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## **Signature Analysis**

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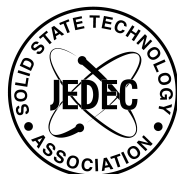
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**SIGNATURE ANALYSIS****CONTENTS**


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	Page
<b>1 Introduction</b>	1
<b>2 Purpose</b>	2
<b>3 Scope</b>	2
<b>4 Definitions</b>	3
<b>5 Signature analysis procedure for an ongoing process</b>	3
5.1 Overview	3
5.2 SA process flow	4
5.3 Signature analysis definition phase	4
5.4 SA validation	5
5.5 Revalidation	5
<b>6 Signature analysis procedure for a finite population</b>	5
<b>7 Examples</b>	6
7.1 Finite population case	6
7.2 Ongoing process	6
<b>Annex A An approach of signature analysis risk assessment procedures for an ongoing process</b>	7
A.1 Statistical terms and variables	7
A.2 Statistical derivation of an estimate for $\theta$	8
A.3 Statistical derivation of confidence intervals for $\theta_A$	9
<b>Annex B An approach to signature analysis risk assessment procedures for a finite population</b>	11
<b>Annex C An approach to signature analysis risk assessment procedures for a process with correlated failures</b>	13
C.1 Statistical terms and definitions	13



## SIGNATURE ANALYSIS

(From JEDEC Board Ballot JCB-98-124, formulated under the cognizance of the 14.6 Committee on Failure Analysis.)

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### 1 Introduction

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Device Analysis is a limited resource that should be targeted at solving unknown problems, rather than analyzing repetitive failures. Signature Analysis (SA) is a lab resource management tool in that it provides a formal method of reducing the number of these repetitive failures requiring full analysis. Two statistical models are presented, both of which assign a confidence level to any number of units with the same failure characteristics (i.e., signature) and same failure mechanism, allowing the statement “I am A% sure that greater than B% of other parts with this signature will also have this failure mechanism”. One model is for use when the failing population size is finite and known, and will be referred to as ‘finite population analysis’ (FPA). It would be used, for example, to define the sampling plan for a low yielding wafer lot, i.e., to determine how many failing dice from each failure category must be fully analyzed in order to infer information about that whole wafer lot. The other model, referred to as ‘ongoing process analysis’ (OPA) assumes the population of future fails is unknown or infinite, and would be used to infer information about failures collected over time from multiple events, lots or labs. The use of two models also allows us to build-in the engineering bias that we would expect higher confidence levels when we do failure analysis by inference on finite population failures, than on ones collected over time.

The backlog of analysis labs often includes device failures for which both the product engineer and analyst ‘know’ what will be found during analysis. However, corporate specifications and/or customer requirements often dictate that the analysis be performed anyway. There is a need to be able to assign a failure mechanism (with a statistically determined confidence level) to devices that are analyzed by inference to historical data.

There is a desire to promote a common definition of this system of analysis by inference, using the same statistical techniques, and to recognize that it is a formal means of doing failure analysis.

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## **2 Purpose**

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The purposes of these guidelines are the following:

- (a) To define a process of analyzing failures by inference to previous traditional analyses of devices with the same failure characteristics, using a statistical and quantitative approach.
- (b) To provide statistical models for assigning confidence levels to analysis by inference.
- (c) To help gain acceptance of analysis by inference techniques through consensus of terminology and methodology.
- (d) To provide examples of its use.

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## **3 Scope**

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This method of analysis by inference may be applied to customer returns, failures from quality conformance testing, reliability failures, qualification failures, and devices from engineering experiments and yield issues.

Analysis by inference may be used either when the failing population is known and finite, (to define a yield analysis sampling plan of a wafer lot, for example), or when the failing population is unknown and assumed to be infinite.

Using SA does not necessarily imply that the root cause is known or understood, nor does it necessarily imply that a corrective action will or should take place, but SA can be used in conjunction with other programs that address these needs.

It is not the intention of this document to do the following:

- (a) Define acceptable confidence levels.
- (b) Define an SA database, reporting or tracking system.
- (c) Provide SA implementation details.

Individual companies may create the policies and procedures to formalize the SA process in line with these guidelines.

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## 4 Definitions

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**Signature:** The necessary and sufficient information about a failure that establishes a strong relationship between failure characteristics and failure mechanism. This necessary and sufficient information could include emission microscopy results, morphology data, test data, IV-curves, environmental history, etc. and therefore could be either electrical or physical in nature. The scope of application may be time-based, lot-based, package-based, design-based, etc.

**Signature Analysis (SA):** A method to reduce the number of comprehensive failure analyses by application of statistical inference techniques.

**Ongoing Process Analysis (OPA):** The application of Signature Analysis to an unknown (assumed to be infinite) population of failures collected over time from multiple lots, events, or labs.

**Finite Population Analysis (FPA):** A special case of Signature Analysis where the signature occurs in a particular finite population of devices.

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## 5 Signature analysis procedure for an ongoing process

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### 5.1 Overview

The Signature Analysis process consists of the following phases:

**Signature Definition** - Determining which characteristics of repetitive failures define the signature.

**Validation** - A sufficient number of devices should be analyzed using traditional physical analysis methods in order to say “we are A% confident that at least B% (the proportion) of all devices with the same signature will reveal the same failure mechanism”. The annexes describe statistical techniques that can be used to determine confidence levels.

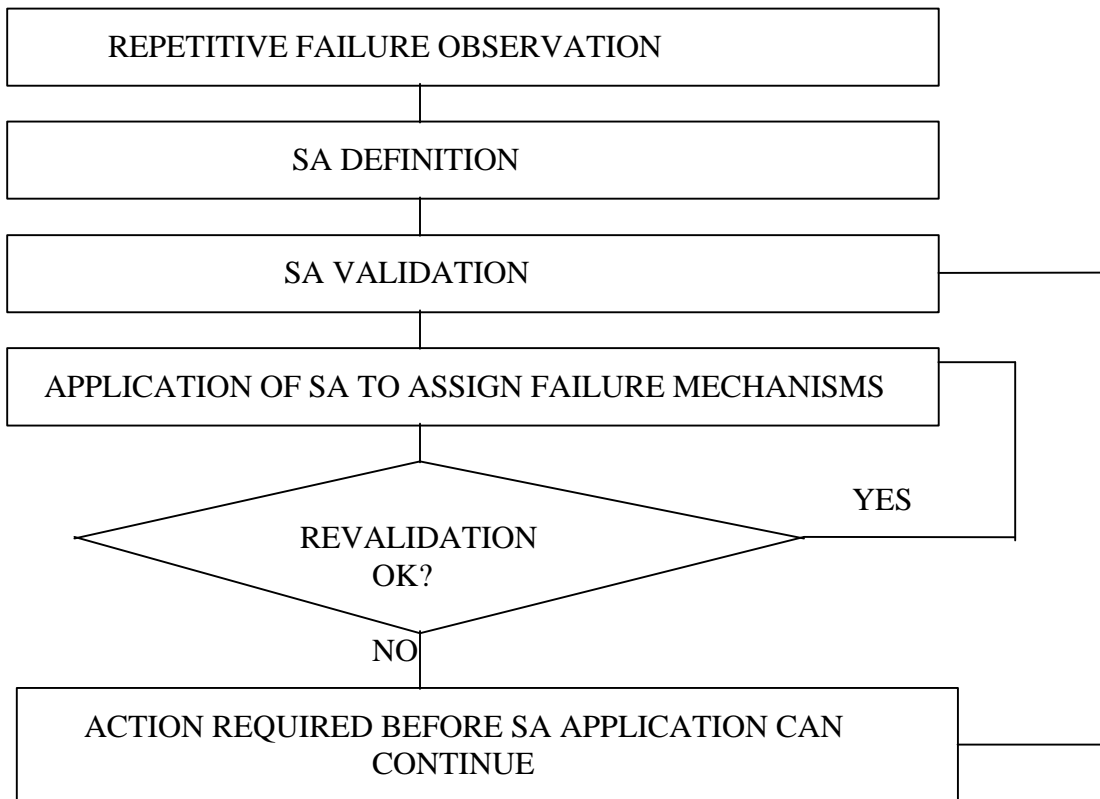
**Application** - Devices may be assigned a failure mechanism without physical analysis, but by inference to previously analyzed devices with the same signature.

**Revalidation** - Periodic reverification of the relationship between the signature and mechanism using traditional physical analysis methods.



## 5 Signature analysis procedure for an ongoing process (cont'd)

### 5.2 SA process flow



### 5.3 Signature analysis definition phase

- (a) Repetitive failures will be used to initiate a Signature Analysis definition. The failures should show electrical or physical evidence supporting the claim that they have the same failure signature and mechanism.
- (b) The repetitive failures can represent FPA or OPA signatures.
- (c) Ongoing process SA samples should be from randomly selected lots.
- (d) Finite population SA samples imply that the scope of the resulting SA report is only for this population. In other words, only additional parts from this same population may be analyzed by inference.
- (e) Historical data should be studied to identify trends that could help define the scope of the failure.

## **5 Signature analysis procedure for an ongoing process (cont'd)**

### **5.4 SA validation**

After signature definition, a sufficient number of devices must be completely analyzed by physical analysis methods with the same failure signature and mechanism to satisfy desired confidence level requirements.

### **5.5 Revalidation**

This procedure is to guard against the possibility that some hidden variables might have changed, causing the reported relationship between the failure signature and the failure mechanism to become invalid.

A revalidation process consists of performing a traditional physical analysis of at least one device with the signature in question to confirm that the inferred failure mechanism remains valid.

Revalidation may be performed based on frequency of units with a given signature or based on time.

If the failure mechanism of the revalidation device does not match the inferred mechanism, then revalidation fails and action should be taken. Suggested actions include

- (a) Reevaluation of the original scope of application of the signature.
- (b) Traditional physical analysis of other devices analyzed by inference to this signature.

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## **6 Signature analysis procedure for a finite population**

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The SA Procedure for FPA would consist of the Signature Definition, Validation and Application steps described in the previous section, with a different statistical model used to determine confidence levels and number of required analyses. The Revalidation step would not apply.

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## 7 Examples

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### 7.1 Finite population case

Ten units in lot 123 have all failed the 168 hour life test readpoint. The failure mode was reported as ‘functional failures’, and further work in the failure analysis lab on one unit showed a photon emission site at the input protection circuitry of pin 1. Curve tracing the ten devices at different biasing conditions shows they all have the same leakage characteristics for pin 1. It is hypothesized that all ten failures have the same signature, defined as the failure mode plus the other observed characteristics. Traditional physical analysis techniques (in this case, layer etching and SEM) are performed on three of the units and all have the same mechanism, poly filamentation at the same location in the pin 1 input protection circuitry, indicating ESD damage. According to Annex B it can be conclude that “we are 90% confident that 70% of the remaining 7 units will also have this same mechanism”. Therefore, the decision as to whether or not to analyze more units depends upon our prescribed level of risk.

### 7.2 Ongoing process

Engineering has noticed that over the last three months they have analyzed 13 units of device ABC from various lots. In each case the device failed after 500 temperature cycles, and the reported failure mode, observed characteristics and failure mechanism are the same. The lab then receives two more units of device ABC, also temperature cycle rejects, with the same signature. Before performing traditional deprocessing analysis on these two latest units the lab can conclude “we are 90% confident that 85% of other units with this signature will also have this mechanism”. (See Annexes A and C).

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## Annex A An approach of signature analysis risk assessment procedures for an ongoing process

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The following section defines and documents the procedure for determining the risk of assigning a failure mechanism to a series of analyses of devices of one particular failure signature. The failing population size is unknown and assumed to be infinite.

### A.1 Statistical terms and variables

“n” denotes the number of devices analyzed with a particular signature; or the number proposed hypothetically in an inference calculation.

“x” denotes the number of analyses (among the n) resulting in the primary failure mechanism: also denoted  $x_A$ .

“ $\theta$ ” (a number,  $0 \leq \theta \leq 1$ ) is the true, long term proportion of devices with the signature in question that would result in the primary failure mechanism, if analyzed: also denoted  $\theta_A$ .

For a given  $\theta$ , x is statistically distributed as a Binomial distribution with parameters n and  $\theta$ . This is denoted

$$f(x|\theta) = \binom{n}{x} \theta^x (1 - \theta)^{n-x} \sim B(n, \theta)$$

The statement that  $\theta$  is distributed as a Beta distribution with parameters  $\alpha$  and  $\beta$  is denoted

$$g(\theta) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \theta^{\alpha-1} (1 - \theta)^{\beta-1} \sim Be(\alpha, \beta)$$

Note: Notice that the Binomial and Beta families of distributions have the same form:  $K_1 \theta^{K_2} (1-\theta)^{K_3}$ , for different “K” values in the two distribution families. To keep from confusing them, remember . . .

- (1) The Beta is a distribution for  $\theta$  and ranges from 0 to 1 continuously. It integrates to 1:

$$\int_0^1 g(q) dq = 1.$$

- (2) The Binomial is a distribution for x (the power of  $\theta$ ) and ranges over the integers from 0 to n discretely.

It sums to 1:  $\sum_{x=0}^n f(x|\theta) = 1.$

## Annex A An approach of signature analysis risk assessment procedures for an ongoing process (cont'd)

### A.2 Statistical derivation of an estimate for $\theta$

The distribution of  $x$  (the number of analyses that result in failure mechanism A, the consistent result) given the true proportion is a Binomial Distribution:

$$f(x | \theta) \sim B(n, \theta) = K_1 \theta^x (1-\theta)^{n-x}.$$

This is called the conditional distribution. The constant  $K_1$  is easily looked up, and not spelled out here to make the development easier to read.

Since  $\theta$  is unknown, there is uncertainty about it that can be expressed as a distribution:  $g(\theta)$ . This is called the prior distribution. We will assume that  $g(\theta)$  is in the family of Beta Distributions, which has a range from 0 to 1:

$$\theta \sim \text{Beta}(\alpha, \beta) = K_2 \theta^{\alpha-1} (1-\theta)^{\beta-1}.$$

We assume the Beta prior for three reasons: (1) it is a tremendously diverse distribution for different values of  $\alpha$  and  $\beta$ , (2) it includes the “non-informative” Uniform distribution in this family, and (3) it makes the calculations that follow very easy.

We now solve for (1) the joint distribution of  $x$  and  $\theta$ , (2) the marginal distribution of  $x$  (not given  $\theta$ ), and (3) the conditional distribution of  $\theta$  given  $x$ :

$$(1) h(x, \theta) = g(\theta) \bullet f(x | \theta) = K_1 K_2 \theta^{\alpha+x-1} (1-\theta)^{\beta+n-x-1}.$$

$$(2) m(x) = \int_0^1 h(x, \theta) d\theta$$

$$(3) \pi(\theta | x) \sim \text{Beta}(\alpha+x, \beta+n-x) = \frac{K_1 K_2}{m(x)} \theta^{\alpha+x-1} (1-\theta)^{\beta+n-x-1}$$

This third distribution is called the posterior distribution of  $\theta$  given  $x$ . We really don't have to solve for  $m(x)$  in this development. We just note that  $m(x)$  has no  $\theta$ 's so  $\pi(\theta | x)$  is of the same form as  $h(x, \theta)$ , so the posterior distribution with this form for  $\theta$  is also the Beta (we can observe the relevant parameters for the posterior Beta from the powers on  $\theta$  and  $(1-\theta)$ ). When the prior distribution,  $g(\theta)$ , and the posterior distribution,  $\pi(\theta | x)$ , are from the same family (the Beta in this case), that family is said to be the “conjugate prior” for this conditional distribution: the Beta is the conjugate prior for the Binomial.

## Annex A An approach of signature analysis risk assessment procedures for an ongoing process (cont'd)

Now to interpret:  $g(\theta)$  is our prior knowledge about  $\theta$ . After we analyze  $n$  devices, we update our information from those analyses to  $\pi(\theta | x)$ .

In our case, since we have no prior knowledge about  $\theta$ , we will use a “non-informative” prior: by selecting  $\alpha = 1$  and  $\beta = 1$  the Beta becomes the Uniform Distribution. This “non-informative” or “diffuse” prior says that we have no information to think that any  $\theta$  are more likely than any others. This is a commonly used, conservative assumption. Now  $\pi(\theta | x)$  becomes:

$$\pi(\theta | x) = \text{Beta}(x+1, n-x+1).$$

This Beta can also be written as  $\text{Be}(x_A+1, x_B+1)$ .

Note — the mean of this distribution is also the minimum mean squared error estimate of  $\theta$ .

Since the mean of the Beta is  $E[\text{Beta}(\alpha, \beta)] = \frac{\alpha}{\alpha + \beta}$ , then in our case

$$E[\pi(\theta | x)] = \frac{x+1}{n+2}.$$

This is our minimum variance estimator of  $\theta$ . It has a smaller variance than  $p = x/n$  by not being restricted to unbiased estimators. So we gained a smaller variance by sacrificing unbiasedness. Notice that even at the extremes, this estimator is never 0 nor 1.

Therefore, the best (in the sense of minimum mean square error) estimate of the proportion of “failure mechanism A” faults among all devices with the given failure mode is

$$\hat{\theta}_A = \frac{x_A + 1}{n + 2}$$

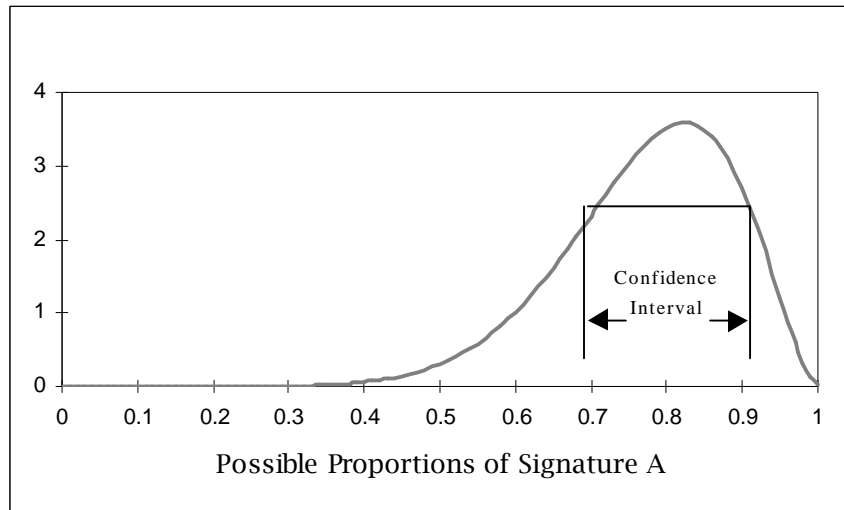
Another good, and often used, estimator is  $\tilde{\theta}_A = \frac{x_A}{n}$

It is the minimum variance, unbiased estimator; but for our application  $\hat{\theta}_A$  is better.

### A.3 Statistical derivation of confidence intervals for $\theta_A$

Confidence intervals for  $\theta_A$  are calculated from  $\text{Be}(x_A+1, x_B+1)$ . The probability that  $\theta_A$  is in an interval  $(k, l)$  is the area under  $\text{Be}(x_A+1, x_B+1)$  over the interval  $(k, l)$ . The optimal interval will “start” at  $x/n$  and “grow” in such a way that the interval will cover where the beta distribution is maximized. See Figure 1.

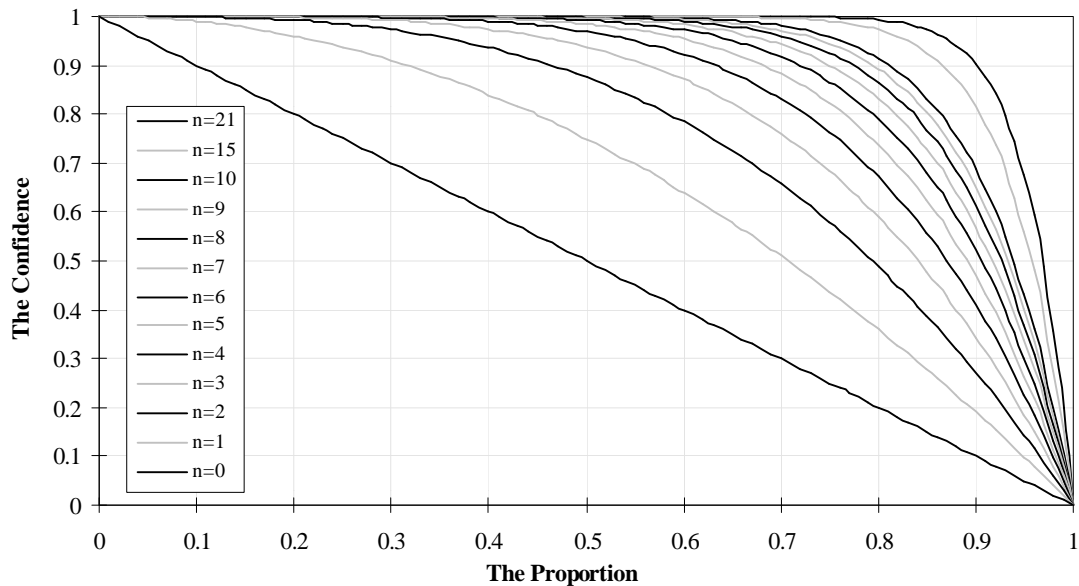
### Annex A An approach of signature analysis risk assessment procedures for an ongoing process (cont'd)



**Figure 1 — Confidence Interval Calculation**

This confidence interval “started” at 0.81 (the high spot in the distribution), and grew in both directions to include the top of the distribution. The growing stopped at  $(k, l) = (0.69, 0.92)$ . There is a trade-off in wanting a short confidence interval,  $(k, l)$ , and a large level of confidence: the area under the distribution over the interval  $(k, l)$ .

Figure 2 can be used to graphically determine the required sample size. If one is required to satisfy 90/80 requirement, for example, than a sample size of 10 is just above the intersection of .8 on the proportion axis and .9 on the confidence axis.



**Figure 2 — Signature Risk Assessment for an Ongoing Process**

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## Annex B An approach to signature analysis risk assessment procedures for a finite population

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The following section defines the procedure for determining the risk of assigning a failure mechanism to a series of analyses of devices of one particular failure signature when the failing population is finite and of known size. The results will not be used to infer anything about future failures. Should similar results occur in a future lot, then the analysis technique should revert back to those in Annex A.

The use of separate risk assessment models for ‘ongoing process’ and ‘finite population’ is an attempt to build-in the engineering bias that we know more information about the latter case and would expect higher confidence levels for the same ‘n’.

- Denote the size of the population with the signature in question by  $N$ , and the number with the candidate failure mode as  $K$  (then  $K \leq N$ ). Further denote the number of devices analyzed by  $n$ , and the number analyzed that result in the candidate failure mechanism by  $k$  ( $k \leq n \leq N$ , and  $k \leq K$ ).

Letter notations	Number of units with the signature of interest	Number of units with the failure mechanism of interest
Population numbers	$N$ (known)	$K$ (unknown)
Sample numbers	$n$ (known)	$k$ (known)

- After a lab has analyzed  $n$  devices, then  $N$ ,  $n$ , and  $k$  are all known, and  $K$  is the parameter of interest.  $K$  is the total number of units with the failure mechanism in question among the  $N$  with the signature of interest.
- For a given  $n$ ,  $N$ , and  $K$ , then  $k$  is statistically distributed as a Hypergeometric distribution with parameters  $n$ ,  $K$ , and  $N$ . This conditional distribution of  $k$  is denoted as:

$$h(k|n, K, N) = \frac{\binom{K}{k} \binom{N-K}{n-k}}{\binom{N}{n}}$$



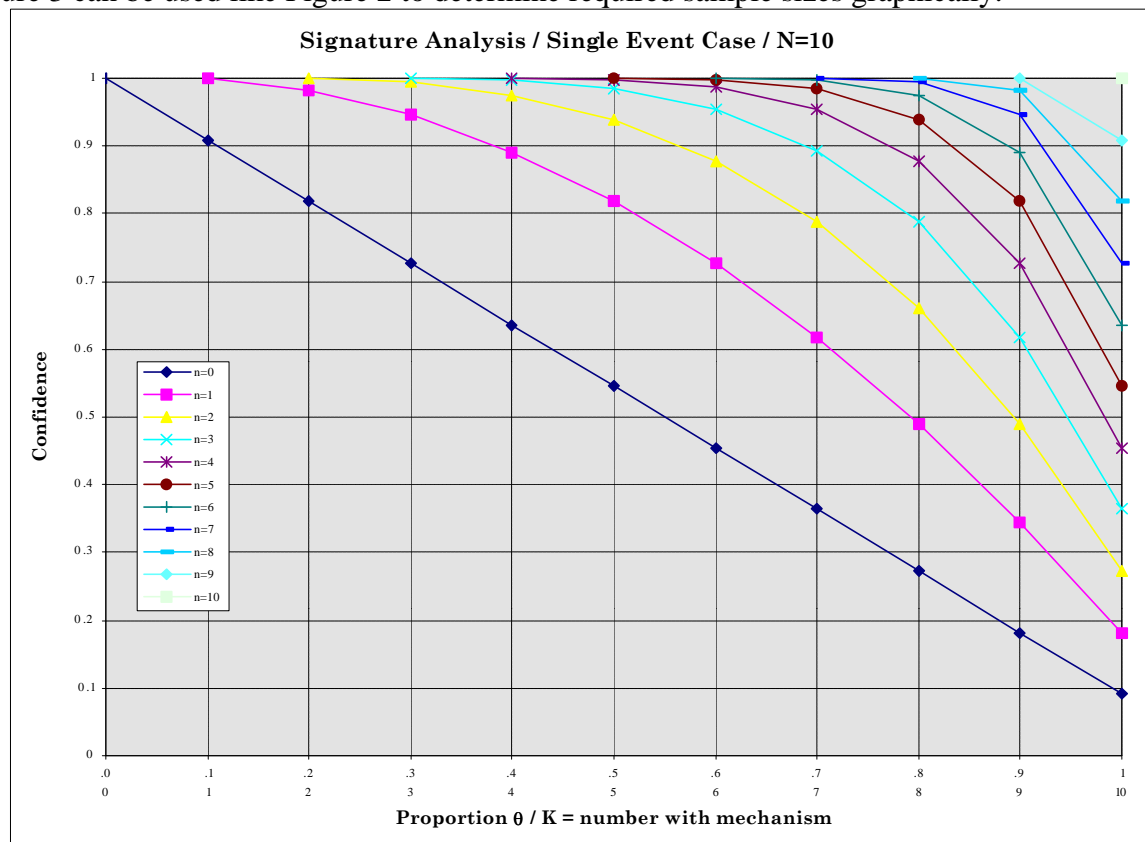
## Annex B An approach to signature analysis risk assessment procedures for a finite population (cont'd)

- If  $k = n$  (that is, all analyses have resulted in the same failure mechanism), then we may use the Bayes Formula as we did in the previous section to derive the posterior distribution of  $K$ :

$$f(K|k,n,N) = \frac{h(k|n,K,N)}{\sum_{K=k}^N h(k|n,K,N)}$$

- For a given  $n$ ,  $N$ , and  $k$  this formula gives the probability that the total number of units with the failure mechanism of interest is  $K$ .
- This formula would be difficult to apply on an individual basis, but can quickly and easily be generated for all possible values of  $K$  in one of the popular spreadsheets, such as EXCEL.

Figure 3 can be used like Figure 2 to determine required sample sizes graphically.



**Figure 3 — Signature Risk Assessment for a Finite Population**

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## Annex C An approach to signature analysis risk assessment procedures for a process with correlated failures

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This section defines and outlines procedures for determining the risk of assigning a signature to a series of parts with a particular failure mode. The population of failed parts are assumed to be correlated and of infinite size.

### C.1 Statistical terms and definitions

“n” denotes the sample size of parts analyzed with the same failure mode

“x” denotes the number of analyzed parts resulting in the same signature

$\theta$  ( $0 \leq \theta \leq 1$ ) denotes the long term proportion of analyzed parts with a specific failure mode due to the same signature.

$\Gamma$  ( $0 \leq \Gamma \leq 1$ ) is a parameter that correlates consecutive parts with a particular failure mode

$\lambda$  ( $0 \leq \lambda \leq 1$ ) is a dependence parameter that correlates consecutive parts with a particular failure mode.

For a given  $\theta$ ,  $x_i$  is distributed as a Bernoulli random variable, with its probability distribution given by

$$f(x_i | \theta) = \begin{cases} \theta^{x_i} (1-\theta)^{1-x_i}, & 0 \leq \theta \leq 1 \\ 0 & \text{otherwise} \end{cases}$$

$x_i$  denotes the  $i$ th analyzed part resulting in the same signature

Define random variable  $Y_i$ , such that

$$Y_i = \begin{cases} X_1 \\ X_i & \text{if } X_i = 1 \\ \max(X_i, X_{i-1}) & \text{if } U_i \geq \Gamma \text{ and } X_i = 0 \end{cases}$$

$U_i$  is a uniform random variable corresponding to the  $i$ th part  $x_i$ . The probability distribution of  $U_i$  is given by

$$f(u_i) = \begin{cases} 1 & 0 \leq u_i \leq 1 \\ 0 & \text{otherwise} \end{cases}$$

### Annex C An approach to signature analysis risk assessment procedures for a process with correlated failures (cont'd)

Random variable  $\gamma_i$  is such that it correlates consecutive parts  $x_i, x_{i-1}$  with a specific failure mode. The probability distribution of  $\gamma_i$  is given by

$$P(\gamma_i=1) = 2\theta - \theta^2 - \Gamma\theta + \Gamma\theta^2$$

$$P(\gamma_i=0) = 1-(2\theta - \theta^2 - \Gamma\theta + \Gamma\theta^2)$$

Extension of the Bernoulli random variables  $x_i$ , with the dependence parameter  $\lambda$  is the following.

$$P(x_i=1 \mid x_{i-1}=1) = \lambda$$

$$P(x_i=0 \mid x_{i-1}=1) = 1-\lambda$$

$$P(x_i=1 \mid x_{i-1}=0) = \frac{(1-\lambda)\theta}{(1-\rho)}$$

$$P(x_i=0 \mid x_{i-1}=0) = \frac{(1-2\theta+\lambda\theta)}{(1-\theta)}$$

When  $\lambda \gg \theta$ , the model comprehends strong correlations among consecutive failed parts.

When  $\lambda = \theta$ , the model degenerates to the standard Binomial distribution

Utilizing the conditional probabilities, the joint probability density of  $x_i$ 's is derived.

Note — The conditional probabilities are derived using the Markov chain property.

The joint probability density of the random variables  $x_i$  ( $i=1,2,\dots,n$ ) is given by

$$\begin{aligned} &P(X_1 = x_1, X_2 = x_2, \dots, X_n = x_n) \\ &= P(X_1 = x_1)P(X_2 = x_2 \mid X_1 = x_1) \dots P(X_n = x_n \mid X_{n-1} = x_{n-1}) \\ &= \theta^{x_1}(1-\theta)^{1-x_1} \prod_{i=2}^n \lambda^{x_{i-1}x_i}(1-\lambda)^{x_{i-1}(1-x_i)} \left( \frac{(1-\lambda)\theta}{(1-\theta)} \right)^{(1-x_{i-1})x_i} \left( \frac{(1-2\theta+\lambda\theta)}{(1-\theta)} \right)^{(1-x_{i-1})(1-x_i)} \end{aligned}$$

Utilizing the joint probability density function above, one can determine the sample sizes ( $c$ ) of failed to be analyzed such that  $x\%$  of future failed parts will result in the same signature with  $y\%$  confidence.

