted for flight.

Figure 6.2-1. TFA KSC S&MA Risk Chart

6.2.1 Causal Factors

The TFAs contain circuit traces (conductors) on an alumina substrate, as well as surface-mounted electronics parts. Some of these parts include high precision resistors that are bias and gain setting elements for op-amps in servo amplifier circuits. Boeing hypothesized that the new process changes introduced the possibility of excess conformal coating material between the TFA modules and the polyamide printed circuit card to which they are mounted and connected. As the conformal coating material cures and shrinks, Boeing suggested that stresses can be induced in the alumina TFA module and can result in cracks.

Following the initial discovery of the problem in 2002, an "enhanced screening" technique was instituted where the box-level acceptance test data was reviewed for parameter changes, or deltas, between the initial Acceptance Test Procedure (ATP) and subsequent ATPs. A threshold for investigation was set to be a parametric change of 5 percent or greater from one ATP to another. The enhanced screening was a manual review of the detailed parametric data collected during the ATP. Cracks in the TFAs were detected by failures which propagated into parts on the boards, most notably high stability precision laser-trimmed resistors that set amplifier gain or biasing. These cracks manifested themselves in observed parametric shifts in the data during the detailed box ATP testing. Absence of parameter shifts between initial and final acceptance testing is considered to be evidence that an E-package that does not contain cracks of concern. These box-level ATPs were run between 201 and 500 days after the cards were originally conformal-coated. It was possible for the boxes to pass original go/no-go functional testing, but still have parametric shifts.

The basis for flight or flight rationale is the understanding of the likely root cause of the failures, and passing the box-level enhanced parametric data screening. The residual risks are that there is less than 100 percent certainty that the true root cause has been identified and there are reasonable questions as to the effectiveness of the screening.

6.3 NESC Risk Assessment

The risk assessment process included the identification of hazards, assessment of hazard consequences, assessment of likelihood of hazard occurrence, and flight rationale and acceptance of the assessed risk. The differences of opinion between the KSC S&MA organization and the Boeing and the LSP were due to subjective assessments based on engineering experience, differences in optional approaches for the application of assessment tools, and translation between limited reliability data and system failure probability.

The overall risk assessment performed by KSC S&MA is shown in Figure 6.3-1. The TFA crack issue was assessed as a medium residual risk item.

Assurance Elements S = Safety M = Mission Success	Program	KSC SMA	Minority Opinion
SMA 1- Thick Film Assembly		M	
SMA 2- GEM Delaminations		M	
SMA 3- Microsemi Transistor		M	
SMA 4- RIFCA Alignment		M	

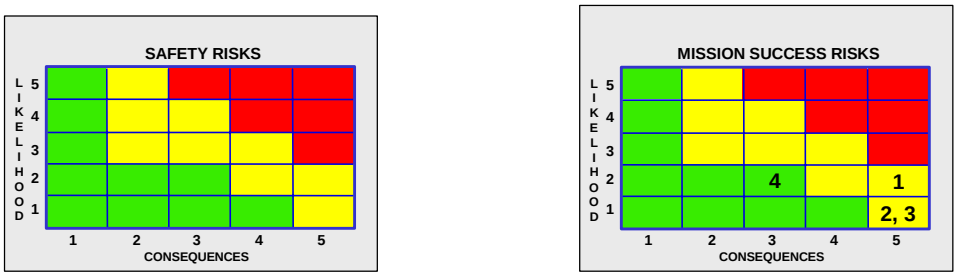

Figure 6.3-1. KSC S&MA Deep Impact Residual Risk Assessment Summary

The LSP and the launch vehicle manufacturer used a risk assessment matrix as shown in Figures 6.3-2 and 6.3-3. An assessment of probability of an issue causing failure within 100 flights was made based on the judgment of program engineering.

Risk Definitions - Probability

Probability Classification					
Level	1	2	3	4	5
Label	Very Low	Low	Moderate	High	Very High
Guidance for Probability Level Selection	*1-5%	6-10%	11-50%	51-90%	91-<100%
	Probability of occurrence is very low. Existing processes and mitigation efforts are strong and very likely to prevent this risk scenario	Probability of occurrence is low. Existing processes and mitigation efforts are usually sufficient to prevent this risk scenario; additional actions may be required.	Probability of occurrence is moderate. Existing processes and mitigation efforts may prevent this risk scenario, but additional actions will be required.	Probability of occurrence is high. Existing processes and mitigation efforts cannot prevent this risk scenario; a different process or mitigation effort might.	Probability of occurrence is very high. Existing processes and mitigation efforts cannot prevent this risk scenario; no alternative processes or mitigation efforts are available.

*Percentages are for comparative purposes only.
SMA does not use percentages shown

Source: Launch Services Program Risk Management Plan (KSC-PLN-2130)

Figure 6.3-2. LSP Risk Definitions

Risk Definitions

Probability of Occurrence	1	2	3	4	5
5 91-<100%	1x5	2x5	3x5	4x5	5x5
4 51-90%	1x4	2x4	3x4	4x4	5x4
3 11-50%	1x3	2x3	3x3	4x3	5x3
2 6-10%	1x2	2x2	3x2	4x2	5x2
1 1-5%	1x1	2x1	3x1	4x1	5x1

Impact

Source: Launch Services Program Risk Management Plan (KSC-PLN-2130)

SMA does not use the percentages shown

Figure 6.3-3. LSP Risk Definition Matrix

Risk Discussion

Until recent times, the term "risk" was equated with "hazard, danger, peril, exposure to loss, injury, or destruction". There was no sense that likelihood of this event actually happening was part of the term "risk". "Risk" only meant a possibility of incurring loss or misfortune, and did not address whether this possibility was likely or unlikely. "Risk" was a one-dimensional term.

Only in the last few decades has "risk" become two-dimensional. The subject of "risk management" supposes that we can both quantify the loss associated with a "risk event", and also quantify the likelihood of this "risk event". A failure effects analysis is designed to help with the first quantification, and some sort of probability analysis is designed to help with the second.

A large practical problem, however, is that resources were never spent to collect the data needed to make a reliable probability analysis for some "risk events", especially for rare events that infrequently happen and happen in expensive systems. Therefore, in many cases, these probability evaluations were made as a guess. In particular, this is the case for the various probability evaluations for the cracking of sintered alumina TFA, used in the GNC system of the Delta II chosen for the Deep Impact launch.

Boeing has offered an explanation for these cracks: the choice of conformal coating material and the manner of its application has caused stresses that have risen to the level of the fracture strength of the sintered alumina. Thus, some have cracked. This explanation is plausible; however, it has not been established with rigor. For example, it does not address the role played by cracks in the surface of these alumina plates (induced by handling and by the laser cuts used to trim the resistors on the surfaces of these plates). These surface cuts are not likely to be "all the same" as one moves from specimen to specimen. No fractrography seems to have been conducted to identify the source of each crack, especially for the ones that have completely shattered the alumina plates. The fraction of the cracked specimens has not been reproduced in any way by Boeing's explanation.

It may be possible to regard these alumina plates as having been subject to a "proof test" by the pre-flight tests. This provides confidence that those alumina plates, that have survived so far, will not fail during the much less stressful launching conditions. However, Boeing has not presented this "proof test" argument in an orderly manner, using the standards now established in areas of fracture mechanics, which report quantitative studies of the effectiveness of different "proof test" designs for particular systems.

Thus, the probability of success "P" is not rigorously known. The value of P or its uncertainty limits, "P minimum, P maximum", are not known in an objective manner. A reliable value for this P is not known, although it can be supposed it is more likely to be "low" (less than 10 percent) than "high" (greater than 10 percent), and even more likely to be "very low" (less than 1 percent) than simply low.

The risk matrix used by US programs follows our legal system does not allow "not known" as a measure of the probability of failure. It compels one to choose a category. In response to this constraint, it is the policy of some organizations to assign "high risk" to the cases when one cannot objectively assign a probability value. This has happened in this circumstance where the KSC S&MA team has reacted to the uncertainty in the value of P with the finding that "this likelihood is appreciable": level two. Level two is also assigned to be consistent with the KSC S&MA's experience base for large number of evaluations.

Boeing has reported that their engineers were surveyed with the question: "Based on your experience, and supposing one hundred launches, what is the number of launches that would fail as a result of using control systems like the ones considered for this Deep Impact launch?" The response was that this was judged to be less than one launch failure per one hundred launches. So, Boeing has concluded that the estimate of the probability of launch failure caused by a crack-induced fault in a TFA is less than 1 percent. This falls below the threshold at which Boeing reports risks. Boeing judged this risk to be "below the chart's lower edge". However, they did not mention whether their engineers agreed to the "less than 1 percent"; whether there were those who supposed a larger value, and only the average of all these estimates was below 1 percent; or whether there were some who declined to make any estimate. These all point to a possible lack of consistency with these engineering estimates.

This discussion explains how the Boeing and the KSC S&MA teams have provided different reports as to launch risk: their policies are different and non-comparable. The elasticity of the term "probability", presently used on risk charts, extends to include these extremely different uses: engineering guesses on the part of Boeing versus an attempt to communicate uncertainty on the part of the KSC's S&MA team. Boeing's choice of "don't report if P < 1 percent" has an implication that is troubling. Most likely there are many hundreds of subsystems like the TFAs of interest. Assume this number as *N*. Suppose that each has a problem that presents a probability for launch failure of "f" that is just under 1 percent, so the probability of success is p = 1 - f = 99- percent. For the launch to succeed, each of these *N* subsystems has to work; the probability of a successful launch is then P = p**N. The table below illustrates values for launch success "P" for various levels of *N*:

N	P
10	90 percent
30	74 percent
100	37 percent
300	4.9 percent

Thus, Boeing could be non-reporting a collection of problems, each falling below their "1 percent" criteria, which could still dramatically lower the probability of a successful launch. The only way for a complicated system to be reliable is for each of its subsystems to be remarkably reliable. As soon as subsystems are accepted that are less than remarkably reliable, launch failures will occur.

Thus, this investigation surfaces some differences in policy between assigning values to the "likelihood of failure", as used by the Boeing and S&MA teams. It also surfaces a reporting policy ("<1 percent" = do not report) on the part of Boeing that can have an ominous

consequence for systems as complex as a launch vehicle. Is there a way to arrive at a better estimate for the probability of failure caused by a crack in a TFA affecting its performance during launch, given the pre-testing that these units have had? Perhaps further exploring the "proof testing" approach may provide a more objective quantitative basis.

7.0 Data Analysis

7.1 Detailed Technical Discussion

To assess the performance of the Delta second stage TFA, it is important to understand the fracture properties of the sintered alumina (Al_2O_3) TFA coating. The alumina coating exhibits brittle fracture characteristics typical of most ceramic materials. This is evidenced by the classic brittle fracture shown in Figure 7.1-1. The following sections briefly describe the typical fracture properties expected for the TFA coating exposed to tensile load. In general, tensile stress rather than compressive stress promote cracking in these materials. Single crystal Al_2O_3 (sapphire) data is used to approximate the general fracture properties of the TFA. (The single crystal data is used here to establish likely trends and not absolute properties).

Figure 7.1-1. Photographs show TFA Cracking

Note: Cracks exhibit brittle "glass-like" fractures. (Reference: NASA Presentation: "Cracked Thick Film Assemblies, Delta II, Stage 2 Servo Amplifier CCA EBR-02043, contributions by Thomas Bulk et al)

7.1.1 Assessment of Material Properties

For the TFAs, the stress has been applied by bending the specimen. This means that the largest stresses are, at the surface, on the outside of the imposed bend (i.e., the side that is stretched as the film bends), and so surface cracks on this surface are of dominating importance. (For practical purposes, the internal defects associated with voids left from incomplete densification during sintering can be ignored). These dominating surface cracks are not defined by knowing that this material is "sintered alumina", but rather on the handling that the specimen has been given.

For example, sintered alumina plates do not have intrinsic fracture strength by the time they have reached service. Rather, the largest bending stress that they can sustain is entirely controlled by the presence of surface cracks installed by the handling they receive up until failing. This handling causes a distribution of cracks of various sizes "a". The largest of these, in a high-stress region, will dominate the observed fracture strength.

It has long been known that glass tubes that have been handled (even by letting one tube touch another) have their resistance to breaking when bent sharply reduced. This strength can be restored essentially back to its "as new" value by polishing the surface (either by the use of rouge, by "fire polishing," or by etching in hydrofluoric acid). This illustrates that brittle materials do not have an intrinsic strength in the field, after handling, but have a strength against bending stresses that is entirely determined by the surface cracks installed by handling.

One common way for a sintered alumina plate to acquire a highly damaging nick is for another plate to brush against it. Contact with hardened steel (such as a file or a scribe) is another way to scratch the surface of the alumina. Placing the sintered alumina plate onto some hard surface can induce edge-cracks.

If the edges of these sintered plates are not chamfered, but are left in the form of right-angles, then edge-chipping is inevitable as the plates are handled. Typically, it may be taken for granted that any bit of optical glass such as a mirror, a window, or a lens will be chamfered. However, in E-Packaging applications, substrates of sintered alumina are typically not chamfered. Usually, these are hard-bonded to a strong backing and not subject to bending. But these TFAs are subject to bending stresses, and so they should be edge-chamfered. One of the pictures of the shattered plates seems to show that the cracks started from edges. The laser-induced cuts used to trim the TFA resistors are classic "cracks" into the surface of the alumina. Some researchers

studying the fracture properties of alumina have taken to using laser-cuts as an especially controlled way of inducing a well-defined crack into the surface of the alumina.

It seems unlikely that each of the sintered alumina specimens comprising the substrate of these TFAs would have the same handling-induced damage. Therefore, it would seem that the family of them would show great variability in the time to fracture (one hundred to one variations are easy to understand), even when subject to the same applied stress.

It is possible that the population of edge-cracks, and perhaps cracks on the surface away from the edges, play a role in the fracturing of the TFAs. This is important in understanding which plates fractured and which ones did not. A positive note is that the rate of crack growth, under applied stress, increases as rapidly as the applied stress is increased that "proof testing" can work if the specimen has passed a given load without fracture. Then, it is highly unlikely it will subsequently fracture under a substantially smaller load. Additional study of "C" and "p" for sintered alumina and these relationships (as described in the “Fracture Properties” section below) may be able to show a quantitative model of the degree to which the Boeing tests have acted as a "proof test". This would give quantitative support to Boeing's position that all the plates that are ever going to crack under launch loads have already been forced to crack by pre-launch stresses. This approach may be useful for future flights.

Alumina Processing

Al_2O_3 can be prepared as equi-axial crystals of a moderately uniform diameter and can be sintered into a solid by exerting pressure at a high temperature. The result is a material with a density approaching that of the single crystal form (and thus one parameter characterizing this sintered form is its density, while another is the grain diameter). A typical value is 98 percent used as an E-Packaging substrate (sometimes the value can be up to 99.8 percent).

Fracture Properties

The fracture mechanics of the sintered form is the subject many publications. Used as a packaging substrate, as it is in the TFAs of present interest, sintered alumina shows "brittle fracture". When subjected to an increasing stress, its strain increases linearly up to a certain threshold of stress and then the specimen shatters. There is no region of ductile deformation in which the sample plastically deforms. Hence, the critical stress that separates "safe" linear deformation from "catastrophic" rupture must be understood.

Many studies show that the sintered alumina is suffused with cracks. One class of these is the micro-cracks surrounding internal voids left from incomplete densification during sintering. Another class is surface cracks of all sizes — from atomic dimensions (always) to as large as

visible (sometimes) — resulting from the formation and the handling of the specimen. Purely compressive stresses force all cracks to close. Alumina is remarkably strong under purely compressive stresses.

Tensile stresses force all cracks, internal as well as surface cracks, to grow. The rate of growth is increased by the presence of catalytic agents such as water (present in the environment as moisture in the air, which is concentrated by surface tension at the tip of a crack into essentially liquid densities). One useful relation is crack growth rate = da/dt = C K^p where "a" is the length of the crack, "t" is the time, "K" is the stress factor, "C" is a pre-factor, and "^{p}" is an exponent. For some alumina specimens, values of "^{p}" as large as 60 have been measured. The value of "C" for silica glass is roughly 10^5 times larger in the presence of moist air than in an excellent vacuum. However, water has a much smaller effect on "C" for sintered alumina. The relation between the stress factor "K" and the applied stress is controlled by the crack length and shape and its orientation to the applied stress. This relation is defined in texts on fracture mechanics.

Crack Growth Properties

The TFA alumina will likely exhibit typical ceramic tensile properties such as high modulus, low total ductility, and low fracture toughness. These result in brittle crack growth and fracture. Typically, resistance to sustained load cracking is poor. Initially, stable crack growth rapidly becomes unstable and leads to fracture at relatively low tensile loads (low crack-tip stress intensity threshold - K_{TH}=1.5 MPa√m) for single crystal alumina (sapphire) in humid air (shown in Figure 7.1-2). As shown, the near vertical slope of the "crack growth rate versus crack-tip stress intensity" curve is typical of the spectacular crack growth characteristics of these materials, which make them potentially dangerous in high-stress applications that can be ruined by cracking.

A small change in crack-tip driving force (tensile stress) results in a dramatic increase in crack growth rate until unstable crack growth and final fracture occurs and fracture toughness is rapidly reached (K_{1C}≈2.1 MPa√m). Similar brittle crack growth characteristics are observed under cyclic loading, also shown in Figure 7.1-2. These data illustrate that the TFA coating material is "crack sensitive", which means that small flaws (micro-cracks) can readily propagate under tensile loading.

7.1.2 Environmental Crack Growth Properties

Alumina is susceptible to environmental-assisted cracking under sustained load, stress corrosion cracking (SCC) and cyclic loading, and corrosion fatigue (CF). Figures 7.1-2 and 7.1-3 show the SCC characteristics of sapphire exposed to different levels of relative humidity air and Ringers solution (NaCl, Na lactate, KCl, CaCl). Figure 7.1-2 also shows that what are commonly

thought to be relatively benign environments (50 percent relative humidity (RH) air) can increase crack growth rates in sapphire. These data show that time-dependent environmental crack growth damage modes can occur in Al_2O_3 materials and should be considered when cracking is possible. Figure 7.1-4 shows that under fatigue loading, a dramatic change in environmental crack growth characteristics is observed. Also depicted, a factor of 10^2 increased fatigue crack growth rates is observed for the Ringers solution compared to humid air. Again, these data show that the environment can have deleterious effects on the crack growth rates of these materials.

7.1.3 Assessment of Cracked TFA Thick Coating

Given the brittle fracture properties of the TFA, it is likely that the rigorous ATP testing screened most damage. The "crack sensitivity" and rapid crack growth characteristic of these materials would likely produce failure during the ATP testing. Whether undetected damage was produced remains a valid point of discussion.

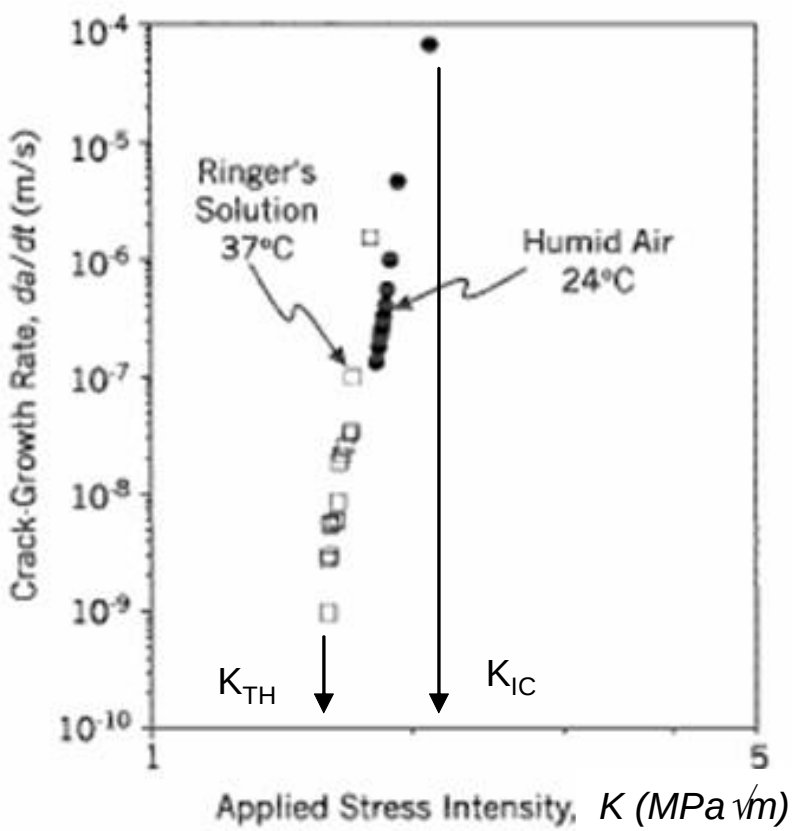

Figure 7.1-2. Crack Velocity Curve for Sapphire in both Moist Air and Ringer's Solution

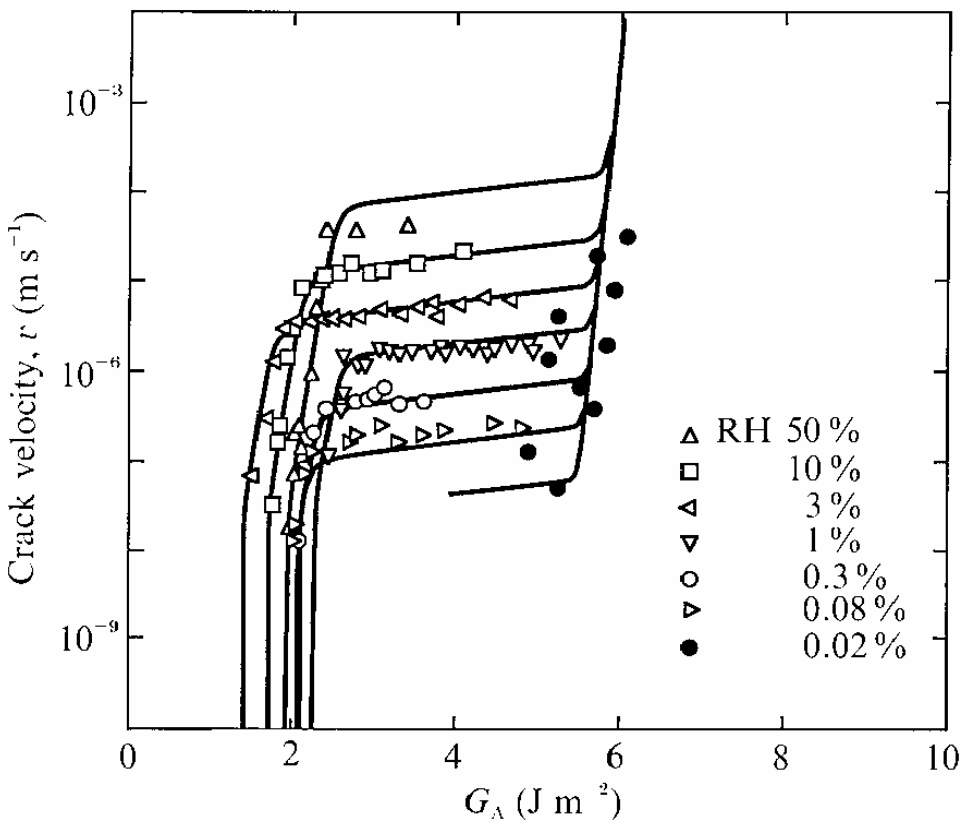

Figure 7.1-3. Crack Velocity Curves for Sapphire Exposed to Air showing Increased Crack Growth Velocity with Increased RH

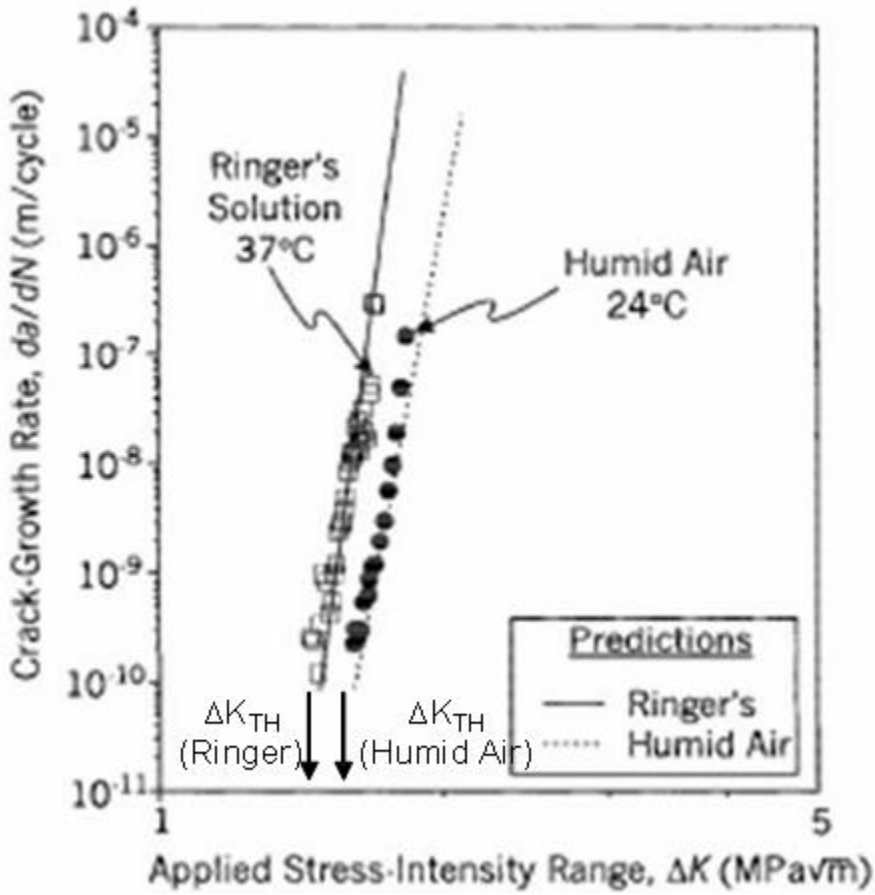

Figure 7.1-4. Comparison of the Environmental Fatigue Crack Growth Characteristics of Sapphire in Moist Air and Ringer's Solution (NaCl, Na lactate, KCl, CaCl)

The technical information, sent by the LSP to the team for review, includes pictures of two shattered TFAs (Figure 7.1-1) taken after removing the TFAs from their circuit cards. The pictures show completely disconnected shards of alumina. It seems impossible that traces crossing these fracture lines could have remained intact during all the stresses applied to them while these alumina substrates were still mounted to the circuit card. There should have been no problem detecting these cracks.

Other pictures of still-mounted TFAs show almost invisible "hair line" cracks that extend for a limited distance along the alumina, and not all the way across a TFA. These partial cracks seem to have the potential to partly separate a conducting trace, but not to separate it completely. The resistance of the partially separated trace would increase somewhat, but not to essentially an

open circuit. Boeing's "enhanced" detection method is aimed (in part) at detecting the partially cracked traces. The completely open cracked trace should be easily detected. The other aim of the "enhanced" method is to detect if any TFA resistors that have been "clipped" by a crack were altered, but not opened electrically.

A quantitative computation of the increase in resistance caused by a "cut" normal to the edge of a trace extending partway through it, shows that the increase in resistance remains essentially invisible until the cut is almost complete, more than 90 percent through. In cases in which there is "in-line" resistance from an interposed resistive element, the crack would have to extend more than 99+ percent through in order to be detectable as an increase in resistance by more than 5 percent.

The reason that the increase in trace resistance caused by a partial cut is so hard to detect is that the increase comes from a disturbance in the flow of the electrical current that is limited to the immediate neighborhood of the cut (i.e., over a length about equal to the width of the trace), while the total resistance comes from the entire length of the trace, and the ratio of the width to the total length is small. Also, in this application, the trace-resistance is not measured by itself in isolation, but is summed with in-line resistors, which makes trace resistance increases even more difficult to detect.

Even the "enhanced" detection method, employed by Boeing to detect cracks that partially cross a trace, will be insensitive to partial cuts. Such a method will see almost complete cuts only. The Boeing "enhanced" detection scheme may or may not see cracks that pass through part of a film resistor. The visibility of such "clipping cuts" requires a different analysis.

Detecting cracks in ceramics is a problem that has been around since the start of NASA's use of ceramics. One of the more powerful methods is to use "vicinal illumination[2]", granted the alumina is translucent and not dark or black, and the optical inspection is possible. Unfortunately, it is too late (without massive impact) to inspect the assemblies mounted in the Delta II about to be launched. It is safe to assume that there will be further use of sintered alumina in E-packaging, and the use of this inspection method may be helpful in the future.

Figure 7.1-5 shows an image at ~50X of a slab of alumina with a pair of cracks making a V-shape. The illuminator was arranged to put a bright spot onto one side of the crack-pair. It is evident that the light did not cross the crack-boundaries, making these especially visible. These cracks were not visible in normal top-down illumination.

[2] The vicinal illumination technique has been successfully used to detect cracks in many types of ceramic materials. This inspection method has become an important tool for inspection and analysis of many ceramic materials for space flight applications.

Figure 7.1-6 is the same image, but mildly enhanced to better show the crack. This image is the ratio of Figure 7.1-5 to an image of precisely the same spot when used to illuminate a featureless region of the ceramic. These two figures illustrate how powerful this non-destructive inspection method is.

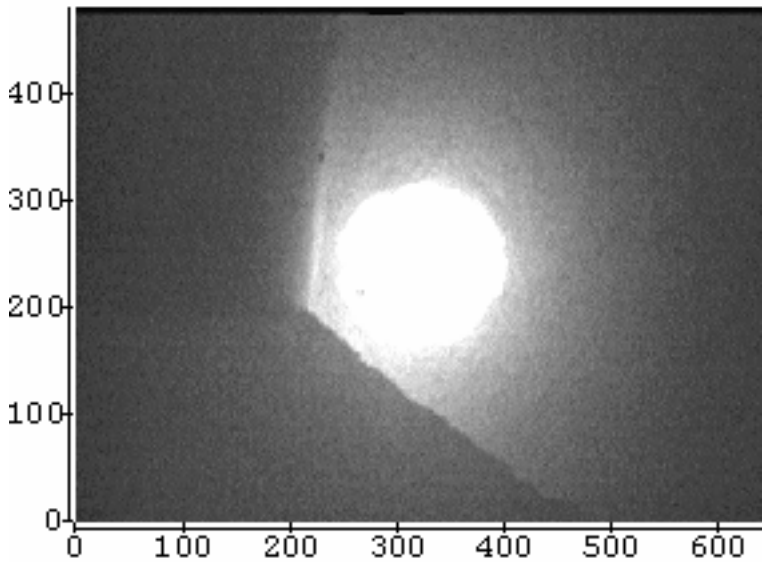

Figure 7.1-5. Pair of Cracks at ~50X of a Slab of Alumina (V-shaped Cracks)

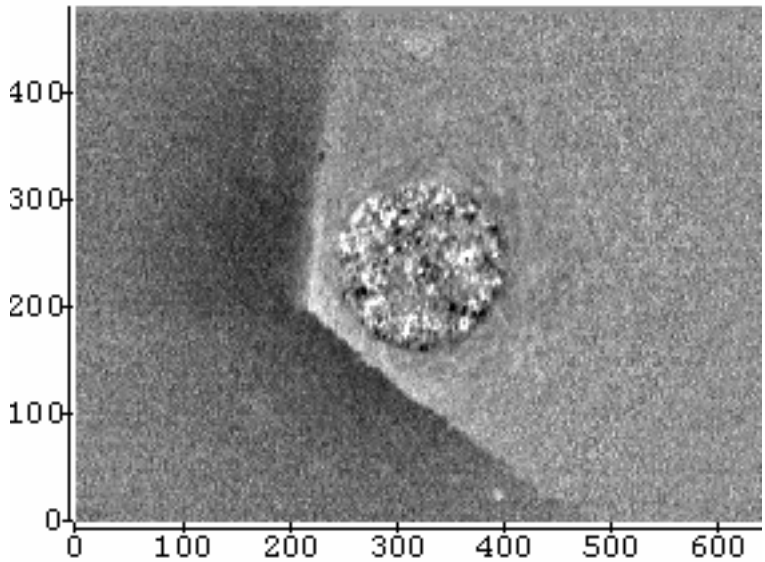

Figure 7.1-6. Ratio of Figure 7.1-5: Closer View of Crack Image

8.0 Findings, Observations, and Recommendations

Team findings and recommendations from this assessment are listed below.

8.1 Findings

F-1. A cracked TFA was detected in a Delta II first stage E-package, which had been built with "non-suspect" TFA.

F-2. The Deep Impact launch vehicle has three E-packages of potential concern, one in the first stage and two in the second stage. The first stage E-package was manufactured in Monrovia, and, to date, none of these units have been found to experience cracks. The second stage E-packages went through ATP five times, with the enhanced screening applied. They were most recently tested in July 2004.

F-3. The TFA crack risk should be considered to be in the range of medium-to-low risk, and represents an acceptable risk for flight. The NESC team concurred with KSC's S&MA that "5x2" more accurately characterizes this risk.

Rationale (F-1 through F-3):

- Although the comprehensive review conducted by Boeing indicated that thick film cracking occurred as a result of manufacturing processing, and ATP testing and analysis indicated that crack propagation, which could lead to faulty TFA performance during flight, is unlikely, there is a finite probability that marginally cracked TFAs could have passed existing ATP testing criterion.
- The LSP acknowledges the probability of failure to be "less than 1 percent", but not zero, as assessed by their subjective methods.
- The likely root cause - excessive conformal coating under the TFA assemblies due to manufacturing changes - has been postulated, but has not been verified by testing.
- Enhanced screening test, which reviews parametric data from box level testing looking for changes, has proven effective to-date, but may not be 100 percent effective because it is an indirect method of detection.

- Because of the potential for undetected micro-cracks to propagate with time or from the launch environment, a residual risk remains for undetected micro-cracks to trigger failure of an assembly under stress.
- KSC S&MA and the NESC team agree that the TFA cracking hazard represents a reportable risk for FRR.

F-4. KSC S&MA, Boeing and the LSP agreed on the nature and cause of the TFA cracking hazard, and on the existing rationale for flight. However, when using a common assessment tool, they used different rationale in assigning risk codes.

Rationale (F-4):

- The LSP Risk Management Plan (KSC-PLN-2130) defines the risk probability code levels (1-5) with both verbal labels and/or numerical percent probability ranges.
- KSC S&MA, Boeing and the LSP all seek to maintain internal consistency in their risk assessments, for continuity of reporting and internal risk management.
- KSC S&MA does not use the percentages as guidance for code assignment, relying more on the verbal and subjective guidance provided in the Plan.
- Boeing uses a subjective assessment of numerical probability as their guide to risk probability assignment, as provided in the LSP Risk Management Plan.
- KSC S&MA, Boeing and the LSP apply subjective engineering judgments in assessing risk and assigning risk codes, as sufficient data is seldom available.

F-5. The flight environmental loads are lower than the box ATP loads.

Rationale (F-5):

- Thermal cycle test margin is a minimum of $+39^{o}$ F.
- Shock test margin is greater than 15 dB.
- Random Vibration test margin is 5.2 dB minimum.

8.2 Recommendations

R-1. The Director of the OS&MA should direct the Deep Impact FRR process to continue with the acceptance of flight rationale for the TFA cracking issue with the acceptable risk, assessed as “5x2”.

Rationale R-1:

- Two boxes with potentially suspect TFAs have been identified: one in the first stage and one in the second stage. Both have passed the enhanced parametric screening.
- The first stage box (20142) was produced in Monrovia. No cracked TFAs have been found in Monrovia-assembled units.
- The second stage box (20166), even though assembled in El Paso, passed the enhanced screening with five data sets reviewed, the most recent being July 2004.
- Flight environmental loads are far less than the box-level ATP loads than the units passed successfully.

R-2. The Director of KSC S&MA should initiate a review of the LSP Risk Management Plan (KSC-PLN-2130) to clarify the guidance for probability level (percent) selections, and make application of the tool more uniform.

R-3. Boeing should continue to pursue other design approaches to further enhance robustness and minimize the likelihood of this type of failure in TFA circuits. Areas recommended include thicker substrates, chamfered edges, handling improvements to preclude the early development of micro-cracks, proof testing, and vicinal illumination inspection.

R-4. For future missions, the Boeing and the LSP should:

- Determine whether enhanced test(s) can be run on the vehicle, which would add confidence without removing the boxes.
- Perform box-level testing and detailed data screening review of all boxes containing TFA, preferably within one year of launch, to guard against the possibility of micro-crack growth.
- Monitor the E-packs during environmental testing to detect electrical intermittent conditions that may indicate a crack.
- Consider the Destructive Physical Analysis (DPA) of an E-pack, which has passed the enhanced screening in 2002 but is from the “suspect” units, to determine whether there are signs of cracking with time.

9.0 Lessons Learned

1. The only way for a complicated system such as a launch vehicle to be reliable is for each of its individual subsystems to be remarkably reliable. When subsystems that are less than reliable are accepted, failures will occur.
2. Effective risk management requires that risks be categorized and communicated with a common understanding. Improved methods at consistency in accurately assessing risk will enhance safety and mission success.

10.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established during the assessment/inspection by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment/inspection that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur.
Problem	The subject of the independent technical assessment/inspection.
Recommendation	An action identified by the assessment/inspection team to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible C/P/P/O in the preparation of a corrective action plan.

Root Cause	Along a chain of events leading to a mishap or close call, the first causal action or failure to act that could have been controlled systemically either by policy/practice/procedure or individual adherence to policy/practice/procedure.

11.0 Minority Report

There were no minority opinions voiced during the performance of this consultation.

Volume II: Appendices

Appendix A	NESC ITA/I Request Form (NESC-PR-003-FM-01)
Appendix B	References
Appendix C	Cutbar Essay
Appendix D	List of Acronyms

Appendix A. NESC ITA/I Request Form (NESC-PR-003-FM-01)

NASA Engineering and Safety Center
Request Form

Submit this ITA/I Request, with associated artifacts attached, to: nrbexecsec@nasa.gov, or to NRB Executive Secretary, M/S 105, NASA Langley Research Center, Hampton, VA 23681

Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt		
Received (mm/dd/yyyy h:mm am/pm) 12/22/2004 4:40 PM	Status: New	Reference #: 04-093-E
Initiator Name: Bryan O'Connor	E-mail: bryan.oconnor@nasa.gov	Center: HQ
Phone: ( )- - , Ext _____	Mail Stop:	

Short Title: Cracked Thick Film Coatings on Electronic Packages on the Delta 2 Launch Vehicle

Description: Bryan O'Connor requested that the NESC provide a materials expert to evaluate two differing risk assessments regarding the start and propogation of cracks associated with thick film coatings on electronic packages on the Delta 2 Launch Vehicle. A FRR is scheduled for the 8th of January 8 and Bryon O'Connor would like a second opinion to brief the AA with before that if date.

Source (e.g. email, phone call, posted on web):
e-mail

Type of Request: Consultation

Proposed Need Date:

Date forwarded to Systems Engineering Office (SEO): (mm/dd/yyyy h:mm am/pm):

Section 2: Systems Engineering Office Screening

Section 2.1 Potential ITA/I Identification

Received by SEO: (mm/dd/yyyy h:mm am/pm): 12/23/2004 12:00 AM

Potential ITA/I candidate? ☒ Yes ☐ No

Assigned Initial Evaluator (IE): No initial evaluation. This was approved Out of Board

Date assigned (mm/dd/yyyy):

Due date for ITA/I Screening (mm/dd/yyyy):

Section 2.2 Non-ITA/I Action

Requires additional NESC action (non-ITA/I)? ☒ Yes ☐ No

If yes:

Description of action: Consultation

Actionee: Ken Cameron 12/23/2005

Is follow-up required? ☒ Yes ☐ No If yes: Due Date: 01/06/2005

Follow-up status/date: Schedule at 6 Jan 2005 NRB to present report/recommendations

If no:

NESC Director Concurrence (signature):

Request closure date:

NESC Request Form
NESC-PR-003-FM-01, v1.0

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Section 3: Initial Evaluation		
Received by IE: (mm/dd/yyyy h:mm am/pm):		
Screening complete date:		
Valid ITA/I candidate? ☐Yes ☐ No		
Initial Evaluation Report #: NESC-PN-		
Target NRB Review Date:		
Section 4: NRB Review and Disposition of NCE Response Report		
ITA/I Approved: ☐Yes ☐ No	Date Approved:	Priority: - Select -
ITA/I Lead: , Phone ( ) - , x		
Section 5: ITA/I Lead Planning, Conduct, and Reporting		
Plan Development Start Date:		
ITA/I Plan # NESC-PL-		
Plan Approval Date:		
ITA/I Start Date	Planned:	Actual:
ITA/I Completed Date:		
ITA/I Final Report #: NESC-PN-		
ITA/I Briefing Package #: NESC-PN-		
Follow-up Required? ☐Yes ☐ No		
Section 6: Follow-up		
Date Findings Briefed to Customer:		
Follow-up Accepted: ☐Yes ☐ No		
Follow-up Completed Date:		
Follow-up Report #: NESC-RP-		
Section 7: Disposition and Notification		
Notification type: - Select -	Details:	
Date of Notification:		
Final Disposition: - Select -		
Rationale for Disposition:		
Close Out Review Date:		

NESC Request Form
NESC-PR-003-FM-01, v1.0

Page 2 of 3

Form Approval and Document Revision History

Approved: _____ _____
NESC Director Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Principal Engineers Office	29 Jan 04

Appendix B. References

1. B. Asoo, J. M. McNaney, Y. Mitamura, and R.O. Ritchie, "Cyclic Fatigue-Crack Propagation in Sapphire in Air and Simulated Physiological Environments", *Journal of Biomedical Materials Research*, vol. 52, 2000.

2. Y.S. Shiue & M. J. Matthewson (2001) "Stress dependent activation entropy for dynamic fatigue of pristine silica optical fibers" *J. Appl. Phys*, 89 [9] 4787-93.

3. NASA Presentation: "Cracked Thick Film Assemblies, *Delta II, Stage 2 Servo Amplifier CCA EBR-02043*, contributions by: Thomas Bulk et al.

4. Leidecker, Henning, American Institute of Physics Handbook, essay entitled *CutBar*, based on a rigorous result for the increase in resistance caused by a "model crack" in a conductor having a rectangular cross section, page 5-24.

Appendix C. Cutbar Essay

On the increase in resistance caused by a crack. This is from page **5**–24 of the *American Institute of Physics Handbook*, published by McGraw-Hill in 1963 (second edition).

Consider a bar with a rectangular cross section; its length is ℓ, its thickness is t and its width is w. The resistivity of the bar is ρ and its resistance is

$$R = \frac{\rho \ell}{tw}. \tag{1}$$

Make a cut into the bar across its width, extending a distance c, so the current is restricted to flow through the gap $w - c$ in the immediate neighborhood of the cut. The increase in resistance caused by the cut is

$$\Delta R = -\left(\frac{4\rho}{\pi t}\right) \ln\left[\cos\left(\frac{\pi c}{2w}\right)\right]; \tag{2}$$

this is a relative increase of

$$\frac{\Delta R}{R} = -\left(\frac{4w}{\pi \ell}\right) \ln\left[\cos\left(\frac{\pi c}{2w}\right)\right]. \tag{3}$$

The factor $\Phi(c/w) = -\ln[\cos(\pi c/2w)]$ is shown in the figure. (Note that $\Phi > 0$, since the cos-term is always less than unity and, thus, the logarithm is always negative.)

The usual case for a wire is that the length ℓ is many times the width w, and so the relative increase is very small indeed. Consider a wire that is one foot long and has a square cross section with $w = 0.05$ inches (close to #18); then, $(4w)/(\pi\ell) = 0.0053$. An increase in the resistance by 1% requires $\Phi = 1.88$, or $c/w = 0.903$. That is, the cut must extend to 90.3% of the width in order to increase the resistance of this choice of wire by 1%.

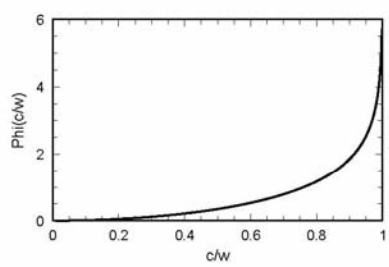

Figure 1: $\Phi(c/w)$ versus (c/w)

Appendix D. List of Acronyms

Al_2O_3	aluminum tri-oxide
ATP	Acceptance Test Procedure
BATC	Ball Aerospace and Technology Corporation
CaCl	Calcium Chloride
CCAFS	Cape Canaveral Air Force Station
CF	Corrosion Fatigue
CIT	California Institute of Technology
DPA	Destructive Physical Analysis
FRR	Flight Readiness Review
GNC	Guidance Navigation & Control
GSFC	Goddard Space Flight Center
H_2O	Water
ITA/I	Independent Technical Assessment/Inspection
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KCl	Potassium Chloride
Km	kilometers
KSC	Kennedy Space Center
LaRC	Langley Research Center
LSC	Launch Services Contractor
LSP	Launch Services Program
NaCl	Sodium Chloride
NASA	National Aeronautics and Space Administration
NCE	NESC Chief Engineer
NDE	NESC Discipline Expert
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
OS&MA	Office of Safety and Mission Assurance
RH	Relative Humidity
S&MA	Safety and Mission Assurance
SCC	Stress Corrosion Cracking
SLC	Space Launch Complex
SMARR	System Mission Assurance Readiness Review
SSP	Space Shuttle Program
TFA	Thick Film Assembly
UMD	University of Maryland

Approval and Document Revision History

Approved:	Original signed on file	11/8/05
	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	NESC Director of Safety Office	