# Neutron Induced Displacement Damage in Commercial Power Management Integrated Circuits

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***Abstract*—Atmospheric neutrons can produce damaging effects in power management integrated circuits (PMICs). Three commercial PMICs have been irradiated with neutrons to investigate displacement damage effects in low drop-out (LDO) and step-down (Buck) voltage regulators.**

***Index Terms*—PMIC, Displacement Damage, Neutron beam, TID, SEE, Radiation Testing**

## I. Introduction

The extreme space environment in the Earth's radiation belts houses protons and heavy ions that can give rise to a myriad of undesired effects in electronic devices and circuits, such as single event effects (SEEs), total ionizing dose effects (TID) and degradation due to displacement damage (DD) in devices [1]. Displacement damage awareness has become more significant in recent years after failures of optocouplers were observed on the TOPEX/Poseidon satellite. These failures were largely due to the current degradation in the devices [2]. This has motivated the scientific community to study the DD effects on various mixed-signal circuits that make up a large part of the electronics and communication systems around us.

Power management integrated circuits (PMICs) are comprised of mixed signal circuits and several linear and switching regulators that supply regulated voltage(s) in cell phones, automobiles and several other electronics. PMICs are made up of complementary-metal-oxide-semiconductor (CMOS) and bipolar devices that can be sensitive to displacement damage. Commercial PMICs have been studied under heavy ion radiation for TID and SEEs [3] [4], but have not been characterized for DD alone. When a high density of mixed-signal circuits is present on an integrated system, it becomes very tedious to quantify the DD hardness of every functional module of the system. In such cases, it is best to gauge the DD hardness of an entire system as a single unit, when it is subjected to radiation.

Neutrons and protons are major contributors to displacement damage on PMIC systems. Protons are a good source of radiation to study DD effects, but they also contribute to TID effects. Neutrons, on the other hand, contribute less to TID effects because they are neutral particles that generate charge through indirect ionization. Neutrons can travel long distances through materials, scattering through elastic and inelastic processes. They are very hard to shield and can pass through slabs of concrete and still not lose all energy. Thus, neutrons were chosen as the radiation source for this experiment.

The terrestrial environment is slightly different than the space environment. Cosmic particles entering the earth's magnetic field create an overabundance of highly energetic free neutrons in the atmosphere that can alter the performance of integrated circuits and even larger electrical systems [5]. This neutron flux is very high at higher altitudes, and it decreases with altitude toward sea level. The high energy neutron flux in the terrestrial environment can reach up to 1GeV and produce damaging effects in CMOS and bipolar devices, which makes it imperative to study the performance of terrestrial application electronic components such as PMICs in a similar environment. Three commercial PMICs manufactured by Texas Instruments, Analog Devices, and NXP have been irradiated with high energy neutrons to characterize displacement damage effects on startup operation and output voltage of low drop-out (LDO) and stepdown (Buck) voltage regulators.

## II. Test Facility and Methodology

The Los Alamos Neutron Science Centre (LANSCE) ICE House I facility's neutron energy spectrum is extremely similar to the terrestrial spectrum which made it a great candidate for the source of neutron beam [6]. The neutron energy spectrum at LANSCE ICE House I has a maximum at 1.5 MeV and

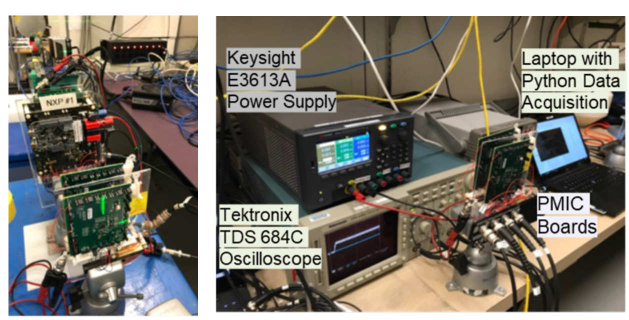


Fig. 1. (Left) LANSCE ICE House set-up and (right) testing at intervals set-up.

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TABLE I
PMIC MANUFACTURERS, PART NUMBERS, AND NUMBERS OF LINEAR AND SWITCHING REGULATORS

| Manufacturer | PMIC part | Number of Regulators |
|---|---|---|
| Analog Devices | LT3383 | LDO x 3; Buck DC-DC x 4 |
| NXP Semiconductors | PF3000 | LDO x 4; Buck DC-DC x 4 |
| Analog Devices | TPS65023 | LDO x 2; Buck DC-DC x 3 |

TABLE II
ACCUMULATED NEUTRON FLUENCES FOR EACH RADIATION EXPOSURE

| Radiation Run No. | Neutron Fluence (n/cm$^2$) |
|---|---|
| 0 | Pre-rad |
| 1 | 3 x $10^{10}$ |
| 2 | 7.78 x $10^{10}$ |
| 3 | 1.19 x $10^{11}$ |
| 4 | 1.65 x $10^{11}$ |
| 5 | 1.94 x $10^{11}$ |
| 6 | 2.36 x $10^{11}$ |
| 7 | 2.89 x $10^{11}$ |

extends to 800MeV. A proton beam strike on a quarter sized tungsten target produces neutrons and charged particles. The charged particles are moved away from the neutron flight path using permanent magnets. The neutrons are concentrated in a single beam using steel collimators and travel about 20 meters until they are incident on the DUT.

Neutron tests were performed at the LANSCE neutron beam facility for a week in July 2021. Two sets of 3 PMIC boards each manufactured by Texas Instruments [7], NXP [8] and Analog Devices [9], were tested. Detailed number of regulators can be seen in table. I. Due to the long range of high energy neutrons, de-lidding of the packaged integrated circuits was not necessary.

The test set-up is shown in figure. 1. Each PMIC was powered using the Keysight E3613A DC power supply, with a supply voltage of 3.5V continuously throughout the irradiation at nominal load conditions set by the evaluation board. The output voltage transients were measured on a Tektronix TDS684A 4channel oscilloscope. A python script was used to record the output voltage using a data acquisition software to

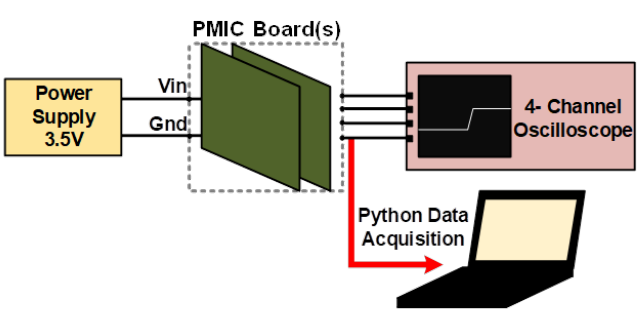


Fig. 2. Block diagram of the test set-up for waveform capture

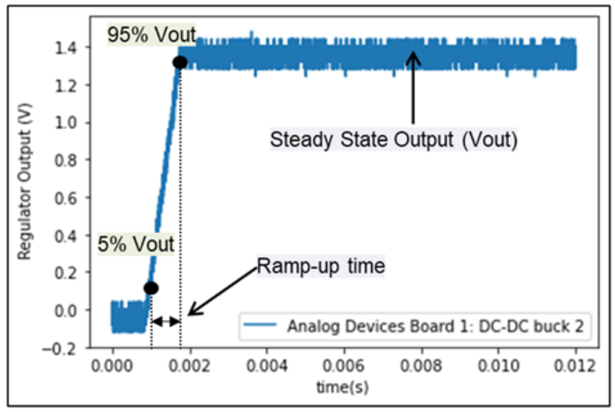


Fig. 3. Typical regulator output voltage waveform showing startup and steady state behavior.

write the data on to a .csv file as seen in figure. 2. The start-up ramp operation and output voltages of the low drop-out *(LDO)* regulators and step-down voltage regulators *(Buck)*in all PMICs were studied before and at intervals as the beam was stopped mid-irradiation to observe the displacement damage effects. The equivalent neutron flux during each radiation run was calculated and can be seen in table. II. Up to approximately 11e11neutrons/cm$^2$ fluence was achieved with the beam.

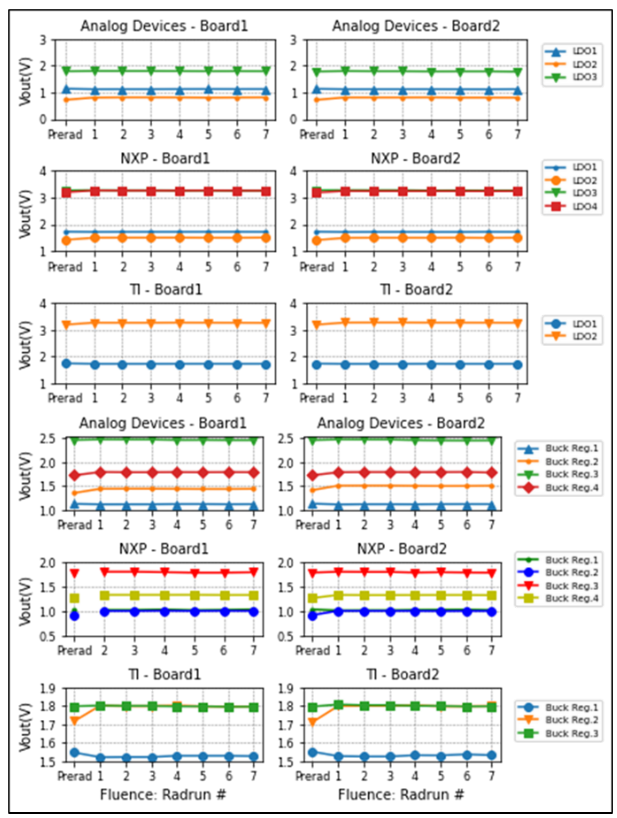


Fig. 4. Plots of output voltage vs neutron fluence measured for LDO and Buck regulators in each PMIC

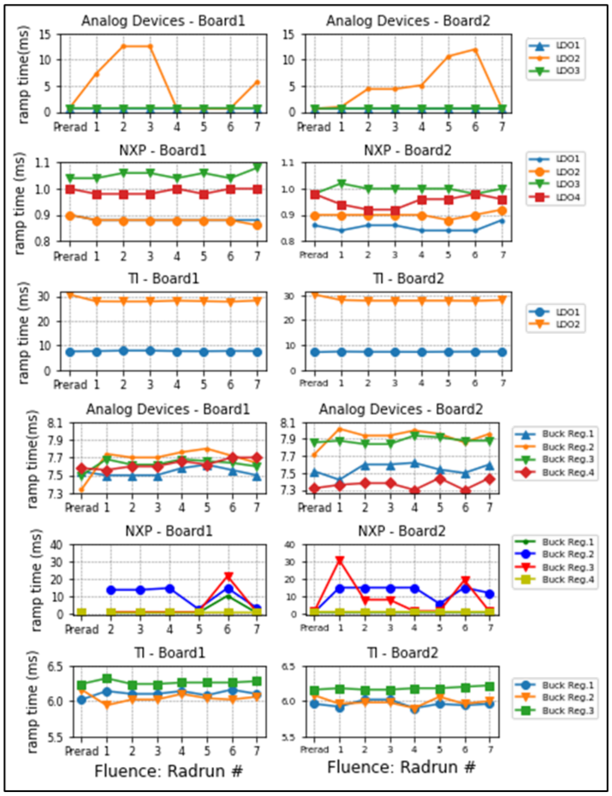


Fig. 5. Plots of ramp up time vs neutron fluence for LDO and Buck regulators in each PMIC

## III. Results and discussions

The typical transient captured at the output of each regulator is shown in figure. 3. Steady state output voltage and output ramp up time were analyzed for each PMIC. The regulator output voltage ‘ramp up time’ is defined as the time to ramp from 5% to 95% of output voltage. Figure. 4 and 5 show plots of irradiated PMIC performance. Figure. 4 shows plots of output voltage vs neutron fluence for all LDO regulators and Buck converters, with PMIC set 1 in the first column and PMIC set 2 in the second column. The plots in figure. 5 show ramp up time vs neutron fluence. No significant changes were observed in output voltage of linear or switching regulators, which implies that the high value of the open loop gain of each regulator regulates the output voltage of all LDO and Buck regulators. This indicates that the PMICs are resilient against displacement damage. However, the ramp up time for LDOs showed slight variation after each testing interval, which could be the result of transconductance(gm) degradation of the power FET from secondary total dose effects due to inelastic collisions from neutrons. Regardless, the PMICs showed no single event effects or degradation up to the total fluence achieved and remained fully functional.

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