Improvised Explosive Devices in Iraq: Countermeasures using an Energetic Electron Beam

MIDN 1/C Gonzales

MIDN 1/C Reichl

United States Naval Academy
Mechanical Engineering Department
2006

Advisors:

Prof. Martin Nelson, Mechanical Engineering Department

Visiting Prof. James Ziegler, Aerospace Engineering Department

This work has been supported by:
Scott Steward
U. S. Department of Defense
Naval Explosive Ordnance Disposal Technology Division
Naval Support Facility Indian Head

Table of Contents

Abstract:

The objective of the project is to research, develop and design an exit window for a portable linear accelerator (LINAC) which is to be used for countermeasures against improvised explosive devices (IED). In order to be practical, the LINAC needs to propel the electron beam into the atmosphere with an effective range of 200 feet. For the system to be cost effective, a commercially available LINAC is being modified. A major problem facing this technology is allowing the electron beam to escape the accelerator and enter the atmosphere without a significant loss of beam energy or dispersion. In order to operate, the LINAC's internal pressure of 10^{-9} Torr must be maintained. Thus, an exit barrier that will not decrease the energy of the beam while still providing the proper structural support was designed and procured. This design report will summarize the research and development of several components of the project and provide information of works in progress and future plans. There were three main choices for this exit barrier at the beginning of the project: the three choices were a metal barrier, a plasma window, and a ferrofluidic seal. While all of these are viable options that offer possible solutions, a fourth option of a combination of a rotating hollow shaft and metal (beryllium) foil structurally supported by a stainless steel mesh was decided upon. Test results of the mechanical properties of a stainless steel mesh and beryllium are also included. The flange design used in the exit window and parts procurement information is also included. Finally, a focusing element was designed and built in order to check the beam location and its dispersion.

Background / Problem Statement:

The United States military is in dire need of countermeasures for improvised explosive devices (IED), such as road side bombs, explosives with electronic delay timers as well as to friendly unexploded bombs with electronic safe and arm (ESA) fuses. The *Washington Post* published an articled entitled "Stronger IEDs Now to Blame for Half of Fatalities in Iraq" which stated IEDs accounted for 214, or 63%, of the total fatalities in Iraq from March to September 2005. These weapons often have electronically controlled detonators that can be activated remotely. Such devices are often constructed with simple communication devices that are readily available (i.e. walkie-talkies, garage door openers, etc.). Today, communication devices contain integrated circuits within their components. The integrated circuits can be deactivated if exposed to high energy electrons.

One promising technology under development by the Office of Naval Research (ONR) is to modify high energy LINACs that are in use today in hospitals and medical facilities. Since there are thousands of these LINACs in commercial use, these machines are both highly reliable and have a relatively low cost. Commercial LINACs can produce electrons with energies of 18 MeV or higher.

The project was initiated with a goal to disarm an IED at 200 feet. Based on recent experiments, only 3 MeV is needed to "kill" the target. Due to energy loss to the air as well as energy loss due to the exit window an initial energy of 18 MeV is required if the beam is disarm an IED. The range of electrons in air as a function of MeVs can be seen in Figure (1). According to the figure an electron with initial energy of 18 MeV would travel about 230 ft in air.

An exit window that can minimize the electron energy loss is a major feature of the system. The backbone of the system is the accelerator head that is one meter in length, which can be seen in Figure (2). This accelerator is a radio frequency type that can produce an electron beam at 6, 12 or 18 MeV with a maximum beam current of 10 mA of electrons on a direct current (DC) basis**.** While the exact kill mechanism is unknown, it is believed the electrons induce displacement damage within the integrated circuits that compose the detonating device of the IED.

A typical device wrapped in burlap is shown in Figure (3). Figure (3) was taken during a preliminary test of the LINAC to determine the effects of the electron beam on potential targets. The energy that the LINAC has is displayed by the damage it did to one such potential target, a battery powered wireless doorbell ringer, which can be seen in Figure (4). The doorbell ringer was “zapped” for duration of one second from a distance of one foot.

The accelerator operates at almost perfect vacuum pressure: 10^{-9} Torr. If the internal components are exposed to an increased pressure, such as atmospheric pressure, catastrophic failure will occur. One of the major difficulties of this project is that exit windows for linear accelerators are not mature technologies. Linear accelerators’ electron beams are rarely brought out into the atmosphere. In medical applications, the exit window is a metal with a high atomic number, such as tungsten, which creates X-rays. The target of the X-rays is usually no more than a meter away from the LINAC, eliminating the concern for beam dispersion. There are no known technologies in which an electron beam has been produced that can travel the distances required for this project while remaining safe for those handling the machine and in the surrounding area. An exit window that allows the project to reach its goal was researched and designed.

Objectives: The main objective of this project was to research, develop and design an exit window that is capable of delivering an electron beam with enough energy to “kill” a target 200 ft away. The current density required to this “kill” a target, or render it inoperable, is $10\mu A/cm^2$, which requires a beam energy of 3 MeV or greater. There were four exit window configurations that have been selected for possible use: a metal barrier, a plasma window, a ferrofluidic seal, and a hollow rotating shaft.

Project Deliverables: The following are the project deliverables**:**

1. Design of exit window based on selected seal type to include:
    - a) Thermal analysis of seal types
    - b) Structural (pressure) analysis of seal types
    - c) Design of supplementary components
2. Vendor selection and system procurement

Concept Design:

The project can be divided into two major technical parts, the choice of vacuum seal and the components for the seal. There were originally three viable options for the vacuum seal, with a fourth being added on as a combination of two options.

The first option was a very thin end window, which would be fabricated out of either nickel or beryllium. A barrier of only a few microns thickness must be used to ensure that enough electrons with sufficient energy passes through to accomplish the overall project goal of destroying the IED at a range of 200 feet. The beam is focused within the LINAC and passes through an area of approximately 1 cm^2. The thermal and structural aspects of the exit window have been examined to determine its feasibility. Calculations of the energy flow of the system, the heat absorbed by the foil and the ability of the foil to dissipate the heat were done based on the thickness and area of the window. The size of the window was also be analyzed based on its ability to withstand the pressure differential necessary to operate the LINAC.

The second option was a plasma window; an example can be seen in Figure (5). A plasma screen is created by running an electric current through an inert gas. The main advantage of the plasma screen is that it would allow the most beam energy to pass through the end window compared to the other alternatives. Unfortunately the plasma window can only withstand a pressure differential of 10^{-3} Torr. A complex pumping system would have to be designed and constructed. The power required to run the plasma window alone is over 6 kilowatts based on a recent Brookhaven National Laboratory memorandum. Thus, in addition to the pumping system, a cooling system would be required to dissipate the heat created by the plasma window and associated pumps. A final caveat of the plasma window is that it is not a proven technology. At present, plasma screens are only produced by one vendor. Reliability and fatigue issues are only two of the many unknowns associated with an unproved technology.

The third option for the barrier is a ferrofluidic seal. A ferrofluidic seal uses a magnetically susceptible fluid contained in a strong magnetic field to create a seal. An example of a ferrofluidic seal can be seen in Figure (6). Current ferrofluidic seals are used for crude devices and would require an elaborate pumping system similar to the plasma window.

The fourth option, which was decided upon after the other three options were evaluated, was to have a hollow rotating shaft with a simple metal barrier at the end. The purpose of having the rotating shaft would be to solve heat dissipation issues. If the beam was placed off center, and the shaft was rotated, the beam would be hitting a different part of the metal as long as the shaft kept rotating. This system required design of multiple flanges and analysis of the structural properties of the metal used in the end window.

Concept Evaluation and Selection

The final selection was the fourth option, a hollow rotating shaft with or without a mesh-supported beryllium foil. There were several reasons for selecting the hollowed shaft set-up. First, it was the one of the simplest designs. In this case, simpler meant less pumps, external power sources, and cooling systems compared to the other alternatives. Second, unlike the plasma screen, it does not rely on technology never before tested or only manufactured by one vendor. Finally, this idea was much less expensive than the plasma window. A plasma window alone costs an estimated \$100,000. There are special parts such as the flanges that have to be fabricated but the cost for the entire system came to an estimated \$86,617.

The ferrofluidic seal was very promising at the beginning of the selection process. However, it was eliminated completely because no company could guarantee a seal beyond 10^{-6} Torr. This completely eliminated the ferrofluidic seal from being a feasible option.

The simplest concept from the beginning used a thin beryllium or nickel foil as the sole barrier between the atmosphere and the near vacuum-like conditions of the

LINAC. The problem with this idea was the foil, because it would have to be thick enough to maintain a pressure differential of one atmosphere, could be too thick to allow the necessary beam energy to pass through it. However, a calculation was done to determine if using such a foil was plausible. Assuming that the beryllium acts as thin walled pressure vessel that behaves the same in compression as in tension, a minimum thickness was calculated. The calculation was completed using Timoshenko and Woinowsky-Krieger's equation for a stressed membrane with a clamped boundary. The maximum stress will occur at the boundary. These calculations were performed using the EES program and the output table is present in Appendix A. However, since the beryllium would be heated up by the LINAC, a series of knockdown factors that correlate the yield strength of beryllium to temperature were implemented. The minimum thickness was plotted over these temperatures, 200 to 1200 degrees F, using the knockdown factors. This plot can be seen in Figure (7).

The thickness ranged from 143.8 microns at 200 F to 297.3 microns at 1200 F. As per the American Society of Mechanical Engineers (ASME) pressure vessel code, a factor of safety of 2 was used. These thicknesses were considered to be far too thick, because they would cause beam dispersion and energy loss that would result in not reaching the goal of having 3 MeV at 200 ft with 10μA/cm^2.

To compensate for the beryllium's lack of required strength, a support system was designed. Adding another foil of a different material would be counterproductive and cause the same effect of increasing the thickness of the beryllium. Instead, a stainless steel mesh support was incorporated into the design.

The stainless steel mesh chosen was a computer woven, optical grade weave that is made of the steel alloy T304. Each mesh has an associated transparency which corresponds to the amount of wires per inch. The minimum transparency was 75%. A minimum transparency was established because if the transparency was lower than 75%, there would be too much interaction between the beam and the mesh, decreasing the energy but, more importantly, causing significant beam dispersion. Beam dispersion would increase the environmental radiation associated with the system as well as deliver less current to the target. A mesh with a high transparency would allow the electron beam to travel through with minimum electron scattering. The mesh is very delicate and can be torn even with careful handling. A picture of the mesh can be seen in Figure (8).

Sample meshes were ordered from TWP Incorporated. TWP Incorporated is a California based company that specializes in meshes. TWP Incorporated had no known material properties for this mesh and did not release the name of the actual manufacturer. Without material properties, the mesh was useless. Consequently, an experiment was developed to test this mesh to determine its strength. The main goal of the experiment was to see if the mesh can withstand a one atmosphere (14.7 psi) pressure differential.

To run this experiment, shop air was applied to the mesh. The mesh was clamped between two brackets. The front bracket would have a threaded hole that lead to the mesh. Shop air would then be supplied through a regulator. The experimental setup can also be seen in Figure (9). Once the mesh failed, the pressure at failure was recorded. Displacement, strain, or stresses were not of concern. The test was strictly to determine the pressure at which the mesh failed.

The two brackets were designed using I-DEAS and SolidEdge. The Naval Academy TSD shop fabricated the two brackets. These brackets can be seen in Figure (9). The front bracket is 0.25 inches thick with a 0.375 inch hole drilled through the entire bracket. This hole was threaded with a National Pipe Tapered (NPT) standard thread for the first 0.125 inches. An air hose was connected with a regulator and was attached to the bracket using the threading. The air blew into a 0.375 inch cavity that was 0.125 inches deep, which is the same diameter that the exit window of the LINAC will have. Attached to the back of this hole was a piece of Mylar®. Mylar® was chosen because it is a weak material that would not withstand much of a pressure differential. The Mylar® was necessary because without some sort of solid barrier, the air would just blow completely through the mesh. Behind the Mylar, the mesh was mounted.

The back plate had the same 0.375 inch hole drilled all the way through it. The plate was 0.25 inches thick. The back plate also had an O-ring groove cut out of it. The two brackets were clamped together with an O-ring, the mesh, and a piece of Mylar in the middle. The O-ring provided the necessary seal to ensure the air was not escaping from in between the brackets. It was very important to have the brackets very smooth and without sharp edges since the steel mesh is so fragile. The TSD shop was notified of these requirements and fabricated the brackets with these requirements in mind.

The experiment was undertaken with few problems. The only safety concern was having a piece of the mesh detach from the rest of the mesh and be thrown into an eye. To prevent this, glasses were worn by all participants. The pressure was applied at a very slow rate (1 psi every 5 seconds). An observer watched the screen to ensure it had not broken. After every 5 psi was added, the mesh was examined by a 10x magnifying lens to look for signs of rupture. The two meshes were tested to failure. The Mylar® was also tested to failure by itself. This was done as a control experiment to see how much of a pressure differential the Mylar could withstand. The results are shown in Table 1.

Table 1: Mesh testing Results

Run	Mylar® (psig)	Mesh 1 (psig)	Mesh 2 (psig)
Run 1	5	23	>31
Run 2	7	24	>31
Average	6	23.5	>31

Mesh 1 was the stainless steel mesh with 50 threads per inch and a transparency of 88%. Mesh 2 was 100 threads per inch and a transparency of 79%. The wires were 0.0012 inches (30.5 microns) in diameter. The only problem with the experiment was with mesh 2. Each time the pressure was increased to greater than 31 psig, the air tubes would blow off the regulator. More tests would have been conducted but since there was a limited supply of meshes and the test was destructive, a limited amount of tests were conducted.

The results from the experiment were encouraging. These results show that the meshes, in support of a beryllium foil, would be able to withstand greater than a one atmosphere pressure differential. A thin mesh of 80 threads per inch and a transparency of 81% was tested as a compromise of the strength and transparency. The results are shown in Table 2.

Table 2: Mesh 3 Testing Results (81% Transparency)

Mesh 3	psig
1	26
2	29
3	27.5
4	27.5
5	28
Average	27.6

The experiment showed that the 80 threads per inch mesh with 81% transparency could hold pressures in excess of what is required for the application. This is well within the constraints of the problem and provides an increased level of transparency over the mesh 2 (79% transparent). Both options are planned for testing.

To ensure the beryllium exit window could withstand the heat that results from the electron beam, a lump capacitance model of the beryllium foil was developed. These calculations can be seen in Appendix B. Based on energy loss calculations done by Professor Zeigler, the amount of heat deposited in the foil (Q) was determined to be independent of thickness. Due to the fact that the heat will be deposited into the foil in a matter of a few seconds, the convection portion of the lumped capacitance model can be neglected. The size of the beryllium window is limited by the rotary shaft diameter of 7.62 cm (3 inches). Since the electron beam has a diameter of 0.5 cm, a beryllium foil annulus with a difference in the inner and outer radius of 1 cm was chosen. The lumped capacitance model was solved for r_i, the inner radius of the annulus. The area of the entire annulus was considered to be absorbing the electrons' heat flux because it will be rotating and exposed to the beam. The change in temperature over time was plotted versus the inner radius to determine the maximum inner radius that could be used without reaching the melting temperature of Beryllium. This graph can be seen in Figure (10).

The largest possible inner radius, due to the beam width is 2.81 cm. The results show that an annulus with an inner radius of 2.81 cm will rise at a rate close to 50 degrees C per second. Since the beryllium will only be on for several seconds at a time, the final temperature of the beryllium will be well below beryllium's melting temperature (1278 degrees C). It takes 13 seconds of the beam being on to reach half of the melting temperature. Thus, system integrity will be maintained.

A lump capacitance model was applied to a stainless steel mesh and beryllium foil. The fact that the surface is a mesh does not affect its heat absorption because as the area is decreased, the amount of heat absorbed decreases proportionally. A comparison of the temperature rise versus exposure time for beryllium foil with an inner radius of 2.25cm and stainless steel mesh at various beam energies can be seen in Figure (11). Figure (11) shows that the temperature of the foil and mesh will fall well below the melting temperature of either the beryllium or stainless steel.

Another factor that affects the thickness of foil used is the added dispersion of the beam that it causes. Simulations run by Dr. Zhao showed that as the foil was made thicker it would greatly increase the beam dispersion. Professor Zeigler ran tests to measure the beam dispersion due to varying thicknesses of Beryllium foil using the

LINAC. The results of his experiment, which can be seen in Figure (12), show that increasing the foil thickness to up to 25 microns had no affect on beam dispersion.

Following this experiment, a test of the beryllium foil's strength was done to determine if it could hold the pressure differential needed. Photos from the test can be seen in Figure (13). The results of the test can be seen in Table 3.

Table 3: Beryllium Testing

Be Foil	psig
10μm	21.5
25μm	33.0

The results of this experiment showed that the beryllium would be able to hold the pressure differential on its own. However, the results are most likely skewed. Due to jagged edges on the testing brackets, stress concentrations were formed and the beryllium ripped around the edges. The beryllium was expected to have a hole punched through the center of it as the stainless steel meshes had done. It is expected that the beryllium would have held more of a pressure differential if the brackets had polished edges.

Only one test was run on each foil thickness because of the high cost of the samples. The two samples cost $1400 combined. The results show that a 25 micron foil could support double the needed pressure differential. This allows for additional options for the end window using a 25 micron Beryllium foil with no stainless steel support.

Overall, to compare the designs, the following concept evaluation table was constructed. Feasibility is how proven the technology is and how likely it is able to be incorporated into the design. Each design was assigned a score from 1-10 for each category. A score of 1 corresponds to the best score and a score of 10 corresponds to the worst.

Table #4: Evaluation Matrix

Device	Feasibility	Energy Absorption	Cost	Total Points
Plain Foil	1	10	1	12
Plasma Window	8	2	10	20
Ferrofluidic Seal	10	3	3	16
Rotating Shaft w/foil	2	4	4	10

The rotating shaft with a beryllium foil was selected, because it had the lowest score.

The entire exit window system had to be designed. A complete system sketch can be seen in Figure (14). A hollow rotating shaft will be the main component of the exit window. The shaft was purchased from Rigaku®. An engineering drawing for this part can be seen in Figure (15). A picture of the rotating shaft to be used in the project can be seen in Figure (16). The rotating shaft comes with a drive wheel to which a motor system will be attached to rotate the shaft. The calculation of the torque required to turn the shaft was just recently received. A motor and drive train selection will be made shortly.

Upstream from the rotating shaft is a fast acting valve and a series of nipples. The fast acting valve was procured as a whole system from VAT and will act as a safety valve in an attempt to save the LINAC from catastrophic failure should an end window rupture occur.

The nipples are needed so roughing and high vacuum pumps as well as the fast acting valve can be integrated into the system. All of the nipples were procured through LDS Vacuum Products, Inc. Catalog pictures of the ordered nipples can be seen in Figure (17). A 6-way cross nipple was procured so a pump could be used to initiate the vacuum. An ISO63 to conflate adapter was purchased to mate the offset flange with one of the conflats.

To ensure that the beam exited near the edge of the rotating shaft, so that the beam energy could be dispersed around the foil, an offset flange was designed using SolidEdge and can be seen in Figure (18). This flange was designed specifically to mate with the Rigaku® shaft. It requires fine finishes where the O-ring from the rotating shaft will be pressed against it in order to ensure the O-ring doesn't tear. The flange offsets the beam by 1 inch.

Flanges to hold the Be foil were also designed using Solid Edge and can be seen in Figure (19). The flanges each have a 1/8th inch thick cut-out at a distance of 1 inch from the center, which is where the beam will pass through the beryllium. The beryllium will be clamped between the two flanges. One flange has two O-rings grooves cut out of it to ensure a good seal is formed. The flanges will mate with the other end of the Rigaku® shaft. The first system that will be tested is a 10 micron beryllium foil with 80 threads per inch mesh. This combination will provide the best balance between electron dispersion and structural support. If there are problems with radiation due to heat absorbed by the stainless steel mesh, a 25 micron thick beryllium foil system will be tested next. The offset and exit flanges drawings were sent to Technical Options for review and fabrication. The flange, foil and mesh set-up can be seen in Figure (20).

One problem the project faced during the testing phase was that there was no true way to measure the location or focus of the beam. While a test could tell if a target was being hit, it could not tell what part of the beam was hitting it. To alleviate the problem, a focusing element was designed.

For this, an 18" by 21" Plexiglas board had a 2" diameter hole cut out of its center. Next, pieces of copper were attached around the hole, filling up an 18" by 18" area around the hole through which the beam should pass. The purpose of the copper was to have the electrons hit the metal and induce an electrical current in it. Altogether, 8 pieces of copper were used each with a quarter inch gap between them. The focusing element can be seen in a drawing in Figure (21) and photograph following its fabrication is in Figure (22). It was important that there be infinite resistance between the pieces of metal or else current would pass from one piece of metal to the next. A metal with a high electrical conductivity was needed so copper was selected. Copper has an electrical conductivity of $59.6\ 10^6/(\text{m}\cdot\Omega)$.

To measure the current, a 4-channel oscilloscope is currently being procured. A copy of a memo listing possible oscilloscope models and vendors was submitted to Prof. Nelson and Prof. Ziegler to be purchased can be seen in Figure (23).

The oscilloscope will assist in focusing the beam and testing its accuracy is that each lead will be attached to a different quadrant on the focusing element. This will produce four different current signals with each signal's magnitude varying. The beam will then be realigned until all four signals have the same magnitude. This will indicate that an equal amount of current is being sent through all four quadrants. At this point, the beam will be centered. Another benefit of this focusing element is that it gives the operators some information of the beam spread. A small current means that the beam spread is relatively small, most of the beam is passing through the 2” hole. This is the reason why 8 pieces of copper were used instead of just 4. The oscilloscope can be hooked up to the outside sheets of metal and to gain a better understanding of the beam spread. The element will stay the same as constructed by the students except the nuts on the back will be changed to wing nuts in order to make attaching the oscilloscope easier.

Program Management: The team members are:

MIDN 1/C Christopher Gonzales
5th Company
410-991-3531
m062310@usna.edu

MIDN 1/C Mathew Reichl
26th Company
207-730-1022
m065610@usna.edu

The Gantt chart (Figure(24)) is a rough timeline estimate. Many large delays have occurred to procurement of components taking more time than estimated. Meetings with Professor Nelson and Prof. James Ziegler were held weekly. Also assisting with the project is Mr. Kelly Delikat, Dr. Zhongxiang “George” Zhao, and CDR Sean Nolan, USNR. A full list of acknowledgements can be seen in Appendix C. Also, members of the current USNA faculty are being utilized for their expertise in different areas, such as Professor Peter Joyce and composites testing. The team charter is in Appendix D.

Budget: The budget for the front window is broken down as follows:

Table #5: Budget

Item	Quantity	Cost (Individual)	Total
Faraday Cup Testing	1	$7,200.00	$7,200.00
Fast Acting Valve	1	$18,095.00	$18,095.00
Be Foil	4	$3,000.00	$12,000.00
Rigaku Shaft	1	$7,500.00	$7,500.00
SS Mesh	1	$100.00	$100.00
Motor System	1	$150.00	$150.00
Vacuum (Nipple) Products	1	$572.00	$572.00
Technical Options			$41,000.00
>Build/Machine 5 Flanges	1	$15,000.00	
> Assemble/Integrate VAT	1	$2,000.00	
>Assemble Exit Port System	1	$4,000.00	
>Assemble Beryllium Window	1	$8,000.00	
>Modifications to E-Zapper	1	$2,000.00	
>Integrate Motor/Beam Alignment	1	$2,000.00	

>Perform 4 Tests w/ E-Zapper	1	$8,000.00	
			$86,617.00

All order requests can be seen in Appendix E.

The final budget costs more than three times the original proposed budget of $25,000. This is due to changing the original concept design from a simple metal barrier to a hollow rotating shaft. This change added an additional 8 pieces of equipment to the design. All of the pieces have to be precision made to ensure the vacuum seal is kept. Some parts are so highly specialized that only a couple vendors are available. In the case of the fast acting valve, not only did the part need to be procured from the company VAT, it also will have to be set up and installed by the Technical Options. This part arrived in 8 boxes with complex circuitry and programming that needed to be done. The technical specialization for such a part was far beyond the students' and Naval Academy staff's scope of operations. While the budget is relatively high compared to many other projects, the Department of Defense has a budget of 3.3 billion dollars for counter IED research and development.

Conclusions and Recommendations:

The final design selected was the rotating hollow shaft with a beryllium barrier supported by stainless steel mesh. A lump capacitance model was used to show that the mesh and beryllium will not reach half of the melting point with the current design. The stainless steel mesh and the beryllium will both support the one atmosphere pressure differential on their own. It is recommended that the stainless steel mesh be used in support of the beryllium as a safety precaution. The flange designs were made in order to mate with the Rigaku rotating shaft. The selection of the valves, conflats, copper gaskets, and conflat to flange adapters were done with respect to the Riagku rotating shaft and ISO standards in order to find the least expensive, most reliable parts that could be procured quickly. The motor selection, although not complete now, will be based on rotating the shaft at a rate of 2 revolutions per second. The motor also has to be capable of being mounted on top of the Rigaku shaft. It is important to note the conclusion of the work done by MIDN Gonzales and MIDN Reichl does not conclude the project. This project is a multiyear project.

For future work, the group recommends more people with a wider variety of skills. The group members would suggest students with the following background be selected: nuclear physics/radiation, energy conversion, electrical engineering, and computer aided drawing. A more rigorous course focusing solely on using a program such as Solid Edge would have helped. Also, if the students had selected their capstone projects prior to the beginning of fall semester, elective classes could have been better selected to benefit the project. Future teams should try to travel to Ohio to see the actual testing and the results of the experiments. The teams should try to speak with Explosive Ordnance Disposal (EOD) teams to ask them if there are any modifications or suggestions for the project. Also, due to the highly classified nature of counter IED research and the inability of the faculty to access some of the information the students can, the students should try to visit government organizations such as the National Ground Intelligence Agency, the Central

Intelligence Agency, and the Marine Corps Counter IED Task Force. The students could receive ideas from outside sources if they presented their project to these organizations.

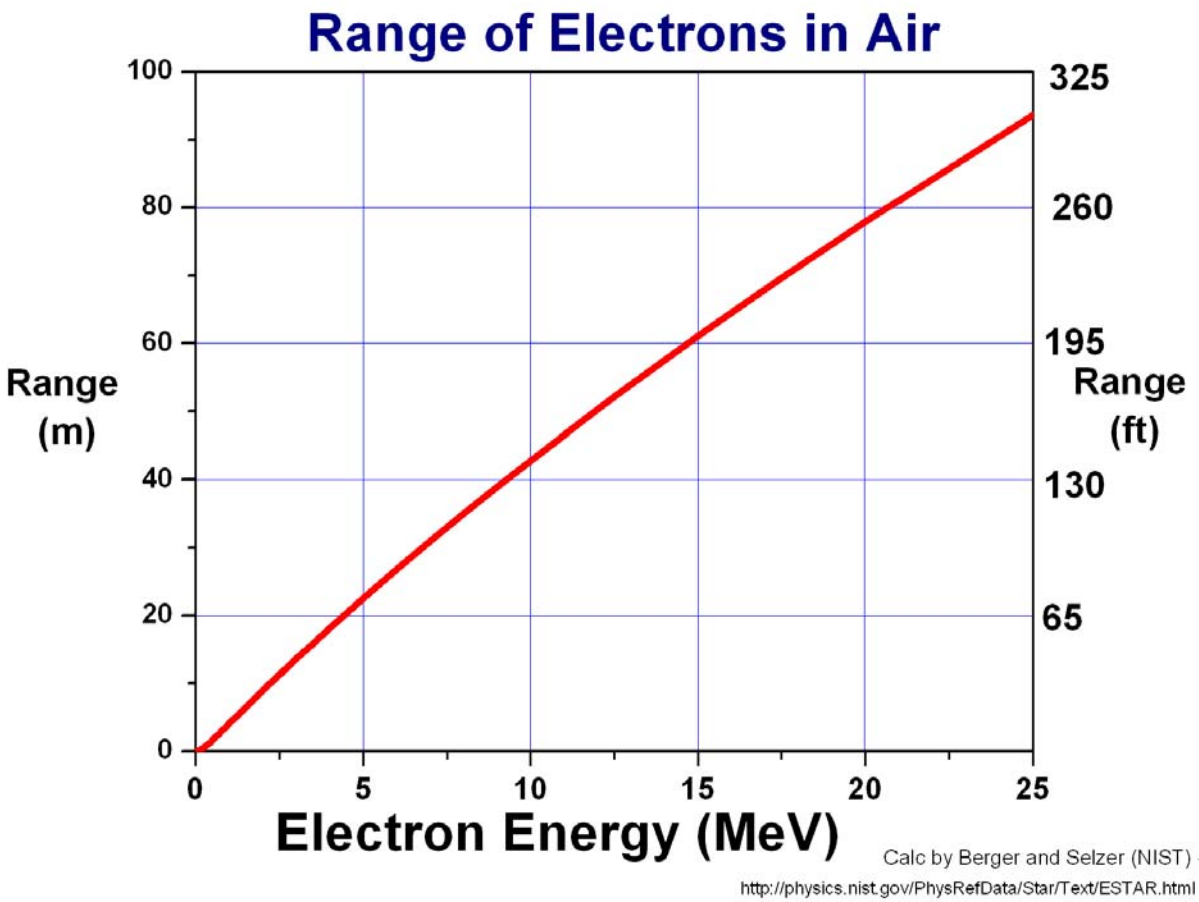


Figure (1)

Linear Accelerator Picture

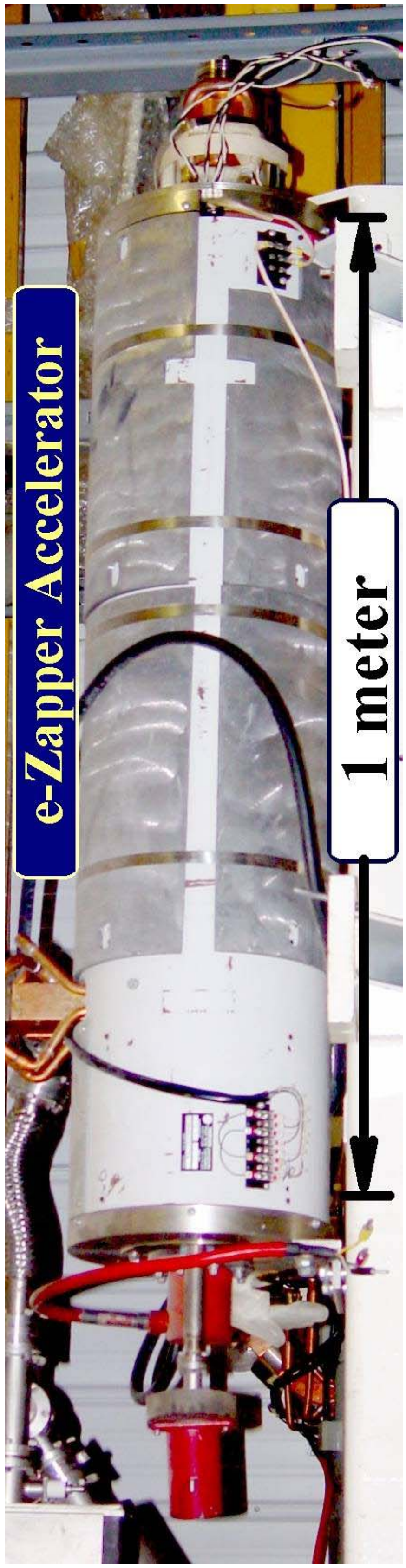


Figure (2)

E-Zapper Testing

Figure (3)

E-Zapper Damage

Damage to a target (remote doorbell ringer) “zapped” 1 second at a distance of 1 ft

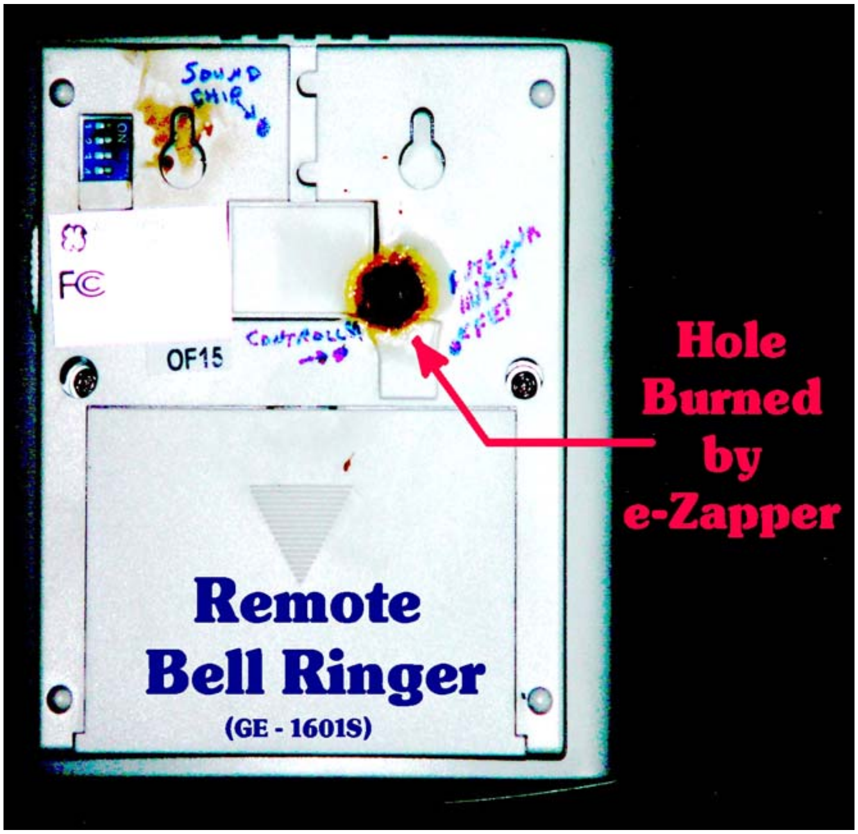


Figure (4)

A Plasma Window

Developed by Acceleron at Brookhaven National Laboratory

The blue is the actual plasma window. The rest is the supporting power, pumping and cooling system.

Figure (5)

Ferrofluidic Seal

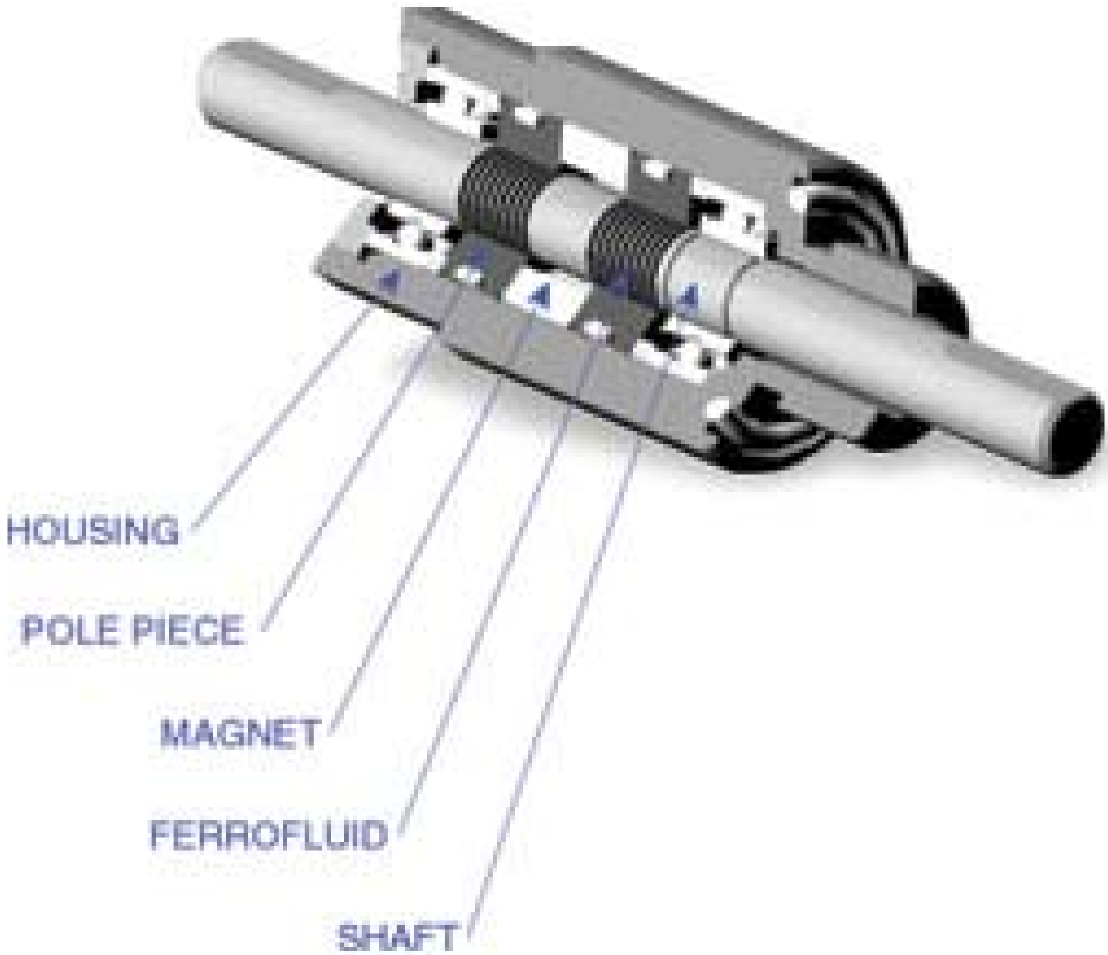


Figure (6)

Knockdown Factors Plot

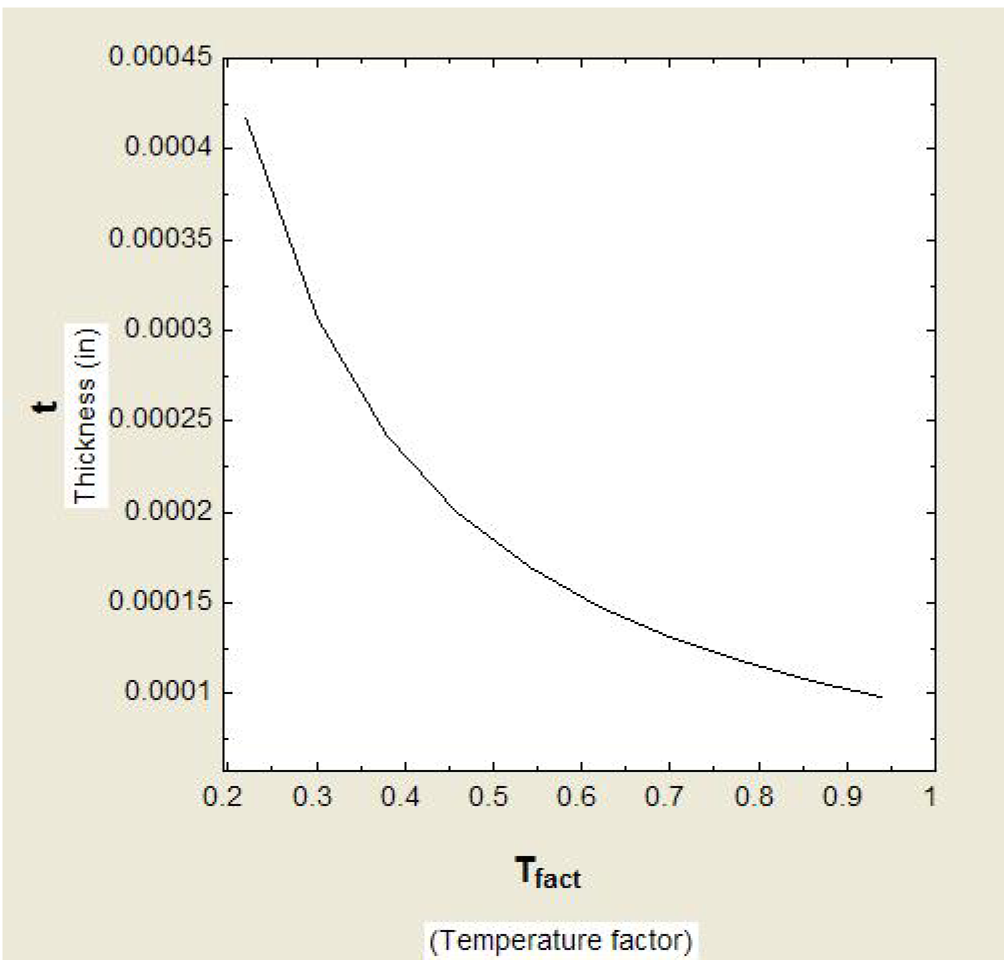


Figure (7)

Stainless Steel Mesh

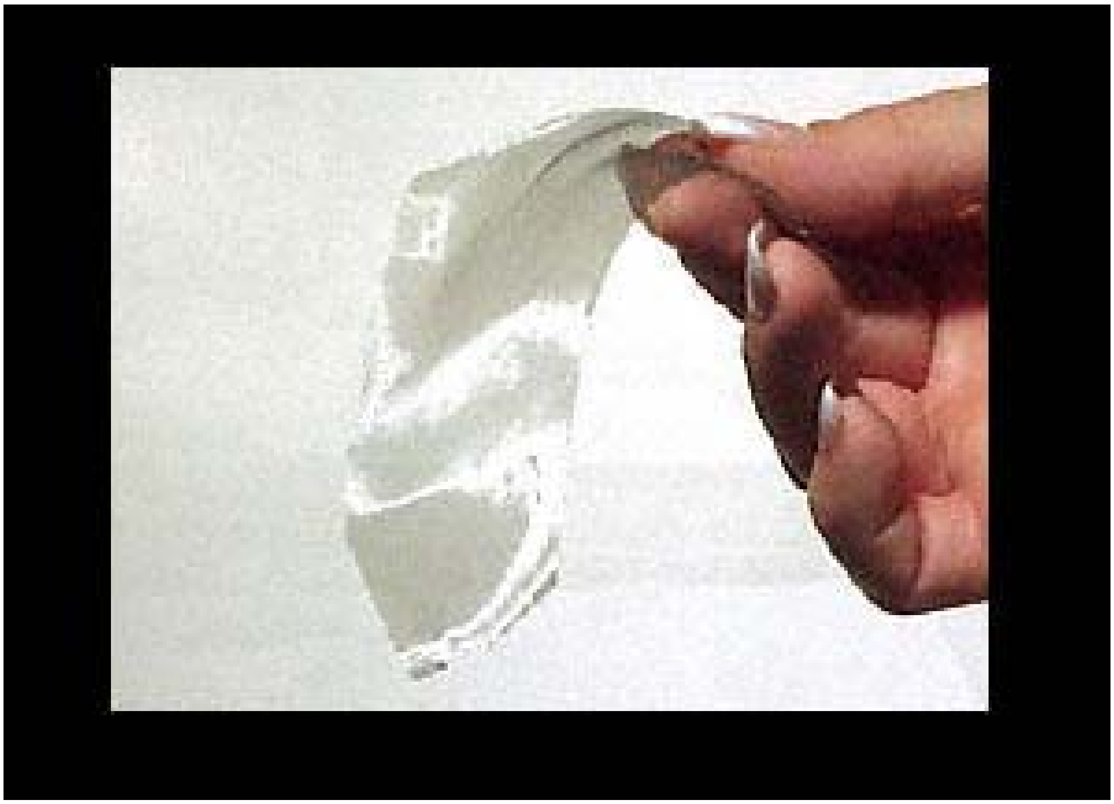
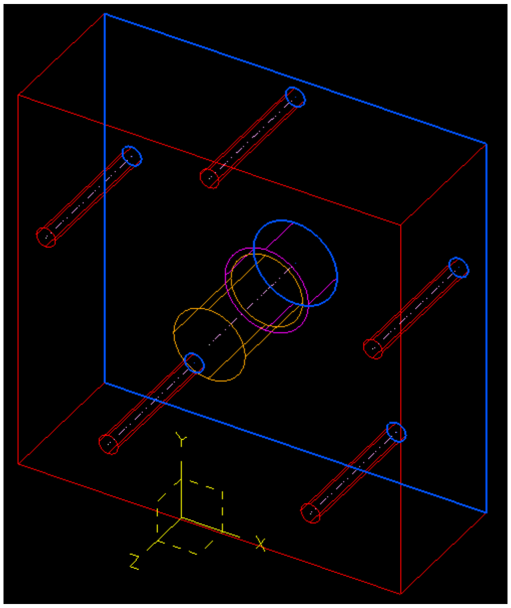


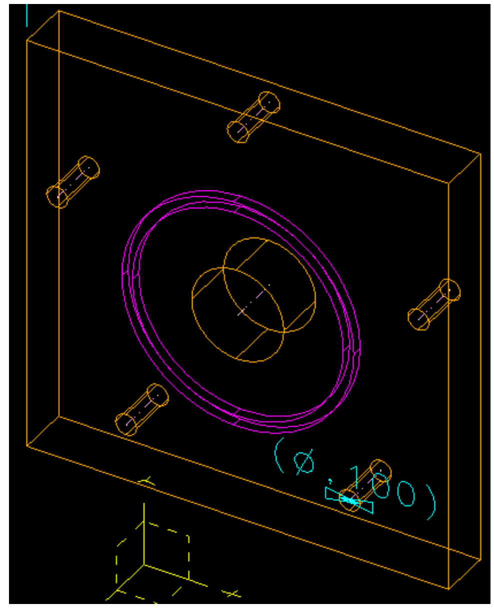
Figure (8)

Bracket Design/Test Set Up

Front Plate



Back Plate



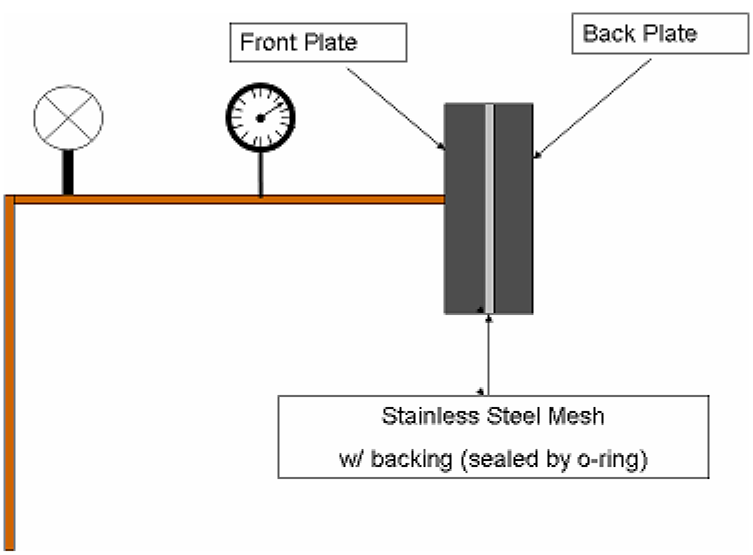


Figure (9)

Lump Capacitance Be Plot

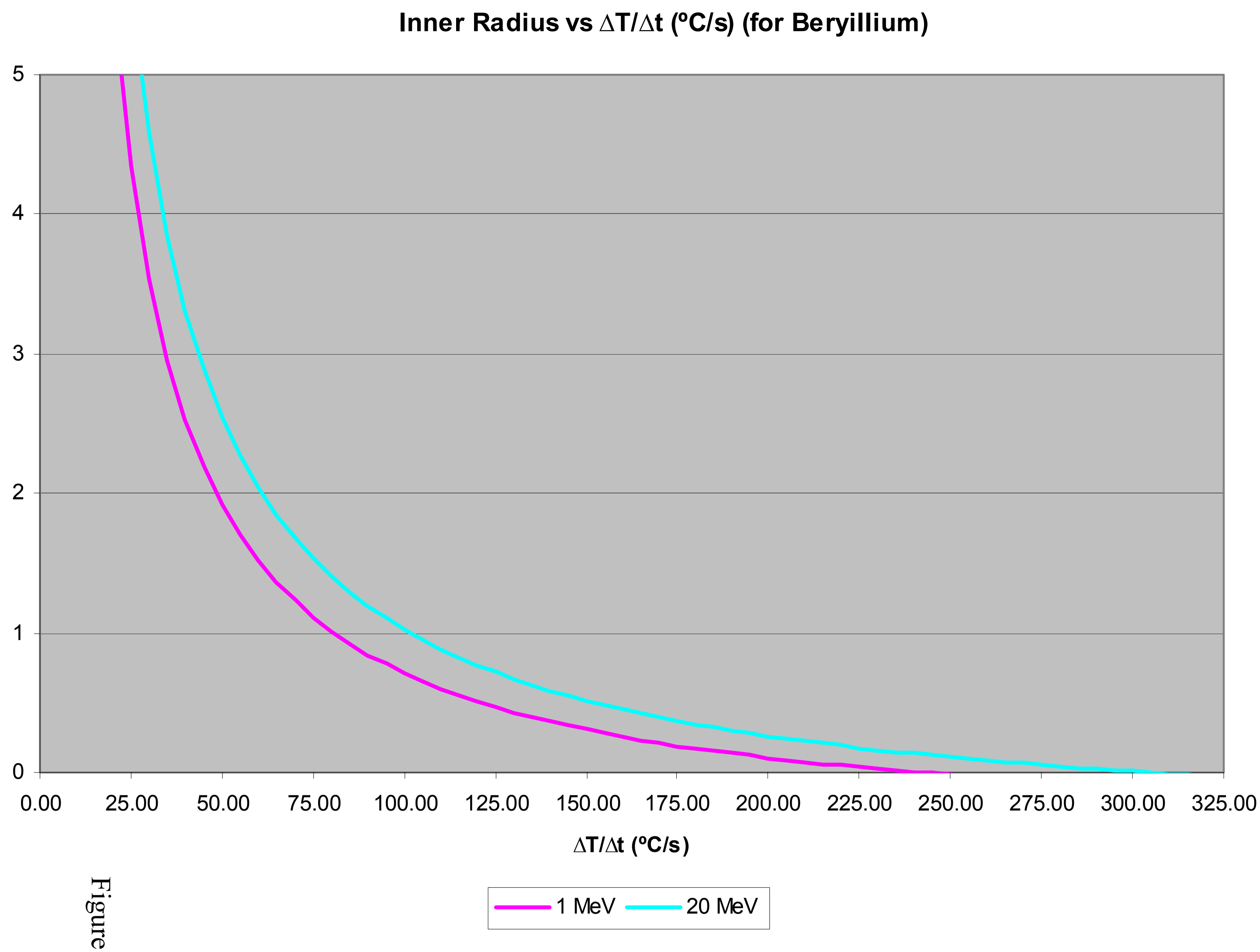


Figure (10)

Lump Capacitance SS Plot

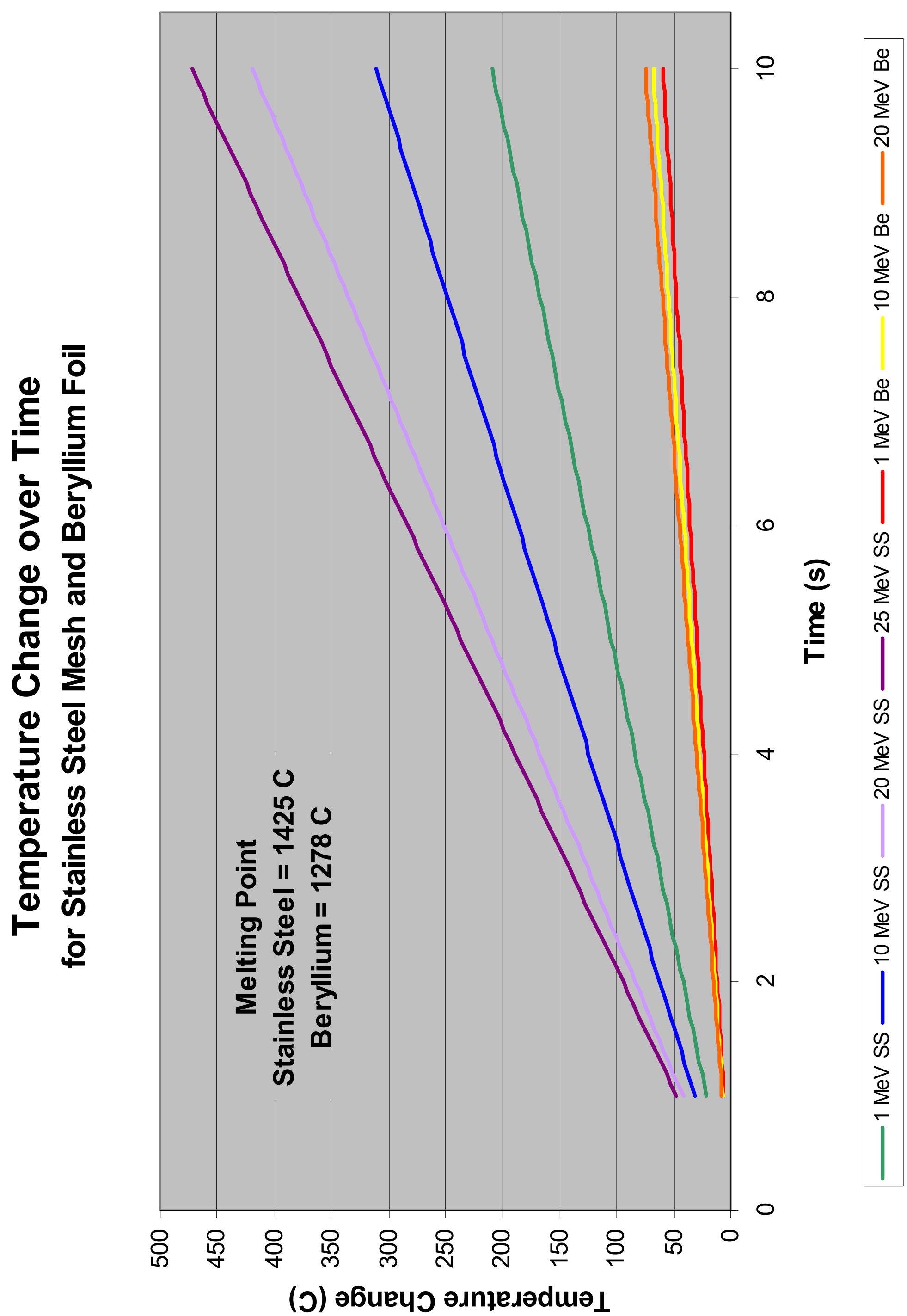


Figure (11)

Be Thickness vs. Dispersion Plot

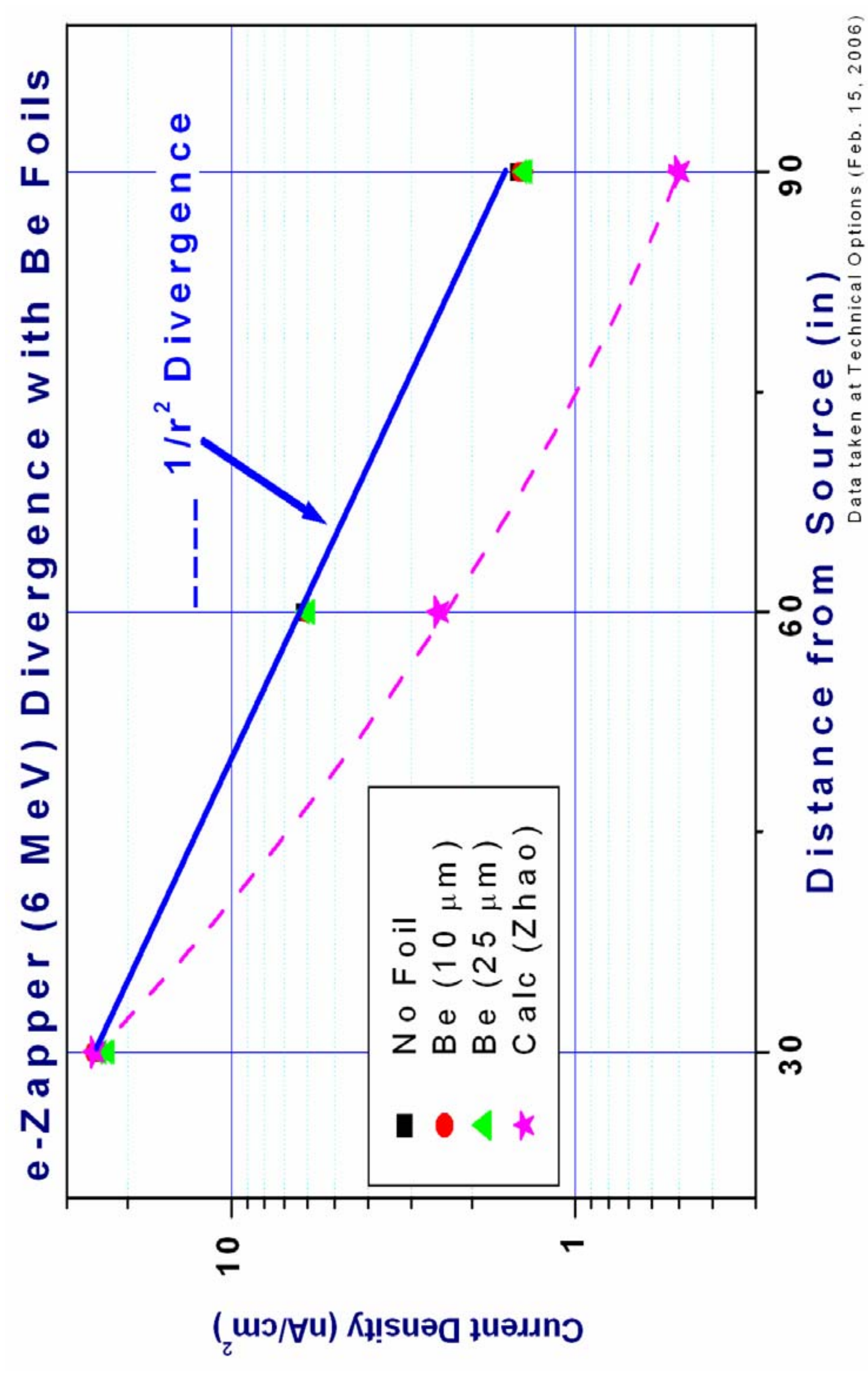


Figure (12)

Be Pressure Differential Test

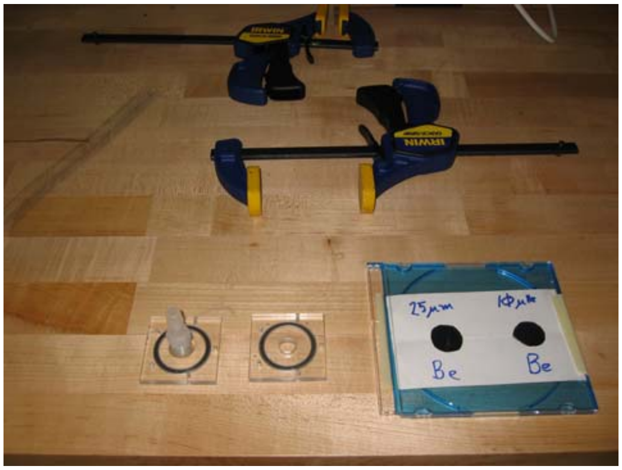
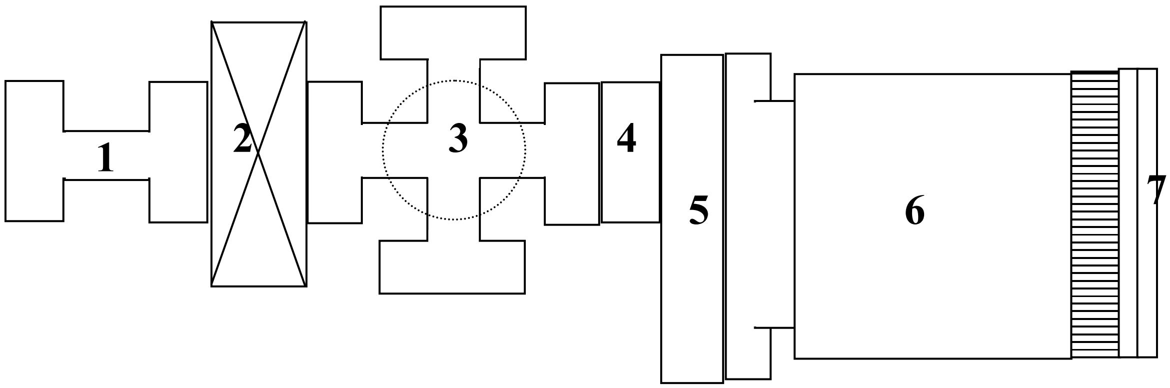


Figure (13)

Full System Schematic



1 - 2.75" Conflat Nipple- used to connect VAT fast acting valve to LINAC.
2 – VAT fast acting valve0
3 - 2.75" Conflat Flanged 6-way cross- used to integrate roughing pump, high vacuum pump, and fast acting valve sensors into system
4 - 2.75" Conflat to ISO63 flange- used to transition form Conflat sealing to the use of O-rings
5 – Off-set flange
6 – Rigaku hollow rotating shaft
7 – Be window flanges

Figure (14)

Rigaku Shaft Engineering Drawing

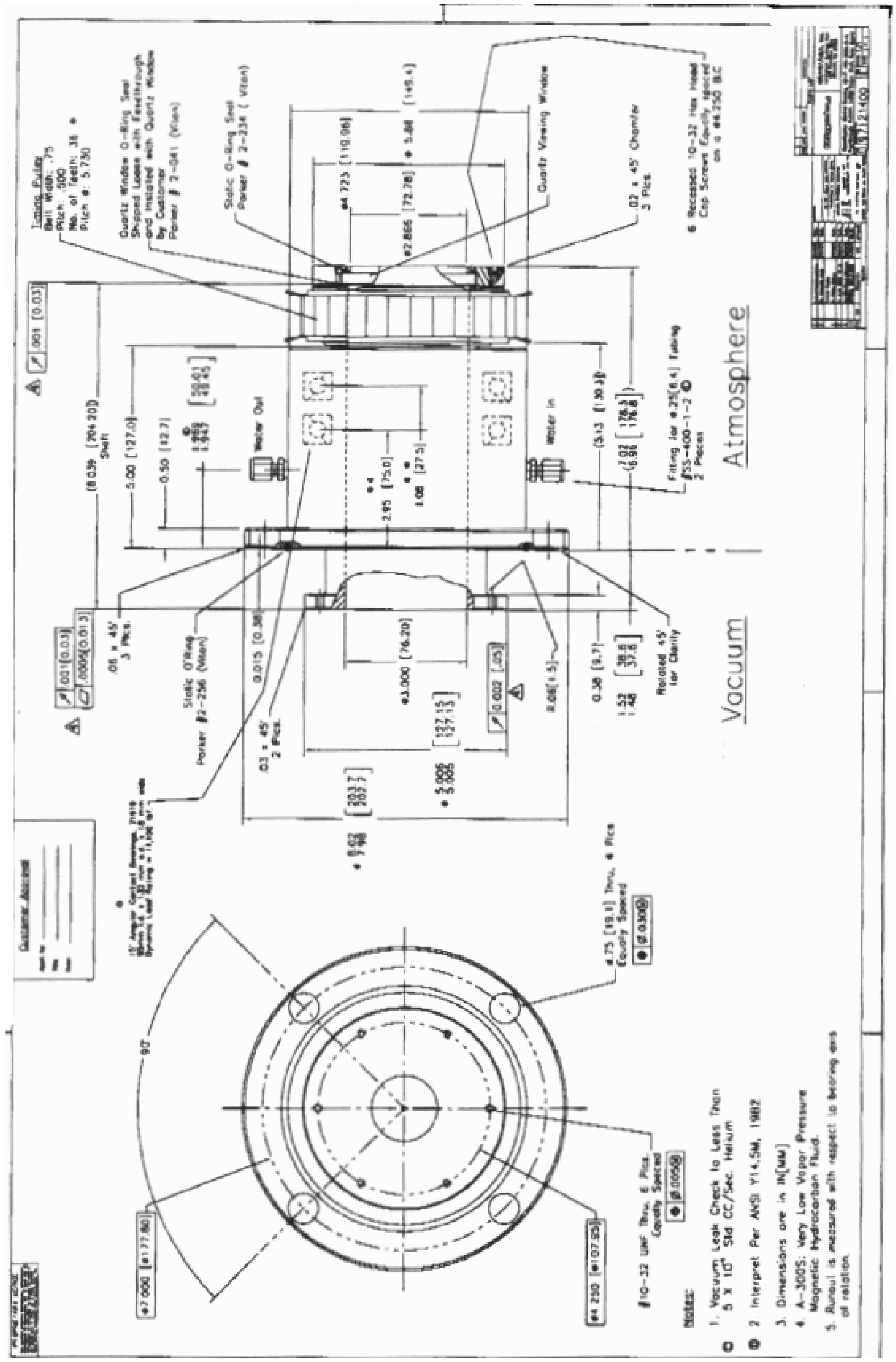
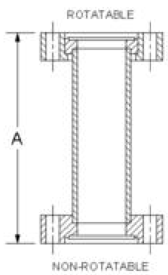


Figure (15)

Rigaku Rotating Shaft

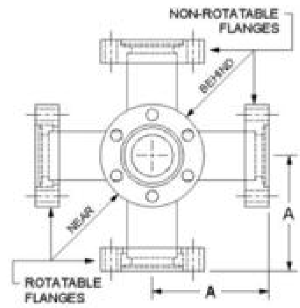
Figure (16)

Nipples and Conflats

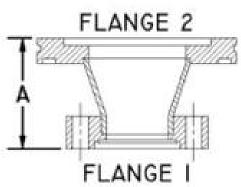


2.75" Flange OD
1.50" Tube OD
Conflat Flange Nipples
Standard 2−3/4" Conflats
One Side Rotatable
One Side Non−Rotatable

- A - 4.93"



Conflat Flanged
6−Way Cross
Flange OD = 2.75"
Tube OD = 1.50"
A = 2.46"



2−3/4" Conflat to ISO63
Conical Reducer
Conflat flange is Non−Rotatable, Through Holes

- Flange 1 - 275-150
- Flange 1, Tube OD - 1.50"
- Flange 2 - ISO63
- Flange 2, Tube OD - 2.50"
- A = 2.834"

Figure (17)

Offset Flange Design

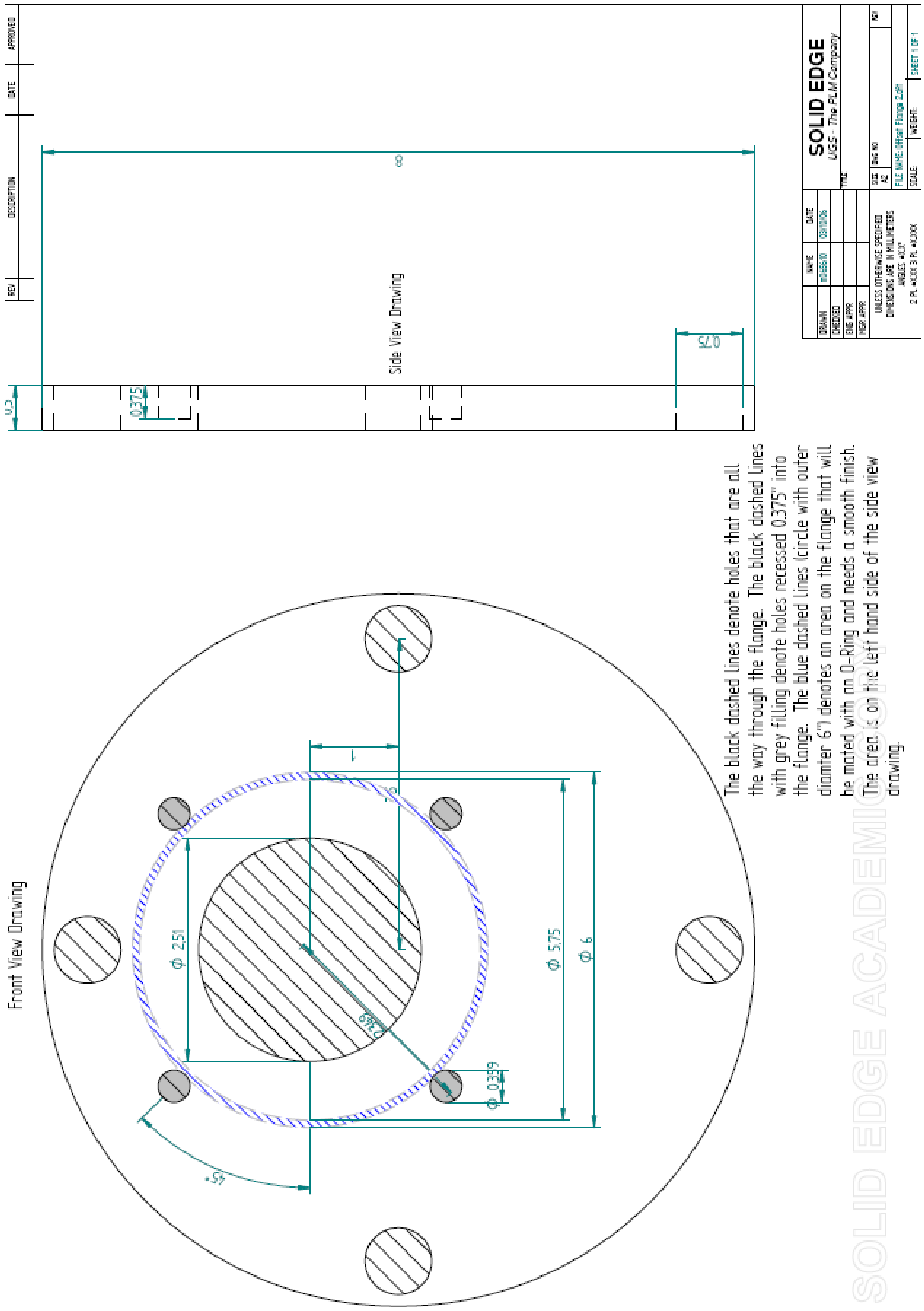
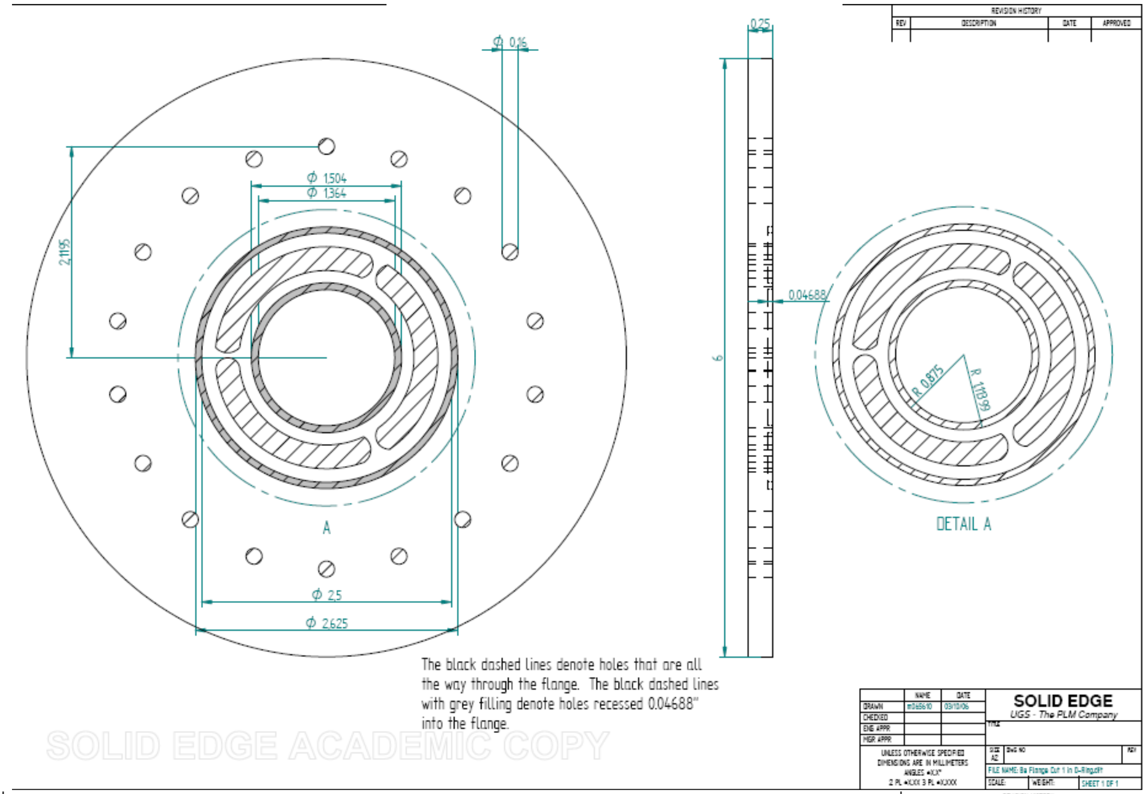


Figure (18)

Be Support Flange Design



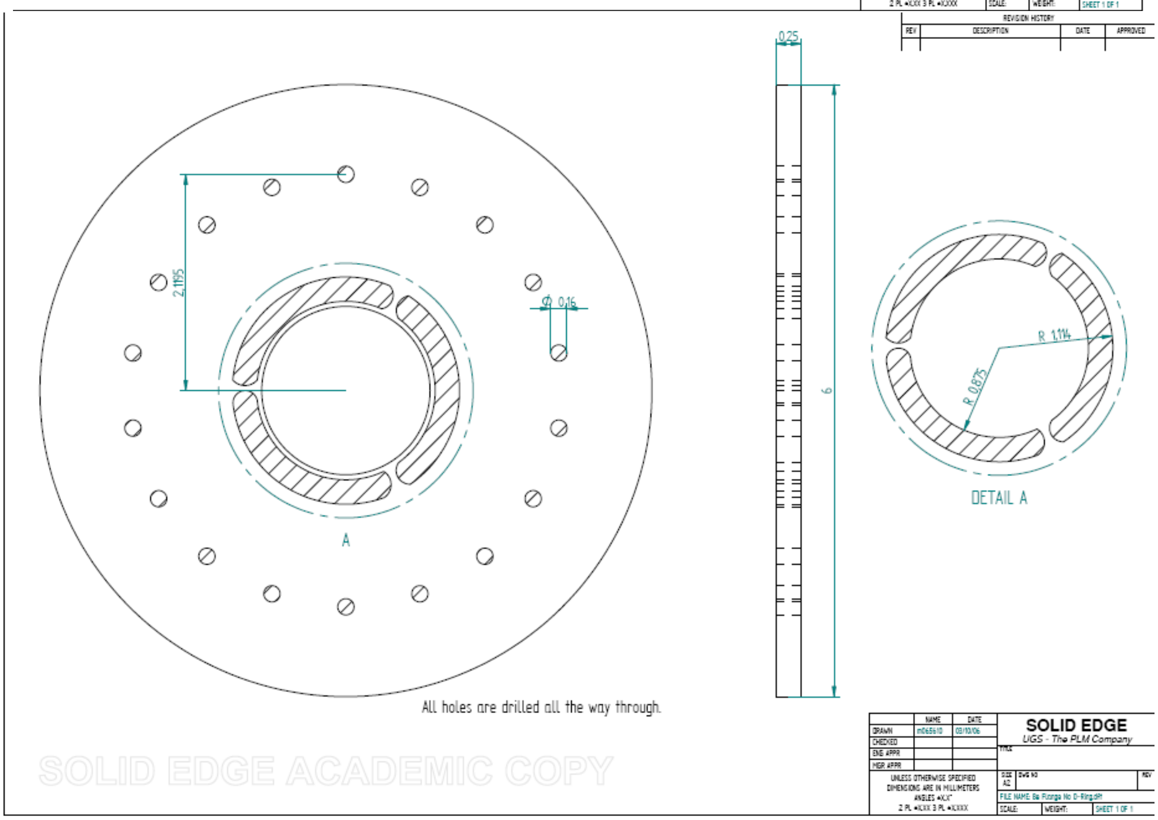
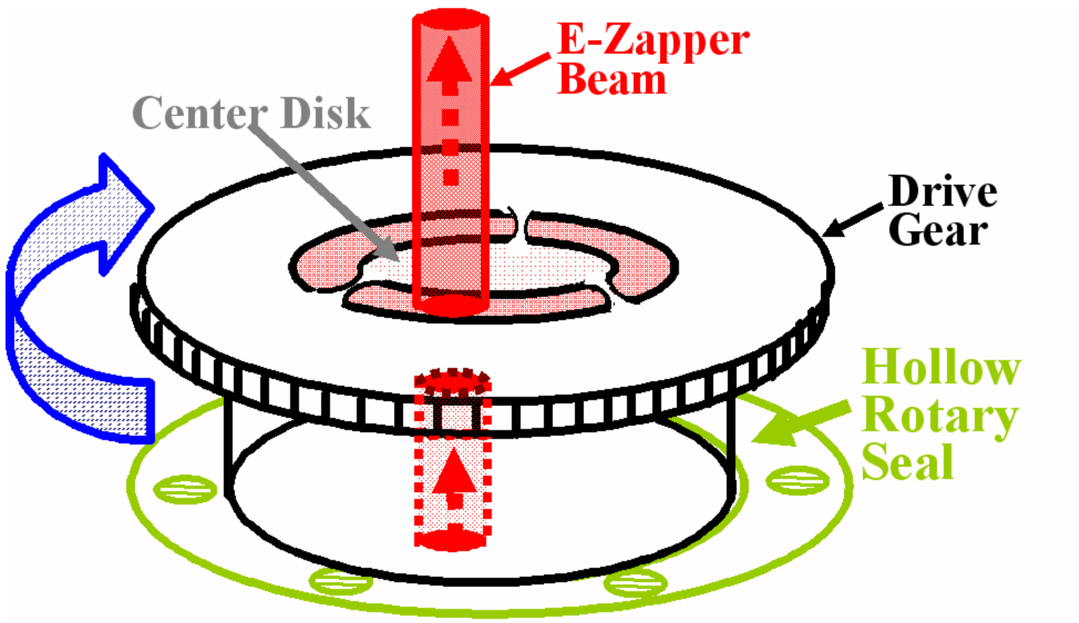


Figure (19)

Be and Mesh System

Rotating Be Foil (Supported)


E-Zapper Beam
Center Disk
Drive Gear
Hollow Rotary Seal

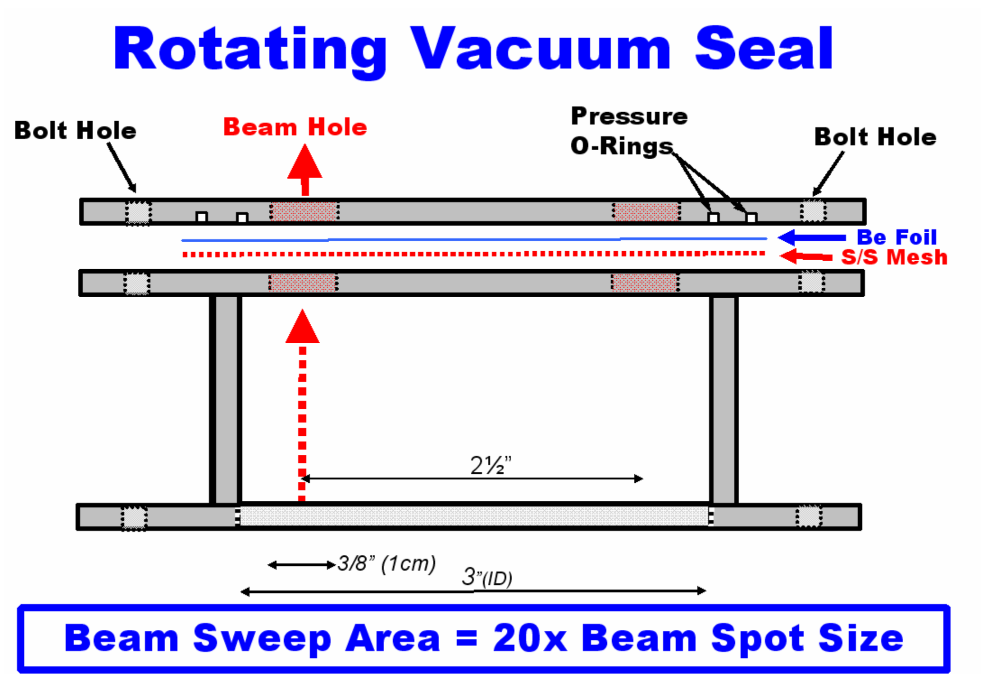

Rotating Vacuum Seal
Bolt Hole
Beam Hole
Pressure O-Rings
Bolt Hole
Be Foil
S/S Mesh
2½"
3/8" (1cm)
3"(ID)
Beam Sweep Area = 20x Beam Spot Size

Figure (20)

Focusing Element

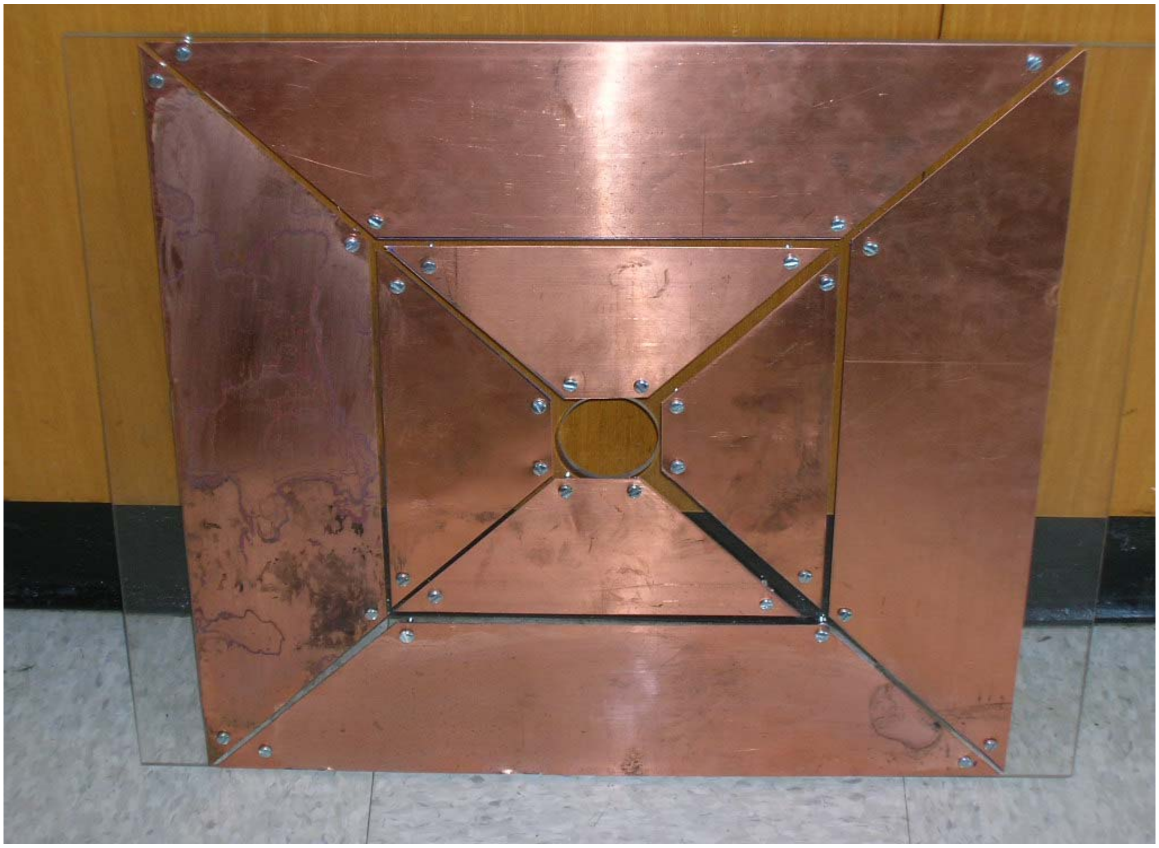


Figure (21)

Focusing Element Wired

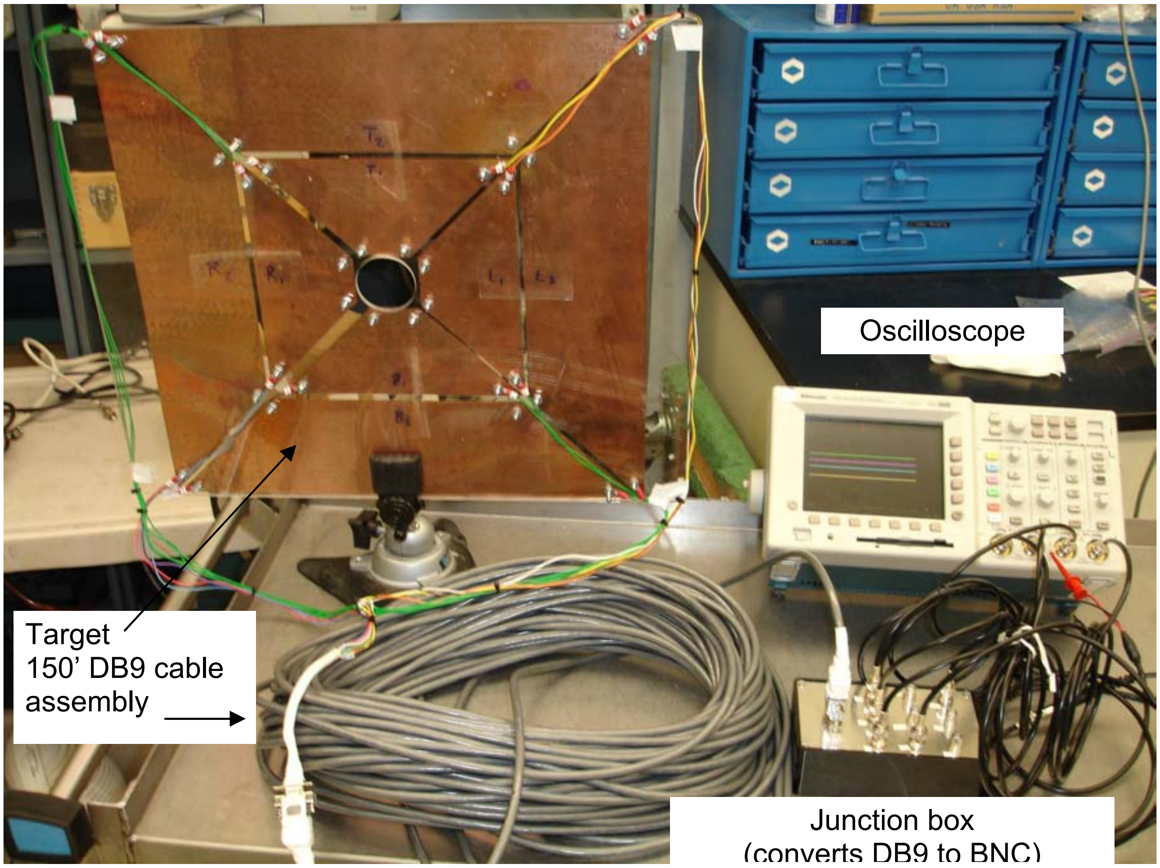


Figure (22)

O-Scope List

26MAR06

MEMORANDUM

From: MIDN 1/C Reichl, USN
MIDN 1/C Gonzales, USN

To: Prof. Nelson, ME Department
Prof. Ziegler, AE Department

SUBJ: 4 CHANNEL O-SCOPES

1. The following are 4-channel O-scopes, all PC based:
   a. PicoChannel 4-channel Oscilloscope
      Cost: $1215.85
      http://www.picotech.com/4-channel-oscilloscope.html

   b. Scope4PC 4-Channel
      Cost: $739-$839
      http://www.scope4pc.com/

   c. Tektronix TDS20244 4 Channel, 200 MHz, Digital Storage Oscilloscope
      Cost: $2800
      https://www.valuetronics.com/Details.aspx?ProdID=5496&Model=Tektronix_TDS2024

   d. HP 54501A 4-Channel 100 MHz Oscilloscope
      Cost: $3550
      http://www.americantest.com/osc1gmd.html

The last site seems to have a lot of o-scopes.

Very respectfully,

M.A. Reichl
MIDN USN

C.N. Gonzales
MIDN USN

Figure (23)

Gantt Chart

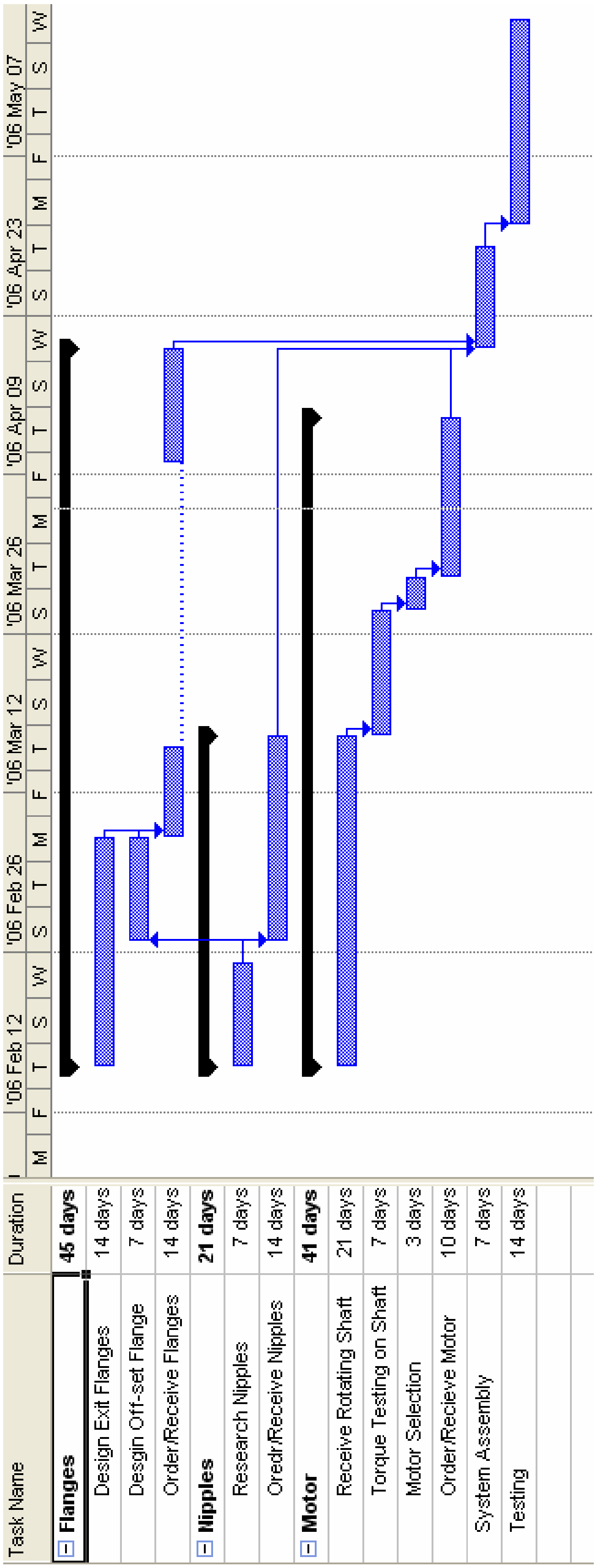


Figure (24)

Appendix A

Givens

σ_y = 35000 Be Yield Strength (psi)

r = 0.21875 Radius (inches)

P = 14.7 Pressure (psi)

FS = 2 Factor of Safety

T_{fact} is a knockdown factor that accounts for the decreasing yield strength of steel as T increases

$$\sigma_y \cdot \frac{T_{fact}}{FS} = P \cdot \frac{r}{2 \cdot t}$$

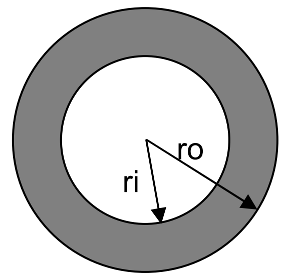
Parametric Table

Table 2

1..10	1 T_{fact}	2 t
Run 1	0.94	0.00009774
Run 2	0.86	0.0001068
Run 3	0.78	0.0001178
Run 4	0.7	0.0001312
Run 5	0.62	0.0001482
Run 6	0.54	0.0001701
Run 7	0.46	0.0001997
Run 8	0.38	0.0002418
Run 9	0.3	0.0003062
Run 10	0.22	0.0004176

Appendix B

Be Window Lump Capacitance Model Calculations



Neglect

$$\rho C_p V \frac{\Delta t}{\Delta T} = Q - h(T_{Be} - T_{\infty})$$

$$V = At$$

$$A = \frac{Q}{\rho C_p 10_{-4}} \frac{\Delta t}{\Delta T}$$ (Thickness is incorporated into the Q value)

$$A = \pi(ro^2 - ri^2)$$

$$ro - ri = 1cm$$

$$ro^2 - ri^2 = (ro - ri)(ro + ri)$$

$$ro^2 - ri^2 = 1(ro + ri)$$

$$ro = 1 + ri$$

$$A = \pi(1 + ri + ri) = \pi(2ri + 1)$$

$$\pi(2ri + 1) = \frac{Q}{\rho C_p 10^{-4}} \frac{\Delta t}{\Delta T}$$

$$ri = (1/2\pi)\frac{Q}{\rho C_p 10^{-4}} \frac{\Delta t}{\Delta T} - 1/2$$

ρ=density (g/cm^3)
Cp=specific heat (J/g- ºC)
A = cross sectional area (cm^2)
t = thickness (microns)
Δt = change in time (s)
ΔT = change in temperature (ΊC)
Q = heat deposited (W/mA-μm)

Acknowledgements

Professor Martin Nelson: Professor Nelson is the group adviser; he has assisted with all aspects of the project and provides a sound engineering background. He has also assisted with the writing of this report and provides constructive feedback of work.

Professor James Ziegler: Professor Ziegler is the secondary adviser. Professor Ziegler has come up with many of the conceptual ideas and works on the administrative side of the project as well. He orchestrates all parts procurement for testing.

Asst. Research Professor Zhongxiang "George" Zhoa: Dr. Zhoa works on the radiation mechanics track of the project that runs parallel with the exit window construction portion. Dr. Zhoa, along with Dr. Taddei, has provided all the simulations of electron scattering in air.

Mr. Kelly Delikat: Mr. Delikat has been the technical adviser. He examines the designs and provides feedback on whether they will work, can be made at the shop, or if they must be outsourced.

Mrs. Louise Becnel: Mrs. Becnel was instrumental in helping with the testing of the mesh. She provided machines and instruments that increased the precision to which the experiment was carried out.

Asst. Professor Phillip Taddei: Along with Dr. Zhoa, he has provided simulations for electron scattering in air and works on the radiation mechanics of the project.

CDR Sean Nolan: CDR Nolan has offered technical support and assisted with the exit window design.

Associate Professor Peter Joyce: Professor Joyce assisted with designing the experiment to test the mesh.

Asst. Professor Michelle Koul: Professor Koul assisted with designing the experiment to test the mesh.

Associate Professor John Burkhardt: Professor Burkhardt has helped with the computer modeling of parts and equations for a membrane under pressure.

Appendix D: Team Charter

As a group, we agree to produce all the deliverables. This is an important project for several different reasons. Not only is this a learning process for how real engineers go about designing a weapon system, but we actually use material we have learned over the past three years. Practical application of material is the best way to show students the material is important and it will help them. More importantly, the project is going to the ultimate cause, to help our troops. This was the best and most important project listed by the faculty. There is no better motivation to do a project and do it well than to help our brothers-in-arms.

Organization is a key part to this project. We will meet at least twice a week after our 5th period or after practice. When we run into a hindrance, we will contact Professor Nelson or a specialist in the area of interest. The workload will be evenly split. When we have free time on the project, we will work on it. The other member doesn't need to be around and we don't need to log hours. It will all even out in the end. If there are any disagreements, they will be resolved in the Octagon. This is a special arena where the group members can let out frustrations all at once.

MIDN Gonzales's Personal Statement: I know that that the result of this project may be used in the future in the real world to protect American lives. This along with the fact that the project is a hands-on, real world application rather than just a theoretical problem will drive me to devote whatever time and energy is necessary to succeed. Obtaining an A on this project is not as important as deigning and constructing a system that is feasible and operable. I feel that if I focus my efforts there the grade will take care of itself.

MIDN Reichl's Personal Statement: I hope to take a lot out of this experience. I am going to use this as gage to see whether or no I will go to graduate school. I'd like to work with different departments and see how a project like this is fully undertaken and incorporated into our defense system. Most importantly I want to help our troops. For this, I am willing to work as hard as possible. I am working for an A and will be content with nothing less.

Very respectfully,

M. A. Reichl
MIDN USN

C.N. Gonzales
MIDN USN