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SEMICONDUCTOR DEVICE DAMAGE ASSESSMENT FOR THE INCA PROGRAM--A --ETC(U)
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Two methods are described for estimating the probability that a given semiconductor device will be damaged by an electrical transient. Both methods are based on existing device damage data which were obtained by step-stressing devices to failure, using rectangular pulses. Both methods require calculation of the time-dependent power waveform in the device, due to application of the transient. One method employs only the largest peak of this power

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waveform, while the other includes the entire waveform in a convolution integral. Modifications to the DAMTRAC circuit-analysis program are presented.

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## 1. INTRODUCTION

An important aspect of the electromagnetic pulse (EMP) vulnerability assessment of electronic equipment is the question of whether a particular semiconductor component will be damaged by the EMP-induced transient. The methods currently used to predict semiconductor damage are based on calculated power dissipation in the device junctions. Most such efforts involve replacing the highest peak of the power-versus-time curve by a rectangular pulse which is approximately equivalent to it in energy content. Then the damage data for that device are scanned to see if the calculated power-width coordinates for the pulse fall above or below the nominal damage curve. Vulnerability assessments in such a scheme are quite imprecise, usually reducing to such statements as the system is "vulnerable" or is "not vulnerable."

This procedure appears reasonable enough, because any such analysis must be based on the existing device damage data, and these were almost invariably obtained by step-stressing a device to failure, using rectangular pulses. It has, however, two serious faults: (1) the treatment of arbitrary power-versus-time waveshapes as rectangular pulses and (2) the lack of a probabilistic treatment.

This report describes two possible improvements on the above procedure. The first improvement addresses the statistical distribution of damage by assuming that the device damage power is lognormally distributed at constant pulse width. The nominal damage level is then used with an estimate of the standard deviation in power to damage, after review of a large amount of data,[1] to calculate the probability of device failure, given power inputs in the form of rectangular pulses. The other improvement, which removes both of the above objections, uses the entire power-versus-time curve directly to calculate the probability of device failure.

## 2. DEVICE DAMAGE DATA DISTRIBUTION

Device damage data are generally obtained by step-stressing a number of devices to failure, using rectangular pulses of various widths. The results of this procedure, after proper curve fitting, provide the device damage curve—a log-log plot of nominal damage power, $P_D$, versus pulse width, $\tau$. There is substantial disagreement about the form of $P_D$, mostly due to the lack of good experimental data, and it is likely that no single form can adequately describe all devices. Still, for very short pulses, the adiabatic approximation[2,3] appears generally valid. That is

$$P_D(\tau) \propto \tau^{-1},$$

while for very long pulses thermal equilibrium can be reached, that is,

$$P_D(\tau) \propto \tau^{0}.$$

For the intermediate region, there is a general tendency to use the Wunsch-Bell[4] model, with

$$P_D(\tau) \propto \tau^{-1/2}.$$

It is not at all clear where these regions should meet. The available data imply that the adiabatic approximation is excellent, at least up to 50 to 100 ns, while the equilibrium

---

[1] Defense Nuclear Agency EMP Handbook, Component EMP Sensitivity and System Upset, Ch. 13 (22 September 1975).

[2] D. C. Wunsch and L. Marzitelli, Semiconductor and Nonsemiconductor Damage Study, Braddock, Dunn, and MacDonald, Inc. (April 1969).

[3] D. M. Tasca, IEEE Trans. Nucl. Sci., *NS-17*, 6 (December 1970).

[4] D. C. Wunsch and R. R. Bell, IEEE Trans. Nucl. Sci., *NS-15*, 6 (December 1968).



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approximation is usable down to perhaps a few seconds. Between these limits is a broad transition region wherein $P_D$ varies smoothly from one limit to the other. On log-log paper, the slope of $P_D$ varies monotonically from $-1$ (adiabatic) to 0 (equilibrium). The Wunsch-Bell model represents the transition region by a line of slope $-\frac{1}{2}$.

Most cases of interest to us involve total times less than about 500 ns. Thus, the equilibrium region, and most of the transition region, as well, can generally be ignored. For this reason, and because of the large amount of scatter in the damage data, it appears practical to approximate $P_D$ by two straight lines which intersect at a certain point, namely,

$$P_D = \begin{cases} K'\tau^{-1}, & \tau < \tau_0 \\ K\tau^{-1/2}, & \tau \geq \tau_0 \end{cases}$$

where $K$ is the Wunsch-Bell damage constant, and $K'$ is determined by the requirement that the two lines intersect at $\tau = \tau_0$. That is,

$$P_D(\tau_0) = K'\tau_0^{-1} = K\tau_0^{-1/2}$$

or

$$K' = K\tau_0^{1/2}.$$

In a later section, we shall represent the probability of device damage, for a power input pulse of amplitude, $W$, as a cumulative lognormal distribution:

$$F_D(W) = \tfrac{1}{2}\left\{1 + \mathrm{erf}\left[\frac{\ln W - \mu}{\sigma\sqrt{2}}\right]\right\},$$

where $\mu = \ln P_D$, and $\sigma$ is the standard deviation in the natural log of the damage power distribution.

Examination of many sets of damage data[1] has shown that the distribution in power to damage, at fixed pulse width, is approximately lognormal and that the typical spread is about a factor of five in power. Thus, in the lognormal description, the standard deviation, $\sigma$, is approximated by

$$\sigma = \ln 5 \doteq 1.61 \qquad \text{(see app B).}$$

The median value of damage power is given by $P_D$. Therefore, the mean, $\mu$, of the damage distribution is

$$\mu = \begin{cases} \ln(K'\tau^{-1}), & \text{adiabatic} \\ \ln(K\tau^{-1/2}), & \text{Wunsch-Bell} \end{cases}$$

These two moments completely describe the distribution. In practice, since damage data are seldom available for pulse widths less than 50 ns, we find $K$ by finding the line of slope $-\frac{1}{2}$ which best fits the data. The value of $K'$ is then determined by the choice of $\tau_0$. In general, we used $\tau_0 = 50$ ns.

## 3. THERMAL RESPONSE

It is well known that, if one obtains the response of a system to a step excitation, the impulse response can be gotten by differentiation, and that the response to any other excitation can be calculated by convolving the impulse response with the arbitrary excitation. Thus,

[1] Defense Nuclear Agency EMP Handbook, Component EMP Sensitivity and System Upset, Ch. 13 (22 September 1975).

consider an initially relaxed system described in terms of an impulse excitation, $\delta(t - t')$, and a response, $h(t - t')$:

$$H^{-1}(t)h(t - t') = \delta(t - t').$$

Here, $H^{-1}(t)$ is a linear differential operator with constant coefficients. If we assume that no signals are applied before $t = 0$, this expression can be integrated once to give

$$H^{-1}(t) \int_0^{\infty} h(t - t')\, dt' = \int_0^{\infty} \delta(t - t')\, dt'.$$

Since no response is possible before an excitation is applied, the integration can be terminated at $t' = t$. Thus,

$$H^{-1}(t) \int_0^{t} h(t - t')\, dt' = \int_0^{t} \delta(t - t')\, dt' = U(t),$$

where $U(t)$ is the unit step function defined by

$$U(t) = \begin{cases} 0, & t < 0 \\ +1, & t > 0. \end{cases}$$

The integral on the left now gives the time-domain response to the unit step. Laplace transforming both sides gives

$$L\left[\int_0^{t} h(t - t')\, dt'\right] = \frac{H(s)}{s}$$

and

$$L\left[\int_0^{t} h(t - t')\, dt'\right] = L[v_u(t)] = V_u(s).$$

Then $H(s) = sV_u(s)$, where $H(s)$ is the transfer function and $V_u(s)$ is the step-function response in the frequency domain.

The impulse response, which is the inverse transform of the transfer function, is then given by

$$h(t) = L^{-1}[H(s)] = L^{-1}[sV_u(s)]$$

$$h(t) = \frac{d}{dt}[v_u(t)] + v_u(0+)\delta(t).$$

The last equation follows from the two standard transforms:

$$L\left[\frac{df}{dt}\right] = sF(s) - f(0+)$$

$$L[\delta(t)] = 1,$$

where

$$F(s) = L[f(t)].$$

The response to a general excitation, $e(t)$, can now be written

$$v(t) = \int_0^t h(t - t')e(t')\, dt'$$

$$v(t) = \int_0^t \left\{ \frac{d}{d(t - t')} [v_u(t - t')] + v_u(0+)\delta(t - t') \right\} e(t')\, dt'$$

$$v(t) = v_u(0+)e(t) + \int_0^t e(t') \frac{d}{d(t - t')} [v_u(t - t')]\, dt'.$$

In the application to thermal damage to semiconductors, we make the following equivalences.

$$v(t) \rightarrow \Delta T(t) = \text{temperature rise}$$

$$e(t) \rightarrow P(t) = \text{power dissipation}$$

$$v_u(t) \rightarrow R(t) = \text{response to rectangular pulse power}$$

$$\Delta T(t) = R(0+)P(t) + \int_0^t P(t') \frac{d}{d(t - t')} R(t - t')\, dt'.$$

The first term can be ignored on physical grounds. That is, the response at zero time to an excitation which began at zero time can be nonzero only for infinitely large power input. Hence,

$$\Delta T(t) = \int_0^t P(t') \frac{d}{d(t - t')} R(t - t')\, dt'.$$

Now, let us assume that the temperature rise at the semiconductor junction—due to application of a rectangular pulse of unit amplitude and width $\tau$—is

$$\Delta T(\tau) = R(\tau).$$

For a linear system, the temperature rise due to any other rectangular pulse of the same width is proportional to $R(\tau)$. In particular, for a pulse equal to the nominal damage power for that width, we expect

$$\Delta T(\tau) = T_C = P_D(\tau)R(\tau),$$

where $T_C$ is the temperature at which damage occurs. Thus, we can write

$$\Delta T(t) = T_C \int_0^t P(t') \frac{d}{d(t - t')} \left[ \frac{1}{P_D(t - t')} \right] dt'.$$

Dividing by $T_C$ gives

$$I(t) = \int_0^t P(t') \frac{d}{d(t - t')} \left[ \frac{1}{P_D(t - t')} \right] dt'.$$

This is a very convenient relation between the instantaneous junction power dissipation and the normalized temperature rise in the junction. As long as $I \ll 1$, we expect no damage. When $I \simeq 1$, we usually make the nominal prediction of damage. In the next section, we shall see how these predictions can be made more quantitative.

Substituting the two straight-line expressions for $P_D$, which we exhibited in section 2, gives

$$I(t) = \int_0^{t_1} P(t') \frac{d}{d(t-t')} \left[ \frac{(t-t')^{1/2}}{K} \right] dt' \mid t - t_1 \geq \tau_0$$

$$+ \int_{t_1}^{t} P(t') \frac{d}{d(t-t')} \left[ \frac{t-t'}{K\tau_0^{1/2}} \right] dt' \mid t - t_1 < \tau_0$$

or

$$I(t) = \int_0^{t_1} P(t') \frac{dt'}{2K(t-t')^{1/2}} \mid t - t_1 \geq \tau_0$$

$$+ \int_{t_1}^{t} P(t') \frac{dt'}{K\tau_0^{1/2}} \mid t - t_1 < \tau_0 .$$

The function h(t) described earlier in this section will be recognized as the Green's function of the operator $H^{-1}(t)$.

## 4. DAMAGE ASSESSMENT

We now have in hand the necessary mathematical apparatus for damage assessment. Basically, all that remains is to exhibit the answers for the two methods mentioned in section 1.

In the first method, we assume power inputs in rectangular pulse form. Since we know that the device damage data are lognormally distributed, we can immediately write down the probability that a pulse of amplitude W and width $\tau$ will cause failure. It is given by the distribution function, F. Thus,

$$F_D(W) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^W e^{-1/2\left(\frac{\ln W' - \mu}{\sigma}\right)^2} \frac{dW'}{W'},$$

where $\mu = \ln P_D$ and $\sigma = 1.61$.

A simple change of variable gives

$$F_D(W) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{\ln W - \mu}{\sigma}} e^{-1/2y^2}\, dy$$

or

$$F_D(W) = \tfrac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\ln W - \mu}{\sigma\sqrt{2}}\right)\right].$$

The survival probability is then given by

$$P_s(W) = 1 - F_D(W) = \tfrac{1}{2}\left[1 - \mathrm{erf}\left(\frac{\ln W - \mu}{\sigma\sqrt{2}}\right)\right].$$

In the second method we are concerned with the distribution in the maximum values of the convolution integral $I(t)$, in those cases where damage results. For rectangular pulses, it is obvious that the distribution in this $I_{max}$ is lognormal with the same $\sigma$ as the pulse power. If the thermal model is to be useful, this must also be true with arbitrary power waveforms, because the distribution is really in junction temperature. Thus, since the median value of $I_{max}$ which

results in junction damage is unity, the damage probability in this case is

$$F_D(I) = \tfrac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\ln I - \ln 1}{\sigma\sqrt{2}}\right)\right],$$

and the survival probability is

$$P_s(I) = \tfrac{1}{2}\left[1 - \mathrm{erf}\left(\frac{\ln I}{\sigma\sqrt{2}}\right)\right].$$

## 5. COMPARISON OF CONVOLUTIONAL AND RECTANGULAR PULSE ESTIMATES OF SURVIVAL PROBABILITY

It is of some interest to compare the survival probabilities gotten by using the maximum value of the convolution integral and the rectangular pulse. Consider a particular example where the maximum free field is about 25 kV/m and the relevant DAMTRAC outputs are

$$I_{max} = 0.747$$

$$W = 9840 \text{ W}$$

and

$$\tau = 13.6 \text{ ns}.$$

### 5.1 Convolutional Case

From the results of section 4 we see that the survival probability is*

$$P_s = 1 - F\left(\frac{\ln 0.747}{1.61}\right) = 1 - F(-0.181)$$

or

$$P_s = F(0.181) = 0.572.$$

### 5.2 Rectangular Pulse Case

#### 5.2.1 Adiabatic Model

First, we compute the most probable value of damage power for pulse width $\tau$, using the formula appropriate for the adiabatic model.

$$\mu = \ln(K'\tau^{-1}) = \ln(K\tau_0^{1/2}\tau^{-1})$$

$$\mu = \ln K + \tfrac{1}{2}\ln\tau_0 - \ln\tau$$

$$\mu = \ln 0.91 + \tfrac{1}{2}\ln 5 + 4\ln 10 - \ln 1.36$$

$$\mu = -0.09 + 0.80 - 0.31 + 9.21$$

$$\mu = 9.61.$$

In addition, we have

$$\ln W = \ln 9840 = 9.19.$$

---

* There is a slight change in notation here. What we previously called $F_D(I)$ is really $F\left(\frac{\ln I}{\sigma}\right)$. This distinction is necessary for use of probability tables.

Putting these into the formula for survival probability gives

$$P_s = 1 - F\left(\frac{9.19 - 9.61}{1.61}\right) = F(0.26)$$

or

$$P_s = 0.60.$$

### 5.2.2 Wunsch-Bell Model

This calculation is entirely analogous to the adiabatic calculation. Thus,

$$\mu = \ln(K\tau^{-1/2}) = \ln K - ½\ln\tau$$

$$\mu = \ln 0.91 - ½\ln 1.36 + 4\ln 10$$

$$\mu = 8.81,$$

and the survival probability is

$$P_s = 1 - F\left(\frac{9.194 - 8.81}{1.61}\right) = 1 - F(0.24)$$

or

$$P_s = 0.41.$$

For this particular problem, the convolutional approach gives a survival probability which is about 5 percent lower than that given by the adiabatic model, but about 39 percent higher than that given by the Wunsch-Bell model. This is not necessarily true in other cases. It is easy to construct waveforms having multiple peaks close together, for which the convolution integral—since it takes account of all peaks—would give a significantly lower probability of survival than would either of the other two models.

## 6. DAMTRAC MODIFICATIONS

One major component of the machinery necessary for damage assessment is a computer program which calculates the response of a circuit to input transients. We used an extended version of a program called DAMTRAC,[5] a version of the TRAC code, which calculates power dissipation in given circuit components as a function of time.

Almost all of DAMTRAC is kept in object form on a permanent file. Subroutine TRAEQ is available, however, and this is where the necessary changes were inserted. Subroutine TRAEQ is called several times for each solution of the circuit equations, and the current values of elapsed time and power dissipation are then available. Each time an acceptable solution of the circuit equations is reached, the current values of the convolution integrals are calculated. At the end of a predetermined interval, the maximum values of these integrals are found and the probabilities of component failure are calculated. At the end of the job, the integrals are plotted as functions of time by specifying appropriate node numbers in the input data deck. Up to 10 semiconductor components can be analyzed for each DAMTRAC run. If necessary, the program can easily be modified to accommodate a larger number of devices. A listing of this subroutine is given in appendix A.

[5] G. H. Baker, A. D. McNutt, D. M. Rubenstein, and G. B. Shea, Damage Analysis Modified TRAC Computer Program (DAMTRAC), Harry Diamond Laboratories TM-75-6 (May 1975).

## 7. CONCLUSIONS

Two improvements in EMP circuit damage-analysis techniques have been described: (1) use of a convolution integral to account for arbitrary power pulse shapes, and (2) use of a routine to give probability of damage rather than purely qualitative results. These changes result in a convenient calculational tool for damage assessment. The increase in running time over the present DAMTRAC, with the rectangular pulse approach, is small. This method is substantially more satisfying because of the quantitative damage probability results and because the entire waveform is taken into account. This method will be used as Harry Diamond Laboratories primary circuit-analysis technique for the INCA program.

---

## ACKNOWLEDGMENT

It is a pleasure to thank W. E. Sweeney, Jr., and K. T. LePoer for helpful comments.

# APPENDIX A.

# SUBROUTINE TRAEQ LISTING

A listing of the subroutine TRAEQ follows. TRAEQ is called several times for each solution of the circuit equations, and the current values of elapsed time and power dissipation are then available.

```
C       SUBROUTINE TRAEQ
        SUBROUTINE TRAEQ(KK4)
        IMPLICIT REAL*8 (A-H,O-Z), INTEGER*2 (I-N)
        REAL*4 ST,VP,XP,ABC,E04,TF
        INTEGER*2 ERR
        INTEGER*4 KK4
        INTEGER*4 CONP,COND,CONT,LIMIT,RSTRT
        DIMENSION DAMP(1000,10),PWR(1000,10),TIME(1000)
        DIMENSION CD(10),DAMMAX(10),PDAM(10)
        COMMON/ALPHA/A(100),E(19,40,2),H(100,100),O,T(100),V(240),AL(50),
       1BV, CT(11,2), DI(30), DM, DR(30), DV(30), EI(20), E2(19),
       2TE,TI,TO,VS(20,5),V1(240),V2(240),BCI(30),
       3BCR(30),BCV(30),BEI(30),BER(30),BEV(30),DIP(30),EP1(20),EP2(20),
       4QCR(30,7),SI1,TEX,TE1,TOO(19),TOP,TO1,VER(9),AAAA(60),BCDT,
       5BCIP(30),BCUR(290),BEIP(30),DTIM,GRSP,
       7PPIC(30), PPID(30), PPIE(30), PWCR(30), PWTR(30), QTAN(30,16),
       8RMAG, TE11, TOL1, TOL2, TOT2, TO11, VAL1(200), VAL2(200),
       9VAL3(200), BCDT1, BCUR1(290), PPIC1(30), PPID1(30), PPIE1(30),
       ASYMB1,SYMB2,TITLE(9),TOLPL,TOMIN,ST(19,2),ABC,
       *E04,COND(30,5),CONP(200,5),CONT(30,5),ERR,IAW,JSJ,IDC,NCUT,
       BKTOT, IBC, NAW, ITOT, KTOT1, NV, NG, JJ, N3B, NBRAN, NBLOCK,
       CITOT1, JUJ, N2B, ISTRK, ISYM4, NZ, ND, NBB, NVM, NCR, NNNN1, ICP,
       DIPRINT, NTPLP, NPP(60), NOP(4), NA, NZ1, ND1, JJJ, KE, NTR,
       EIFGDTC, JV, IPX, NA1, NT, NB, N1B, JCAT, NCORE, JVJ, NP, IPLCON,
       FISYM3, NP1(10,2), JG(19)
        COMMON/BETA/VP(5000),XP(700),TF(350)
        COMMON/GAMMA/PWCRFD(30),PWCRRV(30),BRKVOL(30),DAMNK(30)
        COMMON/DELTA/PWTEFD(30),PWTERV(30),PWTCFD(30),PWTCRV(30)
        DATA M/1/, NPR/0/
C     FOR SUPPRESION OF H*T MATRIX PRINT , SET ERR=2
        ERR=2
        GO TO (9000,9003,9002,9001), KK4
 9000   CONTINUE
C       PART 1 - MATRIX AND TIME FUNCTION EQ"S. AFTER THIS CARD.
        EI(3)=V(21)*.42
        OMEGA=2.*3.1416*30.00E+06
        EI(2)=9.*DSIN(OMEGA*TE)+1.E-6
C       RETURN
 9003   CONTINUE
C       PART 2
        RETURN
 9002   CONTINUE
        RETURN
 9001   CONTINUE
C       PART 4 - AUXILIARY EQUATIONS AFTER THIS CARD.
        V(24)=PWCRFD(1)
        V(25)=PWCRRV(1)
        V(26)=PWTCFD(1)
        V(27)=PWTCRV(1)
        V(28)=PWTEFD(1)
        V(29)=PWTERV(1)
        V(30)=PWCRFD(2)
        V(31)=PWCRRV(2)
```

```
C
C    THE FOLLOWING CARDS ARE FOR DAMAGE CALCULATIONS
C
C    CD     - WUNSCH DAMAGE CONSTANT
C    TO     - CROSSOVER WIDTH, WUNSCH TO ADIABATIC MODEL
C    NDEV   - NUMBER OF VULNERABLE DEVICES
C
      T0=5.E-8
      NDEV=2
      CD(1)=0.91
      CD(2)=0.20
      IF(TE.LE.0..OR.M.GE.1000) GO TO 200
      PWR(M,1)=PWTCRV(1)
      PWR(M,2)=PWTERV(1)
      TIME(M)=TE
      IF(M.EQ.1) GO TO 190
      IF(TIME(M).LE.TIME(M-1)) GO TO 200
C
      DO 10 I=1,NDEV
      DAMP(M,I)=0.
      DO 10 J=2,M
      IF(TIME(M)-TIME(J)-T0) 5,6,6
    5 DAMP(M,I)=DAMP(M,I)+(TIME(J)-TIME(J-1))*(PWR(J,I)+PWR(J-1,I))/2./
     1 DSQRT(T0)/CD(I)
      GO TO 9
    6 DAMP(M,I)=DAMP(M,I)+(TIME(J)-TIME(J-1))*(PWR(J,I)/DSQRT(TIME(M)-
     1 TIME(J))+(PWR(J-1,I)/DSQRT(TIME(M)-TIME(J-1))))/4./CD(I)
    9 V(100+I)=DAMP(M,I)
   10 CONTINUE
C
      IF(NPR.EQ.1) GO TO 190
      IF(TE.GE.CT(1,2)-CT(1,1)) GO TO 150
      GO TO 190
  150 NPR=1
  170 DO 180 I=1,NDEV
      DAMMAX(I)=DAMP(2,I)
      DO 175 J=3,M
  175 IF(DAMP(J,I).GT.DAMMAX(I)) DAMMAX(I)=DAMP(J,I)
      Y=DLOG(DAMMAX(I))/1.61/SQRT(2.)
  180 PDAM(I)=0.5*(1.+DERF(Y))
      WRITE(6,185)
  185 FORMAT(1H1,50X,30HSUMMARY OF DAMAGE CALCULATIONS/)
      WRITE(6,186) (I,DAMMAX(I),I=1,NDEV)
  186 FORMAT(//25X,41HMAXIMUM VALUE OF CONVOLUTION INTEGRAL NO.,I3,2H =,
     1 1PE11.3)
      WRITE(6,187) (I,PDAM(I),I=1,NDEV)
  187 FORMAT(//25X,35HPROBABILITY OF DAMAGE TO DEVICE NO.,I3,2H =,
     1 1PE11.3)
      WRITE(6,188)
  188 FORMAT(1H1)
  190 M=M+1
  200 RETURN
      END
```

## APPENDIX B
## A NOTE ON SEMICONDUCTOR DAMAGE DATA

The value assumed for $\sigma$ in section 2, body of report, may be excessively large in most cases. If so, the reader is free to substitute any value he prefers. It should be pointed out, however, that semiconductor damage tests, in general, were not statistically designed. That is, the experimenter made no effort to plan his tests so that the results would be statistically meaningful. Sample estimates of $\sigma$ and, to a lesser extent, $\mu$, based on such tests may be misleading to an engineer and downright useless to a statistician.

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