X-RAY LATERAL MIGRATION RADIOGRAPHY NON DESTRUCTIVE FLAW DETECTION MEASUREMENTS AND SIMULATIONS

By

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by

Stephanie Brygoo
To my family
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A new backscatter imaging technique, called Lateral Migration Radiography (LMR), originally developed to detect plastic landmines, is now being investigated to detect sub-surfaces defects. Several studies have been done previously on the subject. The goal of this research is to confirm the previous results using an improved experimental setup, to extend the measurements to samples containing actual flaws or defects and to adapt the Monte Carlo simulations to match the actual experimental setup in order to determine limits and performance capabilities for flaw and defect detection with LMR. For the experimental setup, only one collimated detector is used to count incoming photons. Monte Carlo simulations, using this geometry, have shown a really strong dependence between the collimator length and the observed contrast. This important result has been confirmed with the experimental results. The optimal collimator length has to be found to obtain the best contrast. Furthermore, the performance of the
system depends strongly on the energy used. The optimal energy depends on the material sample and the flaw depth.

With the actual experiment setup, the LMR technique is able to point out defects smaller than 100 microns. MCNP simulations have been done to predict the smallest flaw that the LMR system should be able to detect. Ten microns flaws should be detected, but the limits of MCNP may have been reached and these results have to be used with caution.

Several industrial samples have been scanned and the system is able to detect corrosion. These results still have to be confirmed with more test samples.
Detecting flaws in concrete foundations of a building or unveiling cracks in the wing of a plane without destroying either one of them has always been a challenge for engineers and industry. To avoid damaging the samples being examined, scientists have developed various non-destructive techniques. Ultrasound techniques are the most famous, but there are other techniques like magnetic techniques or penetrating photon techniques.

One method developed at the University of Florida is based on penetrating x-ray photons. The typical energy for x-ray photon used in this kind of experiment is between 20 keV and 200 keV which is larger than the visible photon energy that is around some \( eV \). Projection Radiography is the first method developed using penetrating photons. It is based on the interaction of photons inside the material. Photons are more or less absorbed depending on the density of electrons of the tested sample. A sensitive film is placed behind the sample on the opposite side of the x-ray source and it shows variations in intensity due to density difference inside the material. A different technique, called Compton Backscattering Imaging (CBI), is based on backscattered photons. The information is not given by photons which pass through the sample like in transmission radiography, but is given by photons which are reflected back on the same side of the source. The technique developed in the Nuclear Engineering Department in the University of Florida, called Lateral Migration Radiography (LMR), is similar to the CBI
technique, but instead of counting only single backscattered photons, the LMR technique counts both single and multiple scatter photons. It selects the photons coming back. These two techniques, CBI and LMR are explained in more detail in the next two sections.

**Compton Backscattering Imaging (CBI)**

When a photon interacts with matter, three major interactions can occur: photoelectric effect, Compton scattering and pair production. In the photoelectric process, a photon undergoes an interaction with an absorber in which the photon completely disappears. In its place, an energetic photoelectron is ejected by the atom from one of its bound shells with energy equal to the energy of the incoming photon minus the electron binding energy. This phenomena is especially important for high Z material and a low energy incoming photon, energy less than 0.2 MeV.

In Compton scattering, the photon is deflected through an angle $\theta$ with respect to its original direction. The photon transfers a portion of its energy to the electron. All scattering angles are possible and the energy transferred can vary from zero to a large fraction of the photon energy. Figure 1 illustrates this interaction. The energy of the scattered photon can be found by simply using the equations for the conservation of energy and momentum.

$$h\theta' = \frac{h\nu}{1 + \frac{m_0c^2}{m_e^2}(1 - \cos(\theta))}$$

where $m_0c^2$ is the rest mass energy of the electron (0.511 MeV).
The probability of scattering in a certain direction is given by the Klein-Nishina formula.

The third major interaction, pair production, can only appear when the energy of the photon exceeds twice the rest-mass of an electron (1.02 MeV). During the interaction, the photon disappears and is replaced by an electron-positron pair. All excess energy carried in by the photon above 1.02 MeV required to create the pair goes into kinetic energy shared by the positron and the electron. The positron subsequently annihilates after slowing down and two annihilation photons are produced as secondary products of the interaction.

The CBI technique is based on backscattered photons. The x-ray emitter and the detector are both on the same side of the object. The detector senses photons coming back from the sample. These photons have interacted with the medium (Compton interaction) and are reflected back with a different energy. The energy of backscattered photons depends on the medium with which they interact. By counting the number of photons coming back information about the target can be deduced.
Most CBI systems rely on using only first scattered photons from the object to form the image. This technique has an advantage compared to transmission radiography because both sides of the object do not need to be accessed. But surface imperfections and ridges affect the CBI image quality. These features can prevent first-collided photons from reaching the detectors and lead to multiple-collision photons which now enter the detectors. Because of this obstruction and corruption, the CBI image of an object with unknown surface imperfections does not uniquely represent the surface and the regions underneath. Furthermore, slow running complex algorithms are necessary to extract useful information. Additionally, the dependence of CBI systems on first-collision backscatter photons to form images also imposes a constraint on detector size, detector collimation, and mode of detector operation.

Lateral Migration Radiography (LMR)

LMR [1] is a new form of Compton backscatter imaging (CBI) that utilizes both multiple-scatter and single-scatter photons. This modality uses the lateral transport of scattered photons in materials to form images.

LMR systems typically use two sets of detectors to form images (Figure 2). Uncollimated detectors predominantly sense first-collision photons. Collimated detectors are designed so as to predominantly sense multiple-collision photons. The uncollimated detectors primarily generate images of the surface or near surface features and the collimated detector primarily generates images of the subsurface features.
Figure 2: Typical setup for a LMR system.

Red photons are single collision photons and blue photons are multiple collisions photons. The length of the collimator is adjusted to block first collision photons from reaching the collimated detector. The contrast in the collimated detector images is due to multiple-scattered photon lateral transport that is sensitive to the electron density of the transport medium as well as the surface spatial details. This enables us to create an image of objects that contain clusters of subtle imperfections and discontinuities in electron density and identify such electron density differences. The basic principle and setup for the flaw LMR experiments is illustrated in Figure 3.
First collision photons, in red, are stopped by the collimator. Only multiple collisions photons can reach the active detector region. Therefore if an air gap is present in the target, the photons are going to stream down the gap and after further collisions they will be detected with an enhanced probability by the collimated detector.

The ideal situation for the LMR technique is to have a defect with a long dimension in the lateral direction of collimation (Figure 3).

This technique was first developed at the University of Florida to detect buried plastic land mines [2-8]. The air gaps present in the fusewells inside the mines allow for enhanced migration of the photons. After detection, this give us information about the inside of the mine. The excellent results obtained with this project suggested that this technique could be used to detect subsurface material defects. Some previous studies [9-10] on the subject have shown promising results in detecting defects and some comparisons have been made with Monte Carlo simulations. The goal of this study is to confirm the previous results using an improved experimental setup, to extend the
measurements to samples containing actual flaws or defects and to adapt the Monte Carlo simulations to match the actual experimental setup in order to determine limits and performance capabilities for flaw and defect detection with LMR.
CHAPTER 2
EXPERIMENT SETUP AND PRESENTATION OF SAMPLES

Experiment Setup

The experimental setup used to detect plastic mines was constituted of an x-ray source and several detectors, some collimated and some uncollimated, placed around the source. The experiment setup for the flaw detection project is simpler. The uncollimated detector is used to create an image of the surface irregularities. Because the surface of the samples that were used for flaw detection was flat and without irregularities, only the collimated detector was used for the experimental setup.

Geometry

Figure 4 presents a simplified setup of the experiment. All dimensions are in mm, AB=59.6, BD=44, BE(collimator length)=2.5, z(height)=54.
The dimensions shown are typical. Important distances include the source beam-to-detector distance (AB), the height of the detector above the sample, the collimator length and the height of the x-ray source above the sample. The collimator length is calculated to just block first collision photons.

The setup of the experiment is presented in Figure 5.
Figure 5: Experimental setup. A) Overall view of experimental facility; B) View of x-ray generator from bottom
Figure 5. Continued

The x-ray collimator tube enables the user to have a narrow beam focused on the sample. The size of the incident beam can be changed and so, hence, can the exposed area. This gives us the ability to modify the pixel size and, to a degree, the resolution of the image.

X-Ray Source

The x-rays are produced by a LORAD LPX200 generator. The x-ray energy and the current are adjusted with the control unit box. The x-ray energy chosen by the user
depends on the material sample. If the energy is too small, photons are stopped before the flaw and if it is too large, photons go through the sample without interacting with anything. The typical energy range that was used is between 50 and 150 kV. For aluminum, the energy used is 75 kV.

The number of photons emitted by the x-ray tube depends on the adjustable current. In most cases, as many photons as possible is desirable, but too many photons can saturate the detectors.

**Detectors**

The detectors used during the experiment are Bicron NaI scintillator detector. One is presented in Figure 6.

![Bicron NaI scintillator detector](image)

**Figure 6: Bicron NaI scintillator detector.**

The radiation entering the detector excites the NaI medium and, during the relaxation process, photons in the visible range are emitted. Those photons are collected with photoelectrodes. The signal is then amplified in a photomultiplier and a pulse is emitted.
A pulse is emitted for each radiation and a ranger card counts them. The card is set up to detect only pulses within a certain range. Small pulses correspond to background and noise radiation and large pulses to spurious high-energy radiation. So the window width is adapted to avoid these two kinds of radiations.

The high voltage applied to the detector determines the size of a pulse for a given energy. The higher the voltage is, the bigger the pulse is. Figure 7 shows the evolution of the number of detected photons as a function of the high voltage.

![HV curve with Am 241](image)

Figure 7: Number of counts as a function of the high voltage applied to the detector for an Am 241 source.

This curve was obtained using an Am 241 source. Before 550 V the amplification in the photomultiplier is not large enough and pulses are too small to be counted. Above 550 V, pulses enter the detection window. When the high voltage increases, the size of the pulses increases but the number of photons emitted is always the same. This is why the number of counts stays constant. After 850 V, the pulses are too big. They are out of
the finite window and they are no longer counted. The number of counts decreases.

Usually a semi finite window, with only a low limit, is used for these kinds of test and the number of counts does not decrease. A finite window was used here to simulate the same conditions that will be used for the LMR experiment. Above 1000 V, the voltage is so high, that a discharge occurs. Under normal conditions, the number of electrons is directly proportional to the light detected from the scintillator, i.e., proportional to the incoming radiations. Above 1000 V, electrons have so much energy that they themselves create other electrons and the signal is no longer proportional to the initial radiation. This is why the number of counts increases rapidly when the high voltage is too large. The same curve has been obtained with the x-ray generator instead of an Am 241 source. The High Voltage setting for the experiment is 800V.

If the number of incoming photons is too large, there is pulse pile up. The pulses are too close and the card cannot resolve the difference between two different pulses. So the number of counts decreases even if the amount of radiation increases. The detectors are saturating.

Moving Platform

The moving platform used is a silver Motionex positioning table, which forms the base to which the top sample table is connected. A piece of lead has been positioned on the top of the table to avoid noise-backscattered photons due to the platform.
Figure 8: X-ray collimator tube, collimated detector, and sample table.

Figure 8 is a close up of the moving platform and the detector. The detector is surrounded by lead. Only a small opening on the bottom allows photons to reach the detector.

**Image Acquisition**

The moving platform allows the user to move the sample and therefore change the exposed area of the sample. A program has been written to control the motion of the plate during an exposition. The pattern of a scan is presented in Figure 9.
The card counts the number of photons coming to the detector for a given amount of time defined by the user and then the moving platform moves to the next pixel. This is a discontinuous method. The platform stops in between each pixel. A continuous method has been investigated but the final program is not ready yet. Continuous scanning will save a lot of time.

A number of photons is attributed to each pixel and all those values are then pieced together to form the final image. It is usually displayed using either Excel or Matlab depending on what the user wants to do with it.

**Presentation of Samples**

Two kinds of samples have been used for these experiments: some samples have been manufactured with simulated flaws especially for the experiment and others come directly from industry. The positions and characteristics of the flaws are known exactly for the manufactured samples. But for the unknown samples, the focus is to find the flaws. The principal samples used for several experiments are presented in Figures 10 to 14. The other samples are presented later in the thesis as necessary.
There was also a flaw plate machined from plastic (Delrin) that has dimensions which are essentially those of aluminum flaw plate #1 shown in Figure 10.
Figure 11: Schematic of machined aluminum flaw plate #2.
Figure 12: Schematic of top piece of machined aluminum flaw plate #3 with six flaws.

Note: All dimensions in mm
Figure 13: Schematic of bottom piece of machined aluminum flaw plate #3 with six flaws.
Figure 14: Sample #8. Aluminum honeycomb panel; Figure a: view from top; Figure b: view from side. All dimensions are in mm
CHAPTER 3
MONTE CARLO SIMULATION

After deciding on the experimental setup, MCNP (Monte Carlo N Particles) simulations were performed. MCNP can help to understand the physics of the experiment and help to find the best configuration for the collimator.

The MCNP code [11] is used to simulate particle transport. Unlike deterministic methods, Monte Carlo does not try to solve an explicit equation, but rather obtains answers by simulating actual behavior of individual particles and recording some aspects of their behavior. The behavior of each particle is determined probabilistically knowing the properties of interaction of the particle with the medium.

Variance Reduction Techniques Used

To obtain good precision, the code has to be run for a large number of particles. It is easy to understand that the more particles there are, the longer the computation time will be. To reduce this time and to improve the statistics of the results, MCNP uses variance reduction techniques. These techniques reduce the computer time required to obtain results of a given precision.
The measure of efficiency is the FOM (Figure of merit):

\[ FOM \approx \frac{1}{R^2T} \]

\( R^2 \) = sample relative standard deviation of the mean

\( T \) = computer time for the calculation (in minutes)

It is desirable to have the FOM large. This will mean a smaller computer time for a given standard deviation. But the user has to be careful. Even if the FOM is large, this does not necessarily imply that the results are acceptable. The FOM is just one parameter that the user will look at when interpreting the results.

There are four different classes of variance reduction techniques: truncation methods, population control methods, modified sampling methods, and partially-deterministic methods.

**Truncation Methods**

This method is the most intuitive method. When the energy is too small (energy cutoff) or the calculation time accorded to one particle is too long (time cutoff), the particle can be "killed". The particle is not followed anymore. For this work, an energy cutoff of 0.001 MeV was used; no time cutoff was employed. You can also kill a particle when it is outside the geometry of interest.

**Population Control Method**

Population control methods use particle splitting and Russian roulette to control the number of samples taken in various regions of space.
Geometry or energy splitting with Russian roulette

During geometry definition in the MCNP input, an importance, defined by the user, is given to each cell of the defined space. When a particle reaches a region of space of “less interest”, i.e., a cell of smaller importance, the Russian roulette game is played. The particle survives with a probability that depends on the cell’s importance and if the particle survives, its weight is increased. And in the opposite situation, if a region is of higher importance, the particle is split into several particles of a smaller weight.

The second situation where these games are used is when the user wants to play with the energy. In some cases, particles are more important in some energy ranges. Particles can be split when they move up or down in energy. If they fall in a range of energy where they would have no or very few interactions with the medium, Russian roulette is played.

These two methods avoid wasting time in regions of less interest or on particles with insignificant energy.

Weight cutoff

In weight cutoff, Russian roulette is played if a particle’s weight drops below a user specified weight cutoff. The particle is either killed or its weight is increased to a user-specified level.

An often-used method to control population is also the weight window. This is a space energy dependent splitting and Russian roulette technique. This technique is not going to be explained because it was not used for the simulations, but it can be a very powerful technique.
**Modified Sampling Methods**

These methods alter the statistical sampling of a problem to increase the number of tallies per particle. For any Monte Carlo event it is possible to sample from any arbitrary distribution rather than the physical probability as long as the particle weights are then adjusted. Knowing this, sampling is done from distributions that send particles in desired directions or change the location or type of collisions. One that is used in our simulations is forced collisions.

The forced collision method is a variance reduction scheme that increases sampling of collisions in specific cells. The particle is split into collided and uncollided parts. The collided part is forced to collide inside the cell. The uncollided part exits the current cell without collision until it reaches the boundaries of the cell. Its weight is proportional to the probability of exiting without collision and is defined as follow:

\[ W = W_0 e^{-\Sigma_t d} \]

Where \( W_0 = \) current particle weight before forced collision

\( d = \) distance to cell surface in particle’s direction

\( \Sigma_t = \) macroscopic total cross section of the cell material

The collided part has a weight of \( W = W_0 (1 - e^{-\Sigma_t d}) \), which is the current particle weight multiplied by the probability of colliding in the cell.

The collision distance \( x \) is sampled as follows. If \( P(x) \) is the unconditional probability of colliding within a distance \( x \), \( P(x)/P(d) \) is the conditional probability of colliding within a distance \( x \) given that a collision will occurs within the distance \( d \). Thus
the position of the collision must be sampled on the interval 0<x<d within the cell according to ?=P(x)/P(d), where $P(x) ? 1? e^{x?}$, and ? is a random number. It gives

$$x ? \frac{1}{?} \ln(1 ? (1 ? e^{?d}))$$

Because the weight obtained is usually really small, the user has to be careful with the weight-cutoff game and all weight games in general.

This sampling method is particularly useful. Knowing what is happening inside the flaw and how particles travel after is the main interest. So this method was applied to the cells corresponding to the flaw and around the flaw.

**Partially Deterministic Methods (DXTRAN)**

These are the most complicated methods. The most famous and the one that is used is the DXTRAN sphere. This is the only method that it is going to be explained here.

DXTRAN typically is used when a small region is being inadequately sampled because particles have a very small probability of scattering toward that region. To ameliorate this situation, the user can specify in the input file a DXTRAN sphere that encloses the small region. Upon collision outside the sphere, DXTRAN creates a special “DXTRAN particle” and deterministically scatters it toward the DXTRAN sphere and deterministically transports it, without collision, to the surface of the DXTRAN sphere. The collision itself is otherwise treated normally, producing a non-DXTRAN particle that is sampled in the normal way, with no reduction in weight. However, the non-DXTRAN particle is killed if it tries to enter the DXTRAN sphere.
Input File

Geometry

The input file is divided into several parts. The first parts define the system geometry. The user defines each cell completely (position, material, importance…). Each cell is then defined by an association of plans or surfaces. The geometry used for the simulations (Figure 15) is as close as possible to the real experiment but tries to stay simple too.

![Diagram of geometry used for MCNP simulations](image)

Figure 15: Geometry used for MCNP simulations

Additional Cards

After the geometry cards, the user defines the characteristics of the source. The characteristics used here were defined in previous experiments done in the beginning of the project. The energy is set at 75 kV and the X-rays are emitted unidirectionally perpendicular to the sample surface. The materials are then specified. In our experiment,
only two materials (without counting the air) are used: aluminum and lead. The tallies (energy deposition, particle flux…) and special variance reduction techniques are then defined. As previously indicated, the only two techniques that were used are the DXTRAN sphere located around the detector and the forced collision technique applied to the cells around the flaw.

**Results**

The goal of Monte Carlo simulations was to try to better understand the physics of the problem. Two main studies have been done: influence of the collimator length and influence of the flaw height.

**Influence of the Collimator Length**

The collimator length determines the number of first scattered photons reaching the detector. The goal of the collimator is to block first scattered photons and to keep multiple scattered photons, which are more representative of subsurface defects. The number of photons detected decreases rapidly when the collimator length increases (Figure 16). The detected photon tally error for each collimator length is around 2% to 3%.
Figure 16: Number of photons detected as a function of collimator length

Figure 17 presents the evolution of the contrast as a function of the collimator length. The contrast is calculated for a flaw (3 mm deep and 2 mm height) in an aluminum plate. It is defined by the following formula:

\[ c = \frac{I_{\text{flaw}}}{I_{\text{background}}} \times 100 \]

where \( c \) is the contrast and \( I_{\text{flaw}} \) and \( I_{\text{background}} \) are the intensity of the measured signal (in our case, it is a number of photons) for the flaw and for the background, respectively. The flaw intensity signal is the number of photons detected when the source is placed above the middle of the flaw. For the background signal, the source is placed in between two flaws. This is not a perfect background. The flaws can influence the signal. For the simulations examining the influence of the distance between the sample and the detector and the ones examining the influence of the flaw size, the source is placed in the middle of the plate and all flaws are filled with
aluminum (see Appendix for input files). There is no air gap for these background simulations.

The optimal collimator length is around 2.55 cm, which is close to the analytically calculated value, 2.46 cm. The contrast error is big when the collimator length begins to be large because fewer and fewer photons are reaching the detector. Increasing the number of photons used could have reduced this error. But at the time of the experiment, the computer time required was long (2 hours) and only 8 million particles were runs for each case.

Figure 17: Contrast as a function of collimator length
Figure 18 shows the contribution of each photon collision component to the signal detected. The percentage of first scattered photons decreases when the collimator length increases. At the optimal length, 2.55 cm, the contrast is essentially due to second, third and fourth collisions photons. At around 2.3 cm, the fraction of second collision photons collected begins to decrease. The collimator begins to block an increasing fraction of second scattered photons. The fractional contribution of photons with more than two collisions increases and seems to stay roughly constant when the collimator length is larger than 2.8 cm.

Figure 18: Contribution of each category of photons (from one to six collisions) as function of the collimator length.
If, instead of changing the collimator length, the distance between the sample and the detector is changed, the problem is a little bit different. The evolution of the contrast and the contribution of each photons category are presented in Figure 19 and Figure 20.

Figure 19: Evolution of the contrast when the distance between the sample and the detector is changed.

To decrease a little the error, 16 million particles instead of 8 million were run for each case.
A small distance between the sample and the detector and a large collimator are not equivalent. Figure 19 shows that the contrast remains high when the distance between the sample and the detector decreases which should correspond to a large collimator length. But when the collimator length is increased, the contrast decreases (Figure 17). For a large collimator length (> 3 cm), photons with 2 (27 %), 3 (30 %) and 4 (22 %) collisions play an important role. When the distance between the sample and the detector is small, most of the signal is due to 3 (31 %), 2 (25 %) and 4 (24 %) collisions photons. The contribution of 2 and 4 collision photons is the same. So compared to the situation where the collimator length is changed, 4 collisions photons play a bigger role and 2 collisions photons a smaller role.
This difference observed between the two configurations (collimator or z level) is probably due to geometry. The two configurations are not equivalent. The understanding of what is happening is better when the collimator length is changed than when the z level is changed.

Influence of the Flaw Height

The flaw height is really important because if the flaw is too small, the photons are not going to be able to travel in the sample and reach the detector. The influence on the contrast is presented in Figure 21. The flaw is 3 mm deep.

Figure 21: Contrast as a function of flaw height
The contrast increases with the flaw height. The photon can travel easier if the air space is bigger. All the presented runs were done with 100 millions particles which gives a relative error around 0.88%. But the user has to be careful. The absolute error for the contrast is + or – 2 %. It is not large when the contrast is around 10%, but when the contrast is only a few %, this error can play a big part.

These simulations show us that flaws of less than 100 microns height can be seen. The actual results of the experiment confirm these simulations results. They are presented in Chapter 4.
CHAPTER 4
RESULTS

Influence of Energy and z Level

The difference between the LMR technique and the conventional CBI technique, as explained in the introduction, is that the contrast in the LMR technique is due primarily to multiple scattered photons. As many first scattered photons as possible have to be blocked. The ideal situation would be when the first interaction occurs in the flaw, then the photon travels in the flaw and is then detected coming back from the sample after a second or a third interaction. The region of first interaction is determined by the photon’s energy. The optimal energy depends on the material and the flaw’s depth. Given these parameters, the user collimates as best as she or he can. The following measurements show the influence of first the energy and then the collimation.

Energy Dependence

It is easier to see the influence of the settings when the flaw is well defined and is recognizable. The sample used is the aluminum honeycomb panel, shown in Figure 14 with a series of defects that are marked in Figure 14a. The particular spot that was scanned is a 0.5-inch debonding located inside the plate. The different scans presented below are 30x30 pixel scans using 1 mm pixel and a 2 mm beam interpolated to 200 by 200 using Matlab functions.
The 0.5 inch debonding area has been scanned for different energies of the x-ray beam. For the moment the user is the one making the decision if there is a fault or not. There is no computer decision at all. So to increase the visual contrast, the scan time can change between two pictures. Increasing the scan time increases the contrast but this also increases the overall time of the experiment. So the chosen scan time is a compromise between these two parameters (experiment time and visual contrast). The optimal energy (Figure 22 to Figure 26) is around 60-75kv for this particular sample. When the energy is too low, the photon is not able to penetrate deep enough in the material and to come back. When the energy is too high, the photon travels too far and does not come back anymore to the detector.

For each sample and each defect, there is an optimal energy, which depends on the material and the depth of the flaw.

Figure 22: 0.5 inch debond area at 30 kv for a 10 s scan time (on the left); 0.5 inch debond area at 40 kv for a 10 s scan time (on the right)
Figure 23: 0.5 inch debond area at 50 kv for a 0.4 s scan time, (on the left); 0.5 inch debon area at 60 kv for a 0.1 s scan time (on the right)

Figure 24: 0.5 inch debond area at 70 kv for a 0.1 s scan time (on the left); 0.5 inch debon area at 75 kv for a 0.1 s scan time (on the right)
Figure 25: 0.5 inch debond area at 85 kv for a 0.1 s scan time (on the left); 0.5 inch debond area at 95 kv for a 0.1 s scan time (on the right)

Figure 26: 0.5 inch debond area at 85 kv for a 0.1 s scan time (on the left); 0.5 inch debond area at 95 kv for a 0.1 s scan time (on the right)
In this first experiment the contrast is only defined visually. But it can actually be measured. The contrast is defined as:

\[
\frac{I_{\text{flaw}} - I_{\text{background}}}{I_{\text{background}}} \times 100,
\]

where \( c \) is the contrast and \( I_{\text{flaw}} \) and \( I_{\text{background}} \) are the intensity of the measured signal (in our case, it is the number of photons) for the flaw and for the background, respectively. Figure 27 presents a typical scan obtained of a plastic plate (see Figure 10 for a schematic of this plate) at 30 kV. Two lines along the sample have been done and are represented by row 1 and row 2.

![Figure 27: Scan of the middle flaw of the plastic plate at 30 kV](image-url)
The flaw appears to the left because it was not centered during the experiment. Its width on the figure (13 mm) is bigger than the actual one (10 mm). The edges of the flaw as determined by the contrast signal are not vertical and give the impression that the flaw is larger than in reality. This is due to the fact that when the source is close to the edge of the flaw, the photons are still going to travel in the air gap and therefore the intensity is going to be high even if the source is not right above the flaw. The flaw, where the intensity is higher, is from pixel 5 to 17. I_{flaw} is an average of the intensity from pixel 5 to 17 and I_{background} is an average of the rest of the pixels. Using those values, the contrast is 9.84%.

Figure 28 presents the evolution of the contrast in the plastic plate for the middle flaw (2 mm height, 5 mm deep and 10 mm width) for different energies. The contrast increases when the energy decreases. When the energy is too big, the photons are going through the sample without even stopping in the plate and, therefore, decreasing the contrast. For plastic, the optimal energy is around 25 kv. More experiments would have been necessary to show that the contrast begins to decrease after a given energy. But after 25 kV, the number of photons coming back is really small and to have significant results, the time required to scan is too big.
Figure 28: Plastic plate: contrast as a function of the x-ray beam energy

Figure 29 presents a scan done along the 3 flaws of the aluminum plate at 75 kV. The depth of each flaw decreases from left to right. The contrast for the first flaw on the left, the deepest at 7 mm, is 8.82%. For the second flaw at a 5 mm depth, the contrast is 15.54% and for the last flaw at a 3 mm depth the contrast is 27.05%.
Figure 29: Scan of three flaws at different depths in the aluminum plate.

So for a given energy, here 75kV, the contrast changes with the flaw’s depth. The 75kV photons are not able to go deep enough and give as good a contrast for the deepest flaw as for the shallower flaws.

**Z Dependence or Influence of the Collimator Length**

After setting the energy, a crucial part is to determine the collimator length to block the first scatter photons. Z represents the distance between the top of the sample and the bottom of the detector (see Figure 4 in Chapter 2). It was easier during the experiment to change the z level instead of the collimator length. The result is similar but not exactly the same as MCNP simulations show (Figure 17 and 19). The optimal distance, in theory, is the distance where only first photons are blocked. If z is too large, more photons reach the detector and especially more first collisions photons. It is usually
better to over collimate a little, but if z is too small, the collimation can be too large and only multiple collisions photons are going to reach the detector and the intensity of the signal is going to be really low. So the best solution between a large collimation to avoid first collision photons and a collimation too large when not enough photons reach the detector has to be found.

Figures 30 to 33 present scans of the 0.5” debond region for different z levels. The energy is set to 75kv and the scan time to 0.1 s. The colorbar on the right of the image represents the number of detected photons.

Figure 30: 0.5 inch debond area with z=80 mm (on the left); 0.5 inch debon area with z=85 mm (on the right)
Figure 31: 0.5 inch debond area with $z=87$ mm (on the left); 0.5 inch debon area with $z=90$ mm (on the right)

Figure 32: 0.5 inch debond area with $z=93$ mm (on the left); 0.5 inch debon area with $z=95$ mm (on the right)
The optimal $z$ level is around 90 mm. When $z$ is big enough, the image does not change any more. There is essentially no collimation of scattered photons and increasing $z$ is not going to change anything anymore. When $z$ is less than 90 mm, the image is blurrier. The collimation begins to be too large. The $z$ value used in this experiment is not around 50-60 mm as shown in Figure 4, but generally much larger.

The same study has been done with the aluminum plate shown in Figure 17 in Chapter 3. The results are presented in Figure 34. The contrast increases when the collimator length decreases ($z$ level increases). At low $z$, not enough photons are reaching the detector because the collimation is too great. The optimal value appears to be 59 mm, but according to MCNP results (Figure 20), at 59 mm, about 30% of the signal is due to first collisions photons. So in theory this should not be the optimal value. Because of the geometry, it is difficult to explain what is happening. Then after 59 mm, the contrast decreases. Too many first scattered photons (> 30%) are reaching the detector. For large
collimation, the contrast seems to be constant. When the z level is small, the contrast is only due to photons with at least two collisions. The contrast decreases, but not as fast as it can decrease when the z level is too large (too many first scattered photons).

Figure 34: Contrast of a 2 mm thick and 5 mm deep flaw in an aluminum plate as a function of z level

Similar results to the one predicted by the Monte Carlo simulations are obtained. A comparison is presented in Figure 35.
Figure 35: Comparison between the experiment and the MCNP simulations

The general shape of the two curves is the same: the contrast remains high when the distance between the sample and the detector is small. The MCNP simulations show a better contrast than the actual experiment. This is due to the fact that MCNP is ideal. There is no background radiation. Furthermore, the geometry used in the simulations is not the exact same as the geometry in the experiment. This can explain the difference between the results.
Resolution

The resolution is determined, in a large sense, by the choice of the pixel size and the beam size. This can be the limiting factor for really small flaws. The original figures are 30 by 30 pixels and they are interpolated to 200 by 200 pixels using Matlab. Interpolating the images adds an error so the user has to be careful when interpreting them. Figures 36 to 38 show several combinations of pixel size and beam size.

Figure 36: 0.5 inch debond area: on the left a 1 mm pixel size and a 1 mm beam diameter and on the right a 1 mm pixel size and a 2 mm beam diameter.
Figure 37: 0.5 inch debond area: on the left a 1 mm pixel size and a 3 mm beam diameter and on the right a 2 mm pixel size and a 2 mm beam diameter.

Figure 38: 0.5 inch debond area: on the left a 2 mm pixel size and a 3 mm beam diameter and on the right a 3 mm pixel size and a 3 mm beam diameter.
The interpolated image 1 mm pixel and 1 mm beam is too far from the real image. The best combination appears to be a 1 mm pixel size with a 2 mm beam diameter. The honeycomb structure of the plate and the debond appear perfectly. The smallest beam diameter is 1mm. Using a beam smaller than 2 mm has always been difficult because it greatly reduces the number of photons emitted and therefore increases the time needed for the scan. For this sample plate, a 2 mm beam is small enough. This gives good contrast.

**Orientation**

The orientation of the flaw is really important when the user is going to analyze the image. Figures 39 to 41 present three different orientations: parallel to the direction of the detector, perpendicular, and at a 45 degree angle. When the flaw is parallel to the detector, the intensity of each side of the flaw is the same. The flaw appears on the right side because it was not centered during the experiment. When the flaw is perpendicular to the detector, the intensity is low on the detector side of the flaw. The intensity is high on the flaw and on the other side of the flaw, the side far from the detector, the intensity is somewhat reduced but not as low as the first side. When an angle exits between the flaw and the detector, a kind of shadow due to the flaw appears. Indeed depending of the position of the detector and the x-ray beam compared to the flaw, the detected photons do not take the same path.
Figure 39: Scan of a 2 mm thick flaw with the detector parallel to the flaw.
Figure 40: Scan of a 2 mm thick flaw with the detector perpendicular to the flaw.
Figure 41: Scan of a 2 mm thick flaw with the detector at a 45 degrees angle to the flaw

Direction of scan

Al frame

Flaw

X-ray beam

Detector

Al plate

number of photons detected

pixel x

pixel y

1100
1200
1300
1400
1500
1600
1700
1800
1900

1100-1200
1200-1300
1300-1400
1400-1500
1500-1600
1600-1700
1700-1800
1800-1900

1000-1100
Figure 42 presents three different positions for the detector and the x-ray beam. The distance between the x-ray beam and the detector always stays the same.

Figure 42: Three different positions for the detector compared to the flaw

In position 1, photons reaching the detector travel for the most part only in aluminum. They do not interact a lot with the flaw. Because they only travel in aluminum, a lot of them cannot reach the detector and, therefore, give a low intensity on the scan (from pixel 1 to 11 in Figure 40). In position 2, photons travel in the flaw and they do not need to travel a long path in aluminum to reach the detector. Therefore more photons are reaching the detector and the intensity is higher in this region (from pixel 12 to 17 in Figure 40). After this the intensity stays high. Indeed, in position 3, the photon has to travel in aluminum but to reach the detector it has to go through the flaw where the
mean free path is large. The intensity is of course a little less than in position 2 but it stays higher than the intensity in position 1.

The phenomena of shadow is obvious in Figure 41 when a 45 degree angle exists between the detector and the flaw. The intensity is first low (on the right in the figure), it then increases and finally decreases a little after the flaw but stays higher than before the flaw.

There is no shadow in Figure 39. The detector is parallel to the flaw. The intensity is higher when the x-ray beam is on the flaw and is lower on each side.

So depending on the orientation of the flaw, for the same flaw three different scan results can be obtained. The contrast is higher when the detector is parallel to the flaw. This is indeed the ideal situation.

**Flaws with Different Thickness**

One of the goals of the experiment was to confirm the Monte Carlo simulations concerning the thickness of the flaw that the system is able to detect.

Figure 43 presents scan results for the first two flaws of the aluminum plate containing six flaws (Figure 12 in Chapter 2). These two flaws are 0.5 mm in height and 2.5 mm deep and they clearly appear on the graph. The first flaw is 5 mm wide and the second flaw is 3 mm wide. The flaws are 20 mm apart. The scan is done for three lines, which are represented by the three series in Figure 43.
Figure 43: Flaw #1 and #2 from the six flaws aluminum plate #3.

A background slope appears on the graph. This is due to the fact that the sample was probably not perfectly horizontal during the experiment. The distance between the middle of each flaw is 25 mm, which corresponds to their separation distance. The 5 mm width flaw appears 8 mm wide and the 3 mm wide flaw appears 6 mm width. This difference is due to the fact that the flaw influences photons even if the source is not exactly above the flaw. To calculate the contrast, the slope has been removed. The background signal is an average of the number of counted photons in between the two flaws. The contrast for the largest flaw on the left is 5.3% and for the second flaw on the right it is 5.0%.

A scan of the flaw with a 5 mm width, 2.7 mm depth and with a 0.3 mm height has been done and the contrast obtained is 3.16%.
The smallest flaw is a 0.05 mm height flaw in aluminum (Figure 11 in Chapter 2). The scan result is presented in Figure 44. The scan time was 20 s and the energy of the x-ray was 75 kV.

Figure 44: Scan of a 0.05 mm height flaw in aluminum at the depth of 3 mm.

The intensity signal is an average from pixel 17 to pixel 31. The background signal is an average from pixel 1 to 15. Using these values, the contrast is 1.6%, which is pretty small. But the flaw appears definitively on the graph.

The results obtained for the various aluminum plates are summarized in Table 1.

<table>
<thead>
<tr>
<th>Flaw Width</th>
<th>Flaw Depth</th>
<th>Flaw Height</th>
<th>Number of Detected Photons</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mm</td>
<td>3 mm</td>
<td>0.05 mm</td>
<td>144000</td>
</tr>
<tr>
<td>10 mm</td>
<td>3 mm</td>
<td>0.05 mm</td>
<td>145000</td>
</tr>
<tr>
<td>10 mm</td>
<td>3 mm</td>
<td>0.05 mm</td>
<td>146000</td>
</tr>
<tr>
<td>10 mm</td>
<td>3 mm</td>
<td>0.05 mm</td>
<td>147000</td>
</tr>
<tr>
<td>10 mm</td>
<td>3 mm</td>
<td>0.05 mm</td>
<td>148000</td>
</tr>
<tr>
<td>10 mm</td>
<td>3 mm</td>
<td>0.05 mm</td>
<td>149000</td>
</tr>
<tr>
<td>10 mm</td>
<td>3 mm</td>
<td>0.05 mm</td>
<td>150000</td>
</tr>
<tr>
<td>10 mm</td>
<td>3 mm</td>
<td>0.05 mm</td>
<td>151000</td>
</tr>
<tr>
<td>10 mm</td>
<td>3 mm</td>
<td>0.05 mm</td>
<td>152000</td>
</tr>
<tr>
<td>10 mm</td>
<td>3 mm</td>
<td>0.05 mm</td>
<td>153000</td>
</tr>
</tbody>
</table>
Table 1: Contrast as a function the thickness of the flaw in an aluminum plate

<table>
<thead>
<tr>
<th>Height of the flaw (in mm)</th>
<th>2</th>
<th>0.5</th>
<th>0.3</th>
<th>0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrast (%)</td>
<td>15 (28)</td>
<td>5 (7.2)</td>
<td>3.2 (4.16)</td>
<td>1.6 (1.68)</td>
</tr>
<tr>
<td>Flaw width</td>
<td>10 mm</td>
<td>5 mm</td>
<td>5 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td>Flaw depth</td>
<td>5 mm</td>
<td>2.5 mm</td>
<td>2.7 mm</td>
<td>3 mm</td>
</tr>
</tbody>
</table>

The values indicated in parentheses are the values obtained with the Monte Carlo simulation. Monte Carlo results are always a little optimistic. Indeed as indicated before, it is a perfect situation. In reality, the background radiations are present and photons can scatter from everywhere around. But the real difference between Monte Carlo results and experimental results come from the difference in geometry and in the fact that in MCNP detectors are perfect.

These general studies on the influence of energy, geometry, beam size and pixel size, and height of the flaw have been made with samples where the flaw positions were known. More samples have been collected since the beginning of the project. The next results were obtained using those samples and show others applications of the LMR system.
Results with Industrial Samples

A lot of industrials samples have been collected since the beginning of the project. For some of them, the flaw positions were known. Most of them have been tested and the results are presented below.

All the characteristics of each scan are presented on the left of the picture. This is the same for all pictures. The first number indicated is the number of pixels for each direction (x, y, z). However, for a better visualization, the presented scans are interpolated with Matlab to 200 by 200 pixel pictures. The pixel scan time, indicated next, is the exposition time for each pixel. The detector is counting the incoming number of photons during that time.

Below this the “image data information”, containing system settings is given. The first one is the pixel size. This is the increment that the Motionex table moves between each pixel. This information gives the real dimension of the image.

The energy is the energy read on the x-ray control box. This energy defines the energy of the x-ray beam. The current is the current produced by the x-ray generator. The higher it is, the more photons are emitted.

800 Volts corresponds to the high voltage applied to the detector. It is always the same for all experiments.

The lower level of the discriminator setting (lld) for the counting system is 0.4 and the counting system window is 9.6. The lower level window setting prevents the signal from being contaminated with low energy background (noise) photons and the upper level setting, determined by the window size, eliminates contributions from spurious high energy (e.g., cosmic) radiation.
The beam hole size is the x-ray beam diameter. A little piece of lead placed at the end of the collimator tube allows us to change the diameter of the beam.

The lengths indicated next correspond to the collimator length and to the distance between the bottom of the detector and the moving table (distance z on Figure 4). The value indicated in parentheses is the relative z direction distance compared to the initial position of the table.

Figure 45 and 46 present three different scans realized on Sample #2. Sample #2 is the trailing edge of a wing with corrosion in the marked area. In the three scans, the inside structure of the wing appears clearly. Each blue spot is a hole from the honeycomb-like structure. The color blue means that less photons are reflected back. Indeed to avoid background noise from the Motionex table, a piece of lead was placed on the top of the table. Photons are trapped in the lead and they do not come back, giving less intensity in the picture in that spot. The general intensity of the picture is decreasing from left to right because the thickness of the sample is decreasing. Scan 2 is more intense (more red) because the sample is thicker at this spot compared to scan 1. Less photons are trapped in the lead. Scan 3 shows a part with a corroded portion at the top right corner of the picture. The way the scan was done, the image obtained is reversed from the reality. So the corrosion part is actually on the left side on the sample, which is confirmed in Figure 45. The difference compared to the rest of the picture is obvious.

Sample #5, shown in Figure 47, is an aircraft frame member in which there was corrosion between the aircraft skin and frame member. The areas with corrosion are clear. The corroded part is on the right in light blue on scan 1. The intensity of the corrosion part is around 1500-2000. The next scans (Figure 48) are not in the intersection
of a corroded and un-corroded part but directly in the corroded part or in the uncorroded part. The uncorroded part (scan 3) has a higher intensity (~4000) than the corroded part (scan 2, intensity ~1800) which could be expected from the first scan.

Figure 49 and 50 present another aircraft frame member with corrosion, but for this sample, the corrosion is only on one side. The first test has been done with the corrosion facing up in the direction of the x-ray beam. The difference between the “good” and the “bad” part is obvious. The un-corroded part has a higher intensity than the corroded part. The low intensity region in the upper right corner of scan 1 is due to the lead sheet under the sample. Scan 1 in Figure 50 is rotated 90 degrees clockwise relative to the area as displayed in Figure 49. The right corroded area in Figure 49 shows as the low intensity area at the bottom of scan 1 in Figure 50.

A most challenging and interesting scan is the scan presented in Figure 51. This time the scan is performed with the corroded side facing down. So the corrosion is not visible. The limit of the corrosion is less precise but the good part appears with a higher intensity than the corroded part. The low intensity region on the left side of the scan in Figure 51 is the corroded area. Because the scanning was from the reverse side, the left side in the image scan corresponds to the right side of the delimited scan zone in the photograph of the frame member in Figure 51. This scan shows the ability of the LMR system to point out regions of different compositions. But more tests should be done to confirm this result. Sample #6 was our only sample with corrosion on only one side and the result is perhaps just a coincidence.
Sample #8 has been used previously to present the energy dependence, the z-dependence and the resolution problem. Figures 52, 53, 54 and 55 shows scans of additional defects areas present in this plate. Scan 1 is the 1” area debonding. Scan 2 is the 0.5” area debonding. Scan 3 is the scan of a crushed core area. Scan 4 is the scan of a clean area and finally scan 5 is the scan of the pro film area. The honeycomb structure of the plate in all of the scans appears clearly. Each hole appears in blue in the picture, which means with a smaller intensity. Indeed photons, which are traveling inside those holes, are trapped at the bottom of the plate by the lead placed on the moving plate. The intensity decreases from left to right in scan 5. This is due to the fact that the sample was not perfectly horizontal when the scan was done.
Figure 45: Scanned Areas and Scan 1 for Sample #2

Scan 1

- # of z level: 1
- # of y pixels: 20
- # of x pixels: 20
- Pixel scan time: 0.5 s
- Pixel size: 1 mm
- 75 kv and 9 ma
- 800 Volts
- Ild: 0.4, window: 9.6
- Beam hole: 2 mm
- Length: 25 mm
- Z: 75 mm (-10)
Scan 2

# of z level  1
# of y pixels 20
# of x pixels 20
pixel scan time 0.5 s
pixel size 1 mm
75 kv and 9 ma
800 Volts
Ild 0.4  window 9.6
beam hole 2 mm
length 25 mm
z=80 mm (-5)

Scan 3

# of z level  1
# of y pixels 30
# of x pixels 30
pixel scan time 0.5 s
pixel size 1
75 kv and 9 ma
800 Volts
Ild 0.4  window 9.6
beam hole 2 mm
length 25 mm
z=80 mm (-5)

Figure 46: Scan 2 and Scan 3 for Sample # 2.
**Figure 47: Scanned Areas and Scan 1 for Sample #5**

Scan 1

- # of z level: 1
- # of y pixels: 50
- # of x pixels: 50
- Pixel scan time: 0.5 s
- Pixel size: 1 mm
- 75 kv and 9 ma
- 800 Volts
- Ild 0.4 window 9.6
- Beam hole: 2 mm
- Length: 25 mm
- z = 72 mm (-13)
Figure 48: Scan 2 and Scan 3 for Sample # 5
Figure 49: Scanned Areas for Sample # 6.
Scan 1

# of z level 1
# of y pixels 50
# of x pixels 50
pixel scan time 0.5 s
pixel size 1 mm
75 kv and 9 ma
800 Volts
lld 0.4 window 9.6
beam hole 2 mm
length 25 mm
z=65 mm (-20)

Scan 2

# of z level 1
# of y pixels 30
# of x pixels 30
pixel scan time 0.5 s
pixel size 1 mm
75 kv and 9 ma
800 Volts
lld 0.4 window 9.6
beam hole 2 mm
length 25 mm
z=65 mm (-20)

Figure 50: Scan 1 and 2 from sample #6
Sample #6 Flipped

**Settings**
- x-ray generator: 75kv 9ma
- detectors HV: 800V
- lld 0.4 window 9.6
- beam hole 2mm
- collimator length 25mm

- $z=65$ mm (-20)
- # of z level: 1
- # of y pixels: 20
- # of x pixels: 60
- scan time: 2 s
- pixel size: 2 mm

Figure 51: Reverse Side Scan of Sample #6.
Figure 52: Scanned Areas and Scan 1 for Sample #8.

Scan 1

- # of z level 1
- # of y pixels 30
- # of x pixels 40
- Pixel scan time 1 s
- Pixel size 1 mm
- 75 kv and 9 ma
- 800 Volts
- Ild 0.4 window 9.6
- Beam hole 2 mm
- Length 25 mm
- z=85 mm(0)
Scan 2

# of z level 1
# of y pixels 30
# of x pixels 30
pixel scan time 1 s
pixel size 1 mm
75 kv and 9 ma
800 Volts
ild 0.4 window 9.6
beam hole 2 mm
length 25 mm
z=85 mm(0)

Scan 3

# of z level 1
# of y pixels 30
# of x pixels 30
pixel scan time 1 s
pixel size 1 mm
75 kv and 9 ma
800 Volts
ild 0.4 window 9.6
beam hole 2 mm
length 25 mm
z=85 mm(0)

Figure 53: Scan 2 and Scan 3 for Sample #8.
Scan 4

# of z level  1
# of y pixels 20
# of x pixels 20
pixel scan time 1 s
pixel size 1 mm
75 kv and 9 ma
800 Volts
Ild 0.4  window 9.6
beam hole 2 mm
length 25 mm
z=85 mm (0)

Figure 54: Scan 4 for Sample #8.

Scan 5

# of z level  1
# of y pixels 50
# of x pixels 50
pixel scan time 0.5 s
pixel size 2 mm
75 kv and 10 ma
800 Volts
Ild 0.4  window 9.6
beam hole 2 mm
length 25 mm

Figure 55: Scan 5 for Sample #8
Present Limitations of the System

Some other samples have been tested but without giving any good results. The shapes were too complicated or information about the sample was missing to draw any conclusion. This does not mean that the system failed, but all parameters are not known yet. So for the moment only samples where the user knows exactly what is happening should be tested. After understanding simple samples, conclusions for more complicated samples can be drawn.

Figure 56 shows samples from a Pratt and Whitney turbine blade casing with a number of flaws and defects in the deposited coatings on the metal surface, as marked.

![Figure 56: Pratt and Whitney turbine blade casing pieces with defects.](image)
Figure 57 shows the result of a scan from the middle part of sample b (Figure 56). A crack is supposed to be at this spot, but it does not appear in the picture. The curve of the sample appears because of the symmetry of the lower intensity parts on the top and the bottom of the picture, but nothing else shows up. More samples need to be done at higher energies.

Figure 57: Scan of the middle part of a Pratt and Whiney turbine blade

Figure 58 shows a General Motors cast aluminum piece that has been formed with a technique that is being looked at to manufacture engine blocks. There have been problems with inhomogeneities of unknown origin in these pieces. Figure 59 and 60 shows two different scans of the upper left corner of the sample. The lack of information about the sample limits the ability to correctly interpret the image. A comparison image where there is no defect for sure should be done first.
Figure 58: General Motors cast aluminum piece.

Scan of the upper left corner

# of z level  1
# of y pixels 20
# of x pixels 20
pixel scan time 4 s

pixel size 1 mm
75 kv and 9 ma
800 Volts
lld 0.4  window 9.6
beam hole 1 mm
length 25 mm
z=72 mm (-13)

Figure 59: Scan of the upper left corner of the General Motors cast aluminum piece
More tests at higher energies should be done. Although it is aluminum, dimensions and density are not the same as for the manufactured plate (Figure 10).

The system is not perfect yet. All the results cannot be interpreted.
CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

Overview of the Results: Actual Performance of the LMR System

The capacity of the system to point out a flaw or a defect depends on different important parameters: energy, geometry (collimator length, location and orientation of the flaw, size of the flaw), resolution (beam diameter) and sample material.

The energy plays an important role because it determines the region where the photon will most probably interact. Photons that carry the most information are those that first interact inside the flaw and then travel laterally to finally be detected by the collimated detector. The optimal first interaction region is directly inside the flaw. If the photon energy is too big, the photon will travel through the flaw without seeing or interacting with it. If the energy is too small, photons are stopped before the flaw. The optimal energy depends on the material sample and the depth of the flaw. For aluminum, this energy is around 75 kv but for plastic it is around 25 kv.

The collimator length is then the second important thing that the user has to be careful with. The collimator blocks the first scattered photons from reaching the detector. As shown in MCNP simulations, the contrast is mainly due to second and third collisions photons. If the collimation is too great, not enough photons reach the detector and a decrease in contrast is observed. If the collimation is too small, too many first scattered photons are detected and this leads to a decrease in the contrast.
The orientation of the flaw determines the final aspect of the image. The same flaw scanned along different directions can give different images. Therefore the user has to be careful when interpreting these images.

The actual system has been able to detect defects smaller than 100 microns at a 3 mm depth with a 1.6 % contrast. MCNP shows that even smaller flaws should be detected. But these simulation results have to be used with caution because the limits of MCNP have maybe been reached. The previous study done on the influence of the flaw size has shown that the contrast remained constant when the flaw was smaller than hundreds of microns. The study, done in this project, shows that the contrast decreases with the flaw size which is a more intuitive result. The different results are maybe due to MCNP simulations limits. The dimensions are too small and the code is not adapted. The tally errors for the simulations were around 0.88% which gives around 1.7% error for the contrast. This error is still large. Longer simulations should be done to decrease the error to 0.3 or 0.4 % which would give a contrast error of around 0.6-0.8%.

Very encouraging results concerning the possibility of imaging corroded surfaces have been observed experimentally. The LMR system was able to detect corrosion on the reverse side of a 3 mm thick sample.

With knowledge of the dependence of the system on these parameters, an experimental procedure can be defined. The first thing to do with a sample containing unknown defects would be to find the photon mean free path using the Klein Nishina formula and the material composition. This would give the user an idea of the required energy range to use in order to find flaws at different depths. After finding the energy, the user has to find a “clean” spot that he or she can use as a reference or as a background.
The flaw or defect can be identified because a contrast appears in the signal at the flaw location compared to the signal from the rest of the sample. When the background is defined, the user can do contrast measurements. The contrast depends strongly on the collimator length. For each depth, there is an optimal collimator length. If the user has an idea of the flaw’s depth, he or she can estimate the optimum length and then find the optimal length by doing different runs around the calculated value.

**Recommendations For Future Work**

Some of the results like the ability to see corrosion are very encouraging, but they have to be confirmed with a larger number of samples. Only one sample had corrosion on one side. Corroded and composite samples should be machined and tested. The aircraft industry would be interested in these kinds of tests.

Some of the sample and especially the corroded samples are not perfectly flat. An uncollimated detector should be used to see the influence of the surface. Furthermore MCNP simulations with samples with oxide could help to understand why the variations in signal intensity.

The current experimental setup is better than the first one that was used for tests done in the beginning of the project, but improvements are still needed. The setup is optimal when the long dimension of the flaw is parallel to the detector (see Figure 38). In reality the user has no idea of the orientation of the flaw. A system configuration using four detectors around the system would allow the user to have various angles of view of the sample. Such a system has already been designed by Christopher Wells but it has not been yet been implemented.
Another problem of the actual experimental setup is the acquisition time. The time required for a regular 30 mm by 30 mm scan is between 10 minutes and one hour depending on the pixel irradiation time. The time needed for a scan can be an important decision factor for industry. Indeed if it takes 10 minutes to do a 30 mm by 30 mm square, the time needed to do an entire plane is way too long. This can be reduced by different ways. First of all larger detectors would reduce the time needed to collect a lot of photons. The larger the number of detected photons, the better the statistics are. This is really important for low energy measurements where just a few photons are actually coming back and for measurements with really small flaws where a large number of photons is required to obtain a good contrast. A second method to reduce the acquisition time is to change the scanning process. Instead of doing a step-by-step method, a continuous scan should be done. Laurent Houssay is working on a new program, which will allow the system to perform a continuous scan.

Time reductions are also needed for The Monte Carlo simulations. The time required to have an error less than 1% is between 4 and 12 hours depending on the computer. This time can be reduced with the development of a Monte Carlo code specially designed for flaw detection. MCNP is very powerful, but very general. Because the physics of the problem is now better understood, calculation time can be concentrated on specific regions of the system. The general idea behind a new code will stay the same as for MCNP, which calculates the track of each particle. But, for example, because the tracked particles and their energy are now well known, more efficient rejection techniques can be developed. Furthermore, a new code should allow the user to extract as much information as he wants, like the position and energy of each particle coming out of
the sample. Laurent Houssay is working on the development of a specific Monte Carlo code for the LMR flaw detection system.
APPENDIX A
MCNP INPUT FOR THE BACKGROUND SIGNAL

C     2 CM X 2 CM X 2 CM FLAT COLLIMATED DETECTOR
1    1 -7.34E-4 -44 45 -66 65 -4 3 70 IMP:P=1 $AIR ABOVE DETECT
10   1 -7.34E-4 -43 44 65 -66 16 -4 IMP:P=1 $AIR FRONTOF DETECT
11   1 -7.34E-4 -31 39 51 -65 16 -5 IMP:P=1 $AIR LEFT OF DETECT
12   2 -3.667 -44 45 -70 IMP:P=1 $TOP COLL DETECT
13   1 -7.34E-4 -31 39 66 -62 16 -5 IMP:P=1 $AIR RGHT OF DETECT
14   1 -7.34E-4 -44 45 65 -66 16 -4 IMP:P=1 $AIR REAR OF DETECT
15   1 -7.34E-4 -44 45 65 -66 70 -3 2 IMP:P=1 $AIR BELOW DETECT
16   1 -7.34E-4 -44 45 65 -66 16 -2 IMP:P=1 $AIR BELOW DETECT
20   4 -11.35 -42 43 1 -4 65 -66 IMP:P=1 $LEAD
21   1 -7.34E-4 16 -1 65 -66 -42 43 IMP:P=1 $AIR BELOW COLL
22   1 -7.34E-4 -31 39 5 -6 51 -62 IMP:P=1 $AIR
23   3  -2.7 -45 39 2 -4 65 -66 IMP:P=1 $LEAD
24   1 -7.34E-4 16 -2 39 -45 65 -66 IMP:P=1 $AIR
30   3  -2.7 -16 23 -33 37 53 -54 IMP:P=1 $SMPL:FAR LFT SECT
31   3  -2.7 -16 17 -33 37 54 -55 IMP:P=1 $FLAW 1:AL ABOVE
32   3  -2.7 -17 18 -33 37 54 -55 IMP:P=1 $FLAW 1: AIR
33   3  -2.7 -18 23 -33 37 54 -55 IMP:P=1 $FLAW 1:AL BELOW
34   3  -2.7 -16 23 -33 37 55 -56 IMP:P=1 $SMPL:MID LFT SECT
40   3  -2.7 -16 19 -33 37 56 -57 IMP:P=1 $FLAW 2:AL ABOVE
41   3  -2.7 -19 20 -33 37 56 -57 IMP:P=1 $FLAW 2: AIR
42   3  -2.7 -20 23 -33 37 56 -57 IMP:P=1 $FLAW 2:AL BELOW
53   3  -2.7 -16 23 -33 37 57 -58 IMP:P=1 $FLAW 3:AL RGHT S
54   3  -2.7 -16 21 -33 37 58 -59 IMP:P=1 $FLAW 3:AL ABOVE
55   3  -2.7 -21 22 -33 37 58 -59 IMP:P=1 $FLAW 3: AIR
56   3  -2.7 -22 23 -33 37 58 -59 IMP:P=1 $FLAW 3:AL BELOW
57   3  -2.7 -16 23 -33 37 59 -60 IMP:P=1 $SMPL:FRNT BOT DETE
60   3  -2.7 -16 23 -31 32 51 -62 IMP:P=1 $AL FRAME::FRNT
61   3  -2.7 -16 23 -32 38 51 -52 IMP:P=1 $AL FRAME::LFT
62   3  -2.7 -16 23 -32 38 61 -62 IMP:P=1 $AL FRAME::RGHT
63   3  -2.7 -16 23 -38 39 51 -62 IMP:P=1 $AL FRAME::REAR
70   1 -7.34E-4 -16 23 -32 33 52 -61 IMP:P=1 $FRME/SMPLE GAP FR
71   1 -7.34E-4 -16 23 -33 37 52 -53 IMP:P=1 $FRME/SMPLE GAP LF
72   1 -7.34E-4 -16 23 -33 37 60 -61 IMP:P=1 $FRME/SMPLE GAP RG
73   1 -7.34E-4 -16 23 -37 38 52 -61 IMP:P=1 $FRME/SMPLE GAP RE
74   1 -7.34E-4 -23 24 -31 40 51 -62 IMP:P=1 $AIR:FRNT BOT DETE
75   1 -7.34E-4 -23 24 -40 41 51 -63 IMP:P=1 $AIR:LFT BOT DETE
76   2 -3.667 -23 24 -40 41 63 -64 IMP:P=1 $BOT UNCOLL DETECT
77   1 -7.34E-4 -23 24 -40 41 64 -62 IMP:P=1 $AIR:RGHT BOT DETE
78   1 -7.34E-4 -23 24 -41 39 51 -62 IMP:P=1 $AIR:REAR BOT DETE
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MODE  P
SDEF SUR=12 DIR=1 VEC 0 0 -1 ARA=0.785 RAD=D1 POS=5.96 0 2.0 ERG=D2
SI1  0 0.1
SI2  H 0.0 74I 0.0750
SP2  0.0 6R 0.00001 0.00020 0.00129 0.00420 0.00370
     0.00480 0.00689 0.01061 0.01451 0.01842 0.02195
     0.02495 0.02734 0.02915 0.03055 0.03145 0.03194
     0.03208 0.03195 0.03160 0.03107 0.03041 0.02965
     0.02882 0.02797 0.02708 0.02616 0.02522 0.02428
     0.02334 0.02241 0.02148 0.02058 0.01969 0.01882
     0.01797 0.01715 0.01634 0.01556 0.01480 0.01405
     0.01333 0.01263 0.01195 0.01129 0.01065 0.01003
     0.00943 0.00884 0.00827 0.00772 0.00888 0.00956
     0.00615 0.00566 0.00518 0.00472 0.00426 0.00382
     0.00339 0.00387 0.00257 0.00239 0.00167 0.00132
     0.00098 0.00065 0.00032 0.00000
M1    7000 4 8000 1 $ AIR
M2    11000 1 53000 1 $ NAI
M3    13000 1 $ AL
M4    82000 1 $ PB
F206:P 12 $ ENERGY DEPOSITION IN TOP COLL DETECTOR
F106:P 12 $ ENERGY DEP IN TOP COLL DETECT BY COLL COMPNT
FT106   INC
FU106   1 2 3 4 5 6
F101:P 70 $ CURRENT AT THE LEFT OF TOP COLL DETECT BY COLL
         COMPNT
FS101  44 -45 T
FT101   INC
FU101   1 2 3 4 5 6
C101    0 1 T
F111:P 70 $ CURRENT AT THE LEFT/BOTTOM OF TOP COLL DETECT BY
         COLL COMPNT
FS111  44 -45 3 T
FT111   INC
FU111   1 2 3 4 5 6
C111    0 1 T
F201:P 70 $ CURRENT AT THE LEFT OF TOP COLL DETECTOR
FS201  44 -45 T
C201    0 1 T
F501:P 23 $ CURRENT AT TOP OF BOTTOM UNCOLL DETECTOR
FS501  40 -41 -63 64 T
C501    0 1 T
F601:P 3 $ CURRENT MIDDLE LEFT DETECTOR
FS601  44 -45 70 T
FT601   INC
FU601  1 2 3 4 5 6
C601    0 1 T
FCL:P   0 17R 1.0 2R 0 18R
DXT:P   -3.3  0.0  6.9  2.32  2.45
E0      .01 .02 .03 .04 .05 .06 .07 .08 $ ENERGY BINS
NPS     100000000
PHYS:P  0.2
CUT:P   1.0E+16  0.001
PRINT
APPENDIX B
MCNP INPUT FOR THE FLAW SIGNAL

C 2 CM X 2 CM X 2 CM FLAT COLLIMATED DETECTOR
1 1 -7.34E-4 -44 45 -66 65 -4 3 70 IMP:P=1 $AIR ABOVE DETECT
10 1 -7.34E-4 -43 44 65 -66 16 -4 IMP:P=1 $AIR FRONT OF DETECT
11 1 -7.34E-4 -31 39 51 -65 16 -5 IMP:P=1 $AIR LEFT OF DETECT
12 2 3.667 -44 45 -70 IMP:P=1 $TOP COLL DETECT
13 1 -7.34E-4 -31 39 66 -62 16 -5 IMP:P=1 $AIR RIGHT OF DETECT
14 1 -7.34E-4 -44 45 65 -66 16 -4 IMP:P=1 $AIR REAR OF DETECT
15 1 -7.34E-4 -44 45 66 -70 -3 2 IMP:P=1 $AIR BELOW DETECT
16 1 -7.34E-4 -44 45 66 -66 16 -2 IMP:P=1 $AIR BELOW DETECT
20 4 -11.35 -42 43 1 -4 65 -66 -42 39 65 -66 4 -5 IMP:P=1 $LEAD
21 1 -7.34E-4 16 -1 65 -66 -42 43 IMP:P=1 $AIR BELOW COLL
22 1 -7.34E-4 -31 39 5 -61 62 : 42 -31 4 -5 65 -66 IMP:P=1 $AIR
23 3 -2.7 -45 39 2 -4 65 -66 IMP:P=1 $LEAD
24 1 -7.34E-4 16 -2 39 -45 65 -66 IMP:P=1 $AIR
30 3 -2.7 -16 23 -33 37 53 -54 IMP:P=1 $SMPL:FAR LFT SECT
31 3 -2.7 -16 17 -33 37 54 -55 IMP:P=1 $SFLAW 1: AL ABOVE
32 1 -7.34E-4 -17 18 -33 37 54 -55 IMP:P=1 $SFLAW 1: AIR
33 3 -2.7 -18 23 -33 37 54 -55 IMP:P=1 $SFLAW 1: AL BELOW
34 3 -2.7 -16 23 -33 37 55 -56 IMP:P=1 $SMPL:MID LFT SECT
40 3 -2.7 -16 19 -33 37 56 -57 IMP:P=1 $SFLAW 2: AL ABOVE
41 1 -7.34E-4 -19 20 -33 37 56 -57 IMP:P=1 $SFLAW 2: AIR
42 3 -2.7 -20 23 -33 37 56 -57 IMP:P=1 $SFLAW 2: AL BELOW
53 3 -2.7 -16 23 -33 37 57 -58 IMP:P=1 $SMPL: MID RGT SECT
54 3 -2.7 -16 21 -33 37 58 -59 IMP:P=1 $SFLAW 3: AL ABOVE
55 1 -7.34E-4 -21 22 -33 37 58 -59 IMP:P=1 $SFLAW 3: AIR
56 3 -2.7 -22 23 -33 37 58 -59 IMP:P=1 $SFLAW 3: AL BELOW
57 3 -2.7 -16 23 -33 37 59 -60 IMP:P=1 $SMPL: FAR RGT SECT
60 3 -2.7 -16 23 -31 32 51 -62 IMP:P=1 $AL FRAME: FRNT
61 3 -2.7 -16 23 -32 38 51 -52 IMP:P=1 $AL FRAME: LFT
62 3 -2.7 -16 23 -32 38 61 -62 IMP:P=1 $AL FRAME: RGT
63 3 -2.7 -16 23 -38 39 51 -62 IMP:P=1 $AL FRAME: REAR
70 1 -7.34E-4 -16 23 -32 33 52 -61 IMP:P=1 $FRME/SMPLE GAP FR
71 1 -7.34E-4 -16 23 -33 37 52 -53 IMP:P=1 $FRME/SMPLE GAP LF
72 1 -7.34E-4 -16 23 -33 37 60 -61 IMP:P=1 $FRME/SMPLE GAP RG
73 1 -7.34E-4 -16 23 -37 38 52 -61 IMP:P=1 $FRME/SMPLE GAP RE
74 1 -7.34E-4 -23 24 -31 40 51 -62 IMP:P=1 $AIR:FRNT BOT DETE
75 1 -7.34E-4 -23 24 -40 41 51 -63 IMP:P=1 $AIR: LFT BOT DETE
76 2 -3.667 -23 24 -40 41 63 -64 IMP:P=1 $BOT UNCOLL DETECT
77 1 -7.34E-4 -23 24 -40 41 64 -62 IMP:P=1 $AIR: RGT BOT DETE
78 1 -7.34E-4 -23 24 -41 39 51 -62 IMP:P=1 $AIR: REAR BOT DETE
99 0 6:-24;31: -39;51:62 IMP:P=0 $VOID
12 PZ  2.0
16 PZ  0.0
17 PZ  -0.1
18 PZ  -0.2
19 PZ  -0.3
20 PZ  -0.4
21 PZ  -0.5
22 PZ  -0.6
23 PZ  -2.0
24 PZ  -4.0
 1 PZ  2.9367
 2 PZ  4.8
 3 PZ  6.9
 4 PZ  9.0
 5 PZ  9.3
 6 PZ  10.0
31 PX  20.0
32 PX  10.008
33 PX  10.0
37 PX  -10.0
38 PX  -10.008
39 PX  -20.0
40 PX   6.96
41 PX   4.96
42 PX   0.0
43 PX   -0.3
44 PX   -2.0
45 PX   -4.4
46 PX   -8.6
51 PY  -20.0
52 PY  -10.008
53 PY  -10.0
54 PY   -5.0
55 PY   -4.0
56 PY   -0.5
57 PY    0.5
58 PY    4.0
59 PY    5.0
60 PY   10.0
61 PY  10.008
62 PY  20.0
63 PY  -1.0
64 PY   1.0
65 PY   -3.5
66 PY   3.5
70 C/X 0 6.9 1.5

MODE  P
SDEF  SUR=12  DIR=1  VEC 0 0 -1  ARA=0.785  RAD=D1  POS=5.96 0 2.0
ERG=D2
SI1  0 0.1
SI2  H 0.0 741 0.0750
SP2  0.0 6R 0.00001 0.00020 0.00129 0.00420 0.00370
0.00480 0.00689 0.01061 0.01451 0.01842 0.02195
0.02495 0.02734 0.02915 0.03055 0.03145 0.03194
0.03208 0.03195 0.03160 0.03107 0.03041 0.02965
0.02882 0.02797 0.02708 0.02616 0.02522 0.02428
0.02334 0.02241 0.02148 0.02058 0.01969 0.01882
0.01797 0.01715 0.01634 0.01556 0.01480 0.01405
0.01333 0.01263 0.01195 0.01129 0.01065 0.01003
0.00943 0.00884 0.00827 0.00772 0.00888 0.00956
0.00615 0.00566 0.00518 0.00472 0.00426 0.00382
0.00339 0.00387 0.00257 0.00239 0.00167 0.00132
0.00098 0.00065 0.00032 0.00000
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FU106 1 2 3 4 5 6
F101:P 70  $ CURRENT AT THE LEFT OF TOP COLL DETECT BY COLL COMPNT
FS101  44  -45  T
FT101  INC
FU101 1 2 3 4 5 6
C101  0 1 T
F111:P 70  $ CURRENT AT THE LEFT/BOTTOM OF TOP COLL DETECT BY COLL COMPNT
FS111  44  -45  3 T
FT111  INC
FU111 1 2 3 4 5 6
C111  0 1 T
F201:P 70  $ CURRENT AT THE LEFT OF TOP COLL DETECTOR
FS201  44  -45  T
C201  0 1 T
F501:P 23  $ CURRENT AT TOP OF BOTTOM UNCOLL DETECTOR
FS501  40  -41  -63  64  T
C501  0 1 T
F601:P 3  $ CURRENT MIDDLE LEFT DETECTOR
FS601 44 -45 70 T
FT601 INC
FU601 1 2 3 4 5 6
C601 0 1 T
FCL:P 0 17R 1.0 2R 0 18R
DXT:P -3.3 0.0 6.9 2.32 2.45
E0 .01 .02 .03 .04 .05 .06 .07 .08 $ ENERGY BINS
NPS 100000000
PHYS:P 0.2
CUT:P 1.0E+16 0.001
PRINT
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Stephanie Bryggo was born in 1978. She graduated from the pre-engineering school, Hoche High School, in France in 1998 and entered the National School For Physics in Grenoble (ENSPG). The ENSPG is one of the nine engineering schools of the National Polytechnic Institute of Grenoble (INPG). In 2000, she came to the University of Florida in the Nuclear and Radiological Departement as part of an agreement while finishing her degree requirement; she obtained her French engineer diploma in Summer 2001. Since then, she has been pursuing a Master of Science in engineering physics while working as a research assistant under the supervision of Dr. Dugan and Dr. Jacobs.