Preliminary Development and Modelling of a Next Generation Inspection System for CANDU Pressure Tubes

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Abstract

This paper will look at the development of a next generation inspection system for CANDU pressure tubes. The inspection system will be an autonomous crawler and will incorporate a full pressure closure plug which will not require the use of the current Universal Delivery Machine (UDM). By not requiring the UDM this new inspection package will allow for the potential of multiple inspections simultaneously, as well as freeing up the fueling machine bridge for other work. In conjunction with this new inspection system, an MCNP [1] simulation of the offline core conditions is being developed. This simulation will allow for estimates to be made of the dose that the inspection system will encounter, thereby allowing for more accurate prediction of component lifetimes.

1. Introduction

The process of inspecting fuel channels is long and tedious, taking up to twelve hours for a single channel. Inspections are performed during reactor outages, and costs can quickly add up as a result of the lost profits incurred while power is not being generated. The current method of inspection involves using a large and complicated drive system, called the Universal Delivery Machine (UDM), to drive an inspection package down the length of the channel. The UDM is mounted on the fueling machine bridge for the duration of the inspection. This is an issue due to the time it takes to mount and the fact that the bridge cannot be used during the inspection period. The UDM uses a large hollow shaft that passes through a modified closure plug in the end fitting to drive the inspection head. One of the primary sensor heads used for inspecting fuel channels at Ontario Power Generation (OPG) is the Channel Inspection and Gauging Apparatus for Reactors (CIGAR). This sensor head has a long history of performing routine inspections, and has been very successful. The goal in designing the next generation inspection system is to take advantage of the success of the CIGAR system, while improving upon the method of deployment. The existing CIGAR head will be driven by a robotic pipe crawler, and all of the required equipment for inspection will be deployed in the end fitting of the fuel channel. This setup will streamline the design into a set of easily deployed payloads. These payloads will be designed such that the existing fueling machine can deliver them in the same manner that fuel bundles are delivered.

2. Background

The CANDU reactor is arguably one of the safest generation III reactors currently on the market, however every reactor has a sever accident scenario and the CANDU is no exception. One of the most serious accidents that can occur to the CANDU reactor is what is known as a Loss Of Coolant Accident (LOCA), which could be caused by a rupture of the pressure tube. In order to limit the possibility of this happening, the pressure tubes are inspected regularly for any flaws that could pose a threat to the integrity of the pressure tubes.

2.1 Types of Flaws

There are a number of different flaws that can occur, however, almost all of them are measureable from the inner surface of the pressure tube long before they become a threat to the integrity of the tube. The main flaws that occur are: Delayed Hydride Cracking (DHC), Fretting, and Irradiation Enhanced Deformation.

DHC is a process where hydrides introduced to the metal during fabrication allows a small crack or scratch to propagate through the thickness of the tube. These hydrides concentrate at locations of high stress and as such, it is very important to ensure that any flaws detected are monitored closely. Fretting is another major concern and can often be a starting point for DHC [2].

Fretting is a scratch, hole or indentation caused by something vibrating against the inner wall of the tube. Fretting is generally caused by one of two mechanisms, bearing pad fretting or debris fretting. Bearing pad fretting is caused when the fuel bundle vibrates in the coolant flow and one or more of the bearing pads rub against the pressure tube. This leads to a fret in the shape of the bearing pad, at the specific locations where the pads contact the pressure tube. In addition, this type of fretting is more common on the outlet side of the pressure tube due to increased flow turbulence. Debris fretting is the potentially more dangerous type of fretting. Unlike bearing pad fretting, debris fretting can happen anywhere in the pressure tube and can cause complex and deep frets, as opposed to the flat shallow frets caused by bearing pads. Debris fretting occurs when a small piece of metal or other debris is caught somewhere in the tube and rubs against the pressure tube repeatedly [3].

The final flaw type is referred to as irradiation enhanced deformation and generally refers to one of three common phenomena. These phenomena are pressure tube sag, creep, and diametric expansion. All three of these phenomena occur as a result of the large irradiation that the pressure tubes undergo, coupled with the heat and pressure that they are subjected to. Sag is a drooping of the pressure tube over its length, creep is a lengthening of the pressure tube, and diametric expansion is when the pressure tube grows in dimension, often non-uniformly. One of the largest problems that these phenomenon can cause is sufficient deformation of the pressure tube resulting in it touching the Calandria tube. If this were to occur then the large temperature difference between the two tubes could result in the rupture of the pressure tube and a LOCA [3].

2.2 Current Inspection System

There are several different inspection systems that are used for a wide variety of purposes in CANDU reactors. One of the primary inspection systems currently in use is the CIGAR (Channel Inspection and Gauging Apparatus for Reactors). CIGAR uses eddy current and ultrasonic sensors to do a volumetric inspection of the entire length of the pressure tube. These inspections are analysed for any flaws that could pose a problem and then additional, more detailed, inspections can be done as needed.

The CIGAR package is delivered by the UDM by rotating and translating a large hollow shaft through the length of the pressure tube. This rotation and axial translation allows for the CIGAR to inspect the entire inner surface of the pressure tube as needed. This shaft enters the pressure tube through the modified closure plug, and is sealed with a rotary seal, thereby conserving the pressure boundary. The primary issue with this system is that this seal limits the pressure allowed inside of the fuel channel to 262 kPa. This pressure limit can lead to issues if there is ever an increase of heat generation within the core and the coolant pressure needs to be increased to maintain control. Another limitation of the existing system is that the UDM is mounted on the fueling machine bridge and as such only one channel can be inspected at any given time. In addition, the use of the fueling machine bridge also limits what other work can be performed on the face during inspections.

3. Improved Inspection System

The goal of the improved inspection system will be to replace the UDM system with a robotic delivery method, while utilizing the existing CIGAR sensor head. Some modifications to the sensor heads supporting electronics may be necessary, however, the CIGAR sensor head itself is a proven, and reliable tool for inspection. The robotic delivery method will consist of a pipe crawling robot capable of delivering CIGAR, the cabling for power and electronics, and a shielded payload for supporting electronics. The major benefit of the proposed inspection system is that the robotic deployment method can be contained within the fuel channel assembly, and will utilize a full pressure closure plug. This allows for pressure to be increased if needed to control decay heat, without jeopardizing the pressure boundary. Another benefit of the improved delivery system is the independence from the UDM and fueling machine bridge. By not relying on the UDM which must be mounted to the fueling machine bridge during inspections, multiple inspection robots can be deployed simultaneously. This will allow for the inspection campaign to be completed in a fraction of the time, thereby minimizing the duration of outages. It also allows the fueling machine, or the fueling machine bridge, to be used in other places, assisting with, or completing other outage activities.

3.1 System Overview

The robotic deployment of CIGAR is no simple task and requires very sophisticated equipment and careful planning to ensure its safe operation. The basic requirements for the system are that it is capable of moving the sensor head the full length of the fuel channel while rotating continuously to perform a full helical scan. In addition, the system is being designed such that it can be deployed from the existing fueling machine. The system will be automated once inside the fuel channel, and must be able to transmit the data from CIGAR's sensors to outside of the fuel channel. A detailed design plan was put together in order to accomplish all of these tasks. This plan outlines; the design of a robotic pipe crawler for CIGAR, the deployment strategy for this system, the design of a safe control system, and a test plan to examine potential areas of improvement.

3.1.1 Robotic Pipe Crawler

The design of the robotic crawler is under development and is in its initial prototyping phase. As shown in Figure 1, the design consists of the following components: a pair of tracks to propel the robot, a powerful stepper motor to rotate the sensor head, three radiation hardened resolver wheels for position measurements, spring loaded wheels to hold the robot from twisting, and the on-board electronics that will be mounted inside a shielded enclosure.

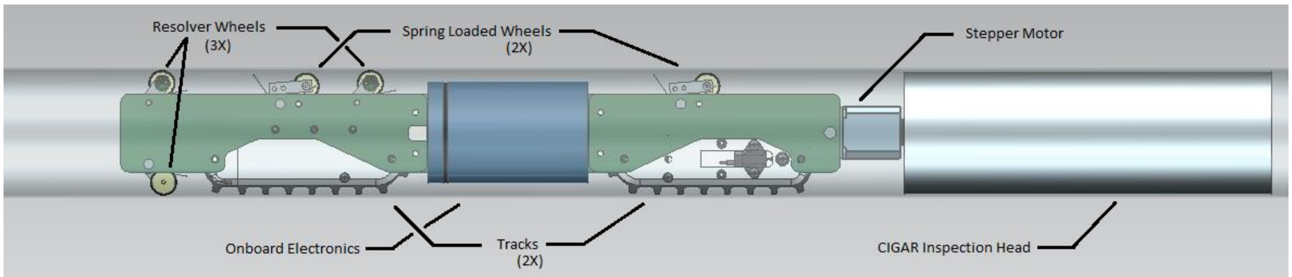

Figure 1: Robotic pipe crawler component breakdown

3.1.2 Deployment Strategy

In order for the inspection system to be deployable by the existing fueling machine it must fit within the space available, approximately the length of two fuel bundles. With the amount of equipment that is required it is impossible to deploy the inspection system as a single payload. The plan is to divide the equipment into three separate payloads: the electrical payload, the cabling payload, and the robot deployment payload. Once inserted inside the end fitting, the payloads will be latched to existing locking locations and electrical connections can be made. Once the robot receives power, it can proceed to crawl out from its deployment package and begin inspecting the pressure tube. Figure 2 illustrates the deployment strategy for the robot with the allowable volumes for each section shown.

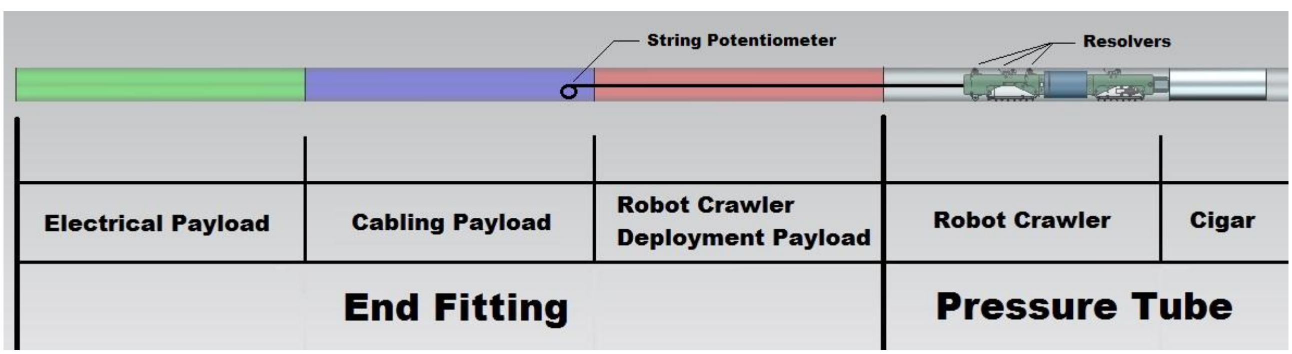

Figure 2: Deployment strategy breakdown

3.1.3 Safe Operation and Control

In order to protect against operational accidents and prevent any potential for damage to the reactor, numerous safeguards will be integrated into the mechanism and control system. The main concern with any pipe crawling robot, is the potential that it may get stuck, or cease functioning mid-way through the pipe. The design includes a high strength stainless steel tether that can be used to pull the robot out of the pressure tube in the event it loses power or is unable to move. This tether also provides an absolute position measurement based on how much cable is unspooled. The robots position measurement system is highly redundant and employs a sensor fusion method to combine the measurements from three resolver wheels. By using three sensors, if any one sensor were to fail, this failure can be quickly and easily detected when compared to the readings of any of the other two sensors. The resolver wheels are also crucial for controlling the speed of the robot, since they provide incremental feedback to track the robot's movement over time.

Another important consideration in the design is that it does not interfere with the operation and control of the plant. The robot may not interfere with the flow of heavy water through the fuel channels and includes adequate clearances for water to flow around it. The design will also include a new modified closure plug that will be pressure tight beyond the full operating pressure of 11.4 MPa. This is important, since it allows operators the ability to raise the pressure to prevent voiding if the temperature gets too high. While raising the pressure in this way may still cause damage to the crawler it will not pose any problem to the pressure boundary, and therefore the reactor safety can be ensured.

3.1.4 Test Plan

To validate that the robot is capable of performing all its functions, and to debug any potential problems, a test bench was developed. As seen in Figure 3, the test bench consists of a transparent PVC pipe and a vision system to track the robot's position. The vision system is used to calibrate and characterize the accuracy of the robots on board position sensors. After performing numerous tests, the vision system is able to generate reasonable estimates of the uncertainties in the position estimates. These uncertainties will then be used as inputs to a sensor fusion method which combines the measurements, from all of the position sensors, with their given uncertainties in order to provide a more accurate position estimate, than any individual sensor could provide.

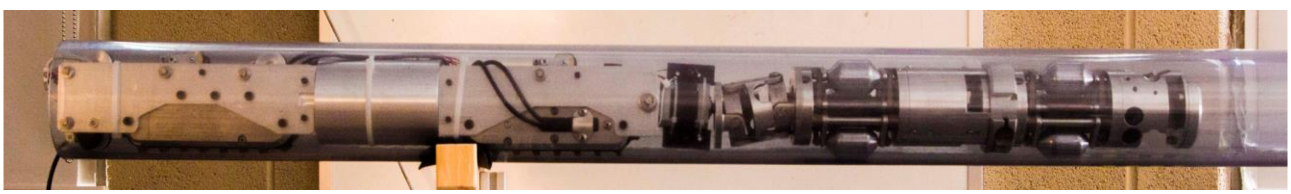

Figure 3: Robotic pipe crawler undergoing testing

3.2 Radiation Hardened Components

The improved delivery system for the CIGAR head has a large number of components that will need to be designed to survive in the harsh environment of a nuclear reactor. The system must be robust enough to survive the radiation exposure that it will encounter within the reactor and must also be able to function in a predictable manner for its entire design life. It must also be designed such that if any component were to fail, they would fail in such a way that the robot can still be safely recovered and removed from the fuel channel.

Table 1: Total Ionizing Doses (TID) for different components

Component	Total Ionizing Dose (MGy)	Maximum Dose Rate (kGy/hr)
Integrated Circuits (Rad-hard) [4]	0.01	-
Drive Mechanisms [5]	10	-
Electrical Cables and Connectors [5]	10	-
Ultrasonic Sensors [4]	10	10
Resolvers (Rad-hard) [4]	10	0.3

The components that are the most susceptible to radiation damage have a certain dose that they will continue to work up to. This dose is called the Total Ionizing Dose (TID) and will govern how long a particular component will last under a given dose rate. Sharp and Decreton [5] conducted a very thorough set of tests to document the TID and max dose rates for a variety of different components. The TID values for the different components that will be used in the improved delivery system are summarized in Table 1. The only component that is not included in this table is the robot's microcontroller. The TID for this component is difficult to estimate, but will be considerably less than the TID for the other components. In order to protect this component sufficient shielding will be included to lower its absorbed dose to a point where it can survive for times that are comparable to the other components. State of the art sensors and electronics can be radiation hardened from the manufacturer, or in other words specifically designed to withstand the highest possible TID. These special radiation hardened devices also offer protection against failures that can be caused due to a single event or interaction with a high energy particle of radiation. Further data on the dose rate and energies within the fuel channel will be critical to ensuring that all components will meet their expected lifetime.

4. MCNP Simulation

Given that the autonomous delivery system being developed will have considerably more electronics that the previous inspection system it will be much more susceptible to radiation damage. In order to ensure that the new inspection system will not fail unpredictably, thereby requiring manual extraction, the dose rates within the channel must be known. No existing prediction of dose rate within the core can be found in the literature. Most of the dose rates available are for the the reactor face or reactivity deck since these areas are of more interest during shutdowns due to the presence of workers at these locations. The existing CIGAR system is designed to operate in ambient dose rates of up to 1 MR/hr [6]**,** however, it is unclear whether this is the actual dose rate or a design dose rate that may include a safety margin. Due to this, an MCNP simulation was constructed in order to estimate the dose rates at any given location within the reactor under shutdown conditions.

4.1 MCNP

MCNP, or Monte Carlo N-Particle, is a radiation transport code that can be used for a variety of radiation types. It generates accurate estimates of flux by using known cross sections of interaction and random numbers to simulate radiation transport though a variety of materials. MCNP has been very well verified and is widely used for simulation purposes across North America and into Europe. These simulations were done using MCNP 6 [1]. Vised [7] was used for visualization, including all of the images of the model that have been included in this paper.

4.2 The Model

In order to get reliable results from the simulation, the reactor geometry must first be modelled. It is important that this model is as accurate as possible because it is this model that the radiation will be transported through and discrepancies in the geometry can lead to errors or incorrect results.

The CANDU reactor that was modelled was the Darlington reactor which has 480 channels and 13 fuel bundles per channel. These channels and bundles are laid out in a lattice arrangement that is uniform across the entire reactor. This uniformity in the construction allowed for the use of the repeated structure feature within MCNP, with the central piece of the entire model being the fuel bundle.

4.2.1 Fuel Bundle and Fuel Channel Assembly

The fuel bundle that was modelled was the standard 37 element bundle. The fuel pellets were modelled as one solid pencil and then the fuel sheath was added around that. There were two simplifying assumptions made at this point. First, it was assumed that the fuel composition was pure UO_2. This was only applied to the material with relation to how it shields and not to the source term that was later added. The second assumption that was made was that there were no end plates on either end of the bundle. This was done because the end plates are very complex geometries and add little material to the system and as such would make little difference to the results. Figure 4 shows a 3D rendering of the MCNP fuel bundle model. Once one fuel bundle was modelled, it was put into a repeated structure, known as a lattice. For the fuel bundles, a full channel was latticed at one time, so 13 bundles were made end to end.

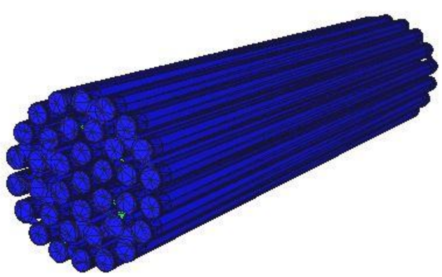

Figure 4 MCNP fuel bundle

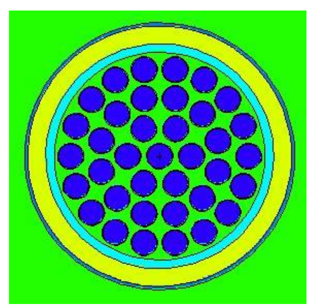

Figure 5 MCNP fuel channel assembly

Once the fuel bundle lattice had been finished, the rest of the fuel channel could be modelled. This consisted of the pressure tube, CO_2 gap, Calandria tube and the surrounding moderator. The lattice of fuel bundles, and the coolant that surrounds them, was then inserted inside of the pressure tube to complete the fuel channel assembly, as shown in Figure 5.

4.2.2 End Fitting

In order to complete the fuel channel assembly, an end fitting was required at either end. The end fittings are an exceedingly complicated shape and as such some small and inconsequential features were left out in order to simplify things, however, all major features were included. Three major simplifications were made. The first simplification was that the bellows for the CO_2 gap system were not included. The second simplification was that the closure plug was modelled as a solid piece with the end fitting body. Finally, the piping connections were not modelled. These simplifications were all made because they reduced the complexity of setting up the model without significantly impacting the results. Figure 6 shows the completed end fitting, and how it integrates with the rest of the system.

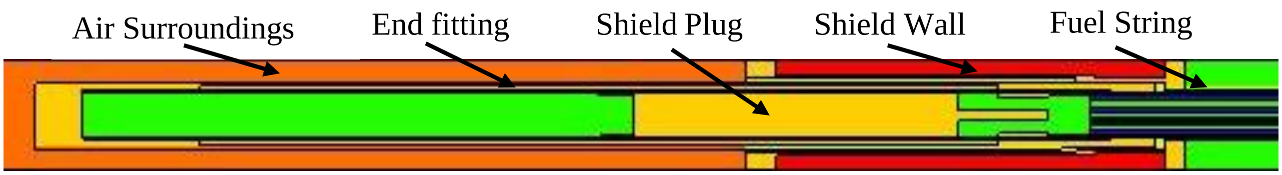

Figure 6 MCNP end fitting

4.2.3 Shield Wall & Shield Plug

In conjunction with the end fitting, the shield plug and shield wall were modelled. The shield wall is a pair of thick stainless steel plates with the area between them filled with a mixture of light water and carbon steel shot balls. This shield is used to reduce the amount of radiation that escapes from the core in both offline and online conditions. The shield plug is a cylinder of solid stainless steel with flow channels cut into the front. This plug is mounted in the end fitting and serves a multitude of purposes including: radiation shielding, flow smoothing for the inlet coolant, and holding the fuel string in place. Figure 7 shows a rendering of the shield plug and both the shield plug and shield wall can be seen in Figure 6.

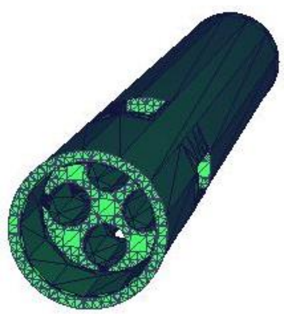

Figure 7 MCNP shield plug

4.2.4 Lattice

Once all of the components of the fuel channel had been modelled, a lattice was formed. This lattice allowed for the single complete channel, from end fitting to end fitting, to be replicated and arranged into the proper layout. Each of the components described previously had an infinite surrounding; the moderator around the Calandria tube, the air around the end fittings, and the shield walls each extend infinitely. These were left infinite because when the lattice was applied it cut the infinite material at the right dimension. If the dimensions were to be set before latticing then problems could arise at the interface of the lattice and the cell. This complete channel was replicated into the 480 channel round layout and the remaining locations were filled with *blank cells*, i.e., cells that had only moderator, air, and shield wall.

4.2.5 Outer Reactor Components

In order to complete the reactor, the core needed to be bounded. This was done by creating a bounding surface which cut off the lattice outside of all of the fuel channels. Around this core boundary is where the reflector volume and Calandria tank are located. A shield tank can be added at a later date if analysis is needed on the outside of the reactor. Figure 8 shows the completed reactor structure from a cross section view.

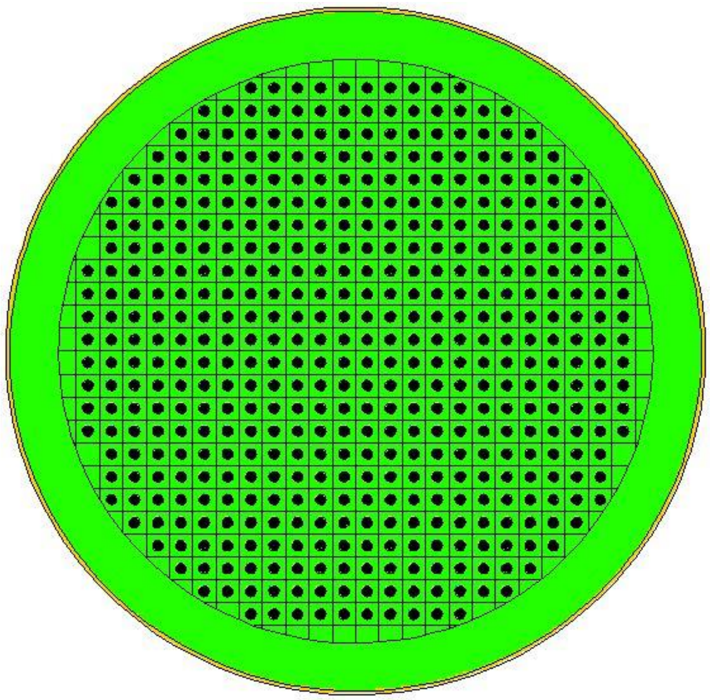

Figure 8 MCNP core

4.2.6 Source

The source term defines the radioactive emissions in the simulation. The previous sections detailed the geometry that the particles will move through, but it is the source term that determines the type of particle, energy, location, and other parameters about the radiation that is transported. For this simulation a discharge fuel burnup was used to construct the source term. It has been noted that using a discharge fuel composition is expected to result in a higher gamma flux, and therefore dose. This can be attributed to the increased concentrations of daughter products as compared to mid-burnup fuel. This approximation is a temporary measure and further work in this area is being done as described in Section 5.2. This source term was used to generate the energy distribution and relative probability of each energy, and the distribution was then spread throughout the fuel locations. The source term was set up such that there is an equal probability of a source particle being generated at any of the fuel locations. The starting location, energy, and various other properties are each determined through random processes. By evenly distributing the source, a realistic and isotropic field is developed at all locations throughout the reactor.

4.2.7 Tallies

With the model of the reactor built and the source term in place, a method of obtaining usable results from the simulation was needed. MCNP generates results through the use of estimators referred to as tallies. Tallies work by counting the number of particles that pass through a target location and separating these counts into pre-defined bins. In this simulation an F4 tally, which is separated into energy bins, was used to calculate the dose rate at a given location. An F4 tally is a volumetric tally that works by measuring the track length, the distance that a given particle travels within the target volume, to estimate the fluence. This track length, divided by the total volume of the area of interest, gives the *tally score*, the number that is added to the appropriate bin.

Once all of the particles have been simulated and the bins have been built up, they are normalized to a single particle. This is done so that the results are not dependant on the number of particles simulated. A dose conversion factor (DCF) was also applied to the different energy bins in order to convert the fluence into a usable dose. Finally, each bin is multiplied by a factor that includes conversion factors, such as converting from seconds to hours, as well as the source activity to obtain an accurate estimation of the dose rate.

4.3 Results

Given the complexity and size of the model, a large number of particles was required to ensure that the results were accurate. For this work a run of $1 * 10^{10}$ particles was chosen. This run resulted in a total dose rate of $1.66 * 10^4$ $(\pm 5.52\%)$ R/hr or approximately $1.454 * 10^2$ Gy/hr (using a conversion factor of 0.00877 Gy/R). A tally fluctuation chart (TFC), which shows how the tally is converging as more particles are run, was also created and is shown in Figure 9. The TFC shows some discrepancy early in the simulation but all of the values are within error of the final estimation, and there is a clear convergence. This run passed all of MCNP's internal statistical checks and has an acceptable error associated with the final estimate.

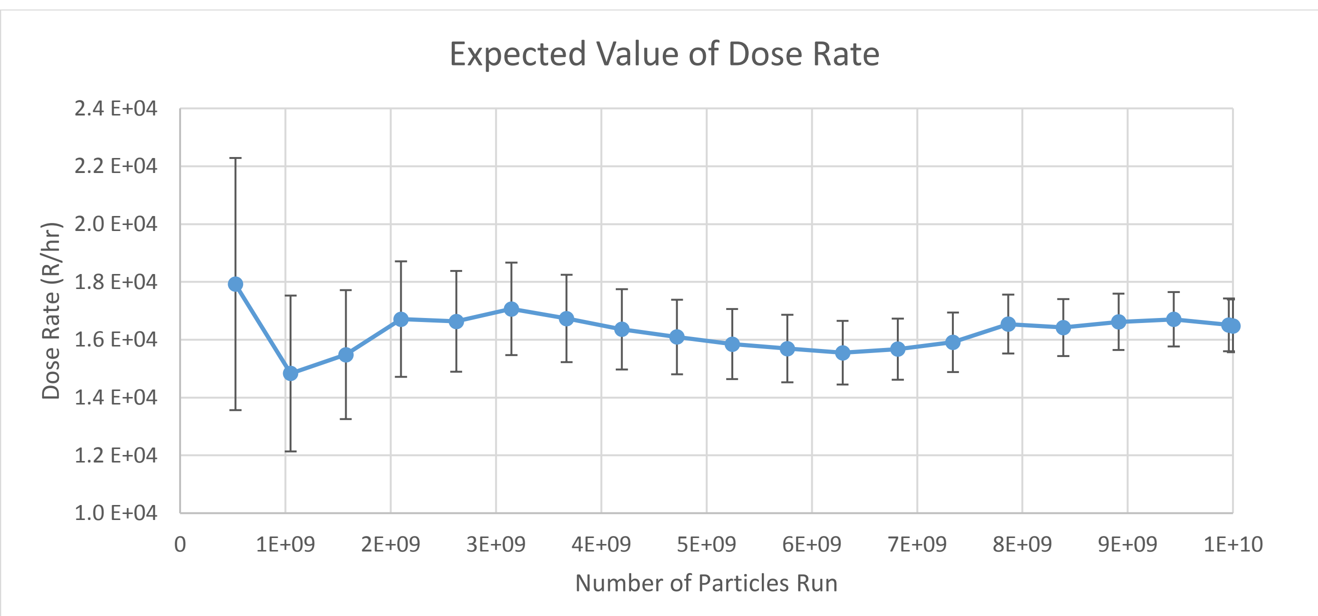

Figure 9 TFC

In an attempt to verify these results a scoping calculation was done with a program called MicroShield. MicroShield is a point kernel approximation software and can be used to deterministically calculate doses for a variety of geometries. MicroShield is not always the most accurate software for complex problems due to the line of sight method that point kernel uses, however, it is sufficient to give an approximate dose, and thereby act as a scoping calculation.

The MicroShield model was built in sections, each containing an empty channel with the dose points, and then a fueled channel and the appropriate shielding in between. After a number of these channel configurations were built up the results of each run were added. The total dose that was predicted from the MicroShield simulations was $3.316 * 10^4\ R/hr$ which is slightly higher than, but still very close to, the MCNP estimate. This agreement adds confidence to the results provided from the MCNP simulation.

5. Future Work

5.1 Inspection System

Plenty of work remains to be done to improve upon the inspection systems initial test results. The materials and geometry of the shielding for the system's on-board electronics will be optimized according to the results of the MCNP model. Further work on the electronics will include developing proper electrical connections for the robot as well as integrating a slip ring for the rotary sensor head. More work needs to be done testing the components to verify that they can survive an acceptable dose for a specified service life. Additionally, testing will be done for the deployment of the robot and finalizing the design of the individual payloads and modified closure plug.

5.2 MCNP Simulation

The first and most important area for improvement would be in increasing the accuracy of the model and in obtaining some sort of reliable benchmark data. If reliable benchmark data is able to be acquired and the simulation could reliably benchmarked to it, then the simulation would be able to be used with a higher degree of reliability in predicting the doses that will be experienced.

Another improvement, which is currently being implemented, is the modelling of the final crawler design. This model could then be placed at any location of interest within the pressure tube being simulated and the MCNP simulation could be done with the crawler. This would allow the estimates of dose to account for the shielding that the crawler will have on it for the more radiation sensitive components.

Another change that is currently being implemented is an improved source term. By creating multiple different source terms at a variety of different burnups, the effect of fuel burnup on the dose can be found. In addition, the implementation of a mid-level burnup would more closely approximate the mixed burnup configuration in the real core, which is caused by fueling different channels at different times. An activation product source term is also being investigated in order to account for the components of the reactor which become radioactive over time, also adding to the dose.

Finally, a Graphic User Interface (GUI) is being developed so that the MCNP simulations, which normally require the user to understand MCNP input code to change, can be changed by almost anyone. This GUI would be user friendly and would allow for changes to be made to the input, and for runs to be done, with the click of a few buttons.

6. Conclusions

Overall, the proposed design for a next generation inspection system for CANDU pressure tubes, while preliminary, shows significant benefit over the current model. The improved inspection package offers a number of benefits, as outlined in Section 3. In conjunction with these benefits there is an increase in the number of electronic components used and, therefore, a potential increase in radiation sensitivity. To assist with the design of radiation mitigation strategies, an MCNP simulation has been prepared. The preliminary results of the MCNP simulation, as outlined in Section 4.3 show that the majority of components will be able to survive the radiation fields, and shielding will be able to be tested for any more sensitive components. There is still additional work to be done to complete this improved inspection system, however, it promises to be a significant improvement over the current system.

Acknowledgements

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