OPERATIONAL AMPLIFIER TYPE 741: CHARACTERIZATION AND RADIATION EFFECTS

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ABSTRACT

    Exposing the "741" Operational-Amplifiers to gamma-rays with different doses up to 3.5×10^6 rads was shown to seriously affect their electrical characteristics. Consequently, the devices lose their main features as a results of major defects that cause deviation in the basic behaviours of the system. The differential-mode gain and input resistance values were dropped from 185 V/mV to 70 V/mV and from 9×10^6 ohm to 1.5×10^6 ohm respectively. Also, the offset voltage adjustment range was decreased from the band (—12 to +14) mV down to (—1.50 to + 2.0) mV. The common-mode rejection ratio which had, as well, an initial vaue of 100 dB before irradiation reaches a value of 2.0 dB after exposure to 3.5×10^6 rads. On the other hand, the power supply rejection ratio and input offset voltage and current were shown to have a pronounced increase as a result of gamme exposure. Their values reach 430 μV/V, 75 mV and 50 nA although they have initial values of 20 μV/V, 5.0 mV and 1.0 nA respectively.

1. INTRODUCTION

    The term "Operational–Amplifier" was originally intended to denote an amplifier circuit that performed various mathematical operations such as integration, differentiation, summation and subtraction. The application of the operational amplifier, however, has been so vastly extended that today this term suggests a device that finds the widest use in such applications as signal amplification and wawe–shaping, servo and process control, analog instrumentation and system design, impedance transformation and many other routine functions. The versatile circuit may also be used in many nonlinear applications such as voltage comparators, analog–to–digital and digital–to– analog converters, logarithmic amplifiers and nonlinear function generators.

1.1. "741" Operational Amplifiers

    The "741" type of integrated circuit "OP–AMP" has achieved universal popularity among users. A simplified schematic of the "741"

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OP–AMP is shown in Fig. 1 [1]. Essentially, the circuit consists of a
differential input stage (Q1 and Q2) followed by a high gain driver stage
(Q16), with a complementary–symmetry output stage (Q13 and Q17).
Diodes (Da) and (Db) represent the circuit used to appropriately bias
the output stage. The combination of (Dc) and (Q7) represents the
active–device collector loads for transistors (Q1) and (Q2). Capacitor
(C1) is 30 pF, used to provide sufficient phase compensation for stable
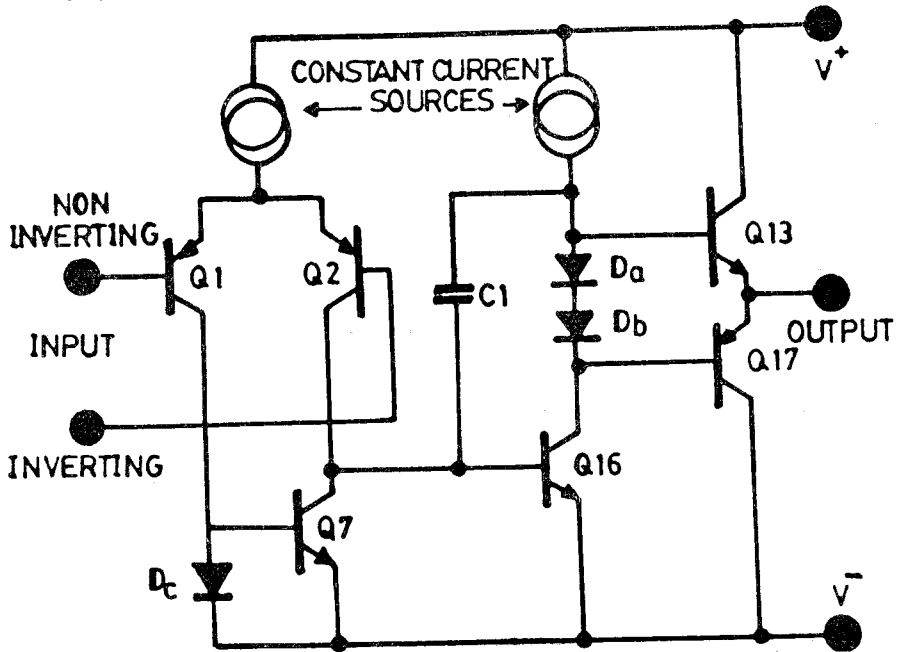unity gain closed–loop operation.

Fig. 1: Simpfilied Schematic of a "741" Integrated Circuit Amplifier.

The detailed schematic diagram for the "741" OP–AMP is shown
in Fig. 2. Low input bias currents are achieved by connection of tran-
sistor pairs (Q1, Q2) and (Q3, Q4) as shown. Transistors (Q6 and Q7)
are used as load resistors for the input stage. The operating collector
current for the input stage is established by transistor (Q9) and resistor
(R4). Darlington–connected transistors (Q15) and (Q16) provide the
stage gain, with their operating current being determined by resistor
(R5) driving the current–mirror formed by diode (D2) and transistor
(Q10). The output-stage transistors (Q13) and (Q14) are connected in a
conventional complementary symmetry arrangement, with transistor

(Q12) in the output short circuit protection network. Transistor (Q11) and associated network are used to bias the output stage for class "AB" operation.
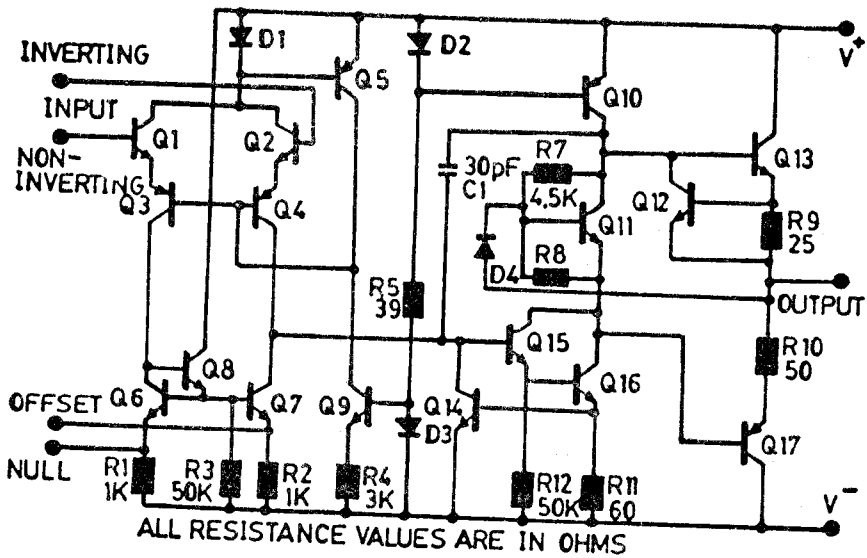

Fig. 2: Schematic Diagram of the "741" Internally Compensated Integrated-Circuit Operational Amplifier.

1.2. Operational Amplifier Architectures

The OP–AMP is a two–input voltage controlled voltage source whose output voltage is proportional to the difference between the two input voltages. Table (1) summarizes the performance of ideal and practical OP–AMP "741" [2–4].

Table 1. Characteristics of "741" OP–AMP

Property	Ideal	Typical
Open - loop Gain	Infinite	Very ihgh ($>>$ 10^4)
Common-Mode Rejection Ratio	Infinite	High ($>>$ 70 dB)
Input Resistance	Infinite	High ($>>$ 10 M. ohm)
Output Resistance	Zero	Low ($<<$ 500 ohm)
Input Current	Zero	Low ($<<$ 0.50 nA)
Offset Voltage	Zero	Low ($<<$ 10 mV and
and Current		($<<$ 0.20 nA)

Since the basic OP–AMP stages are feedback amplifiers, high open–loop gain and hence large return ratio is desirable to ensure exc-

lusive dependence of the closed loop gain on the feedback circuit. A high Common–Mode Rejection Ratio (CMRR) is needed to ensure that the output signal is proportional to the difference between the voltage levels at the two inputs. To approximate the characteristics of an ideal voltage amplifier, the OP–AMP must possess high–input and low–output resistance. The current in each of the two inputs is ideally zero. The offset voltage and current are measures of the degree of mismatch in the circuit, and clearly these should be small.

At present, there is considerable interest among the military services in microelectronic circuits and their potential use in missile and space electronic systems because of the obvious advantages of reliability, light–weight, small volume and low power capability offered by such circuits. Because of this interest it is important to determine the reliability of these circuits in the nuclear radiation environments for which the systems were designed.

2. EXPERIMENTAL PROCEDURE

The investigated operational amplifiers, μA 741C, are high performance monolithic OP–AMP's constructed using the Fairchild planar epitaxial process [3] and have the manufacturing date of June 1987. Their electrical characteristics are identical to MIL–M–385101 [3].

The characteristics of "741" OP–AMP's were examined using a universal 178 linear IC test fixture which is a plug–in device for use with 577–D1 "Tektronics" curve tracer systems [4]. The 577–178 combination with the (D1) display unit module is designed to measure the parameters of OP–AMP's. In conjunction, a standard OP–AMP card which is designed to test devices that require two power supplies, have two (differential) high impedance inputs, and have a single output is used. The basic measurements that have been carried out using this card are:

(1) Input offset voltage and current.

(2) Input bias current.

(3) Common–mode rejection ratio (CMRR).

(4) Power–supply rejection ratio (PSRR).

(5) Common–mode input resistance (CMIR).

(6) Large–signal voltage gain.

(7) Voltage swing.

3. RESULTS AND DISCUSSIONS

Measurements of permanent damage in silicon integrated "741" Operational Amplifier systems caused by gamma irradiation were performed. Irradiation of the passive devices up to a total integated absorbed dose of 3.5×10^6 rads, was obtained applying the GC 4000A, Cobalt–60 irradiation facility with dose rate of 140 rads / sec (at the time of irradiation). All samples were irradiated at room temperature level while their terminals were left free of bias. The change in the OP–AMP parameters was measured direct after each irradiation step. An oscillogram of the studied electrical parameters for "741" OP–AMP are shown in Fif. 3 (a–c). Degradation is manifested as an increase in some parameters namely: input bias current; power supply rejection ratio; input offset voltage and current and output voltage swing. On the other hand, some other parameters were shown suffering a pronounced decrease; common–mode rejection ratio; gain; common mode input resistance and offset voltage adjustment range. The devices fai-
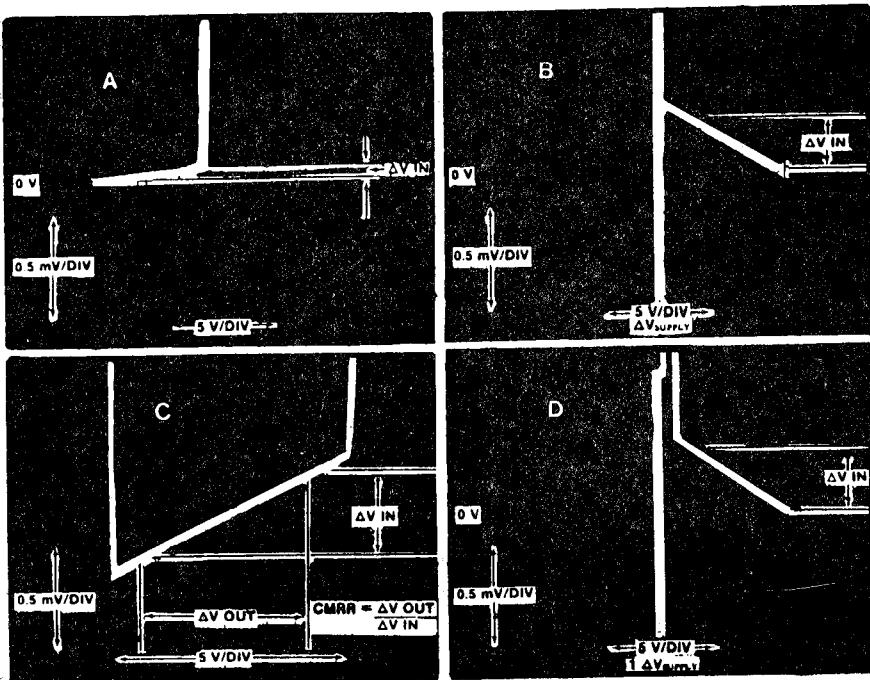

Fig. 3a: Oscillograms of the Electrical Parameters of μA741C Op. Amp; (A) - Supply Rejection Ratio; (B) +Supply Rejection Ratio; (C) Common Mode Rejection Ratio; And (D) ±Supply Rejection Ratio.
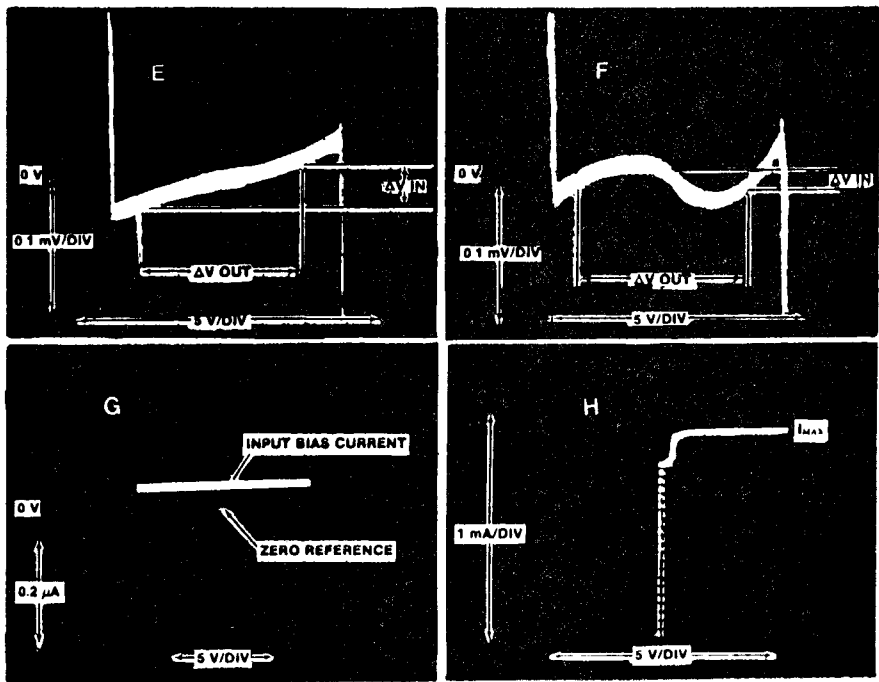
Fig. 3b: Oscillograms of the Electrical Parameter of µA741C Op. Amp; (E) Output Voltage
Sung; (F) Gain Curve; (G) Input Bias Current; And (H) Supply Current.

lure can be explained from a knowledge of damage theory for transis-
tors [5–7], diodes [8–10] and integrated circuits [11–13, 15].

When high energy radiation is incident on a semiconductor device,
energy is deposited in the semiconductor via two mechanisms, atomic
collisions and electronic ionization. The relative importance of these
two mechanisms in a semiconductor structure depends both on the
type of radiation and the nature of the device. For electron, proton,
and γ–ray environments, most of the deposited energy goes into ioni-
zation processes. For fast–neutron environments, on the other hand,
a large fraction of the deposited energy results directly in atomic disp-
lacement damage from collisions.

A theory for permanent damage in monolithic integrated circuits
is derived on the basis of existing theory of the degradation of current
gain in transistors [11]. The degradation of transistor parameters during
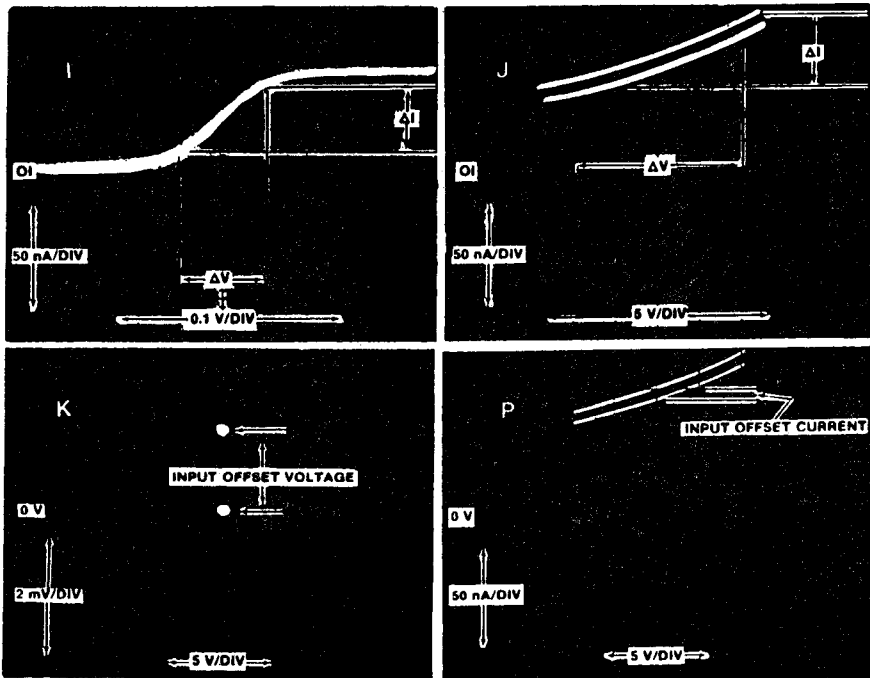irradiation is due to both structural damage in the crystall lattice and

Fig. 3c: Oscillograms of the Electrical Parameters of μA741C Op. Amp; (I) Input Resistance; (J) Common Mode Input Resistance; (K) Input Offset Voltage; And (P) Input Offset Current.

to changes in the surface properties of the crystals. The main para meters of transistors and, in particular the reverse collector current, are very sensitive to the surgace state. A change in the recombination properties of surface layers, particularly in the immediate vicinity of the emitter p–n junction, affects first the base current transport coefficient. The production of inversion layers and of surface channels in the vicinity of p–n junctions leads to a considerable increase in the reverse current across junctions.

Surface processes excited by ionizing radiation occur even at small radiation doses which, usually, are insufficient to produce appreciable bulk damage. Simple bulk–damage theory predicts a linear change in $1/h_{FE}$ (where h_{FE} is the forward current gain factor) with fluence. On the other hand, a transistor is considered to have suffered surface damage when the change in $1/h_{FE}$ does not depend linearly on fluence. The important damage mechanism in transistors is minority carrier degradation, which results in a degradation of the current gain according to [5]:

$$1 / h_{FE1} = 1 / h_{FEO} + \tau_b \, K' \, \varphi \tag{1}$$

where:

h_{FEO}, h_{FEc} : forward current gain before and after irradiation,

φ : radiation fluence,

τ_b : minority carrier lifetime at base region

K' : composite damage constant that includes the effect of recombination in the emitter base junction as well as in the base–region. Typical values for K' for the various radiation are shown [14].

In the monolithic integrated circuit, the construction of the circuit components is achieved by a configuration of p and n regions on a single silicon chip. Isolation between components and from the silicon substrate is accomplished by reverse biasing the p–n junction boundaries. The overriding effect of ionizing radiation in these circuits is the generation of photovoltaic primary photocurrents in the many p–n junctions. Since the magnitude of the primary photocurrent is proportional to the area of the junction involved, the major sources of these currents are the large area isolation junctions between the circuit components and the substrate [11]. The junction leakage is assumed to result from the carrier generation in the depletion layer. This rate is increased by defects in the depletion region created by nuclear radiation displacement damage. The collector–base junction leakage is normally given as [9]:

$$I_{CBO} = q \text{ (Junction volume)} . \text{(Generation rate)}$$
$$= q \, (A_c . \, X_c) . \, (n_i . \, R_i) \tag{2}$$

where·

q : electronic charge,

A_c : collector area,

n_i : intrinsic carrier concentration

X_c : width of depletion layer,

R_i : intrinsic recombination rate.

The effect of nuclear radiation will appear in the form of increase in the recombination rate, thus:

$$I_{CBO} = q \, [A_c . \, X_c] . \, [n_i \, (R_i + \triangle \, R_i)]$$
$$= q \, [A_c . \, X_c] . \, [n_i \, (R_i + K' \, \Phi)] \tag{3}$$

Finally, most IC diffused resistors are made of relatively low resistivity material which show conductivity modulation. Besides, the surface recombination velocity condition at the boundaries of the resistor structure could be included [15].

3.1. Differential Stage

Three important characteristics of the differential input stage (Fig. 4) are the common–mode rejection ratio, the input differential resistance and the differential–mode gain.
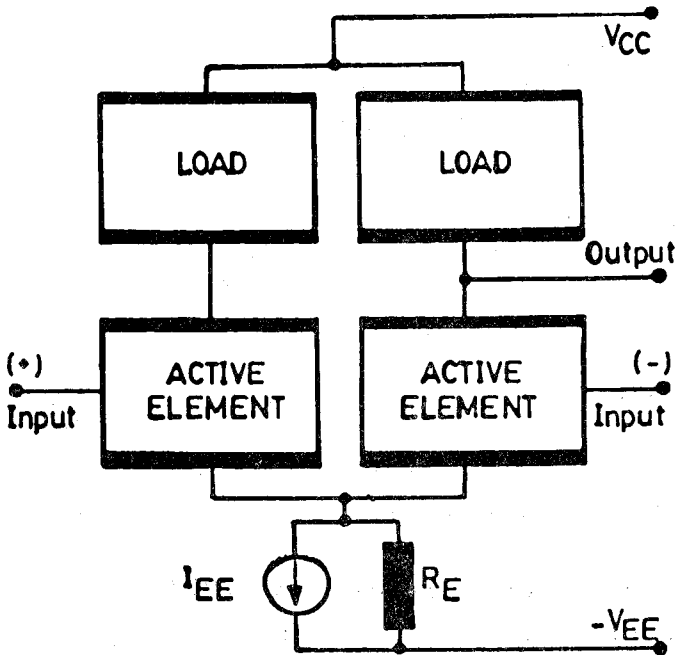

Fig. 4: Basic Topology of a Operational Amplifier.

3.1.1. Common-Mode Rejection Ratio (CMRR)

CMRR is the change in common–mode voltage relative to the change in differential input voltage while the output voltage is maintained at zero level. With high CMRR values, common–mode signals, often containing dc–components, have only a small effect on the amplifier–output. The CMRR is hence given as:

$$\text{CMRR} = 1 + 2 \ g_m \ R_E = 2 \ g_m \ R_E \tag{4}$$

where g_m and R_E are the transconductance and emitter resistance respectively.

Inspection of Equ. 4 clearly indicates that R_E and g_m must be made large if a high CMRR is to be achieved. The curve of Fig. 5 depicts a fall in CMRR from its initial value (100 dB) down to O dB as a result of increasing gamma dose up to around 2.8×10^6 rads.
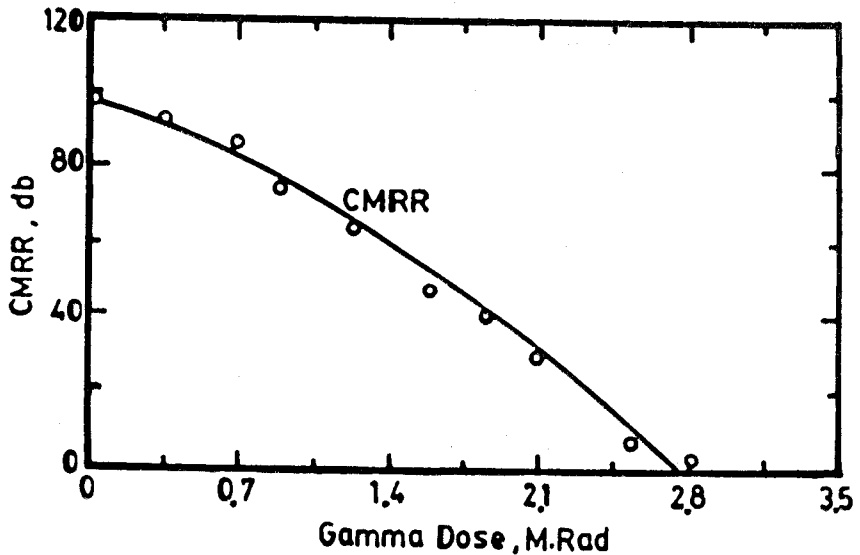

Fig. 5: Gamma Radiation Effects on Common Mode Rejection Ratio.

3.1.2. Common Mode Input Resistance (CMIR)

The differential-input resistance (R_{id}) of the differential stage must be large for an ideal voltage–controlled voltage source, and is given by:

$$R_{id} = 2\,\beta_0 /\, g_m = 2\,\beta_0\, V_T /\, I_C \tag{5}$$

where:

I_C : collector current

V_T : volt equivalent of temperature

In Equ. 5, we observe that to increase R_{id}, high β_0 transistor must be used in the input differential pair. Fig. 6 shows the effect of gamma-exposure in the CMIR in the radiation band up to 3.5×10^6 rads. The differential input stage loses one of its important characteristics as a very high input impedance, and the CMIR was shown to drop from

9×10^6 ohms down to 1.5×10^6 ohms as a result of gamma exposure up to 3 5 $\times 10^6$ rads.
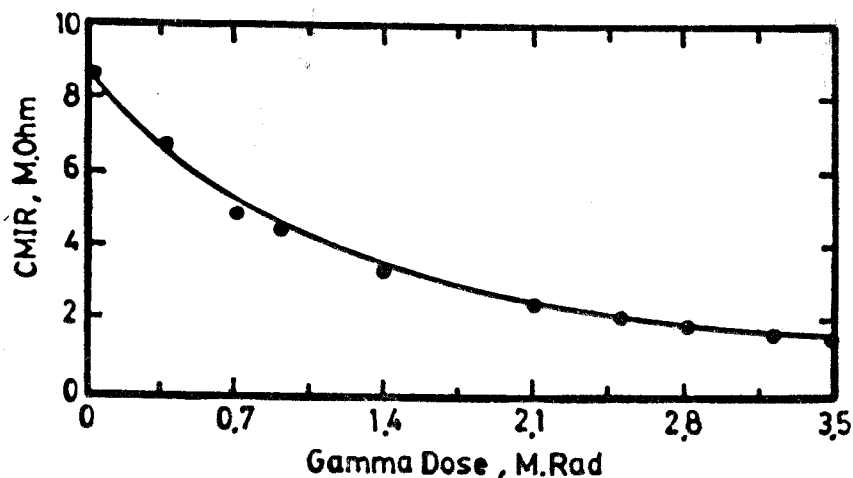

Fig. 6: Common Mode Input Resistance Versus Gamma Dose.

3.1.3. Differential-Mode Gain (ADM)

Since the input stage of the OP–AMP is one of the two gain stages, it is desirable to make the differential–mode gain (ADM) large. Consequently, active loads are employed in these stages. From Equ. 5, we obtain;

$$| ADM | = \beta_0 R_L / r_\pi \tag{6}$$

where:

R_L : parallel combination of the active–load resistance the output resistaace (r_0) of the active element.

r_π : incremental resistance of the emitter–base diode

The gain is shown to be a sensitive function of gamma exposure (Fig. 7), where it loses more than 60 % of its initial value after exposing the OP–AMP to radiation up to 3.5×10^6 rads.

3.2. Offset Voltage and Current

Ideal OP – AMP is perfectly balanced, that is Vo = O when "Vil" = "Vi2" = O. A real OP–MP exhibits an imbalance caused by a mismatch of the input transistors. This mismatch results in unequal bias currents in the input terminals and unequal base emitter voltages. Often, an input offset voltage applied between the two input terminals
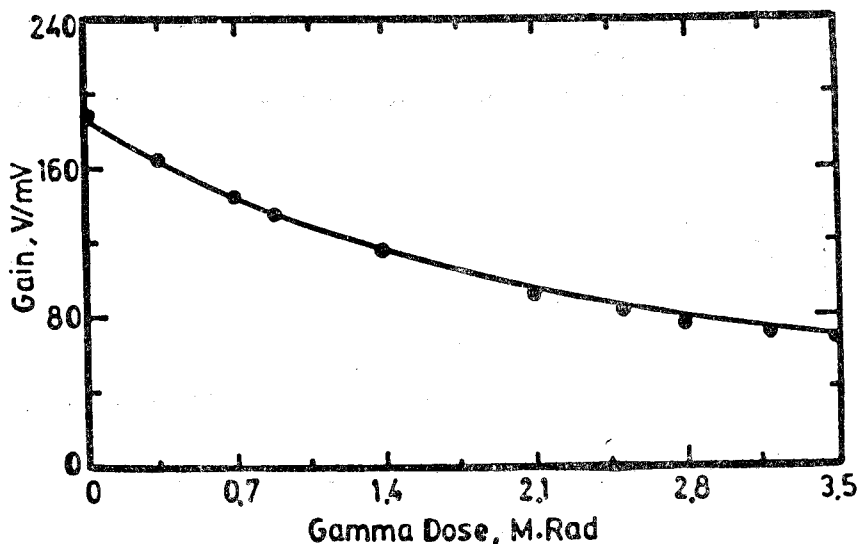
Fig. 7: Differential Mode Gain Decay Due to the Gamma Irradiation.

is required to balance the amplifier. The gamma–rays cause severe distrubance in the input transistors leading to an increase in the mis-match of their input characteristics. As a result, both the input offset voltage and curren t values of the differential amplifier "741" are shown to increase pronouncely (Fig. 8). Their values reach 75 mV and 50 nA although they have initial values of 5.0 mV and 1.0 nA respectively. On the other hand, and as a result of the above disturbance, the OP–AMP suffers a serious damage due to the resultant decrease on its of-fset voltage adjustement range. The offset voltage adjustment range was shown (Fig. 9) to decrease from the band (–12 to +14) mV down to (–1.5 to +2.0) mV.

3.3. Power Supply Rejection Ratio (PSRR)

Power Supply Rejection Ratio (PSRR) is a measure of the ability of the OP–AMP to ignore changes in the power supply voltages and is given by:

$$\text{PSRR} = \left. \frac{\triangle \text{ input voltage}}{\triangle \text{ power supply voltage}} \right| \qquad (7)$$

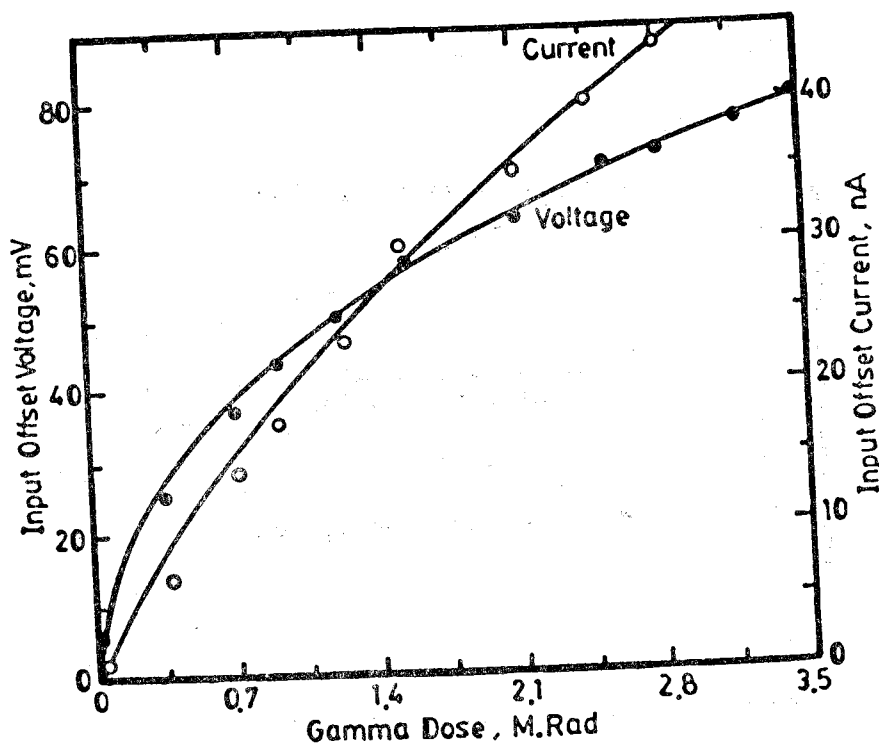$$\text{Constant output Voltage}$$

Fig. 8: Offset Voltage and Current Disturbance in OP.AMP Due to Gamma Exposure.

An ideal amplifier does not respond to changes in the power supply voltages. Fig. 10 shows that the gamma–exposure effects the (PSRR) seriously and cause the device to be sensitive to changes in power supply voltages. The PSRR is shown to increase from an initial value of 100 μV / V up to 430 μV / V under the influence of 3.5×10^6 rads.

3.4. Bias Current

Input bias current is that current flowing into either the "+IN" or "–IN" terminals. These curents are specified, normally, at zero common–mode voltage. In one ideal "741" OP–AMP, the input bias current should be at zero value and in typical devices it has a value of less than 0.50 μA. The measured initial input bias current values of the investigated "741" samples are shown to be as low as (0.25–0.33) μA (Fig. 11). The gamma ray exposure up to 3.5×10^6 rads was shown in Fig. 11 to cause the input current value, of all samples, to increase up to (0.73 – 0.81) μA.
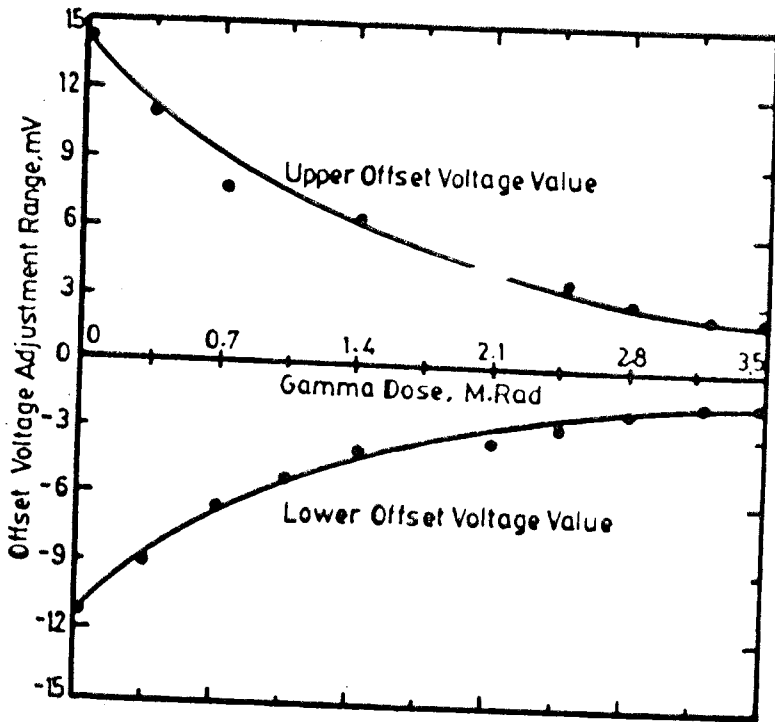
Fig. 9: Offset Voltage Adjustment Range for OP.AMP as a Function of Gamma Dose.
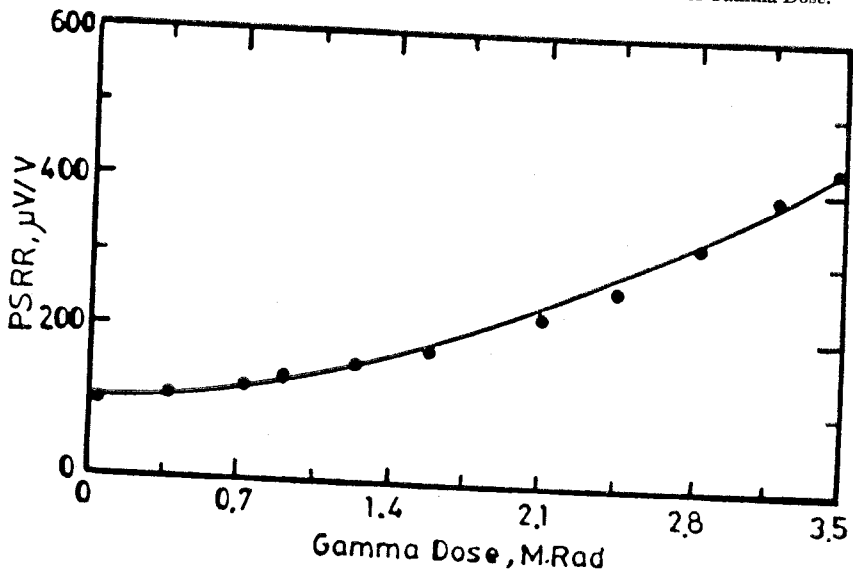
Fig. 10: Power Supply Rejection Ratio Increase as a Function of Gamma Dose.
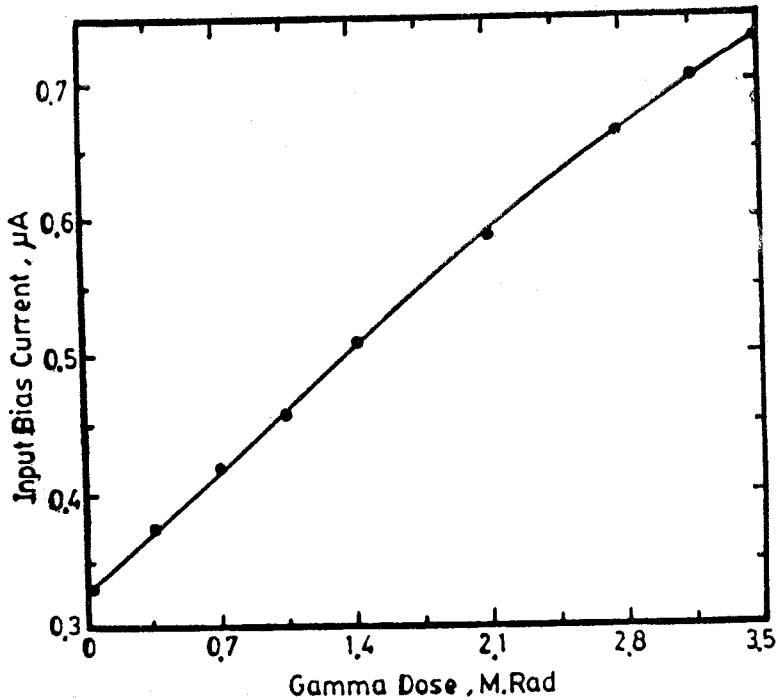
Fig. 11: Input Bias Current for IP.AMP as a Function of Gamma Dose.

3.5. Output Voltage Swing

Offsets appear as changes from the expected output voltage on an OP–AMP circuit these are due to internal imbalances in the differential amplifier of the OP–AMP. Fig. 12 shows the output voltage swing increase as a function of gamma dose. A value of 1×10^{-2} volt was reached, at total gamma dose value of 2.1×10^6 rads, although the initial voltage swing value was 3μ Volt.

Finally, Table 2 summarizes the characteristics of the 741 Operational Amplifier before and after exposure to γ–radiation with doses up to 3.5×10^6 rads.

3.6. Anealing of Radiation Damage

The term anealing is usually used for thermal defect modification and changes in the damage effects with time. Anealing rates of radiation damaged μA 714C operational amplifiers were determined. Reco-
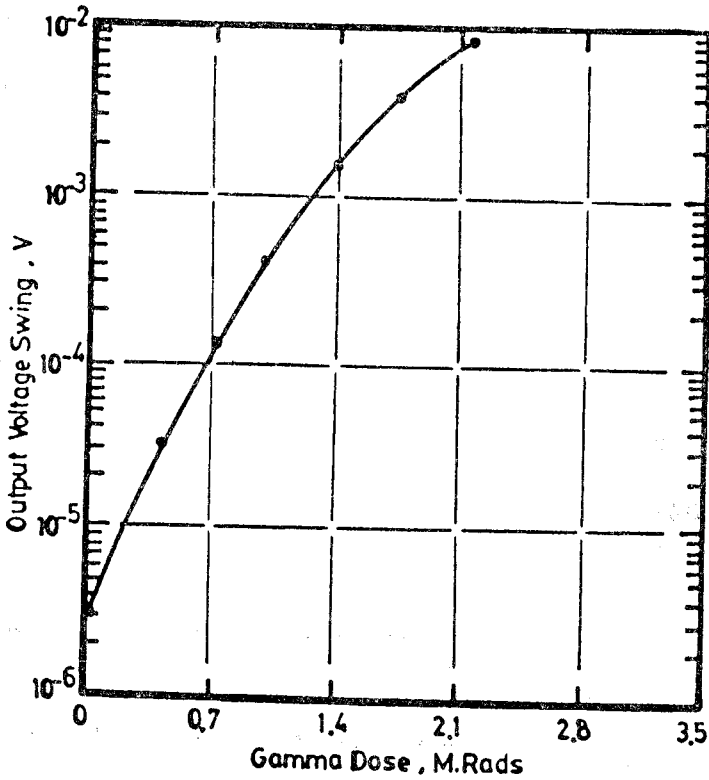
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Fig. 12: Gamma Radiation Effects on Output Voltage Swing for "741" OP.AMP.

Table 2. Characteristics of "741" OP-AMP Before and After
Gamma Exposure up to 3.5×10^6 rads.

Property	Ideal	Typical	
		Before Irrad.	After Irrad.
Gain	Infinite	185 V/mV	70 V/mV
Input Resistance	Infinite	9×10^6 ohm	1.5×10^6 ohm
Offset Voltage Adjustment Range	Large	—12 to +14 mV	—1.5 to +2.0 mV
Common Mode Rejection Ratio	Infinite	100 dB	2.0 dB
Power Supply Rejection Ratio	Zero	20 μV/V	430 μV/V
Input Offset Voltage	Zero	5.0 mV	75 mV
Input Offset Current	Zero	1.0 nA	50 nA
Output Voltage Swing	Zero	3×10^{-6} V	0.0.01 V
Input Bias Current	Zero	0.33 μA	0.73 μA

very in the value of differential–mode gain at room temperatire (25–27'C)
was small. After 90 days, less than 25 % of the original loss was recovered
for Co–60 damaged devices. On the other hand, oven annealing at
15υ °C, for 3 hours, shows that all the damaged units by Co–60, gamma–
–rays, recovered approximately 76 % of the origanal loss. Fig. 13 shows
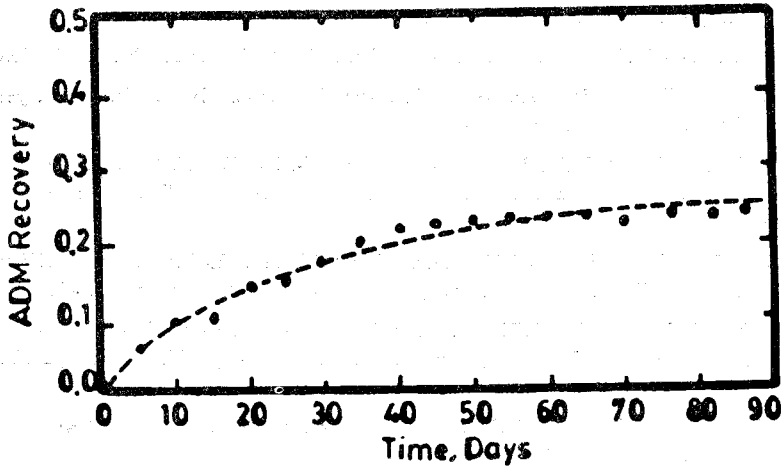the obtained results where the recovery is defined as [16]:

Fig. 13: Recovery in Differential-Mode Gain for μA741C OP.AMP.

$$R = \frac{h_{FE_2} - h_{FE_1}}{h_{FEo} - h_{FE_1}} \tag{8}$$

where:

h_{FEo} : gain before irradiation

h_{FE1} : gain after irradiation

h_{FE1} : gain after annealing

4. CONCLUSIONS

   Exposing the "741" OP–AMP to gamma–rays shows serious effe-
cts on their electrical characteristics, and consequently the devices
lose their main feature. The differential–mode gain and input resis-
tance values were dropped severely. Also, the offset voltage adjustment
range was decreased. Besides, the common mode rejection ratio was
degraded pronouncely. On the other hand, the power supply rejection
ratio and input offset voltage and current were shown to have a pro-
nonced increase.

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