

Radial void fraction measurement of a randomly
packed pebble-bed

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Abstract

This report describes the research that was done on a scaled model (1:10) of the HTR-10 pebble-bed reactor in China. The purpose of the research was to determine the radial void fraction of the pebble-bed. The void fraction distribution of the pebble-bed is key to determining the correct neutronics for sustaining criticality. The porosity of the pebble-bed is very important to the mechanics of heat and mass transfer and also flow and pressure drop of the coolant throughout the pebble-bed.

The void fraction can be determined in a number of ways, in this setup the void fraction is obtained using a gamma ray tomography experiment. The main advantage of the tomography experiment is that it is a nondestructive method of obtaining the void fraction distribution. Since the gamma source has a Poisson distribution, long measurement times will be needed for accurate results.

In this report it is shown that the gamma-ray tomography experiment is an accurate way of determining the radial porosity density. In 4 days time a complete profile of the pebble-bed with a diameter of 229 [mm] +/- 0.5 [mm] could be obtained with steps of 1 [mm]. The collimator, and thus resolution, has a width of 2 [mm] in lateral direction. The measurement was performed by using the γ 's from the 60 [keV] peak of an Am-241 source. It was found that temperature has a significant influence on the background radiation and a negligible influence on the measurements with the Am-241 source. The placing of the source in the mounting piece must be done consistently in the same way, variations of up to 50% can occur if this is not controlled. However by using marking this variation becomes negligible. The attenuation of PMMA at 60 [keV] measured with the PebBEx facility is 0.224 and in good agreement with the theoretical value of 0.229. It was also found that compensating for build up effects is necessary, build up effects have an influence of about 1,5% in the void fraction. The results of the full scan that was performed comply with research done by others like Goodling [5].

Chapter 1

Introduction

Since of couple of years back the political view on nuclear energy in the Netherlands is changing. This change is driven by the need to reduce greenhouse gas emissions and also driven by the need to reduce the dependency on energy from less stable countries to fuel our country. Below is the conclusion from the debate on nuclear power in the Netherlands on March 2008.

Tot 2020 worden geen nieuwe kerncentrales gebouwd, maar het denkproces over kernenergie staat niet stil. Nieuwe technologische ontwikkelingen kunnen ertoe leiden dat op termijn wel nieuwe centrales worden gebouwd. Deze boodschap droegen de ministers van Economische Zaken Maria van der Hoeven (CDA) en minister van Milieubeleid Jacqueline Cramer (PvdA) woensdag gezamenlijk uit in de Tweede Kamer.[1]

There are still a couple of problems facing nuclear energy and one of them is the safety aspect. The fear of an accident happening either because of human error or due to a terrorist attack is large. Conventional nuclear power plants stack defense systems one after the other to improve their 'defense-in-depth'. This brings along quite some problems besides increasing the cost of the plant, the complexity of multiple systems makes it difficult to assess as to how safe the plant really is and the chance for human error could be larger with these complex systems. The pebble-bed reactor, which is one of the generation IV reactors [2], tries to solve this issue by being an inherently safe nuclear reactor.

1.1 Pebble-bed reactors

In pebble-bed reactors the fuel is contained in pebbles of graphite rather than in metallic rods which are used in reactors like the BWR (Boiling-Water Reactor) and PWR (Pressurized Water Reactor). The graphite pebbles of typically 60 [mm] in diameter contain about 5000 to 20.000 coated triso particles. These triso particles contain a fuel kernel of UO_2 . The pebble-bed reactor has two

major benefits. The first one is because of the gas coolant, since the pebbles can moderate themselves (they are like minireactors) the reactor can be cooled with an inert gas like helium. An inert gas is not reactive under normal circumstances and the gas does not get radioactive as fast as water, which is used in 'conventional' PWR. Because of the higher working temperature of the reactor the energy conversion efficiency improves. The low power density and high temperature resistance of the core materials ensure that any decay heat will be dissipated and transported to the environment without the decay heat causing a meltdown.

In Germany a pebble-bed reactor, the AVR (working group test reactor) was build in the sixties to serve as a showcase experimental reactor and as a showcase to how safe this new form of technology was. However in the year 1988, after 21 years of service, the reactor was shutdown in the wake of the Chernobyl disaster and operating problems they had at the reactor. Currently there is one working prototype of the pebble-bed reactor in China the so called HTR-10, standing for High Temperature Reactor (10MW). Multiple pebble-bed reactors are being designed for construction in South Africa to supply a large part of their energy needs and accepting pebble-bed reactors as a solution to their growing energy consumption.

1.2 Outline of the thesis

Chapter two will consist of the theoretical background regarding pebble-bed reactor technology as well as some basics on radiation and nuclear technology. In chapter three the facility used for the measurement will be explained. In this chapter the hardware will be reviewed as well as the possibilities of the facility. Chapter four will explain the approach to get accurate results. Chapter five will discuss the way data is interpreted and handled. After that, in chapter six, there will be room for conclusions and recommendations.

Chapter 2

Theoretical background

In this chapter certain key aspects of working with a gamma ray tomography experiment are explained in detail.

2.1 Radiation basics

Radioactive isotopes decay to stable isotopes by radioactive decay. The energy release of this process is accompanied by emission of radiation in the form of α -, β - and γ -rays. In γ -transmission sources emitting γ -rays are used to measure the attenuation of materials.[3]

2.2 Poisson distribution

The emission of radiation is a statistical process which is a very important aspect while measuring radiation. The radioactive decay of a nucleus is a statistical process where there are two possibilities, a chance p that the nucleus decays and a chance $1-p$ that the nucleus doesn't decay. All of the nuclei in which this process can occur are independent from each other. Because of this independence the total process can be viewed as a repeating decay process. The binomial chance distribution describes the process of k successes by n repeated processes, this is given by

$$P(k) = \frac{n!}{k!(n-k)!} p^k (1-p)^{(n-k)} \quad (2.1)$$

The expected value of this process is $\mu = np$ with a spread of $\sigma = \sqrt{np(1-p)}$. While measuring with radioactive sources the number of possible nuclei n is usually very large. This changes the distribution to the simpler Poisson distribution

$$P(k) = \frac{\lambda^k}{k!} e^{-\lambda} \quad (2.2)$$

With an expected value of $\mu = \lambda$ and a standard deviation of $\sigma = \sqrt{\lambda}$. If in a single experiment a number N has been counted and the above distribution is true then the standard deviation can be guessed as following

$$s = \sqrt{N} \quad (2.3)$$

2.3 Pebble-bed reactors

In the core of the pebble-bed reactor there might be two types of balls, namely graphite and fuel balls. The graphite balls fill the cylindrical centre of the pebble-bed and fuel balls surround the graphite balls. Both the graphite and the fuel balls are extracted from the bottom and reinserted (or replaced in case of burn up) on the top of the pebble-bed. This extracting and reinserting gives rise to a ball velocity of about 4.5[mm/h] [4]. Since this flow is slow we can approximate the pebble-bed as a fixed packed bed.

The porosity of the pebble-bed is very important to the mechanisms of heat and mass transfer and also flow and pressure drop of the coolant throughout the pebble-bed. Because of the sensitivity of those mechanisms to the porosity it becomes important to know the porosity distribution inside the pebble-bed and knowledge of the porosity is necessary for any rigorous analysis of the transport phenomena in the bed.[5]

The geometry in the packing of a pebble-bed is interrupted at the wall and this gives rise to large porosity variations near the wall. The flow through a medium depends on this porosity and because of the wall disturbance in the porosity profile of the pebble-bed the velocity profile (of the cooling gas) is also disturbed. This phenomenon is called wall-channeling.[6]

By researching the wall channeling effect, a better porosity profile can be obtained and this knowledge can lead to better and more efficient pebble-bed reactors. Both the bottom and the sides of a pebble-bed influence the pebble-bed porosity profile. Research has been done by Bedenig [7] and he discovered that up till five pebble diameters the effect of wall channeling (from the bottom plate) could be measured by filling the pebble-bed with water and checking the water level.

Goodling [5] used an epoxy harsh to fill the packed bed and weighted the amount of epoxy harsh to determine the void fraction. With his research he confirmed the wall channeling effect was noticeable to around five pebble diameters deep measured from the sides. According to Goodling the void fraction oscillated around the mean value and reached unity at the wall, figure 2.1 shows this oscillation. A mathematical expression was proposed by Cohen and Metzner [8] to describe the oscillatory variation.

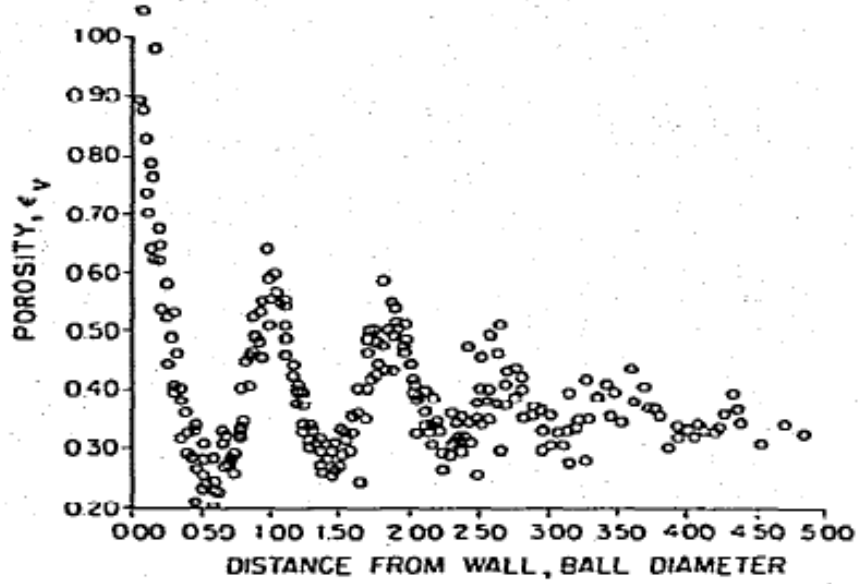


Figure 2.1: Composite data for uni-sized sphere's [5]

One of the concluding remarks of the research of du Toit [9] is that significant local variation can occur in the porosity, so it's important to average values to obtain a radial profile.

2.4 Gamma-ray tomography experiment

The gamma-ray tomography experiment consists of a gamma ray source and a detector with in-between the pebble-bed. The biggest benefits of using gamma-ray tomography is that it is non-intrusive and accurate (given time) [10]. Two collimators are used to narrow the beam of gamma rays to the detectors. The intensity of a narrow gamma ray beam is given by the following relation

$$I = I_0 e^{-\mu d} \quad (2.4)$$

Where μ is the linear attenuation of the material placed in between the detector and the source, d is the thickness of the material in between and I_0 is the count rate measured in vacuum. This equation expands to the following relation when multiple materials are in between the source and detector

$$I = I_0 e^{-\mu_m d} e^{-(\mu_A d_A + \mu_B d_B)} \quad (2.5)$$

The two calibration measurement are given by, where acry (short for acrylic) stands for a completely filled reactor and air stand for an empty (filled with air) reactor

$$I_{air} = I_0 e^{-\mu_m d} e^{-\mu_{air} d_{air}} \quad (2.6)$$

$$I_{pers} = I_0 e^{-\mu_m d} e^{-\mu_{acry} d_{acry}} \quad (2.7)$$

Combining equations (2.5),(2.6) and (2.7) and substituting A for air and B for acrylic we obtain

$$\frac{\ln(I) - \ln(I_{air})}{\ln(I_{acry}) - \ln(I_{air})} = \frac{d_{acry}}{d} = \alpha \quad (2.8)$$

In Eq. 2.8, α is the chordal void fraction. Eq. 2.8 is independent of I_0 which in turn depends on the source strength, detector efficiency and a number of other variables. Simply by using two calibration measurements (filled and empty) there will be enough information to determine the thickness at all of the count rates measured. To ensure that the height of the pebble-bed is equal to the height used for the air and the acrylic layer a calculation of the number of grams needed to fill the pebble-bed to a height of h is made. This gives a total mass M_{pebble} of

$$M_{pebble} = \frac{\rho(1 - \epsilon)\pi D^2 h}{4} \quad (2.9)$$

Where ρ is the density of the acrylic pebbles, $\frac{\pi D^2}{4}$ is the cross-sectional area of the cylinder and ϵ is the average void fraction for a certain d/D ratio, this is the ratio of the diameter of the pebbles to the diameter of the cylinder. This average void fraction is given by [11]

$$\epsilon = 0.375 + 0.34 \frac{d_{pebble}}{D_{cylinder}} \quad (2.10)$$

A perfectly uniform surface cannot be obtained, however when placing the pebbles in the experimental setup great care is taken to make the surface as flat as possible. Using pressure on the surface will influence the total positioning of the pebbles and thus potentially spoiling the experiment.

Chapter 3

”Pebble-bed Experiment”

The PebBEx facility has been built in Q4 of 2007 and Q1 of 2008 at the R3 department of Delft University of Technology. The facility is a scaled down version of the HTR-10, which is currently active in China. The PebBEx facility has been build to research the stacking behavior of packed beds and to get a better understanding of wall channeling effects. The setup was made in such a way that accurate measurements of the radial void fraction/porosity profile could be obtained. The setup consists of a tomography experiment explained in 2.4, a thermocouple setup and equipment for processing the data. A labview code was written to facilitate the long measurement times needed for accurate results.

3.1 Reactor vessel

The facility is supposed to be a scale model of the HTR-10, ideally that would mean a diameter of 20 [cm] and a height of 30[cm]. In the setup an acrylic cylinder is used with an outer diameter of 240 [mm], an inner diameter of 229 [mm] +/- 0.5 [mm] and a height of 300 [mm]. By using acrylic the setup stays transparent which makes the positioning of the detector and the source easier.

The pebbles used, which are also made of acrylic, have a diameter of 12.7[mm] so that

$$\frac{Diameterreactorvessel(D)}{Diameterpebbles(d)} = 18.03 \quad (3.1)$$

which is chosen based on publication in pebble-bed measurements. The HTR-10 has a diameter of 180 [cm] and pebbles with a diameter of 6 [cm] which results in a D/d ratio of 30. [12]

3.2 Motors

The setup uses two step motors of the same type with both a unique function. One of the motors translates the reactor vessel, while the other motor rotates the complete setup. The rotation of the pebble-bed during measurements is very important because (as has been stated earlier) there is a large variation in the void fraction locally. The rotation is low geared by an o-ring belt to accommodate very low rotation speeds.

3.3 Signal

One of the challenges while creating an experimental setup is making sure the efficiency is maximized. Meaning the best possible result is as short as possible time window. One of the largest limitations in the PebBEx facility is that the decay of nuclei is Poisson distributed. A low amount of total (decay) counts will mean high uncertainty in the result. For the course of the measurement the minimum amount of 10.000 counts had to be passed for a measurement was found useful, this gives a standard deviation of \sqrt{N} , 100 counts. Because of the effects of background radiation the actual uncertainty for each measurement is a bit higher than 1% depending on the background/signal ratio.

Using a strong source will allow us to reduce the measurement time, increase the accuracy of the data and decrease the width of the collimator giving us a finer grid of measurement points. The source used in this experiment is an Am-241 source which had an activity of 11,1 GBq on 01-01-1968 with a half-life of 432,6 year. The Am-241 source has an intensity distribution shown in figure 3.1.

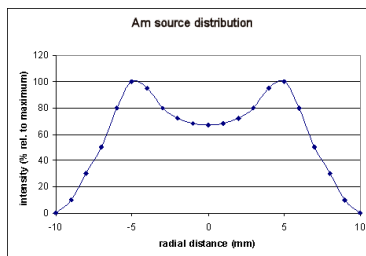


Figure 3.1: The intensity distribution of the Am-241 source

The collimators and detectors are set 5 [mm] from the center of the Am-241 source on the point of maximum intensity. The collimator used is constructed of two connected circles with a 2 [mm] diameter which can be viewed in figure 3.2, by using this form enough signal is kept and the finest detail is 2 [mm] in the radial axis. In the middle using a collimator with this shape will give rise to problems, but since we are interested in what happens in the first five pebble diameters of the pebble-bed we won't have to change it.

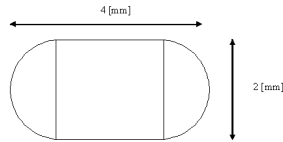


Figure 3.2: The collimator is built up of two connected circles with a 2 [mm] diameter

3.4 Amplifiers and energy windows

The scintillation detectors create pulses caused by the capture of γ -rays. These pulses are amplified by a factor 300 in an amplifier (Appendix A.1). After the pulses have been amplified a certain energy window is selected by using a single channel analyzer (Appendix A.2). This energy window is set from 7.2 [V] to 8.2 [V] so to select the amplified Am-241 60 [keV] peak. In section 5.2 are the measurements that were performed to find these settings. Figure 3.3 shows the spectrum of Am-241.

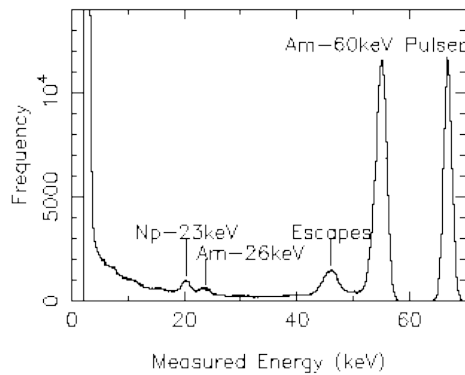


Figure 3.3: A spectrum of Am-241

The data can be read from both the rate meter as well as the labview program. The measurements are very sensitive to the equipment used, changing a piece of the equipment (with the same settings) will change the outcome of the measurements. Figure 3.4 shows an overview of the facility.

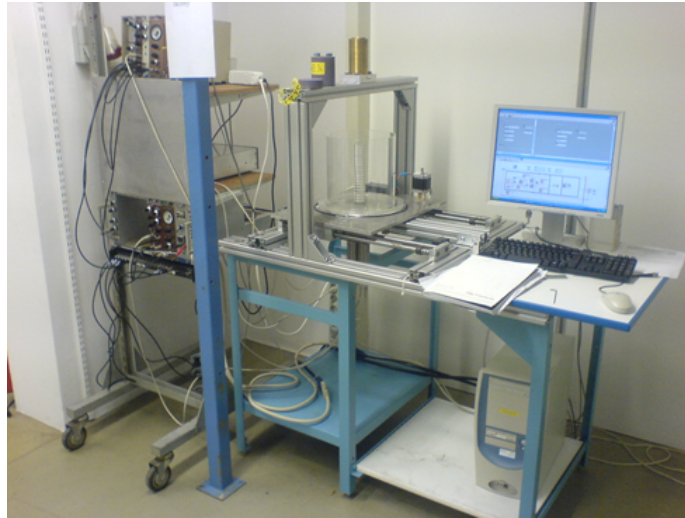


Figure 3.4: The PebBEx Facility

Chapter 4

Experimental procedure

4.1 Focus of the research

As has been stated earlier we are interested in the radial porosity profile because of its importance on flow characteristics. However, before the measurement on the pebble-bed can start there will have to be some checks on whether the theory presented is complete and valid for this case.

4.2 Strategy

Measuring of the void fraction will be done by viewing it as a two phase non-flow problem where the intensities are measured of both the filling substances, namely air and acrylic as reference points. As calibration there will be two measurements, namely one where the pebble-bed is empty and a measurement where the pebble-bed is filled to the maximum. This exact height will have to be reproduced by the pebble-bed. The pebbles are distributed in such a way that the top surface of the pebble-bed is as uniform as possible.

It's very important nothing changes in the setup while measuring because the removal or adding of new equipment will most certainly influence the measurement.

4.3 Validating the theory

To validate the theory 20 acrylic disks were made with a height of 10 [mm]. These acrylic disks had to simulate the pebble-bed with the large advantage that the real void fraction was known beforehand. Using this method a number of errors were removed, errors like faulty equipment and software bugs. By plotting out the real void fraction against the measured void fraction a sense of how accurate the measuring installation is can be obtained and ways to improve the facility can be researched.

4.4 Source angle

One of the early problems was the fact that the source had to be remounted each time a new measurement was to be made. In this mounting of the source there was quite a bit of space to put the source. After measurements it became clear that the source strength was dependent on the angle and position of the source. The obvious solution would be to make sure the source stayed at the same location during all measurements. Since not removing the source was not an option due to the refilling of the reactor the source mount was marked so that the placing of the source would not influence the end result, this measurement will be visible in section 5.1.

4.5 Detector management

At the start of the PebBEx facility there were two detectors used. The idea was that while using two detectors, twice as much data could be obtained while keeping a small resolution. Gathering the same amount of data with one detector would mean an increase in resolution. However a choice had to be made whether to give one detector high amount of signal, by turning the source in the appropriate angle or to give both detectors less signal. The measurement time of a full scan is what is important while measuring, so one detector with a lot of signal was more beneficial then two with a lower signal. The two detectors didn't behave in the exact same way and it wouldn't be possible to add the information given by both detectors, the information would have to be split. Finally the reason for using only one detector came from the way the labview program and facility was build. It is not possible to measure two detectors apart from each other with the amount of equipment available meaning that the slowest detector would set the pace of the measurement.

4.6 The pebble-bed

In the theory there are two calibration points namely a filled bed and an empty one. Creating a certain height h with the acrylic cylinders is no problem. However recreating this exact height with the pebble-bed is impossible due to the fact that the pebble-bed surface layer will never be flat. Techniques could be used to flatten the surface but this would have an effect on the pebble-bed packing and potentially mess up the measurements.

As has been shown by Kose [13] earthquakes can have an impact on the packing fraction of a pebble-bed. This introduces another problem, since an earthquake has such an influence on the pebble-bed we should also be careful as to how we fill the pebble-bed in the first place. Reactors are filled with pebbles one by one and this strategy is partly adopted for filling the PebBEx facility. The first 95% of the pebbles were placed in roughly at the same time and the last 5% were done one by one by hand. This way a (by approximation) flat surface was created.

4.7 Temperature measurements

Since temperature effects can have an influence on the equipment used in the setup, namely the amplifier and energy window, measurements were made to discover the influence of the temperature on the overall system. This is done by adding a thermocouple to the installation and letting labview read the thermocouple measurements.

Chapter 5

Results

5.1 Rotation of the Am-241 source

In this section there are two measurements shown, one where the angle and position is changed and how this influences the two detectors and a measurement whereby the mounting markings are used to place the source in the same place.

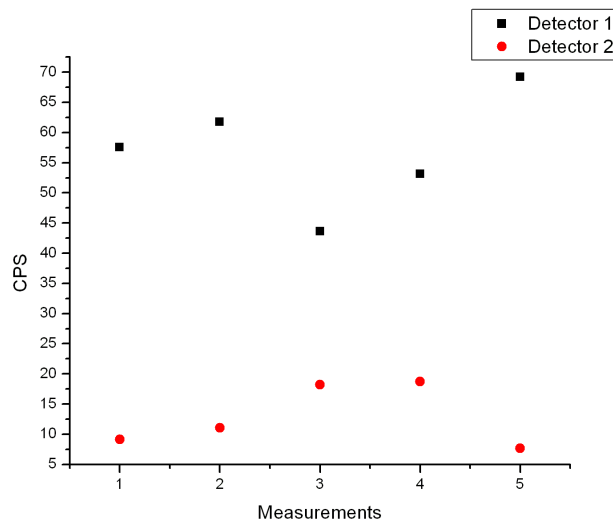


Figure 5.1: Count rate in measurements 1 to 5, in the course of these 5 measurements the source was rotated 360 degree. The count rate changes are larger then what would be expected from Poisson distribution (1%)

In 5.1 we see what happens to the signals when we change the angle of the

source relative to the mounting piece. Besides the rotation of the source, the source was also slightly moved in the lateral direction. The changes in count rate are much larger than what would be expected from Poisson distribution (1%).

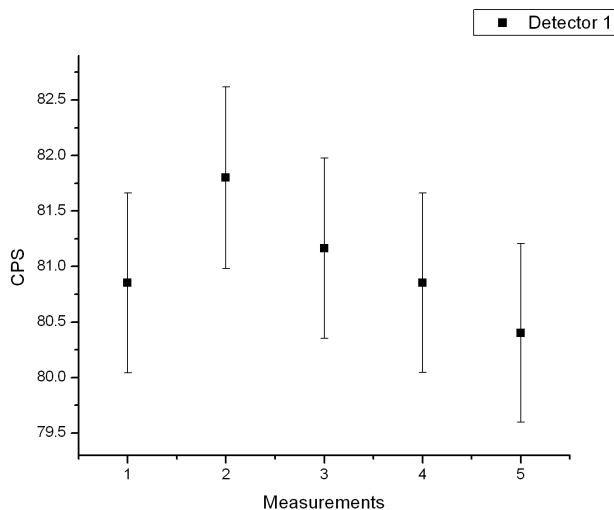


Figure 5.2: Count rate in measurements 1 to 5, the source was placed by using mount markings. The count rate changes are within the variation expected from Poisson distribution (1%)

In 5.2 the mount markings were used to position the source in the same place as before, the plotted error is the amount of error you would expect from just the Poisson distribution, which is again 1%. As can be deduced from the two figures the influence of source rotation is very large but by using the mount marking this influence can be reduced to within acceptable bounds. This rotating of the source only influences the calibration measurements since the measurement of the full pebble-bed will be a single measurement whereby the source will not be touched.

5.2 Amplification and energy window settings

Measurements of the energy spectrum of the Am-241 source were made. One with an amplification of 75 and one with an amplification of 300. These measurements were made to select the ideal amplification and energy window.

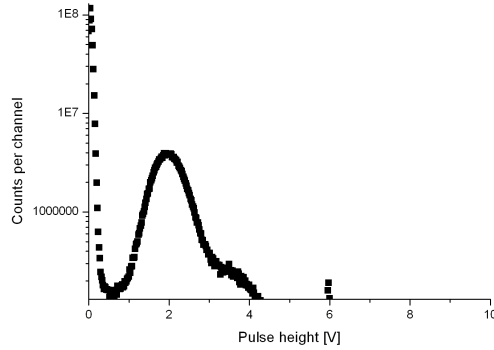


Figure 5.3: Energy spectrum of the Am-241 source with an amplification of 75

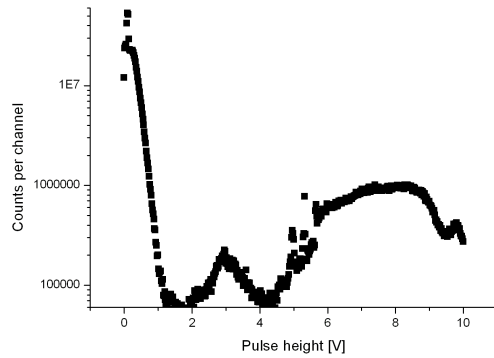


Figure 5.4: Energy spectrum of the Am-241 source with an amplification of 300

In figure 5.3 we can clearly see the 60 [keV] peak, at around 2 volts. In figure 5.4 this peak is smeared out from 6 to 9 volts. The reason the choice was made for an amplification of 300 and an energy window of 7.2-8.2 [V] is that the signal is very stable in this region and small temperature fluctuation will have less effect on the signal than if a peak point would have been selected.

5.3 Calibration measurements

Calibration measurements were performed to validate our measuring setup.

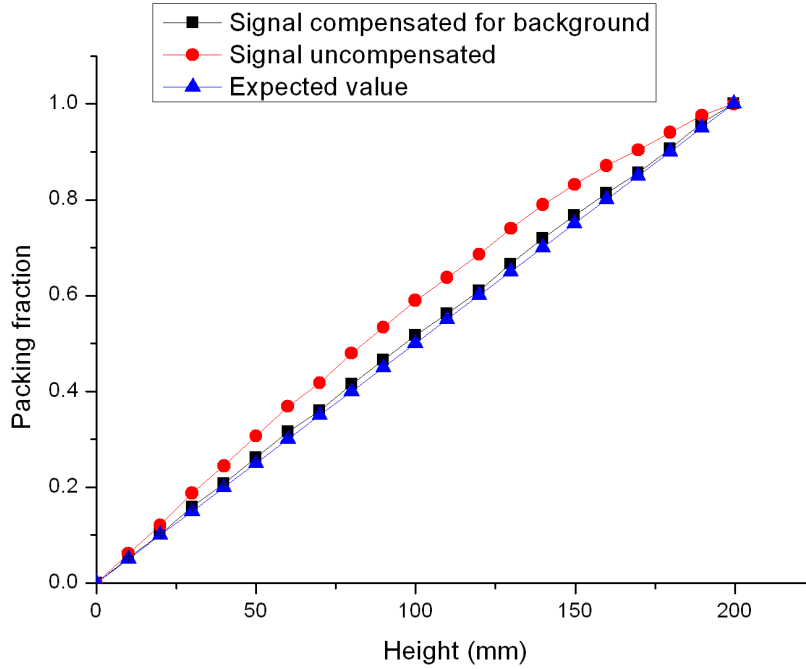


Figure 5.5: Packing fraction of 10 [mm] disks calculated from count rate measurements

In figure 5.5 there are three lines. The red/circle line is the signal not compensated for the background and the black/cube line is that same signal compensated for the measured background radiation. The blue/triangle line is the calculated void fraction, this void fraction is calculated by measuring and adding the height of the acrylic cylinders in the pebble-bed. After compensating for the background there is still a clear difference in measured void fraction and calculated void fraction. The difference might be caused by effects like build-up. To compensate for the effects that cause the difference a fit is made to extract a formula. This formula is used to calculate the void fraction given a certain amount of signal. In figure 5.6 we see this first exponential decay fit.

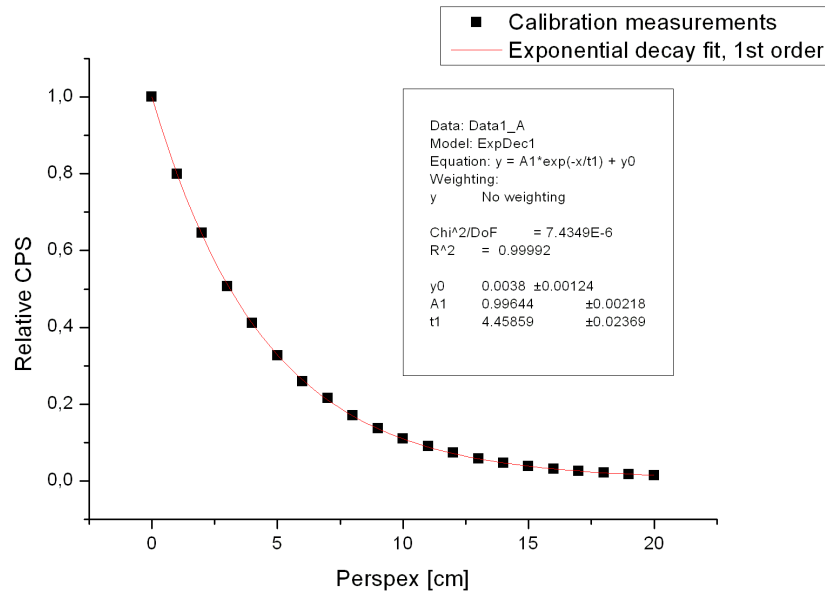


Figure 5.6: Calculated void fraction from count rate measurements by using 10 [mm] disks

From the measurement shown in figure 5.6 the attenuation can be calculated of acrylic at 60 [keV]. The attenuation coefficient is $1/t_1 = 0.224$ and is in compliance of the theory value of 0.229.

5.4 Temperature measurements

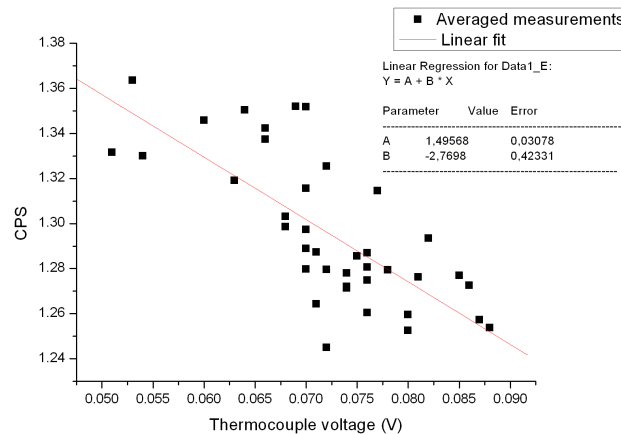


Figure 5.7: Count rates as a function of the voltage measurement by a thermocouple positioned at the PebBEx facility. One degree difference is equal to 4 [mV]. Measured without the Am-241 source

Measurements were performed to determine whether temperature effects had any significant influence on the measurements. Three measurements were performed: one with only the background radiation, one with the source and an empty pebble-bed and one with the source and a full pebble-bed.

In figure 5.7 we see that the background does change when the temperature of the room changes. The amplifier and energy window are sensitive to changing temperatures and this is measured.

Figure 5.8 and also figure 5.9 show that the effect temperature has on the measurement is negligible considering the 1% uncertainty caused by the Poisson distribution of the source. However the effect temperature has on the background radiation is significant and should be taken into account. It has been found that the background does not change significantly from filling the pebble-bed.

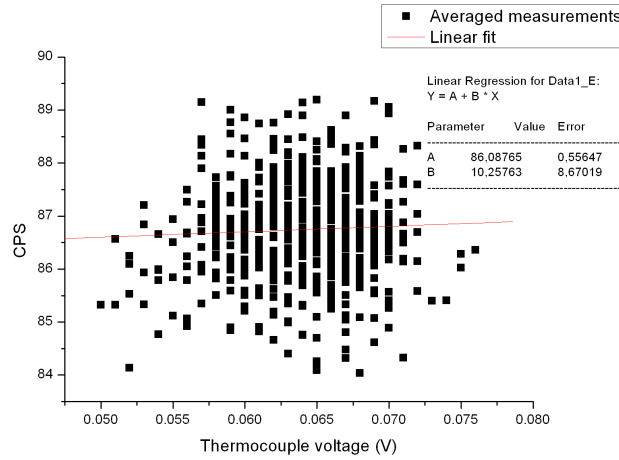


Figure 5.8: Count rates as a function of the voltage measurement by a thermocouple positioned at the PebBEx facility. One degree difference is equal to 4 [mV]. Measured with the Am-241 source and an empty pebble-bed

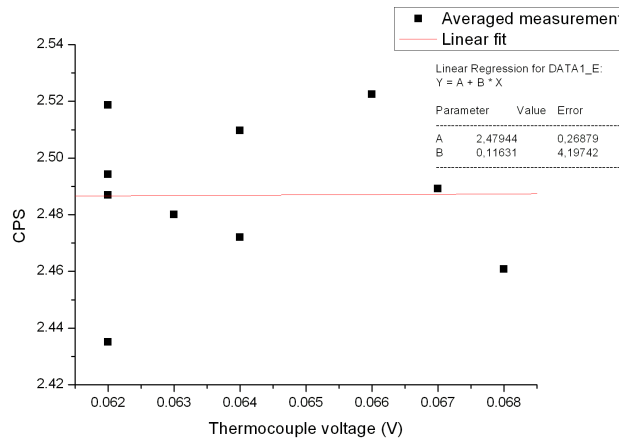


Figure 5.9: Count rates as a function of the voltage measurement by a thermocouple positioned at the PebBEx facility. One degree difference is equal to 4 [mV]. Measured with the Am-241 source and a filled pebble-bed

5.5 Radial porosity profile

In figure 5.10 both the suggested calculated (black/cube) line is visible as well as the results after the calibration fit, shown in figure 5.5, has been used (red/circle line). The numbers 1 to 4 are placed in the picture because these are all points of interest and will be discussed. The experiment wasn't started exactly on the outside of the pebble-bed but on the side of the cylinder that holds all of the pebbles. By using the available hardware count rate meter the cylinder can be found quickly and with ease. Setting the detector and source at exactly the side of the pebble-bed is a difficult task. This is what can be seen at point 1, the first couple points are actually outside of the pebble-bed and on the cylinder. Since the collimator is 2 [mm] thick the first couple of points inside the pebble-bed, at 2, are lower than expected from theory [5] but this is because not only the outer rim of the pebble-bed but also a part of the cylinder surrounding the pebble-bed is measured upon. Figure 5.11 shows the expected behavior.

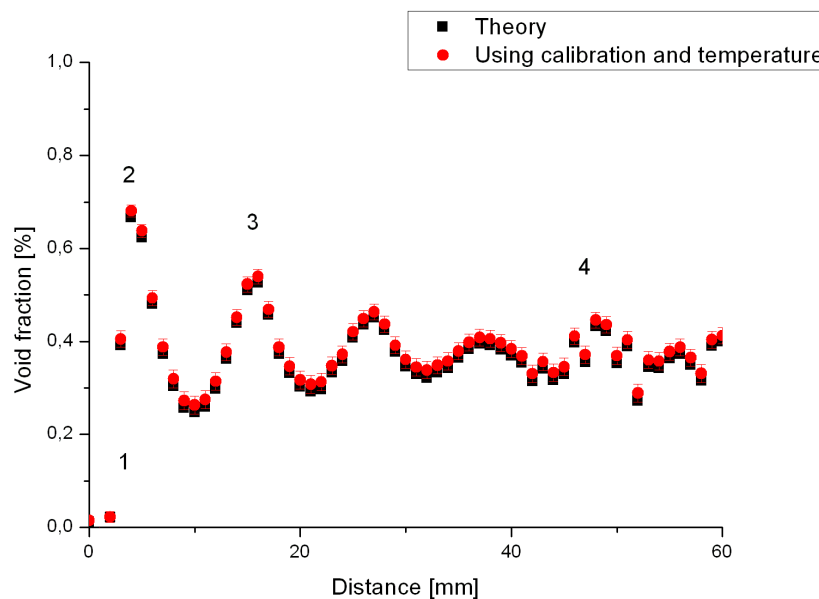


Figure 5.10: Radial porosity profile of the pebble-bed

The measurement data at number 3 is what we expect to be measuring, with a resolution of 2 [mm] on the collimator and a step of 1 [mm] we can clearly see the wall channeling effects. A measurement like the one depicted here takes about 4 days and during the experiment the motor used for rotation bogged down. Because of the motor that stopped working the locally porosity is measured instead of the radial porosity.

This is what we see happening at point 4. The experiment was done with a total of 4580 \pm 5 pebbles. One of the concluding remarks from du Toit[9] was that locally the porosity could change significantly from the average value, so this is in confirmation with the measurement. The uncertainties in figure 5.10 are from the Poisson distribution of the signal, calibration and temperature measurements, these uncertainties vary from 2% to 6%. The uncertainty is the pebble-bed height (as well as averaging over it) was not taken into account.

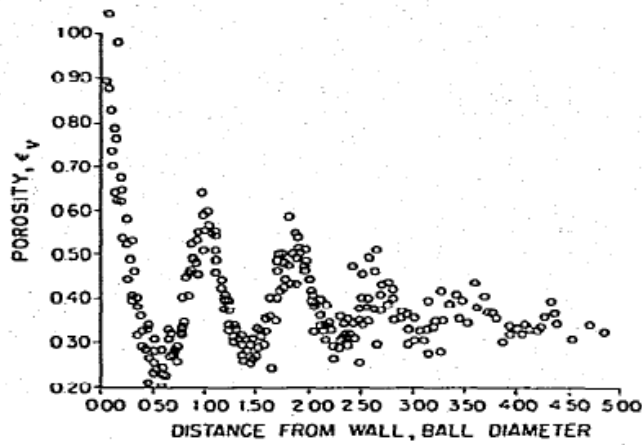


Figure 5.11: Composite data for uni-sized sphere's [5]

Chapter 6

Conclusions

6.1 Conclusions

The gamma-ray tomography experiment that was used has proven useful in determining the radial density profile of a packed bed. The results are accurate and the characteristics of wall channeling are clearly visible. In 4 days time a complete profile of the pebble-bed with a diameter is 229 [mm] +/- 0.5 [mm] could be obtained with steps of 1 [mm]. The collimator, and thus resolution, has a width of 2 [mm] in lateral direction. The measurement was performed by using the γ 's from the 60 [keV] peak of an Am-241 source. It was found that temperature has a significant influence of the background radiation and a negligible influence on the measurements with the Am-241 source. The placing of the source in the mounting piece must be done consistently in the same way, variations of up to 50% can occur if this is not controlled. However by using marking the variation becomes negligible. The attenuation of PMMA at 60 [keV] measured with the PebBEx facility is 0.224 and in good compliance of the theoretical value of 0.229. There were a couple of problems with the measurement method used. First it's not possible to create a flat surface on the pebble-bed which is required by the theory. The collimator used is still quite large (2 [mm]) meaning that at the place where the wall channeling is at its strongest point the measurement data is not accurate. Having a smaller collimator will increase the resolution of the measurement but increase the measurement time for the same amount of uncertainty. Since everything is averaged over the 2 [mm] of the collimator the observed peaks and valleys are likely more extreme. The local fluctuation in porosity profile will become more and more of an issue when center measurement are being made, however this is solvable by using smaller pebbles or a large pebble-bed reactor cylinder.

6.2 Recommendations

The section recommendations will be split up in two subsection namely one subsection that addresses changes on the PebBEx facility that would be beneficial to any type of measurement. The other subsection will consist of topics for follow-up research.

6.2.1 Recommended changes

Mounting of the source The mounting of the source is very important to the amount of signal received. Building a better mounting device so that the source will be easy to place at the same location would be very beneficial to the measurement. The placing is doable without any extra help (using the markings) but it is probably easier and better to build a new mounting device.

Rotational motor When the pebble-bed is loaded it weights over five kilograms making it hard on the motor in place to turn the around. When starting a pebble-bed measurement the cylinder bogs down and further measurements are ruined because of the high local difference in void fraction. Changing the motor belt so that the experiment doesn't stop turning would be highly recommended.

The adding of an additional card As has been stated earlier currently it is not possible to let the rotation motor stop when enough signal is received. They way it is handled now is that beforehand the maximum amount of time needed to measure the required amount of signal is given as input to how long the motor should be rotating. This to make sure the motor is always rotating when the facility is measuring. This could be solved by changing the labview code and letting the rotation motor run continuously on a second interface card. Changing this can reduce the total measurement time for 60% of the current needed time for a measurement.

Influence of temperature effects Since the background radiation is clearly influenced by temperature it is recommended to keep the thermocouple installation to measure the temperature during each measurement and correct the background for the temperature.

Collimators Using a smaller collimator will improve the resolution of the void fraction measurement. If the time allows for it, using a smaller collimator can improve the resolution and create more interesting results. If quicker measurements need to be made larger collimators can be used.

6.2.2 Follow-up research

Mixing different types of pebbles Using different types of pebbles will influence the wall channeling and it will be quite interesting to see how the wall

channeling effects change when smaller pebbles are added. This might also be a way the porosity 'problem' caused by wall channeling can be solved.

Variance of the pebble-bed Research can be done on how different approaches to filling the pebble-bed influence the pebble stacking. Seeing if and how wall channeling changes when the packed bed is filled in a different way might be interesting to see. Moreover, research could also be done on the variance of the pebble-bed after each filling, finding out what kind of variance can be expected when filling the pebble-bed.

Earthquakes Earthquakes are said to have quite some impact on the pebble-bed reactors, in the PebBEx facility earthquakes could potentially be simulated by using the two step motors or at least shake the pebble-bed severely. Discovering how this influence packed beds would be interesting.

Different forms With the setup at hand porosity measurements could be done on a number of different shapes and forms. Wall effects of different shapes could be measured. Another possibility would be to simulate control rods or building an annular reactor.

Pressurizing the pebble-bed The effects of trying to flatten the surface of the pebble-bed could be researched, the fears that were expressed in this report about pressurizing the packed bed could be confirmed or found unjustified.

Acknowledgements

I would like to thank the Multi Scale Physics department for supplying the scintillation detectors and acrylic cylinder for the PebBEx facility.

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Appendix A.1: Ortec 570

ORTEC®

570
Amplifier

- General-purpose amplifier for energy spectroscopy with all types of detectors
- Unipolar output
- Low noise, wide-gain range and front-panel selectable time constants
- Gated BLR with automatic threshold control for excellent counting rate performance



The ORTEC Model 570 Amplifier is a general-purpose spectroscopy amplifier that offers excellent performance for varying counting rates at an economical price.

The low noise, wide-gain range and selectable shaping networks make this instrument ideally suited for operation with semiconductor detectors, proportional counters, and scintillation detectors in a wide variety of high-resolution spectroscopy applications.

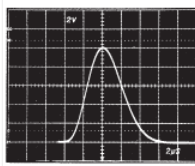
The Model 570 incorporates an automatic gated baseline restorer, which causes the system resolution to be nearly independent of input counting rates. Figure 1 illustrates the peak shift and resolution for a typical gamma spectroscopy system.

The gated baseline restorer (BLR) includes a discriminator that operates the sensing circuits that normally establish the baseline reference for the MCA.

Performance of the spectrometer often depends on the precision of the setting of the BLR threshold. The Model 570 offers the convenience of an automatic threshold control, which typically gives as good or better results than those the most experienced operator could achieve manually.

The active filter networks of the Model 570 generate a very symmetrical unipolar output with optimal signal-to-noise ratio over a wide range of time constants.

The excellent dc stability of the Model 570 output eliminates spectrum broadening caused by dc drift and ensures that the high-resolution capability of germanium detectors is realized.



2 V/cm, 2 µs/cm
UNIPOLAR OUTPUT

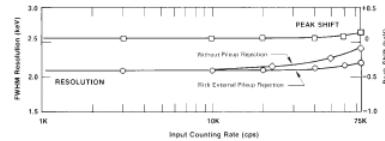


Fig. 1. Typical Resolution and Baseline Stability vs. Counting Rate for the Model 570 in a Gamma Spectroscopy System.

570 Amplifier

Specifications

PERFORMANCE

GAIN RANGE Continuously adjustable from 1 to 1500.

PULSE SHAPE Semi-Gaussian on all ranges with peaking time equal to 2.2 τ and pulse width at 0.1% level equal to 2.9 times the peaking time.

INTEGRAL NONLINEARITY For 2- μ s shaping time, \leq 0.05%.

NOISE Typically \leq 5 μ V for unipolar output referred to the input, using 2- μ s shaping and Coarse Gain \times 10.

TEMPERATURE INSTABILITY
Gain \leq 0.0075%/°C, 0 to 50°C.

DC Level \pm 50 μ V/°C, 0 to 50°C.

BIPOLAR CROSSOVER WALK \leq 3 ns at 0.5 μ s for 50:1 dynamic range, including contribution of an ORTEC Model 562 Single-Channel Analyzer.

OVERLOAD RECOVERY Recovers to within 2% of rated output from X300 overload in 2.5 nonoverloaded pulse widths using maximum gain for Unipolar Output.

SPECTRUM BROADENING Typically \pm 16% FWHM for a ^{60}Co 1.33 MeV gamma line at 85% of full scale for an incoming count rate of 1 to 75,000 counts/s (Unipolar Output, 2- μ s shaping).

SPECTRUM SHIFT Peak position shifts typically \leq 0.024% for a ^{60}Co 1.33 MeV gamma line at 85% of full scale measured from 1 to 75,000 counts/s (Unipolar Output, 2- μ s shaping).

CONTROLS

FINE GAIN 10-turn precision potentiometer with graduated dial for continuously variable direct-reading gain factor of X0.5 to X1.5.

COARSE GAIN 6-position switch selects feedback resistors for gain factors of 20, 50, 100, 200, 500, and 1k. Jumper on the printed wiring board (PWB) selects X0.1 attenuation.

INPUT POLARITY Locking toggle switch selects either Pos or Neg input pulse polarity.

SHAPING TIME 6-position switch selects time constants for active pulse-shaping filter network from 0.5, 1, 2, 3, 6, and 10 μ s.

PZ ADJ Screwdriver adjustable potentiometer to set the pole-zero cancellation to compensate input decay times from 40 μ s to ∞ .

BLR 3-position locking toggle switch selects the source of control for the gated baseline restorer discriminator threshold from:
Auto The BLR threshold is automatically set to an optimum level, as a function of the signal noise, by an internal circuit.

PZ Adj The BLR threshold is determined by the threshold potentiometer. The BLR time constant is also greatly increased to facilitate PZ adjustment; this position may give the lowest noise for count rates under 5000 counts/s and/or longer shaping times.
Threshold The BLR threshold is manually set by the threshold potentiometer.

DC Screwdriver adjustable potentiometer to set the Unipolar Output dc level; range \pm 100 mV.

INPUT

INPUT Front-panel BNC connector accepts either positive or negative pulses with rise times of 10 to 650 ns and decay times of 40 μ s to ∞ . Z_{in} = 1000 Ω ; dc-coupled; linear maximum 10 V, absolute maximum 20 V.

OUTPUTS

UNIPOLAR Front-panel BNC connector with Z_o \leq 1 Ω ; short-circuit proof; prompt with full-scale linear range of 0 to +10 V; active filter shaped; dc-restored; dc-level adjustable to \pm 100 mV.

PREAMP POWER Rear-panel standard ORTEC power connector, Amphenol 17-10090, mates with captive and noncaptive power cords on all ORTEC pre-amplifiers.

BUSY OUTPUT Rear-panel BNC connector with Z_o \leq 10 Ω provides a +5 V logic pulse for the duration that the input pulse exceeds the baseline restorer discriminator.

ELECTRICAL AND MECHANICAL

POWER REQUIRED +12 V, 60 mA; -12 V, 30 mA; +24 V, 80 mA; -24 V, 85 mA.

WEIGHT

Net 1.5 kg (3.3 lb).

Shipping 3.1 kg (7.0 lb).

DIMENSIONS Standard single-width NIM module 3.43 X 22.13 cm (1.35 X 8.714 in.) per DOEER-0467T.

Ordering Information

To order, specify:

Model	Description
570	Amplifier



Specifications subject to change
12/82


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AMETEK
ADVANCED MEASUREMENT
TECHNOLOGY

Appendix A.2: SCA 2030



Model 2030 Single Channel Analyzer

Features

- Independent ULD, LLD, and SCA outputs
- Precise threshold discrimination
- Exceptional stability – dc-coupled input
- External baseline sweep input
- Dynamic range 1000:1
- LLD monitored by LED display
- Source matched logic outputs

Description

The CANBERRA Model 2030 analyzes the peak amplitude of energy pulses from nuclear pulse shaping amplifiers, and generates its primary logic output (SCA) for input analog pulses between the levels referenced by the Lower Level (E) and Window (ΔE) front panel ten-turn controls. Auxiliary outputs from the Lower Level Discriminator (LLD) as set by (E), and the Upper Level Discriminator (ULD) as set by (E + ΔE) are also provided. Timing of these logic outputs is set as the trailing edge of the input signal crosses the (E) reference.


The several outputs may be used together or individually to assist in a wide variety of applications from simple noise removal to extraction of a narrow energy range from a wide spectrum of signals for energy analysis. The sharp, precise threshold discrimination levels are exceptionally stable (drift is less than $\pm 0.005\%/^{\circ}\text{C}$, full scale). The dc coupled input allows excellent baseline stability limited only by the shaping amplifier's restorer. These significant features permit excellent amplitude discrimination, even in high count rate spectra.

The Lower Level (E) threshold is calibrated by reference to the regulated NIM supply voltages, and is usable over the range from +0.001 V dc to +10.0 V dc. Linearity of control is limited only by the specified $\pm 0.25\%$ maximum nonlinearity of the front panel potentiometer. A front panel mounted LED is useful in visually monitoring the setting of the Lower Level (E) reference just above the shaping amplifier's noise level (the LED will fade off).

The Window (ΔE) threshold is also calibrated by reference to the regulated NIM supply voltages, and is usable over the range from the Lower Level (E) setting to +10.0 V dc. A front panel ΔE Range switch allows use of a 1.0 V full scale range for very fine adjustments of the desired window.

An external lower level discriminator (LLD) input on the rear panel may be used in place of the front panel control for applications requiring a ratioed or sweeping baseline reference over the energy range. This input requires a positive polarity reference voltage, and is linear over the full scale of 0 to +10.0 V dc. A locking toggle switch is used to select this input.

All output logic signals are positive logic, and are adjustable in peak amplitude for compatibility with interfacing instruments. All outputs are source matched with 50 Ω series resistive terminations to prevent ringing due to reflections on unterminated cables, and the resulting multiple counting frequently experienced. The instrument is shipped with a socketed resistor which limits the output to +5 V nominal (open circuit) for direct interface with common TTL circuitry. The resistor (1 for each output) can be removed to obtain a



Phone contact information

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For other international representative offices, visit our web site: <http://www.canberra.com> or contact the CANBERRA U.S.A. office. MSP100 2/07 Printed in U.S.A.

Model 2030 Single Channel Analyzer

+8 V nominal open circuit voltage for instruments requiring the NIM pulse level, or +4 V nominal into the 50 Ω load termination which some other instruments provide. This flexibility adapts the output signal to various needs without risking the problem encountered with improperly driven cables. Load end terminations are not necessary.

Careful attention has been paid to minimize reflections of the fast logic pulses back to the analog input. Thus all logic outputs are isolated from chassis to prevent circulating pulse currents in the instrument bin.

Specifications

INPUTS

- **SIGNAL INPUT** – Accepts +0.01 to +10.0 V dc, unipolar or bipolar (positive lobe leading) pulses from shaping amplifier. $Z_{in} = 1 \text{ k}\Omega$. Shaping time constant range 0.1 to 20 μs ; front and rear panel BNCs.
- **EXTERNAL LLD REFERENCE** – Accepts 0 to +10.0 V dc; $Z_{in} = 1 \text{ k}\Omega$; rear panel BNC.

OUTPUTS

- **SCA** – Positive logic +5 V nominal pulse amplitude, adjustable to +8 V nominal pulse by removing socketed resistor; $Z_{out} = 50 \Omega$; pulse width 0.5 μs , nominal, rise time and fall time <25 ns; front and rear panel BNCs.
- **LLD** – Same characteristics as SCA output; rear panel BNC.
- **LLD** – Same characteristics as SCA output; rear panel BNC.

CONTROLS

- **LOWER LEVEL (E)** – Front panel ten-turn locking dial potentiometer to set lower discriminator threshold level.
- **WINDOW (ΔE)** – Front panel ten-turn locking dial potentiometer to set window width (upper discriminator threshold level above lower level).
- **ΔE RANGE** – Front panel toggle switch to set full scale range of WINDOW (ΔE) control as +1.0 V dc or +10.0 V dc.
- **LLD REF MODE** – Rear panel locking toggle switch to select INTERNAL lower level via front panel control, or EXTERNAL input.



INDICATOR

- **LOWER LEVEL** – Front panel LED blinks when input exceeds LLD setting.

PERFORMANCE

- **DISCRIMINATOR NONLINEARITY** – $< \pm 0.25\%$ of full scale.
- **DISCRIMINATOR STABILITY** – $< \pm 0.006\%/^{\circ}\text{C}$ ($\pm 50 \text{ ppm}/^{\circ}\text{C}$) of full scale, referenced to NIM class A supply +12 V dc line.
- **DISCRIMINATOR RANGE** – $\leq 1000:1$.
- **DISCRIMINATOR PULSE PAIR RESOLUTION** – $< 0.65 \mu\text{s}$.

CONNECTORS

- All signal connectors are BNC type.

POWER REQUIREMENTS

- +12 V dc – 155 mA -12 V dc – 5 mA

PHYSICAL

- **SIZE** – Standard single width NIM module 3.43 x 22.12 cm (1.35 x 8.71 in.) per DOE/ER-0457T.
- **NET WEIGHT** – 0.8 kg (1.8 lb).
- **SHIPPING WEIGHT** – 1.8 kg (4.0 lb).

ENVIRONMENTAL

- **OPERATING TEMPERATURE** – 0 to 50 $^{\circ}\text{C}$.
- **OPERATING HUMIDITY** – 0-80% relative, non-condensing. Meets the environmental conditions specified by EN 61010, Installation Category I, Pollution Degree 2.



Appendix B: X-ray mass attenuation PMMA

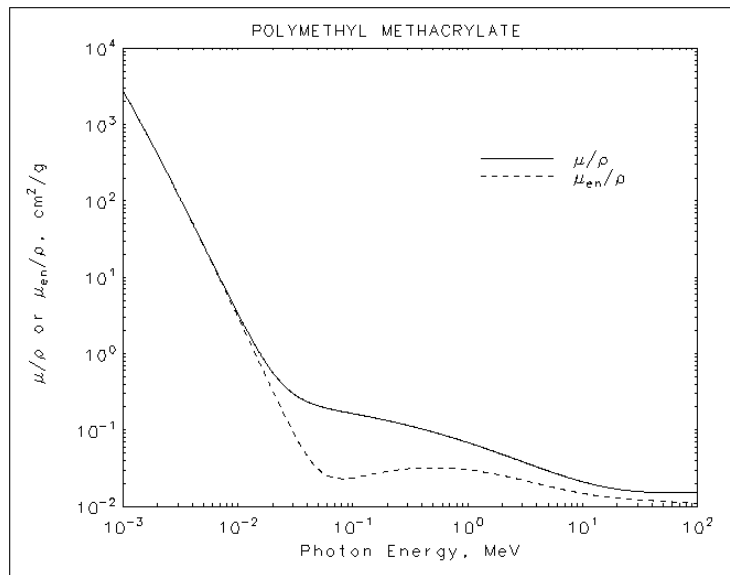


Figure 1: X-ray mass attenuation of PMMA by NIST