System-level testing and qualification of environmental sensors for nuclear decommissioning

A. Urena-Acuna[1*], J. Favrichon[1], E. Cantrel[1], P. A. Robin[2], A. Balier[2], T. Maraine[3], F. Saigné[3], J. Boch[3]

[1] French Alternative Energies and Atomic Energy Commission (CEA, DES, ISEC, DPME, SEIP), Univ. Montpellier, Marcoule, France
[2] ISYMAP society, France
[3] Université de Montpellier, IES-UMR UM/CNRS 5214, France
(*) alejandro.urenaacuna@cea.fr

***Abstract*— In this work, we show the first steps of a system-level qualification methodology for a series of Commercial Off-the Shelf (COTS) environment sensors subjected to Total Ionizing Dose (TID). We demonstrate a correlation between the degradation of electrical signals such as consumption current and functional failures in sensor measurements. The sensors were irradiated using high-energy X-rays and ^{60}Co under different biasing cases in order to determine their worst-case scenario.**

***Keywords* — Consumption current, Environmental Sensors, Qualification Methodology, System-level test, Total Ionizing Dose,**

I. Introduction

Decommissioning of nuclear facilities uses electronic equipment (sensors, mobile vectors, robots, remotely operated arms, etc.) in an irradiating environment. When using Simultaneous Localization And Mapping (SLAM) systems, we require the measurement of multiple sensors to measure the environment and collect data. However, the effect of radiation is one of the main factors affecting the reliability of electronic components and systems. The degradation in the performance of the different blocks could induce electrical disturbances that affect the reliability of the entire system. The effects of the TID in elementary devices such as Metal-Oxide-Semiconductor Field Effect Transistors (MOSFET) and Bipolar Junction Transistors (BJT) are well known [1-3]. Typical effects manifest as a threshold voltage shift (ΔV_{th}), as a variation in the Subthreshold Slope (ΔSS), as an increase in leakage currents (ΔI_{off}) in the case of MOSFETs, and as a loss in the factor gain (β) and the Enhanced Low Dose Rate Sensitivity (ELDRS) in the case of BJTs [2,3]. In complex systems, this causes an impact on the operating frequency, an increase in power consumption, and functional errors in addition to partial or total failures [4]. For instance, it is essential to qualify these systems in order to determine their dose resistance and to ensure the reliability of the measurements during a mission of nuclear decommissioning.

Several standards to qualify COTS devices under TID, such as MIL-STD-883 method 1019, the European Space Component Coordinate (ESCC) standard 22900, and JEDEC Solid State Technology Association, have been established but they only focused on the component level and the dose rates are adapted to space environments. Nevertheless, system-level testing and qualification methodologies for COTS systems under TID are current challenges due to the complexity of actual systems. Their radiation response strongly depends on the type of environment, the biasing conditions, and the different blocks that compose the system (i.e. power, logic, memory, etc) in addition to factors inherent to the manufacturing processes such as lot-to-lot variability. Then, to characterize their radiation response, it is essential to design a strategy that allows us to qualify and determine the blocks prone to fail during a mission in a civilian nuclear environment.

Therefore, the goal of this work is to explore a system-level testing and qualification methodology for COTS environmental sensors. This paper is organized as follows: Section II describes the tested devices, the experimental setup, the radiation conditions as well as the qualification criteria. Section III shows the electrical and functional degradations of the irradiated sensors. In Section IV, we determine the worst-case biasing as well as the qualification of the irradiated devices. Section V explains the first steps of the proposed qualification methodology. Finally, the conclusions of this work are shown in Section VI.

II. Tested devices and Experimental conditions

A. Tested devices

The tested devices were MCP9808 digital temperature sensor and VL53L0X Time of Flight (ToF) distance sensor [5, 6]. Both sensors can communicate via I2C protocol with a host computer. Previous studies have shown the resilience to ionizing radiation of these sensors [7, 8]. In [7] a series of VL53L0X ToF distance sensors were exposed to a 60Co source. Here a progressive increase in the consumption current is shown and at 5.8 kGy, the sensors were still working. In [8], a study is presented where the MCP9808 digital temperature sensor was irradiated. The sensor presents functional failures in its measurements from 80 Gy, however, the possible correlation with the consumption current of the circuit is not shown.

B. Experimental setup

Forty sensors of two different lots (L1 and L2) were irradiated to qualify their radiation response. The tested devices were 20 MCP9808 digital temperature sensors and 20 VL53L0X Time of Flight (ToF) distance sensors. Functional and electrical parameters were monitored before, during, and after irradiation. The consumption current (I_{cons}) was monitored using a Keysight N6705C power analyzer. The devices communicate under the I^2C protocol with a microcomputer (Nvidia Jetson-nano) and a script was designed to acquire two measurements per second in a CSV file for post-data processing as shown in Fig 1. The VL53L0X was positioned at 160 mm from a target to get a distance reference.

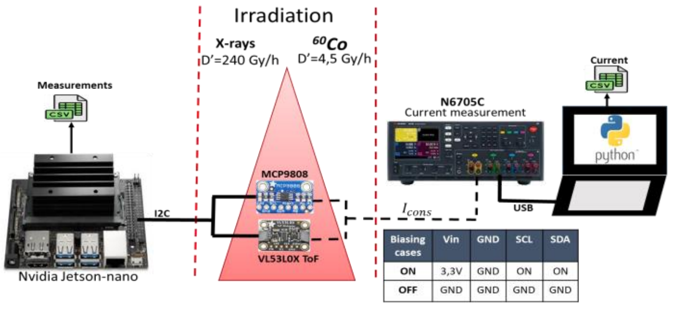


Fig. 1. Experimental setup.

C. Radiation and biasing conditions

All devices were irradiated with the PRESERVE platform at the Institut of Electronics and Systems (IES) in Montpellier, France with a 320 keV X-rays generator with a 2 mm aluminum filter to eliminate photons with low energies and under a ^{60}Co source (Fig. 3). The applied dose rate was 240 Gy/h (SiO_2) for X-rays and 4,5 Gy/h for ^{60}Co. All sensors were biased in two different modes during irradiation to determine the worst-case of biasing as depicted in Fig. 1. The OFF state, with all pins connected to the ground, and the ON state, where the sensor operates in normal biasing mode. The number of tested devices can vary in each experiment. The radiation was done in several steps to monitor the TID-induced degradation until the sensor's failure was reached.

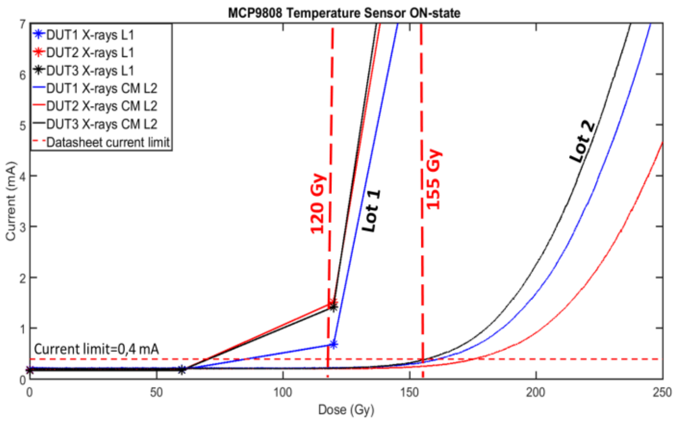
D. Qualification criteria

We seek to demonstrate that the increase in consumption current produced by the TID beyond the datasheet current limit can induce total or partial loss of functions of the sensors. For this reason, the first parameter to monitor is the consumption current of the sensor as a function of the absorbed dose. Therefore, to qualify these sensors, we based on three criteria: a) the communication with the microcomputer, b) The consumption current (I_{cons}), where the limit is set according to the maximum current limit (I_{limit}), reported by the device's manufacturer (datasheet) and c) we propose a tolerance of 10% on the accuracy of the sensor measurements in order to keep good reliability in the functional measurements. We define dose tolerance as the dose limit at which at least one of these three criteria is not satisfied.

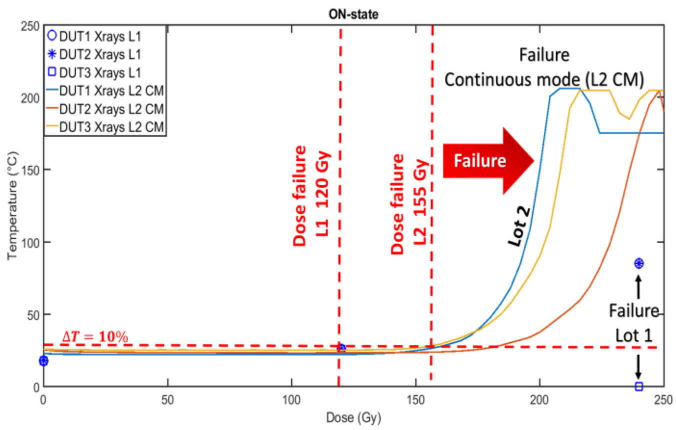
III. RESULTS

A. MCP9808 digital Temperature sensor

We observe in Figure 2 the radiation response of the MCP9808 temperature sensor. The I_{limit} for this sensor is 0.4 mA according to the datasheet [5]. In Fig. 2(a) we show the I_{cons} measurements of L1 and L2 irradiated with X-rays. L1 was irradiated in step-by-step mode while L2 was in continuous mode (CM) with one measurement per minute. We noticed an increase in I_{cons} for both lots when the dose increases beyond 120 Gy. We observe functional failures manifested as errors in the accuracy of the temperature measurements when I_{cons} exceed I_{limit}, as shown in Figure 2(b). Devices from L2 were irradiated with the ^{60}Co source. The degradations of these devices are similar to those irradiated under X-rays. For this reason, only X-ray irradiated devices from L2 are shown in Figures 2 and 3.



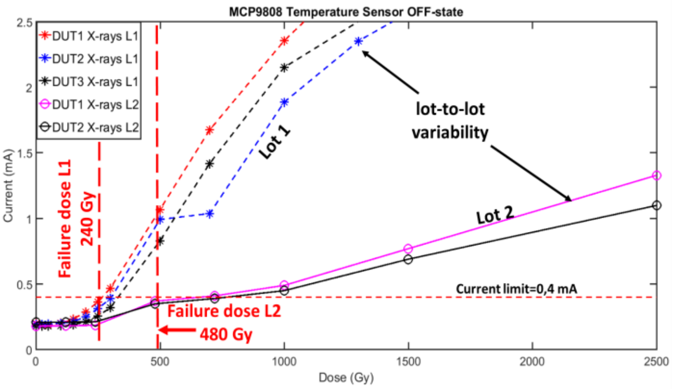
(a) Consumption current of the MCP9808 digital temperature sensor irradiated in ON state



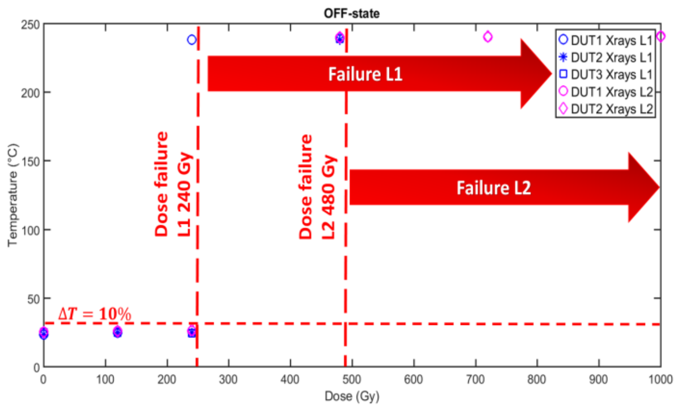
(b) Temperature measurements of the MCP9808 digital temperature sensor irradiated in ON state

Fig. 2. Consumption current and temperature measurements of MCP9808 digital temperature sensor

Figure 3 shows the MCP9808 temperature sensor irradiated in the OFF state. In Fig.3 (a) the increase in I_{cons} is much less important than the case in the ON state. This is due to the absence of an electric field during irradiation. As reported in [9], the probability of non-recombination of charges created by ionizing radiation decreases in the absence of an electric field. That is, the charges created are close to each other, stimulating their prompt recombination. Therefore, the radiation damage in the device is less important.



(a) Consumption current of the MCP9808 digital temperature sensor irradiated in the OFF state



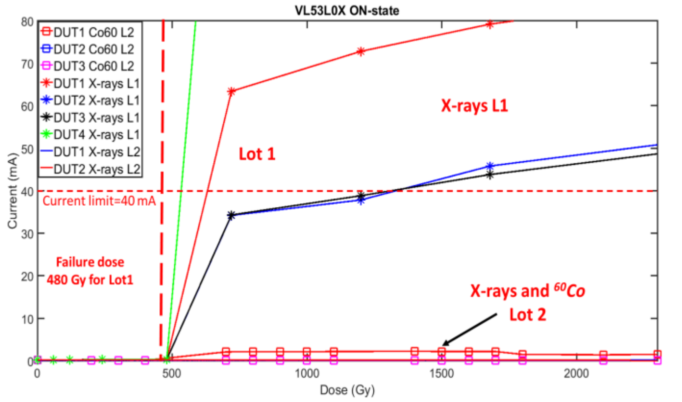
(b) Temperature measurements of the MCP9808 digital temperature sensor irradiated in the OFF state

Fig. 3. Consumption current and temperature measurements of MCP9808 digital temperature sensor irradiated in OFF state

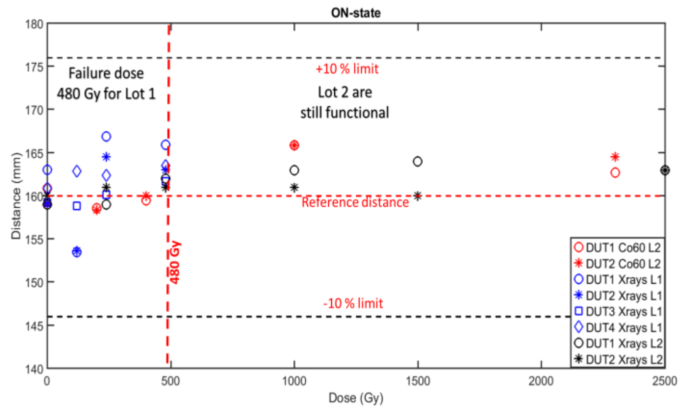
In Figure 3(a) and (b) we noticed the lot-to-lot variability. In Figure 3 (a) we notice that L1 and L2 exceed I_{limit} at 240 Gy and 480 Gy respectively. This has an impact on the functional measurements depicted in Fig 3(b), where the temperature increase from 24 °C to 240 °C at these dose levels. The effect of biasing is clearly identified, where the dose tolerance is higher than the devices irradiated in the ON state.

B. VL53L0X ToF distance sensor

Figure 4 shows the electrical and functional measurements of the VL53L0X distance sensors irradiated in the ON state. The I_{limit} established by the manufacturer is set at 40 mA [6]. We observe in Fig 4 (a) an increase in I_{cons} beyond the 40 mA limit for devices of L1 at 480 Gy. This has an impact on the communication with the host microcomputer. As shown in Figure 4(b), a total loss of measurements is reported for L1 at 480 Gy. L2 irradiated with X-rays and ^{60}Co in both biasing modes never exceeded the current limit so, its functionality and accuracy were not affected during the irradiation. This is due to the lot-to-lot variability of the devices. The devices of L1 and L2 irradiated in the OFF state never exceed the current limit, so, their functionality was not affected at the maximum dose level reached of 3250 Gy.



(a) Consumption current of the VL53L0X ToF distance sensor irradiated in the ON state



(b) Distance measurements of the VL53L0X ToF distance sensor irradiated in ON state

Fig. 4. Consumption current and temperature measurements of VL53L0X irradiated in the ON state

IV. WORST-CASE BIASING

As observed in Figures 3 and 4, sensors irradiated in the ON state showed the highest variation in consumption current and lower dose tolerance than those irradiated in the OFF state. This is well known according to the literature, where the application of an electric field during radiation prevents the prompt recombination of charges in the insulating oxides of single transistors. This factor causes a higher electrical degradation in the device's performance [9]. Based on the previously established qualification criteria, Table 1 shows the qualified dose tolerance for both sensors for the ON and the OFF states.

TABLE I
QUALIFIED DOSE TOLERANCE OF THE DIFFERENT SENSORS

Sensor	Dose Tolerance (Gy)		Worst-case Biasing
	ON	OFF	
MCP9808	120 Gy L1 155 Gy L2	240 Gy L1 480 Gy L2	ON
VL53L0X	480 Gy L1 3000 Gy L2	>3000 Gy L1 and L2	ON

V. SYSTEM-LEVEL METHODOLOGY

The study carried out in this work represents the first steps for a system-level testing and qualification methodology. This work allows us to establish some general rules:

1. - Determine the radiation environment in order to determine the dose rate.
2. - Analyze the system under test (DUT). Radiation effects differ depending on the type of technology. Therefore, certain effects such as (ELDRS) must be considered when using BJTs based devices.
3. - Determine the auxiliary signals to monitor the subsystem's performances (power, logic, etc). This allows the detection of the radiation-sensitive subsystems.
4. - Establish electrical and functional margins and conditions. The limits of the electrical parameters must be chosen according to the manufacturer's datasheet. In addition, to reduce or eliminate lot-to-lot variation, it is recommended to use single-lot systems.
5. - Irradiate the components with an X-rays generator under different biasing modes to determine the worst case.
6. - Confirm the effects with an irradiation in ^{60}Co. An inconvenience of the existing test methodologies arises from the use of ^{60}Co as an irradiation reference. In general, the use of this means of radiation implies a high cost, both in the facilities and in radioprotection. In the long term, the use of high-energy X-rays could be convenient due to their simplicity in terms of maintenance, radioprotection, and speed in obtaining results.

VI. CONCLUSIONS

In this work, we show the first steps of a system-level test methodology. We have demonstrated the correlation between an increase in the consumption current and functional failures in the sensor measurements. This fact is a good indicator to diagnose that a functional failure is approaching when the consumption reaches the established current limit. In addition, we noticed a lot-to-lot variability that influences the radiation response of the devices. A strategy to avoid this situation is the use of systems with similar characteristics (manufacturer, supplier, package material, origin, etc) and only representative samples would undergo qualification testing. In order to validate the test methodology, we confirm the results by a ^{60}Co irradiation. Nevertheless, in the long term, we seek to use only high-energy X-rays. This could represent multiple advantages in terms of cost, speed of testing, maintenance and radioprotection.

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