LEVEL II

UCRL-52804, Rev. 1

AD A095225

Probabilistic approach to EMP assessment

R. M. Bevensee, H. S. Cabayan, F. J. Deadrick,
L. C. Martin, and R. W. Mensing

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Subtask Code R99-QAXEC-301

September, 1980

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract W-7405-Eng-48.

UCRL-52804 Rev. 1
Distribution Category UC-13

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Manuscript date: Sep[redacted]80

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FOREWORD

This is an unclassified version of a paper entitled "Uncertainties in Hardness Specification (U)" presented at the Defense Nuclear Agency-sponsored symposium on "System EMP Hardening," 7-9 August 1979. The present paper contains no reference to environmental data. This work was sponsored by the Defense Nuclear Agency under subtask Code R99-QAXEC-301 "Data Collection and Assessment," work unit code 83 "S/V Confidence Evaluation," prepared for Director, Defense Nuclear Agency, Washington, D.C. 20305.

The authors wish to thank George Baker of the Defense Nuclear Agency and John Bombardt of Research and Development Associates, Marina del Rey, California, for their many suggestions during the course of this work.

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PROBABILISTIC APPROACH TO EMP ASSESSMENT

ABSTRACT

The development of nuclear EMP hardness requirements must account for uncertainties in the environment, in interaction and coupling, and in the susceptibility of subsystems and components. Typical uncertainties of the last two kinds are briefly summarized, and an assessment methodology is outlined, based on a probabilistic approach that encompasses the basic concepts of reliability. It is suggested that statements of survivability be made compatible with system reliability. Validation of the approach taken for simple antenna/circuit systems is performed with experiments and calculations that involve a Transient Electromagnetic Range, numerical antenna modeling, separate device failure data, and a failure analysis computer program.

1.0 INTRODUCTION

The development of nuclear electromagnetic pulse (EMP) hardness requirements and the specification of EMP hardening or protection for a system must account for uncertainties in all areas from the EMP environment to system behavior. For example, uncertainties exist in statements about the environment, particularly how this environment interacts with and propagates throughout the system. Similarly, there are fundamental uncertainties in the components, units, and subsystems that are to be subjected to those uncertain environments. Uncertainties appear in the form of random variations, systematic errors, and judgmental factors. This paper briefly reviews some of the uncertainties in the areas of interaction and coupling, and susceptibility, and it suggests in some detail an approach that can deal with such uncertainties in assessing a system for hardness specification. This is by no means a complete review, but we obtained information on some major programs from the EMP Lead Laboratories of the Services and from some of their contractors. The suggested approach is probabilistic in nature and encompasses the basic concepts of reliability in making statements concerning hardness and survivability.

2.0 GENERAL NATURE OF UNCERTAINTIES

Uncertainties arise in all phases of vulnerability assessment analysis, due to model inadequacies, testing uncertainties, lack of complete knowledge of system parameters, etc. These uncertainties must be accommodated in any analysis, whether it be a deterministic worst-case analysis or a probabilistic analysis where the uncertainties are considered to be nondeterministic.

In risk assessment programs, uncertainties are classified into several types. For vulnerability assessment, three types of uncertainties--random, systematic, and judgmental--can be defined. Although there is no universal agreement on the definitions of these terms or even for the need to differentiate among different types of uncertainty, it is frequently interesting and important to distinguish between uncertainties. In particular, it may be of interest to separate the effect of uncertainties due to "inherent" random variation in the properties of the system from the effect of those in the analysis techniques. The latter can sometimes be reduced by improved techniques, whereas the former cannot. Below we suggest a use of terms that would be appropriate for vulnerability assessment.

2.1 RANDOM UNCERTAINTIES

Random uncertainties are variations in measured response due to inherent natural variations in the physical properties, operation, or behavior of a physical entity. Thus, the variation in the susceptibility (response level at which failure occurs) of like components is considered a random variation (uncertainty). This variation has many causes, such as manufacturing variation, variations in the basic elements within the component, etc., and it includes measurement variation. Similarly, random variation in an incident electric field can be due to environmental variation, random variation in the source, directional variations, etc. All of these variations are outside the direct control of the analyst and will always be a source of uncertainty in the analysis.

2.2 SYSTEMATIC UNCERTAINTIES

Systematic uncertainties are variations in response due to imperfect modeling, testing, design, analysis, etc. The variation introduced into the analysis by modeling (analysis, computer- or scale-model testing) introduces a constant, although unknown, uncertainty in response. (For example, any mathematical model of coupling is only an approximation to the real system.) This constant uncertainty in the response exists as long as the model is used in the vulnerability assessment analysis.

2.3 JUDGMENTAL UNCERTAINTIES

Judgmental uncertainties are variations in response introduced by using subjective opinions about unknown parameters. Frequently, many of the parameters in a vulnerability assessment are unknown and unobtainable. Thus, it is necessary to depend on the judgment of experts for the likely values of the parameters. Anyone who makes such a judgment will be doing so without complete knowledge, thus introducing uncertainty into the assessment. For example a vulnerability assessment of a system must account for the environment. Since it is impossible to know all details about the environment some judgments must be made. Although judgmental uncertainty influences the analysis in much the same way as a systematic uncertainty, a separation of the uncertainty due to modeling, testing, etc., from that introduced by subjective judgments is clearly advisable in most situations.

3.0 UNCERTAINTIES IN COUPLING AND SUSCEPTIBILITY

3.1 INTERACTION AND COUPLING

3.1.1 Nature of Uncertainties

Vulnerability assessment includes the evaluation of EMP-induced currents on conductors that might direct the energy to susceptible circuitry. Various approaches are used to evaluate these currents, the most popular of which are full-scale simulation tests, computer simulations, and scale-model tests supplemented with analysis. Another alternative to full-scale testing is the technique of "current injection" at certain points of the system. A fifth

method of assessment is the evaluation of the EMP response of a similar, often simpler, system. (The Lawrence Livermore National Laboratory (LLNL) has published a set of data on external coupling of EMPs to generic structures.[1] These data provide estimates of EMP-induced current levels.) In several assessment efforts, more than one technique has been used.

In the absence of coupling data from actual high-altitude nuclear bursts, heavy reliance is placed on data generated from full-scale simulation tests. Such tests have also been used to validate other simulation techniques. However, full-scale simulation tests are in themselves prone to uncertainties, which are reviewed and discussed below. There is a large amount of data on simulators and on the taking and processing of data from them.

The nature of the source of interaction and coupling uncertainties are closely connected to the type of system being evaluated. For example, Army communication equipment can be tested in a HEMP (high-altitude electromagnetic pulse) environment similar to that anticipated in field use, with the possible exception of very long lines connected to the equipment. In contrast, most aircraft and missile tests are conducted on the ground while attempting to simulate the vehicle in a flight condition. Problems of extrapolating the test data to the desired operational case is less severe when the system is more closely simulated in both its physical configuration and general operating environment.

Important coupling paths for Army ground communication equipment are from the external field to cables and antennas, and from these to the internal equipment. For aircraft and missiles, the EMP-induced effects enter the system through various points-of-entry (POE), such as apertures and external antenna systems. The aircraft, however, is still a localized system, whereas cables of communication systems may run for kilometers.

The coupling assessment of aircraft has relied more heavily on system-level simulation tests than on less successful analytical and computer simulation techniques. On the other hand, the computer simulation approach has been more successful for Army communication equipment. Various codes have been developed and validated with simulation tests in well-controlled configurations, then used to predict currents on long cable runs where simulator tests are not feasible.

The Navy has also performed many coupling assessments on various ships, using the EMPRESS EMP-simulation facility. The EMP fields couple to the various antenna systems and cables aboard the ships, which in turn propagate the energy conductively through apertures to susceptible circuitry within the hull of the ship. The direct coupling of the EMP fields to internal cables is minimal, in contrast to aircraft coupling modes. This property of ships makes scale-model testing for evaluation of coupling an attractive alternative to full-scale ship simulation tests.

Solution of the coupling problem by computer methods is also attractive because of the availability of many efficient numerical techniques and computer programs. However, the greatest accuracy has been obtained in the prediction of external coupling levels, such as coupling to external antennas (free space and lossy ground) and to the external conducting surface of an aircraft or missile. For external coupling, much validation work has been performed, so that the numerical modeling techniques can be used with high confidence. There has apparently been only limited success in the prediction of internal cable currents, particularly the EMP-induced currents in individual wires. Very extensive and complete descriptive information is needed, unless the configurations are quite simple. Internal coupling estimations have been attempted for complicated systems (aircraft and ships), and aircraft predictions have been validated.

Scale-model tests have been used quite extensively for external coupling predictions, and this technique has been validated. Recently, the scale-model approach has also been used for making some internal coupling predictions for a ship, and the results indicate much promise for this approach. Such scale-model tests should be quite successful and accurate as long as geometrically small details in the full-scale system can be neglected. This implies that very small apertures cannot be allowed to become major PDE for energy into the interior of the ship. For this reason, the technique should be quite useful for ships, but less useful for aircraft. However, scale-model tests are useful to predict external coupling to the aircraft.

We do not wish to imply here that one and one only coupling technique has been used for each system. This discussion refers only to the more common methodology used. Coupling data for aircraft for instance have been generated by computer simulation when such data were not available or were difficult to obtain with system simulation tests. An example might be an aircraft with a long, trailing wire antenna.

3.1.2 Typical Uncertainties

In this section, we review typical uncertainties in the various coupling assessment techniques. We place emphasis on "reasonable and achievable" accuracies, based on well-run tests or analyses. The emphasis is on uncertainties in amplitude in the time domain, since electronic vulnerability is usually much more sensitive to changes in amplitude than to small changes in frequency content.

A. Full-Scale System Tests. The uncertainties in full-scale tests include measurement errors, extrapolations of test data, and intrasystem and intersystem variations.

Measurement Uncertainties. These include simulation variation errors (from shot-to-shot), instrumentation errors, and data processing errors.

Simulator field errors appear to be primarily due to shot-to-shot variations in the discharge circuits, waveform variations, and variations in non-principal ($1/R^2$-$1/R^3$) components. The last two appear to be minor. Examination of a dozen or so simulators suggests that a reasonable and achievable error due to simulator field uncertainty is ± 2 dB.

Instrumentation errors include those in current and charge sensors; circuit elements such as cables, alternators, and power dividers; integrators and differentiators; oscilloscopes; records; and such subsystems as microwave telemetry, screenboxes, ADSET data acquisition, and a similar DASET system.

A well-controlled and calibrated instrumentation system has about the smallest error and uncertainty of any aspect of a coupling assessment, according to studies by several companies. For example, sensor errors can be held to 1 dB, as can integrator and differentiator errors up to 50 MHz; scope errors can be made almost negligible. A good microwave telemetry or screenbox system will have less than 1 dB error over its dynamic range; an ADSET or DASET data acquisition system can be similarly designed. An overall error of ± 3 dB is reasonable for an entire instrumentation system.

Data processing errors can occur during the manipulations of the recorded raw data (digitization, Fourier transformation, etc.), which produce the final scope, film, or recorded f- or t-domain responses. Most of the individual errors are small.

Data processing error estimates have ranged from ±6 dB in one system to essentially zero in another system, in frequency intervals extending to 1 GHz. The maximum error in a DASET or ADSET processing system is about ±3 dB, in the absence of nonlinear effects, which can in principle be removed from the data. This seems to be a reasonable and achievable figure.

Extrapolation Uncertainties. The measured wire currents from a test program must be extrapolated to threat conditions, and this usually introduces additional uncertainties. The extrapolation provides corrections for incident field amplitude and wave shape, incidence angle, and polarization, and a change from ground test environment to threat environment. The ground plane correction can be important for aircraft assessment when in-flight currents are to be extrapolated from test data. Ground conductivity effects can also be important when the system to be tested is to be deployed in physical environments quite different from those at the simulator site. For instance, estimates of the effect of ground conductivity on the reflected wave for various angles of the incident wave and antenna height indicate that it could cause at least a 4-dB change in coupling response.

For an aircraft where free-field penetration into the interior through POE is the critical means of internal excitation, Rockwell[2] has used the surface magnetic field (H_s) at the various POE as the extrapolation quantity. When more than one POE may be driving a given internal wire to an unknown extent compared to other POE, the resultant uncertainty is referred to by Rockwell as the POE location error, an additional source of extrapolation uncertainty.

In Rockwell's assessment method 1 (by computer program) the extrapolation ratio H_s (threat)$^{\text{free space}}/H_s$ (simulator) is estimated by computer programs. The inherent error has been evaluated by comparison with Air Force Weapons Laboratory (AFWL) simulator data. For the EC-135 aircraft, Rockwell estimated the POE error as varying from wire to wire between ±6 and ±10 dB. These errors should be treated as independent to arrive at the extrapolation error.

In Rockwell's assessment method 2 (by scale-model aircraft data), an estimate of the extrapolation ratio error was not separated from the POE error. The net error in predicted threat wire currents due to both sources was computed to lie between ±7 and ±12 dB, depending on the orientation of the aircraft. This was defined as "simulation error" by Rockwell.

Intrasystem and Intersystem Variations. EMP-induced wire currents occur when switching from power-on to power-off operation. In addition, variations have been observed in EMP couplings to the same circuits in identical systems. Even within a given system, variations in internal coupling occur from day to day because of changes in physical layout and changes in electrical configuration. These variations have been reported for aircraft, but they likely apply to other systems as well. These variations are strongly system dependent, and data on them are scarce.

For the EC-135, Rockwell reports a power on-off uncertainty of ±10 dB. Morgan[3] reports a spread of 20 dB at identical measurement points in different samples of one aircraft type.

B. Computer Simulation. Computer simulation has been used to make predictions for both external and internal coupling. In terms of uncertainty, however, better results have been achieved in external coupling. In the following discussion, computer simulation predictions are compared to measured values, and the differences are attributed to prediction errors. The full-scale system test errors discussed in the previous section can produce a total uncertainty between ±5 and ±6 dB.* The adequacy of any computer simulation technique should be judged with these numbers in mind.

In external coupling cases, antennas, cables, and external system envelopes have received much attention. Antennas have been analyzed in free space and over ground (both lossy and perfect) with integral equation techniques. A review of such simulations performed by Harry Diamond Laboratories (HDL) and LLNL shows that peak response time-domain errors in current should be no higher than ±4 dB. Computer code predictions of aircraft surface current tend to have error ranges somewhat higher than this.

Cable coupling studies have been performed using transmission line theory. Cables over perfect and lossy grounds have been modeled. The largest uncertainties in specifying the parameters of the model have been in the terminating

*Measurement and data processing errors are independent random variables and are combined in the usual fashion (i.e., square root of the sum of squares). Instrumentation errors are not random and are added linearly.

impedances. It appears that ±3-dB accuracies can be achieved in predicting the EMP-induced current entering a system on a single coaxial or multiwire shielded transmission line, although in many cases only ±6-dB accuracies have been reported. Skin currents and charges induced on the exterior metallic envelopes of systems have been computed with integral equations (i.e., wire-mesh models) and finite-difference schemes. Objects in free space and over ground have been considered. In particular, aircraft have been extensively analyzed in this fashion. If the modeling is done well, uncertainties can be considerably less than ±10 dB. Cases have been reported where errors of ±3 dB have been obtained for aircraft, using finite-difference codes.

Interior coupling predictions have been made by first computing the currents and charges induced on the exterior envelope of the system, as described in the previous paragraph. These are used to define equivalent sources (both electric and magnetic) on apertures, which in turn drive internal cable systems. These attempts have been characterized by large uncertainties because of the difficulty in modeling complex apertures and random-run multi-branch cables. In addition, it is often not possible to characterize precisely the load impedances. Error intervals for internal aircraft cable currents, computed analytically by Rockwell,[2] using Bethe aperture penetration theory and circuit analysis, have been large, typically 10 dB and more.

C. Scale-Model Tests. For several reasons, scale-model tests have not been as popular in EMP coupling assessment as full-scale system simulator tests and analysis. Chief among these reasons is the difficulty of taking measurements in the picosecond time regime. Furthermore, the scaling laws for nonmetallic objects such as dielectrics with finite conductivity are nonlinear in frequency, thus making scaling very difficult. Most reliable results are achieved for metallic objects, either in free space or over perfectly conducting ground planes. Until recently, scale-model tests have been used for making external coupling measurements only. Recently, internal coupling predictions for a ship have been performed by LLNL, and the predictions have been compared to full-scale simulator test data. Scale-model tests have been used for aircraft predictions by the University of Michigan.

The scale-model transient facilities are prone to measurement uncertainties. LLNL reports a peak time-domain uncertainty in the simulator field of less than ±1 dB. Instrumentation plus data processing errors are estimated to

be less than ±4 dB. The University of Michigan test facility is reported to have a simulator field uncertainty less than ±1 dB at frequencies below 2 GHz (and probably about the same up to 6 GHz), with instrumentation errors less than ±3 dB up to 6 GHz. Because scale models are usually larger than about 1/700 size, this frequency range scales to more than 8.5 MHz for the full-size aircraft. Data processing errors in the Michigan facility typically appear to be ±3 dB, with wide variations over the frequency band for a given scale model.

The University of Michigan model aircraft data contain an extrapolation error (called "simulation error" by Rockwell, as mentioned in the preceding section) between ±7 and ±10 dB for skin current predictions.

The comparison of LLNL predictions with full-scale simulator measurements by the Naval Surface Weapons Center (NSWC)[4] for the Canadian ship Huron shows a discrepancy between ±7 dB and ±10 dB for the antennas (due to measurement errors) and between ±2 and ±20 dB for internal cables.

D. Current Injection Tests. Surface current injection testing has been performed on such systems as aircraft so as to excite the first one or two natural modes reasonably accurately, compared to EMP. But the surface current response has been well matched over only part of the EMP spectrum. The meager amount of published data on systems suggests a reasonable and achievable error of ±6 dB in derived EMP surface temporal response.

E. LLNL Modular Data. Modular data have been generated by LLNL[1] for various generic classes of structures, using both computer models and scale-model tests. These modules provide quick-look external coupling estimates of induced quantities of interest, such as current, voltage, power, and energy. The data are provided in parameterized form and can be easily scaled. Generic classes considered include straight wires and loops in free space, whips and loops on boxes, and whips and loops on cylinders. When compared to actual system test results, the module prediction accuracies ranged between 1 and 9 dB. The accuracy is best for structures that deviate little from the generic form and worsens as the deviation increases.

3.2 SUSCEPTIBILITY

As an element of vulnerability assessment and hardening, subsystem and component susceptibility very rarely can be stated in terms of the exact environment. Usually, susceptibility is determined for a class of environments that in some sense approximates the actual case. The determination or specification of the class relies very strongly on the interaction and coupling technology. Typical classes of environments are families of exponentially damped sinusoids of current or voltage that are used to drive cables or terminals of subsystem units. Another common class is a set of unipolar pulsed signals impressed on the terminals of individual components.

Analytical investigations of the susceptibility of both circuits and components frequently employ the same classes of environmental signals. Thus, if susceptibility depends strongly on the details of an environment, large systematic error is introduced into the assessment. Such errors might not be recognized until a system test is performed. Clearly, the susceptibility of a subsystem or circuit depends on the interior configuration, thus errors are introduced by assumptions concerning this configuration.

3.2.1 Subsystem Assessment

Subsystem assessment work may be faced with different uncertainties, depending on the requirements. There is no standard practice in subsystems work. Instead, there are at least three different ways of approaching the problem:

- Assessment relative to a specification placed on the interface of the subsystem. (For example, the B-1 Aircraft or Advanced Airborne Command Post Pin Specification.)
- Assessment that uses a replica or an extrapolation of the actual signal present in the system (as might be obtained from tests on a missile system).
- Assessment that uses a "representation," because the number of subsystems is so large that it precludes detailed analysis or investigation of all of them. This approach could introduce much judgmental uncertainty, as well as systematic errors.

A. Uncertainties in Methodology Development. By definition, a methodology should be a precise and orderly procedure. In practice, it could be a highly adaptive and ad hoc procedure, designed to fit the situation (e.g., to eliminate or add tests). The compromises made in developing a methodology for a particular program are usually recognized, but their full significance in terms of the errors they generate may not be realized. Each methodology places emphasis on those phases of activity that are important to the project at hand. For example, a decision not to do any testing because of costs or other reasons would create a different set of uncertainties than if both tests and analyses were performed. The Advanced Airborne Command Post (AABNCP) Assessment Program[5,6] is an example of a strong methodology, heavily based on existing data, but backed up with tests on selected subsystems for the verification of predicted failure levels. Chapter 13 of the DNA EMP Handbook[7] includes a generic approach to assessment and lists some of the issues involved.

B. Uncertainties in Analysis. In subsystems susceptibility work, analysis can mean doing a simple screening of susceptible components on a penetration interface, or it can mean performing a detailed circuit analysis from the interface through several critical components.

Uncertainties in analysis arise from the lack of suitable large-signal-level models for components, the lack of information on circuit and device parameters, and a general inability to handle very large problems. Engineering judgment is used to simplify the circuit for analysis, and the errors are not always evaluated by experiment.

C. Uncertainties in Testing. One of the largest uncertainties in testing may result from not being able to inject signals to all circuit terminals simultaneously. This is a good argument for doing a systems test at one point in the development cycle of the system. Ground loops and other problems unique to the type of interconnection may not show up in subsystem or unit tests.

Another uncertainty arises in the simulation of the actual interface EMP signal. It is of interest to compare the set of test signals and their effect on the subsystem or unit with a set of possible EMP signals. The executive summary report[5] of the AABNCP program contains information on the relative

accuracy of subsystem assessment analysis compared to certain test results. The results show that the analysis was generally conservative, with a range of 0.35 to 744 for ratios of failure current (test) to failure current (analysis).

D. Uncertainties in Data Handling. The handling and processing of data in the bandwidths and quantities required for EMP assessments appear to cause concern more for economic reasons than for the errors and uncertainties generated. Reference 6 discusses the handling of subsystem functional description data.

E. Uncertainties in Configuration. A specification may or may not be closely tied to the actual operating environment from EMP-induced signals. Uncertainty arises from the use of an interface specification that permits subsystems design or assessment to conform to a uniform criterion. Regardless of the specification, however, a major uncertainty in the analysis of subsystems results from assuming the basic configuration of the subsystem. Such an uncertainty can not be easily resolved and can therefore cause large errors in assessment. An example is the assumption of no direct conduction path, where in fact there is one. Circuit analysis by computer plays a significant role in subsystem assessment, and it relies heavily on suitable determinations of configuration.

3.2.2 Components Assessment

There has been much investigation of the physics of failure, of various failure modes, and of thresholds for many different devices. Given the large number of devices, however, particularly the more susceptible solid-state components, it is rare that a single device can be controlled and studied in detail. Instead, through use of small samples, attempts have been made to derive general models that can be used with prediction techniques. Such models include the familiar power dissipation formula for a semiconductor junction:

$$P = kt^{-1/2} ,$$

where P is the failure power, t is the pulse width (duration), and k is a constant. An empirical extension to the case of integrated circuits has the form

$$P = At^{-B} ,$$

where A and B are empirically determined constants.

Uncertainties have several sources:

- Use of theoretical models for damage prediction.
- Waveform differences between the actual system and the component test.
- Ranges of distribution of failure parameters.
- Definitions of integrated-circuit damage.

Theoretical models must resort to published data on device parameters, usually based on junction capacitance. Waveform differences are significant when a device exhibits a lower failure level for one polarity than the other, or when the failure level is affected by repeated pulses of varying polarity. Testing, however, is usually performed with step-stressing at one polarity. Sometimes it is actually quite difficult to determine when an integrated circuit has failed. Degradation of certain device parameters is possible without catastrophic failure.

A. Experimental Uncertainties in Component Testing.

Environment Simulation. Very little testing of components is performed with a simulation of the actual in-place or in-circuit environment. For reasons of economy and ease of generation, testing is done primarily with a unipolar pulse waveform. A high degree of automation is employed in testing. Actual environment waveforms (as observed from system EMP simulation tests) are nearly always some variation of a damped sinusoid, with a frequency content that depends on the system configuration.

Instrumentation. Sensing of voltage and current is not a major source of uncertainty. Step-stressing is commonly used, so large errors are unlikely. However, determination of exact time of failure can be a source of error. Pretest instrumentation normally involves an automated parameter-measuring test set; posttest determination of possibly degraded parameters can then be evaluated by the same test set, thereby removing an uncertainty through standardizing. Absolute errors or uncertainties in component use for a particular application, however, are only as good as the completeness of coverage of the original parameter test set. Measurement and digitizer errors have been shown to be less than 25% for worst cases and less than 10% for rms variations. Test methodology and error analysis are discussed in Appendices A and B of Ref. 8.

B. Uncertainties in Analysis. Chapter 13 on "Component EMP Sensitivity and System Upset" of the DNA EMP Handbook[7] also contains some general information on uncertainties or accuracy factors of variables as used in analysis. The three phases of damage analysis methodology are data acquisition, detailed theoretical analysis, and susceptibility screen development.

Data Acquisition. The detail and quality of data on subsystem, circuits, and components available for analysis vary considerably. It is often necessary to infer circuit parameters from schematics, and some circuit details may not be available. The availability and accuracy of failure parameters for devices is one of the most significant constraints in performing an EMP assessment. Some methods for obtaining component failure parameters, in addition to doing actual testing, are the use of data with the AFWL's code SUPERSAP, the use of existing equations (supplemented by measurement), the use of equations and certain published data, and the estimation of damage thresholds in various general categories of devices. Threshold values can easily vary tenfold.

Detailed Theoretical Analysis. Detailed theoretical analysis at the circuit level requires several types of information and tools, each of which can involve a large amount of uncertainty.

The principal tools for complex circuits are the large, general-purpose circuit and system codes, such as CIRCUS, NET-2, SCEPTRE, etc. Complete circuit simulation is possible in principle, but may be prohibitively costly. Much smaller codes, such as HANAP2, are also used. A simplification of the circuit to reduce the complexity could omit important responses. A preliminary analysis by an engineer familiar with the design of the circuit will conveniently eliminate certain sections or components, but there is uncertainty in accounting for the possibility of damaging a "buried" circuit component, with no apparent direct connection to the circuit of concern. Judgmental errors will arise in the simplification of circuits for analysis.

Screening for Susceptibility. Screening of subsystems or components for hardness uses some method of ranking components for inherent hardness. This can be quite simple, involving little uncertainty, such as screening out all semiconductor circuits as being innerently soft. A more sophisticated screen uses values of failure threshold parameters for devices, such as a K (Wunsch

constant) value. Lack of proper data concerning a circuit description can cause a great amount of uncertainty in all cases. For instance, an assumption that a circuit is not a solid-state one, when in fact it must be to function properly, would create serious susceptibility uncertainties regardless of the method of screening used.

3.2.3 Summary

A. Circuits and Subsystems. Sources of uncertainty include:

- Circuit parameters, specific devices/circuits.
- Transformer coil nonlinear effects.
- High-level solid-state device models/response.
- Indirect coupling to "buried" circuits.
- Simultaneous pin- or port-excitation effects.
- Power-on vs power-off effects.
- Function definitions.
- Stray element effects.

It would be very difficult in general to quantify the errors associated with each item on the above list. Many of these uncertainties depend on the level of detail available for the subsystem or circuit being assessed. Correlations of predicted subsystem unit failure thresholds with test results indicate that analysis techniques have been generally conservative.[5] Some of these results are summarized in Table 3.1. The values represent ratios of box-pin-test failure (current and voltage) thresholds (subscript F) to analytically predicted thresholds (subscript T) for fifteen electronics units from eight different subsystems. The posttest comparisons include some modifications in the analysis, such as component test results, revised information on components values, circuits topology, etc., which were absent in the pretest predictions.

In both the AABNCP and EC-135 assessment programs, box-pin tests were performed for several boxes. The more recent EC-135 program included a summary of box-level data points for both assessment programs, shown in Table 3.2.

The EC-135 prediction data include the effects of semiconductor junction bulk resistance, while the AABNCP data do not. The data from the tables suggest that the calculated thresholds provide a reliable lower bound for subsystem boxes.

TABLE 3.1. Comparison of tested failure threshold (F) to theoretical thresholds (T) for subsystem electronic boxes (Ref. 5).

Box number	Posttest (revised) comparisons				Pretest comparisons			
	I_F/I_T		V_F/V_T		I_F/I_T		V_F/V_T	
	Min	Max	Min	Max	Min	Max	Min	Max
1	7.88	8			1.2	8		
2	0.64	156	0.92	258	0.64	156	0.6	258
3	6.7	8.1	8.1	8.6	6.7	8.1	8.1	8.6
4	0.5	3	5	17	0.5	2.4	1.1	9.6
5	0.7	>12	>0.3	>0.6	0.7	>12	>0.3	7.6
6	1.9	7.5	1.3	3.7	1.9	3.1	0.56	1.6
7	1.7	12	1.3	4.0	0.35	9	0.17	2.5
8					78.9	744	71.1	>1.5
9	1.5	11.3	2.0	3.7	0.7	5.1	4.5	25
10	1.9	4.2	1.3	2.8	2.4	9.8	1.3	10.7
11	1.2	1.5	0.44	0.68	0.69	8.5	0.07	3.8
12	No burnout noted--transmissibility assumptions verified							
13	No burnout thresholds noted--arc-over predictions verified							
14	3.7	37	3	9	8	22	1.8	11
15	1.17	10.1	2.02	10.1	1.17	10.1	2.02	10.1

TABLE 3.2. Summary of box-level data points for two assessment programs (Ref. 2).

Program	No. of boxes tested	Number of data points: Burnouts> predicted	Burnouts< predicted	Test stopped> prediction	Test stopped< prediction	Total data points
EC-135 assessment	9	8	0	71	27	106
AABNCP GFE assessment	15	39	1	65 total		105

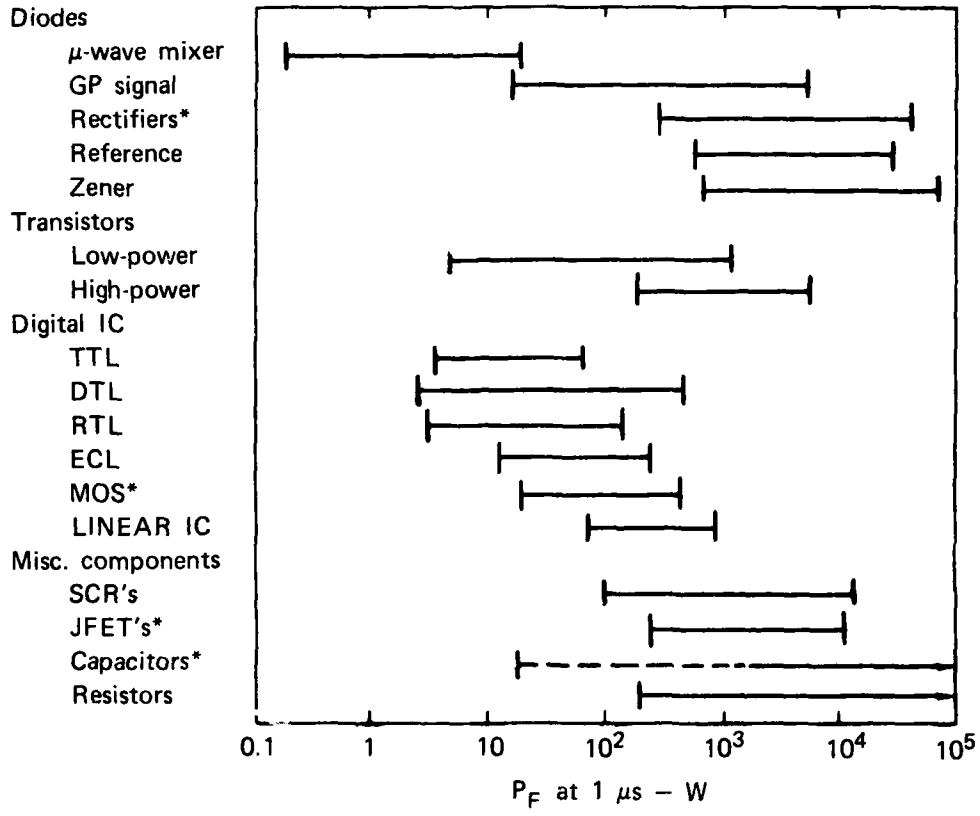
B. Components. Sources of uncertainty include:

- Damage prediction with theoretical models.
- Waveform differences between the actual system and the component test.
- Distribution of thresholds.
- Definitions of integrated-circuit damage.
- Unexpected failure modes.
- Lot-to-lot, manufacturer-to-manufacturer variations.
- Effect of lead inductances in testing.
- Unipolar step-stressing quantization error.

There is much quantitative information on component device threshold variability. Chapter 13 of the DNA EMP Handbook[7] contains information on the relative damage susceptibility of electronic components. (The threshold ranges for the different general classes of components are shown in Fig. 3.1.) The handbook also presents estimated values for K, the damage constant, for different device categories. The information includes K_{mean}, with upper and lower 95% confidence limits, for several types of diodes and transistors. The sample size for each type varies from 2 to 56. Nearly all limits are a factor of 10 (or more) above or below the K_{mean} values. There is also a summary of integrated-circuit threshold variations by category. Limits are given for the parameter A, in the failure model $P = At^{-B}$, for the TTL, RTL, DTL, ECL, MOS, and LINEAR families of devices. These limits range from a factor of 2.1 to 13 above or below the A_{mean} values. Such variation will produce variations in burnout power (1-μs pulse width) of 5 to 200 W for all families, and limits as high as 6 to 1100 W for one family (LINEAR).

Data are also available that compare transistor and diode test results with predicted damage constants (K factors). For example, the data in Table 3.3 illustrate the range of ratios of test K factors to predicted K factors for the junction capacity prediction model. The other models (thermal resistance) have greater variation. Diodes show a greater range of uncertainty, but the sample size was small.

Separate models for classes of devices have also been developed and studied at General Electric Co. One report[9] discusses damage models developed for classes of diodes and uses the existing experimental data base for input. Models are presented in the form of equations that include certain device



*These components exhibit a voltage-sensitive failure mode.

FIG. 3.1. Range of thresholds (P_F) showing relative damage susceptibilities of electronic components. The threshold at 1 μs, in kW, is equal to the K factor.

TABLE 3.3 Comparisons of test K factors to predicted K factors for transistors and diodes, using the junction capacity model.

Measured parameter	Transistors: Collector-base (16 samples) Min	Max	Range	Transistors: Base-emitter (16 samples) Min	Max	Range	Diodes (6 samples) Min	Max	Range
Power	0.78	19	24	0.16	9.2	58	0.014	1.7	121
Current	0.35	23	66	0.05	2.1	42	0.010	1.0	100

parameters (such as breakdown voltages at low level), and that also provide σ factors as multipliers. The value of σ for I_{PR} (reverse current damage) is 1.58 for a 1N4148 diode; 2.51 for rectifiers, diodes, and switches; and 2.14 for zener diodes. In a second report,[10] 252 integrated circuits of several types were tested and modeled, with confidence limits as σ multipliers included. There are models for RTL, DTL, TTL (several types), ECL, and LINEAR circuits. Sigma factors range from 1.4 to 4.8 for models of the form $P = At^{-B}$. References 9 and 10 should be consulted for the appropriate model to be used with each class of device and for each input terminal.

4.0 COMPARISON OF VULNERABILITY ASSESSMENT TECHNIQUES

An assessment technique, whether based on simulated or full-scale testing, system modeling, or analysis, is likely to vary with each problem, depending on the circumstances of the assessment. Several factors which affect the choice of methodology are:

- State of system development: is it a new system, deployed system, upgraded or revised system, etc.?
- Level of knowledge of the threat or of the system and/or the components: to what extent is the environment known, to what extent is the system coupling known, what is known about component susceptibility?
- Availability of resources: what funding, expertise, or time is available for the assessment?
- Other constraints: is the system available for testing, etc.? These and other factors influence not only the choice of overall methodology, but also the particular techniques used within the framework of the overall method.

Whatever the methodology considered, it is important that the technique accommodate the many uncertainties that may affect the assessment results. Again, it is expected that uncertainties be handled differently in different methodologies. Also, the extent to which uncertainties enter into the analysis will change from situation to situation. Certainly, the availability of information regarding the uncertainties in the assessment parameters will determine how extensive an analysis of uncertainties is performed.

The following paragraphs outline briefly some of the methods used in vulnerability assessments of large systems. They are followed by a description and discussion of how uncertainties are handled within the method.

4.1 HDL ASSESSMENT METHODOLOGY

One assessment technique is exemplified by the methodology developed and used by HDL in the Multiple Systems Evaluation Program (MSEP).[11] This technique makes heavy use of analytically oriented coupling and circuit-code models. Test data on system components and system coupling are used both for developing the computer models and as a source of inputs to the system assessment. Uncertainties are included at all stages of the analysis. They include uncertainties in the system model, uncertainties in component susceptibility, uncertainties in component responses due to modeling, etc. These uncertainties are not probabilistically stated, but are used for detailed modeling and calculations to obtain a worst-case assessment.

4.2 ROCKWELL ASSESSMENT METHODOLOGY

An alternative assessment method was applied by Rockwell International to an assessment of the EC-135 aircraft.[2] This method is based on measurements of the transient currents and voltages in the aircraft while it is in a simulated environment. These currents and voltages were analytically extrapolated to threat level, and the dB difference between a component threat current and its susceptibility was defined as a "hardness margin" for that component. The extrapolation of test data to criterion level was based on extrapolation functions determined either from mathematical models or from scale-model tests. Uncertainties in the test measurements, susceptibility data, and extrapolation

functions were described probabilistically and were propagated throughout the analysis, using the methods of statistical error propagation. The final assessment results were stated as a reliability-confidence interval.

4.3 BOEING ASSESSMENT METHODOLOGY

The Boeing Aerospace Corporation has developed assessment methods to predict the communication impairment of communication facilities in a threat environment.[12,13] The method employs both electrical and functional models. The former is used to determine the input at critical components throughout the system. This in turn is compared to the component failure threshold to determine a probability of disruption. These probabilities are then applied to the functional model to determine a probability of communication impairment. Uncertainties in inputs, component and system parameters, etc., are introduced using the concept of "data quality."

4.4 TRW WORK

In other work, TRW[14] studied the general problem of methodologies for vulnerability assessment, specifically as applied to aircraft. Its study suggested that all assessment concept alternatives could be obtained by answering the following seven basic questions:

1. What survivability statements constitute an answer in the assessment?
2. What is the basis for establishing these survival statements?
3. What is the threshold concept? (How is it characterized and referenced?)
4. What is the extrapolation concept? (How is coupling to the threshold point determined?)
5. What is the final assessment analysis concept? (What is the technical basis for data analysis?)
6. What is the simulation philosophy?
7. What is the test object configuration philosophy?

TRW proceeds in the study to enumerate eleven assessment concepts that include three possible threshold reference locations and four possible extrapolation concept alternatives:

Threshold references

T1. Pressure hull interface.

T2. Pressure hull (damage), subsystem box interface (upset).

T3. Subsystem box interface.

Extrapolation concept

E1. Analytical model.

E2. Hybrid analytical model.

E3. Direct extrapolation of system test data by scalar multiplier.

E4. Threat-level direct drive on portions of the system, based on subthreat excitation of total system.

Only the combination of T3 and E1 was considered not viable due to state-of-the-art limitations in internal coupling analyses. The purpose of this phase of the study was to develop the concepts and to identify data and technology needed to implement these concepts. TRW did not choose an optimum candidate concept.

One method based on the concepts outlined by TRW is a probabilistic analysis that makes extensive use of simulation to assess system survivability. One version of the probabilistic analysis, as applied by LLNL to two simple systems, is described in Section 5. With regard to uncertainties, the probabilistic analysis distinguishes between random and systematic uncertainties in all assessment variables. For any fixed systematic error, the effect of random variations on the value of the probability of survival is assessed by Monte Carlo methods. The result is an estimate of the probability of survival. By varying the systematic error, a distribution of estimates can be generated. In turn, a confidence interval (or confidence bound) can be evaluated from this distribution. The final result is an estimate of the probability of survival, stated with a measure of confidence. This method relies heavily on computer modeling, both in terms of the inputs (threat, system parameters, system operation, etc.) and the uncertainties (random and systematic). Thus, TRW has developed several computer codes[14,15,16] (e.g., SANE, SURVIVE, FAST) to perform this type of analysis. Many simplifying assumptions have been made in developing these codes, hence the applicability of such codes to vulnerability assessment is questionable. One of the purposes of the LLNL study was to determine

whether a probabilistic analysis, based on a computer model (FAST), would generate estimates that could be verified by laboratory experiments for simple systems. TRW has recently applied this type of methodology to assess the survivability of a radio system when subject to the EMP of a high-altitude burst.

4.5 DISCUSSION

All of the methodologies outlined above consider uncertainties in the assessment variables, but the degree to which these uncertainties affect the analysis and the types of results differs considerably among methods. The HDL approach to uncertainties is, as taken in MSEP, the simplest. The quantity of real interest in this approach is the largest value of the uncertainty. This is used in a worst-case analysis to evaluate the worst-case margin of safety, thus resulting in a conservative assessment. This type of assessment indicates the vulnerability in an extreme situation; it fails to recognize that such a situation occurs with a very low probability. Also, no matter what value is used for the largest uncertainty, it is likely that this is not an absolute upper bound. Instead, it is likely to be a value that will not be exceeded with high probability. Thus, the HDL approach may not in fact produce a worst-case analysis. The methodologies used by Rockwell and Boeing, and suggested by TRW, treat uncertainties as probabilistic quantities: the values of the uncertainties are assumed to be described by a probability distribution. Boeing introduces uncertainties in the assessment variables through a factor called "data quality" (DQ). It is assumed that the uncertainty in the safety margin (the logarithm of the ratio of the failure threshold signal to the response signal) is due to one of three types of variation:

1. Random variation among similar units, which assumes that the "true" population safety margin is known.
2. System variation in the safety margin of the specific unit being tested.
3. Systematic plus random variation in the observed safety margin.

The distribution in the safety margin, as described by DQ, is used to evaluate the probability of unit survival in case 1 or to evaluate the "confidence" that the unit survives in cases 2 and 3. These probabilities (or

confidences) are combined to evaluate the corresponding measure of system survivability. The initial analyses done by Boeing assumed that the distributional parameters are known. Later work[17] extended the methodology to include situations in which the parameters are estimated from sample data ("extended data quality") and/or mathematical modeling is used to predict the inputs into the vulnerability assessment ("model prediction coefficient").

This method of accommodating uncertainties, as used by Boeing, relies on a single measure to describe uncertainty, whether it is random or systematic. Thus, the effect of these uncertainties cannot be separated in sensitivity analyses. Also, in extending the methodology to include mathematical modeling uncertainties and parameter estimation uncertainties, a simplifying assumption of Gaussian variation was made. This restricts the applicability of the method. Further, the use of the term "confidence" is specialized and could lead to confusion with the more common meaning of the term.

Rockwell uses a reliability-confidence interval as a measure of uncertainty in a variable. We define it as follows:

> A β 100% - γ 100% reliability-confidence interval for a variable I, given by $\pm\Delta I$, means that, based on test data, if I_0 is the "nominal" value of I, then one is γ 100% confident that at least β 100% of the values of I within the appropriate population will be in the interval $(I_0 - \Delta I, I_0 + \Delta I)$

Thus, reliability-confidence intervals are statements of bounds between which a stated percentage of values of a variable can be expected to lie. The "quality" of the methods used to determine these bounds is expressed by the confidence statement. In contrast with Boeing's use of the term "confidence," the usage here is consistent with that usually found in the statistical literature. Rockwell's definition of the term "reliability" is a generalization of the term as it is used in system and component reliability theory. Their definition also includes the more common daily and legal applications, e.g., "That statement, or testimony, is highly reliable." See Ref. 18 for a definition of "reliability" as used by Rockwell. In particular, in the context of the reliability-confidence interval for a variable I, Rockwell uses reliablility to denote a lower bound on the probability that variable I will be within a specified interval. If I denotes the safety margin of a system and the

interval is all values above zero, then Rockwell's use of the term reliability coincides with the use conventional in the world of system and component reliability theory.

Reliability-confidence intervals for all input variables are assumed inputs to the assessment analysis. These variables (and intervals) are analytically combined to evaluate the safety margin (and interval) for individual components. These are ultimately combined for a system safety margin determination. The final output is an estimated lower bound for the probability that the system safety margin is greater than zero, where the estimate is given with a specified level of confidence. One major problem with the approach used by Rockwell in accommodating uncertainties is the method used for combining uncertainties. Two types of reliability-confidence intervals are developed, one assuming Gaussian variables and the other a nonparametric interval. Interval half-widths (errors) are combined as the square root of the sum of squares, even when a Gaussian variable is combined with a non-Gaussian variable. There is some question about the resulting confidence level. (This same question exists even when combining the same types of intervals.) Also, concerning the distinction between systematic and random uncertainties, Rockwell found only one variable to have significant systematic uncertainty in the EC-135. That variable, threshold current, was corrected for its estimated bias (approximately 12 dB). Thus, the only uncertainties combined in constructing the final reliability-confidence interval for the EC-135 were random uncertainties. For a somewhat more detailed treatment of these and other difficulties in the Rockwell approach, see Ref. 19.

5.0 A METHODOLOGY BASED ON PROBABILISTIC ANALYSIS

As indicated in the discussion of alternative vulnerability assessment methodologies, any realistic assessment must take into consideration the uncertainties in the assessment variables. A method based on a worst-case assessment, though it may be practical, is not realistic, since it deals with a situation that generally has a very low probability of occurring. The more realistic approach is to recognize the variation in the uncertainties. A convenient method for describing this variation is a probability distribution. Thus, the tools of probability should be used in the assessment methodology. Two of the methods described in Section 4 use probability to handle uncertainties, but they inadequately separate the effects of random and systematic

uncertainties, and their methods for combining uncertainties in several variables are suspect.

A methodology that recognizes the variation in variable uncertainties and that does not have the deficiencies mentioned above is based on the use of Monte Carlo methods to analyze the effect of uncertainties in the assessment variables. A flow diagram illustrating such an approach is given in Fig. 5.1. This approach relies heavily on computer models to describe the coupling (both exterior and interior) for a system. Inputs are assumed to be environmental data (e.g., EMP electric field data generated by EMP codes), coupling models with appropriate system parameter values, component susceptibility data (perhaps developed from test data), and finally, a system model consistent with the assessment goal. Thus, the system model may depend on whether the aim is to assess vulnerability, hardening, or survivability (the ability to complete a specified mission when subject to a given threat). Additional important inputs are the probability distributions that describe the variation in the uncertainties associated with each of the assessment variables. Separate distributions are used for each type of uncertainty (random, systematic, and judgmental).

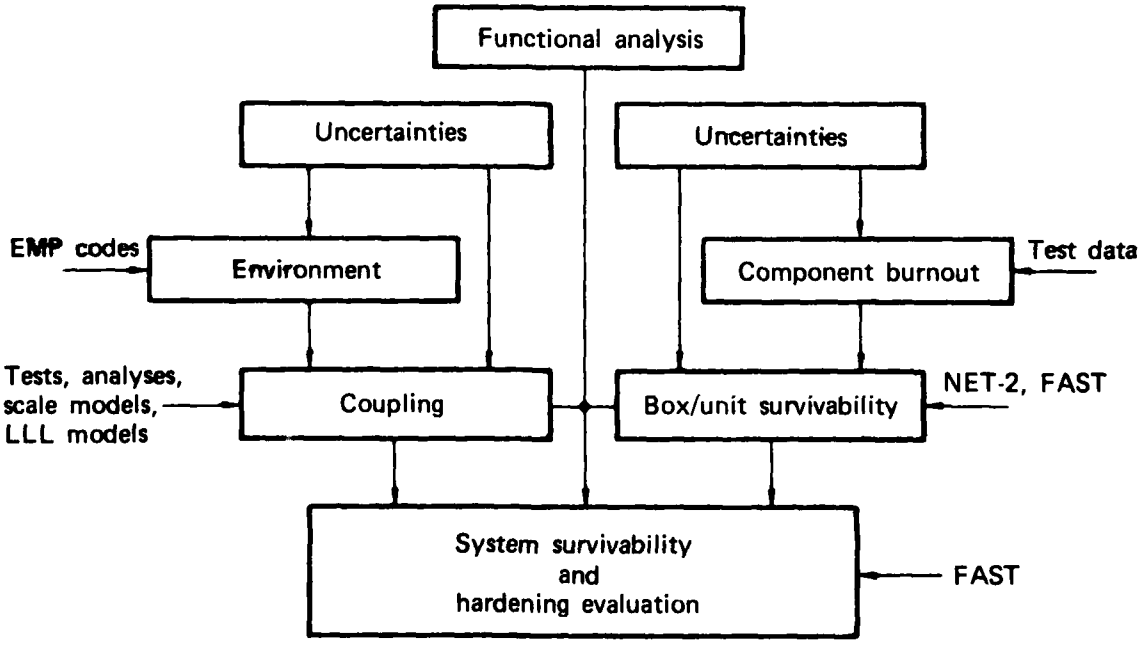


FIG. 5.1. Elements of a probabilistic approach for handling uncertainties.

For fixed values of each systematic (or judgmental) uncertainty, chosen at random from the distribution of such uncertainty, the environment confronting a system is simulated by randomly selecting a random uncertainty for the environmental variable. In propagating the environmental variable through the coupling model, the tools of reliability theory are used to determine the probability of the component surviving by comparing the input to the component with the component failure threshold. The survival probabilities for all the system components are then combined, using the system model, to determine the probability of system survival. Iterating through this procedure and averaging all the probabilities provides an estimate of the expected probability of survival (or failure) for the given systematic (or judgmental) uncertainty. This is an estimate of the probability that the system will survive when confronted by a threat.

This procedure is repeated for additional values of the systematic (or judgmental) uncertainties, and thus a distribution of values of the estimated probability of survival is generated. The average value, taken from this distribution, is the point estimate of the probability of survival for the system. This average is taken over all possible variations of the environment and component susceptibility, as well as uncertainties in modeling, testing, judgment, etc. In addition, the distribution generated in this way can be used to present a range of values for the probability of survival. Although the discussion of this approach has concentrated on taking averages, it is possible to use other measures, for example, the probability of survival exceeded in at least a certain percentage (e.g., 95%) of cases with respect to the random uncertainty. The important thing to recognize is that this approach realistically measures system performance in the environments it is likely to encounter, because it accounts for both the magnitude of the threat and the frequency of its occurrence.

One variation of this approach has been applied to two simple systems at LLNL. These analyses used the computer program FAST[16] to sample the random and systematic uncertainties, and the circuit/systems computer program NET-2 to develop some of the internal coupling data. Both of these programs have shortcomings (e.g., FAST assumes a linear transfer function to describe coupling), but their use illustrates the methodology described above. In fact, the output of this type of assessment compares well with experimentally based data. These results are discussed in the next section.

6.0 VALIDATION EXPERIMENTS

The first validation experiment used EMP radiation of a monopole antenna with a microwave diode load. The second used a transistor multivibrator circuit, which was driven by a potentially damaging electrical pulse. Both experiments, though simple, had the features necessary for validating the probabilistic approach. We obtained input data for the FAST computer program from the experiments and from numerical calculations. We used FAST to predict the overall system probability of failure, as a function of the applied environmental stress.

6.1 MONOPOLE/DIODE EXPERIMENT

We assembled a monopole antenna with a diode load on the LLL Transient Electromagnetic Range,[20] as illustrated in Fig. 6.1. This simple system embodies all of the ingredients needed to demonstrate the application of the FAST program to assessment. Device burnout is specified by diode fragility curves, the environment appears as the incident electromagnetic field (from the monocone pulse antenna), and the network transfer function relates the incident field level to the energy collected by the monopole antenna and delivered to the diode load.

The experiment provided simple systems tests. If the amplitude of the 5-ns pulse generated by the pulser, radiated to the monopole, and delivered to the diode load is sufficently large, the diode will burn out. In each test, only one pulse was delivered to the diode load and each diode load was used only once. At each level of environmental stress (the incident electromagnetic field), FAST predicts the probability of system failure. Therefore, the experiment was performed for three different levels of field intensity, with a sample lot of 26 diodes in each case. Failure of a diode was defined as a 12-fold increase in reverse leakage current.

6.1.1 Fragility Curves

To determine fragility curves, it was necessary to obtain failure data for the 1N23B point-contact microwave diode that was applicable in the short-pulse (5-ns) region. We performed separate tests to obtain these data. Four hundred devices were tested in the configuration illustrated in Fig. 6.2.[21]

The burnout criterion was based on the distribution of leakage current of 234 devices before testing. The mean leakage current was 7.0 μA, with a sample standard deviation of 5.93 μA. The test configuration of Fig. 6.2 uses a

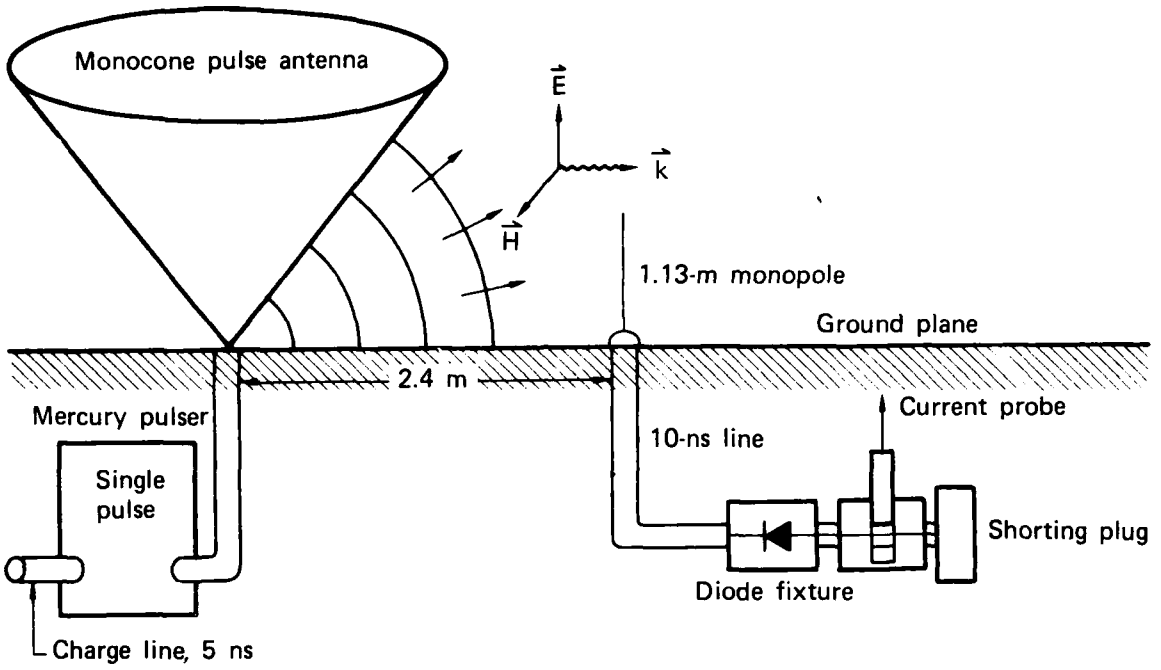


FIG. 6.1. Experimental arrangement for the monopole/diode system tests.

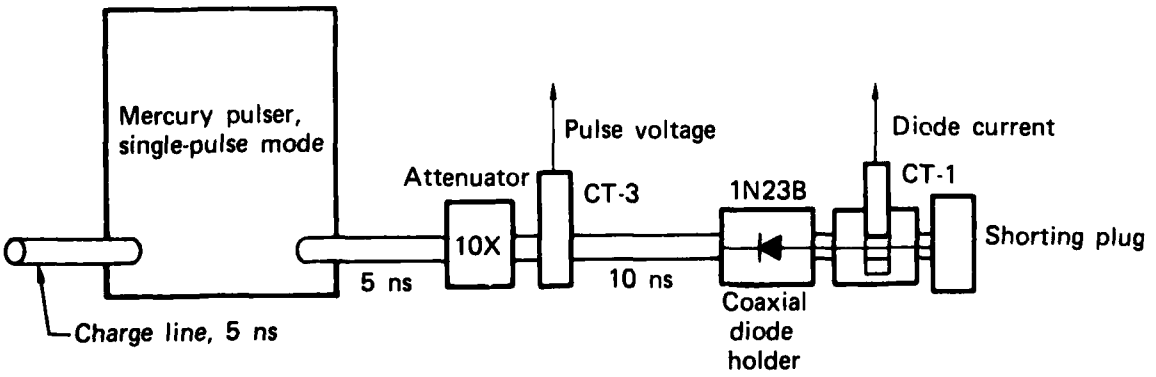


FIG. 6.2. Arrangement used to obtain short-pulse diode burnout data (adapted from Ref. 20).

mercury pulse generator with adjustable pulse amplitude and a 5-ns pulse width. Energy delivered to the coaxial line (in joules) is expressed as

$$E_{LINE} = \int_0^{T_p} \frac{V_p^2(t)}{Z_o} \, dt ,$$

where T_p is the pulse width in seconds, V_p is the pulse voltage (attenuated by a factor of 10), and Z_o is the line impedance (50 Ω). The diode was mounted into a coaxial fixture and probes CT-1 and CT-3 were used to monitor current in the diode and voltage on the line with the diode. The attenuator diminished reflected pulses between the load and the pulse generator.

We performed the diode tests at several levels to obtain estimates of the fragility curves over several percentiles. Twenty-six diodes were single-pulse tested at each voltage level (52 were tested at 80 V), and checked for failure. A summary of the results is shown in Table 6.1.

Point and 90% confidence interval estimates for the probability of failure, $\hat{p}_f$, are based on the following formulas:

$$\hat{P}_f = \frac{\text{number of diodes failing}}{n} ,$$

$$(\hat{p}_{f,\ell}, \hat{p}_{f,u}) = \left(\hat{p}_f \pm 1.64 \sqrt{\frac{\hat{p}_f(1 - \hat{p}_f)}{n}} \right) ,$$

where n is the number of diodes tested. These estimates are given in the last two columns of Table 6.1. Empirical cumulative distribution functions based on these estimates are given in Fig. 6.3. The middle curve is the best estimate of the diode fragility, based on the estimates of p_f. Figure 6.3 also shows the lower and upper limits on the fragility due to the systematic uncertainty of estimating it from test data.

6.1.2 Transfer Function

We obtained the transfer function that relates the incident electromagnetic field level at the monopole to the energy delivered to the diode load, with the help of the computer program WT-MBA/LLL1B.[22] This program permits the modeling of wire structures, such as the monopole, with a series of short interconnected segments. The numerical model of the 1.13-m monopole over a ground plane resembles a 2.26-m dipole in free space, with a 100-Ω

TABLE 6.1. Summary of diode tests.

Pulse voltage, V[a]	Energy, J	Number tested	Number failed[b]	Estimated probability of failure ($\hat{p}_f$)	90% confidence limits for probability of failure
15	2.25×10^{-8}	26	1	0.038	(0, 0.104)
30	9.0×10^{-8}	26	4	0.154	(0.038, 0.270)
40	1.6×10^{-7}	26	9	0.346	(0.195, 0.497)
45	2.025×10^{-7}	26	16	0.615	(0.459, 0.771)
50	2.5×10^{-7}	26	18	0.692	(0.544, 0.849)
60	3.6×10^{-7}	26	19	0.731	(0.588, 0.874)
80	6.4×10^{-7}	52	44	0.827	(0.738, 0.916)
100	1.0×10^{-6}	26	25	0.962	(0.896, 1.0)

[a]Pulse voltage is voltage into coax leading to diode and is equal to the mercury pulser voltage divided by 10.

[b]Diode failure occurs if reverse leakage current exceeds 84 μA.

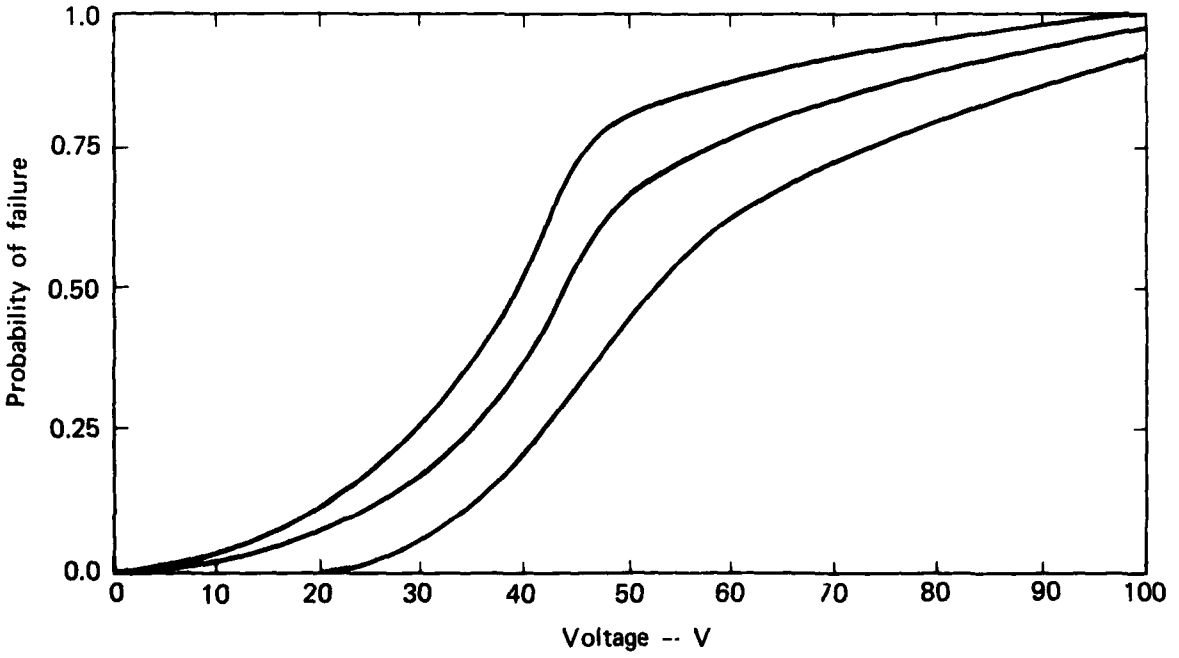


FIG. 6.3. Estimated failure distribution functions.

load as its center. Figure 6.4 shows the calculated voltage across one half of the 100-Ω load for a 1 V/m electric field amplitude, plane-wave incidence, 1-ns rise and fall times, and a 5-ns pulse width (FWHM). The cumulative energy delivered to the 50-Ω load is shown in Fig. 6.5 for the positive half cycles. The asymptotic value of 1.35×10^{-12} J was used in the transfer function for FAST.

6.1.3 Results

To evaluate the assessment methodology, we took two approaches to develop data for comparison with the probabilistic estimate of system failure. One source of data was the experiment involving the monopole/dipole network shown in Fig. 6.1. The diode fixture and cable attached to the monopole are the same as that used in establishing the diode burnout data. Three levels of incident electric field, 256 V/m, 372 V/m, and 460 V/m, were used in the experiment. At each level, 26 diodes were tested. The results of the tests are summarized in Table 6.2.

A second source of validation data was an analytical computation of the probability of system failure. This analysis was based on the assumption that both the diode failure threshold and the energy applied to the system are lognormal random variables. This assumption is consistent with the experimental data, and the values of the parameters of the probability distributions were derived from these data. The analysis is based on the fact that the probability of system failure, p_f, can be computed from the relationship

$$P_f = P(E > T)$$

$$= P\left(\frac{E}{T} > 1\right)$$

$$= P\left[(\ln E - \ln T)\right] > 0 \quad ,$$

where E denotes the applied energy and T denotes the failure threshold. Since both E and T are lognormal random variables, the difference,

$$W = \ln E - \ln T \ ,$$

is a normal random variable. Thus, the probability of failure is the probability that W, with the appropriate mean and variance, is greater than zero.

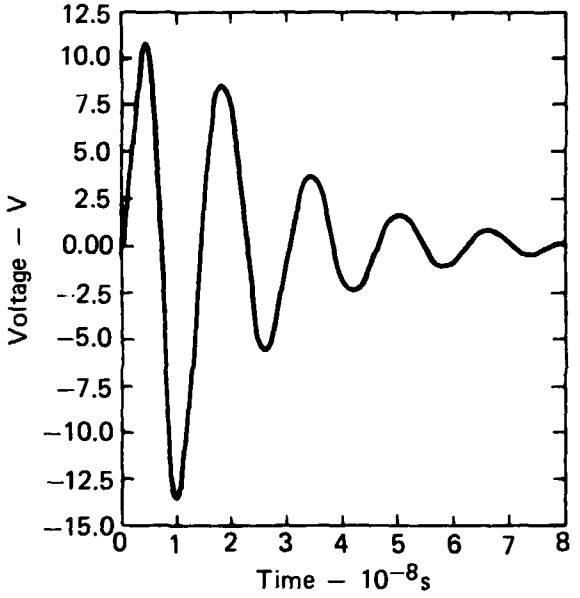


FIG. 6.4. Calculated voltage across a 50-Ω load for a 2.26-m dipole.

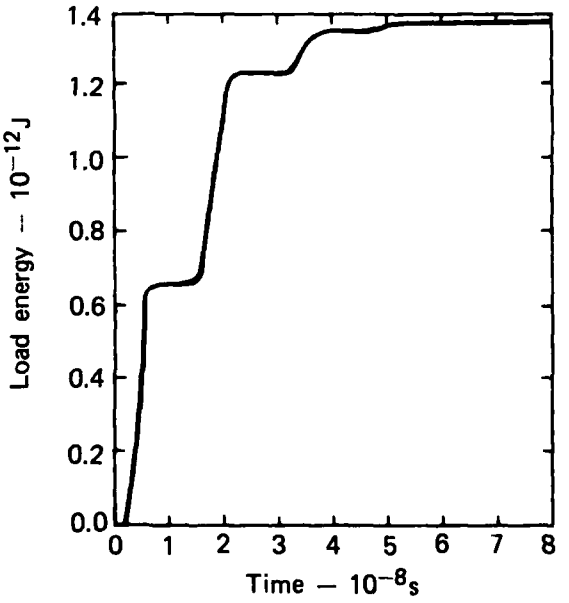


FIG. 6.5. Cumulative energy into a 50-Ω load on a 1.13-m monopole for a 5-ns, 1-V/m incident plane-wave pulse.

TABLE 6.2. Measured failures for monopole/diode experiment.

Incident electric Field, V/m	Pulser voltage	No. of diodes tested	No. of diodes failed	Estimated probability of failure	80% confidence intervals for probability of failure
256	517	26	5	0.192	(0.093, 0.291)
372	752	26	15	0.58	(0.453, 0.701)
460	929	26	18	0.692	(0.576, 0.808)

The results of this probabilistic analysis based on the FAST program are summarized in Table 6.3. The inputs into the FAST program were the environment, transfer function, and fragility data described earlier. The output of the program is the probability distribution for p_f, the probability of system failure. Selected percentiles of the output distribution are the entries in Table 6.3. Reasonable point estimates of P_f are the 50th percentiles, 0.135, 0.490 and 0.679 for 256, 372 and 460 V/m respectively, of the distribution of p_f.

A summary of the comparison of the experimental and analytical results with the probabilistic results are presented in Table 6.4. In general there is good agreement between the validation results and the estimate based on the probabilistic analysis using FAST. Of course, this comparison involves a very simple system. The experimental estimate of p_f is highest at all three electric fields, indicating a possible bias in one or more of the methods. Several factors affect the comparison:

- The experimental estimate is based on a relatively small sample of 26 units (at each field intensity).
- The analytical approach assumed lognormal distributions (an approximation).
- In the probabilistic analysis, all systematic uncertainties were considered negligible except those associated with the fragility curves for the diode.

6.2 MULTIVIBRATOR EXPERIMENT

In the multivibrator experiment, we used both available analysis tools and an existing component data base in combination with laboratory tests for the validation study. For analysis and experiment, a conventional two-battery-biased, collector-coupled monostable multivibrator circuit, using two 2N918

TABLE 6.3. Percentiles, P_α, of the probability distribution of p_f, the probability of system failure, at three incident electric fields.

Probability that $P_f < P_\alpha$	Percentiles (P_α)		
	at 256 V/m	at 372 V/m	at 460 V/m
0.01	0.056	0.313	0.513
0.10	0.102	0.388	0.607
0.30	0.118	0.441	0.658
0.50	0.135	0.490	0.679
0.70	0.155	0.528	0.700
0.90	0.217	0.583	0.750
0.99	0.337	0.675	0.838

TABLE 6.4. Comparison of experimental, analytical, and probabilistic results.

Electric field, V/m	Probability of failure (p_f)		
	Experimental	Analytical	Probabilistic (FAST)
256	0.192	0.172	0.135
372	0.580	0.460	0.490
460	0.692	0.645	0.679

transistors, was contrived. This circuit was modeled and analyzed with version 9.1 of the computer program NET-2. Published failure data[23] on the 2N918 were used to set the component fragility. In the laboratory tests, the multivibrator was subjected to a stress environment of electrical pulses, injected through diodes into the base of each of the transistors, to verify the analytic predictions of failure obtained from the NET-2 simulation results. The configuration used for the laboratory tests is shown in Fig. 6.6.

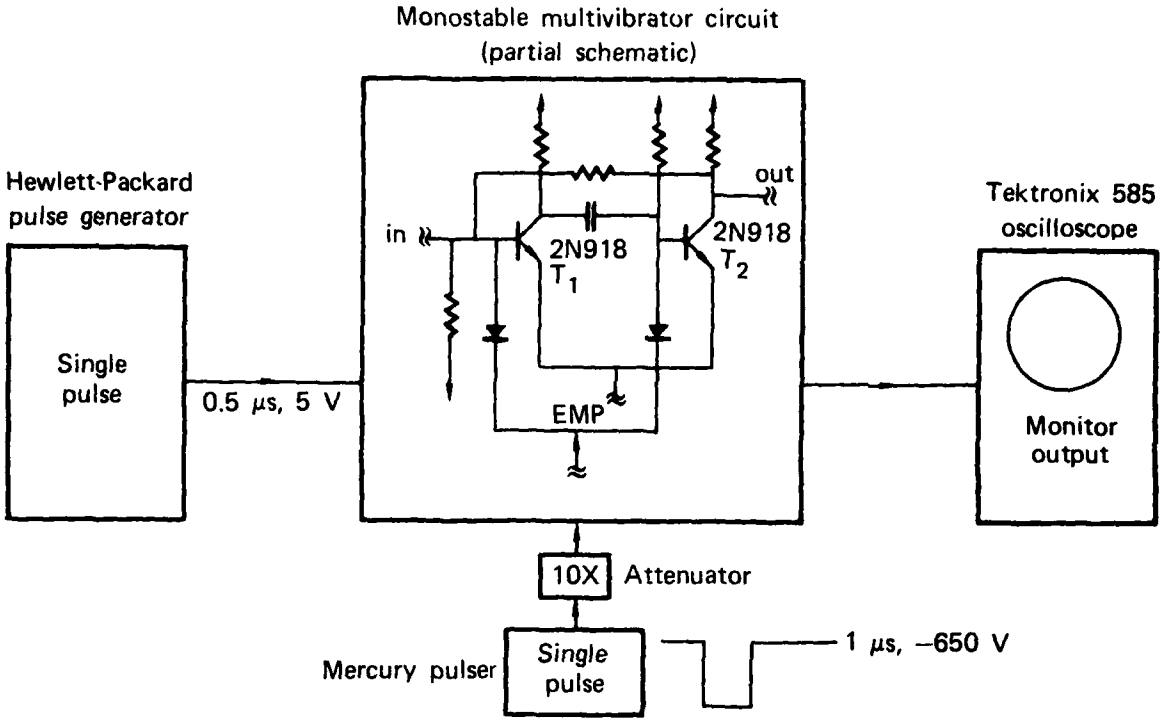


FIG. 6.6. Test configuration for multivibrator circuit burnout experiment.

6.2.1 Circuit Analysis with NET-2

A preliminary examination of the multivibrator circuit indicated that the transistors would be the components most susceptible to burnout. Previous data on the 2N918[23] show that failure is likely for reverse voltages near 13.5 V for the emitter-base junction, for a 1-μs pulse width, with failure currents of 0.4 to 0.5 A. After some preliminary runs with NET-2 established the magnitude of the required burnout pulse, E_{Pulse}, we analyzed the circuit with the Monte Carlo option of the code. A 100-sample Monte Carlo solution was found for a fixed point in time (5.75 μs), where only the parameters V_{BE} (breakdown voltage), R_{BE}, and E_{Pulse} were varied. These parameters are highly significant in the failure predictions, and Gaussian parameter distributions were used to represent their variations. An average value of 8.7 V for V_{BE} was calculated from previous results, and the average value of R_{BE} was estimated as 10 Ω. The 3σ points for NET-2 were 1.1 V and 5 Ω. The pulser voltage was varied between 64 and 68 V.

Table 6.5 presents an example of the output quantities calculated by NET-2. According to these predictions, failure is about equally likely for the two transistors.

6.2.2 FAST Analysis

Using the output of NET-2, we developed fragility curves for the transistors (similar to the curves illustrated in Fig. 6.3). The uncertainty limits were based on confidence interval estimates of the mean. The environmental data used were the E_{Pulse} values with a nominal voltage of 65 V. The estimate of the probability of system survival, $\hat{p}_s$, based on the probabilistic analysis, is 0.368.

6.2.3 Experimental Results

Laboratory tests were performed on the multivibrator circuit, using the arrangement shown in Fig 6.6. The Hewlett-Packard pulse generator was used to check the normal operation of the monostable circuit. Each time the 0.5-μs pulser is actuated, a 10-μs pulse is observed in the output from the multivibrator. Initial burnout tests were performed at 65 V at the output of the 10 x attenuator connected to the mercury pulser. Only a single burnout pulse was applied to the circuit. After each pulse, the cicuit was considered to have survived if it continued to function normally. Transistors T1 and T2 were replaced after each test. The replaced transistors were subsequently checked

TABLE 6.5. Breakdown voltages across the base-emitter junctions of two transistors, calculated by NET-2.

	Breakdown voltage (V_{BE}), V			
Transistor	Minimum	Average	Maximum	Std dev
T1	-15.1	-13.8	-12.4	0.484
T2	-15.1	-13.8	-12.3	0.482

on a curve tracer to determine which device had burned out. Based on this functional criterion, 8 out of 20 circuits survived; thus, the experimental estimate of survival is $\hat{p}_S = 0.4$. This agrees closely with the estimate based on the FAST code, particularly since only 20 units were tested experimentally.

Since the fragility data were based on an assumption of failure whenever the beta gain factor of a transistor exceeded a 10% degradation, a second experiment involving 40 circuits was run using the 10% degradation as the failure criterion. At this level, the circuit can still function; thus, an estimate of the probability of survival based on 10% degradation is close to a lower bound of the survival probability. Among the 40 circuits tested, 11 survived using this criterion; thus, the estimate of the probability of survival is $\hat{p}_S = 0.275$. This figure is lower than both the FAST estimate and the estimate based on a functional criterion of failure. However, since about half of the circuits continued to function after failure (using the 10% degradation criterion), this level of gain degradation is not a realistic failure criterion for this circuit.

7.0 HARDENING AND PROTECTION OPTIONS

A probabilistic design methodology is a logical way to approach vulnerability assessment analysis and hardness specification. There are different options to consider when one is faced with assessing and hardening systems in quite different stages of development. The emphasis here will be more on assessment for hardening when the system is already developed or fielded. The hardening options will necessarily be tied closely to the results of assessment and to the penalties that would be incurred by a redesign or retrofit for hardening purposes. Actual hardening options for existing systems may be quite limited. In the extreme, an operational change may be necessary. A new design would be most flexible in terms of system engineering studies for hardening options. In all cases, however, it is a question of choosing the appropriate set of hardening options when faced with given operating constraints.

There are several types of protection methods available, one or all of which may be used in a particular protection option. A system protection design approach, referred to as "apportionment of protection," is often used.

The idea is to distribute the protection so as to avoid a heavy reliance on a single protection method, such as a shield. A well-balanced apportionment scheme would appear to offer the least risk from an uncertainties viewpoint, as significant factors of safety could overcome the variations in each method used in the apportionment scheme. If uncertainties could be quantified sufficiently and if the system protection and environment interaction were sufficiently well understood, then the probabilistic approach could be used to overcome the heavy reliance on safety factors in protection.

8.0 SUMMARY

In this paper, we examined the general problem of uncertainties and their impact on high-altitude EMP vulnerability assessment of military systems. Typical uncertainties in coupling and susceptibility have been presented. Furthermore, the main methodologies used in vulnerability assessment have been reviewed and their respective handling of the uncertainties discussed. One such methodology, based on probabilistic techniques, has been partially validated at LLNL with two simple system tests, and the results were discussed. In addition, we discussed statistical test techniques used to obtain the necessary data to formulate the vulnerability issue in a probabilistic framework.

Coupling uncertainties can be quite high. For example, uncertainties in test data for internal cable currents of aircraft can be as high as $\pm$20 dB for tests in a full-scale free-field simulator. This includes measurement, extrapolation, and intersystem and intrasystem uncertainties, all combined as the square root of the sum of squares. The coupling uncertainty will be even higher if analytical techniques are used.

Inherent variability in the threshold failure levels of components when subjected to certain types of electromagnetic environments is a large source of uncertainty in doing a subsystem assessment. Frequently, more closely controlled features of a circuit that surrounds a component cause less variation in the susceptibility at a set of circuit interface terminals than would be observed in the component alone. Component parts may have one or two orders of magnitude of uncertainty in failure levels unless subject to parts control procedures. Past programs have shown that calculated threshold levels constitute a high-reliability lower bound on true thresholds as determined by tests. Failure test data also indicate margins of the order of $\pm$13 dB for aircraft-type equipment.

There is considerable diversity in methodologies applied to assessing the vulnerabilities of systems to EMPs. This is particularly true of how uncertainties in the assessment variables are treated, especially how uncertainties are combined for the ultimate evaluation of margins of safety and probabilities of survival. One method based on probabilistic analysis offers an efficient way of combining uncertainties with a minimum of assumptions. Thus, many of the shortcomings of the more analytical methods are avoided. In this study, estimates (based on probabilistic analysis) of the probabilities of survival for two simple systems compared favorably to experimental results. This indicates that an assessment method based on probabilistic analysis has potential for effectively accommodating uncertainties in the assessment variables.

As far as uncertainty reduction is concerned, reduction in certain areas seems much more plausible than in others. In coupling, reduction of measurement uncertainties depends largely on novel simulator and probe technology. The largest payoff, however, will be improved extrapolation techniques, improved cable layout control to minimize intersystem differences, and the conducting of tests in the power-on mode. In the susceptibility domain, with strict control of components and circuits configuration, the uncertainties can perhaps be reduced to ± 6 dB.

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