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A COMPARISON OF THE RADIATION DAMAGE OF ELECTRONIC COMPONENTS

IRRADIATED IN DIFFERENT RADIATION FIELDS

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G E N E V A

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ABSTRACT

Resistors, capacitors, silicon diodes and transistors, TTL integrated circuits, and operational amplifiers have been irradiated in three different radiation environments: in a research reactor with up to 10^{15} n/cm² ($E > 1$ MeV), near a proton beam of the CERN Intersecting Storage Rings with up to 5×10^5 rad, and with a 30 kCi ⁶⁰Co gamma source with up to 1×10^7 rad. Representative parameters, such as resistance, capacitance, forward voltage, reverse current, toggle frequencies, have been measured before and after irradiation. It was found that, in comparison with nuclear-reactor irradiations, the effect of ⁶⁰Co gamma rays can be smaller by a factor of 100 or more, whereas high-dose-rate accelerator irradiation can be up to 5 times more damaging for the same nominal amount of irradiation. It is concluded that care has to be exercised when interpreting the results of radiation damage tests on electronic components in different radiation environments.

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LIST OF SYMBOLS

C	capacitance, in farads
$D_{\text{rad(CH)}}$	radiation dose, in CH-rad ($1 \text{ rad} = 100 \text{ erg} \cdot \text{g}^{-1}$)
DVM	digital voltmeter
e_{os}	input offset voltage
f	frequency
$I_C (\Delta I_C)$	collector current (change in)
I_D	drain current
I_{DSS}	drain source short circuit current ($V_{\text{GS}} = 0$)
$I_{\text{out}}(0)$	output sink current
I_R	reverse current
I_V	base current
$i_{\text{os}}^- - i_{\text{os}}^+$	input offset current
$(i_{\text{os}}^+ + i_{\text{os}}^-)/2$	input bias current
R	resistance, in ohms
R_f	feedback resistance
R_i	input resistance
R_s	source resistance
V_{CE}	collector-emitter voltage
V_{DS}	drain-source voltage
V_F	forward voltage
V_{GS}	gate-source voltage
V_o	amplifier output voltage
Y_{fs}	transconductance in mhos
β	d.c. current gain
Δt	output pulse length in seconds
ϕ	particle fluence

1. INTRODUCTION

The operation of high-energy particle accelerators requires the use of electronic components, many of which are situated in a radiation environment. In order to predict the lifetime of these components, simulated accelerated damage tests are performed. These tests are normally made in radiation sources, i.e. nuclear reactors and γ -cells whose characteristics are different from those of a particle accelerator.

Static and dynamic radiation damage tests have already been reported for various types of components irradiated in a nuclear reactor and near high-energy accelerators¹⁾. This survey has been extended by irradiating 14 representative components in a ^{60}Co γ -cell and near the proton beam of the CERN Intersecting Storage Rings (ISR).

This has allowed a comparison to be made of the damage effects resulting from the reactor, γ and accelerator irradiations, and conversion factors to be given for accelerator radiation damage from reactor and γ -irradiation tests.

2. RADIATION SOURCES

2.1 Nuclear reactor

The most convenient way to compare radiation damage on semiconductors from reactor irradiations is to relate it to the neutron exposure dose (in $\text{n}\cdot\text{cm}^{-2}$) above a given threshold energy. The neutron fluence is measured by means of activation detectors, for example $^{58}\text{Ni}(\text{n},\text{p})^{58}\text{Co}$ with a threshold energy of 2.8 MeV, which is a recognized standard method.

Knowing the reaction cross-section, the average fraction of neutron energy transferred to an atom in an elastic collision and integrating the neutron fluence over the effective range (e.g. 1 MeV to ∞), one can calculate the dose equivalent in various materials. For the irradiation position SNIF in the ASTRA 7 MW pool reactor²⁾, where the irradiations of electronic components were performed, the neutron fluence ($E > 1$ MeV) can be approximated by the following relation

$$\phi(E) = C \int_{E=1 \text{ MeV}}^{\infty} e^{-0.526E} dE ,$$

where $C = 2.5 \times 10^9 - 5.2 \times 10^9$, depending on the reactor core configuration and the distance of the sample container from the core. For our conditions, one can calculate^{1,3)} the neutron-to-dose conversion.

$$D_{\text{rad}}(\text{CH}) = \frac{\phi_{\text{n}}(E>1\text{MeV})}{\text{cm}^2} \times \frac{3 \times 10^{-9} \text{ rad}}{\text{n}\cdot\text{cm}^{-2}} .$$

The damage produced by thermal neutron irradiation can be neglected owing to the low thermal neutron cross-section of semiconductor materials. Even when boron, which has a high thermal neutron cross-section (4000 barns for ^{10}B with a natural abundance of 19.6%), is used as a dopant, its normal concentration of 1 part in 10^6 results in negligible radiation damage.

Energetic γ -rays (1-3 MeV mean energy), present in the nuclear reactor radiation field, greatly contribute to the radiation damage of organic materials. In semiconductors, however, they do not play such an important role, as is demonstrated later when discussing pure γ -irradiations of electronic components.

2.2 High-energy proton accelerator

At CERN the components have been irradiated in two different positions:

- i) in a high dose-rate area about 50 cm from the ISR beam dump where we obtain 3.6 rad per 10^{12} protons dumped; owing to the short dumping time of 3.4 μ sec, the instantaneous dose-rate to the components is 3.6×10^9 rad $\cdot$ h $^{-1}$;
- ii) in a low dose-rate area in the coil covers of the ISR magnets where the typical dose-rate during repetitive injection of 10^{12} protons is about 140 rad $\cdot$ h $^{-1}$ at 11 cm from the beam axis.

The radiation field in the ISR consists of high-energy primary protons (~ 20 GeV/c) and a broad spectrum of secondary protons, neutrons, mesons, etc. Dosimetry at the ISR is performed by the phosphate glass radiophotoluminescent (RPL) system, which has been extensively documented^{4,5)}.

The fluence of strongly interacting particles is also measured at the ISR with threshold activation detectors⁶⁾. Comparison of these fluence measurements with dose measurements by RPL-glass dosimeters allows experimental fluence-to-dose conversion factors to be obtained. Table 1 gives some conventionally used activation detectors and conversion factors⁷⁾ for the fast neutron and high-energy component of the radiation field. Adopting the reaction $^{32}\text{S}(n,p)^{32}\text{P}$ for neutrons of 3-25 MeV and $^{27}\text{Al}(\text{spall.})^{22}\text{Na}$ for high-energy particles (HEP) above 25 MeV, a fluence-to-RPL-dose conversion factor⁷⁾ is obtained:

$$\begin{array}{lcl} \text{RPL-dose} & n, 3 > E < 25 \text{ MeV} & = 6 \times 10^{-8} \text{ rad} \times \phi \text{ } ^{32}\text{P} + 5 \times 10^{-8} \text{ rad} \times \phi \text{ } ^{22}\text{Na} . \\ & \text{HEP, } E > 25 \text{ MeV} & \end{array}$$

This conversion factor also takes into account the components of the radiation field which do not give rise to any response in the activation detectors. Its application is, however, restricted to a radiation field similar to the one present near our accelerators and to fluence calculations with cross-sections given in Table 1.

2.3 Gamma irradiator

The ^{60}Co isotope, with a half-life of 5.3 y, is the source of two γ -rays with energies of 1.17 and 1.33 MeV, respectively. A point source of 1 Ci of ^{60}Co gives an exposure dose at 1 m distance of ~ 1.2 rad $\cdot$ h $^{-1}$. Dosimetry in the γ -cell is carried out by ionization chambers and chemical dosimeters.

The characteristics of the radiation sources utilized in the initial and present investigations are given in Table 2.

3. COMPARISON OF RADIATION DAMAGE RESULTING FROM THE DIFFERENT RADIATION SOURCES

3.1 Experimental procedures

The resistors, capacitors, Si diodes, Si transistors, TTL integrated circuits, and operational amplifiers selected and the parameters measured are listed in Table 3. These parameters were measured both before and after irradiation in order to assess the radiation-induced damage. For each radiation dose in the three radiation sources, as shown in Table 4, a sample size of five components was taken. Test circuits used for parameter evaluation are depicted in Figs. 1 to 10, whilst details of the statistical analysis of the pre- and post-irradiation data are given in Appendix 1, and the pre-irradiation parameter spread values in Appendix 2.

3.2 Experimental results and their analysis

The differences in radiation fields and dosimetry methods make the intercomparison of damage effects from the three sources very difficult, this being particularly true if the doses are measured in rad (1 rad = energy absorption of $100 \text{ erg} \cdot \text{g}^{-1}$). This unit has been proved to be a valid parameter for measurement and intercomparison of radiation damage studies in organic materials, where an equal amount of energy corresponds to an equal amount of damage. This is not the case in semiconductor (generally in inorganic) materials. However, these difficulties were partially overcome by adopting the following two methods of comparison.

3.2.1 Reactor and accelerator

From the RPL dosimeter readings we can estimate the fast neutron and high-energy particle fluences by assuming that both share about 50% in the dose contribution and by making use of the empirical conversion factors given in Section 2.2. Thus the accelerator and reactor damage comparisons are made on the basis of fast neutron fluence.

These are given in Table 5, which shows that the damage effects obtained near the accelerator are higher than those from the reactor. This is to be expected, since the neutron energy spectrum is different in the accelerator and, in addition, also other particles apart from fast neutrons contribute to the damage.

In Table 5 we also make a comparison between the damage obtained from a high dose-rate area and that from a low dose-rate area, which indicates that the accelerator dose-rate cannot be ignored. Devices on the ISR beam dump (high dose-rate) suffered damage up to five times more severe than the damage suffered by those irradiated on the ISR magnet coil covers (low dose-rate).

The results obtained from the low dose-rate irradiations at the accelerator agree within a factor of two with the reactor damage effects. This gives us confidence in the component lifetime predictions, which are made on the basis of reactor irradiations.

3.2.2 ^{60}Co γ -source and accelerator

The comparison is made between the damage effects based on RPL-rads near the accelerator with CH-rads from the ^{60}Co γ -source. This is justified since the RPL dosimeters have been calibrated in ^{60}Co γ -sources. The results of these comparisons are given in the form

of graphs in Figs. 11 to 18 for components where the parameter changes fall outside the manufacturer's tolerance limits. These results show that pure electromagnetic radiation is much less efficient in producing damage than are energetic particles. Factors of up to 100 or more are found in damage when comparing doses of 5×10^5 RPL rad on the beam dump and magnet coil covers, respectively, to 5×10^5 rad of γ -radiation.

Finally, in Tables 6a and 6b we summarize in a simplified way the effects of damage resulting from component irradiations in the reactor, high dose-rate accelerator position, and in the γ -cell.

4. CONCLUSIONS

One has to be extremely careful when interpreting radiation damage results on electronic components if the environment in which they were tested is different from the one in which they are to be used. Experience to date allows the following electronic quality factors to be obtained for the damage effects on electronic components:

- Nuclear reactor irradiation : 1
- Low dose-rate accelerator : up to 2
- High dose-rate accelerator : up to 5
- Pure γ -source : 10^{-2} or less

We must, however, emphasize that the above values are only valid for irradiation conditions and components similar to the ones used in our studies. It is therefore prudent to take these factors only as a guide. For the more complex devices, of which an operational amplifier is typical, it is desirable to perform initial comparative damage tests in a reactor and an accelerator before proceeding with more detailed tests based solely on reactor irradiations.

Owing to the low damage effect of pure γ -rays in electronic devices, it is not recommended to use this source for static radiation damage tests on electronic components, except in the case where they have finally to operate in a pure γ -field.

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Table 1

Activation detectors for fluence measurements
and experimental fluence-to-dose conversion factors
[From the paper by Routti et al.⁷⁾]

Threshold reaction	Reaction cross-section (mb)	Half-life of produced isotope	Principal sensitivity	RPL-glass conversion factor (rad·cm ²)
³² S(n,p) ³² P	300	14 d	3-25 MeV neutrons	6 × 10 ⁻⁸
²⁷ Al(n,α) ²⁴ Na	120	15 h	6-25 MeV neutrons	6 × 10 ⁻⁸
¹² C(n,2n) ¹¹ C	22	20.3 min	HEP above ~ 20 MeV	3 × 10 ⁻⁸
¹² C(p,np) ¹¹ C				
²⁷ Al(spall.) ²² Na	20	2.6 y	HEP above ~ 25 MeV	5 × 10 ⁻⁸

Table 2

Characteristics of radiation sources employed

Radiation source	Radiation type	Field intensity	Radiation detectors
Radiation position SNIF in 7 MW ASTRA pool reactor, Vienna	Fast neutrons E > 1 MeV Thermal neutrons γ-rays	3-6 × 10 ⁹ n·cm ⁻² ·sec ⁻¹ 5-40 × 10 ⁸ n·cm ⁻² ·sec ⁻¹ 1-1.5 × 10 ⁴ rad·h ⁻¹	Activation detectors. Ionization chamber.
CERN ISR beam dump (high dose-rate area). Primary energy ~ 20 GeV.	Mixed radiation field of protons, neutrons, mesons, γ-rays, etc., in MeV to GeV energy region	3.6 rad/10 ¹² protons at 50 cm, dumping time = 3.4 μsec	RPL-glass. Activation detectors.
CERN ISR ring magnets (low dose- rate). Primary energy ~ 20 GeV.	Mixed radiation field of protons, neutrons, mesons, γ-rays, etc., in MeV to GeV energy region	10 ⁴ to 1 × 10 ⁵ rad per operational year at 10-30 cm from the vacuum tube	RPL-glass. Activation detectors.
⁶⁰ Co γ-source	γ-rays: 1.17 MeV 1.33 MeV	30,000 Ci (max. 10 ⁶ rad·h ⁻¹)	Chemical dosimeters. Ionization chamber.

Table 3

Components tested

Designation		Value/type	Parameter	Fig.
Resistor	carbon	1 K, 5%	R	-
"	metal film	1 K, 1%	R	-
Capacitor	mica	22 pF, 300 V	C	-
"	Al electrolytic	220 μ F, 10 V	C	-
Diode	Si, small signal	BAY 72	$V_F I_R$	1, 2
"	Si, " "	1N 914 A	$V_F I_R$	1, 2
"	Si, rectifier	10 D 6	$V_F I_R$	1, 2
Transistor	Si, NPN	2N 918	β	3
"	Si, N-channel	2N 3819	Y_{fs}, I_{DSS}	5, 4
Integrated	TTL gate	SN 7400 N	$I_{out(0)}$	10
"	" monostable	SN 74121 N	Δt	7
"	" bistable	SN 7473 N	Toggle frequency	8
"	" counter	SN 7493 N	" "	9
"	op. amplifier	μ A 741 C	$e_{os}, i_{os}^+, i_{os}^-$ $i_{os}^- - i_{os}^+$	6

Table 4

Exposure doses for the three radiation sources

ISR - Beam dump		ISR - Magnet		^{60}Co γ -source rad
RPL rad	$n \cdot \text{cm}^{-2}$ ($E > 3 \text{ MeV}$)	RPL rad	$n \cdot \text{cm}^{-2}$ ($E > 3 \text{ MeV}$)	
5×10^4	4.2×10^{11}	2.5×10^4	2.1×10^{11}	5×10^4
1×10^5	8.3×10^{11}	1×10^5	8.3×10^{11}	1×10^5
5×10^5	4.2×10^{12}	5×10^5	4.2×10^{12}	1×10^6
				5×10^6
				1×10^7

Table 5

Comparison of damage effects obtained in a nuclear reactor
and near a high-energy accelerator

Devices and parameters	Radiation-induced % change Δ from 100% initial value			
	A SNIF $\sim 1.25 \times 10^{14}$ rad(CH) 4.2×10^{12} n·cm ⁻² (E > 1 MeV)	B ISR dump 5×10^5 RPL rad $\sim 4.2 \times 10^{12}$ n·cm ⁻² (E > 3 MeV)	C ISR magnet 5×10^5 RPL rad $\sim 4.2 \times 10^{12}$ n·cm ⁻² (E > 3 MeV)	
Diode 10 D 6, V_F	+100	+450	+213	4.5
" " , I_R	-	+12441	+3071	-
Transistor 2N 918, β	-19	-28	-26.4	1.5
" 2N 3819, Y_{fs}	-9	-45.8	-5.2	5.1
" " I_{DSS}	-	-16.81	-4.15	-
Gate SN 7400 N, $I_{out}^{(0)}$	-15	-37.31	-25.8	2.5
Op. amp. μA 741 C, e_{os}	+1000	+12292	+21387	12.3
" " i_{os}^+	+1300	+2063	+2454	1.6
				2.1
				4.0
				1.1
				5.0
				4.0
				1.5
				0.6
				0.8

Table 6a

Summary of damage suffered by discrete electronic components
in different radiation sources and different dose ranges

	Nuclear reactor	Proton accelerator (beam dump)	^{60}Co γ -source
	Range: $10^{12} - 10^{15} \text{ n}\cdot\text{cm}^{-2}$ ($E > 1 \text{ MeV}$) Dose equivalent: $3 \times 10^3 - 3 \times 10^6 \text{ rad (CH)}$	Range: $2.5 \times 10^4 - 5 \times 10^5 \text{ rad (RPL)}$ Fast neutron equivalent: $2 \times 10^{11} - 4 \times 10^{12} \text{ n}\cdot\text{cm}^{-2}$ ($E > 3 \text{ MeV}$)	Range: $5 \times 10^4 - 10^7 \text{ rad}$
Resistors	Variation in resistance for carbon and metal film devices within manufacturers tolerances	As for reactor	No damage effects
Capacitors	Mica devices remained stable. 20% reduction in capacitance for Al electrolytics.	No damage effects	No damage effects
Si diodes: Rectifier	Increase in forward voltage by a factor of 7 at $10^{14} \text{ n}\cdot\text{cm}^{-2}$	Increases by factors of 5 and 125 in forward voltage and reverse current, respectively	No change in forward voltage, 75% increase in reverse current
Si diodes: Signal	Rapid increases in forward voltage and reverse current at $10^{14} \text{ n}\cdot\text{cm}^{-2}$	No change in forward voltage, 6% increase in reverse current	No damage effects
Si transistors: NPN 2N 918	50% reduction in β after $2 \times 10^{13} \text{ n}\cdot\text{cm}^{-2}$ and 85% after $10^{14} \text{ n}\cdot\text{cm}^{-2}$	40% reduction in β at $4 \times 10^{12} \text{ n}\cdot\text{cm}^{-2}$	47% reduction in β at 10^7 rad
JFET 2N 3819	Reductions of 50% and 30% in Y_{fs} and I_{DSS} , respectively, for $2 \times 10^{13} \text{ n}\cdot\text{cm}^{-2}$	Reductions of 46% and 34% in Y_{fs} and I_{DSS} for $4 \times 10^{12} \text{ n}\cdot\text{cm}^{-2}$	8% reduction in Y_{fs} , no change in I_{DSS} at 10^7 rad

Table 6b
Summary of damage suffered by integrated circuits in different radiation sources
and different dose ranges

	Nuclear reactor	Proton accelerator	^{60}Co γ -source
TTL integrated circuits	Range: $10^{12} - 10^{15} \text{ n}\cdot\text{cm}^{-2}$ ($E > 1 \text{ MeV}$). Dose equivalent: $3 \times 10^3 - 3 \times 10^6 \text{ rad (CH)}$.	Range: $2.5 \times 10^4 - 5 \times 10^5 \text{ rad (RPL)}$. Fast neutron equivalent: $2 \times 10^{11} - 4 \times 10^{12} \text{ n}\cdot\text{cm}^{-2}$ ($E > 3 \text{ MeV}$).	Range: $5 \times 10^4 - 10^7 \text{ rad}$
	Fan-out factor of NAND gate SN 7400 N degraded by a factor of 3 at $10^{14} \text{ n}\cdot\text{cm}^{-2}$ Monostable SN 74121 N stable up to $10^{13} \text{ n}\cdot\text{cm}^{-2}$ Toggle frequencies of bi- stables SN 7473 N and 4-bit counters SN 7493 N fall to 70% of their initial values for $10^{14} \text{ n}\cdot\text{cm}^{-2}$	Output sink current of NAND gate reduced by 40% for $4 \times 10^{12} \text{ n}\cdot\text{cm}^{-2}$ but remained above the minimum requirement of 16 mA Monostables, bistables, and 4-bit counters remained un- damaged	No damage effects " " " " " "
	Function normally up to $10^{12} \text{ n}\cdot\text{cm}^{-2}$ and fail com- pletely at fluences of $10^{14} \text{ n}\cdot\text{cm}^{-2}$	Severe damage at $4 \times 10^{12} \text{ n}\cdot\text{cm}^{-2}$. Increase of e_{os} by a factor of 125. Increase of $\frac{i_{os} + \bar{i}_{os}}{2}$ by a factor of 27.	For 10^7 rad : Increase of e_{os} by a factor of 3. Increase of $\frac{i_{os} + \bar{i}_{os}}{2}$ by a factor of 23.
Op. amplifier $\mu\text{A} 741 \text{ C}$

Fig. 1 Forward voltage:
Signal diode BAY 72; signal diode
1N 914 A; rectifier diode 10 D 6

Fig. 2 Reverse leakage current:
Signal diode BAY 72; signal diode
1N 914 A; rectifier diode 10 D 6

Fig. 3 Transistor 2N 918 (NPN)
($\beta = \Delta I_C / 50 \mu A$, measured with
B & K 501 A curve tracer)

Fig. 4 JFET 2N 3819 (N-channel) (I_{DSS}
measured with B & K 501 A curve
tracer)

Fig. 5 JFET 2N 3819 (N-channel) (Y_{fs} meas-
ured with B & K 501 A curve tracer)

Fig. 6 Operational amplifier μA 741 C

Fig. 7 Monostable SN 74121 N

Fig. 8 Bistable SN 7473 N

Fig. 9 4-bit counter SN 7493 N

Fig. 10 NAND gate SN 7400 N

Fig. 12 Diode 10 D 6: I_R at 10 V

Fig. 14 JFET transistor 2N 3819 (N-channel): Y_{fs}

Fig. 11 Diode 10 D 6: V_F at 500 mA

Fig. 13 Transistor 2N 918 (NPN): β

Fig. 16 Positive NAND gate SN 7400 N: $I_{out}(0)$

Fig. 18 Operational amplifier μA 741 C: i_{os}^+

Fig. 15 JFET transistor 2N 3819 (N-channel): I_{DSS}

Fig. 17 Operational amplifier μA 741 C: e_{os}

APPENDIX 1

DATA ANALYSIS

The electrical characteristics of all components were measured before and after irradiation to determine any radiation-induced changes.

Let Y = pre-irradiation parameter value

Z = post-irradiation parameter value

$A = (Y-Z)$, the radiation-induced change

M = number of components per radiation dose

N = number of radiation doses

$n = M \cdot N$, the total number of components irradiated in a given radiation field

$\bar{X}$ = mean of pre-irradiation parameter values, for all components of a given type irradiated in a given radiation field

$\bar{x}$ = mean of the differences of pre- and post-irradiation values, for all components of a given type irradiated to a given dose.

ZERO DOSE MEASUREMENTS

Sample mean

$$\bar{X} = \frac{\sum_{i=1}^n Y_i}{n} .$$

Standard deviation of the population σ_0 estimated from

$$\sigma_0^2 = \frac{n}{n-1} \cdot S_0^2$$

where S_0^2 is the sample variance.

The mean value was set to 100% of the initial value with the error bars given by 100% $(\pm 100 \cdot \sigma_0) / \bar{X}$.

POST-IRRADIATION MEASUREMENTS

The mean of the differences of pre- and post-irradiation values for all components irradiated to a given dose was expressed as

$$\bar{x} = \frac{\sum_{i=1}^M A_i}{M} ,$$

and the standard deviation of the set of differences σ_D expressed as

$$\sigma_D^2 = \frac{M}{M-1} \cdot S_D^2 ,$$

where S_D^2 is the sample variance.

In order to relate the radiation-induced percentage (P) changes and their associated errors to the zero dose 100% value, the mean value of an irradiated sample of components was expressed as

$$P = 100 - \left(\frac{\bar{x}}{\bar{X}} \right) \cdot 100\%$$

with the errors given by

$$P \pm \left(\frac{\sigma_D}{\bar{X}} \right) \cdot 100\%$$

APPENDIX 2

Spread of pre-irradiation parameter values from the initial
100% value, for Figs. 11 to 18

Device and parameters	Zero dose error $\pm \frac{100 \sigma_0}{\bar{X}}$		
	ISR beam dump	ISR magnet	^{60}Co γ -source
Diode 10 D 6, V_F	0.7	0.6	1.1
" , I_R	19.8	5.5	29.8
Transistor 2N 918, β	19.2	21.0	18.0
" 2N 3819, Y_{fs}	11.8	11.1	6.6
" " , I_{DSS}	18.5	17.7	16.0
Gate SN 7400 N, $I_{out}^{(0)}$	1.6	1.8	1.8
Op. amp. μA 741 C, e_{os}	741.0	645.0	129.0
" " " , i_{os}^+	77.0	55.0	177.0

APPENDIX 3

ANALYSIS OF OPERATIONAL AMPLIFIER CHARACTERISTICS

The amplifier output voltage is related to e_{os} , i_{os}^- , and i_{os}^+ by:

$$V_o = - \frac{R_f}{R_i} \left(e_{os} + i_{os}^- R_s - i_{os}^+ R_s \right) \quad (A3.1)$$

e_{os} , i_{os}^- , i_{os}^+ and $i_{os}^- - i_{os}^+$ are calculated, respectively, from equations

$$V_o = - \frac{R_f}{R_i} e_{os} \quad (A3.2)$$

$$V_o = - \frac{R_f}{R_i} \left(e_{os} + i_{os}^- R_s \right) \quad (A3.3)$$

$$V_o = - \frac{R_f}{R_i} \left(e_{os} - i_{os}^+ R_s \right) \quad (A3.4)$$

$$V_o = - \frac{R_f}{R_i} \left[e_{os} + R_s \left(i_{os}^+ - i_{os}^- \right) \right] \quad (A3.5)$$