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A STUDY OF ELECTRONICS RADIATION HARDNESS ASSURANCE TECHNIQUES. VOLUME II, PART 2, ELECTRICAL SCREENING FOR IONIZING RADIATION RATE AND TOTAL DOSE EFFECTS

I. Arimura, et al

Boeing Company

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BETRACT (Distributio	on Limitation Statement A)
This program determined physical grated semiconductor devices exposed corments. From physical reasoning p determined which had some probabilit and failure thresholds. It was deter meutron degradation was generally ef for power devices. Other AC and a f potential screens for neutron degrad using electrical storage time consta screening primary photocurrents of integrated circuits were obtained wit topologies to enable electrical meas to's Volume (Volume II), the utility was compared to that obtained from m Excellent correlation was obtained to cuits and the emitter-base turn-on v special leads. Electrical screens f relatively ineffective even with par results were obtained from an evalua- tive device sensitivity varied with	I failure modes of a range of discrete and inte- d to ionizing rate, neutron, and total dose envi- possible electrical parameter measurements were ty of correlating with the radiation sensitivity armined that base transit time normalization for ffactive for low-power transistors, but ineffective few DC measurements also were found to be effective dation. No particular advantage was noted for ant is compared to electrical storage time for low-power discrete devices. In some cases, the ith nonstandard metallization, "special lead," surments to be made at internal circuit nodes. In / of these measurements as correlation parameters measurements nade using unmodified circuits. between the neutron degradation of the logic cir- /oltage obtained from the measurements made using for total dose hardness assurance were found to be rameter correlation factors of 0.7 to 0.8. Similar ation of the low dose screening concept since rela- absorbed dose. A mathematical expression was
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A STUDY OF ELECTRONICS RADIATION HARNESSS ASSURANCE TECHNIQUES

Volume II, Part 2 Electrical Screening for Ionizing Radiation Rate and Total Dose Effects

I. Arimura, et al.

The Boeing Company Seattle, Washington 98124

Final Report for Period 31 July 1970 through 16 July 1973

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IN

FOREWORD

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Principal authors and contributors were Mr. Allan H. Johnston, Dr. L. L. Sivo, and Mr. D. W. Egelkrout. Technical direction and coordination of the program were performed by Dr. R. S. Caldwell and Mr. C. Rosenberg.

Capt J. L. Guidry, Capt G. B. Crocker and Capt P. J. Vail at the Air Force Weapons Laboratory also made significant contributions to the overall planning and execution of the program.

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This technical report has been reviewed and is approved.

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PREFACE

This report describes the results of a comprehensive study which was designed to determine improved techniques for providing radiation hardness assurance on modern electronic systems. The two basic goals considered were () to determine from physical reasoning and large scale testing the effectiveness of established electrical screening parameters and the existence of additional ones which might be correlated with radiation responses and (2) to establish a statistical comparison between the various hardness assurance techniques including electrical screening, lot sampling and irradiate-and-anneal. For reasons of physical convenience, the report is divided into three volumes:

Volume I - Background, Approach, and Summary of Results Volume II - Electrical Screening, parts 1, 2, and 3 Volume III - Lot Sampling and Irradiate-and-Anneal

This Volume (Volume II) contains a detailed description of the results obtained from the electrical screening portion of the program. The electrical screening approach examined correlations between certain initial electrical parameters and the radiation sensitivities of the devices. The correlation parameters were selected on the basis of physical reasoning and the radiation sensitivies were defined differently for the various radiation environments. Neutron hardness assurance is treated first and the various classes of devices such as low-power transistors, high-power transistors, JFETs and ICs are discussed separately. Ionizing radiation rate hardness assurance is treated second with subdivision determined again by the various classes of devices. MTBF results are also discussed for parts subjected to ionizing rate tests. Total dose hardness assurance is discussed third for the low-power transistors and for the op amp separately. Low dose screening is included in this section although it differs slightly from the "normal" techniques of electrical screening. Finally, second breakdown hardness assurance is discussed in its entirety.

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ABBREVIATIONS AND SYMBOLS

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A	Ampere, area, surface area of second breakdown region
A _B	Base area
A _E	Emitter area
A _{EFF}	Effective emitter area
A _{OL}	Open-loop gain
A _{SB}	Cross Sectional area of a second breakdown site
AC	Alternating current
AH1	Effective emitter area determined from gain-bandwidth product, emitter base capacitance and current gain
AH 3	Effective emitter area determined from gain-bandwidth product, current gain, and base doping concentration
AH4	Effective emitter area determined from gain-bandwidth product, breakdown voltage, and current gain
A-0-I	And-or-invert
BOT	Breakout transistor
BV	Breakdown voltage
^{BV} CBO	Breakdown voltage of collector-base junction with emitter open
BV _{EBO}	The emitter-base breakdown voltage of a transistor with the collector open
BVGSS	Breakdown voltage of gate-channel in JFET. Source and drain shorted
BVCBO	Base to collector breakdown voltage, emitter open
BVCEO	Open base collector to emitter breakdown voltage, measured at a collector current of 10 milliamperes
BVEBO	Open collector, emitter to base breakdown voltage, measured at a base current of 10 milliamperes
С	Damage factor, average specific heat, capacitor

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с _{св}	Collector-base junction capacitance
C _{GSS}	Gate-channel junction capacitance of JFET
C _{IB}	Emitter-base junction capacitance
с _{ов}	Collector-base junction capacitance
с _р	Damage factor of wafer transistors
C _{SBL}	Linear second breakdown neutron degradation constant
c _β	Neutron damage factor
C-B	Collector to base
CB - X, Y	Neutron damage factor for current gain measured at a collector current of X amperes and collector to emitter voltage of Y volts
C-E	Collector to emitter
СН	Channel
CMRR	Common-mode rejection ratio
cov	Coefficient of variation
COVAR	Covariance = standard deviation mean
CRO	Cathode ray oscilloscope
CSBLXYZ	Linear second breakdown neutron degradation constant determined from neutron levels ϕ_x , ϕ_y , and ϕ_z
CSBXYZ	C_{SB} determined from neutron levels ϕ_x , ϕ_y , and ϕ_z
D	Diffusion constant
D _B	Diffusion constant for minority carriers in base region
D _E	Diffusion constant for minority carriers in emitter region
DC	Direct current
D.I.	Dielectric isolation

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- DUT Device under test
- E Energy or electric field strength, second breakdown energy measured at $I_{\rm E} = 5A$
- E-5MSIA Second breakdown energy for a 5 millisecond wide, 1 ampere pulse of emitter current
- E-5MSIBO Second breakdown energy for a 5 millisecond wide voltage pulse equal to the collector-emitter breakdown voltage, base open
- E_{SB} Energy required to produce second breakdown: measured at device terminals
- Energy required to produce second breakdown: delivered to a localized site of second breakdown
- F F value
- FSC Fairchild Semiconductor Corporation
- FM1 Transistor figure of merit determined from gain bandwidth product and base doping concentration
- FM3 Transistor figure of merit determined from gain bandwidth product and collector to base breakdown voltage, emitter open
- FM4 Transistor figure of merit determined from gain bandwidth product and collector to base breakdown voltage, emitter open
- FT A constant proportional to the gain-bandwidth product measured at an emitter current of 1 ampere
- HA Hardness assurance
- HFE X, Y Common emitter DC current gain measured at a collector current of X amperes and a collector to emitte. voltage of Y volts

I Current

I^OB

I^s

I_B Base current (bipolar transistors) or input bias current (op amps, sense amps)

Initial (pre-radiation) base current or bias current

The surface component of the base current

S.

I _{B1}	The forward current into the base of a saturated transistor
^I B2	The current flowing out of the base of a saturated transistor when it is switched out of saturation
IBIAS	Input bias current
I _{BS}	Base current of saturated transistor
с	Collector current
^I сво	Collector-base junction leakage current
^I cc	Power supply current in positive supply lead
^I CC(0)	Power supply current of a digital circuit in a 0-state
^I CO	Pre-exponential saturation current
^I CS	Collector current of saturated transistor
^I DS	Drain current in JFET
IDSS	Source to drain saturation current at zero gate bias
Ι _E	Emitter current
IEBO	Emitter-base junction leakage current, collector open
I ^o _{EBO}	Initial (pre-radiation) emitter-base junction leakage current, collector open
I ^s EBO	The surface component of the leakage current across the reverse biased emitter-base junction
I _{EE}	Power supply current in negative supply lead
I _F	Forward current of gate-channel diode in JFET
I IN(R)	Reverse input current measurement for T ^{*1} . circuits
I _{IN(0)}	Current out of TTL input with input voltage low
I _{IN(1)}	Current into TTL input with input voltage high
I _{OS}	Input offset current
Ipp	Primary photocurrent

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I _{OL}	Output leakage current of an integrated circuit
I _R	Reverse current of gate-channel diode in JFET
I _{SK}	The cutput sink current of a TTL device with lower than normal supply voltage
Isp	Secondary photocurrent
IC	Integrated Circuit
ICBO	Open emitter, collector to base leakage current measured at 50 volts
ICEO	Open base, collector to emitter leakage current measured at 30 volts
IEBO	Open collector, emitter to base leakage current at 5 volts
I'V'	Portion of second breakdown power not directly dissipated in a second breakdown site
J _E	Emitter current density
J.I.	Junction isolation
k	Damage constant, an abbreviation for Kilo-ohm used in circuit schematics
Ka	Thermal conductivity at second breakdown site averaged over temperature
κ _F	Carrier removal damage factor
ĸ _Ň	Total delay time normalized damage constant
ĸ _R	Damage constant due to lifetime degradation in emitter- base depletion region
L	Diffusion length, length of JFET channel in direction paralleled to current flow
LC	Diffusion length of minority carriers in collector region
L _E	Diffusion length of minority carriers in emitter region

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LINAC	Linear accelerator
LSI	Large scale integration
М	Mass of material at a localized second breakdown site
Μ _β	Temperature sensitivity of the common emitter DC current gain
MB -3.0	Temperature sensitivity of the common emitter current gain measured at a collector current of 3 amperes and a collector to emitter voltage of 3 volts
MeV	Mega electron volts
MLR	Multiple linear regression
MLRP	Multiple linear regression prediction
MLR-R	Coefficient of multiple linear correlation
MLR-r	Multiple linear regression partial correlation coefficient
MLRr	Multiple linear regression coefficient
MOT	Motorola
MSI	Medium scale integration
MTBF	Mean time between failure
N	Value of exponent in the equation relating second breakdown energy and neutron fluence. N is determined from, carrier concentration 4 fluence levels
N _B	Base doping concentration
^N BO	Base doping concentration adjacent to emitter region
N _E	Minority carrier density in the emitter region
No	Channel doping concentration for JFET in cm^{-3}
NXYZ	Value of exponent in equation relating second breakdown energy and neutron fluence. NXYZ is determined from fluence levels of ϕ_x , ϕ_y and ϕ_z
N(CH)	Channel doping as calculated from ${}^{\rm BV}_{\rm GSS}$ measurements

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Noise (1/f)	Surface component of the 1/f noise
Р	Power
P _{3B}	Power of a square pulse required to produce second breakdown
Q	A symbol for transistors used in schematic diagrams
Ř	Resistance
R _B	External resistance from the base of a transistor in an electrical circuit
R _D	Maximum percentage range in the data
R _E	Radius of emitter region
R _L	Load resistor
R _P	Maximum percentage range in the prediction
RBC	The reciprocal of base impurity concentration.
RBV	A constant inversely proportional to the 2.8 power of the open collector-emitter, to base breakdown voltage measured at a base current of 10 milliamperes
RCA	Radio Corporation of America
RCC	The reciprocal of the collector impurity concentration
RCV	A constant inversely proportional to the 2.8 power of the open emitter, collector to base breakdown voltage measured at a base current of 10 milliamperes
RMS	Root mean square
S	Switch
Sat.	Saturation
SB	Second breakdown
SCR	Silicon controlled rectifier
SLR	Single linear regression
SSI	Small-scale integration

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Т	Absolute temperature (°K), Temperature
Ta	Ambient temperature
T _{off}	The turn-off time of an integrated circuit
^t SB	The temperature at a site of second breakdown at the onset of second breakdown
TI	Texas Instruments
TTL	Transistor-transistor logic
TUT	Transistor under test
v	Volt
V _{BE}	Base to emitter voltage
V _{BEON}	Emitter to base forward voltage
v _c	Collector voltage
v _{CB}	Collector to base voltage
v _{cc}	The positive supply voltage of an integrated circuit
v _{ce}	Collector to emitter voltage
V _{CE(SAT)}	Collector to emitter voltage for saturated transistor
v _{DS}	Drain voltage
V _{EB}	The voltage from the emitter to base of a transistor
V _{EE}	The negative supply voltage of an integrated circuit
v _{GS}	Gate to source voltage
V _{in}	Input voltage
V _{IN(R)}	The reverse input voltage of a TTL circuit
v _{oh}	The 1-state output voltage of a digital circuit
V	The O-state output voltage of a digital circuit

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The offset voltage of an integrated circuit vos Pinch off voltage for JFET VP Voltage across a device prior to second breakdown VSB V-I Voltage-current VBEON-X Emitter to base forward voltage for an emitter current of X amperes VCES-X Collector to emitter saturation voltage at a collector current of X amperes Voltage across a device prior to second breakdown at VSB-5A an emitter current of 5 amperes VSB-5MSIBO Voltage across a device prior to second breakdown at a delay time of 5 milliseconds and with zero base current WB Base width Collector depletion width of a transistor WC Depletion region width of emitter-base junction WD W_{1(2,3,4)} Wafer number 1 (2,3,4)WB The inverse square root of the common emitter gainbandwidth product Channel width in direction perpendicular to thickness Z and length in JFET Channel thickness in JFET а Capacitance С Centimeter cm Common-emitter gain-bandwidth product f Common base cutoff frequency Fa Post-irradiation transconductance 8_m Pre-irradiation transconductance g_{mo}

h _{FE}	Common-emitter DC gain
h _{FE} ,h _{FEI}	Common-emitter DC current gain for inverted transistor
h _{FEO}	Pre-irradiation gain
h _{FE} ¢	Gain after neutron irradiation
i _n	Equivalent input noise current
k	Boltzmann constant
keV	10 ³ electron-volts
mA	10 ⁻³ amperes
mV	10 ⁻³ volts
mW	10 ⁻³ watts
n	Value of exponent in equation relating second breakdown energy and neutron fluence
nI	Exponent of voltage dependence of emitter-base junction capacitance
n _i	Electron concentration in intrinsic silicon
n p	Minority carrier density in a p-type semiconductor
ns	10 ⁻⁹ seconds
Po	Equilibrium hole concentration
pF	10 ⁻¹² farads
P	Electron charge
r	rads
rank-r	Rank correlation coefficient
r _B	Transverse base resistance
r _{B1}	Transverse base resistanc for inverted transistor
r _c	Collector body resistance

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r _{cs}	Resistance of collector region of saturated transistor
rd(on)o	Pre-irradiation value of rd(on)
^r d(on)	The on resistance of a JFET
rad(Si)	A deposited dose of 100 ergs per gram of silicon
s	Second
t	Time
t _B	Base transit time
td	Total delay time
t _{PD}	Propagation delay time of a logic circuit
tOFF	Turn-Off time of the word switch
t _{PLH2}	The delay time of an integrated circuit when the output goes from low to high, measured at 50% of the equilibrium value
t _{rrGS}	Reverse recovery time of gate-channel diode in JFET
t _{SE}	Electrical storage time
tSAT	Saturation time of the word switch
t-statistic	Measure of significance for multiple linear regression analyse:
w _E	Width of emitter stripe
×m	Modulation length
∆I ^S _B (burn-in)The change in I ^S during burn-in
$\Delta I_B^{s}(T)$	The change in I_B^s when measured at different temperatures
ΔI ^S (bura-in EBO	n)The change in I ^S _{EBC} during burn-in
∆I ^s EBO	The change in I_{EBO}^{S} when measured at different temperatures
Δn	Excess electron concentration
^ф ве	Base-emitter junction contact potential

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Ω	Ohm
β	Grounded emitter DC current gain (i.e. h _{FE})
β _F	Forced beta of saturated transistor ($\equiv I_{CS}/I_{BS}$)
βο	Initial (pre-radiation) grounded emitter DC current gain
Ŷ	Ionizing dose rate
ε	Permictivity of dielectric
ε _o	Permittivity of vacuum
θ	The electronic charge divided by the product of Boltzmann's constant and the absolute temperature
^θ нs	Hot spot thermal resistance
ĸ	Dielectric constant
μ	Mobility
^μ B	Carrier mobility in base region
^μ c	Carrier mobility in collector region
^µ n	Electron mobility
^µ р	Hole mobility
μ Α	Micro amperes
μΓ	10 ⁻⁶ farad
μs	10 ⁻⁶ second
ρ _B	Resistivity of base region
^р с	Resistivity of collector region
^ρ se	Emitter sheet resistivity
σ	Electrical conductivity or standard deviation
τ	Excess minority carrier lifetime
τ _B	Minority carrier lifetime in base region

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τ _C	Minority carrier lifetime in collector region
τno	Minority carrier lifetime in highly p-type
τ pc	Minority carrier lifetime in highly n-type
τ s	Electrical storage time constant
τ s	Storage time constant for gate-channel diode in JFET
τ _{SB}	Second breakdown delay time
τsbo	Delay time to second breakdown measured in previous tests
τ	Hot spot thermal time constant
φ	Neutron Fluence
^ф с	Critical dose or threshold dose for failure
¢1	First neutron fluence
¢2	Second neutron fluence
^ф з	Third neutron fluence
ф ₄	Fourth neutron fluence
ω _T	The gain-bandwidth product of a transistor $(f_T) \ge 2\pi$
0-state	The low output voltage state of a digital circuit
1-state	The high output voltage state of a digital circuit
1N1	First neutron irradiation
2N1	Second neutron irradiation
3N1	Third neutron irraliation
4N1	Fourth neutron irradiation

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SECTION III

IONIZING RADIATION RATE EFFECTS HARDNESS ASSURANCE

1. INTRODUCTION

This section discusses hardness assurance techniques for ionizing rate effects in discrete transistors, junction field-effect transistors (JFET), and integrated circuits. For discrete transistors, hardness assurance techniques were investigated for both primary and secondary photocurrent. The transistor types studied include high- and low-power transistors with a wide range of device geometries and electrical properties. The radiation rate dependence of primary photocurrent was also considered. For the JFET, gate primary photocurrent is the fundamental radiation parameter used in the correlation and hardness assurance studies. The integrated circuits included in this study are all dielectricallyisolated, radiation-hardened devices, and include both digital and linear circuit types. The circuit output response to ionizing radiation was used as the parameter of internst for hardness assurance and correlation studies. For the digital circuits, the radiation level was varied to find the particular radiation threshold level at which a given output response occurred.

A detailed description of the various device types and the schematic diagrams for the integrated circuits are contained in Paragraphs 2-a and 2-b, Section IV, Volume 1. A description of the radiation test conditions and techniques is included in Paragraph 4-c, Section IV, Volume 1.

2. LOW POWER TRANSISTORS

a. Primary Photocurrent

Steady-state primary photocurrents were measured for five types of low-power transistors and two types of IC breakout transistors using the Boeing Radiation Effects Laboratory 10-MeV Electron Linear Accelerator as an ionization source. Experimental details of the measurements were described previously in Paragraph 4-b, Section IV, Volume 1. Table 51 is a summary of the parts tested for primary and secondary photocurrents. The electrical screening parameters for primary photocurrents were investigated only for the first seven part types shown in Table 51.

The primary photocurrent, I_{pp} , measured for five types of lowpower transistors are summarized in the sample histograms shown on Figures 49 through 53. The mean, standard deviation, maximum, minimum and range of photocurrents are summarized in Table 52. The range of responses for these part types (given by the maximum I_{pp} divided by minimum I_{pp}) varied from ~1.8 to ~3.5 (excluding one 2N3960 which exhibited a breakdown or anomalous I_{pp} a factor of 10 greater than the other devices of that type). However, the data at the very high rates are of questionabe accuracy, particularly for the rates in the high 10¹⁰ rad(Si)/s range. Accurate dosimetry was difficult at these rates since the electron beam spot was quite small and the position of the beam varied from shot-to-shot.

 I_{pp} , based on the simple theory given in Paragraph 3-a, Section V, Volume 1 for collector-base primary photocurrent, is expected to vary linearly with ionizing radiation rate. The rate dependence of I_{pp} is an important quantity to establish since extrapolation of data to other rates is generally required for analyses of system performance. The rate dependence of I_{pp} was established for four of the part types by measuring I_{pp} at two rates. Table 52 includes a summary of linearity of the rate dependence of I_{pp} ; the ratio of the photocurrent per unit rate at the higher and lower rates indicates the rate dependence is nearly linear for two of the part types with the 2N3960 and 2N2905A of questionable linearity. The linear dependence of I_{pp} is plotted against dose rate for four of the part types. The bars associated with each data point are plus and minus one standard deviation for the distribution of photocurrents for the ~150 devices of each type.

The only well-known electrical technique for screening transistors against excessive photocurrents is the method of measuring electrical storage time, t_{SE} , as developed by Carr (Ref. 17). The technique was originally developed to evaluate different device types and works fairly well for this purpose when restricted (1) to silicon planar diffused and mesa npn transistors with power ratings less than 800 mW, (2) to dose rates between 10⁶ and 10⁸ rad(Si)/s, and (3) to transistors with electrical storage times between 10⁻⁸ and 10⁻⁵ seconds. Although t_{SE} can be used

acceptably when comparing different types of devices, it has not been demonstrated to be useful as a screening parameter for devices of a given type.

However, as discussed in the theory of primary photocurrents (Paragraph 3-b, Section V, Volume 1), the main contribution to I pp originates almost entirely in the collector regions for non-Au-doped planar epitaxial devices. For these cases, the collector lifetime, $\tau_{\rm C}$, and diffusion length are the major parameters controlling I . The electrical screening and correlation parameter then is the electrical storage time constant, $\tau_{\rm S}$, rather than $t_{\rm SF}$ since,

$$\tau_{\rm S} \cong 1/2 \ \tau_{\rm C}$$

where τ_{c} is obtained from

$$t_{SE} = \tau_{S} \ln \frac{I_{B1} + I_{B2}}{I_{CS}/h_{FE} + I_{B2}}$$
(12)

The results of the correlations between I and t_{SE} and τ_S are shown in Table 53. Electrical storage time constant, τ_S , appears to offer practically no improvement as a screening parameter over electrical storage time, t_{SE}. This is partly the result of the poor quality of the "fit" of the data to Equation (12) which produced "noisy" values of τ_S and thus poor rank correlations.

These results are further verified by examining the scatter diagrams (shown in Figures 56 and 57) of I pp versus t_{SE} and τ_{S} for one example in Table 53. It can be seen that, while a trend is obvious, these plots are truly scattered and neither of the parameters are particularly useful as a screen for I pp.

The efficacy of other screens for I were investigated. According to the theory presented in Paragraph 3-b, Section V, Volume 1, collector-base junction capacitance, C_{OB} , and possibly base transit time, t_{B} , should be the next best correlation parameters after τ_{S} . Neither of these parameters were particularly successful as I pp screens. The largest

correlation coefficient for C_{OB} was +0.538 for the 2N2905 which is opposite in sign to that anticipated. At least t_B , however poorly, correlated with the I_{pp} in the proper direction.

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Tables 54 and 55 briefly summarize the order of efficacy of potential screening parameters for the various device types. In general, t_{SE} or τ_{S} are the best screening parameter for primary photocurrent. C_{IB} as a potential screening parameter was unexpected since it was assumed that the junction areas were nearly constant for a given device type. However, C_{IB} is dependent upon the base doping concentration near the e-b junction and, thus could reflect a large gradient in base impurity doping concentration. The electric field produced by this gradient would enhance the carrier flow to the c-b junction and the subsequent photocurrent. The correlation with t_B is <u>reduced</u> by the presence of an internal electric field.

Since no single screening parameter appeared to be successful as a primary photocurrent screen, multiple linear regression (MLR) analyses were performed using the parameters predicted to be effective from theoretical reasons as well as those the data indicated were correlated to I p. These results (summarized in Table 56) were, in general, disappointing and while effective in reducing the prediction errors, were not sufficiently effective to implement as a screening technique.

b. Secondary Photocurrents

Secondary photocurrents, I_{sp} , were measured in a grounded base configuration. The main "turn-on" mechanism for this case is the transverse voltage generated by the IR drop of the primary photocurrent and transverse base resistance. This model (presented in Paragraph 3-b, Section V, Volume 1) predicts that the following parameters are important for screening I_{sp} :

1. I (and parameters for which I is dependent),

2. r_B, transverse base resistance,

3. h_{FF}, common-emitter DC current gain,

4. N_{RO} , base region impurity doping concentration, and

5. t_p, base transit time.

In general, the correlations for I sp were much better than for I. A summary of the correlation coefficient for potential I screening parameters are shown in Table 57.

3. POWER TRANSISTORS

a. Primary Photocurrent

Primary photocurrents for power devices, though considerably larger as a result of larger device geometries, do not differ in principle from those of low-power devices. However, power devices do exhibit greater tendencies for secondary effects such as the onset of "anomalous" photocurrents due to transverse effects enhanced by their larger photocurrents and geometries.

An inspection of a histogram of I pp for the RCA TA8007 in Figure 58 shows seven devices which exhibited these anomalous I s even at rates as low as 3.0 x 10^7 rad(Si)/s. Two are shown on the histogram and the other five had such large I s that they are shown as outside the range of the histogram. These devices <u>all</u> had low values of base doping concentration N_{BO}. The mean values of the doping level for all devices was ~5.6 x 10^{16} cm⁻³, while the devices which exhibited anomalous turn-on all had values ~2 x 10^{16} cm⁻³. This result is apparent in scatter diagrams of I pp versus N_{BO} and r_B (Figures 59 and 60).

b. Secondary Photocurrent, I sp, and Turn-on Threshold

The radiation rate threshold for I sp "turn-on" varied nearly a factor of 25 for the TA8007 and nearly a factor of 4 for the BR200A. These ranges can be seen in the histograms shown on Figures 61 and 62. Based on a simple analytical description for I sp, the key parameters for screening I sp are: (1) h_{FE} , (2) r_{B} , and (3) I pp.

The scatter diagrams in Figures 63 through 66 show the strong correlation between turn-on threshold and both h_{FE} and r_B . Thus, where transient photocurrents constitute the major failure threat, screens on high h_{FE} and r_B values would significantly truncate those failures which occur at the lower rates.

4. DUAL JUNCTION FIELD EFFECT TRANSISTOR

Primary photocurrent was measured at three dose rates for the dual JFET. The experimental arrangement was similar to that used for the bipolar transistors with the collector-base junction being replaced by the channel-gate junction. Source and drain were shorted together in this measurement and 30V was applied across the gate-channel junction.

Figure 67 shows the response (I) as a function of dose rate, $\dot{\gamma}$, for the sample. In this plot the "A" and "B" halves are both shown.

We can see that the primary photocurrent is super-linear over the range of $\dot{\gamma}$ which was used. Therefore, photocurrent is following a relationship

$$I_{pp} = A_{\gamma}^{*n}$$
(13)

where n > 1. For the mean of our sample n was found to be ~1.2.

This super-linearity is expected due to two-dimensional mechanisms and the fact that the reverse bias was relatively near the breakdown voltage of the gate-channel junction (BV_{CSS}) .

a. Correlation Parameters

Parameters which are expected to correlate with I are: the pp reverse recovery time of the gate-channel diode, t_{rrGS} , the storage time constant, τ_S , defined as

$$t_{rrGS} = \tau_{S} \ln \left(1 + \frac{I_{F}}{I_{R}}\right)$$
(14)

and the width of the depletion region which is inversely proportional to the depletion capacitance. It was expected that the lifetime measurements would correlate positively with I and that the capacitance would correlate negatively with I nn.

Table 58 shows a summary of rank correlation coefficients for the various parameters of interest. The parts have been divided into two groups labeled α and β ; group α contains serial numbers 1-35, and

group β contains serial numbers 36-60. The reason for this grouping is that the two groups seem to come from different wafers or diffusions. Histograms of many of the electrical parameters appear as bimodal distributions with the groups appearing as two separate distributions. Hence, when a rank correlation is performed between two parameters which are each bimodally distributed, the correlation may be artifically high because of the separation of the two groups. This is shown by Figure 68 which shows a scatter diagram C_{GSS} (IV) versus I $_{pp}$ [$\dot{\gamma} = 1.2 \times 10^8$ rad(Si)/s]. One can see from this plot and Table 58 that the rank correlation of the total (0.738) is high and that the correlation with capacitance within each group is significantly lower.

It is apparent from Table 58 that the best correlations were obtained with the parameters which are a function of lifetime. The storage time constant, τ_S , in general correlates as well or better than the reverse recovery time, and it appears that this parameter is the most likely candidate for a screening parameter for primary photocurrent. Note that there is a marked difference in the correlations between I and τ_S observed in the two subgroups. The α subgroup data correlates much better than the β subgroup. This is, perhaps, more apparent in Figure 69 which shows a scatter diagram of the "A" chips.

b. Multiple Linear Regression Analyses

Multiple linear regression techniques were used to predict primary photocurrent using the correlation parameters discussed in the preceding section. Since the JFETs were apparently grouped into two subgroups, which implied that the parts came from either two wafers or diffusions, this allowed a measure of the predictive ability of the regression coefficients of the MLR parameters. For this to be the case, the independent variables used in the regression must be variables which physically describe the dependent variable. Were this not the case, the MLR coefficients would fit the data for which the coefficients were generated, but would not accurately fit another set of parts with slightly different physical properties.

MLR's were therefore run using t_{rrGS} , τ_S and C_{GSS} and functions of these parameters. Table 59 summarizes the results of these analyses. We can see from this table that MLR techniques do not work well for the prediction of the response of devices with electrical parameters much different than those of the devices from which the MLR coefficients were generated unless the independent variables are theoretically plausible. The first two sets of MLR's shown used independent variables related to I pp but with a meaningless <u>functional</u> relationship. Hence, the prediction errors are large. The third run, however, used τ_S and $1/C_{GSS}$ which are expected to be related to I pp and, as expected, the regression works well. As Figure 69 showed in the previous material (Paragraph 4-b) the groups (α and β) show quite different degrees of correlation with τ_S . The addition of the capacitance term, however, allowed a much better estimate of I pp than obtained with τ_S alone.

c. Conclusion

As would be expected lifetime measurements give the best correlation and prediction for I in the dual JFET. Therefore, an MLR technique or an electrical screen using t_{rrGS} or several values of t_{rrGS} to give a fitted value of τ_{S} should provide the best HA screen for devices of this type.

5. INFEGRATED CIRCUITS

The transient ionization response of the integrated circuits was measured with direct exposure to 10 MeV electrons from a linear accelerator. The pulse width used was sufficiently wide to assure time equilibrium, and pulse widths ranged from approximately 100 ns for the TTL devices to 3 µs for the op amp. The decision to use a wide radiation pulse was reached because of the difficulty of measuring the response of fast circuits to narrow pulses and because of the more universal applicability of hardness assurance data obtained with wide radiation pulses, .e., if the circuit is hard to a pulse width sufficient for time equiliorium, it is generally hard for any pulse width. Extreme care was taken to assure repeatability in the transient ionization measurements. Threshold response data was in general repeatable to better than ±5% relative
accuracy. Because this type of experimentation forces continual adjustments of the radiation intensity, it is very time consuming, and to minimize the expenditure of effort data was not taken for all sections of multiple devices. Additional general information on the experimental procedures is given in Paragraph 4-c, Section IV, Volume 1.

a. TTL Circuits

(1) Failure Criteria

The TTL circuits were loaded with a resistor-diode network that simulated maximum fanout for both logic states. The loading conditions for the 1-state are particularly important when measuring the ionization response because this causes the pull-up transistor to be in the active region which minimizes the output transient. In general, the failure criterion used for either logic state for these circuits was a 100 mV transient voltage shift at the output terminal, i.e., the failure criterion was equivalent to a 100 mV reduction in the allowable noise margin. This seems low, but it is the typical fraction of the normal 400 mV noise margin which is relinquished by the system designers for transient radiation. Most of the available noise margin is usually required for normal electrical design purposes. Since these circuits fail in either state because of secondary photocurrent in internal transistors, the radiation response is strongly nonlinear with dose rate, and moderate differences in response criteria will cause only slight differences in the radiation level for transient failure. One practical difficulty which arose during the 1-state tests was the stability of the power supply voltage. The 10 μ f capacitor placed close to the device to bypass the power supply leads still allowed V_{CC} to change by as much as several hundred millivolts. This in turn affected the 1-state output voltage. To solve this problem, it was necessary to place a large (4000 μ f) capacitor a few feet away from the experiment, out of the radiation beam. This held the supply voltage to within 20 mV during the transient pulse.

The transient voltage shift was used as a failure criterion instead of the absolute DC output voltage because: (1) it was experimentally more convenient to measure a consistent pulse amplitude, (2) failure mechanisms involving secondary photocurrent are likely to be more

consistent from unit to unit, and (3) circuits which have DC logic levels close to the worst-case values for these parameters will fail with transient output voltages of a few hundred millivolts.

(2) Failure Mechanisms

The expected failure mechanism for the 1-state response of the TTL devices is turn-on of the output transistor. Obvious correlation parameters for secondary photocurrent are the h_{FE} and r_B of the output transistor and the value of the external base resistance. Storage time, capacitance and stored charge were expected to correlate with primary photocurrent.

The expected failure mechanism for the O-state is turn-on of the pull-up transistor. One obvious correlation parameter is the value of the external base resistance. For all of the TI circuits except the inverter, this resistor was significantly lower than for the corresponding circuits made by Motorola (1K Ω versus 4K Ω for the standard gate). Because the secondary photocurrent of the pull-up transistor may cause transient increase in the V_{CE(SAT)} of the output transistor, the dynamic resistance of the circuit in the O-state is also important.

(3) Radiation Data

Transient radiation data for the five TTL device types were taken for approximately 140 units of each type. The sample histogram of the data in Figure 70 shows the transient threshold data for the TI inverter (1-state). The data for all of the device types is summarized in Table 60, which lists the mean, standard deviation, ratio of maximum to minimum value, and worst or most radiation sensitive value. This is simply a tabular presentation of the radiation data which allows the reader to make a comparison of the data for different device types and different test conditions. Since the data for the TI buffer has a maximum to minimum ratio of only 2, one can anticipate more difficulty in obtaining high rank correlation coefficients for this device.

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The limited spread in the radiation data for most of these devices was a major limitation in investigating the effectiveness of various electrical parameters in screening the radiation response distributions. The parts had already been through a stringent selection procedure

because of the electrical specifications and processing controls which were included in the parts specifications. This is probably the reason that the AC and switching measurements were relatively ineffective. Any device with extreme AC parameters had already been eliminated. Another aspect is that the basic resolution and accuracy of these AC measurements are significantly lower than those of the DC parameters and hence, these measurements would be expected to be less effective in correlations with tightly grouped radiation data. An alternative approach would have been to deliberately allow some fraction of the devices in the test population to te out of tolerance. This would have broadened the range of the electrical parameters, and made it easier to assess correlation effectiveness. However, this approach would also raise a question about the applicability to practical groups of devices which do undergo a stringent initial electrical screen.

In the following material, it is apparent that the results are best for devices which have a wide spread in radiation parameters. The relative accuracy of the radiation dosimetry and the electrical measurements are less important for devices with wide spreads in radiation behavior. In most applications, a range of 3 to 4 in the spread of radiation behavior would be acceptable, and there would be no need to apply techniques to further truncate the distribution. The main goal of hardness assurance is to eliminate devices from one end of the distribution, and it is difficult to accomplish this goal if the sample of parts used do not have sufficient variability.

(4) TI Inverter

Some interesting results were obtained for the TI inverter 1-state response. High rank correlations were obtained for h_{FE} , as shown in Table 61. However, when h_{FE} was applied as a screening parameter, eliminating devices with highest h_{FE} values, we devices stubbornly persisted in the lower, more radiation sensitive, side of the histogram, and it was apparent that, in spite of the high correlation coefficient, h_{FE} was not working well as a single correlation parameter. The electrical parameters of the two devices were examined in more detail, and it was found that both devices had abnormal values of V_{OH} , one being very high,

the other very low - in fact, the low device was just beneath the 2.4V specification limit. The reason for the high V_{OH} reading was an open internal resistor. This same problem occurred for one of the Motorola circuits, and is further discussed in Paragraph 5-b of this Section. When V_{OH} was included as a screening parameter, the results shown in Figure 71 were obtained. These results suggest that abnormal device behavior, in spite of electrical test limits, can still affect radiation behavior, and support the concept of monitoring a wide number of device parameters to achieve hardness assurance. The significance of V_{OH} as a parameter for electrical evaluation of TTL circuits is discussed in detail in Paragraph 5-b of this Section. These results show that radiation hardness can be improved by monitoring appropriate data, adding additional tests, and imposing tighter limits for some parameters. The existing limits in the Honeywell specification were not sufficient for this purpose.

A further interesting result was obtained for the TI inverter. Returning to Figure 71, one device is conspicuously located on the leading edge of the histogram even after the h_{FE} and V_{OH} screens were applied. This device had the highest value of propagation delay time, and this value was significantly greater than that of any of the other devices. This is one of the few examples of successful application of switching parameters for the TTL ICs. Conversations with Honeywell at the beginning of this program yielded the information that both manufacturers were having difficulty meeting the switching time specifications for these parts, and this had a major effect on device yields. Certainly, as discussed in Paragraph 3-b, Section IV, Volume 1, storage time is an expected correlation parameter for primary photocurrent, and the fact that measurements affected by storage time were of limited success in this program is probably due to the stringent selection imposed by the vendors in meeting the Honeywell specifications. For more loosely processed parts, theory and the results for the TI inverter support the inclusion of switching times in any hardness assurance program.

(5) TI Buffer

The TI buffer was the only digital circuit which used primary photocurrent compensation. The LINAC test results revealed that this compensation was not completely effective. For a 100 mV transient output response, the uncompensated Motorola buffer was actually harder. However, for higher transient voltage shifts, the compensation worked reasonably well; the dependence of output voltage on dose rate was much less sharp for the TI buffer than for any of the other TTL circuits. For this reason, the responses at a fixed rate could be used to compare different units of this circuit.

The range of responses for the TI buffer was only a factor of 2, and because of the limited range and the compensation, it was difficult to find good correlation parameters for this circuit. Nevertheless, for higher output responses, a single correlation parameter, $V_{\rm CS}$, was found which was reasonably successful. Figure 72 shows a histogram of the output responses, with the high and low offset voltage units eliminated from the distribution. This parameter, which is expected to correlate with lifetime, was successful in eliminating the worst units from the already narrow histogram. Considering the fact that this is a compensated circuit, the results are quite promising. The rank correlation factors of several parameters of interest are summarized in Table 62.

(6) TI A-O-I Gate

The TI A-O-I gate was selected because it contains two phase splitter transistors which are connected in parallel. The increased photocurrent in the common collector resistor of the phase splitter transistors makes these circuits more sensitive to ionizing radiation than the simple gates, which have only a single phase splitter transistor. No abnormal $V_{\rm OH}$ values were observed for any of the A-O-I gates.

Rank correlation coefficients for these devices are summarized in Table 63. There were no parameters with high rank correlation coefficients for this device type. However, the results of an MLR run, shown in Table 64, show a relatively low rms error of 16%, and a maximum error of only 45% when 5 parameters are used to obtain MLR coefficients.

As with all the MLR runs for the ICs, the first half of the devices were used to obtain the MLR coefficients and the radiation response of its entire population was predicted using these coefficients. The rms and maximum errors apply to the prediction of all units.

(7) Motorola Inverter

The Motorola inverter population also had two devices with abnormal V_{OH} behavior, and the radiation thresholds of these units were also abnormally low. One of these devices had extremely high leakage current, and although it passed the vendor's electrical tests, would not have passed an additional 100% test by the user because the I_{OL} measurement was "out of spec". However, even though the other device met all specifications, curve tracer tests revealed that the cause of the high V_{OH} value for this unit was that R_3 , the resistor from the base of the output transistor, was open! This greatly increased the sensitivity of the device to transient radiation. A more detailed discussion of the cause and significance of abnormal V_{OH} values, along with suggestions for eliminating this problem with additional electrical tests, is included in Paragraph 5-b of this Section.

Rank correlation coefficients between several electrical parameters of the Motorola inverter and the ionization threshold are listed in Table 65. Once the two abnormal devices were identified, the range of the ionization response data was reduced an order of magnitude. The results of two MLR computer runs are shown in Table 66. The first run includes all devices; the second run was generated with the two abnormal devices removed. The first MLR run had an rms error in excess of 100%, and the maximum error is even higher. However, when the two devices were removed, large reductions in the rms and maximum errors were obtained. This example illustrates the significant effect of a small number of abnormal devices or bad data points on the results of an MLR calculation. High quality data must be used in order to obtain reasonable results with multiple linear regression.

(8) Motorola Buffer

Results for the Motorola buffer were better for the O-state than the 1-state. Unfortunately, the 1-state is the more sensitive of the two states. Rank correlation coefficients of various electrical parameters vs. ionization response are shown in Table 67. However, an examination of the 1-state data, presented in Figure 73, shows that the data is already well truncated on the lower, more radiation sensitive side. Except for one device, the minimum values are only a factor of 2 below the mean value of the distribution. With this type of histogram, low rank correlations are expected because of the large peak on the low side. Slight errors or "noise" in either the radiation or electrical data will cause large rank differences in such a skewed distribution. When this is considered, the result for the Motorola buffer are not unreasonable. Regression techniques were also applied for the Motorola buffer, and these results are presented in Table 58. Again, the 0-state results are better than the results for the l-state, but the wider range of the 1-state data at the high end would be expected to affect the MLR results for this case.

b. The Effect of Resistor Reliability on Radiation Response

(1) Open Resistor Problem

Che extremely soft device was found 1. each group of inverters from the two manufacturers. The only significant difference in the electrical behavior of these two devices was a slightly higher value of V_{OH} . Additional measurements, which were made on these devices with a curve tracer, proved conclusively that the high V_{OH} readings were caused by an open R₃ resistor from the base of the output transistor to ground (see Figure 74). This also explains the extreme sensitivity of these particular devices to ionizing radiation.

After identifying this problem, it is disquieting to realize that these parts still meet all electrical specifications, in spite of the open resistor. Similar devices could easily be installed in "radiationhard" systems, and would lower the transient failure level of such systems by more than one order of magnitude. In the following section, we will

discuss the means of detecting this problem and implementing tighter electrical specifications to screen this fault at the vendor or at an incoming inspection level.

(2) Method of Detecting Open Base-Emilter Resistors

The V_{OH} readings for the two faulty devices were approximately 300 mV higher than the average value of 2.7V which occurs when $V_{CC} = 4.5V$ and $V_{IN} = 0.8V$ for the inverters. There are several factors which can cause V_{OH} to be high, but the distribution of V_{OH} readings for normal devices is tightly grouped around 2.7V with a total spread of less than 100 mV. High V_{OH} readings can be caused by the following conditions: (1) high leakage in the output transistor, (2) an open R_{λ} , (3) an open R_3 , or (4) a short between base and emitter of Q_3 or Q_4 (see Figure 74 for a circuit schematic). Condition (3), R3 open, can be verifield by examining the V-I characteristics of the 1-state output as the input voltage is changed from 0.4 to 1.2 volts. In normal devices, the output voltage will change approximately 300 mV as the input voltage is changed from 0.4 to 0.8V. This is caused by the phase splitter transistor turning on, because of the inverted saturation of Q_1 . In order for the phase splitter to turn on with 0.8V applied to the input, R_3 must be present. If R₂ is open, the phase splitter and the output transistor will turn on simultaneously at input voltages above 1V but there will be no change in 1-state output voltage until the input level exceeds 1V. The output V-I characteristics of a normal device and a device with R_3 open are shown in Figure 74.

Another resistor which could be open, and still allow the circuit to pass electrical specifications is R_4 . This would greatly increase the sensitivity of the circuit in the O-state, because Q_4 effectively has an open base if R_4 is open. This particular problem was not observed on any of the devices in this program, but is nevertheless an important consideration given the incidence of open R_3 resistors encountered in these devices. The other resistors $(R_1, R_2 \text{ and } R_5)$ are all necessary for proper circuit operation, and the circuit would not pass electrical or functional tests unless these resistors are connected properly within the circuit.

(3) Electrical Screening Methods

One screening method for the presence of R_3 is simply to put a maximum as well as a minimum value on V_{OH} . The maximum value could be assigned as 2.85V with $V_{CC} = 4.5V$ and $V_{IN} = 0.8V$, which would eliminate this particular problem for devices with the pull-down resistor connected to ground. The limit would have to be adjusted upwards for devices which use a pull-down resistor across the base-emitter junction of Q_4 , which is typical of all the TI devices except the inverter. For circuits with different resistor values, such as the buffers, slightly different values of V_{OH} may be required.

For complex MSI circuits, it may be impossible to verify proper resistor connections for points buried within the circuit from measurements with the external leads. There are two approaches to this problem. One is to improve resistor reliability so that resistor contact failures will have a very low probability of occurring. Based on our results, the present technology has not solved this problem. An alternative approach is to measure critical internal V_{OH} values with extra pads during the wafer probing, or the resistor could be measured directly. This approach assumes that the resistor reliability problem is not affected by the die bond, packaging and burn-in. This is probably a poor assumption, because of the high temperatures which occur during the die bonding and electrical stress caused by burn-in procedures.

(4) Conclusions and Recommendations

We have discovered circuits with open internal resistors which are much more sensitive to ionizing radiation than normal circuits. Users of hardened circuits should be aware that this problem does not occur with sufficient regularity to be discovered with the typical sample testing that is done to evaluate hardened parts, but does occur often enough to seriously effect system hardness. Techniques for screening such devices with tighter V_{OH} measurement limits have been suggested, and it is recommended that these methods be applied to eliminate these bad devices. Additional effort should also be made to solve the problem at the manufacturing level.

c. Other Integrated Circuits

This section presents the ionization results of the TI word switch, Motorola sense amplifier and Fairchild µA744 operational amplifier. The ionization test results are summarized in Table 69, which shows the mean value and range of the ionization response data for each of these devices.

(1) TI Word Switch

The primary photocurrent and the radiation threshold for a secondary photocurrent of 200 mA were used as radiation response criteria for the word switch. The ionization response data were very tightly grouped, with a ratio of maximum to minimum value of about 1.5 for both the I ps and the response thresholds. Considering the estimated relative inaccuracy of the dosimetry, which could be as high as 5%, correlation factors would be expected to be somewhat worse for the word switch than for devices with higher spreads in radiation data. A table of rank correlation coefficients for I pp and the I pp threshold is shown in Table 70.

Although the distributions of I_{pp} and I_{sp} were narrow, the increased flexibility of measurements with the word switch resulted in good screening parameters for I_{sp} . Figure 75 shows a histogram of the initial data, and also shows the improvement after using h_{FE} and the external base-emitter resistance value as screening parameters. Storage time also worked as a screening parameter for this circuit. Since the initial histogram was already very tight, with a steep lower side, it is encouraging that the application of these relatively simple parameters (see Paragraph 3-b, Section V, Volume 1 for a theoretical discussion) further narrows the distribution.

A multiple linear regression run was also made to see how well the word switch turn-on threshold could be predicted. The results, shown in Table 71, have an rms prediction error of 3.9% with a maximum prediction error of 11.5%. These were the best MLR results obtained for any of the integrated circuits, and the success of the realits for the word switch is probably due to the increased flexibility of measurements which are possible when the output transistor is accessible.

(2) Motorola Sense Amplifier

Radiation testing of the Motorola sense amplifier was complicated by the wide variations in offset voltage between units, which was further aggravated by the fact that the offset voltage specification was relaxed in order to obtain the devices on a reasonable schedule. The first stage of a plated-wire sense amp always operates in a linear, nonsaturating mode, and the offset voltage problem war resolved by operating the devices at a fixed output voltage of 1.5 volts. This is the center of the operating characteristics of the typical logic gate which would be driven by the sense amp. The radiation failure criterion was that a 3 mV differential input signal from the pulse generator would no longer drive the output beyond the TTL noise margin limits of 0.4 or 2.4 volts during the radiation pulse. The 1.5 volt operating level was achieved by using an operational amplifier to provide the necessary input biasing voltage. The op amp was located in the data room in order to eliminate its radiation response, and a large frequency compensation capacitor was used to prevent the op amp from responding to the radiation transient. A diagram of this experimental arrangement is shown in Figure 76.

The sense amplifier is a complex circuit, and based on the range of offset voltages encountered for the 4-input channels, the internal transistors were not as well matched as the transistors in modern junction-isolated circuits. The internal mismatches in $V_{\rm BE}$ are important in establishing bias currents in the various stages, and the mismatches in V_{RE} make it unlikely that external measurements will correlate with transient radiation behavior. The types of measurements which can be made are also severely restricted by the limited number of pins and fixed resistor values. An examination of the LINAC data showed that, although there was often a correlation between the data for different channels on the same device, there were also cases where large differences occurred between the channels on the same device. Rank correlations of several electrical parameters with the ionization response of the sense amplifiers are shown in Table 72. All of these correlation coefficients are very low, and are an indication of the difficulty of establishing good correlation parameters for this device. The MLR approach was also unsuccessful, as can be seen from the results listed in Table 73.

(3) Fairchild Operational Amplifier - µA744

As mentioned previously in (Paragraph 2-b, Section IV, Volume 1), the Fairchild μ A744 is a radiation hardened, dielectrically isolated operational amplifier which is <u>not</u> gold doped. Therefore, this device exhibits long radiation storage time once saturation occurs, and also is more sensitive to ionizing radiation than some of the newer hardened op amps which are gold doped. Three different ionization response measurements were made on this circuit, (1) the output voltage response at 4.3 x 10⁶ rad(Si)/s, (2) the radiation level required to just saturate the circuit, and (3) the radiation recovery (storage) time at 9 x 10⁸ rad(Si)/s. For these tests, the circuit was connected as an inverting voltage amplifier with a gain of 10. Power supply voltages were ±12 volts.

The rank correlations of several electrical parameters with the radiation responses are summarized in Table 74. As expected, the electrical saturation recovery time was one of the best correlation parameters (see Paragraph 3-b, Section V, Volume 1). However, because of the complex behavior of this device, no single parameter worked very well in screening the more sensitive devices. For the high transient response at the edge of this saturation threshold, the electrical saturation recovery was a good correlation parameter. A multiple linear regression run was made to compare this approach with the single parameter approach. These results are listed in Table 75, and are not particularly good. The five units with the highest low-level response were not screened by either the single parameter screen or the MLR approach.

These results indicate that complex linear circuits will be difficult to handle when measurements are restricted to those possible with external leads. It would be interesting to examine the feasibility of breakout transistor measurements as screening parameters for the ionization response of linear circuits. This would certainly increase the flexibility of measurements, although both pnp and npn transistor types would have to be made available.

d. Summary and Conclusions

The most significant result of the ionization response study on ICs was the discovery that open internal resistors occurred for devices from two manufacturers, which increased the radiation sensitivity of these devices by approximately one order of magnitude. Electrical screening procedures were developed which will screen such devices with tighter limits on one electrical parameter for TTL small scale integrated (SSI) circuits.

The normal ionizing rate response data of most of the devices were tightly grouped. Because of this narrow range of data, the uncertainty in dosimetry and the small errors in electrical measurements tended to obscure fundamencal correlations. The electrical measurement problem was further complicated by the fact that the ICs were procured to a rigid set of specifications which screened out devices with extreme electrical behavior and narrowed the distribution of electrical parameters. This magnified the effect of the errors and resolution limits in the electrical measurements.

In spite of the narrow distributions, correlation and screening parameters were found which further truncated the already narrow distribution. In general, the results were best for circuits which allowed a reasonable inference of internal transistor parameters from external measurements. For very complex circuits, with limited access to internal transistor parameters, such as the sense amp and op amp, results were considerably worse.

6. MTBF RESULTS FOR PARTS SUBJECTED TO IONIZING RATE TESTS

Although the general applicability of a gamma-rate screen was not a part of this program, it was felt that MTBF testing of parts subjected to high dose rate environments would yield results of immediate applicability to some military systems. To this end a group of inverters and buffers were submitted to life testing after exposure to the ionizing rate tests. Neither catastrophic nor drift failures were observed in the exposed group of 49 inverters although the control group (99 parts) showed three failures, 2 catastrophic and 1 drift. For the buffers, 2 drift and 1 catastrophic failure were observed out of the exposed group of

48, although the control group of 94 parts showed no failures of either kind. Converting the catastrophic failure numbers to failure rates at a 60% confidence level results in Table 76.

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Figure 49. Histogram of Primary Photocurrents at 5.3 x 10⁸ rad(S1)/s for 2N696

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Figure 50. Histogram of Primary Photocurrents at 1.35 x 10^{10} rad(Si)/s for 2N2222

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Figure 51. Histogram of Primary Photocurrents at 6.0 x 10^9 rad(Si)/s for 2N2905A

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Figure 53. Histogram of Primary Photocurrents at 8.0 x 10^{10} rad(Si)/s for 2N709

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Figure 55. Dose Rate Dependence of Mean Primary Photocurrent for 2N2222 and 2N3960



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Histogram of Ipp at 3.C \times 10⁷ rad(Si)/s for TA8007 Showing Devices with "Anomalous" Photocurrents Figure 58.

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2.206 17 2.406 17 2 for TA8007 OF JUL 2.006 17 Figure 59. Scatter Diagram of Base Doping Concentration, NBO, versus 1 Primary Photocurrent, I_{pp} , at 3.0 x 10⁷ Rad(S1)/s 2378684729411 46 6656 21424223 3112 11 6.JOE 16 -------2 1 ------2.005 16 4.005 16 1.8003 C-8C00 1.4500 1.3000 0.36.00 0000.0. 2.0000 0002-0 1.~000 1.200 000++-6 1 ----(V)^{dd}1 PRIMARY PHOTOCURRENT,

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Figure 61. Histogram of Threshold Rate for Turn-On (I = 2A) for RCA TA8007 in Shorted-base Configuration

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Figure 63. Scatter Diagram of h_{FE} (3V/1A) versus Trun-On Threshold Rate for RCA TA8007

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Figure 66. Scatter Diagram of r_B wereus Turn-On Threshold Rate for Solitron BE200A

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Figure 67. Superlinearity of Primary Photocurrent, I_{pp} as a Function of Dose Rate for the Dual JFET



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A Sample Histogram of the Radiation Response Threshold Data (TI Inverter 1-State Response) Figure 70.

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Figure 71. Histogram of TI Inverter 1-State Response Thresholds Showing Truncation With Electrical Storage Time

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2.1 1.51-0.4 .010110570.4 2.1 1.51-0.4 .010110570.4 2.1 1.44-0.4 .040 2.1 1.45-0.4 .040 2.1 1.45-0.4 .040 2.1 1.45-0.4 .040 2.1 1.45-0.4 .040 2.1 1.45-0.4 .040 2.0 1.45-0.4 .040 2.0 1.45-0.4 .040 2.0 2.046-0.4 .040 2.0 2.046-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040 2.0 2.146-0.4 .040					
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Figure 73. Histogram of Radiation Response Threshold Data (Motorola Buffer 1-State Response)

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Inverter Schematic Diagram a)





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Figure 74. Method Used to Detect Open Internal Resistors in the Inverter Circuits







Figure 76. Experimental Method Used in LINAC Tests of the Motorola Sense Amplifier

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Mfr.	Device Type	(a) Construction	Gold-Doped	Base Area (cm ²)	Approx. No. Parts Te ste d
FSC	2n696	NPN PE	No	3.43×10^{-3}	150
FSC	2N2222	NPN PE	No	8.47×10^{-4}	150
FSC	2N2905A	PNF	No	9.35×10^{-4}	150
FSC	2N709	NPN PE	Yes	3.65×10^{-5}	417
FSC	2N3960	NPN PE	No	3.65×10^{-5}	150
MOT	MT7111 Hez Inv.BOT	NPN PE IC Breakout (DI)	Yes	4.6 x 10 ⁻⁵	30
мот	MT7113 Buffer BOT	NPN PE IC Breakout (DI)	Yes	3.03×10^{-4}	30
Tī	TI711) Hex Inv BOT	NPN PE 3 IC Breakouts (DI)	Yes		87
TI	TI7113 Bufier BOT	NPN PE 3 IC Breakouts (DI)	Yes		87

Table 51 Summary of Low Power Transistors Tested for Transient Ionization Effects

(a) PE = Flanar Epitaxial
(b) DI = Dielectric Isolation

Table 52Summary of Photocurrent Data for Low-Power Transistors

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		Exposure			Photocurrent		
Device Type	Response Mechanísm	Rate [rad(S1/s]	Mean (mA)	Standard Dev. (mA)	Range (mA)	Max/Min	Normalized mA/[rad(S1)/s]
2N696	Isp Isp Isp	$\begin{array}{c}1.2 \times 10^{8}\\5.3 \times 10^{8}\\5.3 \times 10^{8}\\5.3 \times 10^{8}\end{array}$	18.4 86.1 531	2.3 10.8 67.6	24.9 - 13.6 119 - 63.5 722 - 403	1.83 1.88 1.79	1.47×10^{-7} 1.62×10^{-7}
2N2222	da I Isp ds I	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	50.7 220 668	8.2 34.9 201	65.3 - 29.4 290 - 143 1.08 - 369	2.22 2.02 2.93	1.63 × 10 ⁻⁸ 1.63 × 10 ⁻⁸
2N2905A	dd dd ds I ds I	$\begin{array}{c} 1.3 \times 10^{9} \\ 6.0 \times 10^{9} \\ 6.0 \times 10^{9} \end{array}$	24.4 90.2 226	3.4 16.6 88.5	31.7 - 15.4 135 - 60.6 383 - 40.5	2.06 2.22 9.46	1.88 × 10 ⁻⁸ 1.50 × 10 ⁻⁸
2N709	Ipp Isp	8.0×10^{10} 8.0×10^{10}	50.8 92.5	7.5 66.7	80.9 - 31.9 271 - 36.7	2.537.40	6.35 x 10 ⁻¹⁰
2N3960	dd ₁ dd ₁ ds ₁	1.5 x 1010 6.0 x 1010 6.0 x 1010	36.7 102.7 209.2	8.6 23.5 63.4	320* - 15.6 174 - 49.7 386 - 65.4	20.5 * 3.5 5.90	2.44×10^{-9} 1.71 × 10^9
BOT (MOT Hex Inv)	Ipp Isp	7.3×10^{10} 7.3×10^{10}	26.6 167.7	2.4 39.1	32.5 - 23.2 269 - 108	1.40 2.49	3.65 × 10 ⁻¹⁰ 9
BOT (MOT Buffer)	dd ₁ dd ₁	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	13.9 67.0 493	2.0 12.2 114.5	19.4 - 10.6 99.0 - 43.0 708 - 203	1.83 2.30 3.49	1.07 × 10-9 1.05 × 10-9

*"Anomalous" Ipp due to secondary effects (such as transverse base resistance), decreased $\sim X5$ after repeated testing.

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Comparison of Electrical Storage Time and Storage Time Constant, as Screening Parameters for Primary Photocurrent

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Device	Exposure Rate		ank Correlation C	oefficient of	tp vs:	
Type	[rad(Si)/s]	Electrical Sto	rage Time, t _{SE}	Electrical S	storage Time	Constant, τ_S
		$\frac{I_{CS}}{I_B} = \frac{10 \text{ mA}}{2 \text{ mA}}$	$I_{CS} = 50mA$ $I_{B} = 10mA$	ICS = 5mA	I _{CS} = 10mA	$I_{CS} = 50 mA$
2N696	1.2 x 10 ⁸	. 391	.331	.426	.464	. 398
	5.3 x 10 ⁸	.514	.463	.531	.529	.504
CCCNC	3.0 × 10 ⁹	.283	.264	.274	.278	.309
	1.4×10^{10}	.133	.123	.125	.130	.146
A 2005A	1.3 x 10 ⁹	154	.607	.243	.471	.604
	6.0×10^{9}	050	.594	.289	.470	.586
090ENC	1.5×10^{10}	.566	.570	.559	.557	.482
	6.0×10^{10}	.595	.610	.534	.536	.358
		$I_{\rm CS} = 10mA$ $I_{\rm B} = 4mA$	$I_{CS} = 20 mA$ $I_{B} = 4 mA$	$I_{CS} = 1$	loma I _{CS} =	= 20mA
2N709	8 x 10 ¹⁰	1		ł		
BOT (MOT	1.3 x 10 ¹⁰	. 495	.377	.465		161
Buffer)	6.4 x 10 ¹⁰	.478	.537	.371		425

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[Ranl	< Correla	tion Co	effi ci en	t of I	vs:
Device Type	Dose Rate [rad(Si)/s]	с _{ов}	t _B	^{bv} cbo	h _{FEI}	r _{BI}	C _{IB}
2N696	1.25×10^8	.013	099	.426	.176	.105	282
	5.3 x 10^8	.079	123	.445	.248	.111	354
2N2222	3.0×10^9	334	. 320	.317	066	.156	.413
	1.35×10^{10}	296	.184	.189	237	036	.501
2N2905A	1.3×10^9	.498	246	.249	.501	.182	.013
	6.0×10^9	.538	312	.168	.511	.317	082
2N3960	1.5×10^{10}	305	.566	.478	.000	585	.038
	6.0×10^{10}	232	.299	.354	152	370	.144
MT7113	1.3×10^{10}	.180	.133	.295	.096	100	.284
	6.4×10^{10}	.133	075	.?14	.180	.168	.076

Summary of Rank Correlation Coefficients for Various Screening Parameters versus I for Low-Power Transistors pp

Table 55

Relative Efficacies of Various Screening Parameters for Primary Photocurrents

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۲.			Device	е Туре			
Ran	2N969	2N2222	2N2905A	2N709	2N3960	MT7111	MT7113
(1)	^T S	C ^{IB}	^t SE	с _{ов}	^t se	с _{ов}	t _{SE}
(2)	^t SE	V _{CE} (SAT)	τs	^{BV} CBO	τs	C _{IB}	^T S
(3)	^{BV} CBO	с _{ов}	V _{CE} (SAT)		r _{BI}	t _{SE}	BV _{CEO}
(4)	I _{EBO}		с _{ов}			FLI	h _{FE}
(5)	V _{CE(SAT)}		h _{FEl}				
(6)	C I B						

Device	Dose Rate	No. Screening		Prediction	n Error	s (%)
Туре	<pre>[rad(Si)/s]</pre>	Parameters	Mean	RMS	Max	Min
211696	1.25×10^8	3	1.2	11.5	33.3	-24.8
	5.3 x 10 ⁸	3	1.1	10.6	28.3	-25.9
	1.25×10^8	12	1.2	10.4	36.8	-21.5
	5.3 x 10 ⁸	12	0.7	9.0	31.7	-17.2
2N2905A	1.3×10^9	3	2.2	14.4	49.3	-34.1
	6×10^9	3	2.9	18.3	45.6	- 30.6
	1.3×10^9	12	1.1	11.2	45.6	-19.8
	6 x 10 ⁹	12	-	14.4	37.2	-28,7
2N2222	3 x 10 ⁹	3		17.3	56.5	-26.8
	1.35×10^{10}	3		17.7	52.8	-22.2
	3×10^9	12		15.8	53.5	-22.8
	1.35×10^{10}	12		16.2	52.6	-23.6

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Table 56 Summary of MLR Predictions of I for 2N696, 2N2905A and 2N2222 Low-Power Transistors Using Total Sample

Summary of Rank Correlation Coefficients for $\mathrm{I}_{\mathrm{S}p}$

	Exposure			Rank	correla	tion Coe	fficien	ts of I	sp vs.	
Type	hate [rad(Si)/s]	I FP	$r_{\rm B}$	h_{FE}	N _{BO}	t B	τ ^τ	t_{SE}	VCE(SAT)	Other
2N2905 A	6.0 × 10 ⁹	. 744	.619	. 860	473	744	.818	.845	.839	.865 (h _{FEI})
2N690	5.3 x 10 ⁸	.858	. 334	.426	368	232	.736	.722	.739	.421 (h _{FEI})
2N2222	1.35×10^{10}	. 305	.765	.258	.053	.525	.782	.773	620	.649 (h _{FEI})
2N709			1			ļ				
21(3950	6.0×10^{10}	. 305	.388	.281	.195	.274	.288	.212	.246	.239 (h _{FEI})
MT 7111		1	 				ł		ļ	
MT 7113	6.4 x 10 ¹⁰	.155	.101	.498	594	558	.425	.537	596	0.542 (h _{FEI})

Table 58Summary of Rank Correlation Coefficients for Primary Photocurrent - Dual JFET

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c _{GSS} =20V)	- 239 - 470 - 722 - 510 - 510	- 223 - 471 - 708 - 441 - 420 - 769	- 239 - 577 - 642 - 387 - 387 - 387	
c _{GSS} (V _{GSS} =1V)	479 479 	265 495 .719 249 457 738	278 534 .721 183 383 .717	
νu	.933 .724 .944 .936 .795 .931	.910 .768 .946 .825 .943	. 903 . 781 . 951 . 748 . 748 . 928	
$ t_{rrGS} $ $ I_{F}^{t} = 10mA $ $ I_{R}^{t} = 5mA $. 951 . 758 . 944 . 833 . 795 . 876	.940 .818 .951 .808 .828 .828 .828	.931 .754 .950 .771 .769 .873	n the package.
trrGS Ir = 10mA I _R = 2mA	. 910 . 735 . 946 . 794 . 794	.790 .790 .949 .813 .913	. 525 . 785 . 954 . 762 . 905	ips, A and B, i rs 1-35
(P) (P)	TOT TOT TOT	5 m 5 m 70 10 10 10	υ α DI I OI FOF	s two chi al number
(۳) ^d tup	444888	444 α α α	4 4 4 A A A	FET have serie
Electrical Parameter Dose Rate [rad(S1)/s]	7 x 107 7 x 107 7 x 107 7 x 107 7 x 107 7 x 107 7 x 107	1.2 × 108 1.2 × 108 1.2 × 108 1.2 × 108 1.2 × 108 1.2 × 108 1.2 × 108	6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6	(a) The dual J (h) Group α =

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Summary of MLR for I pp - Dual JFFT

		_										
Range of Uata for 23 Predicted Devices (%)	29.3	22.7	23.7	25.1	29.3	22.7	23.7	25.1	29.3	22.7	23.7	25.1
RMS Prediction Error (%)	26.2	30.8	40.8	17.7	26.6	31.4	45.C	15.1	9.68	10.4	13.0	13.1
fz.	27.4	23.0	20.0	16.3	27.5	20.1	19.2	16.8	64.0	48.3	123	41.2
Coef ^(a) of M.R	.856	.841	.817	. 794	.856	.824	.811	.800	.915	168.	.953	.876
No. of Independent Variables	2 ^(b)	2 ^(b)	2 (b)	2 ^(b)	2 ^(c)	2 ^(c)	2 ^(c)	2 ⁽ 0	2 ^(d)	2 ^(d)	2 ^(d)	2 ^(d)
Dose Rate [rad(Si)/s]	1.25 × 10 ⁸	6 x 10 ⁸	1.25×10^{8}	6 x 10 ⁸	1.25×10^{8}	6 x 10 ⁸	1.25×10^{8}	6 x 10 ⁸	1.25×10^{8}	6 x 10 ⁸	1.25×10^{8}	6 x 10 ⁸
Chip	A	A	ß	£	A	A	ф	£	¥	A	£	£
lent ole												

(a)MLR coefficients were generated using 27 devices and the I $_{pp}$ of the other 23 were predicted usi's these.

(b)Independent variables were τ_S , N (calculated from capacitance data).

(c)Independent variables were t_{rrGS} (I_F = 5 mA, I_R = 10 mA) (J)Independent variables were τ_S , I/C_{GSS} (20V).

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Data
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Summary

Data Description (a) Value	Mean Value 1321010		Worst Value	Standard Deviation	Ratio [Max/Min] 3 7
rate inresnoid (100 mV) 5.6 x10 ⁹	6 x10 ⁹		2.8x10 ⁹	2.2×10 1.2×109	3.4
tate Threshold (200 mV) 9.2 .10 ⁹	210 ⁹		4.0×10 ⁹	2.9×10 ⁹	4.7
ified Response - 1.2×10^9 0.20V	20V		0.32V	V010. 0	≤1
ified Response - 3xlu ⁹ 0.77V	17V		L.12V	VIL.O	~2
odified Response - 3×10^9 0.34V	34V		0.42V	0.038V	2.1
mV Threshold 1.27x10	27×10	5	0.54×10 ⁹	2.6x10 ⁹	۲
mV Threshold 2.47x10	47x10	6	1.5 ×10 ⁹	4.2×10 ⁸	2.7
tate Threshold (Pin 6) 1.03x1C	03×10	10	3.5×10 ⁹	2.5x10 ⁹	60
tate Threshold (Pin 8) 3.45x10	45×10	م	1.2×10^{9}	1.3×10 ⁹	5.3
tate Tireshold (Pin 6) 6.9 x10	9 ×10	6	1.2×10 ⁹	2.0x10 ⁹	6 ~
tate Threshold 8.8x10 ⁹	8×10 ⁹		4.5×10 ⁹	1.9x10 ⁹	2.3
tate Threshold 7.9x10 ⁸	9x10 ⁸		8.7×10 ⁷	3.0x1.0 ⁸	~20

(a) "Modified" refers to the circuits which contain special leads.

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	Correlation Factors for γ Response of Various Parameters			
Initial Electrical Parameter	0-State (Output Low)	l-State (Output High)		
^V OH	-0.616 -0.715	-0.427 -0.493		
IN(I) I _{SK}	-0.647	-0.520 0.738		
^V OS Switching Time (Low to High)	-0.438	0.746		
Active Rise Time ^w T	-0.693 0.422	-0.630 0.591		
^h FE Rise Time	-0.703 -0.591	-0.721 -0.771		
^h FE Rise Time (Low to High)	-0.703	-0.721		

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Table 61 Some Rank Correlations for the $\dot{\gamma}$ Response of the TI Inverter

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	Correlation Factors for y Response of Various Parameters			
Initial Electrical Parameter	1-State Response at 3 x 10 ⁹ rad(Si)/s (Side A)	l-State Response at 3 x 10 ⁹ rad(Si)/s (Side B)		
I _{SK}	0.436	0.462		
ISINK	0.709	0.521		
v _{os}	-0.705	-0.502		
h _{FE}	0.510	0.405		
Active Rise Time (Output voltage)	0.639	0.440		
Switching Time (Low to High)	0.130	0.464		
Switching Time (High to Low)	-0.414	-0.274		
I _{IN(1)}	0.522	0.504		
V _{BE} (Q5) [Note(a)]	0.550			

Table 62 Some Rank Correlations for the $\dot{\gamma}$ Response of the TI Buffer

(a)Special Lead Measurement

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Some Rank Correlations for the Ionization Response

Electrical Parameter	Rank Correlation with TI A-O-I Gate Ionization Response Threshold
I _{OS}	284
I _{CC(0)}	.273
v _{os}	092
t _{PD}	323
Output Capacitance	289
Stored Charge	.170
h _{FE} (I _{SK})	.126
R ₆ ^(a) Resistance	248

Threshold of the TI A-O-I Gaze

(a) $R_{\rm 6}$ is the emitter-to-base resistor of the output transistor.

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MLR Results for TI A-O-I Gate Transient Response Threshold

Parameters Used For Regression	Prediction RMS	n Error ^(a) (%) Maximum
^I CC		
R ₆ ^(b) Resistance (Calculated)		
Propagation Delay Time	16	45
I Correlation Factor		
1/I _{0S}		

(a)The first 70 units were used for regression coefficients which were then used to predict the values of all 140 units.

 $(b)R_6$ is the emitter-to-base resistor of the output transistor.

Some Rank Correlations for Ionizing Rate Response of the Motorola Inverter

	Correlation Factors for y Response of various parameters		
Initial Electrical Parameter	O-State (Output Low)	1-State (Output High)	
V _{OH}	-0.161	-0.342	
^I _{IN} (1)	0.042	-0.131	
I _{SK}	0.049	-0.160	
vos	0.133	0.121	
Switching Time (Low to High)	0.084	-0.304	
h _{FE}	0.083	0.218	

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Effects of Flectrical	Screens on the Regression Results	5
for the Motorola	Inverter 1-State y Threshold	

	Parameters Used For	F	Prediction Error ^(a) (%)		
Description	Regression	Value	RMS	Maximum	
MLR Based on Circuit Measurements (Devices #41 & #47 included)	h _{FE} V _{OH} R ₄ (c)	13.2	136	891	
MLR Based on Circuit Measurements (Devices #41 & #47 excluded) ^(b)	h _{FE} V _{OH} R ₄ (c)	5.2	27	145	

(a) The first 70 units were used to generate the regression coefficients. The 1-state $\dot{\gamma}$ threshold was then predicted for (a) the 2nd 70 units when Devices #41 and #47 were included and (b) all 138 units when the two devices were excluded.

- (b)The two devices were excluded because of faulty pretest electrical characteristics:
 - (1) Device #47 has excessive output leakage current (112 μA at V $_{OH}$ = 5.5V)
 - (2) Device $\sqrt[n]{41}$ had an open base-emitter resistor (R₃)

(c) R_4 is the external base-emitter resistor on the pull-up transistor.

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Some Rank Correlations for the $\dot{\gamma}$ Threshold of the Motorola Buffer

	Correlation Factor of Variou	for ý Response Is Parameters
Initial Electrical Parameter	0- State Re∮ponse (Output Low)	1- State Response (Output High)
I _{SK}	-0.695	0.040
v _{os}	0.217	0.234
V _{OH}	0.331	-0.173
h _{FE}	-0.708	-0.052
Switching Time (Low to High)	-0.532	0.131
Switching Time (High to Low)	0.178	-0.027
Stored Charge (Peak Current)	0.546	0.096
R ₃ ^(a)	-0.267	-0.081
Depletion Width plus Diffusion Length	0.381	0.193

(a) R_3 is the emitter-to-base resistor on the output transistor

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₹.5.+ 215 A

Description	Parameters Used For Regression	F Value	Prediction Err RMS	cor ^(a) (%) Maximun
MLR Based on Circuit Measure- ments for 0-State Threshold	 h_{FE} Stored Charge Rise Time (low to high) Switching time (Low to High) R₃(c) 	27	15.7	36
MLR Based on Circuit Measurements for 1 state Threshold (Device #40 included)	 h_{FE} V_{OL} V_{OS} Switching Time (High to Low) Feil Time (High to Low) R₄ 	2.1	99	964
"LR Based on Circuit Measure- ments for 1-State Threshold (Device #40 excluded) (b)	 h_{FF} V_{OL} V_{OS} Switching Time (High to Low) Fall Time (High to Low) P₄(c) 	2.1	56	163

Table 68 Regression kesults for the Motorola Buffer $\dot{\gamma}$ Threshold

(a) The first 70 units were used to generate the regression c efficients, and then predictions were made on all 140 units.

(b) Device #40 was excluded to observe the effect on the $r_{\rm exc}$ assion coefficients because the measured γ Threshold for Device #40 was a factor of four (4) lower than the other devices.

(c) R_3 and R_4 are the external base-emitter resistors for the output and pull-up transistors, respectively.

Table	69
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Summary of Ionizing Rate Data (Non-TTL Integrated Circuits)

Device	Data Description	Mean	Worst Value	Standard Deviation	Max /Min
TI	$I_{pp} @ 3.5 \times 10^{8*}$	3.59 mA	4.1 mA	0.19 mA	1.33
Word	pp ^(C) 3, 3x10 ⁻	25,1 mA	30.4 mA	2.2 mA	1.5
Switch	I _{sp} Threshold	8,9x10 ⁸ *	7.7x10 ^{8*}	7,2x10 ⁷ *	
Fairchild	Response @ 4.3x10 ^{6*}	0.59V	1.1V	1.5V	9.5
µA744	Sat. Threshold	1.62x10 ^{7*}	7.0x10 ⁶	4.8x10 ^{6*}	8
Op Amp	Sat. Time @ 9x10 ^{8*}	15.6 µs	41 μs	5.8 µs	45
MOT	Threshold	2.26×10 ^{8*}	2.7×10 ^{7*}	7.9x10 ^{7*}	12
Sense Amp	CH 2 Threshold	1.36×10 ^{8*}	1.5×10 ^{7*}	5.1x10 ^{7*}	18

* Dose rates in [rad(Si)/s]

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Tab	le	70

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Some Rank Correlation Factors for the Icnization Response of the Word Switch

	Rank Correlation Coefficient		
Parameter	I @ 3.3 x 10 ⁹ rad(Si)/s pp	I Threshold	
Storage Time	. 308	701	
90 î Resistor ^(a)	166	725	
h _{FE}	240	692	
V BE	167	496	
Capacitance	251	.097	
I Correlation	039	695	
t OFF	.499	.484	

(a) Base-emitter resistor of the output transistor

Tab	le	71

Multiple Linear Regression Results for the I Threshold of the TI Word Switch

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Parameter Used For Regression	Prediction Error ^(a) (%)		F Value
	RMS	Maximum	
Storage Time 90 Ω Resistor Value ^(b) ^h FE Output Capacitance	3.91	1.1.5	71.1

- (a) The first 70 units were used to generate the regression coefficients, and the coefficients were then used to predict all 140 units.
- (b) Base-emitter resistor of the output transistor.

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	Rank Correlation Coefficient		
Initial Electrical	Response Threshold	Response Threshold	
Parameter	Channel 1	Channel 2	
Power Supply Current	.055	.127	
V _{OL}	.057	.141	
V _{OH}	.132	125	
v _{os}	141	177	
I _{OS}	001	037	
1 _{BIAS}	080	.100	
A _{OL}	.129	209	
Recovery Time	053	087	
Channel Select Time	108	238	
Output Resistance	207	149	

Some Rank Correlation Coefficients for the Ionizing Rate Response of the Motorola Sense Amp

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An Example of MLR Predictions for the Ionizing Rate Response of the Motorola Sense Amp

Electrical Parameter	Prediction Error ^(a) (%)		F Value
	RMS	Maximum	
Power Supply Circuit		*	
Output Current (1V)			
V _{OH}	109	676	2.2
v _{os}			
A _{OL}			
Recovery Time			

(a) First 70 units used to generate MLR coefficients. All 140 units used for prediction.

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Some Rank Correlation Coefficients for the Ionization Response of the µA744 Op Amp

Initial	Rank Correlation Coefficients for Tr	ansient Ionization Data
Electrical Parameter	Response at 4.3 x 10 ⁶ rad(Si)/s	Saturation Threshold
Saturation Recovery Time	.515	857
Slew Rate	.506	728
Icc	.625	721
AoL	.127	178
Input Capacitance	.205	502
^I BIAS	.255	533
los	165	.292

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MLR Results for the Ionization Response of the µA744 Op Amp

Initial Electrical Parameters Used For Regression	RMS Prediction Error For Output Response At 4.3x10 ⁶ rad(Si)/s	F Value For Regression	RMS Prediction Error For Saturation Threshold	F Value For Regression
Saturation Time Slew Rate Power Supply Current Input Capacitance Offset Current	107%	18.1	40%	23.6

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Failure Rates for Parts Subject to Ionizing Rate Tests

Device	Catastrophic F (Percent/1,000 h	(a) ailure Rates ours at 60° Confidence)
Group Type	Control	Stressed
Hex Inverter	1.1	.63
Dual Buffer	3.2	1.4

(a) Drift failures were not included in the failure rate calculations, (1) for the reasons stated in Paragraph 1d, Section V, Volume I and (2) because the particular circuits would still have functioned properly in normal practical applications.

SECTION IV

IONIZING RADIATION TOTAL DOSE HARDNESS ASSURANCE

1. INTRODUCTION

This section discusses the results of the work carried out on the total dose aspects of hardness assurance.

The primary objectives of the study were first, to identify certain surface related electrical parameters which could be used as precursors of radiation sensitivity and hence, which could enable one to predict the expected total dose damage. The second objective was to assess the feasibility of the low dose screening technique. Specifically, the objective was to test the assumption that the devices exhibiting the highest radiation sensitivities during a low dose exposure are the ones most likely to fail at higher doses.

Paragraphs 2 and 3 present the electrical and low dose screening results, respectively, for a group of low-power transistor. Similarly Paragraphs 4 and 5 perform the same functions for an operational amplifier.

2. ELECTRICAL SCREENING - LOW-POWER TRANSISTORS

a. Approach

The following material presents the results of the effort expended in evaluating electrical measurement techniques suitable for screening low-power transistors for total dose effects. The devices selected as vehicles for the study were: 2N709 (npn), 2N930 (npn) and 2N2905A (pnp).

The technical approach to the problem of evaluating electrical screening parameters was to determine the rank correlation coefficients between certain promising surface related, initial parameters and radiation sensitivity. The use of the rank correlation technique immediately implies that the scope of the program was primarily geared to the prediction of the relative radiation sensitivities between devices of different types and of a given type.

The rationale behind the selection of the correlation parameters for the bipolar transistors was discussed in Paragraph 4-a, Section V, Volume 1 and will not be repeated here. The summary of the results of the rank correlation calculations are shown in Table 77 in a sort of generalized form which gives an overview of the total dose task. (The specific list which would also indicate the exact bias conditions is prohibitively long.) As discussed in Paragraph 4, Section V, Volume 1 and as is evident in the tables, correlation was sought in the majority of cases between certain surface dependent initial parameters (or combinations of these) and the "radiation sensitivity" of the device. The radiation sensitivity was thought to be adequately represented by the absolute or relative radiation induced change in the base current. For increased measurement sensitivity the base current was measured at low injection levels (with both fixed ${\rm V}_{\underline{B}\underline{E}}$ and fixed ${\rm I}_{\underline{E}}$ conditions) where the surface effects are dominant. Of course, there are other quantities of practical importance in Table 77, besides the radiation sensitivities, for which correlations with initial parameters were sought, e.g., the absolute and relative changes in gain.

Total dose effects are extremely variable both between device types and between devices of a given type. The three types of low-power transistors, 2N930, 2N709 and 2N2905A, had high, moderate and low radiation sensitivities, respectively. This is shown in Figure 77 where the mean value of the relative change in gain is plotted as a function of dose. (The lower end of the operating current range was used in these plots for increased sensitivity.) The histograms of Figures 78 through 89 illustrate the variability in radiation sensitivity of presumably identical devices. The radiation sensitivities are represented here by low injection $\triangle I_{\rm B}$, $I_{\rm B}/I_{\rm B}^{\rm O}$, $\triangle(1/h_{\rm FE})$ (= $\frac{\triangle I_{\rm B}}{I_{\rm C}}$), and $h_{\rm FE}/h_{\rm FE0}$. Tables 78 through 80 show the mean and the covariance of these quantities at various injection levels to give a better overall picture. (Note that the following bias conditions were applied during gamma exposures. 2N709: $V_{\rm CB}$ = +10V and $I_{\rm E}$ = 20 µA, 2N930: $V_{\rm CB}$ = +26V and $I_{\rm E}$ = 50 µA, 2N2905A: $V_{\rm CB}$ = -30V and $I_{\rm E}$ = 40 µA.)

b. Discussions and Conclusions

By scrutinizing the rank correlation tables the following conclusions can be drawn:

- 1. One of the promising initial parameters, the low frequency l/f noise showed little correlation with radiation sensitivity. A possible explanation may be that the l/f noise contains a current dependent term which prevents the determination of the density of the slow states in ungated devices. Hence, any ranking of the devices on the basis of noise will not necessarily mean a corresponding ranking in the density of the slow states. This latter quantity was the one with which correlation with radiation sensitivity was anticipated. Apparently, the current dependence of the l/f noise obscured any significant correlation.
- 2. Surprisingly the radiation induced ΔI_B (low injection) did not always correlate well with ΔI_B (high injection) especially at the high end of the operating current range for the 2N709 and the 2N2905A. The correlation is quite good for 2N930. Consequently the practice of using ΔI_B (low injection) for predicting radiation sensitivity at high injection levels, just because ΔI_B (low injection) offers a great increase in measurement sensitivity, has to be treated with caution. The explanation of this effect is not clear at the present time.
- 3. No significant correlation was found between the radiation sensitivity and various initial parameters, e.g., burn-in changes, I_B , I_{EBO} (or BV_{EBO}) measured at various temperatures, etc. In fact, the correlation is practically nonexistent for the 2N930, slight for the 2N709, and moderate for the 2N2905A. Even the moderate values ($\approx 0.7 - 0.8$) of the rank correlation coefficients for the 2N2905A are far too low to expect any of the various initial purameters to be meaningful screening parameters.

The lack of a strong correlation discussed above is perhaps not too surprising. For example: It is well established that the magnitude of the surface components of the preand post-irradiation I_{R} is conirolled by two primary factors, namely, by the amount of charge within the oxide and by the density of interface states in the mid gap region. Either of these factors can be lominant in certain cases. Also, it has been shown in the past that in certain oxides there was a correlation between the pre- and post-irradiation density of the interface states (Ref. 18). In such cases, one may expect a correlation between the initial I_{R} and the radiation induced change in I_{B} as long as the surface component is always dominated by the interface states; this could have been the case for the 2N2905A. It should be noted that the radiation induced excess base currents (good indicators of radiation sensitivity) tended to be higher in those 2N2905A devices which had higher base currents initially.

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In constrast, the amount of radiation induced charge accumulation has not been found to correlate with the initial amount of oxide charge (or the initial interface state density). Hence, whenever the oxide charge dominates the surface component of either or both of the pre- and postirradiation I_Bs , one does not expect to find any correlation between the initial I_B and the radiation induced changes in I_B . Such might have been the case for the 2N709 and even more so in the 2N930 since the rank correlation coefficients were very low.

4. The consistently high correlation between h_{FEO} and Δh_{FE} is not significant since contrary to expectations it does not guarantee high correlation between pre- and post-irradiation gains, h_{FEO} and h_{FE} , respectively.

the radiation induced base current increase, ΔI_B , is approximately the same for all devices of a given type. Although ΔI_B does vary among the devices (see histograms of ΔI_B in Figures 78, 82, 86) apparently the spread is not large enough to obscure the correlation between h_{FEO} and Δh_{FE} .

5. The utility of the high correlation between h_{FEO} and h_{FE} seems to be limited and the results should be viewed with caution. The correlation appears to offer a useful screening technique against h_{FE} failure [defined by $h_{FE} < (h_{FE})_{min}$] since the initial h_{FEO} distribution can be simply truncated. Figures 90 through 92 containing 2N2905A, 2N709and 2N930 data show the futility of this approach since all of the low gain devices do not fail first. (Incidentally, observe that that the h_{FEO} versus Δh_{FE} correlation is high in all cases; clearly a useless result especially for the 2N930 devices.)

It should be noted that the relatively high rank correlation values for the 2N2905A and in one case for the 2N709 are <u>partially</u> due to the fact that the gain degradations at the higher currents were relatively small. The rank correlation is expected to go down with higher relative gain loss. Furthermore, and this may be the root of the problem, since the degree of correlation between pre- and post-irradiation gain is very much oxide dependent, one cannot be sure ahead of time that a high $h_{\rm FEO}$ versus $h_{\rm FE}$ correlation will exist for any given untested device type. This can be checked out only by extensive experimental work which is just what we are trying to avoid by a simple electrical screen.

In other words, any given <u>initial</u> parameter which shows a good correlation with radiation sensitivity only in certain transistor types but not in others and whose behavior is not predictable, will have only limited significance, if any. Right now such seems to be the case with those initial parameters yielding reasonable good correlation in the 2N2905A but not in the 2N709 or the 2N930.
6. Higher gain devices tend to suffer more relative gain loss $(\Delta h_{FE}/h_{FE})$ in certain device types. The effect is clearly indicated for the 2N2905A, slightly indicated for the 2N709 and is completely absent for the 2N930. Again, the problem of complete inconsistency in behavior among the device types makes it impossible to generalize.

3. LOW-POWER TRANSISTORS - LOW DOSE SCREENING

The basic idea behind low dose screening is that devices which exhibit a relatively large radiation sensitivity during a low dose exposure are the ones which are most likely to fail after exposure to a larger dose. The approach to test this hypothesis was rather direct; comparisons were made of the tails of the histograms of radiation sensitivities at low and at high doses. The radiation sensitivities were defined in terms of I_{R} changes at both low and high injection levels. First, an arbitrary value of Δl_{R}^{*} at high dose was selected and it was asserted that all devices with values of $\Delta I_{B} \geq \Delta I_{B}^{*}$ were to be rejected by the screen. The position of each ${\rm AI}_{\rm R}$ of the devices in this group was then located on the low dose historgrams. Were they also located at the appropriate tail? In general they were not and hence, the reliability of low dose screening is very much in doubt. This conclusion was also supported by the rank correlation coefficients between the quantities ΔI_{R} (low dose) and ΔI_{R} (high dose). As shown in Table 81 the values of the correlation coefficients are much lower than might have been expected.

In the following material, the results and conclusion: for each device type will be discussed separately.

a. 2N930

Histograms of $\Delta I_B @(3.0 \times 10^5 \text{ rads})$ and $\Delta I_B @(1.0 \times 10^5 \text{ rads})$ were compared at four test conditions. Devices in the part of the histogram with the largest $\Delta I_B @(3.0 \times 10^5 \text{ rads})$ were generally scattered through a relatively large part of the histogram showing the $\Delta I_B \text{s}$ at $1.0 \times 10^5 \text{ rads}$ (see Figure 93). These data are summarized in Table 82 where it is shown, specifically, that to eliminate the N devices having largest ΔI_B in the R rows of the 3.0 x 10⁵ rads histogram would require

screening out M devices contained in the P rows of the 1.0 x 10^5 rads histogram. Both Table 82 and Figure 93 emphasize the fact that low dose screening does not seem to be a viable technique for our 2N930 transistors.

Ъ. 2N2905A

The data for the 2N2905A can be treated in the same fashion as that for the preceding device type, 2N930.

To eliminate the N devices having largest ΔI_B in the R rows of the 5.6 x 10⁶ rads histogram would require screening out M devices contained in the P rows of the 1.7 x 10⁵ rads histogram (see Figure 94 and Table 83). On the basis of these data, the low dose screening does not seem to be a viable technique for our 2N2905A transistors.

c. 2N709

Histograms of $\Delta I_{\rm B}$ (1.7 x 10⁵ rads) were compared with histograms of ΔI_{R} (1.3 x 10⁶ rads) at three bias conditions, $I_{E} = 100 \ \mu A$, 10 mA, and 3 μ A. In the I_E = 100 μ A and 10 mA data devices in the part of the 1.3 x 10^6 rads histogram with the largest ΔI_R were found in the higher tail of the lower dose $(1.7 \times 10^5 \text{ rads})$ histogram. The best predictability seems to occur for the 100 μ A bias condition. The results at I_p = 3 μ A showed significantly poorer predictability and were more like the data analyzed for the 2N930 and the 2N2905A. One apparent difference in the histograms of $\Delta I_{_{\rm I\!R}}$ for the 2N709 is that the maximum values of $\Delta I_{_{\rm I\!R}}$ were 1.5 to 4 times the mean, whereas for the 2N930 and 2N2905A device types the large values of ΔI_p were typically only 20% to 50% greater than the mean. In other words, the coefficient of variation for the 2N709 distribution was much larger for the 2N709 than for the other device types. Table 84 summarizes the capability to eliminate the N devices in the R rows of largest ΔI_{R} in the 1.3 x 10⁶ rads histogram by screening out P rows containing M devices in the 1.7 x 10^5 rads histogram. Figure 95 shows an example of the procedure used in the analysis. As seen in this figure and in Table 84, the low dose screening does not seem to be a viable technique for our 2N709 transistors.

4. ELECTRICAL SCREENING - µA744 OPERATIONAL AMPLIFIER

The problems of predicting total dose damage for the μ A744 operational amplifiers are in many ways similar to those encountered with the bipolar transistors. The most sensitive parameters of an op amp in a total dose environment are the input bias currents which are simply the base currents of the input transistors. It is important to note, however, that the radiation induced increase in I_B is somewhat reduced, one might say partially compensated, by the constant emitter current biasing circuit.

The rationale behind the selection of the primary correlation parameters, the bias currents, was discussed in Paragraph 4-b, Section V, Volume 1 in some detail and will not be repeated again. The radiation sensitivity is defined by the absolute or relative changes in the bias currents, similar to the procedure used for bipolar transistors.

The µA744 op amp exhibited a "medium" radiation sensitivity in I_B during total dose exposure. Although not very high it was by no means negligible! (It should be noted that the op amps were irradiated at bias voltages of +15V and -5V respectively in order to maximize the reverse biases across the junctions during exposure.) The initial base current, I_B° distribution is illustrated in Figure 96, and the effects of the radiation are shown in the ΔI_B and the I_B histograms in Figures 97 and 98. The data emphasizes one very important message. The use of a failure level definition of $I_B \geq 750$ µA essentially a Honeywell specification will reject 6%, 17% and 21% of the op amps after doses of 2.7 x 10⁵ rads, 1.3 x 10⁶ rads and 5.6 x 10⁶ rads, respectively.

Table 85 shows the rank correlation coefficients between the various initial parameters (noise and others related to I_B) and the radiation sensitivities of the op amps. As seen, there is a definite hint of correlation between the relative changes in the bias currents and the initial parameters. However, the values of the coefficients (≤ 0.5) are not high enough to have any statistical significance for screening purposes.

5. LOW DOSE SCREENING - µA744 OPERATIONAL AMPLIFIER

The approach to test the applicability to the μ A744 of the basic premise of the low dose screening, "devices exhibiting high radiation sensitivity at low dose are the ones most likely to fail at high dose" was the same as presented for bipolar transistors. Namely, the tails of the histograms of the "radiation sensitivity" (measured by the change in the bias current, I_B) at low and high doses were compared to determine if the devices maintained their relative positions in the two histograms. As for the bipolars, the simple approach to low dose screening did not work. Too many devices would have had to be eliminated after the low dose test in order to make sure that those few exhibiting excessively high radiation sensitivity at the high doses were indeed removed. This conclusion is further supported by the following poor rank correlation value between low and high dose radiation sensitivities.

Low Dose Sensitivity	High Dose Sensitivity	Correlation Coefficient
[I _B (2.7 x 10 ⁵ rads) -I ⁰ _B]	[I _B (5.6 x 10 ⁶ rads) -I _B ⁰]	0.629

After eliminating from consideration all devices with poor or suspect data we found that those devices in the 5 rows of the histogram corresponding to the largest values of ΔI_B at 5.6 x 10⁶ rads were scattered almost randomly through 15 rows of the highest ΔI_B s in the 2.7 x 10⁵ rads histogram. Precisely, to screen out the N devices in the highest R rows of the 5.6 x 10⁶ rads histogram requires elimination of the highest P rows containing M devices in the 2.7 x 10⁵ rads histogram. The results are summarized in Table 86. Again, the conclusion is the same as for the bipolar transistors i.e., the low dose screening did not seem to be a viable technique for our μ A744 op amps.





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Histogram of ΔI_B Illustrating the Variation in the Radiation Sensitivities Among the 2N709 Transistors of Different Wafers (Dose = 1.25 x 10⁶ rads; I_E = 3 µA) Figure 78.

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Histograms of I_B/I_B^0 Illustrating the Variation in the Radiation Sensitivities Among the 2N709^BTransistors of Different Wafers (Dose = 1.25 x 10⁶ rads; $I_E = 3 \mu A$) Figure 79.

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Histogram of h_{FE}/h_{FEO} Illustrating the Variation in the Radiation Sensitivities Among the 2N709 Transistors of Different Wafers (Dose = 1.25 x 10⁶ rads; I_E = 100 µA) Figure 80.

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Histogram of $\Delta(1/h_{\rm FE})$ = $\Delta I_B/I_C$ Illustrating the Variation in the Radiation Sensitivities Among the 2N709 Transistors of Different Wafers (Dose = 1.25 x 10⁶ rads; I_E = 100 µA) Figure 81.

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	PEQ CENT	TES T [9	16=	LUAVCB- 0 V	MEUIAN 1.6726-07	MFA4 1.5326-07	5TD. DEV. 4.539E-08	COVAR.(%) 24.53	
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•	0.0	1-576-09	•						
2	0.0	- 5.455-09	•						
ņ	0.0	2-42E-03							
•	0.0	1.155-08							
0	0.0	2.056-05	•						
c	0.0	2.305-33	•						
0	0.0.	20-312.6	i •						
n,	0.0	4.775-08	•						
o	0.0	53E-JB	•						
r	0.0	c. 2 4c - C3	•		2				
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-	0.0	10-30-1	10	CALLS					
-	0.1	10-2:2-1	201	144155					
2	1.4	1.395-07	:136	143					
2	-+-1	-10-31 -1	0:1	132					
2	1.4	1.566-37	:7C.	25194140149157					
m - 1	1 2	1.655-01	C .	L: 7349C94045045C45C	39 291 061 071 1512	51341411521531	60		
21	1.5	1.756-37	- 042	95 e3710730400960960900	Lais 1111190150				
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- F T	т) • Г	- 2.324-07	. 50.	1901201903903910510510	2012912121236413				
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•	0.0	2.055-07	•						
S	c.0	7.145-07	•						
¢	0.1	2.4 4c-07	•						
0	0.0	2.926-07	•						
^	0.0	3.315-37	•						
1	6.9	3.116-31	-						
1	0.0	3.20E-J7	•						
* *			2	C	14	61	23	67	20

Histogram of ΔI_B Illustrating the Variation in the Radiation Sensitivities Among the 2N930 Transistors of Differenc Wafers (Dose = 3.0 x 10⁵ rads; $I_E = 1 \mu A$) Figure 82.

Y

W. Fish TEST FOUNDER F											
0 0.0 7.2.45 00 0 0.0 1.45 01 0 0.0 1.45 01 0 0.0 1.45 01 0 0.0 1.45 01 0 0.0 1.45 01 0 0.0 1.45 01 0 0.0 1.45 01 0 0.0 1.45 01 0 0.0 1.45 01 0 0.0 1.45 01 0 0.0 1.45 01 0 0.0 0.00 1.45 0 0.0 0.00 0.00 0 0.0 0.00 0.00 0 0.0 0.00 0.00 0 0.0 0.00 0.00 0 0.0 0.00 0.00 0 0.0 0.00 0.00 0 0.0 0.00 0.00 0 0.0 0.00 0.00 0 0.0 0.00 0.00 0 0.0 0.00 0.00 0 0.0 0.00 0.00 0 0.0 0.00 0.00		CENT	TEST I B		1E= 1UAVCB=	20	46014V	MEAN 2.006E 01	510. CEV. 5.296E 00	COVAP. (2) 31.38	
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· 0.0 3.975 01 . 1 0.7 3.995 01 .067 1 0.7 4.115 01 - 1409 0 0.0 4.235 01 . 4 0 5 10 10 5 30 35 30 35 30 35	0	C* 0 :	3.755	10	•			-	and the second sec		
1 0.7 3.975 01 .057 1 0.0 4.235 01 . 3 0.0 4.235 01 . 4 0 5 10 5 5 5 0 5 5 5 5 5 5 5 5 5 5 5 5	•.	0.0	3. 8 7E	10							
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Histogram of I_B^{-}/I_B^{-} Illustrating the Variation in the Radiation Sensitivities Among the 2N930 Transistors of Different Wafers (Dose = 3.0 x 10⁵ rads; $I_E^{-} = 1 \mu A$) Figure 83.

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STRESS 3.00 ES	
TEST 401 TEMP 22.	
DEVICE 2N930	

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06 JUL 73

NU.	1200	TEST	IE= 1MAVC9= 0.V	MED14N 3.0044-01	MEAN 2. 9675-01	5.507E-02	COVAR.(4) 18.50	
0	0-0	7-325-02						
- 0	-0-0							1
e.	0.0	9.055-72	•					
n	0.0	1.035-01						
o	0.0	1.2.75-31	•					
n	0.0	1.315-01						
ņ	0.0	1.4 3E-01						
	0.0.	- 1.55c-01 -	•					
0	C-0	1.635-01						
2	0.0	1. 745-01						
1	0.7	10-uer · ·	.056					
~	2.5	2.015-01	. 245066					
-1	7.4	2.1301	.051052053056058063C6	57078C74057100				
27	2-2	2.444.42	02304304604907037107	2089 999 103				
n	7. F	10-301-71	 344047C5CC57U54073C1 	76115				
¢	4.1	2.4-5-01	+1111101720195024C*					
=	7.4	20-ab6-2	.064074092C9410910	17124126144256				
æ	6.1	10-371-2	.0%469455569413512212	29131145				
*	4.7	2.424-3	.37799609110912413714	••				
	- 5.6	2	019034Cfffferer1311912					
13	8.8	3.)55-01	.014017C26C8233510210	2122139147150151151151	-1			
13	6.3	3.176-01	01510160510201000000	141 30134155				
14	9.5	3.295-01		416418E18211_ 1956	9150	Ĩ		į
9	4.1	3.405-01	-018054C=1130142184					
•	4.1	3.5.25-31	-0200553601411-2157					
-11-		10-2+4-2	- 012015 J222250550410e					-
•	4.1	3.7501	.J347420651 23132152					
\$	2.7	10-31 - 5	<pre></pre>					
* .	- 2.7	10-350 .6	-0 36C491011.4					-
2	0.0	10	•					
	7.0	4.225-01	. Cå7					
-	-0-0	10-366.4						
0	0.0	4.4.55-31						
0	0.0	4.5701						
•	0.0	10-35-01	•					1
S	0.0	4.105-33						
c	0.0	1C-326**						
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0	6.0	10-351.5						
143			, ,	10	15	20	5 .	CE

Histogram of h_{FE}/h_{FEO} Illustrating the Variation in the Radiation Sensitivities Among the 2N930^T Transistors of Different Wafers (Dose = 3.0 x 10⁵ rads; I_E = 1 mA) Figure 84.

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TEST WEDLAW WEDLAW STD. DEV. Coverent 1.55 - 0.0 25.61 25.61 25.61 1.16 - 0.0 1.16 - 0.0 25.61 25.61 1.16 - 0.0 1.16 - 0.0 25.61 25.61 1.16 - 0.0 1.16 - 0.0 25.61 25.61 1.16 - 0.0 1.16 - 0.0 25.61 25.61 1.16 - 0.0 1.10 - 0.0 1.10 - 0.0 25.61 1.16 - 0.0 1.10 - 0.0 1.10 - 0.0 25.00 1.16 - 0.0 1.10 - 0.0 1.10 - 0.0 25.00 1.16 - 0.0 1.10 - 0.0 20.00 20.00 1.16 - 0.0 1.10 - 0.0 20.00 20.00 1.16 - 0.0 20.00 20.00 20.00 1.16 - 0.0 20.00 20.00 20.00 1.16 - 0.0 20.00 20.00 20.00 1.16 - 0.0 20.00 20.00 20.00 1.16 - 0.0 20.00 20.00 20.00 1.16 - 0.0 20.00 20.00 20.00 1.16 - 0.0 20.00 20.00 20.00 1.16 - 0.0 20.00 20.00 20.00 1.16 - 0.0 20.00 20.00 20.00 1.16 - 0.0 20.								
1.56*-06 1.15*-05 1.11*-05	1631			MEDIAN 9.7875-03	MEAN 9.2726-03	STD. DEV. 2.3535-03	COVA0.(5) 25.87	
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2.671-01 3.222-05 4.917-05 4.917-05 4.917-05 4.917-05 4.917-05 4.917-05 4.917-05 4.917-05 4.917-05 4.917-05 4.917-05 4.917-05 4.917-05 4.917-05 4.917-05 4.9111111414 4.915-05 4.917-05 4.917-05 4.917-05 4.91111111416 4.915-05 4.91111111416 4.915-05 4.915-05 4.91111111416 4.915-05 4.91111111416 4.915-05 4.	1.54C.1	. 5						
2.::::::::::::::::::::::::::::::::::::	2.675-0		ļ					
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5.17-05 110107220272903960 5.19-05 1101070220272903960 5.19-05 011010520272903960 5.194-05 011010520272903960 5.194-05 0110110520272903900 5.194-05 0110110220270903060 5.194-05 012010520272903100 5.194-05 012010520270052000 5.194-05 012010520270052000 5.194-05 01101191410 5.194-05 0111131814 5.174-05 0111131814 5.174-05 0111131814 5.174-05 0111131814 5.174-05 0111131814 5.174-05 0111131814 5.174-05 0111131814 5.174-05 0111131814 5.174-05 0111131814 5.174-05 0111131814 5.174-05 0111131814 5.174-05 011111814 5.174-05 011111814 5.174-05 011111814 5.174-05 011111814 5.174-05 011111814 5.174-05 011111814 5.110 0111118144 5.110 <t< td=""><td>5-31.6</td><td>······································</td><td></td><td></td><td></td><td>-</td><td></td><td></td></t<>	5-31.6	······································				-		
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0.35-53 010020210713994.05405562065083119133 7.74-23 01121129140151163 7.74-23 142142 7.75-23 142142 7.75-23 142142 7.75-23 142142 7.75-23 142142 7.75-23 142142 7.75-23 041114112153 7.75-23 0441114112153 7.75-23 0441114112153 7.75-24 0441114112153 7.75-25 0441114112156 7.75-25 0441114112156 7.75-27 044057204507451741141666 7.75-27 0440577505755575557555755575557555755575	- 6.356-0	<pre>> 0 1201 502402502603103</pre>	32034035	0300000000000	1801605101600	701101		
7.11-33 0:9121121640154155 7.74-53 :57130126142 6.275-53 :42149 6.77130126156 :571321124 7.74-53 :4214215153 6.771313138147 :7714155153 7.77-53 :271321124155153 7.77-53 :271321541563 7.77-53 :271313138147 7.77-53 :271313138147 7.77-53 :271313138147 7.77-54 :2717131305195112 7.77-52 :27131313114126156 1.77-52 :2714565766754563171371506126156 1.717-52 :271959767675456317271461651261266 1.717-52 :2719597676754563172714616212212316114126126156 1.717-52 :27195976767575767507507670537467162 1.265-52 :293075117 1.265-52 :293075076707507670537467163 1.355-62 :293076717 1.355-62 :293075076705374670537467053746705 1.355-62 :293076717 1.355-62 :293076707237467053746705374670537467053746705 1.355-62 :293076717 1.355-62 :293076717 1.355-62 :293076717	6-345-0	.01902002103103904105	54055062	06508311913				
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8.275-05 ite2149 6.275-05 ite2149 7.75-05 ite2141141152165 7.75-05 ite2141141152165 1.25-05 ite2127127150 1.25-05 ite20127127150 1.17-02 ite202 ite212515111412012212312911115145155 1.17-02 ite202 ite2120111111214126156 1.17-02 ite202 ite2120111111214126156 1.17-02 ite202 ite2120111111214126156 1.17-02 ite202 ite2120111111214126156 1.17-02 ite202 ite2120111111214126156 1.17-02 ite202 ite205050505174C70551097 1.265-02 ite202 ite20175112 1.55-02 ite202 ite20175112 1.55-02 ite202 ite20175112 1.55-02 ite202 ite20175112 1.55-02 ite202 ite202 ite20175112 1.55-02 ite202 ite202 ite20175112 1.55-02 ite202 ite202 ite20175112 1.55-02 ite202 ite	7-74-0	24135105111.0						
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1.32 -0. 33-0325460317127150 1.24 -0. 247056575555565036700050615(11144140) 1.25 -0. 34045667717151051031231291113145150 1.26 3940567795655755556503103113114126156 312911135145151 1.26 395079117 395075112 1.26 395076117 395075112 1.26 395076117 3950761097 1.26 395076117 3950761097 1.26 395076117 3950761097 1.26 395076117 3950761097 1.26 395076117 3950761097 1.35 455077 3950761097 1.4 507721 100 1.4 507721 100 1.4 507721 100 1.4 507721 100 1.4 507721 100 1.4 507721 100 1.4 507721 100 1.4 507721 100 1.4 50 50 1.4 50 50 20 1.5 50 50 20	0-1.1	3 . 0 . 11 3 1 3 8 1 6 7						
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1117-02 0340446647711351662134164156 1267-02 0340677676767644466771135168124126156 1267-02 03406777676765451097 1267-02 034067776767653103112 1377-02 03406777676765310312014 1377-02 03406777676765360109712 1377-02 045072074071376671097 1377-02 04507207407137671097 1377-02 04507207407137671097 1377-02 04507207407107 1377-02 04507207407107 144072 04707207407107 144072 047072 144072 047072 144072 047072 144072 047072 144072 047072 144072 047072 144072 047072 144072 047072 144072 047072 144072 047072 144072 047072 144072 047072 144072 047072 144072 047072 144072 047072 144072 047072 144072 047072			40046004	16A11513714	2146			
1.55-32 0364667676754450313715116124126156 1.210-07 0351576553565376372374576351097 1.3-5-22 0450375112 1.3-5-22 0450375175715715116124126156 1.3-5-22 04503751757657537675351097 1.3-5-22 0450375176775374575376775351097 1.3-5-22 04503751767753745753745753745753145765351597 1.4-5-22 0450375374575374576353745765376775374576575374576575 1.4-5-22 0450375 1.4-5-22 045037537457676767676767676767676 1.4-5-22 050772374576767676767676767676767676 1.4-5-22 0505205 1.4-5-22 05077237457676767676767676767676767676767676767			201 CADE .	10411411912	223124121135	45151		
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1.4 - 5 - 22 0495054054054054054044 1.4 - 5 - 02 050375117 1.4 - 5 - 02 140 1.4 - 5 - 02 110 1.4 - 5 - 02 110 1.4 - 5 - 02 110 1.4 - 5 - 02 110 1.4 - 5 - 02 110 1.4 - 5 - 02 110 1.4 - 5 - 02 10 1.5 - 5 - 02 10 1.5 - 5 - 02 10 1.5 - 5 - 02 10 1.7 - 10 - 02 10 15 1.7 - 10 - 12 10 15 20 1.7 - 10 - 02 10 15 20 25 30	0+ 11 7 • 1		22.22.21					
1.35-5-22 0.55075117 1.35-5-22 1.455-22 1.455-22 1.455-22 1.455-22 1.455-22 1.455-22 1.455-22 1.455-22 1.455-22 1.455-22 1.455-22 1.455-22 1.7	1-107-1	10011 4000600 50760640 7						
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1	1.355-0	. 2						
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1.05-02 1.546-02 1.546-02 1.846-02 1.846-02 1.846-02 1.846-02 1.9466-02 1.946-	1-450							
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Histogram of $\Delta(1/h_{FE}) = \Delta I_B/I_C$ Illustrating the Variation in the Radiation Sensitivities Among the 2N930 Transistors of Different Wafers (Dose = 3.0 x 10⁵ rads; $I_E = 1$ mA) Figure 85.

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DEVICE 2N25/JA TEST 6D1 TEMP 22. STRESS 5.60 E6 F4000 BRL371

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Histogram of ΔI_B Illustrating the Variation in the Radiation Sensitivities Among the 2N2905A Transistors of Different Wafers (Dose = 5.6 x 10⁶ rads; I_E = 3 µA) Figure 86.

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Figure 87. Histogram of I_B/I^O Illustrating the Variation in the Radiation Sengitivities Among the 2N2905A^BTransistors of Different Wafers (Dose = 5.6 x 10⁶ rads; $I_E = 3 \mu A$)

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Histogram of h_{FE}/h_{FEO} Illustrating the Variation in the Radiation Sensitivities Among the 2N2905A Transistors of Different Wafers (Dose = 5.6 x 10⁶ rads; I_E = 3 mA) Figure 88.

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Histogram of $\Delta(1/h_{FE}) = \Lambda I_B/I_C$ Illustrating the Variation in the Radiation Sensitivities Among the 2N2905A Transistors of Different Wafers (Dose = 5.6 x 10⁶ rads; $I_E = 3$ mA) Figure 85.

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	3.065	52	•							
0-0	- P.85	50	•							
0	5.516	10								
0-0	6.135	10								
0:0	6. 165	10								
0-0	7.395	10	•							
0.0	8.01F	10	•							
0.0	8.646	5								
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Histogram of Low Dose AI_B, Marked to Illustrate the Limitations of the Low Dose Screening. Marked Devices Came From the Upper Tail of the High Dose AI_B Histogram (2N930, High Dose - 3 x 10⁵ rads) Figure 93.

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Low Dose Screening. Marked Devices Came From the Upper Tail of the High Dose ΔI_B Histogram (2N2905A, High Dose - 5.6 x 10⁶ rad)

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DEVICE UA 744 TEST ZER TEMP 22. STRESS 0.0

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- -							
4	2.2	40-346 E-	.163206255305				
-	9.0	-3.79E-04	.157				
+							
2	1.1	+0-36+ E-	.239265				
		-346-04	.17117317420020120824930	•			
n r		195-04	11114135545745141141				
10	9.9	40-36 P-2-	15420221622523323423624	0286378			
			1241291202061861161951	P 20P 20 32 27 28 2 2 2			
12	6.1	-2.5°E-04	.15519820424126426627928	1966622676			
16	8.9	-2-446-04	.15215516917618019219620	320721121 222024	52 87304397		
-	0.01	-2-296-04-	.1 001 621 cel 701 772 1022623	120022+22+24622	096602+62+426	980	
5	12.8	-2-146-04	. 158181 L8720522422923124	025025126026326	77 70271276281	E 8328429730731	76iE
	4.6	-1-986-0+	•2612612212661681681661 ·	7285288300303030	9561865165068		
	1.0			6067071076			
			273133106	2			
4			84484444				
) m	1.7	- 236-04	981786778.				
0	0.0	-1-J8E-04					
4	0.0	10-316		-			
0	0.0	-1-80E-05	•				
•	0-0	-6-305-05	•				
6		60-364	•				
0	•••	-3-296-05					
		CD-30/	•				
		1-735-05		-			
•			•				

Figure 96. Histogram of the Initial Bias Currents Illustrating the Variation Among the Op Amps

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UEVICE UA 744 TEST 4D1 TEMP 22. STRESS 5.60 E6 F4000 BRL331

2 A APR 73

.04	CENT	AIB	8	MEDIAN -3.522E-04	MEAN -3.370E-04	570. Dév. 1.8126-04	CCVAR. (6) 53. 75	
0	0-0	-1-086-03	•					
-	0.0	-1-1-046-01-						
	0.0	-9-366-04						
0	0.0	-9-556-04	•					
- 0 -	0.0	-9.155-04-				a name da ana ana ana ana ana ana ana ana ana		
0	0.0	-8.74E-04						
0	0.0	-8.336-74	•					
0	0.0	-7.926-04	•					
0	0.0	-7.516-04	•					
~	1.1	-7.116-74	.234293					
m	-1.7	-6.70E-04		And and a second a second a				1
4	2.2	-6.296-04	.20822927290					
5	8.2	-5-38E-34	24226227428039	7				
- - 20 -			17819525225430	5082		كالمتعالية والمتعارية والمتعارية والمتعارية والمتعارية والمتعارية والمتعارية والمتعارية والمتعارية والمتعارية		1
16	9 9	-5-06F-04	16216817217718	81932062282372452472913	9729638391			
12	5.7	-4-56E-34	.16418619820020	1521024126627127926 6292				
I	- 6.1	-4-25E-04	.1821852052224	3256257264268284393				
07	1.11	-3-94F-04	.17519119120321	22202302402502832652453	773753813843855	\$ 87392344		
12	6.7	-3.43E-04	.10717619220421	623326329423636389355346				
22	-1.9-	-3:02E-34	17419420121921	- 80610295238281204308				
19	10.6	-2.42E-04	.16516918920221	12172212242442472482512	532 612 99301 3043	378383		
18	10.0	-2.2 IE-04	.16317021321623	22392462552602672702732	772 78282296305	306		
13	2.1		15617117318719	101972262272582652752893	30		And the second s	•
m	1.7	+0-366-1-	.194196303					
•	0.0	-9.84E-05						
Ļ	0.0	-5.766-05	.133					
m	1.7	-1.68E-05	.154156382					
\$	2.2	2.40E-05	.152157158160					
+	1:1	-20-38+-9		an an a success of a state of an angular state of a success of the		and a second sec		
0	0.0	1.06E-U4	•					
•	0*0	1.465-04						
6		-30-318-1						
0	0.0	2.28E-04						
0	0.0	2.69E-04	•					
	0-6-	3.10E-04	.199	and the second s				
0	0.0	3.505-04						
1	0.6	3.916-04	.269					
6	0.0							
0	0.0	4.73E-04						
					16	00	36	00
101			D .	NT C	17	2	63	Š

Histogram of ΔI_B ILlustrating the Variation in the Radiation Sensitivities Among the Op Amps (Dose = 5.6 x 10⁶ rads) Figure 97.

																						1																î
1 201 65																						1																i.
	CUVA+. [4] 22+37																			5.63 CC																		42
151	570. DEV. 1.960E-04																			CTOS NAS MADE																		50
194	MEAN -5.963E-04																			7243264264 - CH		A2U8377384387	0										a state and the second s					15
F 4 00 U	MEULAN -5.8355-04																T01011010	14221261140	50 2 6 3 6 3 6 4 6 6 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7	201221 2012 100 10 10 10 10 10 10 10 10 10 10 10 10	78365352	312582772#130	747753653864557	92289246380														10
PRESS 5.60 E4													300		1		- 1 1		2 11 11 1 11 1 1 1 1 1 1 1 1 1 1 1 1 1	2402010101010101010101010101010101010101	1901 10:05 201 309 1	211215215172	2512602672702	2462442012752					160									5
TEMP 22. SI					-		513			2-1	208228232962	2222562407	Nr201291 1441	112240					01-1-11.11.4	- 1011-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1	1751425 30264	165169171175	1-9224232247	. 70213221226	1651071-11305	157227	154156		152153155158			141			1 30240	107417		
TeST 401	TEST 16	1.405-03	1-355-03	1-246-03	1.235-03	1.1 35-03 .	1.155-03 .	F.111-23-	1.07E-03	1.035-03	9.40E-04	9.505-04		6.55E-04	8.235-04	7.875-04 ·		· •0-100.	• • • • • • • • • • • • • • • • • • •			5-025-04	4.61E-04	4.2UE-U4 .	3.106-04	3.396-04	2.335-04 .	2.53E=U4 .	2.17E-U+	1.765-04 .	1.355-04	9.465-05	5.54E-U5 .	1.326-05			1-506-04	0
UA 744	PER	- 0.0		- 0.0		- 0.0	• •••0	10.0		0.6	2.5			[1						1 1 1 9	10-01	-	6.7	-2.2-	- 1	- 1-1	- 0.0.	2.8 -	- 0.0	- 4:0-	• • •	0.0	2.0			0.0	
DEVICE	2	•		0	•	•	-	0	•	-		•	•	L.	0	•		71	-		3 =		13	12		~	~	0	ŝ	•		- 0		50	> ~	• •	• •	170

Histogram of I_{B} (5.6 x 10⁶ rad) Illustrating the Variation Among the Op Amps Figure 98.

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X vs. Y (a)	· 2N709	2N9 30	2N2905A
(1/f) Noise	0,3	0.2	0.3
I ^o _B vs. I _B (dose) ^(b)	0.5-0.94	0.35-0.7	0.96- 3.9 7
$I_B^o vs. I_B/I_B^o$ (b)	(0.6-0.4)	-(0.3-0.2)	0.8-0.7
I_B° vs. $\{I_B(dose) - I_B^{\circ}\}$ (b)	0.2-0.65	0.2-0.4	0.5-0.7
$1/I_{B}^{o}$ vs. $(1/I_{B}^{o} - 1/I_{B})^{(b)}$	0.91-0.94	0.97-0.8	0.98-0.96
$\Delta I_{B} (\text{low injection}) \text{ vs.} \\ \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad $	0.96-0.55-0.2 ^(e)	0.98-0.90	0.90-0.80-0.55 ^(e)
h _{FEO} vs. h _{FE} (dose)	0.56-0.80-0.95 ^(e)	0.36-0.49-0.68 ^(e)	0.97-0.97
h _{FEO} vs. h _{FEO} -h _{FE} (dose)	0.91-0.94	0.97-0.83	0.96-0.95
hFEC VS. hFE/hFEO	-(0.6-0.4)	-(0.3-0.2)	-(0.8-0.7)
h _{FEO} vs. h _{FE} /h _{FEO}	0.5-0.6	0.3-0.2	0.8-0.7
1/h _{FEO} vs. 1(1/h _{FE})	0.2-0.7	-(0.4-0.2)	-(0.75-0.6)
I ^o (c) B	-0.5	-(0.6-0.55)	0.7-0.85
$1_{B}^{o}(T)^{(d,c)}$	-0.4	-0.4	0.7-0.8
ΔI_{B} (due to T) ^(c)	-0.4	-0.4-0	0.75-0.8
ΔI_{B} (due to burn-in)(c)	ù	-0.3 to 0.3	-(0.3-0.2)
I ^o _{UBO} (or BV ^o _{EBO})	-0.4	-0.3	0.6-0.75
1_{EBO}^{o} (T) (or BV_{EBO}^{o})	-0.4	-0.3	0.6-0.75
ΔI_{EBO} (due to [1]) (or BV_{EBO})	-0.4	0.2	0.6-0.7
ΔI_{EBO} (due to burn-in)	0		
2N930 ((1/f) Noise		0.3	
Pre- (t ^o burn-in B		-0.4	
$(\mathbf{I}_{\mathcal{B}}^{\mathbf{r}})$		-0.4	

Rank Correlation Coefficients for Total Dose Damage Prediction (Overview)

(a)Unless otherwise noted, the Y parameter is Radiation Sensitivity Ξ the

change or the relative change in the low injection $I_B.$ (b)All I_B values were taken at relatively high injection . el.

(c)AII I_B values were taken at low injection level.
 (d)"T" indicates other than room temperature.

(e) These multiple entries represent variation with emitter current. Arrows correspond to the direction of increasing current.

Table 78Summary of Data to Illustrate the Radiation Sensitivity of 2N709

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$3.0 \times 10^{5} \text{ rads} 1.3 \times 10^{6} \text{ rads} 5.6 \times 10^{6} \text{ rads}$	3.4×10^{-9} 166 6.5 x 10 ⁻⁸ 79 2.5 x 10 ⁻⁷ 73	8.1×10^{-8} 8C 5.5×10^{-7} 67 1.1×10^{-6} 37	5.0×10^{-6} 43 1.7×10^{-5} 48 3.5×10^{-5} 36	1.45 39 8.7 79 27.1 76	1.6 25 5.0 56 3.8 52	1.24 7.5 1.8 20 2.66 27		0.74 16 0.41 48 0.20 43	0.81 8.6 0.55 19 0.36 21	0.35 2.7 0.70 5.9 0.55 8.7	9.3×10^{-3} 56 4.7×10^{-2} 64 1.1×10^{-1} 41	5.3×10^{-3} 44 1.8×10^{-2} 48 3.7×10^{-2} 37	-3 -2 -2 -2 -2 -2
rads 1.3 x	166 6.5 x	80 5.5 x	43 1.7 x	39 8.7	25 5.0	7.5 1.8		16 0.41	8.6 0.55	2.7 0.70	56 4.7 x	44 1.8 x	- :: 5
3.0 × 10 ⁵	3.4 x 10 ⁻⁹	8.1 x 10 ⁻⁸	5.0 x 10 ⁻⁶	1.45	1.6	1.24		0.74	0.81	0.35	9.3×10^{-3}	5.3×10^{-3}	2 0 - 1A-3
1.0 x 10 ⁵ rads						8			-	2		8	
	$_{BE}^{RE} = 0.45V$	E = 3 μΑ	E = 1 mA	^{BE} 0.45V	E = 3 µA	E = 1 mA		E = 100 μΑ	E = 1 mA	E = 10 mA	E = 100 μA	E = 1 mA	
	Δ		(Amps.)	Δ	IB at I		۹	I	RE RE SE		 H :	A(1/hre)	L t I y

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Table 79 Summary of Data to Illustrate the Radiation Sensitivity of 2N930

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				1.0 x 10 ⁵ r	ads	3.0 x 10 ⁵ ra	sbi	1.3 x 10 ⁶ ra	ສຸ	5.6 x 10 ⁶ rads	
	1				COV %		COV %		COV Z		COV Z
		VBE	= 0.45V	7.9 x 10 ⁻⁸	77	2.3×10^{-7}	40	3.3 x 10 ⁻⁷	19	4.3 × 10 ⁻⁷	13
ΔIB	ЗБ	IE	= 1 µA	4.4 × 10 ⁻⁸	76	1.4×10^{-7}	41	2.0 × 10 ⁻⁷	20	2.5×10^{-7}	15
(Amps)	a ¹	E	= 100 µA	8.7×10^{-7}	63	2.1×10^{-6}	37	3.C × 10 ⁻⁶	19	3.7 x 10 ⁻⁶	15
		1 E	= 10 mA	2.5×10^{-5}	53	4.5 x 10 ⁻⁵	41	6.8 x 10 ⁻⁵	36	9.2 x 10 ⁻⁵	20
		VBE	= 0.45V	5.7	65	15.0	44	20.0	37	25.7	35
^I ^B	Ţŧ	IE	= 1 µA	6.5	50	18,3	41	23.9	35	32.2	21
0 #	, ^g	IE	= 100 µA	3.0	45	5.8	31	7.7	18	9.4	15
;		I _E	= 10 mA	1.6	22	2.1	21	2.7	12	3.2	10
		I _E	= 100 µA	0.36	34	0.17	24	0.13	18	0.105	16
	зъ	IE	= 1 mA	0.50	29	0.30	19	0.23	15	0.19	13
h_EEO	^{EE} 4	ц. Ц	= 10 mA	0.65	22	0.47	16	0.37	12	0.31	10
		IE	= 50 mA	0.80	12	0.65	12	0.53	11	0.45	8.4
-	F	LE	= 100 µA	8.9 x 10 ⁻³	63	2.2×10^{-2}	36	3.1 × 10 ⁻²	20	3.9×10^{-2}	16
$(1/\dot{h}_{\Xi\Xi})$	e Zi	IE	= 1 mA	4.3×10^{-3}	56	8.7×10^{-3}	36	1.3 x 10 ⁻²	20	1.6 × 10 ⁻²	16
	ų	1 E	= 10mA	2.6×10^{-3}	53	4.6 x 10 ⁻³	40	6.9 x 10 ⁻³	36	9.4 x 10 ⁻³	20

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Table 80 Summary of Data to Illustrate the Radiation Sensitivity of 2N2905A

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8	13	15	10	27	17	5.7	6.7	5.7	2.3	11	11	8.4
5.6 x 10 ⁶ rad	-2.3×10^{-7}	-1.8×10^{-7}	-2.0 × 10 ⁻⁴	4.3	5.6	1.9	0.51	0.53	0.67	7.4 x 10 ⁻³ .	6.7×10^{-3}	1.0×10^{-2}
ads	21	19	13	17	13	4.9	5.5	5.1	1.9	15	13	13
1.3 x 10 ⁶ r	-6.3 x 10 ⁻⁸	-5.3 x 10 ⁻⁸	-1.2×10^{-4}	1.9	2.4	1.6	0.71	0.64	0.80	3.2 × 10 ⁻³	4.2×10^{-3}	5.5×10^{-3}
ads	120	36	19	11	5.4	4.4	2.4	4.5	1.5	31	61	36
3.0 × 10 ⁵ r	-5.1×10^{-9}	-1.5 x 10 ⁻⁸	-9.1 x 10 ⁻⁵	1.1	1.4	1.4	0.87	0.71	16.0	1.2×10^{-3}	3.1×10^{-3}	2.0×10^{-3}
ds 70	250	40	18	7.7	3.9	2.3		1		41	18	43
1.0 × 10 ⁵ ra	1.8 x 10 ⁻⁹	-5.7 × 10 ⁻⁹	-5.6 x 10 ⁻⁵	0.98	1.15	1.25		-	1	3.8 x 10 ⁻⁴	1.9×10^{-3}	5.7×10^{-4}
	= 0.45V	= 3 µА	= 30 mA	= 0.45V	= 3 µA	= 30 mA	= 3 mA	= 30 mA	= 300 mA	= 3 mA	= 30 mA	∺ 300 mA
	VBE	IE	ш	V BE	ΗE	ы Ц	E	E	Е	IE	IE	IE
		3B	al	1	B RI			E ac	⁴ y	1	E S	^l ų
		Δ I _B	(Amps.)	ŀ	<u>ه</u> د	្ក ដា H			DET -		۵(1/h _{FE}	

	Bias	Radiation S I _B (irradia	ensitivity: ted)- I ^o B	
Device Type	Condition for I _B	Low Dose rad(Si)	High Dose rad(Si)	Correlation Coefficient
2N709	$V_{BE} = 0.45V$ $I_{E} = 3 \mu A$ $V_{VE} = 0.45V$ $I_{E} = 3 \mu A$	1.7×10^{5} 1.7×10^{5} 3.0×10^{5} 3.0×10^{5}	1.3×10^{6} 1.3×10^{6} 1.3×10^{6} 1.3×10^{6} 1.3×10^{6}	0.678 0.663 0.893 0.821
2 N 9 3 0	$V_{BE} = 0.45V$ $I_{E} = 1 \mu A$ $V_{BE} = 0.45V$ $I_{E} = 1 \mu A$.	3.0×10^4 3.0×10^4 1.0×10^5 1.0×10^5	3.0×10^{5} 3.0×10^{5} 3.0×10^{5} 3.0×10^{5}	0.699 0.639 0.752 0.726
2N2905A	$V_{BE} = 0.45V$ $I_{E} = 3 \mu A$ $V_{BE} = 0.45V$ $I_{E} = 3 \mu A$	1.7×10^{5} 1.7×10^{5} 3.0×10^{5} 3.0×10^{5}	5.6 x 10^{6} 5.6 x 10^{6} 5.6 x 10^{6} 5.6 x 10^{6}	0.329 0.675 0.296 0.681

Results of Rank Correlations Between Radiation Sensitivity (Low Dose) and Radiation Sensitivity (High Dose)

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Summary of Data Illustrating the Procedure and the Results of the Low Dose Screening (2N930)

		MO	ose screen	(DEENZ) BUT		
	3 x 10	5 rads	1 × 1	.0 ⁵ rads		
	Rows R	Devices N	Rows P	Devices M	N (% of Total Sample)	M (% of Total Sample)
		2	13	60	1.3	40.3
	7	9	13	60	4.0	40.3
5V)	m	11	14	.63	7.4	42.3
	4	19	15	73	12.8	Ú.94
	v.	35	15	73	23.5	42.0
	T	Ţ	10	54	0.7	36.2
	2	Ś	13	64	3.4	63.1
2	m	17	. 13	94	11.4	63.1
	4	32	13	94	21.5	63.1
	г	T	6	51	1	34.2
(Ац	2	Ś	10	53	ŝ	35.6
	3	17	13	81	17	54.4
	1	1	5	39	Ţ	26.2
	7	e	9	48	m	32.2
	m	9	7	57	9	38.3
2	4	17	7	57	17	38.3
	Ś	22	7	57	22	38.3
	Q	29	10	64	29	0.14

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Summary of Data Illustrating the Procedure and the Results of the Low Dose Screening (2N2905A)

	5 x 1(06 rads	1.7 ×	c 10 ⁵ rads		
Bias	Rows P	Devices N	Rows	Devices M	N(% of Total Sample)	M (% of Total Sample)
CONCILCTORS	4	4	-		10-141 Campto	lotding topot
	2	t-	9	36	2.8	25.5
$\Gamma_{R}(I_{F} = 300 \text{ mA})$	٣	15	10	66	10.6	70.2
1	4	26	10	66	18.4	70.2
	4	8	6	32	5.7	22.7
T (T = 1 mA)	ę	16	12	63	11.3	44.7
-B ~E	7	23	18	124	16.3	87.9
	3	5	6	25	3.5	17.7
	ŝ	7	6	25	5.0	17.7
T (T = 3 14)	9	16	13	57	11.3	40.4
-B -E	7	19	13	57	13.5	40.4
	8	25	18	105	17.7	74.5
	e	S	12	93	3.5	66.0
$I_{n}(V_{nn} = 0.45V)$	4	. 91	16	126	11.3	89.4
20	S	22	18	138	15.6	97.9

Bias Condition	Rows *R	De- vices N	N(% of Total Sample)	Rows *P	De- vices M	M(% of Total Sample)
I _p at	1	2	1.5	3	3	2.3
$I_{\rm F} = 10 \rm mA$	2	4	3.0	6	9	6.8
2	5	7	5.3	7	11	8.3
	6	11	8.3	10	33	24.8
	7	15	11.3	10	33	24.8
	8	23	17.3	12	47	35.3
I _n at	1	1	0.75	1	7	5.3
Ι _E = 100 μΑ	3	4	3.0	1	7	5.3
2	4	7	5.3	3	9	6.8
	7	11	8.3	9	22	16.5
	9	14	10.5	9	22	16.5
	11	20	15.0	12	55	41.3
I _n at	1	1	0.75	1	7	5.3
$I_{\rm H} = 3 \mu A$	2	2	1.5	2	8	6.0
Ľ	3	5	3.8	9	17	12.8
	7	10	7.5	9	17	12.8
	9	17	12.8	13	41	30.8
	11	23	17.3	15	84	63.2

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Summary of Data Illustrating the Procedure and the Results of the Low Dose Screening (2N709)

*In these histograms, all devices with good data, but such large ΔI_B as to fall outside the histogram plot, were called row 1.

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Table	85
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Change in Bias Current, ΔI_B vs.:	Rank Correlation
IB	-0.061
low frequency noise current	0.091
I_{B}^{o} (22°C) - I_{B}^{o} (-50°C)	0.112
I_{B}° (75°C) - I_{B}° (22°C)	0.157
I_{B}^{o} (75°C) - I_{B}^{o} (-50°C)	0.190
I ^o _B (-50°C)	-0.099
1 [°] _B (75°C)	0.082
Relative Change in Bias Current, $\Delta I_B / I_B^o$ vs.:	
I ^o B	C.546
low frequency noise current	-0.316
I_{B}^{o} (22°C) - I_{B}^{o} (-50°C)	-0.403
I_{B}^{o} (75°C) - I_{B}^{o} (22°C)	-0.486
I_{B}^{o} (75°C) - I_{B}^{o} (-50°C)	-0.492
I [°] _B (-50°C)	0.463
I [°] _B (75°C)	0.237

Rank Correlation Coefficients for Damage Prediction at 5.6 x 10^6 rads - μ A744

Rows R	Devices N	N(% of Total Sample)	Rows P	Devices M	M(% of Total Sample)
1	2	1.4	13	56	39.7
2	5	3.5	14	74	52.5
3	9	6.4	14	74	52.5
4	14	9.9	15	106	75.2
5	20	14.2	15	106	75.2

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Summary of Data Illustrating the Procedure and the Results of the Low Dose Screening for the $\mu A744$ Op Amp

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