Total ionizing dose response of commercial off-the-shelf microcontrollers and operational amplifiers

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***Abstract*—The response to total ionizing dose of several microcontrollers and operational amplifiers was evaluated under ^{60}Co irradiation. The MSP430FR5994 microcontroller and the ADA4622-1 operational amplifier were fully functional after a cumulated dose of 490 krad.**

***Index Terms*—Microcontroller, Operational amplifier, Radiation effects, Total ionizing dose.**

I. Introduction

THE possibility of extending the operating life span of nuclear power plants beyond their initial design life (30-40 years), which several countries in the world are now considering[], has emphasized the need for a better knowledge of the state of health of components situated in the containment building. As a matter of fact, the concern for safety increases as the materials and structures properties get degraded from their initial values with prolonged exposure to harsh environments. A deeper knowledge of environmental conditions existing in a containment building is thus essential for assessing the state of health of components.

To address this need, Electricité de France (EdF) has initiated with the CEA in the 2000's the study of the Microdose, an autonomous embedded device aimed to measure and record the total ionizing dose (TID) and temperature exposure of electric cables in a Nuclear Power Plant (NPP) []. The goal was to correlate the degradation observed on the cables with the TID and temperature profiles recorded over a long period.

In 2017, after the obsolescence of some electronic components, EdF asked us to make evolve the Microdose as we had designed the initial hardened version. The components that had to be replaced were the microcontroller, the non-volatile memories and some operational amplifiers used in analog measurement circuits.

In this work, several commercial off-the-shelf (COTS) microcontrollers and operational amplifiers from different vendors were tested for evaluating their TID tolerance. The purpose was to identify radiation tolerant components for the design of a new hardened version of the Microdose.

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II. Component selection

A. Background

A survey was first conducted to help select candidate components for the TID testing. We noticed that the majority of currently published work is related to the space domain. Hence, many studies report irradiation results up to only dozens of kilorads.

The radiation tolerance of different flash-based microcontrollers was evaluated for space applications in [1], [2] and [3]. The results showed that all microcontrollers failed between 5 and 30 krad due to their flash memory that could no longer be written. On the other hand, the MSP430FR5739 produced by Texas Instruments was tested in [4]. This microcontroller uses ferroelectric random-access memory (FRAM) as opposed to other flash-based models. The TID test results showed that the MSP430FR5739 was fully functionnal after 212.8 krad at the end of the test. This kind of microcontroller is therefore of great interest to us.

Operational Amplifiers can show large degradation of their characteristics when exposed to radiation, even at TID levels of less than 50 krad. Several studies have shown that the frequency response, input bias currents and offset voltage are the most sensitive parameters [5], [6], [7]. In addition, bipolar operational amplifiers may show ehnanced low dose rate sensitivity (ELDRS) to total dose [8], [9]. However, in [4], this effect was not evidenced with a bipolar operational amplifier equipped with junction field effect transistors (JFET) on its inputs.

B. Components selected for testing

As the good tolerance to TID of a FRAM microcontroller was demonstrated, we have chosen four different models produced by Texas Instruments that embed this type of memory. The main characteristics of these components are summarized in Table I.

Table I
Microcontrollers.

Reference	FRAM	SRAM	ADC	GPIO
MSP430FR5994	256 kb	8 kb	12 bits	54
MSP430FR6989	128 kb	2 kb	12 bits	63
MSP430FR5739	16 kb	1 kb	10 bits	32
MSP430FR4133	16 kb	2 kb	10 bits	60

These MSP430 ultra-low-power microcontrollers use embedded FRAM to lower energy consumption. This memory technology allows low-energy fast writes with nonvolatile behavior.

The operational amplifiers that were selected are low-power CMOS or bipolar types from different manufacturers. The selection criteria were power consumption, single supply voltage, rail-to-rail operation, offset voltage and bias current. One can see the characteristics of these amplifiers in Table II.

Table II
OPERATIONAL AMPLIFIERS.

Manuf.	Reference	VS	Iq	Vos	Ib
TI	OPA197	36 V	1.5 mA	100 μV	20 pA
TI	OPA192	36 V	1.5 mA	40 μV	20 pA
AD	ADA4622-1	30 V	0.78 mA	350 μV	10 pA
AD	AD8663	16 V	0.36 mA	300 μV	0.3 pA
AD	LTC6013	36 V	0.31 mA	135 μV	400 pA

The OPA192, OPA197 and AD8663 are CMOS operational amplifiers while LTC6013 and ADA4622-1 are bipolar components.

III. EXPERIMENTAL DETAILS

A. Testing procedure

Since the Microdose is a battery-powered device, its electronic circuits are switched-on only when needed, i.e. when measurement of the TID and temperature sensors must be realized. This means that most of the time, almost all components are unbiased. A hardware time base, which is continuously powered-on, wakes up the embedded microcontroller at regular time intervals. On the other hand, the MSP430 microcontrollers can be woken by their real-time clock (RTC) when in deep sleep mode. We have planned to test also this possibility during the irradiation. The experimental conditions have been finally defined taking into account these operating modes: we decided to use two samples of each microcontroller for the irradiation test.

Two identical modules (n°1 and n°2) were used for each tested operational amplifier reference. Both modules were biased the same way, i.e. powered-on by the test bench. On each module, the tested device was configured as a unity gain differential amplifier with a 6.2V reference diode connected across its inputs as shown in Figure 1.

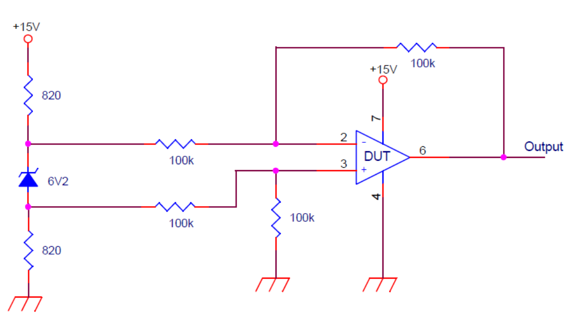

Figure 1. Operational amplifier test circuit.

We used two identical developpement boards by microcontroller reference for the radiation test: the first (board n°1) was powered-up by the test bench, that corresponds to the principle used in the current Microdose, and the second (board n°2) was woken by its RTC in deep sleep mode.

The test program installed in each microcontroller was designed to verify the operation of different internal blocks and transmit the result of these tests over a serial link. The tested functions were the 16-bit cyclic redundancy check (CRC) generator, the 32-bit multiplier, the FRAM memory and the analog to digital converter (ADC).

The CRC generator was tested by comparing its calculation result to that given by a software routine applied to the same data set. The multiplier was tested in a similar way by comparing the result it provided to a theoretical value. To test the FRAM memory, a block of cells was read and written periodically to check the memory retention and writing capability. The test of the ADC was done by digitizing a sinusoidal signal sent to one of its inputs.

A common program was developped for both developpement boards: distinction between the two wake modes was made dynamically at start-up. The flowchart of this embedded program is shown in Figure 2.

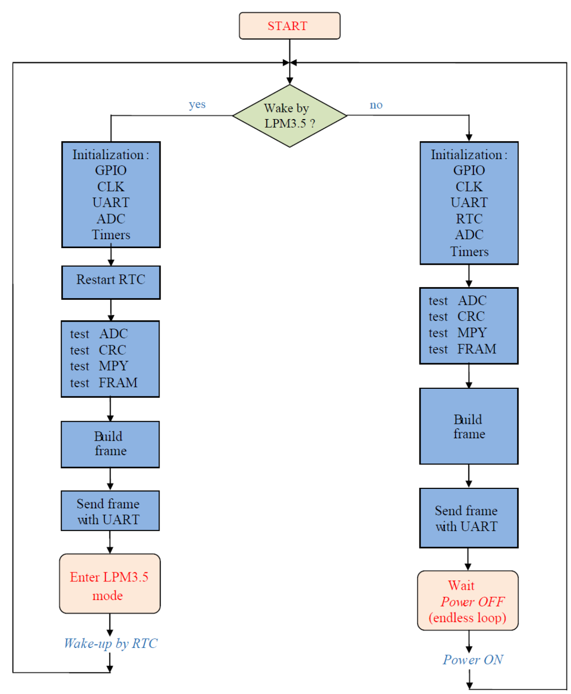

Figure 2. Flowchart of the program in the microcontrollers.

A dedicated test bench was built for the irradiation test. The bench comprized a NI UART-USB probe, an Agilent 34970A data acquisition unit, a signal generator and a control PC. The data acquisition unit ensured signal multiplexing, acquisition of operational amplifier output voltages and switching of the test board power supplies. The signal generator was used to provide a sinusoid on the ADC inputs of the microcontrollers. A Labview program on the PC was in charge of the acquisitions and data backup on a hard drive. The acquisition period was set at 45 minutes on the PC.

B. Irradiation

All the devices have been irradiated in the IRMA facility at the CEA-Saclay research centre (France). This is a gamma irradiator equipped with four ^{60}Co sources (the total activity was 805 TBq in July 2019). This 24 m^3 irradiation cell is used to study the effects of gamma rays on materials. In this facility, the dose rate can range from 1 Gy/h to 12 kGy/h.

The tested devices have been placed in the irradiation chamber before the experiment at locations determined by a preliminary dose rate measurement. A common dose rate of 3 krad/h was used for all components in order to get a culmulated dose of 500 krad after a week of irradiation. This value was determined taking into account the radiation hardness of the current version of Microdose which was qualified for 300 krad.

IV. Results

A. Microcontrollers

Table III shows the results of microcontroller boards n°1 that were powered-on by the test bench. The table includes test data of the CRC generator, the FRAM memory, the 32-bits multiplier (MPY) and the ADC. The percentage value given in the table for the ADC corresponds to the maximum relative conversion error found.

We can see that all microcontrollers on these boards were still functionnal at the end of the test after a cumulated dose greater than 490 krad. The CRC generator, the MPY and the FRAM memory did not show any error during the whole test. The ADC worked correctly but showed a slight drift of their characteristics due to the degradation of the internal volage reference. However, these drifts remain acceptably low and should not penalize the sensor measurement in the Microdose.

Table III
Results for microcontroller boards n°1.

Reference	CRC	FRAM	MPY	ADC
MSP430FR5994	PASS	PASS	PASS	-2.5%
MSP430FR6989	PASS	PASS	PASS	+2.2%
MSP430FR5739	PASS	PASS	PASS	+1%
MSP430FR4133	PASS	PASS	PASS	+2.8%

The results of microcontroller boards n°2, that were permanently in deep sleep mode and woken by their RTC, are given in Table IV. The values in the table correspond to the maximum TID level observed before a failure.

Table IV
Results for microcontroller boards n°2.

Reference	CRC	FRAM	MPY	ADC
MSP430FR5994	7.5 kad	7.5 kad	7.5 kad	7.5 kad
MSP430FR6989	7.5 kad	7.5 kad	7.5 kad	7.5 kad
MSP430FR5739	7.5 kad	7.5 kad	7.5 kad	7.5 kad
MSP430FR4133	70 krad	70 krad	70 krad	70 krad

We see that all the devices on the boards n°2 failed early, between 7.5 and 70 krad. The microcontrollers no longer woke up at the end of the deep sleep period. This mode involves the component being permanently powered, which corresponds to the worst case for CMOS technologies. Moreover, the circuits that manage the internal power supply are probably sensitive to TID. Therefore, the slightest drift could be sufficient to prevent the component from waking up.

The power supply currents of all the different microcontroller boards were measured during the irradiation test. The evolution of the supply current of CMOS devices during an irradiation is indeed a good indicator of their degradation. The plot of the current drawn by microcontrollers on boards n°1 is shown in Figure 3. Currents for boards n°2 are not included as these microcontrollers failed early.

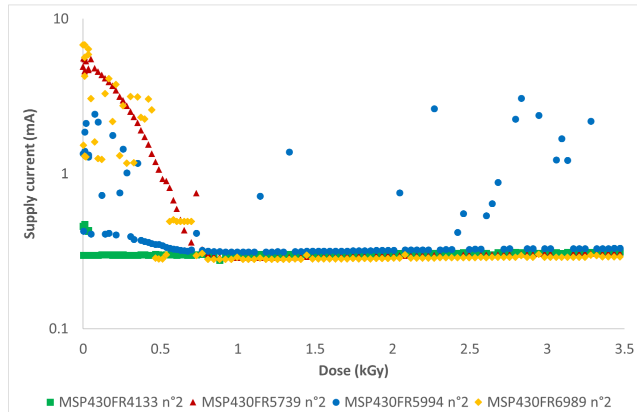

Figure 3. Power supply currents of microcontrollers on boards n°2. The abscissa scale is limited to 350 to highlight the initial variations.

All the current consumption curves show a deacrease tendency up to 80 krad. After that dose level, the power consumption remains stable until the end of the test.

B. Operational amplifiers

We can see the response of the tested operational amplifiers in Figure 4. For each reference, the graph includes the plot of the output voltage of amplifiers n°1 and n°2.

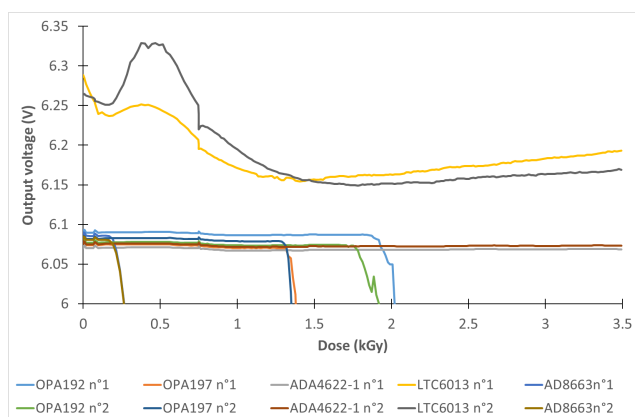

Figure 4. Output voltage of operational amplifiers circuits variation during irradiation. The abscissa scale is limited to 350 to highlight the initial variations.

The AD8663 amplifiers were the first to fail at a dose of 25 krad. Their output voltage dropped sharply from 6V to 0V and then remained stuck at +15V. The OP197 devices withstood a dose of 130 krad before their output voltage started to drop. From that point onward, their voltage drifted to 0V and remained in this state until the end of the test. The best of the OP192 amplifiers worked correctly up to 1.9 kGy without big variations of its output voltage. Then the two devices presented the same decreasing trend towards 0V as other amplifiers. The LTC6013 devices remained functional until the end of the test but presented significant drifts (more than 100 mV) on their output. The increase of input bias currents is most probably the reason of such behaviour. The only devices that passed successfully the test are the two ADA4622-1 from Analog Devices. Their output voltage variation remained below 8 mV, i.e. 0.12%, during the irradiation.

Based on these irradiation results, we chose the micro-controller MSP430FR5994 from Texas Instruments and the operational amplifier ADA4622-1 from Analog Devices for the design of the new Microdose.

V. Conclusion

Four references of FRAM-based microcontrollers and five references of CMOS or bipolar operational amplifiers have been irradiated with ^{60}Co sources up to 500 krad to assess their TID tolerance. The objective of this work was to identify candidate components for the design of a hardened autonomous device aimed to measure environmental parameters in a NPP containment building.

Experimental results show that the total dose tolerance of the tested FRAM-based microcontrollers from Texas Instruments is greater than 490 krad in unbiased mode. The MSP430FR5994 is particularly of interest thanks to its large amount of program memory. However, when these microcontrollers are configured to use the deep sleep mode, their TID tolerance can be much lower.

Almost all of the tested operational amplifiers experienced a total failure or important drifts of their output under irradiation. The bipolar amplifier ADA4622-1 from Analog Devices is the only device which output voltage variation remained low during the test.

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