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Title: Soft Robotics in Radiation Environments: A Prospective Study of an Emerging Automated Technology for Existing Nuclear Applications

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Camille Palmer

Traditional robots have a long history in nuclear-related work because their integration decreases risk to humans in dangerous environments. Soft robotics is one promising new branch of traditional robotics with proposed applications in industry, medicine, and society. Collaborators from the Robotics mLab at Oregon State University (OSU) are currently working on a proof of concept soft robotic manipulator built from 3-D printed silicone elastomer. It is therefore an opportune time to analyze the potential of this new soft robot and similar models to contribute to nuclear environments. This prospective analysis identifies the components of the soft robotic system and representative radiation environments for robotic tasks, then measures the functional capability of these components in the environments. Samples of polydimethysiloxane (PDMS) were exposed to gamma irradiation then studied for changes to mechanical properties, including elongation, tensile strength, and compression. Results from these tests showed less than a 25% gamma-induced change in all but the highest exposure environment. In addition, a 7-hour exposure of PDMS to the mixed radiation flux surrounding OSU's TRIGA research reactor (OSTR) resulted in activation of some unexpected impurities,

including members of the lanthanide series. Liquid metal sensors being considered for use in soft robotics were also tested by measuring resistance during gamma exposure at 0.1 Gy/hr; no changes were noticeable. Electronic components including drive mechanisms, cameras, and signal communications were assessed using past literature. A comprehensive assessment of these individual results concludes that soft robotics have functional potential in radiation environments and therefore warrant further study and engineering.

Soft Robotics in Radiation Environments: A Prospective Study of an Emerging Automated Technology for Existing Nuclear Applications

by

Tyler Oshiro

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Chapter 1: Background

The nuclear field presents a unique set of challenges that require both practical and innovative solutions. More importantly, given the nature of radioactive materials, these challenges have existed for years and will continue to persist in the future. While some solutions have been applied and others are being developed, emerging technologies present new approaches to established challenges. Given the long history of robots in the nuclear industry, soft robotics, an emerging technology in automation, is evaluated for its potential utility in the nuclear field. The following background provides an introduction to the field of soft robotics and through comparison to traditional robots, provides an impetus for pursuing this technology in nuclear settings.

1.1 Definitions

Due to the high diversity of automated systems prevalent in the modern era, basic concepts of robotic systems are defined here as they are used in the following discussion. A generic robot system is provided in figure 1.1, as taken from Harry Poole's *Fundamentals of Robotics Engineering* [2]. Parts 1-5 encompass the "manipulator," the functional component of a robotic system that performs the task. Typically, this is some rendition of motion-capable arm (1) attached to an end effector (2) able to complete a simple task. Not pictured is the transmission system (4) which links the manipulator to the control system (7). The actuator (3) drives the motion of the arm and effector; they are "motors or other mechanisms that convert supplied power into mechanical motion" [2]. It is electric here, but as the introduction to soft robots will

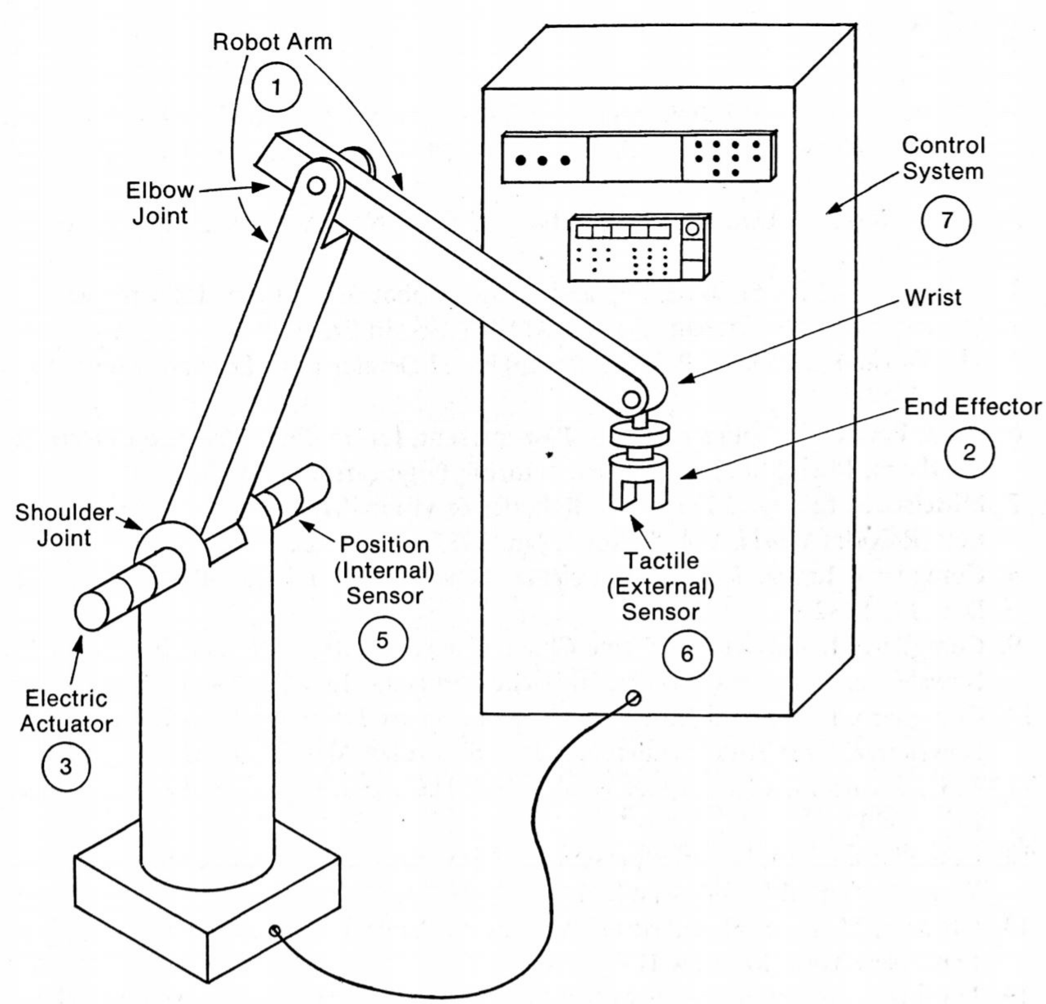


Fig. 1.1. Example of a typical robotic system with arm-based manipulator (from Poole, 1989).

show, can be pneumatic or hydraulic as well. These definitions for robot parts are those used in the following discussion.

Robotic systems are difficult to define, and each country does so differently. The basic American definition provided by the Robotics Industry Association (RIA) requires robots to have an arm that completes a task. In Japan, the Japanese Industrial Robot Association (JIRA) provides additional distinctions by dividing industrial robots into six categories, ranging from a class 1 "manual manipulator," which is a fully operator-controlled robot to a class 6 fully "intelligent robot" with independent sensing, response, and function capability [2]. Currently, the field of soft robotics is still in early development and is therefore confined to class 1. In this sense, it is more appropriate to consider them teleoperated systems. However, since “soft robots” is the term typically used in practice and literature, that is how they will be referenced in this thesis. Other robots in the nuclear industry fulfill a class 2 or 3 definition; they are either single-purpose devices that cannot or must be modified to perform additional tasks or they are reprogrammable, multi-purpose robots with some degree of independent, artificial intelligence [3]. These class distinctions are used in the comparison of robotic systems that follows.

1.2 Use and Performance of Traditional Robots in Radiation Environments

Generally, robots are employed in the “3-D fields:” dirty, dangerous, or daunting [4]. Automating these three types of tasks allows for lower production costs, increased efficiency, and safer working conditions. In the nuclear field specifically, dirty work involves possible radioactive contamination, dangerous work involves tasks in proximity to radioactive material, and daunting tasks are large in scale, whether a highly repetitive task or a logistically difficult task. While work in the nuclear field can cover all these definitions, it is the ability to reduce or eliminate radiation exposure to humans, that makes robots a particularly valuable addition to the field [3].

The Nuclear Regulatory Commission (NRC), which sets the occupational limits for radiation workers in the nuclear industry, limits workers to a stochastic, total body effective dose of 5 rem and a nonstochastic, committed dose equivalent dose of 50 rem annually [5]. Thus, tasks performed by workers in a radiation environment are limited by dose restrictions on those workers. The replacement of workers with automation for tasks that involve radiation exposure can therefore increase productivity in the nuclear industry. Additionally, the NRC has formulated a dollar per person-rem conversion factor to aid in regulations pertinent to radiation exposure. This cost-benefit analysis provides a guide for the amount of effort that should be expended to reduce dose, and can be applied to "safety and generic" issues [6]. While this number should not be used to place a monetary worth on a life or exposure, it can be useful in estimating the contribution that automation would make to the field by reducing radiation exposure. Although the official value is $2000 per person-rem, as calculated in 1995, a revision to that document suggests the value is more accurately within the range of $3000-7500 per person-rem with a practical average of $5100. Regulatory guidance advises use of the $5100 per person-rem, but this value has not been officially updated. Thus, for purposes of estimation, the implementation of a robotic system that replaces a human worker for a task can be valued at about $5100 for each rem that the robot's implementation prevents from being absorbed by human workers. A rem cannot be applied to a non-human object like a robot, but for photons, which is a major component of radiation in nuclear environments, the conversion is 1:1 and therefore each rad tolerated by the robot would save an estimated $5100 if the robot completely replaces a worker.

In addition to replacing workers for certain tasks, robots are valuable because they can perform complementary tasks that humans cannot. Thus, in addition to the cost-savings from the replacement of workers by robots for certain tasks, robots can further increase capability and efficiency of nuclear processes. In 1990, a report on Public Service Electric and Gas Company (PSE&G) noted the success of that company's investments in robots for its three nuclear power plants. These robots included a MiniRover submarine, a spent fuel pool cleaner, and Surbot-T, an all-terrain surveillance bot. According to PSE&G, each $1 spent on robotics returns $2, due to the increased efficiency provided by automation [7]. It is possible that due to the improvements in robotics technologies in the years since that the multiplicity of return has increased even further.

As shown, robots have much to contribute to the nuclear industry, and due to its nature as an industry, cost-benefits are easier to estimate. However, robots are also applicable in additional environments that involve radiation for similar reasons, namely their ability to protect personnel from dangerous radiation exposure and ability to perform otherwise impossible tasks. Thus, robots have a long and closely-linked history in the nuclear field. This history spans three major categories:

1. **disaster recovery** at accident sites like Three Mile Island (TMI-2), Chernobyl, and Fukushima
2. **environmental management** sites like Savannah River, GA and Hanford, WA
3. **nuclear industry** work at electricity generating plants

Following a nuclear accident, much is left unknown about the state of the damaged reactor building and equipment. Robots are useful in this instance to survey and begin the **disaster recovery** process because they can withstand the unknown radiation environments in these sites. After the incident at Three Mile Island in 1979, multiple robots with unique designs facilitated the recovery process. These included surveillance and inspection work performed by SISI (Surveillance and In-Service Inspection), Rover-1, and Louie. Other devices like Rover-2 and Workhorse employed additional functionalities like boring and lifting for decontamination and recovery work [8]. Soon after the nuclear power accident in Fukushima, Japan, the existing Quince robot was modified to perform inspection and sampling tasks in two of the affected units [9]. This robot successfully completed several objectives before becoming irretrievably lost in unit 2 [10]. Recently, equipment specifically designed to operate within Fukushima, including Toshiba's Scorpion and Sunfish models, have been introduced to perform additional surveillance with mixed success [11].

In **environmental management** sites like Savannah River, GA and Hanford, WA, a history of nuclear weapons production has left widespread radioactive contamination in those facilities. Therefore, the work performed in these sites presents a high risk of exposure to humans. As discussed above, robots can both replace humans and fulfill additional needs. Robots at Savannah River meet both of these potentials. The "Shielded Cells Waste Handling Robot" and the "Shielded Cells Sample Handling Robot" replaced humans in glovebox work. The former has prevented approximately 35 rem of exposure to workers where the latter is a multi-tool handler that supplants the need for personnel to contact of vials containing radioactive samples. Both robots strongly resemble industrial robots, and fit the definition of a "single-purpose robot" used for repetitive movements (Class 2 and 3). The "Box Removal Mobile Teleoperator" and the "Lead Counterweight Removal Mobile Teleoperator" allow for additional tasks to be completed by providing a function human workers were unable to accomplish. The former allowed for the removal of a contaminated junction box in a difficult to access position and reduced exposure to personnel by 7 rem. The latter operated in a 5 rem/hr area and allowed for the removal of lead from spent deionizer vessels, an operation otherwise impossible due to the high levels of radiation [12]. This pair of robots more closely resembles the surveillance teleoperators (Class 1) used in Fukushima and TMI-2, as discussed above.

Finally, as discussed above, robots in the **nuclear industry** demonstrate additional applications, both in the two major categories of inspections and decommissioning as well as in construction, maintenance, and waste disposal. For tests and inspections, robots like Pegasys by Westinghouse and SAFIRE (Snake-Arm Feeder Inspection Robotic Equipment) by OC Robotics routinely inspect pipes and structures in nuclear plants. Newer models can also perform repair functions like plugging and part manipulation. Two versions of snake-arm robots by OC Robotics were used to perform repairs in an inaccessible location: an inspecting arm boasted 23 degrees of freedom to provide visuals for a manipulating arm with 8 degrees of freedom [13]. This twisting and bending "snake-arm" is a rigid robot that functions similarly to the soft robotic manipulator under development by OSU that is the focus of this paper. For site decommissioning, both custom and general purpose devices are in use. An example of the former was employed at UK's Windscale advanced gas-cooled reactor where it replaced workers in a 1 Sv/hr environment. Conversely, Brokk AB products are teleoperated and multifunctional, including effectors for crushing, cutting, and grabbing [13]. These robots typify the general arm-based manipulators defined at the start of this chapter and demonstrate the usefulness of such manipulators in the nuclear field. Examples from the minor categories include generating radiation maps of an area and cataloguing drums of low-level nuclear waste [14]. Altogether, robots used in the nuclear industry are highly specific, but also highly useful. An adaptable, multipurpose, teleoperated soft manipulator like the one proposed by OSU robotics, then, would likely be welcomed to address a wide range of applications.

1.3 Shortcomings of Traditional Robots

Despite their widespread use, traditional robots are vulnerable in certain ways, both to high radiation or other difficulties. As an example, examining the shortcomings of the modified Quince robot used in Fukushima provides a reasonable scope of traditional robot limitations in unknown radiation environments. In its first mission, the Quince robot could not complete a turn at an unexpectedly small landing due to its large size. In its second mission, the robot slipped on stairs due to high moisture in the air and on surfaces. When returning from its second mission, the robot also overheated and was unable to cool down because of the high ambient temperature in the environment. In its third mission, its planned path was again interrupted by an unforeseen obstacle, in this case, a large pile of rubble. In its sixth and final mission, “the [robot’s] communication cable got snagged on the piping on the third floor and jammed in the cable reel” [10]. In addition to these concerns, scientists noted that additional components including dust sampling pumps, thermometer, and water sampling rig requested late in development by TEPCO, the owners of the Fukushima Power Plant complicated robot performance and timelines for delivery. Also, the need to deliver the robot closer to the specific site necessitated personnel carrying the robot through narrow passages, which increased exposure to those workers. Similarly, contamination on the tracks of the robot from earlier missions resulted in a dose to handlers of the robot in later missions [15].

Thus, the major shortcomings of traditional robots in unknown radiation environments can be summarized as:

1. inability to overcome unplanned obstacles, including but not limited to narrow landings and rubble
2. slippage in moist/wet environments
3. overheating in hot environments
4. communication cable vulnerable to tangling
5. difficulty in adding components/capabilities
6. contaminated robot required handling

These shortcomings provide a potential avenue for soft robotic implementation. If soft robots can address these problem areas, they can provide complementary functions to existing processes. The capability of soft robots is discussed in the next section, followed by an examination of their qualities as compared to the shortcomings listed here.

1.4 Soft Robots

It is a logical extension that since traditional robots already have applications in disaster recovery, environmental management, and the nuclear industry, it is sensible to consider the potential applications for a new field of robotics to supplement these existing schemes. Soft robotics is an emerging field within the robotics umbrella with a great deal of promise.

Where the previous examples of traditional, rigid robots are composed of correspondingly rigid materials like metals and plastics, soft robots are composed of soft materials: silicone rubber and polymers. Youngs modulus is one metric that describes the rigidity of a material and can be used to differentiate between the two. Rigid robots are composed of rigid materials like metals and plastics and have moduli in the order of 10^9 to 10^{12} Pascals. Conversely, soft robots are composed of soft materials that mimic biological tissue and therefore have moduli in the order of 10^4 to 10^9, several orders of magnitude less than the rigid materials [16]. The degree of "softness" of a robot can vary from mostly rigid bodies with a soft end effector or tail, to mostly soft robots with some sort of support fibers or mesh, to robots composed entirely of soft materials [17]. The robots under development by OSU Robotics are fully soft, with no mechanical reinforcement in the soft robot manipulator. Since these and most other designs require an operator manually directing the movements of the manipulator, all soft robots are more accurately classed as a teleoperated system rather than an independently functioning robot, as discussed earlier. However, the colloquialism "soft robots" will be continue to be used to refer to these teleoperated systems throughout this paper.

Current soft robotic successes are typically designed based on biological models. Different classes of soft robots derive animal inspiration from groups like worms and caterpillars for movement and octopi for gripping and handling [17]. One company, Soft Robotics, designs pick and place soft robot effectors inspired by octopi and starfish that can handle delicate objects [18]. The small, four-fingered grippers were demonstrated on marshmallows and uncooked eggs and are currently used in the food shipping industry on difficult-to-handle items like pizza dough [19]. Another newsworthy soft robot recently made headlines for its ability to mimic a swimming fish. MIT's SoFi is equipped with a soft robotic tail that allows it to swim alongside other reef fish in its underwater explorations. It was successfully tested in Fiji March of 2018, with more improvements and tests scheduled [20].

This soft robotic technology is currently under development, and holds promise for several key reasons. Being composed of soft materials confers the following advantages to soft robotic systems [16]:

1. **potential for infinite degrees of freedom**
2. **intrinsic safety**
3. **high compliance**
4. **potential for underwater applications**
5. **adaptive and responsive to environment**
6. **relatively cheap and disposable**
7. ***separable manipulator from central processor**

One, soft robots have the potential to access **infinite degrees of freedom** due to their lack of confinement to defined planes of movement. As an example, this allows the tip of a soft robot arm to occupy every part of a theoretical, three-dimensional while the arm of the robot can be positioned in an infinite number of shapes and configurations [21]. Two, soft robots are deemed **"intrinsically" safer** than their rigid counterparts because the soft materials that comprise them absorb the energy of an impact or collision, thereby drastically reducing potential damage and injury to a human working with or alongside the robot [16]. This quality makes soft robots appealing in applications with close proximity to humans. By contrast, rigid robots used in manufacturing typically need to be spatially separated from humans to avoid potential injury. Three, due to the small volume and compressible nature of the soft material, soft robots generate little resistance against obstacles. They can therefore fit into smaller spaces and navigate around and through obstacles that traditional, rigid robots cannot. This "**compliance** allows the robot to adapt its shape and function to objects of unknown or uncertain geometry...soft robots can execute pick and place operations without precise positioning or accurate geometric models of the object to be grasped" [16]. Four, hydraulic systems and waterproof material make soft robots well-suited for **underwater applications**. In fact, one approach to compensate for the soft robot's weak load capacity is by operating underwater to allow buoyancy to compensate for gravity. Fifth, soft robots are more **adaptive and responsive** to their environment and to novel tasks, given their ability to move in unique and creative ways. Whereas a rigid robot is confined to a set number of tasks and abilities, a well built soft robot with infinite degrees of freedom is limited only by the materials its made of. Sixth, soft robots are typically made of elastomers which are **relatively cheaper** than the rigid metals and plastics that compose rigid robots. This gives soft robots a cost advantage in relation to maintenance and replacement. One laboratory approximates the material cost of the silicone polymer at 3 cents per gram [22]. While this does not include the more expensive costs of processors, sensors, and production equipment, it highlights the ease of replacement for the silicone end effectors. Last, in a system used by OSU Robotics and certain other groups, the manipulator of the soft robot is **separable** from its central processor. This allows the sensitive component of the robot to be kept a further, protected distance from the functioning component, the manipulator. This is particularly useful in a radiation environment because the distance can decrease the dose delivered to the most sensitive part of the robot.

Despite its advantages, because the field of soft robotics is still emerging, it is limited by significant technological challenges that may or may not be resolved in the near future. The following (1.2) is a list of robotic subsystems that includes their functions, limitations of the current mechanism, and potential solutions, compiled from multiple soft robotic references [16] [17] [21].

Subsystem	**Function**	**Current Mechanism**	**Limitations**	**Solutions**
Actuation	Robot movement, gripping, grasping.	1. Pneumatic actuation 2. Electroactive polymers	1. Slow actuation, rupture failures 2. Still under development	1. Reinforcement with stiffer layers, embedded flexible fibers 2. Active research
Perception	Sensing the environment, sensing robot strain	Liquid metal sensors	Fabrication is difficult	3D printing of sensors directly into the polymeric material
Driving electronics	Store control algorithms, connect actuators, sensors, and power sources	Same as rigid counterparts	Will not allow for a fully soft robot	Need for "stretchable" electronics
Power source	Provide force to the actuators of the robot	Compressors, pumps, and compressed air cylinder	Not soft. Big and bulky.	Pneumatic battery or electrically powered actuators
Computation	Predict and program the robot movements	None	Need a continuous model to manage the infinite degrees of freedom	Inverse kinematics algorithm
Control*	Direct actuator movements through variating power supply	Pressure transducers or volume control; open-loop valve sequencing	Dependent on signals from complex computation	Continuously adjustable variable pressurization, electrically independent controls.

Fig. 1.2. Table of Soft Robotic Progress and Limitations.

Due to the recent emergence of soft robotics, many limitations and shortcomings have yet to be addressed through research and development, as shown in 1.2. Accordingly, if the current state of the technology is used to evaluate its application readiness in the nuclear field, it would surely fail. The current state of the technology is simply not ready for immediate use. Thus, when assessing the potential for soft robotics in the nuclear field, it is important to note that such an assessment should be based on the future potential of soft robotics in current and future nuclear applications. Given the lack of policy progress in nuclear waste management and increase in decommissioning, it is unlikely that current issues will be solved in the time it takes soft robotic technology to progress to practical applications and likely that more issues related to decommissioning and waste management will arise in the same time. Matching the projected potential of soft robotics with current and future radiation environments, then, is a logical approach to assessing the usefulness of soft robotics in the nuclear field. This also allows the development of the technology and its assessment for applications to proceed simultaneously. That is the approach utilized by the research in this thesis.

1.5 The Potential of Soft Robotic Applications

While it is tempting to approach the central question as a direct comparison of rigid, traditional robots against their counterparts in soft robotics, the either/or paradigm does not appropriately address the potential for soft robotics to contribute to the nuclear field. While some soft robot functions and tasks have a counterpart in the rigid robot arena, they are also capable of additional task work. Rather than framing soft robots as replacements for currently used rigid robots, it is more appropriate to consider them as a complementary technology to be used in tandem with human personnel and existing automation. Thus, to prove that soft robotics can be of use in the nuclear field, they do not have to out-compete existing automation but instead, much like the rigid robot applications discusses above, simply show that they have the potential to successfully complete a function in a radiation environment that is otherwise not possible, whether due to risk of exposure to humans or a lack of available technology.

The motivation behind pursuing soft robotics, then, lies heavily in their potential ability to address the shortcomings of rigid robots. To demonstration their potential, recall the shortcomings of rigid robots in an unknown radiation environment as an example of one of the most challenging applications for automated systems. Added below is a proposed mechanism by which future soft robots could address those shortcomings by applying the advantages of soft robotics listed above.

1. inability to overcome unplanned obstacles, including but not limited to narrow landings and rubble
    (a) The high compliance offered by soft robots could allow them to navigate through unexpected and difficult terrain, including through narrow passages and over piles of rubble. Additionally, the ability of soft robots to adapt to the environment through a higher level of inherent movement freedom can allow for creative methods for overcoming unforeseen obstacles.
2. slippage in moist/wet environments
    (a) Although more useful in underwater environments, nothing currently indicates that soft robots are inherently better at preventing slippage.
3. overheating in hot environments
    (a) Overheating affects the processing centers of automated systems, and was complicated in the instance of the Quince robot by its inability to cool those components in an environment with a high ambient temperature. However, in soft robots, drives are not located in the functioning section of the robot. Both drives and processors can be separated from the manipulator arm,

allowing for some distance between the harmful environment and the more sensitive components.

4. communication cable vulnerable to tangling

   (a) The tethered communication system was used at Fukushima because the thick concrete walls and other interfering debris prevented reliable wireless communication. Since soft robotic technology does not introduce new means of communication, this would still be an issue. Additionally, if the manipulator is separated from the processor, they would need to be connected by some sort of cable or tube that could transmit the hydraulic or pneumatic matter to the manipulator. This would potentially add additional vulnerable cables.

5. difficulty in adding components/capabilities

   (a) While additional sensing capabilities would need to be added to a soft robot in the same way that they would need to be added to a rigid robot, additional functions would not necessarily need to be added to the soft robot. The increased adaptability due to the high degrees of freedom allows soft robots to perform movements or functions that may not have initially been planned for them, including but not limited to sample collection, area exploration, and other tasks like closing a valve or retrieving an object. The idea has even been proposed to use the manipulator arm itself as a surface to collect an environmental ”swipe” which can then be detached for processing and analysis. Due to the cheap, disposable nature of the soft robotic manipulators, this concept makes financial and practical sense.

6. contaminated robot required handling

(a) As addressed in the context above, the low cost of soft robotic material means manipulators are easily replaced. Thus, contaminated sections can be detached/removed easily and discarded without serious financial consideration. By disposing of contaminated sections, soft robots can be more safely handled by personnel who interact with the robot as necessary.

In addition to filling gaps in problem areas, soft robots are also able to accomplish additional tasks that rigid robots are either inadequate for or not fully capable of completing. For example, while rigid robots can be designed to be waterproof, the soft robotic manipulators, made out of a silicone polymer, are inherently waterproof. Also, since water is heavily utilized in the nuclear industry as both a moderator and a coolant for reactors as well as in storage of spent fuel, the underwater applications are particularly appealing. Additionally, entry to environmental management and accident sites is sometimes limited either because the site was not designed for remote access or circumstances have blocked traditional entryways. In Fukushima, Toshiba developed both a small submersible robot to investigate small, underwater areas and a shape changing robot that was able to pass through a diameter of 10cm before modifying the position of its crawlers to better navigate open spaces [23]. This is perhaps the most encouraging aspect of soft robots. They essentially operate by changing shape: their high compliance allows for navigation through small spaces yet their high degrees of freedom allow for expansion of compartments for diverse functionality from a single manipulator. In a likely scenario, a well-designed soft robot could both navigate through a pipe to reach an area, then inspect that area, and with a basically unprecedented ability, also perform tasks like valve closing and take samples as issues arise. It is the promising potential of this single, cheap robot for multiple applications that makes soft robots particularly appealing, not as replacements for rigid robots, but as a complementary technology that allows for additional functionality.

Overall, soft robotics is an emerging technological branch with a great potential for contributing to the nuclear field, where innovation is welcome, and where robots have traditionally contributed to that innovation. Though it is still in its infancy, it is an appropriate time to assess whether or not the match is viable and worth pursuing. Assessing so early on in the development of a technology allows for contribution and direction of efforts toward shared goals, and may negate problems that would otherwise be magnified further down the path of development. Perhaps most importantly, if the nuclear field were to become an early adopter of the technology, it would encourage faster and more tailored development for pertinent applications. As shown above, despite the many challenges that have yet to be addressed in soft robotics, it has promising applications in both in industry and environmental management, and especially in accident remediation.

For these reasons, the overall objective of this research is to assess the material components of soft robotic systems against potential radiation environments to determine whether or not the avenue is one that deserves further inquiry. To achieve this goal, the primary focus of this assessment is an evaluation of silicone elastomers in high gamma radiation environments to observe resulting mechanical changes that can be used to predict functional capability for a given task. Additionally, preliminary studies on neutron effects on silicone elastomers and both gamma and neutron effects on liquid metal sensors were considered.

Chapter 2: Approach

Due to the infancy of soft robotics, this is the first consideration of such technology in the nuclear field. Thus, a new framework was needed to comprehensively analyze the potential of soft robotics in radiation environments. As soft robotics is a branch of traditional robotics, an existing logic for rigid robotics was adapted for this purpose. The evaluation in this paper is based on Vandergriff's "system design process to minimize radiation effects" [24]. A technical manual from Oak Ridge National Laboratory, it provides a basic overview of considerations for designing automated systems for nuclear applications, with a focus on fuel reprocessing. The generalized approach presented primarily concerns the interaction between the components of a system and the environment of its application, as seen in Fig. 2.1. Traditionally, a specific environment would be evaluated for a given robotic system. By contrast, in order to assess the overall usefulness of soft robotics in radiation environments, a range of representative environments was selected to provide an wide scope of operating potential. This method of assessment provides a model to predict functionality in a given environment. In these model environments, the components currently under experimentation by the OSU Robotics team were examined for functional capability. In this examination, each component is assessed for its unique functional needs. Then, the changes to this independent functionality are evaluated for the effects of that contribution to the functionality of the entire system. By determining which contribution is limiting, this work seeks to direct further research into uncertain or problematic areas while assuring capability in others.

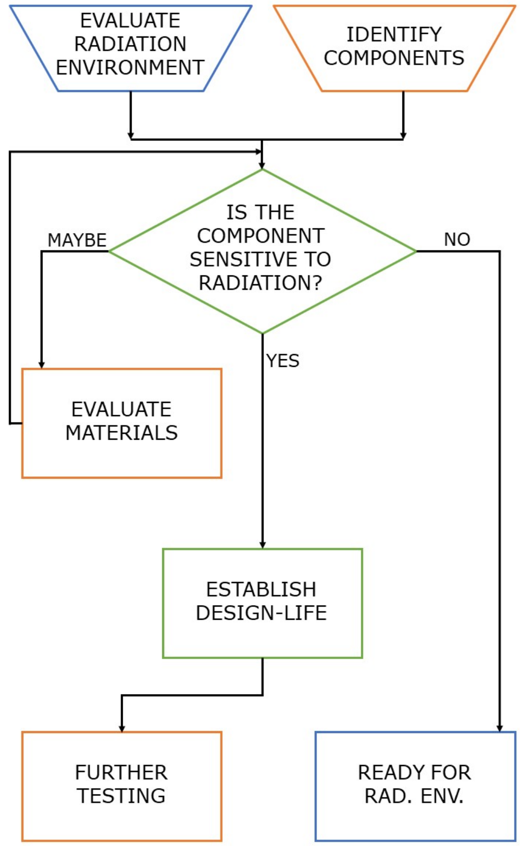


Fig. 2.1. First part of the system design process for robotics engineers to minimize radiation effects on electronic automation by Vandergriff (1990).

2.1 Identifying Components

The first step in the assessment involves identifying the components of the system in question. This directs the experiments to the appropriate materials for independent tests to contribute to the overall evaluation. The typical components for evaluation in robotic systems include drives, sensors, and cables/communication [25]. In rigid robots, component functionalities and hardening techniques in radiation environments are well-researched. However, soft robotic-specific drives and sensors introduce new materials and therefore require novel assessment. The two primary materials unique to soft robotic systems pursued by OSU robotics are polydimethylsiloxane (PDMS) and liquid metal sensors.

2.1.1 PDMS

While traditional robot drives are composed of electrical actuators (as shown in Fig. 1.1), the "drive" of the soft robotic system is typically comprised of a soft manipulator driven by a pneumatic or hydraulic system. The major component of a soft robot in terms of volume and mass is therefore the body of the robot manipulator, which is made up of a cured silicone rubber, mostly the compound polydimethylsiloxane (PDMS). The monomer structure of PDMS can be found in 2.2. By repeating the subunit, a polymer is formed, with higher subunit chains constituting a more rigid structure. The polymer is typically cured by an organometallic crosslinking reaction using heat or ionizing radiation, usually in the presence of a catalyst. By controlling the degree of this crosslinking, it is possible to customize properties such as the elasticity and tensile strength for soft actuation.

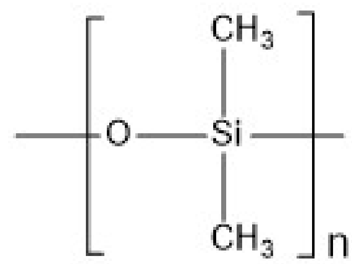


Fig. 2.2. Monomer of polydimethylsiloxane. Cured polymer consists of repeating chains of the pictured monomer where n=200-1500 for room-temperature vulcanizing products, including those used by OSU robotics [1]

These manipulators can be fabricated by use of a mold or through the use of 3D printing. OSU Robotics is implementing a new process that creates 3D-printed manipulators using the commercially available Dragon Skin Fast 10™, by Smooth-On [26] [27]. The material is mostly composed of the silicone elastomer polydimethylsiloxane (PDMS). PDMS is the principle component of the random copolymers found in silicone rubbers and is the most widely available silicone polymer on the market [1].

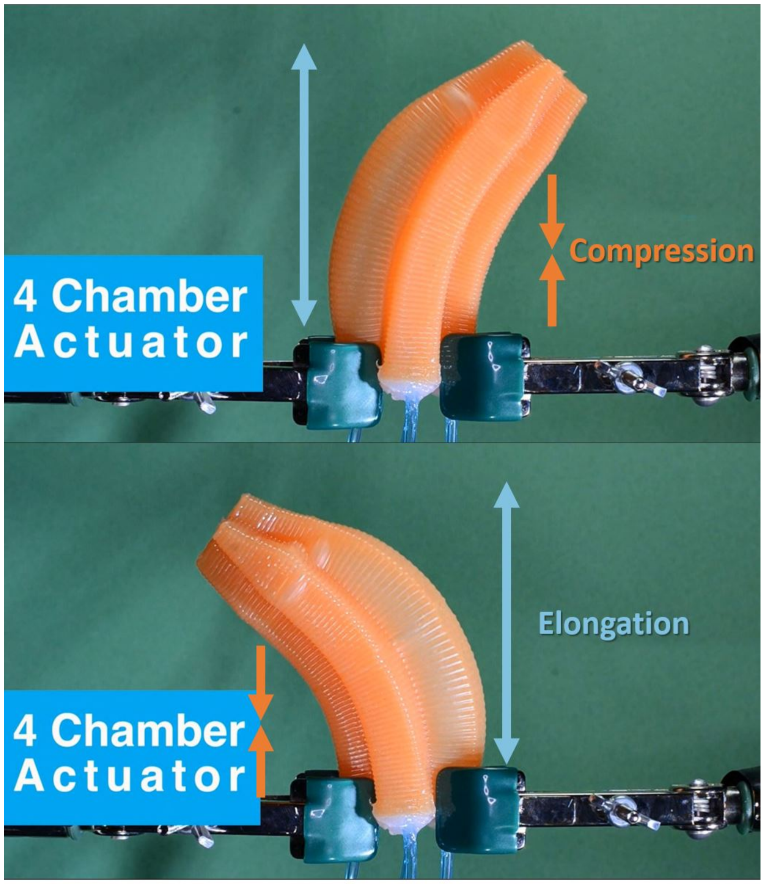


Fig. 2.3. Mechanical characteristics of concern following exposure to radiation.

Because PDMS forms the moving body of the manipulator, functionality concerns for this component include the effects of radiation on elongation, compression, and material strength. Fig. 2.3 displays two frames from a video of an OSU produced manipulator. As shown, the filling of one chamber with pneumatic or hydraulic pressure results in the expansion of that chamber. The opposing chamber(s), with lower pressure, contracts. This contrast of pressures allows the manipulator to bend in the specified direction.

If the properties of elongation are affected, the pressure needed to expand each chamber will change accordingly. With increased stiffness in the material, more pressure will be needed to elongate the material to the same degree. With increased flexibility in the material, less pressure will be needed to elongate the material. If the pressure is not changed accordingly and in response to the changes in stiffness, the manipulator will not move accurately. Likewise, changes to compression will increase resistance to the bending of the manipulator in any direction, again requiring more or less pressure if the material becomes more or less stiff, accordingly. In addition to these concerns, the overall material strength must be considered. In order to properly function, the chambers must be able to fill with increased pressure without bursting. Tensile strength is a measure of this property. This property must be maintained to a certain degree in order to allow for appropriate pressure to be applied to the chamber without losing integrity. Thus, these three functions must be tested to determine functionality and limitations of the PDMS component and its contribution to the soft robotic system in radiation environments.

2.1.2 Liquid Metals

The second unique component of the soft robotic system is a gallium-based liquid metal [28], which is proposed for use as a force sensor. In a process novel to OSU Robotics, liquid metal microchannels linked to force sensors are incorporated into the soft robotic manipulator during the 3D printing process [29]. These liquid metal microchannels are composed of gallium, indium, and tin; OSU Robotics is investigating the proper blend of metals to coincide with the needs of the 3D printing process.

Coupling these liquid metals with the manipulator allows for force sensing in the soft robotic system, which provides important feedback to the control system. As the manipulator bends, some of the channels will contract and some will expand. This contraction and expansions results in thickening or thinning, respectively, of the liquid metal channels. This results in changes to the cross-sectional area of the liquid metal. As the cross-sectional increases or decreases, resistance decreases or increases respectively, as shown in Eq. 2.1.

$$R = \frac{\rho L}{A} \tag{2.1}$$

Eq. 2.1 demonstrates that resistance is directly related to length and inversely related to cross-sectional area [30]. Changes to resistance, R, are due to changes to length, L and cross-sectional area, A to resistivity, ρ. Thus, by measuring changes in resistance of a low current through the liquid metal channel, information regarding the shape of and pressure on the soft robot manipulator can be collected [31]. Because this sensor is dependent on measured changes to resistance assumed to be attributed to physical deformation of the liquid metal, changes to resistance due to any other factor may interfere with accurate sensor functionality. Thus, the influence of radiation on the resistance or liquidity of the metal must be examined to determine potential effects on the functionality of the force sensing mechanism.

2.1.3 Camera and Electronic Components

While not unique to soft robotics, cameras and other electronic components like processors are still crucial to their functioning. Unlike PDMS and liquid metals, which have not previously been studied for functionality in radiation environments, cameras and electronics for traditional robots are well-documented in literature. This work will therefore not investigate their functionality, but provide reference for the components for comparison against the soft robotic-specific components to provide a complete assessment of the soft robotic system. In doing so, we can determine whether electronics are still the most vulnerable components; if they are, then soft robots are on par with their traditional counterparts. If one of the unique components is more vulnerable, it may indicate that soft robots are more sensitive to radiation than rigid robots.

2.2 Selecting Representative Environments

The second step in the evaluation involves selection of the environments in which the soft robotic systems could potentially operate. As this prospective technology should be kept open to many potential applications, this category is kept open as well. To provide context for this assessment, three environments are considered from existing literature to represent the general diversity of potential applications. While the three major categories of disaster recovery, environmental management, and the nuclear industry are appropriate, these are not the categories used for this research. It is difficult to standardize fields as diverse as disaster recovery and environmental management, therefore they are not useful as representative environments. On the other hand, environments in the nuclear industry are well-documented and better characterized. Additionally, the radioactive concerns in disaster recovery are primarily fission products and nuclear waste. In this aspect, an environment that represents nuclear waste processing and disposal may also be valid in other areas. To select the three environments, then, estimates of dose rates in different stages in nuclear power production were compiled from a guide by R. Sharp to create Fig. 2.4 [32]. The criteria for selection was a wide range of dose rates that encompassed as much of the major processes related to nuclear power as possible. In this way, a given application presented by a potential user can be compared to the environment that most closely resembles it. To support this prospective study, the environments are "representative" in the sense that they are meant to encompass the actual, considerable variety of potential applications.

For these reasons, the three representative environments: used fuel storage pools, vitrified waste and waste processing, and deactivation of a generic Pressurized Water

Reactor (PWR) are selected because they represent a wide range of environments with similarities to applications outside the nuclear industry. The three selected environments are highlighted in blue in Fig. 2.4. To determine cumulative doses from the dose rates given, dose rate maximums or averages for these areas were extrapolated to a cumulative dose after 12 hours as a general estimate of robot task time. The higher ends of the ranges were used, if available, to allow for conservative estimates of reliability by estimating higher doses in environments. This resulted in: 120 kGy for spent fuel storage pools, 21.6 kGy for vitrified waste and the vitrification process, and 12 kGy for deactivation of a generic PWR.

The cumulative dose, rather than the dose rate, is applicable here because unlike biological systems in which dose rate is a major factor in the overall damage and recovery of an affected region, past research suggests that the effects of radiation are a function of cumulative dose and is not heavily dependent on dose rate. O'Donnell supposes that the only way dose rate may affect polymers is by the additional damage caused by heating of the material at higher dose rates [33]. This assumption also agrees with past experiments performed on PDMS with ionizing radiation. While actual task times can vary greatly, the range of cumulative doses captures the higher estimates of likely exposure, thus providing a comparison that includes, for example, a longer task period at a lower dose rate.

Environment	Specifics	Dose Range (Gy/hr)	Dose Avg. (Gy/hr)
Fuel Fabrication	highest in powder form	1E-4 to 1E-1	1.0E-03
Reactor System Operation (PWR)	Pressure vessel annulus (on load)		1.0E+02
	Pressure vessel annulus (during refueling)	7E-2 to 2E-1	
	Steam generators (during refueling)		1.5E-01
Spent Fuel Handling and Storage in the Power Plant	Within the fueling machine		1.0E+05
	Storage Pond	1E3 to 1E4	
Spent Fuel Disassembly and Waste Processing	Mechanical stripping and cutting		1.0E+03
	Chemical processing		1.0E+02
	Vitrification		1.0E+04
Waste Handling and Storage	high level waste: 1 m from unshielded vitrified element		2.0E+02
	medium level sludge (@ surface)		6.0E+00
	medium level sludge (@ 1m distance in air)		4.5E-01
	cemented waste		2.0E-03
	high level virtified (@surface)		1.8E+03
	high level vitrified (1m distance in air)		2.0E+02
Decontamination and Decommissioning	2 g spent fuel (@ 1 cm *in air?*)		1.0E+01
	CAGR decommissioning	1E-4 to 50	
	CAGR debris vault		5.0E+01
	PWR decommissioning	1E-5 to 1E3	
	PWR de-activation pool near fuel	1E1 to 1E3	
	PWR vessel mid plane	1E2 to 1E3	

Fig. 2.4. Collected dose rate ranges and/or averages for various environments in the nuclear power industry.

Chapter 3: Literature Review

Given that this is the first prospective study on soft robotic systems in radiation environments, comprehensive assessments do not exist for full comparison. Rather, an assortment of past research on each of the specific components is compared in parts at the experimental and methodological level. The preceding chapter reviewed past approaches to assessing robotic technology which provided the basis for the methodology of this study. This chapter reviews literature on the influence of radiation on the components proposed for use in soft robotic systems: polydimethylsiloxane (PDMS), liquid metal sensors, and electronic components including drive mechanisms, cameras, and signal communications. As noted earlier, this paper seeks to construct a holistic evaluation of the soft robotic system in radiation environments by evaluating the functional effects at the component level.

3.1 Effects of Radiation on Polydimethylsiloxane (PDMS)

The material commonly used for the bulk of soft robotic bodies, polydimethylsiloxane (PDMS), is a silicone-based polymer. In "Fundamentals of Ion-Irradiated Polymers," D. Fink defines polymers as "macromolecules, built up of a large number of repeating molecular units, which are linked together by covalent bonds" [34]. These chains are attracted to each other by weaker, van der Waals forces that result from interactions between electron clouds. Polymers have 4 distinct levels of organization:

1. Primary structure: the repeating chain of monomers
2. Secondary structure: The spatial arrangement of repetitive units within the chain

3. Tertiary structure: The arrangement of the repetitive chains, usually in zigzag or helical configurations, usually wrapped or folded as thread-like, branched, or cross-linked; can be entangled
4. Quaternary structure: three-dimensional arrangements as crystalline or amorphous structures.

Furthermore, polymers can be classified by their degree of entanglement. The least entangled class is "thermoplasts," which have low hardness and elasticity, but high tensile strength and the most entangled class is the"duroplasts" (alternatively, "thermosets") which have high hardness but low elasticity and tensile strength. Between the two classes, "elastomers" are weakly entangled, which gives them moderate values for the properties: they are highly stretchable, have low hardness, and median tensile strength. PDMS is an elastomer, and therefore its degree of entanglement can affect its properties of elasticity, hardness, and tensile strength [1].

For the class of polysiloxanes, some general characteristics in terms of degradation have been observed. They have good chemical resistance against diluted acids and oils, but are weak against concentrated acids, alkalines, and ketones, and even weaker against organic solvents. They generally retain their hydrophobicity and electrical insulation after exposure to environmental stresses, but lose some of these properties in the aging process [1].

The effects of gamma radiation on general polymers are well-documented. The major mechanism of gamma radiation-induced chemical changes to polymers is through the secondary reactions of free radicals. These reactions can include abstractions, double bond additions, decomposition, chain scission, and crosslinking of molecules [33].

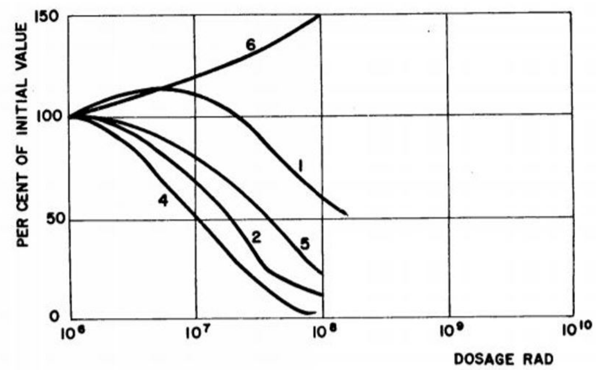
The primary concerns, crosslinking and scission, result in different molecular-level effects that can translate to functional-level changes. Chain crosslinking creates linkages between polymer chains on multiple levels of organization. These linkages can cause stiffening as the polymer chains become increasingly interlocked; embrittlement as this process decreases elasticity and the resulting material cannot compensate for mechanical pressure; and an increase in average molecular weight as individual chains are built upon with additional bonds. Chain scission severs bonds in the polymer chains, from crosslinkages down to the primary level. These smaller, dissociated products result in a decrease in average molecular weight and the loss of longer, interlocked chains leads to degradation of the material, especially though the loss of quaternary crystalline structure. Trapped free radicals can also produce gaseous products which can be measured. Some bonds are particularly sensitive or resistant to these reactions, but none of these bond types are present in PDMS, necessitating measurement to understand the degree of damage caused. These effects can be assessed by measuring the affected properties: changes in molecular weight and production of gaseous products. The impact of these effects on a molecular level can then be assessed at the functional level by measuring mechanical properties such as elongation, tensile strength, and compression [33]. Without knowing the extent of each of the individual molecular effects, it is essential to assess the net mechanical effect of the varying responses on PDMS to determine the reliability of the soft robotic system.

Some of the earliest investigations of the effect of gamma radiation on PDMS specifically were performed by Charlesby [35] and Miller [36]. Their studies determined that the degree of crosslinking induced by radiation is a function of dose and demonstrates a direct-response relationship. Charlesby calculated a 32 eV energy absorption requirement per crosslink and Miller calculated a crosslinking yield of 3.0% for irradiation by electrons. Notably, both studies were performed on a liquid form of PDMS rather than the solid considered in soft robotic applications.

A technical review produced by Oak Ridge National Laboratory (ORNL) determined the functional and physical changes to a material as a result of gamma radiation. This review included the general category of Silicone rubber (specifically, Silastic 7-170), and suggested that observable defects would begin at 10^7 rad for elongation and 10^8 rad for tensile strength. At 10^9 rad, elongation would be affected by 90% of the current value, tensile strength would be reduced by 50% [24].

Another review by Los Alamos National Laboratory (LANL) studied the effects of moderate gamma doses on DC745, which is 62% silicone resin composed of PDMS. This resin uses a peroxide initiator followed by a thermal cure of 170°C. Samples were exposed to cumulative doses of 12.5, 50, and 200 kGy of gamma radiation from a Co-60 source. The effects were then measured using a suite of techniques, including chemical techniques like solvent swelling and solid-state NMR; imaging techniques like scanning electron microscopy (SEM); and mechanical testing including compression tests at various temperatures. Results of the chemical tests showed the production of hydrogen, methane, ethane, carbon dioxide, and carbon monoxide gases following irradiation. Conversely, imaging showed no obvious effects on the surface of the material. Finally, the results of the mechanical tests suggest that stiffness initially decreased at 12.5 and 50 kGy, but eventually increased at 200 kGy. While general trends were apparent, there was no linear fit or predictable response for the stiffness of the PDMS at any given dose. According to the study, "the results of the mechanical testing suggest there are competing mechanisms that are both stiffening and softening the polymer with increased radiation doses," which results in "a complex relationship...which influences the strength of the polymer" [37].

A technical report by the European Organization for Nuclear Research (CERN) performed in 1972 synthesized results from a variety of sources to guide selection of organic materials in nuclear engineering [38]. This report included a review of mechanical effects of radiation on PDMS, as summarized by Fig. 3.1. Notably, three of the effects: tensile strength, elongation, and stiffness (measured in the report by durometer



CURVE Nº	PROPERTY	INITIAL VALUE
1	TENSILE STRENGTH	36 kg/cm^2
2	ELONGATION	95 %
3	SET AT BREAK	—
4	COMPRESSION SET	1.4 %
5	STRAIN AT 28 kg/cm^2	3.4 %
6	DUROMETER HARDNESS	60

Fig. 3.1. Mechanical effects of radiation on silicone elastomer dimethyl siloxane from CERN 1972 report.

hardness), are also considered in the present study. The synthesized results show that following exposure to radiation, tensile strength initially increases to 10^7 rad before decreasing, elongation remains constant to roughly the same dose before decreasing, and stiffness steadily increases. These results appear to agree with the molecular mechanisms posed by the LANL study; although scission and crosslinking both occur, the eventual increase in stiffness coupled with decreased elongation suggest that crosslinking is the dominant effect at higher doses. The overall trend of these results synthesize the results of past research and will therefore provide a useful frame for comparison of the results of this current study.

Another experiment was performed on Sylgard 184, a solid-cure silicone rubber composed mainly of PDMS. Samples composed of different curing ratios were irradiated with Co-60 gamma rays at doses from 100-400 kGy. These irradiated samples were then measured for "Shore A hardness" using a durometer. Over the range of 0-400 kGy, the overall trend was an increase in hardness with increasing dose, but none of the data fit a curve or line. Thus, as in the previous study, the percent or amount of change effected by the cumulative radiation dose cannot be predicted and must be experimentally measured for each formulation [39].

While direct high dose irradiation is known to alter the silicone properties, the extent to which low dose rate, long-term exposure environments may impact the soft robotics is unclear. A more recent review [40] suggests that while crosslinking dominates the observed interactions following irradiation of PDMS, because scission and other bond breakage also occurs, the effects may compensate for each other and result in a negligible net response. Overall, general trends are evident at higher doses: increased stiffness, decreased tensile strength, and decreased elongation. However, the relative change in these properties at the doses under consideration are controlled by the complex interaction between scission and crosslinking. Thus, the experiments herein seek to determine these values for the specific silicone elastomer used by OSU Robotics.

The effect of neutrons on silicone elastomers has been historically less explored. As discussed at length in the following section, there is a potential for neutron-based damage to the polymer matrix which would degrade the material and directly oppose the effects of crosslinking. Additionally, as with any material, there is a potential for activation in a neutron environment. Though the magnitude of these effects is anticipated to be less than that of the liquid metal (by some magnitude, in the case of activation) the effects of neutrons are tentatively explored in this research.

3.2 Effects of Radiation on Galinstan-based Liquid Metal

In solid metals, radiation is known to create point defects. These defects are typically not of concern in the large structures of reactor components, but given the relatively small amounts of metal contained in the soft robotic sensors—typically on the order of milliliters—these defects should be considered. These small defects may result in comparably large effects because liquid metal sensors have functionality dependent on the conductive properties of the metal. There is an additional question, then, of if this functionality will be affected by radiation. This research focuses on the overall effects of radiation on metals to approximate the effects on the functionality of liquid metals.

There are two ways in which energetic particles can affect solid metals: displacement damage production and compositional changes. Displacement damage production occurs when an elastic collision between an energetic particle and an atom results in its displacement from its original position in the regular lattice structure, leaving a vacancy. The displaced atom then becomes an interstitial atom. This pair, the vacancy and interstitial atom, is known as a Frenkel pair. E_d, the threshold displacement energy required to displace an atom is about 25 eV. Because this value is higher than the sum of the formation energies (roughly 5 eV), the formation of this Frenkel pair is irreversible [41].

The interstitial atom, if enough energy is transferred to it by the incident particle, can travel further and lose energy through additional atomic collisions. That atom is referred to as the primary knock-on atom (PKA), which initiates what is referred to as the displacement cascade [42]. From the cascade, clusters of defects form and accumulate. The results of these defects can affect the mechanical, electrical, and other physical properties of materials.

The second way in which energetic particles can affect solid metals is neutron-induced transmutation, which induces compositional change and production of small particles. In the process of transmutation, a neutron is absorbed by a lattice atom. It may then undergo gamma emission, fission, or produce a charged particle like hydrogen or helium. In most cases, this results in a change of the identity of the atom following relaxation by emission. Classic examples include B-10(n,α)Li-7 and Fe-58(n,γ)Fe-59.

The helium atoms resulting from transmutation can cause radiation swelling, an issue in which the swelling of fuel element shells limits the service reserve of fuel assemblies in fast neutron reactors. In this case, helium atoms migrate towards sinks - a dislocation or grain boundary - where it accumulates. This accumulation may lead to the formation of bubbles with the potential to become pores. Expansion of these pores can result in the swelling and potential rupture of the metals in which they form [43].

The relevance of structural damage is uncertain in liquid metals because their liquid properties preclude the contribution of lattice-based crystalline structures to resultant effects. For example, a displaced atom cannot be considered displaced if it has no original lattice position. The liquidity of the metal may allow replacement of such atoms. However, the process of transmutation may be of significance in liquid metals because the changes in element identity and accumulation of helium can result in changes to material property in addition to structural defects. One of those material properties is thermal conductivity, the ability of a metal to dissipate heat. While this property is more concerning in—and therefore mostly studied under the premise of—fusion reactor materials, it is related to electrical resistivity by the Wiedemann-Franz Law [44]. This law is given in Eq. 3.1 where σ is electrical conductivity, K is thermal conductivity, T is temperature, and L is an experimentally determined Lorenz number that is temperature and element dependent. Both energy transport in the form of heat and electrical transport are dependent on free electrons in the metal. When the temperature of this transport is raised, by definition the average particle velocity increases as well. This increase of average particle velocity increases thermal conductivity and decreases electrical conductivity. In the former case, higher particle velocity increases forward transport of energy; in the latter, particle velocity increases collisions which divert electrons from forward transport of charge. Thus, the ratio of the thermal conductivity to the electrical conductivity of a metal is directly proportional to the temperature [45].

$$\sigma = \frac{K}{TL} \tag{3.1}$$

Because sensor functionality is dependent of resistance and liquidity of the liquid metal sensors, transmutation-induced damage to electrical conductivity must be investigated for its potential effects on liquid metal sensor functionality.

3.3 Effects of Radiation on Electronic Components

Work by Sharp and Decreton summarizes the reliability of components used in nuclear robot technology given current technology in 1996 [25]. Fig. 3.2 provides a summary of maximum tolerable doses for different robotic components as estimated by their review. It tends to err on the higher end of estimates, relying on some projections into future technology and assuming components are hardened with the most expensive and protective methods available. However, it still provides a comparison for which specific electronic components are the weakest among the general class. This is useful for the overall analysis of soft robotics because it provides a benchmark for how vulnerable the system can be while still being comparable to traditional robotics. Additionally, though it is likely that the technology has improved since, most advances in this field are achieved by private companies; their results are not published.

Component	**Maximum Estimated Tolerable Dose**
Drive mechanisms	1 MGy
Distance sensors	10-20 MGy
Force sensors	1 MGy
Viewing systems (cameras)	10-100 Gy; 1 MGy for special design
Audio feedback	Very high values
Electrical cables and connectors	1 MGy, 10 MGy
Electronics for signal communication	1 to 10 kGy

Fig. 3.2. Electronic component limitations in radiation environments summarized from Sharp and Decreton (1996).

Additionally, prior to the deployment of the Quince robot at Fukushima, tests of the electronic components were performed. The CCD camera (CY-RC51KD) began losing clarity at 140 Gy and completely failed at 169 Gy cumulative dose. Other electronic devices, including the CPU board, motor driver boards, and laser scanners were still functional after 200 Gy, though tests at higher doses were not performed [15]. This mostly agrees with the upper limit of 100 Gy for the cameras and roughly 1 MGy upper limit for drive mechanisms and sensors provided by Sharp and Decreton's review.

Chapter 4: Methods

In an ideal situation, robotic systems would be tested as a final product in the actual environments in which they would be expected to perform; lifetimes could be generated by determining how long the system reliably functions in this environment. However, this trial-and-error method is difficult, requiring the coordination of the application environment and a final version of the robotic system. This method is therefore impractical and can become costly, especially if modifications need to be made, as typical in the development process. Thus, previously established nuclear radiation test procedures allow for laboratory-based experimentation as an acceptable alternative that allows for testing of individual components to predict comprehensive performance in the field [46]. These experiments allow for the creation of a model that can be used to assess operating parameters for systems under examination.

Additionally, as the soft robotic manipulator in question is still under investigation, this method allows for the simultaneous progression of materials development for soft robotics and materials analysis for those systems in radiation environments. The methods used here capitalize on independent laboratory experiments, testing individual components to predict performance in a variety of radiation environments. The aim of the following experimental research is to evaluate the bulk effects of mixed radiation on the soft robotic system and determine operational parameters for those components.

4.1 PDMS Gamma-Induced Changes

First, the net, physical effects gamma and neutron radiation on PDMS following chemical curing conditions were examined. These procedures were similar to processes developed for an analogous modern investigation of polymers for use in waste storage. That process first irradiated then tested the mechanical properties of various polymers for exposure in a known environment [47]. Conversely, the processes used in this experiment focus on one polymer in various potential environments.

In order to fully evaluate manipulator performance in general radiation environments, samples of PDMS were exposed to both gamma-only and mixed neutron/gamma sources to determine the effects of each type of radiation on the functionality of PDMS.

To address the potential for gamma-induced mechanical damage in PDMS, the following steps were performed:

1. Sample preparation
2. Controlled irradiation of samples
3. Mechanical testing of irradiated samples
4. Comparison of experimental results to representative environments

4.1.1 Sample Preparation

First, samples for the elongation and tensile strength tests were created. 27 “dog bone” shaped samples were prepared from Dragon Skin Fast 10™ silicone by Smooth-On, the same materials used in OSU’s soft robotic manipulators [26]. Reusable molds for tensile tests were 3D printed from an OSU robotics template, measurements can be found in Fig. 4.1.

Second, samples for the test of compression and stiffness were created. 20 disc-shaped samples were prepared from the Dragon Skin Fast 10™ silicone mixture. Disc molds for compression tests were 3D printed to match test specimen 7.1.2 in ASTM standard D6147-97 [48]: a cylindrical disc of diameter 29.0 mm and thickness 12.5 mm.

To create both samples, equal parts by weight of Dragon Skin part A and B were combined and poured into molds. Filled molds were placed under vacuum for 5 minutes, then covered and placed in a 60 °C oven for 15 minutes. Samples were then removed from the mold and allowed to rest 1-5 weeks before irradiation, according to the availability of the irradiation system.

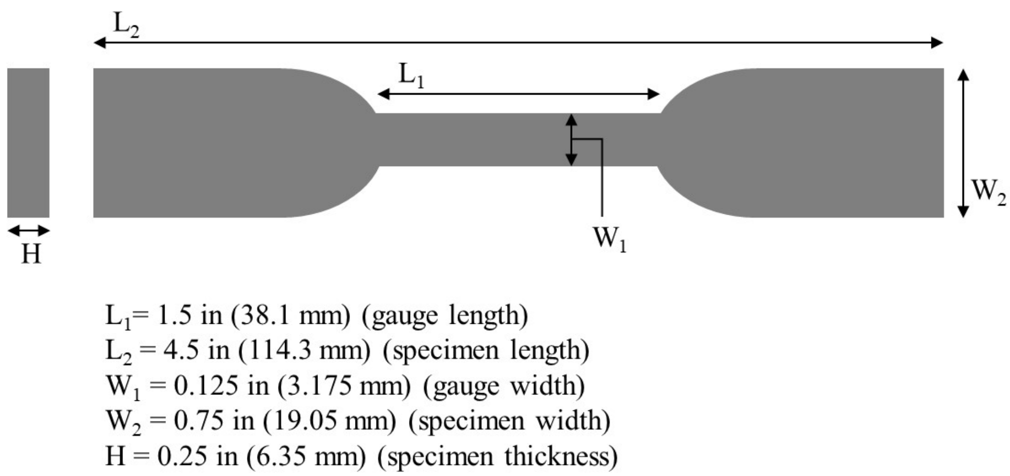


Fig. 4.1. Tensile test ("dog bone") sample dimensions.

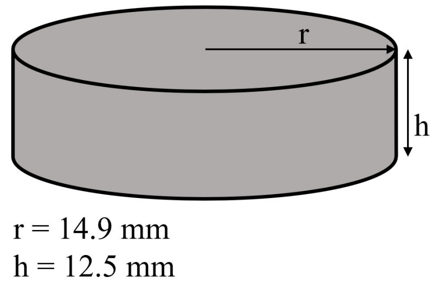


Fig. 4.2. Compression test disc sample dimensions.

4.1.2 Controlled irradiation of samples

In the GammaCell 220, 21 samples were irradiated to a range of cumulative gamma-only doses from 7-400 kGy, with three samples tested at each cumulative dose except 7 kGy, at which six samples were tested. Initially, 400 kGy was selected as the maximum for comparison to existing literature; it was the maximum dose tested out of all the previous experiments. To logarithmically fill the rest of the range, 7 and 55 kGy doses were chosen. These also matched fairly well with existing literature. After determining the extent and range of measurable effects, another set of doses was selected to match a cumulative dose for a task time of 12 hours working at the average or maximum dose rate in the representative environments. As discussed in the "approach" section, these doses were 120 kGy for spent fuel storage pools, 21.6 kGy for vitrified waste and the vitrification process, and 12 kGy for deactivation of a generic PWR. Six total samples were reserved as controls, three from each round of irradiation, to ensure that the samples were prepared consistently and therefore consistent pre-irradiation.

Irradiations were performed in a GammaCell 220, which was recently updated with new Co-60 sources in 2015. This matches the source and energy of gamma rays used in past literature. As of November 2017, when the most recent gamma irradiations of the samples were performed, the center of the GammaCell chamber provided an exposure rate of 5.5E5 R/h.

Fig. 4.3. Mark 10 tensile testing of irradiated PDMS tensile test shape sample at OSU Robotics Lab.

4.1.3 Mechanical testing of irradiated samples

Following gamma irradiation, samples were subjected to mechanical tests in a Mark-10 ESM1500 Motorized Tension/Compression Stand. For tensile test sample testing, the stand was outfitted with G1061 wedge grips and a model M7i force sensor. The wide ends of the sample were inserted into the wedge grips with separation between the grips that did not put tension on the sample. To perform the test, L_1, the length of the narrow portion of the sample, was increased by separating the wedge grips at a rate of 250 mm/min. The samples were extended to break to yield the "tensile strength at break" and "elongation at break" as in Fig. 4.4. Measurements of L_1 and force of tension were taken throughout the elongation.

It is worth noting that during the elongation of the sample, the width of the portion in the grip decreased, causing some slippage and requiring the grips to continuously

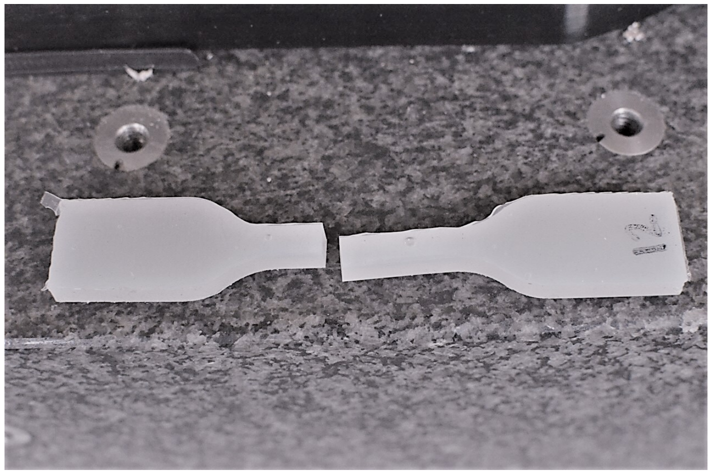


Fig. 4.4. Example of tensile test sample post-irradiation following mechanical stress testing to break.

tighten on the sample. This is mainly due to the elasticity of the sample as compared to the traditionally rigid materials tested in tensile strength tests. This effect was most pronounced in the lower regions, especially at 7 kGy. To account for this effect, a total of six samples were tested in this region and results for slipping samples were compared to the set using a z-test. None were significantly different enough to be discarded, all are present in the reported results. However, if a sample slipped completely from the grip before breaking, it was not included. This is due to the fact that samples did not retain their initial elasticity after the initial stretch due to the extreme lengths of the stretch—this is not expected to be an issue for the soft robot, which may lose some elasticity with repeated use but will not be stretched to such an extreme (7-8 times its initial length).

For compression testing, the stand was outfitted with two parallel flat plates above and below the sample as indicated in ASTM D6147 [48], the top plate was connected to a model M7i force sensor. The plate surfaces were placed flush with the PDMS disc sample so that they did not put tension on the sample. Then, h, the height of the sample was decreased by decreasing the space between the parallel plates at a

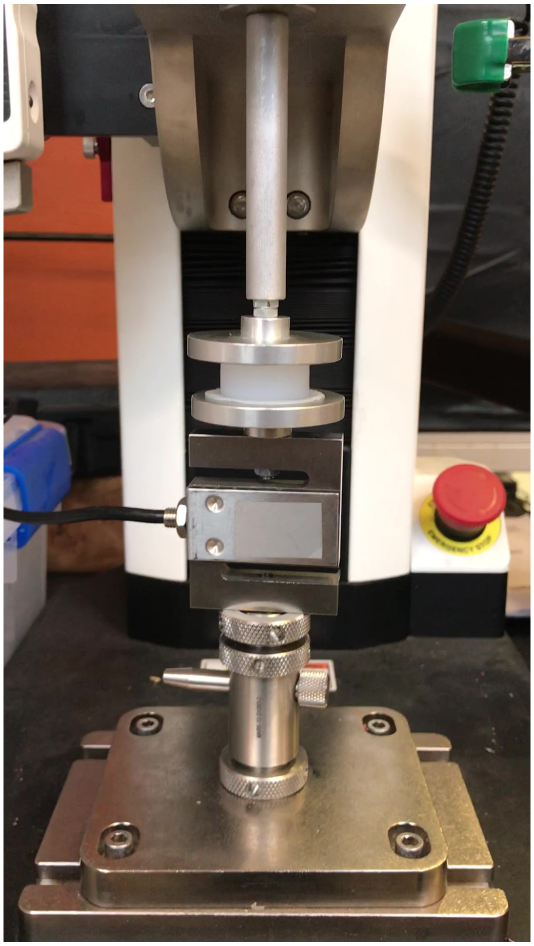


Fig. 4.5. Mark 10 compression testing of irradiated PDMS disc sample at OSU Robotics Lab.

rate of 250 mm/min to 0.75 of the original value, then released. The value 0.75 was selected after testing several control samples to find a point at which compression of the sample put a measurably varied amount of force on the sensor without overloading its maximum rating, 200 N. This matches the 25% compression required by ASTM standards [48]. Measurements of h and the force of compression were taken throughout the compression. For compression testing, it should be noted that the ASTM standard used typically measures for force decay (stress relaxation), a measurement of the ability of a sample to continuously resist a constant pressure with a constant force over a given amount of time. Thus, the standard requires a 30 minute hold after compression by 25%; this 30-minute hold was not replicated in this experiment. The ability to continuously resist a constant pressure with a constant force is not a relevant factor in assessing the types of dynamic changes to PDMS as would be seen by a soft robot in a radiation environment. The experiment performed herein focuses instead on initial force needed to compress an irradiated disc to determine increased stiffness and resistance to compression, from which relative changes due to gamma irradiation can be observed. Thus, the test measures the increasing force needed to compress the disc to the same amount (without a hold) as dose from gamma radiation increases.

4.1.4 Comparison of experimental results to representative environment

Finally, the changes in elongation, tensile strength, and compression were measured and plotted as a function of cumulative dose. These results were then correlated with the three representative radiation environments selected for assessment of components.

4.2 PDMS Mixed Neutron/Gamma Effects

In addition to mechanical changes, neutron exposure also introduces the issue of potential for activation of the polymer. First, estimates of activation were required to initiate actual neutron irradiation testing. They also provided a comparison of the ability of a model to accurately predict activation of components in a neutron environment.

4.2.1 NIST-based activation estimates

To generate the activation estimate, an activation calculator created by the National Institute of Standards and Technology (NIST) was used. The tool is available online from NIST and uses an input of the chemical composition of the sample, characteristics of the neutron beam, and an exposure time to predict a profile of activated radionuclides along with the decaying activity of the activated sample after removal [49]. To calculate these results, the NIST tool uses a database of cross-sections and an activation calculation. Eq. 4.1 gives an example of this calculation where A_0 is the initial activation in microcuries, Φ is the neutron flux given in n/cm^2s, σ is the cross section in barns (from the database), m is the effective target weight in mg, G is the relative element content as a number, h is the relative isotopic abundance in %, $T_{\frac{1}{2}}$ is the half-life of the product, t is the irradiation time, and M is the mass number of the target isotope [46].

$$A_0 = 27.03 * 1.6 * 10^{-13} * \frac{\Phi\sigma mGh(1 - e^{-\frac{ln2}{T_{\frac{1}{2}}}t})}{M} \tag{4.1}$$

To predict the outcomes of exposure to PDMS in OSU's rotating rack, the following parameters were used: 2.0 g PDMS with chemical formula C_2H_6OSi, 7 hours, flux values of 3.85E12 cm^{-2}s^{-1} thermal, a thermal/fast ratio of 2, Cd ratio of 2. A profile of activated radionuclides was generated using the NIST tool.

4.2.2 Neutron Exposure Tests

After obtaining the NIST data for the activation of PDMS, a material-based experiment was performed to compare actual, physical results to computational estimates. The rotating rack (Lazy Susan) of OSU's TRIGA Research Reactor (OSTR), was used to provide a steady neutron flux without an extensive amount of heat or extremely high dose rate. The experiment parameters mostly matched the NIST inputs: 2.0 g PDMS with chemical formula C_2H_6OSi, 7 hours, and reported flux values of 3.85E12±4.89E11 cm^{-2}s^{-1} thermal, 1.95E12±6.78E11 cm^{-2}s^{-1} epithermal, and 1.90E12±3.97E11 cm^{-2}s^{-1}

fast.

Post-irradiation, samples were given 5 days to decay due to unexpectedly high activity from Na-24. HPGe spectra of one of the samples was taken to determine the identities of gamma emitters within 3D printed PDMS. Due to the unexpected appearance of long-lived lanthanides post-neutron irradiation, mechanical tests could not be performed on the samples. Instead, a physical examination of the samples was performed to inspect for signs of radiation-induced damage and qualitative comparison.

4.3 Liquid Metal Gamma Effects on Resistance

As discussed, the liquid metal force sensors proposed for use in the soft robotic manipulator depend on small changes in resistance. To determine the effects of gamma radiation on the resistance of the liquid metal, live resistance monitoring in an active gamma field was performed. A 0.1 g microchannel of liquid metal composed by weight

Fig. 4.6. Liquid metal sample used for live resistance testing under gamma irradiation.

of 66.5% Ga, 20.5% In, and 13% Sn was injected into a small sample of PDMS material to stabilize the metal during testing, shown in Fig. 4.6. This channel was attached to a Hewlett-Packard 34401A Multimeter using a 4-point connection to actively measure resistance. While taking active measurements, the sample was deposited into a Cs-137 gamma well which exposed the sample at a rate of approximately 0.10 Gy/hr. The dose was slowly reduced to near zero before the sample was removed and the resistance measurement terminated.

Chapter 5: Results and Discussion

5.1 PDMS Gamma-Induced Changes

The elongation tests of the tensile test ("dog-bone") samples allowed for measurements of mechanical changes as a function of dose. The tensile tests determined elongation and tensile strength at break according to ASTM D412-16 [50]. As shown in Eq. 5.1, the tensile strength, TS_B is equivalent to the quotient of measured force at break, F_m, and the cross-sectional area, represented by the product of the gauge width, W_1, and the sample thickness, H.

$$TS_B = \frac{F_m}{W_1 * H}. \tag{5.1}$$

The ultimate elongation was defined as the final length (L_f) divided by the initial length (L_i).

$$E = \frac{L_f}{L_i}. \tag{5.2}$$

The results indicate that increased cumulative gamma dose leads to decreased elongation (Fig. 5.1). However, the relationship is not strictly linear. From 7 to 21.6 kGy, elongation decreases slowly, remaining nearly constant. Above 21.6 kGy, there is a steep decrease in elongation up to the highest measured dose, 400 kGy. This agrees with past literature, which shows either a small initial increase [51] or slight decrease [52] [38] followed by an eventual decrease in elongation at higher doses.

For the tensile strength property of the material, results showed a slight initial increase from 0 to 21.6 kGy followed by an overall decrease in tensile strength (Fig. 5.2).

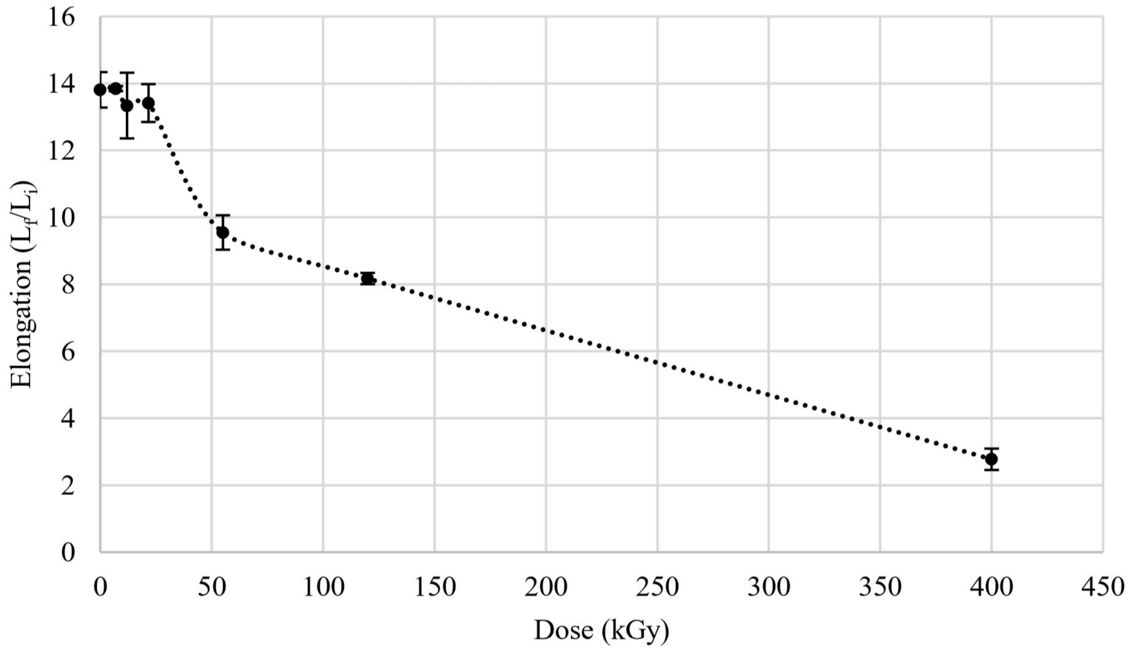


Fig. 5.1. PDMS elongation (L_f/L_0) decreases with increasing gamma dose.

This includes a steep drop in tensile strength at 55 kGy followed by a recovery back to the general decrease trend from 120 to 400 kGy. The overall trend, not including the 55 kGy drop, agrees with results from the CERN technical report which shows an initial increase from 10^6 to 10^7 rad, followed by a gradual decrease to 10^8 rad [38].

Past results do not agree on the overall effects of gamma radiation on tensile strength; Warrick [51] showed an initial increase followed by a sharp decrease while McCarthy [52] showed a constant tensile strength over the range of 200-400 kGy. This may be explained by the difference in the experimental aims of the past two studies and this current one. Where Warrick and McCarthy sought an optimum dose to vulcanize the rubber, this study focuses on already cured, solid silicone rubbers. This suggests that gamma irradiation improves tensile strength of the uncured or incompletely cured material until it achieves a maximum, after which the molecular-level effects become detrimental rather than curative. Thus, the silicone rubber studied here improves to its maximum at roughly 12 kGy then degrades as dose increases above 20 kGy. The

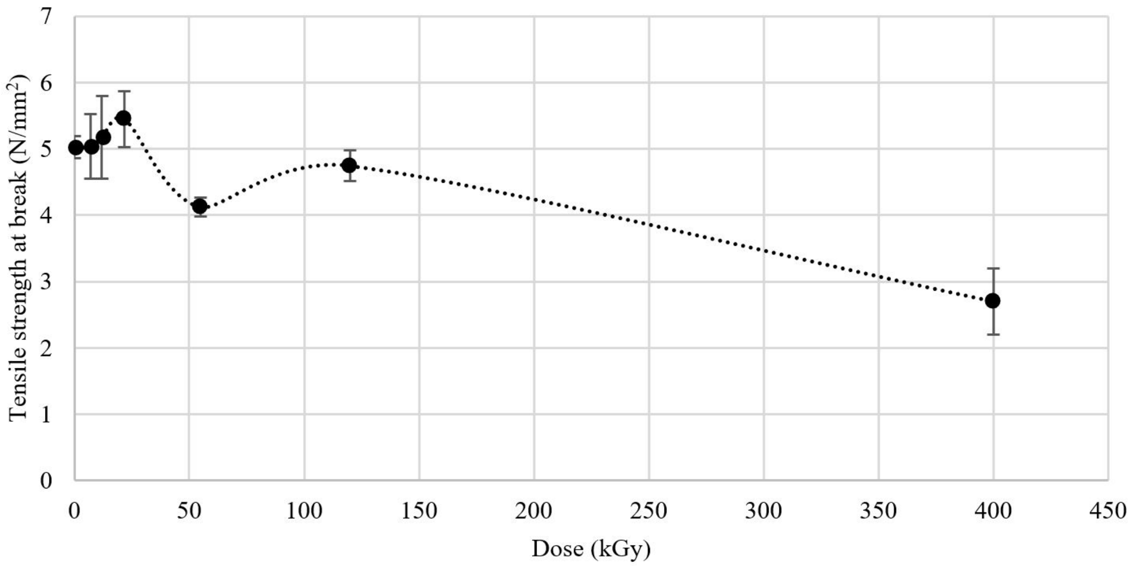


Fig. 5.2. PDMS tensile strength at break for increasing gamma dose.

results from the CERN technical report fit this profile and support this conclusion [38].

The elongation and tensile strength behavior may be explained by the competing molecular responses in polymers to radiation exposure: scission, which shortens polymer chains, and crosslinking, which introduces additional bonds between chains. Crosslinking is necessary in transitioning from the liquid to the solid state because the increase in network density is responsible for the curing process as in McCarthy and Warrick's experiments; the effects seen in the past experiments are indicative of crosslinking as the dominant effect of gamma radiation. Since the overall effects of gamma radiation on PDMS in this experiment are decreased elongation and decreased tensile strength, it indicates molecular crosslinking is likely the dominant effect within the PDMS matrix as doses are increased.

Overall, the competing mechanisms that determine the changes to a mechanical property like tensile strength are complex and cannot be determined with certainty without further experimentation with additional methods. However, an explanation by molecular effects is not necessary to extend the mechanical results and their influence on potential use, as explored below.

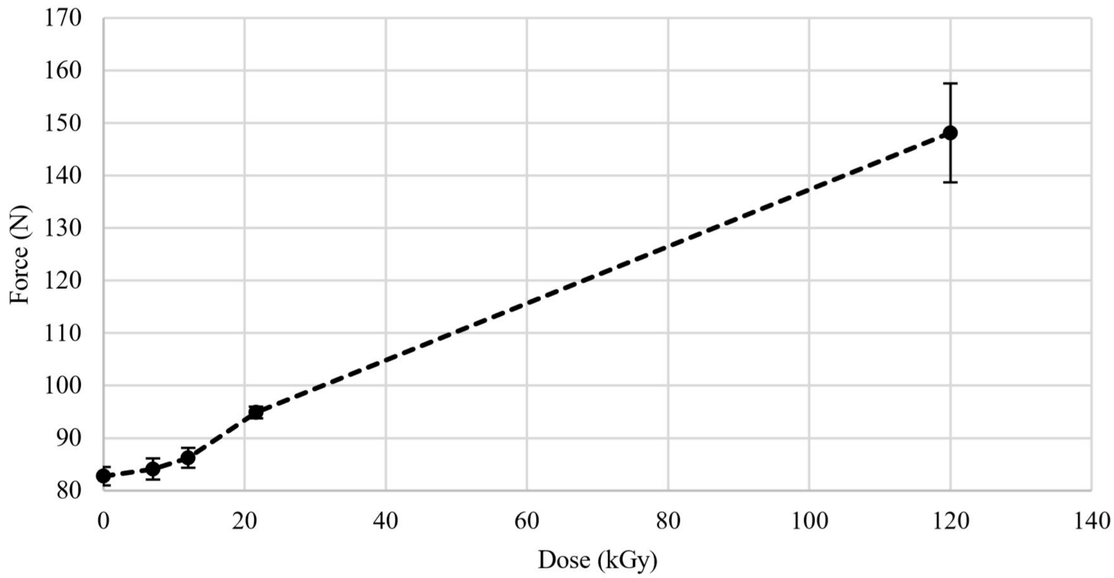


Fig. 5.3. PDMS compression with increasing gamma dose.

The compression tests of the cylindrical samples determined stiffness by measuring increasing force required to compress the disc to 75% of its original height, shown in Fig. 5.3. These results point to an increase in stiffness as cumulative dose increases. This increase in stiffness is likely due to a direct-response relationship between radiation exposure and cross-linking. This agrees with Basfar's research that shows that beta radiation at similar doses results in increased crosslinking and increased resistance to compression [39]. While Basfar's experiment sought to determine the dose required to completely cure a liquid silicone rubber to solid state using radiation, it did indicate that the dominant effect of cumulative radiation is increased crosslinking, which is consistent with the current evaluation of PDMS. The trend profile of increased stiffness at increased doses is more strongly support by the CERN technical report, which matches the trend seen in this experiment near perfectly. Additionally, Labouriau's study showed that stiffness initially decreased at 12.5 and 50 kGy before increasing at 200 kGy [37]. While the overall trend is consistent, the initial decrease in stiffness contrasts with the results of this experiment.

All three mechanical effects measured here show reasonable similarities to the results shown in past experiments by LANL, McCarthy, Warrick, and Basfar. However, the trends bear striking similarity to and therefore strongly support the results of the CERN technical report. A side-by-side comparison is shown in Fig. 5.4.

Overall, with increasing exposure to high dose gamma radiation, the mechanical properties of PDMS decrease in functionality, as expected. The results of the elongation tests suggest that the material retains its original properties until roughly 20 kGy, at which point it gradually loses its ability to extend. The results of the tensile strength tests suggest an initial increase up to roughly 20 kGy followed by a gradual decrease at higher doses. Finally, the stiffness of the material increases steadily as the cumulative dose increases. This supports the suggestion by the LANL report that the relationship between the competing molecular processes is complex. Overall, it seems while both scission and crosslinking occur initially, crosslinking becomes the dominant effect of gamma radiation on PDMS beyond 20-50 kGy. The major concerns for soft robotic manipulators at these higher doses is that more pressure will be needed to create the range of motion expected in low or non-existent radiation environments.

While the results of this experiment point to an overwhelming effect of crosslinking, which increases the density of the polymer network and results in an elastomer more resistant to bending and stretching, scission may also be occurring within the polymer. Scission leads to degradation, which would imply a weakening of the polymer network as molecules are cleaved. Given the overall increase in stiffness, it seems likely that scission is not the dominant interaction between gamma radiation and the PDMS polymer matrix. However, scission may manifest as the eventual weakening in tensile strength as crystallinity decreases. While this experiment did not include investigation

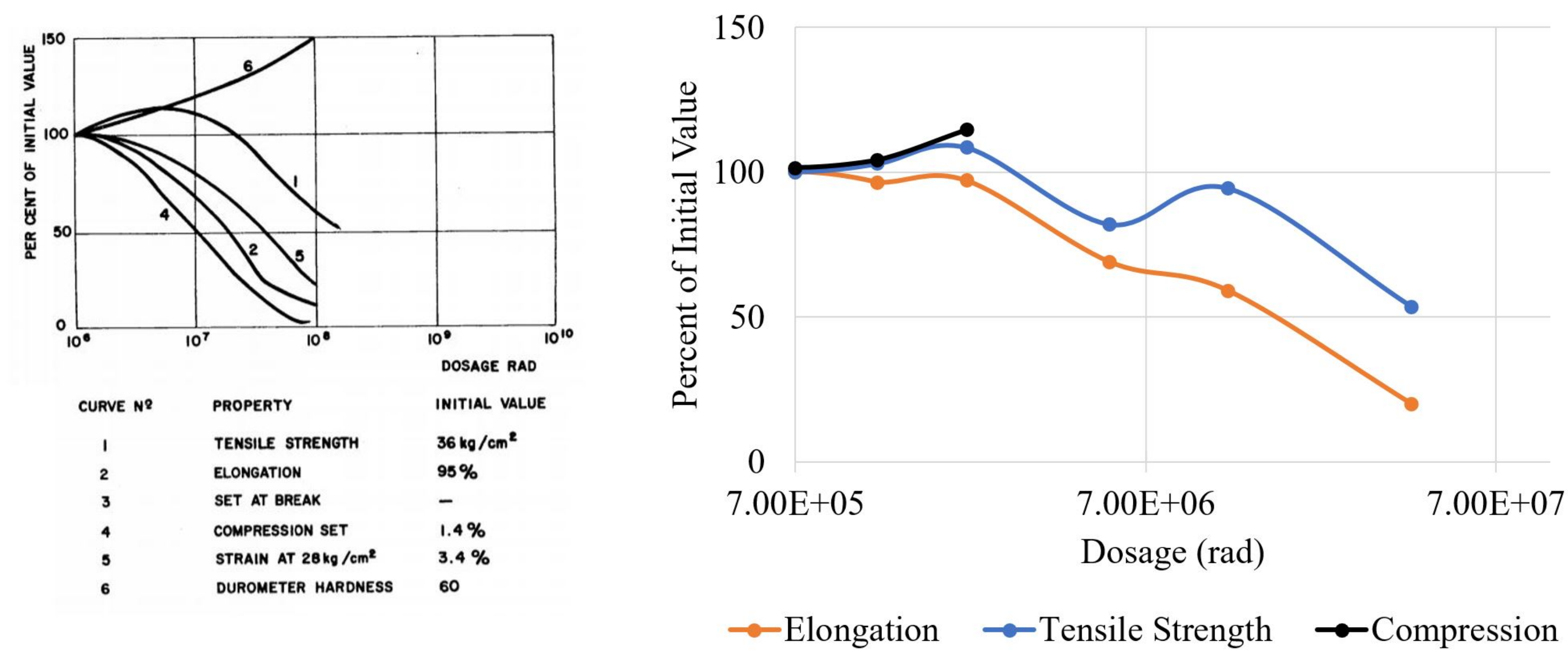


Fig. 5.4. Comparison between CERN technical report and current experiment trends for elongation, tensile strength, and stiffness after radiation dose (given in rads in original literature).

on a molecular level and therefore cannot confirm this overall trend with certainty, it does agree with past research by Hill which suggests that irradiation of PDMS results in a higher crosslinking yield than scission yield [53].

5.2 Considerations of Environment

In order to translate the functionality of soft robotics for potential tasks in the nuclear industry, the cumulative dose at each representative environment was evaluated for its resultant change to the material properties of PDMS. Elongation and stiffness were used as measures of mechanical changes due to their predictable, near linear effects and direct relation to an observable and functionally significant aspect of the material. As a function of dose, the fractional change to each property was measured by taking the difference between the irradiated and control sample values and dividing by the control sample value. The results of this analysis can be found in Fig. 5.5.

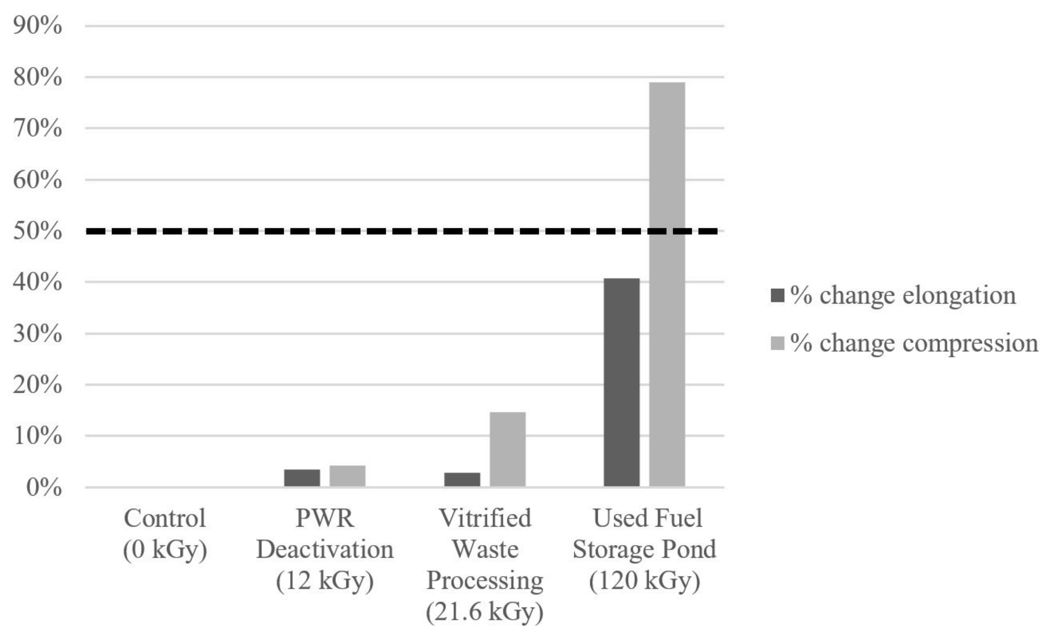


Fig. 5.5. Fractional changes to PDMS mechanical properties compared to representative gamma environments.

As shown, only stiffness changed by more than 50% in the used fuel pool, and only the elongation in the used fuel pool changed by more than 25%. A similar polymer radiation study considered 50% change as a benchmark to assess the viability of a material [47]. By this rubric, the PDMS of the soft robotic system is viable in most radiation environments, which is promising. The soft robotic manipulators will be used as the functional end effector of the system, thus changes to the mechanical properties will result in some corresponding loss of function. However, some of the mechanical changes can be compensated with increased pressure through the hydraulic or pneumatic system. The integration of soft robotic controls is still in development so the impact of these mechanical changes is yet to be determined. However, understanding these mechanical changes as a function of exposure will allow for control systems to accurately compensate to provide consistent manipulator performance. When these results are produced, they will allow for a more specific bound on the range of the radiation environments in which the soft robotic system can reliably perform. However, using the general benchmarks for current data, there are no blatant failures that would disqualify soft robotics from further study for implementation in high dose environments. In fact, the high doses with such small fractional changes in mechanical properties are promising and bode well for the future integration of this new technology.

5.3 PDMS Mixed Neutron/Gamma Effects

One of the concerns for neutron exposure of materials is the potential for activation of certain isotopes. The NIST activation calculation allowed for estimations of primary concern to be made for PDMS based on the non-proprietary formulation of the silicone elastomer [49]. Based on these calculations, one of the most intense activation products of PDMS is Si-31, but its roughly 2.6 hr half life causes its activity to sharply decrease after being removed form the environment [54].

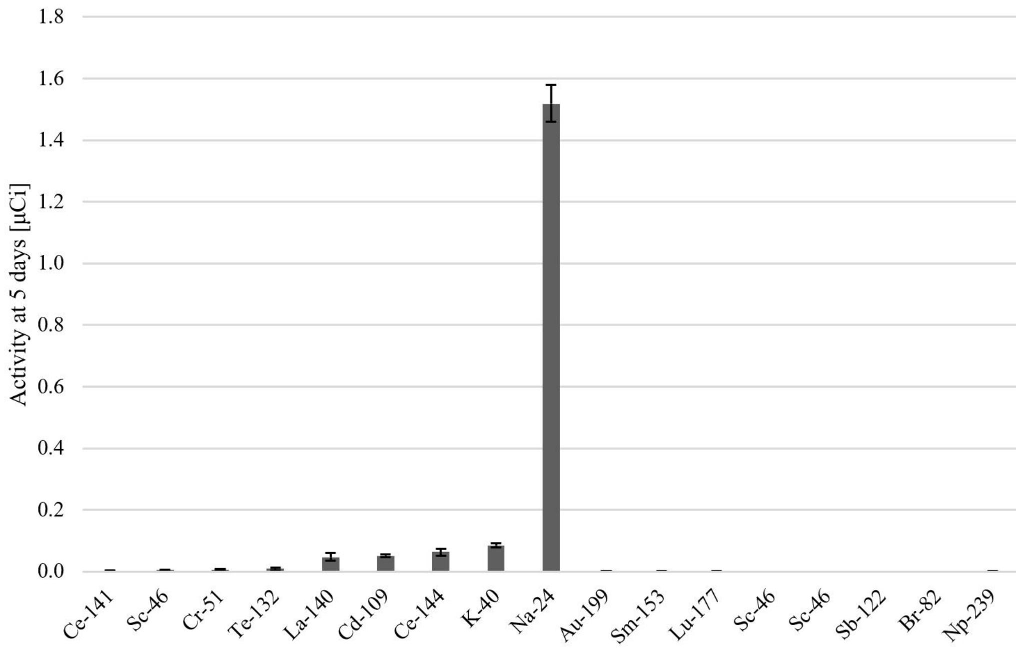


Fig. 5.6. All computed (Ce-141 through Na-24) and manually (Au-199 on) identified gamma-emitting radioisotopes from an HPGe spectrum of activated PDMS.

The neutron activation analysis of the 3D printed sample of PDMS did not match the NIST predictions based on the pure chemical formulation of PDMS. Fig. 5.6 displays the full spectra of isotopes identified via HPGe analysis following a 7 hr exposure in the OSTR rotating rack. Notably, there is a higher than expected activity of Na-24. While this may be partly attributed to handling, it is higher than amounts typically imparted to materials; gloves and clean processes were also used in the final manufacturing of the samples, so an external source is suspected. Na-24 is also by far the largest contributor to activity within the sample. Also, the appearance of lanthanides as shown in Fig. 5.7 in the sample was unexpected and indicates some contamination by heavy metals in either the original materials or the 3D printing process. Finally, trace amounts of platinum were expected in the sample as a result of the Pt catalyst included in the Smooth-On product [55]. The neutron activation analysis of platinum

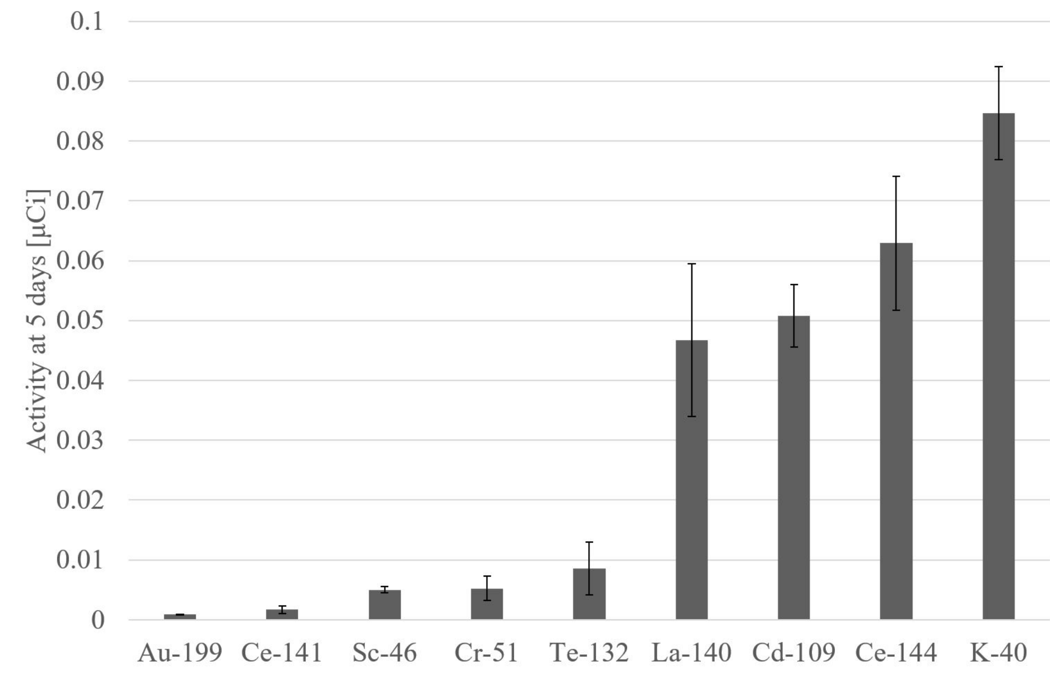


Fig. 5.7. Identified radioisotopes with activities above 0.001 microcuries, not including Na-24, for comparison of significant but lower activity peaks.

is typically observed through gamma emission by Pt-197, which is generated from Pt-196 (natural abundance 25.3%) or Au-199, the daughter of Pt-199, which is generated from Pt-198 (natural abundance 7.2%). The 18 hour half-life of Pt-197 prevents its observation in samples containing Na-24 which require a longer cool-down period [56]. However, the gamma emissions from Au-199, 158.4 and 208.2 keV, were identified in the sample with 1% and 6% peak uncertainty, respectively. This confirms the only expected trace contribution to the overall activity, platinum, but it hardly approaches the unexpected contributions from contaminants.

Physical examination of the 3D printed samples was necessitated by the lingering radioactivity of longer-lived radionuclides, which prevented more quantitative mechanical testing. The irradiated samples can be found in Fig. 5.8. Physical manipulation showed that like the PDMS exposed to gamma irradiation, the neutron-exposed samples also exhibited an increased stiffness and decreased flexibility. Additionally, the

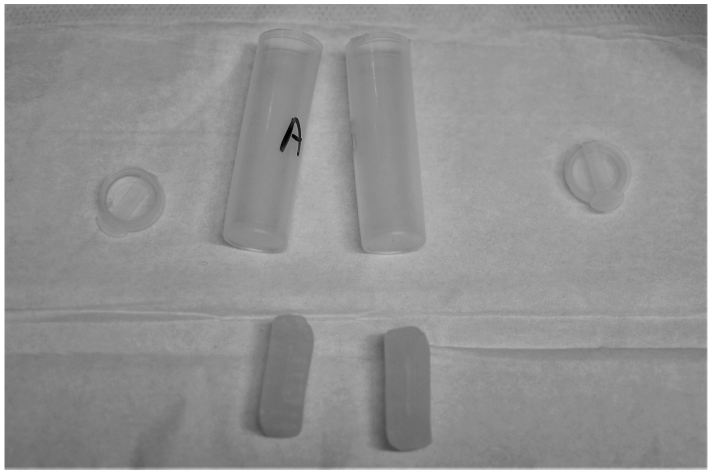


Fig. 5.8. 3-D printed samples of PDMS exposed to 7 hr of neutron flux near the OSTR.

3-D printed samples were slightly discolored, but not as discolored as the 400 kGy gamma-irradiated samples of PDMS. Qualitatively, it appears that the effects of neutrons were not noticeably different in their effects on mechanical properties than the effect of gamma irradiation. To quantify an operating range for soft robotics in neutron environments, however, additional tests must be performed that isolate the mechanical changes induced by neutrons from those induced by gamma in mixed radiation environments. This would generate a cumulative dose from neutrons and gamma that can be used to rate task ability of a soft robot in a given environment.

5.4 Liquid Metal Gamma Exposure

The constant resistance monitoring performed while the liquid metal sample was exposed to the gamma flux allows for a comparison of the effects of different exposure levels on the resistance in the liquid metal. The different levels of exposure are indicated in Fig. 5.9, which tracks the resistance in the sample over time as the flux on the sample changes. In the "Baseline" section of the graph, the sample is not exposed to radiation. This gives the resistance of the wire itself under normal conditions. In the

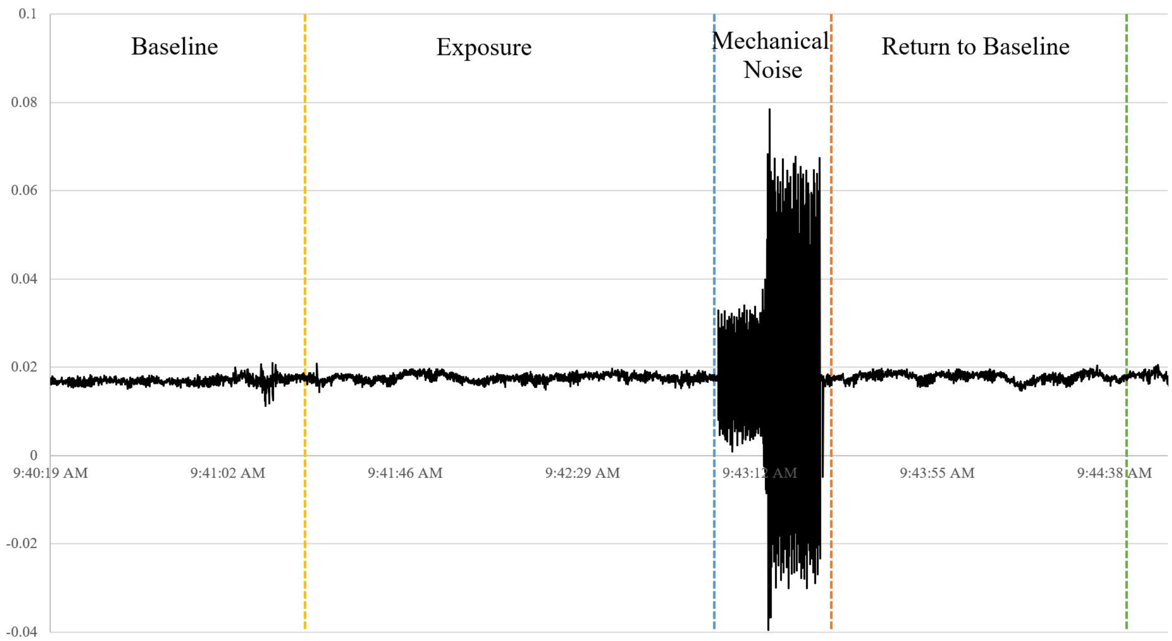


Fig. 5.9. Resistance measurements of a liquid metal sample exposed to various radiation levels.

"Exposure" section, the wire is exposed to 0.1 Gy/hr of radiation. In the "Mechanical Noise" section, an electronic drive mechanically shields the source in the well, creating noise visible on the graph. In the "Return to Baseline" section, the gamma flux is slowly reduced to zero.

Tracking the relative change in resistance through this process demonstrates that exposure to moderate gamma radiation does not create a noticeable change in resistance. Comparing the "Baseline" and "Exposure" sections, the resistance remains mostly constant, save some noise. When comparing the exposure to the magnitude of change that can be experienced by the liquid metal shown in the "Mechanical Noise" section, it becomes clear that electronic noise is a much larger factor than gamma radiation in terms of resistance. The "Return to Baseline" is included because through this section, the exposure decreases; because the resistance measurements remain constant through this period, there is no relationship between resistance and gamma exposure at this level of flux. Thus, by comparing the range of environments and lack of change, gamma flux up to an estimated 0.1 Gy/hr magnitude does not affect the functionality of the proposed liquid sensor.

Chapter 6: Conclusions and Future Work

6.1 Overview of Study Conclusions

Robots have traditionally had an extensive history of utility in the nuclear field and this utility will only continue to increase as technology improves. Soft robots, as one emerging direction for the field of robotics, holds promise for a variety of applications. The results of this study, both by collecting literature and conducting experiments, conclude that work in radiation environments should be further considered as one of the potential applications for the emerging soft robotic field.

A method for assessing the potential for soft robotics in radiation environments has been established and a tentative analysis of PDMS for both gamma and neutron irradiation on mechanical properties has been performed. According to these results, with increasing gamma dose: tensile strength initially increases, then eventually decreases; elongation decreases; and stiffness increases. This points to an overwhelming effect of crosslinking due to gamma exposure, which agrees with past literature. When compared to the representative radiation environments, PDMS retained more than 50% of its functionality in two of three environments, up to cumulative doses of about 150 kGy. This shows great promise for soft manipulators in high dose environments. PDMS samples exposed to neutron irradiation showed contamination by lanthanides and higher levels than expected of Na-24, while also confirming the presence of platinum in the sample. This suggests higher levels and longer-lived activation in the manipulators than expected. Physical inspection of neutron-irradiated samples suggested similar effects to gamma irradiation. However, further testing is necessary to determine the isolated neutron-only induced mechanical changes to find a operable dose range in a mixed radiation environment for the soft robotics. Live testing of resistance in a liquid metal wire during gamma radiation showed no changes in functionality due to exposure. Overall, none of the research presented here suggests that the range would be insufficient to the extent that it would prevent soft robotics from making a valuable contribution in most radiation environments. Thus, further research is warranted.

The effects of gamma and neutron exposure on liquid metal sensor functionality are currently under further investigation, as is the functional range of soft robotic manipulators with increased stiffness and decreased elongation. These additional parameters will be added to the cohesive profile which will compare the magnitude of all radiation effects to the operating parameters of the overall soft robotic system and determine the potential application range in radiation environments.

6.2 Applying Conclusions

To provide a framework within which to deliver the conclusions of this work as well as demonstrate the potential applications of these results, consider a single soft robotic manipulator created as anticipated by OSU robotics performing a simple task in a nuclear waste environment. Assuming current projections are correct, the manipulator itself will be a length of 1 m, composed of roughly 5 kg PDMS and 50 g liquid metal. It will be operated pneumatically, with tubing connected to 40 hollow channels (5 segments of 8 channels) and wires connected to 40 embedded liquid metal channels to measure resistance for force sensing. A small closed circuit camera will be attached somewhere on the soft robot. The wires and tubes from the manipulator will be encased in a single, thick tether of 3 m that leads back to the control board. The control board can be stationary and should be hardened with shielding. It must also contain a wireless receiver for operator command input via remote, pneumatic pumps for each of the 40 channels, some mechanism for interpreting force from the resistance measurements, and a power source.

First, using the approach outlined in this paper, environments and components should be identified. The components are 5 kg PDMS, 50 g liquid metal, and assorted electronics. Referring to the model environments, the estimated cumulative dose for vitrified waste and waste management on average is 21.6 kGy, derived from a rate of 1.8 kGy/hr for gamma, and a small contribution from Pu neutrons in the range of $4 * 10^{-4}$ to 10^{-3} Gy/hr; comparing the magnitudes of these contributions, the Pu neutrons are largely ignored.

Second, each component must be considered for its sensitivity to the radiation environment. Referring to the percent change in function for PDMS at 21.6 kGy, the limiting factor appears to be the stiffness resisting compression, with a 15% change as opposed to elongation, with less than 5% change. If a 50% change is used as a failure threshold, as shown in past literature, neither mechanical property fails in this environment. Not enough is known to assess the functionality of liquid metal sensors in this environment, as they have only been confirmed up to 0.1 Gy/hr. While this does not suggest they will fail, it does point to a need for further testing of this component. To assess the electronic components, including the camera and the control board, the established literature should be used as a reference. According to the literature, a typical camera is rated for a maximum tolerable dose at 10-100 Gy, and would therefore be untenable for the environment under consideration. However, cameras with a special design can tolerate doses up to 1 MGy (1000 kGy); if a hardened camera such as this were used, then the camera would not be the limiting factor for the functioning of the system. Overall, then, all three components are somewhat sensitive to radiation in this environment; following the flowchart, this requires establishing a design-life for the components.

It should also be noted that if signal communications are used, the literature suggests they have a relatively low tolerance compared to the other components: 1 to 10 kGy [25]. Since it is currently unclear what type of communication system will be needed for soft robots, this is not considered the limitation. Additionally, any communication system used for soft robots will likely come from development of traditional robots. If this is also the limiting factor for rigid robots, then soft robots would at least be equal in ability to absorb dose while retaining functionality. This study is interested in comparing the differences between the two robotic systems and will thus delay the inclusion of the generally limiting factor of signal communications system until it proves necessary in soft robotic systems or improves to the point where another factor becomes more crucial to the vulnerability of the system as a whole.

Third, the design lives can be inferred by consulting the literature review or the experimental results. The functionality of PDMS, specifically in stiffness and inability to compress, fails to meet the 50% threshold before 120 kGy. Using a conservative estimate, since no formula-based trend line exists for the relationship between dose and stiffness of the material, the material is likely viable up to roughly 50 kGy. At a dose rate of 1.8 kGy/hr, then, the material can be expected to retain above 50% functionality for about 27 hours. According to the literature, if a specially designed camera is used, the material can be expected to retain functionality for above 500 hours. The overall functionality should be assumed to be limited to the most vulnerable component. Thus, the current lifetime of the soft robotic system is 27 hours not including the liquid metal sensors, which require further testing. In order to increase this lifetime, further testing should be performed on the liquid metal, the weakest component of the system first, followed by further testing of PDMS.

Note, this particular environment did not include a significant contribution of neutrons. Given current experiments, the following can be estimated in cases where neutrons compose a large portion of dose to the system: 1) that stiffness will occur at an increased rate than in purely gamma environments and 2) that the overall activation of the system will be primarily due to the liquid metal sensors. If viable, further tests should be performed on the effects of neutrons on the system, as these have not been established in the literature, and may yield some potential uses for soft robotics. Neutron effects do not necessarily preclude the potential of soft robots, rather, their unknown signals a need for further testing.

Overall, then, the results of the current experimentation and literature suggest that soft robotic systems have a potential future in nuclear applications. By profiling the radiation environment of a proposed task, current knowledge of the system functionality can be used as above to determine the tentative estimated lifetime of the material in such an environment. The current limitations of the entire system are dependent on the limitations of the most vulnerable component of the system. According to past literature and current experiments, this is the liquid metal sensors, since the least has been confirmed regarding its functionality in radiation environments. However, this is not a barrier to soft robots because there is no indication of failure from past testing; this component is simply limited because tests on it have been limiting. To increase the known expected life of the soft robotic system, then, further testing of this vulnerable component is needed.

6.3 Future Potential and Experimentation

Considering the most vulnerable component of the soft robotic system is comparable to that of traditional robots, the conclusion of the comprehensive assessment of its potential is that it warrants further studies. The absence of significant limitations and outright failures indicates that there are no insurmountable nor unexpected barriers to soft robotic functioning in radiation environments. Additionally, several advantages of soft robotic systems, most notably but not limited to their adaptability, compliance, and ability to separate functional from computational components, suggest that soft robots will be able to complement their traditional counterparts by providing additional functionality that is either currently or permanently inaccessible to existing models. This should encourage further cooperation and development of soft robots for nuclear applications, not limited to industry, safeguards, and environmental management. By providing additional automated functionality, both new tasks that increase efficiency and replacement for personnel tasks can reduce dose to radiation workers. This increase in efficiency and decrease in exposure could translate to significant monetary gains and allow for new projects to be explored. Given the long list of existing challenges in the nuclear industry, it is appropriate to consider the application of a new technology such as soft robotics. As this research shows, the potential benefits of this integration are not precluded by functional effects of radiation. This study concludes that soft robotics are a valuable and promising new technology whose capabilities in the nuclear industry warrant further study as the technology of soft robotics progresses.

Potential extensions of this assessment could include, in addition to the already recommended further testing of the liquid metal sensors:

1. Further investigation of neutron-induced mechanical changes to PDMS.
2. Further investigation of gamma and neutron-inducted functional effects on liquid metal-based sensors.
3. A molecular-level evaluation that quantifies changes in molecular weight (indicative of scission or crosslinking) and the production of small molecular products.
4. A comparison in radiation-readiness of other PDMS-based, commercially avail-

able polymers for use in fabricating the soft robotic manipulator.

5. A review of other applications for liquid metal in radiation environments.

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