TITLE

RADIATION TOLERANT D/A CONVERTERS FOR THE LHC CRYOGENIC SYSTEM

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ABSTRACT

The electronic instrumentation of the LHC cryogenic system is supposed to receive a large dose of total radiation dose (10^{13}-10^{14} n·cm^{-2} & 1-2 kGy(Si)) within 10 years of activity so all the electronic devices must tolerate this radiation level without a significant degradation.

This paper focuses on the selection of a radiation tolerant 12-bit parallel input D/A converter, suitable for the system requirements. During a preliminary campaign, some candidates were irradiated to determine the most tolerant device. Once it was discovered, a massive test on this converter was carried out. In this second test, some weak points of the device, as the rad-sensitive voltage reference and the presence of a transresistor, had been removed by means of an external voltage source and a rad-tol op amp.

Thus, tests show that the whole system consisting of the D/A converter, external reference and rad-tol op amp could tolerate a total radiation dose up to $5 \cdot 10^{13}$ n·cm^{-2} & 2100 Gy (Si). Therefore, the problem of the selection of this converter has been satisfactorily solved.

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1. INTRODUCTION

Temperature measurement is a key issue in the LHC, as it will be used to regulate the cooling of the superconductor magnets. An absolute accuracy of 10 mK, below 2.2 K, and 5 K above 25 K is necessary. For resistive thermometers covering the full temperature range this is typically equivalent to a relative accuracy dR/R of $3x10^{-3}$ over 3 resistance decades. On the other hand, the sensing current is limited to a few mA to reduce the thermometer's self-heating. Since commercial signal conditioners cannot meet these stringent requirements, different architectures had to be developed at CERN [1]. Additionally, the signal conditioners will operate in a radiation environment and radiation-tolerant parts must be used. As a part of the collaboration agreement between the Accelerator Technology Division of CERN and the Universidad Complutense of Madrid, the selection of a D/A converter to be used in the development of the temperature control system has been performed and the results are shown in this work.

The requirements for the D/A converter were the following: 12 parallel inputs and tolerance to the background radiation originated from the particle beam. Previous simulations have predicted a leakage of neutrons, charged particles and gamma rays from the inner parts of the collider so the electronic instrumentation will be affected by this radiation. The maximum expcted total dos for a period of 10 years, including safety factors, is predicted tobe $5 \cdot 10^{13}$ n·cm^{-2} for neutrons and 1-2 kGy (Si) for gammas [2]. The energy spectrum of the neutrons is expected to be similar to one of the fission of ^{235}U. Radiation tests were carried out at the Portuguese Research Reactor (RPI), using a facility designed to reproduce the LHC radiation environment [3]. The devices received neutron fluences in the 2-$5 \cdot 10^{13}$ n·cm^{-2} range and a gamma dose in the 1.2-2.1 kGy (Si) range in five up to eight sessions of 12 h followed by a 12-h interval, due to the working schedule of the reactor.

At the beginning of the study, two lines were explored: Fast bipolar, as well as CMOS technology devices. However, the results obtained with the CMOS devices were not as good as expected because of TID damage [4] so this line was abandoned, in favour of bipolar technology.

2. IRRADIATION FACILITY

The RPI is a 1 MW, light-water moderated reactor working since 1961. A dedicated dry irradiation facility was built around one of the beam tubes, with an irradiation chamber with 100 cm x 60 cm x 60 cm (l x w x h) at the end of the tube, as well as a prolongation inside the beam tube, made through the introduction of a 100 cm long cylinder with 150 mm inner diameter, attached to the face of the beam tube housing. The neutron beam size is 150 mm, as defined by the diameter of the beam tube close to the core [3]. The shielding of the facility is a combination of polyethylene lined with Cd and high density concrete. Insertion and removal of the circuits is done with the reactor stopped and the beam tube flooded. The arrangement of the outer radiation shield allows the use of relatively short connecting cables (ca. 4 m) to the measuring instruments.

In order to obtain a neutron/photon ratio close to the one expected for the location of the signal conditioners at the LHC, a Pb filter was placed inside the irradiation tube to reduce the gamma field and a Boral filter to reduce the thermal neutron component. The neutron spectrum in the irradiation facility is essentially a leakage spectrum in a light-water moderated ^{235}U fission reactor. The energy distribution of fission neutrons is highly asymmetric, with most neutrons in the 1 - 2 MeV range. Although there are still neutrons with energy in excess of 10 MeV, these contribute with only about 0.1% of the total neutron flux above 1 MeV. The actual spectrum in the irradiation cavity was simulated using the Monte-Carlo code MCNP-

4C, using a detailed three-dimensional model of the core validated with extensive measurements in the core region [5]. The calculated spectrum was further adjusted to activation measurements using sets of foils with different energy-dependent cross sections, following a procedure previously described [6].

Fig. 1 shows the adjusted spectrum per lethargy unit, inside the irradiation chamber, at the point closest to the core. A spectrum corresponding to a core position close to the entrance of the beam tube is also shown for comparison. The removal of a significant part of the thermal neutron component is clearly visible. At the point closest to the core in the irradiation cavity the neutron fluxes are: fast neutron flux of 1.0×10^{9} n•cm^{-2}•s^{-1} ($E > 1$ MeV), epithermal flux of 4.0×10^{7} n•cm^{-2}•s^{-1} ($E = 1$ eV) and thermal of 2.7×10^{8} n•cm^{-2}•s^{-1} ($E < 0.5$ eV).

During the irradiations, the fast neutron fluxes were measured with Ni foils, considering the averaged neutron cross section for the ^{58}Ni(n,p)^{58}Co reaction in a fission spectrum. The ^{58}Co isotope has a half-life of 70.78 d, which is convenient for an activation taking several days. For the neutron spectrum in the irradiation cavity, the fluences obtained in this way with the Ni foils are 40% higher than the total fluence above 1 MeV, determined using multiple foils as described in ref. [6].

The fluences in the irradiation of electronic devices are normally expressed in terms of a 1 MeV neutron equivalent neutron fluence for Si. Following the procedure detailed in ref. [7], the hardness parameter in the irradiation cavity was determined to be 0.81(5). The equivalent 1 MeV fluence is 78% higher than the total flux above 1 MeV, i.e., 28% higher than the fluence determined with the Ni foils. In this paper, all the fluences in the results below are expressed in terms of the Ni foils and they can be expressed in terms of 1-MeV n·cm^{-2} just multiplying by 1.28.

3. DEVICE MEASUREMENT SYSTEM

The system designed to characterise of the devices during the irradiation consisted of a personal computer (PC), where a program developed in Testpoint® controlled several instrumentation devices using the standard GPIB protocol: a Keithley 7002 switching system, a Keithley 2002 digital multimetre and a Keithley 236 source measure unit. Digital inputs are provided by the PC by means of a digital PIO12 card, also managed by the program. The PC could determine the main parameters of the converters every few minutes during the irradiation and stand-by periods. This automatic system was continuously working for periods of 5 - 10 days, without interruptions. The devices under irradiation were placed on test boards, connected to the digital multimetre and to the power supplies by a low resistance and shielded 4-metre cable. All the instrumentation devices were supplied by an uninterrupted power source (UPS) to minimise the action of unexpected power failures.

The program made a digital input sweep to determine the main non-idealities of the DACs: Offset and gain errors and the relative number of bits, N_{REL}, which is a useful parameter to calculate the non-linearity of the DAC. Complete information about these parameters can be found in ref. [8]. Selected devices for the test were AD565AJD, AD667JN (Analog Devices) and DAC703KH (Texas Instruments), whose datasheets are available on the manufacturers' websites [9,10].

The offset and gain errors were calculated in LSB. This unit is defined as 1 LSB=range/2^N, where *range* is, in most cases, a reference voltage and N the number of inputs. Usually, bipolar DACs have an implemented voltage source to be used as a reference. E. g., on the AD565AJD and AD667JN converters, the integrated voltage reference is 10 V and this is the range value; therefore, 1 LSB= 2.44 mV. In contrast, the value of the DAC703KH reference voltage is 6.3 V although the actual output range is 20 V (1 LSB = 4.88 mV).

Unlike the other devices, the AD565AJD has a current output so it needs an operational amplifier to convert its output into voltage. Usually, the operational amplifier is placed close to the converter but, in order to avoid that the predictable degradation of the op amp should be attributed to the converter, the op amps were placed outside the irradiation cavity. After the irradiation, other parameters such as the modification of the power consumption or the frequency behaviour were checked. Finally, the temperature inside the cavity was monitored during the irradiation and kept between 30-35 ºC.

Thus, this work complies with the standard CERN protocols concerning the set-up of neutron tests on electronic devices [11].

4. RADIATION TEST RESULTS

4.1) AD565AJD

During a preliminary test, several samples of this device received a fast neutron fluence between $2.5\cdot10^{13}$ $n\cdot cm^{-2}$ and $3.3\cdot10^{13}$ $n\cdot cm^{-2}$, with a gamma dose between 1.2-1.3 kGy. The conclusion of this test was that the most sensitive parameter was the internal voltage reference, where an increase of about 32 $mV/10^{13}$ $n\cdot cm^{-2}$ was observed, as shown in Fig. 2. This phenomenon can be related to the increase of the line regulation coefficient, very common in irradiated voltage references. When the neutron fluence is about $2.6\text{-}2.7\cdot10^{13}$ $n\cdot cm^{-2}$, the output voltage suddenly plunges down to 8.0 V. This fall is subsequently followed by a steady decrease that only ceases at the end of the irradiation, with a final value of about 6.9 V. Some days later, the voltage output returned to a value about 10 V, most probably due to a partial recovery of the semiconductor lattice. The reason of this drop must be sought in the degradation of the operational amplifier attached to the voltage reference, theory that has been fully developed in [12].

In contrast, the offset and gain errors kept almost constant during the irradiation. The only exception was a sample that underwent a sudden increase of the gain error up to 1000 LSB at a neutron fluence about $2.7\cdot10^{13}$ $n\cdot cm^{-2}$; this increase was not found in the other samples. Besides, the initial relative number of bits was about 11 and was not affected by the radiation. This drop is related to the degradation of the internal voltage reference, which had previously fallen down to 7-8 V. Examining the internal AD565 structure, it is evident that the highest voltage output is the reference voltage. Thus, in spite of the fact that the expected device output voltage is in the order of 10 V supposing the input equal to 4095, the actual output is about 7-8 V. In other words, the gain error is 2-3 V, value that, in terms of LSB, is in the order of 800-1200 LSB. Thus, the anomaly has been explained.

Also, a slight decrease was observed on the supply current. E.g., a sample that received $3.3\cdot10^{13}$ $n\cdot cm^{-2}$ required before the irradiation 12.7 mA and after only 11.1 mA. Finally, before the irradiation, the converter output needed 120 ns to change from –10 V to 0 V and, after the irradiation, this value had not been modified in any device. Therefore, we conclude that there is no significant change of the frequency response at this level of radiation.

4.2) AD667JN

Like the previous converter, the samples of these devices showed an increase of the reference output voltage. Nevertheless, the increase is only 10-12 mV (Fig. 3) in the samples irradiated to a higher fluence ($\sim2.8\cdot10^{13}$ $n\cdot cm^{-2}$). In these devices, the offset error was the most affected parameter. When the neutron fluence is $0.8\text{-}0.9\cdot10^{13}$ $n\cdot cm^{-2}$, the offset error soars from 0-1 LSB up to 22 LSB (Fig. 4). Afterwards, the error continues to increase, but at a lower rate and, eventually, a top value of 40-45 LSB is reached at $1.3\cdot10^{13}$ $n\cdot cm^{-2}$. Later on, the higher the neutron fluence, the lower the offset error. During the subsequent stand-by intervals, the offset error increased.

This evolution was not observed in the gain error, which remains quite constant, being found only a small and not significant decrease (~1 LSB/10^{13} n·cm^{-2}). The relative number of bits, N_{REL}, decreases in proportion to the neutron fluence although, in any sample, its value never became lower than 12.5, value above the system requirements. To conclude, a decrease of power supply current and a worsening of frequency response were observed. Thus, the first parameter changed from 19.76 mA to 17.50 mA on the most irradiated devices. On the contrary, the degradation of the frequency response is much more important: Before the irradiation, the output of the DAC need about 0.5 μs to change the output from 0 to 10 V. Later, this transition was not possible in less than 7 μs.

4.3) DAC703KH

Two samples of this device received 3.3·10^{13} n·cm^{-2} and 1.3 kGy. This is a 16-bit converter so the four least significant bits were grounded to adapt the device to the 12-bit digital card of the measuring system. The voltage reference output is about 6.3 V and, unlike the other converters, it is not directly related to the value of the full-scale range, which begins at 10 V and ends at -9.9951 V. During the irradiation, the behaviour of this voltage reference (Fig. 5) did not follow the pattern of the other devices - the value of the voltage decreased with the neutron fluence.

The offset error hardly increases at the first stage of the irradiation but, when the error is about 20 LSB, the offset error suddenly skyrocketed, as shown in Fig. 6. This threshold value of the offset error was reached at a neutron fluence strongly dependent on the sample. In fact, one of them suffered the change at 1.8·10^{13} n·cm^{-2} while the other one showed it at 2.6·10^{13} n·cm^{-2}. Whatever the neutron fluence threshold, the increase rate is always higher than 100 LSB/10^{12} n·cm^{-2}. The evolution of the gain error is quite similar to the offset error and, finally, the relative number of bits is shown in fig. 6. In this figure, we can observe a sudden fall that happened at the same time as the beginning of the offset error increase.

The cause of the decrease of the relative number of bits, a parameter to estimate the DAC output linearity, arises from the change of the input-output function. Fig. 8 shows the relationships between the input and the output values at different fluence levels. At the beginning, the function is a straight line from 10 V to –10 V. Afterwards, the output becomes a broken line since the input values which are lower than the offset error cannot be correctly converted. Thus, the function is very non-linear and this causes a dramatic drop of the relative number of bits. Also, this fact explains the increase of the gain error because of its mathematical dependence on the offset error [8].

5. PHYSICAL ORIGIN OF DEGRADATION OF DEVICES

In most situations, the change of the characteristics cannot be accurately explained without a deep knowledge of the internal structure of the device. Unfortunately, this information is proprietary and the manufacturers are reluctant to share it. However, most changes can be understood. Neutron irradiation leads to an increase of the semiconductor resistivity, decrease of the bipolar transistor gain, etc. [13]. Thus, DC errors and the relative number of bits must be modified by the variation of the internal elementary components and the subsequent change of the operating point of the internal networks of the devices.

The strange jump observed in AD667JN could not be explained since the information provided by the manufacturer was not enough. In contrast, the degradation of DAC703KH and the strange shape of its input-output function was related to the damage suffered by the internal output operational amplifier. In fact, D/A converters with voltage output usually consist of a R/2R ladder network, able to convert a digital input into current, and an additional integrated op amp to obtain a voltage output. We believe the observed behaviour is due to the inability of the internal output op amp to bias the resistor feedback network, as discussed in a previous work [12].

As it was pointed out in a previous section, shifts of line regulation coefficients are usual in irradiated voltage references, leading to the observed evolution of the integrated references. Also, the consumption decrease is usual in bipolar devices when irradiated with neutrons, such as the authors have reported in other devices [14] and it is corroborated by other results found in different public databases [15] or in the literature [16]. Finally, the worsening of the frequency behaviour of op amps is a well known phenomenon [12] and this can explain the slower response of the converters with an internal output op amp (AD667, DAC703). In contrast, devices without an integrated op amp, such as the AD565, do not suffer a modification of the frequency response. Thus, the main advantage of current output D/A converters is that the operational amplifier can be selected from a set of rad-tol devices, eliminating the constriction of the use of an internal op amp whose radiation tolerance may not be large enough.

VI. RAD-TOLERANT D/A CONVERTERS

Among all the tested devices in the preliminary campaign, the most interesting was the AD565. The reason to do this choice was that the most affected parameter was the internal reference voltage, with the other parameters being hardly affected. Thus, one only has to replace the internal voltage reference by an external one, in order to harden the system. Besides, the external op amp needed by the DAC can be selected from those devices whose neutron tolerance has been established. Previous tests on op amps [8] allowed to know the large tolerance of OPA627 (up to 10^{14} $n \cdot cm^{-2}$ without a significant degradation) so this device was selected to be connected to the converter. In order to account for the tolerance of the whole DAC in this situation, a set of six samples of the device was irradiated with an external reference of 10 V but, unlike the preliminary tests, the op amp was placed on the same board as the converter.

As expected, the converter tolerated a neutron fluence of $5\cdot10^{13}$ n·cm^{-2} and 2.1 kGy without significant degradation. Figures 9 & 10 show the evolution of the main parameters of the most irradiated devices during the test. Neither the gain error nor the offset suffered a significant increase whereas the relative number of bits underwent a slight decrease. In any case, N_{REL} isalways higher than 11.

In short, the set of an AD565, plus an OPA627 op amp and an external reference is a satisfactory solution to be used in the LHC cryogenic system. The external reference voltage will be built by means of special rad-hard regulators developed at CERN [17], or with the output of a rad-hard ASIC, whose radiation tolerance has been proved in other neutron tests [18]. Nevertheless, the AD667JN and DAC703KH converters are recommended instead of the AD565AJD when the neutron fluence is lower than 10^{13} n·cm^{-2} because of the larger accuracy and absence of external devices.

VII. CONCLUSIONS

Electronics to be used in the LHC cryogenic system are expected to receive a significant radiation dose. Radiation tests are necessary in order to select the most suitable devices for the system. The problem of the selection of D/A converters has been solved after determining that the AD565 is able to tolerate the radiation levels forecasted for the LHC. The main handicap of this device is the large sensitivity of the internal voltage reference, which must be replaced by an external one. Finally, the op amp needed to convert the output current from current into voltage must also be radiation tolerant. We have proposed the use of OPA627 due to the extraordinary radiation tolerance observed in previous tests.

Accomplishing all these requirements, the tolerance of the D/A converter up to $5\cdot10^{13}$ n·cm^{-2} and 2.1 kGy (Si) is guaranteed.

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FIGURE CAPTIONS

Fig. 1: Neutron spectrum per lethargy unit, inside the irradiation chamber, at the point closest to the core. The spectrum corresponding to the core is also shown for comparison.

Fig. 2: Evolution of the AD565AJD voltage reference. The continuous line shows the evolution of the parameter all over the full range of values and is related to the Y-axis on the left. The dashed line is a zoom of the parameter when its value is around 10 V and the scale is shown on the right side.

Fig. 3: Evolution of the internal voltage reference of the AD667JN.

Fig. 4: AD667JN offset error. A large increase of 22 LSB at $8 \cdot 10^{12}$ $n \cdot cm^{-2}$ was observed during the irradiation. The small jumps of the graph are the results of the annealing during the stand-by intervals and their origin is not related to the first sudden increase.

Fig. 5: The voltage reference of the DAC703KH converter. The sharp increases are a result of the stand-by intervals, where the damage was partially annealed.

Fig. 6: Offset error of DAC703KH. The fast decrease of the value is a consequence of the reactor stand-by intervals and the partial annealing of the devices.

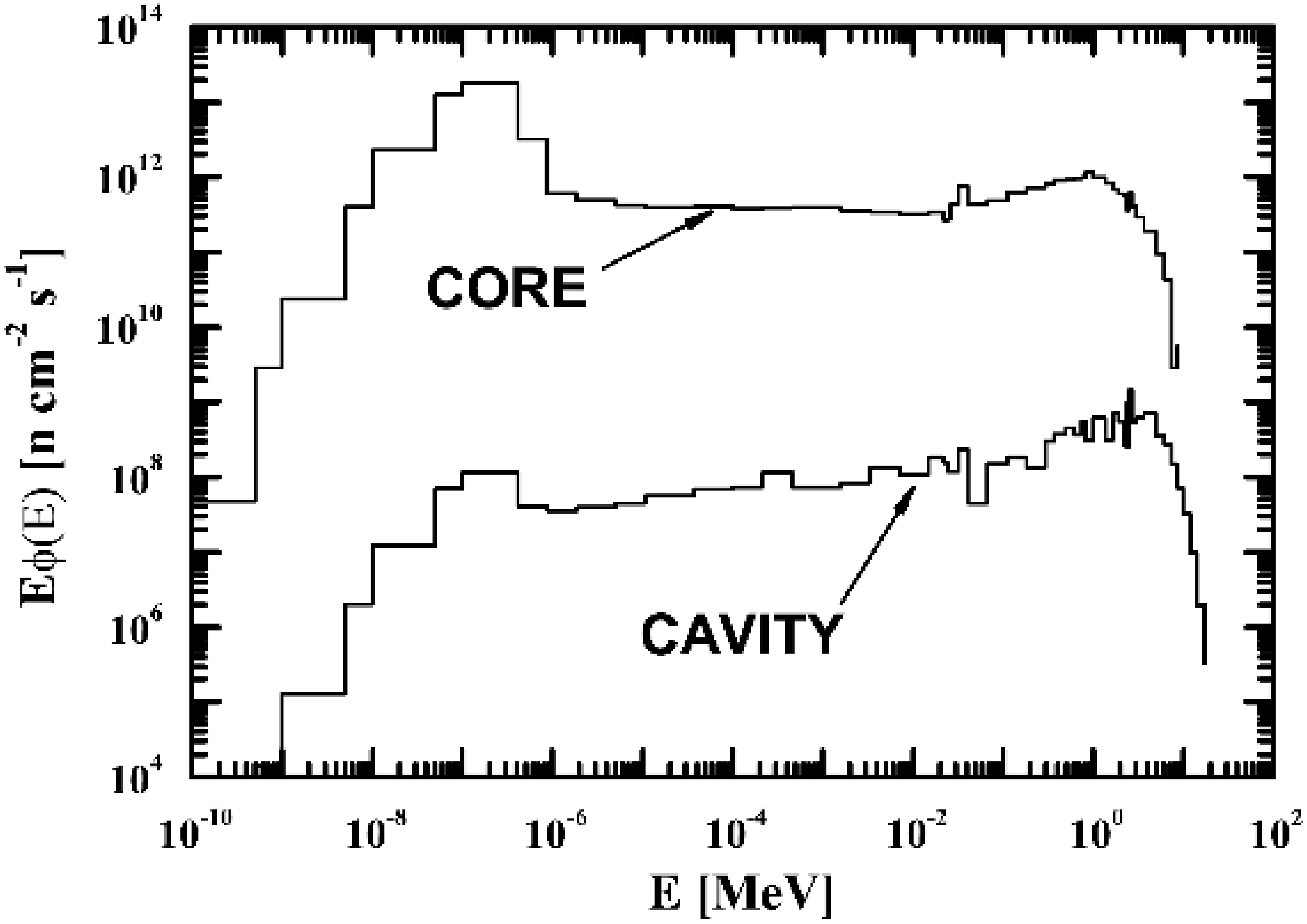
Fig. 7: The relative number of bits on irradiated DAC703KH. The fast increase observed around $2 \cdot 10^{13}$ n·cm^{-2} corresponds to a reactor stand-by interval.

Fig. 8: Relationship between the digital input and the output of the DAC703KH converter. All the functions are similar if the input is high but the differences are very big in the range of low inputs.

Fig. 9: Offset & gain error of irradiated AD565 with external voltage reference

Fig. 10: Relative number of bits, $N_{REL,}$ of irradiated AD565 with external reference

FIGURE 1



10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
$E\phi(E)$ [n cm^{-2} s^{-1}]
CORE
CAVITY
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
E [MeV]

FIGURE 2

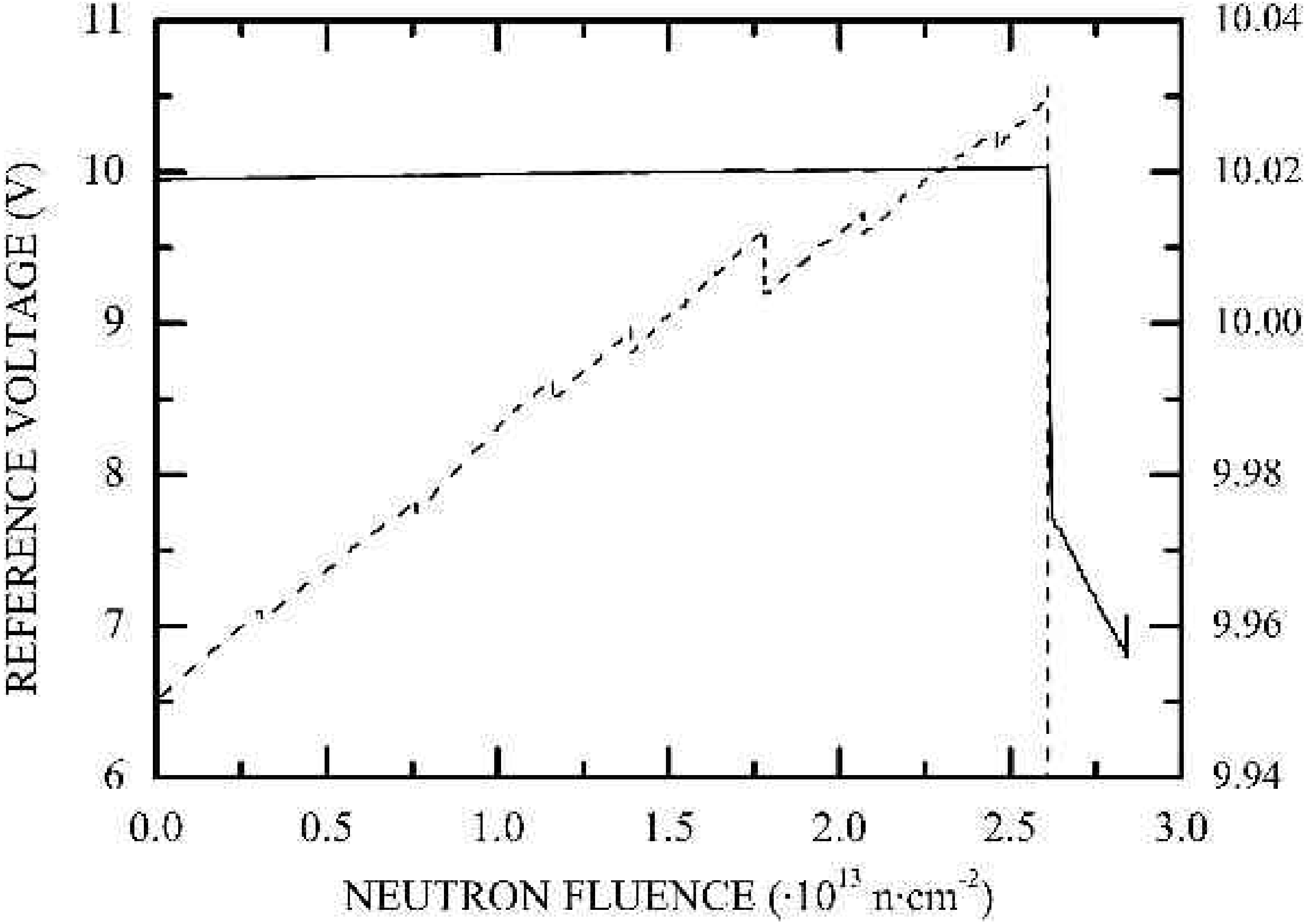

REFERENCE VOLTAGE (V)
11
10
9
8
7
6
10.04
10.02
10.00
9.98
9.96
9.94
0.0
0.5
1.0
1.5
2.0
2.5
3.0
NEUTRON FLUENCE ($\cdot 10^{13}$ n$\cdot$cm^{-2})

FIGURE 3

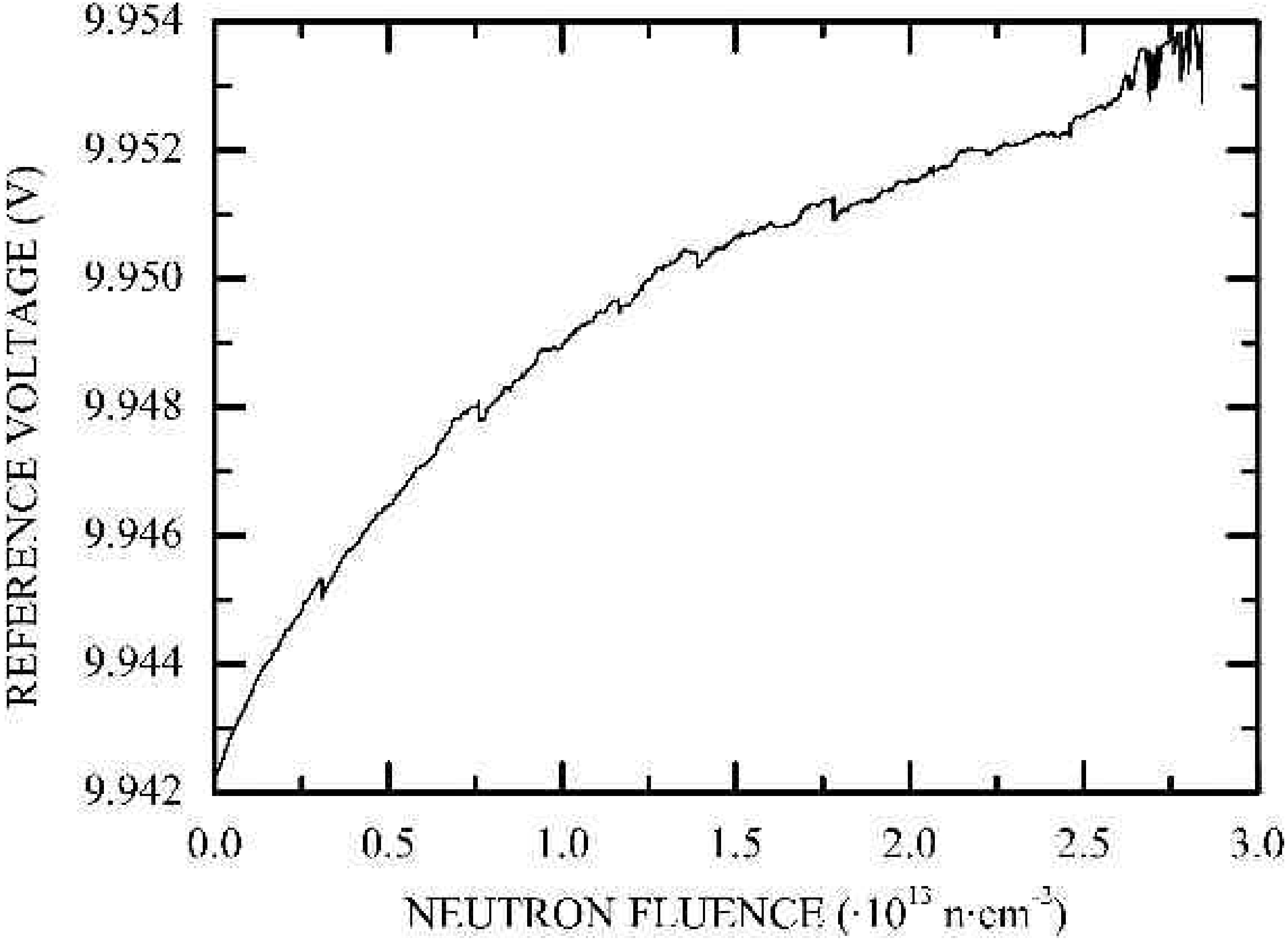

9.954
9.952
9.950
9.948
9.946
9.944
9.942
REFERENCE VOLTAGE (V)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
NEUTRON FLUENCE (·10^{13} n·cm^{-2})

FIGURE 4

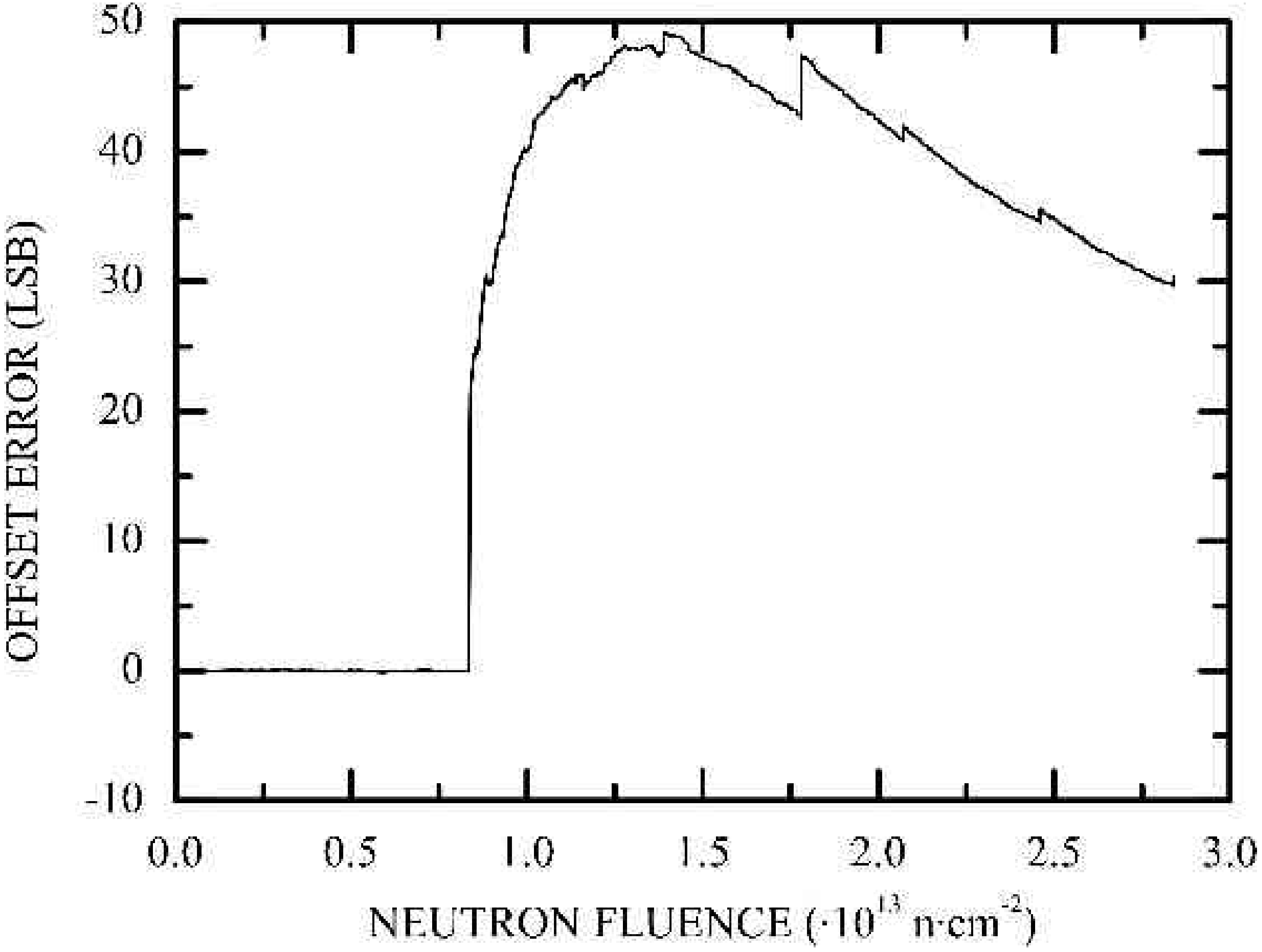

50
40
30
20
10
0
-10
OFFSET ERROR (LSB)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
NEUTRON FLUENCE (·10^13 n·cm^-2)

FIGURE 5

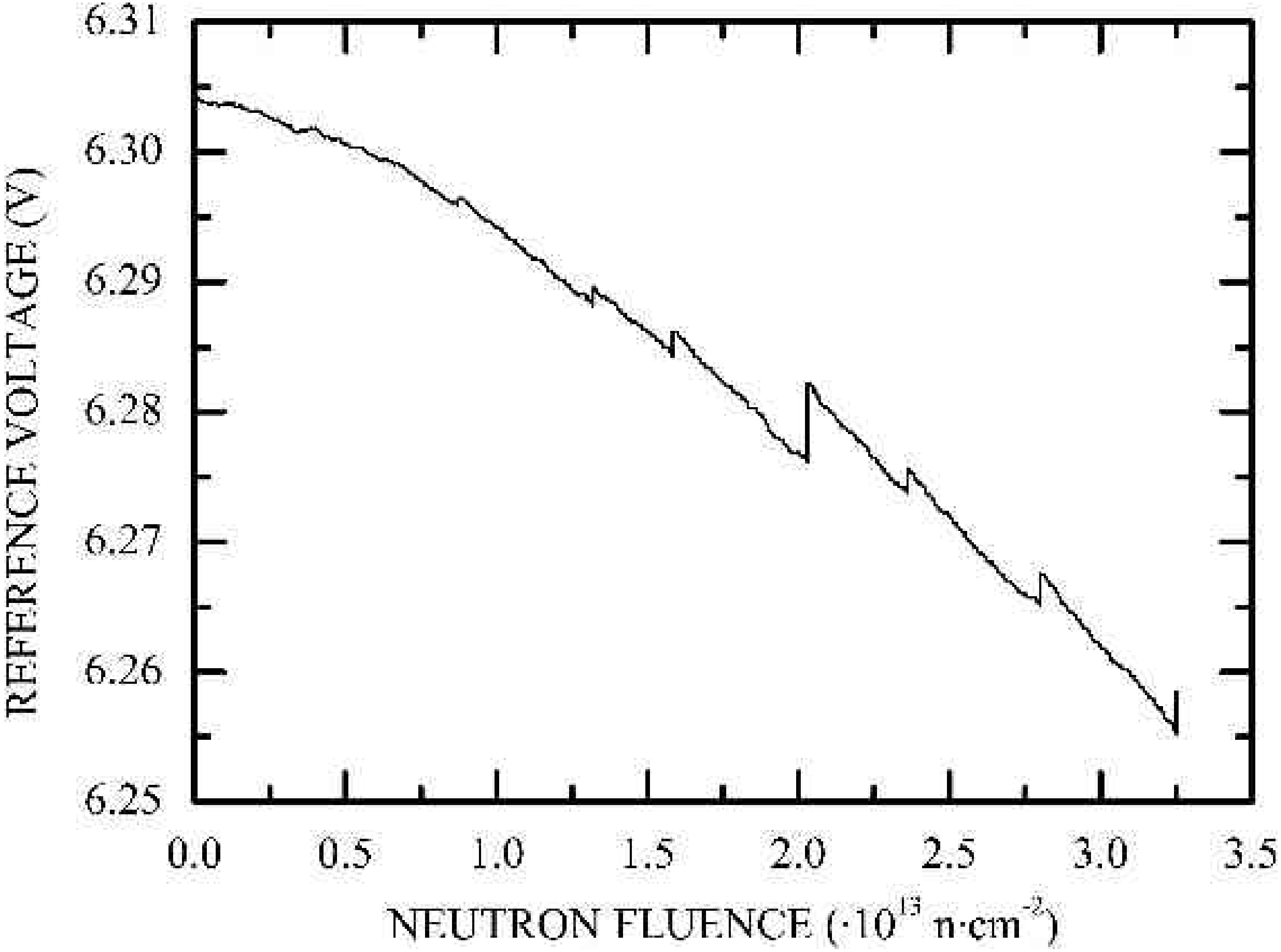

6.31
6.30
6.29
6.28
6.27
6.26
6.25
REFERENCE VOLTAGE (V)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
NEUTRON FLUENCE ($\cdot 10^{13}$ n·cm^{-2})

FIGURE 6

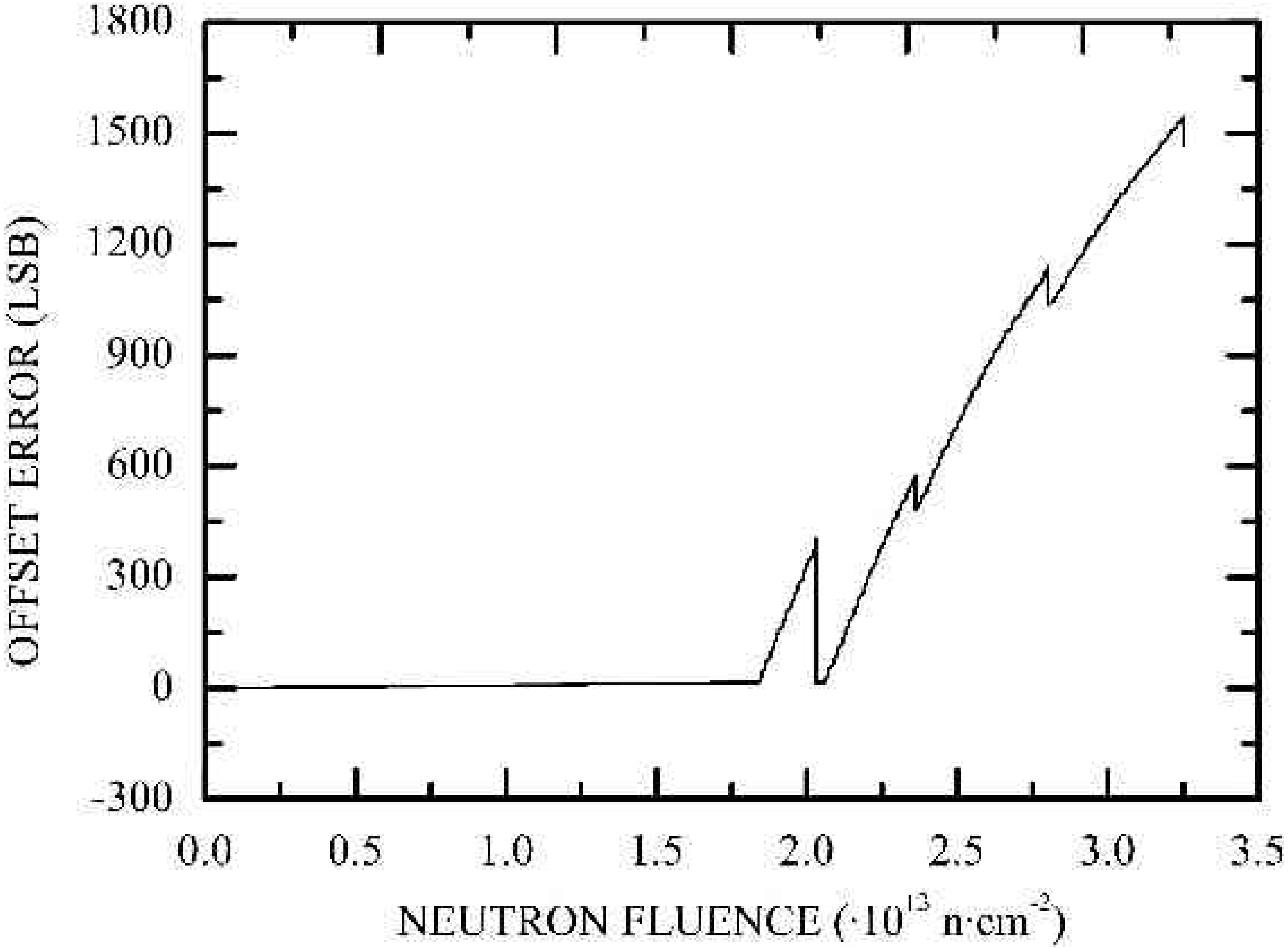

1800
1500
1200
900
600
300
0
-300
OFFSET ERROR (LSB)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
NEUTRON FLUENCE (·10^13 n·cm^-2)

FIGURE 7

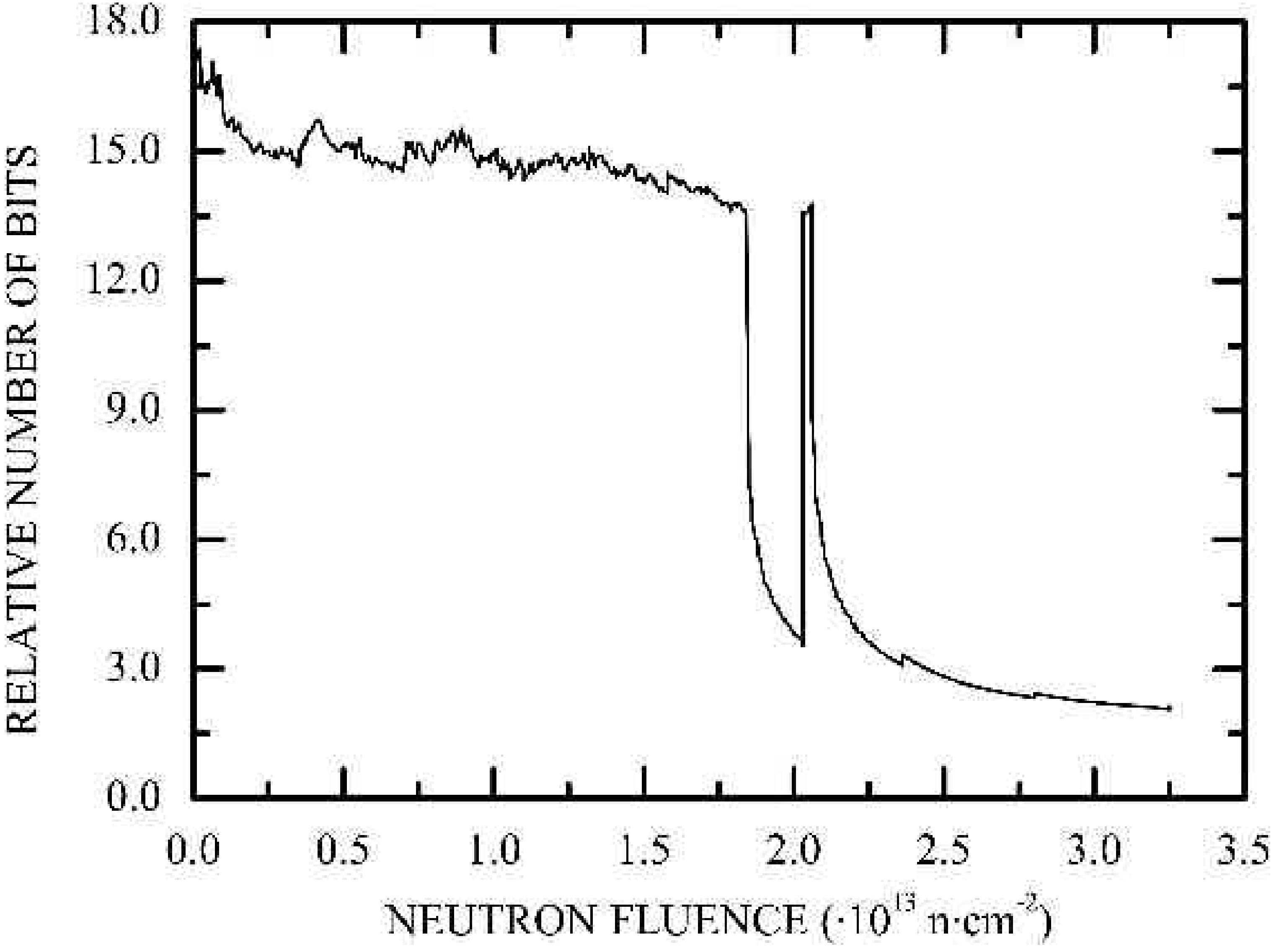

RELATIVE NUMBER OF BITS
18.0
15.0
12.0
9.0
6.0
3.0
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
NEUTRON FLUENCE ($\cdot 10^{13}$ n·cm^{-2})

FIGURE 8

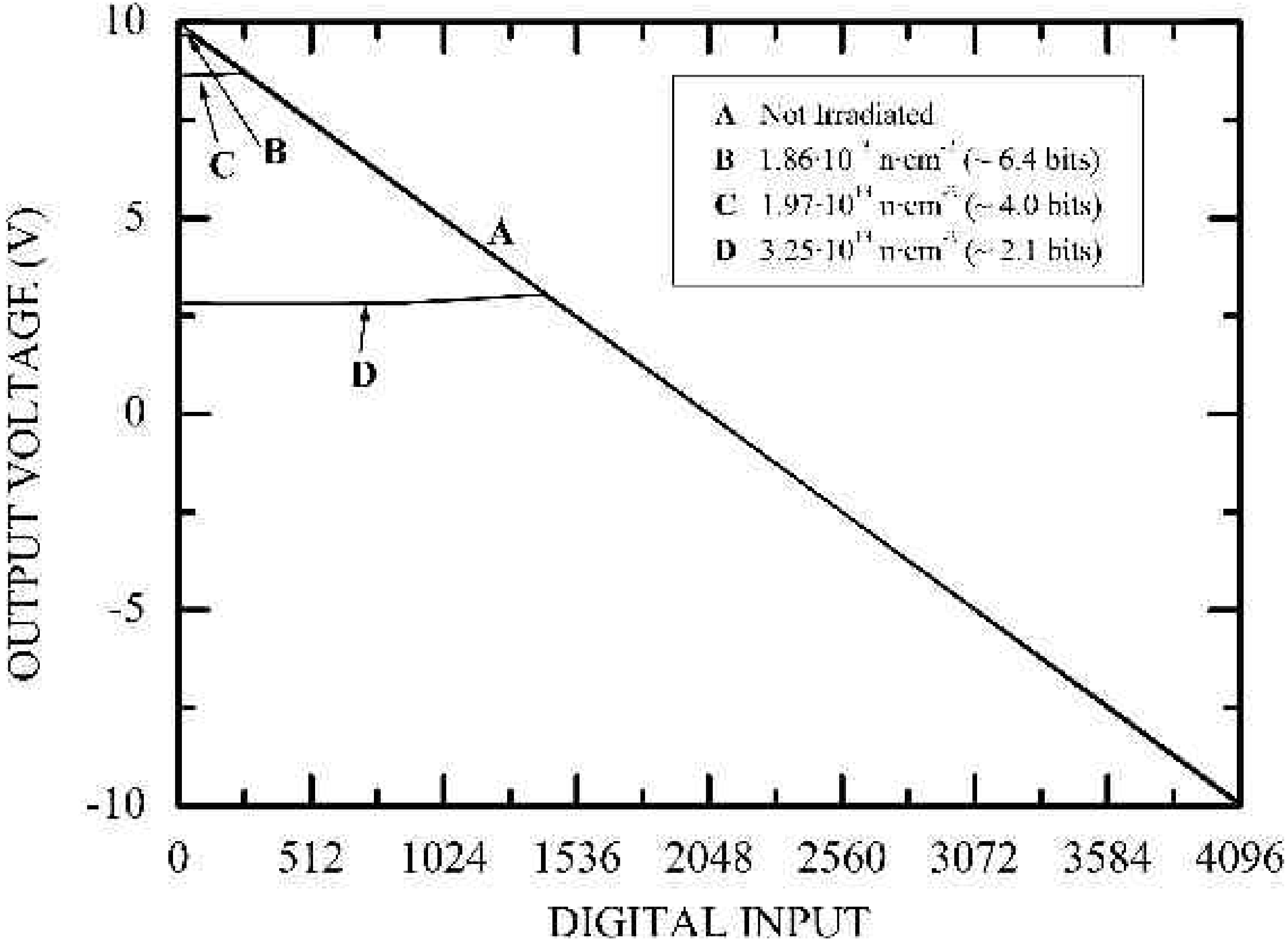

10
5
0
-5
-10
OUTPUT VOLTAGE (V)
0
512
1024
1536
2048
2560
3072
3584
4096
DIGITAL INPUT
A
B
C
D
A Not Irradiated
B $1.86 \cdot 10^{14}$ $n \cdot cm^{-2}$ (~ 6.4 bits)
C $1.97 \cdot 10^{14}$ $n \cdot cm^{-2}$ (~ 4.0 bits)
D $3.25 \cdot 10^{14}$ $n \cdot cm^{-2}$ (~ 2.1 bits)

FIGURE 9

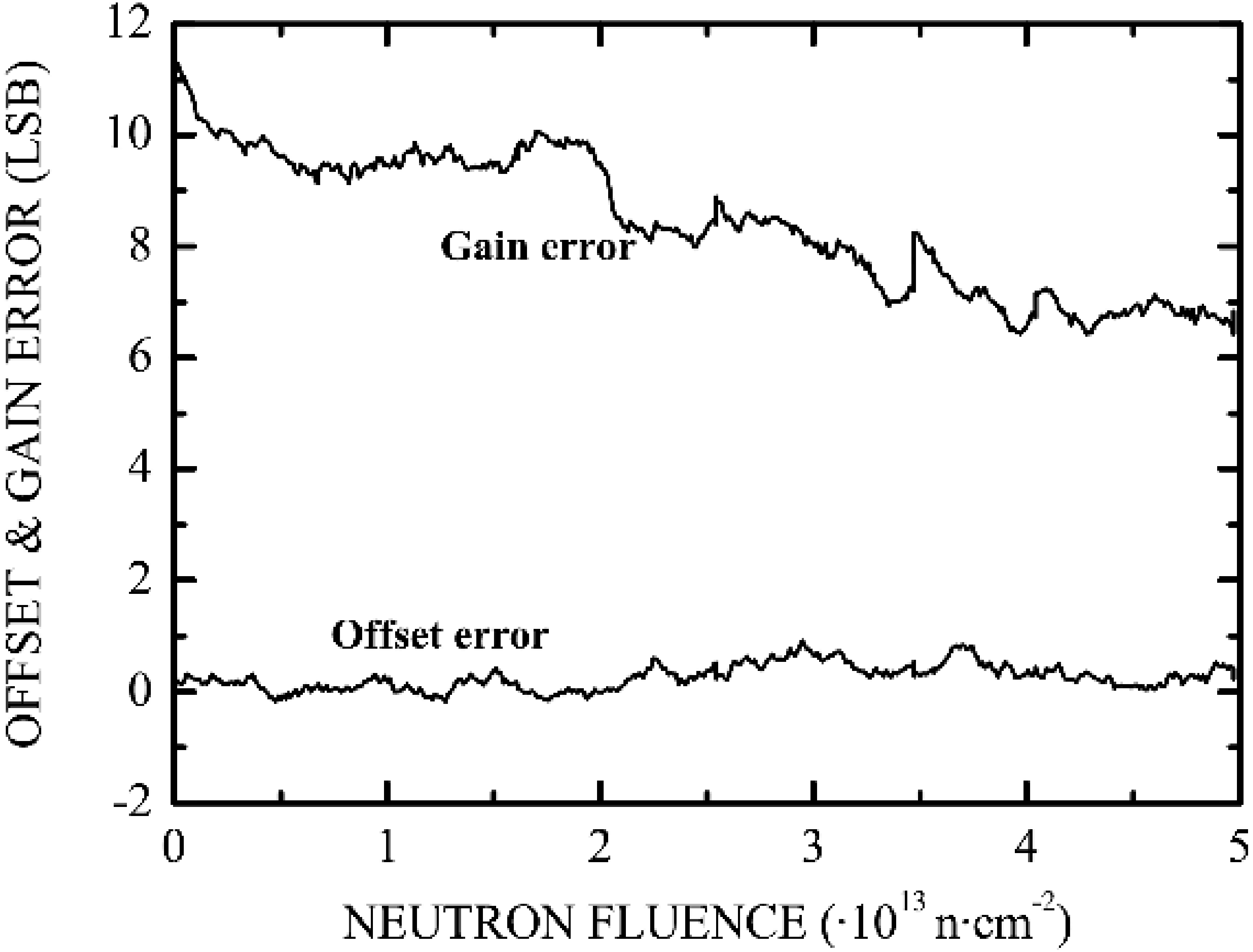
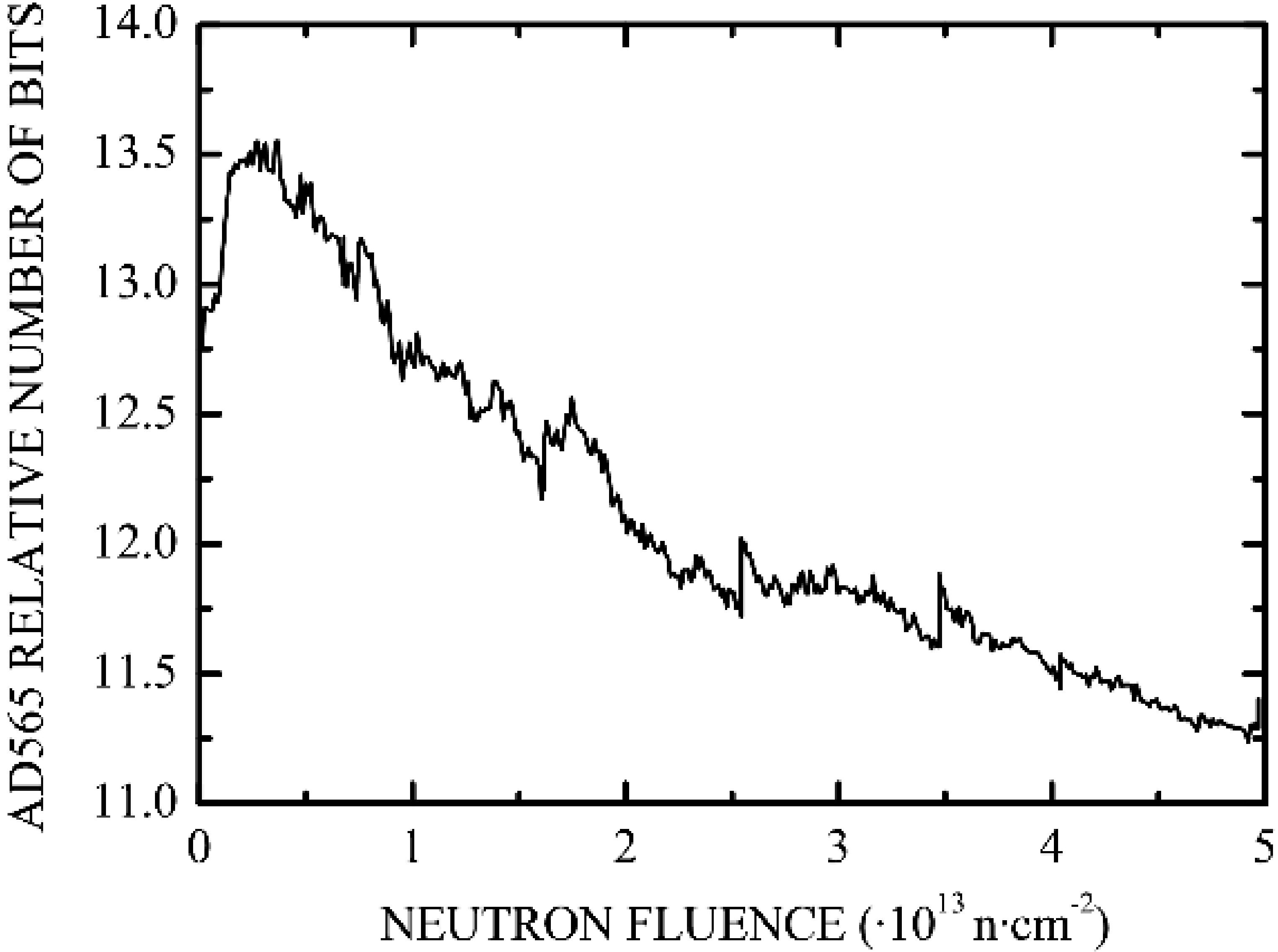

OFFSET & GAIN ERROR (LSB)
NEUTRON FLUENCE ($\cdot 10^{13}$ n·cm^{-2})
12
10
8
6
4
2
0
-2
0
1
2
3
4
5
Gain crror
Offset error

FIGURE 10


AD565 RELATIVE NUMBER OF BITS
14.0
13.5
13.0
12.5
12.0
11.5
11.0
0
1
2
3
4
5
NEUTRON FLUENCE (·10^13 n·cm^-2)