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DEVELOPMENT OF COUNTING SYSTEM FOR WEAR MEASUREMENTS USING THIN LAYER ACTIVATION AND THE WEARING APPARATUS

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ABSTRACT

This paper focus on developing a counting system for the Wearing Apparatus, which is a device previously built to generate measurable wear on a given surface (Main Source) and to carry the fillings from it to a filter (second source). The Thin Layer Activation is a technique used to produce activity on one of the Wearing Apparatus' piece, this activity is proportional to the amount of material worn, or scrapped, from the piece's surface. Thus, by measuring the activity on those two points it is possible to measure the produced wear. The methodology used in this work is based on simulations through MCNP-X Code to find the best specifications for shielding, solid angles, detectors dimensions and collimation for the Counting System. By simulating several scenarios, each one different from the other, and analyzing the results in the form of Counts Per Second, the ideal counting system's specifications and geometry to measure the activity in the Main Source and the Filter (second source) is chosen. After that, a set of previously activated stainless steel foils were used to reproduce the real experiments' conditions, this real experiment consists of using TLA and the Wearing Apparatus, the results demonstrate that the counting system and methodology are adequate for such experiments.

1. INTRODUCTION

Wear is the cause of financial and environmental damages through several fields of work. For example, the automotive industry spends large amounts of resources every year to minimize wear on cars' engines.

To minimize wear researches are conducted on which specifications return the smaller wear rate. These researches need methods, or techniques, to obtain its data and in Tribology (the field of science that studies attrition and wear) there are several techniques available. In the nuclear context the Thin Layer Activation has several advantages for the objectives purposed in this work. TLA's principle is to induce radioactivity proportional to the wear rate in the body of study (a piston ring, for example). This is the technique used in this work.

An useful resource used to study wear is to reproduce the working conditions of a given system/machinery in the laboratory. This way, there is more control over all variables involved and also opens the possibility to study the contribution of each variable over the wear rate, the piston ring alloy's chemical composition, for example.

The built Wearing Apparatus generates wear on one of its pieces and also allows the control of some of its parameters: easiness to switch the worn piece (Main Source); lubricant oil and; the worn piece's rotation speed.

The measurement of wear using the TLA technique is done by measuring the Source's activity using two different methods: the Thin Layer Differential Method (TLM) and the Concentration Measurement Method (CMM), direct and indirect methods, respectively. To do so, the counting system must be adequate for the Wearing Apparatus' dimensions and characteristics and to be able to obtain reliable data on the wear produced through the counting rate registered.

In order to achieve this, simulations through the MCNP-vs. Code were performed, simulating several possible scenarios, which will differ from one another by the use or not of a lead shielding, the use of 1x1" or 2x2" NaI(Tl) detectors, for example and after that a series of experiments reproducing the change in the Source's activity caused by the wear to validate the counting system.

Thus, the objective of this work is to obtain an adequate counting system for the Wearing Apparatus based on the TLA technique.

2. THEORETICAL FUNDAMENTALS

2.1. Thin layer activation

The TLA induces activation on a small area from the surface to a few dozens of microns of depth. It is done by focusing a charged particles' beam onto the desired body of study and thus inducing the desired activation of nuclei in that specific volume. The activation produced by TLA is semi-constant, this is extremely necessary to keep the decrease on the Source's activity directly proportional to the amount of material removed (through wear) from the body of study. The activated piece is always referred as Main Source.

Fig. 1 shows an example of the resultant activation, with specific activity vs. depth and was produced using AIEA's TLA simulation tool [6]. This tool requires input data. The input used are the parameters most suited for our installations and resources available: proton beam at ^{56}Fe resulting in total activity of 3 MBq and specific activity of $13kBq/\mu m$, these values are used as the reference in the methodology section for the simulations using MCNP-X Code, for Main Source and filter, Counting Point One and Two, respectively. This is due to the fact that in this work the focus is the definition of the counting system and no activation using TLA will be performed.

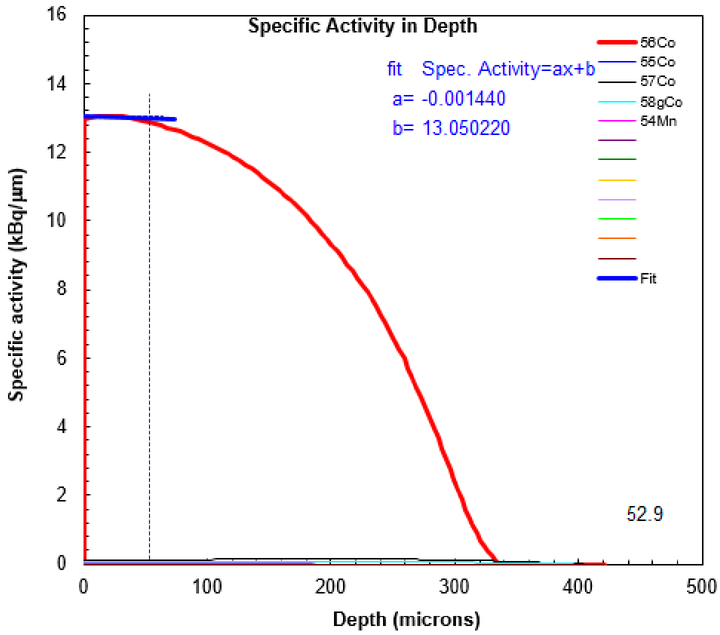

Figure 1: Specific Activity ($kBq/\mu m$) vs. Depth (μ) [6].

2.2. CMM and TLM Measuring Methods

There are two methods to measure the wear in TLA: Concentration Measuring Method (CMM) and Thin Layer Difference Method (TLM). For a better visualization on how they work it is useful to use the classic example of a combustion engine, more specifically to measure the wear on the piston ring. Also, the TLM and CMM Counting Points will be referred as One and Two, respectively, from now on.

On Fig. 2 (a) is the CMM, an indirect measuring method based on the removed material (filings) from the main activated source and the subsequent deposition of such material on a filter. This method requires some form of lubricant or refrigeration liquid to carry the filings. On Fig. 2 (b) is the TLM, the direct method. This one consists of analyzing the removal of material directly over the Main Source - the activated region on the piston.

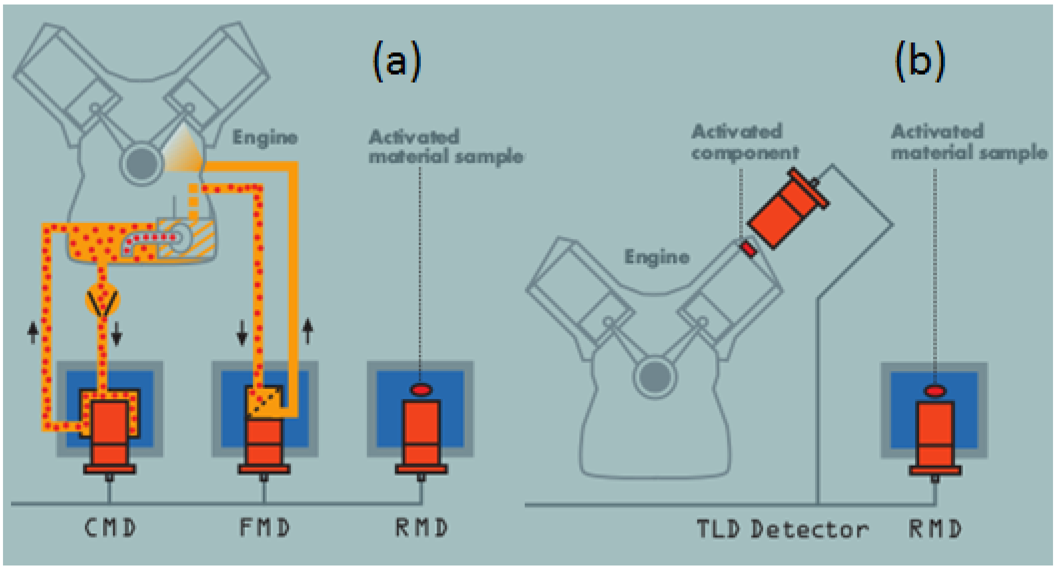

Figure 2: (a) CMM and (b) TLM [8].

2.3. Wearing Apparatus

With the activation method (TLA) and the two measuring methods (TLM and CMM) set, a description of the device that will produce the wear must follow. The description of it was shortened to contain only the parts relevant to the counting geometry studies for this work.

The Wearing Apparatus' main pieces, around which the remaining pieces will be constructed are the main disc (which is the Main Source) and the piston, both solid pieces of steel 1010 and can be seen in detail on Fig. 3, already with both bearings.

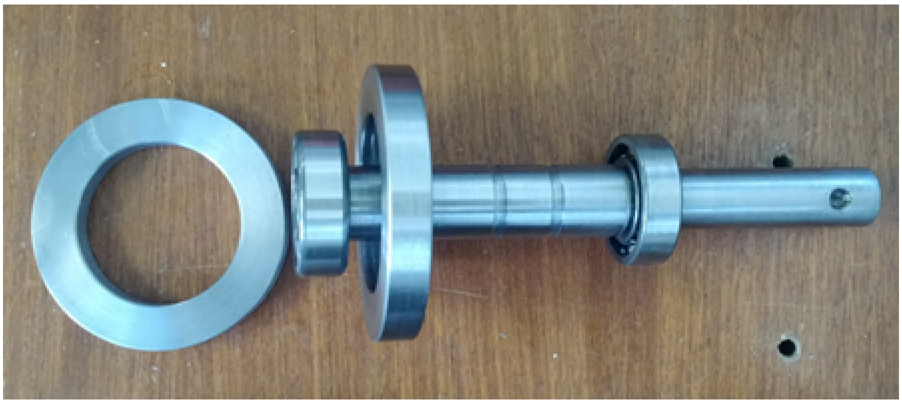

Figure 3: Main Disc (left) and Piston with bearings (right). Author, 2017

These two pieces will be rubbed together to create attrition, or wear (from this the Wearing Apparatus name comes from). The disc is fixed, unlike the piston which has a rotational movement produced by an external motor.

Those two main pieces are located inside the carapace, which is made of industrial aluminum, divided in two pieces, superior and inferior. On Fig. 4 (a) and (b), respectively we have them side by side, already with the sealing ring and retainer placed for leaking containment. In turn, the carapace has an inlet and an outlet for lubricant flow.

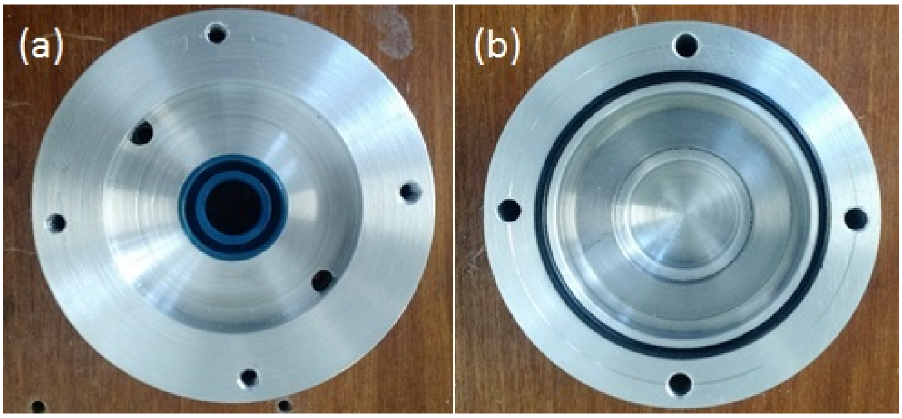

Figure 4: Carapace's two pieces. Author, 2017

Fig. 5 has a 2D scheme of the engine parts of the Wearing Apparatus with dimensions. This part is directly related to the TLM measuring method.

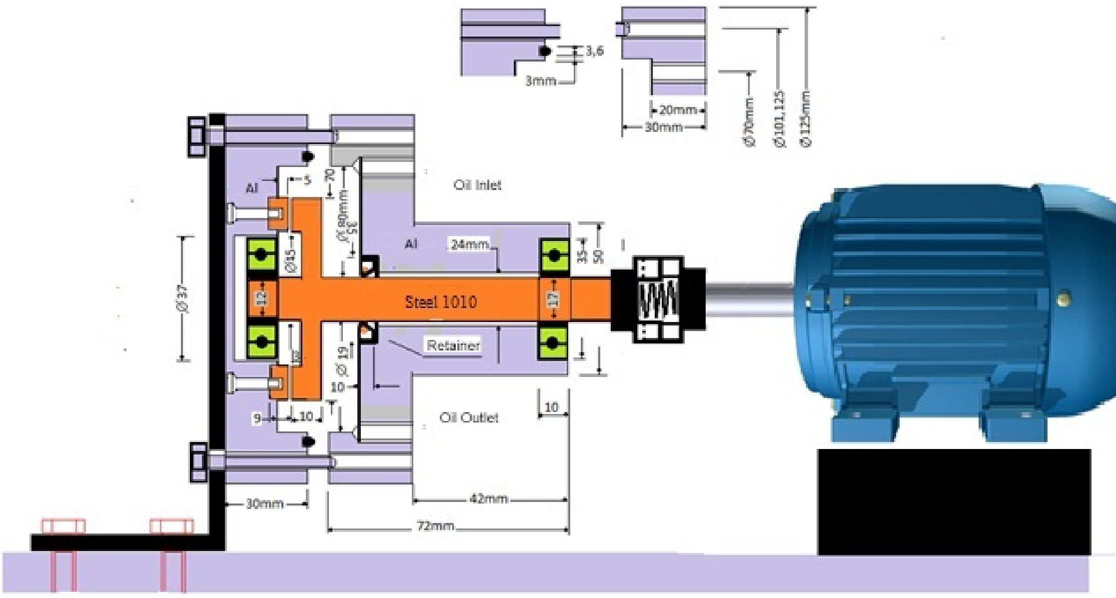

Figure 5: Wearing Apparatus 2D scheme. Author, 2017

For the CMM method there is the filter at one end of the lubricant path. Its position and the lubricant transport system, along with a wide picture of the whole Wearing Apparatus can be seen on Fig. 6.

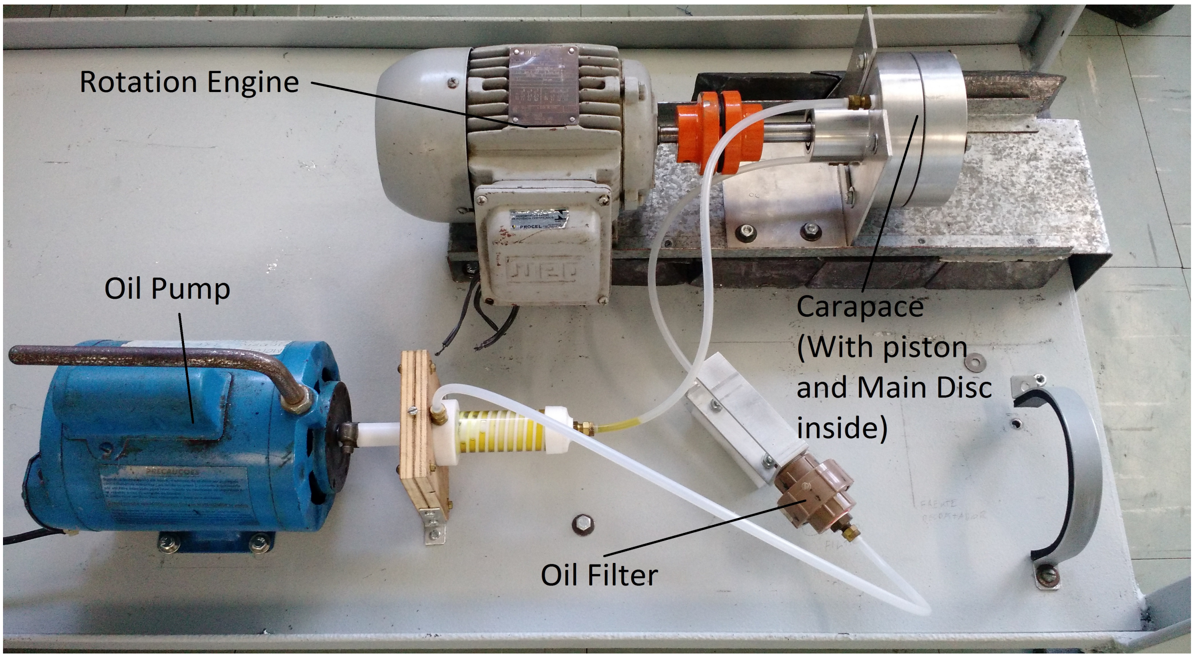

Figure 6: Complete Wearing Apparatus. Author, 2017

2.4. MCNP (Monte Carlo N-Particle)

The MCNP-X Code is a program that uses the Monte Carlo Method to simulate nuclear interactions of a variety of particles. In it, it is possible to create geometries as complex as the human body and then analyze the interaction of particles such as neutrons, photons and protons from a source with the whole geometry, the air, a human body, detectors and so on. [9]

The utility for such tool on this work is one type of result it is capable of through its built in F5 function: the efficiency distribution at a given cell, more specifically a NaI(Tl) detector. Multiplying this efficiency distribution by the number of events emitted by the source at a given time and the result is a regular Pulse Height Distribution.

3. MATERIALS AND METHODOLOGY

This section contains the description of the methodology used in the definition of the counting geometry, the detectors' specifications, solid angles, shielding and collimation. This methodology has two steps: nuclear interactions' simulation using MCNP-X Code to define the best counting geometry and system for the Wearing Apparatus and; experiments to validate efficiency, precision and stability of the counting system.

3.1. Shielding and counting geometry

Fig. 7 shows the fixed part of the simulations' geometry. It was kept the same through all scenarios. This part includes the Main Source, which is a small region of the Main Disc inside the carapace and is related to the TLM. The detector included in this image

(Detector One - TLM) helps to visualize the position of the Main Source since it is align to the activated point in the Main Disc.

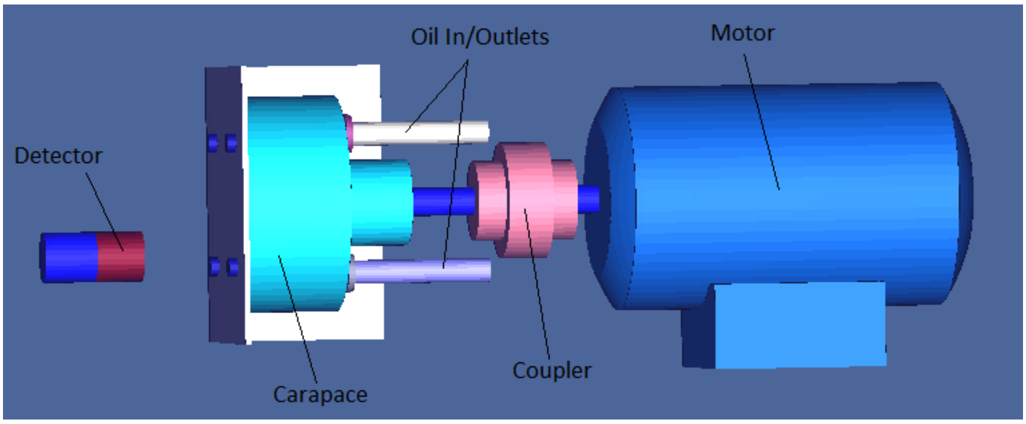

Figure 7: Wearing Apparatus from Vised 3D visualization for MCNP-X. Author, 2017

Other parts built in the simulations' geometry were: the oil filter seen on Fig. 6; the Detector Two (CMM); the table's shelves, where the Wearing Apparatus is mounted; dry air around the whole geometry; lubricant oil inside the carapace (of generic lubricant oil composition); oil in/outlets and; the sources used in the simulations, Main Source (a small activated region in the Main Disc) and the Filter (a small disc of activated filling inside of it).

Several scenarios were simulated and for every simulation, only one source was active at a time. Using the F5 function the Detectors' efficiency was obtained for each scenario for each source. This efficiency then is multiplied by the source's emitted events for one second, the final results are Counts Per Second (CPS) for each simulated Detector. Based on these CPS's the ideal scenario was chosen. The activity used for the Main Source was 3 MBq and for the filter 13 kBq, as described in the TLA section.

The simulated scenarios were composed of every possible combination for each parameter to be defined. For the Shielding there were the following possibilities: to use or not a lead shielding; square shape or cylindrical shape and; 5.1 cm or 3 cm thick. The collimation for each detector had its possibilities in the form of front hole's diameter: 1mm, 3mm, 5mm or no front side collimation, only a side/back shielding around the detectors. Detector One: 1x1" or 2x2" and; positioned 6.75 cm or 10.75 cm from the Main Source. Detector Two: 1x1" or 2x2".

3.2. Counting System and Wear Emulation Experiment

Since shielding, collimation and both detectors are set with the results from the previous section, this counting system was used on a series of experiments reproducing the increase of activity as the amount of activated material adds into the filter to test its capabilities to obtain such data.

A set of previously activated stainless steel foils were used for these experiments. Their activity and its uncertainties are listed on the Table 1.

Table 1: Foils' individual activity. Author, 2017

Foil's Number	Activity (Bq)	Uncertainty (Bq)
1	289	6
2	304	6
3	236	4

The equipment used was the 2x2" NaI(Tl) detector with coupled preamplifier and a 3 cm thick side/back shielding, spectrometer MOD-13002 with built in high voltage source. The geometry was kept the same for all experiments: foils attached to an aluminum plate in front of the detector with a 6cm gap between them. This geometry can be seen in detail in the Fig. 8.

Figure 8: Experimental geometry. Author, 2017

The background for the defined geometry was measured with 3 experiments of 20 minutes each. Then, using the same experimental standard, the foils are added to the geometry. At first only one foil was used at a time. Following, a combination of Foils 1 and 2 and later Foils 2 and 3 was used. In the final set all three foils were added to the geometry.

4. RESULTS

4.1. Shielding and counting geometry

As discussed on methodology this section aimed to define three geometry points, shielding, detectors and collimation. The results are listed below followed by details and discussions.

The ideal scenario for our experiments is: 3 cm thick square shaped lead shielding around the Wearing Apparatus and Detector One; use of 1x1" NaI(Tl) Detector on Point One; use of 2x2" NaI(Tl) Detector on Point Two and; use of 3 cm thick side/back lead shielding on Detector Two only. With these specifications the ideal scenario had the following results: Detector One with 100 CPS; Detector Two with 20 CPS and; Detector Two registering 2 CPS from the Main Source.

This scenario was defined as ideal for the Wearing Apparatus and TLA applications based on two factors: the minimal counting rate for each detector, which was defined as 10CPS in order to obtain statistically reliable data with 1% or less uncertainty for experiments of 30 min and; the counts registered on Detector Two from the Main Source must not be over 10% of the counts it will register from its own source (fillings in the filter). Also, more scenarios met these conditions, but the choice for the one described above was made based on logistic parameters. Below, are the discussions on these scenarios.

Without the shielding around the Main Source (including Wearing Apparatus and Detector One) the counts on Detector Two are greater than the ones registered from its own source, which will render it useless. The 3 cm thick option also resulted in incompatibility with the second parameter described above. Also, the cylinder shaped shielding had compatible results but was far less practical than the square shaped one. The choice for shielding, the 5.1 cm thick square shaped lead, brought the counts from Main Source on the Detector Two to 6 CPS, which is still not ideal.

For Counting Point One, both 1x1" and 2x2" are viable options from the counting rate perspective, as they registered adequate count rates, of 100 CPS and 800 CPS, respectively. The option for the 1x1" was made to keep the shielding as compact as possible, for the same reason, the distance from Main Source to Detector was defined as 6.75 cm. For Point Two, the 1x1" gave 8 times less efficiency on average, and was considered inviable, as it would require a specific activity on the Main Source greater than it is recommended for radiological protection. The 2x2" NaITl option held around 20CPS, which is reasonable but still rather close to those 6 CPS of the Main Source's influence on it.

Lastly, the collimation, as briefly discussed above, is necessary on Point Two to control the the number of events from the Main Source on the Detector Two. However, a front end collimation would result in less CPS for it. Thus, a side and rear end shielding is the choice for Detector Two, it is 3 cm thick and with it, the before mentioned counts was reduced from 6 to 2 CPS. Counting Point One does not require collimation as it has its own main shielding and the activity from the filter is vestigial compared to the Main Source.

4.2. Counting System and Wear Emulation Experiment

Now, it is possible to compare the results as a Counts vs. Source's Activity graphic. The result obtained here is seen on Fig. 8. This result was obtained only using the 2x2" NaI(Tl) Detector because the 1x1" would not be able to obtain statistically reliable data for a source with such a low activity, as seen through the simulations.

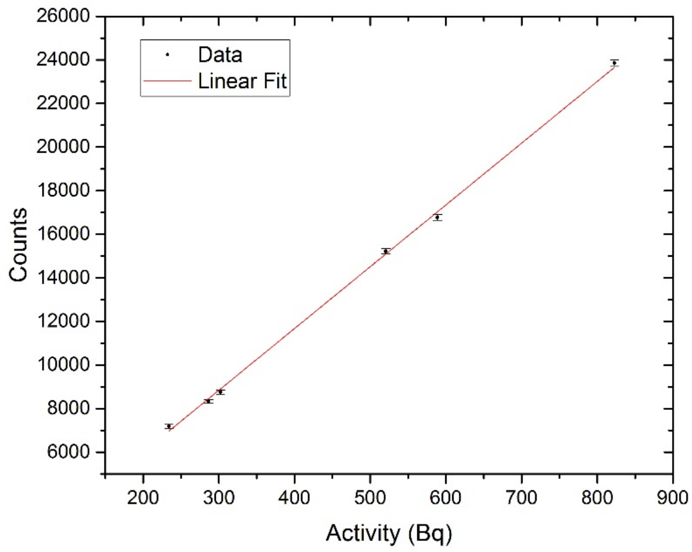

Figure 9: Wear simulated experiment, Activity vs. Counts. Author, 2017

On the real experiment as the filings will accumulate inside the filter for Counting Point Two, the expected result, as described on TLA's introduction section, is a perfect straight line. Visually all points are well adjusted to the trend line. Statistically, the $r^2 = 0.99935$ obtained through least square fitting confirms that the results are reliable and this detection system is well fit for the task.

It is important to note that the experiment had an excellent result even though the scenario used in this series of experiments is far less adequate than the ones the real experiments will face, specially the activity of the source, which is 15 times smaller than the expected (0.83 kBq compared to the 13 kBq), and the change in the geometry caused by the wear and accumulation of fillings in the filter, which will be in the order of a few microns, not millimeters. Thus, since this system was able to acquire data in this conditions, it will perform well for the real experiments. Also, this experiment could not determine wear through counts, because the foils do not have the same activity, thus the "quasi-constant" activation condition required by TLA experiments was not met. However, as seem in the previous point, the system is ready and well fit to receive an activated Main Source and perform the real experiment through it.

5. CONCLUSIONS

Throughout this work a counting system was developed with the use of simulations on MCNP-X Code. All parameters, including lead shielding, collimation, detectors specifications and solid angles were defined within limits of optimization to be fit for its task: measure the wear generated by the Wearing Apparatus on one of its pieces.

Afterwards, the counting system was put to test through a series of experiments reproducing the expected variation of activity on the filter. The result was a well fit trend line of $r^2 = 0.99935$ which confirms the system's precision and stability through the experiments. This results can be extended for the 1x1" NaI(Tl) Detector for the Main Source, because its conditions are better, with fair more activity and the change in the source's geometry even smaller.

Thus, the counting system is defined and tested as fit for its task, which was the objective of this work. Its consequences are the next works based on this system, which at first will be activation of the Main Source, after the activation the Wearing Apparatus, Counting System and Source will be available and the Thin Layer Activation line of research will be complete and ready for usage, specially those listed at the introduction of this work, for example: the ability to determine which alloys are more resistant to wear and which oil lubricant is better for a certain engine. From this point of view, this work is one of the major steps to a line of research of importance and many applications.

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