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The Development of Military Equipments: Reliability and Nuclear Survivability
Considerations

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Abstract

This paper discusses the development cycle of Army equipments including the influences exerted by various concerned agencies and individuals involved in the development cycle and the ways in which these pressures affect nuclear survivability and reliability.

The design-to-cost philosophy is described. The viewpoints of both the contractor and Project Manager are given along with the features each considers most important (profit and performance for the former, cost and schedule for the latter).

The importance of military standards and specifications and their impacts on reliability are discussed. This paper stresses the importance of considering nuclear survivability and reliability at the beginning of the development cycle plus the use of contractors with experience in nuclear survivability.

The various nuclear radiation effects (meutrons, gamma dose, gamma rate, and EMP) on electronics are discussed, and the association between reliability and nuclear survivability is explored. Usually, nuclear survivability tends to be aided by reliability considerations, but the relationship between the two is not one of dependency, because many of the controlled parameters are different for the two problems. But the fact that parameters are controlled for each constitutes a major similarity between solutions of the two problems.

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1. INTRODUCTION

Recently, increasing interest has been shown for the nuclear surviv- ability of fielded and developmental tactical Army electronic equipments. The Harry Diamond Laboratories (HDL), Army Materiel Command* lead laboratory for Nuclear Weapons Effects, is concerned about this problem, to more intelligently support the Project Manager (PM) in development programs and provide Department of the Army (DA) staff with timely information on the vulnerability of current inventory items.

Herein is addressed a specific and limited aspect of the nuclear survivability problem. This paper is in response to a request from the Army Director of Telecommunications and Command and Control through the Defense Nuclear Agency. But many people in the business of supporting the development of military hardware could benefit from an outline of the model development cycle and the real world pressures and processes. Most of the statements in this report regarding nuclear survivability and reliability apply equally to all military services.

The specific problem addressed in this paper is the association of electronic system reliability considerations during development with the equipment survivability to transient nuclear radiation effects (TRE) (i.e., neutrons, gamma dose, gamma dose rate) and electromagnetic pulse (EMP). Specifically excluded are the problems associated with nuclear blast and thermal radiation, since these effects are not dependent on electronic piece-part selection, circuit design, or circuit/subsystem interfaces. Areas covered are life cycle management, reliability requirements, military standards and specifications that apply, the considerations of semiconductor technology, and the nuclear surviv- ability implications. How the system should work is discussed, and the practical problems are illustrated.

2. DISCUSSION

2.1 Life Cycle

To understand the framework of events related to reliability, it is best to first consider the life cycle for developmental hardware programs. In appendix A, there is a more complete discussion of the approved Life Cycle System Management Model (LCSMM), which includes the documentation and decision events. The LCSMM that applied before 1975 is not addressed here, since the differences are not critical to this paper. It suffices for our purposes to lay out the general flow of events. There are four primary phases: (1) conceptual, (2) validation, (3) full-scale development, and (4) production and deployment.

Now the US Army Materiel Development and Readiness Command.

In the conceptual phase, threat projections, technological forecasts, and Joint Service and Army plans are examined to determine operational capabilities and potential materiel systems that will improve Army effectiveness. During this time, the technical and economic bases for proposed systems are established by tradeoff analyses through the development and evaluation of experimental hardware (experimental prototype/breadboard). The planning and experimental work in this phase is designed to identify the critical issues and problems that must be addressed in the subsequent phases, to minimize risks and control costs. The duration of this phase is in part controlled by the resource constraints and the urgency of the operational threat. What comes out of this phase must be acceptable and credible tradeoffs among operational needs, performance requirements, cost, and schedule. Since both reliability and nuclear survivability are performance requirements, they should be considered in this first phase. The cost figures used are unit-production cost goals in fixed fiscal year dollars.

The validation phase is intended to verify the preliminary design and engineering, reevaluate the tradeoffs, and validate the hardware concept for full-scale development. In this stage, the advanced development (AD) prototype (brassboard) is made, and upon its acceptance as a viable and necessary equipment, the Required Operational Capability document is initiated. During this validation phase, the first formal Research and Development Acceptance Test (RDAT) is performed by the contractor, and the first set of Development and Operational Tests (DT/OT)-I is initiated by the Armed Services. These are system level tests, for the most part. Reliability and/or nuclear survivability subassembly and piece-part tests by the Government or the contractor in both the conceptual and validation phases should precede these scheduled, formal tests. The results of the RDAT and DT/OT are used to estimate the proposed system's military utility, cost, and performance and to refine the configuration prior to full-scale development. These advanced development prototypes are designed to closely represent the complete system to permit a thorough evaluation and tradeoff analysis. However, the quantity and level of prototype hardware and software validation is very much dependent on the nature of the program and the risks and tradeoffs involved. In fact, more than one contractor may be used to produce AD prototypes if resources permit.

In the full-scale development phase, the engineering problems are to be identified and solved so that a decision can be made as to the acceptability of the equipment. The engineering development (ED) prototypes undergo RDAT and DT/OT-II, and if the test results are favorable, the equipment is type classified, indicating that it is ready to be placed into the inventory. All the necessary support equipment and documentation must now be finalized. Even at this stage, tradeoffs among stated operational requirements, cost, schedule, and operational readiness data are conducted with the design-to-unit-production-cost (DTUPC) figure as the controlling parameter. The main reason for using

cost as the controlling parameter is that cost can be quantized and measured very easily. However, it is not always possible to accurately predict cost over the lifetime of a system.

In the final phase, there are usually an initial production run and an RDAT and DT/OT-III before full-scale production. After production and deployment, maintenance and product improvements become the critical issues.

2.2 Design to Cost

Up to this point, we have glossed over the concept of Design to Cost (DTC). The DTC philosophy is to manage and control the DTUPC by adequate research and development efforts in the preproduction phases. In general, this requires more time and more dollars (15 to 20 percent more), especially in the conceptual and validation phases. The payoff is that some investments have been shown to reduce the DTUPC up to 80 percent. The reason for this potential savings is that changes brought on by identifying deficiencies, modifying performance requirements, or chasing technology late in the development program are very expensive from the engineering, tooling, and hardware aspects--that is, the nonrecurring costs. To assist in this DTUPC concept, some contracts contain incentives for the contractor to produce cost-savings ideas.

There are several problems with this concept and implementation. Instead of DTUPC, the goal should be design-to-life-cycle costs. This is recognized as a laudable goal in DA Pamphlet 11-25 (LCSMM for Army Systems, p. 45), and the reliability community feels it can be achieved,* but in practice, DTUPC dominates. Performance tradeoffs are too likely to be made under DTUPC, where unit production cost is the dominant factor. This may seriously impact the maintenance and logistics problems of fielded equipment. In the absence of design-to-life-cycle cost constraints, contractors are likely to make proposals that are optimistically priced, often based on the benefits of advanced technology or custom-built integrated circuits (IC's). But without life-cycle cost data, the costs inherent in such proposals can be much higher than those indicated by unit production costs.

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*A member of the Army Electronics Command Reliability group cited these figures: a 20-percent-cost impact in development and production costs for piece part and design could save up to five times the invested dollars in lifetime maintenance costs. Joseph B. Brauer from RADC expressed it another way--in development it might cost $2 to detect and fix a defective part. In the field, the detection and fix might cost $500.

Contractor incentives also are likely to reduce the reliability. This follows from the fact that in practice, the PM has the final say on the matters that ultimately impact system reliability and nuclear survivability. What this means is that even though the PM has an engineering staff, in many cases, reliability engineers and nuclear survivability experts are not on the PM staff. (We know of no formal requirement or guidance on the inclusion of reliability* or nuclear survivability experts on the PM staff.) This limitation often does not deter a PM from accepting contractor recommendations concerning piece-part selection and circuit design that can impact both reliability and survivability. It is very unlikely that the reviewing committee (namely, the In-Process Review, Army Systems Acquisition Review Council, or Defense Systems Acquisition Review Council) would be made aware of kinds of tradeoffs on the piece-part and circuit level that the PM has made.

The classic, yet common, example of the problem cited above is the use of contractor-specified semiconductor piece parts in place of military standard parts. Traditionally, the contractors have found it easy to obtain waivers based on the cost and availability of military standard parts. The difficulty with this approach is that although production costs may be lowered, reliability, maintenance, and logistics may bear the burden of this move. In fact, production costs usually increase when commercial devices are used throughout, because after initial production, serious problems occur requiring additional work and testing. The cost for this extra work is typically two to five times the total parts cost. As an example, the Air Force Rome Air Development Center (RADC) traced failures to several commercial IC's. The extra cost to rework the IC's was $6.74 per IC. A JAN replacement was found for only $2.47 per device.

Another not so obvious example is the following. The initial performance criteria of a circuit can be met by using a capacitor rated for 20 V in such a way that 20 V or more is applied across it. However, the lifetime of this device is seriously affected because of this underdesign. Good reliability engineering practice calls for an overdesign factor of two in capacitor voltages to insure the maximum capacitor lifetime. The point is that piece-part cost or volume could be the desired traits, while the reliability consideration may be unwittingly sacrificed.

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*The suggestion is made in AR 70-17, System/Project Management (16 June 1975), para. 2-1b(9), that among authorized PM staff might be Reliability, Acceptability, Maintainability personnel.

Yet another problem is the inadequate allowance of time and dollars in the preproduction stages to allow the DTC philosophy to work properly. There is no point in speculating why this condition can and does exist. Nevertheless, DTC can and does work when given the proper conditions and valid cost data, and DTC can add support to both reliability and nuclear survivability requirements.

2.3 The Project Manager and Contractor Viewpoints

Another barrier to logical, effective program management is the nature of the PM position within the Army. In most if not all instances, the PM is military. Even though the Army policy is that the PM position is to be considered a select career assignment, some officers feel that a PM assignment is a mixed blessing and a risky assignment for career purposes. The Army is working to counteract these attitudes. Assume that this factor by itself is not a barrier to effective management. The PM position is, like other assignments, military or civilian, in part a means of getting a promotion. The measurable "success factors" are cost and schedule goals. This position is mainly caused by management preoccupation with these factors. This position is borne out by the fact that up to this time there were no plans to determine reliability performance in the field. This fact was a problem for the logistics people or the basis for a product improvement.

On the other hand, the contractor performs an economic analysis to assess the tradeoffs that lead to maximum profit. Next to profit in importance to the contractor is performance. No known contracts have been terminated for cost or scheduling violations, but some contracts have been terminated for lack of critical performance characteristics. In all fairness, it is best to mention that fixed fees have been lost due to cost overruns. Nonetheless, the Army has established the precedent of accepting equipments that have not met the reliability requirements when the principal operational requirements are met.

2.4 Military Standards and Specifications

It is a matter of record that poor reliability is associated with many military equipments.[1] In spite of this poor record, the Army apparently has no way of accumulating data from the field to find the exact causes or trends that influence materiel reliability. Meanwhile, the reliability community has been trying to cope with this problem by emphasizing the manufacture and production of reliable semiconductor piece parts. Here is where military standards and specifications can be

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[1]H. P. Gates, B. S. Gourary, et al, *Electronics X: A Study of Military Electronics with Particular Reference to Cost and Reliability, Vol. 2: Complete Report,* DARPA R-195, Institute for Defense Advanced Research Projects Agency, AD-A001065 (January 1974).

important. But reliable systems do not depend only on piece-part selection. It is absolutely essential that this be coupled with good circuit design practices. Little useful military documentation exists to provide guidance on circuit design, specifically in the area of piece part derating factors, which is an important facet of reliable design.

There is available to the PM a vast array of documents to help him and the contractor sort out the proper approach to reliability. Particularly in the late 1960's, military (i.e., tri-Service) standards, specifications, and handbooks relating to the reliability considerations for electronic equipment began to be recognized for their potential influence on the reliability problem. Two of these documents are particularly important to the reliability and survivability aspects of the semiconductor device technology. These are MIL-S-19500 (the specification document for discrete transistors and diodes) and MIL-M-38510 (the specification for IC's). These specifications treat the mechanical and electrical parameters of qualified parts, production assurance measures, and lot acceptance techniques that are designed to lead to producible, predictable, and uniform devices. Both of these documents are being updated to reflect the latest thinking on semi-conductor reliability.

A related document, MIL-STD-701H, indicates that military equipment should be built from military-qualified parts. But an obvious evolution in thinking has taken place over the years; under the heading of MIL-S-19500E (1968), it was stated that, "This specification is *mandatory* [italics ours] for use by all Departments and Agencies of DoD." In the following supplements and amendments to MIL-S-19500 and in MIL-M-38510A (1972), the citation reads, "This specification is *approved* [italics ours] . . . ."

For putting together the contract package, at least two standards can be used to assist in the reliability engineering of a system. MIL-STD-701 lists the diodes and transistors, and MIL-STD-1562 lists the microcircuits that are approved for use. Military specifications and standards are binding only if they are cited in the procurement package. Even when these and similar documents are cited, approval of nonstandard parts is easy to obtain in actual practice, since the approving official is the PM, and he is influenced mostly by the cost and availability problems associated with military standard parts.*

The assumption in requiring the use of military standard parts is that reliability is an inherent quality of these parts. This assumption is not always correct. If the parts are made to the

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*The requests must be formalized through MIL-STD-7498, *Military Preparation and Submission of Data for Approval of Non-Standard Parts.*

for dose rate). The device response could be expressed as a damage threshold or a damage constant. This in turn can be related to changes in the appropriate device parameter over a specified linear range of the degrading environment. For example, $I_{pp} = K_p\dot{\gamma}$, where I_{pp} is the gamma-induced device photocurrent, K_p is the experimentally determined damage constant, and $\dot{\gamma}$ is the gamma radiation peak dose rate.

Over the next year, this subcommittee hopes to work out the details of (1) dosimetry and simulation facility selections, (2) simulation test methods and procedures, (3) piece-part parameter specifications, (4) production process controls, (5) lot acceptance tests, and (6) periodic requalification of the vendor process and product.

Again, good as this approach sounds, there are some basic shortcomings. In theory, reliability and nuclear survivability considerations should be applied beginning in the conceptual phase. In practice, through at least the validation prototype development, only a few military-qualified parts are now used. This is an essential part of the reliability growth concept[3] for which, in each phase of the program, the reliability is supposed to improve. Therefore, the reliability and nuclear survivability tests and predictions will not be realistic until the piece part list is firm and based on the maximum use of military standard parts. (For Army field equipment, this is never expected to be 100 percent and is currently 50 to 75 percent.)

Two drawbacks exist to the reliability-growth concept. The first is that if the decision to use military-qualified devices is put off until the validation or full-scale production phases, the PM is more likely to refuse the proposed changes, no matter how small the cost increase is. The second drawback is that if military-qualified parts are not insisted on early enough, contract renegotiations may be unavoidable.

2.6 Semiconductor Device Classes

The assumption that the expected reliability of military standard (Joint Army-Navy or JAN) parts is better than commercial parts has been borne out by the available data. But MIL-S-19500 and MIL-M-38510 provide for more than one class of device, because these general specifications satisfy the needs of a broad spectrum of users. The equivalent designations, reliability figures, and cost are listed in table I.

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[3] AR 702-3, *Army Materiel Reliability, Availability, and Maintainability (15 May 1973)*.

TABLE I. RELATIVE FAILURE RATES AND ITEM COSTS FOR VARIOUS CLASSES
OF DEVICES

Device classes	Approximate relative failure rate[1]	Relative cost per gate[1]
Captive line product (nonstandard)	≤1	30 to 100
MIL-S-19500 (MIL-M-38510)		
JANA (A)	1	5 to 15
JANTX (B)	2 to 10	2 to 5
JAN (C)	16	1
Commercial product (nonstandard)	30 to 150	0.2 to 0.5

[1]*Joseph B. Brauer, The Development and Status of MIL-STD-883 and MIL-M-38510, Rome Air Development Center [n.d.].*

More often, the designer and the PM are exposed to the data of the last column, i.e., the cost, without appreciating the relative reliability figures in column 3. Naturally, they would conclude that anything more than a commercial part would at least double the UPC. Information available from RADC indicates that only 5 to 10 percent of the UPC for ground equipment is in the piece parts. Therefore, the use of class B or JANTX parts compared with commercial parts would be expected to impact the UPC by 25 to 50 percent. However, in actual practice, the impact is typically closer to 10 to 20 percent. What this buys is a very significant improvement in the piece-part failure rate, a factor of 15 to 75. In addition, the cost may be completely offset by savings in rework and retest which generally range from 10 to 40 percent of the manufacturing cost.

MIL-M-38510 and MIL-S-19500 list the types of inspections and tests that must be performed on the various classes of devices (to sort out the suspect and defective parts). Both specifications list a Lot Tolerance Percent Defective (LTPD) table. Given the part reliability figure, this matrix is used for selecting the minimum number of devices that must be sampled in a given lot size and the number that must pass the specified test. In the case of devices with a desired reliability figure of 95 percent (LTPD = 5 percent) with 90 percent confidence, the minimum sample size is 45 with no rejections allowed, 77 with one rejection allowed, 105 with two rejections, and so on.

Piece-part reliability is related to system level mean time between failure (MTBF), mean time to repair, and equipment availability by a series of generally simplified assumptions and formulas. More often than not, the system level specifications are not validated either through careful monitoring of the semiconductor vendor tests on the piece parts or by tests of statistically significant numbers of equipments. In fact, the sample size of the equipments tested is an inverse function of the system cost.

No mention is made in any DoD-level document of the use of the various classes of JAN parts. In practice, informed designers prefer to use class B or JANTX parts* in the validation and full-scale development phases. These provide a good reliability figure at a modest cost. In fact, ECOM requires waivers for the contractor to use class C (JAN) or commercial devices (because of their lower reliability) or to use class A (JANA) devices (because of their higher cost).[4] However, the burn-in requirements for class B or JANTX devices can cause availability and cost problems in the production phase, and waivers at this stage often lead to commercial devices, but not to JAN or class C devices, because it appears that the design engineers are far removed from these decisions. However, the availability problem of class B or JANTX parts is more apparent than real, since the parts require only a 1-wk (168 hr) burn-in time plus time for testing. Some of these parts are available off the shelf. The cost for class B and JANTX parts would be lower if more were employed.

2.7 Reliability of the System

Through the ED prototype phase, inadequate tests and imprecise calculations tend to characterize the reliability aspects of program development. But these tests and analyses, whatever their quality and quantity, end at DT/OT-III. For the production phase of the reliability program, quality assurance techniques are assumed adequate to preserve the reliability figure, and therefore, reliability of production line equipments is tested only in the field. The quality assurance techniques are controls and inspections.

Current emphasis within the developing community is the use of commercial off-the-shelf equipments. This approach is justified by both reliability and cost. Reliable commercial systems have evolved without the need for military-specified parts, because the production has continued over many years without significant product changes, and this continuation was backed by good data from the field on failure modes. This evolution led to an optimum combination of piece parts, circuit design, derating factors, and cost. The most reliable equipments were found to be made with the equipment manufacturers' own production-line semiconductor parts, wherein they could assure the uniformity of the products. When commercial off-the-shelf items are procured, sufficient historical data should exist, i.e., get items that are field proven, not those that just recently commenced production. In addition,

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[4] ECOM specification MIL-P-11268, Parts, Materials, and Processes Used in Electronic Equipment.

*These parts are burned in at high voltage and temperature stresses to weed out the weak parts.

modifications should be avoided, since they alter the status of the equipment such that it can no longer be considered the same field-proven equipment. Also, one must be careful not to confuse off-the-shelf *designs* with hardware, because the former have no field history on reliability.

This is an opportune place to reflect on what has been said so far. First, in practice, reliability is subjugated to cost and schedule goals. Second, military hardware development programs have often chased technology and changed performance requirements throughout the development cycle. Both of these practices are contrary to good reliability practices. Third, adequate documentation (regulations, standards, and specifications) may exist, but all too often these proven procedures are not followed.

2.8 Nuclear Survivability

The discussions above have centered on the models, technology, aids, and problems of reliability requirements. The nuclear survivability criteria application to system development has an even rockier road to travel. There is little, if any, formal documentation (regulations, standards, and specifications) to lay out a road map for the system developer. The DNA Handbooks are available for the equipment designers, but they are formidable piles of paper for the designer without previous experience in nuclear survivability design. These problems are currently being addressed at HDL. But the lack of the appropriate documentation is a good reason or excuse for unhardened equipment in the inventory.

A substitute, although not a good substitute, is nuclear survivability design expertise early in the development cycle. As in the case of reliability, advice on hardening considerations often is not sought until the whistle is blown, i.e., when somebody recognizes late in the development cycle that nothing has been done about the nuclear requirement. At this time, the cost and schedule impacts can be quite serious and may result in a decision to waive the nuclear requirement or reduce it to the level at which hardware can meet the requirement without modifications.

For the most part, the nuclear survivability requirement associated with tactical equipments can be treated with a modest effort and low cost if considered from the time of the conceptual phase. The estimate for the SAM-D system was on the order of 3 percent R&D cost impact for balanced, man-limited nuclear survivability. However, the tradeoffs, design, and validation must be performed with the support of experienced Government or contractor personnel or both.

Our experience has been that when the contractor had the nuclear expertise available, his cost estimates were reasonable, and the hardness was achieved. The problem is with the unknowledgeable contractor, since estimates of the cost for nuclear hardening are quite often inordinate. This problem alone has been the overriding cause of the cancellation of nuclear survivability requirements for tactical systems with modest criteria. This response of the unknowledgeable contractor is to be expected since he is unsure of his capability to solve the problem and most likely has to include learning costs or subcontract for expertise. Here is where suitable documentation could possibly provide sufficient insight and understanding of the nuclear hardening requirements. Unfortunately, the closest approach to such documents is the DNA Handbooks. However, they are much too long. They discuss measures of hardening for all survivability levels, and they cannot keep up with the state of the art. What is required is something concise and to the point, applicable to the specific criteria of concern, and current.

2.9 Association between Nuclear Survivability and Reliability

The nuclear effects on electronic piece parts for the tactical survivability criteria are generally confined to the semiconductor parts (i.e., diodes, transistors, and IC's). It is rare that a specially hardened semiconductor device is required to produce tolerable responses in a system with these modest criteria when survivability is designed into the system from the start. However, there are many semiconductor devices whose nuclear responses are far more favorable than others for survivable designs. The key is to select these less susceptible parts and couple survivivability with the proper circuit design.

No military standard or specification can be associated with nuclear survivability. Rough calculations of the piece-part response can be made based on some device parameters (e.g., minimum gain, gain-bandwidth product f_T). When the device parameters used for nuclear response determinations are controlled parameters and are designated as such in the appropriate military specifications, then nuclear survivability begins to resemble reliability by the nature of the controls imposed. The Hardness Assurance Subcommittee is evaluating the device parameters and process controls necessary to control and predict the device response as a possible approach to nuclear survivability. However, piece-part response is not the whole story. Circuit design considerations, hardness assurance controls, and verification of survivability are also essential ingredients to a sound nuclear survivability program.

In general, reliability and nuclear survivability tend to follow the same trend because both require controls. However, these controls are not necessarily the same for both problems. An example of the differences is in the f_T requirement. Low frequency minority-carrier devices are in general more susceptible to neutron damage than high frequency ones. However, the reliability of a device is not dependent upon f_T, but rather on many other parameters controlled by the military standards and specifications.

2.10 Nuclear Radiation Effects on Electronics

The primary degrading effect of neutrons is a reduction of minority-carrier lifetime in bipolar transistors. This causes a reduction in gain, an increase in saturation voltage, and an increase in leakage current. In analog IC's, this usually results in some loss in device gain, a reduction in gain-bandwidth product, and changes to the input offset voltage. In addition, the device may no longer be able to drive a heavy load. In digital IC's, fanout is reduced, because the changes in the output transistor parameters reduce the maximum current that the device can sink. In addition, the HIGH and LOW voltages may degrade somewhat so that the protective voltage difference (guaranteed noise voltage margins) between the two levels is reduced. Thus, the circuit may be vulnerable to logical changes in state caused by smaller noise signals than before irradiation.

The piece-part reliability and neutron response require control of different parameters. However, on a circuit level, the two requirements are more closely related. For example, to insure the reliability figure, large derating factors may be used so that less power is dissipated in the transistors and larger variations in the ageing of piece parts can be tolerated.

The total ionizing dose effects on electronics at the levels of interest to field Army equipments are generally limited to IC latchup. This phenomenon, which can occur at very low doses but only for high dose rates, affects both complementary metal oxide semiconductors (CMOS) and junction-isolated bipolar IC's. The occurrence of latchup in bipolar IC's is relatively rare. On the other hand, bulk silicon CMOS devices appear to be plagued with this problem. Unfortunately, these technologies comprise the bulk of the IC's being manufactured today, and avoiding them is not a viable solution. There are special manufacturing techniques available for avoiding latchup in CMOS, even at very high dose rates.[5] Among these techniques are gold doping, dielectrically isolated substrates, mask layout design, and even neutron irradiation.

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[5]B. L. Gregory and B. D. Shafer, *Latchup in CMOS Integrated Circuits*, *IEEE Transactions on Nuclear Science*, NS-20, No. 6 (December 1973), 293-299.

The goal is either to reduce the minority carrier lifetimes so that all possible gain (h_{FE}) products between parasitic NPN and PNP transistor pairs are less than unity or to isolate the layers so that no SCR-like action is possible. A possible solution for latchup in the case of the standard, unhardened CMOS is to isolate the IC from the power supply by the addition of a small series current-limiting resistor. It is unclear as to whether this is a universal solution, and if it is not, avoidance of CMOS would be advisable. Since latchup in junction-isolated bipolar IC's is infrequent, response data on the specific device type is required. Reliability considerations alone would not preclude the use of these susceptible devices. However, once these susceptible devices are identified, controls like those available to the reliability engineers are necessary to keep these susceptible devices out of survivable system designs.

The only other significant total dose effect at tactical system survivability levels is the degradation of lasers.[6] Doses of a few hundred rads(Si) have been shown to alter the threshold for lasing in some materials. This change leads to cessation of lasing action or loss of output power. This effect can be mitigated by operating the laser well above the threshold. In this case, the only effect is that the laser power is degraded. Where power consumption is critical, the system operating point is designed to be near the lasing threshold (e.g., in a man-pack laser range finder, the margin might be less than 10 percent). Our information leads us to believe that for reliability, the same philosophy would apply, since lower operating voltages on capacitors and less power dissipated in flash lamps imply longer part lifetimes. The implication is that where power consumption or reliability dominates the laser system design, the nuclear response of the system is more likely to be a problem.

The nuclear dose rate effects are transient false signals, device burnout, magnetic logic upset, and reversible and irreversible changes of state. In general, Army equipments do not have an operate-through requirement for nuclear survivability. Therefore, transient false signals and logic upsets can be compensated for (e.g., the bad data can be discarded, or a retransmission of a message can be requested, and a way to reestablish stored information can be provided). In most military equipments, logic upset is provided for, since the commonly occurring power transients and outages can produce the same effect.

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[6]J. J. Halpin, A Progress Report on the Transient Radiation Effects on Laser Materials FY'71, NRL Memorandum Report 2337, Naval Research Laboratory (30 June 1971).

Semiconductor burnout in discretes and IC's is strongly associated with reliability considerations and good design practice. There are two types of burnout: metallization and thin conductor burnout and junction burnout. Both types are caused by the large currents induced in the circuit by the gamma pulse or coupled from the external or system-generated (internal) EMP. Most metallization burnouts are due to defective metallization, which can be avoided by proper reliability methods. Another major consideration is good design practice. To preclude generation of currents capable of burning out the metallization or junction, it is necessary to properly isolate the piece part from its primary source of current, i.e., its power supply. Proper isolation is normally achieved with limiting resistors. This is not found in nonnuclear survivable designs.

Many dose rate effects fall into the reversible and irreversible categories. For example, silicon controlled rectifiers (SCR's) are triggered by the transient gamma pulse and can be reset only by removing primary power to them. Power supplies designed to shut down when an overcurrent or overvoltage is sensed are reversible events if they are easily reset. Semiconductor burnout is one example of an irreversible action produced by the transient gamma pulse. Other examples are nonresettable timers that may be started by a false signal or fuses or electrically activated squibs that may be destroyed by the false signal induced by the gamma pulse. In general, there are categories of devices to be avoided and certain circuit design guidelines to be followed to prevent such events from occurring, many of which are not included in the standard practices of reliability engineering.

The EMP response of a system is a complex phenomenon involving electromagnetic coupling, cross coupling, and device burnout. Shielding of cables, cable connectors, and electronic enclosures combined with protection devices at the terminations of antennas, cables, and other critical entry ports are the commonly applied EMP hardening techniques. The intent is to reduce as much as possible the amount of EMP energy coupling into a system and then use circuit hardening and circumvention techniques as required to survive the effects of that energy that does penetrate to the circuit and device level. Electromagnetic compatibility (EMC) and lightning requirements come closest to ameliorating, but not solving, the EMP problem. Therefore, normal reliability considerations associated with EMC and lightning protection are not enough to protect a system against EMP.

In summary, reliability considerations by themselves can work contrary to nuclear survivability considerations (e.g., laser systems); they can work in consonance with nuclear survivability requirements (e.g., metallization burnout, transistor piece-part derating in circuits); and these two requirements can be unrelated (e.g., latchup, semiconductor piece-part response determinants, metallization or junction burnout current limiting requirements). A generalized statement might be that nuclear survivability tends to be aided by reliability considerations, but the relationship between the two is not one of dependency, because many of the controlled parameters are different for the two problems. However, the fact that parameters are controlled for both problems constitutes a major similarity between solutions of the two problems.

The final item for consideration is the effect on the MTBF due to the exposure of an electronic system to the nuclear TRE and EMP environments. Assuming that the system survives the single-burst, nuclear encounter, the electronic systems performance is most likely degraded somewhat if the exposure level was at or near the "typical" nuclear survivability requirements for tactical systems. The performance degradation results from piece-part degradation. The net result would be to narrow the circuit design margins, making the circuit more sensitive to device parameter changes due to normal ageing or to the increased power dissipated in the device. The conclusion is that without proper consideration to the nuclear response of the electronic system, the MTBF is expected to be degraded. The extent of this effect is dependent on the design margins in the circuits.

The effects of ageing are virtually nonexistent for good quality semiconductor devices, however. In addition, the effect on the MTBF is small even for equipment exposed to the maximum expected nuclear environment. The effects on the MTBF over the inventory of equipments is even smaller because of the small probability of exposure.

3. SUMMARY

There is an orderly process for developing reliable and nuclear survivable equipment. The reliability community has documented the procedures, controls, and management insight into military regulations, standards, and specifications. The nuclear community, however, does not have this type of supporting documentation that the users and developers find most useful. However, the methodology has been developed and used for more than 10 yr, and during this time, systems have been hardened to much higher levels than Army field equipments require. Now, HDL is supplementing the nuclear effects documentation. In spite of the

existing documentation, the logic and orderliness are often perturbed by pressures and priorities that subjugate reliability and nuclear survivability to cost and schedule.

For any important performance characteristic, it is necessary to have expert advice from the conceptual phase to assist in supplying informed inputs, making the tradeoffs, and assuring that adequate time, money, and equipment are available for verification of the system performance. The plan should include the concept of performance growth because new, unproven devices and materials are often being applied, and their capabilities, response, and lifetime have to be validated. But it is important that the entire emphasis not be placed on favorable piece-part characteristics and response, since circuit design and component derating are also critical factors in both reliability and nuclear survivability.

The comparison of reliability and nuclear survivability is valid in that similarities of planning, expert assistance, and control procedures are indicated. However, the controlled parameters and the circuit design philosophies are somewhat different. A system may be very reliable and yet quite vulnerable to nuclear radiation, and vice versa.

The constraints on a design engineer are performance, cost, schedule, size, and weight. These are the immediate, measurable system features. Reliability and nuclear survivability are more distant, abstract, and often less important.

Reliability engineering and nuclear survivability design are specialties of design engineering. To assume that a competent design engineer has a working knowledge of the nuances of reliability and nuclear survivability is fallacious.

When one addresses the reliability and nuclear survivability of equipments from the concept phase following a logical and firm path, the reliability and survivability goals can be met cost effectively and timely. But all too often the near-term influences dominate the long-term payoffs.

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ACKNOWLEDGEMENTS

APPENDIX A.--THE LIFE CYCLE SYSTEM MANAGEMENT MODEL FOR ARMY SYSTEMS

This material is extracted from DA Pamphlet 11-25, Life Cycle System
Management Model for Army Systems (23 January 1975). The model is a
simplified flow chart representing the life cycle of an Army system from
conception to fielding of finished equipment, personnel training,
product improvement, maintenance, and phase out or disposal of unneeded
equipment. In this brief description, only the major events are
related. In a given system development program, certain events (or
possibly entire phases) may be bypassed if the information already
exists or if the required developmental work has already been performed
or is otherwise unnecessary. However, if there is any controversy
regarding cost, complexity, or high visibility, the event or phase may
then become mandatory. There are four phases in the life cycle of any
Army system: conceptual, validation, full-scale development, and
production and deployment.

In the conceptual phase, the combat development agencies, usually
the Army's Training and Doctrine Command (TRADOC), examine threat
projections, technology available and forecasted, and Joint Services and
Army plans to determine the operational capabilities and potential
materiel systems that could improve the Army's effectiveness. A Letter
of Agreement (LOA) is signed by the combat and materiel developers in
which they outline basic agreements for further investigation of a
potential materiel system. During this phase, the basic research and
the applied research are performed that lead up to the breadboards or
experimental prototype. They also agree in the LOA upon the nature and
characteristics of the proposed system and the tests required to
validate the system concept.

A Special Task Force (or Special Study Group) is then assembled by
the Army Chief of Staff and is normally composed of the Charter Task
Force Director, representatives of the materiel and combat developers,
the trainer, the operational tester, and perhaps a Project Manager
designee. This group prepares a Decision Coordinating Paper (DCP,
previously called Development Concept Paper) or an Army or Defense
Program Memorandum, which presents the rationale for starting,
continuing, reorienting, or stopping a development program. It
identifies the issues in a decision and assesses the important factors
such as threat, risks, military and economic consequences, and critical
problems to be resolved by test and evaluation. They also prepare a
Concept Formulation Package, which includes tradeoff determination and
analysis, best technical approach, and cost and operational
effectiveness analysis. The tradeoff determination studies the
technical and economic feasibility of each approach to a realization of
a potential system including the risks involved with each. In the

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tradeoff determination, the Special Task Force decides which technical approaches are best. From these documents (including a final report), an Outline Development Plan (ODP) is prepared that records program decisions and analyzes technical options and plans for development of the system in the validation phase.

These documents, plus an Independent Parametric Cost Estimate (performed by the Comptroller of the Army before entry into each succeeding phase), are submitted for review and acceptance at the first meeting of the Army Systems Acquisition Review Council (ASARC-I). After favorable review, the Army accepts the DCP. Then it is submitted at the first meeting of the Defense Systems Acquisition Review Council (DSARC-I) and then to the Secretary of Defense for final acceptance. These ASARC and DSARC reviews are performed for major systems to determine whether a phase is complete and if the program is ready for the succeeding phase. The level of review (i.e., ASARC or DSARC) is determined by the importance of the dollar value of the system. For nonmajor systems, the final review could be at the Army Materiel Development and Readiness Command level and is called the In Process Review.

In the validation phase, preliminary design and engineering are verified experimentally and analytically. Tradeoff proposals are analyzed, and logistics problems are identified. A contract is awarded to develop prototypes representing complete systems (advanced development prototype). The prototypes are then submitted for the first set of Development and Operational Tests (DT/OT-I). Development testing is performed to determine that the design risks are minimized, the engineering is complete, solutions to problems are at hand, and the system meets or will meet its specifications (including nuclear, if applicable). Operational testing is conducted to determine a system's military utility with representative users in an environment as realistic as possible, its operational effectiveness, and its operational suitability, including compatibility, reliability, availability, maintainability, logistic support, tactics, and training requirements. If possible, the new equipment should be compared with existing equipment.

These test results are used in preparing the Required Operational Capability (ROC), the Development Plan, and the Provisional Qualitative and Quantitative Personnel Requirements Information. The ROC is a short document stating the essential operational, technical, logistic, and cost information required to initiate development or procurement of a system. The Development Plan contains the ROC and expands upon the ODP. The Development Plan is submitted for review and approval by ASARC-II or DSARC-II or both, as appropriate, to determine whether the program is ready for full-scale development.

During the full-scale development phase, the system, including all items necessary for its support, is fully developed and engineered, built, and tested. The resulting engineering development prototype should be a preproduction system closely approximating the final product. Also included in the output for this phase is the documentation to enter the production phase, including draft field manuals, and test results of DT/OT-II supporting entry to the production phase. Producibility Engineering and Planning (PEP) is conducted during the full-scale development phase to assure facility of volume production. These PEP activities include developing data packages, designing special production equipment or tooling, and possibly designing computer models of the production process to identify production problems. Long-lead-time requirements also must be identified. Again, the DT/OT-II results and the updated Development Plan are presented for review and approval by the appropriate-level committee to determine the system's readiness for transition to Low-Rate Initial Production (LRIP) in the production and deployment phase.

Finally, the production and deployment phase begins with a contract for LRIP. This is intended to provide an adequate number of production-line items for final DT/OT-III. The purpose is to minimize the government's exposure to large retrofitting problems and expenses if production deficiencies are discovered or modifications are proposed for product improvements. A production validation In-Process Review may be conducted if initial production items do not meet their required specifications. This is conducted by the materiel and combat developers and the Deputy Chief of Staff for Research, Development, and Acquisition. First editions of technical and field manuals are submitted for publication. The test results from DT/OT-III and the newly updated Development Plan are submitted for review and approval to enter full production and deployment.

Full-scale production is then authorized, including any necessary retrofitting. Final Qualitative and Quantitative Personnel Requirements Information is determined and is used to determine whether new Military Occupational Specialties should be created. A new Table of Organization and Equipment is drafted, reviewed, approved, and published. Personnel are trained, and an Initial Operational Capability is achieved by a troop unit using production items. After a period of time, the materiel developer accumulates maintenance data from field units for developing an Annual Maintenance Man-Hours data package. This package is provided to TRADOC for preparation of the Manpower Authorization Criteria, which is used to revise the Table of Organization and Equipment. Unneeded or obsolete equipment is scheduled for phase out or disposal. When adequate numbers of new equipment and spare parts are available, production may cease until further units are required.

APPENDIX A

    Recently, according to the magazine AMC News, the Army changed its development test procedure to reduce duplicate testing. More reliance will be placed on contractor testing, and the Army's role will shift from that of independent tester to independent evaluator. The Army Materiel Systems Analysis Agency will perform the independent evaluation for the Army. The Test and Evaluation Command will become more of a service organization, providing facilities and expertise and performing test services for the government and its contractors. Contractor data from the Research and Development Acceptance Test will be validated to determine whether additional testing is necessary.