



# NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

## THESIS

**RADIATION-HARDENED MICROELECTRONICS  
WORKFORCE DEVELOPMENT GUIDELINE**

by

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September 2023

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**RADIATION-HARDENED MICROELECTRONICS  
WORKFORCE DEVELOPMENT GUIDELINE**

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## **ABSTRACT**

The United States government (USG) has observed that there is a technical readiness gap within one of its key technical capabilities (TC) in its nuclear defense: radiation-hardened (RH) microelectronics. The objective of the research is to develop a training plan/guideline for current and future workforce in the field of radiation-hardened microelectronics in order to provide them with the knowledge and skills needed to perform radiation effects testing, development, and analysis. This research utilized a qualitative research method conducted by one-on-one interviews with SMEs and electronic surveys aimed to answer the following questions: What is the ideal way to develop the current and future DOD workforce in the field of radiation-hardened microelectronics? How can we effectively develop the workforce to become subject matter experts (SMEs) in the field of radiation-hardened microelectronics? The responses from the workforce confirmed the gap within the field and the need for a robust training plan/guide for the current and future workforce. This thesis develops a training plan/guide that prescribes academic courses, software, and testing development for evolution and accession into SMEs within radiation-hardened microelectronics.

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## LIST OF ACRONYMS AND ABBREVIATIONS

AFRL	Air Force Research Laboratory
CBRN	Chemical, Biological, Radiological and Nuclear
COI	Community of Interest
CRÈME	Cosmic Ray Effects on Microelectronics
DNWS	Defense Nuclear Weapons School
DOD	Department of Defense
DRS	Dose Rate Survivability
DRU	Dose Rate Upset
DTRA	Defense Threat Reduction Agency
EMP	Electromagnetic Pulse
EOD	Explosive Ordnance Disposal
EPA	Environmental Protection Agency
FinFET	Fin Field-Effect Transistor
FPGA	Field Programmable Gate Arrays
GaN	Gallium Nitride
GCR	Galactic Cosmic Ray
GDD	Global Deterrence Defense
GOMAC TECH	Government Microcircuit Applications & Critical Technology Conference
HEART	Hardened Electronics and Radiation Technology
IC	Integrated Circuits
IEEE	Institute of Electrical and Electronics Engineers
MDA	Missile Defense Agency
MRQW	Microelectronics Reliability and Qualification Workshop
MTT	Mobile Training Team
NASA	National Aeronautics and Space Administration
NCRP	National Council on Radiation Protection and Measurements

NSERC	Nuclear & Space Radiation Effects Conference
NSWC Crane	Naval Surface Warfare Center, Crane Division
OJT	On-The-Job Training
OUSD	Office of Under Secretary of Defense
PCB	Printed Circuit Board
R&E	Research and Engineering
RAB	Radiation Adjudication Board
RAD-E3	Radiation Aware Design, tEst, & Evaluation Ecosystem
RH	Radiation Hardened
RHA	Radiation Hardness Assurance
RHET	Radiation Hardened Electronic Technologies
SCALE	Scalable Asymmetric Life cycle Engagement
SEAM	Systems Engineering and Assurance Modeling
SEB	Single Event Burnout
SEE	Single Event Effects
SEFI	Single Event Functional Interruptions
SEL	Single Event Latchup
SiC	Silicon Carbide
SME	Subject Matter Expert
SPE	Solar Particle Events
SRIM	Stopping and Range of Ions Matter
T&AM	Trusted and Assured Microelectronics
TC	Technical Capabilities
TCAD	Technology Computer Aided Design
TID	Total Ionizing Dose
TIM	Technical Interchange Meeting
USG	United States Government
WMD	Weapons of Mass Destruction

## EXECUTIVE SUMMARY

The United States government is facing a challenge in one key technical capability in its nuclear defense: radiation-hardened (RH) microelectronics. The challenge is a technical readiness gap within the radiation effects workforce. Current radiation-hardened subject matter experts (SMEs) are at or past retirement age, with no definitive pipeline of trained and skilled RH engineers. Radiation in microelectronics is a specialized skillset; very few universities and colleges offer any course or curriculum geared toward this subject. Therefore, expertise is primarily obtained via on-the-job training. Currently, there is no training program developed to provide new engineers the required knowledge and skills needed to perform radiation effects testing, development, and analysis upon their arrival to the workforce, and the learning curve is steep, resulting in a significant gap in this area within the workforce.

The development of future state-of-the-art space and strategic systems requires personnel that fully understand radiation effects, their effects relative to the various technology types to be used in those systems, natural and manmade radiation environments which those systems may encounter, and the effects of those technology types within those different radiation environments.

This research introduces a qualitative research method, conducted by employing one-on-one interviews with SMEs and electronic surveys of the current workforce within the field of radiation effects. Analysis of data collected confirmed the gap within the field and the workforce need for a robust training plan/guide for the current and future workforce. Thus, this research introduces a preliminary pilot training plan/guide meant to progressively educate the current and future workforce in radiation effects; in solidifying the field of RH effects, the USG's key technical capabilities in nuclear defense are maintained for future generational systems.

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# I. INTRODUCTION

The United States government (USG) has observed that there is a technical readiness gap within one of its key technical capabilities (TC) in its nuclear defense: radiation-hardened (RH) microelectronics. In the radiation effects community, the current radiation-hardened microelectronics subject matter experts (SMEs) are past retirement age, with minimal pipeline of trained and skilled RH engineers. There is no training program developed to provide new engineers the required knowledge and skills with regard to radiation-hardened microelectronics testing, development, analysis, etc., upon their arrival to the workforce. Most learn as they go with guidance from their peers. In order to make sure that there are trained and knowledgeable radiation-hardened microelectronics engineers to maintain the USG nuclear deterrence, a detailed plan or guideline to train personnel in the field of radiation-hardened microelectronics is required. This thesis introduces the tools and training necessary to develop SMEs in the area of radiation-hardened microelectronics. The research data collected will assist in answering the following questions: What is the ideal way to develop the current and future DOD workforce in the field of radiation-hardened microelectronics? How can we effectively develop the workforce to become subject matter experts in the field of radiation-hardened microelectronics?

## A. BACKGROUND

“Radiation is energy that comes from a source and travels through space at the speed of light” (Centers for Disease Control and Prevention [CDC] 2022). The energy associated with radiation contains associated electric and magnetic fields. Radiation can take the form of ionizing or non-ionizing radiation. Non-ionizing radiation includes microwaves, visible light, and radio waves. This type of radiation’s energy is not sufficient to remove electrons from atoms in contrast to ionizing radiation. Ionizing radiation is the capability of particles, protons, electrons, and neutrons to produce enough energy to produce ions (Nuclear Regulatory Commission [NRC] n.d.), meaning it deposits enough energy to remove electrons from atoms. There are different types of ionizing radiation:

alpha particles, beta particles, gamma rays, x-rays, and neutrons. Figure 1 shows penetration power from least to greatest of the aforementioned types of ionizing radiation.

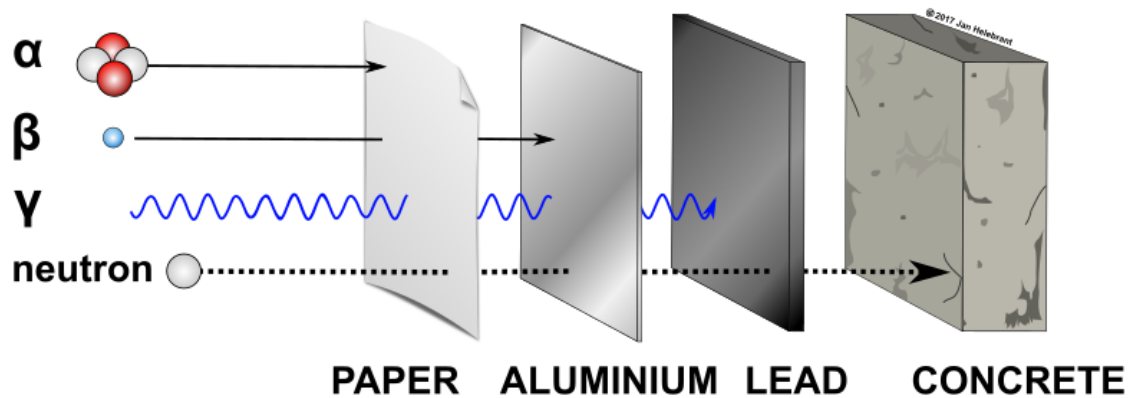


Figure 1. Ionizing Radiation Penetration. Source: Occupational Safety and Health Administration (n.d).

## 1. Radiation Environments

This section will provide a brief background of different radiation environments: space radiation and man-made.

Natural radiation can be found everywhere from cosmic rays that originate from the sun, terrestrial radiation found in building materials from deposits of uranium and thorium, inhalation from radioactive minerals such as radon and thoron found in soil and solid rock foundation, and ingestion from radioactive minerals that can be found in water and food (i.e., vegetables). Thus, natural radiation exposure can be obtained from anywhere: indoor and or outdoor sources. Figure 2 depicts the different types of natural radiation.

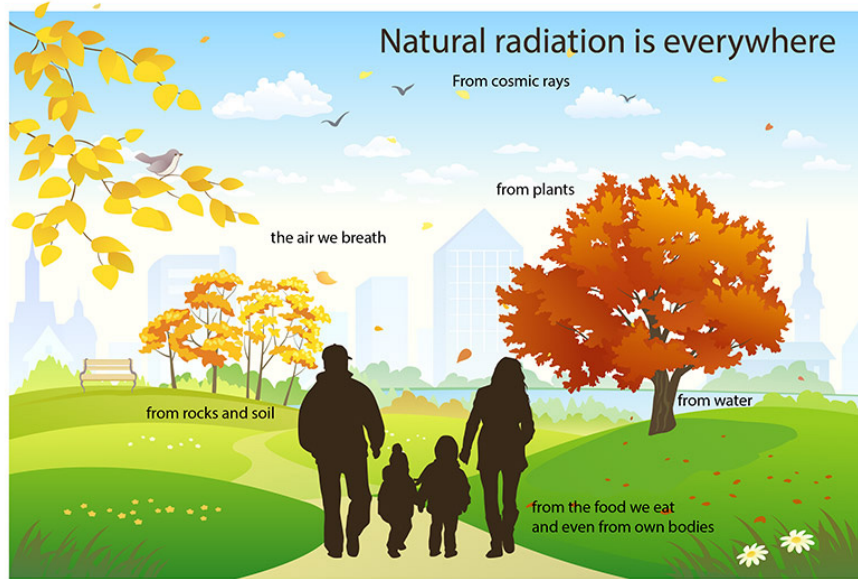


Figure 2. Natural Radiation. Source: Washington State Department of Health (2002).

For exoatmospheric systems like satellites, there are two primary types of natural radiation: galactic cosmic rays (GCR) and radiation that emanates from the Sun (Nuclear Engineering [NE] 2004). GCR contain energetic protons and heavy ions. Although the source of the GCR is unknown, it has a peak energy of 1 GeV/n (NE 2004). Its fluence can be affected via solar events decreasing by a factor of 10 dependent on the solar event on the magnetic field (NE 2004). The sun produces a low energy particle, primarily protons, known as the solar wind. Solar flares caused by magnetic storms are the main source of the radiation hazard attributed to the sun. The sun radiation also creates solar particle events (SPEs). These events create high energy protons and other heavier type particles, which can damage the earth's magnetic fields. Due to the damage created by these events on the inability of the protons to be trapped within the Van Allen Belts, disruption to communication and electronics on earth in the form of "soft errors" can occur. "Soft errors occurs when a radiation event causes enough of a charge disturbance to reverse or flip the data state of a memory cell, register, latch, or flip-flop" (Baumann 2005, 305). The error in this case is constituted as "soft." Reason being is if new data is written to the bit on the device, the device will restore and continue functioning as intended, thus not showing any

permanent damage by the radiation event. Figure 3 shows the three regions of space around earth where penetrating radiation occurs. Refer to aforementioned SPEs within this figure.

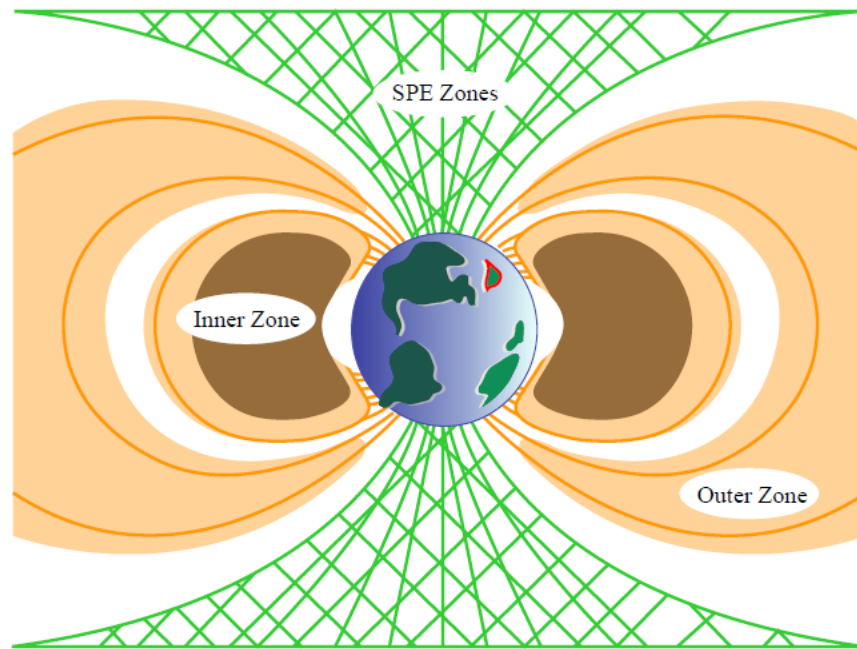


Figure 3. Space Regions around Earth. Source: Nuclear Engineering (2004).

“Van Allen Radiation Belts, discovered in 1958 by James A. Van Allen, an American physicist, are characterized as a zone of energetic charged particles” (Space Center Houston n.d.). “These particles consist of relativistic electron and proton populations trapped in the earth’s magnetic field” (Li and Hudson 2019, 8320). The magnetic field protects earth from high energetic electrons. Figure 4 depicts Van Allen Radiation Belts. “The outer belt is made up of high energy particles originating from the Sun that become trapped within the magnetic field, known as the magnetosphere. The inner belt results from interactions of cosmic rays with the earth’s atmosphere” (Space Center Houston n.d.).

Although the magnetic field provides earth protection from space radiation, the inner region of the radiation belts pose concern for space satellites. Satellites have a

susceptibility as the integrated circuits and sensors have a vulnerability to radiation within the space atmosphere.

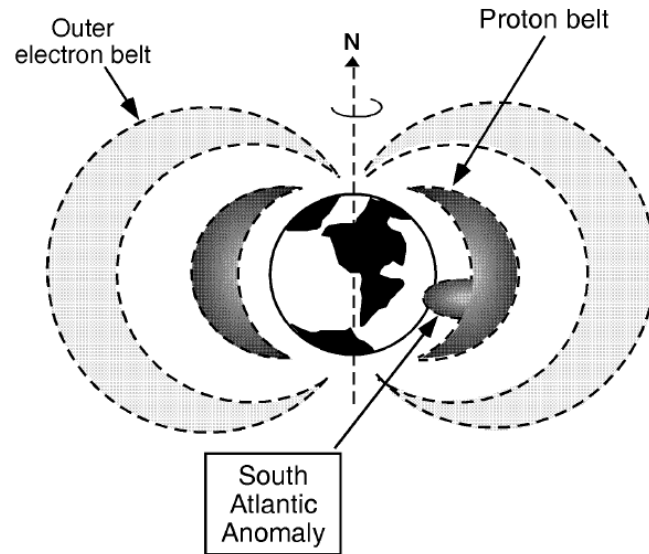


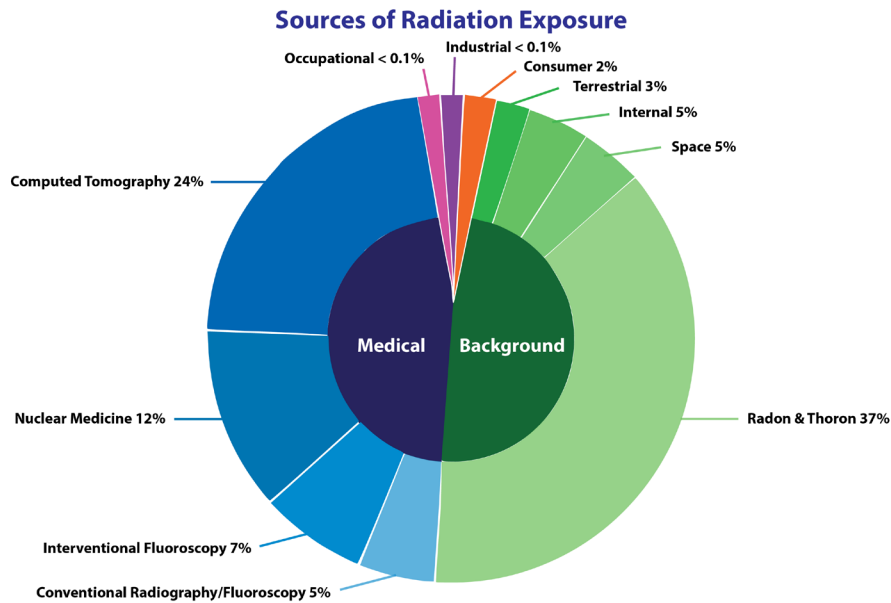
Figure 4. Earth's Trapped Radiation Belts. Source: Johnston (1998).

As introduced, space radiation can have a permanent effect on electronic devices. Devices affected by space radiation can have permanent damage and see issues caused by transient effects. Satellites are not the only devices that can be affected by space radiation. Space radiation can also affect communication systems, GPS navigation systems and other technology systems within the earth's atmosphere. The effects of space radiation on these devices and systems can be catastrophic (system shutdown) to insignificant. Thus, it is imperative that engineers within the field of radiation effects understand the space radiation environment. This understanding assists with risk minimization within systems and their internal parts for better performance and system lifespan.

Man-made radiation is generated in a range of medical, commercial, and industrial sources (Washington State Department of Health 2002), the largest source of man-made radiation being attributed to medical procedures using x-ray type machines. Other than medical sources, man-made radiation can also derive from consumer products (televisions,

natural gas heating and cooking fuel), research institutions (colleges and universities), nuclear reactors, uranium mills, fuel preparation plants, and federal facilities. All that are sources utilizing radioactive material as part of their regular business activities.

As stated earlier, sources of radiation are everywhere. We all receive daily exposure from both natural and man-made radiation sources. According to the National Council on Radiation Protection and Measurements (NCRP), the average radiation dose per person in the U.S. is 620 millirem (Environmental Protection Agency [EPA] n.d.). Figure 5 illustrates the different radiation sources and percentages personnel in the U.S. are exposed to. Figure 6 gives an insight into relative dose levels received from common radiation sources.



Average Annual Radiation Dose											
Sources	Radon & Thoron	Computed Tomography	Nuclear Medicine	Interventional Fluoroscopy	Space	Conventional Radiography/Fluoroscopy	Internal	Terrestrial	Consumer	Occupational	Industrial
<b>Units</b>											
mrem (United States)	228 mrem	147 mrem	77 mrem	43 mrem	33 mrem	33 mrem	29 mrem	21 mrem	13 mrem	0.5 mrem	0.3 mrem
mSv (International)	2.28 mSv	1.47 mSv	0.77 mSv	0.43 mSv	0.33 mSv	0.33 mSv	0.29 mSv	0.21 mSv	0.13 mSv	0.005 mSv	0.003 mSv

(Source: National Council on Radiation Protection & Measurements, Report No. 160)

Figure 5. Sources of Radiation Exposure. Source: EPA (n.d.).

# RELATIVE DOSES FROM RADIATION SOURCES

All doses from the National Council on Radiation Protection & Measurements, Report No. 160 (unless otherwise denoted)

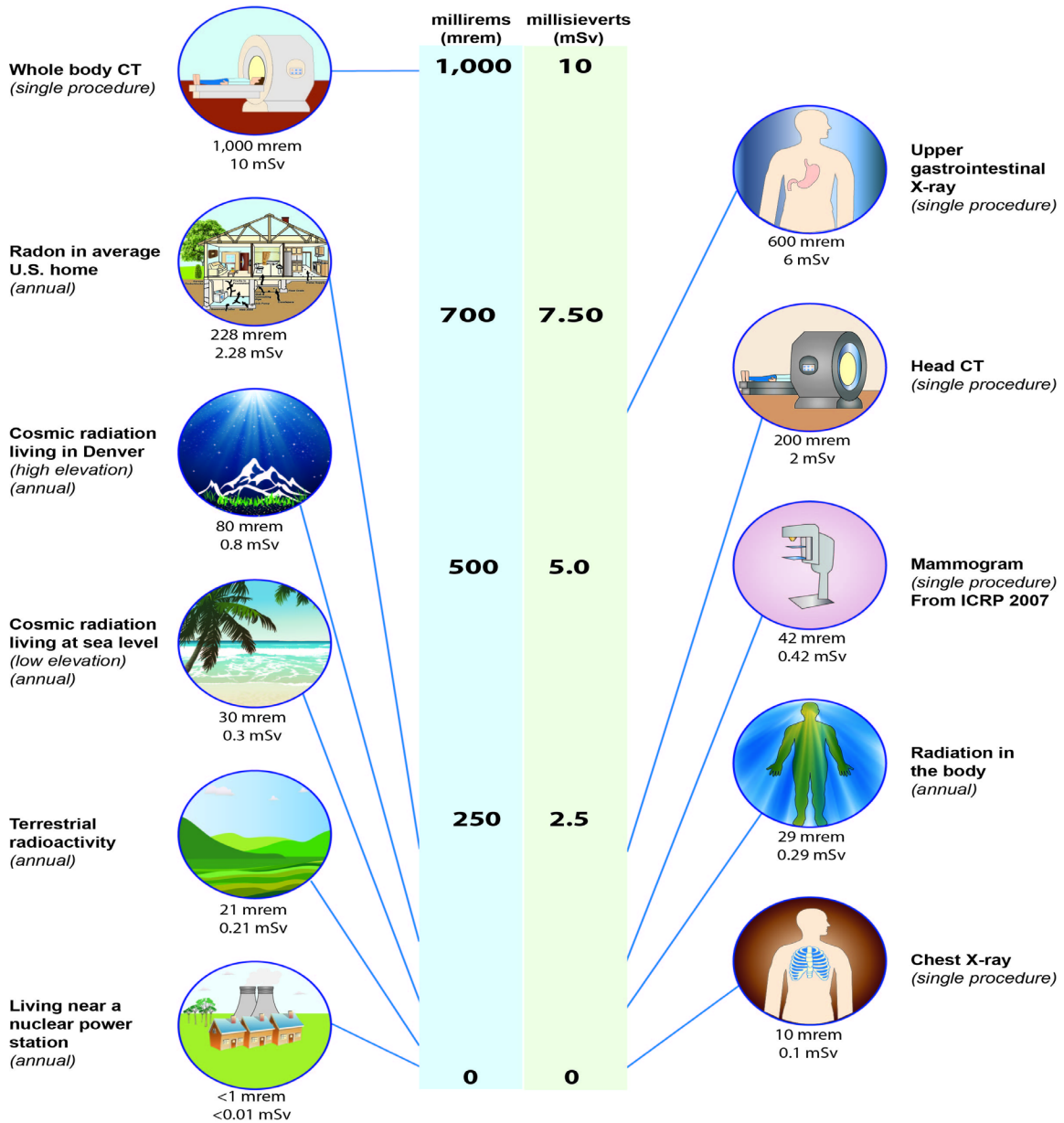


Figure 6. Common Radiation Sources Source: EPA (n.d.).

## 2. Radiation Effects on Microelectronics

This section will provide a brief background on the different types of radiation effects: neutron, gamma ray, and space radiation effects and their effects on microelectronic devices. Radiation hardening is the process of determining if microelectronic devices will be resistant to any damage or failure within a space or strategic radiation environment. Radiation effects on electronic devices have 4 main proponents: single event effects (SEE), total ionizing dose (TID), displacement damage, and prompt dose. SEEs are caused by energetic particles, which can cause bit flips, single event latch up (SEL), single event functional interruptions (SEFI), and single event burnouts (SEB) in digital and analog circuits. Latch-ups and SEFIs have the ability to recover despite causing minimal system damage or failure, while SEBs are a complete system failure with no recovery method.

TID “is an accumulating effect of the dose rate and the total time a circuit is exposed to radiation” (Nuclear Engineering International [NEI] n.d.), which can cause leakage current increases and threshold voltage shifts in devices.

Displacement damage, primarily from neutron interactions, is a principal cause of radiation damage to electronic devices. Neutrons are uncharged particles that, when interacting with the lattice atoms of a semiconductor, cause displacement which results in disruption of the lattice structure, which causes defects and or damage to the device. Refer to Figure 7. Device damage can lead to shorter system lifespan, intermittent system interruption or failure.

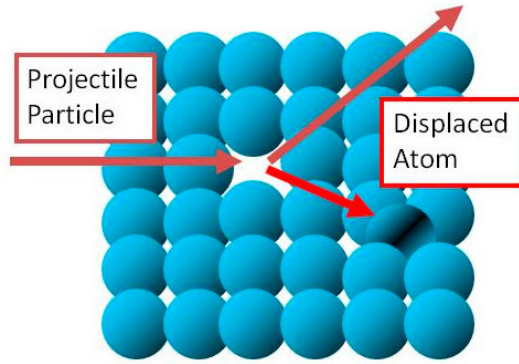


Figure 7. Neutron Displacement Damage. Source: Alter Technology Tüv Nord (2015).

Gamma ray irradiation, known as total dose, modifies the material properties of semiconductors, particularly within the electronic structure. As mentioned earlier, long-term exposures to total dose causes leakage current between the circuits, which can cause degradation to the device.

Prompt dose or prompt radiation effects come from gamma rays produced by a nuclear weapon and appearing within a second or less after a nuclear explosion (*Oxford* 2002).

## **B. THESIS ORGANIZATION**

The remainder of this thesis is organized in such a way to provide the reader with an understanding of the process for developing a training guideline/plan for RH microelectronics. Chapter II is focused on the current programs geared toward radiation effects workforce development. Chapter III introduces the research methodology and survey. Chapter IV examines the qualitative analysis research performed via survey, interviews, and ethnographic method in the form of observation. Finally, Chapter V concludes and provides further recommendations.

## **C. THESIS OBJECTIVE**

This thesis introduces a qualitative research method, where the analysis of the data collected will be used in the development of a training model/guideline focused on training the current and future workforce within the field of radiation effects, which are the first

steps in solidifying the USG's key technical capabilities in nuclear defense, RH microelectronics, maintained for future generational systems. Demand for knowledgeable radiation effects personnel will increase with the development of future state-of-the-art space and strategic systems. It will require personnel that fully understand radiation effects, their effects relative to the various technology types to be used in those systems, natural and manmade radiation environments which those systems may encounter, and the effects of those technology types within different radiation environments.

## **II. RADIATION EFFECTS PROGRAM ASSESSMENT**

The development of future state-of-the-art space and strategic systems is going to require personnel that fully understand radiation effects in microelectronics, its effects relative to the various types of microelectronics to be used in those systems, natural and manmade radiation environments to which those systems may encounter, and the effects of those technology types within those different radiation environments. Knowledge of radiation effects in microelectronics is a specialized skillset and not easily transferrable; it takes years of training and actual testing application to develop the required expertise that is going to be needed for current and future USG nuclear modernization efforts. This assessment will focus on programs geared toward radiation effects workforce development.

### **A. SCALABLE ASYMMETRIC LIFE CYCLE ENGAGEMENT**

The Trusted and Assured Microelectronics (T&AM) program under the purview of the Office of Under Secretary of Defense Research and Engineering (OUSD(R&E)) has developed a program called Scalable Asymmetric Life cycle Engagement (SCALE). “SCALE is the preeminent U.S. program for semiconductor workforce development in the defense sector” (Purdue University [PU] n.d.). The development of SCALE came as the DOD microelectronics community realized the need for safe, reliable, and trustworthy microelectronics in conjunction with a need for a skilled microelectronics workforce. The SCALE program led by Purdue University focuses on semiconductor workforce development in the defense sector. The rad-hard microelectronics topic area of the SCALE program “provides unique courses, mentoring, internship matching and targeted research projects for college students interested in the area of radiation-hardening” (PU n.d.). Although the program is led by Purdue University, there are over fifteen partner universities within the SCALE programs and more than fifty public-private partners, including government agencies and organizations and industry partners (PU n.d. ). The rad-hard university partners provide a unique curriculum that includes (but not limited to): introduction to radiation effects in electronics, radiation environments, space radiation

effect and modern microelectronics, Technology Computer Aided Design (TCAD) and circuit simulations, radiation interaction with materials, and deeper dives into Stopping and Range of Ions Matter (SRIM), Cosmic Ray Effects on Microelectronics (CRÈME), SPICE, and Systems Engineering and Assurance Modeling (SEAM) simulations tools (PU n.d.). Students' involvement with the program provides them with the opportunity for internships with the various program partners, focused research topics and the potential for full time employment with the program partners in the focused technical areas (PU n.d.).

## **B. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

“In February 2022, NASA’s radiation effects community collaborated with Texas A&M University (TAMU) academia and Radiation Effects Facility staff to develop a radiation effects training ‘boot camp.’” The boot camp focused on “giving radiation effects experts and junior engineers an opportunity for hands-on experience” and immediate knowledge transfer from personnel testing experience at a single event effects (SEE) radiation facility (National Aeronautics and Space Administration [NASA] n.d.). Training included personnel from government, industry, and academia. Personnel participating in the “boot camp” were a mixture of experience levels from entry level to SMEs. Per Greg Allen from NASA’s Jet Propulsion Lab, “This span of experience level was intentional on our part when we chose the class and the class size” (NASA n.d.). As the ratio between participants and instructors allowed for significant one-on-one training. Hence, the dialogue between the participants provided poignant questions from those different vantage points being inquired. Per Allen, “The overall, goal of the boot camp is to get the radiation effects community to more sustainable place.” Combination of classroom training with hands-on time in the facility, participants were provided the expertise and understanding of pretest activities, actual test execution and post-test activities when testing microelectronics for radiation effects.

## **C. LOS ALAMOS RADIATION EFFECTS SUMMER SCHOOL**

The Los Alamos Radiation Effects Summer School, a program sponsored by the Center for Space and Earth Sciences, hosted by LANL’s Intelligence and Space Research division, is geared towards graduate students currently enrolled in a master’s or Ph.D.

program in electrical engineering, physics, computer science, computer engineering, aerospace engineering or a related field. Students that have completed bachelor's degree programs only are considered for the program on a case-by-case basis. The programs are "dedicated to radiation effects testing and data analysis for semiconductor devices exposed to a variety of radiation environments" (Los Alamos National Laboratory [LANL] n.d.). The program provides students with hands-on experiments at LANL accelerators. This experience allows students the opportunity to "investigate radiation effects in space specific devices and high-performance computing applications through total ionizing dose (TID) testing, single-event effects (SEE) testing and laser testing." Students also attend lectures from researchers visiting from government laboratories, universities and industry.

Students choose from various research topics ranging from: "radiation response of emerging electronic devices; the resilience of algorithms, machine learning and CubeSat applications exposed to harsh radiation environments; and system-level electrical behavior caused by single events and total ionizing dose" (LANL n.d.). Where at the "conclusion of the summer program students will present their research and complete first-author abstracts ready for submission to conferences in the fields of radiation effects or high-performance computing" (LANL n.d.)

#### **D. RADTOWN**

The Environmental Protection Agency (EPA) offers a radiation education website called RadTown. RadTown contains material that explains different types, sources, and uses of radioactive material or radiation. The material is "designed to help students understand the properties of ionizing and non-ionizing radiation"; activities are broken down into four different interactive categories: neighborhood, outdoors, waterfront, and downtown. The activities provide students with the ability to "identify sources of non-ionizing and ionizing radiation present in the world today" (EPA 2019). "Students examine how they may be exposed to ionizing radiation, evaluate the benefits and risks associated with radiation exposure, identify situations in which they may choose to control or limit their exposure to ionizing radiation, and learn about the penetrating powers of different types of radiation" (EPA 2019). RadTown also provides classroom material for teachers

complete with activities for concise education learning. The activities depicted in Table 1 provide teachers with required background information, “resource lists for student research, and detailed lesson plans with activities and worksheets. These activities are intended for use with middle school and high school students, but can be adapted for classroom requirements” (EPA 2019).

Table 1. RadTown Classroom Material Activities. Adapted from EPA (2019)

Activity Quantity	Activity Lessons
Activity 1	Types of Radiation
Activity 2	Sources of Annual Radiation Exposure
Activity 3	Penetrating Powers of Ionizing Radiation
Activity 4	Exposure Pathways
Activity 5	Radiation Health Effects
Activity 6	Acute versus Chronic Exposure
Activity 7	Radiation: Fact or Fiction

#### E. DEFENSE NUCLEAR WEAPONS SCHOOL

“Defense Threat Reduction Agency (DTRA) Defense Nuclear Weapons School (DNWS) provides unique training to the Department of Defense (DOD), federal, state, and local agencies on: Nuclear and Radiological Weapons; Nuclear Accident/Incident Command, Control and Response; Explosive Ordnance Disposal (EOD) Threat Awareness/Assessment; Weapons of Mass Destruction (WMD); and Chemical, Biological, Radiological and Nuclear (CBRN) modeling” (Defense Threat Reduction Agency [DTRA] n.d.).

Per COL Christopher M. Whelan, Commandant, Defense Nuclear Weapons School: “the Russian invasion of the Ukraine has upset the geopolitical balance of Europe, and the world. Their threats of nuclear retaliation put new emphasis on the training and education that DNWS offers.”

DNWS provides core competencies and radiological/nuclear WMD training in nuclear weapons to ensure a strong nuclear deterrence. “The school’s objectives are to

create, develop, and implement professional training through both traditional methods and innovative training technologies” (DTRA n.d.). DNWS training “helps to ensure that the nation maintains a safe, reliable, and credible nuclear deterrent.”

DNWS offers eight different training type courses: Nuclear Weapons Orientation and Policy; Nuclear Weapons Incident, Accident, and Response Training; CWMD Radiological and Nuclear Training; Explosive Ordnance Disposal Specialty Training; Emerging Requirements; Developing Courses; Distance Learning Training; and DTRA-RD & Hosted Courses. The courses are delivered via “instructor-led courses both in-residence and via Mobile Training Teams (MTTs), and distance learning courses via online method.”

Prospective students are encouraged to review the DTRA DNWS catalogue and register for the pertinent courses with respect to their discipline.

#### **F. MISSILE DEFENSE AGENCY**

“Missile Defense Agency’s (MDA) mission is to develop and deploy a layered Missile Defense System to defend the United States, its deployed forces, allies, and friends from missile attacks in all phases of flight” (DOD n.d.).

MDA has two (2) strategic goals dedicated to workforce development: “optimize available resources and capitalize on the creativity and innovation of the nation’s universities and small business community” (DOD n.d.). With a view to develop a capable workforce in RH, MDA instituted their Radiation Aware Design, tEst, & Evaluation Ecosystem (RAD-E<sup>3</sup>) program, where one of the building blocks is geared to educating current and future workforce on key radiation hardness assurance (RHA) principles to support MDA programs (Ahlbin 2022). In the program there are a set of expectations and goals for new hire workforce.

## **1. Expectations**

- (1) Survivability seminar series,
- (2) Single Event Effects university seminar (live/repository),
- (3) Onsite testing boot camps,
- (4) Hands-on lab,
- (5) Supporting a program radiation adjudication board (RAB) (Ahlbin 2022).

## **2. Goals**

- (6) Learn to review piece parts to meet RHA PMP requirements,
- (7) Learn to review radiation test plans & test data/reports,
- (8) Identify outside organizations that can support; space vehicles directorate, air force research laboratory (AFRL-RV), aerospace, sandia, MITRE, NSWC Crane,
- (9) Learn about all radiation test facilities capabilities (Ahlbin 2022).

MDA hosts a webinar series on the different types of radiation effects for space applications. The webinars provide attendees basic physics knowledge behind space radiation effects, effects space radiation can have on electronic components, as well as program specific examples and analysis on previous data taken from space environments; in particular single events effects and total ionizing dose.

MDA also looks to leverage radiation effects educational material with the purpose of leveraging community expertise to deliver live material on rad effects to current and future workforce in need of basic “101” training (govt, industry, academia) (Ahlbin 2022); build out library of on demand material with recorded material on nano Hub (Ahlbin 2022); refresh and/or add new material with new series as applicable; and pair with experiential learning at radiation test facilities (Ahlbin 2022).

Similarly, MDA is leveraging relationships, products, and experience to deliver an eleven (11) week basic overview of radiation effects concepts that specifically support test facilities that DOD is investing in and their respective education institutions (Ahlbin 2022).

## **G. RADIATION EFFECTS CONFERENCES**

Annual radiation effects conferences such as Institute of Electrical and Electronics Engineers (IEEE) Nuclear & Space Radiation Effects Conference (NSERC) and Hardened Electronics and Radiation Technology (HEART) Technical Interchange Meeting (TIM) brings together SMEs in radiation effects and radiation facility testing from government and government contractors to promote understandings and knowledge sharing at the classified and unclassified levels with specific topic features. These conferences feature oral and poster sessions, technical programs consisting of technical sessions of contributed papers including topics such as: nuclear and space radiation effects on electronics, integrated circuits, sensors and systems, design techniques, and semiconducting material processing technology; “describing the latest observations in radiation effects, short courses on radiation effects issues, radiation effects data workshop, and industry exhibits” (Cannon 2023).

The conference short courses provide valuable skills training for new and current employees within the radiation effects community. Short courses are organized into multiple sections, featuring introductory material and advanced topics. Topics covered are intended to benefit new and experienced engineers and scientists to the field of RH effects, by providing up-to-date material and insights.

This review of the radiation effects programs demonstrates that a gap between education and on the job training in the field of radiation effects is still prevalent. Although, the USG is providing funding to stand up educational programs in partner institutions geared toward radiation-hardened effects, the application to the theory learned in these programs is missing when the students come into the workforce. As per assessment there are very few programs geared toward the nonstudent workforce, leading to a significant gap in regard to adequate training for the current workforce.

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### III. SURVEY METHODOLOGY

This research utilizes a qualitative research method. The research was conducted by employing one-on-one interviews with RH effects SMEs and internally and externally focused electronic surveys. Interviews were conducted in person and virtually; utilizing Microsoft Teams (hereby referred to as Teams). Electronic surveys were conducted utilizing Qualtrics XM Platform.

The analysis of the data collected from the aforementioned methods will be used to develop a training model/guideline for personnel within the field of RH effects.

Qualtrics XM is an experience management company that spans across the globe, partners with 18,000+ brands, and 900+ XM professionals. Qualtrics states their purpose “As our technology scales from people and companies to communities and governments, we will begin to close gaps in ways we never dreamed possible. Not only will our technology power the world’s greatest companies, but by understanding human emotions, beliefs, sentiments and values, we will close some of the world’s biggest gaps: political misunderstandings, human rights issues, health care disparities, gender equality, education, and income. Because many of the world’s most pressing problems occur from a lack of understanding—and that’s a problem we can solve.” (Qualtrics n.d.) Qualtrics employs three different platforms for their distinct customer set: XM for Customer Frontlines, XM for People Teams, and XM for Strategy & Research. This research utilized the Strategy & Research XM platform.

Strategy and Research platform utilization of an easy-to-use online survey software platform, its emphasis on advanced quantitative and qualitative research, its data and text iQ analysis tools, and its export survey data analysis formatting tools for ease of analysis made it an ideal choice for this research. The survey software provided simple templates that provided the necessary multiple choice and drop-down tools that were utilized to develop the online surveys. The data and text iQ analysis tools allow for easy analysis of the data. The data analysis section provides the ease of merging, filtering and cleaning up the data for easy analysis. As this survey incorporates text boxes for completion, the text

iQ tool will produce the necessary graphs and charts for word frequency and allows for creation of multiple topics for further analysis and dissection of text responses, which will contribute to seeing the pattern of development detailed by the workforce.

Within this research two online surveys were deployed using the Qualtrics platform. The surveys were focused internally; current command organization and externally with DOD partner and government agencies with radiation effects focuses. Surveys titled Radiation\_Hardened WFD and Radiation\_Hardened WFD\_Ext compiled of 9 multiple questions and 9 short answer questions.

## **H. INTERNAL SURVEY**

### **1. Multiple Choice Questions**

1. How long have you been at NSWC Crane?
2. What is your engineering discipline?
3. How long have you worked in the field of radiation effects?
4. Before coming to Crane, how many years of experience have you had with radiation (ionizing or non-ionizing)?
5. Before coming to Crane, how many years of experience did you have with microelectronics?
6. Do you understand the difference between strategic and space radiation environments?
7. Do you know the different radiation environments to which are tested in both strategic and space?
8. Upon arriving, were you provided a technical mentor?
9. Did you feel that there was a plan for your development upon your arrival to radiation effects area?

## 2. Short Answer Questions

10. What training should be provided for a new person reporting to the Radiation Test and Evaluation branch to enable them to carry out their responsibilities?
11. Upon your entrance into the Radiation Test and Evaluation branch what type of guidance and/or information wrt radiation effects, microelectronics, digital and analog design, etc., would you have liked to receive in order to effective in understanding and completing your tasking efforts?
12. What is your idea of the best type of training to provide someone just coming into the field of radiation effects to assist with their development?
13. What radiation environments would you like to get more experience?
14. What type of training would you like to receive on the different radiological systems used for testing?
15. What device types and/or technology nodes would you like to obtain more experience?
16. What's the estimated timeframe you think it would take someone to become a subject matter expert in radiation effects?
17. During your time within the field of radiation effects, have you attended any radiation effects conferences or taken any short courses in rad effects? If so, please elaborate on the conferences that you have attended and how many times you have attended, as well as in what capacity (session chair, speaker, attendee). Also, elaborate on the short courses you have taken within the field of radiation effects.
18. Additional thoughts?

## **I. EXTERNAL SURVEY**

### **1. Multiple Choice Questions**

1. How long have you worked at your current organization?
2. What is your engineering discipline?
3. How long have you worked in the field of radiation effects?
4. Before coming to your organization, how many years of experience have you had with radiation (ionizing or non-ionizing)?
5. Before coming to your organization, how many years of experience did you have with microelectronics?
6. Do you understand the difference between strategic and space radiation environments?
7. Do you know the different radiation environments to which are tested in both strategic and space?
8. Upon arriving, were you provided a technical mentor?
9. Did you feel that there was a plan for your development upon your arrival to radiation effects area?

### **2. Short Answer Questions**

10. What training should be provided for a new person reporting to your organization to enable them to carry out their responsibilities?
11. Upon your entrance into your organization what type of guidance and/or information wrt radiation effects, microelectronics, digital and analog design, etc., would you have liked to receive in order to effective in understanding and completing your tasking efforts?
12. What is your idea of the best type of training to provide someone just coming into the field of radiation effects to assist with their development?
13. What radiation environments would you like to get more experience?

14. What type of training would you like to receive on the different radiological systems used for testing?
15. What device types and/or technology nodes would you like to obtain more experience?
16. What's the estimated timeframe you think it would take someone to become a subject matter expert in radiation effects?
17. During your time within the field of radiation effects, have you attended any radiation effects conferences or taken any short courses in rad effects? If so, please elaborate on the conferences that you have attended and how many times you have attended, as well as in what capacity (session chair, speaker, attendee). Also, elaborate on the short courses you have taken within the field of radiation effects.
18. Additional thoughts?

Survey sample size was approximately 79 people within the Radiation Effects Community. The survey was sent internally to approximately 54 personnel within Naval Surface Warfare Center, Crane Division (NSWC Crane), Global Deterrence Defense (GDD) Department and externally to approximately 26 personnel within the Radiation Effects Community within the DOD. Of the aforementioned sample size, about 26 responses were received, giving a 33% response rate to the survey.

Interview requests were sent to roughly 15 personnel via email. Of the requests nine responses were received, thus a 60% percent response rate. Interviews with SMEs were conducted on one-one basis, in person and virtually via TEAMS.

## **J. SME SURVEY QUESTIONS**

### **1. Demographic Questions**

1. What is your age?
2. What is your ethnicity?
3. What is your engineering discipline?
4. How long have you worked at your current organization?
5. How long have you worked in the field of radiation effects?

### **2. Short Answer Questions**

6. What do you think constitutes becoming a SME?
7. Do you consider yourself an SME within the field of radiation effects? If so, how many years until you felt you became a SME.
8. What are some of the things that you did that assisted you in becoming a SME within the field of radiation effects?
9. What is your idea of the best type of training to provide someone just coming into the field of radiation effects to assist with their development into becoming a SME within the RH field?
10. Additional thoughts?

Interviews with SMEs are a vital piece of this research. As stated, the purpose of this research is to develop a training model or guideline that will assist current and future workforce to becoming SMEs within radiation effects. In order to do that, you first need to understand what constitutes SME and how current personnel within the workforce became SMEs; timeframe, education background, training, mentoring, projects, radiation understanding, etc. Without this understanding one can't fully build a successful model or guideline. Thus, their experience is significant to this research.

## IV. ANALYSIS

This chapter will discuss the analysis of the data taken for this research.

As stated in Chapter 3 Methodology, this research was conducted through surveys and SME interviews. The survey consisted of multiple choice and text questions that included demographics, experience, knowledge, and ideas for effective RH training. The below analysis presented in graphs and data table form, will provide a workforce demographic snapshot (that includes age, engineering discipline, etc.), past and current experience of the workforce in the field of radiation effects and microelectronics, and an idea of the training needs from the workforce perspective. As stated in previous chapters, the data collected will be utilized to develop a training plan and/or guideline for the RH workforce.

The training plan/guideline will advance the workforce gradually through RH learning focusing on classroom guidance, self-paced training, literature, conferences, test development, test execution, analysis, and reporting through a four-five-year span.

### A. SURVEY MULTIPLE CHOICE DATA ANALYSIS

The data from the survey in Figures 8–15 and Tables 2–7 show the age of workforce, length in organization, technical make up, current and prior radiation experience, and prior microelectronics experience. This information is to provide an idea of the current construct of the workforce.

Figure 8 and Table 2 provide data with respect to the age of the workforce. Of the 26 respondents, 40% of the workforce is between the ages of 31–45 years of age. While 30% are of 20–30 years of age or 55 and over years of age and 4% are within the 46–55 age range. The presented data show that 30% of the workforce is at the minimum age of retirement (55 and over), meaning that there is a substantial amount of expertise that could retire at any time. It also shows that a small subset is retirement eligible in the next nine years. Although 65% of the workforce between 20–45 years of age offers a good pipeline source, over a span of 10 years or so, approximately 31% of the workforce in this critical technical area could retire. Thus, leaving a gap in expertise and knowledge in a

critical technical area that will be required to be filled in order to provide technical competency for the USG nuclear modernization efforts.

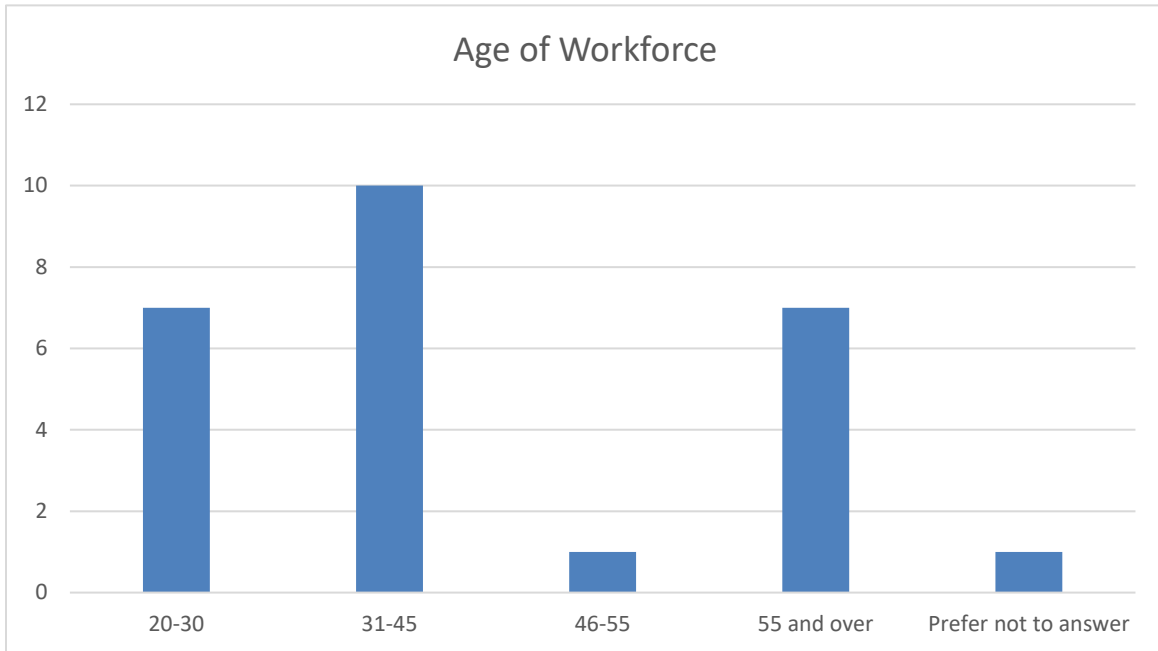


Figure 8. Age of Workforce

Table 2. Data for Age of Participants

20-30	27%
<b>31-45</b>	<b>38%</b>
46-55	4%
55 and over	27%
Prefer not to answer	4%

Figure 9 and Table 3 show the workforce’s length of service at their current organization. This data does not take into account previous service at other organizations. The data shows that 65 % of the workforce has been at their current organization from 0–15 years, with the remaining 35% of the workforce being at the organization for over 16 years. This data shows that personnel are invested in their organization, which can give a good indication of the ability to continue to grow expertise in RH effects.

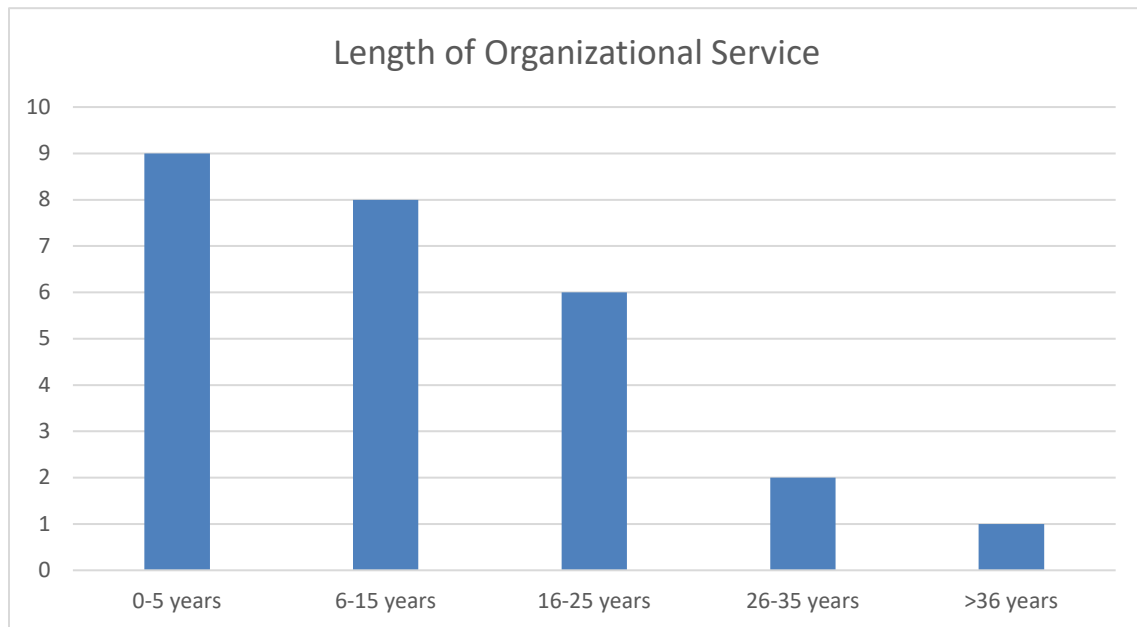


Figure 9. Length of Organizational Service

Table 3. Data for Length of Organizational Service

<b>0-5 years</b>	<b>35%</b>
6-15 years	31%
16-25 years	23%
26-35 years	7%
>36 years	4%

Due to the nature of radiation hardening and its process of producing microelectronic devices and components that are resistant to radiation damage in various

strategic and space radiation environments it's imperative to hire personnel with experience and knowledge in microelectronics, alpha, beta, and gamma rays. Thus, organizations look to hire personnel within the field of electrical engineering, nuclear engineering, and physics. Figure 10 and Table 4 below provide the engineering disciplines of the workforce. The data presented shows that 62% of the workforce holds degrees in electrical engineering with a small subset holding physics and nuclear engineering degrees. It can be seen that there are no mechanical engineers or electronics technicians reported. As stated earlier, historically personnel with certain backgrounds are hired within the field of radiation effects. However, there are outliers of personnel with mechanical engineer background that are hired within the RH workforce because they possess an understanding of electrical engineering and/or radiation effects from previous work experience. Although the data shows 0% electrical technicians, there are electrical technicians within the workforce. Technicians are personnel utilized for operational aspects of the systems (maintenance, operations, etc.) So, although it is not shown here there are occasions where you will have these disciplines within the workforce.

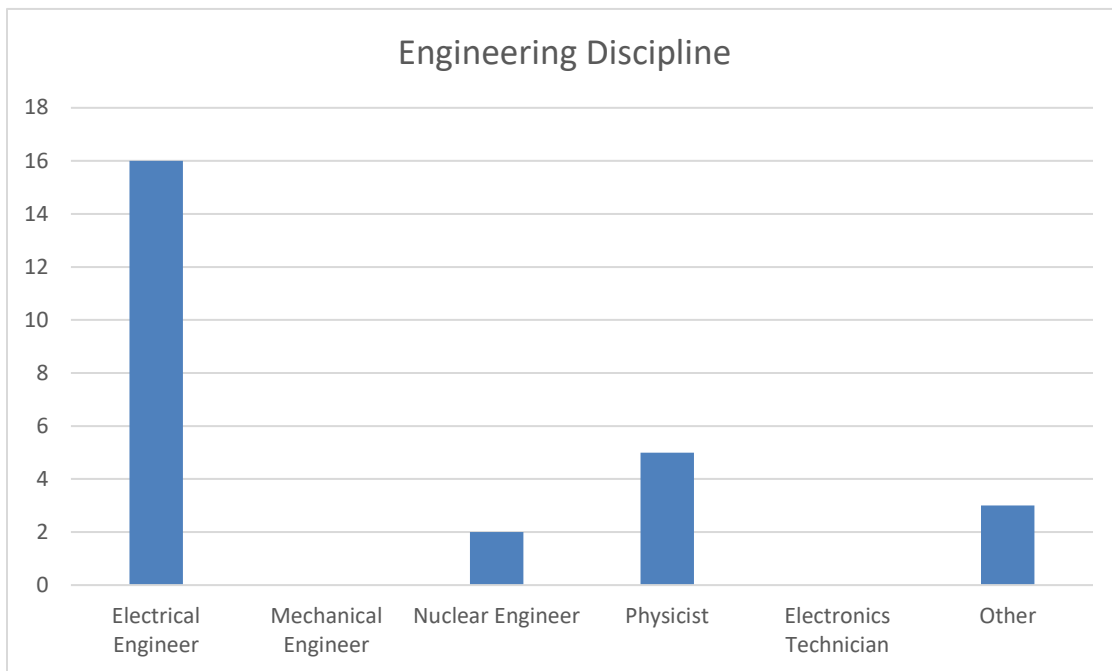


Figure 10. Engineering Discipline

Table 4. Data for Engineering Discipline

<b>Electrical Engineer</b>	<b>62%</b>
Mechanical Engineer	0.00%
Nuclear Engineer	7%
Physicist	19%
Electronics Technician	0.00%
Other	12%

Figure 11 and Table 5 show the workforce’s current radiation effects experience. As shown, there is a moderate gap variance in the workforce RH effects experience. The data shows an approximately 12% experience gap between the workforce with 26 years or greater of experience to that of the workforce with 16 to 25 years of experience. Data also shows an approximately 15% experience gap between the workforce with 26 and greater years of experience to those with five years or less of experience. The moderate experience gap can be contributed to a number of variables, years of organization service, service with respect to radiation discipline, etc. Examining Figure 9, an almost direct correlation with years of service and current RH experience can be seen, with slight differences being attributed to personnel not spending their whole careers at their current organization within the field of radiation effects.

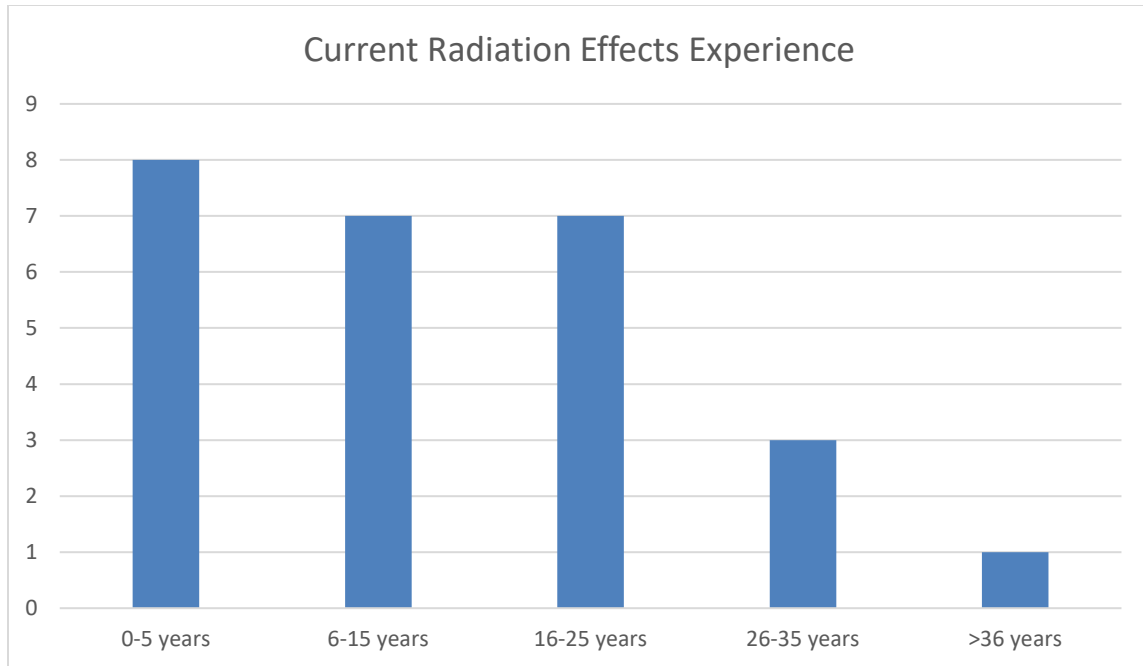


Figure 11. Current Radiation Effects Experience

Table 5. Data for Current Radiation Effects Experience

<b>0-5 years</b>	<b>30%</b>
6-15 years	27%
16-25 years	27%
26-35 years	12%
>36 years	4%

The aforementioned data presented the length of service of the current workforce. As stated, it did not take into account previous work service experience. Figure 12 and 13 data shows workforce previous experience in the field of radiation effects and microelectronics prior to coming into their current organization. Figure 15 data states, 89% of the workforce had 0–5 years of prior radiation experience, with the remaining 12% showing 20–25 prior years of radiation experience. This data further confirms the need for a training plan/guideline in RH effects as a substantial portion of the workforce show no

prior radiation experience, thus deducing that their first interaction with radiation effects is when they first enter the workforce.

Figure 13 data shows the same percentage with respect to personnel's prior microelectronics experience as in Figure 12. On average, the prior radiation and microelectronics experience per 26 participants is 3.31 and 3.42 years respectively. There are slight deviations observed in the participants' prior microelectronic experience versus previous radiation experience.

These variations in microelectronics experience but not radiation experience can be related to participants gaining experience in microelectronics from previous education efforts, projects, work experience, personal hobbies, etc. The inverse can be presumed that the participants' previous radiation experience did not involve efforts with microelectronic devices.

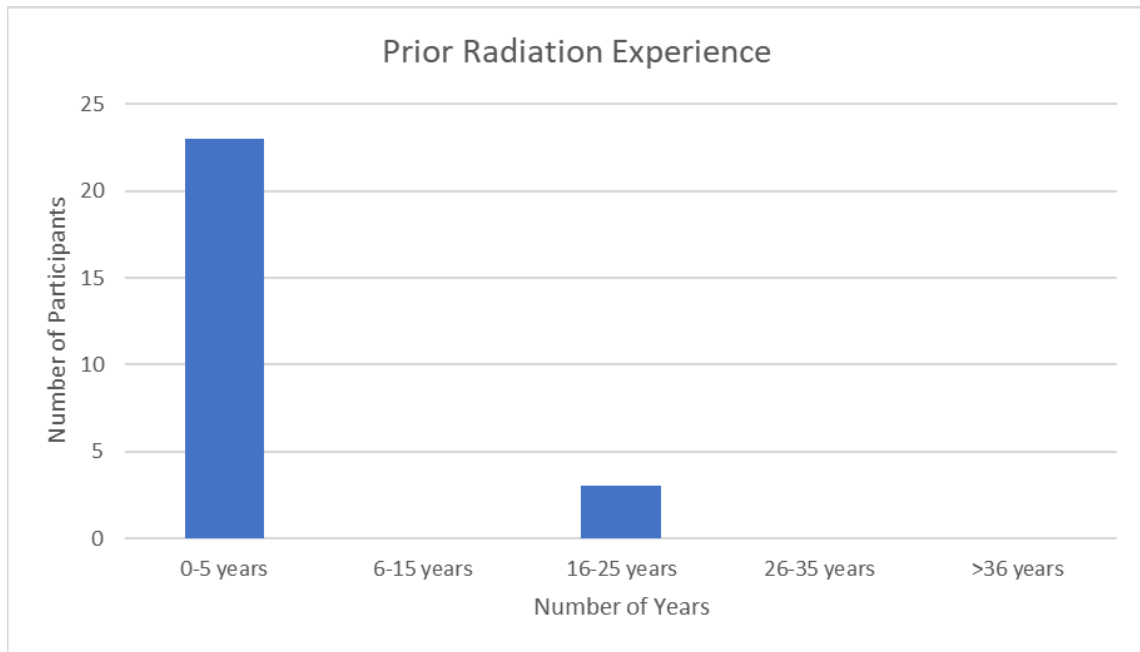


Figure 12. Prior Radiation Experience

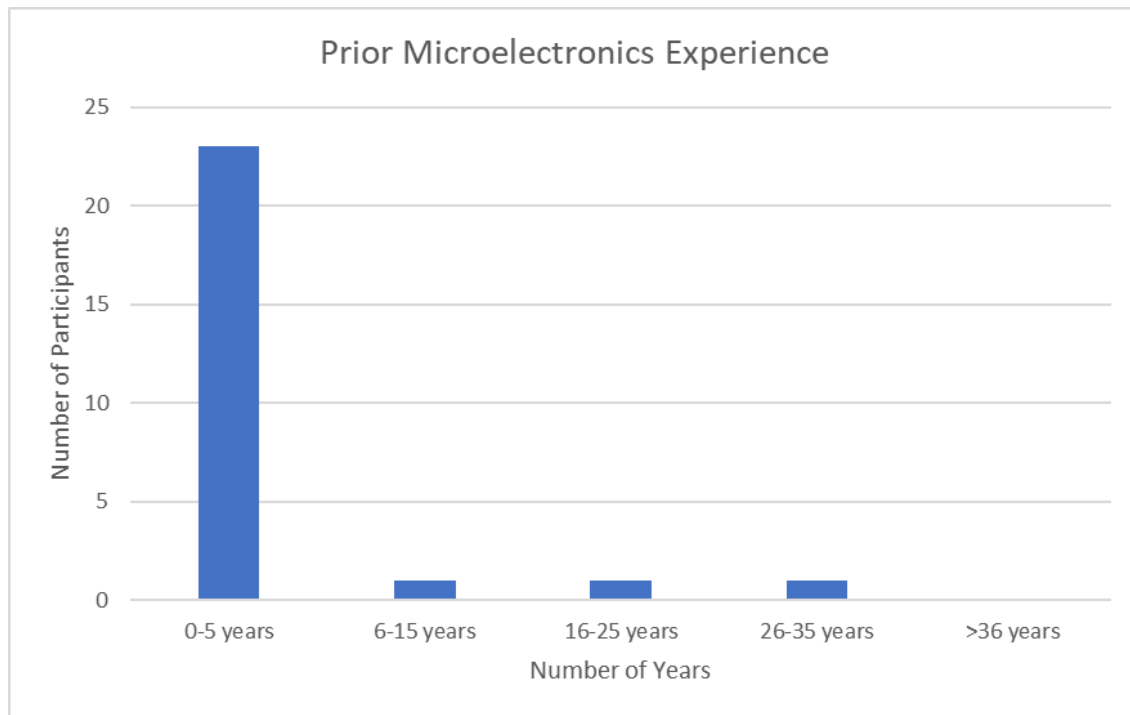


Figure 13. Prior Microelectronics Experience

## B. SURVEY QUESTIONS – DATA ANALYSIS

As stated, the survey consisted of questions to provide the workforce with the opportunity to provide their input on effective training for RH test engineers. This section will provide insight into their input.

The survey comprised of 7 questions (reference Chapter 3). The questions included the training that should be provided to new employees, effective guidance on microelectronics, training ideas, radiation environments, device types, and conference attendance.

There was a consensus from the workforce that training in radiation effects, microelectronics, radiation, devices physics, and solid-state physics was of utmost importance. It was also ubiquitous that a form of hands on or on-the-job (OJT) training would be beneficial in the form of providing employees with a project that they are accountable for; in respect to test development (printed circuit board (PCB) development, software development, and test plan development), test execution, analysis, and report

development allowing them to be involved early and understanding the process. Gaining experience in the following radiation environments: neutron, neutron single event effects (nSEE), proton, SEE, electromagnetic pulse (EMP), dose rate upset/dose rate survivability (DRU/DRS), dose rate and device types/technology: passives, processors, field programmable gate arrays (FPGAs), 90nm node size, fin field-effect transistor (FinFET), memories, gallium nitride (GaN), transistors, silicon carbide (SiC), and integrated circuits (ICs) is significant to the workforce for their development in understanding strategic and space environments for the various nuclear systems. Lastly, personnel indicated that they have familiarity with the well-known radiation conferences: NSREC, HEART, Radiation Hardened Electronic Technologies (RHET), Microelectronics Reliability and Qualification Workshop (MRQW), Government Microcircuit Applications & Critical Technology Conference (GOMAC TECH), etc., in capacity of attendees, speakers, chairs, and poster sessions.

### **C. SME DISCUSSION ANALYSIS**

For the second portion of the research, interviews were conducted with SMEs within the field of radiation effects. Figures 14 and 15 provide the age demographics and radiation experience of the participating SMEs.

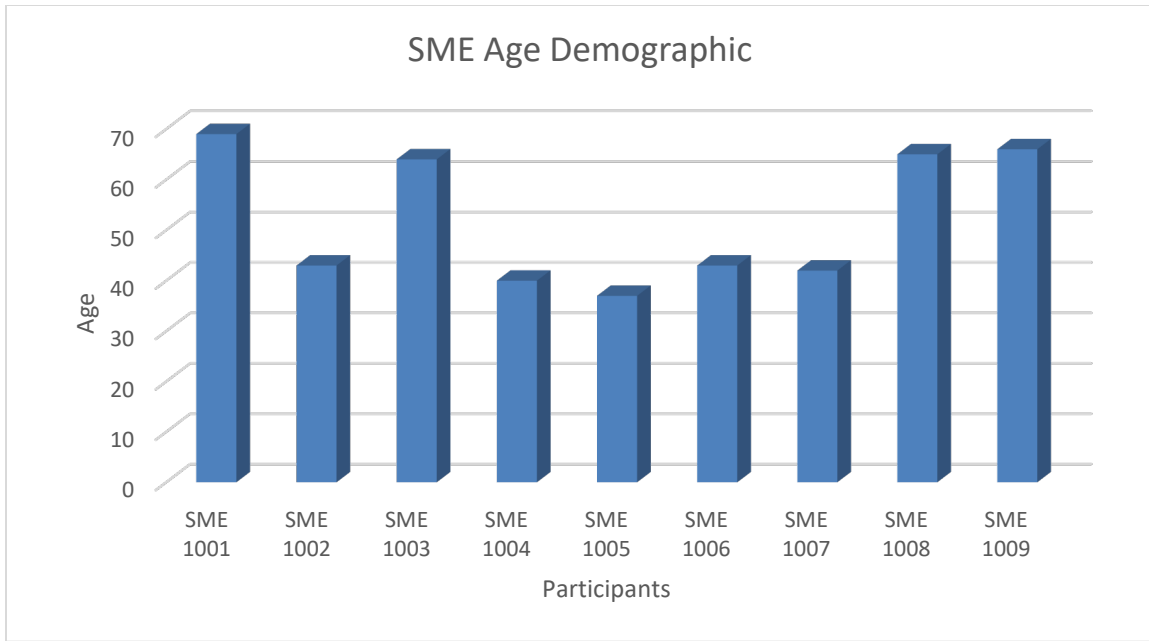


Figure 14. SME Age Demographic

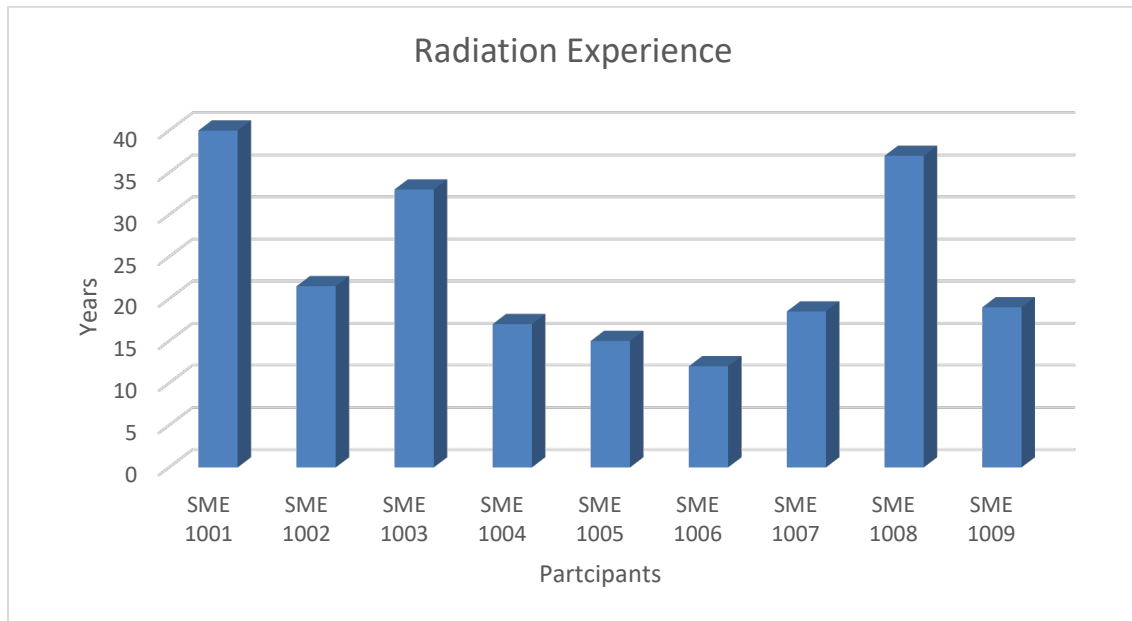


Figure 15. SME Radiation Experience

Figure 14 shows 55.5% of the SMEs are between the ages of 35–45 with 12–22 years of experience and 44.5% between the ages of 60–70 with 20–40 years of radiation experience. This data provides insight into the age range of SMEs interviewed and the level

of radiation experience that can constitute a SME. As shown in the data, one SME had only 12 years of experience but is considered a SME due to the developmental training, both formal and self-paced, that they received. This shows that if the workforce is given adequate training, they can potentially be constituted as a SME under 15 years.

The questions were geared toward understanding the groups' thoughts on what constitutes a RH SME, training that helped them to become SMEs in RH effects, and lastly, best training to assist an employee just coming into the field of radiation effects. The consensus from the group was that experience and knowledge in RH effects, understanding of the radiation environments, different systems, semiconductor radiation response, and knowing and having a good contact base within the radiation community of interest (COI), etc., to be good foundations that make up a SME within the field of radiation effects.

Mentoring, meeting involvement, participation in requirements development, designing and executing a test for microelectronic components, and conference attendance were all effective training and efforts that assisted them in their path to becoming radiation SMEs. All the SMEs talked about how they took control of their own learning and improvement by reading literature with respect to radiation effects (books, technical papers), microelectronics, radiation environments, etc.

General viewpoint from the group is that the understanding semiconductor physics, general radiation concepts, performance of testing (development, execution, etc.), project involvement (lead or assisting SME), comprehension of requirements and standards documentation, online and classroom training, and conference attendance are best types of training for employee development in radiation effects.

This data analysis provided in this chapter offers an insight into the current workforce structure in the field radiation effects, firsthand training needs and desires from the workforce, and SMEs. The data collected and presented in this chapter will be used to develop a training plan/guideline that will assist in the advancement of the workforce gradually in their RH education.

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## V. CONCLUSION AND RECOMMENDED FUTURE RESEARCH

There is a technical readiness gap within RH microelectronics. Many of the current RH SMEs are past retirement age and there is a minimal pipeline of trained and skilled RH engineers to carry on these critical tasks. In addition, there are minimal training programs developed to provide new engineers the required knowledge and skills with regard to radiation hardened microelectronics testing, development, analysis, etc., upon their arrival to the workforce.

The research conducted and data collected from the workforce and current SMEs demonstrated a proposed training approach to effectively develop SMEs in the field of radiation-hardened microelectronics. Per responses from the workforce and SMEs, a pilot training guide was developed. The training guide referenced in section A is a phased approach intended to gradually develop the workforce in the field of RH microelectronics.

Phase I is meant to provide the workforce with basic entry level knowledge on radiation effects. This phase incorporates a combination of academic classes specific to radiation effects offered via the SCALE program, training in vital software (LabVIEW) used in test development, combined with hands on test development efforts focusing on discrete type components.

Phase II introduces the workforce to tools used in radiation effects modeling and simulation, continues their software skills development and test development, introducing them to IC type components.

Phase III goal is to provide workforce training on the effects of nuclear weapons, giving them a more well-rounded understanding of the whole system vs. just the microelectronics specific understanding, while continuing their software and test development skills.

Lastly, a self-paced training section provides them with additional classes and literature for their continuous improvement in the field.

**A. RADIATION EFFECTS MICROELECTRONICS PILOT TRAINING GUIDE**

**1. Phase I**

**a. Courses provided via SCALE**

1. Participation in Radiation 101 Series
2. Introduction to radiation effects in electronics
3. Radiation environments
4. Space Radiation Effects and Modern Microelectronics
5. Moore's Law and Radiation Effects
6. Hierarchy of radiation response – atoms to systems
7. Radiation interactions with materials

**2. Phase I Continued**

8. LabVIEW Core 1–2 Training
9. Perform a test development effort (design, execution, analysis, reporting) on a discrete component (assist with understanding of basic testing techniques and disciplines)
10. Attend minimum one radiation conference(s) – HEART, NSREC, MRQW, GOMAC, RHET

**3. Phase II**

1. Introduction to CRÈME and SRIM
2. TCAD and Circuit Simulations
3. Overview of Radiation Effects Simulation Tool Flow
4. Overview of EMP
5. LabVIEW Core 3 and Data Acquisition Training

6. Perform a test development effort (design, execution, analysis, reporting) on IC device

7. Attend minimum one radiation conference(s) – HEART, NSREC, MRQW, GOMAC, RHET

#### **4. Phase III**

1. Nuclear Weapons Effect Training

2. LabVIEW Object-Oriented Design and Programming Training

3. Perform a test development effort (design, execution, analysis, reporting) on memory device

4. Attend minimum one radiation conference(s) – HEART, NSREC, MRQW, GOMAC, RHET

#### **5. Self-Paced Training**

1. Introduction to Semiconductor (Free classes available online)

2. Literature Review – conference short courses, radiation effects literature

3. Review of Military Standards and Requirements Documentation

4. Radiation Effects and Analysis – Free online training at <https://radhome.gsfc.nasa.gov/top.htm>

### **B. RECOMMENDATION FOR FUTURE RESEARCH**

#### **1. Testing Execution Observation**

The initial research method was to include an ethnographic method. This method was to include observation of SMEs, journeymen, and entry level radiation test engineers performing test execution at various radiation facilities within the field of radiation effects. This observation was intended to provide additional information and verification as to whether or not the test engineer is adequately trained to perform testing and analysis in order to provide the customer with a quality product. However, due to insufficient time this method was not employed during this research. Thus, as RH training is continuously

developed and improved it would be beneficial to perform this research method and incorporate the results to enhance the training program.

## **2. Government Entity Partnerships**

Additional government agencies, DOD partners, and academia partners with equities in radiation hardened microelectronics can improve their workforce in this area by employing radiation hardened curricula, programs, and trainings. Potentially sending the workforce to the trainings, establishing potential rotational assignments at other government and private radiation facilities can also provide the workforce alternative frames of reference in radiation-hardened test development, environments, etc. Applying these partnerships could be vital to the training and knowledge enhancement for the current and future RH workforce.

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