System of control of the quantity of liquid in soda cans based on gamma radiation transmission.

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ABSTRACT: Quality control is key in industrial applications. This paper is a depiction of the montage of a transmission gauge based on gamma radiation that provides a precise measurement of the volume of water inside a standard aluminum can. It is a non-invasive method production, which is an edge on industrial processes.

I. INTRODUCTION

In many industrial processes, quality controls are primordial whenever approaching a product. This paper addresses a common problem in industrial beverage production: measuring the volume of liquid inside an aluminum can with a non-invasive process. The solution given is the use of a transmission gauge via γ rays.

As it will be seen in the coming sections, the goal of this project is to design a transmission gauge and evaluate the results. Moreover a theoretical approach of the nuclear engineering concepts behind the instrumentation will be given.

II. DESCRIPTION

A. Energy of radiation and detector

The use of γ particle radiation justifies itself in a very clear way. In order to ensure minimum interaction between radiation and media the designated radiation of use is γ radiation, as α and β radiations have shorter ranges that would not go through a filled can.

The conditions on the system to measure will determine an optimal energy of the emitted particles to make sure there is a useful signal at the output. This optimal energy can be calculated in the following simplified way. It is an equation that models an exponential attenuation, not taking into account the source of attenuation (absorption, scattering, etc) and provides only the optimal energy corresponding to the position of the photopeak maximum of the γ ray used to measure. Nevertheless this is a good approximation for the application of interest. The aim of a system of control quality is to ensure that the 11.3 cm height cans are filled. Consequently, a lenght of $x = 10$ cm as the operating point. The approximate lineal attenuation coefficient is computed as

$$\mu(E) = \frac{2}{x} = 0.2cm^{-1}$$

Now, consulting the masic coefficients for water [1], taking a density of water of 1 g/cm^3, the final result can be linearly interpolated as $E_{opt} = 58.2\ keV$

At this particular energy it is needed to address the different possibilities of photon interaction with matter. With the current energy there is no possibility of pair production, so only Compton and photoelectric effects will be present. During the measuring process only the energies corresponding to the photopeak will be taken into account for the calculation of the volume inside the can.

In order to measure how much the γ radiation is transmitted through the water can there is a need for a detector. To obtain a constant measurement of the incident photons on the detector the surface of detection of said apparatus must be large enough. This leaves semiconductor detectors out of range for our current problem, as they have a tiny but precise surface of detection. This means they do not have a great efficiency and therefore a more active source or more counting time would be required. There are two options left, from which the proportional counters (Geiger Counter) will be discarded as they do not have any resolution nor consistency whatsoever for our problem.

The selection of the material was intended to achieve the best resolution possible. However, other aspects such as price, size, disponibility and the feasibility for our application must be taken into account. For example, a liquid detector is not viable for an industrial application as it would require an operator to place and remove the sample under study. Only the scintillation crystals (inorganic) will be compared, as organic materials have a much lower resolution than the inorganic detectors.

Firstly, BGO is not appropriate due to, once again, its low resolution. Secondly, $CaBr_3$(Ce) is discarded, despite of its high resolution, because of its high price and its undesirable high intrinsic background radiation. Furthermore, CsI(Tl) is discarded not only because of its poor resolution, but also because it is a non hygroscopic material, so it would require a photodiode, which is too small for our object of interest. Consequently, the final choice is be Na(Tl), which is a low cost material that gives an appropriate resolution and light output using a photomultiplier. The photomultiplier gives an appropriate size detection, and is only feasible to be used if the material is hygroscopic as Na(Tl) is. [2]

B. Source of radiation

The UPC laboratory has the following radioactive sources available: ^{22}Na, ^{60}Co, ^{90}Sr, ^{137}Cs, ^{204}Tl and ^{241}Am. Among all of these available sources, it is convenient to choose the one that emits the desired radiation with the maximum of probability. In this way, americium arises as a commonly used radioactive source used in fire alarms. It decays to ^{237}Np in α mode. The main particles and radiation emitted in this decay are: an α particle of 5485.56 keV, a variety of β^- electrons and a 59.5409 keV γ ray, with a 36% probability. This latter being the useful radiation for the given application. As previously calculated the optimal energy for water interaction is $E_{opt} = 58.2\ keV$ which is very close to the γ ray emitted by ^{241}Am. This means that because of its particular energy this γ ray will be highly interactive with water, and therefore can be used to measure transmitivity effectively.

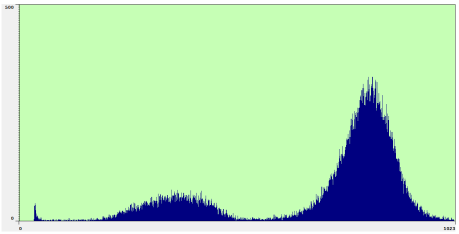

FIG. 1. ^{241}Am energy spectrum showing the 59.54 keV photopeak corresponding to the γ ray of interest (number of counts for each of the 1024 channels)

C. Set up and procedure of detection

In this section the set up of the project will be described, including the electronic devices that are outlined in figure 4.

As it has been mentioned in last section, the americium source emits gamma radiation that is transmitted through the volume of the can. Such radiation is attenuated by the water contained following an exponential relation whose parameters will be the key of the estimation of amount of water. For the moment the focus will be to understand the process that translates the radiation into information about the water.

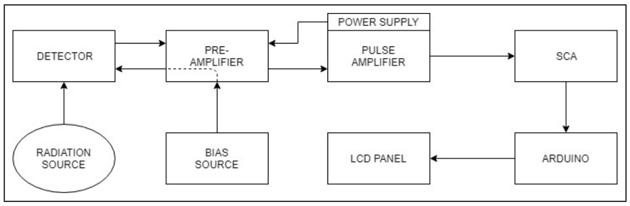

FIG. 2. Diagram of the main blocks

After leaving the can, gamma radiation fall upon the active volume of the detector. Such active volume is made of Na(Tl), which is basically Na with Tl impurities. Therefore, the gamma radiation by Compton, photoelectric and pair generation effects produce secondary electrons that ionize their surroundings of the Na(Tl), producing jumps of other electrons from BV to BC in the Na material. Subsequently, the Tl impurities have an energy such that thermal fluctuations allow the holes generated in the BV to jump to the impurity band, leading to the recombination with excited electrons in the Tl impurity energy band. Consequently, in this process Tl impurities gain an excess of energy that is emitted generaring the scillintation photons that will be interpreted by the detector.

Next, the scillintation light is converted by a photoamplifier into current in order to be quantified. The detector itself has an electron multiplying part consisting in a series of dynodes supplied by a bias source. Coming back to figure 4, this current of electrons proportional to the amount of gamma energy is converted to voltage and isolated from the rest of the system by the pre-amplifier block, while introducing a voltage gain. Subsequently, the output signal is transmitted to the amplifier, which filters overlapped pulses in order to achieve a clear signal in which the pulses for each energy (and associated voltage) are distinguishable in a spectrum. The following single channel analyzer (SCA) produces an output logic pulse under the condition that the peak amplitude of its input signal falls within the pulse-height window that is established with two preset threshold levels. These logic pulses are the input of the Arduino Due microcontroller, whose function is to make counts of how many interruptions due to these pulses take place in one minute. By callibrating the system, it is possible to derive the parameters of exponential relation between these counts and the volume of water in the can. Lastly, Arduino is connected to a LCD panel that displays both the exact amount of water and the number of counts made by the system.
In figure 3 the final setup is shown. The left of the picture shows the box in which the can under test is placed, right above the americium source and below the detector. This means the gauge is working in transmission mode, as it is the most efficient method of detection that does not imply including a tracer in the sample. The center part of the image shows the pre-amplifier, the amplifier and

the SCA, which is connected to the LCD panel through the Arduino MCU. After shedding light on the general setup, it must be taken into account that most of the processes involved in the procedure of detection involve a certain efficiency that will now be discussed.

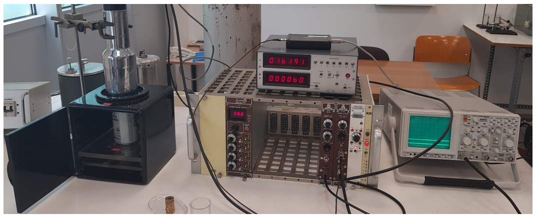

FIG. 3. Image of the final setup

D. Efficiency and resolution

In this section the efficiency of the whole system will be addressed, which is defined as the product of the scillintation efficiency (ϵ_s) and the detection efficiency (ϵ_d). On the one hand, ϵ_s is defined as the total number of scillintation photons per 1 MeV of incident radiation energy. Even though it depends on the material, the type of particle and temperature, its usual value is 12%. On the other hand, ϵ_d is theoretically computed as the product of a series of efficiencies that will now be mentioned.
The source radiates in all directions, which makes that radiation will follow highly different paths. Therefore a series of geometrical parameters are defined, including the geometric factor (f_g), retrodispersion coefficient (f_b), reabsorption factor (f_a) and medium coefficient (f_m). Also, the intrinsic efficiency ϵ_i is dependent of the energy of the radiation. It is given by the possibility that some photons that correctly reach the detector are not actually detected. [2] [4]

All in all, the total efficiency would be computed as the product of the above. Nevertheless, the calibration curve of the number of counts in relation to the amount of water will be ellaborated instead. Even though such counts are affected by the efficiency, it will not have any effect on the results.

However, it is important to have a good resolution of the number of counts. Ideally, the spectrum associated to a radiation of a certain energy E_0 would be only a peak at that value. Nevertheless, the processes involved in the active volume (generation of secondary electrons and scintillation light emission) have an associated standard deviation that produce fluctuations in the charge collected by the pre-amplifier. This will be translated into a broadening of the peak of energy at the spectrum of energies. Consequently, a good resolution would allow to distinguish two peaks of close energy. In order to improve it, the setup includes a collimator that focalizes the output radiation of the source in a certain direction, decreasing the influence of the geometric factor and the loss of precision due to dispersion. It is placed between the source and the sample. [2]

E. Background influence

Without the presence of a source a detector will always measure radiation, this is called radiation background. It is due to a variety of natural phenomena that produces radioactive emissions. This said background will always be present in all the measurements. But as a calibration is performed, this background radiation will not affect the measurement since it will be the same for all the calibration points. If for any reason this background affected the measure the detection setup would need to be isolated from the external radiation, this is achieved through lead armor-plating. This would be necessary if a calibration process was not carried out, but for this application it is not necessary and would complicate the setup since a specially tailored armor for the setup would be needed.

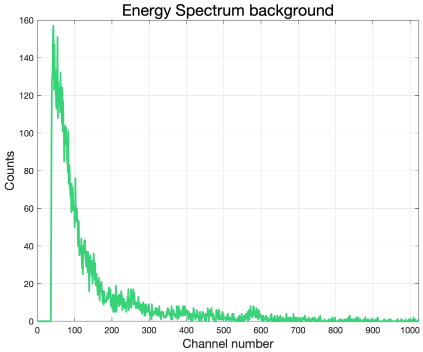

FIG. 4. Energy Spectrum Background

III. CALIBRATION PROCESS

After the setup is mounted, the next step is to calibrate it for the desired purpose. To do so it is necessary to know first the energy range of the gamma ray viewed by the electronics. This is achieved by using an MCA (Multiple Channel Analyzer), this device is used to observe the full spectrum and to adjust the voltage and gains accordingly. After adjusting the photopeak on the range of 6-9V a simpler device can be used: the SCA (Single Channel Analyzer) since now the working range is known. To further tune the best SCA window a test was performed trying diferent windows with width 0.5V. Those tests revealed that adjusting the SCA window to $[6.5, 8]$ V is the best as the number of counts yielded is the highest. Thus the SCA will give the number of counts in this voltage range that correspond to the photopeak. Using the relation between counts and volume a precise measurement of the volume can be achieved.

To obtain a good $Volume(counts/min)$ expression, which has an exponential form, an experimental calibration is needed. Measuring several times the number of counts per minute for known volumes and computing the average value of those gives an experimental calibration curve. This curve can then be interpolated using an exponential approximation. For the chosen setup the calibrated $Volume(counts/min)$ expression is:

$$Volume = 2084 - 200 \cdot ln(counts\ in\ 1\ min)$$

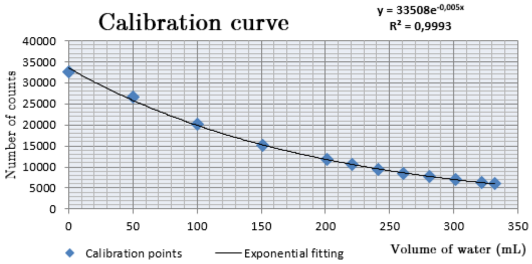

FIG. 5. Calibration curve representation and equation

With this relation Arduino is capable of computing the volume of liquid inside the soda can. It accumulates the number of counts in a minute using an interrupt command. Subsequently, the computed volume is displayed in the LCD panel.

IV. RESULTS

From the calibration done and the coded program the system is tested with different volumes of water inside the can, all performed in the same initial conditions regarding temperature, background, geometric distribution and source. The results in table I show how the relative error is below 5%.

Weighted mL	Radiated mL	Relative error (%)
85.2	85.4	0.223
173.13	166.81	3.78
218.76	220.11	0.61
269.83	266.92	1

TABLE I. Experimental tests results. Weighted and radiated mL make reference to the way each volume is calculated (using a scale and the transmission gauge respectively)

V. CONCLUSIONS

The present project shows how the elaboration of a calibration has a really good performance in terms of finding out information of the system, even without the knowledge of certain variables. In this case, it is possible to figure out the volume of the water inside the can without taking into account the exact dimensions of the can nor the efficiencies of the different processes described in sections II C and II D, for example. Carrying out a meticulous averaging of a series of measurements for a certain amount of water, it is possible to achieve good results, regardless of the aleatory behaviour of intrinsic variables of the detection process that inevitably introduce an error on the measurement. It must be mentioned that the paper does not take into account such error within the calculations.

Other important aspect to be mentioned is the sensitivity of the systems to small changes in the initial conditions. A slight change in the detector position, the amplifier gain, the temperature or even the periodically changes of the background radiation can have a significant impact. In any case, these variables can be controlled or considered so as to maintain good results. Lastly, the measurements could be improved by choosing better detection material and instrumentation devices, which is a trade-off with the application that the system might take. Also averaging each point of the calibration curve over a higher number of experiments would increase the precision of the gauge. The measurements could also be improved by maintaining the initial conditions as fixed as possible (geometric distribution and voltages) or by choosing a more costly detector ($LaBr_3(Ce)$ or SrI_2).

From the results obtained the conclusion is that the assembled transmission gauge has a precise functioning and fulfills its original objective in an economic, and simple way in an industrial context.

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[1] ”Measurement and detection of radiation” Taylor Francis, 1995.

[2] ”Radioisotope Gauges for Industrial Process Measurements” Geir Anton Johansen Peter Jackson, 2004.

[3] `https://www.nndc.bnl.gov/nudat2/`

[4] ”Radiation Detection and Measurement” Glenn F. Knoll, 2010. ”X-ray and gamma-ray standards for detector calibration” IAEA, 1991.