Radiation-Induced Destruction Testing of Microcontrollers.

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Abstract: Microcontrollers are crucial microchips that have a wide range of applications in electronic circuits. They are used in systems as simple as IoT-based home automation to sophisticated satellite systems orbiting the planet. Depending on the industry, microcontrollers may be exposed to different types of radiation. For instance, in power stations, they may be exposed to nuclear radiation while monitoring background radiation levels. Similarly, in satellite systems, they may be exposed to cosmic radiation. This study aims to determine the safe levels of exposure of microcontrollers to concentrated gamma radiation before they malfunction. Additionally, the paper highlights some materials that can be used for shielding to protect and prolong the microcontroller's operating life during an irradiation process.

1. Introduction:

In many electronic circuits and printed circuit boards (PCBs), microcontrollers serve as the foundation where programs are stored, run, and connected to various sensors, motors, and other peripheral inputs and outputs based on the designers' specifications. There may be instances where microcontrollers will be utilized in applications or systems that operate in extremely hazardous environments, such as the energy sector (Nuclear, Oil, Gas, and Electricity) to observe and document environmental factors or obtain readings from sensors. They can also control valves, servos, lights, and alarms, dictate the flow of materials or services, make decisions based on sensor readings, and send alerts or alarms for emerging situations. In the nuclear industry, microcontrollers can be utilized in sensor networks to monitor environmental factors and record details of background radiation. In areas of high radiation, microcontrollers and their peripherals may become contaminated and malfunction. This study aims to determine the levels of radiation that microcontrollers can handle before malfunctioning, succumbing to radiation, and being damaged beyond further use.

2. Literature Review:

This is a short literature review, as there has only been one recorded project like what is being researched within this paper. Violette, D.P (2014)[1] explained in his PowerPoint presentation that the National Aeronautics and Space Administration (NASA) conducted an irradiation experiment in 2014 at the Goddard Space Flight Centre (GSFC) for their CubeSat programme, which entailed irradiating several Arduino Uno's containing the ATMEL ATMega 328 8-bit microcontroller.

The Arduinos were individually placed inside a box (Shielding) consisting of Aluminium and Lead, this experiment conducted at NASA only used one type of shielding for this experiment; it also does not state the type of radiation source used.

The research project investigated the Total Ionising Dose Degradation of both the Arduino Uno microcontroller and the Raspberry Pi minicomputer for their CubeSat programme.

The results that they have produced differ from this project. This could be because of the type or source of radiation (Cobalt, Caesium etc) or the type or irradiation process (e.g.: Ion Beams, Gamma Chambers, X-ray etc), or the materials used in the shielding.

3. Proposed Method:

For this project, the most important pieces of equipment were the

1. Arduino Uno Rev 3[2],
2. 16x2 Liquid Crystal Display (LCD) with I2C Controller[3] for reading outputs from the Arduino microcontroller,
3. Foss Services Model 812 Self-Contained Gamma Irradiator[4, 5]
4. Various shielding materials are used to prolong the life of the microcontroller during the irradiation process.

3.1: The Shielding Materials:

The following materials will be tested to identify their radiation-shielding properties:

1. Lead (10mm Thickness)
2. Code 3 Lead Flashing (1.32mm Thick) – Midland Lead[6].
3. 100% Concrete (10mm Thickness)
4. PLA 3D Printing Filament (10mm Thick)
5. PLA+ 3D Printing Filament (10mm Thick)
6. PETG 3D Printing Filament (10mm Thick)
7. Steel (10mm Thick)
8. Aluminium (10mm Thick)
9. No Shielding Materials (No.1)
10. No Shielding Materials (No.2)

3.2: The Gamma Irradiator and source of radiation:

The Foss Services Model 812 Self-Contained Gamma Irradiator[4, 5] contains 3 source rods of Cobalt-60 (^{60}Co), with activity evenly distributed along each rod.

3.3: The Irradiation Dose Rates and Irradiation Times:

Cycle	Dose Rate	Time	TID	cTID
1	10Gy/Min	5 Mins	50Gy	50Gy
2	20Gy/Min	5 Mins	100Gy	150Gy
3	30Gy/Min	5 Mins	150Gy	300Gy
4	40Gy/Min	5 Mins	200Gy	500Gy
5	50Gy/Min	5 Mins	250Gy	750Gy
6	60Gy/Min	5 Mins	300Gy	1050Gy
7	70Gy/Min	5 Mins	350Gy	1400Gy
8	80Gy/Min	5 Mins	400Gy	1800Gy
9	90Gy/Min	5 Mins	450Gy	2250Gy
10	100Gy/Min	5 Mins	500Gy	2750Gy

Table 1: Irradiation Dose Rates.

TID = Total Ionising Dose.
cTID = Combined Total Ionising Dose.

3.4: The Setup of the Microcontroller:

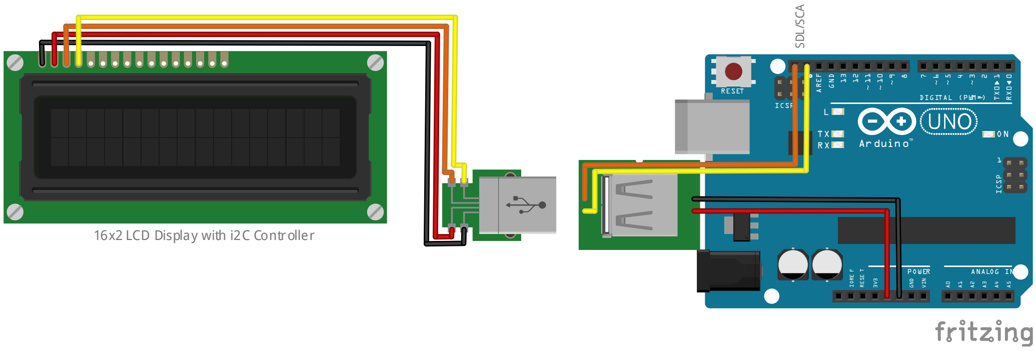

Figure 1: Microcontroller Setup for Irradiation.

3.5: The LCD Display Outputs:

When the microcontroller is going through the chamber test, there would be a 16x2 LCD connected via USB to the microcontroller, this will be connected to power pins 5v and Ground (GND) and also the data lines from the LCD will be connected to the SDA/SCL pins on the microcontroller, this allows data to be sent from the microcontroller to the LCD via an I2C controller on the back of the LCD unit.

3.5.1: The Correct Output to the LCD from the Microcontroller:

The correct output to the LCD will be as follows, anything displayed on the LCD that is not shown in figure 2 will be deemed a failure and a bench test will need to be conducted on the microcontroller.

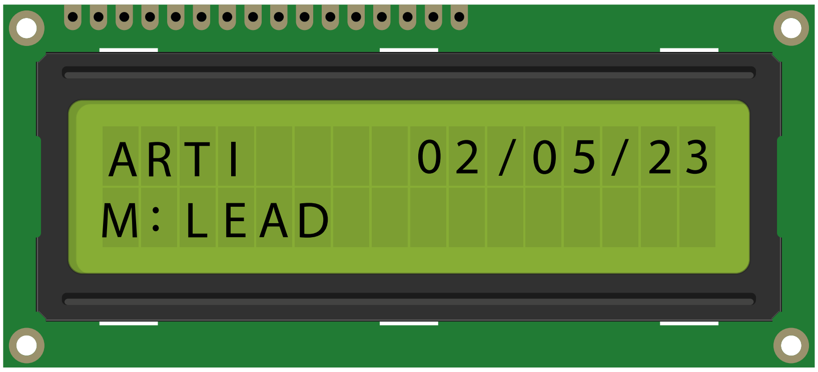

Figure 2: Correct Output to LCD Display.

3.6: The Irradiation Cycle

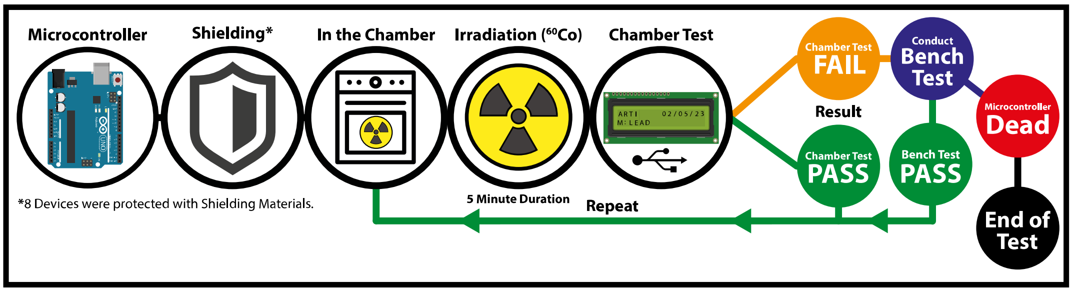

Figure 3: Irradiation Lifecycle per irradiation.

3.7 Grant Funding:

An application was submitted to the National Nuclear Users Facility[7] in November of 2022 to apply for a small users grant. The application was successful.

4. Implementation

As shown in Figure 3, the irradiation cycle entails placing the Microcontroller in its respective shielding material (as described in section 3.1) and exposing it to Cobalt-60 (60Co) radiation in the gamma chamber for 5 minutes. Following the completion of the irradiation process, the chamber door will be opened, and a test will be conducted. The microcontroller will be connected to an LCD via USB connections, and if the correct output is displayed, the microcontroller will be moved to the next location in the chamber for the subsequent irradiation cycle. However, if the LCD shows an incorrect output after an irradiation cycle, the microcontroller will be removed from the chamber, and a bench test will be conducted.

4.1 The Bench Test:

To ensure the successful execution of the Bench test, it is imperative to establish a connection between the microcontroller and a laptop while ensuring the Integrated Development Environment (IDE) recognizes it. Subsequently, it is necessary to upload a test sketch onto the board and attach additional peripherals, such as a Neo Pixel 8x1 RGB lightbar, Servo Motor, and an LCD. It is important to note that if the Bench test fails, it may indicate that the microcontroller has been irreparably damaged due to radiation exposure.

5. Results and Discussion

Irradiation Dose Rates Used Chart:

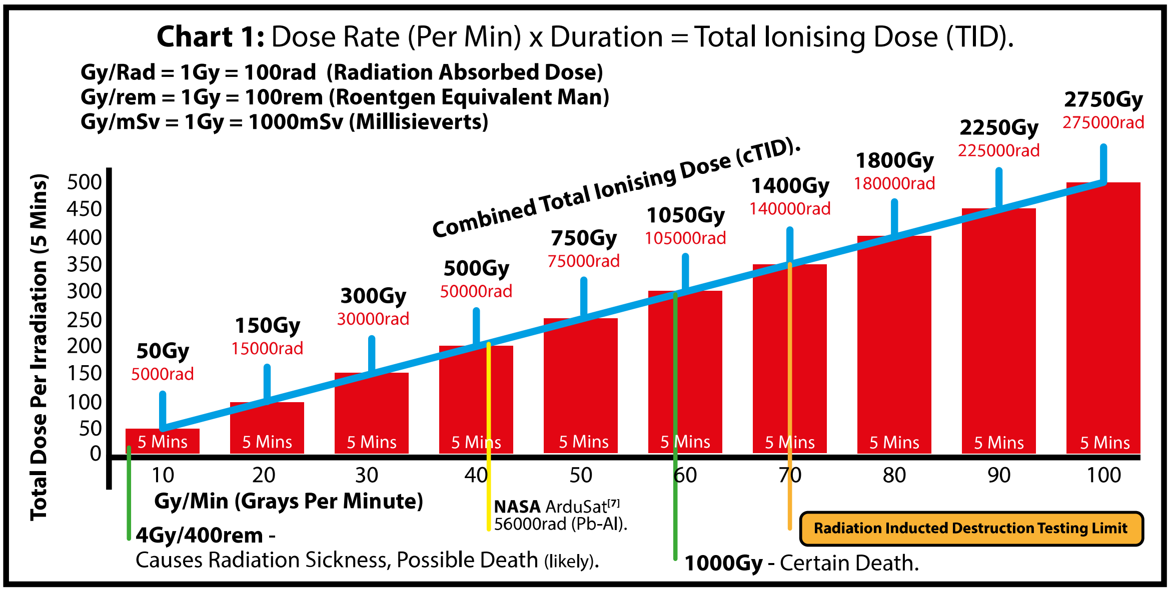

Figure 4: Irradiation Dose Chart - Dose Rates Used.

Observe Figure 4, which displays a linear graph showcasing the irradiation dose rates utilized and the increments in dosage during each cycle. The graph represents the dose rate in Gray's per Minute (Gy/Min), which is the standard unit of measurement for radiation on the SI scale. Notice the red bars that signify a 5-minute duration and provide the total ionizing dose (TID). Additionally, the blue line reveals that the microcontroller is exposed to a combined total ionizing dose (cTID) throughout the entire irradiation process.

Irradiation Results:

				Metals								Plastics						Other		No Shielding			
			Material:	Alu		Steel		Lead[1]		Lead[2]		PLA		PLA+		PETG		Cement		No.1		No.2	
			Thickness:	10mm		10mm		10mm		1.37mm		10mm		10mm		10mm		10mm		10mm		10mm	
Irradiation Details				02/05/2023		03/05/2023		03/05/2023		03/05/2023		02/05/2023		02/05/2023		02/05/2023		02/05/2023		02/05/2023		03/05/2023	
Dose Gy/Min	Time (Mins)	Total Gray's	TID Gray's	PWR	LCD	PWR	LCD	PWR	LCD	PWR	LCD	PWR	LCD	PWR	LCD	PWR	LCD	PWR	LCD	PWR	LCD	PWR	LCD
10	5	50	50	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
20	5	100	150	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
30	5	150	300	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
40	5	200	500	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
50	5	250	750	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P		
60	5	300	1050	P	P	P	P	P	P	P	?	P	P	P	P	P	P	P	P	P	P	TEST START	
70	5	350	1400	P	F	P	F	P	P	P	F	P	F	P	F	P	F	P	F	P	F	P	P
80	5	400	1800					P	P													P	P
90	5	450	2250					P	F													P	F
100	5	500	2750					TEST END														TEST END	

P = Live Test Pass, F = Live Test Failed and also Bench Test Failed, ? = Signs of Abnormal Functionality.
1 = Lead melted and poured into 10mm thick mould.
2 = Lead Flashing (Commercial Builders Code 3 Lead Flashing Material.) 1.37mm.

Figure 5: Irradiation Results.

The results of the irradiation process conducted on May 2nd and 3rd, 2023, at the Dalton Cumbrian Facility (DCF) are presented in Figure 5.

No Shielding Results:
The microcontroller underwent two tests under radiation without a protective shield. During the first test, it performed well, surviving until it reached the 60Gy/Min mark. However, it failed at the 70Gy/Min mark, just like the other microcontrollers with shielding. In the second test, a new microcontroller was used and exposed to radiation starting at 70Gy/Min. It showed remarkable resistance, surviving until 80Gy/Min and ultimately reaching its limit at 90Gy/Min.

5.1: Shielding Properties of materials used:
The tested materials, namely Aluminium, Steel, Lead Flashing, PLA, PLA+, PETG, and Concrete, proved ineffective in providing any supplementary shielding for the microcontrollers during the irradiation process. The microcontrollers were able to endure as much as 60Gy/Min or an overall ionising dose of 1050Gy. Nonetheless, at 70Gy/Min, the microcontrollers experienced a malfunction, and a bench test verified that all microcontrollers had sustained damage and were non-functional.

Based on our thorough testing, it has been determined that a lead thickness of 10mm provides the optimum protection against radiation. This specific lead can withstand doses of up to 70Gy/Min (1400Gy) and 80Gy/Min (1800Gy). However, it is crucial to consider the weight of the lead when deploying systems that require heavy lead shielding.

It has been conclusively proven that the claims made by lead flashing manufacturers regarding the radiation shielding capabilities of their Code 3 Lead Flashing at 1.32mm[7] were entirely false. This product provided no protection whatsoever for the microcontroller against radiation, rendering it just as ineffective as steel or aluminium.

6. Conclusion

It is evident from the tests conducted on various shielding materials that none of them can guarantee the protection of the microcontroller beyond the 70Gy/Min mark or 1400Gy Total Ionising Dose (TID) Rate. However, by using a 10mm thick Lead, additional protection can be provided, enabling the Arduino to withstand gamma radiation up to 90Gy/Min or 2250Gy TID. Despite being the most effective shielding material, the weight of Lead must be considered before deploying microcontrollers or electronic systems in hazardous environments.

Further research is imperative to investigate alternative materials that can act as shielding materials to protect the microcontroller and increase its longevity. Furthermore, it would be prudent to consider utilizing microcontrollers that have undergone the radiation hardening process.

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