Radiation Effects on XFET Voltage References

F. J. Franco, Y. Zong, J. A. Agapito and A. H. Cachero, *member IEEE*

Departamento de Física Aplicada III - Facultad de CC. Físicas
Universidad Complutense de Madrid
28040 Madrid (SPAIN)
e-mail: monti@fis.ucm.es
fax: +34-91 394 51 96

***Abstract*— XFET references make up a new kind of voltage references different from the popular band-gap or buried Zener devices. These references are built by means of a reference cell consisting in a couple of p-channel junction field effect transistors with different pinch-off voltage values and an operational amplifier with the purpose of improving the output characteristics of the whole device.**

An irradiation in a mixed gamma and neutron environment were performed at the Portuguese Research Reactor and a complete characterization of the devices. Some of the parameters were measured during the irradiation while the rest of them were obtained once the samples were drawn out of the neutron facility. Experimental results eventually show that some references belonging to this class are interesting candidates for a later design of radiation-tolerant electronic systems based on COTS devices.

Keywords- COTS, neutrons, TID, voltage references.

I. Introduction

Electronic designers know that the existence of an accurate reference voltage is a necessary condition to guarantee the correct working of any instrumentation systems. In order to accomplish this requirement, precision voltage references are essential in that kind of systems. Most of these devices consist of a reference cell and an op amp with the double purpose of increasing the stability of the cell by means of a feedback network and, also, to improve the output characteristics. Cell references usually belong to two categories: Band-gap and Buried Zener [1]. Cells of the first class make use of a base-emitter and equivalent thermal voltages to obtain a stable output. On the contrary, those of the second group have a reverse biased Zener diode to set a primary voltage level, which is eventually amplified by the op amp.

In the late 90s, Analog Devices launched a new kind of reference voltage based on a different electric parameter: The pinch-off voltage of e**X**tra implanted junction **F**ield **E**ffect **T**ransistors (fig. 1) [2]. According to the manufacturer, they show low output noise, as buried-Zener devices do, and low consumption, as band-gap ones. However, in spite of the fact that they are susceptible to be used in electronics for space or nuclear systems, there is not any set of irradiation data related to this kind of devices. This fact contrasts with the large amount of works dealing with the other two kinds of references, e.g., [3] -[7]. The main purpose of this paper is to fill this gap in technical literature.

This work was supported by the collaboration agreement K476/LHC between CERN and UCM, by the Spanish Research Agency CICYT (FPA2002-00912) and partially supported by ITN.

II. An overview of XFET references

According to fig. 1, a couple of sources are injecting similar currents in each of the transistors. Supposing the operational amplifier of fig. 1 is ideal and working in the linear zone, voltages in both inverting and non-inverting inputs must be equal. Therefore, the drain-to-source voltage is the same for both transistors.

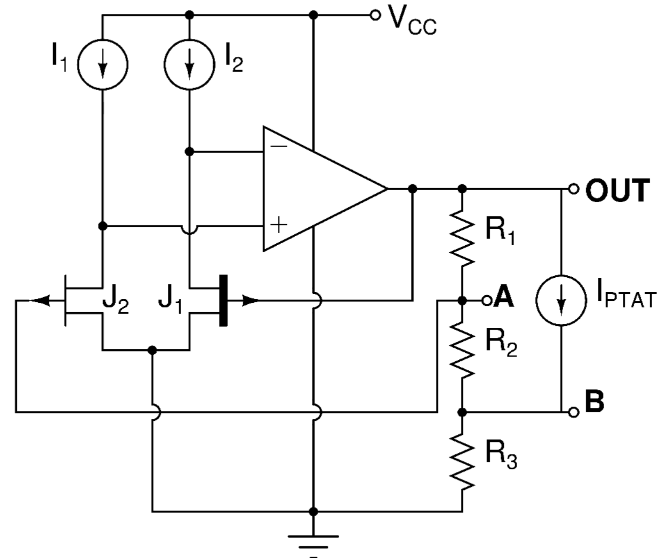

Figure 1: Internal structure of an XFET reference. The output voltage is a function of the difference between J1 & J2 pinch-off voltage values, and of I_{PTAT}.

First of all, let us accept that the transistors are operating in the linear zone. This supposition is set since it is better to bias the devices in this zone since the necessary supply current is much lower than in the case of biasing the transistors in the saturation zone. In that case, the values of the currents crossing them are:

$$I_1 = I_{DSS,1} \cdot \left(1 - \frac{V_{GS,1}}{V_{P,1}}\right) \cdot \frac{V_{DS,1}}{V_{P,1}} \tag{1}$$

$$I_2 = I_{DSS,2} \cdot \left(1 - \frac{V_{GS,2}}{V_{P,2}}\right) \cdot \frac{V_{DS,1}}{V_{P,2}} \tag{2}$$

$V_{P,X}$ and $I_{DSS,X}$ are the pinch-off voltage and the saturation current of the J_X transistor. However, because of the presence of

the operational amplifier, $V_{DS,1} = V_{DS,2}$. Besides, the current sources are matched so $I_1=I_2$. Therefore:

$$\frac{I_{DSS,1}}{V_{P,1}}\cdot\left(1-\frac{V_{GS,1}}{V_{P,1}}\right)=\frac{I_{DSS,2}}{V_{P,2}}\cdot\left(1-\frac{V_{GS,2}}{V_{P,2}}\right) \quad (3)$$

If $I_{DSS,1}\cdot V_{P,2}^2 = I_{DSS,1}\cdot V_{P,1}^2$, condition that is easily accomplished by means of trimming the lengths of the channels, the following result is eventually deduced:

$$\left(V_{P,1}-V_{GS,1}\right)=\left(V_{P,2}-V_{GS,2}\right) \quad (4)$$

$V_{GS,1}$ and $V_{GS,2}$ are identified in fig. 1 with the output of the operational amplifier and the node labeled A. Therefore:

$$V_{OUT}-V_A=V_{P,1}-V_{P,2} \quad (5)$$

Applying Kirchoff's laws, this expression for the value of the output voltage is finally calculated:

$$V_{OUT}=\left(V_{P,1}-V_{P,2}\right)\cdot\left(1+\frac{R_2+2\cdot R_3}{R_1}\right)+I_{PTAT}\cdot R_3 \quad (6)$$

The difference between the pinch-off voltages is achieved after the additional implantation process. The presence of another current source, I_{PTAT}, is caused by the small but not negligible dependence of the pinch-off voltages on the temperature. In fact, $V_{P,1}$-$V_{P,2}$ decreases in proportion to the temperature so a device with the opposite behavior is required to remove the influence of the temperature on the output voltage value. Unlike the core of the voltage reference, the manufacturer does not provide any information about the nature and structure of the temperature compensation current source.

III. Test proceeding

Three samples of ADR291, ADR420 and ADR430 were irradiated in the neutron facility of the Portuguese Research Reactor [8]. Thus, there is a sample of each series of XFET references (ADR29X, ADR42X & ADR43X). Besides, samples of any model belonged to the same batch. They were distributed on three PCBs so that the total radiation dose in each board should be different. Therefore, the samples received different radiation values so an off-line test could be performed on the devices after the irradiation. During the irradiation, the references were biased with a 15V power supply. Besides, no resistor was loading their outputs.

The samples were irradiated in three rounds of 10 h each. Nevertheless, the whole test took five days since the reactor was periodically shutdown for fourteen hours due to safety reasons. Also, after the later reactor stop, the test lasted for two additional days in order to investigate the room-temperature annealing of the devices. An instrumentation system, managed by a personal computer, measured the output voltage of the reference as well as the quiescent current. Thus, both parameters could be measured every few minutes within the complete duration of the experiment. Finally, off-line parameters were measured one month after the irradiation, once that unsafe radioactive isotopes had vanished.

Devices received a total neutron fluence of $2.9\cdot10^{13}$, $9.7\cdot10^{12}$ and $3.8\cdot10^{12}$ $n\cdot cm^{-2}$. The energy spectrum of the neutron beam was similar to that of the ^{235}U fission after removing the component of thermal neutrons. According to the calculations performed in the Portuguese Research Reactor [9], the correction factor value is 1.28. In other words, all the neutron fluence values measured by means of ^{58}Ni foils can be expressed in the standard unit of 1 MeV-neutrons/cm^2 just multiplying it by 1.28. From now on, this will be the standard unit used in this paper to express displacement damage. Finally, along with it, devices suffered the action of total ionizing dose, which was measured with an ionization chamber and which reached values of 450, 325 and 225 Gy (Si) after 30 h of irradiation. That means that the dose rate was between 15 Gy/h and 7.5 Gy/h. In alternative dose rate units, these values are 0.42 rad/s and 0.21 rad/s.

IV. Results: output characteristics

Inside this category, we have arranged all the parameters related to the device output: Output voltage value, line regulation (also known as influence of power supply), output noise and short circuit current, which is the highest current that the device can provide. Besides, the influence of the power supply on the short circuit currents has been investigated.

A. Output voltage

Output voltage was measured during the irradiation. Doubtlessly, the most sensitive device was ADR291. In fact, the output value kept stable until the neutron fluence reached a value of $1.9\text{-}7.7\cdot10^{12}$ 1 MeV-$n\cdot cm^{-2}$ (about 90 Gy in all the samples), stage followed by a steady shift of output voltage. Later, a sudden drop down to 1.25 V and a final slow decrease down to 0 V would eventually make this device useless (fig. 2).

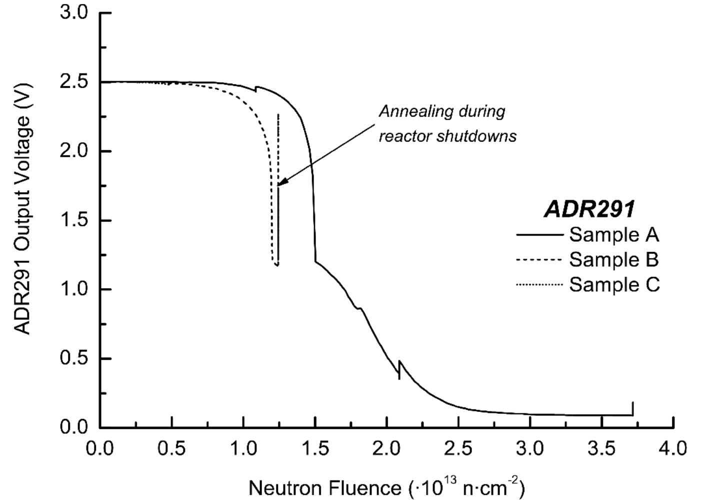

Figure 2: Evolution of ADR291 output voltage

On the contrary, ADR420 & ADR430 showed a larger tolerance to radiation (fig. 3). AD420 output voltage is hardly affected if the total radiation dose keeps below $1.3\cdot10^{13}$ 1-MeV $n\cdot cm^{-2}$ & 225 Gy. If it does not, a growth in the output voltage should be expected. In fact, the most irradiated sample ($3.7\cdot10^{13}$ 1-MeV $n\cdot cm^{-2}$ & 450 Gy) had undergone an increase of 20 mV (0.97 %) at the end of the irradiation. The behavior of ADR430 was a little different since a small decrease, which reaches a value of 7 mV at $2.3\cdot10^{13}$ 1-MeV $n\cdot cm^{-2}$ & 290 Gy. This behavior

is immediately followed by an increase that compensates the previous decrease of the output voltage.

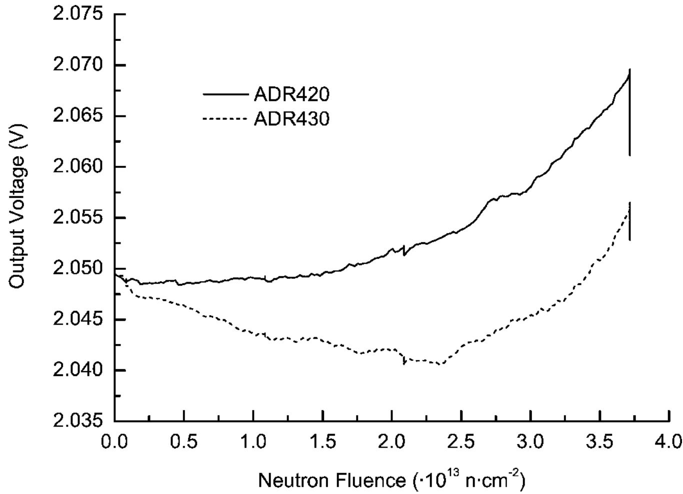

Figure 3: Evolution of ADR420 & ADR430 output voltages

B. Line Regulation

After the irradiation, an increase of line regulation value, defined as $L.R = \delta V_{OUT} / \delta V_{CC}$, was found in all the tested devices (fig. 4). This growth is very important in ADR291, where a total radiation dose of $1.25 \cdot 10^{13}$ 1-MeV $n \cdot cm^{-2}$ & 325 Gy makes the L.R. value rise up to 8 mV/V (About 50 times the initial value). In the case of the other references, this increase appeared as well but it is never as important as that of ADR291. In fact, the most irradiated sample of ADR430 showed an L.R. value of only 0.5 mV/V (just 10 times the initial one).

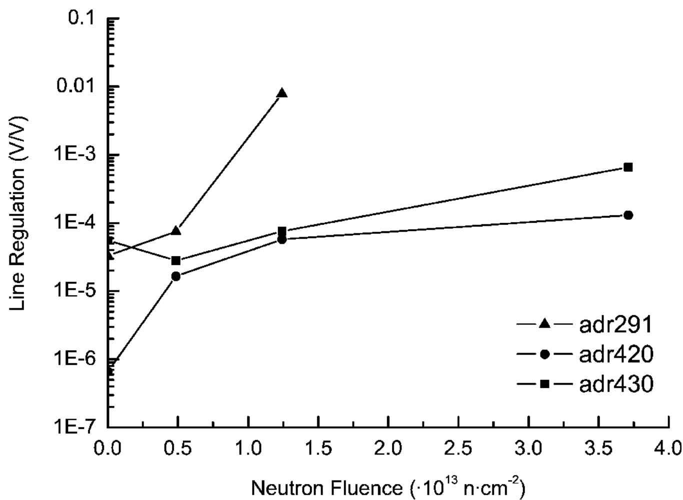

Figure 4: Line regulation of irradiated XFET references

C. Output noise

Fig. 5 shows the evolution of the output noise voltage of all the tested devices except the most irradiated sample of ADR291. This parameter was measured with very accurate power supplies so that the random variations of the power supply value should not be transmitted into the output voltage value and misled with the actual output noise signal.

In any case, this figure brings evidence of the fact that the size of the output noise increases in all the irradiated samples. This increase is much more important in the case of ADR291 samples, where a noise signal in the order of 200 μV_{pp} was found in one of the samples despite being less than 8 μV_{pp} at the beginning.

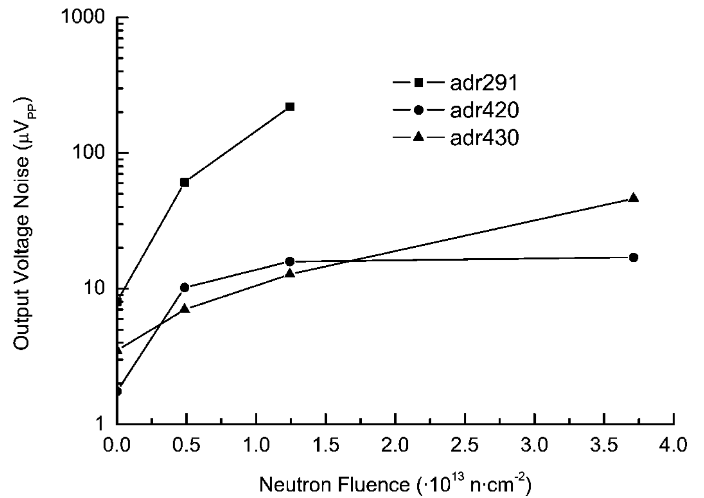

Figure 5: Output voltage noise of irradiated devices

D. Short Circuit Current and Load Regulation

The short circuit current exhibited a decrease in all the tested devices (fig. 6). This phenomenon was specially important in the case of ADR291, where even the less irradiated sample had suffered a reduction down to 30 % of the initial value. On the contrary, in spite of the fact that the other devices also underwent a decrease, by no means it is as significant as that of ADR291. E.g., the most irradiated sample of ADR430 only showed a decrease from 45 to 38 mA. Such values are so close to each other that the irradiated references must be expected to bias similar loads like a not damaged device.

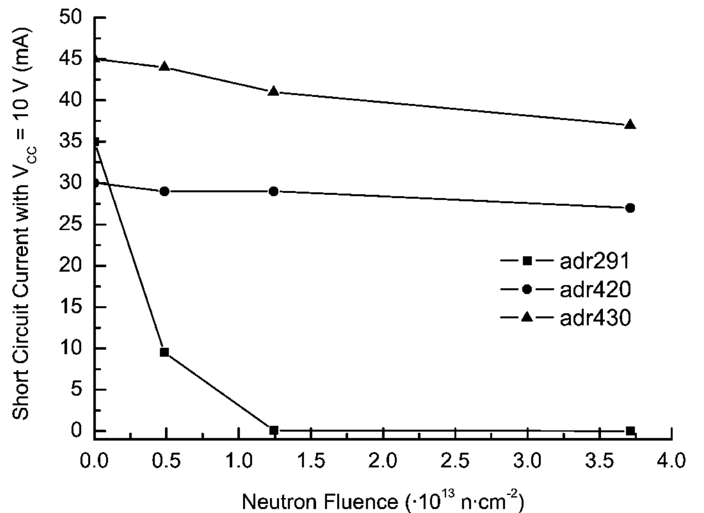

Figure 6: Short circuit current of irradiated devices

Related to this parameter is the load regulation, which is the parameter that regulates the shift of the nominal output voltage value in proportion to the modification of the load resistor value, $Lo.R = \delta V_{OUT} / \delta I_{Load}$ and it is usually expressed in terms of p.p.m/mA.

The evolution of the load regulation appears in fig. 7, parameter was measured with a power supply of 10 V. This graph gives evidence of the the load regulation growth after the irradiation. However, even though the increases may seem very important, they are not as large as those observed in the ADR291 references. Indeed, the increase observed in this family was the most important by large since, e. g., in the less irradiated sample ($4.96{\cdot}10^{12}$ 1-MeV n·cm^{-2}), a value of 24000 ppm/mA was measured or, in other words, -60 mV/mA. This means that the load regulation value is about 1000 times higher than the initial one. It is interesting to highlight this fact since this parameter had been hardly affected in the samples of the other families.

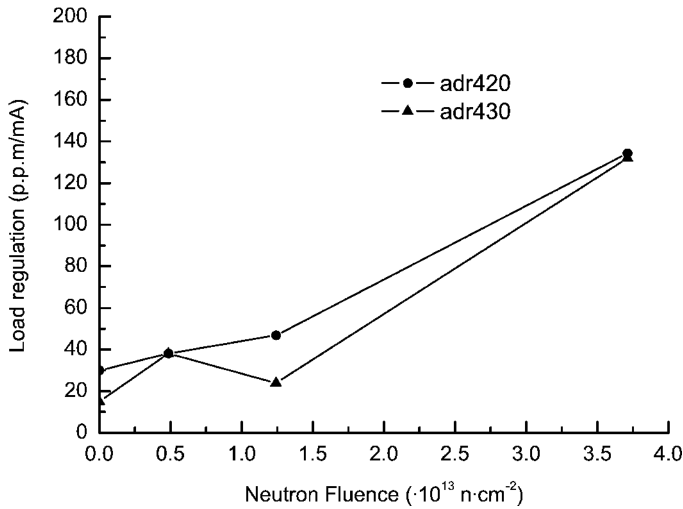

Figure 7: Evolution of load regulation of ADR420 & ADR430 samples. Data about ADR291 were withdrawn due to a scale problems.

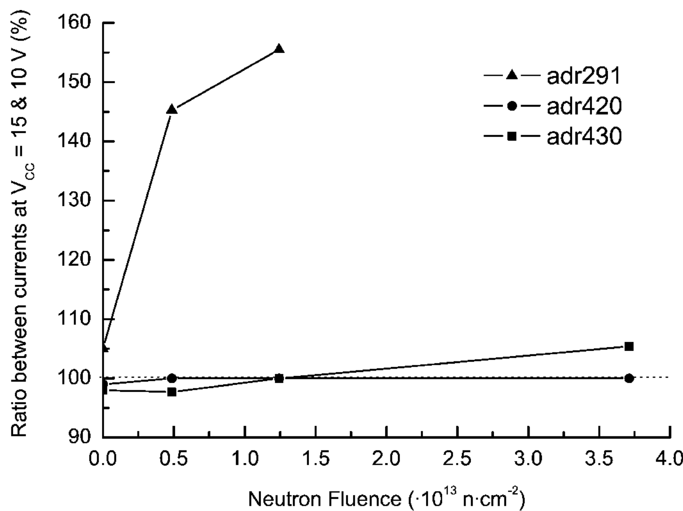

Figure 8: Influence of power supply value on the short circuit current. This graph represents the ratio between the values of I_{ShCC} with two different power values.

E. Line regulation on short circuit currents

Finally, an increasing influence of the power supply value on the short circuit current was observed. Fig. 8 shows the ratio between the short circuit currents with V_{CC} = 15 and V_{CC} = 10 V. At the beginning, both values are very close but the ratio between them rises in proportion to the neutron fluence. Like in the case of previous parameters, the most damaged device was ADR291. According to the graph, a growth in the order of 50-60% is expected in the short circuit current of the irradiated samples if the power supply value increases from 10 to 15 V. In the other models, this increase is negligible since it is never larger than 5 %.

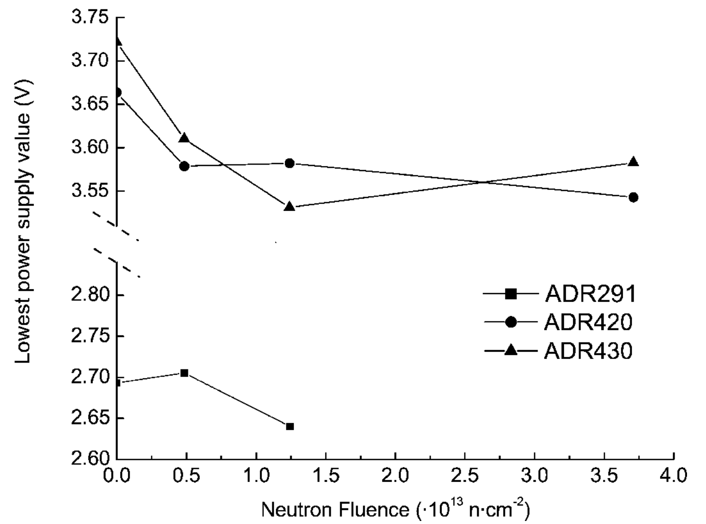

Figure 9: Lowest power supply value necessary to reach the nominal output voltage value.

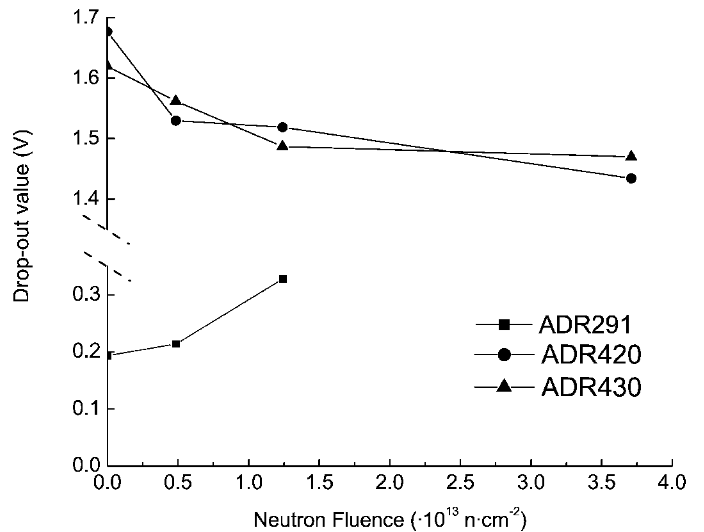

Figure 10: Drop-out value in irradiated XFET references.

V. Results: bias parameters

The first parameter in this category is the minimum value of power supply voltage, V_{CCMIN}, defined as the lowest value of V_{CC} that guarantees a top value for the output voltage, $V_{O,TOP}$, supposing the line regulation negligible. According to fig. 9, this parameter decreases in all the samples. Nevertheless, the value of $V_{O,TOP}$ depends a lot on the neutron fluence so it is advisable to use the drop-out value, V_{DO}, defined as the difference between V_{CCMIN} and $V_{O,TOP}$, instead of $V_{CC,MIN}$. Concerning this parameter, references show different behaviors since the value of V_{DO} increases in ADR291 while decreases in the other models (fig.10).

Table I: Results of irradiation tests on several kinds of commercial voltage references

Model	Company	Type	NIEL	Vout	Line Regulation (L.R.)		L. R/V_{OUT}		Sh. Circuit Current	
					Previous	Irradiated	Previous	Irradiated	Previous	Irradiated
REF02	Analog	B. Gap	4,7	5	0,070	4,4	0,014	0,880	25,0	5,6
REF02	Maxim	B. Gap	4,7	5	0,070	4,1	0,014	0,820	25,0	3,5
REF102	Texas	B. Zener	4,7	10	0,006	9	0,010	0,900	26,0	1,1
ADR291	Analog	XFET	3,7	2,5	Destroyed					
ADR420	Analog	XFET	3,7	2,048	0,010	0,1	0,005	0,050	45	37
ADR430	Analog	XFET	3,7	2,048	0,050	0,5	0,025	0,250	30	28
			$\cdot 10^{13}$ n/cm^2	V	mV/V		mV/V^2		mA	

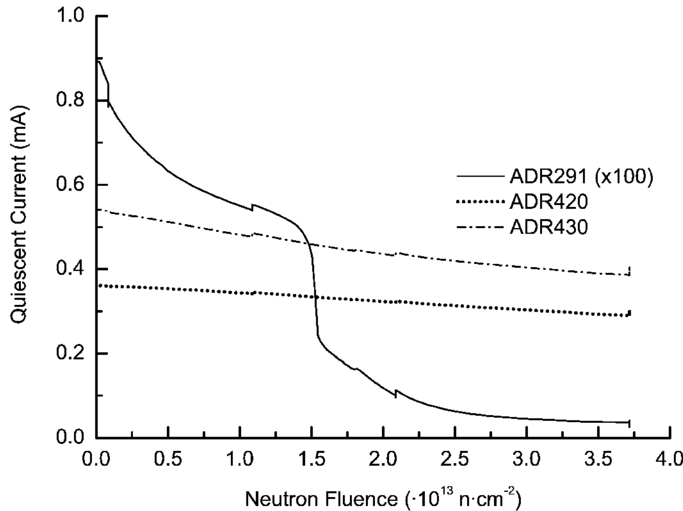

Figure 11: Evolution of quiescent current of XFET references during the irradiation. ADR291 value must be divided by 100 to get the actual measured value.

Quiescent current also belongs to this set of parameters. It was measured on-line by means of the instrumentation system and a reduction in its value was observed in all the samples. Fig. 11 shows the evolution of this parameter in the most irradiated samples, being the most affected device that of ADR291. In fact, the quiescent current of this device is close to disappear.

Finally, quiescent current shows a slight dependence on the power supply value. For instance, the quiescent current of not irradiated ADR420 samples, with an average value of 0.57 mA, increases 0.5 μ A/V in proportion to V_{CC}. After the irradiation, this ratio is a little higher (0.8 μ A/V) but, in any case, it keeps being negligible.

VI. Discussion

Experimental results shown in this paper have described the evolution of XFET references in a mixed neutron & gamma radiation environment. The following step should be to explain the reasons of this behavior. In a previous work [3], the degradation of band-gap references was successfully described as a consequence of the degradation of the core cell. Unfortunately, the same thing does not go for XFET references. The reason of this is the existence of a current source, I_{PTAT}, with the purpose of balancing the thermal drift of the JFET cell and with no information about provided by the manufacturer. Therefore, the absence of data about it eventually avoids the development of a theoretical study.

However, most observed phenomena have equivalence in the irradiation of other kinds of voltage references. In fact, the modification of the output voltage and the increase of line regulation coefficient are typical of any class of irradiated references [10]. Besides, phenomena as the decrease of the quiescent current or the degradation of the short circuit current can be explained by means of the degradation of the internal op amp since the diminution of the quiescent current has been found in bipolar op amps, whether irradiated with neutrons [11] or gamma rays [12]-[13]. The main drawback of this explanation is that a fraction of the quiescent current is related to the current sources that bias the pair of JFET's. No information about the structure of the sources is provided by the manufacturer. However, we could accept that its value becomes lower since other works have demonstrated that the output of integrated current sources usually decreases because of radiation [12]. On the other hand, the degradation of op amp also explains the diminution of the short circuit current of any kind of reference as well as the increasing influence of power supply value, as other works have underlined [14].

The reasons of the shift of dropout output value are not so easy to identify. Perhaps, it is related to the modification of the saturation voltage swing of the operational amplifiers, phenomenon that has been reported in irradiated bipolar op amps. A necessary condition for a correct working of the reference is that the saturation voltage of the op amp must be higher than the nominal value. In other words, $V_{SAT+} \geq V_{O,NOM}$. Supposing V_{SAT+} very close to $V_{O,NOM}$ but higher, the dropout value must be identified as V_{CCMIN}-V_{SAT+}, which is the definition of the positive saturation voltage swing of the op amp. Although this is not usually a parameter of interest during irradiation tests, data about it can be found in some public websites [15]. These sets of data show that values of saturation voltage swing in some discrete irradiated op amps can either increase or decrease some tenths of volt. This fact depends on the kind of device but, in any case, they are in the order of the shift of dropout shown in this paper. Therefore, a hypothetical shift of S.V.S. value may explain the evolution of dropout.

Another interesting topic to deal with is whether XFET references are good candidates for a later use in radiation environments. Other tests on other kind of voltage references were carried out in the same facility, being the results summarized in Table I.

Despite the first three references received a bit higher neutron fluence, we realize that the degradation of ADR420 & ADR430 is not as important as that observed in the other references. An example of this is the behavior of line regulation. An increase of

10 V in the power supply value would drive the output voltage of the irradiated REF102 to undergo an increase of 0.9 %. On the contrary, ADR420 would show an increase of only 0.2%.

The short circuit current, which is a witness of the degradation of the output stage, brings more interesting data. In fact, while other references only provide a current of several mA, that of ADR420 has been scarcely affected since the highest output current is of several tens of mA. On the contrary, the tolerance of ADR291 is so low that it has been put aside in this discussion and its use in rad-tolerant systems should be avoided.

VII. Conclusion

XFET voltage references in a radiation environment will suffer a degradation characterized by a shift of the output voltage, an increase of line regulation, a lower consumption and, finally, a diminution of the short circuit current. Moreover, this degradation seems to be much more important in the micropower models of the XFET family (ADR291). The physical mechanisms that explain the degradation of the references have not been completely identified because of the presence of an internal source current with unknown characteristics. However, other details of the degradation have been related to the degradation of the internal op amp or to the degradation of other kinds of voltage references.

Finally, a comparison among XFET references and models based on the band-gap and Zener cells has proved that some models of XFET family would be good candidates for a use in electronic systems supposed to be exposed to radiation.

Acknoledgments

The authors would like to thank to the staff of the Portuguese Research Reactor all the help and support shown during the performance of the irradiations, as well as the measure of the total radiation dose from the nickel foils and the ionization chamber.

References

[1] P. R. Gray and R. G. Meyer, *Analysis and Design Analog Integrated Circuits*, John Wiley & Sons, 1993.

[2] W. Jun, “References and Low Dropout Regulators”, *Technical Article from Analog Devices*

[3] B. G. Rax, C. I. Lee and A. H. Johnston, “Degradation of precision reference devices in space environments”, *IEEE Transactions on Nuclear Science, Vol. 44, nº 6, pp. 1939-1944, December 1997*

[4] J. F. Krieg, C. J. Norman, M. W. Savage, J. L. Titus, D. Emily, G. W. Dunham, N. Van Vonno and J. Swonger, “Comparison of total dose effects on a voltage reference fabricated on bonded-wafer and polysilicon dielectric isolation”, *IEEE Transactions on Nuclear Science, Vol. 47, nº 6, pp. 2561-2567, December 2000*

[5] C. I. Lee et A. H. Johnston, “Comparison of total dose response on high resolution analog-to-digital converter technologies”, *IEEE Transactions on Nuclear Science, Vol. 45, nº 3, pp. 1444-1449, June 1998*

[6] W. Abare, F. Brueggeman, R. Pease, J. Krieg and M. Simons, “Comparative analysis of low dose-rate, accelerated, and standard cobalt-60 radiation response data for a low-dropout voltage regulator and a voltage reference”, *IEEE Radiation Effects Data Workshop, pp. 177-180, July 2002*

[7] S. S. McClure, J. L. Gorelick, R. L. Pease, B. G. Rax and R. L. Ladbury, “Total dose performance of radiation hardened voltage regulators and references”, *IEEE Radiation Effects Data Workshop, pp. 1-5, July 2001*

[8] J. G. Marques, A. C. Fernandes, I. C. Gonçalves an A. H. Ramalho, “Test facility at the Portuguese Research Reactor for Irradiations with Fasts Neutrons”, *Proceedings of the Workshop on Radiation Effects on Components and Systems, RADECS 2004, Madrid (Spain), September 2004, pp. 335-338*

[9] J. G. Marques, head of Portuguese Research Reactor, private communication

[10] G. C. Messenger and M.S. Ash, *The Effects of Radiation on Electronic Systems, 2nd Edition,* Van Nostral Reinhold, NYC, 1992

[11] A. H. Johnston, “Hand analysis techniques for neutron degradation of operational amplifiers”, *IEEE Transactions on Nuclear Science, Vol. 23, nº 6, pp. 1709-1714, December 1976*

[12] P. C. Adell, R. D. Schrimpf, W. T. Holman, J. L. Todd, S. Caveriviere, R. R. Cizmarik and K. F. Galloway, “Total dose effects in a linear voltage regulator”, *IEEE Transactions on Nuclear Science, Vol. 51, nº 6, pp. 3816-3821, December 2004*

[13] J. Boch F. Saigne, S. Ducret, R. D. Schrimpf, D. M. Fleetwood, P. Iacconi and L. Dusseau, “Total dose effects on bipolar integrated circuits: characterization of the saturation region”, *IEEE Transactions on Nuclear Science, Vol. 51, nº 6, pp. 3225-3230, December 2004*

[14] F. J. Franco, Y. Zong, J. Casas-Cubillos, M. A. Rodríguez-Ruiz and J. A. Agapito, “Neutron Effects on Short Circuit Currents of Bipolar Op Amps and Consequences”, *Proceedings of the Workshop on Radiation Effects on Components and Systems, RADECS 2004, Madrid (Spain), September 2004, pp. 213-220.* Also accepted for publication in the 2005 October issue of IEEE Transactions on Nuclear Science.

[15] Erric database, *http://erric.dasiac.com*