Defense Nuclear Agency
Alexandria, VA 22310-3398

DNA-TR-93-24

Methods for Developing and Validating Survivability Distributions

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October 1993

Technical Report

CONTRACT No. DNA 001-89-C-0080

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	931001	Technical 921001 – 921228

4. TITLE AND SUBTITLE

Methods for Developing and Validating Survivability Distributions

5. FUNDING NUMBERS

C - DNA 001-89-C-0080
PE - 63224C
PR - SB
TA - SE
WU - DH057780

7. AUTHOR(S)

R. Larry Williams

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Kaman Sciences Corporation
P.O. Box 7463
Colorado Springs, CO 80933-7463

8. PERFORMING ORGANIZATION REPORT NUMBER

K-92-57U(R)

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Defense Nuclear Agency
6801 Telegraph Road
Alexandria, VA 22310-3398
OTA/Yoho

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

DNA-TR-93-24

11. SUPPLEMENTARY NOTES

This work was sponsored by the Defense Nuclear Agency under RDT&E RMC Code B7664D SB SE LTHKT PRPD 1950A 25904D.

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution is unlimited.	

13. ABSTRACT (Maximum 200 words)

Discusses methods that can be used to develop survivability distributions based upon three sources of knowledge. These are (1) available test results; (2) little or no available test data, but a good understanding of the physical laws and phenomena which can be applied by computer simulation; and (3) neither test data nor adequate knowledge of the physics are known, in which case, one must rely upon, and quantify, the judgement of experts. Describes the relationship between the confidence bounds that can be placed on survivability and the number of tests conducted. Discusses the procedure for developing system level survivability distributions from the distributions for lower levels of integration. Demonstrates application of the techniques by defining a communications network for a Hypothetical System Architecture. A logic model for the performance of this communications network is developed, as well as the survivability distributions for the nodes and links based on two alternate data sets, reflecting the effects of increased testing of all elements. Shows how this additional testing could be optimized by concentrating only on those elements contained in the low-order fault sets which the methodology identifies.

14. SUBJECT TERMS		15. NUMBER OF PAGES
Survivability	Confidence	44
Probability	Monte Carlo	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

CLASSIFIED BY

N/A since unclassified.

DECLASSIFY ON

N/A since unclassified.

Summary

A previous report, "The Meaning and Utility of Confidence," DNA-TR-92-83, April 1992, explored and discussed statistical methods and procedures that may be applied to validate the survivability of a complex system of systems that cannot be tested as an entity. It described a methodology where Monte Carlo simulation was used to develop the system survivability distribution from the component distributions using a system model that registers the logical interactions of the components to perform system functions.

This paper discusses methods that can be used to develop the required survivability distributions based upon three sources of knowledge. These are (1) available test results; (2) little or no available test data, but a good understanding of the physical laws and phenomena which can be applied by computer simulation; and (3) neither test data nor adequate knowledge of the physics are known, in which case, one must rely upon, and quantify, the judgement of experts.

This paper describes the relationship between the confidence bounds that can be placed on survivability and the number of tests conducted. It discusses the procedure for developing system level survivability distributions from the distributions for lower levels of integration. It demonstrates application of these techniques by defining a communications network for a Hypothetical System Architecture. A logic model for the performance of this communications network is developed, as well as the survivability distributions for the nodes and links based on two alternate data sets, reflecting the effects of increased testing of all elements. It then shows how this additional testing could be optimized by concentrating only on those elements contained in the low-order fault sets which the methodology identifies.

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SECTION 1

INTRODUCTION

This paper discusses methods for developing survivability distributions for components, subsystems, and systems based upon three types of knowledge: (1) test data; (2) physical principles; and (3) engineering judgment. It also elucidates the relationship between the confidence bounds that can be placed on component and system survivability and the number of tests conducted. The exposition portrays the system survivability distribution for a simple series and a simple parallel system comprised of two components whose survivability distributions for a specified environment have been developed. Finally, a Hypothetical System Architecture (HSA) communication network is conceptualized, a logic model for its performance is developed, and the survivability distributions for the composite system are developed for two alternate data sets. The survivability distributions developed and employed for the communication nodes and data links, given the imposition of a specified nuclear environment, reflect the effects of increased testing. Attention is also given to optimizing ways to increase the confidence that a certain survivability is achieved or to improve system survivability by prioritizing which components or subsystems should undergo additional testing or simulation to cost effectively enhance confidence and survivability.

In this paper we assume that one of the desired and required results from any weapon system development and deployment program is to demonstrate system survivability with high confidence. Indeed, the way to discriminate between alternate survivability protocols will be to compare estimates of the quantitative survivability at fixed confidence, say 90%, or, alternatively, to compare the confidence at which a specified system survivability, say 0.95, can be achieved. The purpose of this paper is to describe how such system-level survivability-confidence measures are developed from available knowledge sources.

As discussed in the references, we treat survivability (S) - the probability of component, subsystem, or system survival - as a random variable and develop its cumulative probability distribution. With developed survivability distributions, we make statements about the certainty or probability with which S lies within specific intervals. The probability that random variable S lies within a specified interval is termed confidence.

In this exposition we have confined the family of probability distributions considered to beta distributions. The reasons for doing so are four-fold: (1) the domain of the beta distribution is the range from 0 to 1, the proper range for a probability (i.e., S); (2) the beta distribution can take an infinite number of shapes by varying its two parameters to accommodate and approximate virtually any single mode probability density function; (3) the beta distribution is the continuous counterpart to discrete binomial distributions which reflect the results of many, if not most, tests, making its use both direct and natural in many situations; (4) an intuition about the meaning of the two beta parameters that relates them to the numbers of successes and failures in n binomial tests provides a method for developing distributions when engineering judgment must be employed.

SECTION 2

DEVELOPING SURVIVABILITY DISTRIBUTIONS

To quantify and place confidence bounds upon system survivability employing the procedures exemplified herein, and more fully developed in Williams et. al., April 1992 and July 1992, requires developing the underlying component, subsystem, and system survivability distributions for the nuclear environments of concern. Obviously, few, if any, nuclear tests of actual component or subsystem hardware will be conducted, and none will be conducted of complex, spatially-distributed systems of systems. The basic question then becomes, how can the survivability of complex systems be quantified and validated from the knowledge bases available or possible to be acquired?

To be credible, survivability distributions for both components and systems must rest upon available knowledge sources - test data, known physical laws and phenomena and engineering judgment. In this section we address methods for deriving quantitative survivability distributions from three knowledge sources: (1) available test results; (2) little or no test data, but known physical laws and phenomena can be applied by computer simulation; (3) the judgment of experts, which must be quantified and used because neither test data nor sufficient knowledge of the governing physical laws are known.

2.1 DEVELOPING SURVIVABILITY DISTRIBUTIONS BASED UPON TEST DATA.

Survivability distributions based upon actual test data in the stressing environments are most direct, acceptable, believable, and valid. If such data are available, they can be used directly with minimal subjective judgments. Standard statistical manipulations can be employed, hypotheses can be postulated, and inferences and conclusions can be drawn. All other procedures and techniques for quantifying the probabilities of survival require further rationalizations, assumptions, and judgments, often compounded to many levels.

2.1.1 Using Binomial Test Results.

A major source of test information comes from binomial or attribute test results where components or subsystems are subjected to one or more environments, singly or in combination, and the device response is binary - it either survives or fails. Treatment of binomial test data is highiy developed and commonplace.

It is well known that classical confidence bounds on the true, but unknown, survivability of a component, subsystem, or system in a specified environment can be developed from test results that record the number of times the equipment survived in n tests. Hence, using well-known procedures, if there were zero failures in ten trials, we can state that a 90% lower confidence bound (LCB) on the survivability of the component is 0.79. Using the same test results and procedure, but choosing another confidence level, say 50%, we develop the 50% LCB to be 0.93. Tables 2-1 and 2-2 record the 50% and 90% LCBs for various test results from 10, and from 100, trials. By choosing various confidence levels a continuum of confidence bounds from 0 to 100% can be developed from the results of any binomial test. This continuum is the cumulative survivability distribution inferred from the binomial test data available.

There is a general relationship between binomial LCBs and the cumulative beta probability distribution (U.S. Army Armament Research and Development Command, 1981). If 100*γ is the confidence, n the number of binomial tests, f the number of failures experienced, s the number of successes (s = n - f), and b(α,β) the beta density function with parameters α,β, then the associated cumulative beta distribution

$$\gamma = \int_0^y b\,(s, f+1)dt$$

provides the binomial LCB at the 100γ % confidence to be y. The associated beta distribution with parameters s,f+1 provides the binomial LCBs for any γ.

Table 2-1. 90% LCBs for different test results.

Component A		Component B	
Failures - 10 Trials	90% LCB	Failures - 100 Trials	90% LCB
3	0.45	30	0.63
2	0.55	20	0.74
1	0.66	10	0.85
0	0.79	0	0.98

Table 2-2. 50% LCBs for different test results.

Component A		Component B	
Failures - 10 Trials	90% LCB	Failures - 100 Trials	90% LCB
3	0.45	30	0.63
2	0.55	20	0.74
1	0.66	10	0.85
0	0.79	0	0.98

2.1.2 Relationship Between Confidence Bounds And Numbers Of Tests.

Say we have tested component A ten times in a specific environment and observed that it failed (did not survive) three times. The mean survivability point estimate is 0.7, and the sample variance (the second moment about the sample mean) is 0.021. Now, let us further assume that we continued to test the same component in the same environment accruing 100 tests with 30 failures experienced. Again, the mean survivability point estimate is 0.7, but the sample variance is 0.0021, a ten-fold reduction over the results from only ten tests. A plot of these survivability distributions (the binomial LCBs) in Figure 2-1 reflects the reduced variability in the survivability estimates from increased testing resulting in higher LCBs at higher confidence. At 90% confidence (10% cumulative probability) the LCB with 10 tests is 0.45, whereas it is 0.63 with 100 tests for results yielding the same 70% proportion of successes.

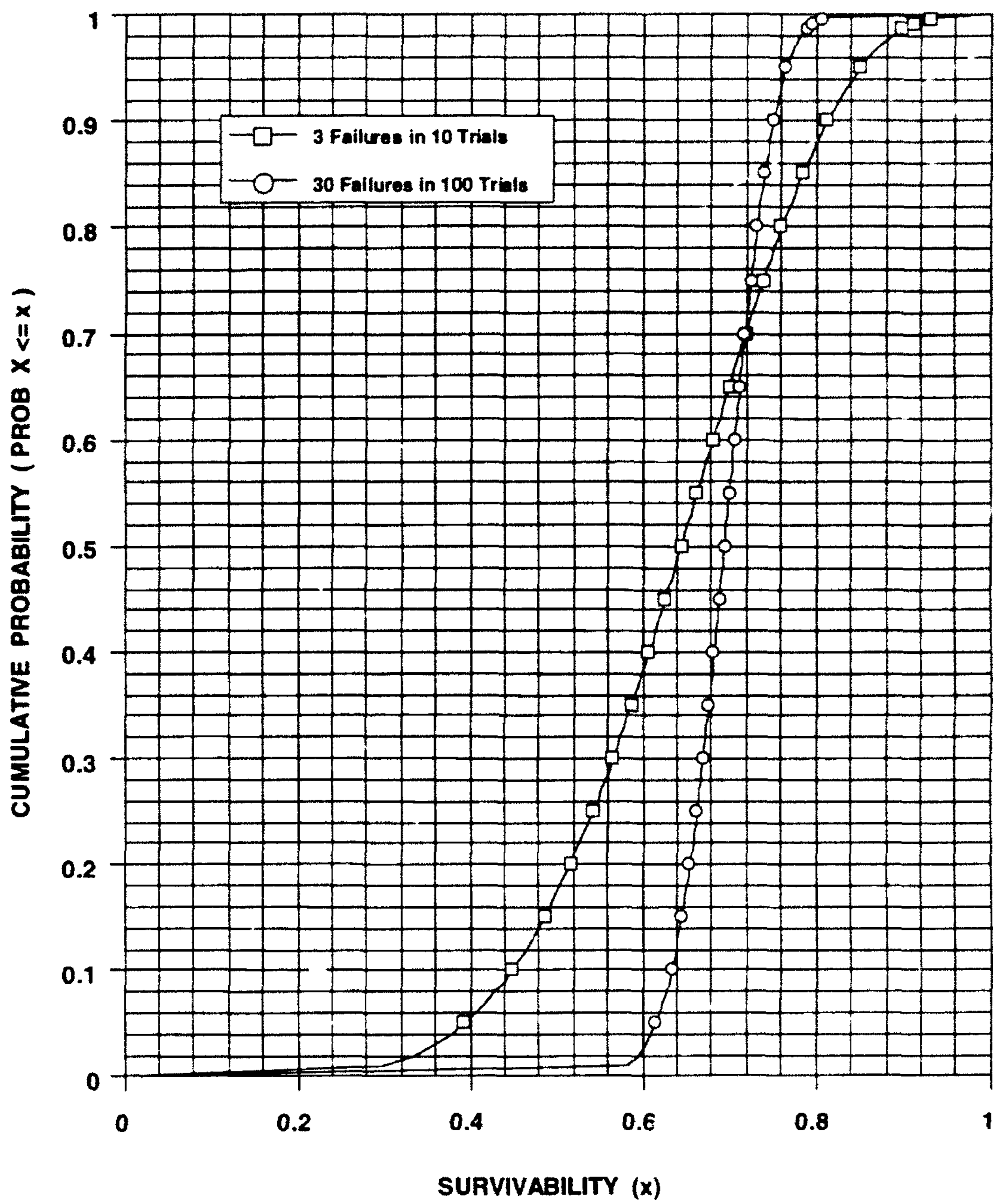


Figure 2-1. Survivability distributions.
(effects of additional testing for one component)

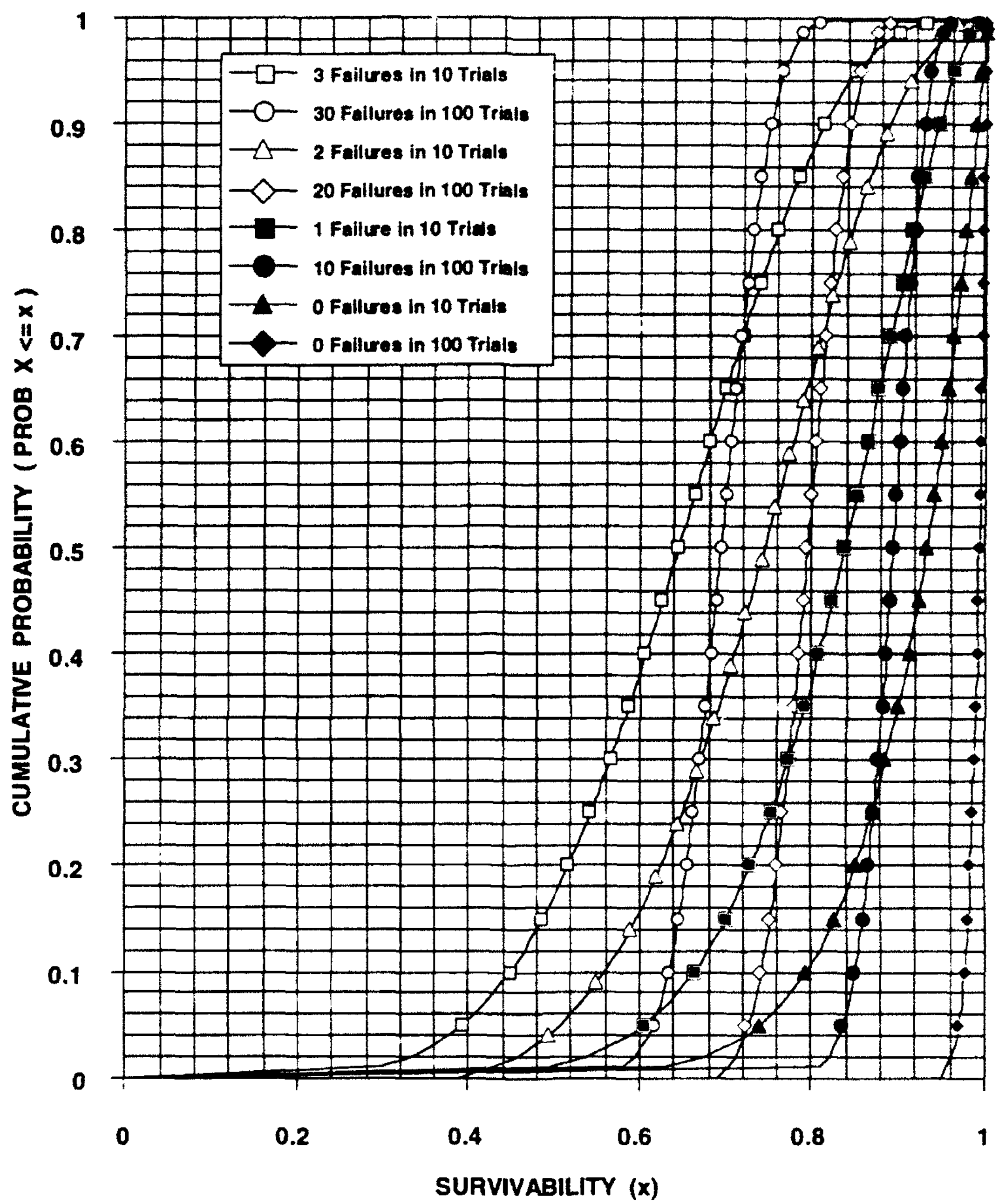


Figure 2-2. Effects of additional testing on survivability distributions.

Similar results occur for other sets of test results as shown in Figure 2-2. Increased testing reduces the variance of the distributions essentially proportional to the increased numbers of tests. It also increases the LCBs at higher confidence levels for data sets having the same success proportions.

Figure 2-3 records the survivability distributions that result from zero failures in n trials for n = 100, 500, and 1000 trials.

2.2 DEVELOPING SURVIVABILITY DISTRIBUTIONS BASED ON KNOWN PHYSICS.

The Defense Nuclear Agency, its contractors, and other scientists studying the effects of nuclear environments on structures, electronics, equipment, and personnel have gathered data, conducted tests, explored the phenomena, and developed a solid understanding of many underlying nuclear effects and mechanisms (upset, damage, noise generation). These scientists have developed algorithms relating damage to stress - radiation, overpressure, temperature, and shock. In many cases these algorithms have been checked with results from tests and incorporated into various nuclear effects damage codes. Hence, given the signature and location of a nuclear detonation, the expected damage upon equipment, structures, and personnel can be simulated with acceptable accuracy.

In cases where there are no directly applicable test data, the survivability distributions for components and subsystems can be developed from the simulation data from validated nuclear effects codes as an alternate data source. When uncertainties are addressed in these simulations, the results can be treated as those from actual tests as above. Again the results are binomial - the equipment either survives or fails. Consequently, the simulation results can be used to develop survivability distributions just as were test results as discussed in Section 2.1 above.

2.2.1 Lognormal Stress-To-Failure Distributions.

It has been observed that on occasion the probabilities of equipment failure are distributed lognormally with stress, e.g., electronic part failures with radiation. Where experience has established this relationship, use of the lognormal distribution implies known physics. With relatively few test samples, one can establish the parameters for the appropriate approximating failure distribution.

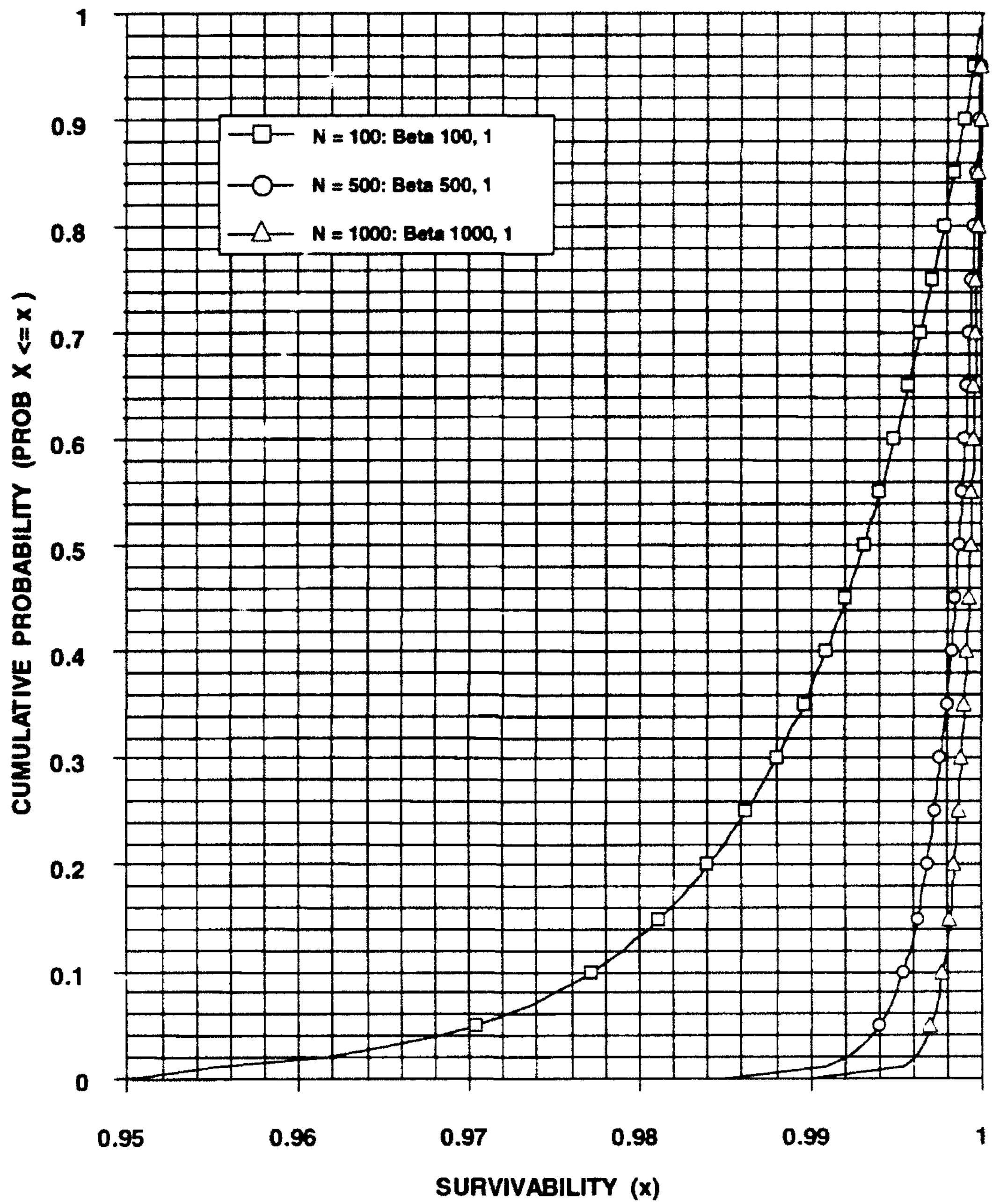
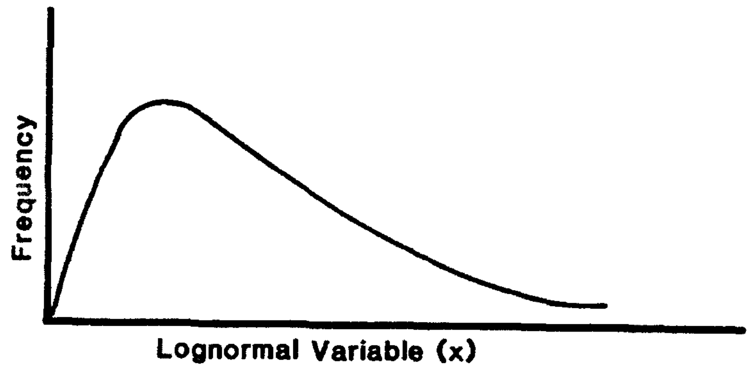


Figure 2-3. Survivability distributions for zero failures in n trials.
(n=100, 500, 1000)

The lognormal distribution is common and natural for describing data that varies by factors. It relates to the application of the normal distribution for data that varies by additive or subtractive increments. For the lognormal distribution the exponent (or logarithm of the raw variable) varies normally.

A common approach (U.S. Atomic Energy Commission, 1974 and Institute of Electrical and Electronics Engineers, Inc., 1976) is to consider that a 90% confidence interval from the 5% (X_L) and 95% (X_U) bounds of the distribution can be defined from the median X_0. In this case $X_L = X_0/f$ and $X_U = X_0 * f$ so the extent of variation between X_L and X_U is f^2 where f is the factor of variation between the 5% and 95% bounds. If f = 10, for example, the range of variation in this interval is two orders of magnitude (10^2). If f = 5, the range of variation is from .2 to 5 (5^2), etc.

With μ and σ representing the mean and variance of the normal distribution which the logarithms of the original variable follow, then the mode, median, mean, and variance of the original lognormally distributed variable are defined in Figure 2-4.



Log Normal Properties

Frequency (density) function: $f(x) = \frac{1}{\sqrt{2\pi}\,\sigma x} \exp - \left[\frac{(\ln x - \mu)^2}{2\sigma^2}\right]$; $x \geq 0$

Mode (most probable value): $X_m = e^{\mu - \sigma^2}$

Median : $X_{0.5} = e^{\mu}$

Median (in terms of Upper and Lower bounds: $X_{0.5} = \sqrt{X_U X_L}$

Mean: $\bar{X} = e^{\mu + \sigma^2/2}$

Variance: $V = e^{2\mu + \sigma^2}(e^{\sigma^2} - 1)$

Figure 2-4. Lognormal density function.

The cumulative lognormal failure distribution of Figure 2-5 depicts the developed relationship between the stress level and the probability of failure (P_f). For a specific stress there is an associated P_f point estimate. The probability of survival point estimate $P_s = 1 - P_f$. To conduct our Monte Carlo sampling to determine survivability distributions for higher levels of integration, we need a survivability distribution for this component, not just a point estimate.

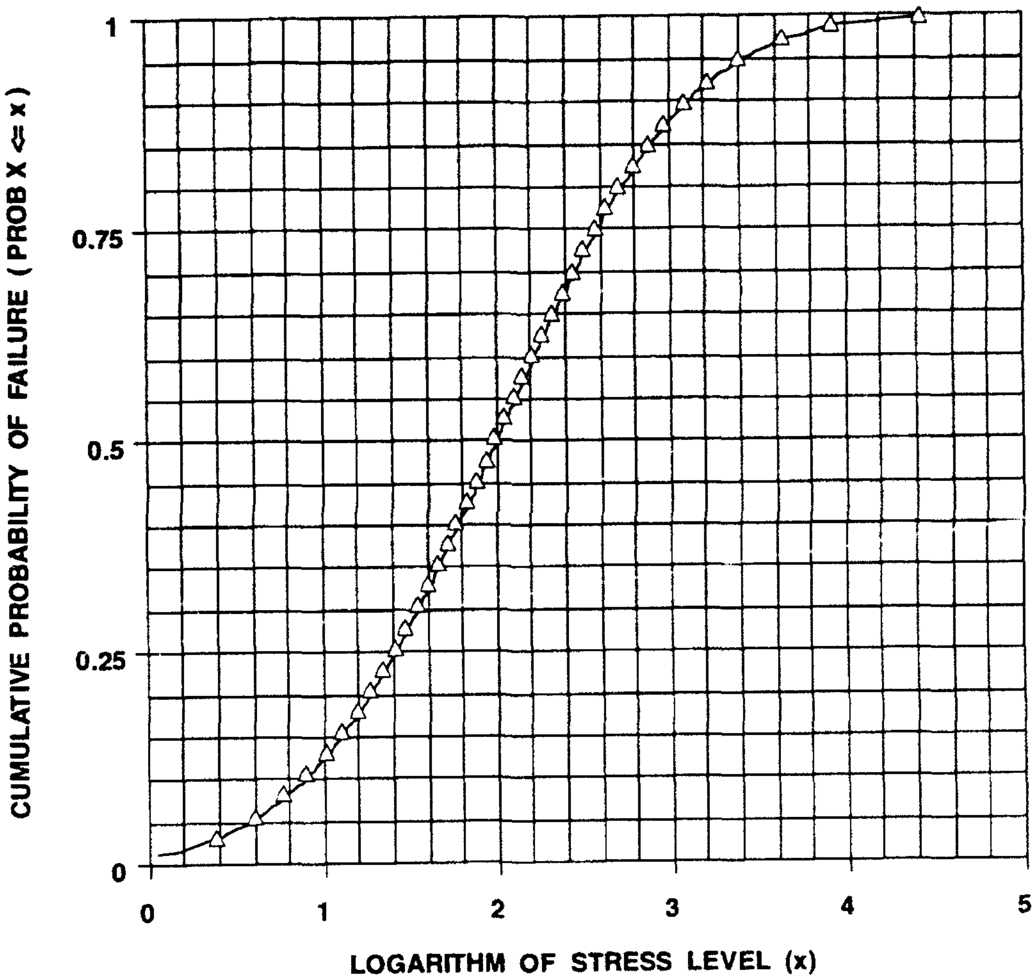


Figure 2-5. Lognormal failure distribution.

We know that there are uncertainties in developing the lognormal distribution above due to sparse data, the assumption of the distributional form, variations in parts, the effects of integration, etc. Consequently, if we let the P_s point estimate derived as above be the mean (m) and specify its variance (v) for this stress level from engineering judgment (or from repeated sampling at the specified stress), the beta parameters specifying this component's survivability distribution for the stress level of interest can be derived from the relationships

$$m = \alpha/(\alpha+\beta),$$

$$v = \alpha\beta/((\alpha+\beta)^2(\alpha+\beta+1).$$

Hence, given m and v, the beta parameters are:

$$\beta = (m/v)(1\text{-}m)^2 - (1\text{-}m),$$

$$\alpha = (\beta m)/(1\text{-}m).$$

For example, if the mean P_S for a specified stress were found to be 0.95 and we estimate the variance to be 0.001, the corresponding beta parameters are

$$\beta = 2.325,$$

$$\alpha = 44.175.$$

From Section 2.1 above this is roughly equivalent to the results from one failure in 45 trials at this stress level.

Instead of specifying the variance directly, an alternate approach to developing the requisite beta parameters is to specify the number of successes (s) in n trials that produce the P_S estimate. Then $\alpha = s$, $\beta = n\text{-}s\text{+}1$. Using this approach, if P_S were found to be 0.95 and we consider that there is a large uncertainty, we may postulate that P_S = 19/20, 19 successes in 20 trials. Hence, $\alpha = 19$, $\beta = 2$. In this case the mean is 0.95 and the variance is 0.0039.

Postulating a smaller variance, we increase the number of tests and let the ratio, which equals P_S, remain constant. If we let n = 40, then P_S = 38/40. Consequently, $\alpha = 38$, $\beta = 3$ and v = 0.0016.

So, by supplying some measure of the uncertainty in the survivability point estimate developed from the lognormal failure distributions, the requisite beta survivability distributions can be explicitly defined.

2.2.2 Nuclear Radiation Stress-To-Failure Survival Margins and Failure Probabilities.

Methods have been developed for extrapolating estimates of the probability of survival of electronic systems operating in nuclear radiation environments from small sample sizes of components exposed to increasing radiation stress until failure. A report (Jordon, 1989) of work funded by the Navy Standard Missile Program Office, PMS-422, the Theater Nuclear Program Office, PMS-423, the Office of Naval Research (ONR), and the American Society for Engineering Education (ASEE) developed a lognormal radiation stress-failure distribution based on the results of numerous tests on semi-conductors.

The basic concept is that there are relationships between the threshold of failure (TF), the lowest level of radiation stimulus that produces a response that can cause part or system failure, and the specification (SPEC). The survival margin (SM) is the dimensionless arithmetic ratio of the TF (which corresponds approximately with the 90% P_S at the 90% confidence level) and the SPEC level: SM=TF/SPEC.

Figure 2-6 portrays a 90% confidence lognormal density function. The SPEC level, the TF, and the geometric and arithmetic means are noted. In this figure, the area under the curve to the left of TF is 0.1; that is, 90% of the time a higher radiation level would be required to cause failure, or the probability is 0.9 that the component would not fail up to the TF radiation level. The variance estimates for the lognormal distributions are either **inferred from engineering judgment** or obtained from experimentally measured data **assuming a lognormal failure distribution.**

In the samples taken the parts are exposed to increasing levels of radiation until failure occurs. If r_i are the radiation levels at which part failures occur for each of n samples, then the arithmetic mean (AM) of radiation failure is

$$AM = \frac{1}{n} \sum_{i=1}^{n} r_i$$

The logarithmic mean (LM) is defined

$$LM = \frac{1}{n} \sum_{i=1}^{n} \ln (r_i)$$

and the geometric mean (GM) as $GM = e^{LM}$. The authors state that the GM is a better average measure of the mean failure level for a lognormal failure distribution than is the AM, but using either provides an estimate for the P_S at the 50% confidence level.

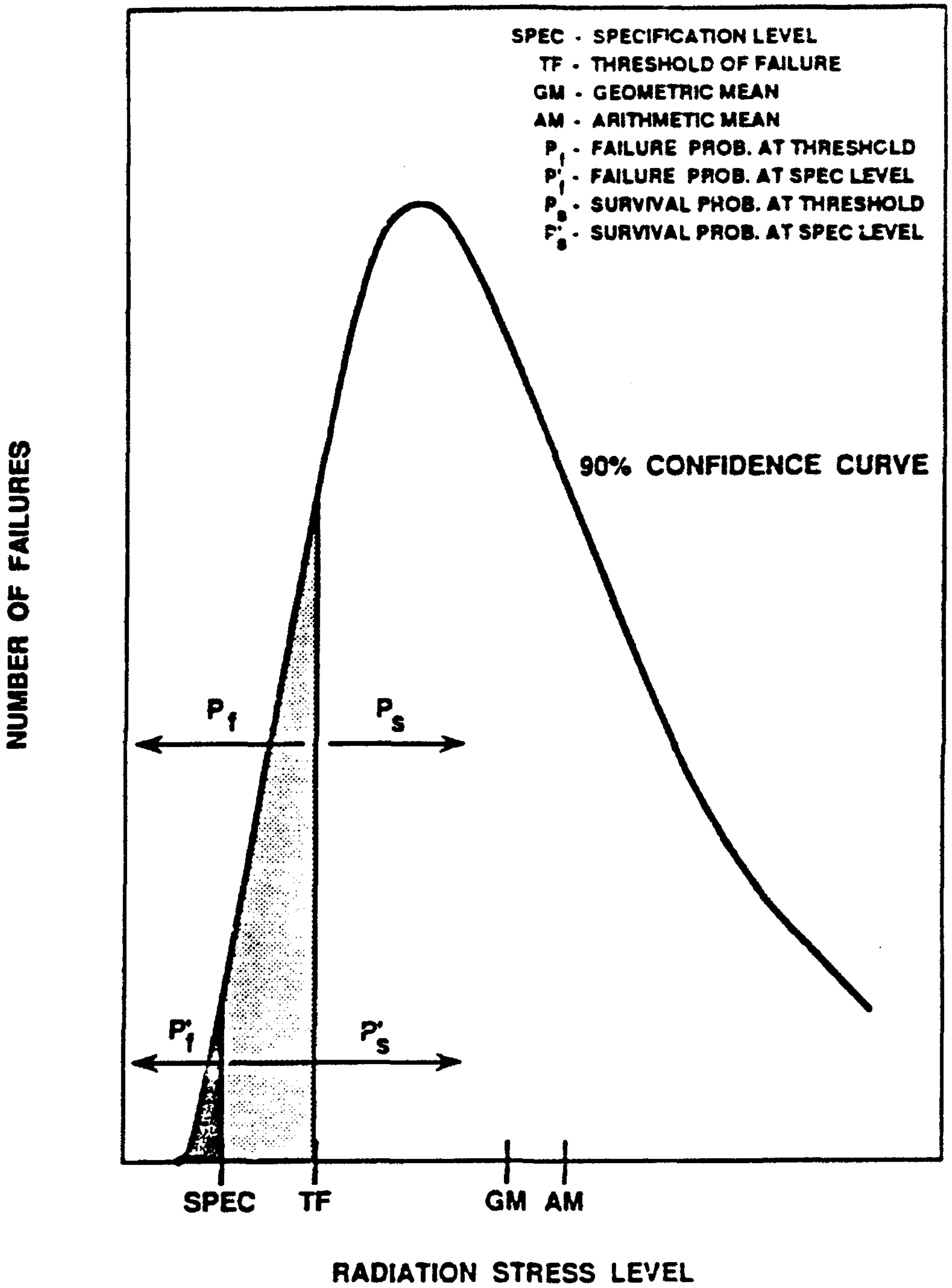


Figure 2-6. Radiation lognormal density function.

2.3 DEVELOPING SURVIVABILITY DISTRIBUTIONS FROM ENGINEERING JUDGEMENT.

Procedures for developing survivability distributions based on test data and knowledge of physics were discussed in Sections 2.1 and 2.2 above. When neither of these data sources exist, survivability distributions can still be developed, albeit with less credence and employing wholly subjective judgments.

In these cases, we invite knowledgeable experts to provide their judgment of the survivability of the components or subsystems. (This is the Delphi method: see Institute of Electrical and Electronics Engineers, Inc., 1977, Appendix B, p. 25.) This can be done in various ways. One approach is to ask the experts to provide estimates of the stress levels that produce 5% and 95% Pfs. Given this information we proceed as in Section 2.2.1. An alternate approach is to ask them to specify the beta parameters for the survivability distributions directly. If several experts provide data, it will be important to perform excursions employing each data set to ascertain the system sensitivities to these inputs. One may also average the means and variances of the survivability distributions provided by the experts to develop a composite representative distribution.

Because we have less credence in this approach, it will only be employed when there is no alternative. When employing it, the uncertainties understandably will be large. However, the results may still be acceptable for systems with numerous redundant sets of equipment. The important point is that even in the absence of statistically significant test data and lacking understanding of the physics of failure, survivability distributions for components and subsystems can still be developed. The fact that the survivability distributions will exhibit large uncertainties will be highlighted and the system effects quantified. This fact, and other procedures mentioned below, will alert decision makers where additional data and research are needed and will help them prioritize the allocation of resources to obtain the necessary information to increase both confidence and survivability measures.

SECTION 3

SYSTEM SURVIVABILITY DISTRIBUTIONS FOR SIMPLE SERIES AND PARALLEL SYSTEMS

We now develop the system survivability distributions for a simple series and a simple parallel system comprised of two components A and B (See Figures 3-1 and 3-2). We chose the survivability distribution for component A as being that derived from test results of 3 failures in 10 trials; that for component B as from the test results of 30 failures in 100 trials.

Figure 3-1. Simple series system.

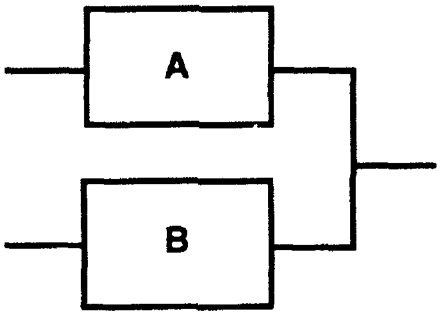


Figure 3-2. Simple parallel system.

Using the methodology developed in Williams, 1992, we randomly sampled each of the component A and component B distributions (assuming statistical independence) 1000 times and developed the survivability distributions for the composite series and parallel systems. The results are shown in Figure 3-3.

Note that the results for the series system are always lower than those for either of the two components alone because both components must survive for the system to survive. Conversely, for the parallel system where the survival of either component results in system survival, the system survivability is always better than that for either component. Variability is also reduced for the parallel system (more vertical distribution).

For these simple system configurations and employing the distributions postulated for components A and B, we are 90% confident that system survivability exceeds 0.30

for the series system, but that it exceeds 0.82 for the parallel system for this environment. The redundant configuration buys a lot of assurance in survivability for this case. It does so in general as well.

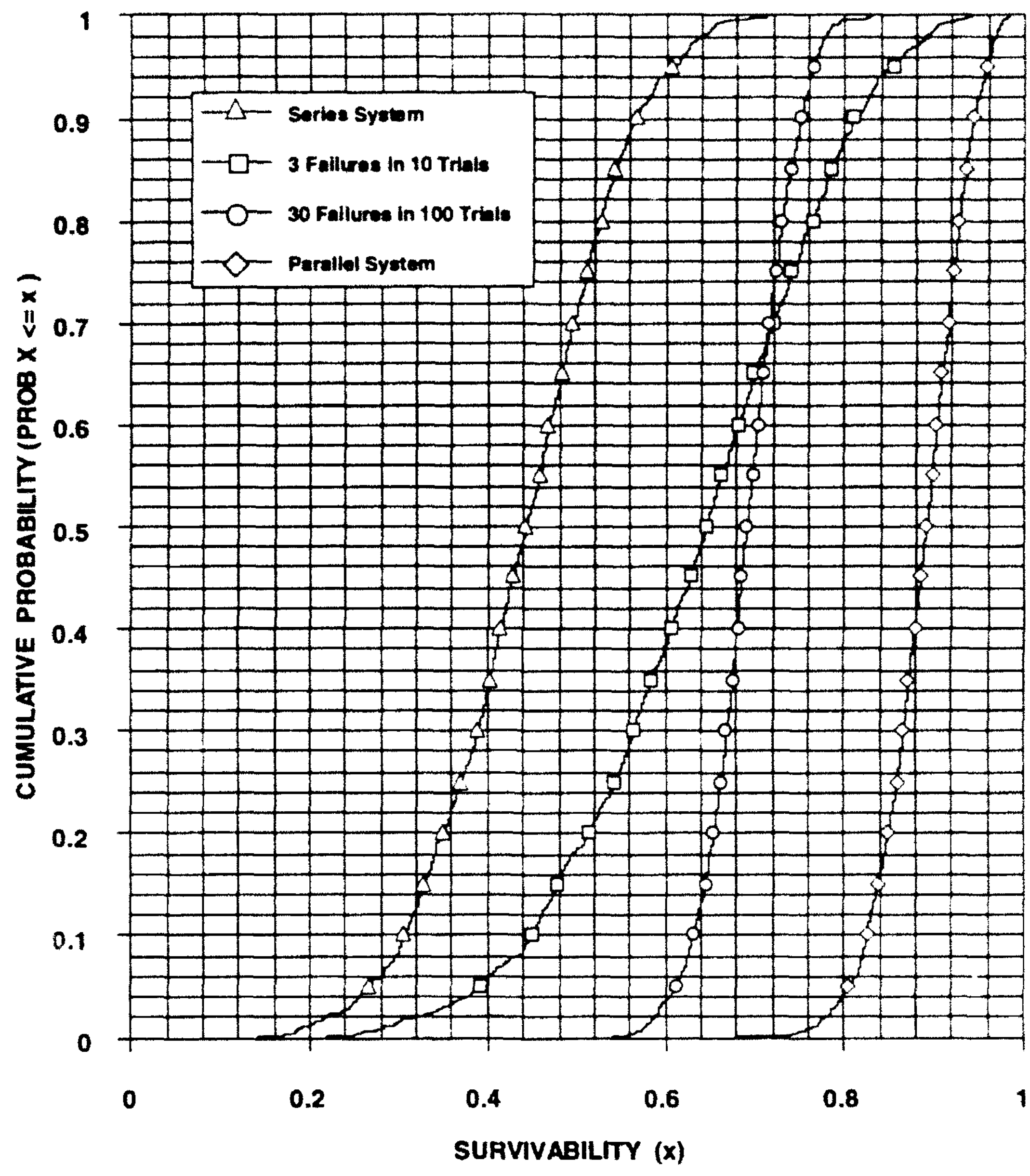


Figure 3-3. Survivability distributions for two components in series and parallel configurations.

SECTION 4

DEVELOPING THE SURVIVABILITY OF A REALISTIC SYSTEM

Survivability protocols are developed to provide assurance that large systems meet survivability goals and requirements. The measure of the relative merit of alternate protocols is the developed survivability at specific confidence or, alternatively, the associated confidence at fixed high survivability. Consequently, to be able to discriminate between the merit of alternate protocols requires that system survivability distributions be developed for each. As the prior discussion has highlighted, the amount of test data available, and the system configuration both play important roles influencing the resultant system survivability distributions.

It is also important to recall that the entire discussion to this point has been conducted assuming that the data on the several components were for the **same environment** and that the component responses were assumed to be **statistically independent.** To extrapolate such results to other environments, or to begin to address statistical dependencies among component responses, or both simultaneously, requires either additional testing at higher levels of integration in the right environment, or the use of subjective judgment to develop the survivability distributions.

Assuming that appropriate survivability distributions can be developed for the constituent subsystems, we develop the model and the system survivability distribution for the conceptual HSA communication network of Figure 4-1. This network is further described in Table 4-1.

For the purpose of our example, we postulate the following:

1. There are 3 Space-Based Launch Sensors (SBLSs), each of which communicates with each of the Space-Based Communication Nodes (SBCNs).

2. There are a total of three 4 SBCNs, each of which communicates with each Ground-Based Communication Node (GBCN).

3. There are 4 GBCNs, each of which communicates with the North American Air Defense Command (NORAD). (GBCN #4)

4. There are 3 Space-Based Mid-Course Trackers (SBMCTs), each of which communicates with each SBCN.

5. All other equipment and communication links are single entities.

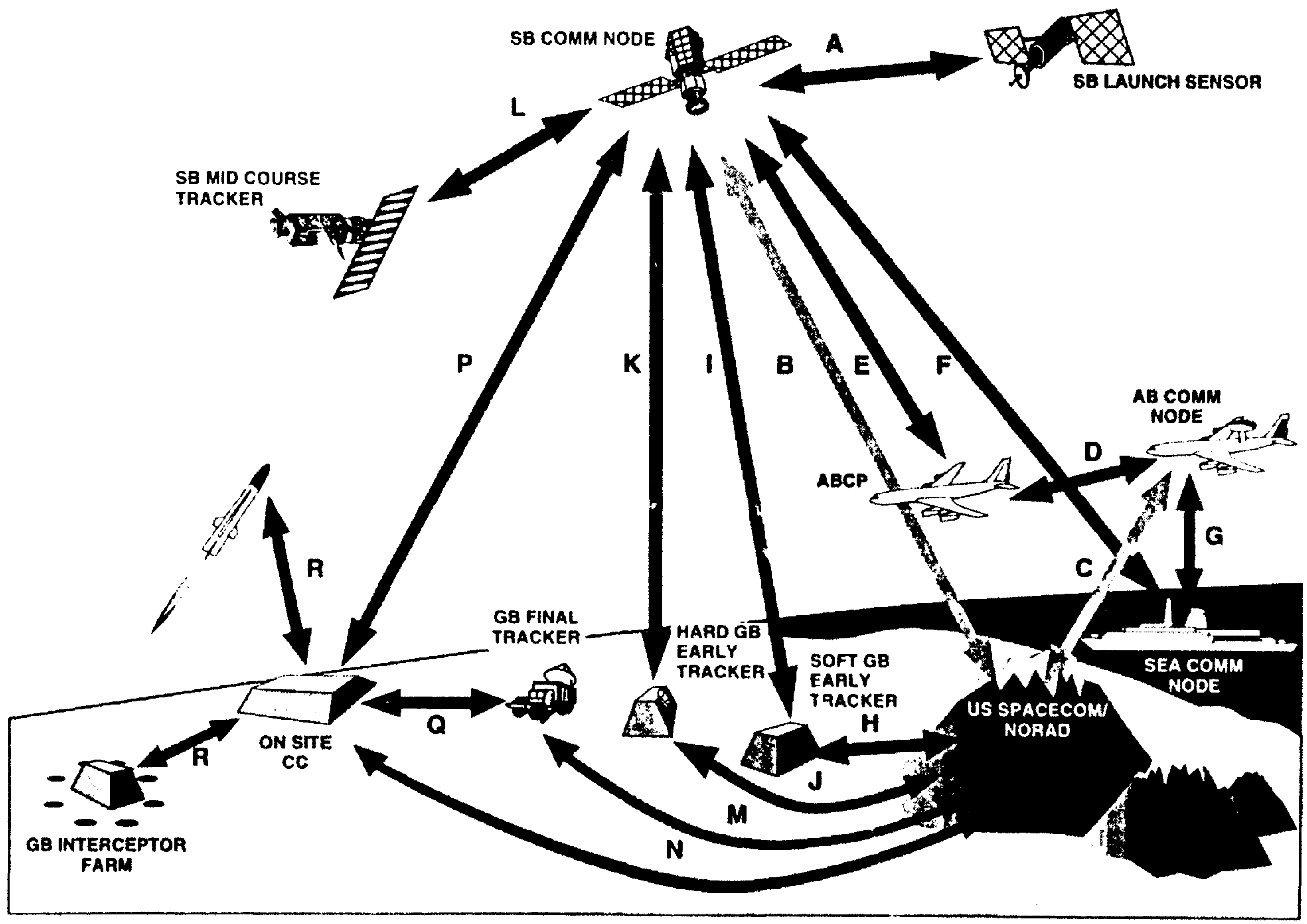


Figure 4-1. HSA communications network.

Table 4-1. HSA communication network.

Category	Element(s)	Abbreviation	Function	Comments
Sensor	Space-Based Launch-Detecting Sensor	SBLS	Bell-ringing launch detection	Constellation at geosynchronous altitude
Sensor	Space-Based Midcourse Tracker	SBMCT	Midcourse fine tracking, discrimination, kill assessment	Constellation at approx. 1000 km altitude
Weapon	Ground-Based Exo Interceptor	GBEI	Homing exoatmospheric intercept	Farm of interceptors
Sensor	Soft Ground-Based Early Tracker	Soft GBET	Coarse trajectory data collection	Unhardened sensors
Sensor	Hard Ground-Based Early Tracker	Hard GBET	Coarse trajectory data collection	Hardened sensors
Sensor	Ground-Based Final Tracker	GBFT	Final tracking, discrimination, kill assessment	Farm of mobile radars
C3 Node	National Airborne Command Post	ABCP	NCA Command and Control	
C3 Node	C2 Element	NORAD	Off-site data collection/fusion, command and control	USSPACECOM/NORAD
C3 Node	Command Center	CC	Command/control of interceptors	May be co-located with GHERKIN & GBFT
C3 Node	Space-Based Comm Node	SBCN	Relay for multiple elements	
C3 Node	Airborne Comm Node	ABCN	Relay for Sea-Based Comm Node & ABCP	
C3 Node	Sea-Based Comm Node	SeaBCN		
Comm Link A	SBLS -->SBCN		Satellite cross-link	
Comm Link B	NORAD <--> SBCN		Ground <--> space link with USSPACECOM/NORAD	
Comm Link C	NORAD <--> ABCN		Ground <--> air link with USSPACECOM/NORAD	
Comm Link D	ABCP <--> ABCN		Air <--> air link with ABCP	
Comm Link E	ABCP <--> SBCN		Air <--> space link with ABCP	
Comm Link F	SBCN <--> SeaBCN		Space <--> sea link	
Comm Link G	ABCN <--> SeaBCN		Air <--> sea link	
Comm Link H	Soft GBET <--> NORAD		Landline link with USSPACECOM/NORAD	
Comm Link I	Soft GBET <--> SBCN		Ground <--> space link	
Comm Link J	Hard GBET <--> NORAD		Landline link with USSPACECOM/NORAD	
Comm Link K	Hard GBET <--> SBCN		Ground <--> space link	
Comm Link L	SBMCT <--> SBCN		Satellite cross-link	
Comm Link M	GBFT <--> NORAD		Landline link with USSPACECOM/NORAD	
Comm Link N	CC <--> NORAD		Landline link with USSPACECOM/NORAD	
Comm Link P	CC <--> SBCN		Ground <--> space link	
Comm Link Q	CC <--> GBFT		Landline link	
Comm Link R	CC <--> GHERKIN		Landline link (R1) + ground <--> space (R2) for status/handoff	

Figure 4-2 is the GO Logic Model of the HSA communication network. Each of the elements of the model represent equipment for which associated survivability distributions, given exposure tc a postulated nuclear detonation at a specified location with a specified signature, have been developed. Each of the elements of the HSA communication network is represented with a pair of "type"-"kind" numbers separated by a hyphen. The "type" number captures the logical essence of the component and refers to one of 17 defined logical operators in the GO methodology (Gately, et al., 1983). A type 1 operator represents the logical operation of an equipment which either performs, or fails to perform, its function given a proper input or stimulus. The associated "kind" number is simply the sequential number in an array that references the probabilities with which that component takes its several operational states - e.g., good, bad, premature. Arrows depict the recorded input and output "signals" (a carryover from electrical schematics) that are really discrete random variables that take pre-defined values representing success or failure. For this example, the random variables take only two values - 0 for success, or 1 for failure. In Figure 4-2, for example, the success event that Space-Based Launch Sensor Number 1 (labeled as type-kind 1-1) operates properly and sends a signal (11) to Space-Based Comm Node Number 1 (labeled 1-7) via Comm Link A (labeled 1-4) when the model is exercised, is expressed as the event that signal 11 takes value 0, or simply 11_0.

Elements of the model that simply represent logical operations - "and" gates, "or" gates, or "m out of n" gates have no associated probabilities, and, consequently no associated "kind" numbers. For example, the type 2 operators represent "or" gates and the type 10 operators represent "and" gates in Figure 4-2. "Signal" 500 near the lower left corner of Figure 4-2 represents the logical output for the HSA communication network. It represents the system survivability whose distribution will be developed.

The postulated survivability distributions for the constituent subsystems and communication links are all identical beta distributions with the same parameters. For simplicity we gave all components the same survivability distributions and explored the system survivability distributions for two cases. In the first case all components have beta parameters 100,1 reflecting the fact that there were no failures in 100 trials on any component (subsystem). In the second case the parameters are 200,1 (200 tests with no failures on any component). The two output distributions are shown in Figure 4-3. (These results were generated on an MS-DOS 386 PC using the KSC GO software.) The corresponding confidence functions are graphed in Figure 4-4. In case 1 (represented on the graph by squares every 5th data point) where the results reflect zero failures in 100 tests on all components, we are 90% confident that system survivability exceeds 0.82. We have zero confidence that it will equal or exceed 0.95.

For the 200 test case (circles) we are 90% confident that system survivability exceeds 0.91. We are 15% confident that it equals or exceeds 0.95.

Because it would be astronomically expensive to have tested all components (subsystems) to the levels reflected in Case 2 (200 tests for each of the 40 communication nodes and links), system decision makers need to know how to optimize testing. Consequently, we employed the KSC GO software on the system configuration of Figure 4-2 and identified the low-order fault sets (see Table 4-2). In the HSA system there are 14 first-order fault sets, two third-order fault sets, and 61 fourth-order faults sets. A fault set is a set of components or elements whose simultaneous failures fail the system. Components whose single failures cause system failures (first-orders) are most critical to system success. Components in all other fault sets are redundant in increasing degrees with fault set order.

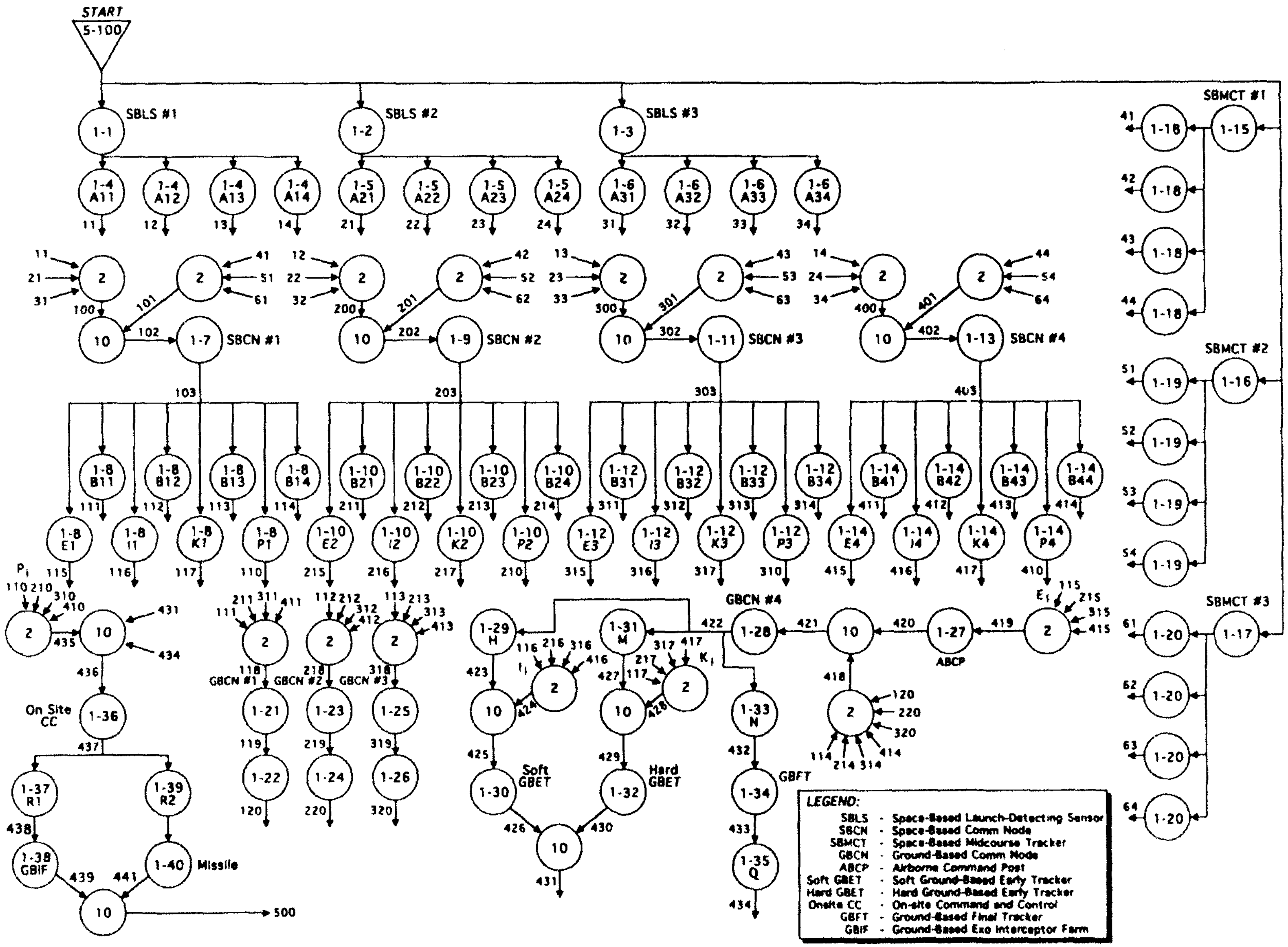


Figure 4-2. KSC GO survivability model of HSA communications network.

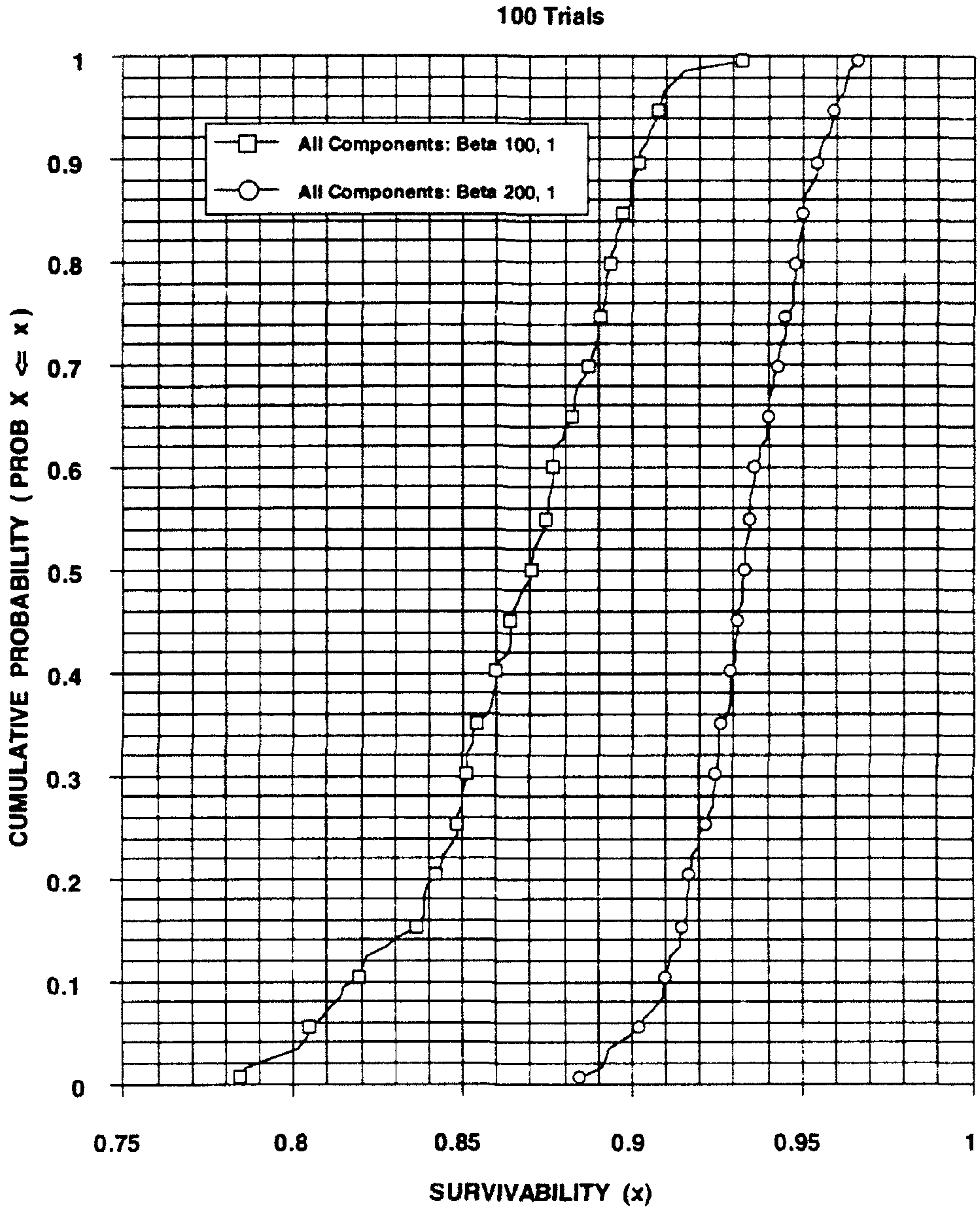


Figure 4-3. HSA communication network survivability distributions.

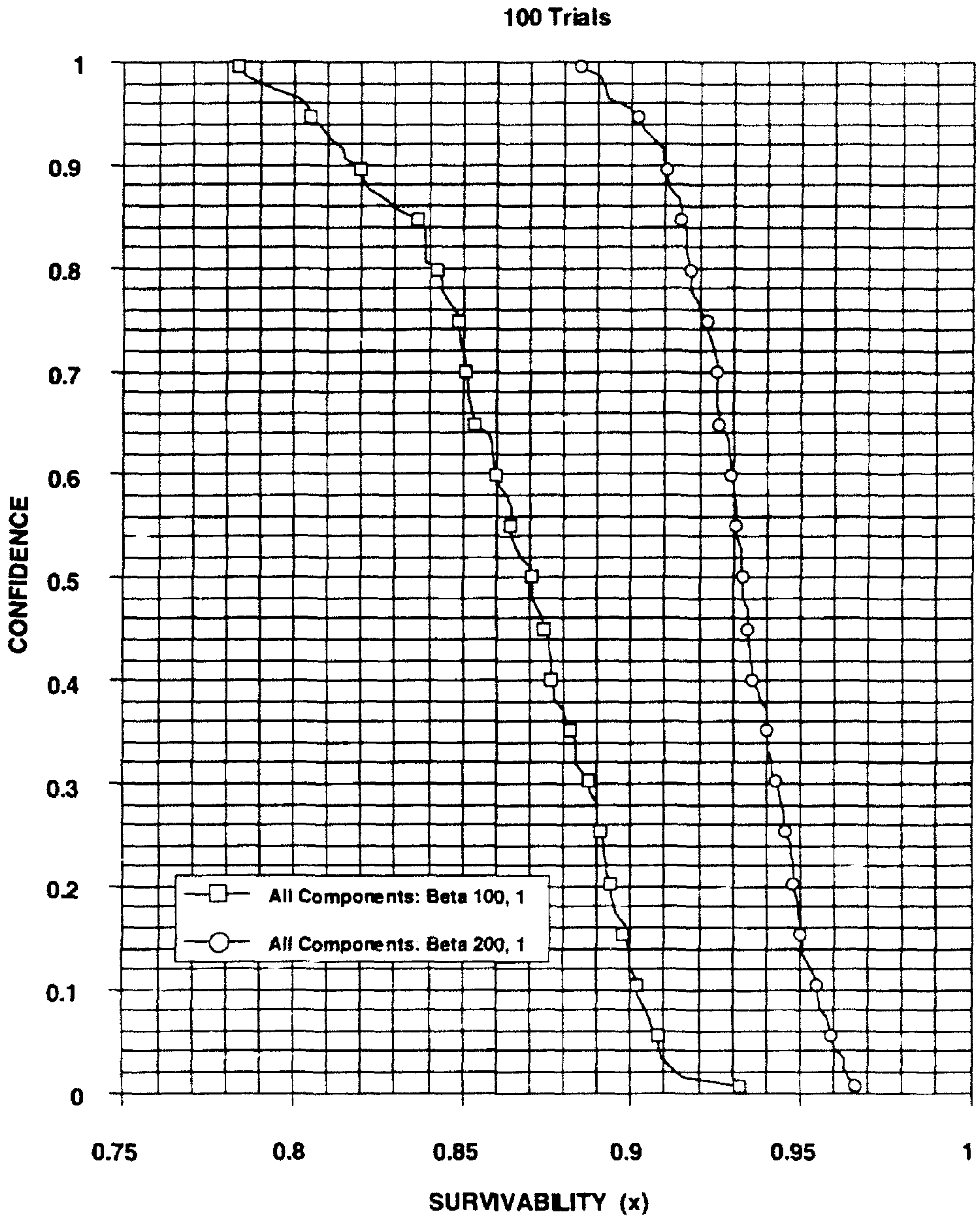


Figure 4-4. HSA communication network survivability confidence functions.

With this fault set information, decision makers could prioritize component or subsystem testing to those in low-order fault sets. Alternatively, they could change the system configuration to provide additional redundancy. For this HSA communication network, if only the 14 first-order components have increased testing performed, say to 200 tests with no failures (resulting in beta survivability distributions with parameters 200,1), and all other components have no further testing but remain with the knowledge from the former 100 tests with no failures (beta parameters 100,1), the system survivability distribution (triangles) is shown in Figure 4-5 along with the other two distributions. The corresponding confidence functions are portrayed in Figure 4-6. The curve with every 5th data point represented by triangles reflects optimized testing of only system elements in first-order fault sets. It overlies the case where all components had been tested 200 times (circles), differing only in the random draws. To have tested all the other components so extensively would have been a significant waste of resources. The knowledge of their performance available from the prior 100 tests in this environment was sufficient. Indeed, it was probably excessive, but we did not perform an excursion to see how few tests would have been required on all but first-order fault set components to maintain the system survivability distribution at the level registered in the 200-sample curves of Figures 4-3 and 4-5.

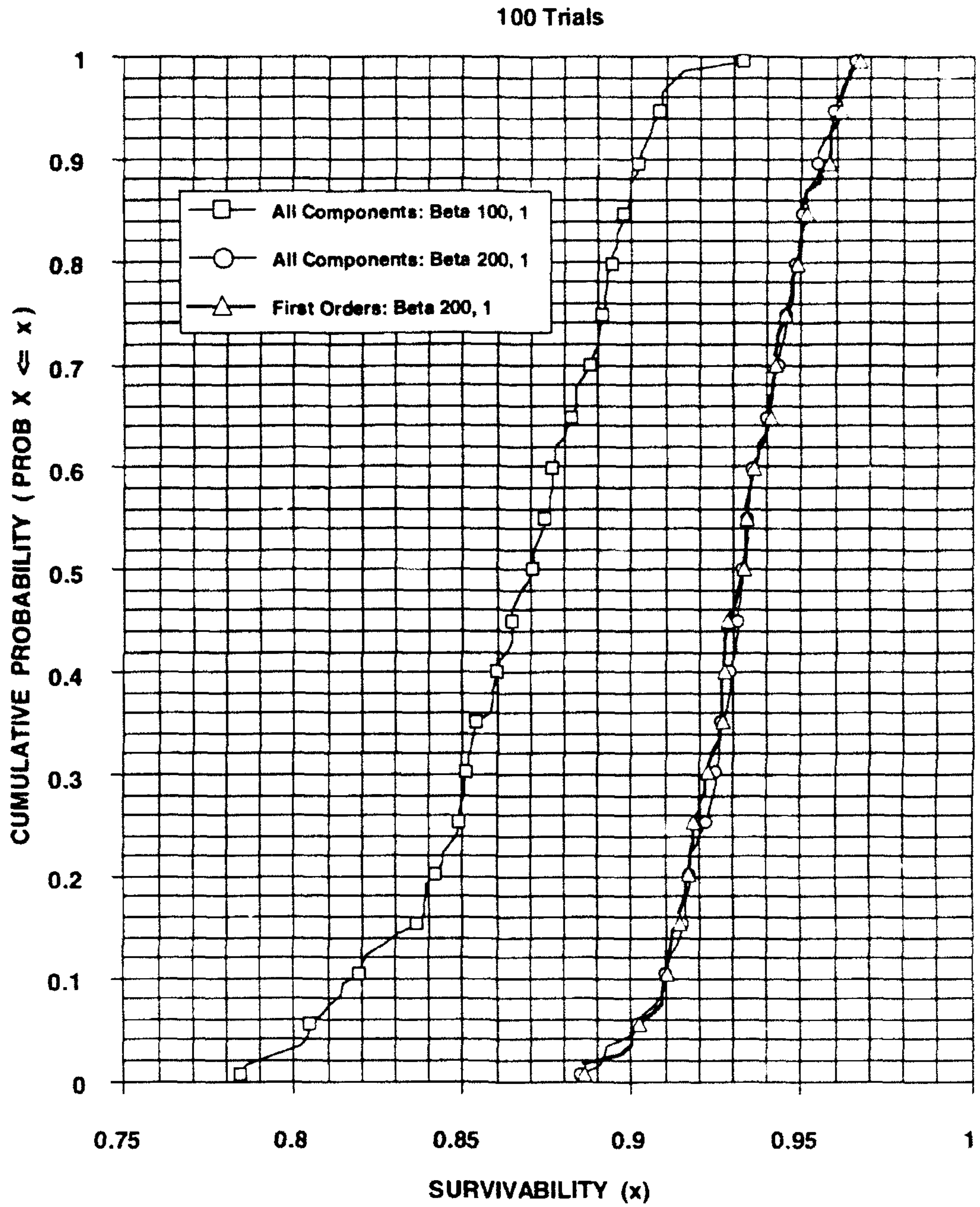


Figure 4-5. Survivability distributions from optimized testing.

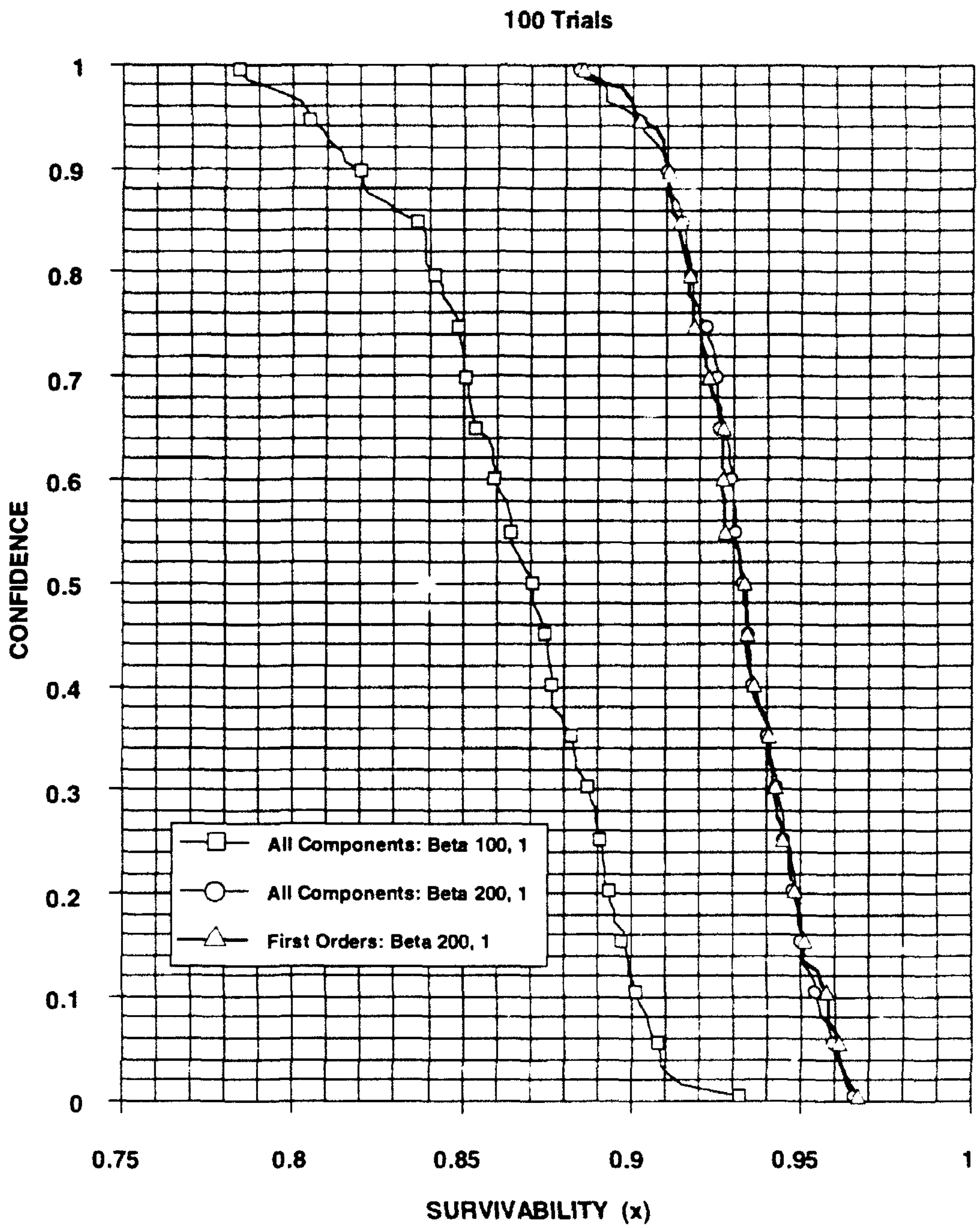


Figure 4-6. Survivability confidence functions from optimized testing.

Table 4-2. Low order fault sets for HSA communication network.

FIRST ORDER FAULT SETS

No.	Component
1	Airborne Command Post (ABCP)
2	Ground-Based Communication Node #4 = NORAD
3	Comm Link H (Soft Ground-Based Early Tracker <-> NORAD)
4	Soft Ground-Based Early Tracker (Soft GBET)
5	Comm Link M (Ground-Based Final Tracker (GBFT) <-> NORAD)
6	Hard GBET
7	Comm Link N (On-Site landline to NORAD)
8	GBFT
9	Comm Link Q (On-Site landline to GBFT)
10	On-Site Command Center (CC)
11	Comm Link R1 (On-Site CC landline to missile in silo)
12	Ground-Based Exo-Interceptor (GBEI) Farm
13	Comm Link R2 (On-Site CC RF link to missile in flight)
14	Missile

SECOND ORDER FAULT SETS

None

THIRD ORDER FAULT SETS

No.	Component	Component	Component
1	SBLS#1	SBLS#2	SBLS#3
2	SBMCT#1	SBMCT#2	SBMCT#3

FOURTH ORDER FAULT SETS

No.	Component	Component	Component	Component
1	SBCN#1	SBCN#2	SBCN#3	SBCN#4
2	SBCN#1	SBCN#2	SBCN#3	P4
3	SBCN#1	SBCN#2	SBCN#3	E4
4	SBCN#1	SBCN#2	SBCN#3	I4
5	SBCN#1	SBCN#2	SBCN#3	K4

NOTE: The naming convention for these communication links from the SBCNs to the ABCP (E_i), to the Soft GBET (I_i), to the Hard GBET (K_i), and from the GBCNs to NORAD (P_i) are subscripted with the communication node number.

Table 4-2. Low order fault sets for HSA communication network (Continued).

FOURTH ORDER FAULT SETS (CONT.)

No.	Component	Component	Component	Component
6	SBCN#1	SBCN#2	P3	SBCN#4
7	SBCN#1	SBCN#2	P3	P4
8	SBCN#1	SBCN#2	SBCN#4	E3
9	SBCN#1	SBCN#2	SBCN#4	I3
10	SBCN#1	SBCN#2	SBCN#4	K3
11	SBCN#1	SBCN#2	E3	E4
12	SBCN#1	SBCN#2	I3	I4
13	SBCN#1	SBCN#2	K3	K4
14	SBCN#1	P2	SBCN#3	SBCN#4
15	SBCN#1	P2	SBCN#3	SBCN#4
16	SBCN#1	P2	P3	SBCN#4
17	SBCN#1	P2	P3	P4
18	SBCN#1	SBCN#3	SBCN#4	E2
19	SBCN#1	SBCN#3	SBCN#4	I2
20	SBCN#1	SBCN#3	SBCN#4	K2
21	SBCN#1	SBCN#3	E2	E4
22	SBCN#1	SBCN#3	I2	I4
23	SBCN#1	SBCN#3	K2	K4
24	SBCN#1	SBCN#4	E2	E3
25	SBCN#1	SBCN#4	I2	I3
26	SBCN#1	SBCN#4	K2	K3
27	SBCN#1	E2	E3	E4
28	SBCN#1	I2	I3	I4
29	SBCN#1	K2	K3	K4
30	P1	SBCN#2	SBCN#3	SBCN#4
31	P1	SBCN#2	SBCN#3	P4
32	P1	SBCN#2	P3	SBCN#4
33	P1	SBCN#2	P3	P4
34	P1	P2	SBCN#3	SBCN#4
35	P1	P2	SBCN#3	P4
36	P1	P2	P3	SBCN#4
37	P1	P2	P3	P4
38	SBCN#2	SBCN#3	SBCN#4	E1
39	SBCN#2	SBCN#3	SBCN#4	I1
40	SBCN#2	SBCN#3	SBCN#4	K1

Table 4-2. Low order fault sets for HSA communication network (Continued).

FOURTH ORDER FAULT SETS (CONT.)

No.	Component	Component	Component	Component
41	SBCN#2	SBCN#3	E1	E4
42	SBCN#2	SBCN#3	I1	I4
43	SBCN#2	SBCN#3	K1	K4
44	SBCN#2	SBCN#4	E1	E3
45	SBCN#2	SBCN#4	I1	I3
46	SBCN#2	SBCN#4	K1	K3
47	SBCN#2	E1	E3	E4
48	SBCN#2	I1	I3	I4
49	SBCN#2	K1	K3	K4
50	SBCN#3	SBCN#4	E1	E2
51	SBCN#3	SBCN#4	I1	I2
52	SBCN#3	SBCN#4	K1	K2
53	SBCN#3	E1	E2	E4
54	SBCN#3	I1	I2	I4
55	SBCN#3	K1	K3	K4
56	SBCN#4	E1	E2	E3
57	SBCN#4	I1	I2	I3
58	SBCN#4	K1	K2	K3
59	E1	E2	E3	E4
60	I1	I2	I3	I4
61	K1	K2	K3	K4

SECTION 5

CONCLUSION

This paper has discussed methods for developing the component and subsystem survivability distributions from various data sources that are necessary to develop the survivability distributions for higher level systems which cannot be tested. Methods for developing the fundamental and lower-level distributions based upon test data, knowledge of physics, and engineering judgment have been presented. The relationship between discrete binomial test results and continuous beta distributions was shown. The effects of increased testing were explored and documented.

The procedure for developing system-level survivability distributions from lower-level distributions was discussed and the method applied to two simple configurations, then to a realistic HSA communication network. The final result, a system-level survivability distribution which quantifies system survivability, is also used to place confidence bounds on system survivability. Developing system-level survivability distributions for varying survivability protocols permits direct comparison of the results. The system survivability can be compared at a fixed confidence level, or the confidence levels at a fixed system survivability can be compared to measure the merit of alternate protocols.

SECTION 6

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