

# Adjustable Anti-Scatter Grid System for Mammography Tomosynthesis Final Report

**Client:**



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Dear Dr. Labossiere,

We are pleased to submit our final design report. This report has been prepared in accordance to the guidelines outlines in MECH 4860 Engineering Design.

Thirteen Engineering Co. has been tasked with a design problem from CancerCare Manitoba on designing an anti-scatter grid that can be used in conjunction with a mammography tomosynthesis machine. This report details an outline of x-ray tomosynthesis and anti-scatter grids, the project objectives and a detailed design of two previously selected concepts.

After performing a detailed design and analysis of each concept, it was determined that the adjustable septa design exceled in the areas of sweep angle, number of images per sweep and time to complete a sweep. It is recommended that CancerCare further develops the adjustable septa concept using x-ray modeling and prototyping to better determine the required x-ray dosage, reliability and costs associated with the adjustable septa design.

We would like to thank our advisor Dr. ElMekkawy for the guidance he has offered us on the project and we would also like to thank CancerCare Manitoba and Harry Ingleby for giving us this opportunity for such a fulfilling project that may one day lead to further developments in breast cancer detection.

Yours sincerely,

Graeme Crawford

Nathan Dueck

Jordan Bull

Brian Kirkbride-Taylor

## Abstract

Thirteen Engineering Co. (TEC) was tasked with developing a concept for an anti-scatter grid system that is compatible with mammography tomosynthesis machines, for Cancer Care Manitoba (CCM).

In the initial phases of the project, 16 concepts were generated. This was then narrowed down to the four most promising designs, from which two concepts were chosen to be developed further. The two designs chosen are the adjustable septa, and the multiple grid changer designs. In the adjustable septa concept the x-ray absorbing septa are redesigned so that they can be rotated. These septa can then be moved to the desired angle for each image along the tomosynthesis sweep. The second concept is the multiple grid changer. In this design multiple anti-scatter grids with differing set septa angles are used. These grids are stored in a grid rack and then individually moved into the imaging position, as needed for the sweep. After an image is taken the anti-scatter grid is retracted and the next grid is then placed for imaging. To save space the grids are rotated half way through an imaging sweep and then reused. In this report these two designs are developed further and their performance is compared against a previously selected set of criteria.

It was found that the adjustable septa design had superior performance in the sweep angle, number of images per sweep, reliability and sweep completion time categories. The grid changer was better in the minimizing radiation dosage exposure category and both designs had a similar source to image distance. Due to the proprietary nature of tomosynthesis mammography machines, it was not possible to obtain dimensions for an existing device, because of this it was not possible to evaluate the designs based on device size.

When both designs were compared to the project objectives, the adjustable septa designs' performance exceeded the performance of the multiple grid changer design in many of the design criteria. Thirteen Engineering Co. recommends that CancerCare Manitoba should further develop the adjustable septa design. Further development in the areas of computer x-ray modelling and production of prototypes to properly establish the adjustable septa designs x-ray absorption properties, reliability, and manufacturing costs.

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## Glossary

- 1) **Septa:** The attenuating strips in an anti-scatter grid [1].
- 2) **Grid Ratio:** The ratio of anti-scatter grid height to the distance between each septa.
- 3) **Source to Image Distance (SID):** The distance from the x-ray tube to the image detector.
- 4) **Attenuation:** A materials ability to absorb photons instead of letting them pass through unaffected.
- 5) **Sensitivity:** Ratio of correctly diagnosed positives to total positives.
- 6) **Specificity:** Ratio of correctly diagnosed negatives to total negatives.
- 7) **Breast Table:** The table that the breast rests on and contains the anti-scatter grid and detector.



# **1. Introduction**

CancerCare Manitoba (CCM) is tasked, through provincial legislation, with the responsibility of helping Manitobans deal with cancer. This task is accomplished through promoting cancer prevention, providing early detection and care, performing research and educating Manitobans. CCM performs clinical care and research out of multiple sites in Winnipeg and throughout the rest of Manitoba.

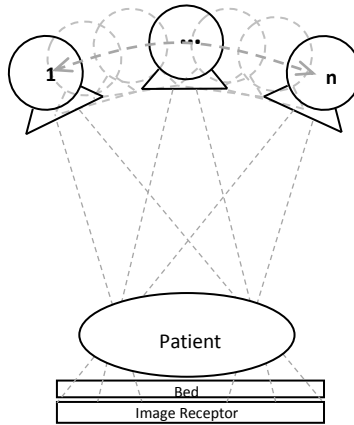
Breast cancer screening in Manitoba, is carried out mainly through x-ray mammography. The effectiveness of breast cancer screening is derived from the sensitivity and specificity of the device used. The sensitivity and specificity values vary from 70-90% and 90-98% respectively [2]. Although these numbers are good, misdiagnoses in the form of false positives and false negatives can put added emotional stress on patients and families. It is also estimated that misdiagnoses make up one third of total breast cancer screening costs. The emotional trauma and the cost associated with misdiagnoses are the two main reasons that further developments in the field are currently being pursued.

## **1.1 Problem Statement & Background**

Thirteen Engineering Co. (TEC) has been tasked with the development of a system that enables the use of anti-scatter grids with mammography tomosynthesis. Since the design will involve modifying the current technologies of anti-scatter grids and tomosynthesis machines, a brief overview of both technologies is provided in the following sections.

### **1.1.1 X-Ray Tomosynthesis**

In x-ray tomosynthesis, numerous x-rays are taken in a shallow arc above the patient, as shown in Fig. 1, and are then combined using computer software. The computer processing yields a series of two-dimensional slices, each at a different depth within the body, which can be individually examined.

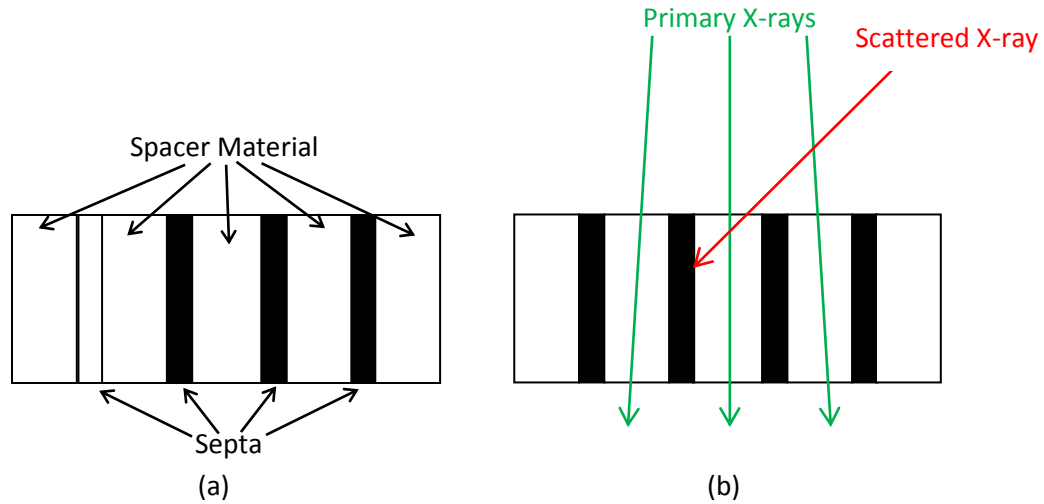


**Figure 1. Tomosynthesis sweep [3].**

Use of x-ray tomosynthesis for breast cancer screening is slowly replacing traditional single x-ray mammography. The ability to examine individual slices at varying depths leads to increased diagnostic accuracy over standard single shot x-rays [4]. Mammography tomosynthesis is not currently used in Manitoba; however, the CCM is exploring the possibility of using this technology in the future [5].

### **1.1.2 Anti-scatter Grids**

Anti-scatter grids improve x-ray image quality by reducing the amount of scattered x-rays that reach the detector. There are four forms of scatter, although in diagnostic x-ray imaging the dominant form is Compton scattering [6]. This form of scatter occurs when a high-energy photon from an x-ray collides with an electron, which causes the electron to be ejected from its orbit and the photon to be deflected from its original trajectory. This collision usually happens as the x-ray passes through the body or the x-ray table, as the probability is much higher than when the x-ray is travelling through the air. This deflected photon continues on its new trajectory and strikes the detector at an incorrect location. Therefore the image quality is affected because the detector is unable to distinguish scattered photons from non-scattered photons. The solution to this problem is anti-scatter grids, which are made of alternating thin vertical strips of lead, called septa, and a non-x-ray absorbing spacer material, as shown in Fig. 2a [7]. The septa are aligned with the primary x-ray path, allowing the primary x-rays pass through to the detector while the scattered x-rays are absorbed, as shown in Fig. 2b.



**Figure 2. a) Spacer material and septa within anti-scatter grid [3].**

**b) Primary and scattered x-rays [3].**

By reducing the amount of scatter that reaches the detector, the image quality is improved [7]. Nevertheless, when an anti-scatter grid is used, some of the primary x-rays are absorbed by the septa and because of this, the power of the x-ray needs to be increased. This increase leads to a radiation dosage increase to the patient of two to five times that of an x-ray in which no grid is used [1]. This creates a tradeoff between improved image quality and limiting the dose of radiation received by the patient.

## 1.2 Project Objectives

The goal of this project has been to design a system that will permit an anti-scatter grid to remain aligned with the x-ray source of a tomosynthesis mammography machine during a scan. The combination of these two technologies will increase image quality, which will improve doctors' abilities to properly diagnose patients, resulting in an improvement in early detection of breast cancer.

TEC met the project goal by establishing and designing to CCM's needs. The following list is CCM's primary needs, in order of importance:

1. **Radiation Dosage:** Ensure that the dosage remains within acceptable limits of anti-scatter grids currently in use.
2. **Sweep Angle:** Allow for a change in x-ray tube angle of up to +/- 25 degrees.
3. **Device Size:** Maintain similar dimensions to current breast tomosynthesis machines due to limited space between the patient and receptor.

4. **Number of Images per Sweep:** Allow for 20 images to be taken per sweep.
5. **Source to Image Distance (SID):** Maintain an SID of 0.65 m, which is the current SID of breast tomosynthesis machines.
6. **Reliability:** Capable of 1000 scans before requiring maintenance.
7. **Time to Complete Sweep:** Complete the tomosynthesis sweep in less than 60 seconds.
8. **Cost:** Must not exceed \$15,000.

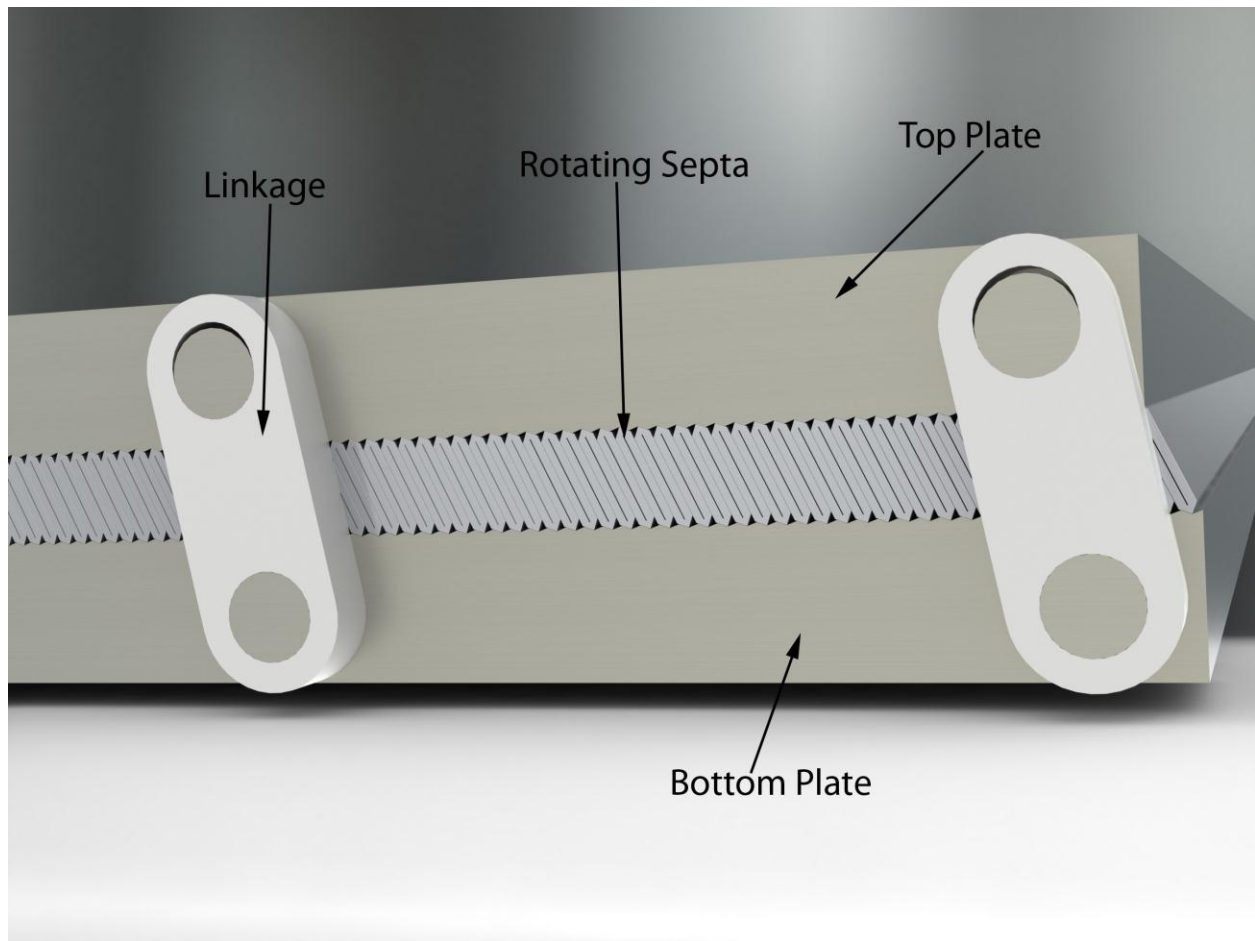
Consideration has also been given to the patients of the proposed system. The patients will be women 50 years of age and older, who are being screened for breast cancer. Due to the devastating possibility of potentially having breast cancer, having a breast exam can be emotional. To ensure that women feel comfortable when receiving their scans, the device must not negatively impact how women interact with the machine. The machine must be as accurate as possible. A better performing machine can directly translate into extended lives and or improving quality of life. As well, false positive exams must be minimized for obvious emotional reasons. These user issues have also been a main objective for TEC.

## **2. Detail of the Designs**

In order to generate optimal designs that meet the project objectives, TEC went through a rigorous concept generation and selection process. The process, summarized in Appendix A, involved a brainstorming session, concept screening phase, concept synthesis phase, concept selection phase, and sensitivity analysis. This process yielded four concepts, of which CCM selected two for TEC to pursue further. The two concepts chosen by CCM were the adjustable septa and the multiple grid changer. The details of both designs are summarized below.

### **2.1 Adjustable Septa**

The first concept that was chosen to be further developed by TEC is the adjustable septa. This design is based on changing the angles of the lead septa to correspond with the changing angles of the x-ray source in a tomosynthesis sweep. Changing the angle of the septa in the anti-scatter grid will allow the primary x-rays, at each image position, to pass through the grid to the detector, while at the same time, absorbing the scattered x-rays. The following sections will discuss all major components of the design, a process flow diagram, time considerations and a bill of materials and cost analysis.



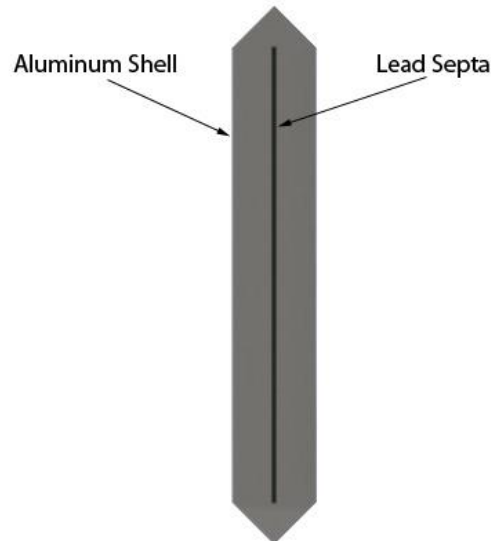
**Figure 3. Adjustable septa design overview.**

This design consists of four main components including the rotating septa, top and bottom plates, linkages, and mechanical actuators. The angles of the septa are changed by the use of an actuator to push or pull the top plate, which in turn rotates all of the septa simultaneously.

### **2.1.1 Rotating Septa**

In a standard anti-scatter grid, the septa are made of a lead foil and are used to absorb the scattered x-rays while allowing the desired x-rays to pass between the septa and reach the detector. In this adjustable septa design, the septa use a lead foil strip, of the same dimensions to maintain the same level of scatter absorption as a standard grid. However, in this new grid design, the angle of the septa needs to be adjustable in order to track the moving x-ray source. In order to achieve this, the interstitial material supporting the septa needs to move as well. Because of this, it was decided to surround each

lead septa with an aluminum shell to provide support and to help transfer the motion when the septa angle is being adjusted. An image of this combined aluminum and lead septa is shown in Fig. 4.



**Figure 4. Front view of single rotating septa.**

The aluminum shells are 0.135 mm thick on either side of the lead foil core. By keeping the septa spacing and the height of the lead strips the same as standard in grids, the final grid ratio remains the same when the septa are perpendicular to the bottom plate. As the septa are moved, the distance between each lead strip does change which causes the grid ratio to change slightly. However, the grid ratio at any septa position remains close to the desired ratio. When each of the septa shells are set to the maximum angle of 25 degrees, the sides of the septa will be touching the sides of the two surrounding septa shells. However, the contact between two moving aluminum surfaces introduces the possibility of wear in the septa as they are adjusted. To avoid this problem, the aluminum shells should be coated with Teflon, which will reduce the wear that occurs between the surfaces. In Fig. 4 it can be seen that the top and bottom of each septa ends with a pointed chamfer. This chamfer sits in a groove that is cut into the top and bottom plates. Doing this helps keep the septa in position and allows them to rotate as the top plate is moved.

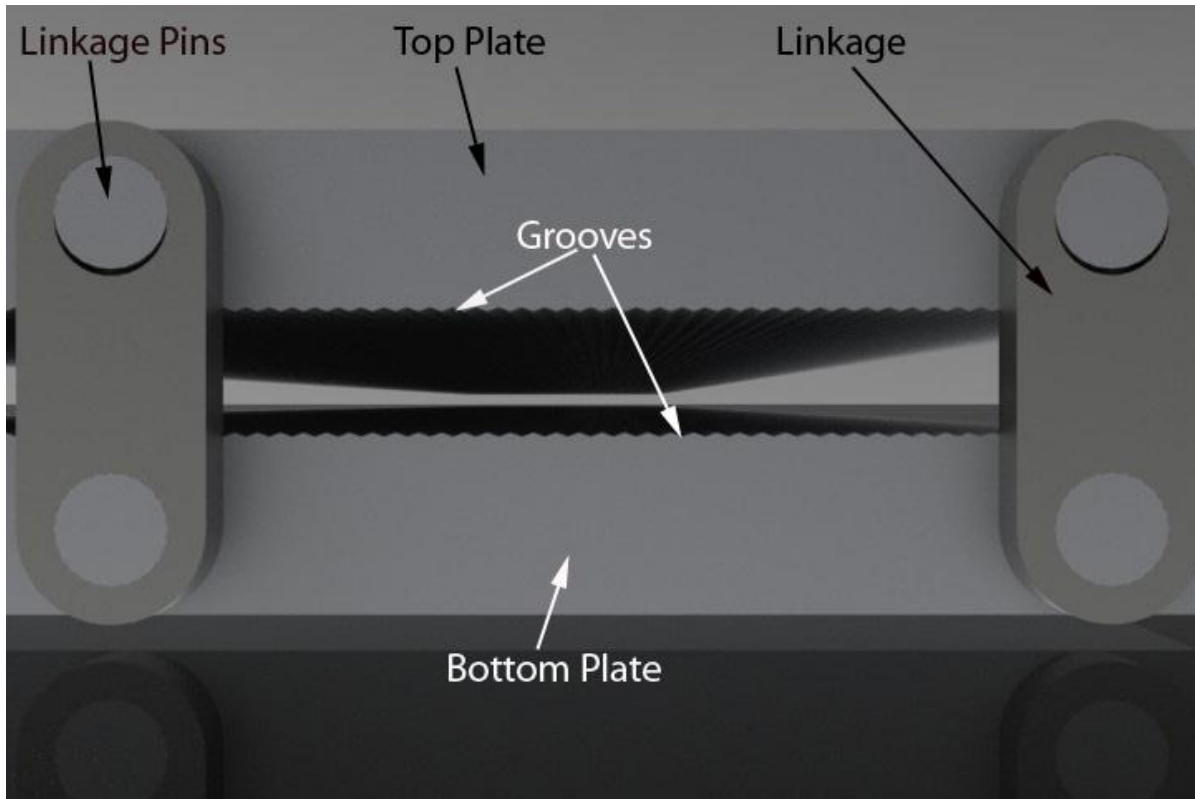
Each of the septa assemblies will have a height of 1.8 mm, a width of 0.286 mm and a length of 240 mm in order to maintain the dimensions of a standard grid. The use of aluminum in the construction of the outer shells was chosen for two reasons. The first reason is because aluminum is used in older grid

designs and is known to have a low x-ray attenuation level that still allows x-rays of the desired energy levels to pass through to the detector. The second reason is because aluminum is a material that can be worked easily. Each adjustable grid requires 1000 of these adjustable septa, which means that these septa need to be manufactured in a repeatable, consistent way. One method to achieve this would be to surround a bar of lead with aluminum and bond them together with a thin film adhesive. This lead and aluminum block could then be rolled to the desired thickness, and the top and bottom chamfer features could also be rolled during this process. The rolled septa can then be cut to the required length and installed in the bottom plate.

### **2.1.2 Top and Bottom Plates**

The purpose of the top and bottom plates is to hold each of the adjustable septa in position as the grid is being adjusted. These plates are made of aluminum and are 2.5 mm thick, 240 mm wide and 300 mm long. Due to time constraints, x-ray modeling could not be performed on the overall design to determine if the extra thickness added by these plates will absorb too much of the x-rays when compared to standard grid designs. If the plates do absorb too much of the x-rays then the energy of the x-rays may need to be increased to compensate for the loss, which would result in an increase in radiation dosage received by the patient. One way to decrease the x-ray absorption of the top and bottom plates would be to use a material with lower x-ray attenuation than aluminum. One possible alternative is carbon fiber since it is already used in the construction of some anti-scatter grids. On the top face of the bottom plate, triangular grooves with a width of 0.300 mm and a depth of 0.055 mm are cut along the width of the plate, with a spacing of 0.316 mm between the centers of each groove. There are a thousand grooves spread across the entire plate, one for each septa. The bottom edge of each septa is to sit in this groove which will help to hold them in position. The top plate has the same grooves cut into its bottom side and is placed on top of the adjustable septa once they are all placed on the bottom plate. Together, the top and bottom plates will hold each of the septa in place during movement and when the grid is stationary. An image of the top and bottom plates with the grooves cut can be found in Fig. 5.





**Figure 5. Top and bottom plates without rotating septa.**

To ensure that the plates remain aligned and do not put too much weight on the adjustable septa, linkages connect the two plates at regular intervals. The linkages are attached to the top and bottom plate using pins with a spacing of 15 mm between each pin.

### **2.1.3 Actuation**

The adjustable septa design is based on changing the angle of the septa for each x-ray exposure along the tomosynthesis sweep. In order to change the angle of the septa for each exposure, the top plate of the anti-scatter grid must be linearly displaced. This linear displacement will be transformed into a change in angle of the septa. For the adjustable septa design, the total range of motion of the septa to meet the sweep angle project objective of  $-25^\circ$  to  $+25^\circ$ , requires a linear displacement of  $1520\ \mu\text{m}$ . Due to the micro scale of the septa, a linear actuator must be able to provide very precise movements in order to slightly change the angle of the septa for each image. An actuator type that is capable of these precise movements is known as a piezo linear actuator [8]. Piezo actuators are known for their fast motion and very high precision. Both of these traits will help the design meet the project objectives of 20 images per sweep and completing the sweep in less than 60 seconds.

Piezo actuators have a limited range of travel, thus finding an actuator that is capable of a linear displacement of 1520  $\mu\text{m}$  proved to be difficult [9]. The longest linear displacement for a piezo actuator was found to be 1000 $\mu\text{m}$ . Therefore, in order for the grid to be able to travel along its full range of motion, the point of force application must be moved from the top plate to a lower point on the grid. The maximum height of force application was calculated to be 1072  $\mu\text{m}$  from the bottom plate.

An appropriate piezo actuator for our application is a P-602.8 PiezoMove Flexure Actuator manufactured by Physik Instrumente (PI). The device specifications are shown in Table I.

**TABLE I**  
**PIEZOMOVE SPECIFICATIONS [8]**

Type	Dimensions (mm)	Mass (kg)	Length of Travel ( $\mu\text{m}$ )	Push/Pull Force (N)	Voltage Range (V)
PiezoMove	126x34x14	0.355	1000	400	20 to 120

One of these piezo actuators would be suitable to move the septa into position for each grid angle throughout the tomosynthesis sweep. The actuation necessary to complete a tomosynthesis sweep is further discussed in the following section.

#### 2.1.4 Process Flow

A process flow diagram illustrates all of the tasks that need to be completed for each of the tomosynthesis processes. For the adjustable septa concept, the process flow diagram, shown in Fig. 6, clearly displays all of the steps that the adjustable anti-scatter grid must perform in order to complete one tomosynthesis sweep.

The process begins with the operator selecting a tomosynthesis scan and the number of images per sweep ( $n$ ), which can be adjusted to meet the desired scan results. Once the number of images per sweep has been determined, the computer can calculate each angle that the septa must be at for each exposure and then match the speed of the septa rotation to the speed of the x-ray source. Once these operations are complete, the adjustable grid system waits for the operators input to begin the tomosynthesis scan. After the scan button has been pressed, the tomosynthesis scan can begin. A voltage is applied to the piezo actuator in order to move the grid to position  $i$ , where  $i=1$  for the first

position. Then, the x-ray is exposed to the patient at position 1. After the exposure is complete, the computer checks if the current grid position ( $i$ ) equals the total number of images per sweep. If not, the computer adds one to the value of  $i$  in order to iterate the process to the next step. Then the actuator proceeds to the next grid position and another exposure is taken. This process is repeated until the grid has reached the final position ( $i=n$ ). When  $i=n$ , the scan has come to completion. A prompt is then sent to the operator to determine if the procedure is complete. The operator may want to repeat the scan or take a scan from another angle. If this is the case, then the entire process can begin from the start. If not, the septa will be moved back to the start position and the machine will power down.

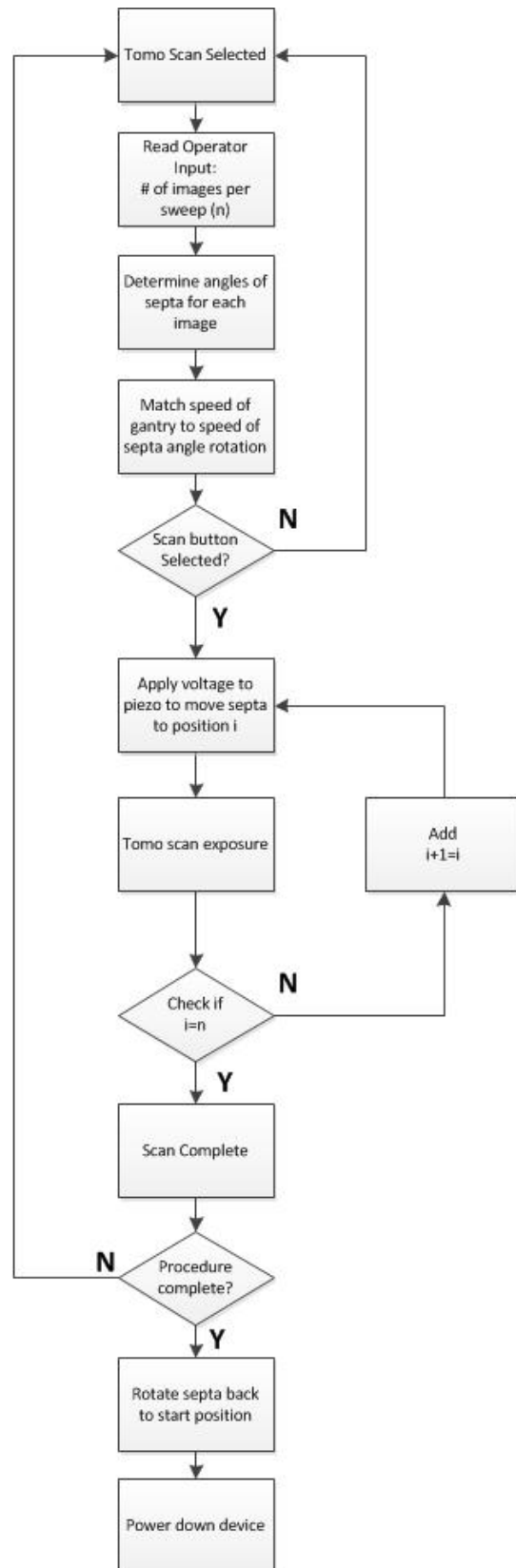


Figure 6. Adjustable septa process flow diagram.

As shown in Fig. 6, the process flow for the adjustable septa design requires an iterative process in order to complete the required number of images per sweep. The adjustable septa design incorporates the use of a computer and micro-controllers in order to align the grid with the desired angles for each image. The iterative process in the flow diagram can be completed in a very quick manner due to the speeds at which computers and micro-controllers can operate. The time considerations for the entire grid movement will be discussed in the following section.

### 2.1.5 Time Considerations

One of the main project objectives is for the anti-scatter grid to be able to achieve one complete tomosynthesis sweep in less than 60 seconds. Employing the use of piezo actuators for the adjustable septa design, helps keep the time to complete a sweep to a minimum. Piezo actuators are able to expand at a very fast rate. In general, these actuators have a minimum time to expand to the desired length that is related to the resonant frequency,  $f_o$ , of the actuator using the relationship below [10].

$$T_{min} \approx \frac{1}{3f_o}$$

For the PiezoMove Flexure Actuator that has been selected, the resonant frequency is 150 Hz [9]. Therefore, the minimum time to expand is 2.22 ms. Considering a complete tomosynthesis sweep from -25° to +25°, with 20 exposures, the total time required for the actuators to complete the motion would be 44.4 ms. Given that a current tomosynthesis sweep takes approximately 3-4 s, the speed of the septa rotation will not be a limiting factor for the time to complete a sweep. Therefore, the adjustable septa design will be capable of maintaining the time to complete a sweep of mammography tomosynthesis machines without anti-scatter grids.

### 2.1.6 Cost Analysis and Bill of Materials

The cost of the adjustable septa design comes from three main categories: material, manufacturing, and actuation system costs. The adjustable septa design does not require a large amount of material to construct and because of this the materials are the smallest portion of the overall cost. These material costs are summarized in Table II.

**TABLE II**  
**ADJUSTABLE SEPTA DESIGN RAW MATERIAL COST**

	Cost/unit	Quantity	Price
<b>3003 Sheet Aluminum [11]</b>	\$20623.29/m <sup>3</sup>	0.0003096 m <sup>3</sup>	\$ 6.38
<b>Lead [12][13]</b>	\$22339.8/ m <sup>3</sup>	5.76*10 <sup>-6</sup> m <sup>3</sup>	\$ 0.13
<b>Total</b>			\$ 6.51

In the adjustable septa design, a piezo actuator was chosen to move the septa. This works well with the design as it provides a large amount of accuracy for the very small movements required. However, a piezo actuator that is capable of the range of motion required in this design is very expensive. The total cost to use this actuation method is \$4584.00 which is the majority of the target cost. This cost is summarized in Table III.

**TABLE III**  
**ADJUSTABLE SEPTA DESIGN COMMERCIAL PARTS COST**

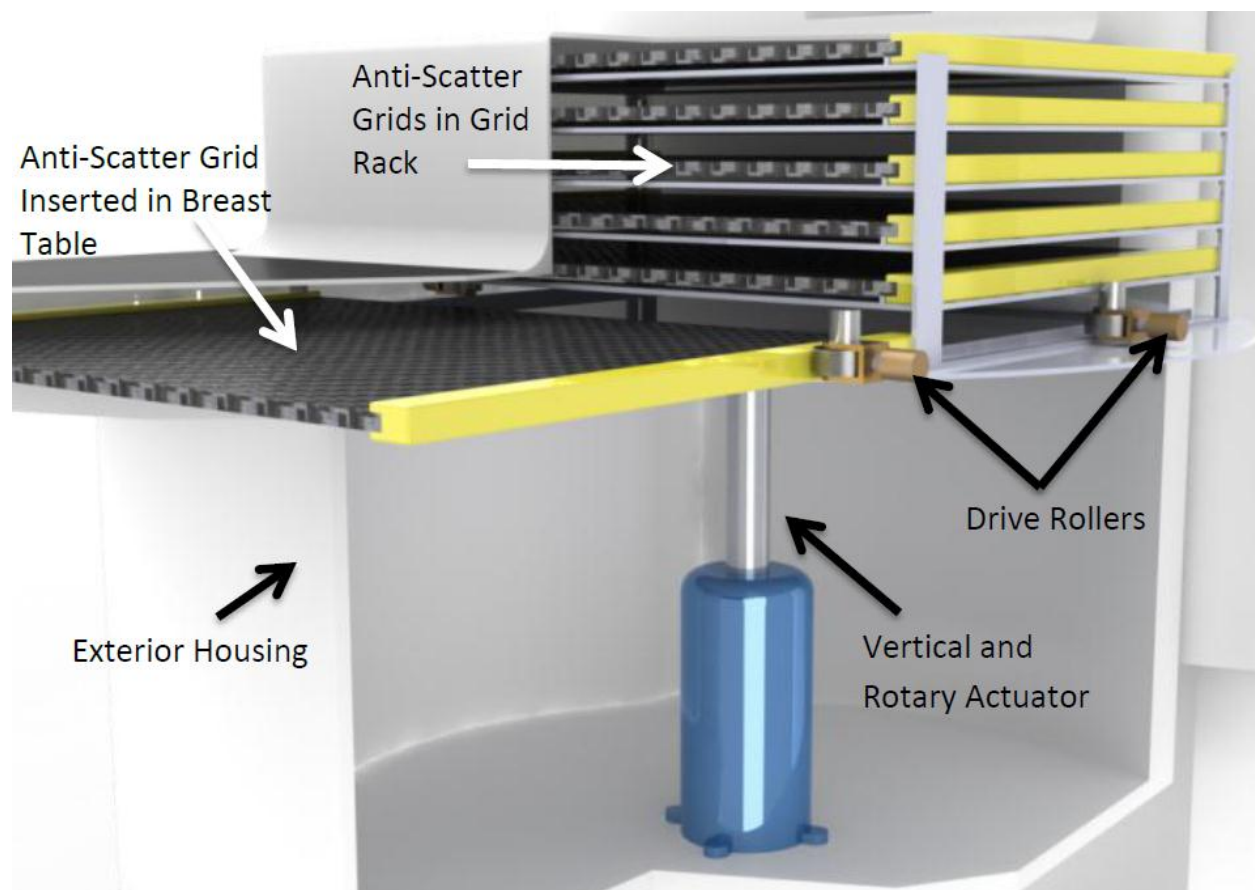
	Cost/unit (\$)	Quantity	Price
<b>Actuator [14]</b>	4584	1	\$ 4584
<b>Total</b>			<b>\$ 4584</b>

The final component of the total cost is the manufacturing costs. The top and bottom plates are simple in their design and should not cost too much to manufacture. However, the cost to manufacture the rotating septa is difficult to determine. This is due to the small dimensions of each septa and the need to create 1000 of the septa in order to manufacture one anti-scatter grid. Each of these rotating septa would need to be uniform in their dimensions, which will result in an increased cost to ensure consistency. The final difficulty is in the final assembly of the grid as each rotating septa must be placed accurately and without causing damage. All of these factors make it difficult to estimate an actual cost of manufacturing for the adjustable septa design.

The total known costs of this design are less than \$5000, which is below the target costs. However, the final costs of the design may exceed the target costs depending on the actual manufacturing costs. The use of a different actuation method could help to reduce this cost. Since this design would be manufactured in large quantities there is also potential for costs savings if mass production occurred.

## 2.2 Multiple Grid Changer

The second concept that was developed by TEC is the multiple grid changer. This concept is substantially different from the adjustable septa concept in that instead of attempting to move the septa, multiple grids are moved. The multiple grid changer, shown in Fig. 7, would accomplish the sweep angle project objective by using numerous anti-scatter grids to get from  $-25^{\circ}$  to  $+25^{\circ}$  sweep angle. Each grid in the system would have a different grid angle and the grids would be swapped in and out to correspond to the different sweep angles.



**Figure 7. Multiple grid changer design overview.**

As shown in Fig. 7, the grids would be stored on top of each other in a rack next to the breast table, and the mechanical changing system would be synchronized with the machine's current system. Rotation of the rack would allow for each grid to be used twice. In this design, there would be a limited number of grids due to storage constraints. To meet the constraint of 20 images per sweep, 10 anti-scatter grids

would be required. However, it is also possible that the tomosynthesis sweep could take images with and without anti scatter grids and software modifications could be used to assign different weightings to different images [1]. Another option is to take multiple images with the same anti-scatter grid from slightly different angles, which would produce acceptable images [1]. Both of these options would require fewer grids and still meet the requirements of 20 images per sweep with comparable quality. Due to the cost and space requirements, the concept model has six grids.

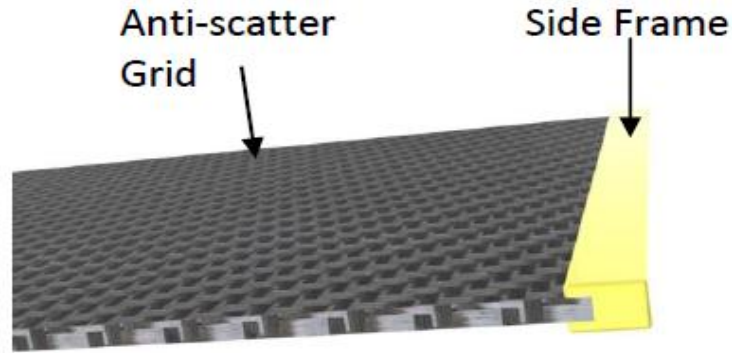
There are three major systems to this design including; the grid storage system, vertical and rotary motion system, and grid drive system. The grid storage system includes additions required to the individual grids and the grid rack. The vertical and rotary motion system is the system that moves the grid rack up and down so that different grids can be moved into the breast table. As well, the rotary motion is required so that the grids can be used for two images at opposite angles. The grid drive system encompasses how the grids are moved from the grid rack to the breast table. The following sections will provide information on the design of each of the three systems. As well a process flow diagram and a bill of materials and cost analysis will be provided for the design.

The multiple grid changer design appears to be much simpler than the adjustable septa design. However, this design has its own complexities. It was important not to affect the SID of the machine, and thus the grids had to be moved in and out of the breast table. Space in the tomosynthesis machine is limited and it was important to avoid affecting any rotating parts. This made the design of the grid rack challenging. Using each of the anti-scatter grids twice further complicated the design because the grid drive mechanism had to work in both directions and not block the grids. Overall, this design had many challenges to make it optimal and meet CCM's needs.

### **2.2.1 Grid Storage System**

The storage of the grids within the machine consists of two parts, the side frame and the grid rack. The side frame, shown in Fig. 8, made of polyethylene, would have a slot in which the grid would fit. An adhesive would be used to permanently bond the grid to the side frame. The side frame acts as the wear surface for the sliding in and out of the grid of the grid rack.





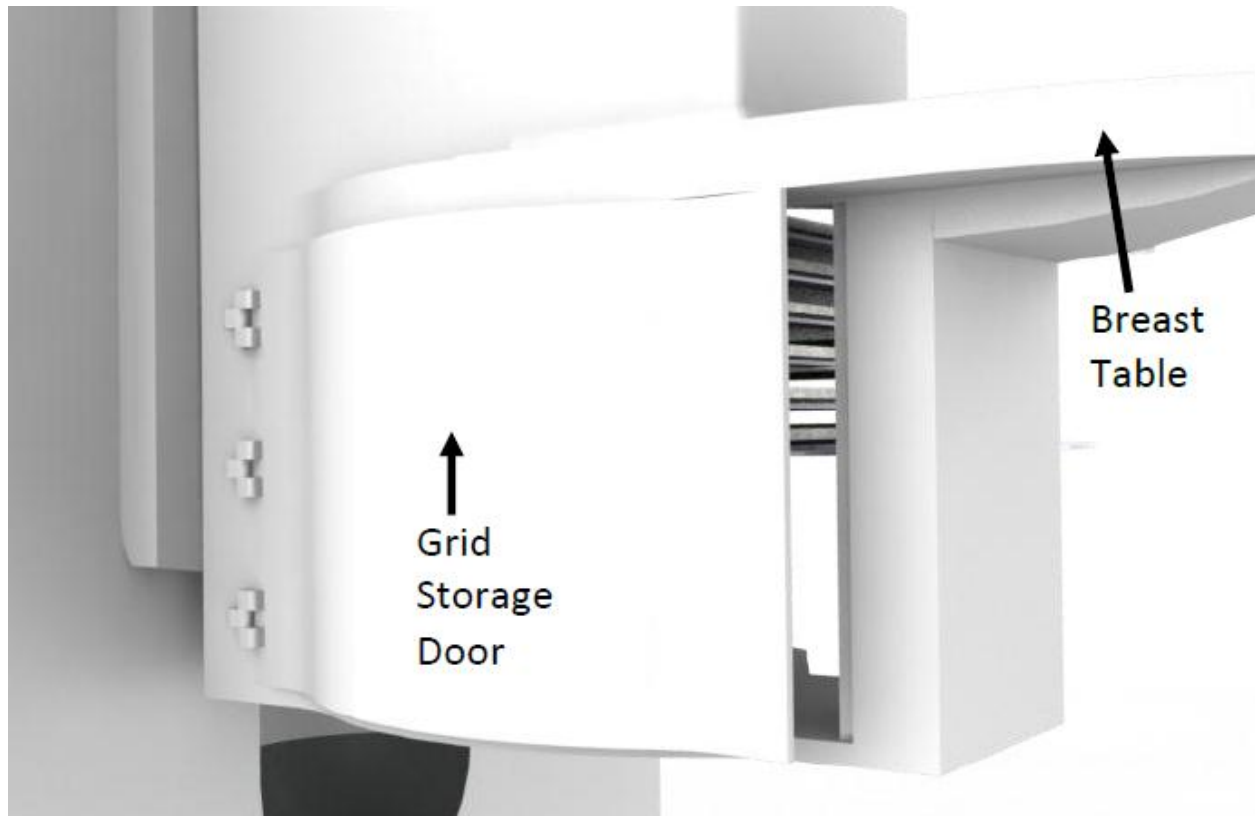
**Figure 8. Anti-scatter grid with attached side frame.**

The grid rack, made of AISI 1020 cold rolled steel, is shown in Fig. 9. Each level of the rack consists of a thin outer frame upon which the grid side frame will slide in and out of the breast table. Each corner of the rack features a gate that holds the grids in place.



**Figure 9. Grid rack to hold the anti-scatter grids for the multiple grid changer design.**

On the outside of the grid storage area, a door, shown in Fig. 10, would provide access to the inside of the machine to perform maintenance on the system or to switch the grids in and out of the rack.



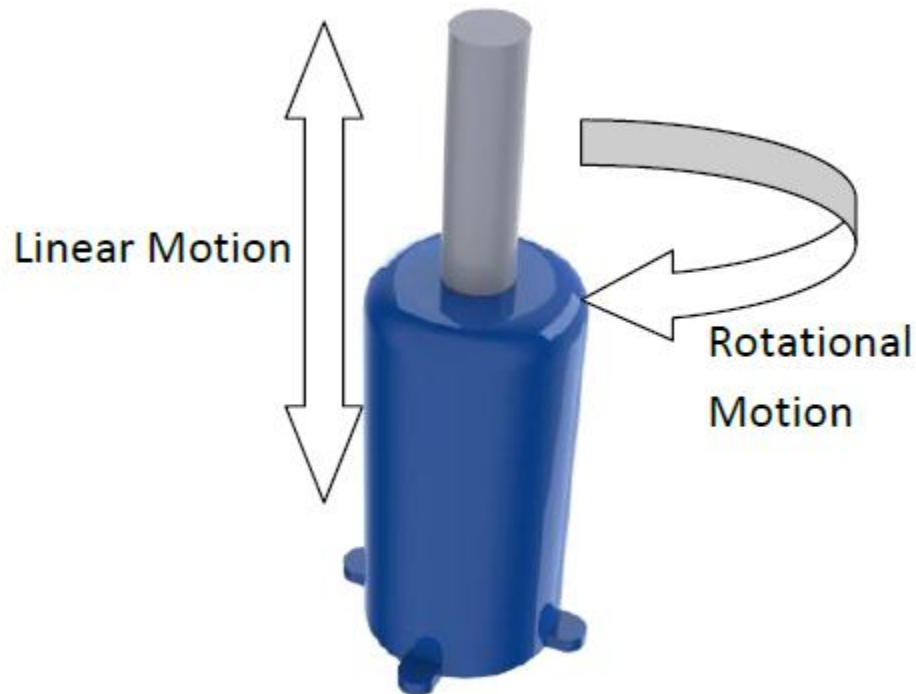
**Figure 10. Grid storage access door for the multiple grid changer design.**

When designing the grid storage system, many considerations governed the design. The grid rack was designed to be lightweight and store the anti-scatter grids. The side frame of the grids was also designed to be lightweight and unobtrusive. There were no additions to the front or back of the anti-scatter grids because when the grids are in the breast table, it is important that the actual grid surface is as close the patient's chest as possible. This ensures that the scan detects the whole breast and does not miss the areas close to the patient's chest. As well, the side frames make the radius of the anti-scatter grids larger, which require more room to rotate. The grid storage system was designed to have a small footprint on current tomosynthesis machines while being functional.

### **2.2.2 Vertical and Rotary System**

The vertical system's function is to move the grid rack up and down to allow different grids to be inserted into the breast table. The rotary system's function is to spin the grid rack 180° when it is in its lowest position. The method chosen to perform these two functions was a rotary linear actuator. This device is capable of the vertical motion as well as the rotational motion. A conceptual picture of this

system can be seen in Fig. 11. The actuator sits below the grid rack inside a round drum that is large enough to allow the grid rack to spin when it is inside.



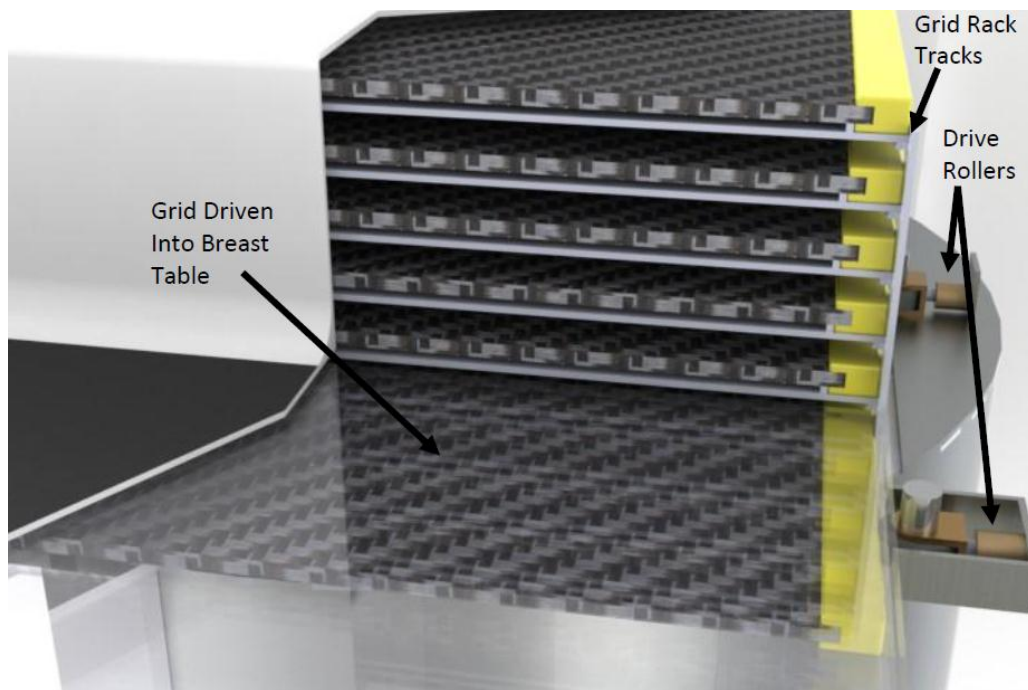
**Figure 11. Conceptual image of the vertical rotary actuator.**

An analysis was performed to determine the size of the linear and rotary components. It was determined that the linear component would have to be capable of supplying a force of 113 N. This would allow the grid rack to move from one grid position to the next grid position in 0.25 seconds. This vertical distance is 20 mm. The rotary component was determined to require a power of 98 W. This would allow the grid rack to be rotated 180° in a time of 0.5 s. The full analytical analysis can be reviewed in Appendix B.

### **2.2.3 Grid Drive System**

The grid drive mechanism's purpose is to move grids from their position in the grid rack to the inside of the breast table above the detector, and back into the grid rack. As well, the system must be capable of performing the same function when the grid rack is rotated 180°. Numerous designs were analyzed to decide which one would best perform. The factors that had the highest impact on a selected design

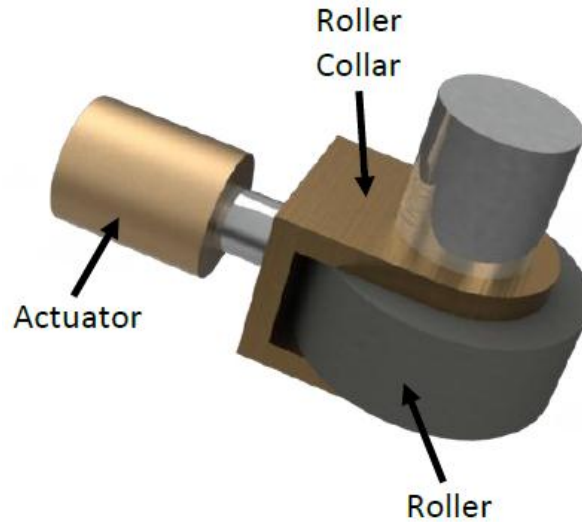
were the size, speed, and simplicity. Since space in the tomosynthesis machine is limited, it is important that the drive system takes up as little space as possible and does not have protruding parts. The speed with which the mechanism can move the grids is important because the longer the movement takes the longer the total scan duration. Longer scans can result in poor images due to the increased likelihood of patient movement. For this reason, the speed that the grids are moved is a major consideration. It is important to note that the movement of the grids from the grid rack to inside the breast table is 250 mm. The drive mechanism can be seen in Fig. 12.



**Figure 12. Grid drive system, with an anti-scatter grid being driven into the breast table.**

As illustrated Fig. 12, the drive rollers are mounted to the encasement on the side of the exterior housing. This location was selected because it was best suited to driving in the grids in both directions into the breast table. As well, since the grids rack rotates in a planar circle, there is room in between the sides of the grids and the side of the exterior housing where the rollers can fit. For the final design, four rollers were chosen for installation because this ensures that at least two rollers will always be in contact with the grid. Two rollers would be installed in the breast table and two on the exterior housing.

The drive rollers will be stationary in the vertical direction. This means that the grid rack will move vertically relative to the drive rollers. To avoid binding the drive rollers, they need to be capable of being moved in and out of contact with the grids. A small actuation system was designed so that the drive rollers can apply a force onto the grids. These actuators can be seen in detail in Fig. 13.



**Figure 13. Conceptual drive roller assembly showing the required components of the roller and actuator.**

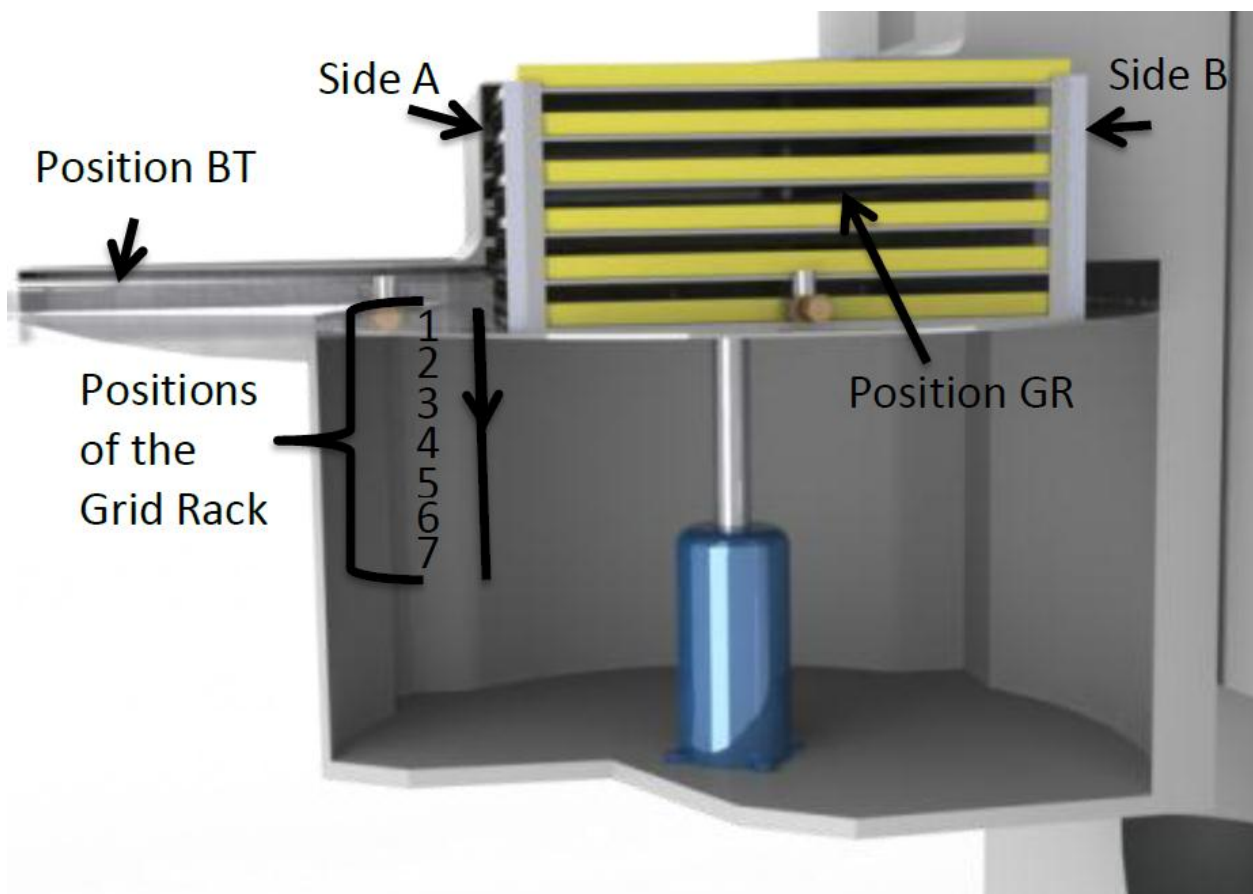
The drive rollers move the grids by friction. A detailed analysis of this movement was performed and can be reviewed in Appendix B. It was found the total power required for each drive roller is 3 W, and the force required by the actuators is 3.5 N. This force is applied to the side frames of the grids. The side frames are taller than the grids themselves and sit in a track on the grid rack. The track absorbs the force applied and no force is transmitted through the anti-scatter grids. The anti-scatter grids sitting in their respective tracks can be seen in Fig. 12. The drive rollers were also designed to be made of a rubber compound that would have a high coefficient of friction with the sides of the grids.

The time to move the anti-scatter grid in and out of the breast table was also determined. The acceptable time determined was 0.5 s to move into the breast table, and 0.5 s to move out of the breast table and into the grid rack. The grids would be accelerated and then decelerated by the drive rollers. The actual electronics and automation process is beyond the scope of this report and thus it will not be specified. However, the analysis provided in this report has been designed for a system that would be automated.

#### **2.2.4 Process Flow**

The multiple grid changer is a complex design. Therefore, it is helpful to provide a process flow diagram to aid in explaining the process. The multiple grid changer has three different types of movement, including vertical movement of the grid rack, rotational movement of the grid rack and horizontal

movement of the anti-scatter grids. These movements can be explained by assigning names to the different positions of the multiple grid changer. The position numbers one to seven correspond to the vertical movement of the grid rack. In position one, the grid rack is at its highest position and the lowest anti-scatter grid in the grid rack can be driven into the breast table. In position seven the grid rack is at its lowest position and the grid rack can be rotated in the lower portion of the grid storage area. Positions two through six correspond to the positions where other anti-scatter grids can enter the breast table in between positions one and seven. The front and back of the grid rack have been given names side A and side B respectively. The process starts with side A of the grid rack facing the breast table and then during the process, rotates to side B so the anti-scatter grids can be inserted into the breast table in reverse. The last two positions, BT and GR correspond to the horizontal movement of the anti-scatter grids. Position BT is when the anti-scatter grid is in the breast table and position GR is when the anti-scatter grid is in the grid rack. These positions are illustrated in Fig. 14.



**Figure 14. Rendering describing the different positions of the multiple grid changer design. These positions correspond to the process flow diagram.**

After gaining an understanding of the multiple grid changer positions, the process flow can be explained. The process demonstrates how the whole system would function during the tomosynthesis sweep. The process flow diagram is shown in Fig. 15.

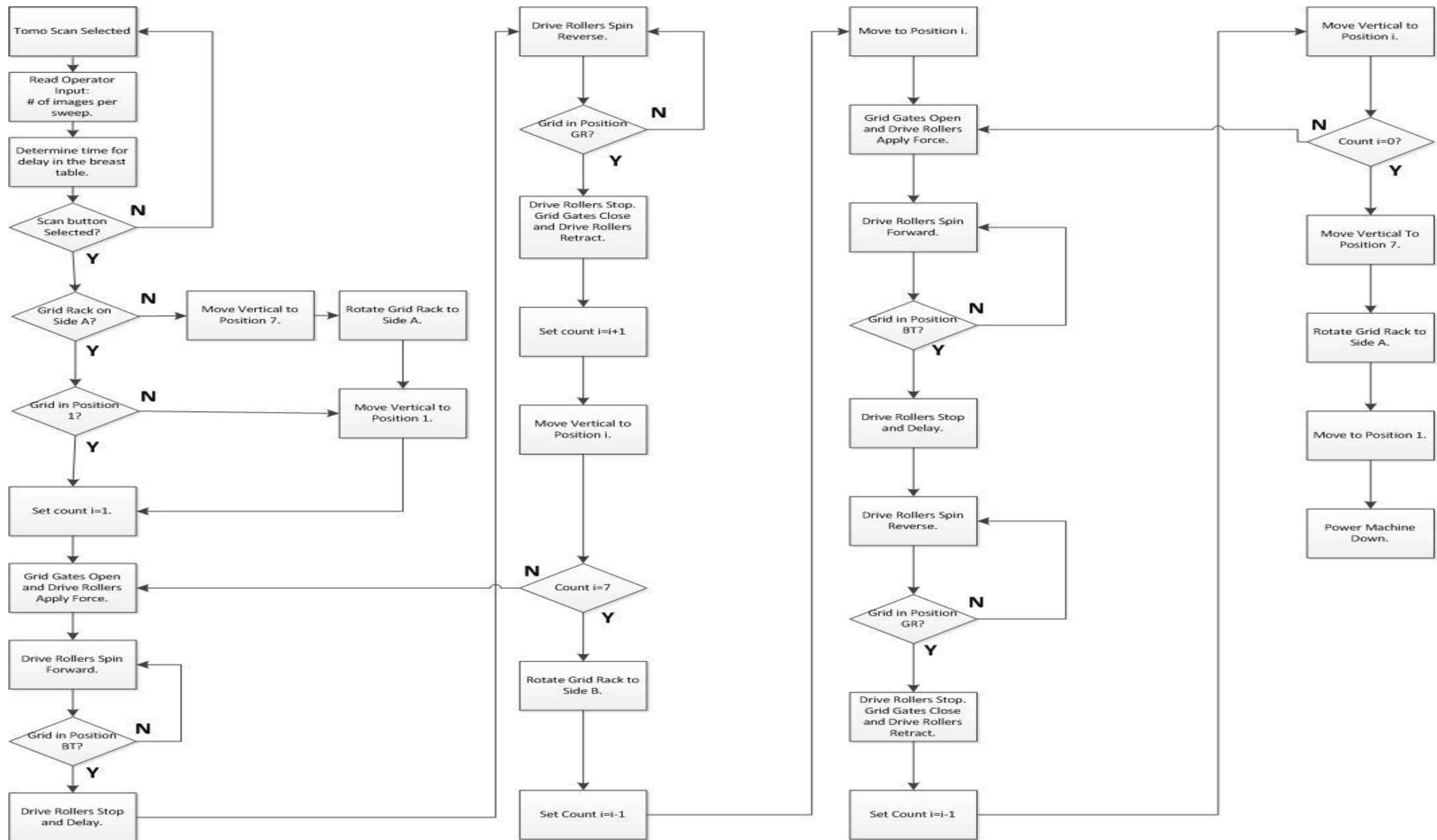


Figure 15. Multiple grid changer process flow diagram.



The process flow diagram demonstrates the multiple grid changer process. As can be seen from Fig. 15, the process has many different steps to perform the different functions. The tomosynthesis machines have computer processors in them to control other functions and they could be used to control this process as well. If this system is to be built, it may be necessary to build some fail-safe devices so that the machine cannot damage itself. One such measure could be a system that mechanically locks the grid rack when an anti-scatter grid enters the breast table. This would prevent the grid rack from accidentally rotating or moving vertically and damaging the grid that is in the breast table. Overall, the process flow diagram has demonstrated the movements of the multiple grid changer.

### 2.2.5 Time Considerations

Since CCM has specified that the length of time to complete the sweep is important, it is necessary to consider the amount of time required for the grid changer system to complete one sweep. As noted in Section 1.2, CCM has specified that the length of time required to complete the sweep should not exceed 60 seconds. It is important to note that keeping the sweep time to a minimum will result in enhanced x-ray clarity due to decreased chance of patient movement. The process flow diagram, listed above in Fig. 15, breaks the down the process into individual steps. The various steps of the process fit into four distinct time duration categories which are listed in Table IV.

**Table IV**  
**TIME DURATION CATEGORIES IN GRID CHANGER PROCESS**

<b>Time Duration Category</b>	<b>Length of Time (s)</b>
Take X-ray	0.1
Move Grid Rack Up/Down	0.25
Rotate Grid Rack	0.5
Move Grid In/Out of Breast Table	0.5

The duration for taking the x-ray is conservatively assumed to be 0.1 seconds. The durations for moving the rack up and down, rotating the rack, and moving the grid in and out of the breast table are all taken from Appendix B. Using these values along with the process flow diagram, shown in Fig. 15, the total time for one sweep can be determined.

Table V shows the breakdown of all the events in one sweep assuming that the rack begins at position one.

**Table V**  
**TIME TO COMPLETE SWEEP**

Process	Rack Position	Move Grid Rack Up	Move Grid Rack Down	Move Grid In	Take X-ray	Move Grid Out	Rotate Grid Rack
A	1			1	1	1	
B	2		1	1	1	1	
C	3		1	1	1	1	
D	4		1	1	1	1	
E	5		1	1	1	1	
F	6		1	1			
G	H		1				1
H	6	1				1	
I	5	1		1	1	1	
J	4	1		1	1	1	
K	3	1		1	1	1	
L	2	1		1	1	1	
M	1	1		1	1	1	
<b>Column Totals</b>		<b>6</b>	<b>6</b>	<b>11</b>	<b>10</b>	<b>11</b>	<b>1</b>
		x	x	x	x	x	x
<b>Duration (s)</b>		0.25	0.25	0.5	0.1	0.5	0.5
<b>Subtotals (s)</b>		<b>1.5</b>	<b>1.5</b>	<b>5.5</b>	<b>1</b>	<b>5.5</b>	<b>0.5</b>
<b>Total</b>							<b>15.5</b>

The passage of time in the table progresses from process A to M and left to right within each process line. Binary values are used to indicate the sub-processes that are included in each main process. A 1=YES and a blank cell indicates NO. For instance, in Process B, the rack is moved down to position two, grid two is then moved into position BT, an x-ray shot is taken, and then grid two is moved out of the breast table into position GR.

The number of 1's in each column is totaled and then each total is multiplied by its corresponding time duration. These subtotals are then added up to determine the total time for one sweep. As Table V

shows, the total time to complete one sweep is 15.5 seconds, well under the maximum time of 60 seconds laid out by CCM.

### 2.2.6 Cost Analysis

The cost of the multiple grid changer can be broken down into three distinct categories: raw material, manufacturing, and commercial parts costs. The costs given below are based on estimates. The accuracy of these estimates will put the overall cost of the design within the right order of magnitude.

The raw materials used in the multiple grid changer are AISI 1020 cold-rolled steel sheet metal for the grid rack, and polyethylene for the grid side frame as shown in Table VI. The values listed in the quantity section are taken from the design calculations in Appendix B. The referenced cost values are listed in the units that correspond to the quantities needed.

**Table VI**

#### **MULTIPLE GRID CHANGER DESIGN RAW MATERIAL COSTS**

	<b>Cost/unit</b>	<b>Quantity</b>	<b>Total Cost</b>
<b>AISI 1020 Cold Rolled Steel Sheet Metal [15]</b>	\$10/m <sup>2</sup>	0.3 m <sup>2</sup>	\$ 30.00
<b>Polyethylene Sheet [16]</b>	\$80/m <sup>2</sup>	0.05 m <sup>2</sup>	\$ 4.00
<b>Total</b>			<b>\$ 34.00</b>

The total estimated raw material costs for the grid changer design is estimated to be \$34.

The two parts of the grid changer design that would need to be custom manufactured would be the grid rack and the side frame. An estimated manufacturing cost per hour of \$100 was used in Table VII to determine the projected overall manufacturing cost.

**Table VII**

#### **MULTIPLE GRID CHANGER DESIGN MANUFACTURING COSTS**

	<b>Cost/hour</b>	<b>Quantity (hr.)</b>	<b># of Units</b>	<b>Total Cost</b>
<b>Grid Rack</b>	\$100	2.0	1	\$ 200.00
<b>Side Frame</b>	\$100	0.05	12	\$ 60.00
<b>Total</b>				<b>\$ 250.00</b>

The total manufacturing costs of the grid changer design is estimated to be \$250.

Along with the raw material and manufacturing costs, the grid changer design also required numerous commercial parts. Table VIII displayed below highlights the six commercial parts used and the number of each required.

**Table VIII**

**GRID CHANGER DESIGN COMMERCIAL PARTS COSTS**

	<b>Cost/unit (\$)</b>	<b>Quantity</b>	<b>Total Cost</b>
<b>Grids [17]</b>	500	6	\$ 3,000.00
<b>Linear Actuator [18]</b>	150	1	\$ 150.00
<b>Rotary Actuator [19]</b>	150	1	\$ 200.00
<b>Stepper Motor [20]</b>	25	4	\$ 100.00
<b>Gate Motor [21]</b>	15	4	\$ 60.00
<b>Total</b>			<b>\$ 3560.00</b>

The total commercial parts cost for the multiple grid changer design is estimated to be \$3510.

The total estimated cost of the multiple grid changer design is \$3794, which is well below the objective of keeping the costs less than \$15,000. The main cost of this design is the six grids at \$3000 dollars.

### 3. Design Comparison

The final designs can be compared based on the original project objectives in order to determine a design that best meets the needs of CCM. The ability of both designs to meet these project objectives is discussed in the following sections, in order of importance.

#### 3.1 Radiation Dosage

It is difficult to compare the level of radiation necessary to produce quality images for both designs without working prototypes or software modeling. The multiple grid changer design utilizes current standard carbon fiber anti-scatter grids, so the increase in radiation dosage will be similar to the current radiation level increases needed for stationary x-rays with anti-scatter grids.

From a materials perspective, as the atomic number of an element increases, the level of attenuation of a material also increases [1]. Since the adjustable septa design uses aluminum, which has a higher atomic number than carbon, for the main grid construction, the increase in radiation necessary will be higher for the adjustable septa. Also, the adjustable septa design uses a thicker grid than the multiple grid changer, thus the level of attenuation will also increase. These two factors contribute to a need for a higher radiation dosage when using the adjustable septa design, in comparison with the multiple grid changer design. The increase in radiation dosage necessary is currently unknown. In order to calculate the radiation dosage, software modeling or prototypes must be created and tested.

Due to time restrictions on the project, x-ray modeling on each design was not performed, although there is software available for this purpose.

#### 3.2 Sweep Angle

The second objective is that the designs must be capable of a sweep angle of  $\pm 25^\circ$  in order to be used with current tomosynthesis machines. As discussed in Section 2.1, the adjustable septa design utilizes rotating septa that are infinitely adjustable between the required  $\pm 25^\circ$  sweep angles, thus meeting the project objective for the sweep angle.

The multiple grid changer design has a fixed number of grids available due to the device size limitations. The design has six grids which will be able to be used twice along the  $\pm 25^\circ$  sweep. As stated in the detailed design, there are two possible software modifications that can be used to increase the number

of images per sweep. Using these two software modifications will result in clearer images than without the use of anti-scatter grids. Therefore, the multiple grid changer design will be able to meet the project objective for the sweep angle, but some software modifications will be required.

### **3.3 Device Size**

The third objective for the designs was the device must have similar dimensions to current tomosynthesis machines, due to the limited space between the patient and the detector. Due to the highly confidential nature of devices in the medical industry, it is unknown if there is the necessary space required for either design within the machine. This has the potential to cause problems during installation of either design into current machines. Overall, the dimensions of the adjustable septa design are smaller than the dimensions of the multiple grid changer. Therefore, there is a higher likelihood that the adjustable septa design would be able to fit into current tomosynthesis machines. Both designs would be able to be incorporated into new mammography tomosynthesis devices if they were placed in the machine in the initial design stages.

### **3.4 Number of Images per Sweep**

The fourth project objective is that each design must be capable of reaching 10-20 discrete positions along the entire 50° tomosynthesis arc, corresponding to 10-20 x-ray exposures. The adjustable septa design is capable of surpassing this design objective due to the use of piezo actuators. These actuators have a resolution of 7 nm, so within the 50° arc, the septa can be rotated to over 200 000 different positions. The limiting factor here is the precision of the micro-controller that will control the actuators. The controller must be able to have very precise voltage increments in order to achieve close to 200 000 positions. Since current tomosynthesis machines only require 20 images per sweep, a lower precision controller can be used that would be able to move the septa into 20 different positions. Therefore, the adjustable septa design will be able to achieve 20 images per sweep. The advantage of this design is that minor software changes can be used to customize the number of images per sweep and the precise septa angles required to achieve correct septa alignment.

As discussed in Section 2.2, the multiple grid changer design with six grids is capable of achieving 11 different exposures with anti-scatter grids along the entire tomosynthesis sweep. These 11 images can also be combined with nine exposures without anti-scatter grids to meet the project objective of 20

images per sweep. The weighting used by the software to process the final images can be altered to incorporate higher weightings for the exposures with grids, and lower weightings for the images without grids. These alterations on the software side of the system will help improve the image quality from this system.

### **3.5 Source to Image Distance**

The fifth project objective was the designs must maintain the current source to image distance of 0.65 m from the x-ray source to the detector. Since neither of the designs changed the dimensions of the breast table associated with the SID, the SID will remain at 0.65 m. Therefore, both designs are capable of meeting this project objective.

### **3.6 Reliability**

The sixth project objective is that each design must be able to perform a minimum of 1000 scans before requiring maintenance. Determining the reliability of both designs is very difficult without the construction of working prototypes. Another reason that comparison is difficult is both designs are very different in their construction.

The adjustable septa design incorporates 1000 aluminum and lead septa that are rotating constantly throughout the tomosynthesis sweep. The application of a Teflon coating to each wear surface on the septa will help reduce the chances of the septa failing due to wear.

The multiple grid changer design has several motors and a rotating grid rack that may be prone to failure after repeated use. The life of these components will depend greatly on the manufacturer and the level of precision used. An advantage of the multiple grid changer design is that it uses stationary anti-scatter grids so they will not be exposed to the constant rotation of each septa, as is required in the adjustable septa design.

Creating prototypes and testing each device under normal operating conditions would help determine the feasibility and reliability of each device.

### **3.7 Time to Complete a Sweep**

The seventh project objective is to complete the mammography tomosynthesis sweep within 60 seconds. Current mammography tomosynthesis machines are capable of performing a sweep within 3 to 4 seconds, so the time to complete a sweep for the designs should be kept to a minimum in order to reduce the potential for patient movement.

As calculated in Section 2.1.6, the adjustable septa design is able to complete a sweep at the same speed as current mammography tomosynthesis machines because piezo actuators have very fast movements and are not the limiting factor in the design.

Section 2.2.5 detailed the time considerations for the multiple grid changer design. Due to the complex motions required to insert, image, remove, change and insert another grid for each new position, the time required for a tomosynthesis sweep needs to be extended. A conservative estimate of 15.5 seconds was calculated for the multiple grid changer design. This duration may be decreased if possible when performing prototype testing.

### **3.8 Cost**

The eighth project objective considered is that the overall cost of each design must not exceed \$15,000. This cost is another objective that is difficult to obtain figures for manufacturing costs. The detailed designs of each concept have highlighted the raw material costs and the costs associated with commercially available components. Also, in the manufacturing industry, there are discounts based on quantities of materials ordered. These discounts will all depend on the number of anti-scatter grids produced.

The adjustable septa design has very low raw material costs because the overall size of the grid is small. The nature of foil lamination needed for the septa construction is difficult to obtain cost figures for. The manufacturing process used to roll the two layers of aluminum foil and one layer of lead together is a feasible process and the cost associated with the rolling process will depend on the manufacturer. The piezo actuators needed for the adjustable septa design are commercially available from PI and they have a cost of \$4584.

The multiple grid changer design uses current anti-scatter grids with slight modifications to the grid angle in order to achieve numerous grid angles. Assuming the cost of the modified grids is similar to



current anti-scatter grids, the total cost for six anti-scatter grids is \$3000 [17]. This cost has the potential to decrease due savings associated with purchasing larger quantities.

Overall, the costs associated with both designs are highly subjective and strongly correlate to the unknown costs associated with manufacturing each design. The cost to manufacture one-off prototypes of both designs will be higher than the cost of mass production due to the complex nature of the designs, tooling and processes required to manufacture the unique components.

### 3.9 Design Comparison Summary

After completing the comparison of each design to the project objectives, the results can be tabulated. Detailed below in Table IX are the known results from the comparison. Each design was ranked first or second based on the designs ability to meet or exceed the design objective.

**TABLE IX**  
**DESIGN COMPARISONS**

Objective	Criteria Met?		Rank	
	Adjustable Septa	Grid Changer	Adjustable Septa	Grid Changer
1 Radiation Dosage	unknown	yes	2	1
2 Sweep Angle	yes	yes	1	2
3 Device Size	unknown	unknown	?	?
4 # of Images/Sweep	yes	yes	1	2
5 SID	yes	yes	1	1
6 Reliability	unknown	unknown	?	?
7 Time to Complete Sweep	yes	yes	1	2
8 Cost	unknown	unknown	?	?
Overall Rank			1	2

Overall, the adjustable septa design was able to better meet the requirements for sweep angle, number of images per sweep, and the time to complete the sweep than the multiple grid changer, whereas the multiple grid changer design excelled in the area of radiation dosage. The adjustable septa design was determined to be the most suitable design for CCM because it was able to meet or exceed more of the project objectives than the multiple grid changer design.

## 4. Recommendation

After performing the design comparison, as detailed in Section 3, it was determined that the adjustable septa design outperforms the multiple grid changer design in the areas of sweep angle, number of images per sweep, and the time to complete the sweep. Therefore, the adjustable septa design is recommended as the design for CancerCare Manitoba to further develop.

The adjustable septa design was capable of achieving a sweep angle from  $-25^{\circ}$  to  $+25^{\circ}$  by using a grid of rotating septa that are infinitely adjustable within the required sweep angle. Combining the rotating septa with a piezo actuator makes the adjustable septa design capable of adjusting to over 200,000 different angles throughout the entire sweep angle range, far exceeding the 20 positions necessary to achieve the objective of 20 images per sweep. Piezo actuators are also capable of very fast motions; this allows the adjustable anti-scatter grid to move faster than the current mammography tomosynthesis machines. Therefore, the time to complete a sweep will remain at the current 3-4 seconds per sweep, meeting the project objective for the time to complete a sweep in less than 60 seconds. The project objective for the source to image distance of 0.65 m is met by the adjustable septa design because the SID is not altered in the design of the new anti-scatter grid system.

Due to the highly confidential nature of devices in the medical industry, it is unknown if there is the necessary space required for either design within a tomosynthesis machine. This has the potential to cause problems during installation of either design into current tomosynthesis machines.

Overall, the costs associated with both designs are highly subjective and strongly correlate to the unknown costs associated with manufacturing each design.

The adjustable septa design will require further developments of computer model and prototypes to test the x-ray dosage, feasibility and reliability of the design. The cost to manufacture one-off prototypes of both designs will be higher than the cost of mass production due to the tooling and processes required to manufacture the unique components. Software and micro-controllers to automate the adjustable septa concept will also have to be designed or purchased. These items are all beyond the scope of this report due to time and budget constraints.

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# **Appendix A – Concept Selection Process**

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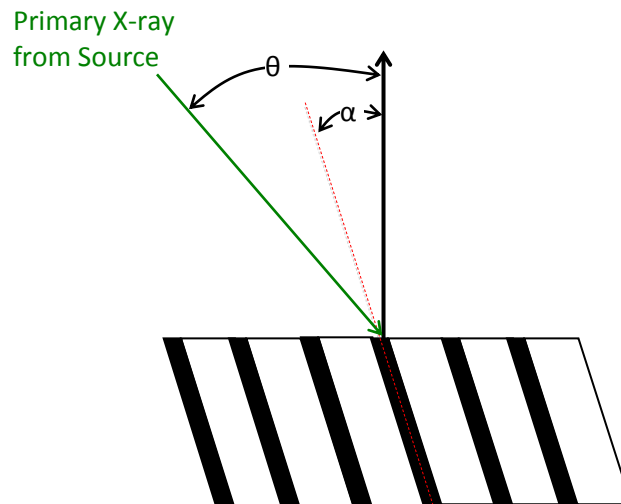
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## Concept Generation Phase

Thirteen Engineering Co.'s (TEC's) concept generation process consisted of a group brainstorming session during which every idea was accepted as a possibility and group members were encouraged to contribute ideas without feasibility considerations. This openness allowed 16 concepts with varying degrees of uniqueness, innovation and practicality to be generated. The 16 concepts are listed below along with brief descriptions.

For consistency in the descriptions of each of the concepts, Fig. 1 shows two important parameters that are used throughout the descriptions. The grid angle and sweep angle,  $\alpha$  and  $\theta$  respectively. In simplest terms, TEC has been tasked with finding a way to alter  $\alpha$  to correspond with  $\theta$  throughout the tomosynthesis sweep.



**Figure 1. Grid Schematic with Primary X-ray Showing  $\alpha$  and  $\theta$  [1].**

### Concept A - Multiple Grid Changer

The idea of a Multiple Grid Changer is based on a multiple-CD changer. Each grid in the system would have a different  $\alpha$  and they would be swapped in and out to correspond to the different  $\theta$  values within the sweep. The grids would be stored stacked on top of each other next to the platform and the mechanical changing system would be synchronized with the machine's current system.



**Concept A.1 – Multiple Grid Changer with 180° Planar Rotation**

The Multiple Grid Changer with 180° Planar Rotation would take the idea of the Multiple Grid Changer and reduce the number of grids needed by using each grid twice. Each grid would be used once for  $+\alpha$  and once for  $-\alpha$ . The changing mechanism would have to be able rotate each grid 180° within the plane of the grid.

**Concept B – Overhead Projector**

Concept B is based on the traditional overhead projector in that the septa would be placed inside a long sheet that could be rolled up. The length of the sheet would be split up into different sections, each having a different  $\alpha$ . The sheet would then be passed over the image detector from one roll to another with the  $\alpha$  value of each section corresponding to  $\theta$  value throughout the sweep.

**Concept C – Rotating Wheel**

Like the Multiple CD Changer, the Rotating Wheel would require numerous grids, each with a different  $\alpha$  value that would correspond to the different  $\theta$  values within the sweep. The difference for this concept is that the grids would be mounted on a wheel that would rotate each different grid into place.

**Concept D – Rolling Septa**

In the Rolling Septa concept, the septa would be situated inside a solid cylindrical shell. The rolling of these cylinders would align  $\alpha$  to  $\theta$  throughout the sweep.

**Concept E – Adjustable Mirrors**

The Adjustable Mirrors concept would involve adjusting the alignment of the x-ray after passing the through the breast to align the beam with a standard anti-scatter grid. This would be accomplished by deflecting the x-rays with tiny mirrors that would rotate about their central axis in order to adjust the path of the incident x-rays from  $\theta$  to a vertical alignment.

**Concept F – Side Shooter (radiation deflection)**

The Side Shooter concept is similar to the Adjustable Mirrors in that the alignment of the x-ray would be modified after it passes through the breast, allowing the use of a standard vertically positioned anti-scatter grid. In this concept, the x-rays would be bombarded with a stream of particles that would change the alignment of the x-rays before they hit the grid.

### **Concept G – Grid Central Axis Rotation**

The Grid Central Axis Rotation concept would allow for a standard vertically aligned anti-scatter grid to be used. The grid and the image receptor, located below the platform, would be rigidly connected and would rotate about their central axis in order to align the grid with  $\theta$  throughout the sweep.

### **Concept H – Liquid Adjustable Grid**

The Liquid Adjustable Grid concept involves septa that would be able to rotate about their central axis. The pump would push fluid into the grid in such a way that it would force the septa to rotate, thus aligning  $\alpha$  to  $\theta$ .

### **Concept I – Adjustable Septa**

The Adjustable Septa concept is similar to the Liquid Adjustable Grid concept except for the fact that the individual septa would be moved by a mechanical process. The movement of the septa, connected to a linkage system, would be powered by a motor which would accurately align the septa.

### **Concept J – Adjustable Grid Layers**

The Adjustable Grid Layers concept would involve stacking numerous grids on top each other. Each grid layer would have a thickness substantially smaller than current anti-scatter grids and each layer would be able to independently move left or right. These movements would be synchronized in such a way that off-setting the septa of each level compared to the next would make the  $\alpha$  of the grid correspond to  $\theta$ .

### **Concept K – Moveable Grid**

In the Moveable Grid concept, the detector and standard vertically aligned anti-scatter grid would be rigidly fixed to the arm which moves the tomosynthesis source in an arc. In this way, as the source rotates in the arc, the grid will always be properly aligned to  $\theta$ .

### **Concept L – Mercury Grid**

The Mercury Grid concept involves flowing mercury into different cavities that are aligned to different  $\alpha$  values. The design could include different layers stacked on top of each other, each having differently aligned cavities or each layer could have cavities aligned to numerous  $\alpha$  values.

### **Concept M – Semi-Conductor Grid**

The semi-conductor grid concept makes use of an array of septa constructed from a sheet of doped semi-conductor material. The array would be manufactured so that there are multiple different angles

of septa in the grid that become active when they are charged with a current. This design would allow instant adjustments in the grid angle to coincide with the angle of the x-ray source along a tomosynthesis sweep.

#### **Concept N – Heavy Water Flow**

The Heavy Water Flow concept is the same as the Mercury Grid concept, except for the fact that it uses heavy water instead of mercury.

#### **Concept O – Lead Sandwich**

The Lead Sandwich concept is similar to the Adjustable Septa concept except that the individual lead septa are coated with another material in order to protect it and give it extra strength.

### **Concept Screening Phase**

The concept selection process began with screening the 16 concepts using a concept screening matrix consisting of the categories listed in Table I.

**TABLE I**  
**CONCEPT SCREENING MATRIX CRITERIA**

<b>Criteria</b>
Sweep Angle
Images Per Sweep
Time to Complete Sweep
Device Size
SID
Cost
Grid Ratio
Dosage
Manufacturability
Reliability
Danger/Risk/Safety
Level of Attenuation
Simplicity
Ease of Operation
Adaptability
Feasibility

Each team member scored each concept as a positive, neutral or negative in 16 categories. The totaled team results of the concept screening matrix are listed in Table II.

**TABLE II**  
**TEAM CONCEPT SCREENING RESULTS**

	<i>A. CD Loader</i>	<i>A.1 CD Loader w/ Rotation</i>	<i>B. Overhead Projector</i>	<i>C. Rotating Wheel</i>	<i>D. Lead Sandwich Rollers</i>	<i>E. Adjustable Mirrors</i>	<i>F. Side Shooter (radiation deflection)</i>	<i>G. Central Axis Rotation</i>	<i>H. Liquid Adjustable</i>	<i>I. Adjustable (rotating) septa</i>	<i>J. Adjustable Grid Layers</i>	<i>K. Movable Grid</i>	<i>L. Mercury Grid</i>	<i>M. Semi-conductor</i>	<i>N. Heavy Water Flow</i>	<i>O. Lead Sandwich</i>
<b>Pluses</b>	<b>34</b>	<b>36</b>	<b>30</b>	<b>31</b>	<b>21</b>	<b>10</b>	<b>12</b>	<b>50</b>	<b>21</b>	<b>27</b>	<b>23</b>	<b>44</b>	<b>13</b>	<b>26</b>	<b>11</b>	<b>33</b>
<b>Zeros</b>	<b>19</b>	<b>17</b>	<b>24</b>	<b>22</b>	<b>12</b>	<b>23</b>	<b>7</b>	<b>10</b>	<b>27</b>	<b>20</b>	<b>15</b>	<b>15</b>	<b>22</b>	<b>13</b>	<b>12</b>	<b>19</b>
<b>Minuses</b>	<b>11</b>	<b>11</b>	<b>10</b>	<b>11</b>	<b>31</b>	<b>31</b>	<b>45</b>	<b>4</b>	<b>16</b>	<b>17</b>	<b>26</b>	<b>5</b>	<b>29</b>	<b>25</b>	<b>41</b>	<b>12</b>
<b>Net</b>	<b>23</b>	<b>25</b>	<b>20</b>	<b>20</b>	<b>-10</b>	<b>-21</b>	<b>-33</b>	<b>46</b>	<b>5</b>	<b>10</b>	<b>-3</b>	<b>39</b>	<b>-16</b>	<b>1</b>	<b>-30</b>	<b>21</b>
<b>Rank</b>	<b>4</b>	<b>3</b>	<b>6</b>	<b>6</b>	<b>12</b>	<b>14</b>	<b>16</b>	<b>1</b>	<b>9</b>	<b>8</b>	<b>11</b>	<b>2</b>	<b>13</b>	<b>10</b>	<b>15</b>	<b>5</b>

Concepts that received negative scores were removed from further consideration. It was decided that the similarity between the Adjustable Septa and Lead Sandwich concepts made it unnecessary to continue to consider both designs separately. Since the Lead Sandwich scored considerably better overall than the Adjustable Septa, it was decided that the Adjustable Septa concept would be removed from further consideration.

### Concept Synthesis Phase

Throughout the concept screening phase each team member was encouraged to continue to develop new concepts or synthesize current concepts to produce new concepts. Only one synthesized concept was produced in this manner.

#### Concept AG – Multiple Grid Changer with Central Axis Rotation

Combining the Multiple Grid Changer and Central Axis Rotation concepts, this design would allow a greatly reduced number of grids. Each grid used would be rotated about its central axis as much as the space between the platform and the image detector would allow. This would allow a grid with a specific

$\alpha$  value to be used for a number of different  $\theta$  values in the sweep, which would also reduce the number of grids needed.

Since Concept AG was made up of two concepts that passed the concept screening phase, it automatically moved on to the concept scoring phase.

### Concept Scoring Phase

The concept scoring phase utilized a matrix much like the concept screening matrix. However, for the concept scoring matrix, a much finer scale, +5 to -5 was chosen. This was done to allow for a more accurate representation of each concept's varying ability to meet each individual criterion. The goal of the concept scoring phase was to further narrow down the list of concepts that will be pursued.

Each criteria used in the concept scoring was assigned a weight from 1 to 4, in order to represent its relative importance compared to the other criteria. The weights shown in Table III were approved by CCM.

**TABLE III**  
**CONCEPT SCORING MATRIX CRITERIA WEIGHTING**

Criteria	Weight
Sweep Angle	4
Grid Ratio	4
Dosage	4
Level of Attenuation	4
Adaptability	4
SID	3
Manufacturability	3
Reliability	3
Images Per Sweep	2
Time to Complete Sweep	2
Device Size	2
Cost	1
Danger/Risk/Safety	1
Simplicity	1
Ease of Operation	1

Only the nine concepts that passed the concept screening phase, as well as the one synthesized concept, Concept AG, were graded in the scoring matrix. Once again, each team member individually scored the concepts. Table IV shows the team totals.

**TABLE IV**  
**GROUP RESULTS OF CONCEPT SCORING (IN RANKED ORDER)**

	Score	Ranks
<b>K - Moveable Grid</b>	561	1
<b>G - Grid Central Axis Rotation</b>	556	2
<b>O - Lead Sandwich</b>	547	3
<b>A.1 - Multiple Grid Changer with 180° Planar Rotation</b>	515	4
<b>AG - Multiple Grid Changer with Central Axis Rotation</b>	485	5
<b>A - Multiple Grid Changer</b>	451	6
<b>H - Liquid Adjustable Grid</b>	402	7
<b>C - Rotating Wheel</b>	309	8
<b>B - Overhead Projector</b>	300	9
<b>M - Semi-conductor</b>	157	10

It is the intent of the TEC to pursue the top four designs in a more in depth fashion. As Table IV shows, the concept scoring phase yielded the Moveable Grid, Grid Central Axis Rotation, Lead Sandwich and Multiple Grid Changer with 180° Planar Rotation as the concepts to be pursued further. Before this happens, however, it is important to conduct a sensitivity analysis on the concept scoring results in order to validate the results.

### Concept Scoring Sensitivity Analysis

In order to legitimize the concept scoring matrix results, a sensitivity analysis was conducted. This was done by altering the weights of certain chosen criteria to produce alternate concept rankings. Comparing the concept rankings obtained from the original scoring scheme to those obtained from the additional scoring schemes displays whether the original top four concepts remain at the top despite some chosen weighting changes Table V shows the rankings from the sensitivity testing compared to the original results, by highlighting the top four concepts with each modified scoring scheme.

**TABLE V**  
**WEIGHTING CHANGE SENSITIVITY ANALYSIS OF GROUP RESULTS**

Concept	Normal	Manufacturing = 10	Dosage = 0	Dosage = 10	Cost = 0	Cost = 10
K - Moveable Grid	1	1	1	3	1	2
G - Grid Central Axis Rotation	2	2	2	2	2	1
O - Lead Sandwich	3	5	3	1	2	3
A.1 - Multiple Grid Changer with 180 Planar Rotation	4	3	4	4	4	4
AG - Multiple Grid Changer with Central Axis Rotation	5	4	5	5	5	5
A - Multiple Grid Changer	6	6	6	6	6	6
H - Liquid Adjustable Grid	7	8	7	7	7	7
C - Rotating Wheel	8	7	8	8	8	8
B - Overhead Projector	9	9	9	9	8	9
M - Semi-conductor	10	10	10	10	10	10

The modifications to the original weightings shown in Table V were chosen for specific reasons.

Increasing the manufacturing weight to 10 was based on the idea that if it is not easy to manufacture then it is not a good design. Changing the dosage weight to 0 and 10 was chosen in order to see what effect, if any, this would have. Since dosage is dependent on both grid ratio and SID, including it along with the others could have too heavily weighted this consideration. Finally, changing the cost weighting to 0 and 10 was chosen to see what effect totally neglecting or heavily weighting cost would have.

Table V clearly shows that although there were slight ordering changes, there were no large changes to the top four regardless of what scoring scheme was chosen. Only the scoring scheme with the manufacturing weight increased to 10 produced an anomaly. In this scheme, the Lead Sandwich placed 5<sup>th</sup> overall. This change can be attributed mainly to the TEC's uncertainty of manufacturing costs at the micrometer level. The other three designs in the top four do not involve movement of the individual septa and for this reason they scored better in terms of manufacturing.

Another method used to evaluate the validity of the concept scoring matrix results was to check whether the results would change if individual group members would be left out of the results. The notion behind this evaluation was that individually, a group member could be unduly biased either for or against a concept. The results from this analysis are summarized in Table VI below.

**TABLE VI**  
**CONCEPT RANKINGS WHILE EXCLUDING INDIVIDUAL TEAM MEMBERS**

Concept	Normal	Excluding Nathan	Excluding Jordan	Excluding Graeme	Excluding Brian
K - Moveable Grid	1	2	2	2	1
G - Grid Central Axis Rotation	2	1	3	4	2
O - Lead Sandwich	3	3	1	1	4
A.1 - Multiple Grid Changer with 180 Planar Rotation	4	4	4	3	3
AG - Multiple Grid Changer with Central Axis Rotation	5	6	5	5	5
A - Multiple Grid Changer	6	5	6	6	6
H - Liquid Adjustable Grid	7	7	7	7	7
C - Rotating Wheel	8	8	9	8	9
B - Overhead Projector	9	9	8	9	8
M - Semi-conductor	10	10	10	10	10

It is clear from Table VI that the top four concepts remain unchanged even though there is some change in the order. These four designs were presented to CCM who in turn chose the Lead Sandwich and the Multiple Grid Changer with Central Axis Rotation for further consideration. It is important to note that the Lead Sandwich name was changed to the Adjustable Septa and the Multiple Grid Changer with Central Axis Rotation name was changed to the Multiple Grid Changer for further researching of these concepts.



## References

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# **Appendix B – Multiple Grid Changer Analysis**

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This appendix provides an analysis for the components of the multiple grid changer design.

### Weight of an Anti-Scatter Grid

This section of the appendix calculates the weight of an anti-scatter grid.

Septa width = 0.016 mm

Interspace width = 0.3 mm

Height of septa = 1.5 mm

Added materials on top and bottom = 3.5 mm

Assume that septa material is lead, interspaced material and added material is carbon fiber.

Density lead = 11.34 g/cm<sup>3</sup> [1]

Density carbon fiber = 1.8 g/cm<sup>3</sup> [2]

$$\text{Percent lead in septa layer} = \frac{\text{septa width}}{\text{Total width}} = \frac{0.016}{0.016+0.3} * 100 = 5\%$$

$$\text{Percent septa layer is in entire grid} = \frac{\text{septa height}}{\text{Total height}} = \frac{1.5}{1.5+3.5} * 100 = 30\%$$

$$\text{Percent lead in entire grid} = 5\% * 30\% = 1.5\%$$

$$\text{Total volume of anti-scatter grid} = \text{width} * \text{length} * \text{height} = 240 * 300 * 5 = 360000 \text{ mm}^3 = 360 \text{ cm}^3$$

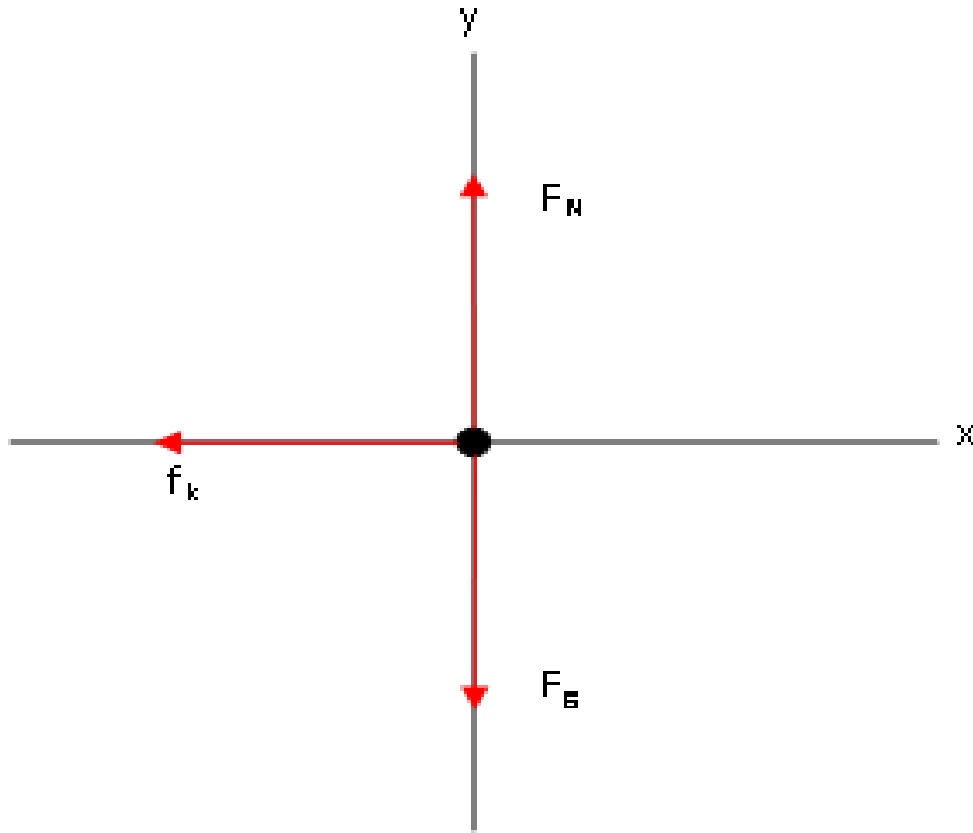
$$\text{Therefore total weight of grid} = \text{volume} * \text{density} = (360 * 0.015 * 11.34) + (360 * 0.985 * 1.8) = 700 \text{ g}$$

Therefore we can assume that the total weight of the grid is 1 kg. This is a conservative estimate and will also account for additions to the grids to reinforce them and provide a surface that can be slid along.

### Grid Drive System

The first analysis is to determine the motor requirement for the grid drive system. It will be assumed that each set of two wheels will be powerful enough to move the grid. The grid holder will be made of steel and the grid frames on the sides of the grids will be made of polyethylene. This material

combination will create a coefficient of friction between the two of  $\mu_k = \mu_f = 0.07$  [3]. Therefore the force required to move the grid is calculated as show in Fig. 1:



**Figure 1. Force diagram of the friction when sliding the anti-scatter grids on the grid rack.**

$$F_k = \mu_k * F_N = 0.07 * 1kg * 9.81 \frac{m}{s^2} = 0.69 N$$

The anti-scatter grid must travel a distance of 250 mm allowing a 10 mm space between the grid holder and the entrance to the breast table. An acceptable time to complete this distance is about one half of a second. If we assume that the grid undergoes constant acceleration and then constant deceleration the required values would be as follows:

$$x - x_0 = v_0 t + \frac{1}{2} a t^2$$

$x = displacement$

$x_0 = \text{initial displacement}$

$v_0 = \text{initial velocity}$

$t = \text{time}$

$a = \text{acceleration}$

If there is constant acceleration and constant deceleration then to calculate the value of acceleration half of the distance and half of the time will be used for the calculation. As well it will be assumed that the initial velocity and position are equal to 0.

$$\frac{250}{2} = (0) \left( \frac{0.5}{2} \right) + \frac{1}{2} a \left( \frac{0.5}{2} \right)^2 \rightarrow a = 4 \left[ \frac{m}{s^2} \right]$$

From the required acceleration this means that the required force to be put on the grids by the rollers is as follows:

$$F = ma = F_{\text{applied}} - f_k$$

$$F_{\text{applied}} = ma + f_k = 1kg * 4 \frac{m}{s^2} + .69 = 4.69 N$$

This force is then split between each of the rollers contacting the grids. Therefore the maximum force required by one roller is as follows:

$$F_{\text{roller}} = \frac{F_{\text{applied}}}{2} = \frac{4.69}{2} = 2.35 N$$

Since these are friction rollers it will be important that the rollers are forced against the grid frames with enough force to not slip. It will be assumed that it will be possible to have rollers that are made of a rubber compound and have a coefficient of friction of 0.8 with the polyethylene [3]. The required force will be as follows:

$$F_{\text{roller-normal}} = \frac{Fr}{\mu_k} = \frac{2.35}{0.8} = 2.94 N$$

The grid frames sit in a track. This track resists the force applied by the rollers onto the grid frames. This ensures that no force is transmitted through the grids themselves. The sides of the track will also add to the force required to move the grids since there will be friction. The extra friction force will be:

$$F_{friction-guides} = F_{rn} * \mu_k = 2.94 * 0.07 = 0.21 \text{ N}$$

Therefore we can conservatively assume worst case that the forces will be as follows:

$$F_r = 3 \text{ N}$$

$$F_{rn} = 3.5 \text{ N}$$

Now since the diameter of the drive rollers are 0.02 m the torque will be as follows:

$$T = F * \frac{d}{2} = 3 * 0.01 = 0.03 \text{ N} \cdot \text{m}$$

Now to find the maximum rpm of the motor we can find the maximum velocity of the grid.

$$v = at$$

$$v_{max} = 4 * 0.25 = 1 \frac{\text{m}}{\text{s}}$$

$$rpm = \frac{v}{\pi d} = \frac{1}{\pi * 0.02} * 60 = 955 \text{ rpm}$$

Therefore the maximum power supplied by the motor is as follows:

$$P = T * \omega = 0.03 * 955 * \frac{1}{60} * 2\pi = 3 \text{ W}$$

## Linear and Rotary System

The weight of the grid rack is calculated as follows:

$$\text{Grid weight} = 6 * 1\text{kg} = 6 \text{ kg}$$

$$\text{Rack weight} = 4.2\text{kg} \text{ (from solidworks model)}$$

$$\therefore \text{Total weight} = 6 + 4.2 = 10.2 \text{ kg}$$

The static force on the bottom actuator will be as follows:

$$F_{static} = m * g = 10.2 * 9.81 = 100 \text{ N}$$

The maximum acceleration the grid rack can move down without having the grids become detached from the grid rack is that of gravity. When the grid rack moves to a new location it moves a distance of

20mm. If we assume that the required time complete this movement would be 0.25 seconds. We can also assume that the linear actuator would be capable of constant acceleration and constant deceleration. The analysis is as follows:

$$x - x_0 = v_0 t + \frac{1}{2} a t^2$$

$$a = 0.01 * \frac{2}{0.125^2} = 1.28 \frac{m}{s^2}$$

Now the dynamic force on the actuator would be as follows:

$$F_{dynamic} = m * a = 10.2 * 1.28 = 13.06 N$$

$$\therefore F_{total} = F_{dynamic} + F_{static} = 100 + 13.06 = 113 N$$

When the grids are rotated it is necessary to determine the torque that will be required.

$$T = \alpha I$$

$$T = \text{torque}$$

$$\alpha = \text{angular acceleration}$$

$$I = \text{mass moment of inertia (grids and grid rack)} = 154538871.3 \text{ g} * \text{mm}^2 \text{ (Solid works model)}$$

$$\phi = \frac{1}{2} \alpha t^2$$

$$\phi = \text{angle (rad)}$$

Again to determine the acceleration to get to half of the rotation in half the time the following formula is used.

$$\alpha = \frac{\pi}{2} * 2 * \frac{1}{0.25^2} = 50.3 \frac{rad}{s^2}$$

$$T = 50.3 * 154538871.3 * \frac{1}{1000} * \frac{1}{1000^2} = 7.77 N \cdot m$$

We can also find the maximum angular velocity to determine the maximum power required for the rotation.



$$\omega = \alpha t = 50.3 * .25 = 12.6 \frac{rad}{s}$$

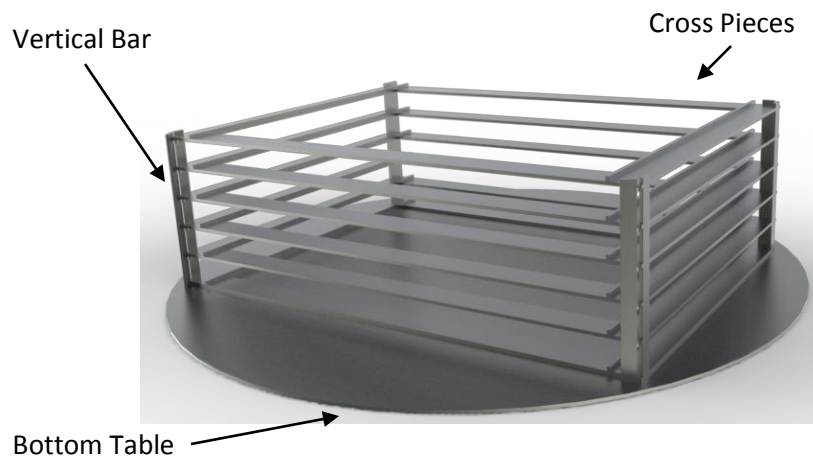
Now the power is calculated as follows:

$$P = T\omega = 7.77 * 12.6 = 98 \text{ W}$$

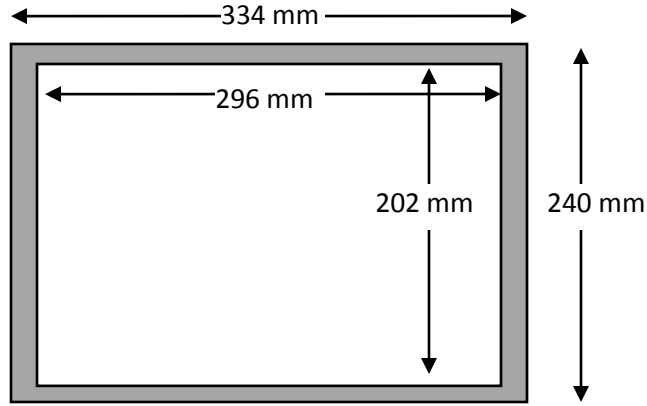
## Raw Material Calculations

### Sheet Metal Required for Grid Rack

The grid rack is made of sheet metal, so the total area of the sheet metal needed is required to estimate the cost. The rack can be broken down into three different categories as shown in Fig 2. the cross pieces on which the grids sit, the vertical bars at the corners of the rack and the bottom circular table. Detailed calculations showing the amount of sheet metal needed to construct the grid rack are shown.



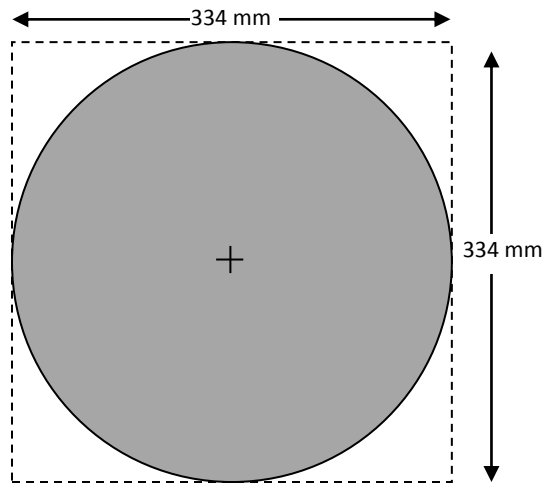
**Figure 2. Grid rack with three different categories Indicated.**



**Figure 3. Schematic of cross-piece area.**

The area of sheet metal required for each individual cross-piece shown in Fig. 3, is given by the following equation:

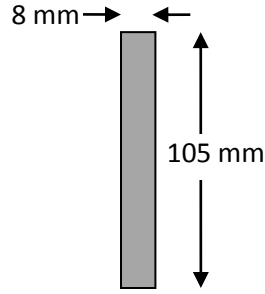
$$A_{crosspiece} = (334 \times 240) - (296 \times 202) = 20,368 \text{ mm}^2 \times \frac{1\text{m}^2}{1000^2\text{mm}^2} = 0.02\text{m}^2$$



**Figure 4. Schematic of bottom table area.**

The area of sheet metal required for the bottom plate of the grid rack, shown in Fig. 4, is given by the following equation:

$$A_{bottomtable} = 334 \times 334 = 111,556\text{mm}^2 \times \frac{1\text{m}^2}{1000^2\text{mm}^2} = 0.112\text{m}^2$$



**Figure 5. Schematic of vertical bar area.**

The area of sheet metal required for each corner piece of the grid rack, shown in Fig. 5 is given by the following equation:

$$A_{verticalbar} = 8 \times 105 = 840mm^2 \times \frac{1m^2}{1000^2mm^2} = 0.00084$$

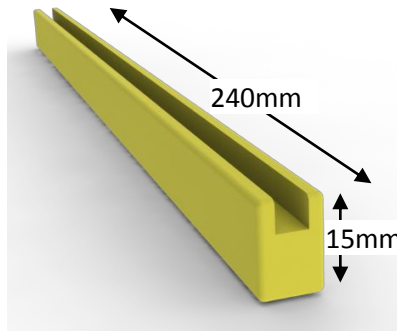
The grid rack includes six cross-pieces, one bottom plate and four corner pieces thus the total amount of sheet metal needed is given by the following equation:

$$A_{total} = 6(A_{crosspiece}) + A_{bottomtable} + 4(A_{verticalbar}) = 6(0.02) + 0.112 + 4(0.00084) = 0.24m^2$$

For simplicity within the report, the total amount of sheet metal required will be rounded up to 0.3 m<sup>2</sup>.

### **Polyethylene Required for the Side Frames**

The side frames are made of polyethylene, so the amount of polyethylene is required to estimate the cost. A detail picture of the side frame can be seen in Fig. 6. Detailed calculations showing the amount of polyethylene required to construct the side frames are shown below. The side frame could be machined from a 10 mm sheet of polyethylene and for this reason area measurements of the dimensions other than the 10 mm thickness are used.



**Figure 6. Side frame with dimensions**

$$A_{sideframe} = 15 \times 240 = 3600mm^2 \frac{m^2}{1000^2mm^2} = 3.6 \times 10^{-3} m^2$$

There are two side frames for each grid and there are six grids, therefore the total amount of polyethylene is as follows.

$$A_{sideframeTotal} = 3.6 \times 10^{-3} \times 6 \times 2 = 4.32 \times 10^{-2} m^2$$

For simplicity within the report, total amount of polyethylene needed will be rounded up to  $0.05 m^2$ .

## References

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