

Radiation-Hardened Data Acquisition
System Based on a Mask-programmable
Analog Array

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ABSTRACT

Data acquisition systems capable of extreme temperature and radiation environments are of dire need in an era of great nuclear energy generation. Efforts to respond to recent nuclear accidents, such as those caused by natural disasters at Fukushima, have suffered in promptness and effectiveness due to the lack of information gathered from these sites. Currently, there are no systems available that accurately acquire, digitize, and remotely report this data in the presence of harsh radiation.

Using a mask-programmable analog array prototype chip designed for Triad Semiconductor and an FMI frequency synthesizer, both verified to beyond 300 kRad and 125°C and capable of analog signal conditioning and digitization, a radiation-hardened data acquisition system is produced. This system will report three parameters of importance to the assessment of a nuclear reactor environment: gamma radiation, temperature, and pressure. Through a three-task development process, the discrete part selection and overall system will be outlined, detailed board design will be shown, and end-to-end system calibration and radiation testing will be performed and analyzed. The evaluation of target environments will provide specifications for system performance, as well as determine successful completion of the work.

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CHAPTER I

INTRODUCTION AND GENERAL INFORMATION

1.1. INTRODUCTION

The need for tele-robotic technologies capable of high dose rate radiation environment operation is paramount in a world abundant with nuclear energy generation. As the recent accident at Fukushima Daiichi so vividly reaffirmed, these severe nuclear accident scenarios, where human entry is impossible, require timely operation, repair, and recovery of reactor stability in order to prevent widespread, prolonged disaster. In order to implement tele-robotic technologies in harsh radiation environments for remote operation, the core electronics themselves must be radiation insensitive to some degree. Therefore, radiation tolerant electronics are one of the major limiting factors preventing successful deployment of tele-robotic technologies into extreme radiation environments present under severe nuclear accident conditions [1].

Radiation-hardening of circuitry is an ever growing research topic as the applications for nuclear and space environment rated electrical systems becomes abundant [2]. Over the last several years, radiation effects mitigation techniques for digital circuits have been well documented and implemented at the commercial level, mostly through nominally rad-hard field programmable gate arrays (FPGAs). This has resulted in increased versatility in digital design, allowing for more widespread use of these systems [1].

Conversely, rad-hard analog circuitry has previously been highly application specific in nature, and are generally fabricated to meet the specifications of an individual system. This results in the necessity to optimize new designs for each specific system, long fabrication turn-around, and high cost. For instance, radiation-hardening by process (RHBP) methods are expensive due to their high complexity and limited market, and typically sacrifice some performance characteristics in comparison to standard, commercially available processes. Radiation-hardening by design (RHBD) methods are slightly more common because they can be migrated across technology platforms, but are usually not supported by process design kit (PDK) libraries or schematic simulation models, meaning these techniques will need to be repeated for each design and carefully optimized. Thus, radiation-hardening techniques for analog circuitry are mostly sub-commercial.

The limiting factor to achieving a radiation-hardened system is the most basic circuits themselves. If the system cannot perform elementary functions accurately in the presence of harsh radiation, it is useless for our application. Existing radiation-hardened designs are available to us in the form of a Triad via-configured array (VCA) integrated circuit (IC), which includes various operational circuits verified up to 1 MRad [3]. The Triad VCA technology offers an important step forward beyond current radiation-hardened circuitry for analog functions

with respect to cost, configurability, versatility, and accelerated fabrication. Careful assimilation of these circuits results in the capability to digitize analog data that a sensor would produce. This digital data may then be processed by a controller and transmitted to an end user to assess current reactor environment conditions, and if necessary, a course of action. Accomplishment of this project will include the integration of the Triad rad-hard VCA circuits with temperature, pressure, and radiation sensors, as well as an FPGA controller, which can be easily substituted for with rad-hard components, into a robust, accurate system.

“This project will develop and demonstrate a general-purpose data acquisition system built from commercial or near-commercial radiation-hard analog arrays and digital arrays that will be the building blocks of a family of future fieldable radiation-hard systems. The outcome will result in the prototype rad-hard data acquisition system that will be constructed and tested to demonstrate functionality and rad-hardness of the identified commercially available technology, as applied to a nuclear reactor environment. The system prototype will be delivered along with measured functional metrics for both pre- and post-radiation scenarios. Comparison of this data will be performed and will validate the radiation survivability of this technology path. In addition, the measured degradation observed in each of the circuit functions will also be summarized. Successful completion of this project will demonstrate the feasibility of using commercial or near-commercial radiation-hardened custom circuits for this application” [1].

1.2. GENERAL INFORMATION

The Nuclear Energy Enabling Technology (NEET) 2 program, under the U.S. Government Department of Energy, supports and funds this work. The majority of this work was completed at Oak Ridge National Laboratory, including system and detailed individual printed circuit board design, hardware selection, FPGA and LabVIEW programming, system calibrations, and report writing. System radiation testing was completed at Arizona State University in Dr. Keith Holbert’s Laboratory. ASICs used in this system, particularly the Triad VCA and Frequency Management Inc. (FMI) frequency synthesizer ASICs, were previously designed and verified. The University of Tennessee was involved in the design and verification of both the Triad VCA and the FMI frequency synthesizer. The Air Force National Laboratory (AFRL) and FMI granted their use to this project, respectively. Proposal of this project [1] was submitted to NEET-2 in 2012 jointly between Oak Ridge National Laboratory and the University of Tennessee. The proposal was accepted and the project work began in October 2013. The overall project was divided into four tasks, each of which is quoted below from the project proposal.

1.2.1. TASK 1 – ELECTRONICS DESIGN AND HARDWARE SELECTION

A detailed functional block diagram of the proposed data acquisition system will be developed. The level of detail will include the commercial and pre-commercial parts to be used, the functional interconnect between the various parts, and the overall signal flow and data format definitions. This system will be capable of monitoring at least three parameters of importance to nuclear reactor monitoring: temperature, radiation level, and pressure. Electronic components as well as appropriate sensors will be chosen.

1.2.2. TASK 2 – DETAILED SYSTEM DESIGN AND FABRICATION

Using the analog blocks available in our currently pre-configured VCA, we will perform a detailed schematic design of our system to include the signal-processing blocks for temperature, radiation and pressure. Control and data acquisition will be implemented with the Spartan-6 FPGA as well as wired serial communications with a remote computer to be used with this project. In addition, batteries and associated voltage regulators will be selected for powering the system. Fabrication may include a polyimide, printed circuit board (PCB) for improved radiation and temperature tolerance. The PCB will go through a layout process by one of the organizations we utilize for this function and be fabricated by another external vendor. Population of the system board will be performed using one of our in-house technicians or an outside vendor we commonly use. Five prototype systems (sensors, electronics board, battery power supply, and PC serial communications port) will be constructed to support the testing objectives of this work. Quality assurance will be performed at each step by both the submitters and the vendors.

1.2.3. TASK 3 – SYSTEM TESTING AND VALIDATION (PRE- and POST-IRRADIATION AND TEMPERATURE)

Evaluation of the performance of the system for both pre- and post-irradiation as well as operation at elevated temperature will be performed. Detailed performance of the system will be documented to ensure the design meets requirements prior to any extended evaluation. A suite of tests will be developed which will allow evaluation before and after irradiation and during temperature. Selection of the radiation exposure facilities will be determined in the early phase of the project. We have used both in-house and external irradiation facilities in the past and have extensive experience in the setup and testing in such facilities. Radiation exposure will consist of total integrated dose (TID) up to 200 kRad or above with several (to be determined) intermediate doses during test. Dose rates will be in various ranges determined by the facility

that will be used but a target maximum will be 20 kRad/h. Many samples of the pre-commercial devices to be used will have been tested in previous projects to doses of at least 300 kRad and temperatures up to 125°C. The complete systems will therefore be tested for performance at intermediate doses and up to the system failure dose. Temperature testing will be performed up to 125°C which should be adequate for most target environments [4]. The test suite performed at each test point will consist of operational testing of the three basic measurement functions plus electronic functional testing (power dissipation, voltage offset changes, bandwidth changes, noise variations, etc.). This suite will be developed as part of this task.

1.2.4. TASK 4 – DATA ANALYSIS AND PRESENTATION

Data taken from the pre- and post-radiation/temperature evaluation will be analyzed to quantify variations. Measured performance changes will be identified and the root cause at the circuit level will be determined. This will give us a good measure of the overall performance of the system that can be clearly communicated to potential users of this technology. The project timeline for each of these tasks is outlined in Table 1, based on the Oak Ridge National Laboratory fiscal year calendar.

Table 1: Project Timeline

Task	Year 1				Year 2			
	<i>Q1</i>	<i>Q2</i>	<i>Q3</i>	<i>Q4</i>	<i>Q1</i>	<i>Q2</i>	<i>Q3</i>	<i>Q4</i>
Task 1. Electronics design and hardware selection								
Task 2. Detailed system design and fabrication								
Task 3. System testing and validation (pre- and post-radiation and temperature)								
Task 4. Data analysis and presentation								

CHAPTER II

LITERATURE REVIEW

The application and necessity for robotic assessment of nuclear reactor environments is ever increasing. This statement is indisputable, as incident scenarios, such as the recent accident at Fukushima Daiichi, provoked local responders and national decision-makers to probe for information regarding plant damage awareness of radiation releases [5]. The hazards of the nuclear disastrous environment made it humanly impossible to gather this information, while the highly radioactive conditions rendered data acquired by automated equipment useless or irrelevant to the desired information. These events induced the desperate need for remote robotic systems for deployment in current and future accident scenarios; however, there were no radiation-hardened systems available for such reconnaissance activity, nor reliable information to quantify and map the radiation fields surrounding the plant needed to justify the use of specific robotic platforms. A review of a wide variety of target environments for nuclear radiation-hardened electronics uses is presented to gather, analyze, and summarize potential requirements for such a system.

2.1. REACTORS

Nuclear reactors are primary locations where the deployment of remotely operated radiation-hardened electronics would be useful. The Taiwan Power Company conducted a detailed safety report of the nuclear plant Lungmen units 1 & 2 in Taiwan that outlines the projected radiation environment for both the primary and secondary containment [6]. The worst-case values in Tables 2 and 3 for primary containment and secondary containment show potential gamma dose rates up to 200 kRad/h and total gamma integrated dose for 6 months of 300 MRad in accident scenarios [4]. In addition, neutron exposure is irrelevant in accident scenarios. These radiation levels are unlikely to be encountered by remote monitoring systems, but, currently, there aren't any circuits available that can survive comparable dose rates for extended periods of time. Thus, some shielding will be required; however, the implementation of radiation-hardened electronics can significantly reduce the size and weight of excessive shielding [1].

2.2. HOT CELLS

Another environment where the need for a robotic monitoring system is appropriate is a hot cell. A hot cell is a location that has been mainly used for the characterization of spent fuels and high-level waste [7]. There are multiple hot cells at the Pacific Northwest National

Table 2: Radiation environment for normal and accident scenarios at Lungmen units 1 & 2 [4]

Operating Scenario	Primary Containment		Secondary Containment	
	γ	N	γ	N
	[R/h]	[cm ⁻² • s ⁻¹]	[R/h]	[cm ⁻² • s ⁻¹]
Normal Operations	20	6E4	2	Low
Shutdown, pumps operating	0.2	Low	0.02	Low
Cladding, RPV, and pipe rupture	2E5	Low	2E3	Low

Table 3: Integrated gamma dose for 6 months following a loss of containment accident at Lungmen units 1 & 2 [4]

	Primary Containment	Secondary Containment
Integrated γ dose [R]	3E8	6E7

Laboratory (PNNL), including the C-Cells of buildings 324 and 325. The C-Cells include two oil-filled, leaded viewing glasses and a set of manipulators. A truly radiation-hardened sensing system could aid in the data collection and accuracy in performance of the collection process.

2.3. WASTE STORAGE AND HANDLING

The storage and handling of radioactive waste materials can produce relatively high radiation environments. These materials are often used for experimental reasons and cannot generally be disposed of easily. The canisters used in the Hanford Waste Treatment Plant Immobilized High Level Waste Interim Storage Project are an example [8]. These canisters are filled with glass-encapsulated waste and subsequently placed in a canister storage facility. Dose rates within the canister can reach up to 100 kRad/h, while exterior dose rates are less severe and decrease exponentially with distance from the canister (Table 4). Radiation-hardened electronics could assist in assessment and efficient transportation of waste and waste storage, respectively.

2.4. MATERIAL PROCESSING

Another location in which a radiation environment study was performed on sludge stored in containers was at the T plant [9]. Gamma dose rates were measured at radial distances from the large diameter containers filled with sludge retrieved from K basins for different mixes (Table 5). These include 80/20 and 60/40 floor sludge to KE canister sludge mixes, as well as varying container volumes, from nominal load (2 m^3) to safety basis load (4.083 m^3).

Table 4: Immobilized high-level waste canister maximum radiation dose rates [8]

Distance/position	Dose Rate
Contact (@ 1 cm)	5.76 kRad/h
@ 30 cm	2.3 kRad/h
@ 100 cm	0.964 kRad/h

Table 5: Dose rates at various radial distances from the side of loaded sludge containers [9]

Distance (m)	Nominal Load 80/20 Mix Dose Rates (mRad/h)	Nominal Load 60/40 Mix Dose Rates (mRad/h)	Safety Basis Load 60/40 Mix Dose Rates (mRad/h)
Contact	1.94E+5	3.25E+5	3.28E+5
1	3.66E+4	6.16E+4	9.61E+4
10	7.23E+2	1.21E+3	2.46E+3
20	1.79E+2	3.00E+2	6.11E+2
30	7.61E+1	1.27E+2	2.60E+2
40	4.06E+1	6.81E+1	1.39E+2
50	2.46E+1	4.12E+1	8.42E+1
75	9.43	1.58E+1	3.23E+1

2.5. PREVIOUS NUCLEAR REACTOR MONITORING SYSTEMS

In the past, robots have been used in the general aforementioned target environments for exploring disaster situations, such as the earthquake and tsunami that demolished eastern Japan and the Fukushima Daiichi Nuclear Power Station. For instance, Quince, a robot designed to traverse stairs and rubble, was redesigned for Fukushima and tested against harsh radiation environments to determine if its components could withstand realistic radiation exposure levels [10]. It should be noted that these are conventional, non-radiation-hardened components and are tested to determine the survivability and total dose at which these components will malfunction. There are currently no radiation-hardened systems in use for nuclear reactor monitoring that can withstand the extreme radiation exposure for extended periods of time.

Quince utilized electric components outlined in Table 6, such as cameras, CPUs, and wireless communications. All of these were exposed to gamma radiation from a Cobalt-60 line source at a 0.6 meter distance, producing a 20 Gy/h, or 2 kRad/h, dose rate. Alanine dosimeters, also called Aminograys, were used to precisely measure the accumulated dose for each component during two 5 hour test periods separated over two days, for a nominal total dose of 200 Gy, or 20 kRad. On the second day, 2-D (URG-04LN, UTM-30LX, UXM-30LN: HOKUYO AUTOMATIC CO., LTD.) and 3-D (Eco-scan FX8: THE NIPPON SIGNAL CO., LTD.) range scanners that would be used to gather range data for the robots navigation were added to the test at a distance of 0.45 meters from the source, producing a 40 Gy/h, or 4 kRad/h, dose rate. As shown in Table 7, most of the components survived their total dose, but a 2-D range sensor and the CCD camera malfunctioned after 169 Gy and 124.2 Gy, or 16.9 kRad and 12.42 kRad, respectively. In addition, another 2-D scanner survived 22.9 kRad total dose, but

Table 6: Electric components of Quince [10]

Maker	Model	Function
(1) AXIOMTEK Co. Ltd.	SBC84823	CPU Board (AtomZ510PT)
(2) Technocraft	V-8	Motor driver board (Renesas SH7147)
(3) Lawicel AB	CAN/USB	CAN-USB converter (FT245BM)
(4) Contec Co. Ltd.	FXDS540STDMS	Wireless com. device
(5) Techno Broad Inc.	PoE-ZS251T	POE power feeding
(6) Panasonic Corp.	CY-RC51KD	CCD camera
(7) Axis Inc.	Axis212	Wideview camera
(8) Axis Inc.	Axis282	Video server
(9) TI Inc.	PT6883A	DC-DC Converter
(10) TI Inc.	PT6886A	DC-DC Converter
(11) IDX Co. Ltd.	PowerCube	Battery
(12) PLANEX Com. Inc.	FX-08Mini	LAN Hub
(13) Sanwa Supply	225GBK	USB Hub

Table 7: Total dose and condition of each Quince device [10]

Position	Total dose (Gy)	Condition
Test board: left	191.5	It survived.
Test board: center	206.0	It survived.
Test board: right	193.5	It survived.
CAN-USB converter	188.5	It survived.
USB Hub	187.5	It survived
UTM-30LX	232.0	It survived
UXM-30LN	229.0	The output was always unstable, but it survived.
Eco-scan: front	225.0	It survived.
Eco-scan: rear	209.5	It survived.
Axis 212	219.5	It survived.
Camera on test board	169.0	It broke after 169.0 Gy
URG-04LN	124.2	It broke after 124.2 Gy

showed instability in its output throughout the test. The highest total dose survived by any component was 23.2 kRad.

Although the conventional components used on Quince showed some level of radiation tolerance, they would not last long in the harshest radiation environments of nuclear reactor malfunctions. At an assumed dose rate of 5 kRad/h, which is a conservative rate based on the target environments aforementioned, some components of Quince would begin to malfunction in less than 2.5 hours. A radiation-hardened system that can survive beyond 300 kRad, as this work will attempt to show, could perform necessary functions for at least 60 hours and could survive for 1.5 hours in the most severe conditions of 200 kRad/h documented. This improvement in system survivability and performance justifies the effort of this project prototype and future projects for target environment implementation.

CHAPTER III

ELECTRONICS HARDWARE SELECTION AND FUNCTIONAL DEVELOPMENT

3.1. PRELIMINARY ELECTRICAL BLOCK DIAGRAM

The high-level block diagram, shown in Fig. 1, illustrates the electrical signal-processing paths for three distinct types of sensors [11]. In order to transform the output signals from the environmental sensors, a few steps must be taken. First, each sensor will output a specific type of signal, and these signals must be converted to a digital structure so that a computer processor or controller can process and relay this information to the user in a useful format. The conversion methods for each signal will differ slightly, and those variations can be considered on a lower sublevel. The controller will convert the data into a format that the user will find easy to understand (for example, temperature, pressure, and radiation count in standard units). Ultimately, each conversion will result in a binary output value, or DN, that the controller will prepare and display for the user. The sensor and electronics signal flow will be presented in the following sections. The three channels of signal conditioning/signal processing will be implemented using the circuitry present on the Triad VCA. Each VCA application-specific integrated circuit (ASIC) contains multiple single-ended operational amplifiers, biquadratic filters designed as input anti-aliasing filters for the sigma-delta modulators, which are also on the ASIC, and a bandgap voltage reference.

ASICs are very important to electronic systems for multiple reasons. First, ICs have the inherent capability of performing numerous electrical functions and operations within one area efficient space. Not only do ICs optimize circuit density, but they also offer improved matching behavior performance when compared to using individual functional blocks to accomplish the same operation. This is because the IC fabrication process, although precise, is not perfect, and silicon substrate variations from chip to chip are inevitable. Combining multiple functions into one IC effectively reduces matching errors and provides minimal variation from expected results.

Secondly, as their name implies, ASICs are application specific, which means they can be designed to perform precisely to the exact requirements of an application. On the other hand, general ICs must be designed to satisfy a wide variety of applications, and nothing comes for free with circuit design. Tradeoffs must be made, thus certain performance characteristics of the IC will diminish relative to an ASIC. This advantage over general ICs makes ASICs almost necessary, especially when stringent conditions such as extreme environment operation are required.

As a side note, the stated scope of the proposal is to develop a small data-acquisition demonstration system whose circuitry will be tested for radiation hardness [1]. Development of rad-hard sensors is outside of the scope for this particular proposal; however, the system is

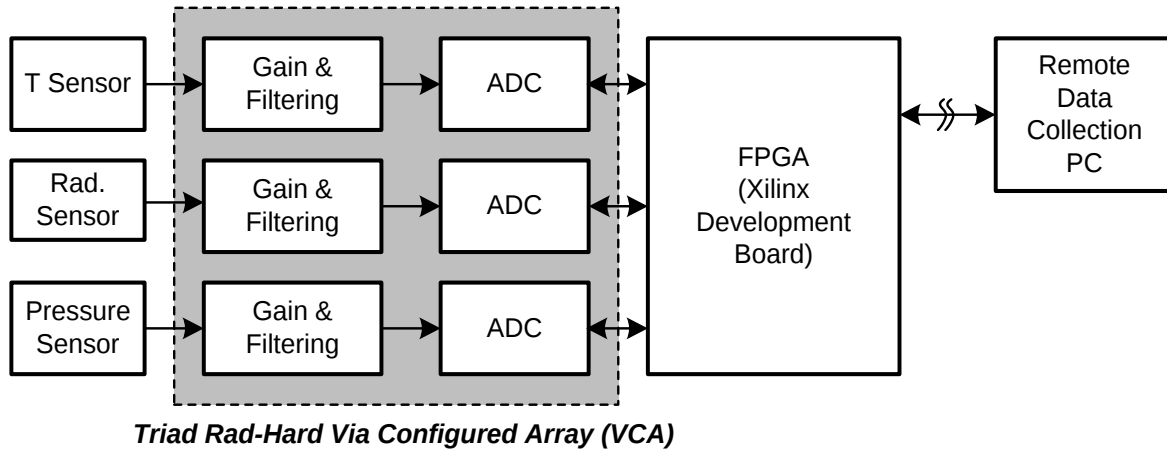


Fig. 1: Data acquisition system based on near-commercial rad-hard circuits [1]

designed so that, with only minor PCB tweaks, existing rad-hard sensors can easily replace their soft counterpart on the sensors board.

3.2. SENSORS & SUPPORT COMPONENT EVALUATION

3.2.1. TEMPERATURE SENSOR

Within potentially harsh radiation environments such as nuclear reactor sites, ambient temperature can be a significant parameter for monitoring normal and stable reactor operating conditions, as well as detecting early signs of nuclear disaster situations. As a result, accurate and frequent temperature measurements are necessary. For extreme scenarios, these sensors will need to withstand temperature ranges from 0 to 125°C, TID radiation exposure of at least 300 krad, and potential dose rates up to 200 kRad/h in order to effectively relay data for processing [1]. Although providing extreme environment hardened sensors was not within the scope of this project, selecting these sensors, budget willing, would go above and beyond expectations.

Throughout the search for temperature sensors, the Intersil ISL71590SEH transducer proved to be a formidable rad-hard solution. Along with its current output, which is useful for application specific design, the rad-hard sensor boasted -55 to 125°C temperature range and 300 krad total dose operation within 1°C of accuracy. The nominal current output value is 298.2 μA at 25°C (room temperature) and the delta output is 1 $\mu\text{A/K}$. Unfortunately, at a cost of approximately \$325/unit, and with many other components to purchase, it was decided that soft

(non-radiation hardened) sensors would be chosen.

With this in mind, the ideal solution was to find a sensor matching all of the performance specifications of the Intersil ISL71590SEH, excluding radiation hardness. The Analog Devices AD592 came very close to matching these expectations, claiming -25 to 105°C temperature range, 0.5°C measurement accuracy, and equivalent current output characteristics. Therefore, the AD592 was selected as our temperature-sensing element. A few of the compatible Intersil ISL71590SEH temperature sensors could be purchased and substituted to demonstrate the capability of radiation-hardened sensors within the system.

3.2.2. PRESSURE SENSOR

Much like temperature, pressure is another parameter that can be monitored in reactor environments to reveal ideal or non-ideal operating conditions and also if unsafe conditions may be developing. For harsh environments, we want to measure pressure relative to normal atmospheric pressure, or gauge pressure, up to 2 atm (3 atm absolute). These pressure ranges are not extreme and do not require high pressure capable sensors. Rather, a low pressure range, higher resolution sensor would allow for full pressure range swing and the ability to precisely monitor small pressure changes to better fit this application. In addition, we want to establish an output voltage range for the sensor so the analog-to-digital conversion parameters may be easily designed. This can be done with an analog ratiometric pressure sensor, which relates its output voltage proportionally to its input voltage supply, and allows for direct analog-to-digital conversion without any pre-conditioning. Since we are designing and constructing PCBs for this system, a board mount sensor is preferred.

During our initial search for rad-hard sensors, the market was very scarce for pressure sensors in particular. Only one sensor was discovered that remotely reached our requirements, the Omni Instruments Radiation “Resistant” Pressure Sensor. However, the sensor lacked test data to specific radiation total dose tolerance level and was not a board mount sensor. The Omni Instruments pressure sensor could potentially have been radiation verified locally and implemented within the data acquisition system, but it was not the ideal solution. After relaxing our search requirements to include non rad-hard sensors, many more options were available, and Honeywell stood out as the leading supplier. Honeywell provides various styles of pressure sensors, and combines all of our project needs into one compact, silicon-based sensor with their ASDX Series. This series has multiple custom variations and specifications, such as a variety of pressure ports, pressure ranges, transfer function limits, and supply voltages. For our project, we have selected an axial vented port, 30 psi gauge pressure range (~ 2 atm), 10 – 90 % calibration, and a 5 V supply. All of these specifications will suffice for our application, denoting the Honeywell ASDXAV030PGAA5 as our pressure sensor of choice.

3.2.3. GAMMA DETECTOR

Radiation detection is the key parameter in identifying a nuclear reactor disaster scenario. Radiation will escape the reactor containment before ambient temperature or pressure changes are realizable. Among the most prevalent forms of radiation detection are ionization chambers, proportional detectors, and Geiger-Müller (G-M) tubes, which are all based on the effects of charged particles passing through a gas [12]. All three of these methods can be used for our application. However, ion chambers and proportional detectors both output relatively small electrical signals, which require amplification. Their upside is that they can resolve higher dose rates than a G-M tube. The G-M tube achieves inherent amplification through the use of large electric potential biasing (~ 500 V), which results in an intense “avalanche effect,” causing ion pairs freed by high energy gamma radiation to collide and trigger additional avalanches during their paths toward the electrodes. Although this produces an amplified charge output, the additional particle collisions slow down transit speed of the charge carriers and effectively increase total time from initial excitation to final output. As a result, G-M tubes exhibit large dead times, or length of time for which the G-M tube is inoperative, because the tube needs to reset itself by evacuating all charge carriers from the gas chamber. The positive charge carriers, or holes, are heavier and inherently move much slower than the electrons; thus take longer to evacuate. Because the G-M tube generates an increased number of these ion pairs, they take longer to reset, which limits their high dose rate resolution capability.

Nuclear applications beyond design basis can require dose rate resolution of up to 200 kRad/h. G-M tubes can only resolve, at maximum, about 1 kRad/h. While ion chambers and proportional counters can measure much higher dose rates, they complicate the interfacing circuitry with the need for low-noise amplification. In addition, reliable G-M tubes are much more accessible and cost-efficient than their counterpart. For simplicity of signal interface design and cost, an LND 714 G-M tube will be used as our gamma radiation-sensing element. In order to address the inherently low dose rate resolution of approximately 100 Rad/h for the LND 714, we will shield the tube. This technique will reduce the radiation dose incident on the G-M tube by a certain factor, which we will characterize for accuracy, and will result in a higher effective dose rate capability for the G-M tube.

3.2.4. SUPPORT COMPONENTS

Some additional components are necessary to provide the power required by the system and enable full circuit operation. All circuits within the system will need a specific level of voltage and current supply generated from a voltage regulator, and for radiation rich environments, this supply must be very robust across a large range of dose rates, potentially up to 200 kRad/h. Microsemi produces a variety of radiation hardened voltage regulators with

differing total dose capabilities, but the SGR117A model stood out with the highest TID capability of all, claiming total doses exceeding 1 Mrad. This voltage regulator can produce output voltages ranging from 1.25 to 34 V, supply at least 1.5 A of current across all operating conditions, and maintain a 0.3 % load regulation specification. The SGR117A is available in a 3-pin K package with a thermal dependence of only 3 °C/W and operating temperatures up to 150°C. These voltage regulator specifications can satisfy power requirements for every circuit within the system, with the exception of the G-M tube which will require a high voltage DC converter to reach a 500 V potential.

The LND 714 G-M tube recommends a 500 V potential for operation to capture high-speed freed electrons and holes, but does not require significant current supply because the charge produced comes directly from the tube itself. EMCO produces numerous high-quality, high voltage DC converters for avalanche photodiode and photomultiplier tube applications, which is very similar to and would be ideal for our system. The EMCO A05P5 1W, positive adjustable DC converter can output up to 500 V at a maximum current of 2 A, with only a 5 V and less than 200 mA input at no load. This EMCO DC converter is not radiation hardened and will be placed on the shielded sensors board to minimize high power transmission lengths and optimize board density. The 5 V, 200 mA converter input will be supplied by the Microsemi voltage regulator from the radiation-hardened board. High current power will need to propagate across multiple PCBs; however, twisted pairs can be used to transmit this power with low losses and minimal interference.

3.3. TRIAD RAD-HARD ASIC CAPABILITIES

3.3.1. OVERVIEW

Programmable digital circuitry like rad-hard FPGAs can be configured to perform nearly any suitable digital function in the presence of extreme radiation environments [2]. This level of versatility affords digital designers the ability to establish systems for numerous applications with one consistent platform. Certainly, an array of various fundamental analog circuits constructed much like an FPGA could provide analog designers with application adaptability far beyond the custom analog standard. Ideally, this array would include the analog tiles necessary to configure essentially any analog function. Although analog operations are more complicated at the sublevel than digital, which somewhat limits the scope of this notion, there are some basic building block circuits that are useful to almost every analog system. These circuits include operational amplifiers, analog-to-digital converters (ADCs), voltage references and regulators, filters, and digital-to-analog converters (DACs). Multiple variations of these circuits, if fabricated on the same die, exhibit a broad array of analog functionality. In addition, by utilizing RHBD techniques, these analog building blocks can be optimized for admirable performance

under extreme total ionizing dose (TID) radiation environments. In order to reduce the package footprint necessary to implement each individual circuit, the top layer of chip metal, or mask, is not deposited, but the ability to interconnect any circuit on-chip, or route necessary I/O off-chip remains. The routing is determined by the user's specific needs, and is programmable for each individual analog array. The result is a mask-programmable analog array that only lacks top metal layer interconnects, unequivocally reducing cost and fabrication time, all while enhancing versatility and configurability of analog structures.

The concept of mask-programmable analog arrays can be realized using the technology of Triad Semiconductors via-configurable array. This technology uses via-only routing where necessary to interconnect and configure desired resources. With the use of Triad Semiconductor's VCA technology, a radiation tolerant analog array prototype test chip, applying RHBD techniques such as annular-gate (enclosed transistor) NMOS and dynamic threshold MOS (DTMOS), was developed and tested to greater than 300 kRad TID. The array was also optimized for wide temperature operation over mil-spec temperature range (-55 to 125°C).

3.3.2. OPERATIONAL AMPLIFIER

For data acquisition applications, operational amps (opamps) play an important role in the processing of analog data. Opamps are gain blocks that are designed to provide high voltage gain and negative feedback in order to implement controlled-gain functions as well as signal buffering and filtering. Opamps have been around in various forms since the 1950's and are ubiquitous in today's electronic devices, being found in almost any circuit that has any analog functionality. For this project, these op amps will be used within the sigma-delta modulators for analog-to-digital conversion of temperature and pressure data, as well as being used as a comparator for verification of gamma radiation counts.

The Triad rad-hard ASIC [3] contains various radiation hardened by design (RHBD) circuits commonly used in analog circuit design, with specific alterations to each individual block, allowing for increased application versatility. The first circuit is fundamental to any analog system, the operational amplifier. The chip contains several different types of operational amplifiers, all of which are considered proprietary. We will not be discussing the specifics of the design characteristics of the amplifiers in this and future reports because of their proprietary nature.

3.3.3. SIGMA-DELTA MODULATOR

Highly important to any modern data acquisition system is the ability to precisely digitize sensor data at acceptable rates. The Triad rad-hard ASIC includes a 2nd-order, sigma-delta

modulator that can be used as an analog-to-digital converter. Like the operational amplifiers, the sigma-delta modulators are also proprietary. We will therefore not be discussing the specifics of the design characteristics of the modulators in this and future reports because of their proprietary nature.

The digital output is a pulse density modulated bit stream that will be digitized with digital sinc filtering [3]. Each of the sigma-delta modulators were implemented with their respective operational amplifiers.

3.3.3.1. Sigma-Delta Modulator Background

An analog-to-digital converter (ADC) converts an analog signal composed of a continuum of values to a digital result [13]. The ADC output is a digital ‘best’ approximation of its input signal, with the approximation error (or quantization error) being related to the ADC resolution. ADCs can be classified as one of two types: Nyquist-rate or oversampling. Nyquist rate converters sample the input signal at approximately twice the highest frequency of the input signal using a number of different architectures including successive approximation, pipeline, algorithmic, and flash. Oversampling converters achieve improved resolution at the expense of conversion speed. In oversampling converters, improved performance is accomplished by sampling the input signal at rates much higher than the Nyquist rate and shaping the quantization noise using a noise-shaping filter.

Since an analog-to-digital converter produces a digital approximation of an analog input signal, every ADC operation produces error, known as quantization error. Typically, the quantization noise has a flat power spectral density so that the total noise increases as the bandwidth increases (or sample rate increases). This becomes a limiting factor in the realization of very high resolution ADCs.

The sigma delta ADC architecture uses two techniques to improve the signal to noise ratio: oversampling and noise shaping. By oversampling, the quantization noise power is spread out over a larger bandwidth, resulting in reduced integrated noise in the signal bandwidth. In addition to oversampling, noise shaping is also accomplished in the modulator, which significantly reduces the integrated noise in the signal bandwidth, depending on the order of noise shaping. Oversampling of the input signal further distributes the shaped noise as the peak of the noise distribution is stretched to the new sampling frequency/2 ($f_s/2$) resulting in a reduced noise power in the signal bandwidth of interest. This is demonstrated graphically in Fig. 2.

Using a combination of these two noise reduction methods allows for a significant improvement in the theoretical resolution of the ADC. Table 8 shows this effect as a function of oversampling ratio ($M=f_s/f_o$) and the quantization noise shaping order (or modulator order). Following noise shaping and oversampling, the modulator output is digitally filtered and decimated to remove the out of band noise and downsample the signal back to the desired digital

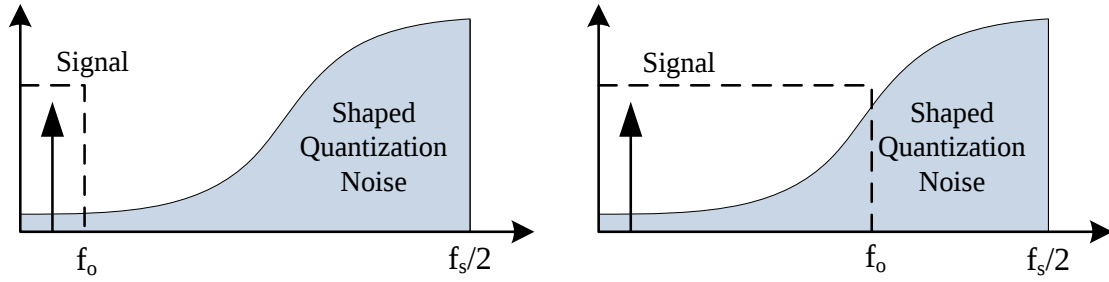


Fig. 2: Effect of quantization noise shaping and oversampling on the in-band noise in a sigma delta ADC. The left plot shows a higher oversampling ratio than shown on the right. The signal bandwidth is marked with dashed lines [13]

Table 8: Theoretical Sigma Delta ADC resolution as a function of modulator order and oversampling ratio (M) [13]

Modulator Order	M = 64	M = 128	M = 256	M = 512
1	8.14	9.64	11.14	12.64
2	12.86	15.36	17.86	20.36
3	17.45	20.95	24.45	27.95
4	21.98	26.48	30.98	35.48
5	26.74	31.97	37.47	42.97

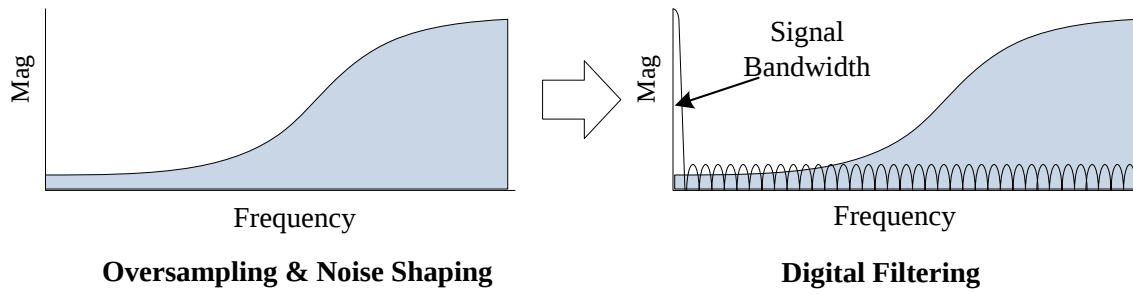


Fig. 3: Digital filtering of the signal bandwidth following oversampling and noise shaping [13]

output rate (f_0). This is graphically demonstrated in Fig. 3.

The actual implementation of the sigma delta ADC is composed of two primary modules, the modulator and the digital filter. Note that the input is an analog signal, the modulator is an encoded bit stream, and the output of the digital filter is the digitized output signal. Digital filters can be implemented using a number of different filter topologies. An example is a sinc filter topology, which provides reasonable performance and can be implemented using simple FPGA elements, such as shift registers and adders, similar to the topology that will be later implemented for this project.

3.4. DIGITAL CONTROLLER SEARCH

The digital control module handles the control and sequencing of all instrument functions including data acquisition, data processing and packetizing, command interpretation and execution, and data and command communication. The design approach selected for this program is to use a programmable device for the digital controller to enable iterative development of the system without the need to replace hardware modules. Common programmable hardware devices considered for this application include micro-controllers, field programmable gate arrays (FPGAs) and complex programmable logic devices (CPLDs). Given the control functions required for this application (state machine sequencing, simple digital filtering, data packet generation, command execution, and serial communications) FPGAs were selected over the other candidates as the optimum target device architecture for the digital controller in this development.

A study was carried out to assess the commercial availability of rad-hard or rad-tolerant field programmable gate arrays (FPGAs). Table 9 summarizes the findings of this study indicating that only a very limited number of commercial FPGA products are available for

Table 9: Comparison of commercially available rad-hard or rad-tolerant FPGAs

Manufacturer	Family	TID (Rad)	Gates Logic Cells	Availability/Unit Cost
Xilinx	Virtex-4QV	> 300k	> 200k	2015, N/A
Xilinx	Virtex-5QV	> 1M	131,072	2015, ~\$80k
Atmel	AT40KEL	300k	46k	No stock found
Atmel	ATF280	300k	280k	No stock found
Microsemi	RT ProASIC3	> 100k	$\leq$ 3M	Now, ~\$8k

applications requiring rad-hard ($\geq 1\text{MRad}$) or rad-tolerant ($\geq 300\text{ kRad}$) operation. Note that these products allow true in-field programmability, thus accommodating anticipated iterative design revisions. In addition to those shown in Table 9, many other commercial programmable logic solutions were also considered that are based on anti-fuse technology, but were deemed unsuitable since only a single programming of the device is allowed. Also shown in Table 9 are the availability and cost of reprogrammable devices. For FPGAs having $\geq 300\text{ kRad}$ TID, all components were out of stock with no availability until 2015. Due to the very high cost and long delivery times, the rad-hard/rad-tolerant commercial FPGAs will not be used in the prototype system developed in this program.

After determining the high difficulty and cost associated with acquiring rad-hard FPGAs, the approach selected for this program was to use a commercially available ‘soft’ FPGA or CPLD, a lower complexity and cost programmable logic device. This approach will maintain the full functionality of the system, allow for re-programmability, is low cost and has strong industry support. Specifically, the Xilinx family Spartan 6 FPGA was chosen. This device family has low-cost development systems (includes a single board with device and development tools/software) and is well supported by the manufacturer. A further advantage of using the Xilinx device over other commercial equivalents is the migration path to rad-hard Xilinx Virtex family devices (Virtex-4QV and Virtex-5QV) is likely easier. The development kits are shown in Fig. 4 for both the Spartan 6 (left) and CoolRunner II (right) devices. Both units provide a USB interface, switches, and various other resources for adding peripherals to aid in system development.

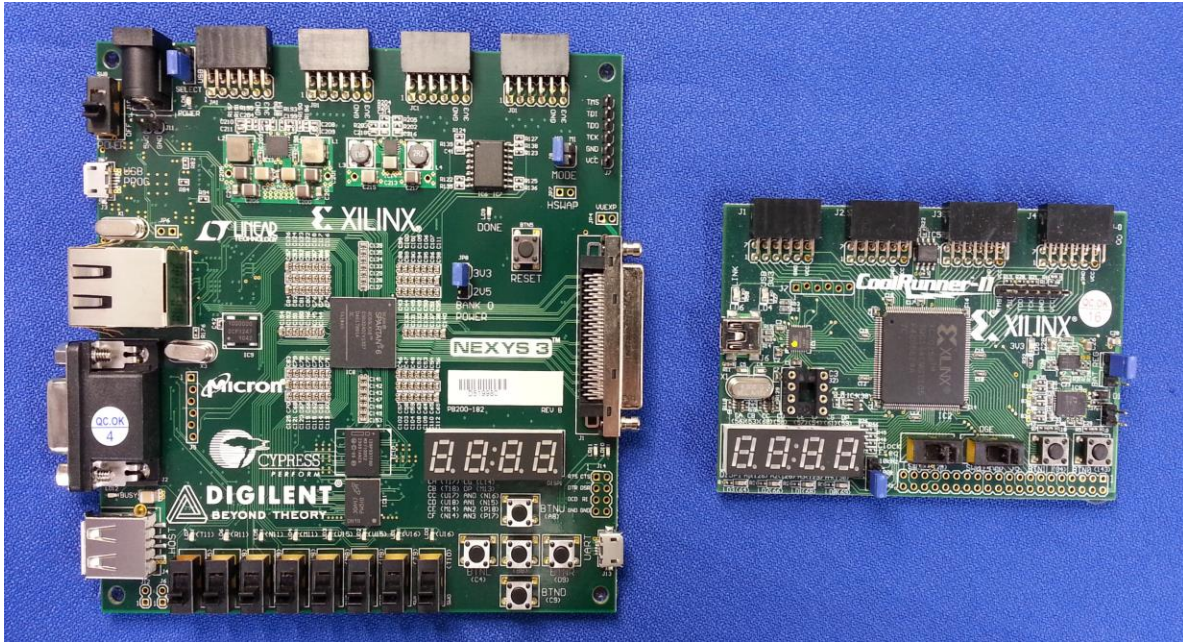


Fig. 4: Development kits purchased for the digital controller development

3.5. FUNDAMENTAL BOARD DESIGN

Due to the unavailability of affordable rad-hard FPGA controllers, the data acquisition system design must be split into three board designs. One board will support the temperature and pressure sensors, as well as the gamma detector, but will not be directly irradiated due to the presence of soft sensing components. However, this board will be placed within certain proximity of the radiation source during testing, so that some level of gamma events can be counted, while avoiding damage to soft components. Another board, which houses the entire radiation hardened analog signal conditioning circuitry, will be directly irradiated by a gamma source for proof of concept. A third board will provide processing and control for the system through the use of the soft FPGA. This board will not be irradiated at any level, but will be designed so that future work toward a radiation-hardened controller would be easily interchangeable with the current interface. This setup will satisfy the radiation hardened data acquisition system project requirements, considering all components within the system that are not radiation tolerant are commercial or pre-commercial parts that can be easily replaced with a sufficient budget.

3.5.1. SENSORS SIGNAL CONDITIONING BLOCK FLOW

As aforementioned, the sensors board will provide temperature, pressure, and gamma radiation detection elements. For each of these nuclear environment critical measurements, data is converted to electrical form by the sensors and needs conditioning so that they may be digitized. Specifically, voltage waveforms dependent on their respective environment parameters, as seen in Fig. 5 below, are required for the available Triad analog-to-digital converters (ADC). The Analog Devices AD592 temperature sensor outputs a nominal current at room temperature ($\sim 25^{\circ}\text{C}$) of $298.1\ \mu\text{A}$ and will vary at $1\ \mu\text{A/K}$. The sensor also requires a supply voltage between 4 and 33 V, which will be provided by the selected Microsemi rad-hard voltage regulator. Placing a $10\ \text{k}\Omega$ resistor at the sensor output converts this current into a DC voltage of $2.981\ \text{V}$ with a variance of $10\ \text{mV/K}$. This resistance value optimizes the $V_{\text{out,DC}}$ and ΔV components of the temperature sensing circuit output voltage V_{out} , so that the common voltage of the ADC is not exceeded and temperature change resolution is measureable. This voltage is passed to rad-hard block sigma-delta modulator for digitization.

The Honeywell ASDX pressure sensor previously selected outputs a voltage dependent on gauge pressure and proportional to supply voltage. Based on the sensor characteristics, such as 5 V supply and 10 – 90 % calibration, the output voltage will be 0.5 V minimum plus $1.66\ \text{V/atm}$ above the sealed 1 atm reference pressure, up to 2 atm, as seen in the detailed sensors block diagram below. These voltages ranges are sufficient for analog-to-digital conversion without signal conditioning; therefore this voltage is connected directly to the Triad sigma-delta modulator circuit input.

The LND 714 Geiger-Mueller (G-M) tube is a purely gamma radiation detection device, and requires a large electric field, in the range of 500 V, in order to gather quickly moving electron-hole pairs freed by high energy incident radiation. When a radiation event occurs, the G-M tube essentially “shorts” as a result of numerous charge carriers traveling toward their respective electrodes. Sizeable current limiting resistors are required to prevent any significant current spikes as a consequence of shorting a 500 V electric field, as shown in Fig. 5. As the G-M tube shorts, electrons move toward the positive supply, producing a fast positive current spike at the cathode. Since this waveform has a very high frequency AC characteristic, the charge will take the low impedance path through the capacitor and be converted to voltage by the potentiometer. This voltage is then passed to the rad-hard comparator for event validation. Since it is unclear how much charge will be converted and gathered with each radiation event, characterization of the G-M tube and potentiometer, and thus the output voltage, will need to be done before accurate output behavior can be stated.

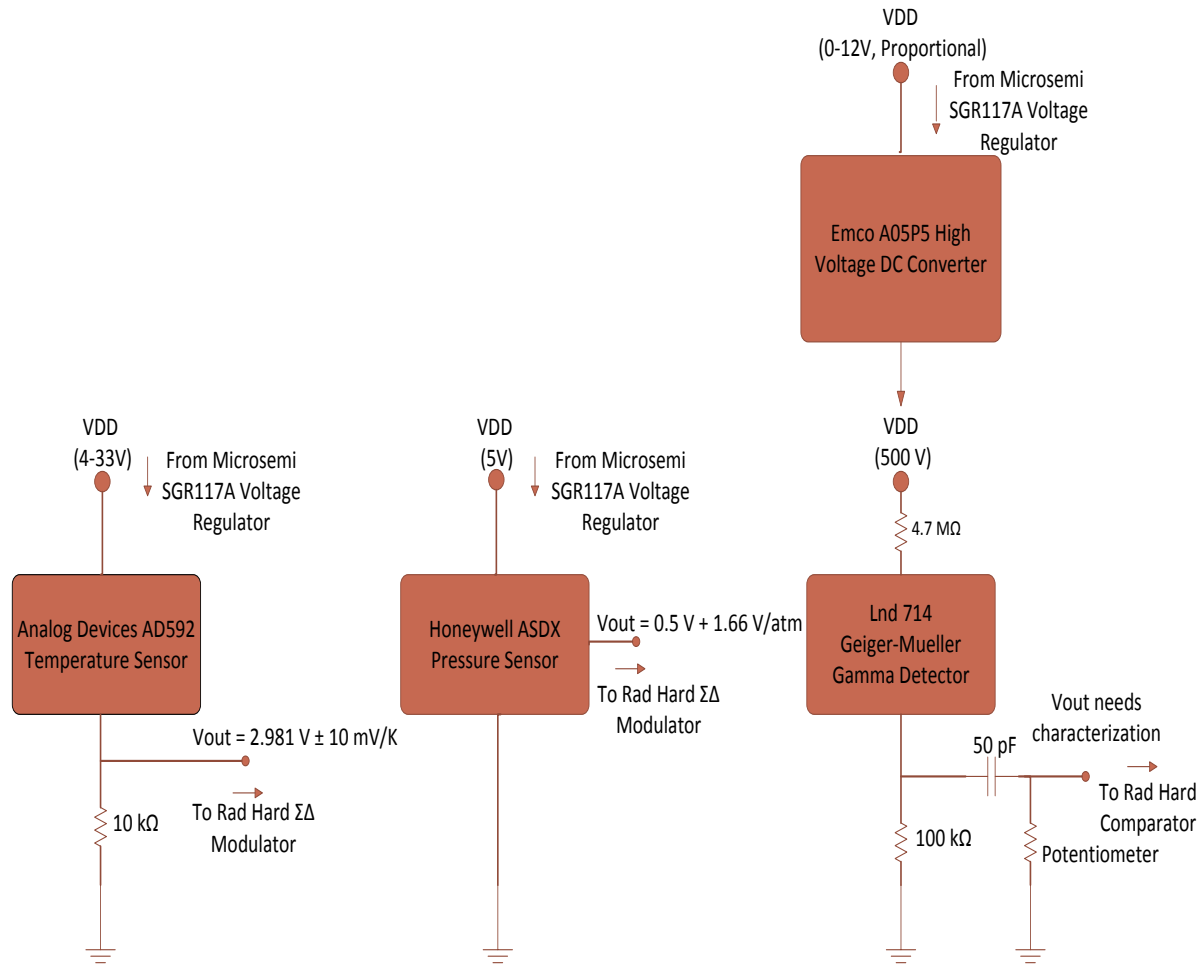


Fig. 5: Fundamental Sensor Block Diagram

3.5.2. RADIATION HARDENED ANALOG BLOCK FLOW

The temperature, pressure, and gamma radiation sensors will supply voltage waveforms to radiation hardened analog circuits on the Triad chip to begin analog-to-digital conversion. Since these measurements are inherently low frequency in nature, low-frequency single-ended op amps, and thus low-frequency single-ended sigma-delta modulators will be chosen from the Triad chip selection in order to increase noise filtering and reduce power consumption.

Both the temperature and pressure sensor analog data will undergo sigma-delta modulation to generate a digital pulse density modulated bit stream. This bit stream will then be converted into a digital number (DN) through proper filtering. The sigma-delta modulator works by increasing the output bit stream pulse density as the input analog waveform voltage increases, and decreasing the bit stream pulse density as the input analog waveform voltage decreases. Given a stable loop, the output bit streams are passed to the FPGA digital sinc filter for final translation into a DN, as seen in Fig. 6. Different values of V_{cm} , V_{refp} , and V_{refn} for sigma-delta modulation will be needed for their respective temperature and pressure data, considering these waveforms exhibit differing peak voltages and DC offsets.

Digitizing radiation events is much different than analog waveforms, in that the charge generated by the event is only present for a short period of time and needs to be classified. The current spike output from the G-M tube is converted to voltage through a resistor, and, depending on the peak level of current, the voltage will also reach a certain peak value. In order to discern whether a voltage spike is in fact a radiation event, a certain voltage threshold must be met. This can be achieved by comparing the voltage spike with a reference voltage that is unachievable by any excitation other than a radiation event. If the voltage spike surpasses this threshold, the comparator will output a digital ‘high’ value, representing one event, and subsequently return to a digital low in preparation for the next event. These events can be summed with an FPGA digitally implemented counter, which will notify users of the TID, as well as the dose rate, which is derived through the rate of change of the event count. Due to the absence of a comparator circuit on the Triad chip, a high gain-bandwidth, open-loop configured op amp will be used so as to replicate a comparator and produce a full-swing digital output that can be counted.

Two other components will be present on the rad-hard PCB, the Microsemi voltage regulator and the FMI frequency synthesizer. The rad-hard voltage regulator, which is radiation hardened beyond 1 Mrad TID, will supply the 3.3 V and 5 V rails, as well as the current, necessary for all circuits to operate, and will itself be powered by a battery. Two copies of the voltage regulator will be present for the circuits with varying voltage requirements. The rad-hard frequency synthesizer is capable of precise operation to at least 300 krad TID and will serve as the clock generator for the FPGA controller.

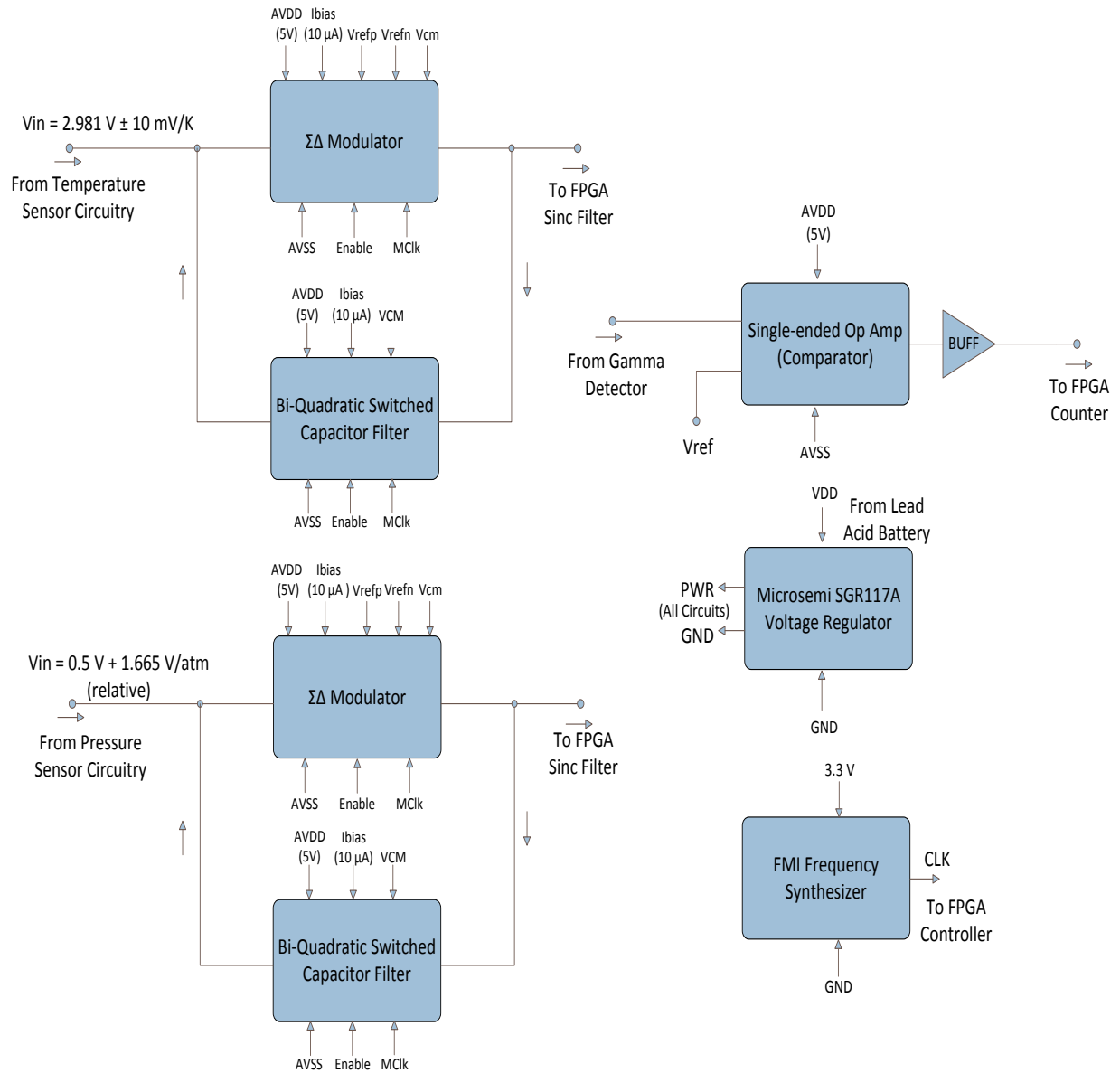


Fig. 6: Fundamental Radiation-Hardened Block Diagram

3.5.3. NON-RADIATION HARDENED CONTROL BLOCK FLOW

The final stages of data analog-to-digital conversion will be implemented digitally with the soft Xilinx Spartan 6 FPGA. Bit stream data output from the temperature and pressure data circuitry will need sinc filtering to produce a DN, while gamma radiation event data requires a counter to sum each event and report a continuous DN count. Both the sinc filter and counter will be programmed to accurately condition their respective signals into final digital format. This digital data will then be converted to serial format, and transmitted via USB to a remote PC for observation, as shown in Fig. 7.

Some components from the rad-hard board, such as the sigma-delta modulator and bi-quad filter, require certain digital control and clock signals to enable proper operation. These signals will also be precisely timed and managed by the FPGA. All blocks, control signals, and external communication will be designed and coded accordingly using FPGA VHDL language.

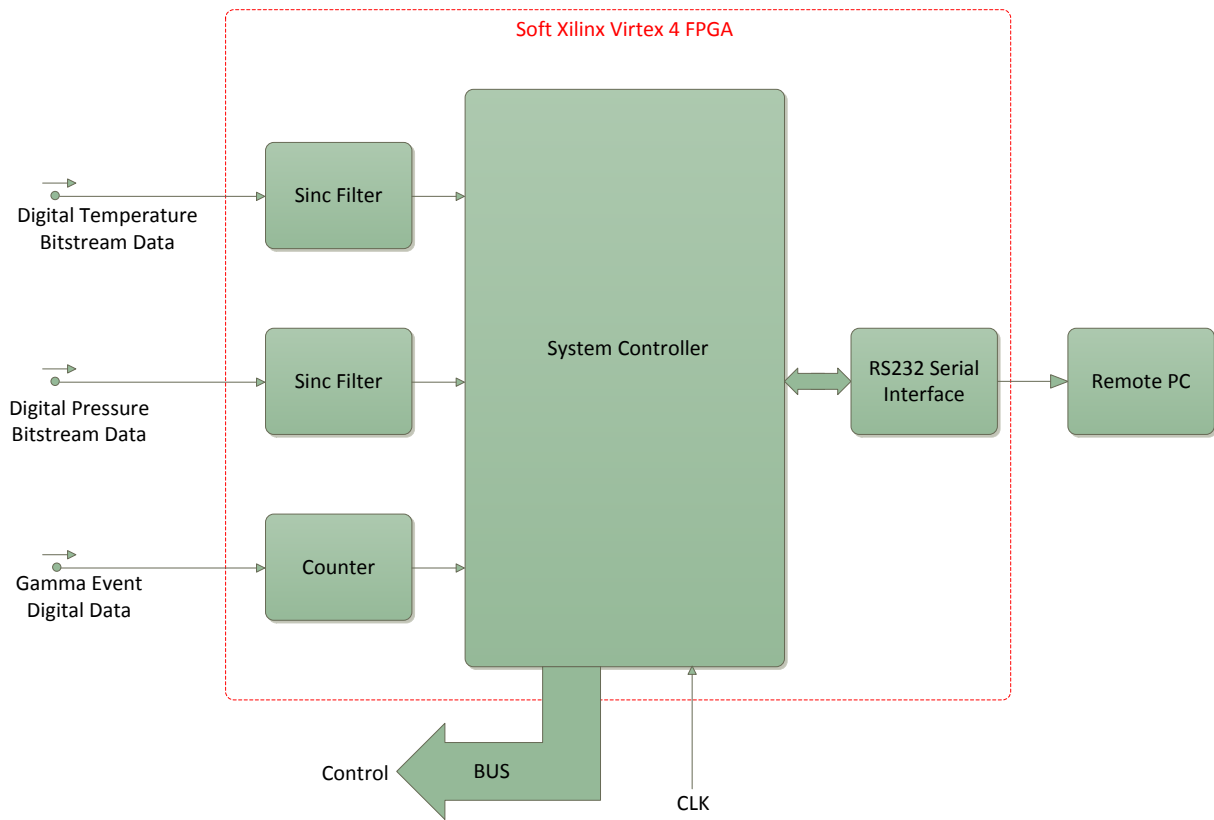


Fig. 7: Fundamental Soft (non-rad hard) Block Diagram

CHAPTER IV

DETAILED SCHEMATIC DESIGN AND SYSTEM FABRICATION

4.1. FUNDAMENTAL SYSTEM BLOCK DIAGRAM

Based on the individual preliminary board designs from Chapter 3, a complete radiation hardened data acquisition system block diagram can be devised, featuring three board sets and descriptions of their functions and interconnects [14]. This system diagram (Fig. 8) consists of power input to the analog rad-hard board and distributed to both the FPGA interface and sensor boards. Power is the only external, electrical input to the system, meaning the system is sustainable in data acquisition as long as power is available. The sensor data are transmitted on a bus to the analog rad-hard board then to the FPGA board for final analog-to-digital conversion. A control line is also implemented to enable distribution of a system clock signal. Finally, sensor data is remote transmitted in bit form to the end user in a safe location for easy display.

4.2. SYSTEM DEVELOPMENT

4.2.1. OVERVIEW

The system was developed and partitioned as shown in Fig. 9, which is a complete realistic rendition of the system diagram shown in Fig. 8. The boards labeled sensor board, rad-hard board, and interface board were designed at Oak Ridge National Laboratory (ORNL). The Nexys 3 board is the commercial development board sold by Digilent, Inc., that contains the Spartan 6 field-programmable gate array (FPGA) chosen in Chapter 3, along with the communications hardware interface. Of all the boards shown, only the rad-hard board has hardened components. The other boards were not designed to be exposed to radiation. The system, with the exception of the commercial Nexys 3 board, is designed to operate off 9 V DC so that either NiMH batteries or lithium batteries can be used. The Nexys 3 board actually uses a 110 V to 5 V DC universal adapter and was not redesigned to be used with a battery, but this could be done. The board developments and associated software will be individually presented.

4.2.2. RAD-HARD BOARD

As previously mentioned, the rad-hard board implements the interface functions between the sensors and the final digital blocks on the FPGA board. The rad-hard board consists of the

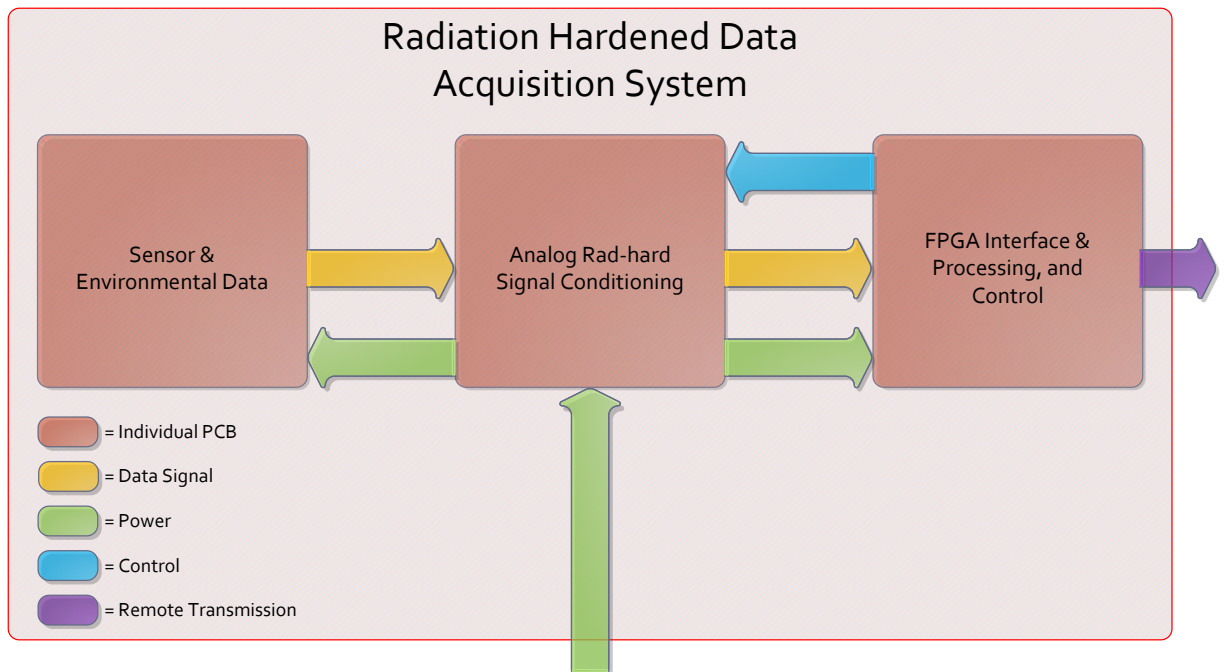


Fig. 8: System functional description

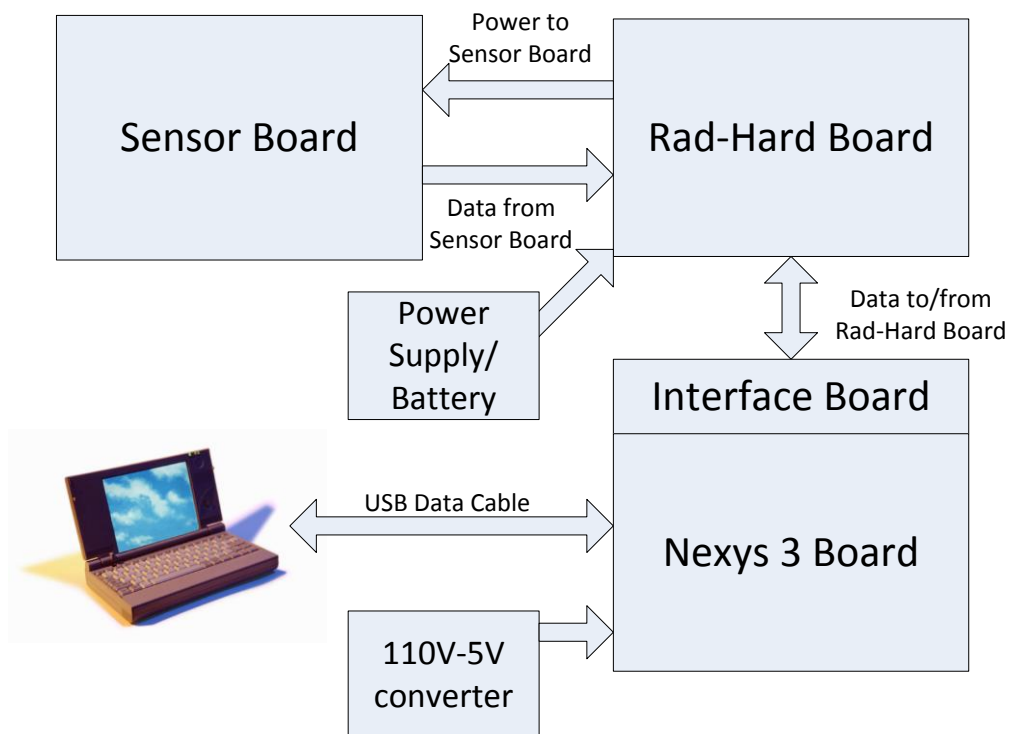


Fig. 9: System partition and functionality

Triad ASIC, the FMI synthesizer ASIC, and Microsemi voltage regulator, all of which need specific biasing requirements to operate accordingly for this application. In particular, the Triad ASIC contains sigma-delta modulators and opamps that require current biases and voltage references to establish peak to peak input ranges and, in the case of the opamp, gain-bandwidth settings. The FMI frequency synthesizer has digital bit configuration used to state the oscillator frequency, set the frequency division coefficients, and specify the output clock frequency. The Microsemi voltage regulator only requires precise resistor selection on its output as instructed by the parts datasheet to achieve the desired voltage.

For sigma-delta modulators, the voltage reference inputs are the most important factor for achieving low quantization noise in the digital data. These voltages determine the upper and lower limits of possible input signal levels, as well as the central level to which these signals will be compared for conversion. In particular, the sigma-delta modulators on the Triad VCA can accept inputs of approximately 80% of the upper and lower reference voltages without producing any visible saturation in the output pulse-density modulated bit stream. The maximum peak to peak input voltage range for the sigma-delta modulators is $1.4 V_{pp}$ [3]. The Triad VCA is also operated on a 5 V supply rail. So in order to maximize the dynamic range and the digital resolution, as well as respect the 80% of reference voltage input limitation, the positive and negative (V_{refp} and V_{refn}) reference voltages were chosen to be 3.5 V and 1.5 V respectively, centered around a common mode voltage of exactly mid-rail, 2.5 V, for both sigma-delta modulators used in temperature and pressure data signal paths. This voltage difference produces an 80% value of $1.6 V_{pp}$, allowing the entire peak to peak input voltage range possible of 1.8 V to 3.2 V to be used.

As previously mentioned in Chapter III, the selected pressure sensor outputs a ratiometric analog signal ranging from 0.5 V to 4.5 V. This range is too large to be entirely digitized by the sigma-delta modulator and needs to be scaled down to equal or less than $1.4 V_{pp}$. In addition, the scaled voltage range should remain centered about a 2.5 V reference to match the common mode voltage of the sigma-delta modulator. This functionality can be implemented through a gain and shift inverting op amp. The Triad VCA contains a radiation-hardened single-ended op amp that will be utilized for this need. Based on the standard equation describing an inverting op amp configuration (1), if the input is at maximum, 4.5 V, the output is supposed to be the minimum allowed, 1.8 V, and the reference voltage is set at 2.5 V, a scale factor of -0.35 can be calculated. This scale factor can also be calculated using the minimum input, maximum allowed output, and same reference voltage, along with any other combination of matched input and output voltages. This method ensures a consistent gain and shift for all possible voltages the

$$V_{out} = (V_{ref,p} - V_{in}) \cdot \left(\frac{R_F}{R_1}\right) + V_{ref,p} \quad (1)$$

pressure sensor outputs. This means the resistors R_F and R_1 must be selected to provide a ratio of 0.35. Standard resistor manufacturing values, as well as the optimum resistance range for noise and op amp output drive performance, leads to the selection of resistors R_F and R_1 to be 1.75 k Ω and 5 k Ω , respectively. The pressure sensor output is now converted in an inverting fashion from a 4 V_{pp} range at 0.5 V to 4.5 V to a 1.4 V_{pp} range at 1.8 V to 3.2 V that the sigma-delta modulator can use. The inverted data can be easily calibrated for at the system level once the design is completed and functional.

Also important to the desired operation of the sigma-delta modulator and the gain and shift opamp is setting the proper current bias. The specified input current is 10 μ A, and the known output voltage from the drain of the internal, diode connected, current mirroring transistors at a 10 μ A bias is 1.99 V [3]. The same 5 V power supply is used to set a voltage potential across a known resistance to produce the specified 10 μ A bias current. At 3.01 V across a resistance (5 – 1.99), a resistor of size 301 k Ω is implemented to supply the necessary Triad VCA circuits with a 10 μ A input bias current. Common practices to filter noise coming from the DC supply or electromagnetic coupling, such as adding large bypass capacitors, were implemented on all voltage and current biasing nodes to further increase the performance of the circuits. In addition, these circuits utilize an enable input to minimize unnecessary power consumption, which is controlled on board by implementing a pull-up or pull-down jumper to connect to the 5 V or ground voltage nodes, respectively.

For the FMI frequency synthesizer, binary inputs are required to configure the internal digital loop and output functionality. The synthesizer has the option to utilize a CMOS or low voltage differential signalling (LVDS) output, as well as divide an input oscillator frequency to any multiple of division by 2. For this application, the CMOS output will be chosen and an approximate 1 MHz system clock will be selected for the sigma-delta modulators to limit excessive sampling of low frequency inputs and reduce decimation filter requirements. Almost any frequency may be used as an input, as long as it is at least twice the desired frequency. A standard 20.48 MHz crystal oscillator was chosen to provide the waveform to be synthesized. To acquire roughly 1 MHz from 20.48 MHz, a frequency division of 20 is necessary, resulting in a 1.024 MHz clock signal. The binary input settings required to produce a 1.024 MHz CMOS output clock from a 20.48 MHz input signal are shown in Table 10 below and are produced on board with pull-up and pull-down jumpers. Bypassed capacitors are placed in close proximity to the input power pins to improve the synthesizer's performance. The synthesizer operates on 3.3 V, thus, outputs a full swing 3.3 V clock signal. Since the sigma-delta modulators operate at the 5 V node, some voltage level shifting will be needed to merge the two ICs into a single system. Fig. 10 shows the entire detailed block diagram for the rad-hard board.

The Microsemi voltage regulators are configured based on the desired output voltage. The product data sheet suggests a current setting resistance of 240 Ω and a voltage selecting resistor based on an internal nominal 1.25 V reference voltage. The calculated voltage selecting resistance values necessary for a 3.3 V and 5 V configured voltage regulator are 386 and 706 Ω ,

respectively. Bypass capacitors are also used on the input and output of the regulator to ensure stability across all frequencies.

4.2.2.1. Interposer Board

Extreme caution must be taken to avoid placing any radiation sensitive components on the rad-hard board. Doing so could be detrimental to the system's performance, survivability, and cost. All of the components used so far have been standard or radiation hardened parts that are generally immune to TID radiation effects. The FMI frequency synthesizer IC is packaged in a 56-pin QFN logic package and would require a highly customized socket to allow easy substitution of other chip copies. These sockets are typically made of plastic materials and do not feature option variety due to their limited and custom nature. A precisely manufactured, plastic package would likely not survive large TID radiation, especially at high dose rates. Because of this, the FMI frequency synthesizer chip must be mounted directly to the PCB, but substitution of chips is still necessary. Both needs can be achieved by the fabrication of an interposer board, which houses the FMI chip, in addition to all of its support components, and essentially maps the output pins to pins on the rad-hard board. The interposer board would 'plug' into the rad-hard board vertically with standardly spaced headers on its solder, or bottom, side. This allows ejection of the interposer board and FMI synthesizer from the rad-hard board, while eliminating radiation sensitive components from the design. A photograph of the physical rad-hard board is shown in Fig. 11 and the schematic for the interposer board can be seen in Fig. B.1 of Appendix B.

4.2.2.2. Clock Feedthrough

After the rad-hard board design was received from fabrication, some initial functional tests were performed to verify the design. These tests included checking for expected voltages, bias currents, input and output signal waveforms, and clock distribution on certain nodes. Most of the test results were as expected; however, when viewing the sigma-delta modulators input waveform on an oscilloscope (Fig. 12), small spikes were occurring at two specific frequencies. At first, it is only apparent that one set of spikes is consistent, occurring about every 300 ns. This rate corresponds to the edges of the 1.5 MHz clock signal generated by the FPGA to be a backup option for the FMI frequency synthesizer clock. For this test, the FPGA auxiliary clock was not used, but travels in proximity to the actual system clock, inducing some crossover edge coupling. This phenomenon can be seen in Fig. 13, which shows the 1.024 MHz system clock with small spikes at the 1.5 MHz frequency. In addition, both of these frequencies are coupling to the input of the sigma-delta modulator, essentially producing noise as Fig. 12 portrays. This effect is called clock feedthrough and can result in some quantization error if not addressed.

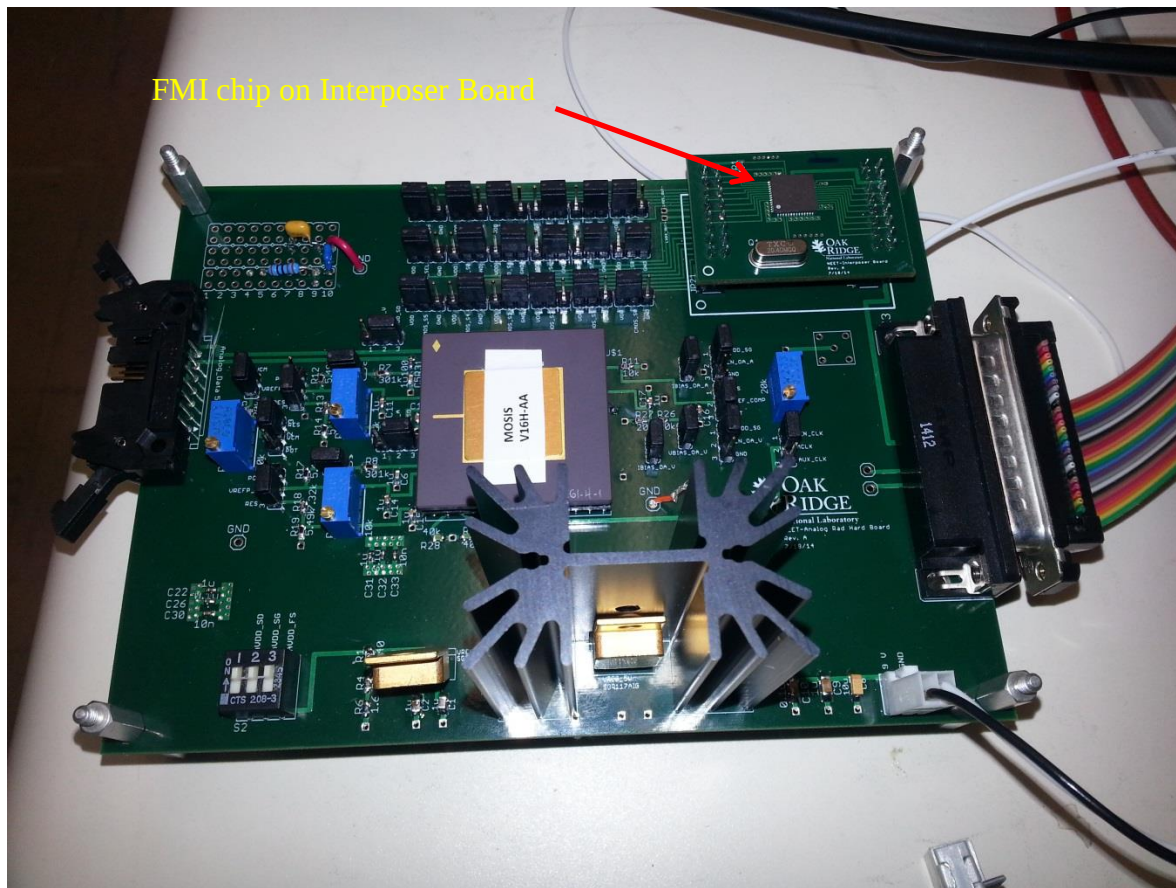


Fig. 11: The completed rad-hard board

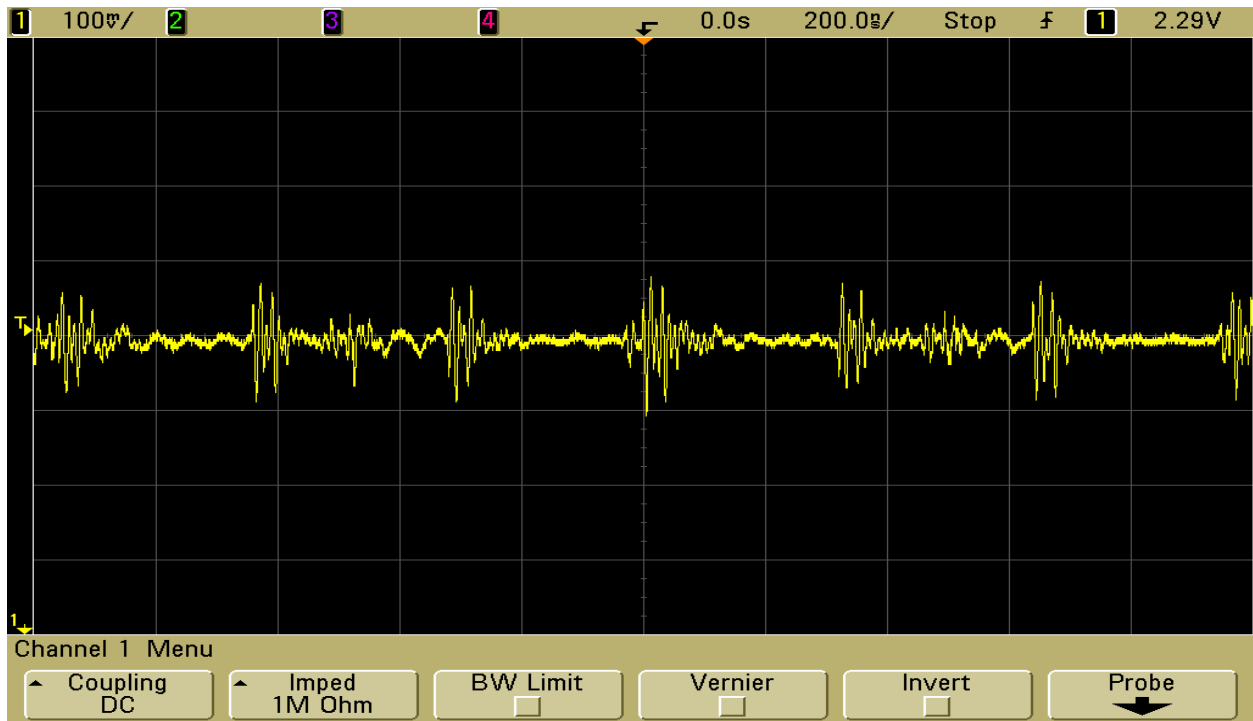


Fig. 12: Sigma-delta modulator input with clock feedthrough

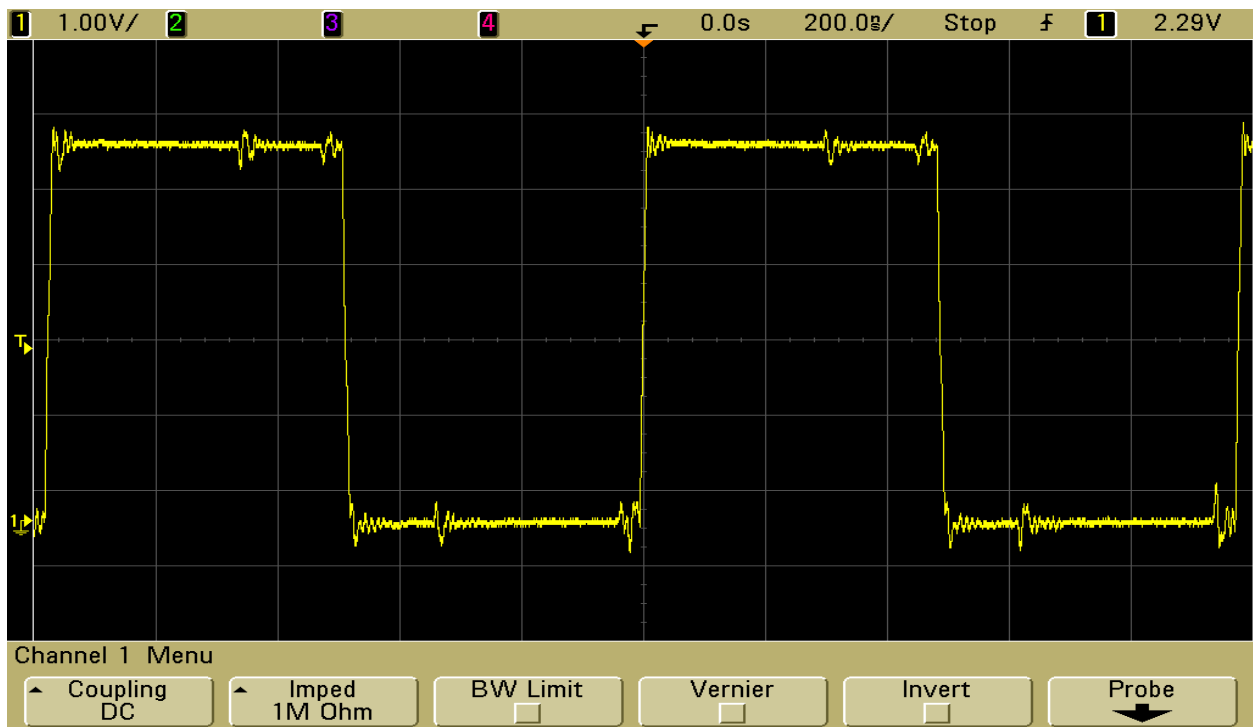


Fig. 13: System clock signal with visible auxiliary clock coupling

The simplest and most effective method for removing unwanted, high frequency noise from a signal is to implement a low-pass filter. In the case of the temperature sensing signal path, the output of the temperature sensor is a current, which means a capacitive load will not affect stability. Thus, no resistance is needed in series and a large ceramic capacitor is placed directly at the input to that sigma-delta modulator for filtering. For the pressure path, the sensor output is a voltage from an internal feedback loop, and a direct capacitive load is not recommended. A traditional low-pass filter can be used to isolate the capacitance from the sensor output and achieve filtering. It is important to keep in mind that downstream from the pressure sensor output is a gain and shift op amp with input resistance of 5 k Ω , and any added resistance will change the op amps gain factor. Therefore, the 5 k Ω resistor is split into 1 k Ω and 4 k Ω resistors, with the 1 k Ω now coming before the large capacitor and the 4 k Ω coming after, such as in a T-network, to preserve the effective input impedance to the gain and shift op amp while also creating a traditional low-pass filter. Using these modifications, as well as some other minor mistakes made during the first revision, another set of boards was fabricated. The final rad-hard board schematic is shown in Fig. B.2 of Appendix B.

4.2.3. SENSOR BOARD

As previously mentioned, the sensor board provides temperature, pressure, and gamma radiation detection elements. The outputs of these elements need to interface properly with their respective downstream signal conditioning and digitization blocks. The AD592 temperature sensor outputs a 298.2 μ A nominal current at 25°C temperature with a 1 μ A/K adjustment. The target temperature range to be measured is 0 - 100°C within a 1.8 – 3.2 V voltage span. This can be achieved using a 7.68 k Ω current to voltage resistor on its output. For this resistor value, a 0 - 100°C temperature span produces a 2.098 – 2.866 V range, with a 2.29 V nominal output and a 7.68 mV/K temperature coefficient, that can easily and accurately be digitized by the sigma-delta modulator.

For the G-M tube, the amount of output charge, and thus current and voltage spikes, per gamma event can only be characterized once the system has been fabricated. Considering the G-M tube operates based on numerous charge collisions and collection by a large electric field, or avalanche effect, it is likely that there will be more charge produced than needed to verify an event, rather than too little charge. Because too much charge in a short time span can damage downstream electronics, an attenuating resistance of 1 k Ω is added in series with the charge path to limit excessive charge carriers from traveling towards the Triad VCA op amp. In addition, because the amount of charge produced is unknown, a 500 k Ω potentiometer shunts the output of the G-M tube to provide amplitude control over the voltage that will be present on the comparator input. The final detailed sensor board block diagram, physical board, and schematic are shown in Figs. 14, 15, and Fig. B.3 of Appendix B, respectively.

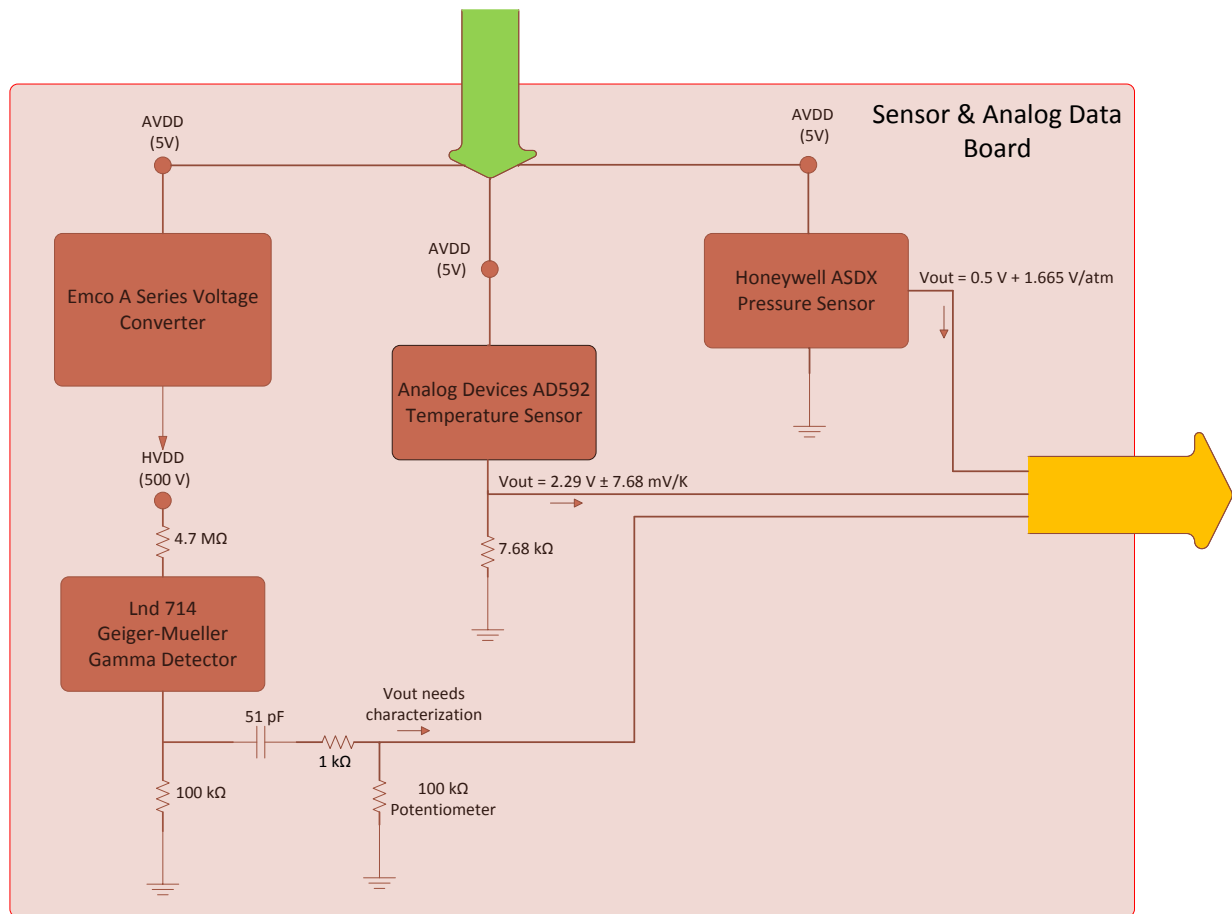


Fig. 14: Detailed sensor board block diagram

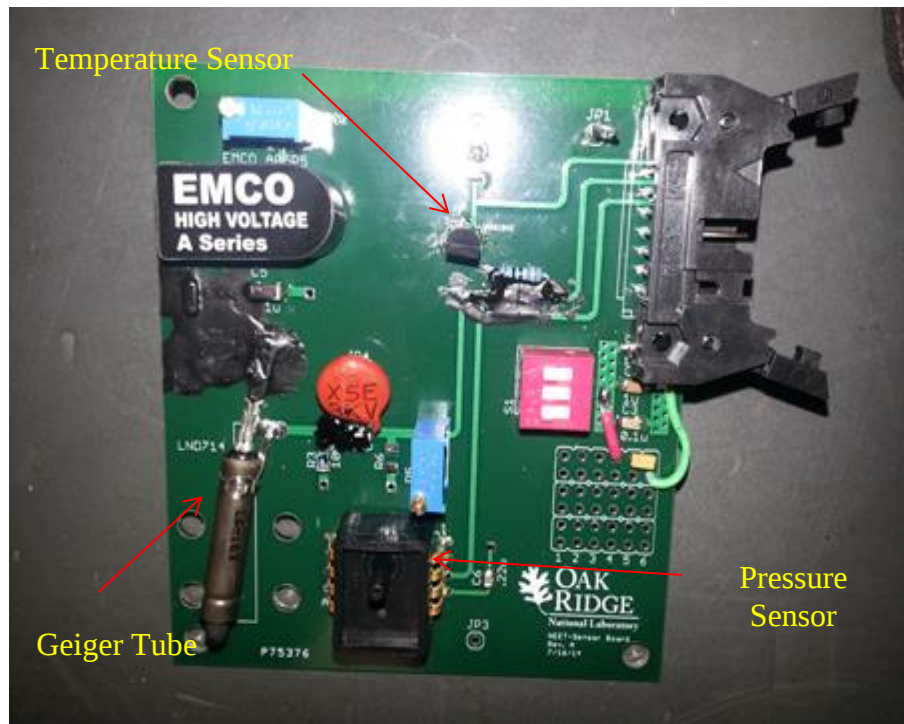


Fig. 15: The Sensor board with insulation coatings

The pressure sensor output is uncontrollable externally; however, downstream gain and shift operations conform the 0.5 – 4.5 V output to acceptable values for the sigma-delta modulator. The 500 V supply required by the G-M tube is generated by the EMCO A series voltage converter from the 5 V board supply and also precisely controlled by a potentiometer.

4.2.4. INTERFACE BOARD

The function of the interface board is to translate and buffer digital voltages to their proper levels. For instance, operations completed by the Traid VCA IC will be 5 V signals, while the FMI frequency synthesizer and the Nexus 3 digital controller operate on 3.3 V. In order for the sigma-delta modulators to use the system clock generated by the FMI synthesizer, a voltage level shift from 3.3 V to 5 V of that clock signal is necessary. This type of conversion will be done on the interface board for the 3.3 V ADC clock, the 3.3 V AUX clock, and all of the 5 V data and clock streams. The ISO7240 and ISO7242 chips used to perform these voltage translations are from the Texas Instruments ISO isolator family of interface devices. These circuits allow different supply voltages (in this case, 5 V and 3.3 V) to be used on either side of the devices; they can transmit or receive digital pulses of the appropriate amplitude. The 5 V and 3.3 V power required is supplied to the interface board from the rad-hard board voltage regulators. In addition, the interface board is used to perform the physical connections between the Nexys 3 board and the cable which connects the interface board to the rad-hard board. The data flow block diagram for the interface board is shown in Fig. 16 below and the board schematic can be seen in Fig. B.4 of Appendix B.

4.2.5. NEXYS 3 BOARD FIRMWARE/COMPUTER INTERFACE

The program created for the FPGA controller was written as a state machine implementation of a universal asynchronous receiver transmitter (UART) communications interface. The UART provides a serial data interface to a standard universal serial bus (USB) found on all modern personal computers. The USB interface provides fast data transfer between the data-collection computer and the radiation-hardened data acquisition system. The electrical hardware portion of the interface, made by FTD International, is already resident on the Nexys 3 board (Fig. 17) and requires code to implement the software functionality. The UART interfaces to a standard personal computer USB port and is configured to operate at a baud rate of 9600. The top-level program also features a counter used for summing gamma events, a decimation filter for downsampling the sigma-delta modulator output data stream into final digital bit format, and an auxiliary clock generator for backup system clock purposes, all implemented in VHDL. Figure A.1 of Appendix A illustrates the functional flow of the FPGA program and each block is described in detail in the following sections.

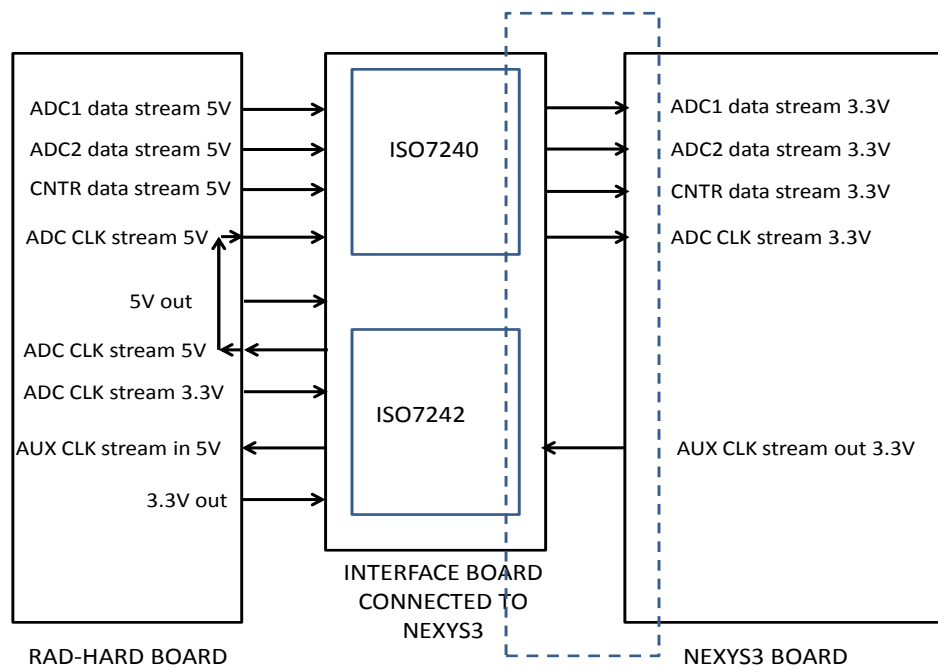


Fig. 16: Detailed interface board data flow block diagram

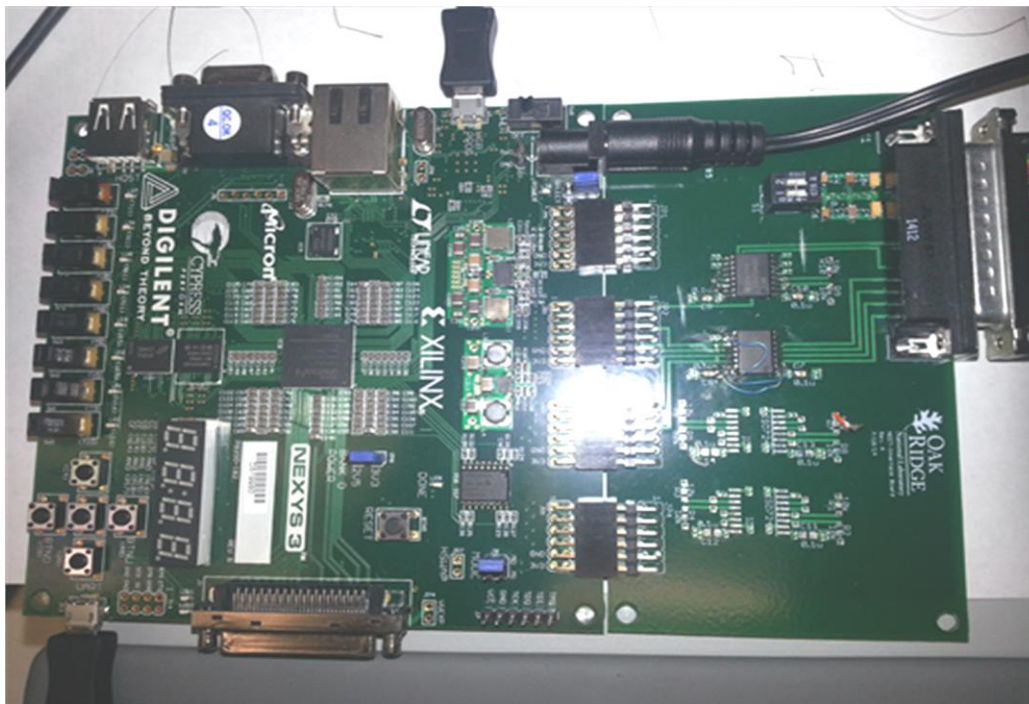


Fig. 17: The interface board (right) connected to the Nexys 3 board

4.2.5.1. UART (t_serial)

The “t_serial” block is the UART state machine code. This code was taken from open-source VHDL code developed by Bainville [15] and modified for this project’s purpose. The code implements a single-byte receive and retransmit UART which was minimally modified to receive a command byte and then retransmit either a status byte or a data byte, depending on the code sent. The UART is programmed to receive any of nine different ASCII byte commands and then parse them in a state machine. If the byte is a valid command, there is a predefined action that takes place. The list of these valid commands and their corresponding functions and actions are shown in Table 11 below. For these commands, “temp” denotes the temperature ADC, and “press” denotes the pressure ADC.

The command architecture is designed such that combinations of these commands can be issued to perform a greater overall function than any single command. For example, issuing system-wide reset, system wide data load, adc1 (temp) low-byte load, adc1 (temp) high-byte load would read the entire data set from the temperature ADC for a single cycle. This functionality enables automated communications between the Nexus 3 board and the end-user through the use of a local program such as LabVIEW. The data gathered by LabVIEW software can then be compiled and displayed for the user in a simple, standard unit format.

4.2.5.2. Counter (Ctr_16_dp).

The “Ctr_16_dp” block is the counter which maintains a running count of the individual events received from the G-M tube’s gamma validation comparator for a specified length of time. After the interval of time, determined by the LabVIEW software, the counter binary value is latched and read from two 8-bit registers into the computer using the UART commands. The

Table 11: UART command, function, and return character list

COMMAND	FUNCTION	RETURN CHARACTER
hex 20 (space)	system-wide reset	hex 20 (space)
hex 21 (!)	counter reset	hex 21 (!)
hex 22 (")	system-wide data load	hex 22 (")
hex 30 (0)	counter high-byte load	(data)
hex 31 (1)	counter low-byte load	(data)
hex 32 (2)	adc1(temp) low-byte load	(data)
hex 33 (3)	adc1(temp) high-byte load	(data)
hex 34 (4)	adc2(press) low-byte load	(data)
hex 35 (5)	adc2(press) high-byte load	(data)

counter is then reset and resumes counting for the next time interval. The time interval for each data set read can be calculated, and can be used to convert total events during that time to standard units of counts per second (cps). A cps measurement from the G-M tube will provide the ability to classify the current radiation environment situation, whether that be normal operating conditions or unstable conditions that need attention.

4.2.5.3. Decimation Filter (Decimation_filter_top).

The “decimation_filter_top” block is a decimation filter whose purpose is to filter the out-of-band quantization noise from the sigma-delta modulator oversampled data. The sigma-delta modulator shapes a large portion of the quantization noise to reside outside of the bandwidth of the analog data so it may be filtered out. Input to the filters are two single-bit data buses with variable pulse density that corresponds to the signal level at the modulator input. In this particular case, the input data represent slowly changing temperature and pressure measurements. For all practical purposes, the modulator input can be considered as a DC signal.

The decimation filter can be implemented as a low-pass, sinc filter. One way to create a low-pass, sinc filter is with a Cascaded Integrator-Comb (CIC) structure. The standard structure for a CIC filter is shown in Fig. 18 below. The “N” variable represents the filter order, and “R” is the filter decimation ratio. For this application, a third-order ($N = 3$) CIC filter with decimation ratio of 256 ($R = 256$), which is consistent with the sigma-delta modulator oversampling ratio, was designed. All of the sub-blocks are digital and designed in VHDL for FPGA implementation. Fig. 19 shows the frequency response of the filter before decimation

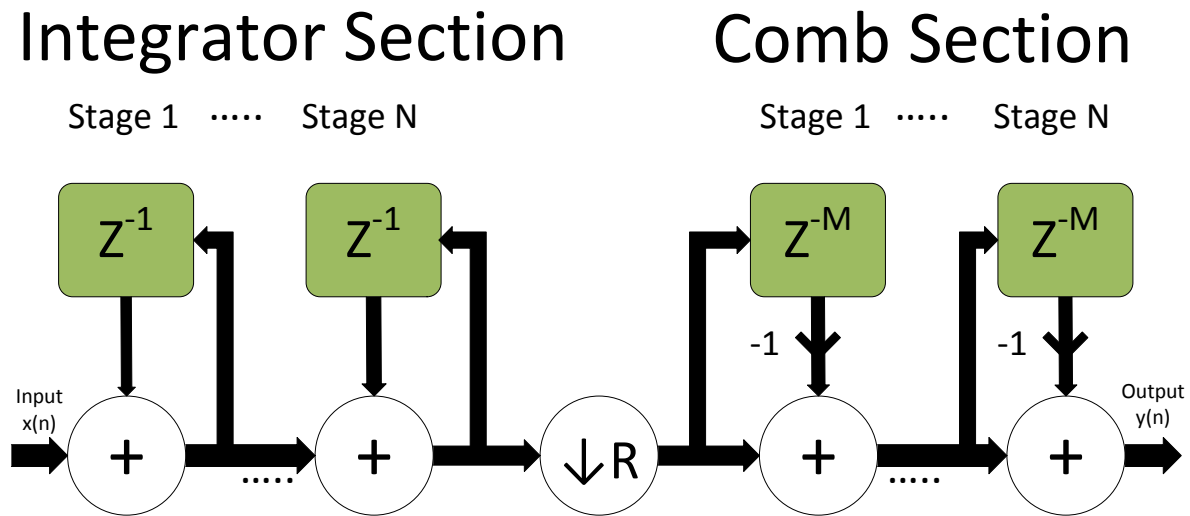


Fig. 18: Decimation filter mathematical structure

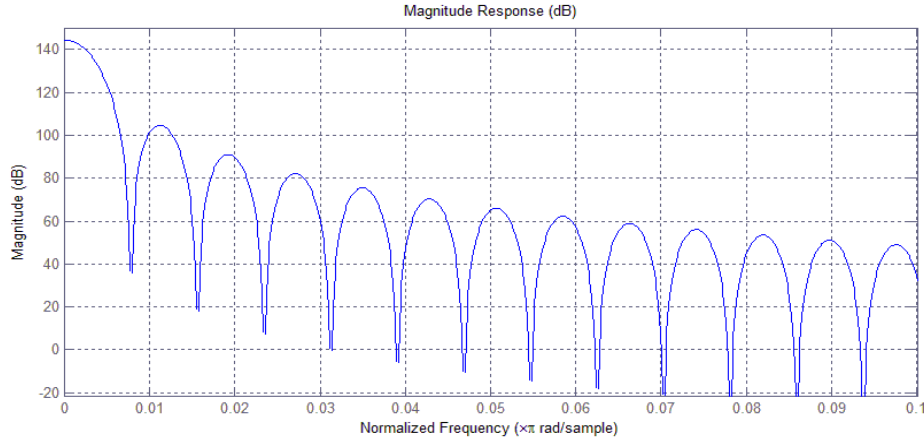


Fig. 19: Decimation filter frequency response

occurs. The performance of the decimation filter was simulated using Simulink. When using the first-order modulator to feed the decimation filter, the dynamic range of the filter's output was approximately 80, which corresponded to more than 13 bits of resolution. The decimation filter structure's proper behavior was confirmed through hardware testing and final DN readout expectations.

4.2.5.4. Clock Generator (ClkGen).

The "ClkGen" block is a clock generator that was used for system functional test purposes and serves only as a backup clock generator option. It is implemented by a frequency division of the 100 MHz Nexys 3 development board system clock. The output value of the clock generator is 100 MHz divided in half six times ($100 \text{ MHz}/2^6$), or 1.5625 MHz. This clock is a 3.3 V, 50 % duty cycle square wave and is level shifted to 5 V for use with the rad-hard board sigma-delta modulators.

4.2.6. LABVIEW INTERFACE PROGRAM

Initially, a LabVIEW program was written to simply gather and report digital data to the user. This was necessary for system calibration purposes, but will not be sufficient for the final system. The LabVIEW interface program collects data from the Nexys 3 board FPGA program and displays the value of the raw data. It transmits the selected command outlined in the UART section and displays the return value of the requested command. It also configures the COM port on the computer to the appropriate settings. A screen shot of the program is shown in Fig. 20.

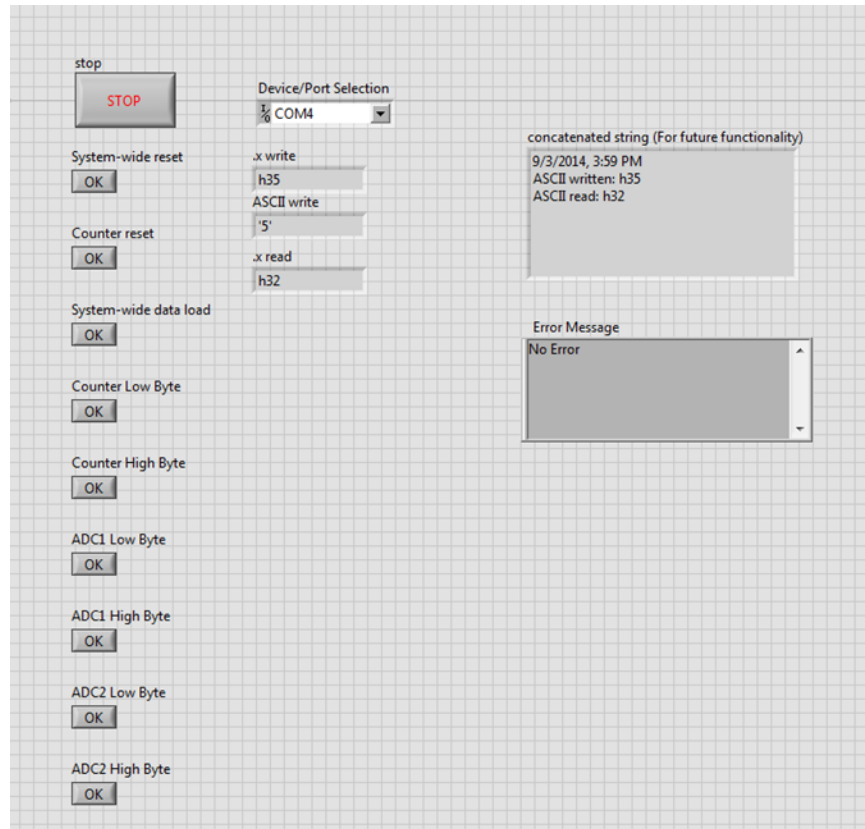


Fig. 20: Screen shot of the initial LabVIEW interface program

CHAPTER V

SYSTEM PERFORMANCE VALIDATION

5.1. TEST-SUITE DEVELOPMENT

The development of a test to extract relevant and accurate results from a system is vital to a projects integrity, documentation, and presentation [16]. This data acquisition system based on radiation-hardened mask-programmable analog arrays, previously outlined in Fig. 8, requires a suite of tests to completely capture the functionality and performance in extreme environments such as nuclear reactor monitoring and disaster scenarios. These environments are capable of wide temperature and pressure ranges, as well as high dose rate radiation. The suite of tests must encompass all boundaries of which these environments are capable. This section illustrates those tests using color-coded interconnect consistent with Fig. 8 and provides detailed descriptions of each.

5.1.1. TEMPERATURE CALIBRATION TEST SETUP

Within potentially harsh radiation environments such as nuclear reactor sites, ambient temperature can be a significant parameter for monitoring normal and stable reactor operating conditions, as well as detecting early signs of nuclear disaster situations. As a result, accurate and frequent temperature measurements are necessary. The data acquisition system is capable of measuring ambient temperature, but the performance of this measurement needs to be characterized.

The obvious way to complete this characterization is to setup the system for normal operation and place the sensor board inside an environmental chamber that can precisely control the temperature within. The chamber would be used to sweep the temperature across a wide range and let the system report temperature data points along the way. By recording the temperature chamber reading at certain intervals, as well as the system temperature data, any error can be approximated and factored out, also called calibration. To ensure a stable and consistent temperature throughout the chamber and that the sensor board has reached equilibrium temperature, a period of time is allotted at each data point interval in which the chamber temperature setting is unchanged. Fig. 21 below illustrates this test setup, including the sensor board within the temperature chamber, appropriate interconnect between each PCB, power supplies, and FPGA UART interface to the end-user PC. A voltmeter is also used to record the output voltage of the temperature sensor, which will provide insight into any nonlinearity that may be present.

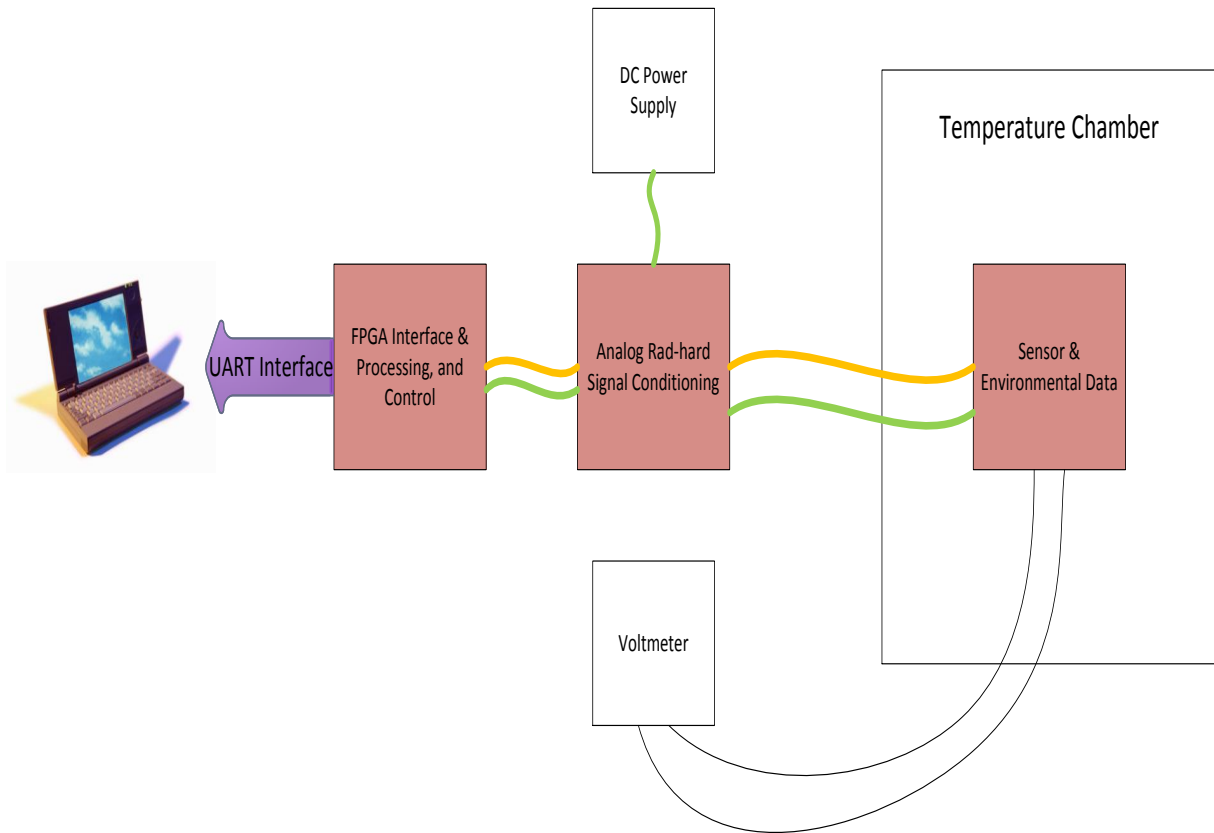


Fig. 21: System temperature calibration testing setup

5.1.2. TEMPERATURE DRIFT CALIBRATION SETUP

Also of importance to characterizing the measurement performance of the data acquisition system is testing for any drift effects to due change in temperature of the rad-hard board. In realistic scenarios, it is likely that the entire system's temperature will change along with the sensor board. Thus, it is necessary to sweep the temperature of the sensor board and rad-hard board simultaneously. For the purposes of this project, the FPGA board is not required to operate at elevated temperatures, but future prototypes could incorporate this feature.

This test setup will not differ significantly from Fig. 21, as only the rad-hard board will be moved into the temperature chamber along with the sensor board. However, this requires a slight change in wiring. Previously, only a single power and data cable were routed into the chamber. In this case, that power and data cable will remain in the chamber, while an additional power cable and data cable will need to be routed in to power the system and provide a data path to the digital controller that remains outside the chamber. Fig. 22 below portrays this temperature drift test setup, along with FPGA UART interface to the end-user PC. Once again, a voltmeter is used to document temperature sensor output voltage readings to assist in analyzing any nonlinearity that may be apparent from the system calibrations.

5.1.3. PRESSURE CALIBRATION TEST SETUP

Much like temperature, pressure is another parameter that can be monitored in reactor environments to reveal ideal or non-ideal operating conditions and also if unsafe conditions may be developing. For harsh environments, we want to measure pressure relative to normal atmospheric pressure, or gauge pressure, up to 2 atm (3 atm absolute). The data acquisition system pressure sensor is capable of measuring up to 30 psi relative pressure, which covers this range requirement, but needs characterization to accurately report instantaneous ambient pressure data.

Creating pressure in a test environment is different than that of creating temperature, since pressure is typically distributed through some tube or pipe instead of pressure sealing an entire chamber. The ASDX series Honeywell pressure sensor features an axial vented port, which can be easily pressure sealed using a silicon tube at such relatively low pressure levels. Therefore, a pressure generator with a fine-tunable regulator is sufficient for sweeping across the specified pressure range in 2.5 psi increments. This allows normal operating condition setup of the data acquisition system for pressure calibration with only the addition of a pressure generator and tubing connected directly to the vented axial port of the pressure sensor. This test can be executed much quicker than the temperature test, since pressure change and equilibrium is reached abruptly, and no time allotment between data points is needed. The pressure calibration test setup is shown in Fig. 23 below.

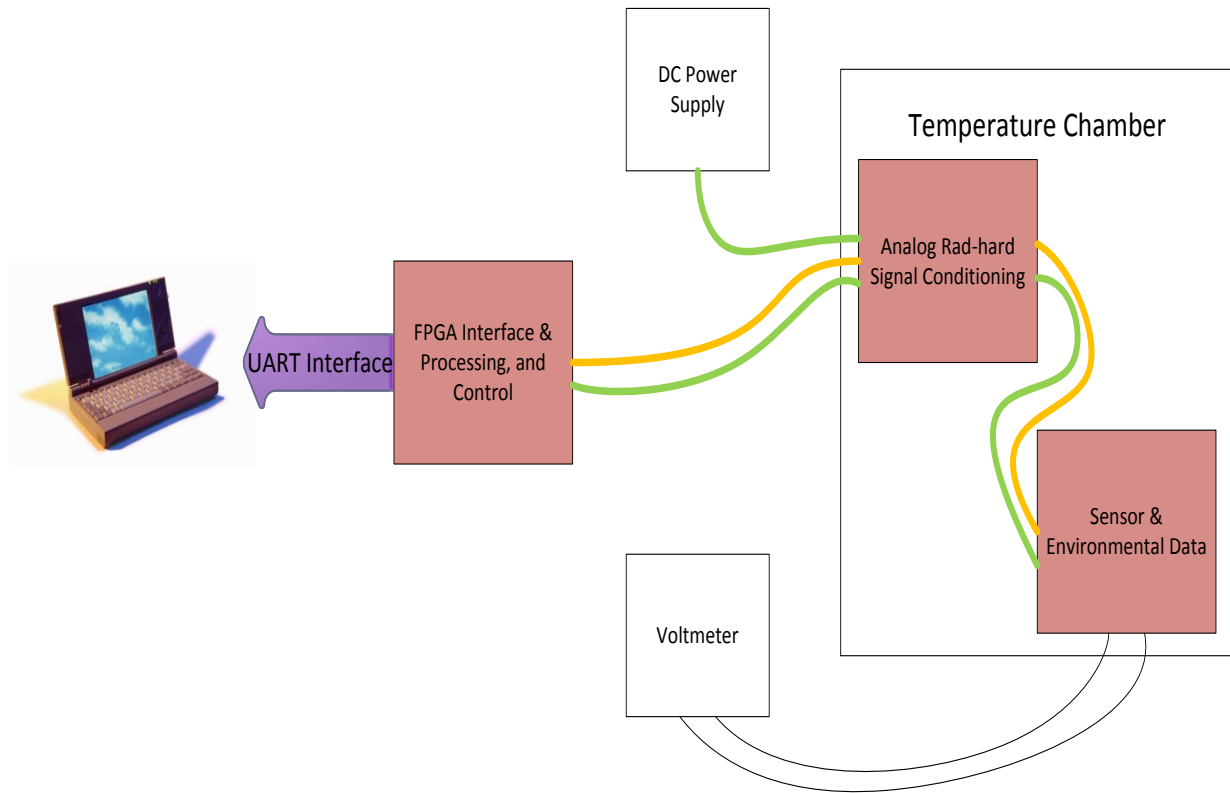


Fig. 22: System temperature drift calibration testing setup

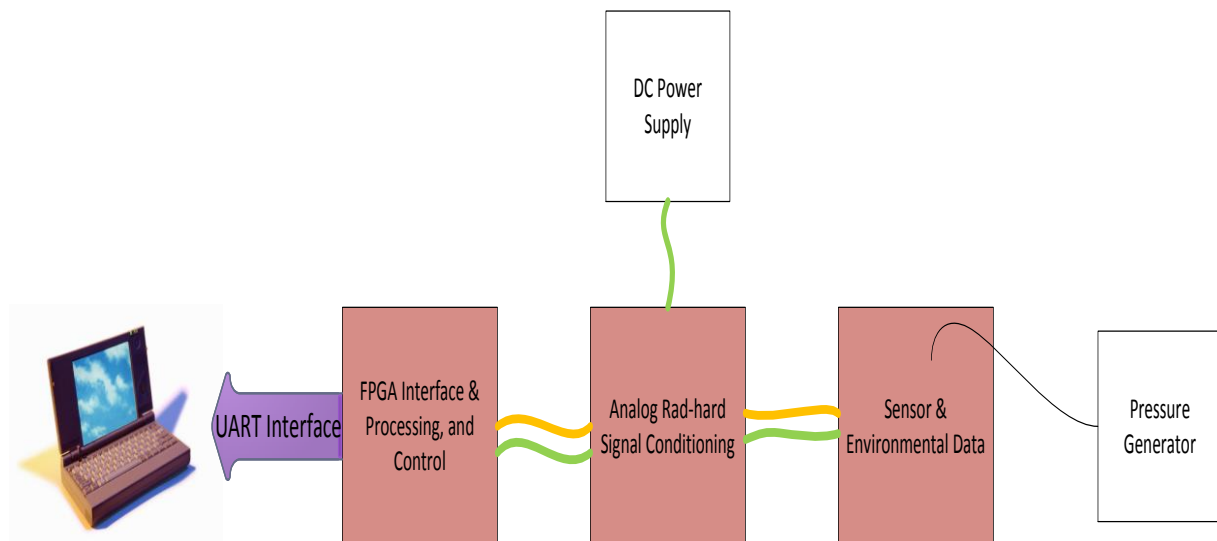


Fig. 23: System pressure calibration testing setup

5.1.4. RADIATION TESTING SETUP

5.1.4.1. Site Selection

There are many parameters that classify a radiation test site, including radiation source type, dose distribution, and dose rate. All of these parameters can vary greatly depending on the exposure facility. The application often determines which configuration would be best for obtaining realistic, useful system radiation tolerance data. For the data acquisition system in particular, we are interested in TID radiation potentially up to 300 kRad at a target dose rate of 30 kRad/h. In addition, a 360° dose distribution is also useful for this system due to the large area required of the rad-hard board (5.84x4.305 in²) to mount all of the necessary ASICs. This will help provide an even distribution of radiation dose across the entire board area and ensure proper radiation exposure to all circuit elements designed for radiation hardness.

TID radiation comes from charged particles such as gamma rays, or high-energy photons. The most common and cost efficient radiation source with nuclear decay that fits these specifications is Cobalt-60, which has photopeaks at 1.186 MeV and 1.348 MeV. Numerous radiation exposure facilities house Cobalt-60 sources, but all specifications must be met. Many facilities were considered, including options on-site at Oak Ridge National Laboratory. The conclusion was made that Dr. Keith Holbert's lab, which contains a Gammacell 220 at Arizona State University, was the best fit for our application. The Gammacell 220 is a 360° distributing Cobalt-60 source with isodose curve in Fig. 24 below [17]. The source will produce a dose rate of 28.62 kRad/h during the time period (Feb. 2-5, 2015) we will commence radiation testing. A chamber that contains the devices to be irradiated is lowered into the pool with a path out the roof for cabling. Dr. Keith Holbert is also a primary investigator for another project under NEET-2.

5.1.4.2. Test Setup

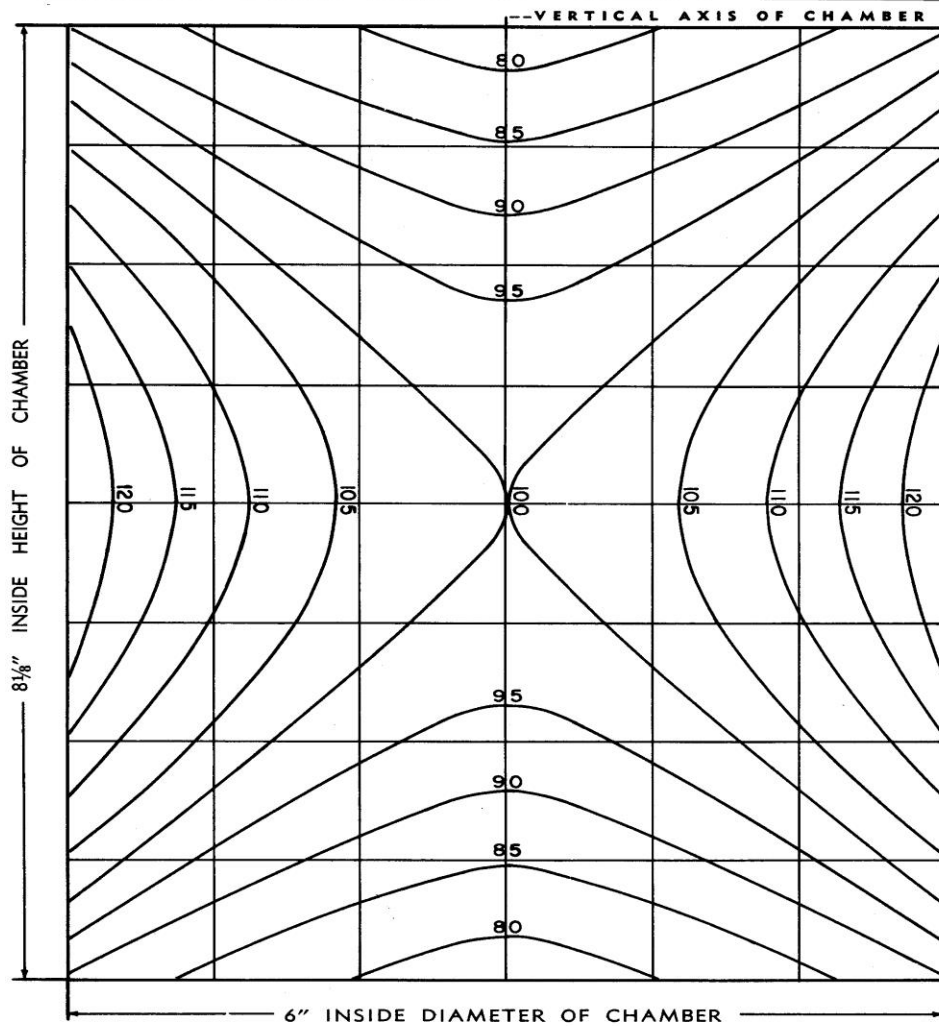
Radiation detection is the key parameter in identifying a nuclear reactor disaster scenario. Radiation will escape the reactor containment before ambient temperature or pressure changes are realizable. A test setup that exposes the proper boards to gamma radiation and protects the vulnerable components from harmful dose rates, all while allowing ambient parameter and power consumption data to be taken is crucial to the accuracy and prolonged operation of the entire system.

Because only the rad-hard board will be lowered in the radiation pool, multiple cables and wiring will need to be irradiated as well. This includes power cable from the voltage supply, data and power cables to the sensor board, and power and data cables to the FPGA controller board. These cables will need to be recycled after each system is irradiated because the PVC

ISODOSE CURVES

Gammacell 220

STANDARD LOADING ONLY



The isodose distribution in the irradiation chamber of all Gammacell 220 Units having standard loading should agree within $\pm 5\%$ with the relative values shown on the above isodose chart.



Atomic Energy of Canada Limited • Commercial Products

P.O. Box 93 • Ottawa • Canada
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Fig. 24: Gammacell 220 isodose curves [17]

insulating material will begin to deteriorate at high TID. Also, since the G-M tube will be in use to monitor any background radiation or report faulty data due to radiation effects, the sensor board will need to be placed in a high voltage protection box to safeguard against any incidental contact with the existent 500 V supply. In addition, power consumption is an important parameter that is susceptible to radiation effects if not properly mitigated, so voltage and current are measured throughout the duration of the test. This is done by simply connecting a voltmeter across the terminals of the voltage supply, as well as an ammeter in series with the positive referenced current supply. Finally, due to the immobility of DC power supplies, a battery better suits the application of radiation hardened data acquisition for nuclear reactor monitoring; thus, a 9.6 V nickel-metal hydride battery is used as the power supply during radiation testing. Fig. 25 below illustrates the radiation testing setup.

5.1.5. LABVIEW INTERFACE SOFTWARE CODE DEVELOPMENT

The previous version of the LabVIEW interface program was sufficient to gather data during calibration testing, but was unable to use the curve coefficients found during calibration to convert the raw digital data back to useful ambient data. The final goal of the data acquisition system is to provide intelligible data to the end users so that they can assess a reactor environment operating condition.

In order to achieve this functionality, modifications to the LabVIEW software were necessary. First, mathematical functions such as multiplication, division, addition, subtraction, square roots, and squaring were implemented to enable solving of equations. These equations differed between the temperature and pressure calibration coefficients due to the temperature curves using a polynomial fit and pressure curves using a linear fit, as later summarized in their respective calibration sections. In addition, since five complete systems were calibrated for both temperature and pressure, an array subset function was implemented to allow users to select which system is being tested, hence which set of calibration coefficients to use.

Second, this converted data needs to be actively plotted so users can visually discern the operating conditions of the system's ambient environment as a function of time. This requires using LabVIEW's graphing palette and array builder to construct an array of x and y coordinate points, x being time and y being ambient data. This was done for all three sets of ambient data: temperature, pressure, and gamma radiation events. The temperature and pressure displays need be instantaneous, so a simple plotting of the x and y coordinate points would suffice. The gamma event display, however, should be a dose rate measurement. This means the y data is normalized to number of counts per second (cps). This conversion requires calculating the time elapsed between each data point, and dividing the number of counts that occurred within that cycle by the measured time. Now a true dose rate with units of cps can be used to create an array that can be plotted by LabVIEW's graphing block. All of these graphs, along with all other

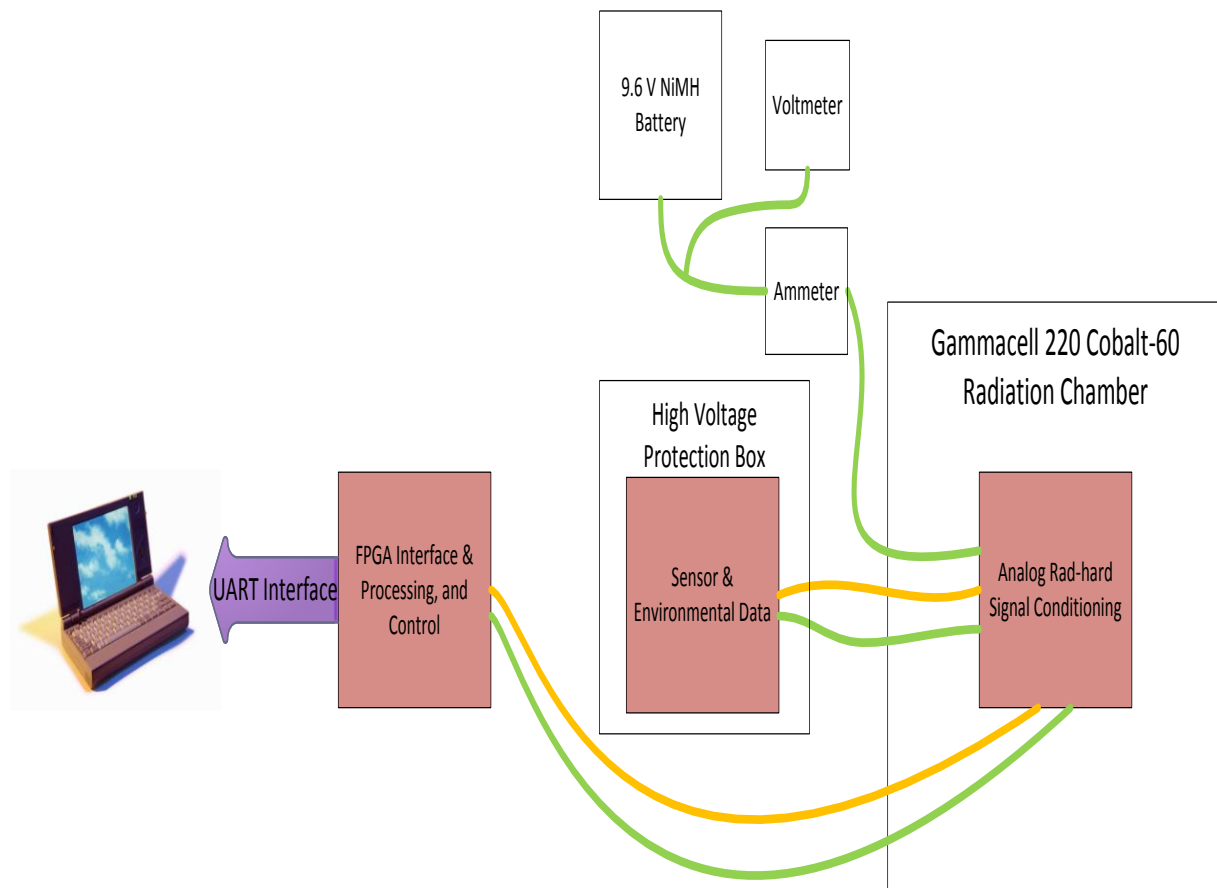


Fig. 25: System radiation testing setup

functionality implemented within the LabVIEW software used for final testing, are shown in Fig. 26 below.

Lastly, all of the data in the arrays used for visual graphing not only needs to be displayed continuously to the end user for active monitoring, but also should be stored as pure data into a local file for later examination. For each system tested, a separate location can be assigned to write the data into a specific comma separated value (.csv) file as the arrays are updated. LabVIEW features a block called “write to spreadsheet” that executes this functionality with options such as append file, transpose data, and data formatting for complete customization of the csv file in which the data is written. Completely developed LabVIEW software visual code for top level and sub VI interfacing can be seen in Figs. A.2-A.4 of Appendix A, respectively.

5.2. PRE-IRRADIATION CALIBRATION TESTING

Due to the extremely high cost of radiation hardened parts, such as sensors and FPGAs, the radiation hardened data acquisition system from Fig. 8 was partitioned across three board designs. One board houses all the necessary radiation hardened integrated circuits (ICs), such as the Triad VCA, FMI frequency synthesizer, and voltage regulators, while the other two boards allow mounting of the selected commercial sensors and digital controller, respectively. Because the system is spread across three boards, the required cabling and longer wire traces create parasitics that induce some variations between each system. Inherently, there will be system to system variation regardless of board partitioning. This is because the IC fabrication process, although precise, is not perfect, and silicon substrate variations from chip to chip are inevitable. Although these variations at the chip and board level are typically small, they need to be accounted for in order to preserve the integrity of the data acquisition process.

An easy way to mitigate variations is to calibrate each system individually. This includes recording the final system output DN of each data path for a specific known input value. The input value is swept across the entire range of possible inputs at a certain interval, and data is recorded at each step. If enough data points are taken, the final output DN can then be plotted versus the input range to portray each system’s specific output value curve for the same common input range. By fitting each curve with an equation, output DNs can be mapped back to input ambient environmental data precisely for each system for easy display to the end-user. Curve fitting is done by selecting the type of curve that best approximates the systems calibration data, which is quantified with the coefficient of determination, or r-squared, value. A value of r-squared is always between 0 and 1, and a higher value denotes a better fit of the selected curve type to the measured data. After a curve type decision is made, the coefficients of the equation describing that curve, or trendline, can be extracted and used to directly convert digital outputs to proper inputs. These coefficients are static for each system, and only need to be measured once.

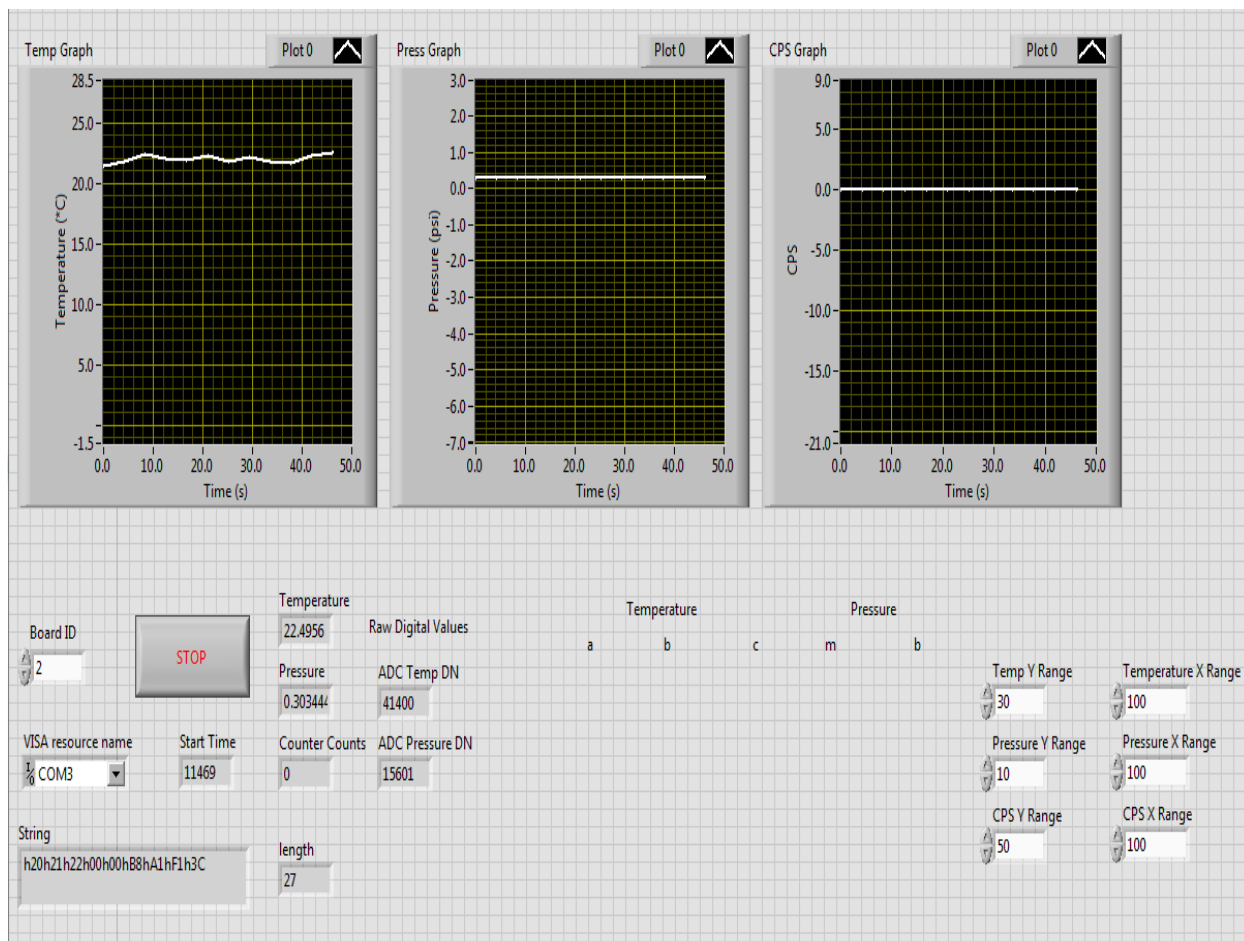


Fig. 26: LabVIEW interface software used for calibration and radiation testing

LabVIEW then uses these coefficients to automatically calculate the ambient input data based on the instantaneous system output.

5.2.1. TEMPERATURE CALIBRATION

The main focal points when analyzing calibration data are linearity and continuity. A linear response signifies little to no outside or unexpected factors are affecting the system data, while continuity denotes a continuous time system with consistent behavior. To ensure the signal conditioning and ADC circuits on the radiation hardened board were linear with respect to input, the output ADC DN data were taken with respect to input voltage for both the temperature and pressure ADCs. The temperature ADC data is shown in Fig. 27 below with great linearity over the entire ADC input dynamic range at an r-squared value of 0.99985.

Based on the excellent linearity of the circuits within the temperature data path on the radiation hardened board, it can be stated that any nonlinearities in the overall system calibration measurement are attributed to the sensor board components. Some slight exponential behavior is expected from the sensor board, which is due to the requirement of a current-to-voltage resistor on the output of the temperature sensor. It is well known that resistance changes to some degree as function of temperature, even with high precision, low temperature coefficient resistors. The sensor board is subjected to the most extreme temperature range of any board in order to model realistic operating conditions. Thus, there will be an inevitable shift in the current-to-voltage resistance, resulting in a voltage shift as well, according to Ohm's Law.

Our published final project specification [1] requires five complete data acquisition systems be functional and tested across temperature and pressure. The result of temperature calibration for all five systems is shown in Figs. 28-32 below. The blue data points represent sweeping the temperature of the environmental chamber from -5 to 70°C in 7.5°C increments with only the sensor board inside the chamber (Fig. 21). The rad-hard board and controller board are left outside the chamber in ambient room temperature.

As shown in the temperature calibration data, there is some apparent nonlinearity with an upward concavity. This behavior was expected and is in line with the resistance shifting explanation. For instance, as the chamber temperature decreases, the current-to-voltage resistance also decreases, resulting in a shift down in voltage. This voltage reduction produces an increase in output DN, according to Fig. 27. Conversely, the opposite shift happens when chamber temperature increases. This behavior results in a concave up behavior curve.

Considering the slight nonlinearity of the temperature calibration data, a linear trendline will not best approximate the curve. All five other regression types were auditioned, and a polynomial approximation produced the highest r-squared value for all five systems. Table 12 below summarizes for each system the polynomial r-squared values and coefficients that are used by LabVIEW to convert output DNs to ambient data.

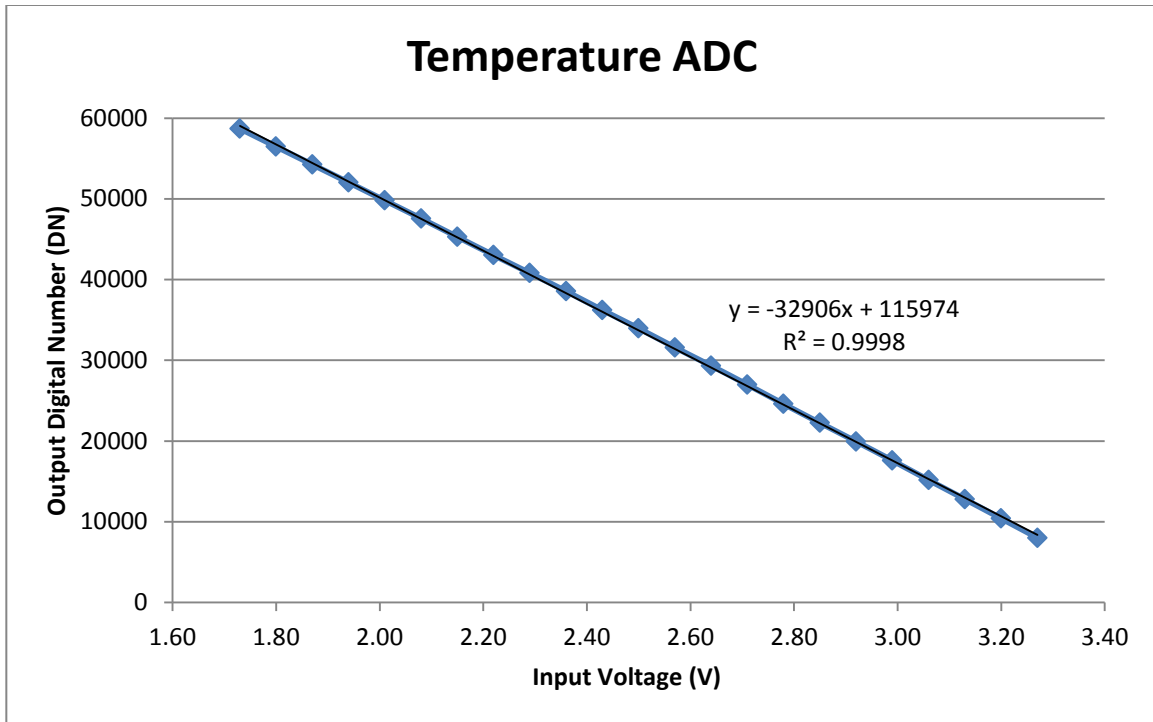


Fig. 27: Preliminary temperature ADC output DN vs input voltage

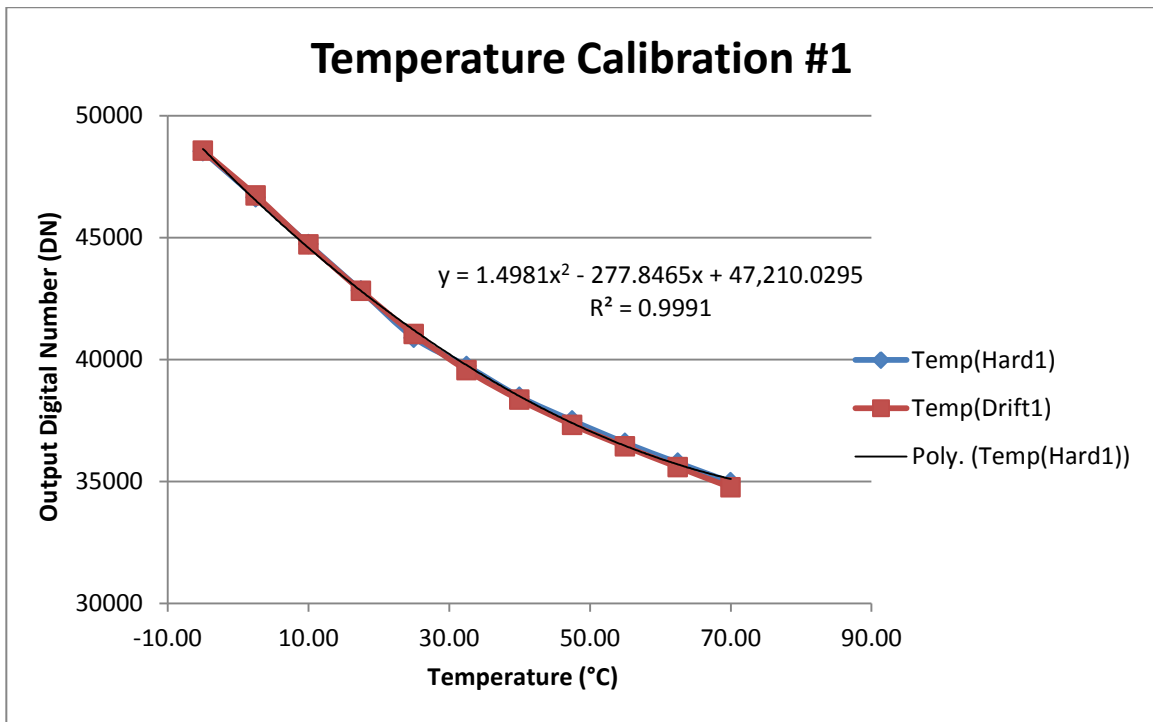


Fig. 28: System 1 temperature output DN vs ambient temperature

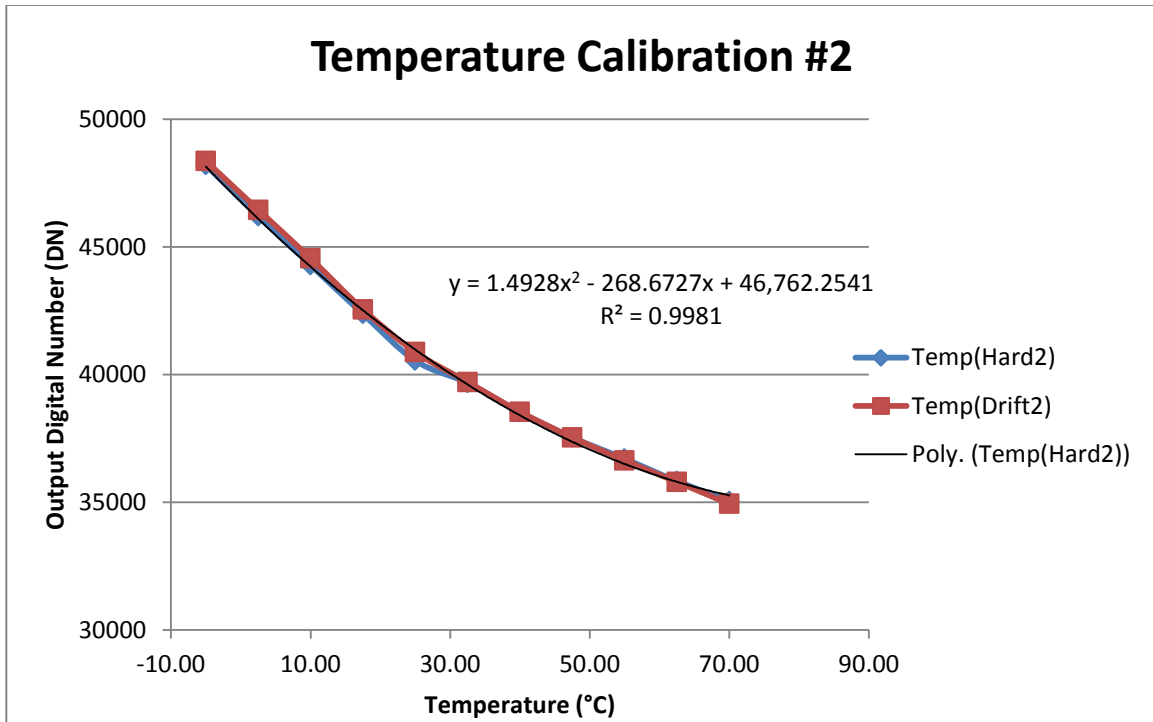


Fig. 29: System 2 temperature output DN vs ambient temperature

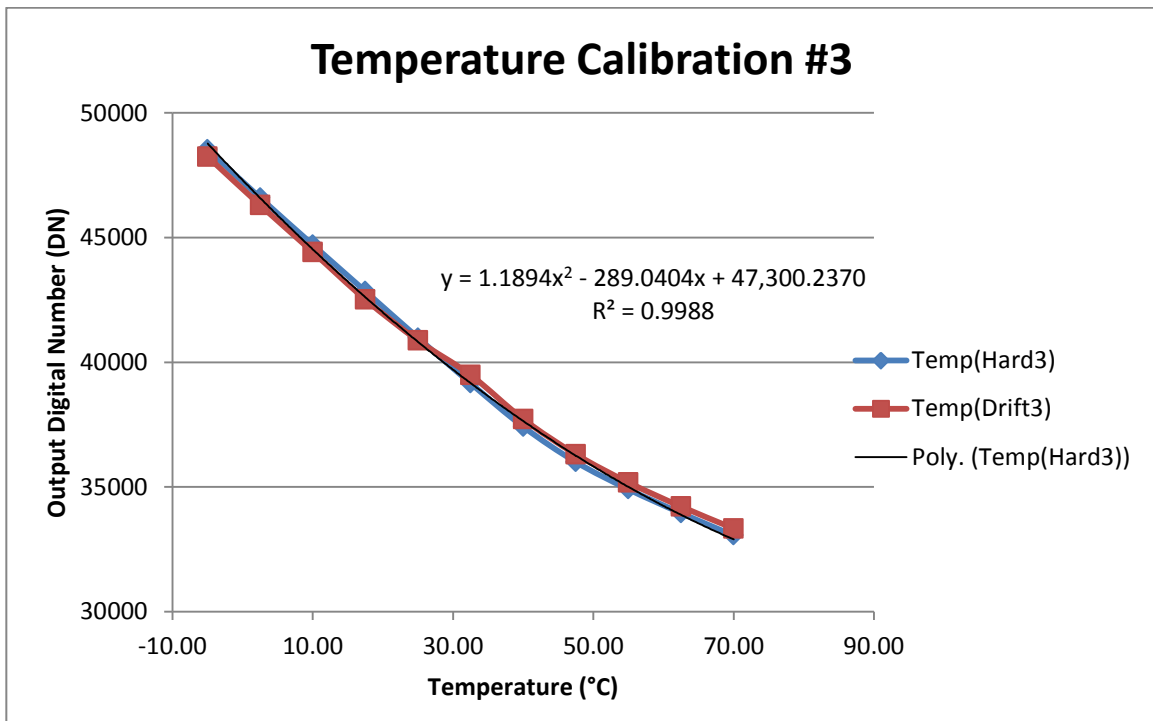


Fig. 30: System 3 temperature output DN vs ambient temperature

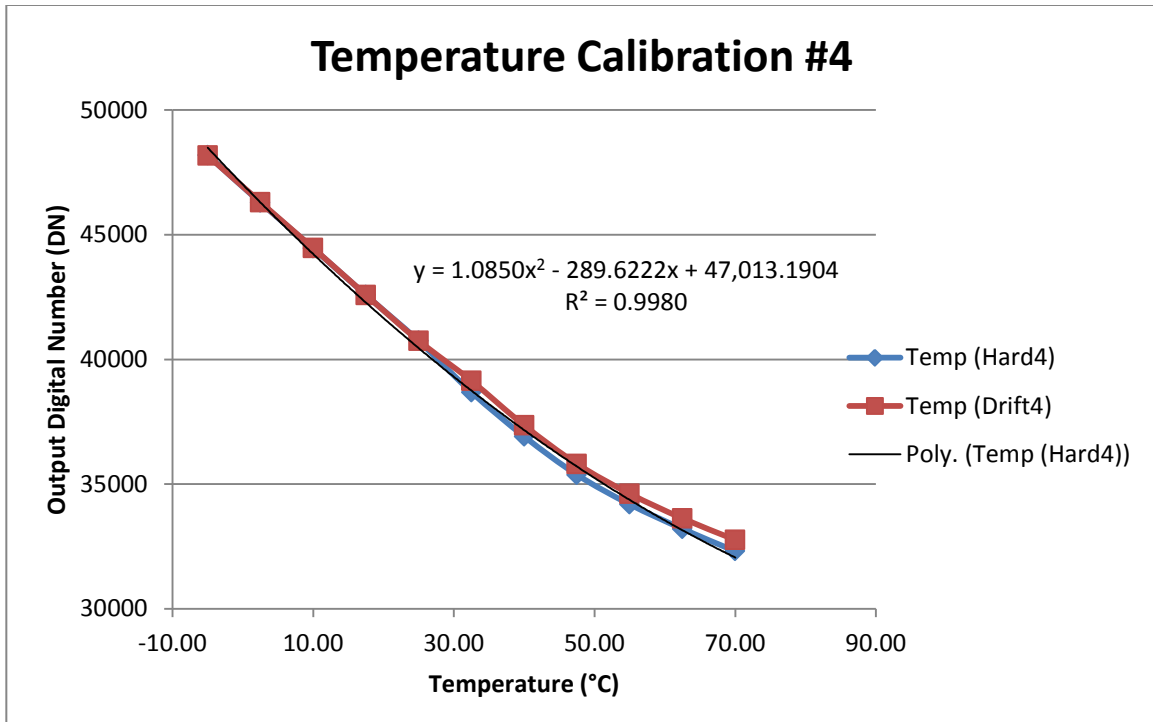


Fig. 31: System 4 temperature output DN vs ambient temperature

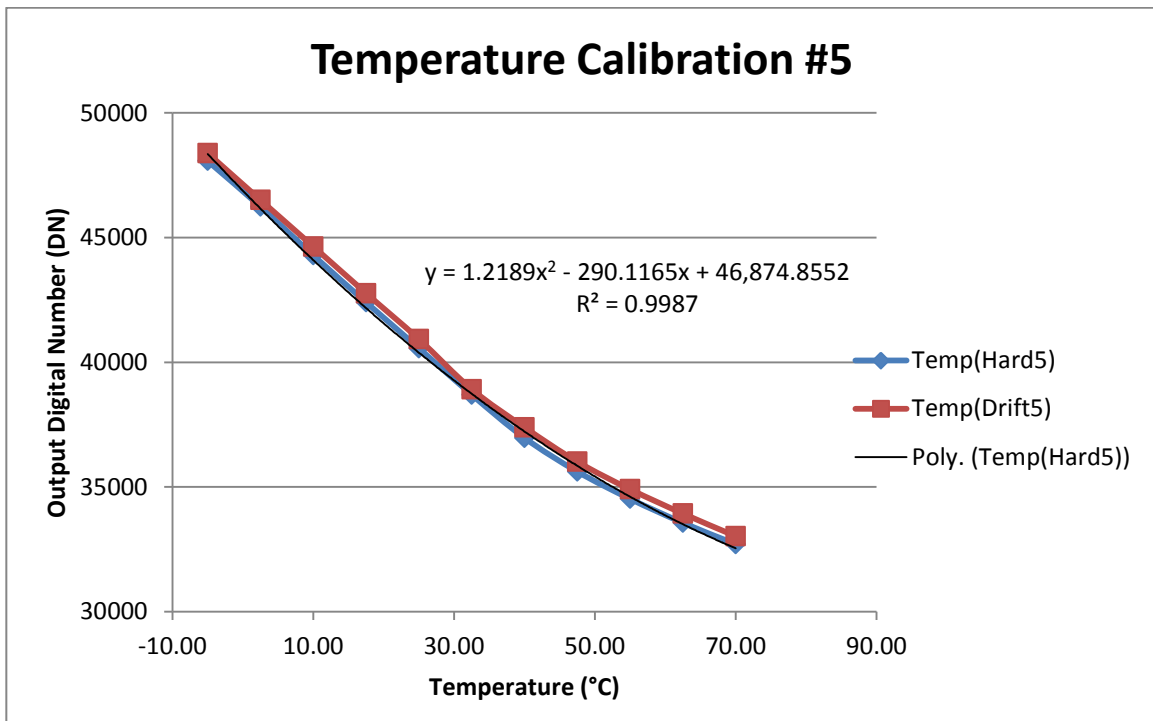


Fig. 32: System 5 temperature output DN vs ambient temperature

Table 12: Summary of system temperature calibrations fit values and coefficients

SYSTEM	COEFFICIENTS (a, b, c)	R-SQUARED FIT VALUE
1	1.4981, -277.85, 47210.03	0.9991
2	1.4928, -268.67, 46762.25	0.9981
3	1.1894, -289.04, 47300.24	0.9988
4	1.0850, -289.62, 47013.19	0.9980
5	1.2189, -290.12, 46874.86	0.9987

In order to analyze any drift effects in the output DNs due to wide temperature variation of the radiation hardened circuitry, as well as meet stated project objectives, complete system calibration data is also taken sweeping the temperature of both the rad-hard and sensor board in the environmental chamber, as previously shown in Fig. 22. Results of this test will provide insight into the temperature performance capabilities of the system up to the final digitization of the pulse width modulated bit stream output of the sigma delta modulators.

As depicted by the red data points in Figs. 28-32, the drift of the output data as a function of temperature relative to the temperature calibration data (blue) is minimal. In fact, the data sets almost overlap exactly for all five systems. These outcomes are outstanding, considering all of the electrical biasing and functions that are temperature dependent and critical to the accuracy of the system, such as voltage references and current biases, the frequency synthesizer, and input node impedance within the temperature data path. Furthermore, the data verifies the wide temperature capabilities of the Triad VCA and FMI frequency synthesizer ICs, as well as all other ICs and designed circuitry present on the rad-hard board.

5.2.2. PRESSURE CALIBRATION

Just as with the temperature calibration, a measure of output pressure ADC DN while sweeping input voltage was performed to ensure the signal conditioning and ADC circuits on the radiation hardened board were linear with respect to input. These were preliminary tests to verify linearity of the radiation hardened ADCs before moving on to complete system data calibration. Fig. 33 below shows the results of this input voltage sweep over the entire range of possible pressure sensor output voltages.

The pressure ADC also shows great linearity at an r-squared value of 0.9998. This is consistent with the preliminary temperature ADC measurement. It is also apparent that the pressure measurement shows an opposite slope as the temperature ADC. This is because the pressure sensor outputs a voltage between 0.5 and 4.5 V. This voltage range is too large for the common mode input range of the ADC, so an inverting gain and shift operational amplifier was

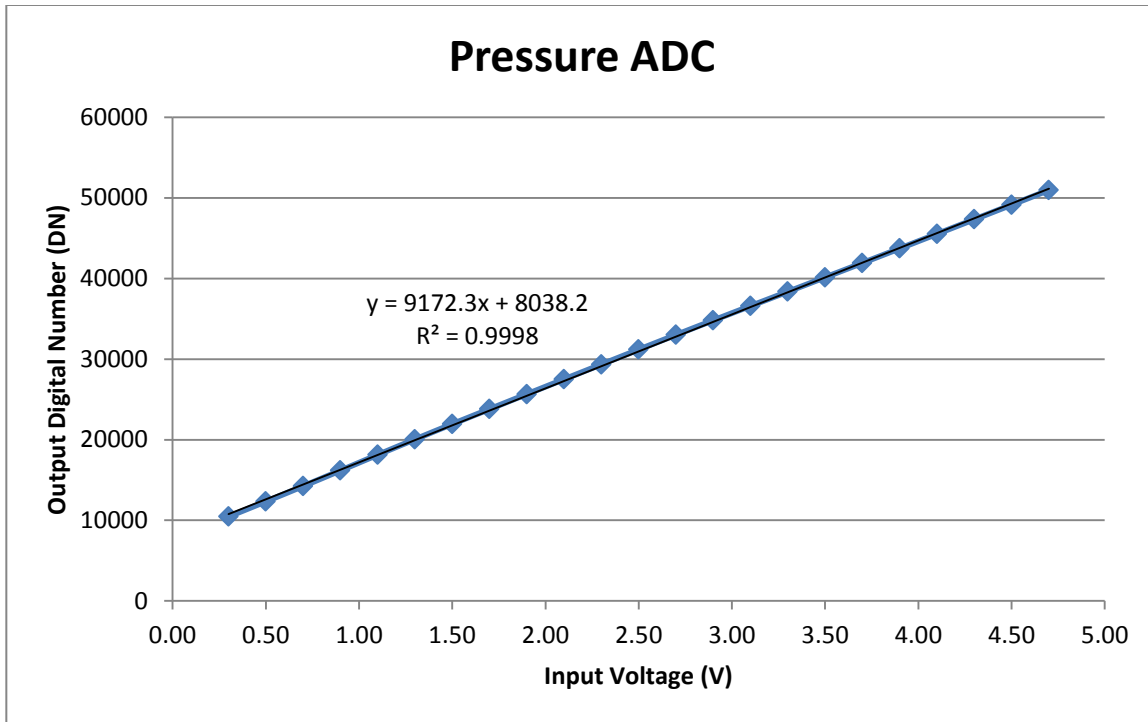


Fig. 33: Preliminary pressure ADC output DN vs input voltage

implemented to scale the 0.5 to 4.5 V range down to 1.8 to 3.2 V. This prevents the ADC from receiving voltage levels beyond its input common mode range and outputting invalid data. This scaling is done easiest with an inverting configuration, thus the pressure signal conditioning and digitization shows an inverted behavior with respect to the preliminary temperature ADC test (Fig. 27).

Differing from the system temperature calibrations, a highly linear system pressure calibration is expected. This is because the pressure sensor outputs a voltage controlled by internal feedback loop, instead of a current; thus is not dependent on temperature sensitive output node impedance. The result of pressure calibration for all five systems is shown in Figs. 34-38 below. The blue data points represent sweeping the pressure input to the pressure sensor in 2.5 psi increments (Fig. 23).

The pressure calibration data for all five systems shows great linearity. This result matches the expectations of the pressure sensor, and validates the consistency and accuracy of both the pressure sensor and rad-hard circuitry, making for a simple trendline approximation. A linear fit produces the best approximation for all five systems, and Table 13 below summarizes for each system the linear r-squared values and coefficients that are used by LabVIEW to convert output DNs to ambient data.

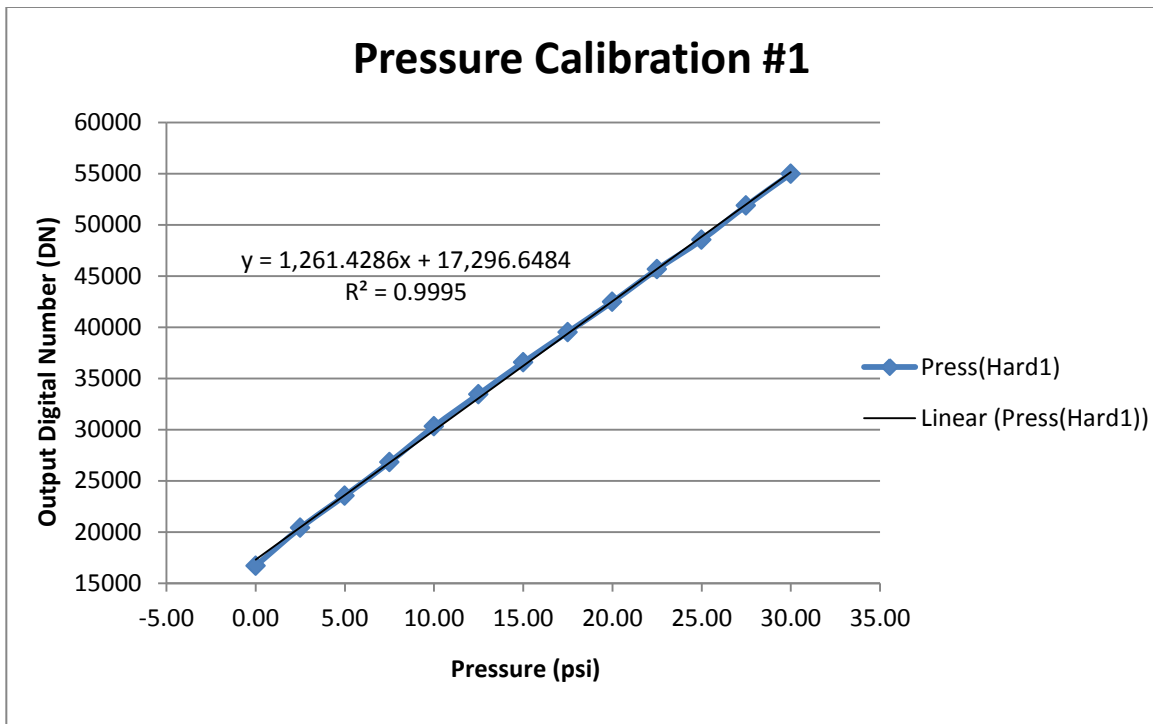


Fig. 34: System 1 pressure output DN vs ambient pressure

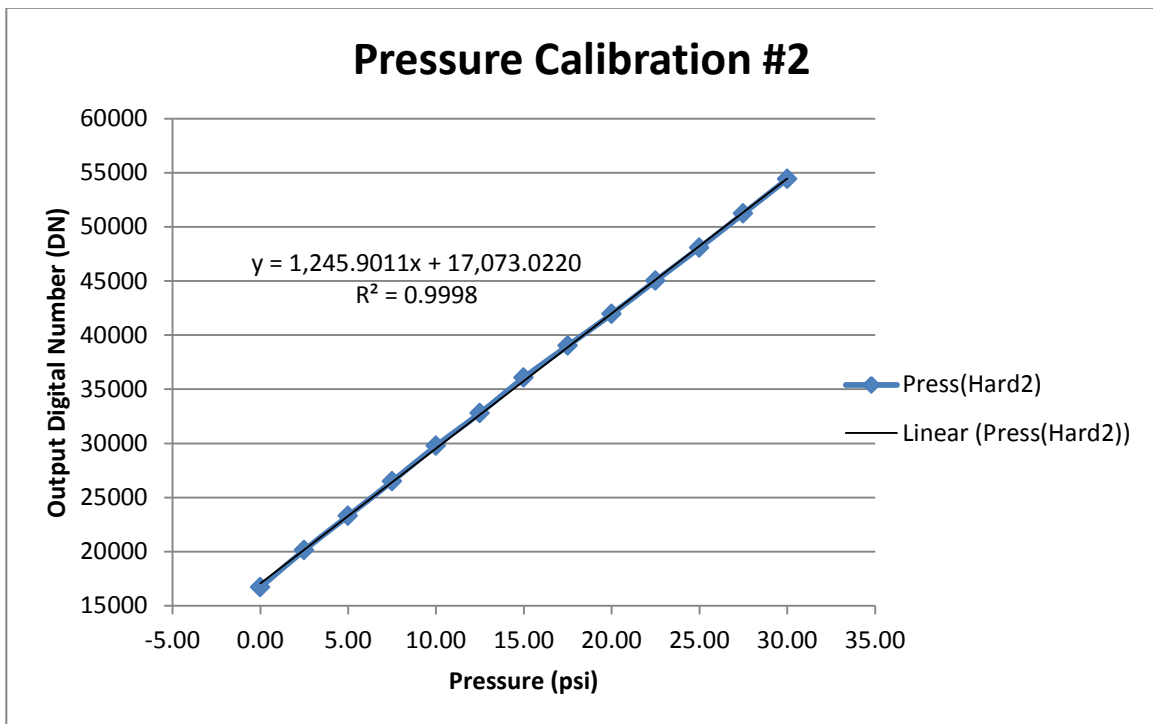


Fig. 35: System 2 pressure output DN vs ambient pressure

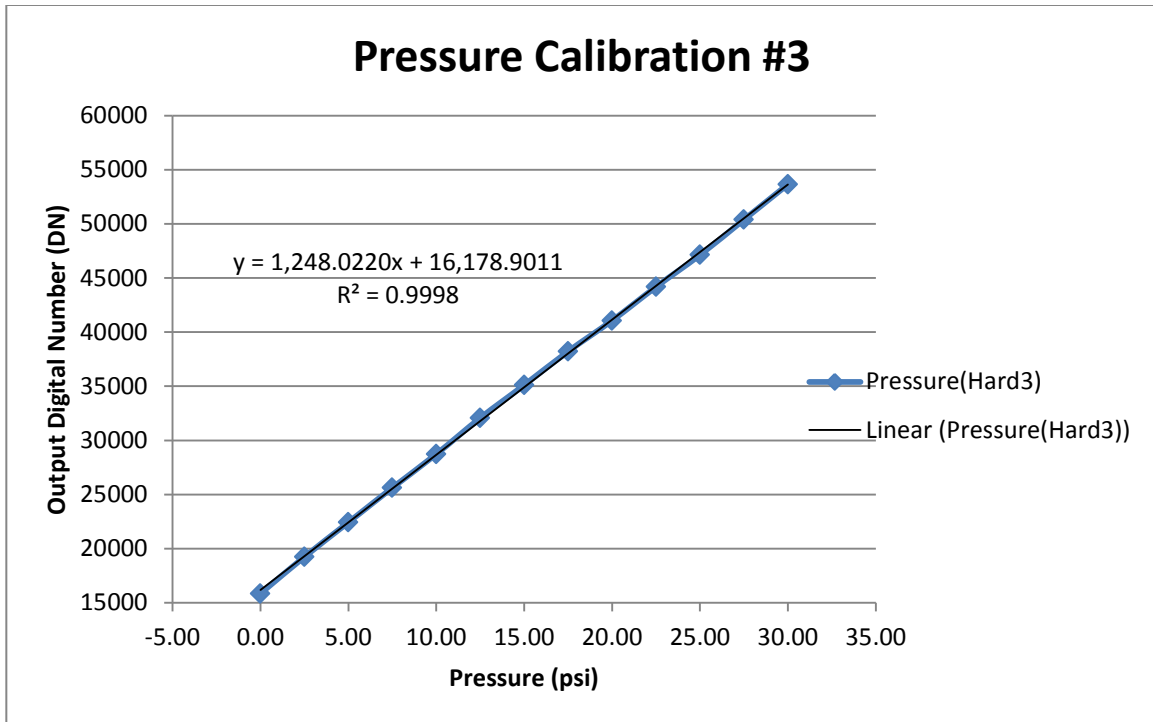


Fig. 36: System 3 pressure output DN vs ambient pressure

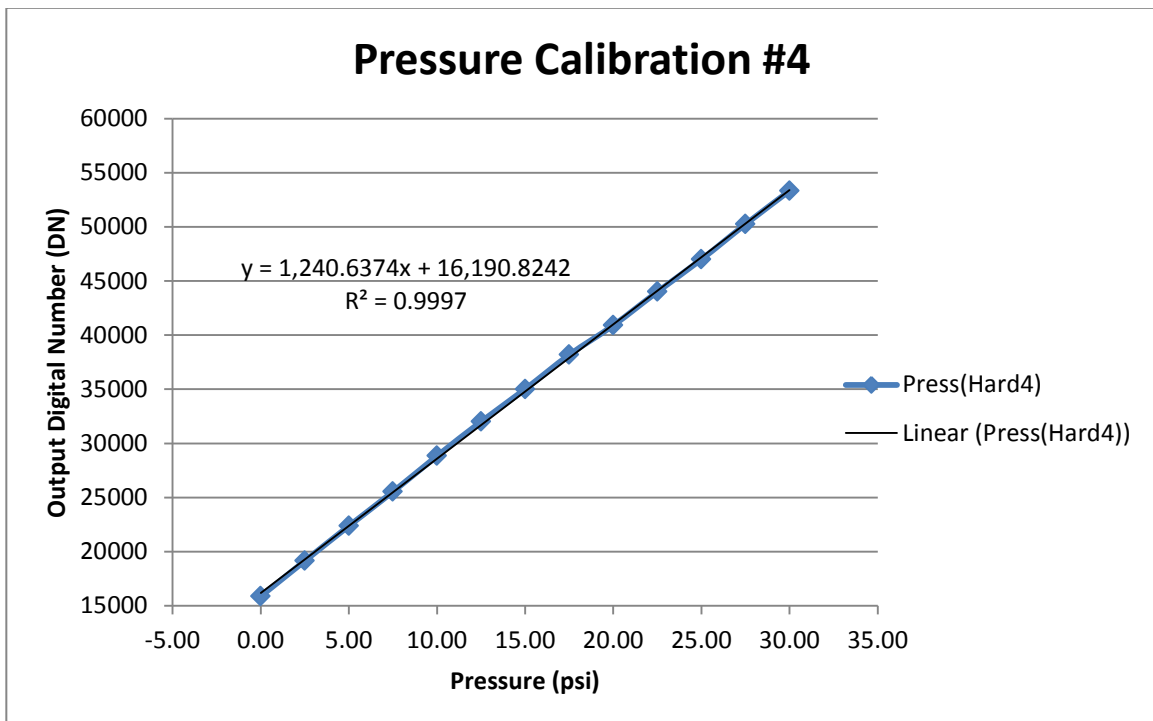


Fig. 37: System 4 pressure output DN vs ambient pressure

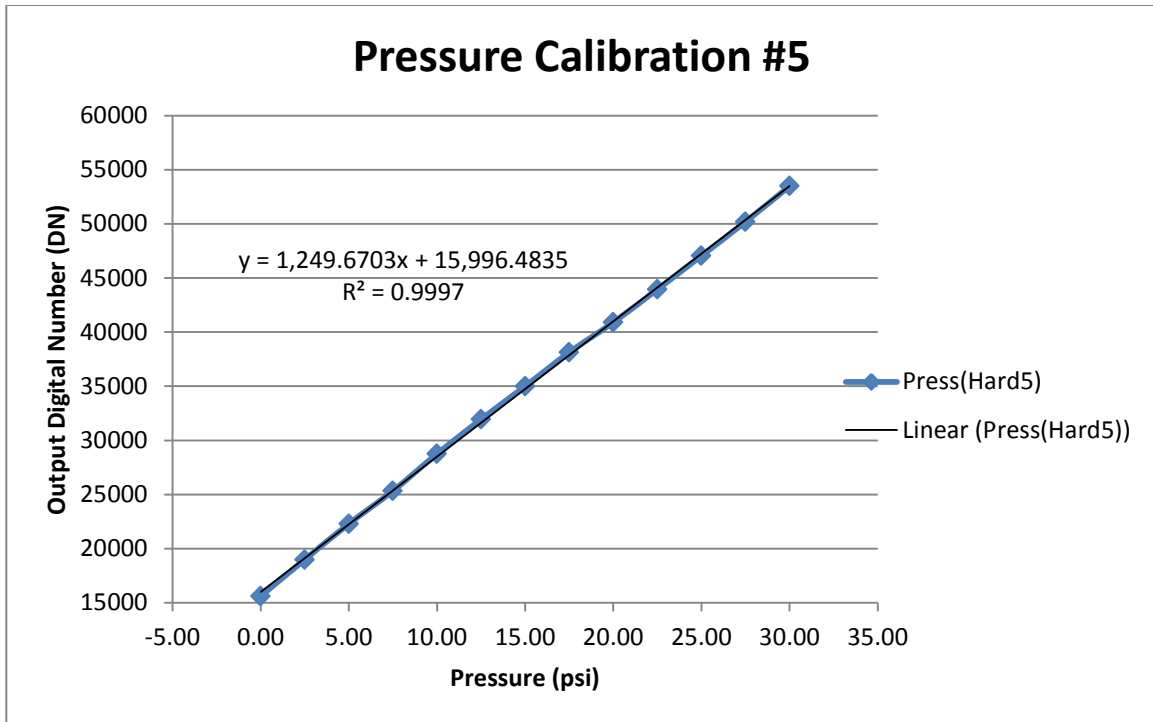


Fig. 38: System 5 pressure output DN vs ambient pressure

Table 13: Summary of system pressure calibrations fit values and coefficients

SYSTEM	COEFFICIENTS (m, b)	R-SQUARED FIT VALUE
1	1261.429, 17296.65	0.9995
2	1245.901, 17073.02	0.9998
3	1248.022, 16178.90	0.9998
4	1240.637, 16190.82	0.9997
5	1249.670, 15996.48	0.9997

5.2.3. GAMMA DETECTION CALIBRATION

The gamma detection calibration is different in nature than both the temperature and pressure calibrations, in that the charge generated by the event is only present for a short period of time, and it needs to be classified. The current spike output from the Geiger-Mueller (G-M) tube is converted to voltage through a resistor and, depending on the peak level of current, the voltage will also reach a certain peak value. In order to discern whether a voltage spike is in fact a radiation event, a certain voltage threshold must be met. This can be achieved by comparing the voltage spike with a reference voltage that is unachievable by any excitation other than a radiation event. If the voltage spike surpasses this threshold, the comparator will output a digital ‘high’ value, representing one event, and subsequently return to a digital low in preparation for the next event. These events can be summed with an FPGA digitally implemented counter, which will notify users of the total ionizing dose, as well as the dose rate, which is derived through the rate of change of the event count.

The first step in calibrating the gamma detection performance is optimizing the GM tube output voltage amplitude for compatibility with the system. The “downstream” so-called comparator operates on a 5 V supply, and could be damaged if voltage spikes larger than this value are present on its input. A potentiometer is used to scale the current to voltage conversion down to the necessary amplitude of about 4.5 V. This waveform was captured on an oscilloscope and is shown as the yellow spike in Fig. 39 below.

The next step is to ensure that the comparator exhibits sufficient rise and fall times to record every gamma event output from the GM tube without overlap. Maximizing the gain-bandwidth of the comparator through all available parameters will produce the fastest rise and fall times possible for the given comparator design. In this case, we have control over the input bias current, which was increased to a maximum 150 μA . The result is a 30 nanosecond rise time, also shown in Fig. 39 below as the green waveform. The maximum event rate of the G-M tube is 50,000 counts per second, which is equivalent to 20 μs per count [11]. This means that the comparator needs to produce a digital ‘high’ value and return to a digital ‘low’ within 20 μs of the initial gamma event pulse. Fig. 39 shows the comparator easily achieves this requirement, with about a 600 ns pulse width and only about 800 ns until the output completely settles back to digital ‘low’. With these specifications, the comparator, assuming the voltage threshold reference is set properly, will capture every gamma event.

Lastly, the voltage threshold for the comparator must be optimized to allow classification of each gamma event, but reject any other voltage spikes that may be induced by noise, incident radiation, etc. Because the GM tube functions based on an avalanche effect and produces a large amount of charge, the potentiometer resistance must be set relatively low in order to achieve the 4.5 V pulse from Fig. 39 below. At such a low resistance, it is unlikely that any voltage spikes from charge deposition, other than those produced by the GM tube, will result in a signal with amplitude larger than 0.5 V. Thus, the voltage threshold reference for the comparator can safely

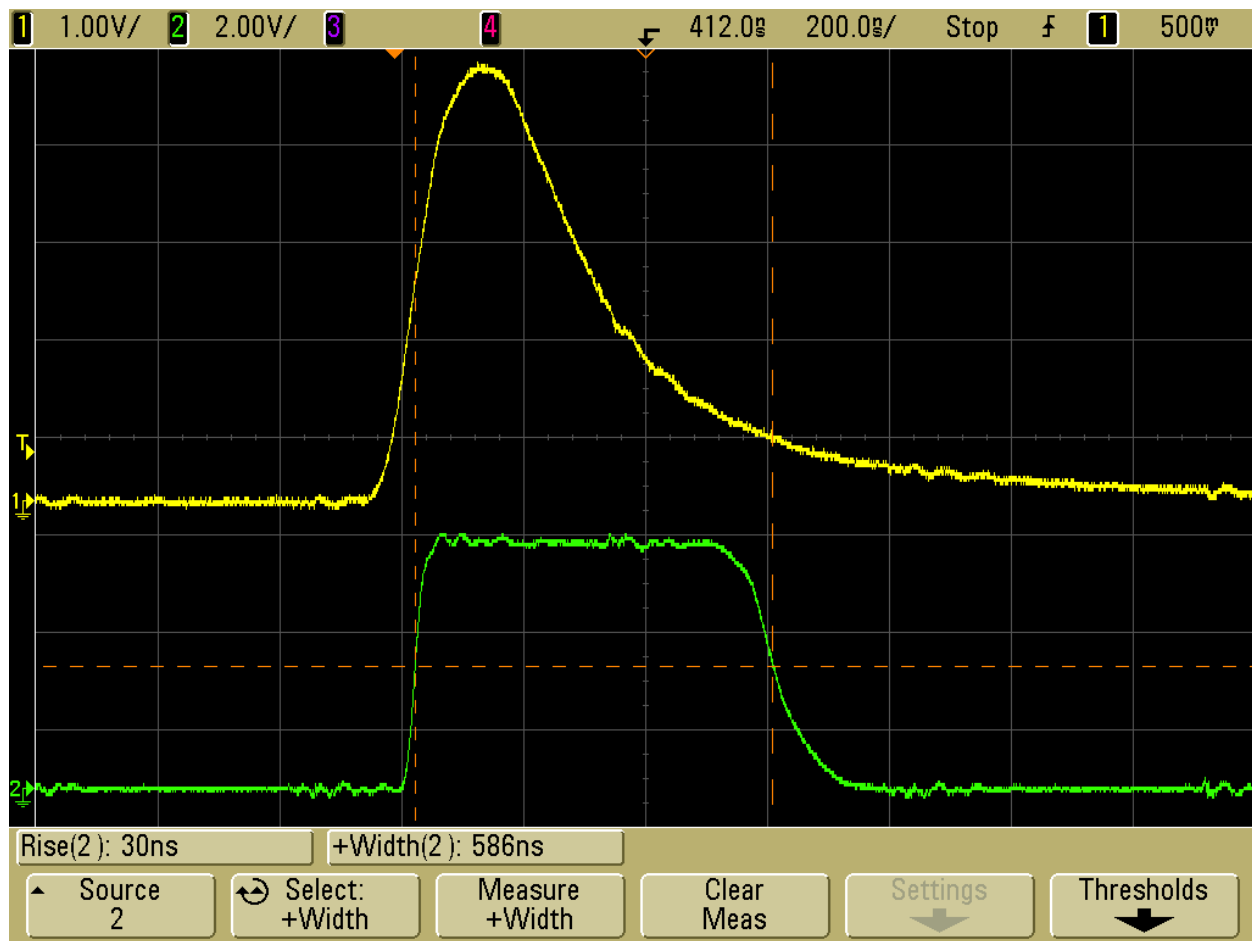


Fig. 39: Gamma event and comparator output pulse response

be set to 0.5 V to produce large enough pulse widths for the counter to recognize, while also discarding any unwanted, spurious signals.

5.3. POST-IRRADIATION PERFORMANCE TESTING

For circuits that are unprotected against TID radiation, severe non ideal behavior can result as a function of increasing total radiation dose. These effects include shifts in device threshold voltages, increased leakage currents, and extreme uncharacteristic variation in circuit performance. In modern sub-micron processes, voltage threshold variations have been almost completely mitigated due to reduced gate oxide thickness and charge trapping ability. However, leakage currents and performance variations still pose issues, and circuits designed for radiation hardness need to be verified against these effects.

Annular gate and guard ring layout techniques are popular methods for mitigating increased leakage currents and, thus, extreme performance variation. These techniques are featured in the Traid VCA and FMI frequency synthesizer ASICs used for analog-to-digital conversion on the rad-hard board. Consequently, the expectation for leakage current and system performance variations as a function of TID radiation is minimal. Although, as seen in the temperature calibration data, if any radiation chamber temperature change induces a shift in node resistance on the output of the temperature sensor, some slight nonlinear increase in data will be apparent. Significant increases in leakage current will manifest in system current consumption data since a large portion of the system's power expenditure is on the rad-hard board itself. It is also likely that severe leakage currents will induce changes in circuit quiescent points and be apparent in the system performance data.

For the purposes of radiation testing, three complete systems will undergo radiation exposure within the Gammacell 220. This should be enough of a sample size to effectively analyze the radiation tolerance of the system, while also preserving two systems for any future pre-radiation uses. System 5 is irradiated to a total dose of 200 kRad, and the remaining two systems, system 1 and 4, are irradiated to a total dose of 300 kRad. The project proposal [1] states a requirement of only 200 kRad total dose exposure for each system, but typical radiation "tolerant" qualification for circuitry is at the threshold of 300 kRad total dose, and this qualification is useful for making claims about the system in conference or journal report submissions. Fig. 40 below shows an image of the rad-hard board inside the containment chamber before being lowered into the gamma radiation pool at test commencement.



Fig. 40: Rad-hard board setup before test commencement

5.3.1. CURRENT CONSUMPTION RADIATION PERFORMANCE

The first parameter susceptible to radiation effects to consider is leakage current. Significant increases in device leakage current will produce large changes in the current consumption of the system. Therefore, values of system current consumption were recorded for all three irradiated systems every hour throughout the duration of the test. The recorded measurements for system 1 (Fig. 41) show a small dip in current consumption approaching the mid-point of the test, and a slight increase during the latter portion of the test, but not beyond the pre-dose measurement value of 142.88 mA. System 4 measurements (Fig. 42) reveal only just resolvable variation throughout the duration of the test, beginning at 150.69 mA and ending at 151.28 mA. System 5 measurements (Fig. 43) depict a slow, consistent decrease in current consumption of about 13 μ A/kRad until the 200 kRad stopping point. The maximum percent error from pre-dose measurement for systems 1, 4, and 5 are 1.64 %, 0.45 %, and 1.71 %, respectively. Not enough variation in current biasing has occurred to induce shifts in device quiescent points. All of these small variations signify large amounts of excess charge being generated and escaping the circuit nodes by electric field through the power supply terminals, but do not represent induced leakage current effects as a function of TID radiation. Moreover, at these levels of percent error, the radiation hardness of the exposed circuitry is proven with respect to radiation induced leakage current.

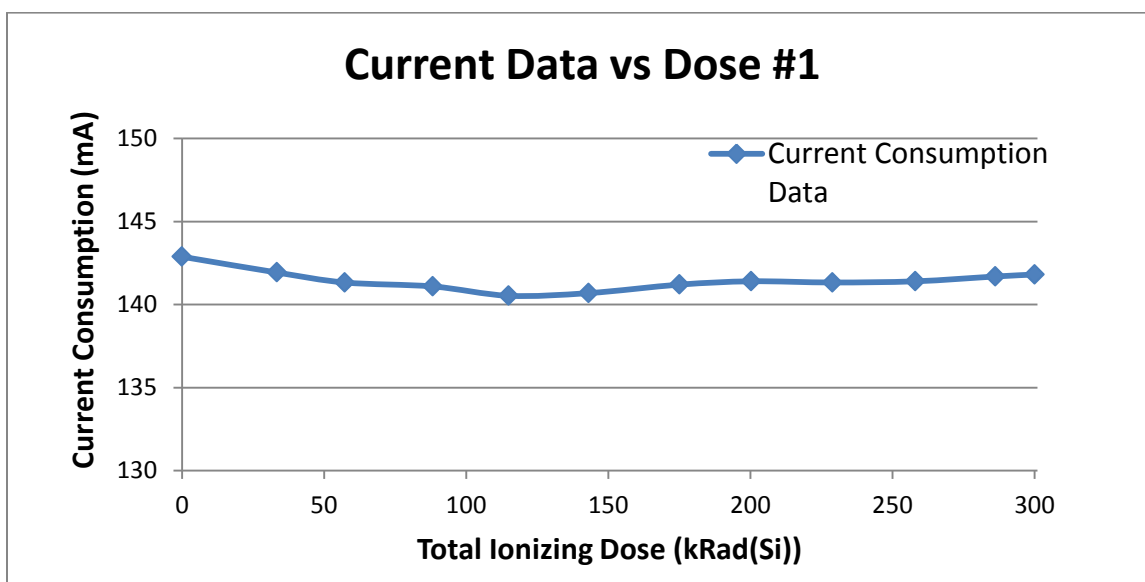


Fig. 41: System 1 current consumption vs TID radiation

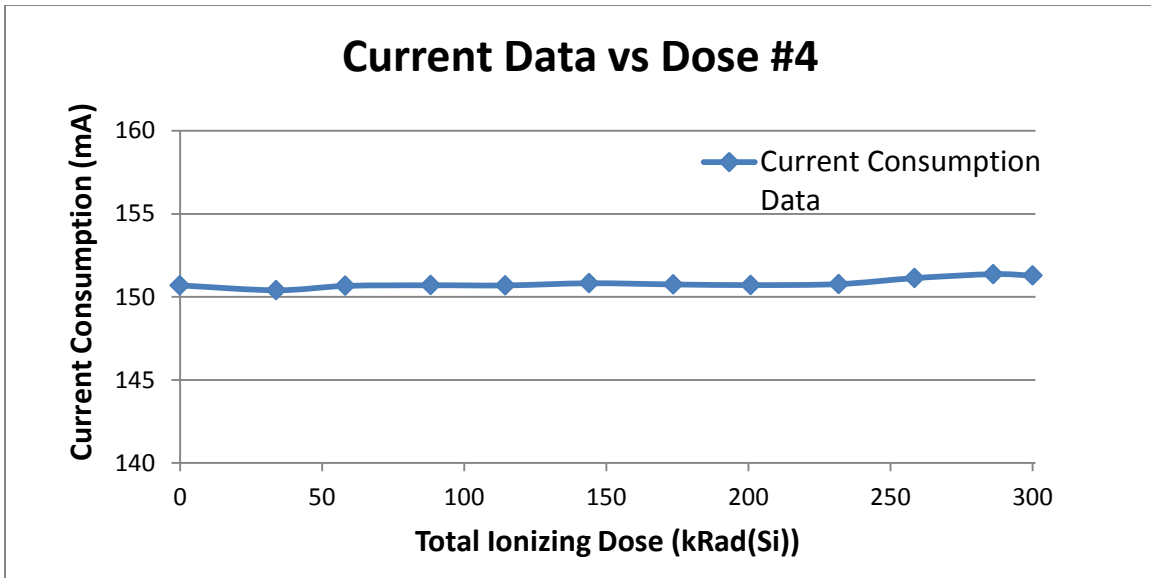


Fig. 42: System 4 current consumption vs TID radiation

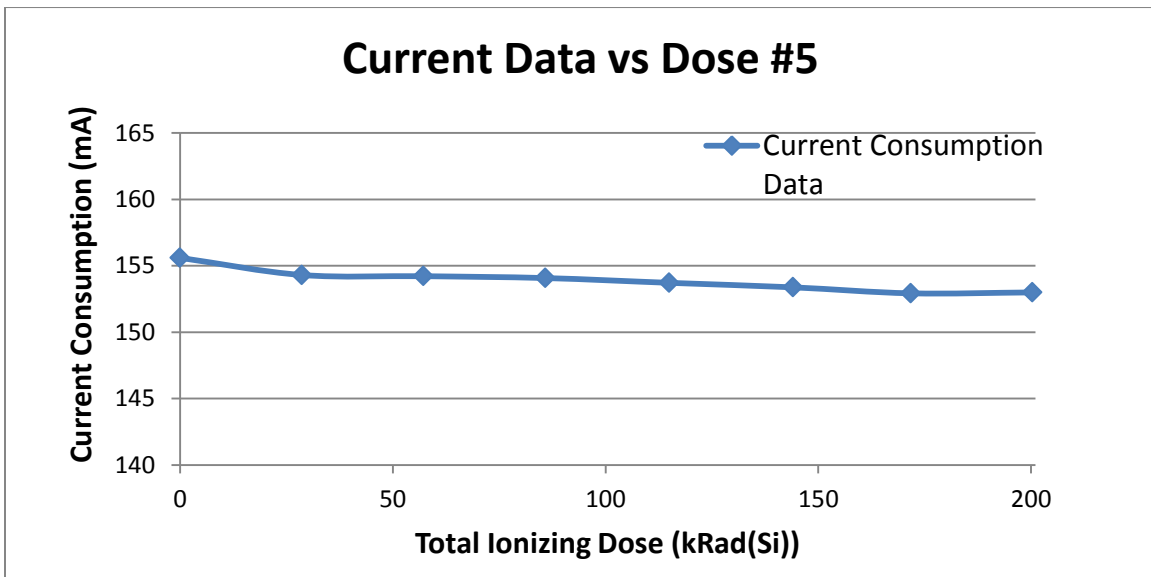


Fig. 43: System 5 current consumption vs TID radiation

5.3.2. TEMPERATURE DATA RADIATION PERFORMANCE

After ensuring that leakage current effects were not a detriment to the performance of the data acquisition system, the actual ambient data output from the system needs to be examined as a function of radiation. The LabVIEW software recorded ambient temperature output data once every ten cycles. This was done to prevent excessive amounts of data from being taken, but also gathers enough data for interpretations such as noise analysis to be performed. In addition, it is known that temperature sensors typically exhibit some initially unknown offset when compared to real temperature, unless trimming is implemented using additional devices. To echo the statement that the mask-programmable analog arrays are capable of numerous applications, including those lacking sophistication, temperature trimming was not included, although it is possible to notice trends in active temperature data, which can sometimes be more important than a truly accurate temperature reading for reactor monitoring applications.

The graphs of Figs. 44-46 relate the data acquisition system temperature data to ambient room temperature as a function of radiation. All three systems show a temperature data slope slightly more positive than the slope of the ambient room temperature. The larger slope of the temperature data is attributed to heating of the radiation chamber, in which radiation and heat from power dissipation in a small space are contributors, that induces inherent resistance shifts on the temperature sensor current output node, resulting in a voltage change. This is consistent with all three systems; even though the ambient temperature for system 5 was actually decreasing, system 5 also exhibits the least positive slope of all systems irradiated. The offsets

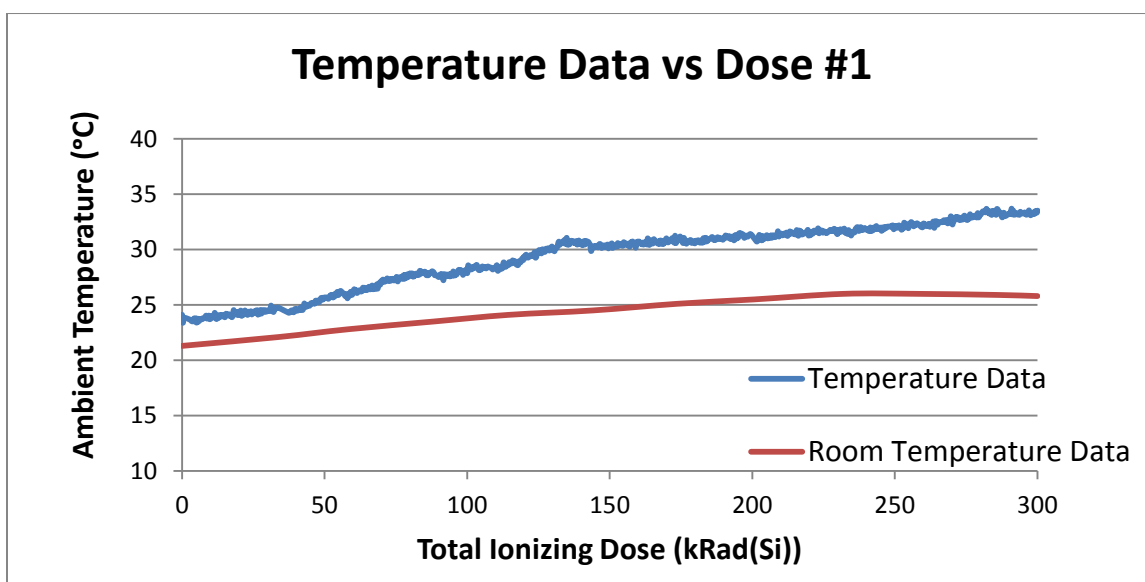


Fig. 44: System 1 temperature reading vs TID radiation

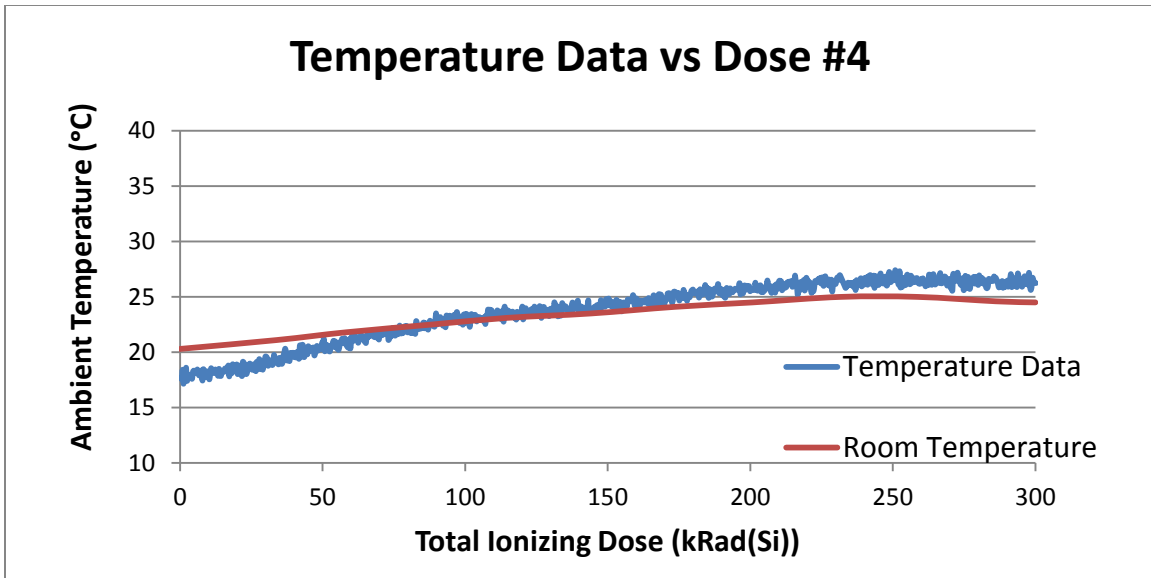


Fig. 45: System 4 temperature reading vs TID radiation

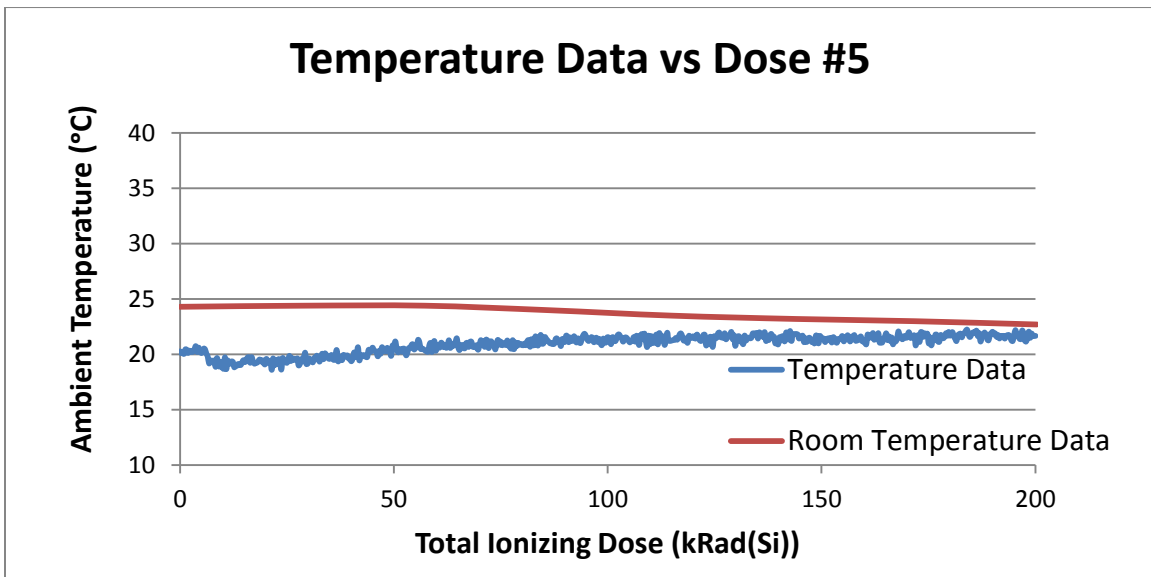


Fig. 46: System 5 temperature reading vs TID radiation

of each sensor are also independently apparent, as two system's pre-dose temperature data was below the room temperature, while the other system shows temperature data initially above the room temperature curve. By factoring out the effects of temperature sensor offset error and output node resistance temperature sensitivity, which are both due to the temperature sensor performance itself, the mask-programmable analog array can closely replicate ambient temperature data within a data acquisition system for nuclear reactor environment applications under extreme radiation conditions.

5.3.3. PRESSURE DATA RADIATION PERFORMANCE

As with the data acquisition system temperature radiation data, the LabVIEW software recorded ambient pressure output data once every ten cycles. Since the pressure sensor selected outputs a voltage that is closely controlled by an internal feedback loop and compensated against temperature and nonlinear effects, the output itself is not dependent on any other ambient parameter it will be exposed to, except pressure. This fact bodes well for the accuracy in performance of the data acquisition system pressure data as a function of radiation without the need to factor out any non-ideal effects. The same sigma-delta modulator digitizes both the analog temperature and pressure data, so this improvement in sensor tolerance to atmospheric nonlinear effects should result in enhanced accuracy and stability relative to the temperature radiation data.

The graphs of Figs. 47-49 display the data acquisition system pressure data for systems 1,

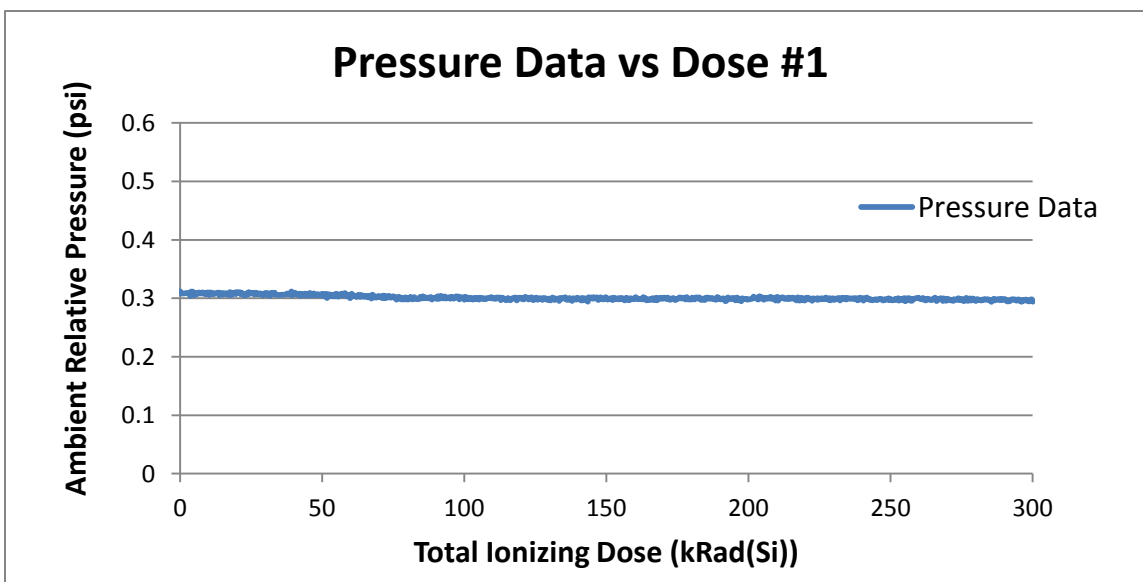


Fig. 47: System 1 pressure reading vs TID radiation

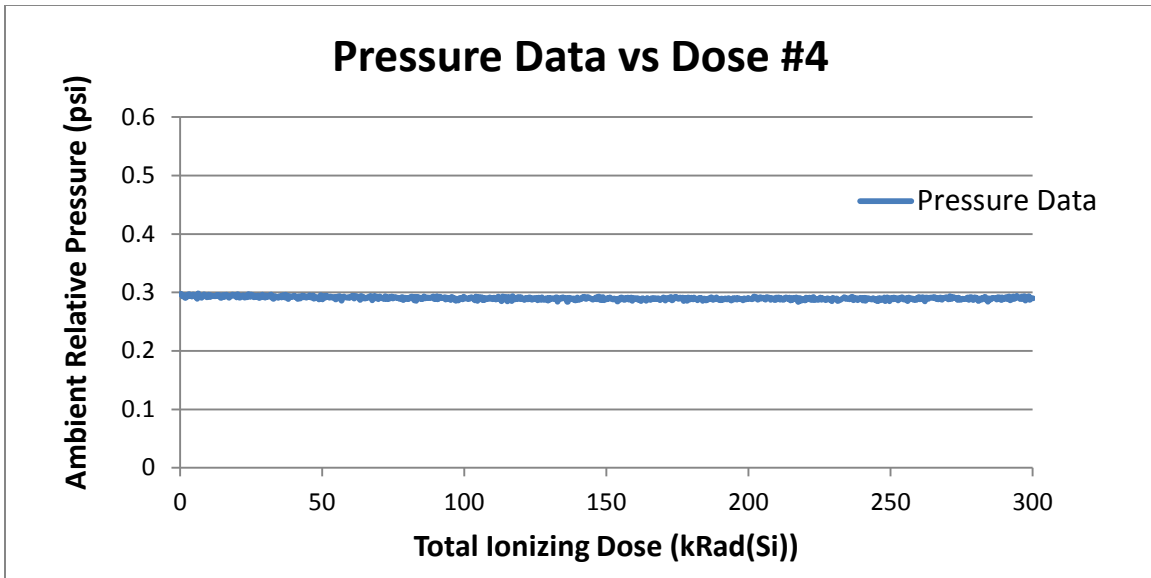


Fig. 48: System 4 pressure reading vs TID radiation

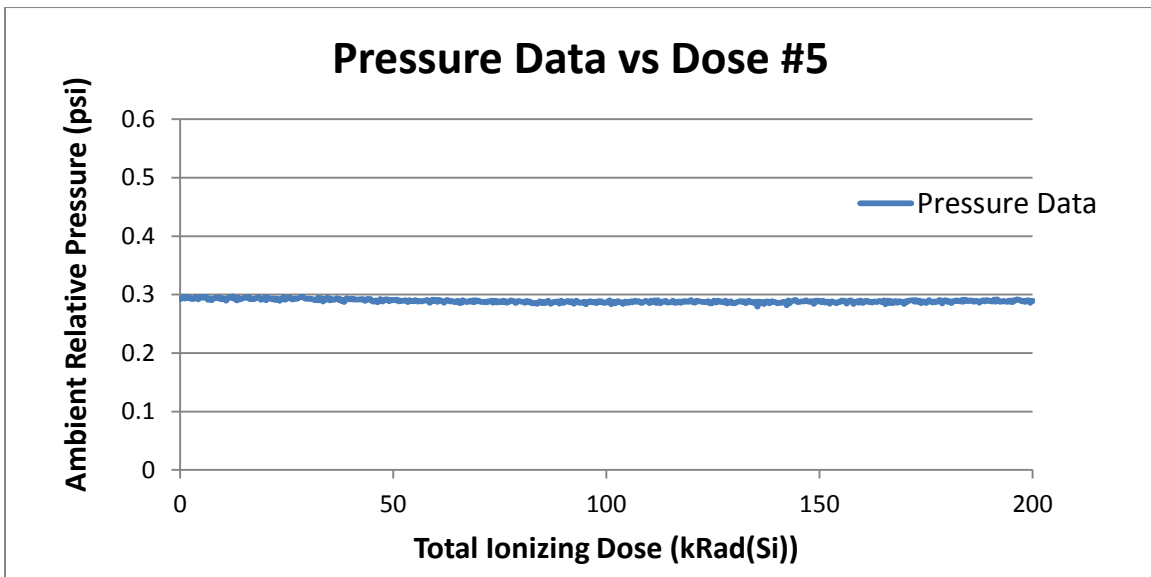


Fig. 49: System 5 pressure reading vs TID radiation

4, and 5, respectively. All three systems show extremely consistent pressure data centered about 0.3 psi, relative pressure. They also exhibit highly stable pressure data that's variation is only just visibly resolvable. The maximum percent error from pre-dose measurements for systems 1, 4, and 5 are 4.51 %, 2.66 %, and 2.9 %, respectively. A significant portion of that maximum percent error for each system is due to noise variations in the pressure data, although the pressure data noise is noticeably smaller in magnitude relative to the temperature data variations. Nonetheless, this pressure data exemplifies the performance capabilities of the mask-programmable analog array in radiation rich environments such as the data acquisition system for applications such as nuclear reactor environment monitoring, as well as the improvement in authenticity of reported ambient data with the use of sensors qualified for specific implementations.

5.3.4. GAMMA EVENT DATA RADIATION PERFORMANCE

The data gathering rate for gamma events is the same as for the temperature and pressure parameters, the LabVIEW software recorded ambient pressure output data once every ten cycles. The G-M tube used for gamma radiation detection has the capability of measuring up to 50,000 gamma counts per second, which saturates at roughly 400 Rad/h of Cobalt-60. This rate is well above typical background radiation levels, so any significant count errors reported due to radiation exposure of the rad-hard electronics will be visible in the gamma event data. Since the gamma events are singular in nature and require digital electronics such as comparators and counters to quantify, it is unlikely that TID radiation will induce populous bit count errors, but it is possible.

Normalized gamma events in units of cps are counted, calculated, and then plotted for systems 1, 4, and 5 in Figs. 50-52 below, respectively. These plots show a seemingly random distribution of single gamma counts throughout the duration of the test. Nearly all of the relevant readings shows about 0.3 cps, which equates to one gamma count in slightly less than a four second data gathering cycle. System 4 registered nothing higher than 0.3 cps during the entire duration of the test, while system 5 reported two 0.6 cps cycles (two gamma counts slightly less than a four second cycle). System 1, in particular, shows a series of 0.6 cps cycles between the 100 kRad and 150 kRad TID radiation range. This data for system 1 is slightly peculiar, but does not signify any count error due to radiation effects; an event rate of 0.6 cps still equates to background radiation levels, especially in a small laboratory containment housing multiple radiation sources. The data soon returned to the 0.3 cps standard level for these systems. This data concludes radiation tolerance testing for the data acquisition system and confirms the ability of the mask-programmable analog array to condition and digitize analog signals accurately and efficiently in the presence of harsh radiation environments such as nuclear reactor containments.

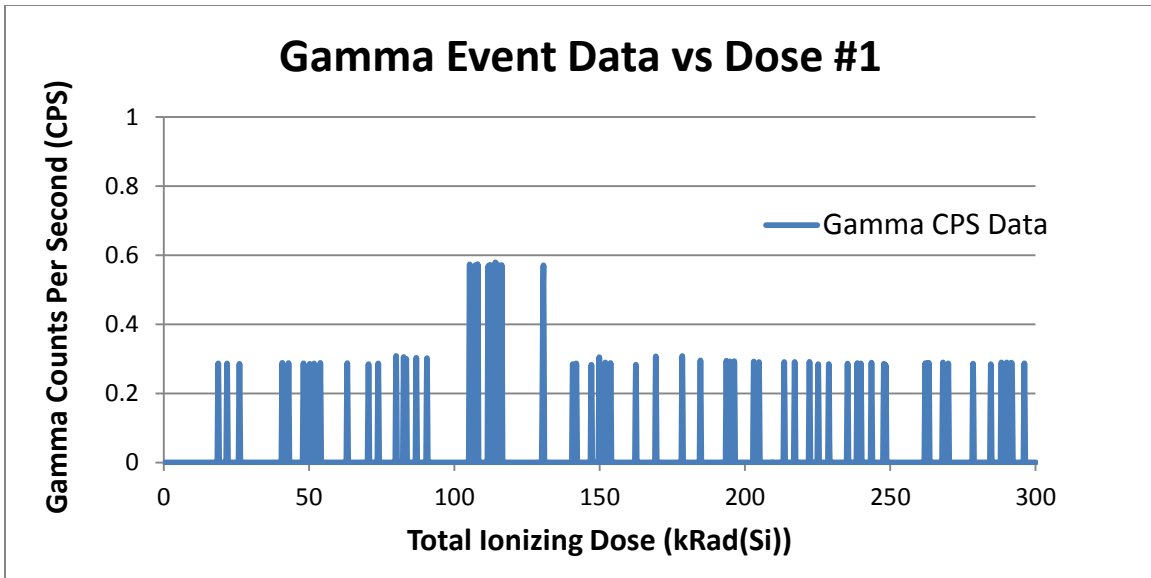


Fig. 50: System 1 gamma count rate vs TID radiation

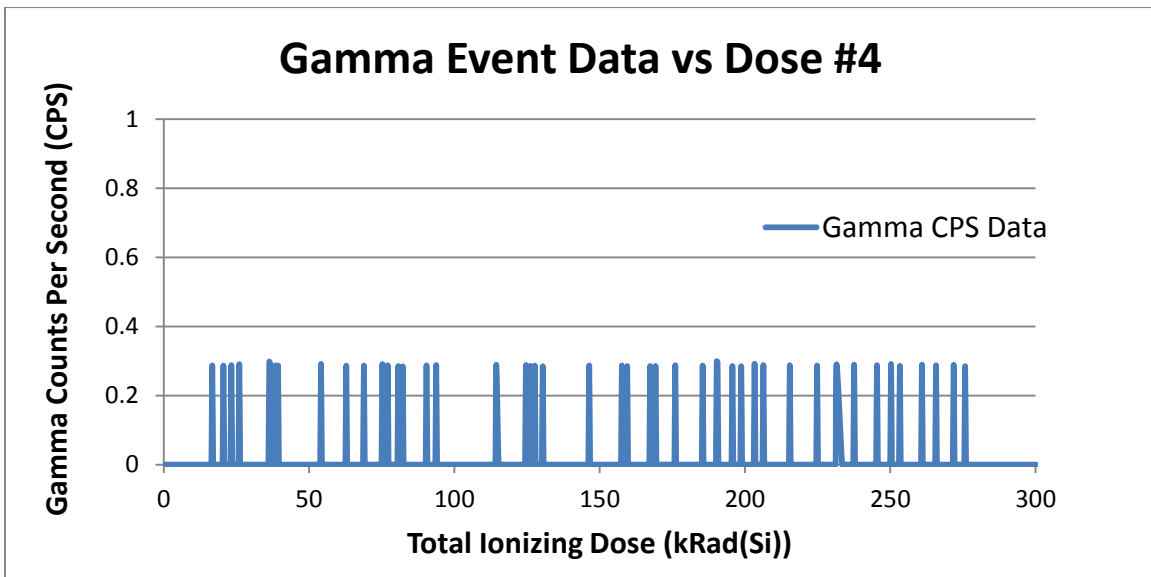


Fig. 51: System 4 gamma count rate vs TID radiation

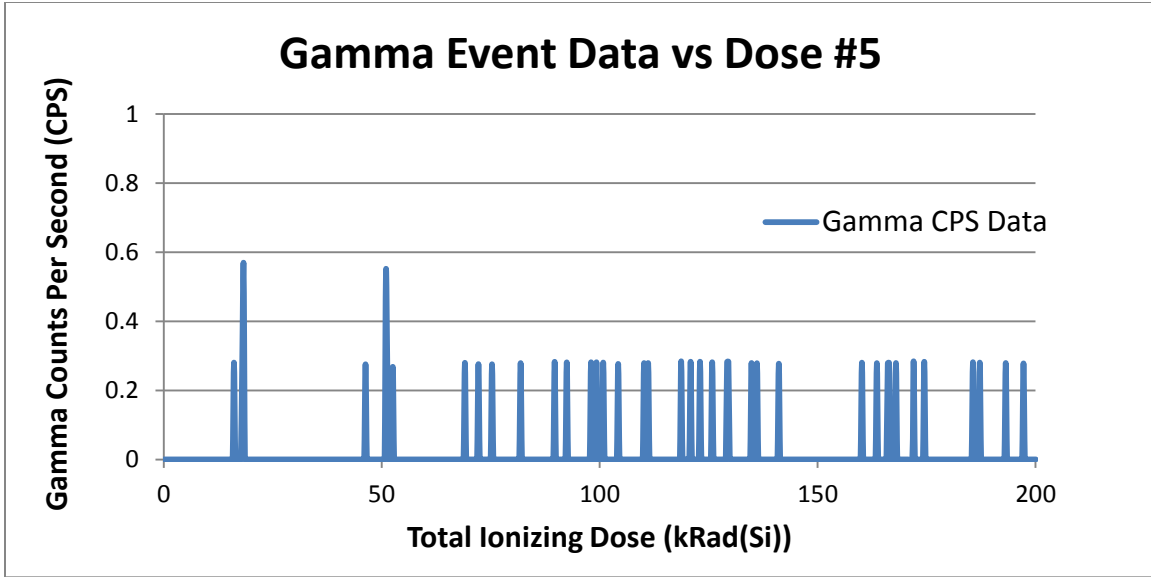


Fig. 52: System 5 gamma count rate vs TID radiation

5.3.5. INPUT VOLTAGE VARIATION PERFORMANCE

As mentioned during the clock feedthrough discussion, unwarranted voltage variations on the input of the sigma-delta modulator can result in erroneous and inconsistent output data. This data, if read often, depicts an alternating waveform with significant differences in the maximum and minimum raw DN. It is apparent from Fig. 12 that clock feedthrough can account for up to 200 mV peak-to-peak input voltage variation. The maximum output DN variation over a short time period can be recorded after low-pass filter implementation, converted to input voltage variation by equating proportions, and compared to the initial 200 mV mark to evaluate any improvement in sigma-delta input noise.

The final version of the LabVIEW software is capable of converting DN readout to input ambient parameters using the measured calibration coefficients. The DN readout is also displayed after each data point is stored and can be used to calculate input voltage change for a certain amount of DN variation. This is possible because the output of the sigma-delta modulator is proportional to its input. The proportionality is extremely linear for the pressure ADC and linear enough for the temperature ADC to use a direct proportion to convert output DN to input voltage with sufficient accuracy, shown in equation (2).

$$\frac{DN_{variation}}{DN_{range}} = \frac{V_{variation}}{V_{range}} \quad (2)$$

By inspection, for system 1, the maximum variance for the temperature and pressure DN

data is roughly 75 and 5 DNs, respectively, and is consistent across the entire temperature and pressure ranges. These numbers also coincide with the expectation of a higher variation in the temperature signal path, due to the current output and direct parallel resistance driving the input of its sigma-delta modulator, as well as clock feedthrough effects. The voltage range, and thus DN range, for the temperature and pressure ADCs will differ because of the varying nominal output voltages of each sensor. For the temperature and pressure ranges used for system calibration, the absolute DN range for temperature and pressure is 13810 (48565 – 34755) and 38290 (54990 – 16700), respectively. The input voltage ranges, which correspond to these DN ranges, are found using sensor output equations reliant on specific system setup and equal 0.576 V (2.6356 – 2.0596) for temperature and 1.4 V (3.2 – 1.8) for pressure. Using these numbers, equations can be developed to solve for voltage variation ($V_{variation}$) on the input of the temperature and pressure sigma-delta modulators, as shown in equations (3) and (4) below.

$$\frac{75}{48565-34755} = \frac{V_{variation,temp}}{2.6356-2.0596} \quad (3)$$

$$\frac{5}{54990-16700} = \frac{V_{variation,press}}{3.2-1.8} \quad (4)$$

Solving these equations results in a 3.072 mV and 0.1866 mV peak-to-peak voltage variation for the temperature and pressure ADC inputs, respectively. In comparison to the prior 200 mV measurement, the input voltage variation is significantly reduced through the use of low-pass filters and the output is minimally influenced by the effect of clock feedthrough, thermal noise produced by resistance, or sensor generated noise.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

This thesis has been a presentation of the evaluation, design, and verification of a radiation-hardened data acquisition system based on a mask-programmable analog array. The Triad Semiconductor VCA analog array was a prototype chip designed to portray a wide variety of analog functionality, similar to digital arrays such as FPGAs, for an ideally infinite number of applications. The implementation and effective performance of the Triad VCA in a nuclear environment monitoring application further validates the concept behind the mask-programmable analog array.

The radiation-hardened data acquisition system itself exemplified results consistent with a realizable and useful deployment. System calibrations showed continuous performance over a wide range of inputs. Radiation testing verified its ability to operate precisely in the most severe, relevant reactor environments. The design allows pertinent data to be gathered, digitized, and reported in a realistic nuclear disaster scenario to assist in the assessment and prompt decision making for the necessary actions to follow. Five complete systems were fabricated and tested to successful end.

There were many factors that contributed to the success of this work, including the initial application review, thoughtful project outlining, and setting feasible milestones and project goals. Dedication to meeting those goals in a timely manner allowed the project to continue making progress toward final completion. Assistance from project team members regarding design decisions and support was paramount to the proper operation and functionality of the system within the designated budget. The work environment provided by Oak Ridge National Laboratory enabled the focus to be shown that is required on a daily basis to complete the project.

The strategy to partition the system into three boards allows easy integration of radiation-hardened sensors and digital components into the design to form a completely radiation-hardened system. A follow-on project would need minimal effort to finalize that process. In addition, one suggestion for improving the performance of the system for future implementation would be to select a temperature sensor that produces a voltage instead of a current. This is because the resistor required to transform the current to voltage for this system is itself dependent on temperature, which produced some slight, undesired nonlinearity in the output response. An output that is independent of resistance could better represent the ambient temperature, as well as be directly measured by the sigma-delta modulators.

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APPENDICES

APPENDIX A

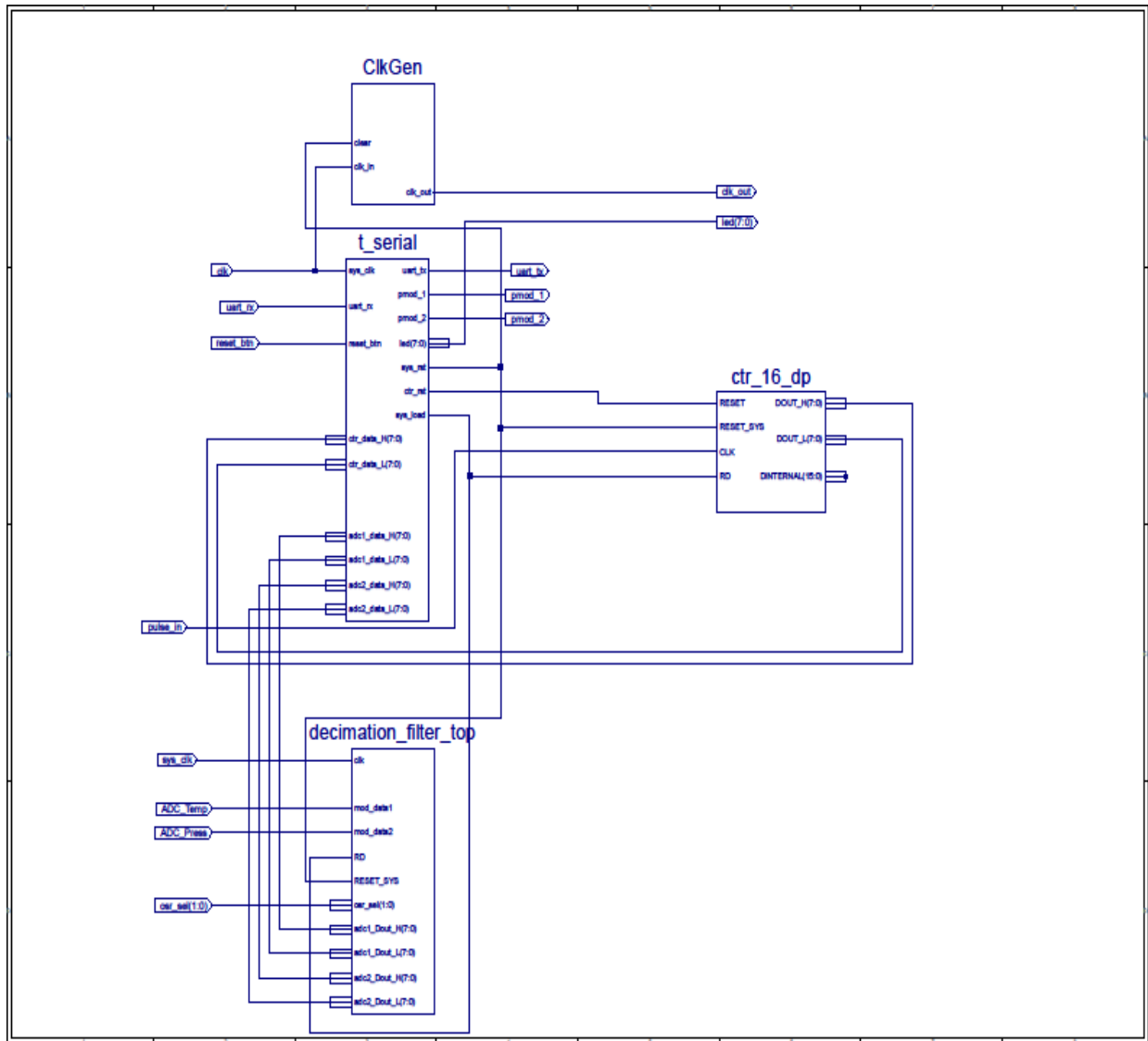


Fig. A.1: Top-level instantiation of VHDL code

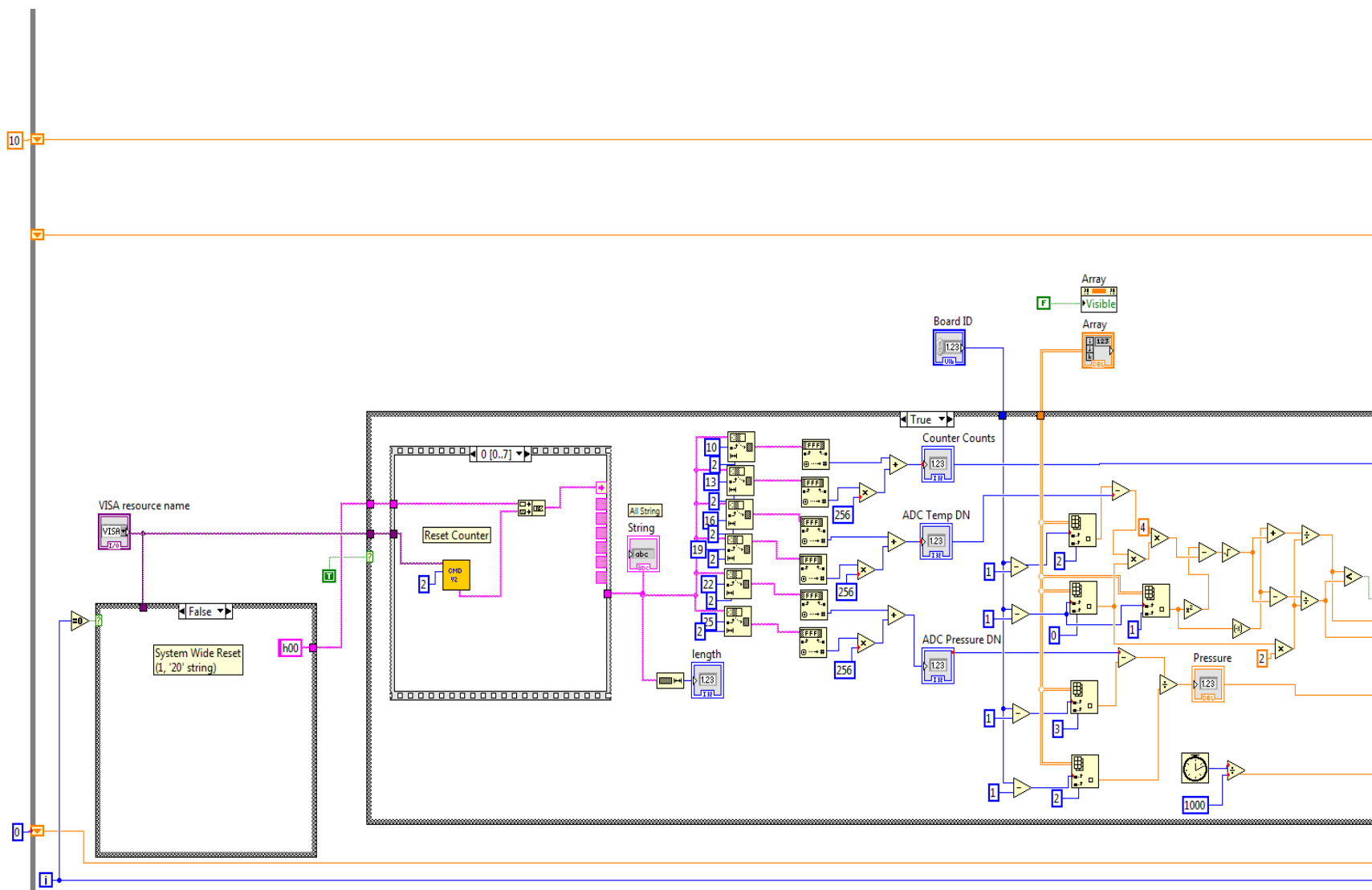


Fig. A.2: Front-end LabVIEW visual code

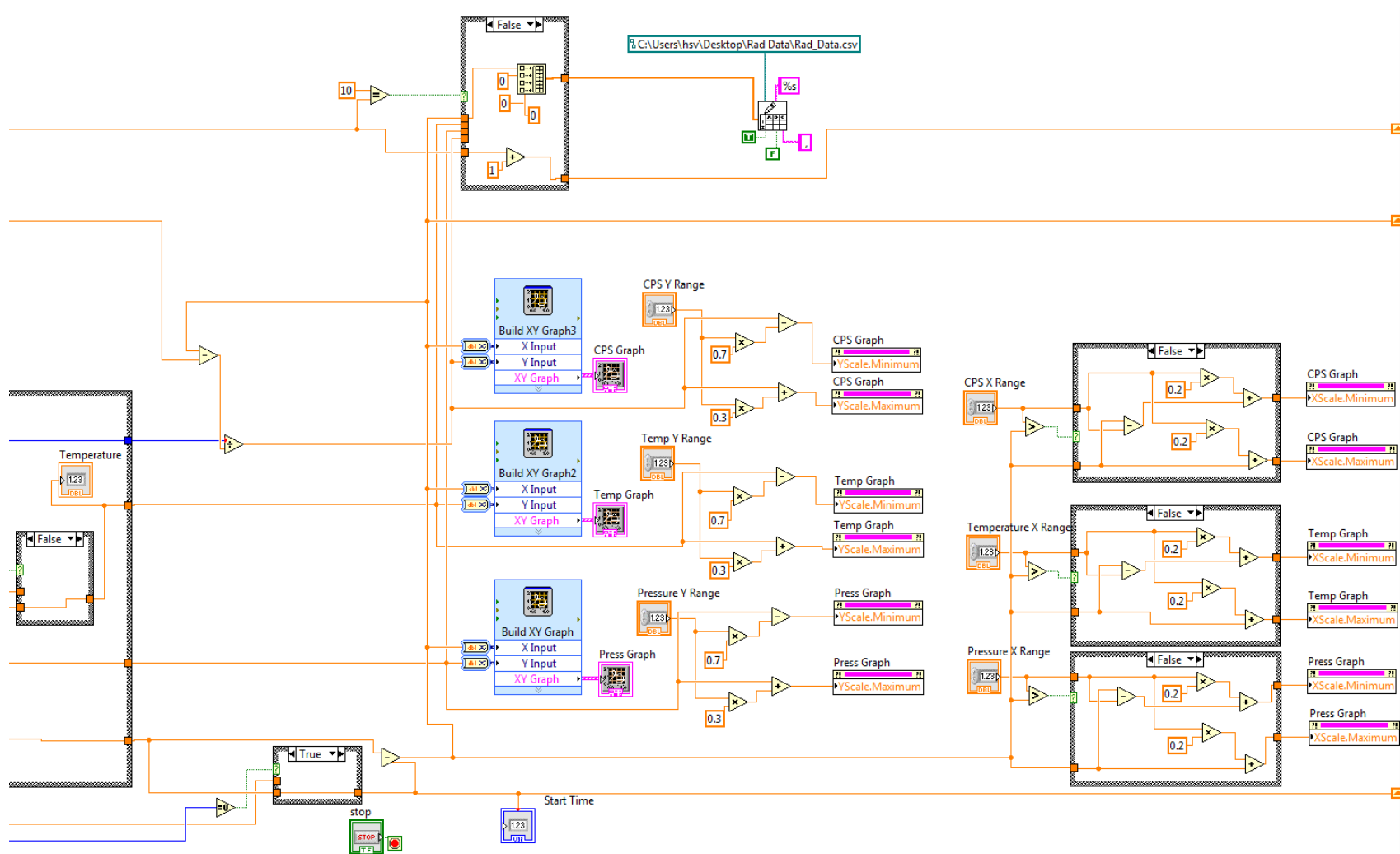
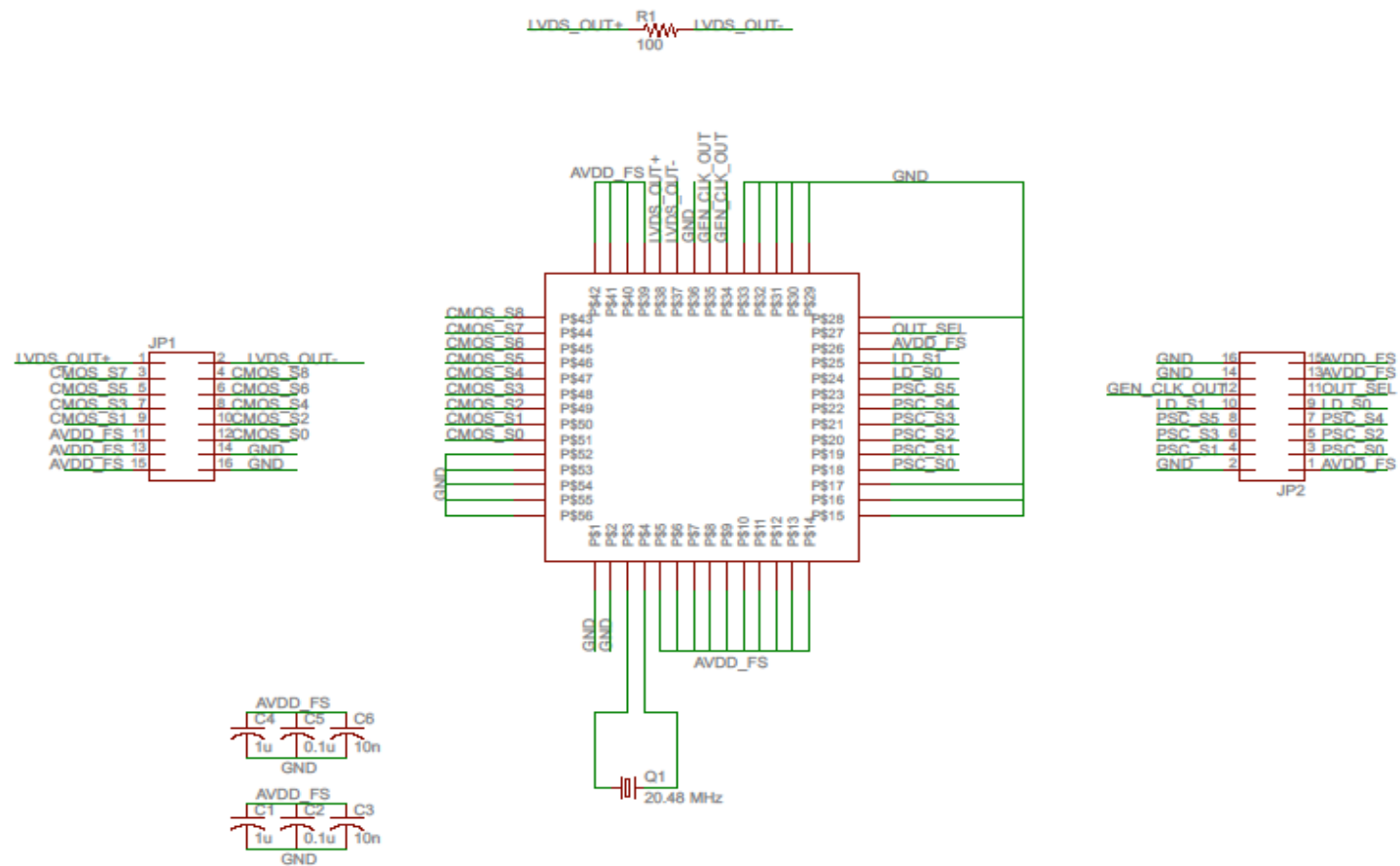


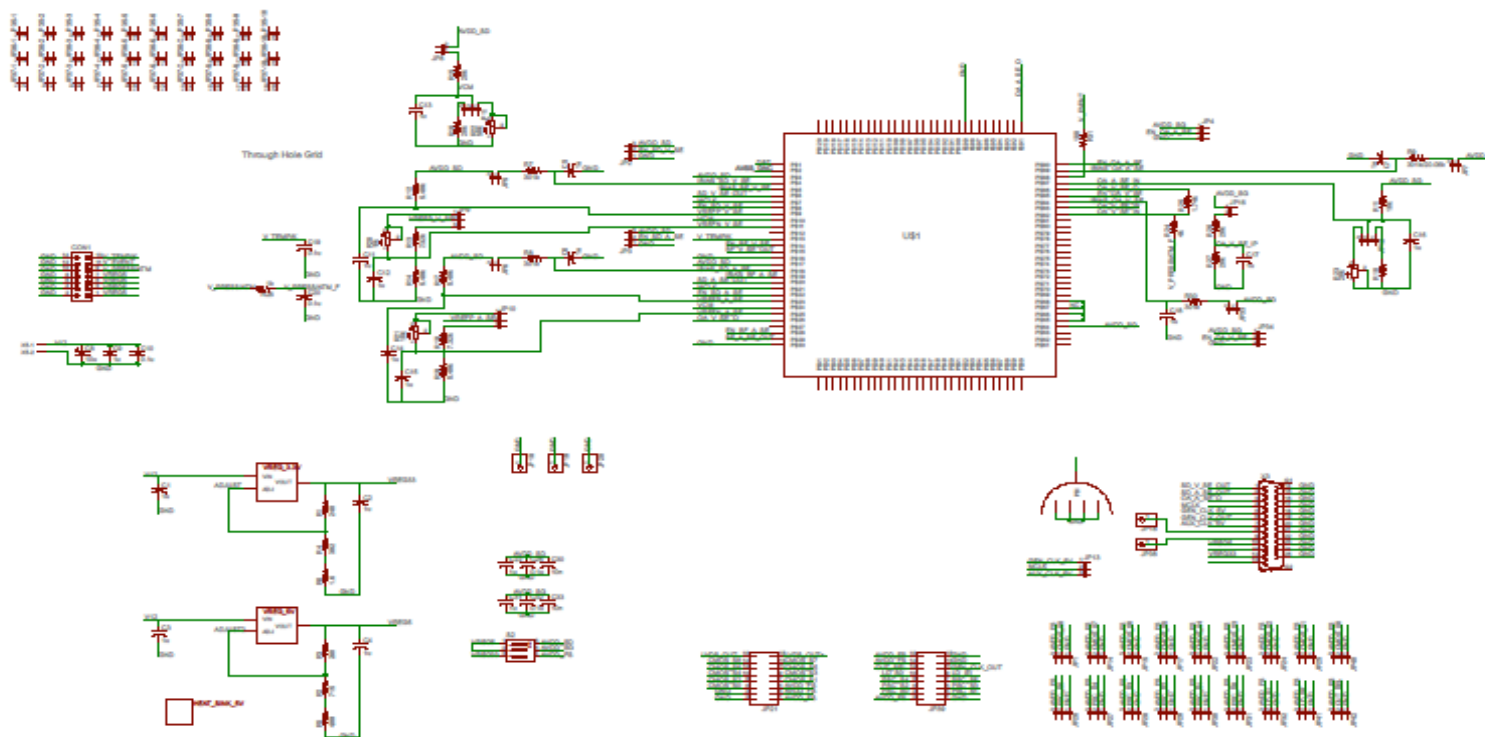
Fig. A.3: Back-end LabVIEW visual code

APPENDIX B



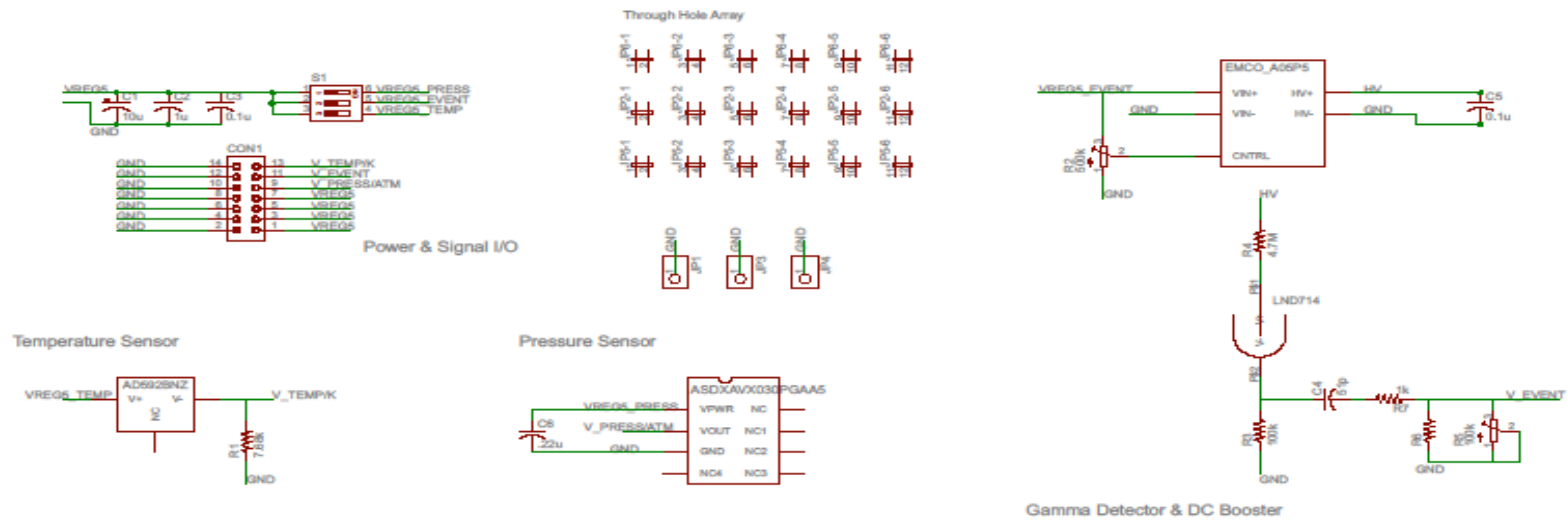
9/3/2014 4:14:00 PM f=1.20 C:\Users\hsv\Documents\leagle\RH System\InterposerBoard.sch (Sheet: 1/1)

Fig. B.1: Interposer board schematic



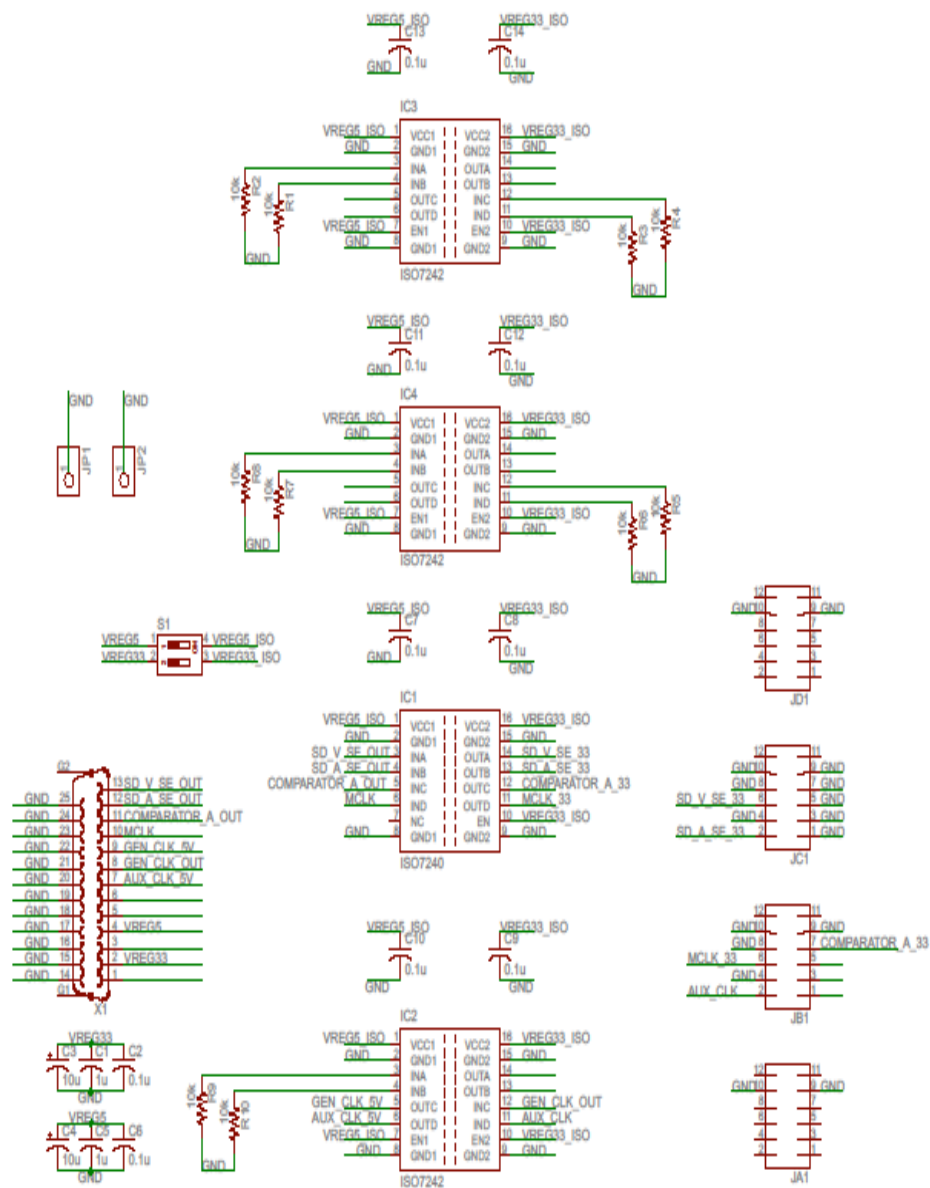
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Fig. B.2: Rad-hard board schematic



9/3/2014 4:17:17 PM f=0.87 C:\Users\hsv\Documents\leagle\RH System\SensorBoard.sch (Sheet: 1/1)

Fig. B.3: Sensor board schematic



9/3/2014 4:15:05 PM C:\Users\hsv\Documents\leagle\RH System\InterfaceBoard.sch (Sheet: 1/1)

Fig. B.4: Interface board schematic

VITA

Jacob H. Shelton was born on March 8, 1991, in Newport, Tennessee. He graduated with his B.S. and M.S. degrees in electrical engineering from the University of Tennessee, Knoxville, in May of 2013 and 2015, respectively. While at the University of Tennessee, he was a Bodenheimer Fellow and held multiple assistantships, including graduate research assistant positions in the Integrated Circuits and Systems Laboratory (ICASL) and at Oak Ridge National Laboratory (ORNL). He participated in an internship at the NASA Jet Propulsion Laboratory in the Advanced Instruments Electronics Group during the summer of 2013. His research focus at UT was in extreme environment (both wide temperature and radiation) circuit design at the transistor and board level. He wrote his thesis on a radiation-hardened data acquisition system based on a mask-programmable analog array project developed at ORNL for nuclear reactor monitoring applications.