



Optimisation of Digital Radiographic Parameters for Carbon Fibre Reinforced Polymers Component Evaluation

Chris Rowden BSc (Hons)

A thesis submitted to the University of Wales Trinity St David in accordance with the requirements for the award of MSc Non-Destructive Testing and Evaluation.

Supervised by: Dr. P Charlton
Submission Date: September 2015
Incorporation with: TWI



Declaration/Statements page

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Acknowledgements

For the guidance and support I have received to complete this thesis, I would like to express my thanks to my academic supervisor Dr. Peter Charlton and my industrial supervisor Malini Vieyra. I would also like to acknowledge my industrial placement TWI Technology Centre (Wales) for the access provided to the laboratory facilities and unconditional support.

Furthermore, I would like to acknowledge and recognise the Access To Masters (ATM) for their financial support, as well as the help that was provided from the University of Wales Trinity St David.

Abstract

A method to optimise the digital radiographic parameters for carbon fibre reinforced polymers components has been proposed within this thesis. The material has excellent mechanical properties, which ensures its growing demands for a number of applications. This demands a requirement for developments of Radiographic Non-Destructive Testing methods to provide confidence in component inspections. Much speculation is found for the correct parameters for inspecting carbon fibre, with a consensus of low energy producing the most efficient radiographs. The theory to why this statement is true, is discussed and tested using both theoretical and experimental means. Due to limitations in the simulation software, a comparison was conducted using aluminium filtration, from which the linear absorption coefficients could be recovered. Once confidence was verified with the results, the method concentrated solely on carbon fibre components. A repeat of the experimental procedure using carbon fibre filtration, rather than aluminium showed high attenuation decays occurring at 50kV, which were the lowest limitations of the X-ray system. A series of radiographs are presented at the end of the document showing the 50kV parameters displaying the clearest contrast, enhancing the weave construction and specific materials which would have attenuated the photons differently.

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1 Introduction.

1.1 Motivation

Carbon Fibre Reinforced Polymers (CFRP) are a category of lightweight materials, which produce an excellent high strength to weight ratio, and rigidity. This has led to the material being sought for an increasing number of applications, predominantly within the aircraft industry. Recent aircraft designs show the benefit of reduced structural weight incorporating over 50% CFRP resulting in lower fuel consumption and CO₂ emissions, increasing range and enhancements to the aircrafts performance. (Carsten Beine, 2010)

Due to the increasing application of this advanced material, requirements of NDT techniques and standards which produce results equivalent to those known so far for their metallic counterparts are essential. The reliability of detecting small damage mechanisms expected during operation are vital and when considering current NDT techniques, this is a time consuming and costly operation.

There are two established NDT techniques used for aeronautical CFRP component inspection; Radiographic and Ultrasonic. Conventional radiographic inspections on composites are not as compliant as metallic counterparts are; therefore require complex procedures in order to achieve a respectable image. A polymer matrix and some fibres such as carbon have low absorption cross sections, making it difficult to achieve a good contrast. Similarly, ultrasonic sampling produces a poor signal to noise ratio and require a skilled interpreter to provide a signal and image processing procedure. Achieving an advanced knowledge and operation of CFRP mechanical properties, would improve the resolution of this material, respectably enhancing damage detection speeds hence, cost and the optimisation of CFRP evaluation.

1.2 Digital Radiography

During a radiographic inspection, a component is subjected to a bombardment of X-ray radiation. The component absorbs the radiation energy to a certain degree, which can be characterised into three main types of interaction; Photoelectric effect, Compton Scattering or Pair production. The unabsorbed radiation passing through the component hits a radiation-sensitive target, known as the detector. Variations in the intensity of detected radiation appear as shades of grey. General rules specify that radiation with high intensity show white, high absorption are black. The evaluation of the radiograph is based on the comparison of the difference in density (greyscale).

Key parameters such as X-ray voltage and current are essential in image contrast, however exposure times, focal spot size and magnification all play a key role in enhancing radiographs.

1.3 CFRP

Carbon Fibre Reinforced Polymers (CFRP), material is produced for a number of applications which require excellent mechanical properties. This makes it commonly used within aerospace, civil engineering and automotive industries. An increasing number of evolving industries are also showing emerging interest in the material.

The composite material consists primarily of two parts; a matrix, usually a polymer resin such as epoxy, and reinforcement, which is Carbon Fibre. The matrix binds the reinforcement together which in turn gives CFRP its strength and rigid status. These properties are dependent on the layout and proportion of the carbon fibre relative to the polymer, therefore suggesting that CFRP has a directional strength.

1.4 Aims and Objectives

It has been established that CFRP produces poor resolution with current NDT methods; however, there is an absence of knowledge into the materials' characteristics. A radiographic inspection to investigate these parameters has been projected within this study. Previous techniques have been proposed into enhancing flaw detection, such as introducing a contrast medium, usually referred as a radio-opaque penetrant. These consist of high radiation opacity chemicals that produce high X-ray absorption coefficients when compared with an untampered composite. This chemical however, can only be applied into the component during manufacturing, which may compromise the materials' properties.

The principal hypothesis for this work proposes that a correlation between bremsstrahlung spectral distribution and the resultant greyscale count, may allow for a respectable linear attenuation coefficient estimation of CFRP. This parameter is dependent on the X-ray energy and material density, however a contribution towards the optimisation of radiographic parameters for CFRP evaluation, without compromising the material, would be the outcome.

The objectives of this research all adhering to CFRP were as follows;

- To enhance the understanding of X-ray production and interaction with a filtered material, by defining a complete parametric study, from source to detector.
- To produce a theoretical configuration between experimental images and simulated spectral distributions, to determine absorption coefficients.
- To design, test and analyse a radiography inspection for CFRP filters, to establish the materials properties, allowing for enhancements of radiographic image contrasts.

1.5 Research Methodology

The research literature on CFRP inspection show a range of techniques to increase image efficiency, however a contradiction between inspection parameters are notably published. This suggests a potential for an improved inspection method, with use of different target or filtration materials. An initial literature review highlighting similar investigations were proposed in achieving the aims of this thesis and primarily identifying the techniques that can be incorporated with CFRP radiograph inspections. These techniques were interpreted to form an experimental section of work, which was carried out on the premises of a sponsoring company. The test procedure was restricted to the capabilities of the companies' HMX-225 radiography system and the comparable software abilities.

The SpekCalc software provided a computational model simulating X-ray spectra emitted from an X-ray tube. The program calculates and displays photon spectra from a tungsten anode by relying on deterministic equations for bremsstrahlung productions combined with numerically calculated electron distributions, such as characteristic radiation. Filtration is selected in mm, for seven materials: Al, Cu, W, Sn, Be, water and air. It is noteworthy to specify the limitations within the software as it is restricted to a particular range of tube potentials (40-300 kVp) and the recommended anode angles 6-30°.

These parameters revealed a basis from which the experimental work was developed, allowing for validation with a degree of accuracy between the computational model and the experiment results.

1.6 Contribution to Knowledge

There is a selection of novel contributions to knowledge shown within this thesis. Primarily these contributions are;

- Modification to Kramers Model, for a relationship between SpekCalc and theoretical spectral distribution.
- Developed methods for determining X-ray energy states, via comprehending the greyscale intensity contrast on the detector.
- Procedure for parameter optimisation- using low-end energy states to ensure that some absorption takes place for clearer contrast.
- Enhancing Real Time (RT) imaging of CFRP components, understanding of CFRP mechanical properties and experimenting a selection of filtration sources.

1.7 Organisation of Thesis

This thesis is partitioned into five major chapters, excluding **Chapter one**. For each counterpart of the thesis, an introduction and literature review is presented, to emphasise value and purpose for that chapter. The organisation of the chapters are as follows:

Chapter two consists of the background research required to expand the understanding of the proposed project. A review into the literature on the following topics are presented:

- CFRP (description and appliances, including layup and manufacturing techniques)
- NDT of CFRP (previous methods with advantages and disadvantages to examine CFRP)
- Radiography Theory (The physics and methodology in producing an X-ray)
- Literature Review (Kramers equation and Beer Lambert Law)

Chapter three introduces the following simulation packages and hardware used within the experimental stages of the thesis. Some key areas are shown within this chapter such as:

- Computer simulation packages (Excel, SpekCalc, ImaSim, Image J description)
- Mirco-Focus CT (X-Tek HMX ST 225 CT at sponsoring company facilities)
- Safety Precautions

Chapter four introduces the approach taken to simulate and optimise radiography parameters. Included, is a feature designed experimental procedure carried out at the sponsoring company (TWI). This is essential for replicate studies and the validation of the research.

Chapter five shows the comparative data between simulated and experimental investigations. The chapter is subdivided into appropriate sections exhibiting an analysis of those corresponding results. The displayed sections are;

- Simulation (results)
- Experimental (results)
- Comparable Analysis
- CFRP Evaluation (results)
- Analysis

Chapter 6 discusses the findings within the thesis and summarises the previous chapters. It also includes recommendations and an approach to future experimental parameters, such as the use of different target materials.

2 Background Research

Within this chapter, the background research required to expand the knowledge and understanding of the proposed thesis is illustrated. Several topics have been discussed in depth and had relative points highlighted, which will be used to model the experimental methodology. These are presented together within the conclusion to this chapter.

The topics in question begin with an introduction to Composite materials (describing the layup and manufacturing techniques for a number of samples. This leads onto the description of CFRP and the relevant applications of this growing material technology. It also shares the advantages and disadvantages of CFRP.

Following on from this, a comparison of CFRP NDT techniques is formed which represents Ultrasonic and Radiography which are the most efficient in finding discontinuities within CFRP components. The research is principally towards Radiography from this point, defining the physics and methodology in producing an X-ray, with the introduction to the hardware required to achieve radiographs.

Lastly, a literature review is available which documents the first approximation of Bremsstrahlung spectra known as Kramer equation, from which most predicted X-ray characteristics are displayed. Including simulation software such as SpekCalc, which is also documented within this section. The software's limitations and discrepancies are demonstrated here, which are also required in the development of the experimental process.

2.1 CFRP

2.1.1 Introduction to composite materials

The definition of a composite simply means “made up of different parts or materials.” This relates to the composite material used within manufacturing industries, as it describes the structures layup. All composite materials are constructed of two or more constituents and the final properties of the component is derived from these individual elements. Therefore, the resulting material may have the combined characteristics or have substantially different properties than the individual element counterparts; all dependant on the manner the material is manufactured. In some cases this can be used to develop advanced materials which exceed the constituent’s properties. (Zafer Gurdal, 1999)

2.1.2 Classification of composite materials

The general classification of the composite material can be found using a number of techniques, from stress / strain testing to examining the form presented or simply justifying them based on the constituent characteristics. All of which will be either organic origination such as carbon, or inorganic which cannot be classified as organic matter, for example metals. Pure organic materials are avoided for the use of highly loaded structures. This is due to them having generally low stiffness and strength properties. Furthermore, they are sensitive to environmental effects such as temperature or moisture and have a low resistance to chemicals or solvents. Despite their disadvantages, organic materials are commonly included in composites as they bring in required characteristic, unachievable through the use of just inorganic constituents. Polymers are a prime example of this as it acts as a supporting material; this arrangement is referred to as a matrix material. (Zafer Gurdal, 1999)

For inorganic composites, commonly all constituents are metallic, or a combination of metals and minerals. These are primarily used for the highly loaded structures due to the high compressive strength they possess. A disadvantage of this classification becomes apparent when applying the composite to weight critical applications, such as aerospace and competitive automotive designs. A compromise to this is using both organic and inorganic constituents together including a polymeric matrix to enhance all aspects of the material.

The polymer matrix are organic molecules acting as a chain structure within the material. They are generally classified as thermoset or thermoplastic substances, which categorises their considerably different characteristics as a matrix.

The thermoset matrix are soft and malleable constructed with fibres pre-impregnated within, this makes it adaptable to fabricate complex shapes with ease. They require low processing temperatures with long curing times, where a chemical change takes place creating the cross-linking of polymer chains. This supports the structures strength however once cured it is irreversible to reprocess. Thermoset matrices include Epoxy, Polyimide, Polyester and Phenolic materials which tend to have operating temperatures up to 250°F (120°C).

The thermoplastic matrix do not require a curing procedure which allows it to be reshaped and reused. The characteristics of this matrix show it is hard and board like due to the plastic prepregs. This unfortunately makes it harder to handle and work, however using very high temperatures, shaping is possible. Thermoplastic offer high resistance to moisture and can be applied to high operating temperature applications, reaching temperatures up to 500°F (260°C). Among popular thermoplastics are Polyethylene, Polystyrene, and Polyetheretherketone (PEEK). (Zafer Gurdal, 1999)

As stated before the structural form they possess can determine the composite material, usually examined at a magnified resolution. There are several forms that the material can take, shown below.

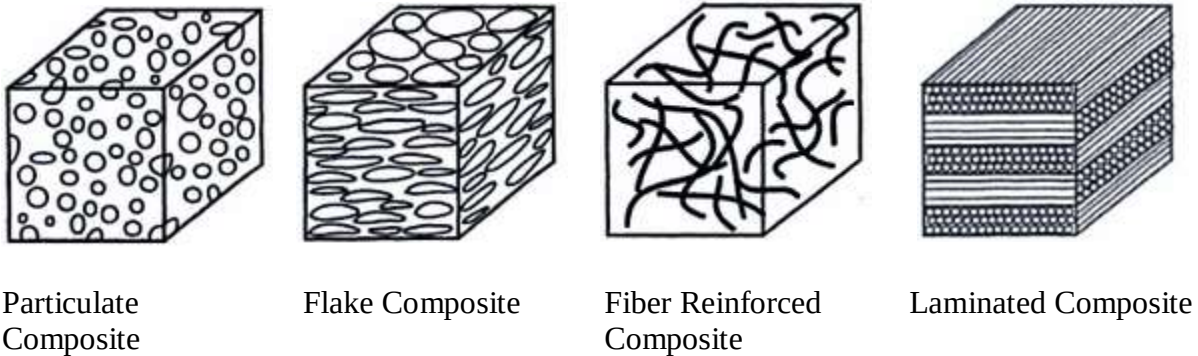


Figure 2-1 Structural Forms

To begin with, particulate composites have metallic particles, which are randomly dispersed, within a softer matrix. A widely used example for particulate composite is concrete, where gravel is mixed in with cement. (Zafer Gurdal, 1999)

Flake composites are formed by randomly dispersing thin flakes within the matrix material. The flakes can be made to align with one another forming a more ordered structure compared to particulate composites. This is achieved by exciting the molecules electronically or magnetically. The alignment provides for more uniform properties throughout the material in one desired plane. Typical examples of flakes are glass, mica, some metals and carbon. The size and shape of the flakes depend on the type of application, which also determines the amount of matrix material.

Fibre Reinforced composites are the most commonly used form of the constituent combinations. The fibres within these composites are generally strong and stiff and therefore serve as the primary load carrying constituent, being held together by the chosen matrix.

The fibres within these composites are generally strong and stiff and therefore serve as the primary load carrying constituent, being held together by the chosen matrix.

The matrix also serves as an agent to redistribute loads from broken fibres, due to excessive loads, to adjacent fibres within the material.

This property is one of the most important characteristic for fibre-reinforced composites. Other properties consist of the improvement of strength and stiffness when compared to its counterparts. (Konstantinos Tigkos, 2014)

The final form of composite material is known as composite laminates. They consist of thin layers of similar or different material fully bonded together. The layers may be composites such as fibres and built up in different orientations so that the material has different properties in various directions.

This type of composite is most commonly used in design of high performance structures. The individual layers may assume a number of different forms, depending on the arrangement of the fibre constituent. The various forms of laminated composite materials are shown below.

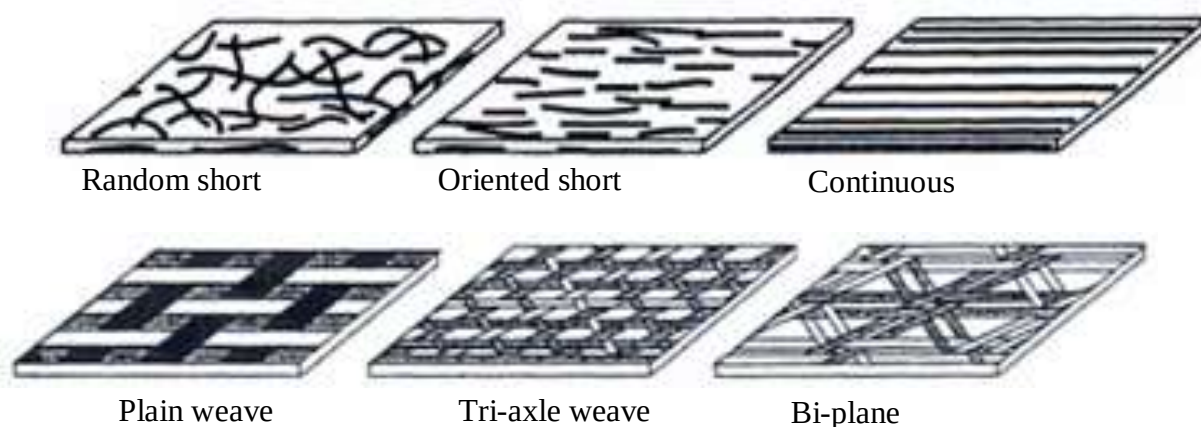


Figure 2-2 Fibre Arrangement

The first two layers are composed of short fibres which are distributed at random orientations, or can be aligned in some manner forming orientated short fibre composite. A common example of this arrangement is fibreglass. (Zafer Gurdal, 1999)

Continuous Fibre reinforced layers are made up of bundles of small diameter circular fibres which stretch across the component. The fibres set in this one plane direction provides a unique feature of the materials properties of fibre reinforced composites, for example different stiffness properties along the mutually perpendicular directions occur. The fibres are pre-impregnated with the matrix material. An example of this layup is reinforced tapes.

Another form is woven fabric type composite. This is where fibre tows, which are large bundles of fibres, woven in two or more directions. Various types of fabrics with different weave patterns produce a variation of material characteristics. The more complicated examples are tri-axial weave and Bi-plane weave which have enhanced properties. However, more variables can reflect higher failure mechanisms. The most predominant current design of this type of layup is Carbon fibre reinforced plastics CFRP.

2.1.3 Carbon Fibre

Carbon fibres are thin strands of material ranging between 5-10 μ m (Micrometres) in diameter, the majority of which are composed of carbon atoms. The atoms are bonded together in microscopic crystals that are approximately all aligned parallel along the axis of the fibre. This crystal alignment is what gives carbon fibre its strength. Several thousands of these fibres are twisted among each other to create a yarn, which can be used to be woven into a fabric. The yarn or fabric is combined with epoxy and wound or moulded into a desired shape forming the composite material.

Carbon fibre-reinforced composites are used with a number of applications such as aircraft aero engines and space craft components, performance car chassis and bodies, bicycle frames, fishing rods and a number of other components where light weight and high strength are a requirement.

Carbon fibres are classified by the tensile modulus of the fibre measured in units of psi. They can be categorised in ascending order of tensile modulus which include, “low modulus,” “Intermediate modulus,” “High modulus” and “Ultrahigh modulus.” The Ultrahigh modulus carbon fibre have a tensile strength ranging $72.5\text{-}145 \times 10^6$ psi, when in comparison to steels which have a tensile modulus of about 29×10^6 psi. The strongest carbon fibre is respectably 5 times stronger than steel and aluminium, giving advantages of weight reduction. In addition to this, their fatigue properties and corrosion resistant are superior to all known metallic counterparts, when coupled with correct resins during the manufacturing process. (CompositesWorld, 2015)

2.1.4 Manufacturing of Carbon Fibre

Carbon fibre begins its manufacturing as a raw material known as precursor; a polyacrylonitrile (PAN) substance which 90% of carbon fibre is produced from. The remaining 10% are made from substances such as rayon or petroleum pitch, all of which are organic polymers, characterised by long strings and molecules bound together by carbon atoms. During the manufacturing of carbon a variety of gases and liquids are introduced to fibres, to either cause a specific reaction or to prevent a reaction occurring at all. The exact compositions of many of these process materials are subjected to intellectual property protection.

The whole process for making the carbon filter is split between a number of operation sequences, some of which are chemical based and some of which are mechanical. The precursor

is drawn into the long strands of fibre and then heated to high temperatures, without being subjected to oxygen to reduce the risk of combustion. The very high temperatures cause the atoms within the fibre to vibrate vigorously, which expel any non-carbon atoms.

The process is known as carbonization, which produces a fibre composed of tightly interlocked chains which are carbon atoms based with only a few non-carbon atoms remaining. This five step process is commonly used to achieve this outcome;

2.1.4.1 Spinning

First stage of forming the carbon fibre is creating the polyacrylonitrile plastic. This is achieved by following a simple polymerization process where acrylonitrile plastic powder is mixed with an adjacent plastic, such as methyl acrylate or methyl methacrylate. The mix is reacted with a catalyst in a conventional suspension to form the polyacrylonitrile.

This plastic is then spun into fibres using one of several methods; either the plastic is mixed with specific chemicals and pumped through small jets in a separate chemicals quench chamber, where the plastic coagulates and solidifies into fibres.

Alternatively the plastic mixture can be heated and pumped through the jets into a chamber where the solvents evaporate leaving solid fibres. The spinning step is crucial as it is when the internal atomic structure of the fibre is first formed. The resultant fibres are then washed to clear any unwanted solvents or chemicals which may affect later manufacturing and stretched to the desired fibre diameter. The stretching also aids in the alignment of the molecules within the fibre and provides a basis for the formation of the tightly bonded carbon crystals after the carbonization, supporting strength characteristics. (CompositesWorld, 2015)

2.1.4.2 Stabilising

Before the carbonization of the fibres, a bonding issue needs to be adjusted. The fibres are converted from linear atomic bonding to a more thermally stable ladder bonding by chemical alterations. To accomplish this the fibres are heated in air to temperatures reaching between 200-300°C for 30-120 minutes.

This allows the fibres to attract oxygen molecules, which interact and rearrange their atomic bonding pattern. This stabilising chemical reaction can become complex and involve several steps, some of which occur simultaneously. The reaction also generates its own heat which needs to be controlled to avoid overheating of the fibres, which weakens it.

Industry uses a variety of techniques during the stabilisation process to reduce this outcome, for example; a series of heat chambers which the fibres are drawn through or they can be passed over hot rollers and loose materials held in suspension by a flow of hot air. Industries favourite process is to use heated air mixed with certain gases that chemically accelerate the stabilization.

2.1.4.3 Carbonisation

Carbonisation can take place once the fibres are stabilised. They are once again heated however, this time with more intensity. The fibres are placed within a furnace filled with a gas mixture which doesn't contain oxygen to prevent the fibres from burning.

The temperatures within the furnace range between 1000-3000°C, the fibres only require several minutes within this condition. Within these minutes, the fibres begin to lose their non-carbon atoms, which form various gases including water vapour, ammonia, carbon monoxide, carbon dioxide, hydrogen, nitrogen and a series of other greenhouse gases, making this a dirty process of manufacturing. As these atoms are expelled, the remaining carbon atoms form tightly bonded carbon crystals that are aligned parallel to the long axis of the fibre.

Some manufacturers provide two furnaces operation at different temperatures to better control the rate of heating during carbonisation, this also aids with recycling the greenhouse gases being expelled. (CompositesWorld, 2015)

2.1.4.4 Treating and Surface

Once the carbonization process is complete the fibres have to have the surface treated as it does not bond well with epoxies and other materials which make up the composite materials. To solve the bonding disputes the surface is slightly oxidized, which will enhance the surfaces chemical bonding properties due to the introduction of oxygen atoms. It will also support etching and roughness which aids with mechanical bonding properties.

This is achieved by immersing the fibres in various gases such as, air, carbon dioxide or nitric acid. Other methods of coating are electrolytically applied where one end of the fibre is subjected to a positive terminal and placed within a bath filled with various electrically conductive materials. This treatment process is carefully controlled as it promotes surface defects which could inevitably cause component failure. (CompositesWorld, 2015)

2.1.4.5 Sizing

Finally, after the surface treatment, the fibres are coated which protects them during the winding or weaving process. The coating materials include epoxy, polyester, nylon, or urethane and are chosen for their compatibility with the adhesive used to form the composite material. These fibres are wound onto cylinders called bobbins and distributed to the corresponding company who will use spinning machines which twist the fibres into yarns of a desired size, ready for composite material specification. (Zoltek Toray Group, 2015), (Soo-jin Park, 2010)

2.1.5 CFRP Manufacturing techniques

The manufacturing of CFRP moulds can be achieved using a number of different moulding techniques. The approach chosen will produce a variety of composite materials and can be used to control the desired properties. These techniques can be separated into two categories; Open moulding or Closed Moulding.

Open moulding is the less common technique used in the modern age. However, it was widely used before evolved technology. A process called wet/hand layup was widely used for many years. The resins were impregnated by hand rollers into the fibres which were previously woven and sized.

Once an appropriate coating was delivered, the laminates were left to cure under standard atmospheric conditions. This technique used simple principles making it easy to teach. It also had an advantage of low tooling costs, primarily if room temperature cure resins were used. However, there are a number of health and safety considerations with using this technique, principally during the curing process where a concentrations of airborne styrene is released from polyesters. Legislated levels of these are becoming increasingly enforced and require efficient extraction systems, adding to cost. The process itself can produce a variety of CFRP characteristics as resin mixing, laminate resin content and laminate quality are all dependant on the skills of the operator. A low resin content laminate cannot be achieved without the series of voids, due to the resin needing to be of a low viscosity in order to be worked by hand. This generally compromises their mechanical and thermal properties due to the need for high diluent and styrene levels.

Closed mouldings have a number of processes which are commonly used within industry as they are much more controlled in developing the desired mouldings. These processes include pultrusion, vacuum bagging, prepreg moulding and autoclave moulding. A brief distribution of the autoclave design is also presented as it is industries primary method.

Pultrusion, as the name describes, is a process where the fibre is pulled from a creel through a resin bath towards a heated die. The die aids the impregnation of the fibre and accurately controls the resin content. The fibres are then clamped and pressed into a mould during which a curing process takes place. The desired shape is finally cut to length producing the finished product. The fibres can also be influenced by the material guides to provide cross sectional patterns. The pultrusion method is usually a continuous process producing sheets of carbon fibre promptly, however it can also accommodate for more complex shapes compromising its fast production rate. The final products from this method produce good structural properties since the profiles have very straight and high content of fibres. This process is applied to framework structures, i.e. bridges and beams.

The second process is vacuum bagging which is an extension of the open moulding technique. A plastic film is tailored over the wet laid up laminate and sealed. The air under the bag is then extracted by a vacuum pump. The pressure difference is applied to which improves its consolidation. The vacuum bag reduces the amount of volatiles such a styrene being emitted during the cure, which is an advantage over the open moulding technic however, the results of the material is still determined largely by the operator's skill.

Prepreg moulding introduces the use of an autoclave. The fabric is pre-impregnated by the materials manufacturer, as previously described. The resin is usually a near-solid state at ambient temperatures after being cured, however impregnated materials may retain a tacky feel within the fabric. Prepregs are laid up onto the mould surface with the fibre and vacuum bagged as seen previously. It is then heated to typically 120-180°C to allow for the resin to take shape of the mould. This method can take place within an autoclave which adds additional pressure to the moulding and laminate, this will enhance structural optimisation and allow complex layups to be achieved. The disadvantage of using an autoclave are size limitations and the core materials need to be able to withstand the process pressure and temperatures. (Paxford Composites, 2015)

2.1.6 Autoclave Design

To maximise the performance of CFRP, the ratio of fibre to resin can be adjusted, or the removal of air voids can be achieved using an autoclave. The material is evaluated to high pressures and temperatures within a pressure vessel. The resin/ fibre layup is initially pressurized within a vacuum bag, however within the autoclave the uniform pressure is greater than one bar, expelling any unwanted gases from the material.

The design of the autoclave is to achieve the following criteria;

Adaptable temperature control and uniform heat distribution

Programmable pressure control

Monitoring and data logging processes.

Safety systems are essential.

The autoclave has several systems employed to control uniform temperature within the vessel. This is critical as industries set tight tolerances towards the material production. Two main systems are used; direct or indirect heating.

Direct heating has a heat source within the autoclave, which aims to maximise the heat transfer from elements to the pressure medium. Indirect heating systems use a heat exchanger to source air from outside of the autoclave. (Netcomposites, 2015)

Pressurisation controls are used to set the internal pressure conditions within the autoclave, required for the cure cycles. The pressure is controlled by a series of modulating valves on the inlet and exhaust pipe works systems of the autoclave. The pressure can be in form of a series of pressurisation gradients, dwells or de-pressurisation gradients.

The electronic controlled systems enable the user to monitor the cure parameters in real-time whilst logging and optimizing the data.

The safety systems of the autoclave is the most important aspect it possesses. The door for example, ensures the autoclave cannot pressurise until it has been fully locked. Whilst under operation the door cannot be opened until the atmosphere and temperatures have reached safe levels. It also prevents violent opening if residual low pressure is present. The vessel itself is fitted with a mechanical pressure relief valve, which is typically set to 10% above stipulated maximum working pressures. This prevents pressure overload and isn't affected by electronic control system failing. It also warns the operator of any residual pressure, prior to door opening. Due to the critical nature of these devices they are all tested and monitored throughout working cycles. (Netcomposites, 2015)

Autoclaves are still the predominant curing systems for the CFRP industry and with new and advancing technologies the products they produce will only be enhanced, requiring advancing NDT techniques to keep up with the trend. (Dr.Ralph Lassig, 2013)

2.2 CFRP NDT Methods

The seemingly increasing application of these advanced materials require NDT techniques and standards which deliver results equivalent to those known for their metallic counterparts. Previous speculation shows that damage mechanisms in CFRP are much less known, as well as any damage progression behaviour. Nevertheless, it is crucial to be able to reliably detect any damages fairly small in size, regardless of damage progress, on components during operation. Considering the NDT techniques being standardised for some industries such as aerospace, this process is time consuming. Any enhancement in damage detection speed, resolution and hence cost would further enhance the performance of CFRP structures and might allow CFRP to even become damage tolerant one day.

Emerging state of the art NDT techniques being used for CFRP component inspections include radiographic and variable ultrasonic techniques involving immersion, contact and squirting techniques. The squirting technique uses water jets to couple ultrasonic waves to the material and is only applied to components which are very large or complex designs which enable them to be immersed into a basin or deliver an accordance with hand held transducers.

Previous NDT techniques which may deliver great potential for speeding up inspection processes are also being conducted for CFRP components. These techniques include Sampling Phased array for Ultrasonic testing, Eddy current or thermography. Within the following paragraphs, the principles of these techniques and computed tomography are obtained and discussed. (Carsten Beine, 2010)

2.2.1 Ultrasonic Testing (Sampling Phased Array)

Conventional ultrasonic testing is one of the more common practises of NDT methods. The manual testing utilises high frequency mechanical energy, sound waves, to examine and measure a desired test area. The system consists of a pulsar/ receiver, transducer and a display unit.

Typically, the pulsar/receiver device produces a high voltage electrical pulse delivered to the transducer which in turn generates a high frequency ultrasonic sound energy into a material in the form of sound waves. If the material is subjected to any discontinuities such as, inclusion, porosity, cracks; the sound wave will be reflected off that flaws surface.

The sound waves travel times can be directly proportional to the distance that the signal had travelled. Therefore, a back wall echo can be calibrated to the thickness of the component. The reflected sound received by the transducer is transformed back into an electrical signal, signalling intensity, which is displayed on the display unit. The signal will determine information such as defect location, size orientation and other features. (Ajay Kapadia, 2012)

An ultrasonic technique which has been qualified for CFRP testing is Sampling Phased Array due to its versatility. A Phased Array (PA) system operates through the use of point-source transducers elements. The elements are triggered with time delays to produce an acoustic beam which can be steered at different angles or focusing depths and returning signals can be time corrected. Therefore, a propagating wave front (beam) can be swept through a wide volume without the probe itself having to move. An advanced signal and image processing developed by Fraunhofer IZFP known as Sampling Phased Array (SPA) has generally resulted in greater inspection sensitivity and hence increased probability of detection.

SPA acquires the data by all the elements of the array; when one element acts as a transmitter and each time domain signal is stored separately. They are then processed off-line but in real time by means of Synthetic Aperture Focusing Technique (SAFT). (Carsten Beine, 2010)

2.2.2 Electromagnetic Methods

Various Electromagnetic methods are adopted for NDT references, all of which induce electric currents or magnetic fields to examine the electromagnetic response. Primarily Eddy Current Testing (ECT) was intended for Electromagnetic Testing (ET), however an expanding number of tests have developed meaning ET can be a selection of either (ECT), Magnetic Flux Leakage (MFL) or Magnetic Particle Inspection (MPI).

MLF and MPI technologies are very similar as in both cases a component is magnetised to a level at which presence of a significant local reduction in material thickness causes sufficient alteration of the magnetic field, causing flux lines to break the test surface signifying discontinuity. Traditional MPI uses a ferromagnetic wet or dry powder to distinguish this leakage marking the location so that it is visible by the inspector. With MFL, sensors produce an electric signal, which operates an audible or visual alarm once the leakage site is detected. The sensors can range from Coils, Hall effect to Magnetostrictive devices. Thus, both techniques require a magnetisation methods; achievable using electro magnets or permanent magnets, and a method of detecting the leakage field. (Drury, 2014)

A competent ET method for CFRP evaluation is ECT. Introducing an alternating current in a coil generates a magnetic field surrounding the coil, which when placed near to a surface of a conductive material, Eddy Currents are induced in the material. The Eddy Currents generate reciprocating magnetic fields in the opposite direction to the exciting field. Any discontinuities within the component causes disturbance of the circulation of Eddy Currents varying the resulting reciprocated field measured by the coil. These variations signify impedance changes within that coil. ECT is generally applied to electrically conductive materials such as metallic counterparts, however carbon provides a low content of conductivity making it acceptable for CFRP tests. (Carsten Beine, 2010)

For a safety factor it is necessary to demagnetise a component after conducting a magnetic particle inspection to reduce; machining complications, interference with electronic equipment and abrasive particles which may cling to bearing or fraying surfaces.

Remnant magnetic fields can be removed using a number of procedures, the most common one being curie tempered. Once the component is heated above its curie temperature in metallic terms it becomes austenitic and losses its magnetic properties. This process is inconvenient for CFRP, which introduces using an AC coil and an electromagnetic yoke. Subjecting the component to a reversing and decreasing magnetic fields will return the dipoles to a near random orientation throughout the material. Industry standards usually require that the magnetic flux be reduced to less than 3 gauss after completing a magnetic particle inspection. (Drury, 2014)

2.2.3 Thermography

Thermography testing is typically separated into two types; passive thermography and active thermography. Both use the basic principle where a camera containing a large number of infrared sensors, which detect and measure small temperature changes, is subjected at a component. During passive thermography the test piece is untampered with, resulting in a thermal image from which a temperature map is constructed.

Active thermography involves an external heat source to rapidly heat the components surface. The surface is then observed to witness the temperature decay in relation to time. Any flaws within the material will display a varied temperature decay rate. A technique adopted for testing CFRP through thermography means is lock in thermography. This is characterised by a periodic modulation of thermal excitation; where a “thermal wave” is generated through a component under inspection. The wave is controlled by modulation frequency and is reflected at interfaces due to material changes such as, delamination, cracks or inclusions.

A thermographic camera can then examine the components surface, recording image sequence. These are then correlated to a sine and cosine function with similar frequency to that of the modulation frequency. As a result, an amplitude and phase value is calculated for every pixel. The final image produced is ideally free from disturbing influences like emissivity variations or inhomogeneous heating. (Carsten Beine, 2010)

2.2.4 Computed Tomography

Radiography theory is heavily described within the following subheading however, a brief introduction to an evolving form of radiography testing computed tomography, is presented here. X-ray computed tomography is an image-forming NDT and evaluation method which delivers truly three dimensional images of an object replacing the previous two dimensional conventional radiography. Limitations are applied such as complexity of the object shape and size. The component is placed between an X-ray source and flat panel detector, its position determines the voxel size. During the operation the component is rotated 360°, whilst some hundred radiographs, projections, are taken. Once completed the projections are calculated and processed by a computer, resulting in a 3D model of the component, which can be sectioned layer by layer. The advantage of CT is that the volume image can be easily interpreted and an absolute measure for the radiation absorbed in each volume element. Therefore, the linear attenuation coefficient μ which is dependent on the X-ray energy and material density can be discovered. It is important to note that the component has to be symmetrical in shape so that the material density is similar throughout. Furthermore, CFRP components have low absorption cross sections, due to the polymer matrix and reinforcement fibres having similar absorption coefficients. To achieve good contrast the operator would tend to use low energy X-rays to ensure that some absorption takes place ideally between 10kV to 50kV. (Ajay Kapadia, 2012)

2.3 Radiography Theory

The theory of radiography is understanding the nature of any penetrating radiation, being either X-ray or gamma ray. Both are part of the electromagnetic spectrum and only differ from their source of origin. They are characterised by frequency, wavelength and velocity, suggesting they are waveforms such as light rays, micro and radio waves however, they cannot be seen, felt or heard. They possess no charge and no mass and, therefore are not influenced by electric or magnetic fields and generally travel in straight lines. They can be diffracted in a manner similar to light rays. (NDT Resource Centre, 2009)

Peculiarly X-rays and Gamma rays act somewhat like a particle, in that they occur as small parcels of energy known as “Photons.” The photons have short wavelengths, hence more energy to pass through matter. The degree of penetration is dependent on their energy and the matter they are travelling through during which scattering and absorption takes place when a photon encounters with an atomic particle. Some photons have enough energy to ionise matter and can damage or destroy living cells, more commonly seen with gamma ray applications.

2.3.1 X-ray Tube

The photons are achieved by accelerating a stream of electrons into a heavy target material (anode), within a vacuum. The electrons velocity is controlled by applying a voltage at the cathode, reaching several hundred kilovolts. This determines the energy at which the electron will collide with the target. (Ramsey, 2014)

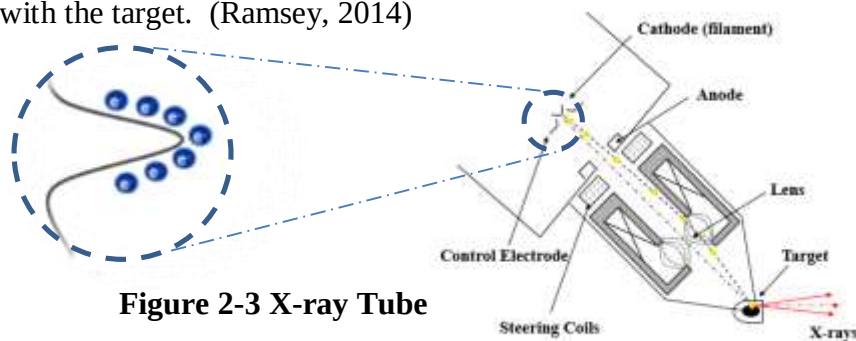


Figure 2-3 X-ray Tube

This procedure is carried out within an X-ray Tube (gun). Figure 1 shows the schematic of the tube. The electrons move from the negatively charged cathode to positively charged anode, within the vacuum glass case. The vacuum prevents a reduction in electron speed due to colliding with gas mols, oxidation and burnout of the filament. The cathode or filament is a tungsten wire that is heated by passing a current through it. When reaching operating temperature, electrons are continuously boiling off and emitted towards the target by a strong electrical potential difference. They are accelerated away due to the filament possessing a high negative potential and so repelling the electrons. The anode is at ground; completing the circuit, and can either be positioned before the target or in some systems be the target itself. Once the electrons are fired, steering coils ensure the electron beam enters the centre of a magnetic lens. The lens focuses the electrons so that they all strike the target in a specific spot which is a micron or so across. This is known as the focal spot.

A control electrode located at the cathode influences the flow of the electrons, by varying two key parameters being voltage or current. The voltage describes the energy of each X-ray, therefore the intensity level. If an electron is accelerated through a certain voltage, which is measured in kilovolts (kV), it acquires an energy measured in Kiloelectron volts, keV.

An electron accelerated through 100kV has an energy of 100keV. This is the maximum energy that an X-ray generated by this electron could have however, most X-rays will have less energy. The average energy of the X-rays generated by electrons accelerated through a certain voltage in kV is roughly half to two-thirds of this in keV. (Ramsey, 2014)

The current is measured in microamps, μA and varies the amount of electrons being accelerated towards the target. A linear relation is made suggesting the more electrons striking the target, the more X-rays being generated. This proposes more X-rays are detected, which will enhance signal to noise ratios improving quality of the images. (Ajay Kapadia, 2012)

Lastly, the target material can also influence the X-ray production. More common than not, tungsten is chosen as a target material due to its heavy atomic number, which stimulates more atomic interactions to occur. As mentioned the high energy electrons are focused onto the target surface where they interact with electrons surrounding the target's atoms. These interactions produce X-rays in all directions. The target absorbs most of the X-rays produced and disperses the energy through heat. It is stated that less than 1% of the energy is carried away by the generated X-rays, making it necessary to cool the source. Most target designs incorporate cooling methods which include, rotatory or hydro means. Some introduce embedded materials, such as copper into the target, due to it possessing high thermal conductivity, without compromising X-ray production. (NDT Resource Centre, 2009)

There are two different atomic production mechanisms. Most commonly is Bremsstrahlung; German term for “braking radiation” and the other is Characteristic radiation. They both occur within the target at an atomic resolution and involve a change in the state of electrons.

2.3.2 Bremsstrahlung Radiation

Bremsstrahlung is the radiation produced when charged particles are subjected to a change in velocity. Once a highly energised negatively charged electron enters the target material, it is repelled by the electrons in an atom. This repulsive force produces an acceleration that causes the electron trajectory to curve away from its original path, producing braking radiation; as a photon. Fig.2-4 (a).

The energy of the emitted radiation depends on the size of the acceleration and therefore how strong the repulsive force is. For example, the repulsive force increases as the electron path gets closer to the atom. Controversially the incident electron can be attracted by the nuclei of the atom causing an elastically or in-elastically scattering of that electron.

The in-elastically scattered electron loses a large percentage of energy, submitting more photons. Fig.2-4(b). An elastically scattered electron are subjected through larger angles. Both interactions produce many photons of different wavelengths, however no photon has more energy than the initial incident electron.

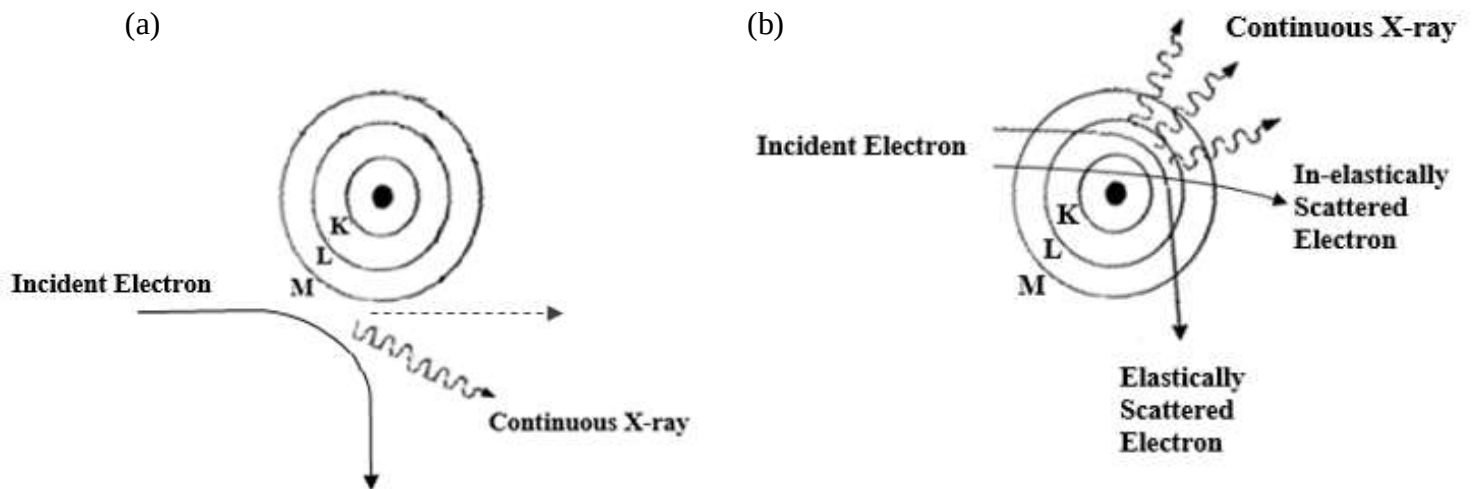


Figure 2-4 (a) Elastically Scattered, (b) In-elastically Scattered

The energy of the photons varies from very high, where all the electron energy is lost in a single “collision,” to very low where the electron is hardly affected by the atom, because the distance between the electron paths and the atoms is infinitely variable. (Fessler, 2009)

2.3.3 Characteristic Radiation

Characteristic emission is the production of a much defined X-ray energy that is characterised by the target material founded by W.H Bragg and systematized by H.G Mosely. When a high energy electron approaches the target atom it can knock electrons out of any inner shells (or electron orbits) that surround the nucleus of the atom. This occurrence leaves an excited unstable atom with a “hole” in its inner electron orbit.

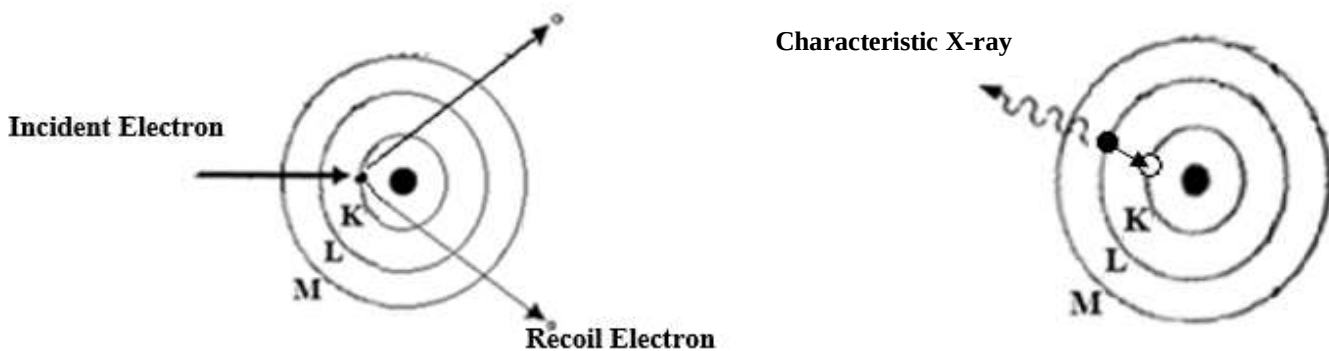


Figure 2-5 Characteristic Radiation

The excited unstable atom cannot exist in this state for long. To stabilise itself the atom uses an electron from an outer orbit to fill the hole. When the electron moves between the two orbits an excess of energy, equal to the exact difference between the two shells, is emitted by the atom in the form of a photon. The energy of the atomic shells are dependent on the target material hence the X-ray energy of the emission is also dependent on the target material. (Faiz M. Khan, 1984)

2.3.4 Properties of the Spectrum

The production mechanisms previously stated are what form the properties of the X-ray spectrum. Concentrating primarily on the continuous spectrum, a classic theory of EM radiation can be applied; the intensity of the radiation photon is directly proportional to the deceleration of the particle. The upper limits of this energy is determined by a number of variables.

Firstly, an electron with kinetic energy E cannot produce a photon energy greater than E . This maximum energy lost $E(\text{max})$ defines the shortest wavelength, $\lambda(\text{swl})$, which represents the start of the continuous spectrum. This is expressed using the following equation. (Fessler, 2009)

$$E = eV = hc / \lambda$$

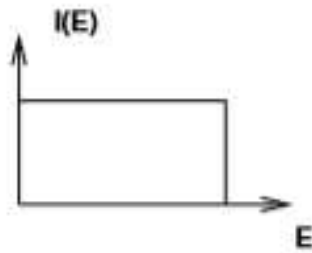
Where e is the charge of an electron, V is tube voltage, h is plank's constant and c is speed of light. Rearranged for $\lambda(\text{swl})$.

$$\lambda = 12.398 / V$$

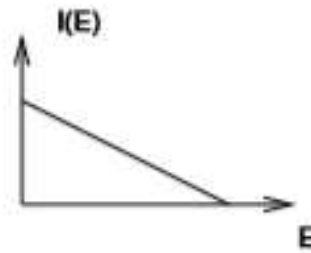
The equation terms a relationship between wavelength and voltage; the higher the accelerating voltage of the X-ray tube, the shorter the minimum wavelength that can be obtained. (Faiz M. Khan, 1984)

Another variable is the target thickness. For an infinite thin target, it is predicted that the intensity of the photons produced is constant up to the electron energy. However, with a thick target the spectrum is modelled as the superposition of a number of thin layers, where the energy decreases to zero through the target. When plotted of intensity over energy. (Fessler, 2009)

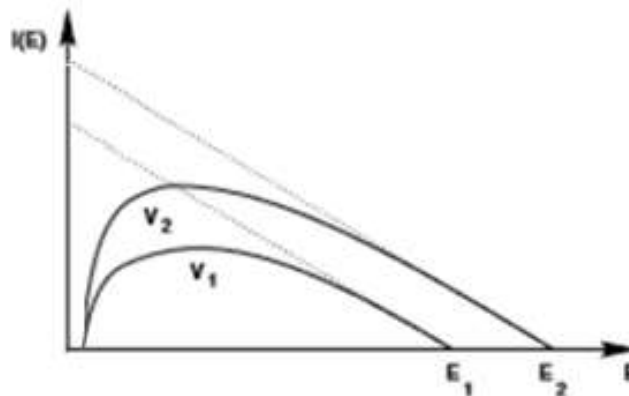
Thin target



Thick Target

**Figure 2-6 Height Proportion**

The thick target show a linear relation to the continuous spectrum, yet many photons, especially with lower energies, are absorbed before they leave the X-ray tube. Filtering also takes place within the target and the glass envelope, thus the continuum spectrum usually is displayed in the following form. (Fessler, 2009)

**Figure 2-7 Voltage Proportions**

The figure shows two voltages being applied to the same target material. The height of the curve is proportional to the voltage, as it increases the photon energy. The position of the energies have shifted also representing the change in maximum energy, therefore the shortwave length limits. (Faiz M. Khan, 1984)

The total intensity of the radiation is approximately proportional to the filament current I , the atomic number of the anode target and the square of accelerating voltage V .

This is expressed with incorporation of wavelength using Kramer's equation shown within the literature review of this chapter. The total spectrum includes the influences from characteristic radiation, which represent peaks of intensity. The most common being, $K\alpha$ where a quantum leap between the L-shell to K-shell occurred or $K\beta$, a leap between M-shell to K-shell. These X-rays are shapely defined frequencies associated with the difference between the atomic energy levels of the target atoms. (Watanabe, 2009)

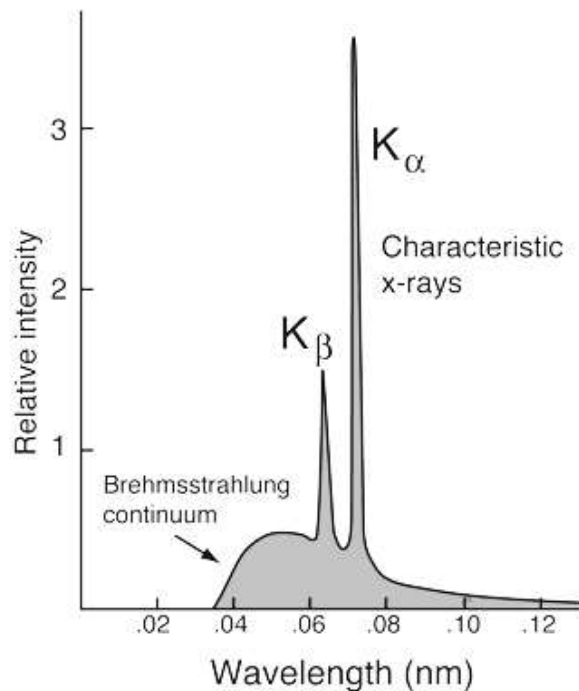


Figure 2-8 X-ray Spectra

The figure shows a generic spectrum of molybdenum relative intensity over wavelength. The peaks of characteristic radiation solely depend on the metal target choice. $K\alpha$ is relatively double in intensity than $K\beta$, which correspond to the transitions of the molybdenum electrons. It can be predicted from a Bohr model, where measured frequencies of the characteristic X-rays are referred in the periodic table creating a plot showing the energies of an electron orbiting an atom of a specific material. (Modern Physics, 2011). The spectrum curve is instituted primarily to witness the trend of the intensity.

The X-ray source is polychromatic meaning it emits photons which have a wide range of energies, which is somewhat undesirable. By reducing this trend and making it more monochromatic would enhance analysis and interpretation of X-ray imaging. This is achievable by filtering out all but a narrow range of photon energies. A shift in the spectrum therefore comes down to the interaction of the photon and matter.

2.3.5 Attenuation relationship.

A photon passing through matter interacts with particles of mass or pass unaffected. Any interactions such as, scattering or absorption, which removes a photon from the beam is known as attenuation. This relates to the overall decrease of beam intensity. (Fessler, 2009) The amount of attenuation is dependent on two factors:

- The depth of penetration (thickness of the material (x))
- The characteristics of the material (Linear attenuation coefficient (μ))

The intensity decreases exponentially with the distance travelled, expressed using Beer-lamberts Law, *(full derivation of the equation(s) are found within appendix A.)*

$$I = I_0 e^{-\mu x}$$

where I_0 is initial intensity and I is the output intensity; seen within the schematic below.

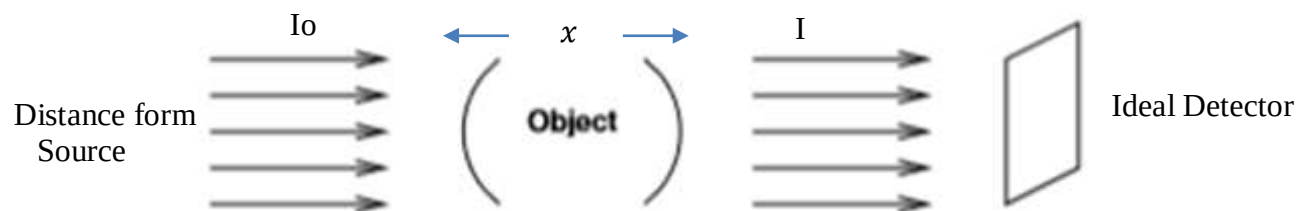


Figure 2-9 Beer Lambert Law

Beer-Lamberts law substitutes for a monoenergetic beam passing through a uniform material of a thickness (x) with a linear attenuation (μ). Thus larger thicknesses or higher attenuation means fewer photons can penetrate through. The expression is for homogenous materials with a constant (μ), which isn't ideal as most objects, especially CFRP, are inhomogeneous.

A statistical term which is analogous to the half-life is applied for such inhomogeneous materials known as the Half-Value-Layer (HVL). It defines the thickness required of an absorber to attenuate an intensity of the beam to half its original value. This is expressed as;

$$HVL = \frac{\ln 2}{\mu} \approx \frac{0.693}{\mu}$$

The HVL is inversely proportional to the attenuation coefficient and is often used in radiography for shielding calculations. If a thickness which attenuates half the initial intensity is found, this is known as the first HVL. (HVL_1). A secondary thickness reduces the beam half of its intensity after it's been transmitted through HVL_1 . This is known as HVL_2 . Similarly HVL_3 is once again halved, to two of HVL_1 . As the relationship is exponential, from a heterogeneous beam, the HVL_1 is less than the subsequent HVL_3 . (NDT Resource Centre, 2009)

A quick note on detectors also reveals they cannot discriminate between photons of many different energies, so the recorded intensity is proportional to the averaging of photons impinging on the detector. Therefore, the output intensity must be examined between the object and detector. The projected radiograph should describe the complete description of (μ). This can be enhanced by variable setup parameters, such as low energies selectivity to aid the detectors discrimination, however most importantly, to interpret images of μ , the relation to the physical properties of the material is required. (Fessler, 2009)

2.4 Mass Attenuation Coefficient (μ/ρ)

When discovering the linear attenuation coefficient μ of a material, the same density and for different thicknesses, are assumed. A related coefficient can be sourced by including the density, ρ , of the absorber known as the Mass attenuation Coefficient, which is defined as;

$$\frac{\text{Linear Attenuation coefficient}}{\text{Density}} = \frac{\mu}{\rho}$$

As previously mentioned, the photons are scattered or absorbed creating this coefficient with the main three mechanisms being either;

- Coherent (Rayleigh) scatter
- Photoelectric absorption
- Compton Scatter.

Other mechanisms can occur, however these require high energy photons such as pair production; where a photon > 1 MeV interacts with an atomic nucleus, resulting with an electron and positron. (J.H. Hubbell, 2009)

2.4.1 Coherent (Rayleigh) Scatter

Coherent scattering is where the photon interacts with the materials atom and scattered with no change to it's or the atoms initial energy state. It is remitted at the same wavelength, however they may have changed in direction. This type of scattering is not a major contributor to the attenuation over a diagnostic energy range, (below 200 keV).

2.4.2 Photoelectric Absorption

The photoelectric effect is the absorption of a photon by a bound orbital electron. The kinetic energy of the electron increases due to the energy of the photon, which overcomes its binding energy and ejects itself from the atom. This ionizes the atom which may return to neutral state with the emission of a characteristic radiation.

Electrons in the K-shell are predominantly involved with these mechanisms.

Photoelectric absorption is random however, the most dominant process of X-ray absorption and the probability of this interaction increases as higher photon energy, close to the binding energy of the electron, is applied. (NDT Resource Centre, 2009)

2.4.3 Compton scattering

The Compton scattering signifies when an incident photon collides with a free or loosely bounded electron in an outer shell. The electron will gain energy, once again ejecting it from its orbit and the deflected photon which has lost energy will divert in an altered direction. As the scattered photon has less energy from the incident state it now has a longer wavelength. The energy shift between photon and electron is dependent on the angle of interaction.

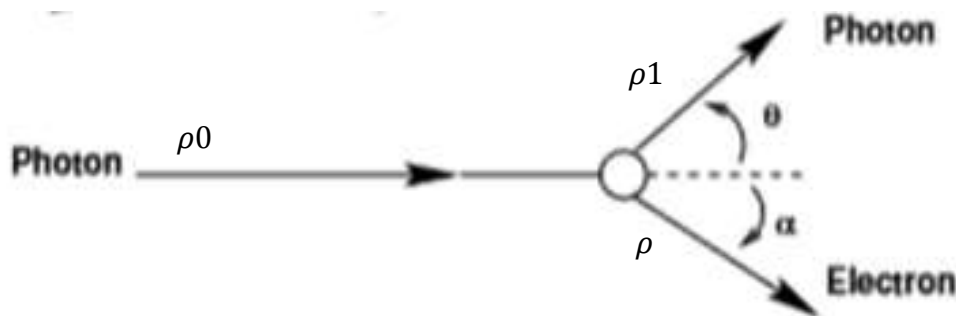


Figure 2-10 Compton Scattering

Compton scattering considers that the interacting electron is at rest, therefore for a true measurement of energy shift, a correlation between the photons and electron momentum is required. (Fessler, 2009) Usually the event is described using momentum (ρ) and energy conservation expressed:

$$\rho_0 = \rho_1 \cos \theta + \rho \cos \alpha$$

$$\rho_1 \sin \theta = \rho \sin \alpha$$

At lower energies where small change to wavelength occurs, the scattering angle is insignificant, meaning Compton scattering at these levels is relatively unimportant. Therefore, in relation to photoelectric;

- Low energies and high atomic numbers, photoelectric absorption is dominate.
- High energies and low atomic numbers, Compton scattering dominates.

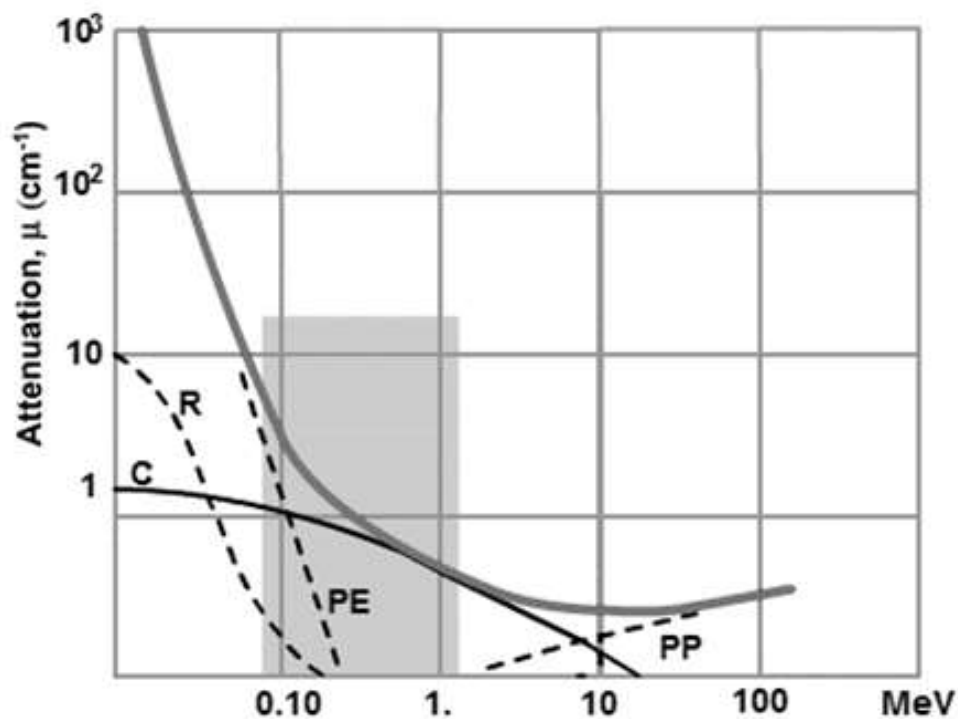


Figure 2-11 Attenuation Plot

The graph reveals the mechanisms plotted in correspondence to their attenuation at increasing electron voltages. The shaded area represents an area where most industrial radiography testing is accomplished, ranging between 0.1 to 1.5 MeV. Within this shaded area Photoelectric (PE) and Compton scattering (C) encounter the majority of attenuation. The Rayleigh (R) and Pair Production (PP), are just outside of the X-ray testing range, nevertheless, can be significant for specific testing requiring high or low energy interactions. Gamma- rays primarily encounter Pair Production as its main attenuation mechanism. (NDT Resource Centre, 2009)

2.4.4 Filtration

The X-ray spectrum is a composed curve from several X-ray lines essentially, which are very polychromatic; especially at higher tube voltages as characteristic radiation occurs. Filters are added to attenuate some of the lower energy photons, and preferentially reduce the intensity of $K\beta$ lines. Unfortunately unwanted $K\alpha$ radiation is harder to remove, as energy levels are higher. The choice of filter mainly depends upon the choice of anode or object being examined; a general industry technique for metal counterparts is to use a similar material for the filter that is being tested. (Poole, 2015)

If this is unpractical, filters can also be chosen on their exploitations of the X-ray absorption edge. The edge or 'critical excitation' refers to incident photon energy within the absorber material. Exemplified is a typical absorption edge for nickel metals. Longer wave lengths than the absorption edge has considerably less absorption than the shorter wavelengths, which defies the edge on the curve.

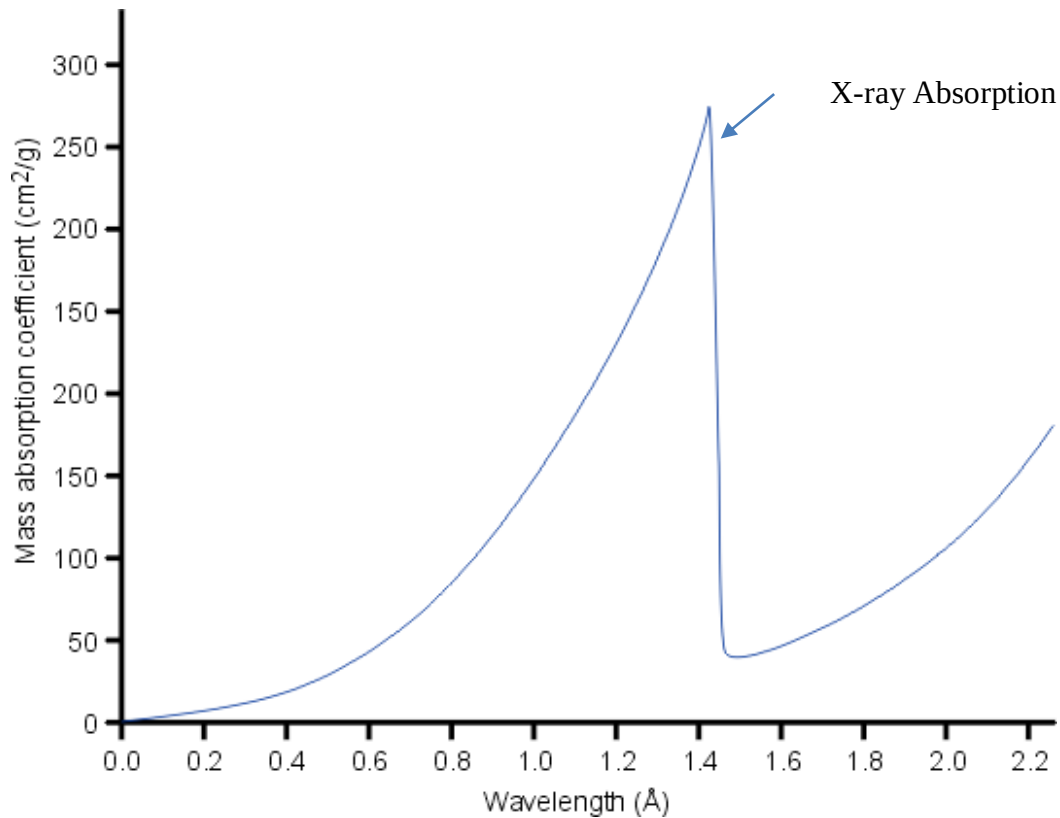


Figure 2-12 Example of Nickel Absorption edge.

The fall within the curve shows nickel metals mass absorption coefficient falling with photons that have a wave length of 1.4Nm. The fall indicates an incident photon, has energy or wave lengths equal to the binding energies of an electron shell in the absorber material. (Poole, 2015)

This curve can be compared against test anodes to witness where the edge occurs within their distributed spectrum. For example nickel filters are used for copper anode testing, as the nickels absorber edge is just after $K\beta$ lines of copper, therefore are large amount of $K\beta$ photons which are more likely to be attenuated within the nickel. Making the output intensity more monochromatic.

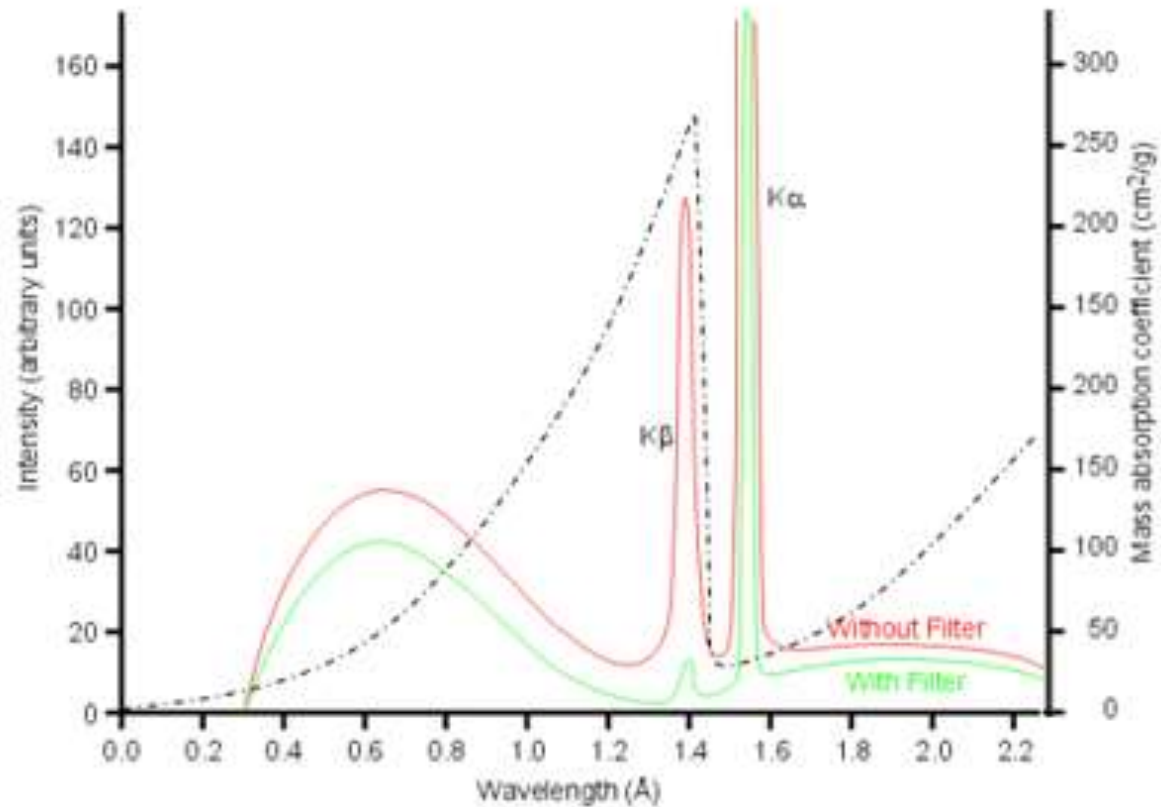


Figure 2-13 Effects of filtration on Bremsstrahlung curve

The optimum thickness of the filter is a compromise between reducing the unwanted intensity of $K\beta$ and only slightly reducing the continuum spectrum. Some filters are required to reduce the low energy, long wave length, intensity primarily for medical use as low energy ionises cells, which can lead to medical implications.

Tungsten is the industry choice of anode for many applications, as the spectrum produced is more monochromatic than most of its counterparts. It too has a similar relationship seen with copper and nickel, which is aluminium. (J.K. Cockcroft, 2006)

Aluminium filtration is highly used due to its ability to utilise the X-ray beam sourced from tungsten. Aluminium absorption edge appears at fairly low energies, short wave lengths, allowing for it to filter any K radiation occurring at low energies.

They are indicated in the shell designation. The graph below shows the mass attenuation coefficient (μ/ρ) and the mass energy-absorption coefficient (μ_{en}/ρ) as a function of photon energy, of aluminium.

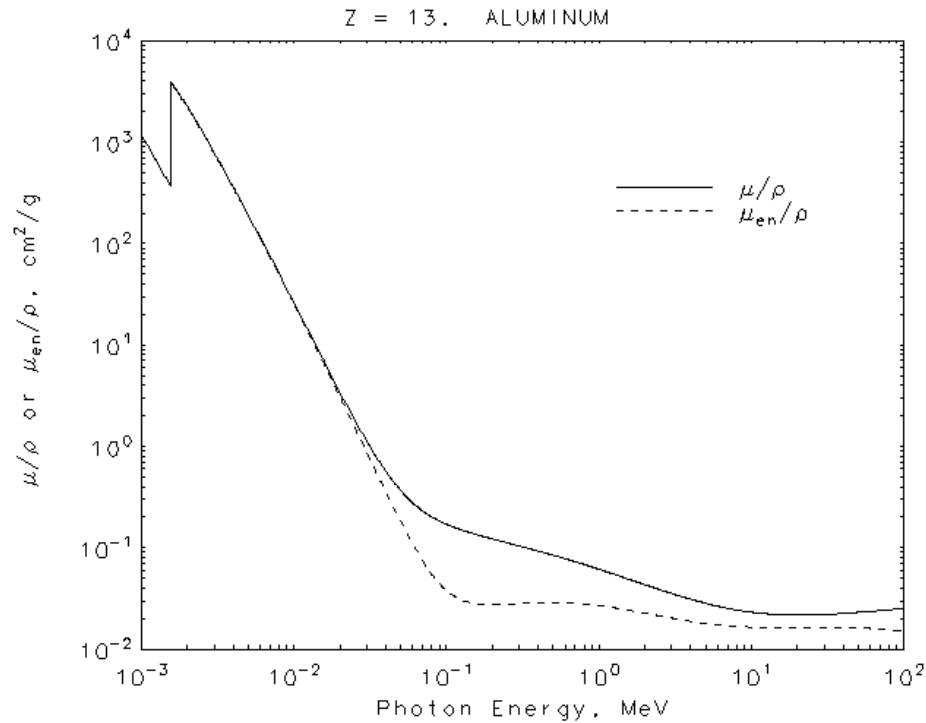


Figure 2-14 Aluminium attenuation

The mass attenuation coefficient is a product from the beer lambert exponential law previously mentioned with the input of density (μ/ρ). The mass energy-absorption coefficient (μ_{en}/ρ), introduces the further emission of radiation produced by charged particles travelling through a medium, which are disregarded for the purpose of this paper, as the theoretical approach concentrates solely on the attenuation coefficients produced by Beer-lamberts law. (National Institute of Standards and Technology (NIST), 2009)

2.4.5 Detectors

Computed radiography detectors have the potential to replace conventional film based radiography, due to not requiring any chemical processing to acquire an image. They have a wide dynamic range when compared to film, which has advantage of inspecting composite structures. They are most commonly used for live security imaging for inspection of suspicious packages as seen within airports.

Within digital radiography the use of flat panel detectors are the most attractive digital imaging system currently available. They are usually faster and have a very high dose efficiency, allowing for milliseconds of exposure to record a good image. The pixel resolutions of these detectors are continuously improving along with several image processing techniques to enhance the image quality, refining the reliability of X-ray inspections. The conversion for X-rays into an image technique in a flat panel detector is broadly classified into two categories; Indirect and Direct.

The indirect conversion has two stages, the first being is to convert X-ray photons to light photons in the visible range of the spectrum. This is achieved by reducing the X-rays energy emitting visible light during the de-excitation process. This conversion occurs within a scintillator, which are specific kinds of materials such as phosphors or Cesium Iodide (CsI). The second stage is transforming this light into a digital signal using technologies such as charged-coupled devices (CCD). The density of the scintillator material plays a very important role in deciding the stopping power for X-rays.

The direct conversion consists of an X-ray photoconductor layer made typically from amorphous selenium. It transforms X-ray photons into an electrical charges which offers very high spatial resolution. (Munshi, 2007)

Although direct conversion is a more favourable way of forming X-ray images and amorphous selenium does provide a good X-ray conversion efficiency, the dose efficiency is compromised, when compared to indirect conversion detectors. A schematic of the two conversion techniques are shown below.

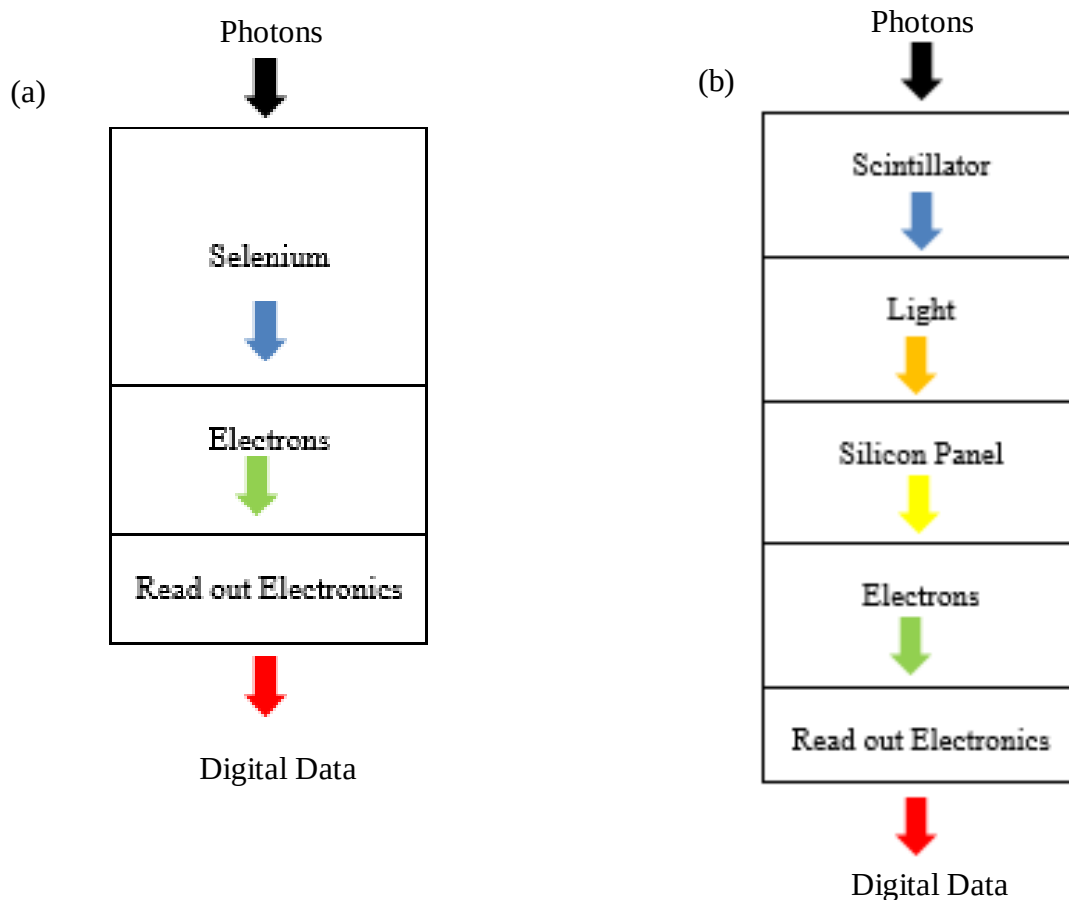


Figure 2-15 X-ray conversion techniques- (a) Direct and (b) Indirect

X-ray detectors are usually expected to have certain performance properties, which are related to image quality for various applications. These performances include Linearity, dose sensitivity, spatial resolution, dynamic range and minimum artifacts. (Munshi, 2007)

2.4.5.1 Linearity

Linearity of the detector response is an important feature in producing high quality digital radiographs. All detectors display some degree of spatial inhomogeneity in their X-ray response. This is a product from slight variation in pixel by pixel sensitivity, therefore to produce a smooth clean image these variations need to be compensated. This correction is commonly referred to as flat fielding or normalisation. This procedure is accomplished by applying a linear transformation on a pixel by pixel basis to the raw image data, using offset and gain calibration techniques. The purpose for this normalisation procedure is to achieve a basic linear response over a wide range of exposure conditions. An example plot of the linearity of a typical flat panel detector is displayed where the grey value counts (Y axis) are plotted over the relative exposure (X-axis).

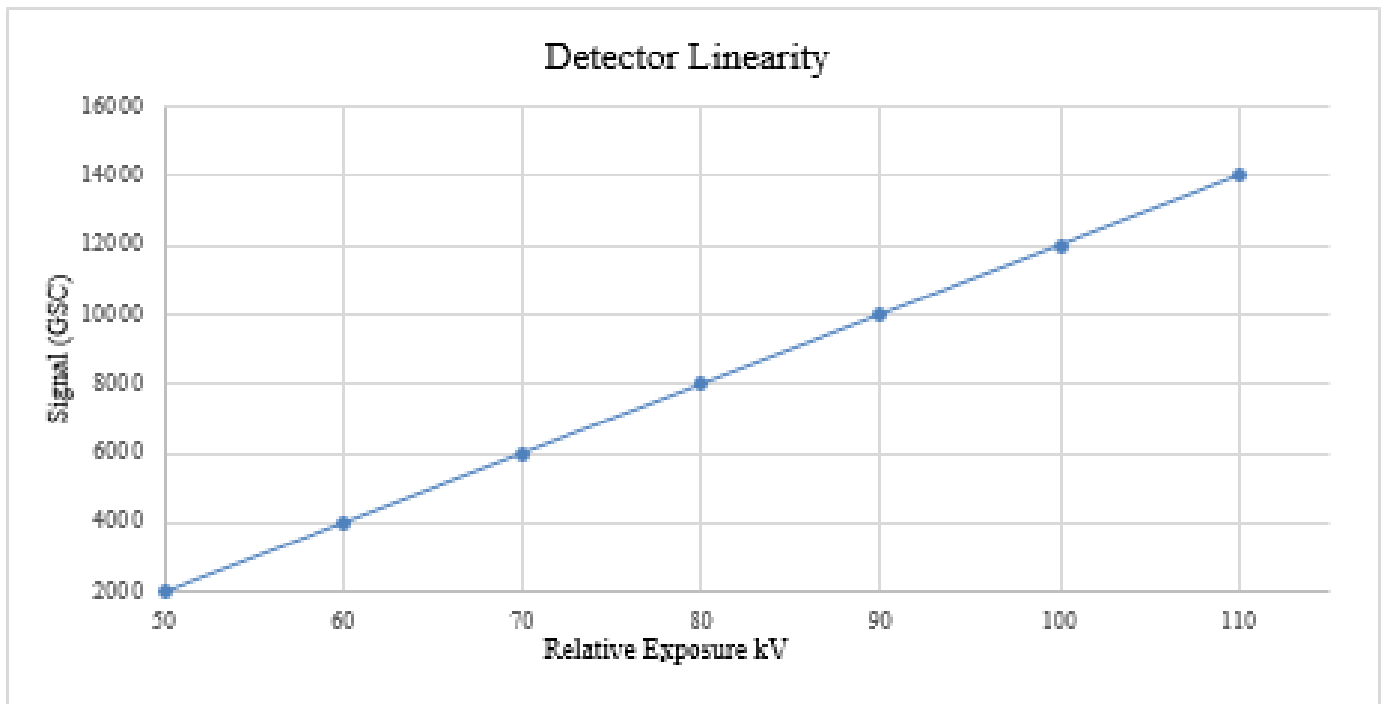


Figure 2-16 Linearity of digital detectors

The detector ideally wants to be strictly linear with the incident dose.

2.4.5.2 Dose Sensitivity

Lowering the dose sensitivity is an ideal condition for industrial applications as it improves productivity of inspections on components with similar material coefficients and minimises radiation damage to the semiconductor and phosphors used in the detectors, improving detectors life. Image quality (noise) is directly related to dose sensitivity of the detector and there are a couple of options to minimise the noise. One way is to increase X-ray tubes current, which will increase the mean count of photons on the detector. As long as saturation of the detector is not reached this will enable reducing relative noise in the image, as more pixels will be responding.

The second method is to acquire a series of images over a time domain and average them. The information of each pixel can have the distribution mean estimated providing a noiseless image without introducing artificial blurring in the image.

2.4.5.3 Spatial resolution

Higher spatial resolution is desired for better clarity on small features and is achievable with finite size pixels where the X-ray quanta are discretized to electrical signals. The pixel size determines the resolution capability. However, the detector and the imaging systems layout, limit the spatial resolution. Focal spot sizing and magnification ratios all play a key part in degrading the spatial resolution. While magnification is an attractive imaging technique to resolve small features, it along with focal spot sizing creates a problem in terms of geometrical un-sharpness. This scenario is later explained within chapter 3 and the systems layout.

2.4.5.4 Dynamic Range and Artefacts

A wider dynamic range allows more usable area of the detectors response. In the contrast response a detector using 16 Bit analog to digital converter can determine grey values ranging between 0 and 20000. For grey values of 10000 onwards the visibility is very clear. Hence the larger the bit the more contrast is available to distinguish between. A wider dynamic range also helps cover more variation in depth of a 2D image of the objects material.

The artefacts within images refer to the distortions which are unique to different detectors. The common two are distortion itself or blooming, however blooming is becoming less seen within new flat panel detector designs.

2.5 Literature Review

2.5.1 Kramer's Theory

Kramers theory was proposed in 1923 to express and calculate the continuous Bremsstrahlung spectrum from a thick target. It was developed on the basis of semi-classical assumptions to describe the reaction of kinetics. The theory has taken several forms to express this calculation, however the most basic form is;

$$I(E)dE = -C(E - E_0)dE, \quad E < E_0$$
$$= 0, \quad E \geq E_0$$

In summary; $I(E)dE$, is the intensity of the X-ray per unit energy interval E , E_0 is the tube voltage, and C is a constant.

The equation is a form of Fokker-Planck equation which describes the Brownian motion in potential; discovering a solution to a one dimensional distribution function for a position in velocity space. Developments to the initial theory gave Kramer's equation a more general application to X-ray systems parameters. To begin with, an introduction to the atomic number of a Target material was initiated.

$$I(E) = KZ(E_0 - E), \quad E < E_0$$
$$I(E) = 0 \quad \text{when,} \quad E \geq E_0$$

Where, Z is the atomic number and K is the system constant. As previously mentioned, the maximum possible energy that a bremsstrahlung photon can possess has to be equal to the energy of the incident electron. Therefore, the equations predict that the intensity of a photon is zero when the two energies equal one another. (Krammers, 1923)

The previous equations assume the energy spectrum has no filtration subjected, resulting in a linear trend where the intensity can go on to infinity when zero tube voltage is presented. The spectrum however, is never linear as inherent filtration within the X-ray tube and the addition external filters will modify the trend considerably. The purpose of filters is to enrich the beam with higher-energy photons, which is achieved by absorbing low energy components from the spectrum. The transmitted beam after filtration has a higher average of energy for better penetration power. Another method to achieve this of course is by increasing voltage. A good beam quality is a ratio between filtration thickness and voltage input as these parameters influence the spectrum is shape; (Krammers, 1923)

- alternating applied voltage, (increases the area of the curve)
- filtration of the beam (decreases the area of the curve)
- current (increases the multiple bremsstrahlung interactions within the target)

If these parameters were kept at a constant the beam would still be heterogeneous in energy due to the multiple Bremsstrahlung interactions within the target resulting in the different energy photons, which is relative to the systems current.

This leads to the commonly used Kramer's representation, which models the curve over photon wavelength. This introduces the systems current and allows for the λ_{swl} to be revealed once the curve is created.

$$I(\lambda) = \frac{K \cdot i \cdot Z}{\lambda^2} \cdot \left(\frac{\lambda}{\lambda_{swl}} - 1 \right)$$

where $I(\lambda)$ is the intensity of the photon, K is system constant, i is the systems current, and Z is the atomic number of target material.

The λ are related to its increasing voltage until λ_{swl} is reached at the maximum voltage. (J. C. Villforth, 1958)

Kramer's equation can therefore approximate the Bremsstrahlung X-ray energy spectrum for a system that uses a specific anode material, a desired current and a range of tube voltages. A complication occurs when trying to predict filtration effects to the initial intensity. As previously seen, Beer lamberts law is used to approximate an intensity potential difference through a thickness of material however, if the materials absorption coefficient is unknown, there are too many variables to conduct a study. This problem led to the development of state-of-the-art spectrum calculation programming. (J. C. Villforth, 1958)

2.5.2 *SpekCalc*

SpekCalc is a software program which simulates X-ray spectra emitted from thick target tungsten anode X-ray tubes. Similar to most industries radiography systems. It was developed to efficiently predict X-ray emission spectra from a given tube, as well as beam qualifiers such as HVL_1 and HVL_2 . It is primarily used for medical physics research, however it is adaptable to predict radiation physics for other applications. The range of tube voltages the software covers, was introduced such that an interest for medical physics or orthodox diagnostic radiology could have accurate data retrieved.

The SpekCalc model relies on a series of Bremsstrahlung production equations such as Kramer's, combined with numerically pre-calculated electron distributions which have been developed elsewhere. These calculations are illustratively compared with Monte Carlo code such as BEAMnrc.

Previous semi-empirical models of X-ray production have been seen to treat the penetration and energy loss of the electron beam crudely, which is where the Monte Carlo codes differ as they treat the particle transportation more strictly. Even to a degree of survival probabilities for an electron reaching certain depths with the target are pre-calculated within the BEAMnrc. The Bremsstrahlung cross-sectional area is a product of analytical theory and semi-empirical approaches, which satisfies the comparison between the SpekCalc predicted and experimental measurements for the X-ray Spectra. (G. Polundniowski, 2007)

The advantages of SpekCalc over comparative software models, is that;

- Firstly, it is computationally very fast, to produce the required spectra
- Secondly, extends its predictions to orthovoltage X-ray beams, improving accuracy.
- Thirdly, it allows for quick and easy interpretations of information, such as the spectra at a desired voltage or HVLs.

The third point indicates SpekCalc is user friendly, and provides several options to achieve and interpret the desired spectrum. To begin with the software allows for the user to input the electron energy (tube voltage) in kV, the X-ray take-off angle from the anode and an amount of filtration (thickness). Several filtration materials can be selected in mm; being either AL, Cu, W, SN, Be, Water or Air. This allows for the exploration of the filtration effects of materials of different atomic numbers. The data can be presented as a plot or in raw numerical form to be used elsewhere. In addition several beam qualifiers are pre-calculated such as the HVLs for both Au and Cu, the mean of the energy of the Spectrum, E_{mean} , and the effective energy, E_{eff} . The E_{mean} is defined as the mean beam energy averaged over the fluence spectrum. (Gavin G. Poludniowski, 2007)

There are some limitations with the software which can cause discrepancies with experimental testing. The range of X-ray tube voltages which can be modelled is (40 -300kV) which is within diagnostic tolerances for medical application. Any energies outside this parameter is deemed untested compromising the accuracy. The software is also limited to tungsten being the only anode material. This is the preferred target material but comparing the effects of anode atomic numbers is restricted. Limitations arise also when trying to compare to Kramer's equation, as the Monto Carlo coding does not require the use of system current as another parameter. Exploiting these limitations have led to the basis of the experiment conducted within this thesis, as it has provided crucial information for the comparison between experimental and theoretical analysis. (Poludniowski, 2007)

2.6 Conclusion

This chapter has discussed a number of topics required to understand the difficulties of CFRP characteristics. Whether it be testing the material or simply recording it's interaction with an X-ray beam. The material hasn't a consistence attenuation coefficient due to the difference in matrix and reinforcement particles. In conjunction with this, CFRP has low absorption cross section, which requires the use of low energy X-rays (10-50kV), to be used to ensure some absorption takes place, which suggests a uniform coefficient can be gathered.

The detector will play a key role in discovering the coefficient, however the research has shown there is a linearity issue which will have to be implemented into the final calculations, to provide a linear response of the detector is achieved.

The research has also shown that a coefficient can be found by implementing Beer Lamberts law, as a function (altering) thicknesses (x). All that is required, is the initial and resultant intensity, which can be developed using an addition of Kramer's equation. Kramer's theory represents an approximated Bremsstrahlung X-ray energy spectrum which indicates the maximum energy of photons which is equal to the accelerating potential, and the intensity of photons is proportional to the atomic number of the target material. Unfortunately, this is restricted to one component (filtration) thickness, which is where SpekCalc has the advantage to determine absorption coefficients. SpekCalc has been presented for the simulation software which can calculate the X-ray spectra from a tungsten anode X-ray tube. This is to be used to optimise the parameters required to determine the absorption coefficient of CFRP.

3 *Software and Hardware*

This chapter introduces the software and hardware used to gather and analyse the essential data from the theoretical and experimental testing. As there are two means of testing the chapter is split into two sections; Software and Hardware. The software covers the computer simulations used to retrieve and analyse the data. To begin with, an additional look into SpekCalc is presented. The background of the simulation software has been described in previous Chapter 2, however within this chapter the interpretation of the software is explained. This is followed by a series of spreadsheets created in excel, showing the relevant process required in using them. The spreadsheets are gathered in order of usage within the analysis, and begins with the theoretical SpekCalc data. The remaining spreadsheets display Beer Lambert laws and uniform absorption coefficients predictions. The next stage shows the experimental spreadsheets and their relation to Beer Lamberts law, however the methodology is explained in detail within the following chapter 4. This section also introduces image j, which is an image processing program.

The hardware section simply describes the Micro focus radiography system used to examine the effects of filtration and produce the required radiographs. A brief report into the detector linearity response is provided at the end..

3.1 Computational Software

3.1.1 SpekClac

The background of this software has been presented in chapter 2 explaining the limitations with the software nevertheless; the software is exceptional for the parameters it does offer. This section gives the user an explanation into how to manifest the desired data from this software. To begin with, a screenshot of the software with its generic pre-set inputs including the resulting simulated continuum curve.

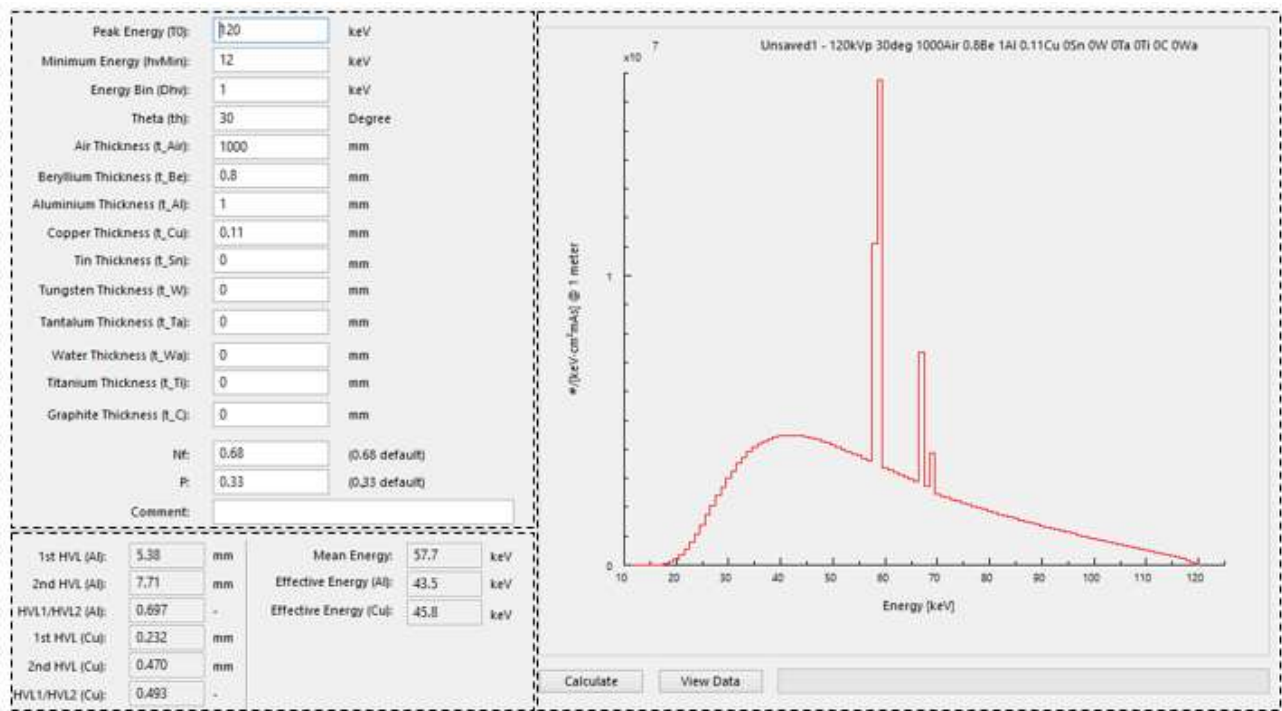


Figure 3-1 SpekCalc screen shot

The image shows a screenshot of SpekCalc, which has been sectioned into three parts, which will subsequently be described.

3.1.1.1 Section 1 The Parameters.

Peak Energy (T0):	120	keV
Minimum Energy (hvMin):	12	keV
Energy Bin (Dhv):	1	keV
Theta (th):	30	Degree
Air Thickness (t_Air):	1000	mm
Beryllium Thickness (t_Be):	0.8	mm
Aluminium Thickness (t_Al):	1	mm
Copper Thickness (t_Cu):	0.11	mm
Tin Thickness (t_Sn):	0	mm
Tungsten Thickness (t_W):	0	mm
Tantalum Thickness (t-Ta):	0	mm
Water Thickness (t_Wa):	0	mm
Titanium Thickness (t_Ti):	0	mm
Graphite Thickness (t_C):	0	mm
Nf:	0.68	(0.68 default)
P:	0.33	(0.33 default)
Comment:		

Figure 3-2 The parameters within SpekCalc

From the top the parameters are described as follows:

- $T(\theta)$ – is the energy of the electron beam impinging on the tungsten anode. Maximum tube voltage measured in keV, it was originally tested within a range of 50-150keV, however it has been agreed that a suggested working range can extend to $40 < T \theta < 300$ keV.
- hvMin – represents the centre of the minimum energy bin for which a spectral contribution is calculated. This is constrained by this implementation to satisfy:

$$v_{Min} < 0.1 * T \theta \text{ measured in keV. (G. Polundniowski, 2007)}$$

- Dhv- Is the Bin width of the spectral contribution. The minimum suggestion for this figure is 0.5 keV.
- Th- Is the take-off angle from the anode. Any angle can be generated here, however a warning is giving that below 6 ° the prediction of characteristic radiation becomes increasingly unreliable. Above 30° the reliability of the whole model is untested.
- T- are the thicknesses in mm of the filtration materials listed is (Air, Beryllium, Aluminium, Copper, Zinc, Tungsten, Tantalum, Water). The air filter represents the distance between source and detector. Beryllium is a common material used as voltage tube casing.
- Nf- is an output normalisation factor, which can be adjusted to match the predicted output to a measured output on particular tube. For this example Nf = 0.68 was found to describe one particular tube over a range of tube potentials so therefore has been kept as a default constant.
- P- Similarly this is a normalisation factor for the characteristic radiation, relative to the Bremsstrahlung component. The value 0.33 was found as an acceptable normalization factor during the development stages of the software and therefore will remain a default constant. (G. Polundniowski, 2007)

3.1.1.2 Section 2 Numerical Results

1st HVL (Al):	5.38	mm	Mean Energy:	57.7	keV
2nd HVL (Al):	7.71	mm	Effective Energy (Al):	43.5	keV
HVL1/HVL2 (Al):	0.697	-	Effective Energy (Cu):	45.8	keV
1st HVL (Cu):	0.232	mm			
2nd HVL (Cu):	0.470	mm			
HVL1/HVL2 (Cu):	0.493	-			

Figure 3-3 SpekCalc Numerical Results

The second section reveals a quick analysis referring to the input parameters in section 1.

This analysis displays several beam qualifiers being HVL_1 and HVL_2 for both AL and CU measured in mm. These are thickness required to attenuate to the HVLs levels in that specific material. Under each material, a homogeneity factor (HF) is presented which describes the polychromatic nature of the beam.

Other information given, is the mean energy of the spectrum which is simply defined as the mean beam average over the spectrum, found by the integral of the curve.

Finally, effective energy shown for both Al and Cu is the energy of a monoenergetic beam that would produce the same HVL_1 value in both the materials.

3.1.1.3 Section 3 Graphical User Interface

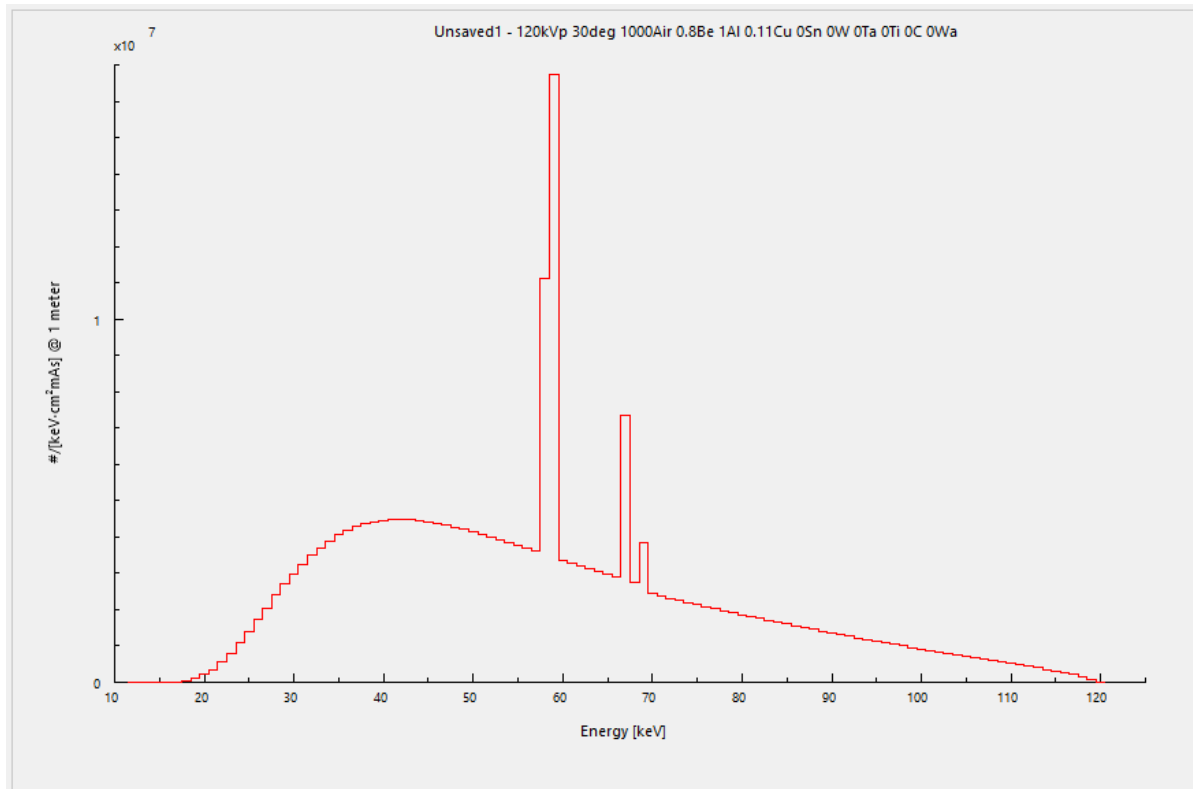


Figure 3-4 SpekCalc interpretation on Bremsstrahlung curve

The third section is the illustrative display of the X-ray spectra, once again influenced by the parameters inputted in section 1. The curve is plotted as $\#/[keV-cm^2mAs]@1\text{ meter}$ which represents the Monte Carlo code for intensity above Photon Energy (keV).

This graphical representation delivers a large amount of information, which can be easily interpreted. For example, the intensity of characteristic radiation and its position along the X-axis to determine the photon energy required to produce them. Once filtration is added it will also show the relation between attenuation and the effect it has on the spectra.

This information can be gathered, by using the curve or there is a quicker option that allows for the discovery of intensities over the increasing photon energy.

Under the curve is an option called **view data**, which will bring up a background file from which the curve was created. The window supplies the information from all three sections in text form to be implemented, within different software's. It also gives the coordinates from the calculated spectrum beginning from the hvMin value. This can be used as a fast method to discover key information accurately. Sampled with retrieving the characteristic radiation ordinates.

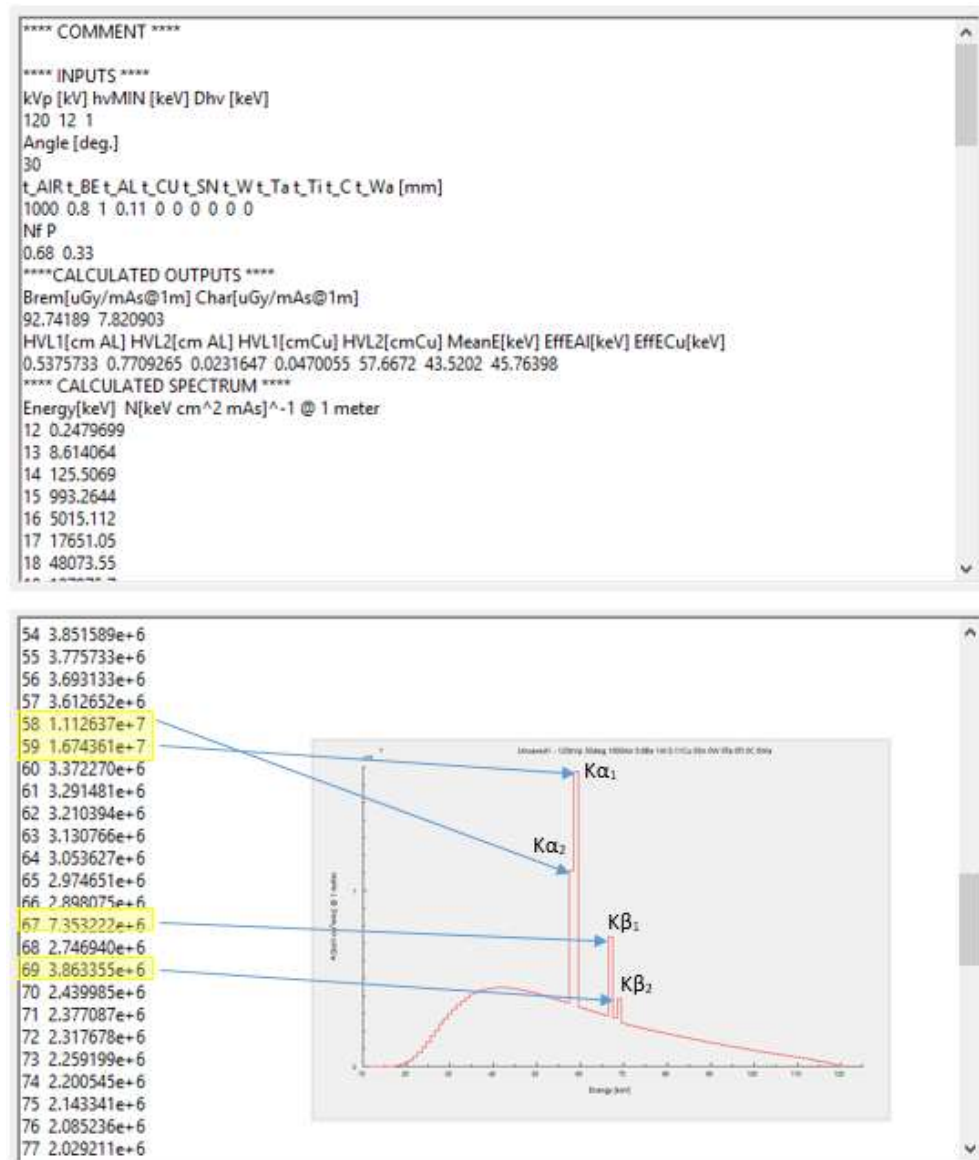


Figure 3-5 Numerical Data for Bremsstrahlung curve

3.1.2 Spreadsheets.

The information gathered from SpekCalc was displayed within the first of several excel spreadsheets. The spreadsheets are used to organise the information for the beginning of the analysis. This thesis is supplied with a CD-rom with the full working spreadsheets.

3.1.2.1 Aluminium (SpekCalc Spreadsheet)

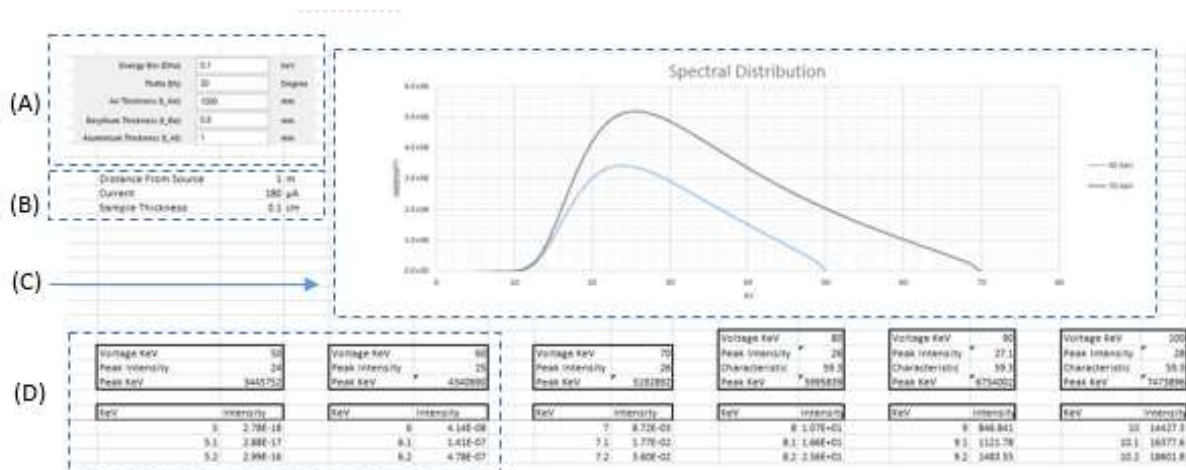


Figure 3-6 SpekCalc spreadsheet screen shot.

The screen shot of the spreadsheet has four areas of interest, which will be explained individually.

(A)

Energy Bin (Dhv):	0.1	keV
Theta (th):	30	Degree
Air Thickness (t_Air):	1000	mm
Beryllium Thickness (t_Be):	0.8	mm
Aluminium Thickness (t_Al):	1	mm

Figure 3-7 Theoretical Parameters

Shows the parameters from which the SpekCalc data was created. The key factor within this table is the aluminium filter thickness. The initial sheet used data calculated for 1mm filtration. Additional sheets use increasing filtration data by 1mm, presented within the CD-ROM.

(B)

Distance From Source	1 m
Current	180 μ A
Sample Thickness	0.1 cm

Table 3-1. Experimental Parameters

This section show key notes which correspond to the SpekCalc and experimental information. The information such as distance from source has been set as the air filtration thickness in SpekCalc and source to detector distance during the experiment.

The current of 180 μ A was for the experimental reference. The sample thickness is noted in cm due to its relation with finding the coefficient.

(C)

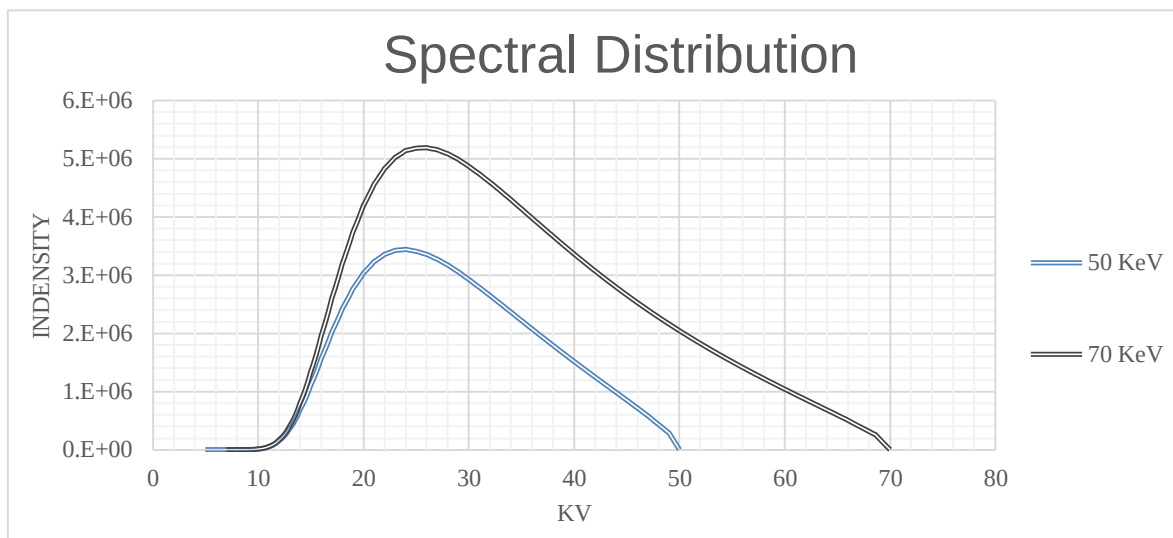
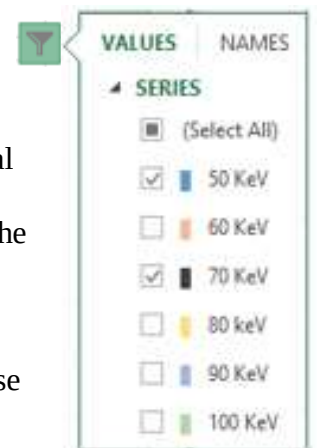


Figure 3-8 (Above) Spectral distribution curve. (Right) Legends series tool

Section (C) displays the beginning of the analysis. The graph is created by plotting the Intensity over the kV respectable to SpekCalc mirroring the spectral distribution curve. A series of curves can be plotted against one another using the legends series tool. For this example, the data for 50 and 70 kV are compared, keeping the parameters the same (A) with the only adjustment being the increase of kV. The series range between 50-100 kV in 10kV intervals.



(D)

Voltage KeV	50	Voltage KeV	60
Peak KeV	24	Peak KeV	25
Peak Intensity	3445752	Peak Intensity	4340690
KeV	Intensity	KeV	Intensity
5	2.78E-18	6	4.14E-08
5.1	2.88E-17	6.1	1.41E-07
5.2	2.99E-16	6.2	4.78E-07

Table 3-2 Theoretical Calculations

The final section shows a small percentage of the data supplied from SpekCalc. The informative cells have the corresponding data's key information. Firstly, the tube voltage required to create the data set. This acts as a reference to ensure the right data set is being used. Secondly the peak keV relates to the X-axis and the position at which the maximum intensity occurs, on the curve (C). The third cell, peak intensity, relates to the Y-axis and the positional peak of keV. It retrieve's the peak intensity producing the co-ordinates for the peak of the curve. Exemplared are 50 and 60 keV, however the data set continues to 100 keV. A trend occurs within the data after 80 keV, which requires an extra informative cell.

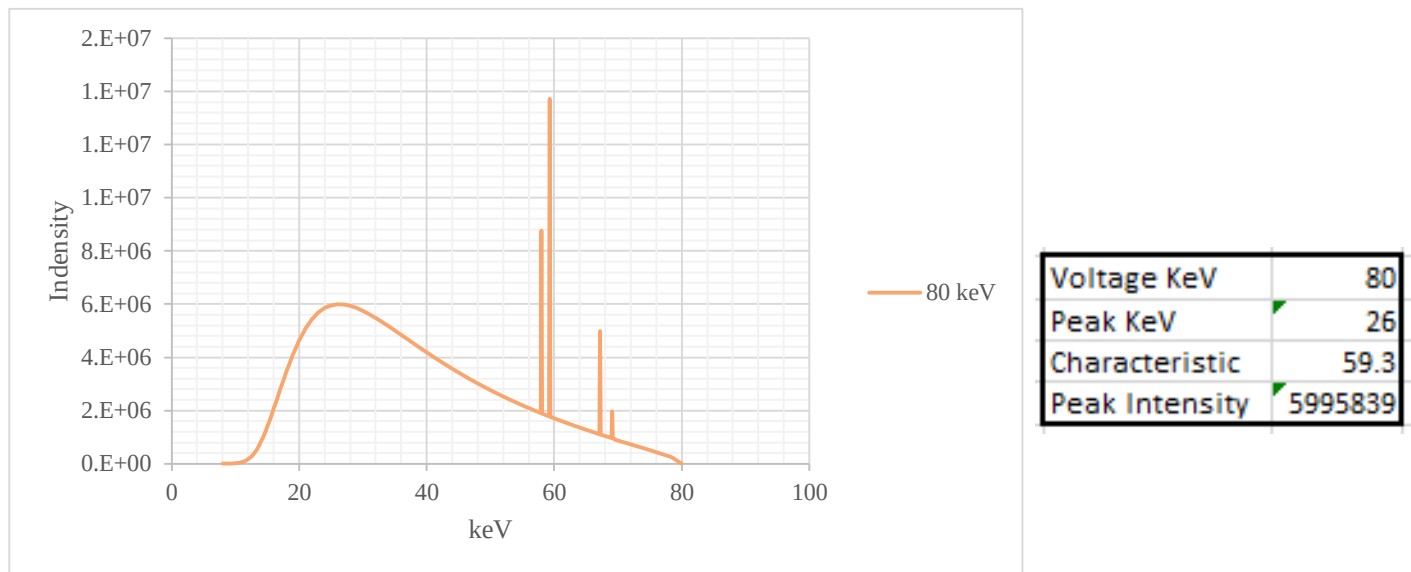


Figure 3-9. 80keV Spectral Distribution with Characteristic Radiation position table.

The addition of characteristic radiation requires another peak location in kV. The peak of the Bremsstrahlung radiation is also presented, for further analysis.

The spreadsheet is supplied with a number of sheets with repetitive layouts, with the addition of increasing filtration thicknesses. 1-4mm of aluminium. Once all the information was gathered the following sheets were created, to resolve the desired coefficients, and present attenuation curves. Note that curves display the full data set; however, within the analyse the curves are respectably scaled for clearer representation.

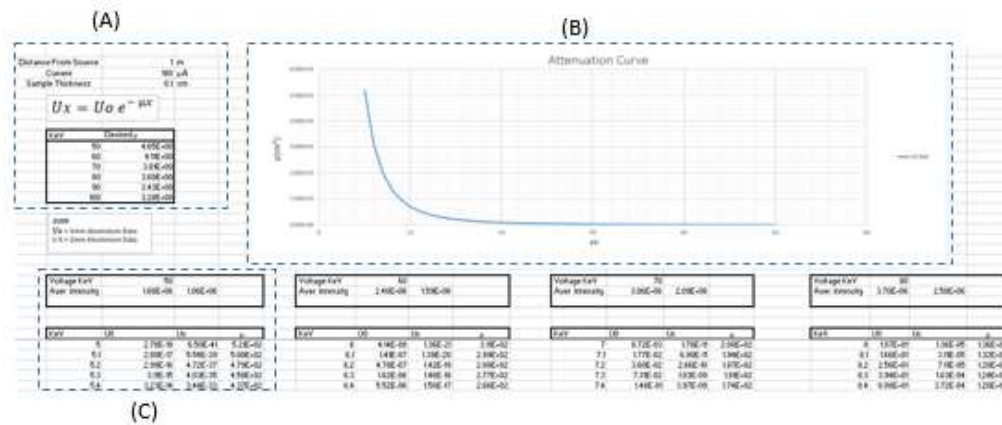


Figure 3-10 Coefficient Spreadsheet Screenshot

There are three areas of interest, which are sectioned and explained individually.

(A)

Distance From Source	1 m
Current	180 µA
Sample Thickness	0.1 cm
$U_x = U_o e^{-\mu x}$	
KeV	Desired μ
50	4.65
60	4.11
70	3.81
80	3.60
90	3.43
100	3.28

Table 3-3 Desired Coefficients

The first section shows the parameters required for experimental justification; and most importantly the sample thickness, represented as x within the equation shown. The table lists the desired coefficients for a representative tube voltage; which were calculated, shown within the (C) section. These figures will be used within the analyse stage.

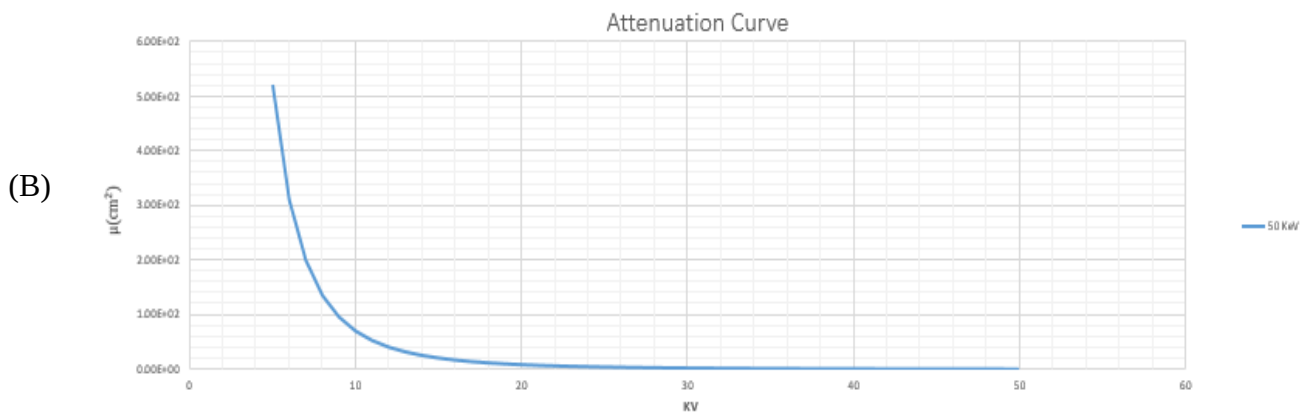


Figure 3-11 50kV Attenuation Curve

This section shows the attenuation curve from which a respected attenuation figure can be found for a specific kV value. Previewed here, is a range to 50kV. The integral of this curve is found to be the desired coefficient. This is repeated at the following kV ranges. 50-100kV.

(C)

Voltage KeV	50			Voltage KeV	60		
Aver Intensity	1.68E+06	1.06E+06		Aver Intensity	2.40E+06	1.59E+06	

KeV	U0	Ux	μ	KeV	U0	Ux	μ
5	2.78E-18	6.50E-41	5.21E+02	6	4.14E-08	1.36E-21	3.11E+02
5.1	2.88E-17	5.54E-39	5.00E+02	6.1	1.41E-07	1.39E-20	2.99E+02
5.2	2.99E-16	4.72E-37	4.79E+02	6.2	4.78E-07	1.42E-19	2.88E+02
5.3	3.11E-15	4.03E-35	4.58E+02	6.3	1.62E-06	1.46E-18	2.77E+02

Table 3-4. Attenuation Theoretical calculations

The final section displays the data inputs from the previous SpekCalc sheets. Concentrating with the first data set, the keV column refers to the increasing tube voltage in inclinations of 0.1 keV. For the 50 keV this ranges between 5-50kV. The secondary column Uo is the initial intensity for 1mm aluminium, Ux is the intensity produced after 2mm aluminium filtration. The Ux column will differ dependant on the sheet reference to the amount of filtration applied. For example in sheet 3mm aluminium, Uo will remain constant. 1mm aluminium data set and Ux will have 4mm aluminium data set. The x reference in section one will have increased to 3mm (0.3 cm) filtration thickness. The final column μ , is the resultant number of the equation shown in section one, respectable of Uo and Ux at a certain keV and thickness.

The upper cells show key information of the data set such as the referenced tube voltage and the average of the data sets, used within the analyse to determine the desired coefficient. This process is completed for the range of 50-100KeV for the three thickness variations.

3.1.3 Image J

In order to retrieve the data required for experimental analysis an imaging software known as Image J was used. This software allowed for interpretation of radiographs and provided key information towards the analysis. A brief demonstration of the software is presented here however, the full process is highlighted within the methodology of this thesis.

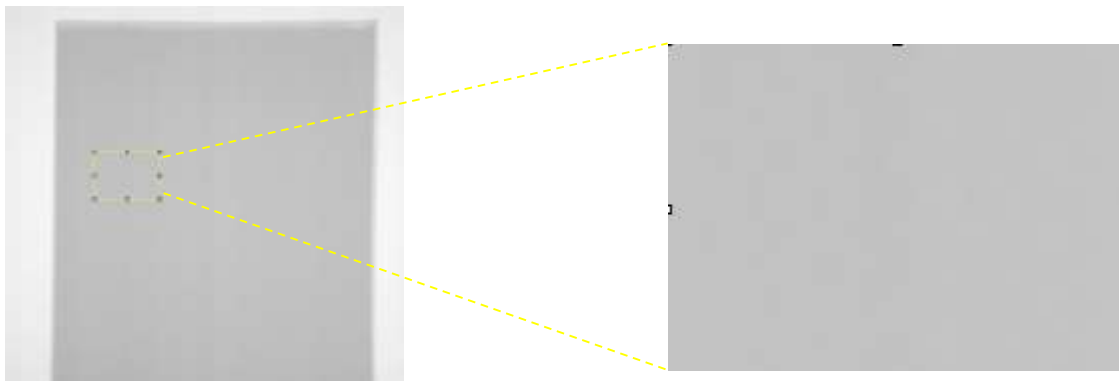


Figure 3-12. Image J example of CFRP

The first image shows a 2D radiograph of carbon fibre opened within the image J software. The parameters used initially show a uniformed contrast within the materials structure, making it difficult to obtain any information such as defects or layup characteristics. A small section has been sampled in an area of interest shown on the right of the image. Image J has the capabilities to adjust the contrast of the radiograph to obtain a more suitable image. This is achieved by examining and altering the histogram function.

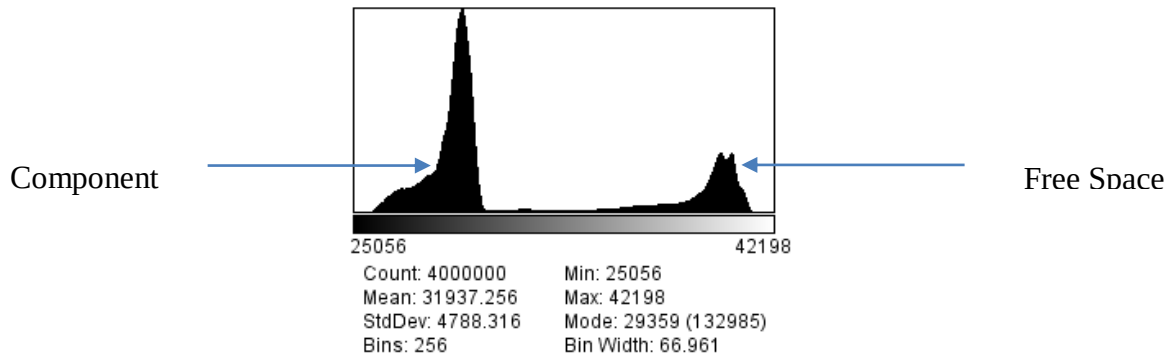


Figure 3-13 Full uniform histogram

The histogram displays the radiographic contrast, which defines the difference in densities between various regions. In methodological terms, an image that shows high and low variation in greyscales has either high contrast or a short grey scale, as there are a few shades of grey from one extreme to the other. This is presented here with this image, as a uniform contrast is set across the image. The histogram presents this as a sharp peak, which is undesirable. The histogram function also present some key statistical information about the full image, which will be used within the analysis stages.

As earlier stated there is an area of interest which initially shows poor contrast. If this section is analysed solely a more productive histogram can be sourced which doesn't take in affect the surrounding free space around the component.



Figure 3-14 Area of interest with corresponding histogram

The histogram has plotted the number of pixels within the image with a particular brightness value (greyscale). Algorithms within image J allow for alterations to these brightness values of a signal pixel to enhance the image and show the variation in the materials density and absorption characteristics. The end result is an image acceptable for investigation. This imaging processing is interpreted by the operator.

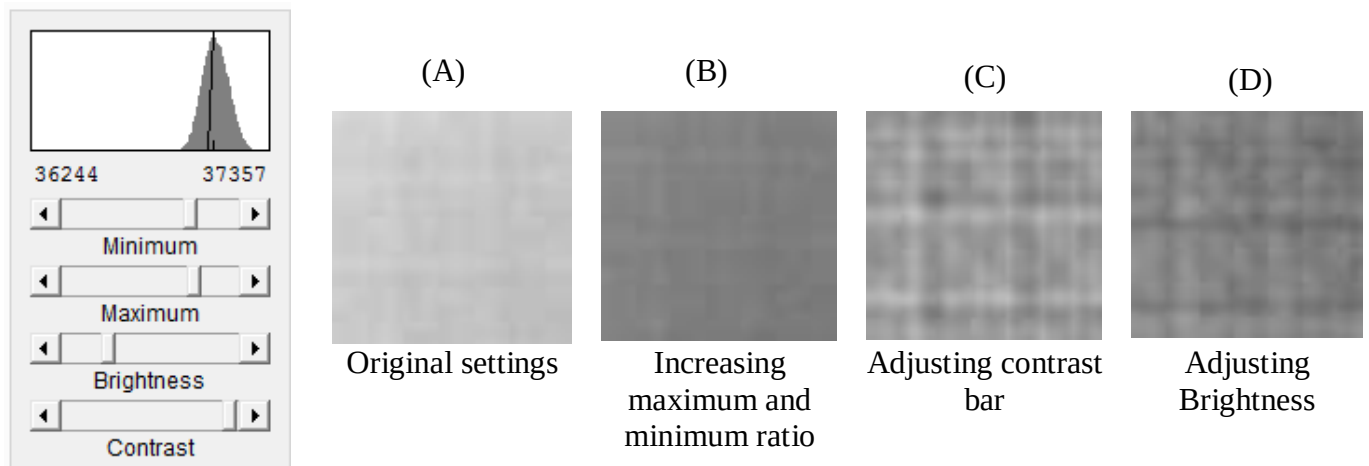


Figure 3-15 Adjusting Histogram levels.



Figure 3-16 Final Image quality.

3.1.4 X-ray Spread Sheet

The imaging software is fundamental as it supplies the data from the experimental radiographs, which is presented within the next set of spreadsheets. Both aluminium and carbon filters have been examined and have had their histograms converted into numerical form. This procedure is required for the analysis.

The spreadsheet below shows an example of an aluminium 1mm filter, with a range of 50-100 KeV subjected through it. Once again this example is repeated for the remaining filtering thicknesses and for carbon materials.

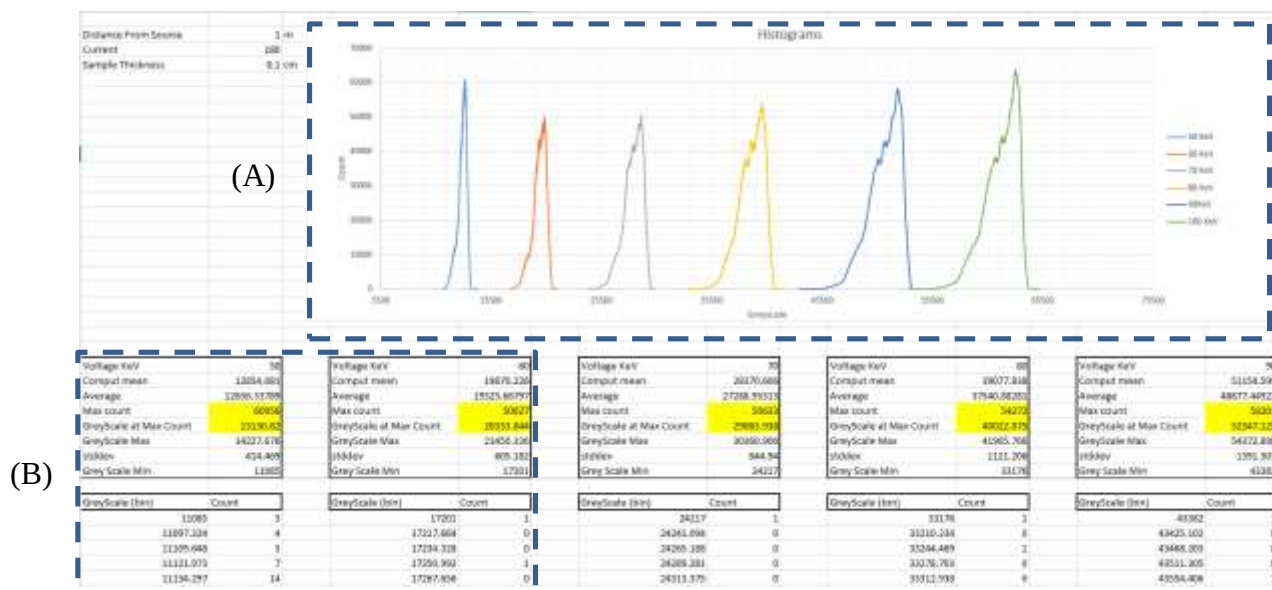


Figure 3-17 X-ray spreadsheet screen shot.

The screen shot of this spreadsheet has sections of interest which, will be individually described. In reference to the previous spreadsheet, the experimental parameters are discovered within the right hand side of the spreadsheet.

(A)

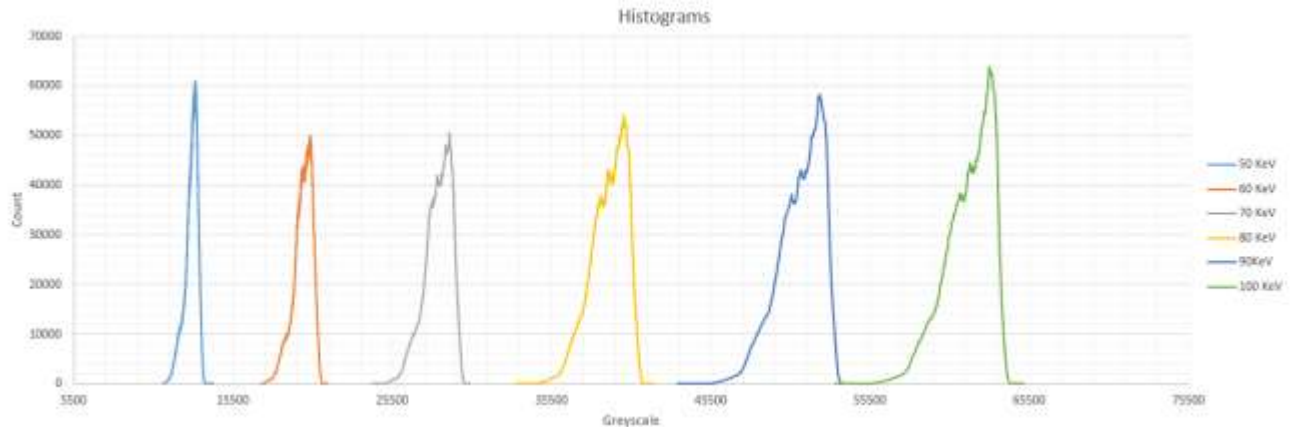


Figure 3-18 Histogram representation curves 1mm Aluminium

The graph shows the outline of the histograms ranging from 50-100KeV (left to right). The data requirements are annotations of these curves however, the comparative positions also reveal a trend of their own. For example; the X-axis of the graph represents the tonal variations, shades of grey, while the Y-axis represents the number of pixels which have that particular tone. The left hand side of the axis are black and dark areas, the middle sections are medium grey and the right hand side are light (pure white). Thus, 50KeV interactions produce dark imaging and as the voltage increases the lighter the images become. The scenario, is later seen within the results. The shape of these histograms are also vital, as can be seen with the lower energies a uniform distribution occurs. As energy increases, the data becomes more skewed.

(B)

Voltage KeV	50	Voltage KeV	60
Comput mean	12854.081	Comput mean	19870.226
Average	12656.33789	Average	19325.66797
Max count	60956	Max count	50027
GreyScale at Max Count	13130.82	GreyScale at Max Count	20333.844
GreyScale Max	14227.676	GreyScale Max	21450.336
stddev	414.469	stddev	605.182
Grey Scale Min	11085	Grey Scale Min	17201
GreyScale (bin)	Count	GreyScale (bin)	Count
11085	3	17201	1
11097.324	4	17217.664	0
11109.648	3	17234.328	0
11121.973	7	17250.992	1
11134.297	14	17267.656	0

Table 3-5 Experimental Calculations.

The outlined histograms are displays for the numerical data columns greyscale (bin) and the counts. This information is retrieved from image J analyse. The upper cells supply statistical information such as the integral of the histograms at a desired KeV.

- The first cell is the representative KeV used in the experiment.
- The next two cells are the greyscale averages taken during the experiment and Image J's contribution. Differentials are caused due to computational overlap.
- The following cells highlighted yellow are the positional coordinates of the peak of each histogram.
- The last three cells represent the maximum and minimum greyscale count and the software's interpretation of the Standard deviation in correspondence to the shape of the histogram.

3.2 Hardware

3.2.1 *Micro focus CT*

The experimental procedure required a series of X-rays, which was completed at a sponsoring company using their micro focus CT machine. An overview of the machines specifications are discussed within this section, including a description into the internal features of the machine.

2D imaging was used solely for the experiments, however, a brief discussion into CT operations are also covered within this section. A full specification sheet for the comparative systems are found within appendix B.

3.2.1.1 *XT H 225 Industrial CT Scanner*

Nikons version of industrial X-ray and CT systems known as the XT H 225 was used for the experiments due to its ability to cover a wide range of applications, including the inspection of CFRP parts, small casting and complex mechanisms. The system offers a microfocus X-ray source, which generates high image resolution over a large inspection volume, ideal for CFRP components. (Nikon, 2015)

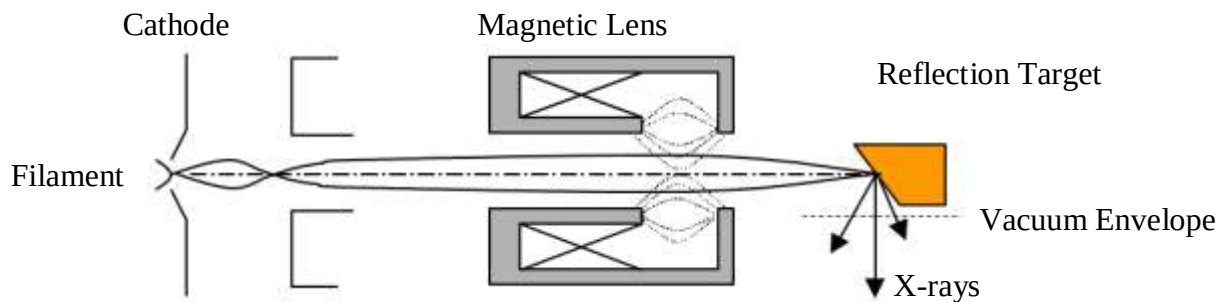
The key benefits of the system are;

- Proprietary 225kV micro focus X-ray source with 3 μ m focal spot size
- Simplistic system operation and low cost of ownership
- High performance image acquisition and volume processing
- Safety applications.

3.2.1.2 Micro Focus X-ray Source

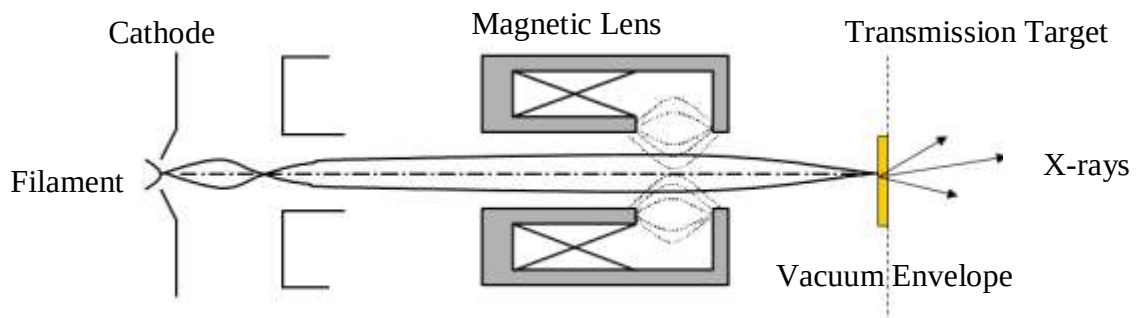
The 225kV micro focus X-ray source refers to the X-ray tube seen within chapter 2. This system is equipped with a reflection target, as opposed to transmission targets, which can offer smaller focal spot sizes and higher magnification capabilities, therefore producing a sharper image. The difference in the two sources, are shown within the schematics below.

Reflection Target X-ray source



The reflection target limits the maximum magnification as the target is behind a vacuum window.

Transmission Target X-ray source



Transmission target enables higher magnification as the target is the vacuum window.

Figure 3-19 Comparison of reflection and transmission targets.

The compromise of using a reflection target source is minute when comparing the effects of micro focus X-ray sources to mini focus X-ray sources. The reflection target offers a $3\mu\text{m}$ focal spot size, where a typical mini focus system would offer a spot of $\approx 1\text{mm}$. This focal spot refers to the interception between the electron beam and the target material. Radiation does not originate from a single point of the target but rather over an area. The smaller this area the cleaner the image as seen within the relationship below. (N.Serman, 2000)

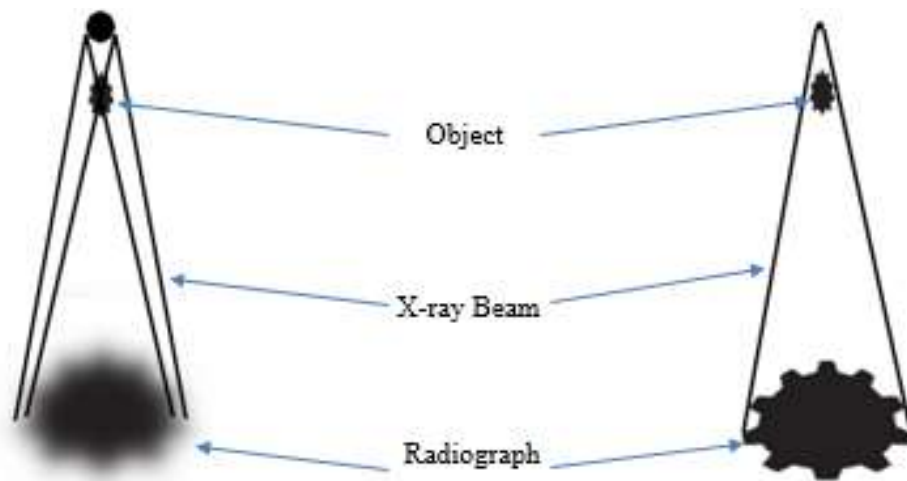


Figure 3-20. (A) Large Focal spot

(B) Small focal spot

This relationship is known as the geometric unsharpness effect. It refers to the loss of definition due to geometric factors of the radiographic equipment and setup. As seen in figure (A) the paths of the radiation have originated from a large spot. This causes the edges of the object to be less defined. The paths of the radiation have variations in density at these edges producing a blurred image edge known as the penumbra. The small focal spot causes very little geometric unsharpness, therefore more defined edges. There are three factors, that can be used to control the unsharpness which are; source size, source to object distance and object to detector distance. (NDT Resource Centre, 2009)

This relationship is commonly expressed using the following equation, as seen within the schematics below;

$$Ug = F \times \frac{b}{a}$$

Where;

a = distance from X-ray source to the front surface of the object.

b = distance from the front of the objects surface to the detector.

Ug = Geometric un-sharpness.

F= focal spot size.

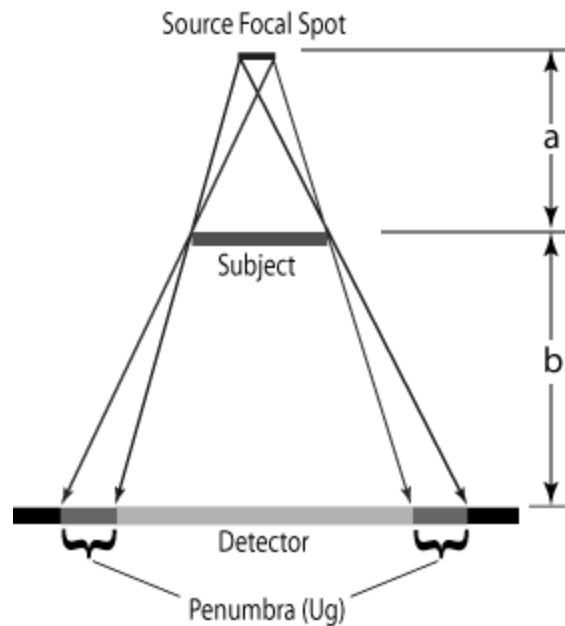


Figure 3-21 Geometric Un-sharpness

The ratio between a and b positions refer to the magnification of the final image. In simple terms, the closer to the source the object is, the higher the magnification. The system can be setup for a variation of magnification. Higher magnification requirements require a small focal spot and large pixel size for better detection efficiency. (NDT Resource Centre, 2009)

3.2.1.3 System Layout

The XT H 225 system has three main components within a large cabinet, which encloses the X-ray radiation for safety aspects. It is capable of housing a variety of samples, which are either too large or heavy for comparable systems. It has characteristic, for example large inspection envelope, tilt adjustment and a choice of target materials, which makes the system versatile for a number of inspections.

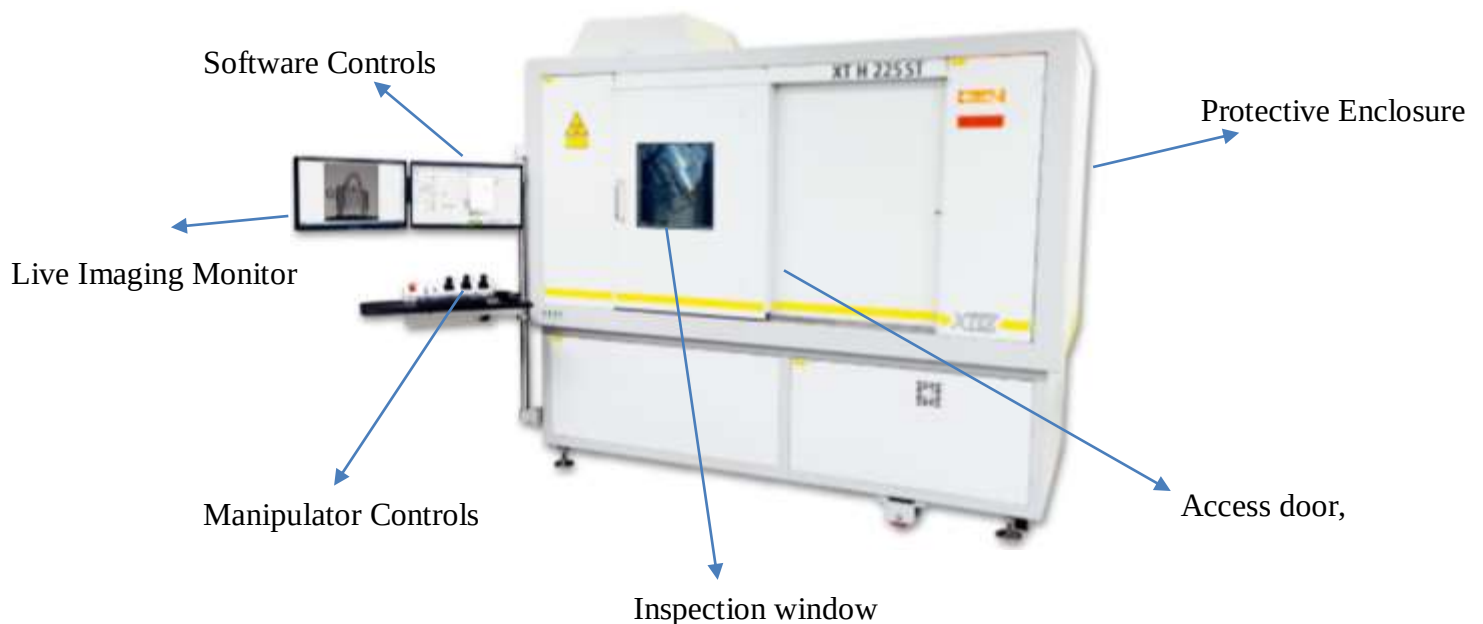


Figure 3-22 XT H 225.

The system includes a fully protective enclosure that is compliant to CE and DIN 54113 radiation safety standards. The radiation shielding is equivalent to 1 μ Sv/hour external exposure, which suggests no radiation badges or special clothing is required, however it is still advised. The system also includes continuous fail/safe monitoring during operation, and dual fail-safe switches/relays on the access door to ensure safe operation. (Nikon, 2015)

The system is most commonly used for Computed tomography which is where a 3D volumetric image of the object is created. To generate the 3D CT volume a series of sequential 2D X-rays images are captured as the object is rotated on a turntable through 360°. These images are then reconstructed to generate a 3D volumetric representation of the object. The representation contains all the information of the interior surfaces of the structure as well as information of the materials structure. The 3D model can then be examined by navigating through the CT volume at any given point or through any plane, using appropriate software. The capability to obtain information such as interior measurements, localising structural material imperfections and identifying assembly errors which are usually missed using traditional NDT methods are all advantages of CT inspections. (TWI, 2008), (Nikon, 2015)

As mentioned the internals of the system can be categorised into three main components, which are;

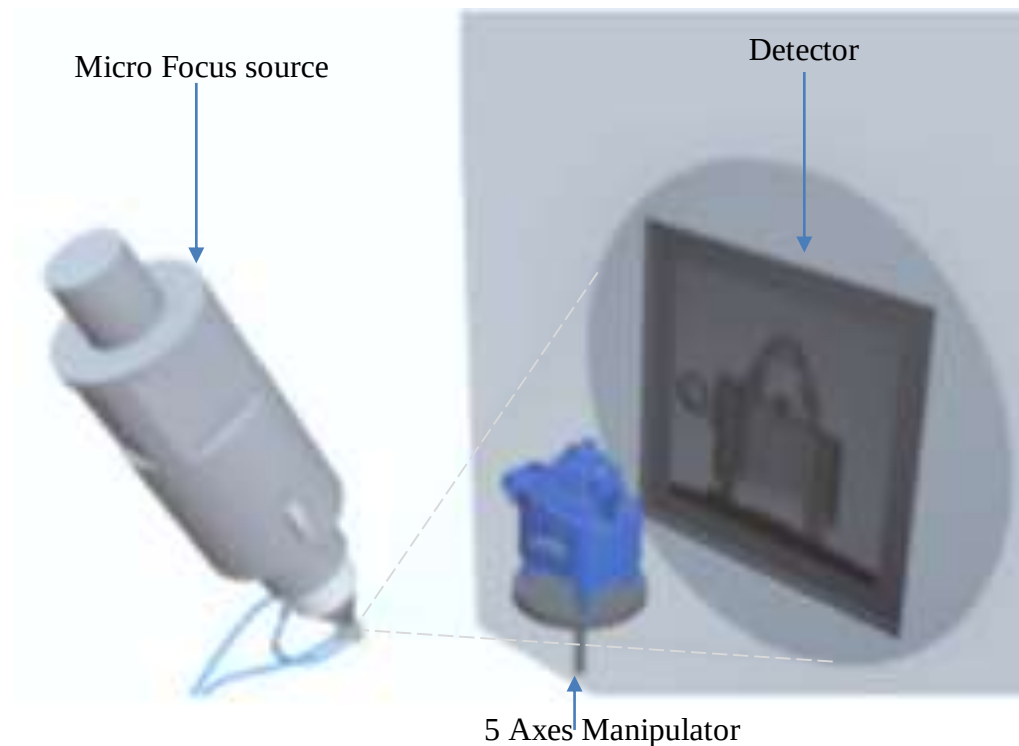


Figure 3-23. Internals of CT

3.2.1.3.1 Micro focus source

The micro focus has been described in-depth, resulting with the reflection target type being applied for the experimental work. The specifications of this X-tube is shown in the table below. (appendix B)

Micro Focus Type	Max kV	Max Power	Focal spot size
225kV	225 kV	225 W	3µm up to 7W 225µm at 225W

Table 3-6 Micro focus source specifications

3.2.1.3.2 5 Axes Manipulator

As the name suggests the manipulator has 5 degrees of axis which can be controlled during operation using the external controls. The 5 axis are the X, Y, Z, tilt and rotation. This degree of movement is used for magnification and centralising the component in respect to the detectors position, to ensure the best image is achieved. It is also used during the CT operation by rotating the component 360°. (Nikon, 2015)

Manipulator Type	# Axis	Axis Travel	Max Sample Weight
XT H 225 ST	5	(X) 450 mm (Y) 350 mm (Z) 750 mm (Tilt) +/- 30° (Rotation) n*360°	50kg

Table 3-7 Manipulator specifications

3.2.1.3.3 Detector

The system uses a Pelkin Elmer 1620 flat plane detector. The advantage of this detector is its high dynamic range of over 84db and frame rates up to 7.5 frames per second (FPS), allowing for high resolution voxel data specifically seen within CT scans. It also has a broad range of energy levels from 20kV to 150MV dependant on the scintillator option.

The detector is in conjunction with inspect X-software, which makes the collection of photon data easy to convert into a live image, or stored for later CT reconstruction for example.

The specification of this detector is exemplified below.

Detector	#Bits	Active Pixels	Pixel Size	Max. frame rate at 1x1 binning	Max. frame rate at 2x2 binning
Perkin Elmer 1620	16-bit	2048x2048	200µm	3.75 fps	7.5 fps

Table 3-8 Perkin Elmer 1620 specifications

- #bit- represents the Analog to Digital Converter (ADC)
- Active pixels- is the pixel count across the detector. For a slower frame rates this is 2048x2048. Where the pixel size is 200µm. If a faster frame rate is desired the detectors active pixels becomes 1024x1024 with the pixel size increasing to 400µm. (Nikon, 2015)

3.2.2 Detector Linearity

An investigation of the signal linearity behaviour of this type of flat panel detector has shown irregularities in the mechanical and electrical properties and which can entail strong differences in pixel behaviour. (N.Serman, 2000) To achieve the best possible image quality all these pixels must behaviour identically to the applied radiation. If these parameters are not met, the signal to noise ratio will be effected as intensity increases shown as an extreme example of the linearity below. (Telesystems, 2011)

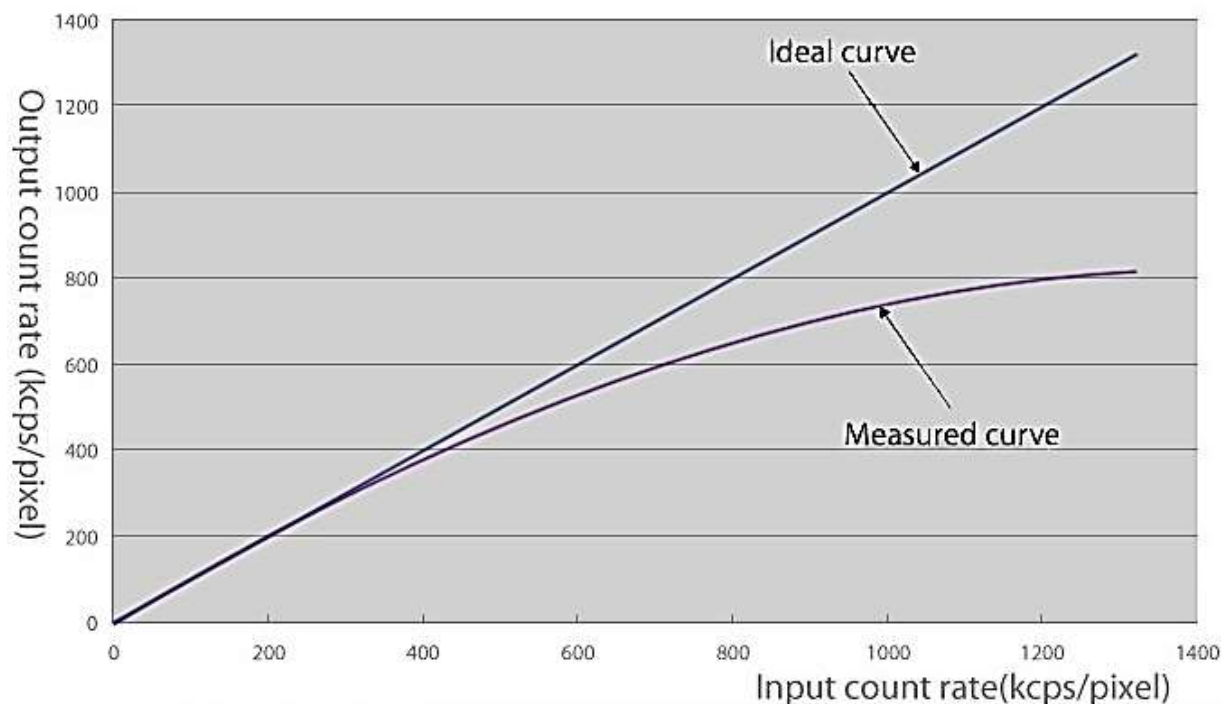


Figure 3-24. Linearity response behaviour

An investigation led by the University Erlangen-Nurnberg, Germany has presented the linearity of the detector by producing several flat field images (FFI) at multiple intensities levels. The images had the offset corrected, by taken the mean of a single pixel value and comparing against the mean detector level for the different irradiation levels.

The plot they created used a fit function $y=m*x$ which gave information about the pixels sensitivity and the coefficient of determination (R^2) about the linearity. The figure shows the curve they created for this detector after normalisation.

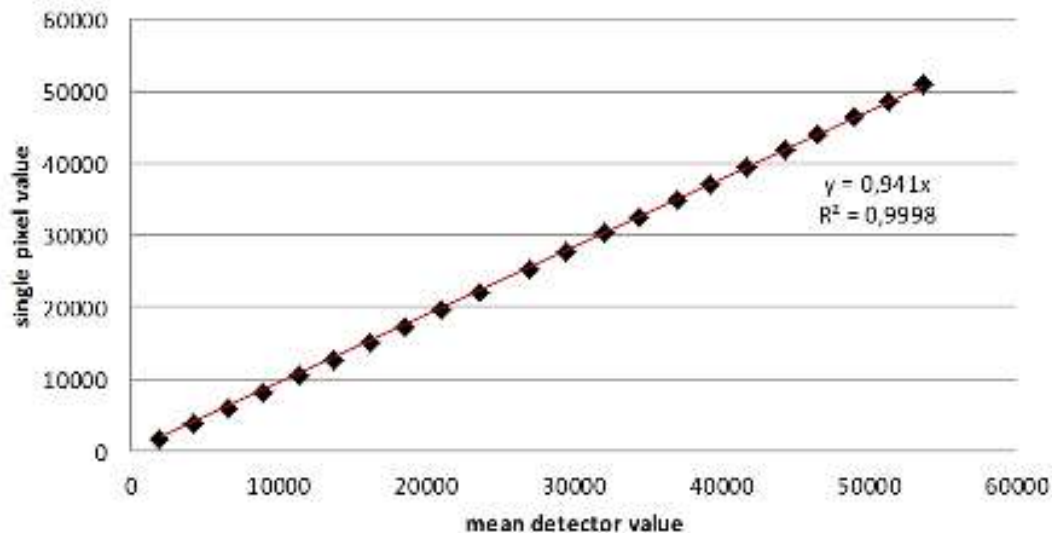


Figure 3-25 Single pixel value vs. mean detector value

The results show that there is a nearly linear relation between a single pixel value and mean detector value. The slope of the linear fit differs from one, which is an indication for the pixel to pixel sensitivity variation, also the spatial variation of the X-ray source. The R^2 value also differs from 1 slightly, which is a factor for the non-linearity of one detector pixel.

The non-linear correction has shown to improve the linearity of noise and therefore image quality. Another improvement is seen within a filtration test where the spectral response was addressed by generating the FFIs when using filter variations. This produced a more uniform density and allowed for accuracy in the averaging of quantum distribution on the detector.

(Thomas Hofmann, 2011).

3.3 Conclusion

This chapter has demonstrated the software and hardware used for the comparative analysis described within this thesis. For the theoretical analysis, SpekCalc is used to source the intensity reference to aluminium filtration thickness variations. This is presented over a range of 50 to 100kV due to the research implying it is difficult to distinguish between CFRP materials. As the software is restricted to aluminium filtration the comparison is made with experimental means to find a similar attenuation coefficient for aluminium. This can then be applied for carbon fibre reference. The spreadsheets for the data justification have been explained in depth and are provided on an attached CD-ROM.

The specifications for the XTH 255 ST system has been described showing it's key features and advantages over it's counterparts. Also shown was the systems limitation and set up parameters which will have to be taken into consideration during the experimental stages. This includes the detectors linearity response which may be the cause of any misleading data.

4 Methodology

Radiographs are generated by the quanta hitting the detector and being converted into a digital representation. The quanta has a statistical nature therefore the image pattern can be used to predict the attenuation properties of a material. The quanta will fluctuate randomly but will produce a mean greyscale value. The radiation is characterised by its Poisson nature of photon distribution in time. Hence, how the absorption coefficient can be calculated proportional to its attenuation interaction with the material. (Munshi, 2007)

This is the basis of the experiment procedure, which will be compared to the theoretical approach supported by the Beer Lamberts theorem. This chapter will describe the process for one chosen kV and filter thickness, beginning with the theoretical simulation. The source for the detailed graphs are presented throughout Appendix C, in the order they are presented within the results.

4.1 Theoretical Optimisation

The theoretical approach will show examples of 50kV simulations with a 1mm filter thickness differential. The initial intensity data, from which the basis of (I_o) in Beer Lamberts law, will have a 1mm filter pre-set. As the filtration thickness, increase the (x) will be the difference in filtration thickness in mm. For example;

$$I = I_o e^{-\mu x} \quad \longleftrightarrow \quad \mu = -\frac{1}{x\Delta} \cdot \ln \frac{I}{I_o}$$

Rearranged for μ

kV	I_o	I	$x \Delta$	
50	1mm dataset	2mm dataset	1 mm	Solve for attenuation in respect to thickness change
50	1mm dataset	3mm dataset	2 mm	
50	1mm dataset	4mm dataset	3 mm	

Table 4-1. Data relations

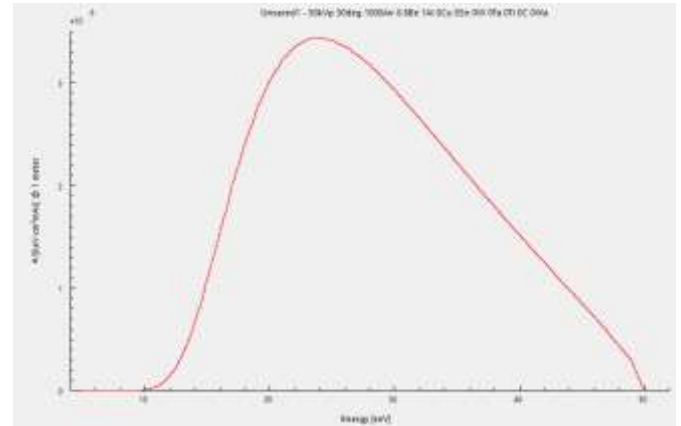
The purpose for this step was to initiate a correlation with the experimental data. If no filtration was used for experimental reference, the detector limitations would be reached and saturation would occur with the increasing kV levels.

4.1.1.1 Data Resourcing

The first stage is to gather the intensity data required from SpekCalc. This was completed by running a simulation within the software using the appropriate parameters.

Peak Energy (T0):	50	keV
Minimum Energy (hvMin):	5	keV
Energy Bin (Dhv):	0.1	keV
Theta (th):	30	Degree
Air Thickness (t_Air):	1000	mm
Beryllium Thickness (t_Be):	0.8	mm
Aluminium Thickness (t_Al):	1	mm

Figure 4-1 Initial data from SpekCalc.



This is repeated with changing the Aluminium thickness by 1mm intervals to obtain intensity data which can be plotted over one another. The integrals of these curves are then taken to establish the quanta average, which will be hitting a theoretical detector.

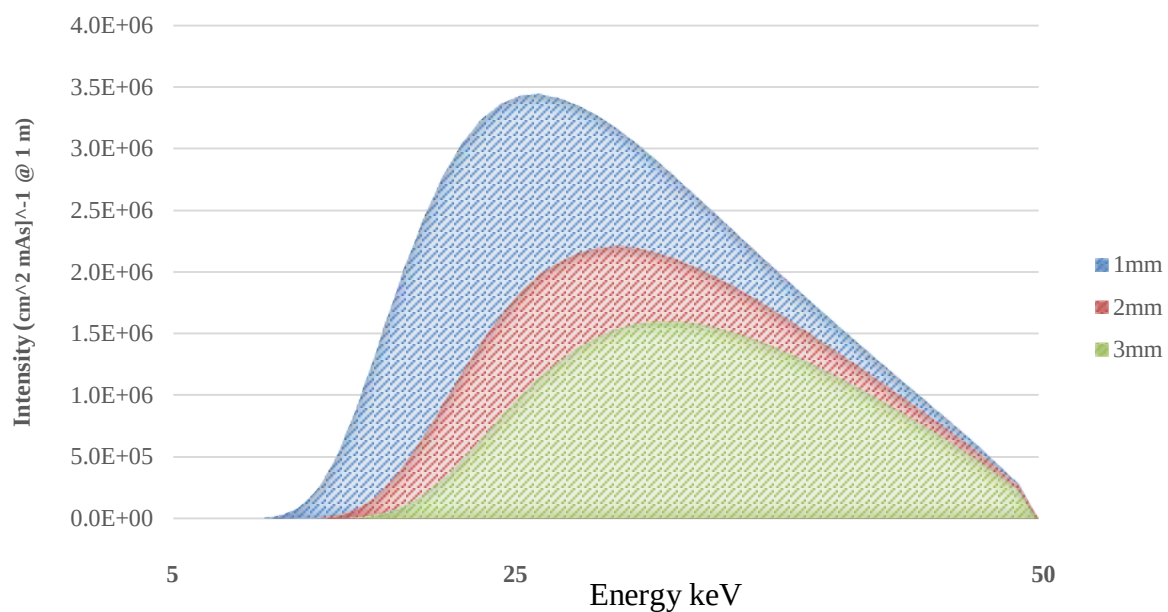


Figure 4-2 Comparative 50kV in relation to filter thicknesses

The integral numbers were then used within the Beer Lambert equation to find their attenuation trend as thickness is increased.

kV	I ₀	I	$x \Delta$	$\mu = -\frac{1}{x\Delta} \cdot \ln \frac{I}{I_0}$
50	1mm dataset	2mm dataset	1 mm	4.65 cm ⁻¹
50	1mm dataset	3mm dataset	2 mm	4.1 cm ⁻¹
50	1mm dataset	4mm dataset	3 mm	3.73 cm ⁻¹

Table 4-2 Attenuation data set from SpekCalc spreadsheet

Plotting this data, results in an attenuation curve showing a section of the exponential decay of attenuation in relation to thickness.

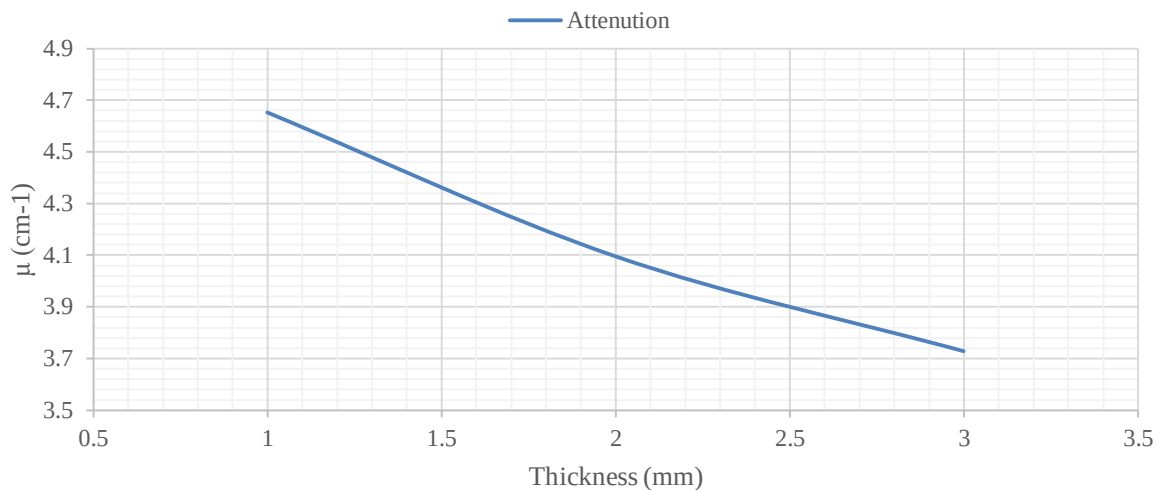


Figure 4-3 Attenuation curve of Spectrum integrals

This process is repeated from 50 to 100kV, which will produce attenuation figures for a single thickness in accordance with increasing kV. This trend, can also be plotted to witness the effects of kV on attenuation.

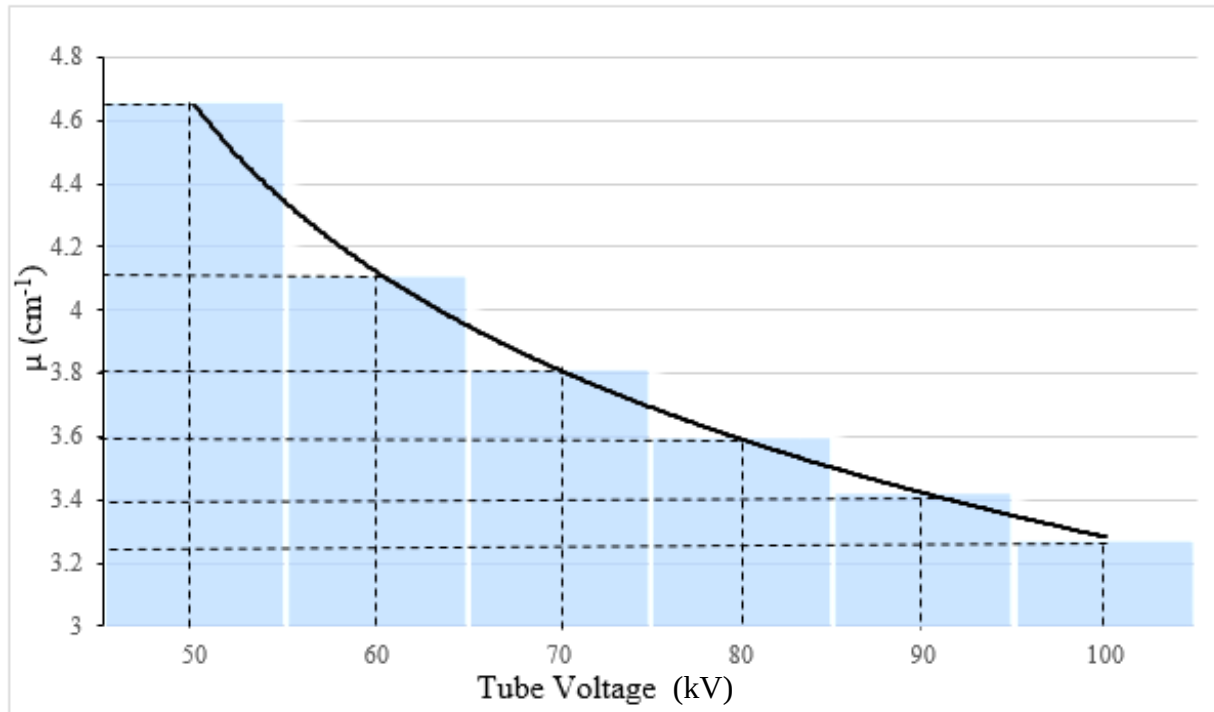


Figure 4-4 showing 1mm filter attenuation in relation to increasing kV.

The blue section shows the attenuation figure is an average of the full spectrum range, as there is a random distribution in contact with the detector. This statically method is incorporated to ensure a clear correlation with the theoretical data.

The justification of this method is proven by referring to pre-determined, linear attenuation figures for aluminium exemplified at 100keV. (Nuclear Medicine, 2014).

Absorber	μ @ 100 keV
Aluminium	0.435 cm ⁻¹

(a) Nuclear Medicine Results

kV	I_0	I	$x \Delta$	μ
100	1.08x10 ⁴	1.03 x10 ⁴	1 mm	0.46 cm ⁻¹

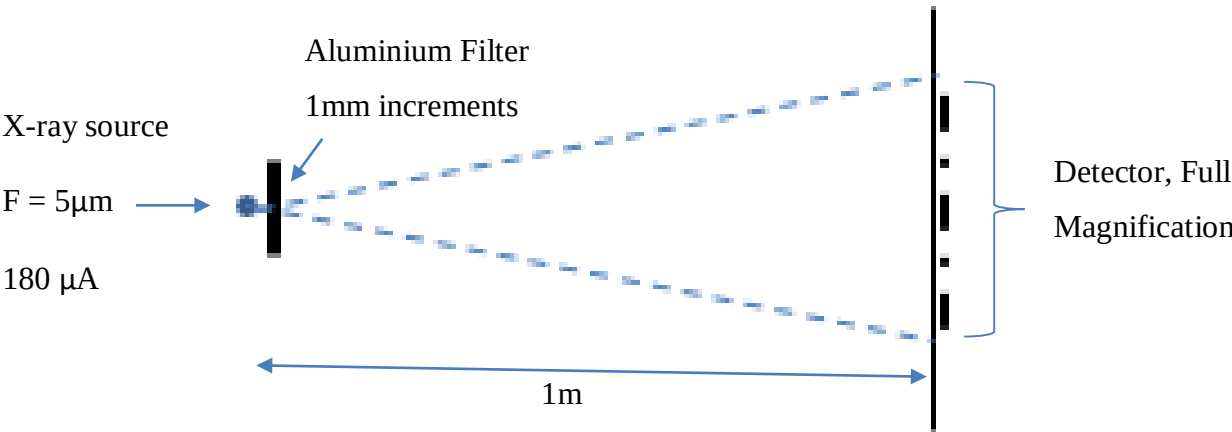
Table 4-3

(b) Results from SpekCalc

4.2 Experimental Optimisation

The experimental procedure was the same approach for both aluminium and CFRP filtration therefore for the methodology for aluminium is solely explained. The test had strict parameters to ensure a clear comparison could be obtained.

- Test layout



The current is kept constant throughout the test for both materials. A radiography was collected for each increasing kV increments. Once the range was completed, an addition for a 1mm filter was added, taking the FFI into consideration. The test examined 1 to 4mm filter thickness to achieve three points on an attenuation graph to get the initial trend. Examples of the radiographs are shown below.

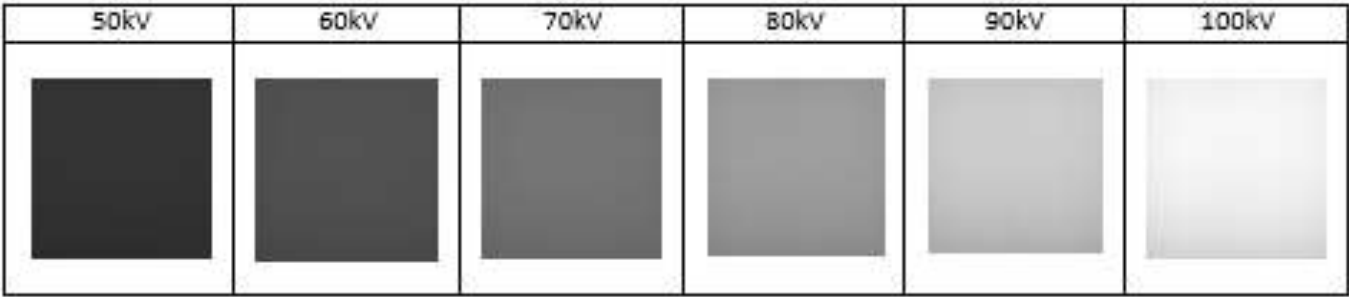


Figure 4-5 1mm Aluminium radiographs with increasing kV.

Similar to the theoretical approach, an attenuation curve can be plotted, for increasing filter thicknesses or increasing kV. The addition of the detector response is also required to ensure the attenuation is acceptable for a comparison.

- Filter increments

Concentrating on 50kV, the filter radiographs have their histograms calculated to find an average greyscale, which corresponds to the quanta hitting the detector.

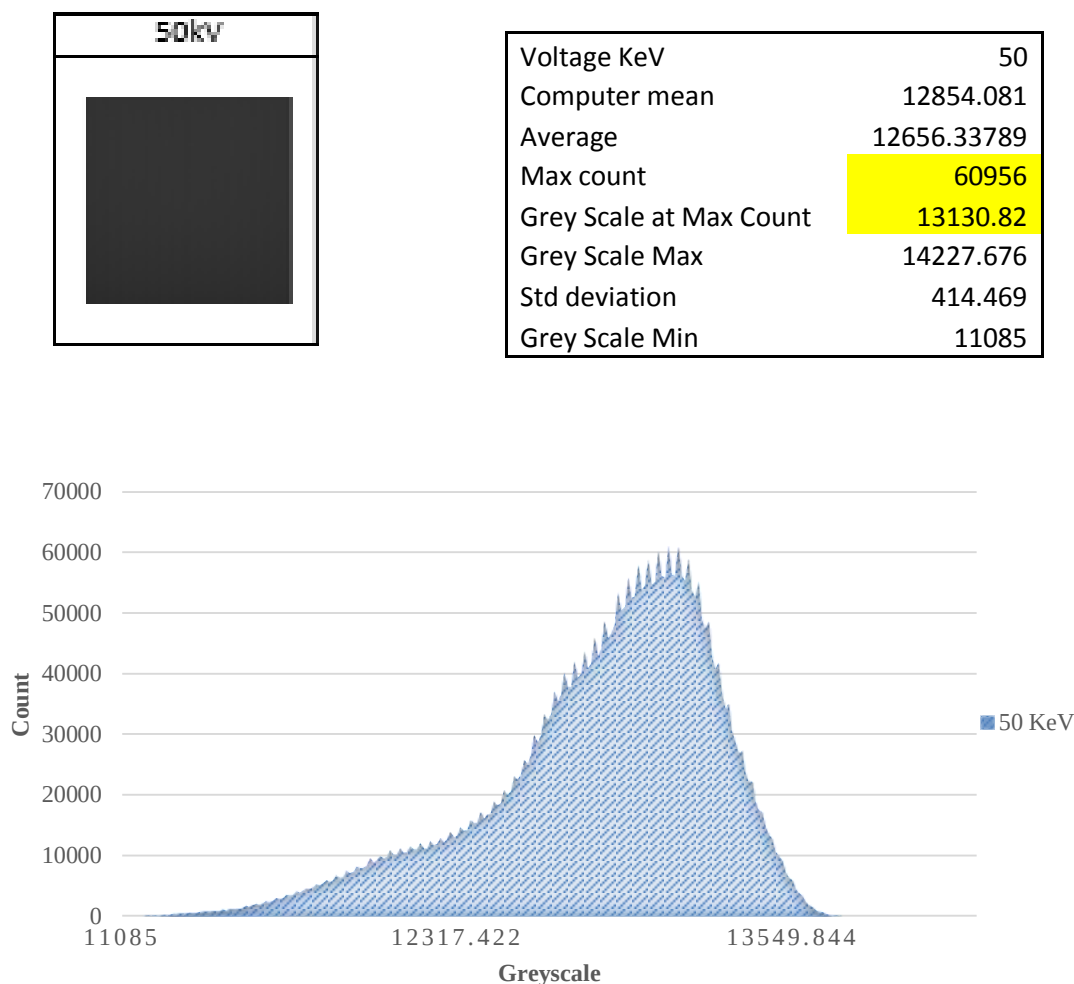


**Figure 4-6 (above) Radiography of 50kV 1mm aluminium and image J information.
(below) Histogram plot of the 50kV radiograph, count over Greyscale.**

The integral of the histogram is taken for each increasing filter thickness. This data was supplied by image j shown as the average across the detector in the previous table.

Using an interpretation of Beer Lambert law the averages are used to find the attenuation of the material in reference to thickness.

kV	A _o	A _x	$x \Delta$	$\mu = -\frac{1}{x\Delta} \cdot \ln \frac{Ax}{Ao}$
50	1mm dataset	2mm dataset	1 mm	1.99 cm ⁻¹
50	1mm dataset	3mm dataset	2 mm	1.74 cm ⁻¹
50	1mm dataset	4mm dataset	3 mm	1.56 cm ⁻¹

Table 4-4 Attenuation of aluminium data set from X-ray spreadsheet.

- Detector response

In comparison with the theoretical data, there is a correlation factor required to be added to the experimental results. The theoretical data displays an assumption of quanta before interacting with a detector. For a comparison, a normalisation ratio between the two data sets is created. This ensures the hypothetical detector response is similar for both methods of testing. The normalisation ratio is displayed in table 4-5, for 50kV with increasing filter thicknesses. The factor will change in response to increases in kV. As seen within the detector linearity plot the higher the intensity input the worse the greyscale output. *Figure.3-24*

Filter thickness Δ	Theoretical (μ)	Experimental (μ)	Ratio Ther/Exp	Corrected (μ)
1mm	4.65 cm ⁻¹	1.99 cm ⁻¹	2.34	4.46 cm ⁻¹
2mm	4.1 cm ⁻¹	1.74 cm ⁻¹	2.35	3.83 cm ⁻¹
3mm	3.73 cm ⁻¹	1.56 cm ⁻¹	2.4	3.35 cm ⁻¹
Correction average of detector non-linearity			2.36	

Table 4-5 Attenuation with non-linearity normalisation.

When plotting the attenuation trends in relation to thickness increments, a clear comparison can be seen, between the corrected and uncorrected data. Within the results, the curves will have the linear corrections applied for the comparison of the two methods.

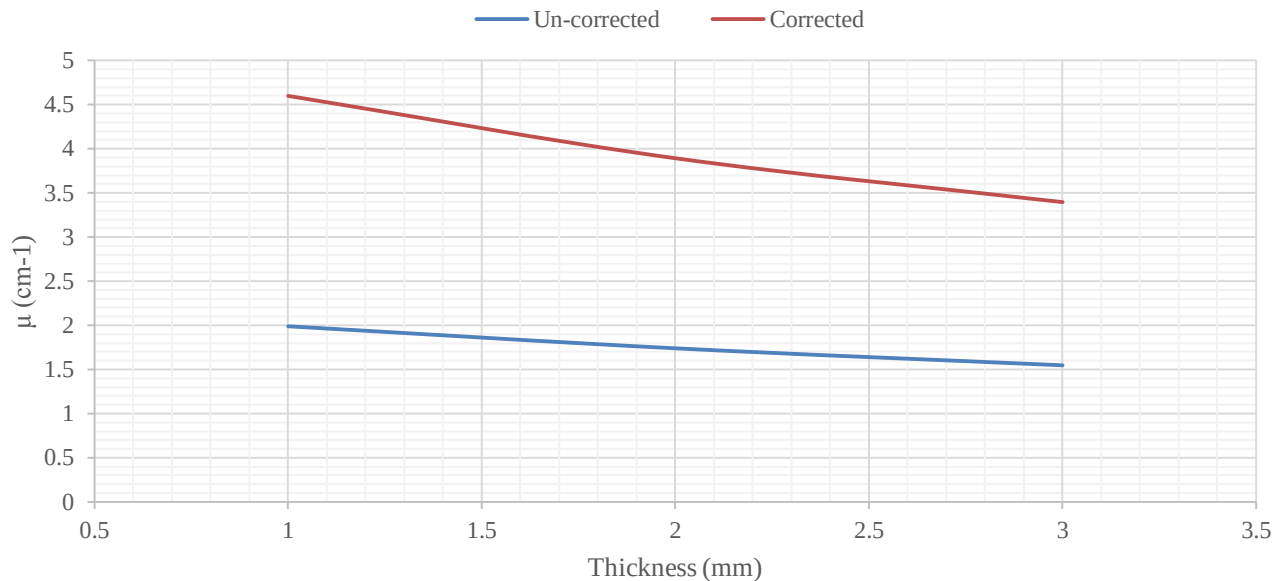


Figure 4-7 Comparison of uncorrected and corrected attenuation curves for 50kV, in relation to thickness intervals.

The next stage is to develop the attenuation trend for increasing kV values. This is achieved, by averaging the radiographs histograms for a single filtration thickness.

50kv	60kv	70kv	80kv	90kv	100kv
					
4.6	4.4	4.1	3.7	3.3	2.9

Table 4-6 1mm Aluminium radiographs grey scaling average attenuation.

With the addition of the detectors response for increasing kV values, the trend showing attenuation values over the kV range is presented for 1mm filtration. This will be critically analysed at a later stage.

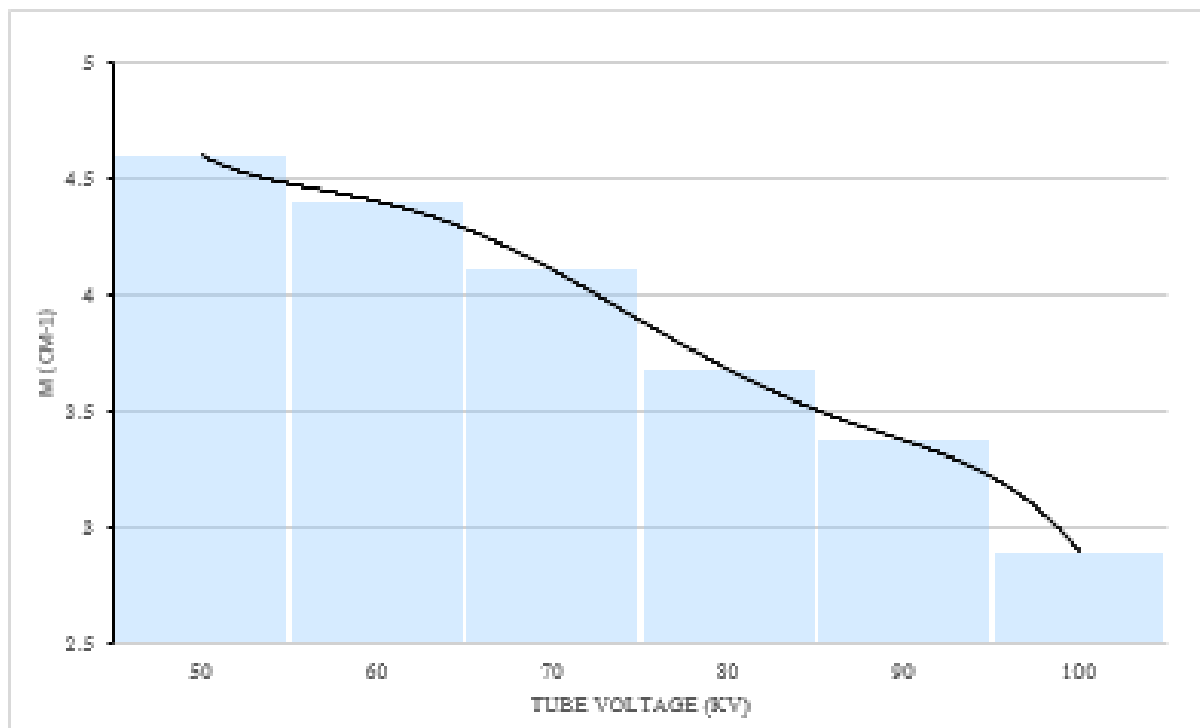


Figure 4-8 1mm Aluminium attenuation response of increased tube voltage.

4.3 Conclusion

This chapter has presented the methods used to obtain the attenuation figures for both theoretical and experimental investigations. As a representation aluminium was selected as the sole material, to be examined as it is used for justification of the method for carbon fibre optimisation.

The theoretical approach used SpekCalc to gather the intensity information, which can be implemented to find attenuation figures using the classic Beer Lambert equation. The software's parameters are kept constant with the only differential being either increased kV or aluminium filtration thicknesses.

The experimental procedure used the XTH 255 system to source radiographs of aluminium and CFRP filters. The analytical procedure showed that the radiographs had variations in their greyscale count as different settings were applied, presented in histogram form. The mean value of these histograms was then used in an interpretation of Beer Lamberts law to achieve an attenuation figure. A detector linearity correction factor was used to obtain a clear comparison between the aluminium datasets from both theoretical and experimental sources.

This method has been justified with previous experiment findings which were compared with the SpekCalc value of 1mm aluminium filtration at 100kV, where a difference of 0.02cm^{-1} is seen, which is well within comparative tolerance.

5 Results and Analysis

Within this chapter, three kV values were critically analysed for the theoretical and experimental procedures. These values are 50, 70 and 100kV for the aluminium filters, and 50, 70 and 90kV for the CFRP filters. These values were chosen, as they are the representative points of an attenuation trend in relation to increasing kV. The remaining data plots can be found in appendix C documentation of this thesis.

Four-filtration thicknesses were also used to develop three attenuation figures, where the change in filtration thickness is a key factor. These were used to plot an attenuation trend for their respectable kV values. Both filter materials were justified with pre-experimental examples, which warrants the accuracy of these methods.

The first stage was to evaluate the theoretical and experimental results of aluminium filtration. An analysis was then conducted in comparing the two methods allowing for confidence in the CFRP evaluation. The results were then used to provide the best parameters for optimising digital radiographs for CFRP components, with comparable exemplified radiographs.

5.1 Theoretical Analysis

5.1.1 50, 70 and 100kV Evaluation

The initial evaluation for 50kV examined the attenuation exponential from using the appropriate data parameters.

Peak Energy (T0):	50	keV	50	keV	50	keV	50	keV
Minimum Energy (hvMin):	5	keV	5	keV	5	keV	5	keV
Energy Bin (Dhv):	0.1	keV	0.1	keV	0.1	keV	0.1	keV
Theta (th):	30	Degree	30	Degree	30	Degree	30	Degree
Air Thickness (t_Air):	1000	mm	1000	mm	1000	mm	1000	mm
Beryllium Thickness (t_Be):	0.8	mm	0.8	mm	0.8	mm	0.8	mm
Aluminium Thickness (t_Al):	1	mm	2	mm	3	mm	4	mm

Figure 5-1 50kV simulation parameters.

The data is represented as the linear trace of the quanta reassembling the spectral distribution. The variation in these curves show a relationship occurring between the increasing thicknesses.

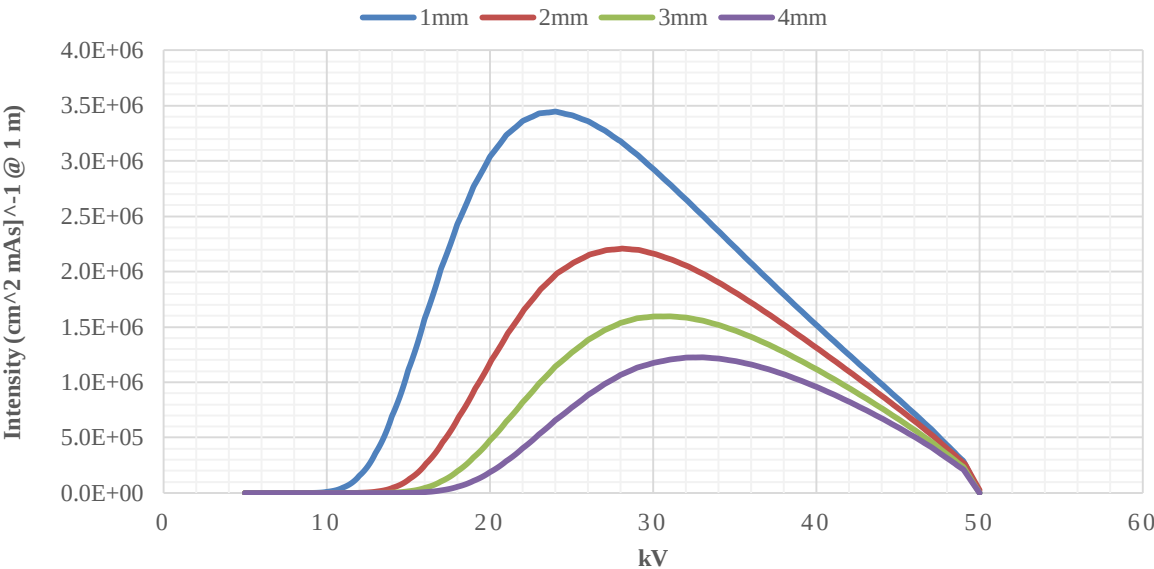


Figure 5-2. 50kV Spectral distribution

The difference between the 1mm and 2mm plots seems to double the difference between the 2mm and 3mm at a specific point of kV. This suggests that at any kV value within this range, regardless of the filtration thickness, the attenuation would be linear. This is exemplified below with 25kV, where the intensity peaks are shown.

kV	A _o	A _x	$x \Delta$	$\mu = -\frac{1}{x\Delta} \cdot \ln \frac{Ax}{Ao}$
25	3.41E+06	2.08E+06	1 mm	4.97 cm ⁻¹
25	3.41E+06	1.26E+06	2 mm	4.97 cm ⁻¹
25	3.41E+06	7.69E+05	3 mm	4.97 cm ⁻¹

Table 5-1 25kV Attenuation

With the three thicknesses plotted on one curve, the attenuation trend is witnessed to be effected by increasing kV, not thickness variations. The curve also shows that at 50kV, there is no intensity produced which refers to the radiation production mechanisms, where a photon is limited by the maximum voltage energy.

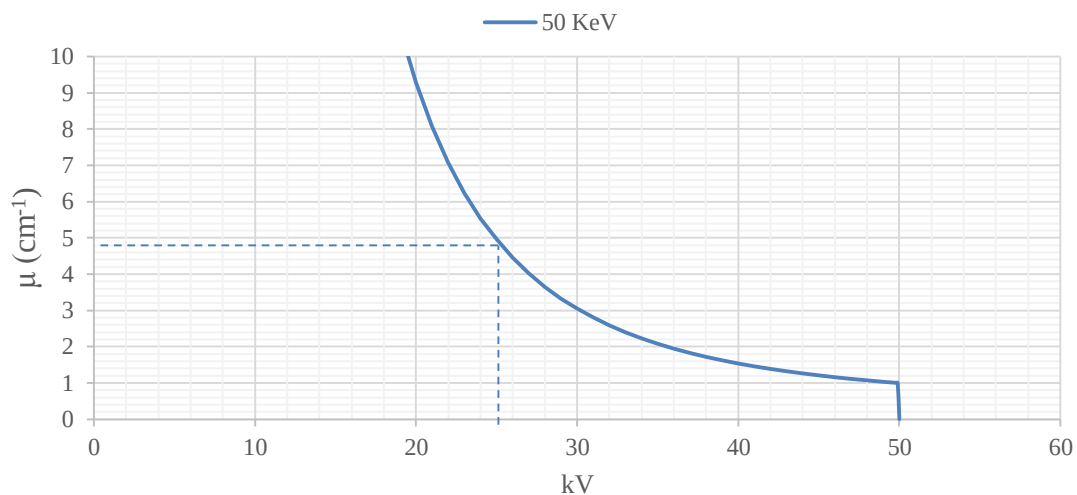


Figure 5-3 example of 1mm, 2mm, 3mm attenuation curves for 50kV range.

In reality, the detector will receive a random distribution of this quantum, which is described by taking the integral of the distribution and therefore an average of the previous attenuation curves for each thickness. As previously seen, the increasing thickness does alter the spectrums trends, which produces a different intensity average across the range. These figures are more suitable to be used to find the attenuation coefficients for increasing filter thickness in correspondence to the average of the spectrum.

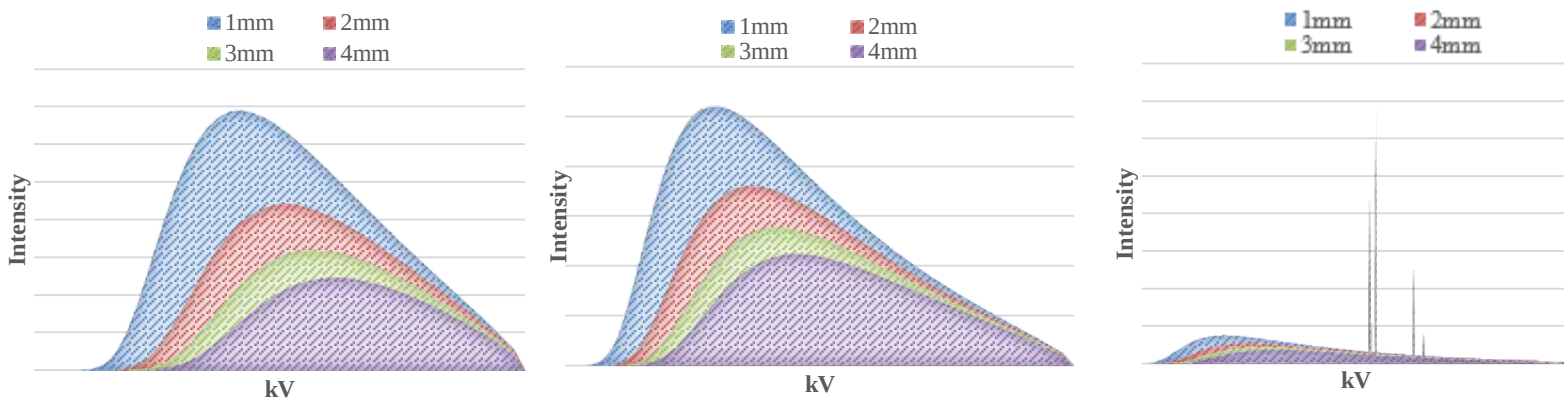


Figure 5-4 Comparative Spectrum of 50, 70 and 100kV

50kV	Intensity Average				Attenuation Coefficient		
	1mm	2mm	3mm	4mm	1mm	2mm	3mm
	1.68E+06	1.06E+06	7.42E+05	5.50E+05	4.65 cm ⁻¹	4.10 cm ⁻¹	3.73 cm ⁻¹
70kV	Intensity Average				Attenuation Coefficient		
	1mm	2mm	3mm	4mm	1mm	2mm	3mm
	3.06E+06	2.09E+06	1.56E+06	1.21E+06	3.81 cm ⁻¹	3.37 cm ⁻¹	3.08 cm ⁻¹
80kV	Intensity Average				Attenuation Coefficient		
	1mm	2mm	3mm	4mm	1mm	2mm	3mm
	4.94E+06	3.56E+06	2.75E+06	2.21E+06	3.28 cm ⁻¹	2.92 cm ⁻¹	2.69 cm ⁻¹

Table 5-2 (right) Intensity Averages (left) Resulting Attenuation Coefficients

Using the intensity averages with the Beer Lambert law, attenuation coefficients are discovered for the distribution spectrums. These are plotted to show the attenuation trend as thickness is increased. A comparison of the three tube voltages is witnessed below.

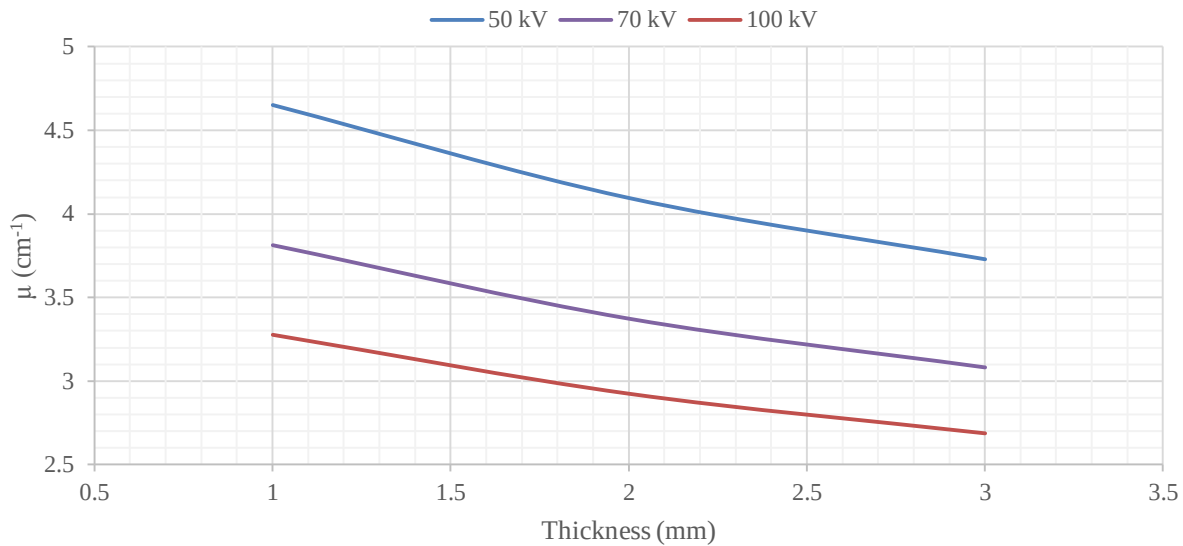


Figure 5-5 Attenuation comparison of increasing thickness.

The simulated curves show a linear response trend where, as the thickness is increased, the attenuation values reduce. This refers to the concentration of the photons, which can penetrate through this distance. The smaller the distance, the more absorption reactions due to a bombardment of low energies are emitted, therefore higher attenuation.

As the kV is increased, the photons have higher energies and smaller wave lengths, allowing them to penetrate further into the material. Less attenuation is produced at the lower thicknesses. There is a larger difference between 50- 70kV in respect to 70-100 kV. This suggests that as an average the 70 and 100kV have a higher and closer intensity than the 50kV, all of which reduces their attenuation coefficient values.

When the tube voltage is increased past 70kV, there are signs of characteristic radiation taking place, shown within the 100kV spectral distribution curves. The characteristic radiation was a concern due to it not being clear how it would manipulate the data. This led to the justification procedure to be carried out.

The kV leading up to 100 had each intensity value converted into an attenuation coefficient which was plotted displaying a curve. The scaling was adjusted to highlight the low-end attenuation figures due to correlation with an outsourced experiment results.

		Intensity		
KeV	μ	KeV	1mm	2mm
100	0.435 cm^{-1}	99.99	10833.09	10346.53
				0.46 cm^{-1}

Table 5-3 (left) (Nuclear Medicine, 2014) Results for 1mm Aluminium filtration. (right) SpekCalc results for 1mm Aluminium filtration differential.

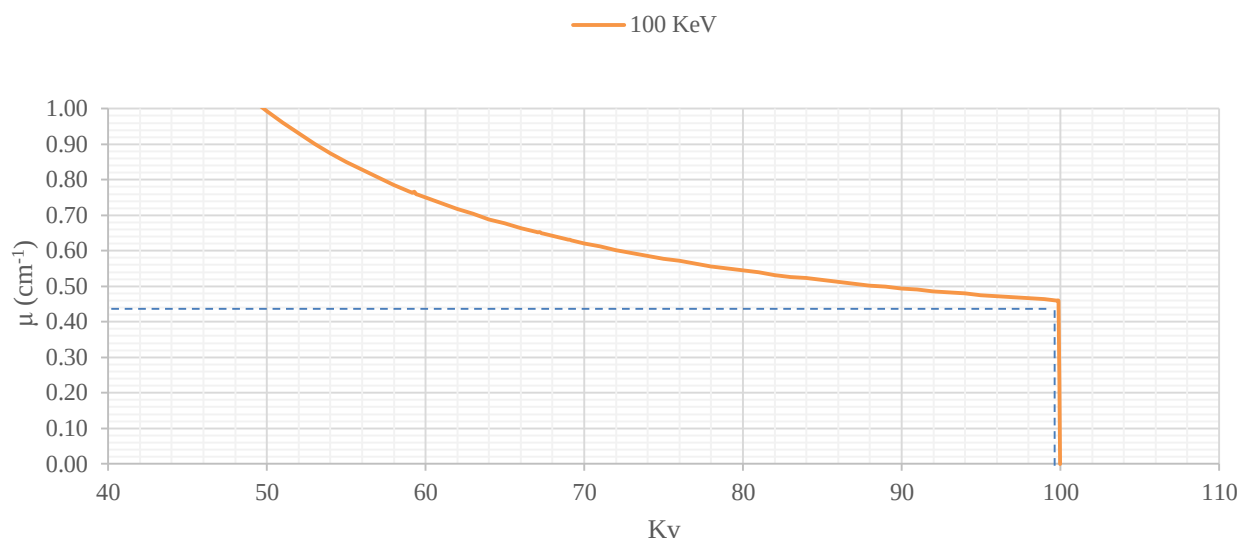


Figure 5-6 Attenuation curve of 1mm Aluminium over 100kV range

99.99kV was chosen for this reference as no intensity values were produced at 100kV.

To end the theoretical analysis the three thicknesses have their attenuation curves produced in relation to increasing tube voltage. Each curve shows that as the voltage is increased the attenuation coefficient reduces. These trends show an exponential decay which is expected with the increasing kV. These curves will be used for a comparison to the experimental data as they should show the similar trends.

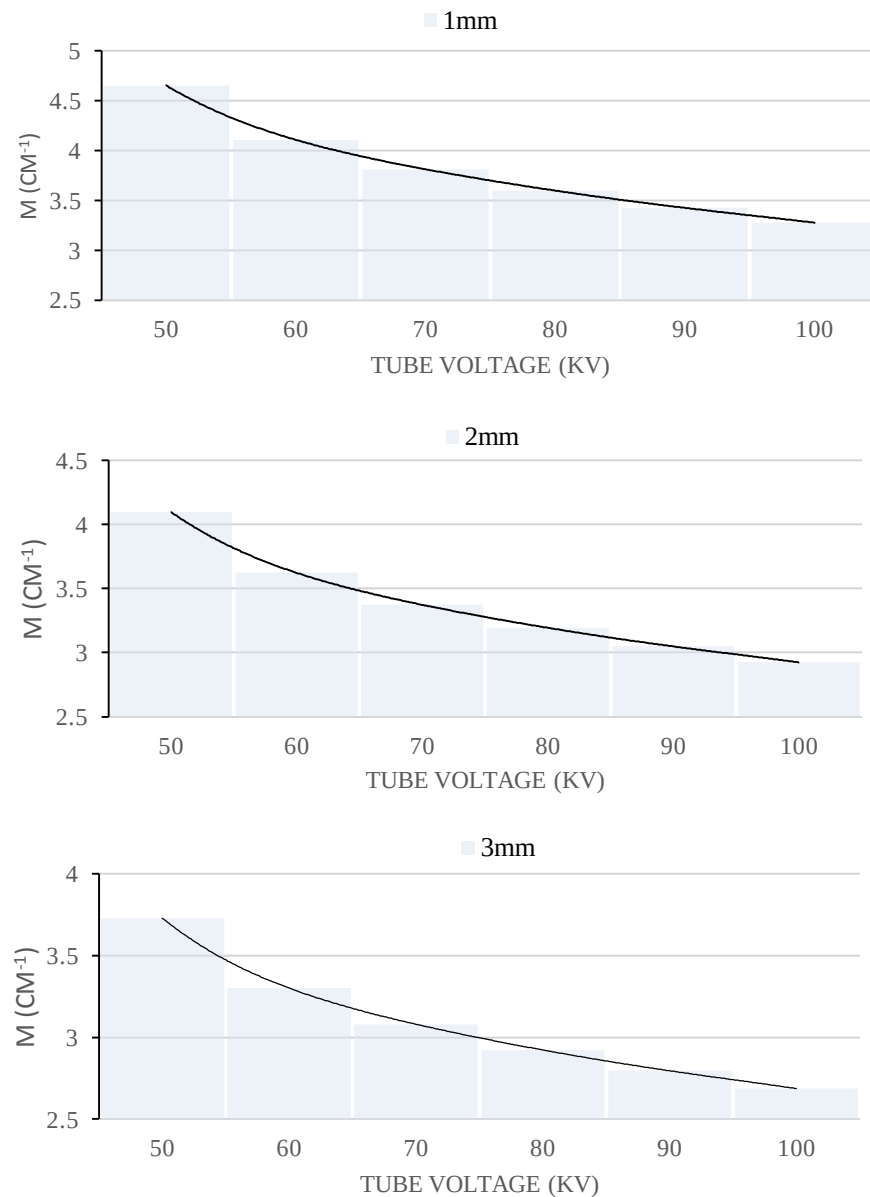


Figure 5-7 Attenuation curves of 1, 2, 3mm aluminium filtration differentials over increasing kV.

5.2 Experimental Aluminium Analysis

5.2.1 50, 70 and 100kv Evaluation

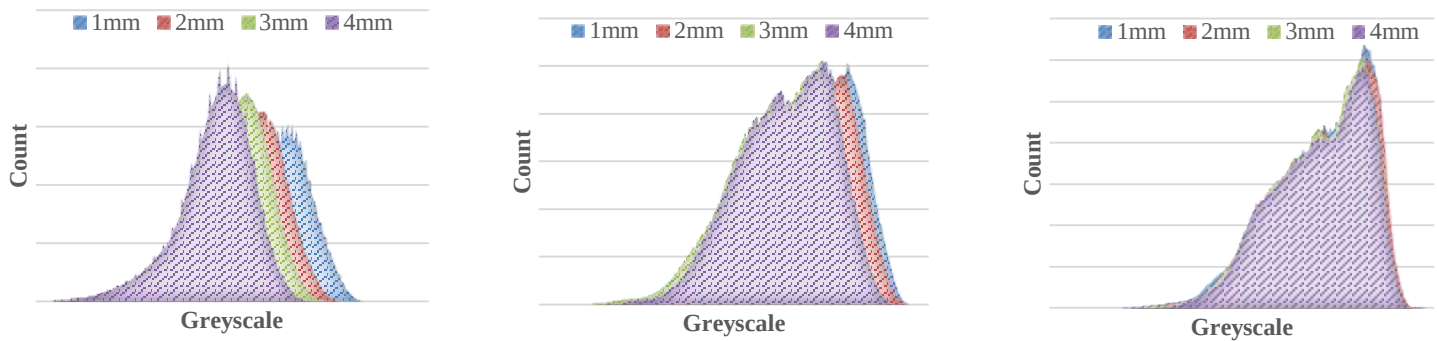


Figure 5-8 Radiograph histograms of 50, 70 and 100kV with increasing filtration.

At	Greyscale Average				Attenuation Coefficient		
	1mm	2mm	3mm	4mm	1mm	2mm	3mm
	12656	10373	8938	7958	4.6 cm ⁻¹	3.9 cm ⁻¹	3.4 cm ⁻¹

At	Greyscale Average				Attenuation Coefficient		
	1mm	2mm	3mm	4mm	1mm	2mm	3mm
	36987	31548	27403	24228	3.7 cm ⁻¹	3.4 cm ⁻¹	3.1 cm ⁻¹

At	Greyscale Average				Attenuation Coefficient		
	1mm	2mm	3mm	4mm	1mm	2mm	3mm
	59170	52215	46497	41870	2.9 cm ⁻¹	2.7 cm ⁻¹	2.5 cm ⁻¹

Table 5-4 (right) Greyscale Averages (left) Resulting Attenuation Coefficients

A similar trend is created, where the thickness is increasing and the average attenuation figures are reducing. The coefficients have been corrected to resolve for the detector linearity issue using the stated methods. This allows for the figures to be used in conjunction with the SpekCalc findings, improving the comparable evaluations.

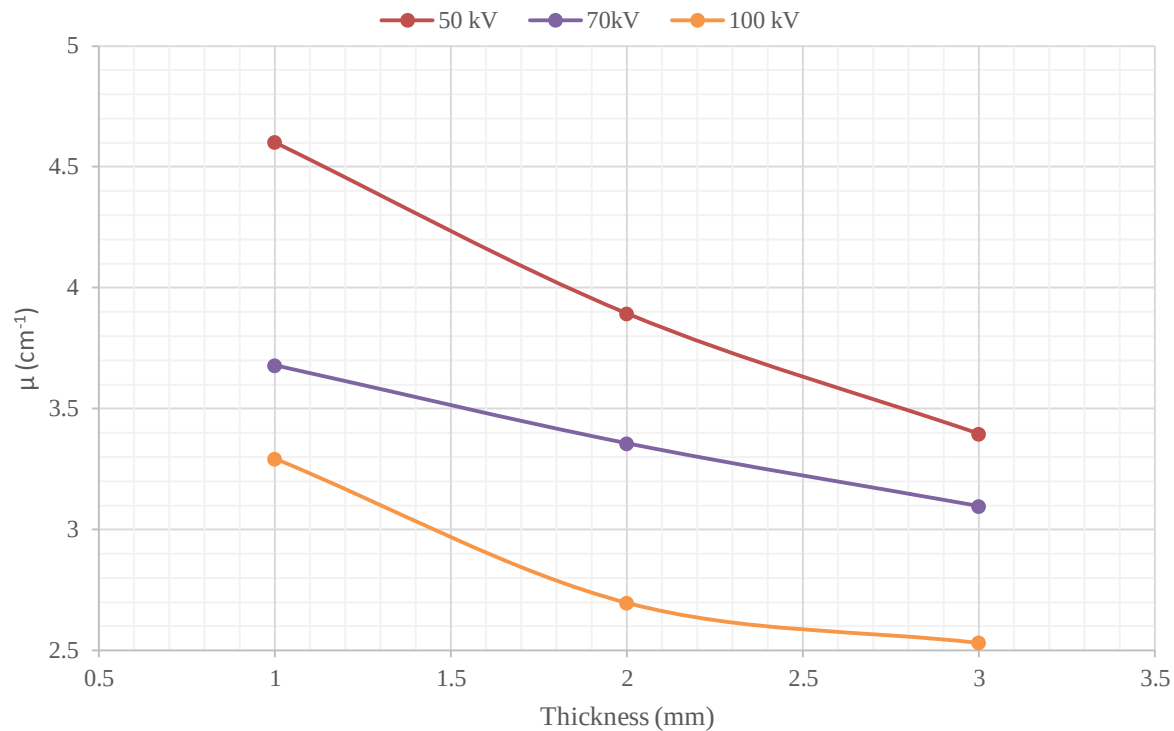


Figure 5-9 Attenuation comparison of increasing thickness.

For 50 and 100kV a comparable decay rate is produced, where both trends follow suit. The middle kV shown as 70kV, display a different reaction to the aluminium filtration. The average photons count at these energy levels seem to not differ as much as the other two tube voltages. The largest change in attenuation is witnessed with 50kV, which results in aluminium filtration as not ideal at these energy levels because the majority of the photons are absorbed by the material. With 100kV the photons which are produced after 1mm filtration are less attenuated for the second two thicknesses.

The radiographs presented show the variations of increasing kV values. The higher the kV, the higher the intensity developed by the detector, therefore a brighter image. With adding an additional filter, the greyscale is increased, producing darker images shown predominantly with the 100kV. This relationship is presented in the graph below, where the variations become more distinguishable as the kV is increased,

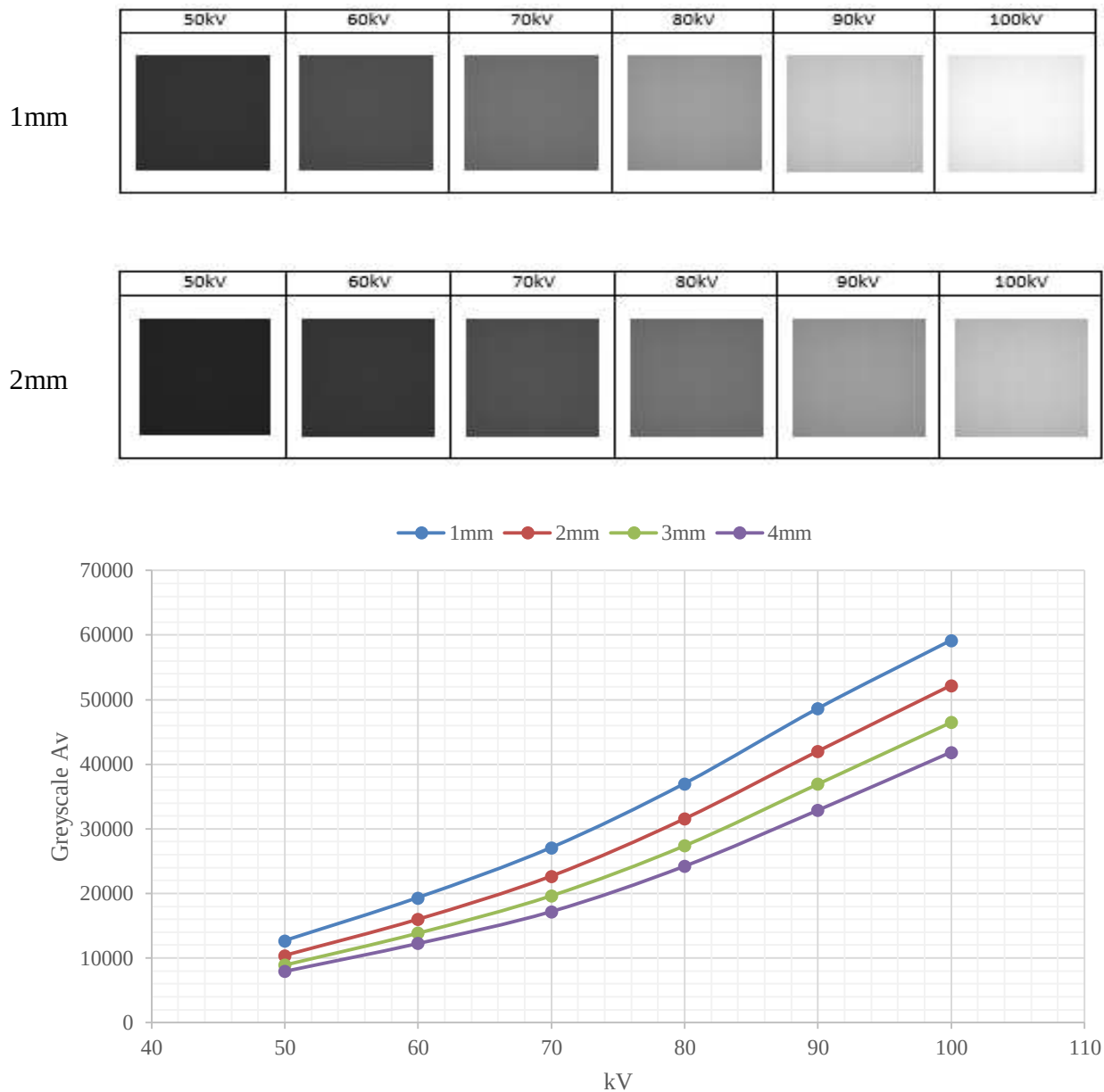


Figure 5-10 Variation of greyscale as tube voltage is increased in accordance to the aluminium radiographs.

The final evaluation is to present the attenuation curves as kV values are increased. If the exponential function is fitted to these graphs, a correlation can be discovered between the theoretical and experimental data. The bars are used to represent the attenuation coefficient in reference to the full spectrum created by that specific kV value. The decay curves again prove that as kV is increased, the attenuation average reduces.

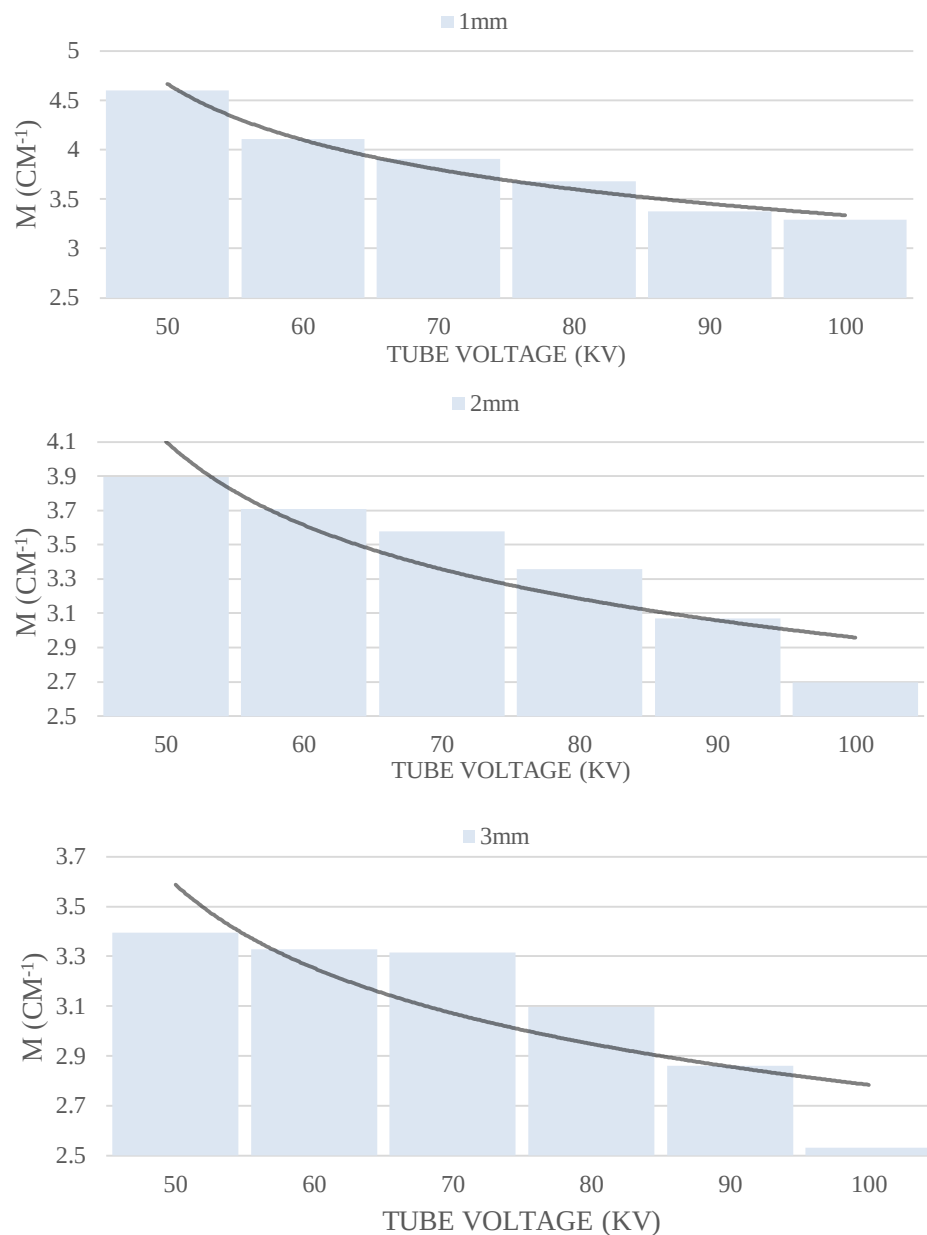


Figure 5-11 Attenuation curves of 1, 2, 3mm aluminium filtration differentials over increasing kV.

5.2.2 Theoretical and Experimental Analysis

The exponential trends from both aluminium data sets are used as a comparison presented for the three differential thicknesses. With the addition of the detector linearity correction the two aluminium data sets should resemble, similar decays rates of attenuation as kV is increased. The simulation data curve (shown in red) will set the standard as the simulation is using controlled parameters. The experimental traces are expected to follow the same trends however any deviations from the standard curve will be due to system constants.

5.2.2.1 1mm Evaluation

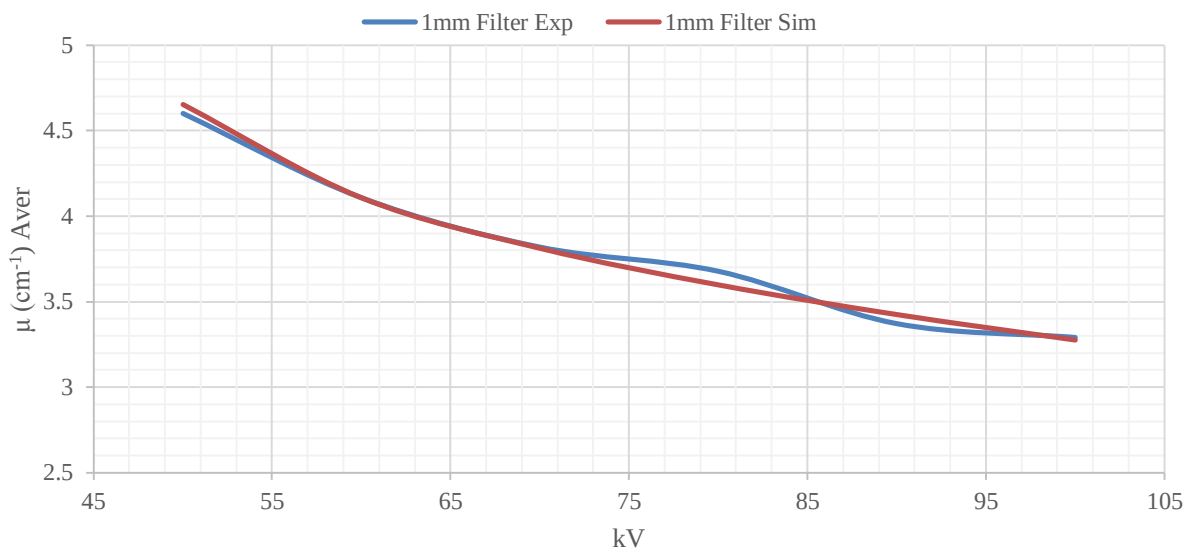


Figure 5-12 1mm Data sets comparison

The graph shows that the comparison between the two 1mm data sets are quite respectable throughout the increasing kV. The trends are consistent to one another with slight deviations shown between the 75-85kV range where, it is witnessed that characteristic radiation could manipulate the data. However, there is a notable correlation between the two data sets.

5.2.2.2 2 mm Evaluation

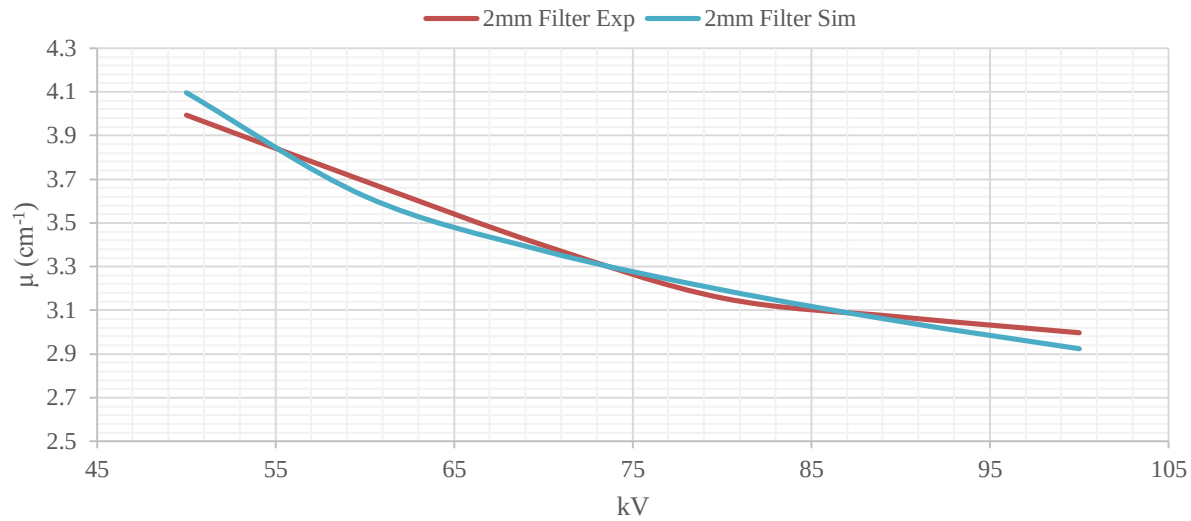


Figure 5-13 2mm data Sets Comparison

The 2mm evaluation also shows continuity within the two data sets. By adding a secondary filter the attenuation figures have reduced when compared to the 1mm curve. The trends show a fall as increased kV is applied, which is expected. The variations in the two data sets may be caused by the setup of the experiment. Where it is crucial, the filters are placed perpendicular to one another and the source, air gaps in between the filter and source to filter will slightly deviate the results. For the purpose of the comparison small allowances are applied to the data sets as the experimental procedure is less controlled, however as an overall comparison there are promising results that the method used is viable.

5.2.2.3 3mm Evaluation

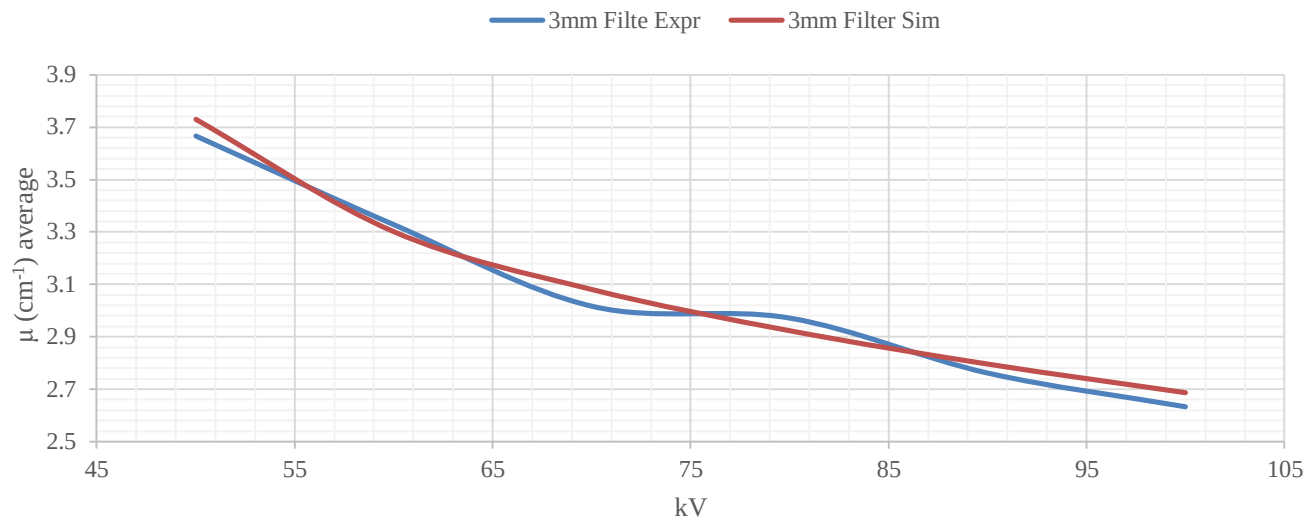


Figure 5-14 2mm data Sets Comparison

The 3mm evaluation shows larger discrepancies within the data sets at the higher kV range. This became apparent in the experiment results where the trend for 70kV was notably different to the 50 and 100kV trends. Again, this may have been caused by experiment factors or interpretation of the detectors linearity. Nevertheless, the resulting average coefficient values are well within an order of magnitude to one another, which again produces confidence within the method used.

The comparison between the two datasets has shown likeness within the trends and has been approved for the CFRP evaluations. The detector linearity correction was applied to justify the experimental data by normalising it with the SpekCalc data. For the CFRP analysis the detectors linearity factor doesn't apply, as there are no means of normalisation with SpekCalc data. Nevertheless the CFRP findings are justified with the experimental findings (Nuclear Medicine, 2014).

5.3 Experimental CFRP Analysis

The CFRP experiment was completed with two sets of filtration samples. The first test used sections of CFRP sourced from a component, which was 1.5mm thick. This wasn't ideal as the properties of this material were unknown, such as layup or manufacturing technique. The second test was carried out on filtration samples which were sourced from a 1mm thick sheet, which was sourced in house. The sheet had been created within an autoclave and the properties of the material were more controlled. The sheet was sectioned into the same dimension as an aluminium filter to ensure it was suitably adapted within the X-ray system. Initial testing showed that 100kV results would saturate the detector, which wouldn't provide appropriate data, therefore the tests were carried out within a range of 50 to 90kV settings. In addition, the current was kept constant throughout the experiment.

5.3.1 Test 1

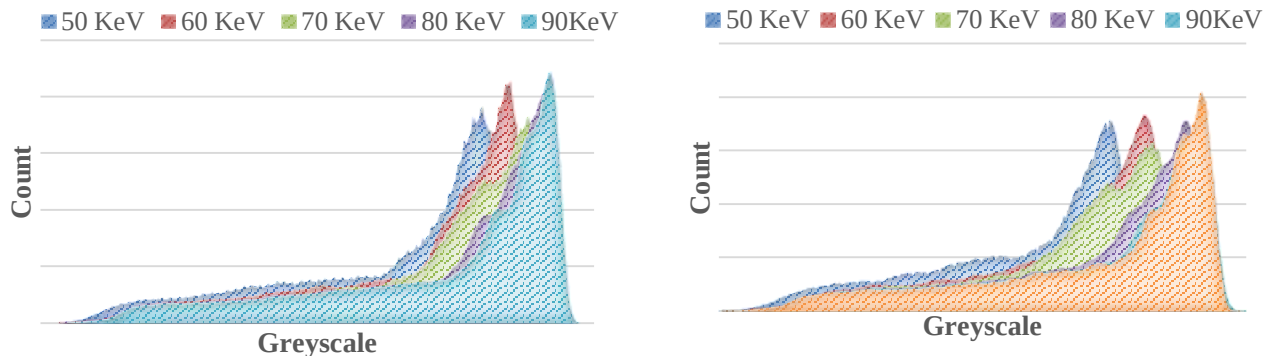


Figure 5-15 Radiograph histograms of 50, 70 and 90kV with increasing filtration.

The initial histograms show a large amount of spurious data, which was a concern, as the average greyscale wouldn't give a clear indication of the attenuation coefficients. The preliminary thought was to examine the radiographs to establish a reasoning for these histograms.

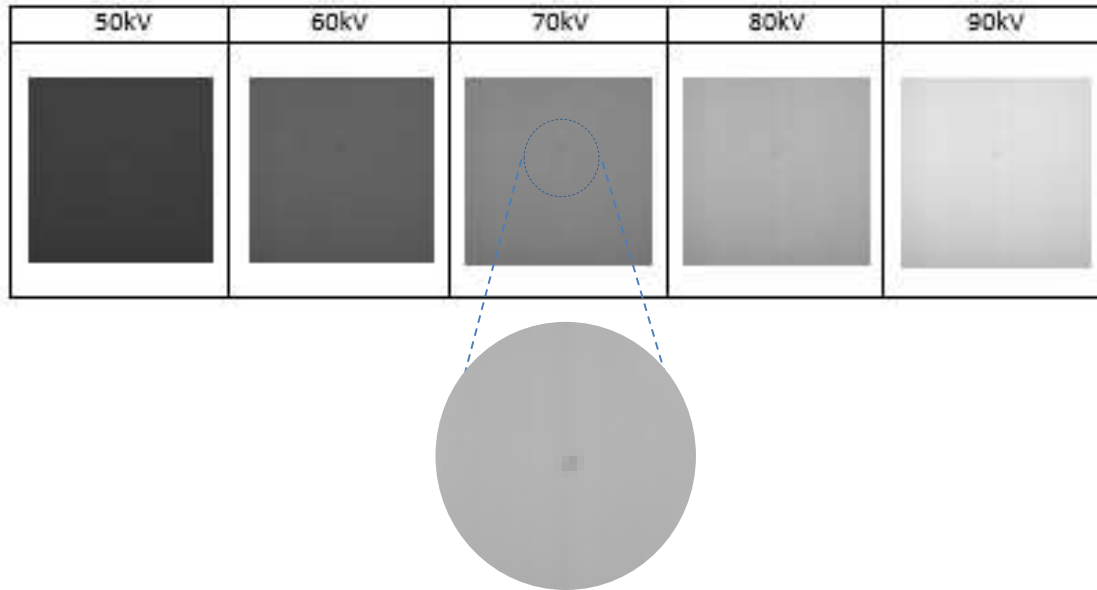


Figure 5-16 2mm radiographs of increasing kV.

The results of the radiograph examination shows an in-conclusion discovered within the addition of a CFRP filter. This is witnessed at 70kV and distinguishable throughout the range. The defect influenced the greyscale trends there,fore; the data was compromised, shown on the graph below.

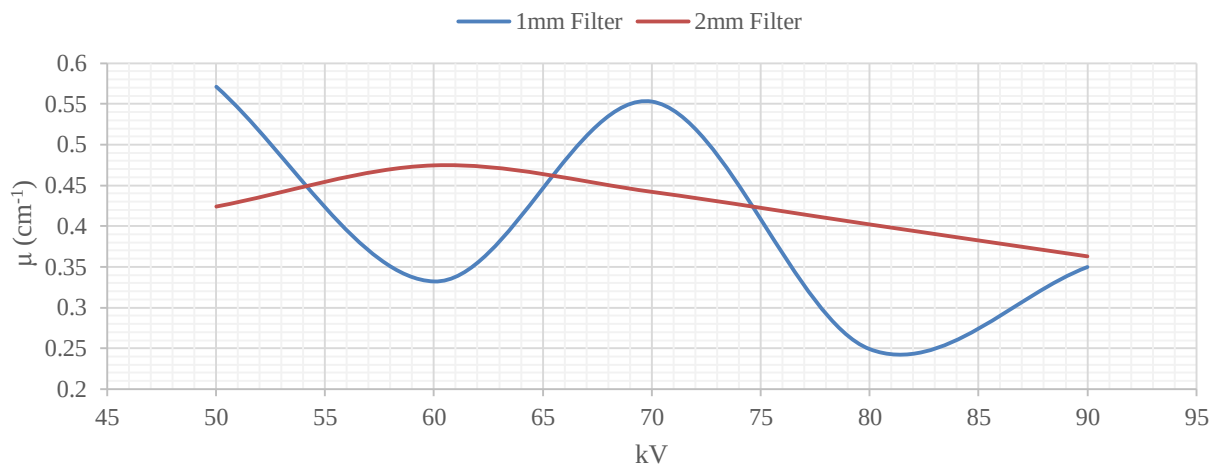


Figure 5-17 Attenuation comparison of increasing thickness.

This led to the second test having more controlled parameters, being applied to find the average attenuation coefficient for CFRP optimisation.

5.3.2 Test 2

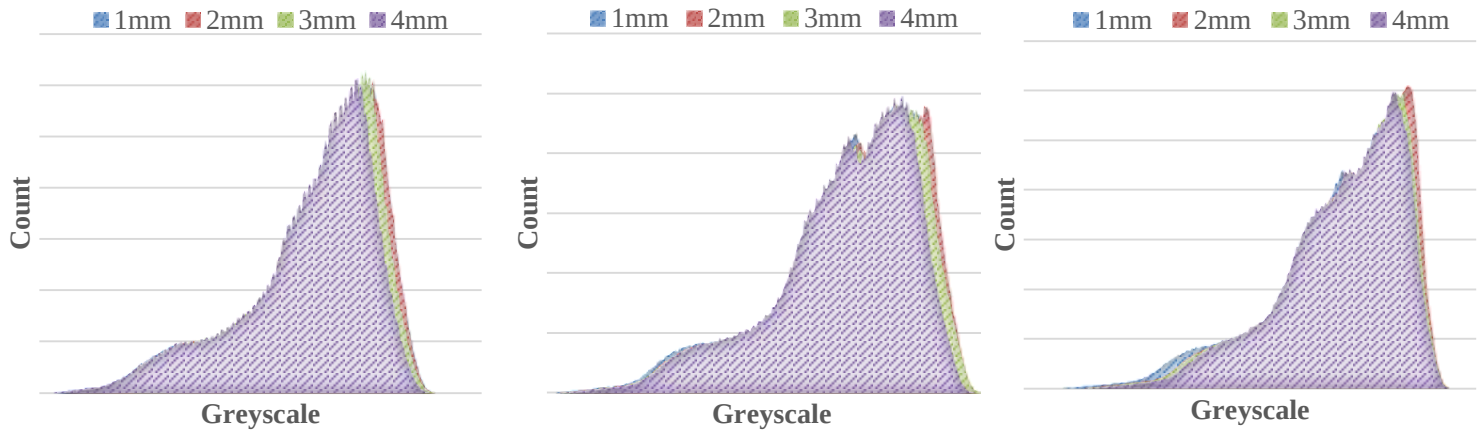


Figure 5-18 Radiograph histograms of 50, 70 and 100kV with increasing filtration.

At	Greyscale Average				Attenuation Coefficient		
	1mm	2mm	3mm	4mm	1mm	2mm	3mm
50kV	17913	17164	16372	15851	0.42 cm ⁻¹	0.45 cm ⁻¹	0.4 cm ⁻¹

At	Greyscale Average				Attenuation Coefficient		
	1mm	2mm	3mm	4mm	1mm	2mm	3mm
70kV	36987	31548	27403	24228	0.43 cm ⁻¹	0.40 cm ⁻¹	0.38 cm ⁻¹

At	Greyscale Average				Attenuation Coefficient		
	1mm	2mm	3mm	4mm	1mm	2mm	3mm
90kV	59170	52215	46497	41870	0.34 cm ⁻¹	0.31 cm ⁻¹	0.30 cm ⁻¹

Table 5-5 (right) Greyscale Averages (left) Resulting Attenuation Coefficients

A similar procedure to find the average attenuation coefficients is used with the CFRP data, where the greyscale are averaged and used within an interpretation of Beer Lamberts law. The filtration was added in 1mm thick increments. During this test, the filters were placed in accordance to directional layup properties. This was to ensure that accuracy within the data was achieved.

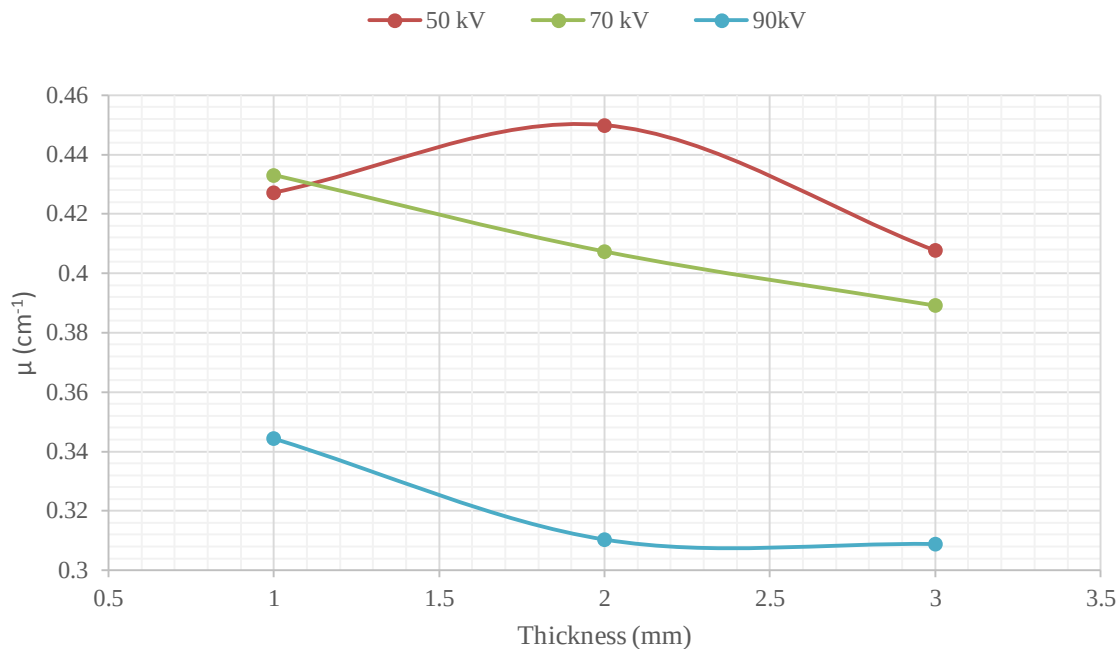


Figure 5-19 Attenuation comparison of increasing thickness.

The 50kV trend shows an anomaly within the data, found at 1mm thickness. This figure should show the highest coefficient, however the ratio between the two grey scales are relatively small compared to the other filter interactions. At 50kV, the linear absorption coefficient should show the most influential change at this lower energy, which is affectively shown within the curve.

The 70kV and 90kV are unaffected and show the classic curves expected for this type of interaction. The 90kV shows the least attenuation occurring suggesting the higher kV values wouldn't give affective means of distinguishing the properties within CFRP.

The radiographs presented show the range of kV and their relativity to greyscale variations with increasing filtration. The 90kV was the maximum voltage used for the inspection as the detectors limitations were reached. The graph shows the greyscale differential between the increasing kV and there relation to increasing filter thickness, are a lot closer in proximity to one another when compared to the aluminium results, due to the materials having different densities.

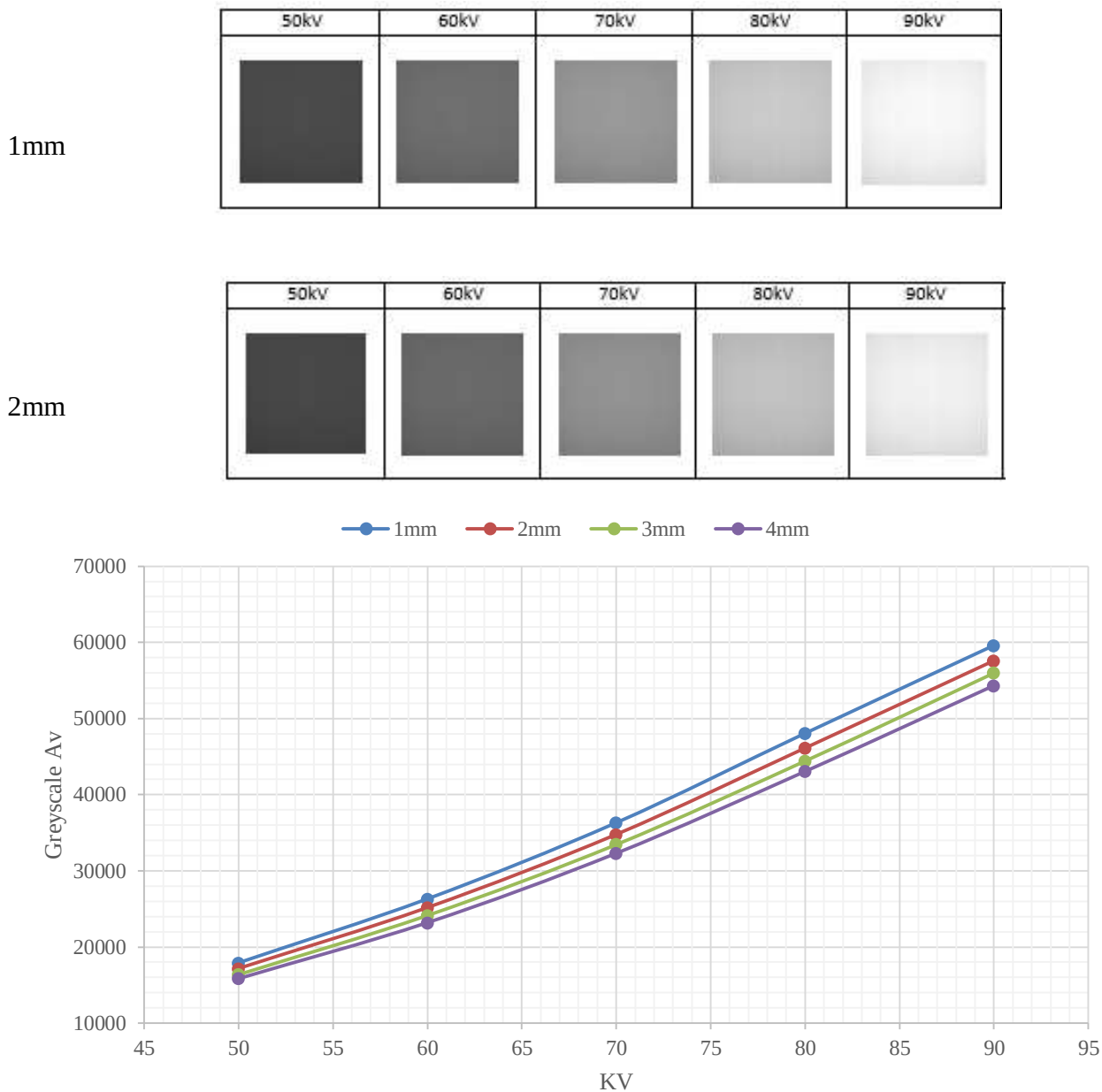


Figure 5-20 Variation of greyscale as tube voltage is increased in accordance to the CFRP radiographs.

The linear absorption trends are finally presented below for the individual filter thicknesses. An exponential trend has been fitted to the graphs, to show the decay of the absorption coefficients in relation to the increasing kV. The biggest changes are seen at the lower kV values, which illustrates the best chance of discovering material properties where the attenuation is similar.

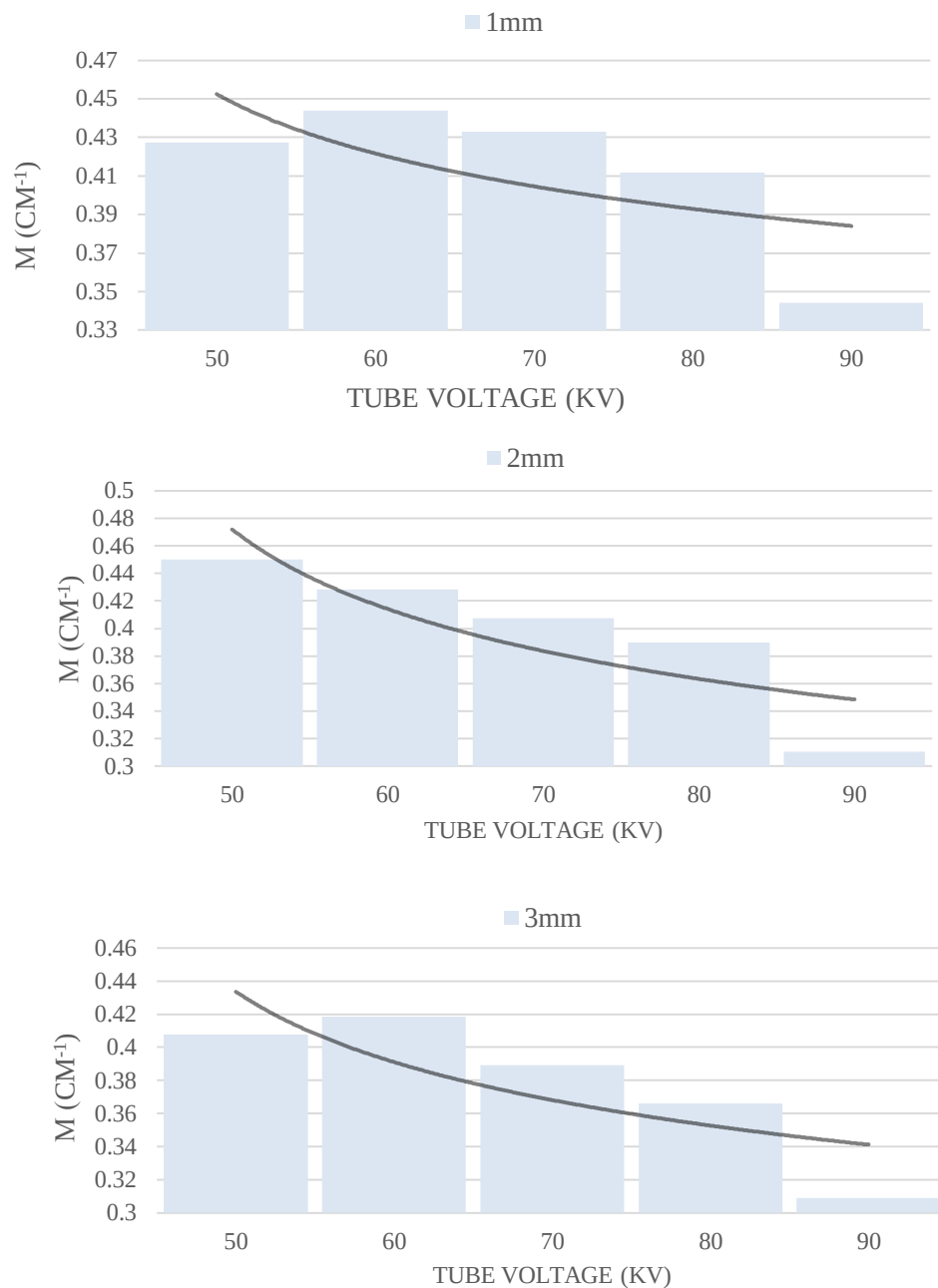
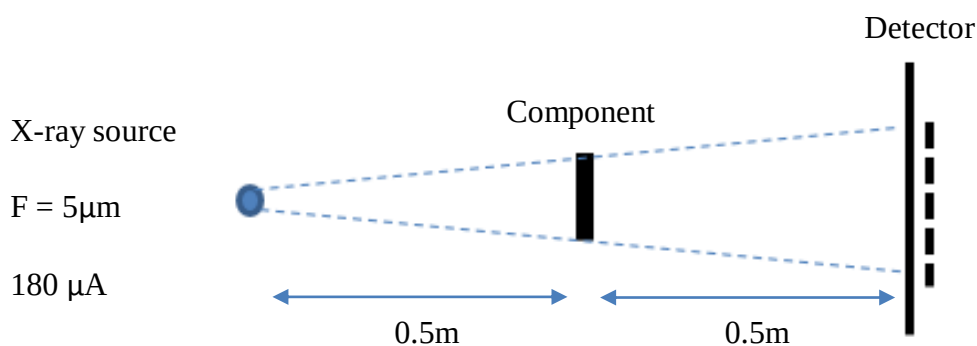


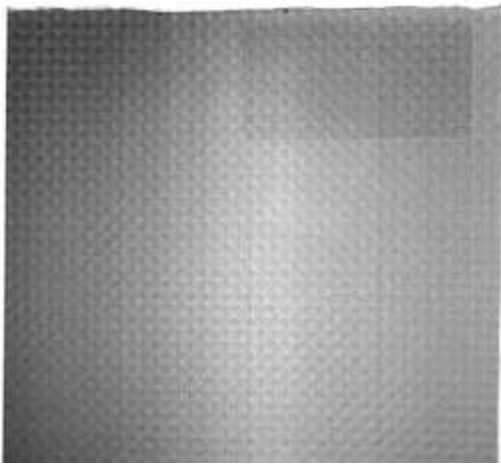
Figure 5-21 Attenuation curves of 1, 2, 3mm CFRP filtration differentials over increasing kV.

The 1mm filtration shows at 90kV the estimated linear absorption coefficient is 0.34cm^{-1} , which can be compared to the findings of the (Nuclear Medicine, 2014) experiment. Their results show that the attenuation of carbon at 100keV is 0.335cm^{-1} . A direct comparison couldn't be verified at this level of energy as the detector limits were reached during the experiment however, with the 90kV showing results within the same order of magnitude, the confidence in results justify the method to obtain the coefficients.

5.4 Optimised parameters for CFRP inspection.

The final stage was to examine a CFRP component using the preferred series of setup parameters without the use of image J interpretation. The raw radiographs, presented below show, a comparison of 50, 70 and 90kV, with the addition of a 1mm aluminium filter to witness the affects. For continuity between these images, the current of $180\mu\text{A}$ was applied and the object was positioned 0.5m from the source.





50kV no Filter

The raw image of the 50kV with no filtration shows good initial contrast, enhancing the materials weave properties. The darker shaded area is a paper label, which will attenuate the radiation further, clearly witnessed at this particular setting.



70 kV No Filter

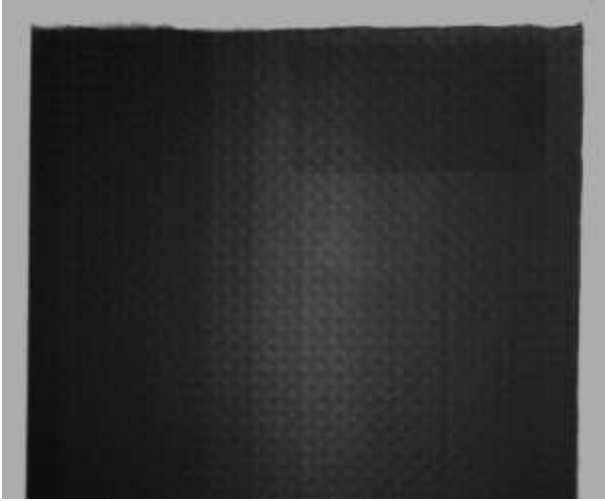
As the energy is increased the contrast between the carbon and polymer matrix becomes less intense. This is particularly poor within the centre of the piece where the detectors are more sensitive. Possible due to alignment complications.



90 kV No Filter

The 90kV level loses all contrast between the materials properties causing the weave pattern, seen within the previous examples, becoming less distinguishable. This setting is inappropriate for CFRP inspections as defects or important artefacts could easily be missed.

Figure 5-22 Radiographs of CFRP with no filtration



50kV 1mm Aluminium Filter

With the addition of a 1mm aluminium filter, the raw image is too dark to establish a good examination of the component. The filter absorbs the low energy, therefore emitting weak quanta of photons, which eventually interacts with the component. This again produces poor contrast.



70 kV 1mm Aluminium Filter

The quality of the 70kV shows improvements, as larger regions become visible, however the distinguishability of the materials properties, are still not accurately portrayed.



90 kV 1mm Aluminium Filter

The addition of the aluminium filter has reduced the intensity which allows an image to be presented, however not as clear as the low energies presented with no filter.

Figure 5-23 Radiographs of CFRP Component with 1mm Aluminium Filtration

5.5 Conclusion

The results show that comprehensive methods were efficient in determining the linear absorption coefficients for both aluminium and CFRP materials. The theoretical process used a selection of parameters, which could be applied to experimental testing. The parameters were simulated using SpekCalc, which produced a spectral distribution of quanta intensities. These were then manipulated to find the attenuation coefficient for both a range of kV and additional aluminium thicknesses. The experimental process used the same procedure for clarity of the comparison. The initial results were out by an order of magnitude which required the addition of a detector correction factor. This was achieved by normalising the theoretical and experimental data together, which would link a hypothetical and true detector's response. The correlation between the methods showed nearly identical linear absorption decays for increasing kV, which gave confidence in applying the method to CFRP evaluation. This was enhanced by justifying the simulated data with the (Nuclear Medicine, 2014) findings. Their results showed a 0.44 cm^{-1} attenuation coefficient found at 100kV. The simulation results showed this figure to be 0.46 cm^{-1} . (Appendix D).

The CFRP evaluation displayed some irregularities within the second 50kV analysis, which was unexpected as stricter factors were applied during this test. The increasing kV graphs showed an improved representation of the linear absorption decay and was verified once again to the findings of the (Nuclear Medicine, 2014).

The optimisation parameters for CFRP inspection showed example radiographs with variations in their setup. The finest image produced without interpretation of image j was seen with 50kV-no filter. The materials structure were clearly distinguishable as contrast between the materials were enhanced due to better attenuation mechanisms at this level of intensity.

6 Conclusion and Recommendations

6.1 Conclusion

It was initially stated that conventional radiography inspections on composites were not as compliant as metallic counterparts, due to their material properties having similar absorption characteristics. This was the cause of poor contrast within the radiographs, which instigated a number of techniques to overcome this issue, many of which used large variations in their testing parameters. A general consensus of these techniques used low energy levels to optimise the CFRP component evaluation, however with little explanation into the theory.

The principal hypothesis for this work was to achieve the following aims and objectives;

- To enhance the understanding of X-ray production and interaction with a filtered material, by defining a complete parametric study, from source to detector.
- To produce a theoretical configuration between experimental images and simulated spectral distributions to determine absorption coefficients.
- To design, test and analyse a radiography inspection for CFRP filters, to establish the materials properties, allowing for enhancements of radiographic image contrasts.

These were accomplished which led to the method, which proposes a correlation between Bremsstrahlung spectral distribution and the resultant experimental radiograph greyscale count, to allow for a respectable linear attenuation coefficient estimation of CFRP. The parameters are dependent on the X-ray energy and material density; nevertheless, a contribution towards the optimisation of radiographic parameters for CFRP evaluation, without compromising the material, has been presented here.

The detectors linearity played a key role in normalising the aluminium datasets and with implementing an edition of Beer Lamberts law, the linear absorption coefficient was discovered. Once the method was justified by comparing the findings of both theoretical and experimental means on aluminium filtration and verifying the results to the findings of an external experiment, the CFRP analysis could be carried out. The experimental procedures required a series of constants to ensure the linear absorption coefficients were reprehensively estimated to the desired alterations being either filter thickness or increased kV. These constants were;

- The current setting of $180\mu\text{A}$, which was chosen as it gave the best detector response through the range of 50 to 100kV, with 1mm aluminium filtration.
- Distance from source to detector, which was 1m, which facilitated for the CFRP component investigation.
- Positioning of the filters to ensure directional properties were accounted for.

It was established that at lower tube voltages a greater change in attenuation was apparent, shown on the exponential decay curves. Therefore, this would enhance the contrast on a radiograph of a component where the internal structure has similar absorption characteristics. The examination of the CFRP component showed this to be true, as the 50kV displayed the distinctive weave pattern most predominantly, including the transparency of the paper label.

More justification would be required to prove this method for the interpretation of finding defects however, the work has provided the best method for Optimisation of Digital Radiograph Parameters for CFRP component evaluation – to be used in an increasingly important design material for many industrial manufacturing applications for the future.

6.2 Limitations

A series of limitations became apparent in the early stages of this project, selectively with the restrictions from SpekCalc software. The initial thought was to complete a comparison with CFRP simulations however, due to the complications of this material the justification between theoretical and experimental procedure had to be carried out with aluminium materials. An advance version of software was also considered to present the full transition between SpekCalc to simulated radiographs. Unfortunately, the complications within this software, such as object geometry and material selection concluded its absence within this study.

6.3 Recommendations and future work.

For consideration of future work, it is recommended to conduct a study into the correlation between SpekCalc and Krammers theory. This would allow for an analysis into different target materials to be incorporated to the proposed method. It is also suggested that a study into the detectors linearity be carried out using the approach seen within (Thomas Hofmann, 2011) study.

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Appendices

Appendix A

Beer lambert Law deviation

The magnitude of ΔI is dependent on the radiation intensity as well as the thickness of the absorber:

Minus sign indicating that the intensity is reducing by the absorber

$$-dI \propto I \cdot dx$$

The constant of proportionality, μ , is added.

$$-dI = \mu I \cdot dx$$

Dividing across by I

$$-\frac{dI}{I} = \mu \cdot dx$$

This basic equation describes the situation of any tiny change in the absorber thickness. To solve for a complete thickness of an absorber the small thickness are added up, this is expressed by integrating the above equation, so that for a thickness $x = 0$ to an increased thickness of x , the radiation intensity will decrease from I_0 to I_x :

$$-\int_{I_0}^{I_x} \frac{dI}{I} = \mu \int_0^x dx$$

$$\therefore \ln \left(\frac{I_x}{I_0} \right) = -\mu x$$

$$\therefore \frac{I_x}{I_0} = \exp(-\mu x)$$

$$\therefore I_x = I_0 e^{-\mu x}$$

Half value layer deviation. A relationship between the half-life and the decay constant.

$$Ix = \frac{Io}{2}$$

When

$$x = x_{\frac{1}{2}}$$

Inserted into the exponential attenuation equation gives:

$$\frac{Io}{2} = Io \exp(-\mu x_{\frac{1}{2}})$$

$$\therefore \frac{1}{2} = \exp(-\mu x_{\frac{1}{2}})$$

$$\therefore 2^{-1} = \exp(-\mu x_{\frac{1}{2}})$$

$$\therefore \ln 2^{-1} = -\mu x_{\frac{1}{2}}$$

$$\therefore \ln 2 = \mu x_{\frac{1}{2}}$$

$$\therefore 0.693 = \mu x_{\frac{1}{2}}$$

$$\therefore \mu = \frac{0.693}{x_{\frac{1}{2}}}$$

$$\therefore \mu = \frac{0.693}{HVL}$$

Appendix B

Microfocus source	Max. kV	Max. power	Focal spot size		XT H 160	XT H 225	XT H 225 ST	XT H 320	XT H 450	Custom cabinet
160 kV Xi, Reflection target	160 kV	60 W	3 µm up to 7 W	60 µm at 60 W	●					○
160 kV Reflection target	160 kV	225 W	3 µm up to 7 W	225 µm at 225 W	○					○
180 kV Transmission target	180 kV	20 W	1 µm up to 3 W	10 µm at 10 W		○	○			○
225 kV Reflection target	225 kV	225 W	3 µm up to 7 W	225 µm at 225 W		●	●	○		○
225 kV Rotating target option	225 kV	450 W	10 µm up to 30 W	113 µm at 450 W			○	○		○
320 kV Reflection target	320 kV	320 W	30 µm up to 30 W	300 µm at 320 W				●		○
450 kV Reflection target	450 kV	450 W	80 µm up to 200 W	320 µm at 450 W					●	○
450 kV High brilliance source	450 kV	450 W	80 µm up to 200 W	113 µm at 450 W					○	○
750 kV with integrated generator	750 kV	750 W	30 µm up to 70 W	190 µm at 750 W						○

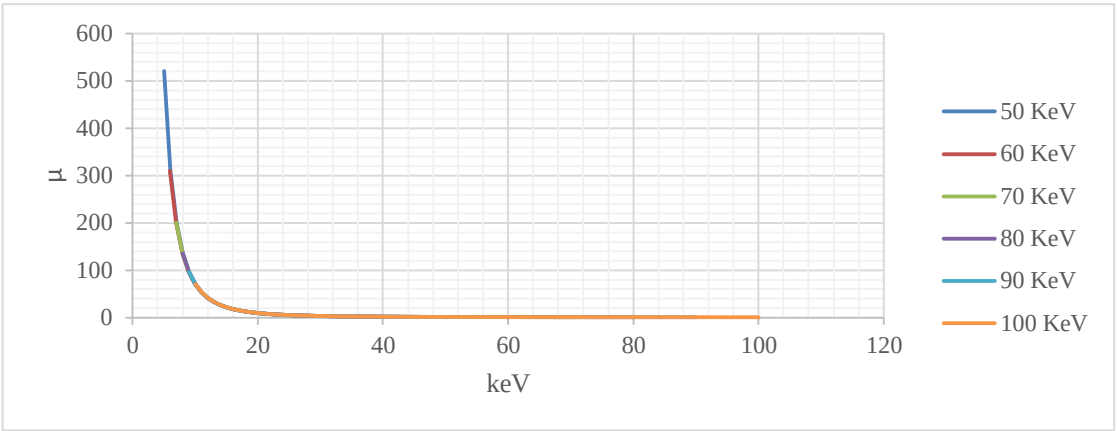
Detectors	# Bits	Active pixels	Pixel Size	Max. frame rate at 1x1 binning	Max. frame rate at 2x2 binning						
Varian 1313	14-bit	1000 x 1000	127 µm	10 fps	30 fps	○					○
Varian 2520	14-bit	1900 x 1516	127 µm	7.5 fps	15 fps	○	○	○	○ (1)		○
Varian 4030	14-bit	2300 x 3200	127 µm	3 fps	7 fps		○	○			○
Perkin Elmer 0820	16-bit	1000 x 1000	200 µm	7.5 fps	15 fps	○	○	○	○		○
Perkin Elmer 1620	16-bit	2000 x 2000	200 µm	3.75 fps	7.5 fps			○	○	○	○
Perkin Elmer 1621 EHS	16-bit	2000 x 2000	200 µm	15 fps	30 fps			○	○	○	○
Nikon Metrology CLDA	16-bit	2000	415 µm	50 fps						○	○
Combination PE162x & CLDA	Configuration with both Flat panel and Curved Linear Diode Array detector									○	○

(1) only with 225 kV source ● Basic configuration ○ Alternative configuration

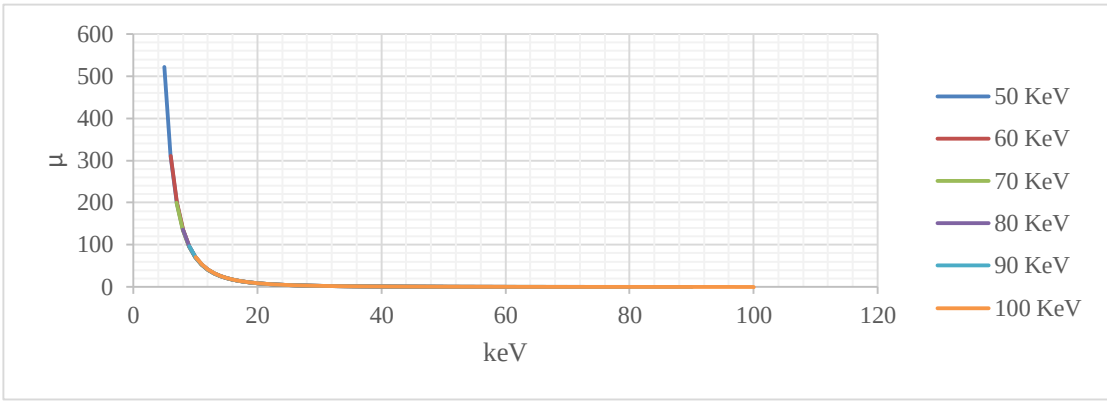
	XT H 160	XT H 225	XT H 225 ST	XT H 320	XT H 450
Manipulator					
# Axes	5	5	5	4 (optional 5 th axis)	4 (optional 5 th axis)
Axes travel	(X) 185 mm (Y) 250 mm (Z) 700 mm (Tilt) +/- 30° (Rotate) n*360°	(X) 185 mm (Y) 250 mm (Z) 700 mm (Tilt) +/- 30° (Rotate) n*360°	(X) 450 mm (Y) 350 mm (Z) 750 mm (Tilt) +/- 30° (Rotate) n*360°	(X) 510 mm (Y) 610 mm (Z) 800 mm (Rotate) n*360°	(X) 400 mm (Y) 600 mm (Z) 600 mm (Rotate) n*360°
Max. sample weight	15 kg	15 kg	50 kg	100 kg	100 kg
General specifications					
Cabinet dimensions (LxWxH)	1,830 mm x 875 mm x 1,987 mm	1,830 mm x 875 mm x 1,987 mm	2,414 mm x 1,275 mm x 2,202 mm	2,695 mm x 1,828 mm x 2,249 mm	3,613 mm x 1,828 mm x 2,249 mm
Weight	2,400 kg	2,400 kg	4,200 kg	8,000 kg	14,000 kg
Safety	All systems are manufactured to IRR99				
Control software	All systems are controlled by Nikon Metrology's in-house Inspect-X software				

Appendix C

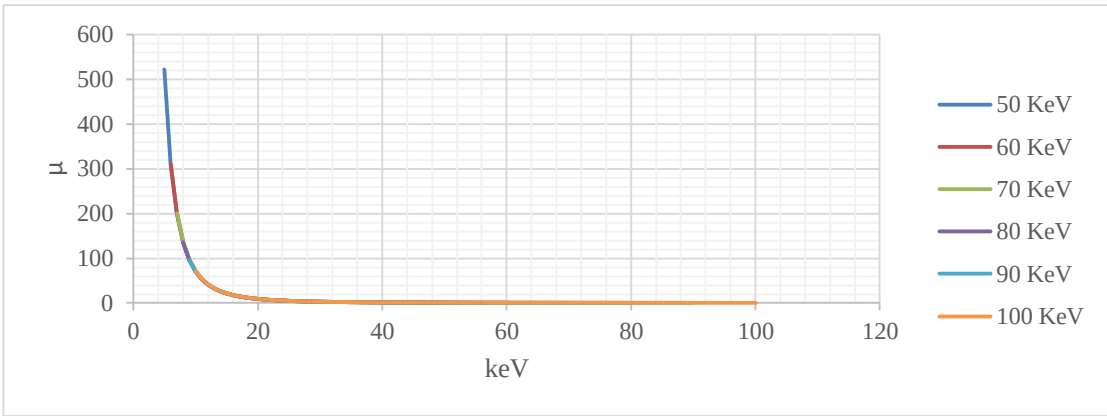
Theoretical Data Sets



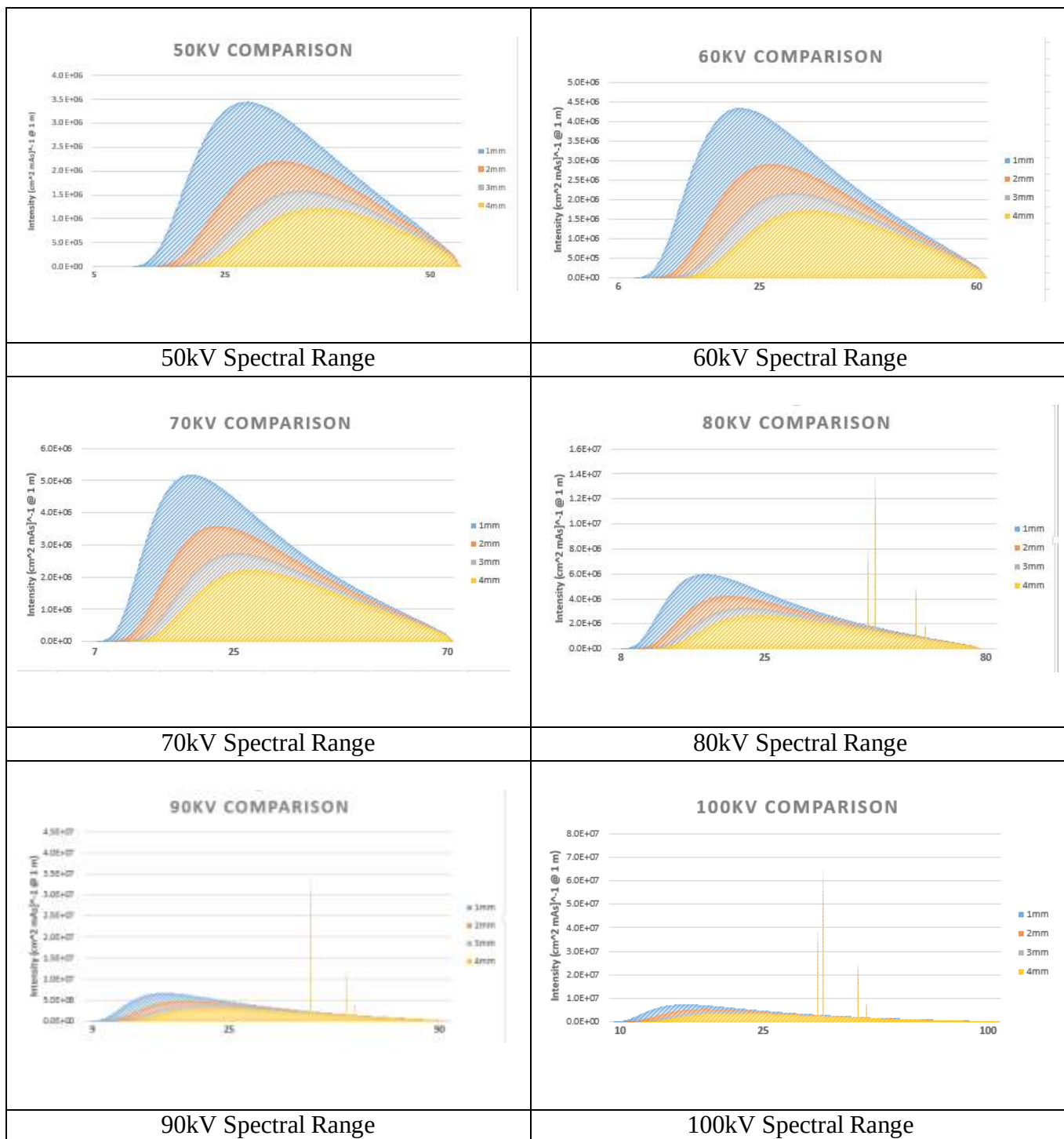
1mm Attenuation Curve over Full Range

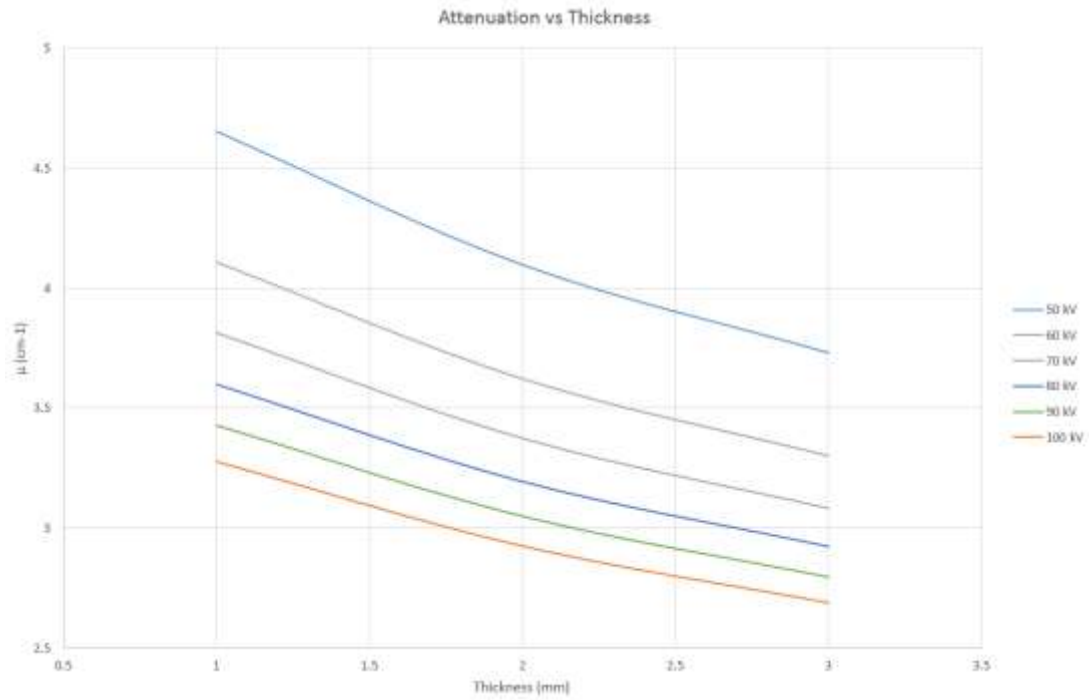


2mm Attenuation Curve over Full Range

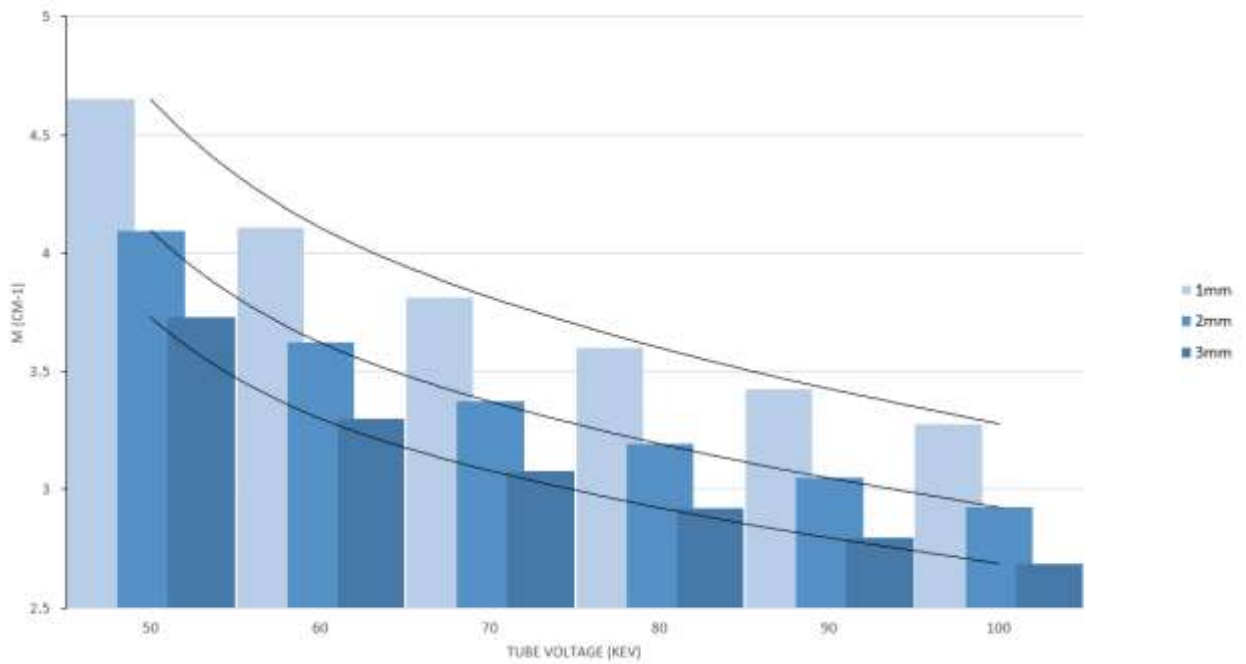


3mm Attenuation Curve over Full Range





Attenuation decay over thickness



Attenuation decay over increasing voltage

Experimental Aluminium

1mm Aluminium

50kv	60kv	70kv	80kv	90kv	100kv
					

2mm aluminium

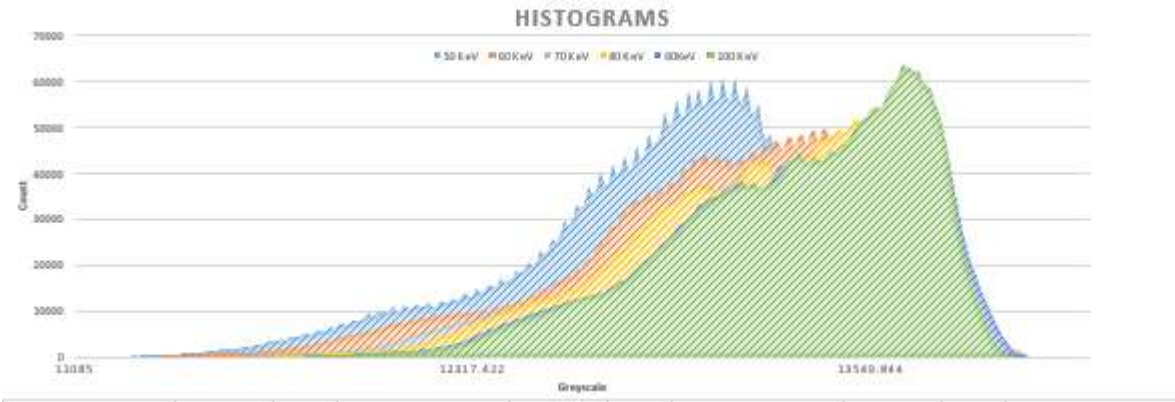
50kv	60kv	70kv	80kv	90kv	100kv
					

3mm Aluminium

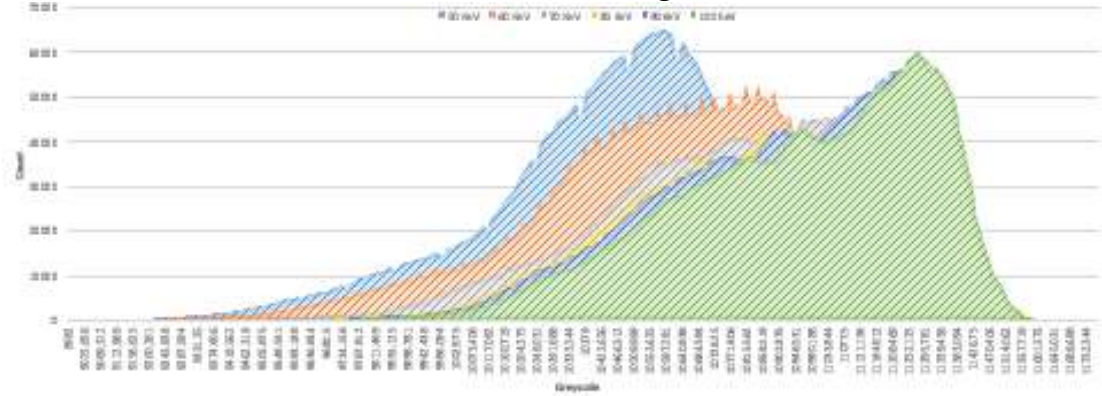
50kv	60kv	70kv	80kv	90kv	100kv
					

4mm Aluminium

50kv	60kv	70kv	80kv	90kv	100kv
					



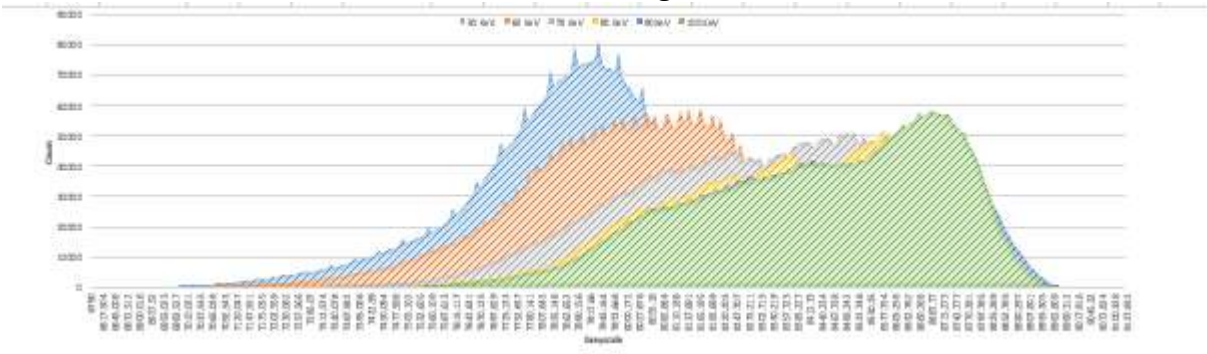
1mm Histogram



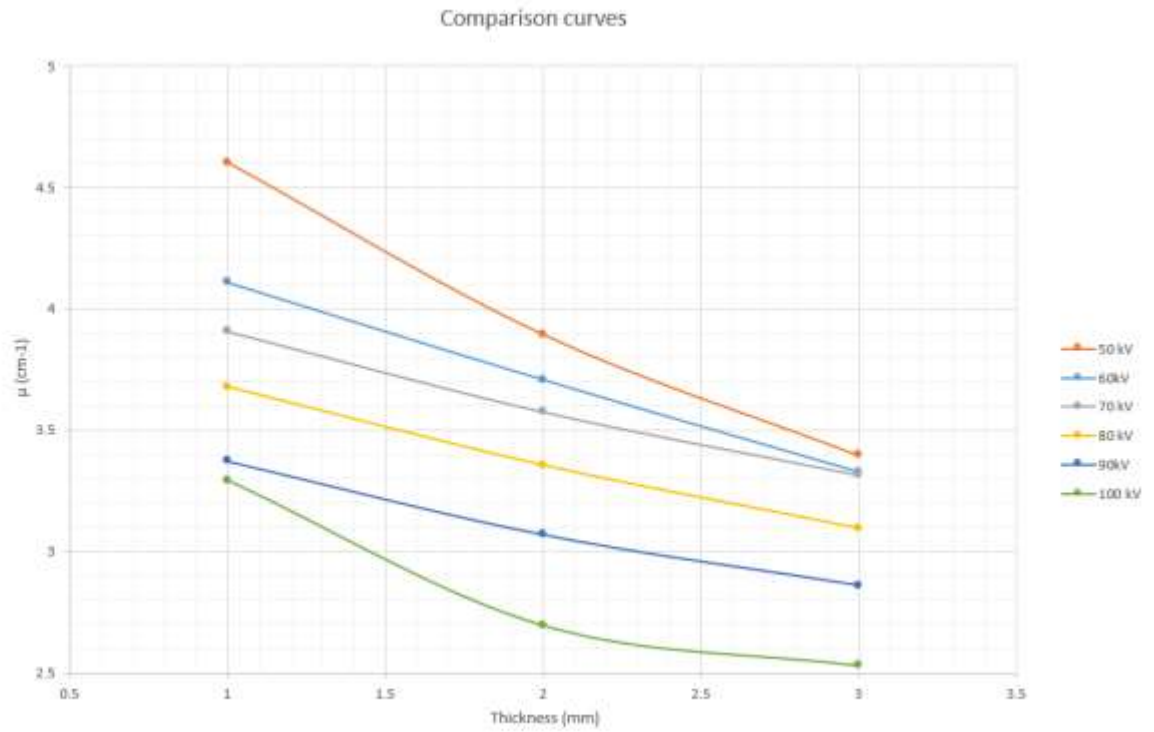
2mm Histogram



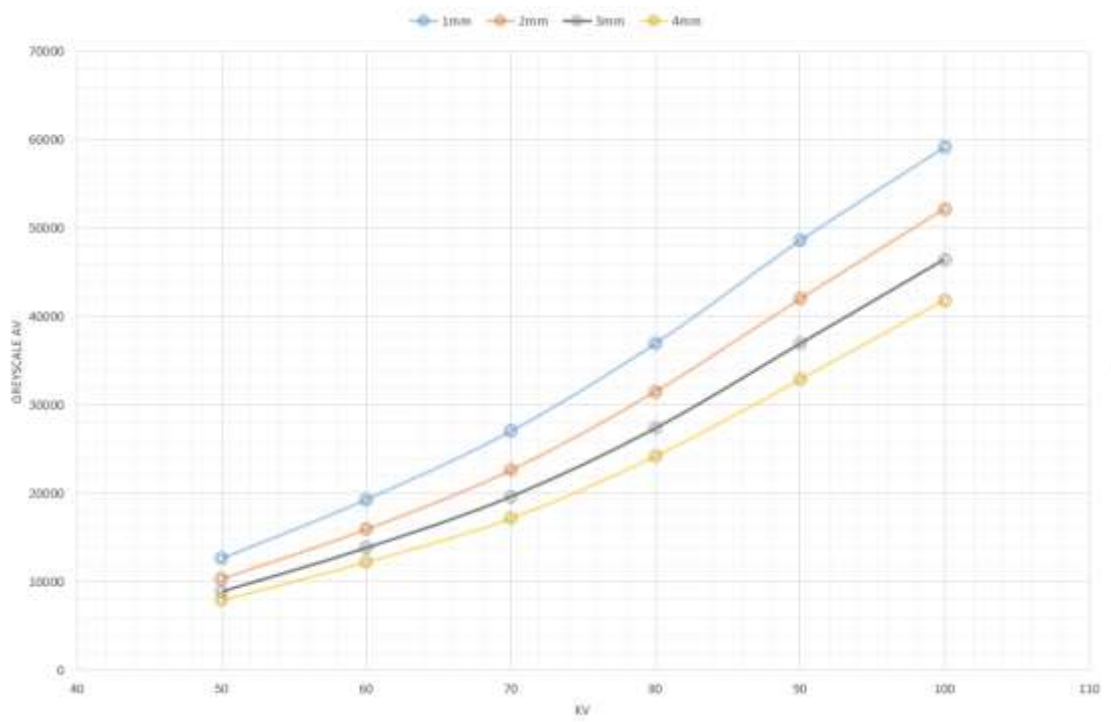
3mm Histogram



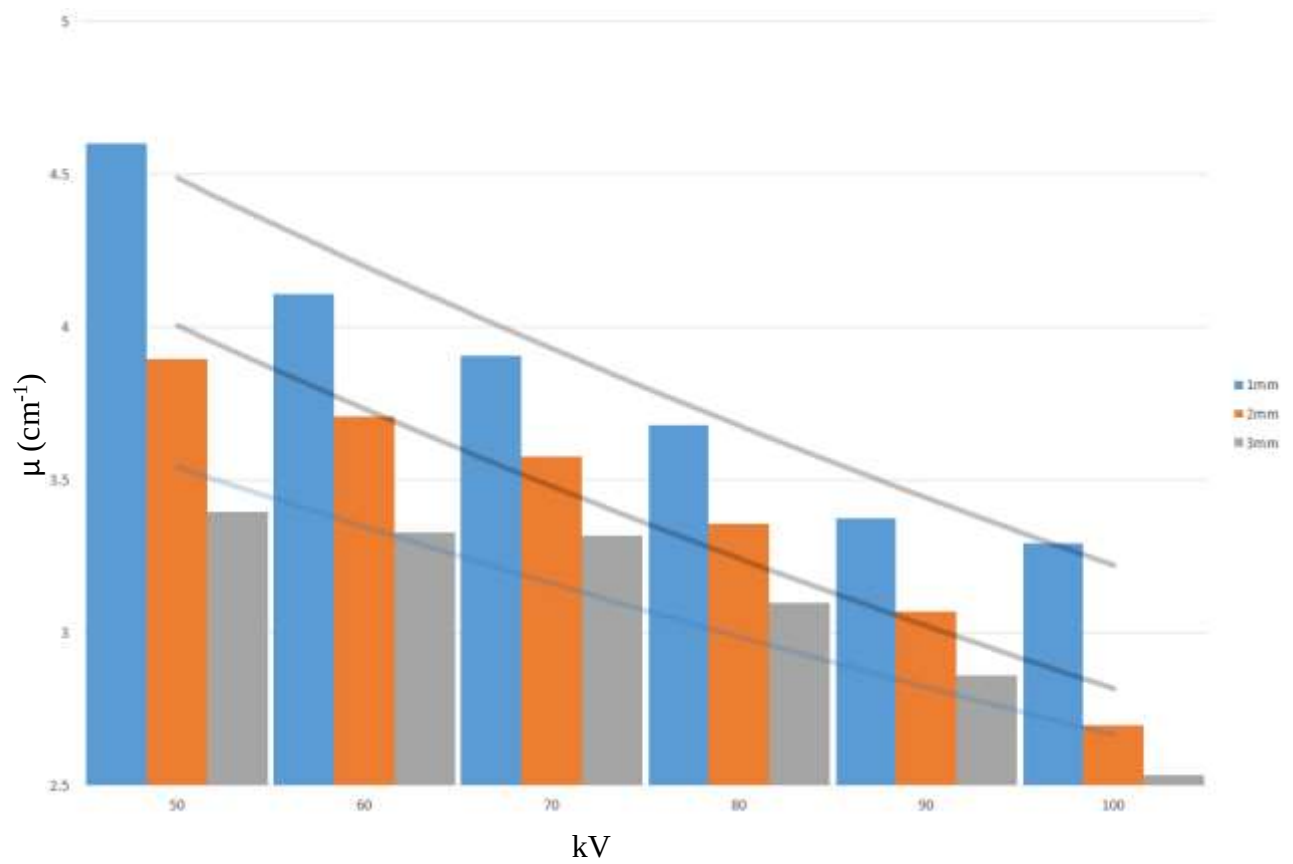
4mm Histogram



Attenuation decay over thickness



Greyscale Average over increasing kV



Exponential Decay of linear absorption coefficient over kV

Experimental CFRP (test one)

1mm Carbon Fibre

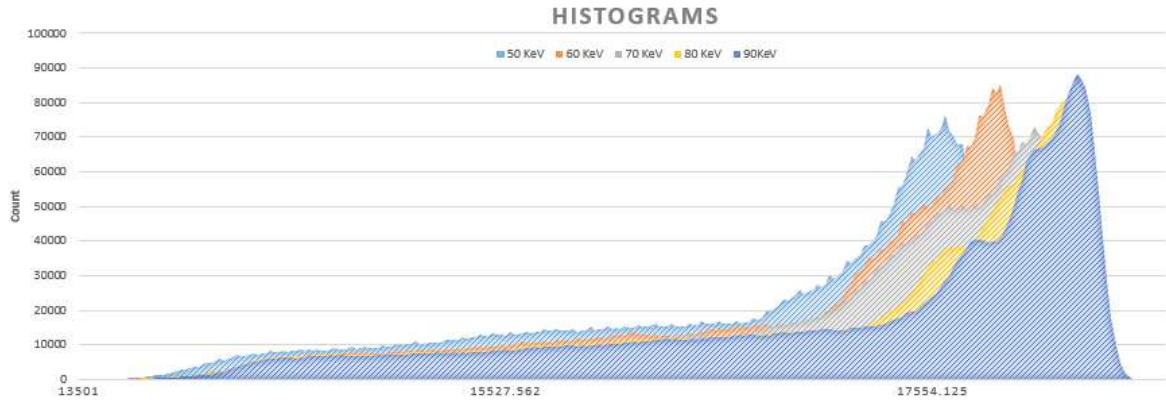
50kv	60kv	70kv	80kv	90kv	100kv
					

2mm Carbon Fibre

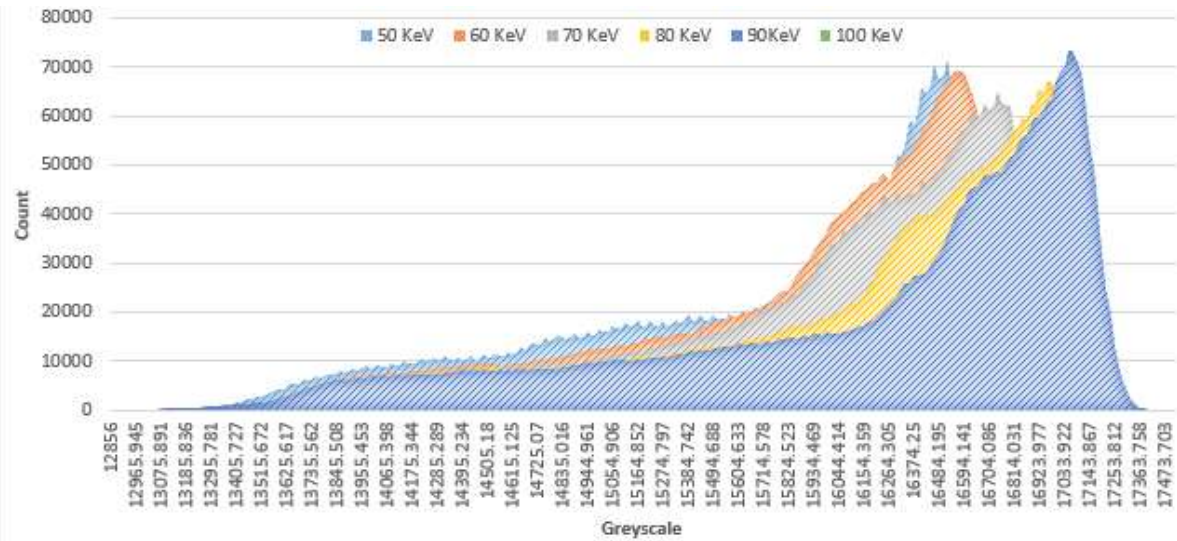
50kv	60kv	70kv	80kv	90kv	100kv
					

3mm Carbon Fibre

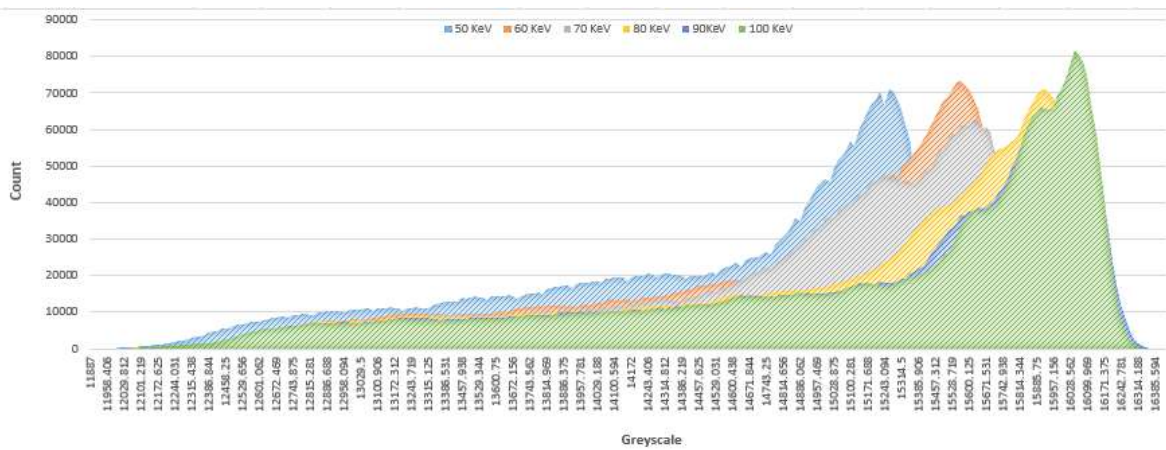
50kv	60kv	70kv	80kv	90kv	100kv
					



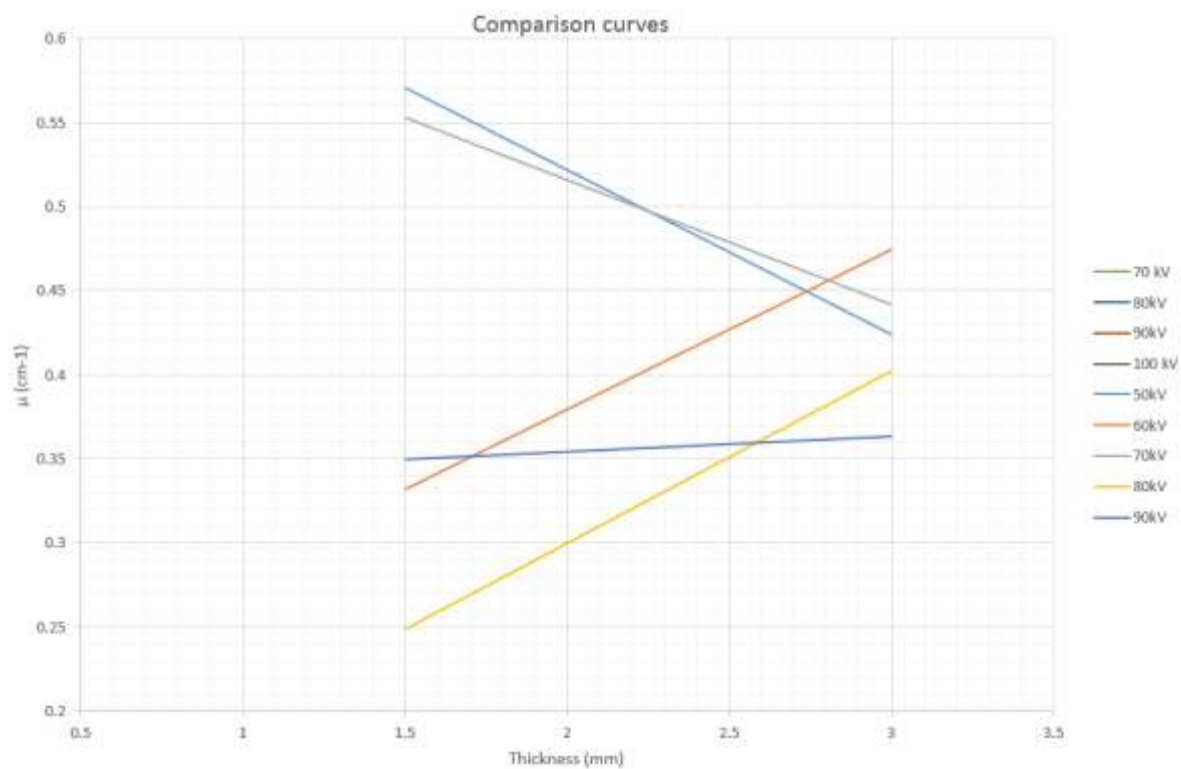
1mm Histogram



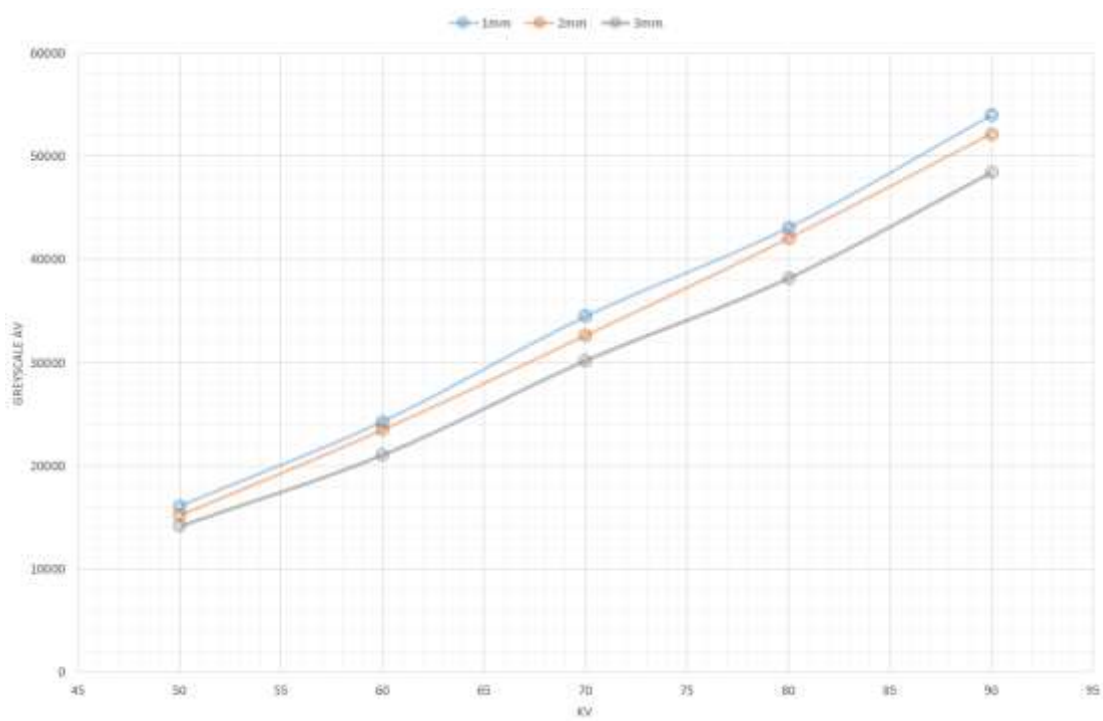
2mm Histogram



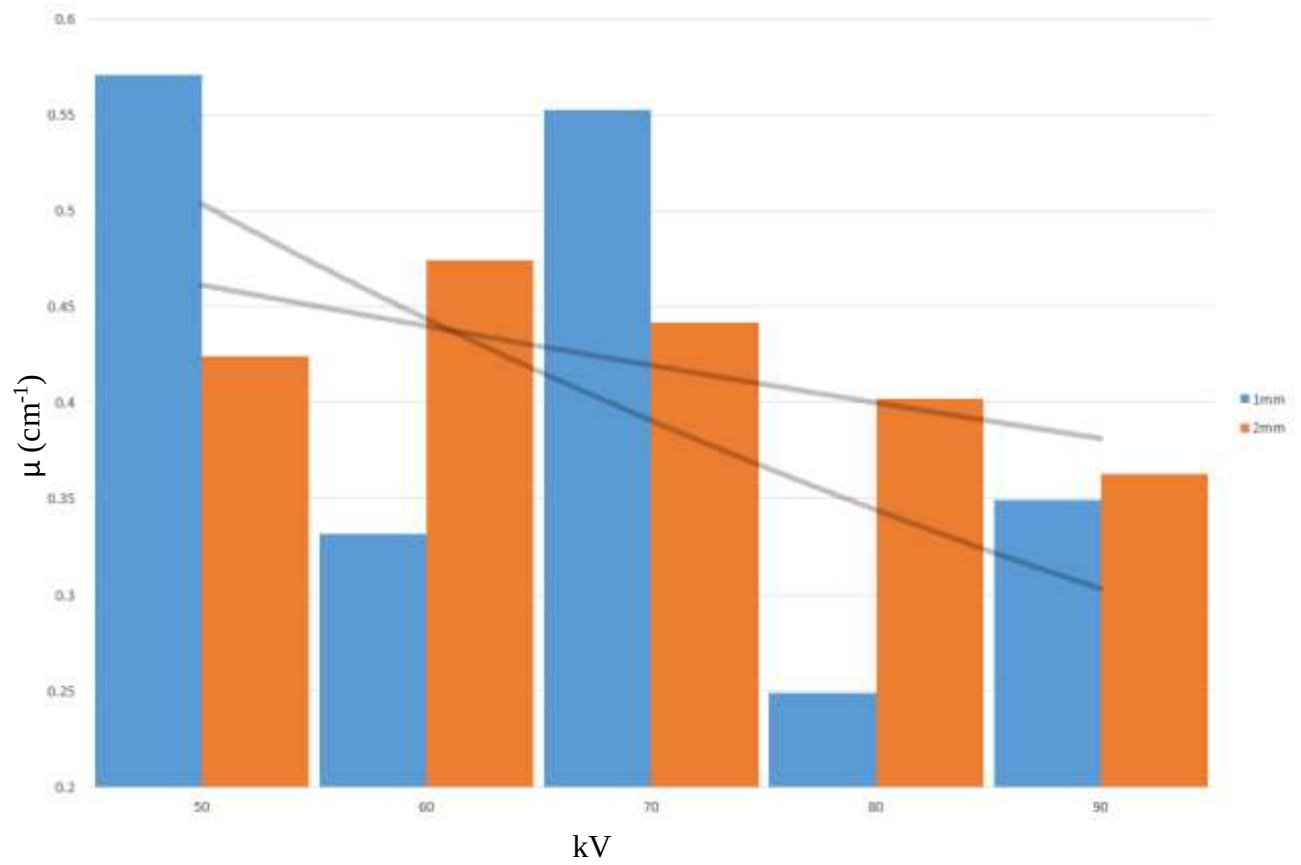
3mm Histogram



Attenuation decay over thickness



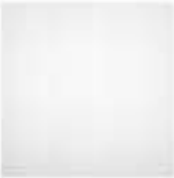
Greyscale Average over increasing kV



Exponential Decay of linear abortion coefficient over kV

Experimental CFRP (test two)

1mm Carbon Fibre

50kv	60kv	70kv	80kv	90kv	100kv
					

2mm Carbon Fibre

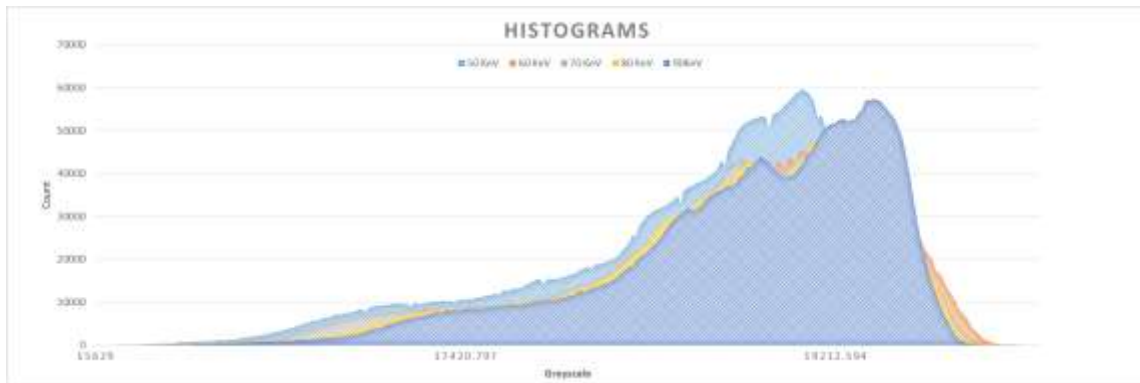
50kv	60kv	70kv	80kv	90kv	100kv
					

3mm Carbon Fibre

50kv	60kv	70kv	80kv	90kv	100kv
					

4mm Carbon Fibre

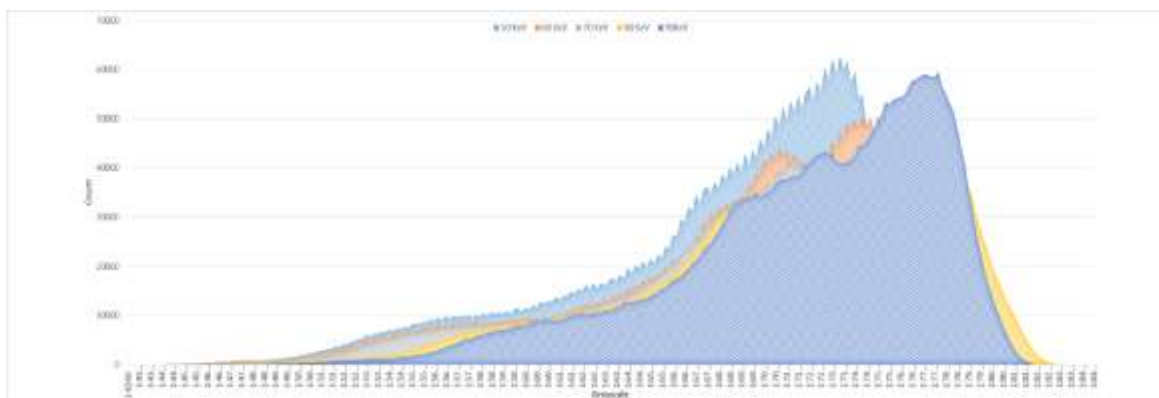
50kv	60kv	70kv	80kv	90kv	100kv
					



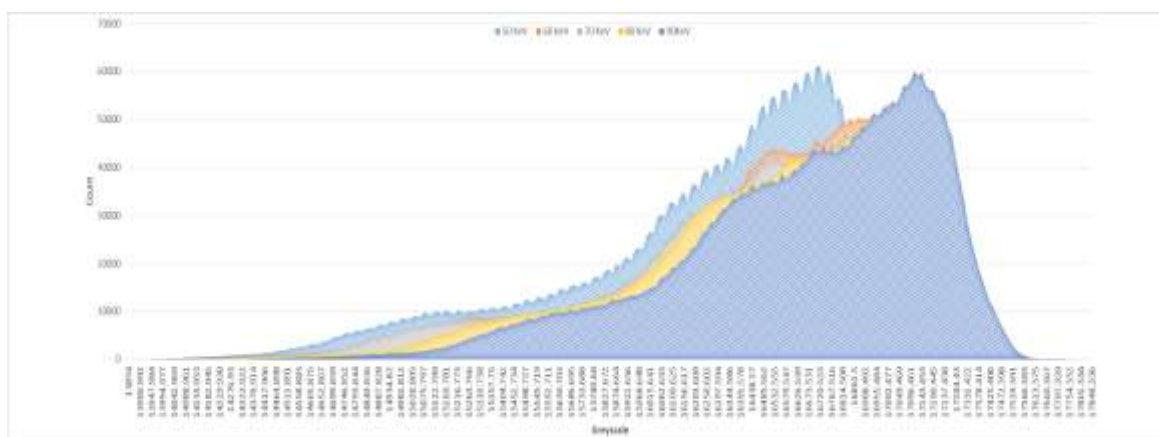
1mm Histogram



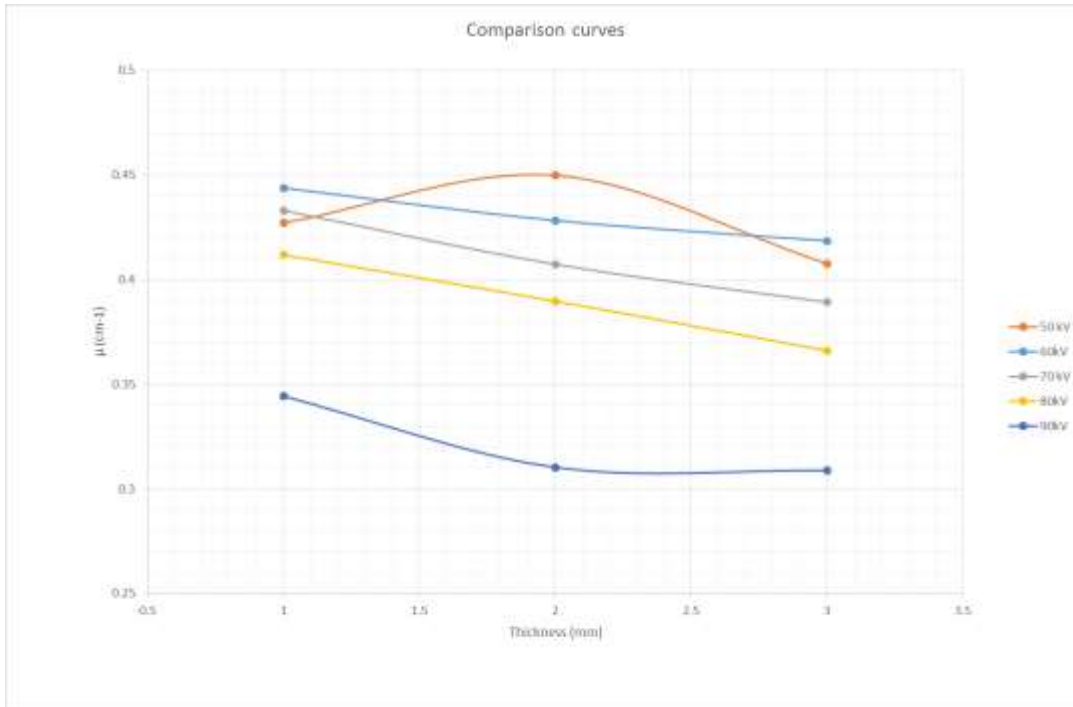
2mm Histogram



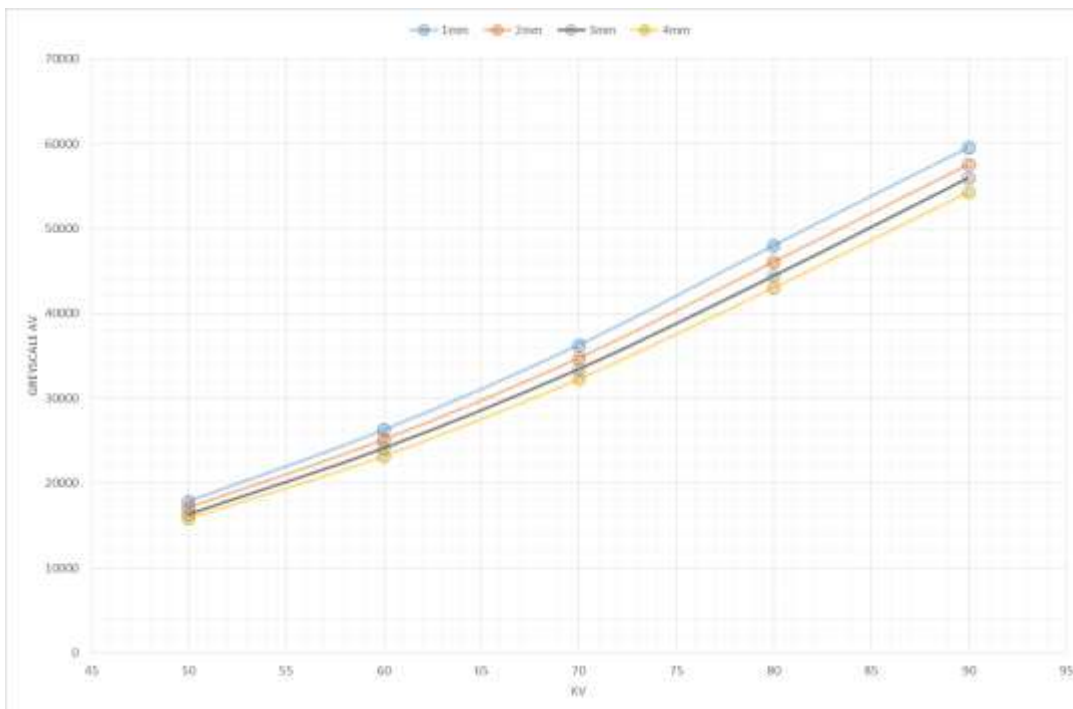
3mm Histogram



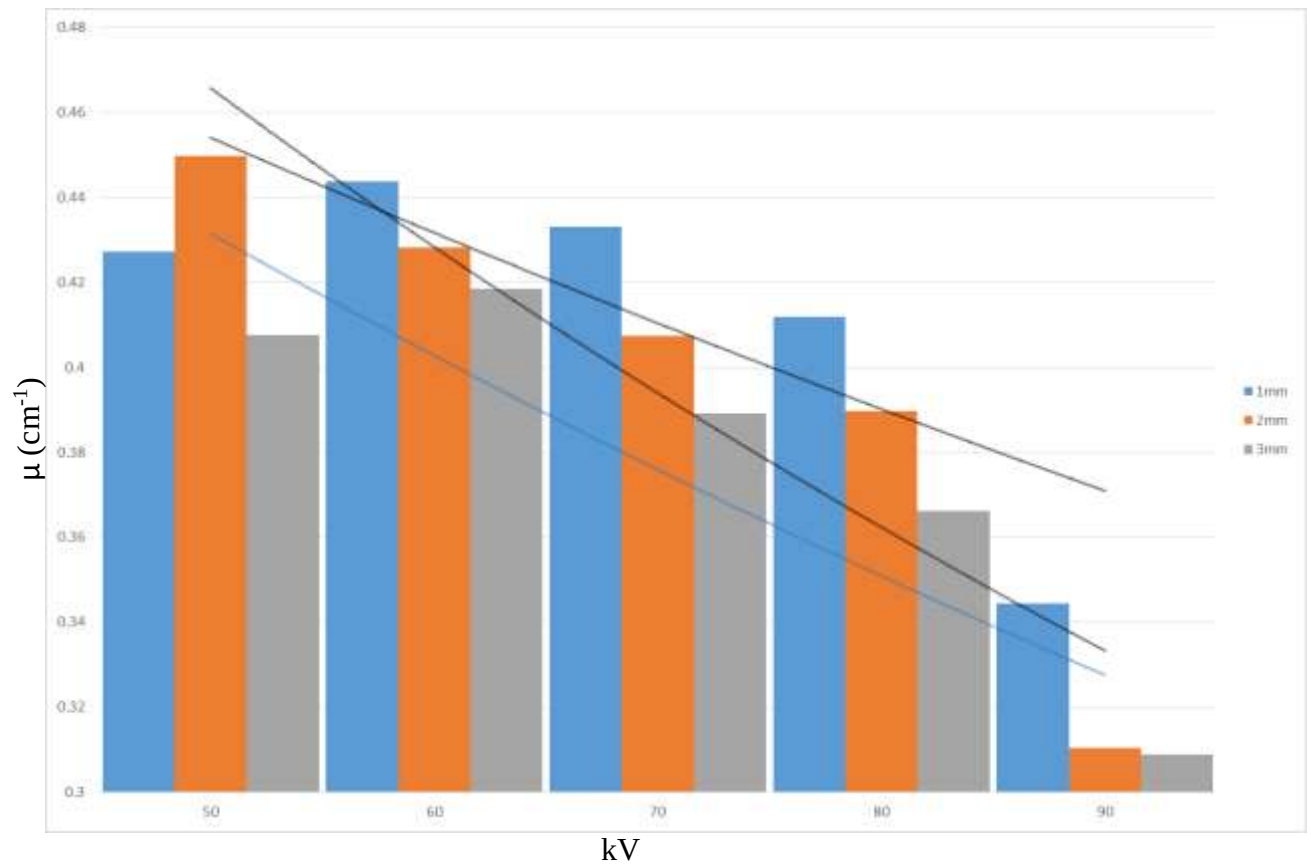
4mm Histogram



Attenuation decay over thickness



Greyscale Average over increasing kV



Exponential Decay of linear absorption coefficient over kV

Appendix D

**Linear Attenuation Coefficients (in cm^{-1})
for a range of materials at gamma-ray
energies of 100, 200 and 500 keV.**

Absorber	100 keV	200 keV	500 keV
Air	0.000195	0.000159	0.000112
Water	0.167	0.136	0.097
Carbon	0.335	0.274	0.196
Aluminium	0.435	0.324	0.227
Iron	2.72	1.09	0.655
Copper	3.8	1.309	0.73
Lead	59.7	10.15	1.64

Results from (Nuclear Medicine, 2014) Study