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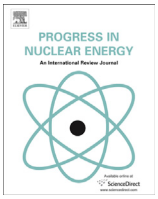

# Theoretical neutron damage calculations in industrial robotic manipulators used for non-destructive imaging applications

Joseph Hashem [a, b, *], Erich Schneider [b], Mitch Pryor [b], Sheldon Landsberger [b]

[a] *Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA*
[b] *University of Texas at Austin, Austin, TX 78712, USA*

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ABSTRACT

This paper describes how to use MCNP to evaluate the rate of material damage in a robot incurred by exposure to a neutron flux. The example used in this work is that of a robotic manipulator installed in a high intensity, fast, and collimated neutron radiography beam port at the University of Texas at Austin's TRIGA Mark II research reactor. This effort includes taking robotic technologies and using them to automate non-destructive imaging tasks in nuclear facilities where the robotic manipulator acts as the motion control system for neutron imaging tasks. Simulated radiation tests are used to analyze the radiation damage to the robot. Once the neutron damage is calculated using MCNP, several possible shielding materials are analyzed to determine the most effective way of minimizing the neutron damage. Neutron damage predictions provide users the means to simulate geometrical and material changes, thus saving time, money, and energy in determining the optimal setup for a robotic system installed in a radiation environment.

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## 1. Introduction

Penetrating radiation has been used throughout history for imaging purposes dating back to 1895 when Roentgen discovered x-rays. Emerging threats to national security from cargo containers and improvised explosive devices have reinvigorated efforts using tomography and compact radiography. Additionally, unusual environmental threats, like those from underwater oil spills and nuclear power plant accidents, have caused renewed interest in fielding radiography in severe operating conditions. Today any particle type can be combined with an increasingly wide range of digital detectors to image almost any conceivable object in extreme environments. These severe operating conditions pave the way for remote handling systems, such as robots, where they are increasingly deployed in remote and hazardous environments such as in nuclear waste cleanup and other radioactive environments. The DOE has in particular targeted robotic handling of hazardous waste to be an essential element in its efforts of environmental restoration and waste management (DOE, 1990). Within the DOE complex, the primary purpose of robots are to replace (or augment) human operators to increase safety without adversely impacting process efficiency.

In this work, a Yaskawa SIA5 7 Degree-of-Freedom (DoF) industrial manipulator (YASKAWA, 2012) handled the imaged parts and provided advanced and flexible motion capabilities and imaging techniques. Remote-operated robots like the one studied here allow access and manipulability to areas that would otherwise be inaccessible due to radiation levels, enabling repairs, maintenance work, inspections, or other tasks. A good example of this is the Fukushima plant in Japan, which is using robotic inspection to determine the extent of damage inside the contaminated reactor buildings (Nagataniet al, 2012). These robotic servants are not invulnerable however, and radiation exposure will result in damage to the components. Monte Carlo tools like MCNP (Goorley et al., 2012) can enable us to easily perform the high-fidelity calculations necessary to determine the neutron damage rate. MCNP provides a powerful tool for determining radiation fields in a defined environment (Gilbertet al, 2013). High enough levels of neutrons or photons will eventually affect the reliability of electronic components. Thus radiation tolerance is critical to the reliability of the imaging process. Therefore, the radiation damage to the robot and its electronics must be quantitatively evaluated.

Exposure to a radiation field, including neutron flux, leads to damage, including weakening in materials, metal embrittlement,

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[*] Corresponding author. Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545, USA.
*E-mail address:* jhashem@lanl.gov (J. Hashem).

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and reduced semiconductor efficiency. The incident radiation carries a certain amount of energy, which is transmitted to the material through various processes (e.g. elastic and inelastic scattering of neutrons). If enough energy is transmitted to an atom of the material, that atom can be displaced from its position in the molecular structure leaving a vacant site behind (vacancy), and the displaced atom eventually comes to rest in a location among lattice sites, becoming an interstitial atom. The interstitial vacancy pair is of main importance for radiation effects in solids and is known as a Frenkel Pair (FP). The presence of the FP and other consequences of irradiation damage determine the physical effects, and with the application of stress, the mechanical effects of irradiation. The radiation damage event is finished when the displaced atom (also known as the primary knock-on atom, (PKA)) comes to rest in the lattice as an interstitial (Was, 2007). As the vacancies, interstitials, and voids caused by repeated displacements build up, the crystalline molecular structure of the material is weakened. For materials like metals and semiconductors, where key properties like material strength and conductivity are highly dependent on the crystalline structure, repeated radiation-induced displacement can severely impact the material's ability to perform its intended function, reducing the service life of any component made of that material.

Monte Carlo methods have been used to determine neutron-induced displacements and radiation damage primarily for reactor vessel applications. At Oak Ridge, Monte Carlo tools were used to assess neutron and photon induced embrittlement in the High Flux Isotope Reactor (HFIR) reactor vessel as demonstrated by Risner and Blakeman (Risner and Blakeman, 2016). A limited evaluation of neutron displacements per atom (DPA) rates at a beam port nozzle corner region at HFIR using a Monte Carlo model was performed in (Blakeman and Bucholz, 2004). DPA rate maps using three-dimensional cylindrical mesh tallies were used to visualize the spatial map of neutron and photon DPA rates. Mascitti and Madariaga (Mascitti and Madariaga, 2011) also implement Monte Carlo tools to identify where the Atucha II reactor pressure vessel neutron radiation from fast neutrons is highest and perform DPA rate calculations in those areas.

The sensitive components installed on advanced manipulators can be divided into three categories: 1) the drives (usually electrical actuators with bearings, gear boxes and position feedback devices); 2) the sensors (distance and force sensors, cameras, etc.); and 3) the cables and other communication devices (including line drivers, multiplexing circuits, analog to digital converters, radio links and even the preamplifiers needed for some sensors). For each category, the radiation hardening level required will depend on their location with respect to the radiation sources (near the end effector or near gantry tracks or walls) and on their frequency of use (e.g., a tool used a small number of times, compared with protection systems in use permanently) (Houssay, 2000). The robot's controller can and should be kept out of the radiation environment due to its large amount of electronics.

Potentially, the most radiation sensitive parts of a robotic system are the electronic components. The electronic parts that are the most susceptible to radiation effects are the semiconductors, the semi-insulators, and insulators. The most important of these are the silicon family of parts. Non-semiconductor based electronic and electromechanical components such as servo-motors generally exhibit much greater radiation resistance. For robotic applications in radiation environments, the primary radiation effects of concern are total ionizing dose and the neutron-induced displacement damage. Single event upsets produced by high energy neutrons and space radiation are only of minor importance for the vast majority of robotic applications except for those in space.

### 1.1. Displacements per atom

A standard parameter in the determination of radiation damage in materials is the displacement per atom (DPA), an integral magnitude that includes information about the material response (displaced atoms) and the neutron fluence (magnitude and spectrum) to which the material was exposed. DPA is not a measure of initially created lattice defects in the material but a measure of the harming energy deposited by neutrons in terms of the number of atoms permanently displaced from their position to a stable interstitial position. DPA is the magnitude usually used to correlate damage on materials irradiated under different neutron conditions and is the value of interest. The DPA rate is a derived quantity, which can be obtained dividing $R$, the number of displacements per unit volume and time, by the atomic density $N$ of the material,

$$R_{DPA} = \frac{R}{N} = \frac{\sigma_D \varphi}{2E_D} = \eta_{MC} \frac{R_{D,MC}}{2E_D} \tag{1}$$

where $E_D$ is a certain threshold energy that must be overcome before an atom can be displaced. This threshold energy is fairly small and represents the amount of energy required to overcome the atom's mass and the bonds holding it in place. The displacement cross-section, $\sigma_D$, is the product of the number of atomic displacements produced by a radiation particle at a given energy times the differential probability that the radiation particle at that energy level will transfer enough energy to an atom to knock that atom out of its matrix site, integrated over all energies above the displacement threshold. That is, the damage cross-section accounts for both the probability of interaction and the total number of expected interactions across a radiation particle's life. This is unlike most cross-sections, which solely represent the probability of a given interaction occurring. The particle flux is given as $\varphi$. MCNP can calculate the cross-section times flux value and provide the damage rate, $R_{D,MC}$. Since this is a computational tool to evaluate the damage rate, an efficiency factor, $\eta_{MC}$, accounts for deviations between calculation and reality. The standard efficiency factor for these calculations is 80%, based on binary collision models to account for realistic scattering (Wootan, 2014).

### 1.2. Application overview

We are going to use MCNP Ver. 6.1 (Goorley et al., 2012) to evaluate the rate of material damage incurred by exposure to a neutron flux. The example we use is that of a remote-operated robot intended for use in high-radiation environments, which is tested using one of the TRIGA beam port facilities. To do this we use macrobodies to create the robot geometry, define composite materials, and use tally multipliers to obtain a specific reaction rate. We discuss each of these features as we develop the model and then look at the specific post-processing needed to get neutron damage results. This work uses the application of a robotic manipulator installed in one of the beam ports at the University of Texas at Austin's (U.T. Austin) TRIGA Mark II research reactor for part placement, manipulation, and exchange for neutron radiography and computed tomography imaging. The use of robots can provide additional flexibility and autonomy to automated non-destructive imaging applications.

### 1.3. Beam port flux image

The MCNP detector flux pinhole camera tally was used to estimate the flux image at the image plane of the beam port to measure the beam size and beam uniformity. The pinhole size can be adjusted to the region of interest to improve statistics. The FIR tally