Computing Risk of Pyrotechnic Devices Using Lot Acceptance Testing

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ABSTRACT

This paper presents an application of statistical engineering to solve the problem of determining the effects of reducing test sample sizes and environment levels in lot acceptance testing (LAT) of ordnance devices used by NASA and DoD space systems. Unlike environmental testing of dedicated qualification hardware, ordnance devices have a test-like-you-fly exception and use lot acceptance sampling or LAT. LAT is performed by randomly selecting a predefined number of devices from an individual lot and exposing them to a more severe dynamic shock and vibration testing environments than flight (sometimes as high as 6 decibels over flight environments) and then performing a destructive test on the device. Recent trends have been suggested to reduce LAT costs by reducing environment test levels or the number of devices per LAT, or both. A method is

given here to compute flight risk, so the proposed methods can be compared by subject matter experts to the baseline LAT methods. In addition, this method can be used to determine the best methods to include in future LAT standards for pyrotechnic devices.

INTRODUCTION

Pyrotechnic devices consist of explosive-actuated mechanisms used in space systems to perform several functions, including crew escape, launch vehicle stage separation, fuel shutoff valves, and vehicle destruction (Lake , Thompson & Drexelius, 1973). A robust verification process is used to show compliance that pyrotechnic devices meet design requirements which include reliability. Thorough development testing is first completed to determine that the design is acceptable for the intended function, and that the pyrotechnic device contains both positive and negative margins. Positive margin testing is performed to show that the structural integrity is maintained under excessive explosive output. The negative margin testing ensures the device still functions if the explosive material degrades. Upon successful completion of development testing, qualification testing is performed. The quantities of devices in the qualification testing must represent a sample size that is statistically significant and can meet the predetermined values for reliability and confidence. The qualifying environmental conditions are established to provide significant margin over those predicted when in actual use.

The subject of this paper is the final phase of testing performed before devices are used for flight, called lot acceptance testing (LAT). LAT is performed on single lots. The LAT first performs non-destructive tests on the entire lot. If the lot passes non-destructive testing a small sample is selected from the lot. For example, if the lot size is 100 units then 10 devices would be selected for destructive testing. The sample of devices is first exposed to launch environments, e.g. random vibration and shock at a predefined level usually 3 to 6 dB above the maximum estimated flight environment. These environments are usually less harsh than those assessed during qualification testing. Any failure during LAT testing usually leads to a lot rejection. NASA mandates that the number of devices expended during this process be 10% of the manufactured lot size, or 10 units, whichever is greater (NASA, 2003).

LAT is concerned with inspection and decision-making on a lot-by-lot basis and is one of the oldest aspects of quality assurance. For pyrotechnic devices, newer quality assurance methods are used to improve and control the manufacturing process performance using statistical process control. The most effective use of LAT is not to increase quality, but as an audit tool to ensure that the output of a process conforms to the requirements. The problem we are unravelling here is what percent of the lot should be tested and at what environmental levels should LAT be performed. Statistical engineering, which provides a structure for strategical and tactical deployment of statistical tools, is used to solve this problem. Most LAT plans are not designed to construct precise estimates of device reliability, but we will demonstrate how these lot acceptance tests can be used to measure the risk of using devices that have successfully passed LAT.

Notation

EED	Electronic explosive devices
LAT	Lot Acceptance Test
OC	Operating-characteristic
P_a	Probability of accepting a lot
p	Probability a device will fail the LAT
n	Number of sampled devices in the LAT
c	Acceptance number
dB	Decibels
MPE	Maximum predicted environment
μ_F	Mean of the logarithms of the flight spectral values at a given frequency
σ_F	Standard deviation of log flight spectral values at a given frequency
μ_D	Mean of device capability distribution
σ_D	Standard deviation of device capability distribution
$Z_{.95}$	95-percentile of the standard normal distribution
Y	Logarithm of the flight spectral environment spectral value

X Device capability in log space

$\mathbf{\Phi}$ Standard normal cumulative distribution function

Δ_{LAT} Number of dB above MPE of the LAT environment test level

P_f Probability a device fails during flight

LOT ACCEPTANCE TESTING

Lot acceptance tests are conducted to demonstrate that the design and manufacturing process of a fully qualified device produces hardware that meets specification requirements with adequate margin (DOD, 1996). Each lot of pyrotechnic devices undergoes non-destructive testing. A typical list of non-destructive tests includes visual inspection, weight and dimension measurements, leakage test, and x-rays (Scott & Hinkel, 2015). After the full lot passes non-destructive testing, a sample of devices is randomly selected from the lot and destructive environments are applied to the sample. The sampled devices are subjected to high temperature storage, thermal cycling, shock, and random vibration. Following the application of destructive environments, the devices may undergo another round of non-destructive testing (used for informational purposes only) and electrical bonding tests. The sample of devices is then fired, and post-fire examination is used to determine if the devices operated correctly. If any devices in the sample fail then the lot is rejected, otherwise the lot is accepted for flight use.

For this single-sample LAT the plan is defined by the sample size *n,* the acceptance number *c*, and the environmental level defined as the intensity of the random vibration and shock test. If the observed number of failed devices in the LAT is less than or equal to *c*, the lot will be accepted. For electronic explosive devices (EEDs), 30 devices or 10% of the lot, whichever amount is greater, are tested. For non-EEDs, 9 devices or 10% of the lot, whichever amount is greater, are tested (DOD, 1996). For pyrotechnic devices *c* is usually equal to 0, so a lot is accepted for flight use if all the tested devices pass the LAT.

An important measure of the LAT performance is the operating-characteristic (OC) curve (Montgomery, 2005). The OC curve depicts the discriminatory power of an acceptance sampling plan. The OC curve plots the probability of accepting a lot, P_a, versus the fraction defective, or in this case, the probability a device will fail the LAT, *p*. The OC curve is used to determine the sampling risks. The probability of accepting a lot when $c = 0$ is

$$\boldsymbol{P_a = P\{0\ defectives\ in\ n\ tests\} = (1 - p)^n} \qquad (1)$$

The OC curves are plotted in Figure 1 for several different sample sizes.

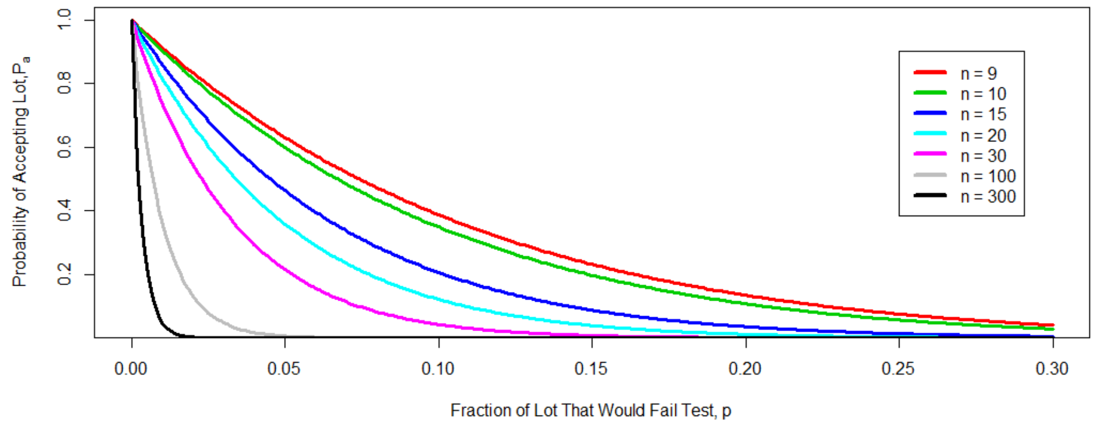

Figure 1: OC When $c = 0$

The OC curve shows the power of the LAT plan. The actual value of p is unknown, so what this plot does is show the probability of accepting the lot for all p values. For example, in the plan with $n = 9$, if 5% of the lot has devices that would fail the LAT, the probability of acceptance is about .63. This means we would expect to accept 63% lots that contain 5% LAT failures and reject 37% of the lots. Now if the sample size is $n = 100$, then we would almost always reject lots with 5% or more devices that would fail in LAT.

The environmental levels used in LAT, shock and random vibration amplitudes, are usually set at the maximum predicted environment (MPE), defined as the upper 50% confidence bound on the estimated 95th percentile of the flight environment, plus a margin of 6 dB (DOD, 1996). The random vibration is applied for a sufficient amount of time, and the shock is applied a specified number of times along each axis. For more details see (Air Force Space Command, 2014, MIL-

STD-1576,1984, and AIAA Standard, 2005). So, a device passing a LAT is not equivalent to operating during flight after seeing a flight environment. In the next section we show how LAT results can be used to measure the risk of devices failing during flight.

LAT ENVIRONMENT LEVELS AND DEVICE CAPABILITY

Flight-to-flight variability of the spectral value at a frequency for acoustic, random vibration, shock, and sinusoidal vibration environments is baselined to be log-normally distributed (Pendelton & Henrikson, 1983). That is, the normal distribution applies to the logarithms of the spectral values at a given frequency. Consequently, the logarithmic values of the available spectral values have a normal distribution with mean denoted by μ_F and standard deviation denoted by σ_F. Figure 2 shows the distribution of the log-spectrum and the maximum predicted environment (MPE), and LAT environment level.

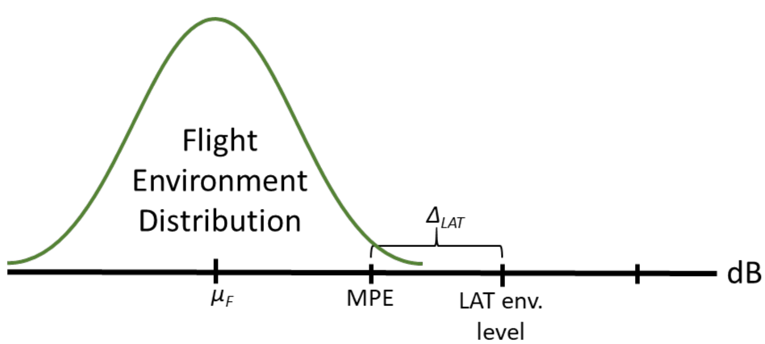

Figure 2: Distribution of the Logarithm of the Flight Spectral Values at a Given Frequency

Tolerance bounds on flight environments are defined by a probability P that the logarithm of the spectrum will not be exceeded in flight and a upper one-sided confidence level of C (denoted P/C). MPE is the 95/50 upper tolerance bound (P = 0.95 and C = 0.50) which is equal to $\mu_F + \sigma_F Z_{.95}$, where $Z_{.95}$ is the 95th percentile of the standard normal distribution (Womack, 2014 and Meeker, Hahn & Escobar, 2017). Lot acceptance testing is performed at MPE plus a margin of Δ_{LAT} , usually 6 dB (DOD, 1996). One approach for deriving test levels is by assuming σ_F = 3 dB, which was shown to be a reasonable upper bound for flight environments (Pendelton & Henrikson, 1983). The MPE is then calculated as $\mu_F + 3Z_{.95} = \mu_F + 4.9$ dB. The lot acceptance tests are then performed at μ_F + 10.9 dB. Another approach for deriving qualification and lot acceptance test levels is to derive parameter estimates of the flight distribution from actual flight data.

Device capability is defined to be the amount of shock and vibration that the device can withstand before it will fail to operate when fired. The distribution of device capability describes variability associated with a lot's ability to survive shock and vibration environments (e.g. structural capability). Figure 3 shows the device capability distribution with the flight environment distribution.

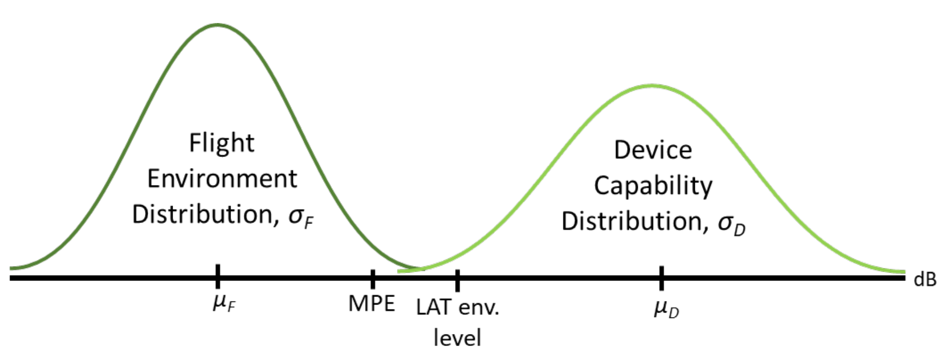

Figure 3: Distributions of Log Flight Environment and Log Device Capability

When a device's capability is exceeded by its test or flight environment the component fails.

Here we define device reliability as the probability the device will fire after experiencing the flight environment for a single launch. Unfortunately, the device capability distribution along with its mean, μ_D, and standard deviation, σ_D, are not known. The objective of LAT is looking for lots with a mean or standard deviation that throw the tail of the distribution too far to left underneath the flight environment distribution.

The larger the separation between the flight environment and device capability distributions the better the device reliability. So, if the environment level used for the LAT is large enough and the lot is accepted then we can say the reliability of the devices in the lot is high.

USING LAT RESULTS TO CHARACTERIZE DEVICE RISK OF FAILURE

The probability that a device fails during flight is

$$\boldsymbol{P_f = P(X < Y)} \tag{2}$$

Where Y is the flight environment and X is the device capability. Equation 2 can also be rewritten as a function of the device capability and flight environment parameters and the normal cumulative distribution function, **Φ**,

$$\boldsymbol{P_f = P(X - Y < 0)}$$

$$\boldsymbol{= P\left(\frac{X - Y - (\mu_D - \mu_F)}{\sqrt{\sigma_D{}^2 + \sigma_F{}^2}} < \frac{-(\mu_D - \mu_F)}{\sqrt{\sigma_D{}^2 + \sigma_F{}^2}}\right)}$$

$$\boldsymbol{= P\left(Z < \frac{-(\mu_D - \mu_F)}{\sqrt{\sigma_D{}^2 + \sigma_F{}^2}}\right)}$$

$$\boldsymbol{= \Phi\left(\frac{-(\mu_D - \mu_F)}{\sqrt{\sigma_D{}^2 + \sigma_F{}^2}}\right)} \tag{3}$$

The probability that a lot with a sample size of n devices passes LAT (Equation 1) can also be computed as a function of the device capability and flight environment parameters,

$$\boldsymbol{P_a = P(all\ n\ devices\ tested\ have\ X > MPE + \Delta_{LAT})}$$

$$\boldsymbol{= [P(X > MPE + \Delta_{LAT})]^n}$$

$$\boldsymbol{= \left[1 - \Phi\left(\frac{MPE + \Delta_{LAT} - \mu_D}{\sigma_D}\right)\right]^n} \tag{4}$$

The common variables in Equations 3 and 4 are μ_D and σ_D, the mean and standard deviation of the device capability distribution. The variable μ_D can be eliminated in Equation 4 by solving for μ_D in Equation 3 and substituting into Equation 4 giving

$$\boldsymbol{P_a} = \left[\mathbf{1} - \boldsymbol{\Phi}\left(\frac{\boldsymbol{MPE} + \boldsymbol{\Delta_{LAT}} - \boldsymbol{\mu_D}}{\boldsymbol{\sigma_D}}\right)\right]^{\boldsymbol{n}}$$

$$= \left[\mathbf{1} - \boldsymbol{\Phi}\left(\frac{\boldsymbol{MPE} - \boldsymbol{\mu_F} + \boldsymbol{\Delta_{LAT}} + \boldsymbol{\Phi}^{-1}(\boldsymbol{P_f})\sqrt{\boldsymbol{\sigma_D^2} + \boldsymbol{\sigma_F^2}}}{\boldsymbol{\sigma_D}}\right)\right]^{\boldsymbol{N}} \tag{5}$$

Because the flight environment standard deviation is either known from previous flight measurements or it can be bounded using SMC-S-016, MPE – $\mu_F = \sigma_F Z_{.95}$ is a considered a known value, and the test level, Δ_{LAT}, is also known. The only unknowns in Equation 5 are P_f and σ_D. We plot P_a versus P_f for given values of σ_D to show the risk of failure during flight for a lot of devices together with the probability the lot is accepted. The device standard deviation, σ_D, is unknown but subject matter experts believe it is bounded between 1 and 3 dB.

Consider first the baseline LAT case using the bounding flight environment case given in SMC-S-016 (Air Force Space Command, 2014) which has σ_F = 3 dB and so MPE = $\mu_F + Z_{.95}\sigma_F = \mu_F$ + 4.9 dB. Figure 4 is called a risk plot for a LAT with a sample size of 10 and an environmental test level of MPE + 6 dB.

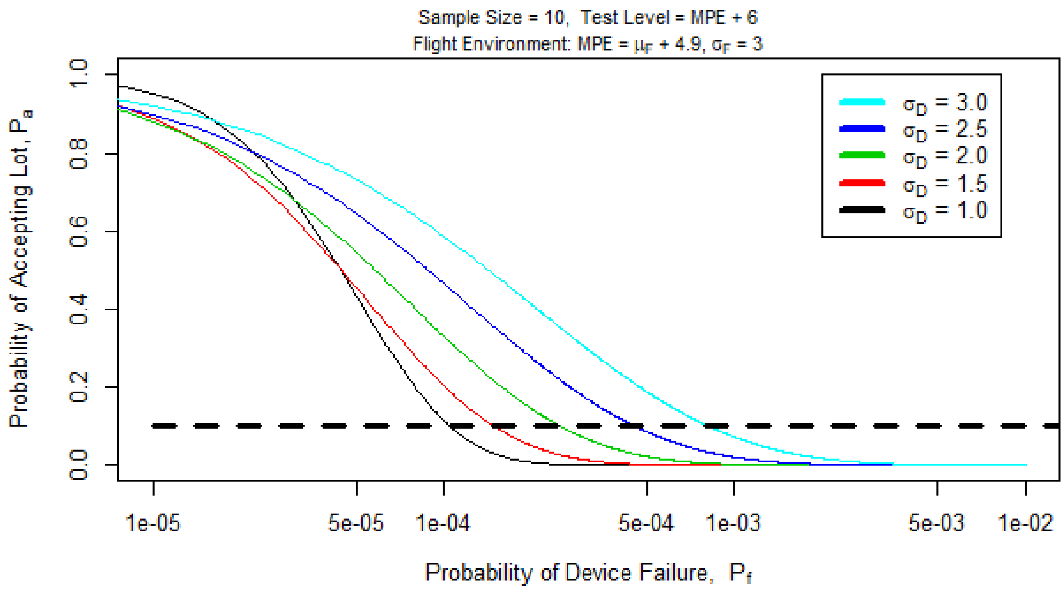

Figure 4: Baseline Risk Plot (P_a Versus P_f) for n = 10, Δ_{LAT} = 6, and SMC-S-016 Flight Environment

When P_f approaches zero the probability of accepting the lot approaches 1 and as P_f increases the probability of acceptance decreases. The faster P_a decreases the better the LAT plan. In Figure 4 the smaller device capability standard deviations, σ_D, the better the LAT plan. Hence at this test level, $\Delta_{LAT} = 6$, the smaller the standard deviation of the device the better the test plan. The horizonal line at $P_a = .1$ is a reference line used as a guideline. When P_a is .1 or larger we say there is significant risk of accepting a lot. The value of P_f when $P_a = .1$ is called the risk level. For the baseline case in Figure 4 the worst-case risk level is .0008 (< 1 out of 1000) which occurs when σ_D = 3 dB.

Additional baseline cases are shown in Figures 5 and 6 for larger lot sizes. Figure 5 is for a lot size of 300, n = 30, and Figure 6 is for a lot size of 1000, n = 100.

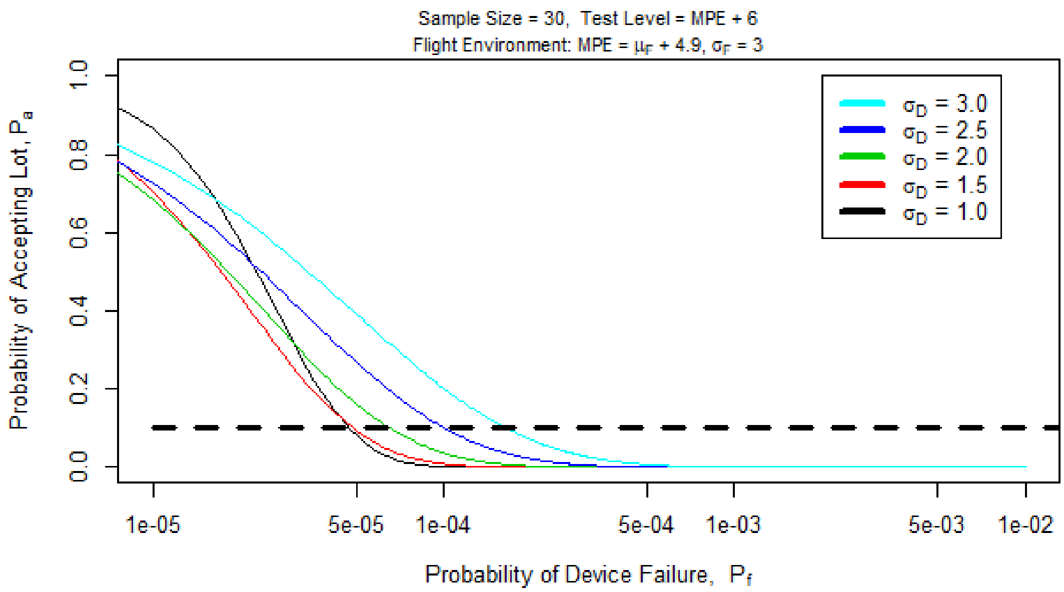

Figure 5: Baseline Risk Plot for n = 30, Δ_{LAT} = 6, and SMC-S-016 Flight Environment

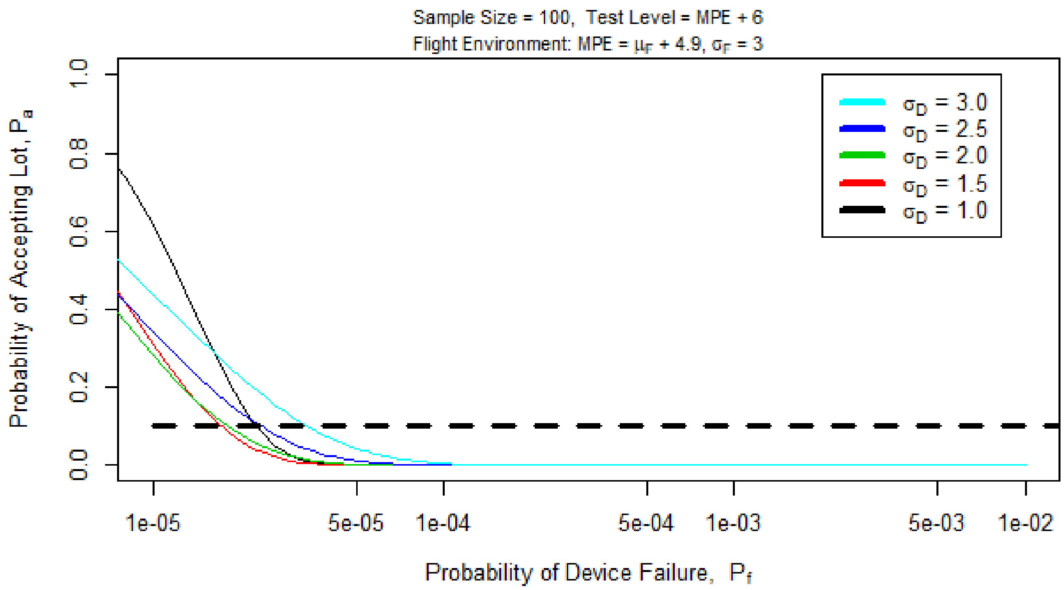

Figure 6: Baseline Risk Plot for n = 100, Δ_{LAT} = 6, and SMC-S-016 Flight Environment

When n = 30 the worst-case risk is less than .0002 and when n = 100 the worst-case risk is less than .00004. If the acceptable risk level is higher than these values, then the baseline LAT can be modified by reducing the sample sizes or reducing the LAT environmental test level.

MEASURING RISKS ASSOCIATED WITH MODIFIED LAT

Recently, modifications of test methods have been proposed to reduce cost of testing flight units. The main objective is to reduce the chance of having failures due to possible over testing during lot acceptance environmental testing, thereby removing costs for root cause investigations and process delays at the cost of increased program risk. The approach is to reduce the environmental test levels or sample size of LAT. One proposed modification is to reduce the level of environmental stress used in the LAT to as low as MPE + 3 dB and reduce the sample size in lots greater than 300 devices. The increase in program risk can be quantified using the methods described in this paper.

Figures 7-8 show the risk plots for n = 10 with test levels from baseline MPE + 6 dB to MPE + 3 dB for σ_D = 1 and 3 dB using the SMC-S-016 flight environment.

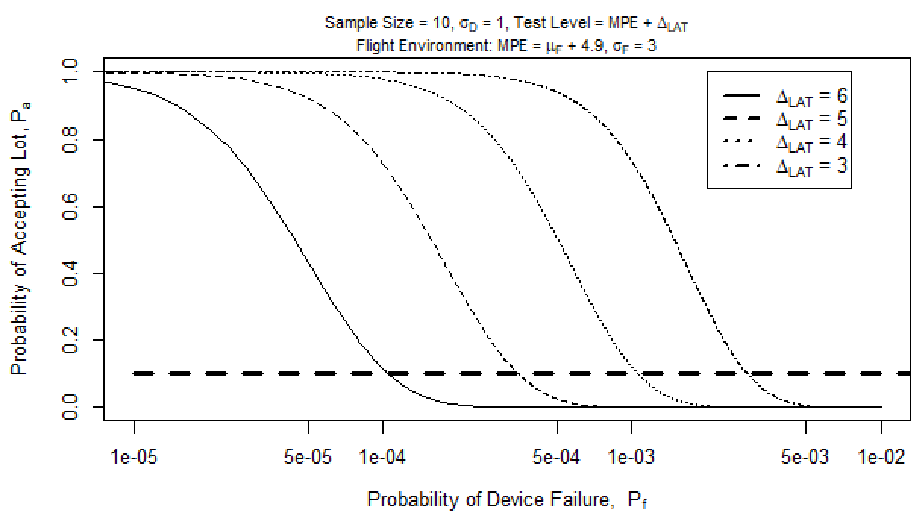

Figure 7: Risk Plot for n = 10, σ_D = 1, and SMC-S-016 Flight Environment

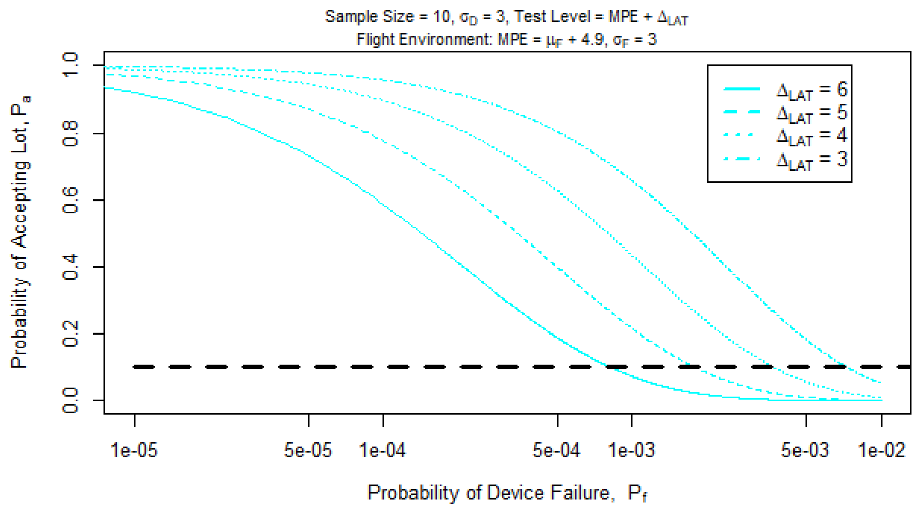

Figure 8: Risk Plot for n = 10, σ_D = 3, and SMC-S-016 Flight Environment

In these cases, there are major increases in the risk levels over the baseline case with Δ_{LAT} = 6 dB. In Figure 8 the worst-case risk is over .007 (when Δ_{LAT} = 3 dB). It is not recommended to reduce the LAT test level for small sample sizes.

Figures 9-10 show the risk plots for n = 30 with test levels from baseline MPE + 6 dB to MPE + 3 dB for σ_D = 1 and 3 dB using the SMC-S-016 flight environment.

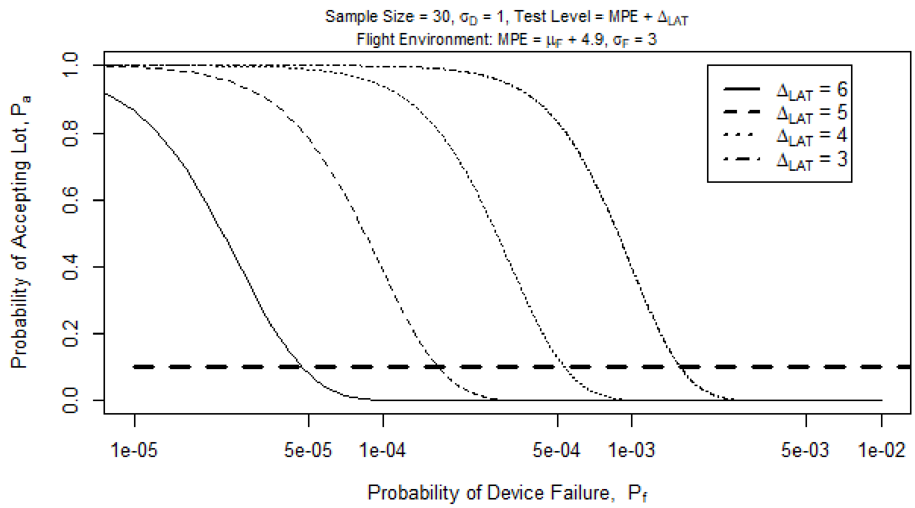

Figure 9: Risk Plot for $n = 30$, $\sigma_D = 1$, and SMC-S-016 Flight Environment

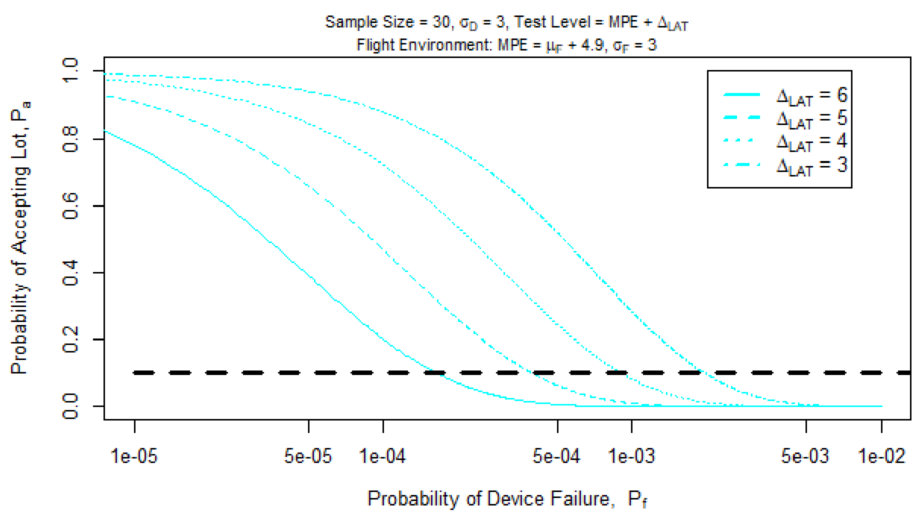

Figure 10: Risk Plot for $n = 30$, $\sigma_D = 3$, and SMC-S-016 Flight Environment

In these cases, if an acceptable risk level is 1/1000, the LAT environmental test level could be reduced to MPE + 4 dB but not to MPE + 3 dB.

Figures 11-12 show the risk plots for n = 100 with different test levels from baseline to MPE + 3 dB for σ_D = 1 and 3 dB using the SMC-S-016 flight environment.

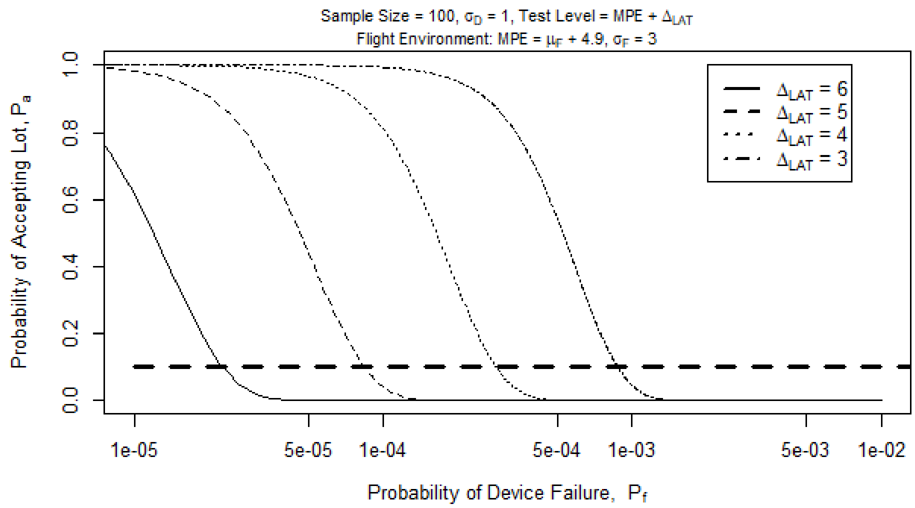

Figure 11: Risk Plot for n = 100, σ_D = 1, and SMC-S-016 Flight Environment

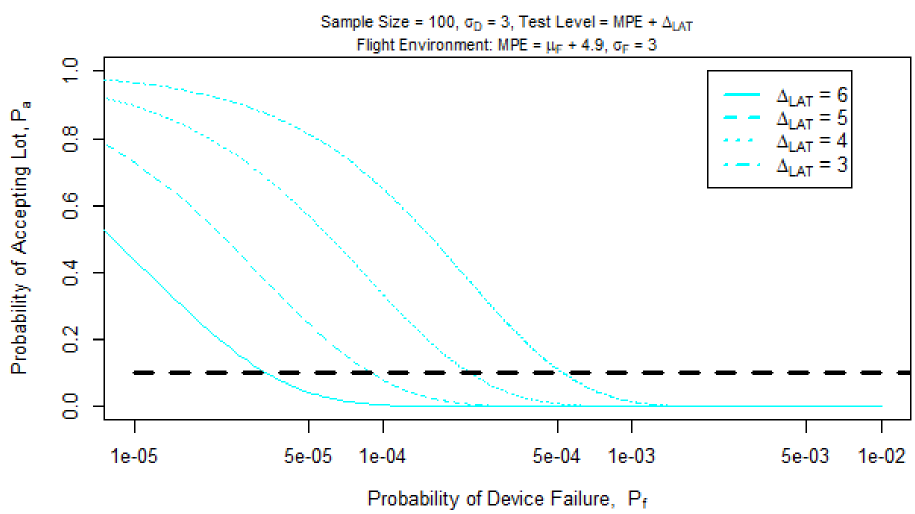

Figure 12: Risk Plot for n = 100, σ_D = 3, and SMC-S-016 Flight Environment

In these cases, if an acceptable risk level is 1/1000, the LAT environmental test level could be reduced to MPE + 3 dB. In fact, the sample size can also be reduced to n = 80 as shown in Figure 13. Another interesting observation from Figures 11 and 12 is the fact that the smaller the device standard deviations, the higher the risk. This is because for larger sample sizes the device mean must be smaller for the small device standard deviations to obtain the same P_a as devices with larger standard deviations. This then affects the P_f as can be seen in Equation 3. This effect does not occur when the environmental test levels are larger.

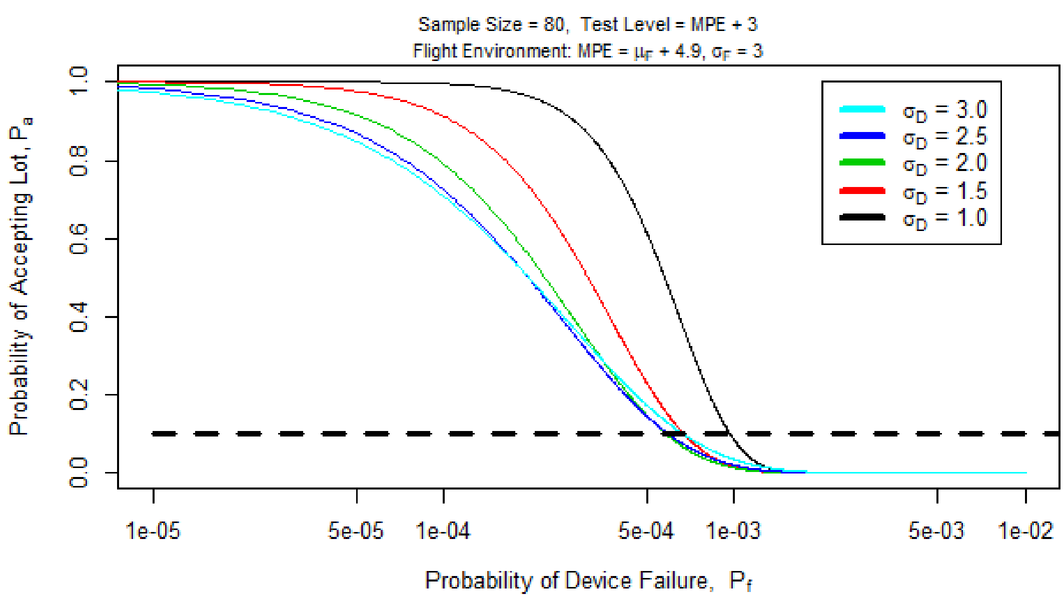

Figure 13: Risk Plot for n = 80, Δ_{LAT} = 3, and SMC-S-016 Flight Environment

Another effect on these risk plots is the assumed flight environments. If actual flight data is available, it can and should be used to estimate the flight environment distribution parameters. Suppose there is enough flight data to determine that a reasonable estimate of σ_F is 1.5 dB. Then MPE = $\mu_F + \sigma_F Z_{.95} = \mu_F$ + 2.5 dB. Figure 14 shows the small sample case of n = 10 and LAT test level of MPE + 6 using the estimated flight environment. Compared to the SMC-S-016 flight environment the maximum risk level has reduced from .0009 to .0006.

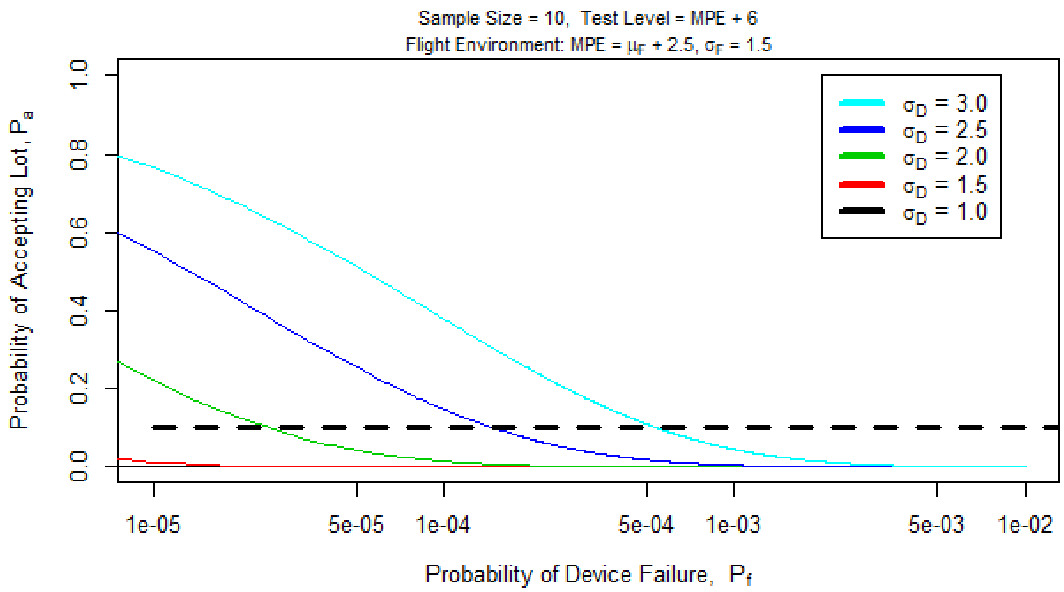

Figure 14: Risk Plot for n = 10, Δ_{LAT} = 6, and Estimated Flight Environment with σ_F = 1.5

Figure 15 shows the medium sample size case of n = 30 and LAT test level of MPE + 4 using the estimated flight environment. Compared to the SMC-S-016 flight environment the maximum risk level has reduced from .0008 to .0006.

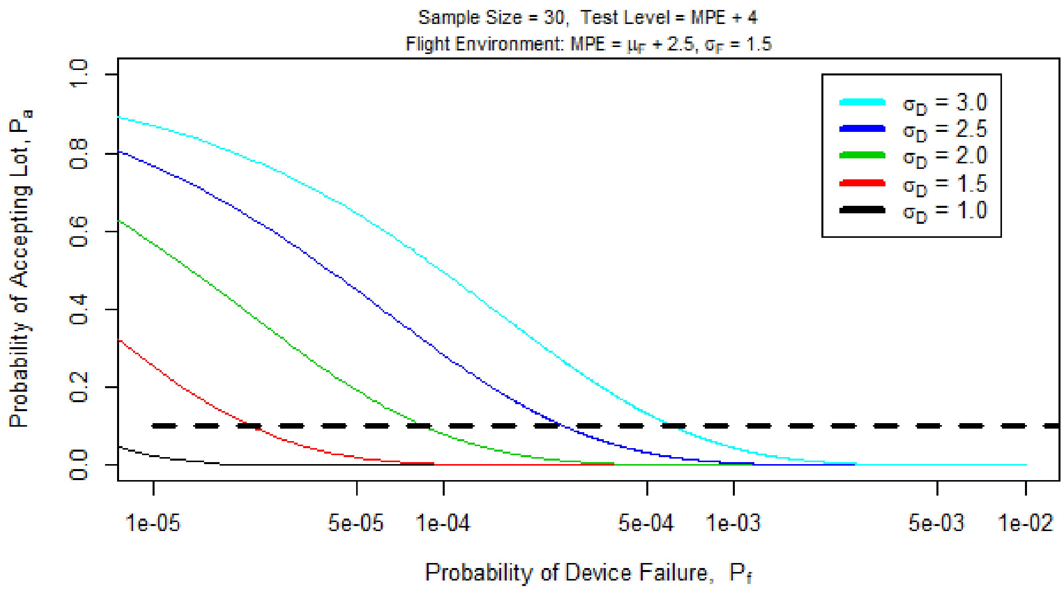

Figure 15: Risk Plot for $n = 30$, $\Delta_{LAT} = 4$, and Estimated Flight Environment with $\sigma_F = 1.5$

Figure 16 shows the large sample case of $n = 80$ and LAT test level of MPE + 3 using the estimated flight environment. Compared to the SMC-S-016 flight environment the maximum risk level has reduced from .001 to .0004 which would allow a further reduction of the LAT sample size if desired.

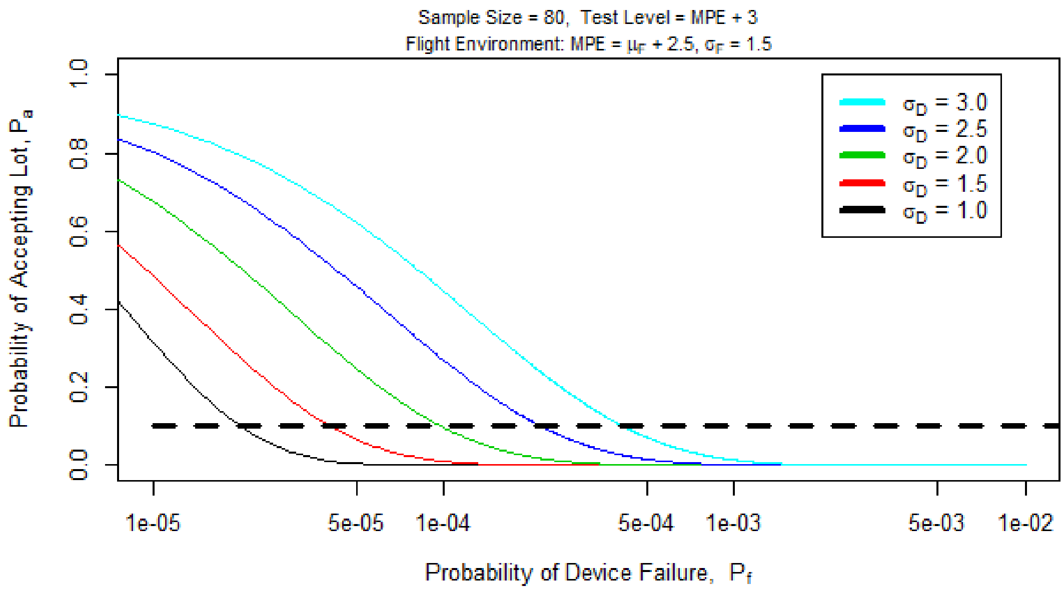

Figure 16: Risk Plot for n = 80, Δ_{LAT} = 3, and Estimated Flight Environment with σ_F = 1.5

SUMMARY/CONCLUSIONS

A statistical method to evaluate flight risk in pyrotechnic devices using results from lot acceptance tests has been developed and used to show the impacts to flight risk from reducing LAT sample sizes and LAT environmental test levels. It has been shown that for small lot sizes, reducing environmental test levels significantly increases the risk of device failure during flight. For larger lots, from a well-controlled process, it is possible to reduce the environmental test levels and even the sample size if the lot is large enough. It was also shown that using actual flight environment distribution parameters has a small but not insignificant effect on determining the best values for sample size and environment test levels for lot acceptance testing. This statistical method of computing risks should be used in developing new LAT standards which account for the many variables in lot acceptance testing of pyrotechnic devices.

Additional improvements to estimating evaluating flight risk from LAT would be to perform tests to estimate the device capability distribution. The methods described in (Dixon & Mood, 1948 and Neyer, 1994) can provide estimates of the device capability distribution but require testing under environments they would produce device failures. Perhaps this type of testing could be done during qualification testing and then the methods described in this paper could be applied during lot acceptance testing using the estimated value for σ_D during qualification testing.

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