Rifle and Shotgun Recoil Test System

A Senior Project

presented to

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In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science in Mechanical Engineering

by

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Statement of Disclaimer

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Abstract

This project for Weatherby, Inc. requires a simple device to test the recoil force of their shotguns and rifles to determine the effectiveness of recoil suppression methods. A bench mounted device that secures the gun and records firing data to a portable computer was created. This project was completed for the Senior Project requirement for a Bachelors of Science in Mechanical Engineering from California Polytechnic State University, San Luis Obispo. The completed prototype was successful in measuring the recoil force and energy for Weatherby's rifles. The recoil energy from the prototype differed from the calculated theoretical recoil energy with a small enough percent error to be deemed accurate. The differences between these values are lower than the margin of error for all measurements.

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1. Introduction:

The main goal of this project was to create a simple device that can be used to measure the recoil force of Weatherby's products. This device will be used by Weatherby to determine the effect of different calibers, powder charges, bullet masses, rifle masses, butt pads, muzzle brakes, or any other recoil suppression methods.

Weatherby, Inc. is a rifle and shotgun manufacturer located in Paso Robles, CA. The company was founded in 1945 and is best known for their Mark V bolt action rifles. The company also produces high velocity hunting ammunition. In order to remain competitive, Weatherby needs an accurate method for measuring the recoil force of their rifles, shotguns and ammunition. Currently no commercial product has been located for testing their guns, so no methods are being employed; however, it appears that other firearm manufactures have this data, so custom systems exist.

The system will mount on a bench, either at Weatherby's range or at local gun ranges, and should be able to be used without much training. Weatherby currently produces the Accubrake™, a muzzle brake that redirects combustion gasses to the side of the rifle to reduce recoil; however, only empirical data exists to support the claim that it actually reduces the recoil force. The project will produce quantitative values to substantiate these claims. Also, as the designer of long guns, Weatherby would benefit from having quantified data regarding felt recoil of future rifles and how they compare to current and competitors' products.

The Weatherby range is located at their manufacturing site and has technology to measure muzzle velocity as well as sonically determine precise bullet location at the end of the range. The current rifle rest, shown below in Figure 1, allows a rifle to be placed in the support so that some of the recoil force is absorbed by the system. This allows one shooter to fire many rifles for testing purposes without suffering discomfort from the recoil.

Figure 1 - Current Table Rifle Rest

The final system comprises a similar rest, but also fully constrains the rifle so it can be fired without a shooter having to hold gun. Also, a force sensor leading to a laptop is located behind the rifle to record the recoil data.

This report includes a detailed design of the final system with engineering drawings, a three-dimensional computer model, bill of materials and cost information. Manufacturing and testing data is also reported for the final prototype. Multiple concepts were ideated which are outlined in the Concept Design section. This report also includes a Gantt chart of deadlines for each individual aspect of this project to showcase the iterative process and project timeline.

The system was built at the California Polytechnic State University machine shops with material ordered from off site. Testing of the design with live rounds was conducted at Weatherby's on site range. The project was finished in less than one year and was presented at the Senior Project Expo on Thursday, November 21, 2013.

Through this project, the team hopes to gain a more hands on approach to the design and manufacturing of products. This project will tie together all the information learned from prior mechanical engineering coursework at Cal Poly, and will allow us to learn valuable lessons which can be used throughout our engineering career such as: the formal design process, time management, design of machinery, and teamwork. All these are excellent opportunities for professional growth as engineers, and will make each members of the team a valuable asset to any company.

2. Background:

There are many factors that can be measured when firing a rifle or shotgun. The impulse or momentum of the gun and the force felt by the shooter can be measured. The momentum of an object is the product of its mass and velocity and also can be calculated by the change in force over time. The recoil force felt by the shooter has two components: "acceleration of the projectile itself… and the second component is associated with the acceleration of the gases created by the combustion of the gunpowder propellant" (Hall 2008). The force created by the acceleration of the projectile can be calculated using conservation of momentum, however, the force due to the combustion gas acceleration cannot be accurately calculated. The force felt by the shooter is the combination of these two forces and thus has to be measured instead of calculated.

The amount of 'kick' or push against the shooter is determined by the peak force. The area under the force versus time graph is proportional to the momentum, and the momentum caused by the projectile acceleration cannot be changed without changing the gun or projectile. Thus, the peak force can be decreased by increasing the amount of time the gun is recoiling. The use of a soft butt pad against the shoulder can absorb some recoil but it also increases the time over which the force is acting. The second component can be reduced by directing the expanding gasses perpendicular to the bullet's path. For our system, there must be a way to determine the effect that adding a butt pad or muzzle brake has on the force felt by the shooter.

In this search for similar products, the project team has have been unsuccessful in locating any commercially available recoil testing systems; however, there have been a few devices created for research purposes. One system suspends the firearm of known mass from two known lengths of rope. When the cartridge is fired, the firearm recoils backwards in an arc. By measuring the change in vertical height, it is possible to determine the energy of the blast by conservation of energy. This method is inadequate because it can only calculate momentum instead of the peak force. Also, by hanging the rifle in the air, possible control issues arise during firing and could lead to possible safety hazards.

Another system uses a bearing surface that supports the butt of the gun and another that supports the gun from beneath the hand guard (Lee, Joon-Ho, et al.). The rear of the firearm is then placed against a force transducer. This method has the advantage of positively locating the firearm so that it can only slide directly backwards. Also, the sensor allows the user to measure energy, time, and force data. This method also requires the user to account for the weight of the bearing and clamping fixtures if absolute numbers are required.

These two methods are adequate for comparing the effects of one firearm to another, but they may be inadequate for yielding true force values. It remains unclear whether the system can account for the additional inertia present from the bearings.

The force sensor and measuring equipment is an important factor in the design. A sample force versus time graph was located and appears to show a refresh rate of between 1kHz and 100kHz. The total area under the graph and peak force is also an important measurement, thus the force sensor must take enough samples throughout the duration of the shot to produce a smooth curve. The graph shows that the shortest shot recoil time appears to be less than 0.01

seconds. The graph of a sample output can be found in Appendix A. As shown in Appendix A, if 100 samples of a shot are required, then a 10,000Hz sensor is required. After testing at the Weatherby facility, it was found that the Weatherby .300 Magnum and Weatherby .25-06 had recoil times of roughly .008 seconds each. With this fast recoil time, a sensor of 25kHz to 50kHz is necessary. The sensor selection can be seen in Section 6.3.2 of this report.

Referencing the quality function deployment (QFD) document, shown Appendix B, informs the team of important aspects of the design. Using the QFD, it shows that a force sensor that can connect to a laptop is a top design requirement. Also of importance is the use of a suitable material and a design that will accommodate different guns without lifting off the table. As seen in this report, the final design includes all of these factors and appears to be a more than adequate system for testing recoil forces.

3. Specifications:

The objective of this project was to create a recoil force test apparatus for use by Weatherby, Inc. for the purpose of determining the effect of various recoil suppression systems. More specific requirements are outlined below:

- Test peak recoil force of fired rifle and shotgun
    - Rifle highest priority. Future design of shotgun test fixture is possible
- Export data to portable device, such as a laptop
    - Graph of Force vs. Time required
    - Peak force displayed
    - Resolution of 1 ft-lb
- Design can use modified stock to test, but testing unmodified rifles is ideal
- System must be portable.
    - Must be able to be carried to different gun ranges in small personal vehicles
    - Must be able to mount to different range tables
    - Should not require outside power other than laptop (battery operated)
- Must be able to handle loads of largest Weatherby round.

4. Design Procedure:

4.1 Method of Approach

As a general idea of the method of approach, the team followed the set of design guidelines which were illustrated to us in Cal Poly's mechanical engineering design classes. The design process starts with a need, which has already been presented, as this project is in response to a specific need. This report documents the exact problem definition as well as the entirety of the project. The problem definition intends to accurately state the problem corresponding to the need in such a way that it provides guidelines, but with minimal restrictions. With the problem clearly defined the next step is ideation. In this process, the team brainstormed many different ideas that tried to solve the problem. The goal was to not be limited to any one solution and come up with as many ideas as possible. From there, the list of designs was compared with basic analysis and the top six designs were selected. To choose a top design candidate, a weighted decision matrix was utilized to analyze and evaluate the six solutions. Once the top design was chosen, the team began the detailed design process, which can be seen in this report. Engineering design of each component was completed in order to be confident that the system performs as expected. This step included making detailed drawings of all parts, a three-dimensional model, force analysis, sensor analysis, and bill of materials with cost estimates. This work went through a critical design review by the team's project advisor and was approved by Weatherby before the manufacturing process began.

Throughout the entire design process, significant milestones such as the selection of a final design were dependent on the approval of Weatherby and the project advisor. To reiterate, this is a general idea of the method of approach that was taken. More details on the individual aspects of this project will be discussed in the sections to follow, as well as a timeline of events.

4.2 Ideation

As seen in the overview section, one important step in the design process is ideation. Since most of the team is already very familiar with the mechanics of rifles and shotguns when they are fired, the team understands the basics of this project and how to solve the problem. With that being said, more detailed research going beyond what is discussed above was required. This research included analyzing current firearms data that can be found online as well as taking data from the shooting range at Weatherby. The team studied the motion of the firearm when discharged as well as the potential forces that the discharge creates on the firearm.

4.3 Analysis

Once all of the designs created during the ideation phase were compared against the design requirements, the top six designs were chosen for a detailed analysis. Reference Appendix C for the concept analysis data and procedure. These designs were narrowed to the final design using weighted decision matrix that can be seen in the Concept Design section. From this, the final design was selected and engineering design and analysis was performed and can be seen in the Final Design section. This analysis was performed to make sure that the design will be safe

and able to accurately measure the recoil force of rifles and shotguns for an extended amount of time without failure. This design was modeled in a computer aided design (CAD) program in order to help with the analysis and to give a better idea of how the system was to be machined. The team has attempted use everything at their disposal to accurately analyze the systems and determined that they have provided a safe solution for measuring the recoil force.

4.4 The Build

Once the design was approved through a critical design review, parts were ordered and the build began. William Meijer was be the member that will be heading the build, as he has numerous years of experience as both a machinist and welder. The Cal Poly machine shops have every machine and tool that will be needed and the team was able to conduct the build on campus. Since firearms are not allowed on campus, the team required a stock to use while building the system to accurately dimension and test the system and the corresponding fixtures that may be incorporated.

Testing of the apparatus with conservation of momentum can only be measured when no muzzle break is used. Using bullet mass, bullet velocity, and rifle mass, kinetic energy can be calculated which can be compared to the output from the system. This procedure is one method to ensure the system is accurate, and a more detailed discussion of this verification can be seen in Section 6.5.

4.5 Timeline

The Senior Design Project class sequence at Cal Poly has a set schedule proposed for this project that spanned from January, 2013 until the Senior Project Expo which was held November 21, 2013. This schedule was created so that no aspect of this project was overlooked, and that the project was carried out in an organized fashion.

A Gantt chart was created in an effort to ensure the timely completion of the project through the completion of key project milestones. The chart is broken up into the three quarters where the team has worked in Winter 2013 and into Spring 2013 and Fall 2013. The team was not able to meet during summer quarter, so no milestones were planned. Summer work is not required for the competition of the project on schedule. The Gantt chart is located in Appendix F.

4.6 Management Plan

In order to successfully function as a team, some members were responsible for certain aspects of the project. Benjamin Canfield-Hershkowitz was responsible for planning team meetings and submitting project updates to Doctor Noori. Ben was also responsible for the analyzing the force sensor and other required equipment to accurately measure the recoil force. William Meijer, as stated above, was in charge of the build and was the point of contact with Greg King at Weatherby, Inc. Wil was also responsible for the CAD model and part drawings. Trevor Foster was responsible for organizing the engineering analysis and design to ensure each step was finished according to the time frame.

5. Concept Design Development

5.1 Ideation

Ideation is the process of creating as many solutions to the problem without regard, at first, to feasibility or practicality. During the beginning of this phase the team segregated so that many independent ideas were created. Then, the team reconvened and combined similar proposals to reduce the list of concepts. Brainstorming was done together as well so that an active discussion could aid in generating ideas. Top concepts were selected that fit with the customer specifications and could be manufactured with available tools. Since the scope of this project was somewhat constrained as to what type of device can be used, most of the devices have similar qualities; however, there are key factors which set theses designs apart from one another.

5.2 Top Designs

Described below are the top concept design ideas for this project. The illustrations of each design variation can be seen in Appendix C.

- **Solid base with 2 rails:** This design incorporates a solid aluminum base for the fixture. This solid base will allow for enough weight on its own to withstand the upward force that the discharge of the firearm could create on the frame. This design also incorporates two separate sets of linear precision rails. The front rail is secured to the gun with straps and moves when fired. The rear rail is secured to the stock of the gun and also moves when fired. These rails would allow for the gun to slide freely in a controlled linear manner into the force sensor located at the rear of the device. The force sensor would be inset into the rear panel for deflection purposes.

- **Solid base with 1 rail:** This design is much like the solid base with 2 rails, except it only has one rail to slide the rear of the gun into the force sensor. With only having one rail, the front of the gun would not have to be mounted down and could sit on a leather rest. To prevent the gun from leaving the device, it could be loosely constrained by a Teflon loop or other restraining device to prevent the gun from lifting up and out of the device when discharged.

- **Frame base with 2 rails:** Like the solid base with 2 rails, this design would incorporate two sets of precision rails to accurately transfer the discharge force into the force sensor, while accurately locating the firearm as well. However, this design incorporates a frame that would be made of steel tubing, rather than a solid piece of aluminum. The frame would have locations where weights could be added to hold down the system while in use.

- **Frame base with 1 rail:** This system is the same as the solid base with 1 rail, but with a frame base instead of a solid base. This system would also use a loose constraint on the front of the gun to ensure it would never lift off the device but would not reduce the force of the recoil.

- **Hanging pendulum:** This system is one in which instead of the gun sliding on rails into the force sensor, it would swing into the force sensor by means of two pendulums. The gun would ultimately act as a hanging pendulum, and when fired, the system would swing backwards into the force sensor. This system would require a frame to be built up in order to hang the gun, and would potentially require weights such as those described in the previous frame designs.

- **Spring deflection:** This system is much like that of the solid base designs; however, instead of a force sensor with a digital readout, the maximum recoil force would be measure by means of a spring(s). The recoil would compress a spring, and would incorporate a distance gauge to measure the distance that the spring was deflected, which would be calibrated to the spring(s) to read out force.

5.3 Concept Selection

A decision matrix was used to select the best performing design. The categories of the decision matrix are: safety, cost, accuracy, weight, set up, life, damage, manufacturability, and versatility; these categories were weighted from 1 to 5 depending on importance. The safety category was of the upmost importance and evaluated aspects of the designs that keep the rifle pointed down range and keeping the rifle from misfiring and ensuring it never separated from the device during firing. The cost was important due to customer request about keeping costs as low as possible. The accuracy of the device focused upon measuring the recoil force from the firearm; since this is the overall purpose of the project it also received the highest weight of 5. The overall weight and set up time received weights of 3 and 2, respectively; these were focused on because a requirement was that the device be portable. The life of the device category was added because this device must operate without service or labor by the original senior project team. Since some of the firearms being tested cost many thousands of dollars, the device must not damage the gun and thus the damage category received a high weight of 4. Manufacturability of this project is relatively important due to the fact that we would like to be able to easily manufacture this system so that adequate testing time is available. The versatility of the machine regarded its ability to accept shotguns and different makes of rifles; however, the customer was more focused upon making the device work for rifles first and thus versatility of working with shotguns was not of high importance.

Table 1 - Decision matrix comparing the top 6 design ideas

Criteria	Weight	Solid Base		Base Frame with weights		Hanging pendulum	Spring Deflection
		2 rails	1 rail	2 rails	1 rail		
Safety	5	10	8	10	8	5	7
Cost	5	5	7	5	7	5	6
Accuracy	5	8	9	8	9	5	4
Weight	3	4	5	5	6	6	6
Set up	2	8	9	7	8	6	5
Life	2	8	8	7	7	7	5
Damage	4	9	8	9	8	6	8
Manufacturability	4	6	7	4	5	3	5
Versatility	2	7	8	7	8	5	6
Total		**233**	**245**	**224**	**236**	**165**	**187**

After evaluating all top concepts in the weighted decision matrix, the **Solid Base with 1 Rail** was the top selection.

Figure 2 - Top design choice of a single rail solid base system

This device was selected because the solid base is strong enough for the application and is easier to manufacture. When compared to the frame base, the solid base is simpler and will be

easier to set up. The safety is similar to all top 4 designs because the gun is secured in the rear and sits in a deep grooved leather pad at the front that keeps the barrel pointed down range. The inclusion of a strap over the leather rest to prevent the gun from flying away is also included, which is important in both the safety and damage category. Since the only constraint is at the rear of the rifle, it could be adapted to shotguns so the versatility score is high. Also, with the inclusion of only 1 rail bearing the parts that could need servicing are reduced. Also, when compared to either of the two rail systems, the one rail proves to have less moving mass, which will lead to more accurate force results. This chosen system meets all the objectives required of the product. The recoil force will be recorded with the force sensor which will be exported to a laptop. The system attaches to an unmodified stock of both rifles and shotguns and the analysis uses values expected from the largest Weatherby round. The solid base is slightly harder to transport than the frame base because it does not have the removable weights, however, the system will still be light enough for a single person to carry.

5.4 Prototype

A prototype of the type design was created. The prototype was constructed out of medium density foam and is a good basis for the actual system that we hope to create. Appendix D shows the prototype model with a corresponding stock.

5.5 Analysis

A basic analysis was performed for the top concept design to check that the maximum deflection that the rear of the system will encounter will not be too large. All other forces that occur on the system will be negligible in comparison the rear recoil force, and since the system will be made out of either steel or aluminum, the resulting stresses will be of little importance. Based on the prototype, basic predicted dimensions were taken and the rear of the system was modeled as a cantilever beam with an intermediate load, providing for a simple analysis that can be seen in Appendix E. This analysis proved that the deflection of the beam at the sensor will be approximately less than 0.05 inches.

5.6 Testing

Testing of the device is necessary to ensure that the system is producing accurate results. Several different methods were employed to check the force and energy readings of our system. The force sensor was professionally calibrated by Piezotronics to ensure that it will accurately read force data. The area beneath the force versus time plot is the impulse energy of the impact. This energy should be constant for one rifle, except for when there is an inclusion of a muzzle brake. Because of this characteristic of impact, we should be able to fire the rifle with various butt pads and continue to measure the same recoil energy.

From the desired force vs. time data, the force can be converted to an acceleration using the known rifle mass. The acceleration vs. time data can then be integrated to give the maximum velocity. That velocity can be then be input into the kinetic energy equation to find the total recoil energy.

The recoil energy can then be compared to the theoretical values we received from Mr. King at Weatherby, which were calculated using the theoretical kinetic energy equation. These values were determined by accurately measuring the muzzle velocity, the mass of each bullet, the charge weight and the gun weight. For more information on the testing and design verification, see the Design Verification section.

6. Final Design

The final design of this system is much like the final concept design; however, after analyzing the concept design, several key changes were made to improve the system. This section will show the details of the final design in every aspect.

6.1 Design Description

As seen in Figure 3, the final design is a simple, yet effective system for measuring recoil force. The rifle will sit on shooting bags as shown, and will be strapped down by Velcro straps. The shooting bags sit on moveable sleds that will allow the shooter to get the correct position of the rifle. This final design, unlike the concept design, incorporates two shooting bags instead of having the rear of the stock on a linear precision rail. It was determined that the friction force from the rear shoot bag is negligible due to the light weight of the rifle and the recoil force is much larger. The butt of the gun is placed against a piece of HDPE plastic that is secured in place with Velcro. This is to ensure that that the sensor is able to utilize the damping of the entire butt pad and measure the force that the shooter will actually feel. The plastic piece also provides a flat surface to contact the force sensor, which is located directly behind the mold and is attached to the back plate of the system. The flat surface will make sure that the force sensor does not encounter a bending moment, which could harm the sensor.

Figure 3 - Final Design

The back plate of the system is screwed onto the base plate using high strength grade 8 steel bolts, and provides a rigid surface for an accurate recoil force reading. Located on the front of the system is an aluminum piece, called the table catch. This table catch is incorporated in order to apply a reactant force against the recoil force on the shooting table, which will keep the system on the table. Since there is minimal upwards force, the weight of the system should be enough force to keep the system from lifting upwards, but for safety reasons a Velcro strap has been added to ensure that the rife stays on the testing system. The rifle will be fired from a distance using either a hydraulic trigger mechanism or a trigger hook and the force sensor system will record the recoil force and be able to be read from a laptop. The use of an external trigger-pulling device will not only guarantee safety for the shooter, but will also allow for a more accurate force reading.

The detailed part descriptions and part drawings can be seen further in this report, as well as a detailed description of the program for recording the recoil data. Three dimensional solid modeling using SolidWorks can be found in Appendix I.

6.2 Analysis Results

This system is overall a simple system when it comes to force analysis and calculations. The main analysis contains calculations for safety factors and deflections from the recoil force. However, this system also required much analysis for the necessary force sensor. This section contains both the force analysis and the sensor analysis.

6.2.1 Force analysis

A major part of this project has to do with the issue of safety, as this system will be supporting firearms and will be undergoing large forces. Using Engineering Equation Solver (EES), every major component that could be a source of failure was analyzed. Knowledge from previous design courses, as well as Shigley's Mechanical Design book (Budynas et al. 2011), allowed for the analysis of these components. The biggest potential safety hazard is the back plate of the system, where the butt of the stock meets the force sensor. Rifles are designed to shoot accurately, which means that the rifles primary motion is in the direction of the barrel axis. This system is designed to record the backwards recoil force along this axis using the force sensor, meaning that the back plate of the system is going to be experiencing most of the force from the discharge; hence, the safety of the back plate is of utmost importance. The front of the rifle stock may "kick" upwards; however, this force is not substantial enough to be of any concern, as it will not overcome the weight of the system. Furthermore, the design includes a Velcro strap that will prevent the gun from becoming dislodged from the testing machine.

As stated above, the back plate experiences most of the recoil force and thus must be secured to the horizontal support. Calculations were completed in EES to show that bolting these two parts together is substantial enough to prevent failure. While welding the two pieces together was discussed, since the bolts are adequate, no calculations were required.

A program was written in EES to find all of the safety factors, forces, and other relevant values, shown below. This was done so that the dimensions and other variables of the system could be easily changed and the results can quickly be observed. Using this EES program, calculations were done to find the following:

- Deflection of the back plate at the sensor, δ_{Back}
- Weight of the System, W_{System}
- Infinite life safety factor using Goodman criteria, n_f
- Number of expected cycles, N
- Yielding safety factor for the screws, n_{yield}
- Load safety factor of screws, n_{load}
- Fatigue safety factor for screws, n_f, screws
- Design factor for bolted joints loaded in shear, n_d

These calculations were based on 6061 T6 Aluminum base and back, two SAE Grade 8, ¾"-16 UNF screws in the back plate, estimated recoil force from a Weatherby .460 of 3200lbf, and estimated weights of the front and back rifle rests. The front table catch is very similar to the back plate, but it is much shorter, as it just needs to hook around the front of a table. Analysis was not completed for the table catch because it is the same design as the back place but less than half the height. Thus, the moments are diminished at the front and the critical failure location is the back plate.

Below are the detailed descriptions and reasons for finding each of the components listed earlier. The equations for each calculation can be seen in the EES program in Appendix G, and the resulting values can be seen in Table 2.

Deflection of the back plate at the sensor, δ_{Back} :

In order to find the deflection of the back plate, the back plate was modeled as a solid cantilever beam with an intermediate load for simplification. This assumption is fine for analysis because in the actual system, the two steel screws strengthen the back further, resulting in a smaller deflection. Also, since this back plate is not seeing a static load, a Dynamic Load Factor of 2.0 was taken into account.

Weight of the System, W_{System} :

The weight of the system was estimated from the sled base, back plate, and table catch volumes along with the unit weight of aluminum, and from an estimation of the rifle rest and the liner rail. This estimation is slightly higher than the actual system, because the actual system will have material removed in the manufacturing process.

Infinite life safety factor using Goodman criteria, n_f :

Using the Modified Goodman and Langer Failure Criteria, the fatigue factor of safety was found. Since the system does not undergo opposing forces, the amplitude and midrange stresses were set equal to half of the maximum stress, which took into account the dynamic load factor of 2.0. The modified endurance limit was found for a machined surface finish, the correct size factor, pure bending, and a reliability of 99.99%.

Number of expected cycles, N :

Although the infinite life safety factor was found, the expected number of life cycles was found as well, just to be safe. This calculation was done using the same modified endurance strength as the infinite life and a fatigue strength fraction of 0.9.

Yielding safety factor for the screws, n_{yield} :

The yielding safety factor is for statically loaded tension joints with preload. The screws in this system see mainly shear forces; however, this calculation was done so that on the off chance that the screws experience tension, the system will not fail. Since this calculation is also for static loads, the dynamic load factor of 2.0 was taken into account.

Load safety factor of screws, n_{load} :

This load safety factor is to guard against joint separation. This safety factor is calculated to be sure that the base, spacer, and back plate do not separate due to the recoil force. This calculation uses variables from the yielding safety factor, but does not take into account the proof strength or tensile stress area of the bolt.

Fatigue safety factor for screws, $n_{f,bolt}$:

Much like the fatigue safety factor for the back plate, the Goodman equation was used to find the fatigue safety factor of the screws as well. This equation is also used for bolts in tension, but it still applies to this problem. The dynamic load factor was also taken into account for this calculation.

Design factor for bolted joints loaded in shear, n_d :

For each of the previous safety factor calculations for the screws, the assumption was that the screw was loaded in tension. For this design factor, n_d, the bolt is assumed to be in shear, which is a better representation of the system. This safety factor was found for the worst case, in which the bolt threads extend into the shear plane. Using the maximum anticipated recoil force with the dynamic load factor, the design factor was obtained.

Table 2- Values from Force Analysis

δ_{back} (in)	0.0054
W_{system} (lbs)	33.99
n_f	3.373
N (cycles)	3.11E+09
n_{Yield}	1.279
n_{Load}	7.807
$n_{f,screws}$	2.091
n_d	7.595

The deflection of the back plate is small enough to not be noticed and the cycles until failure will withstand 100,000 cycles a day for 85 years. All the safety factors are larger than 1 and thus the system will not fail.

6.2.2 Sensor Selection

The team conducted preliminary testing of Weatherby's rifles to determine an estimate of max recoil force the sensor would need to record. To gather this data, the team checked out equipment from the Cal Poly Mechanical Department and tested rifles at the Weatherby range in Paso Robles, CA. The team used a PCB load cell, signal conditioner, USB data acquisition system, and software package which allowed recording at 98 kHz. Tests were completed using a Weatherby .25-06 Rifle and a Weatherby 300 Magnum and the data gathered using the borrowed equipment is shown in Appendix G. The data acquired for the .25-06 rifle appeared to be accurate but the force of the 300 Magnum overloaded the sensor above 1040lb for 174 and 206 data points for the first and second test, respectively. This equates to 1.8 and 2.1 milliseconds, respectively. The sensor overload notwithstanding, the borrowed equipment performed in a fashion the team hopes to recreate with the final design. However, in an effort to reduce costs as much as possible, a less vigorous system will be specified and purchased.

To estimate the peak force for the 300 Magnum, a parabolic curve fit to the data was created to estimate the overloaded data points. The region just before the sensor overload was sampled, and repeated across the overloaded points. The curve fit very nearly intersected with the real data points after the overloaded region and thus was assumed to be a good fit. The estimated peak force for the .460 Weatherby Magnum was assumed to be double to triple the peak force for the 300 Magnum. Thus, a sensor that could read over 3600lbs was deemed necessary, and with a safety margin, a 5000lb load cell was purchased.

To determine the slowest refresh rate for the USB data acquisition unit that will still yield accurate results, a Matlab program was created that would artificially reduce the number of data points. The program is shown in Appendix L. This was done to simulate the scenario of a lower refresh rate system and was used to simulate refresh rates of 50 kHz, 25 kHz, 10 kHz, 5 kHz, 1 kHz, 500 Hz and 250 Hz. By comparing the graph of the force vs. time, the recoil energy, and peak force for all refresh rates, a sensor package that could attain 25 kHz to 50 kHz was deemed

to be necessary. Refresh rates lower than 25 kHz affected the peak recoil force and recoil energy and thus are not adequate for this project.

A data acquisition unit's resolution is rated by bits, which represent the maximum number of unique values it can record. For example, a 2-bit digital value can represent 4 numbers and for a load cell that reads 0 to 5000 pounds, it would be divided into 4 pieces. This yields a resolution of ±1250 pounds. For our system to have the resolution desired, a 14-bit system will be used. This will yield a resolution of $5000/(2^{14})$ or 0.3 pounds.

The accuracy of the system is affected by the load cell and data acquisition unit. The load cell sensitivity is 0.9720mV/lb with 0.3% nonlinearity over the full 5000lb scale and 1% uncertainty. The data acquisition unit absolute accuracy is ±3.66mV over the full range of ±5V. Thus, for a reading of 5000 pounds, the sensor would have an accuracy of <±50 lbs and the data acquisition unit would be ±3.66mV, for a total uncertainty of ±54lbs. However, for a reading of 1000 pounds, the total uncertainty would be ±14lbs. This uncertainty may seem large, but it makes up a very small percentage of the total force, enough so that it can be considered negligible. This will not noticeably affect the recoil energy calculations.

The chosen data acquisition unit (DAQ) is a Measurement Computing Corporation USB-1408FS, a PCB 208C05 load cell, a PCB 428A21 signal conditioner, and a program are used to gather the data on a computer. The program was written in C# using the MCC provided libraries, which can be used to read data from the DAQ. The program analyzes the data, producing a graph of force vs. time, recoil energy and peak force. The program can then output the data to excel for storage. The program has a graphical user interface and automatically computes the required values for Weatherby.

6.2.3 Program Operation

The software was written in C#. This language was chosen due to the operating system, and MCC DAQ Company provided examples and functions in this language as well. The first draft of the Matlab code that analyzed and plotted the peak force and recoil energy is shown in Appendix K.

Figure 4 shows the initial screen of the program. The rifle details allow the user to select a rifle where the mass is already known by the program. If any additional mass is added, such as a scope, it can be inputted as well. If a new rifle is being testing, the user can input the rifle name and weight for the test. Once the user is ready, they will press the "Start" button. The program will wait for the trigger, which can be set by the user. Once the trigger force is surpassed, the program will record a set amount of time before and after the trigger and illustrate a graph of the data as well as display the peak force and recoil energy. The user is then able to export the plot to a PDF file and the data to a CSV file for later inspection. Figure 5 shows an exported graph of a test run conducted at Weatherby's range, however, the range of force values shown is off by a factor of 1000 due to programming errors. These errors have been corrected.

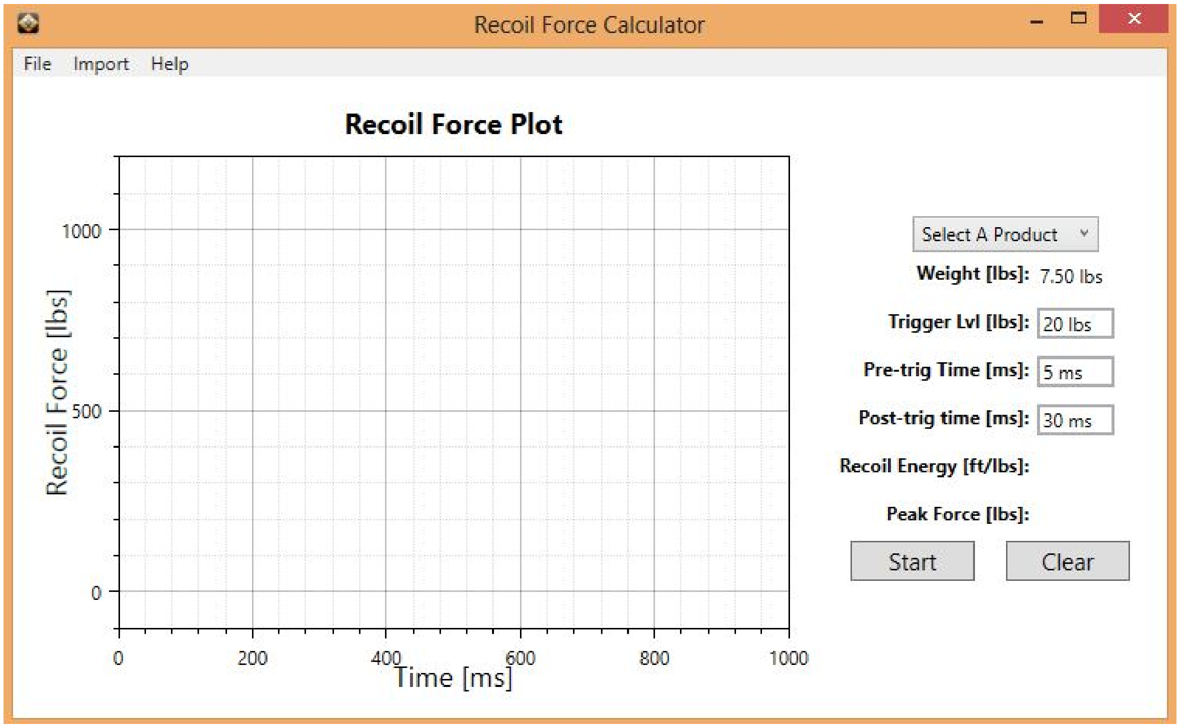

Figure 4 - Program Screen

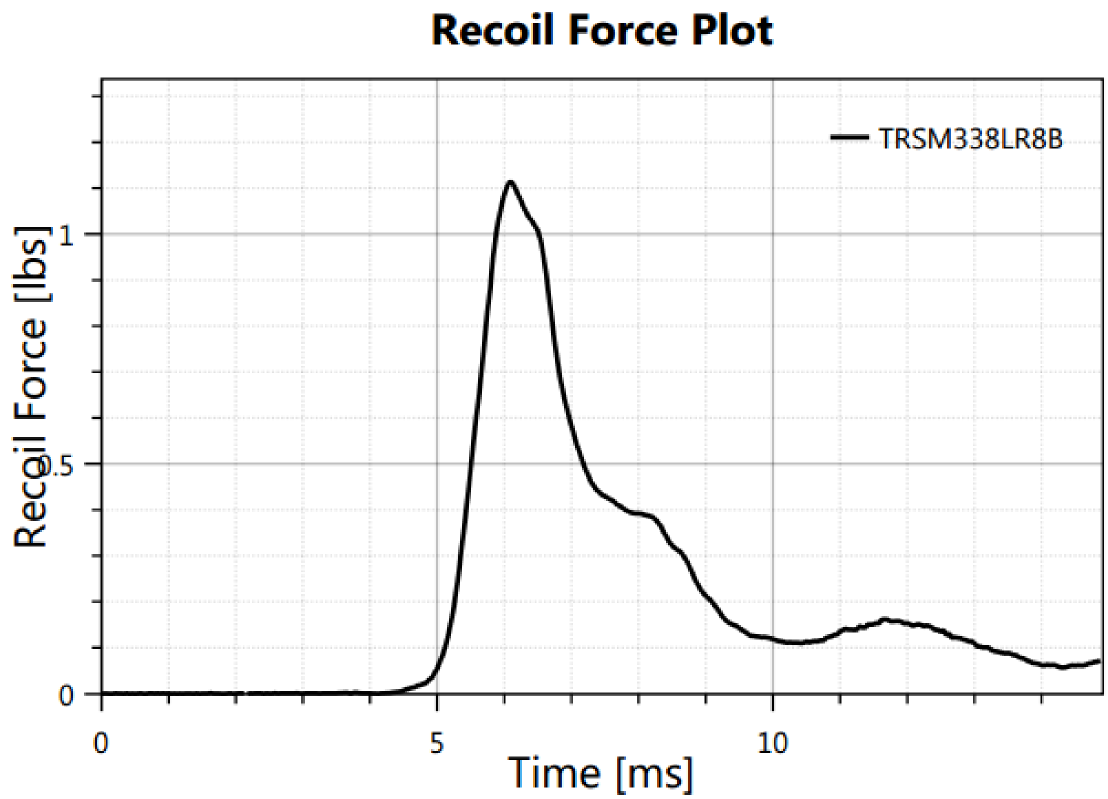

Figure 5 - Export plot of sample data

6.3 Cost Analysis

The finalized design required many individual parts as well as raw material for machining. The load cell and signal conditioner are PCB Piezotronics equipment. The data acquisition unit is from Measurement Computing. The screws and unfinished aluminum were purchased from McMaster Carr, and the other components were purchased from varying locations. The total cost of all materials was estimated to be $1608.92 before tax/shipping and final cost was estimated to be $1747.27. This estimate does not include a laptop computer as Weatherby will be providing a system for the test apparatus. The final cost of materials was $1624.39 before tax/shipping and final cost was $1802.37. This is $55.11 over the estimated cost due to unforeseen components such as poster and presentation supplies. Appendix M shows the bill of materials with the estimated and final costs.

7. Product Realization

The team completed the machining and manufacturing of the final system primarily in the machine shops on the Cal Poly campus. Manual mills and lathes as well as CNC mills were the primary equipment used to machine the aluminum. Other hand tools and necessary tools were also used as needed. The machining took place throughout the Spring and Fall 2013 quarters, and was completed by all members in the group. Each aluminum piece needed to be machined down from the purchased stock sizes. The base plate took the longest to machine, which is why the entire rear half of the base plate was milled on a CNC mill with the help of Manufacturing Engineering student Trevor Heglund. The CNC mill was also used on the front table catch in order to remove material quickly. All other pieces were primarily machined on manual mills, with the exception of the pegs for the sliders, which were turned and faced on a manual lathe. All pieces received a surface finish, which was created with an orbital sander. All edges were smoothed with a polishing wheel to reduce risk of injury.

Figure 6 - Ben (top left) and Wil (bottom left) machining aluminum components of the system, such as the sled peg (bottom right)

The shooting bags that sit on the sleds were attached by industrial strength Velcro. Velcro was also used to attach the DAQ unit to the signal conditioner for ease of transportation, and Velcro straps were used to secure the firearm to the testing system.

While manufacturing the system, a different method of attaching a butt spacer was decided. Instead of encasing the butt of the gun with a HDPE mold, we created an adjustable holster out of Velcro straps to secure a butt spacer to the rear of the firearm. A piece of HDPE was used for the butt spacer, and slots were milled out in the spacer to attach the holster. The holster was sewn into place by Ben in order to secure the adjustable straps to the spacer.

The spacer was welded to the base plate. This spacer allows the heads of the fasteners to be recessed into the base plate, without having an excessively thick piece of aluminum for the base.

Figure 7 - Final system displayed at the Senior Project Expo

8. Design Verification

The purpose of this project was to create a system that can accurately measure the recoil force of rifles and shotguns so that different ammunitions, muzzle brakes, and butt pads can be compared for their effect on the felt recoil by the shooter. As the purpose states, this project needs to be accurate. In order to validate the accuracy of the system, the team has come up with a design verification plan.

The theoretical recoil energy for the discharge of a gun with no muzzle brake can be calculated using the following formula

$$R.E. = \frac{1}{2} M_g V_g^2$$

Where

M_g= mass of the firearm (lb_m)

V_g= velocity of the recoiling firearm, which can be calculated from the equation

$$V_g = \frac{W_e V_e + (Chg.Wt)V_e f}{7000 W_f}$$

Where

W_e = weight of ejected projectile (bullet or shot and wad) in grains

V_e = Velocity of the projectile in ft/s

Chg. Wt= charge weight (grains of powder)

f = conversion factor for propellant gases

High powered rifles – f=1.75

Shotguns (average length barrel) - f= 1.5

Shotguns (long barrel) - f=1.25

Pistols and revolvers - f=1.5

W_f = weight of firearm in lbs

Each variable in this equation can be measured at Weatherby's facility. Weatherby has actually created an excel program that calculates theoretical energies for most of their guns, and the energies can be compared to the experimental recoil energy. The experimental recoil energy can be calculated from the force vs. time data using the same equation as the theoretical energy

$$R.E. = \frac{1}{2} M_g V_g^2$$

However, in this case the velocity is found from the data. The data gives a force vs. time graph. Dividing the force by the mass of the gun will give the gun's acceleration, and then integrating the acceleration data will yield the velocity of the gun.

$$Acceleration = \frac{Force}{m_g}$$

$$\int \frac{Force}{m_g} dt = V_g$$

The program automatically calculates the recoil energy from the data using the above equations, and it can then be compared to the theoretical energy for that given rifle.

Since the discharge of a firearm is created by expanding gases, the discharge is not the same every time. This means that the theoretical energy for a given firearm is only an estimate, and cannot be precisely calculated, hence for the verification of the theoretical energies against the experimental energies, the team would like to be within 20% of the theoretical energies.

8.1 Testing

As stated above, adequate testing was necessary to determine if this system is accurate. Testing was conducted at Weatherby's range, and proved that the system is safe and records recoil energy.

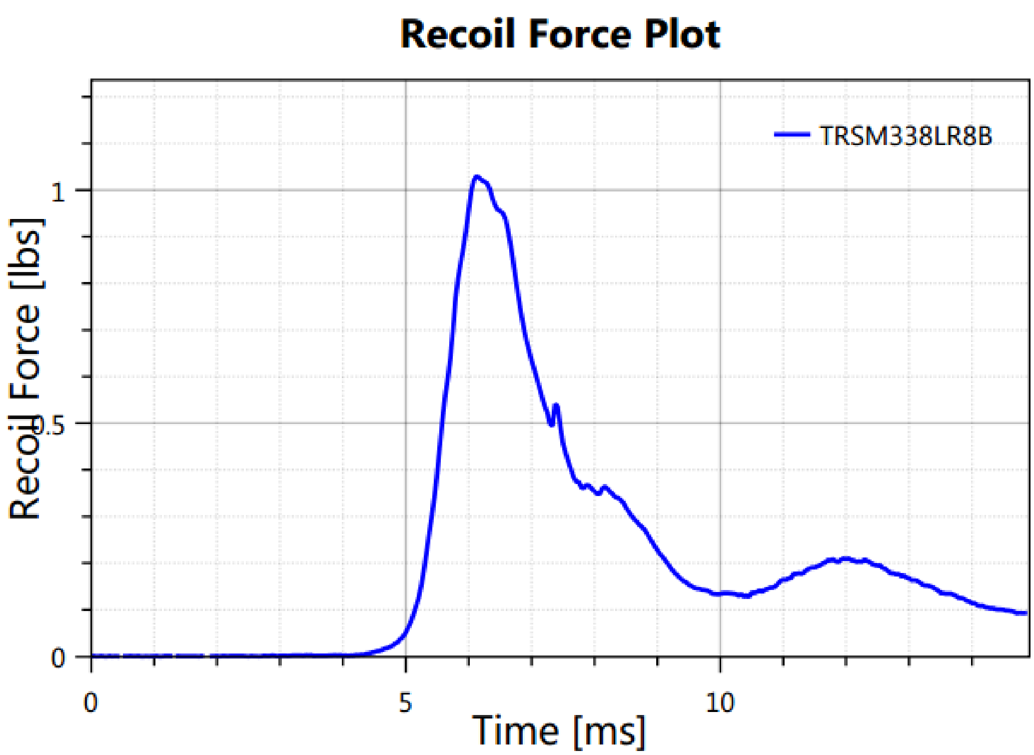

Figure 8 - Experimental test results from final system

More experimental plots from two separate rifles that were tested on the final system can be seen in Appendix G.

During the testing of the final system, the weights of the guns were approximated; therefore the calculated recoil energies were also approximations. However, PCB Piezotronics calibrated the load cell before it was shipped to us, therefore we are confident that the force readings are accurate. See Appendix N for load cell specification and calibration sheets. Greg King at Weatherby expressed that the recoil energies seemed to be accurate, but these values could not be proven to be completely accurate due to the issues stated above. Further testing will be conducted by Weatherby during the initial phases of use of this prototype to ensure the recoil energies are consistent with theoretical values. Prior testing on a very similar system proved that this method of recording recoil force and calculating recoil energies for different firearms was accurate, and the results can be seen below in Table 3

Table 3 - Experimental and Theoretical Recoil Energies

	Recoil Energy (ft-lb)			
Rifle	Test	Theoretical	Experimental	% Difference
300 Weatherby Mag	1	43.90	46.88	6.57%
300 Weatherby Mag	2	43.90	44.86	2.17%
Weatherby .25-06	1	19.92	18.51	7.34%
Weatherby .25-06	2	19.92	20.03	0.53%

9. Conclusion

The designed system meets all specifications and was thoroughly analyzed. The team is confident that the engineering analysis performed ensures the test apparatus is safe for using with live rounds. Moreover, the data acquisition is of high enough quality to produce accurate results, and will provide Weatherby with a system that can accurately measure recoil force and recoil energy. We believe that this system is a great solution to our specified need and with this system, Weatherby will be able to accurately test recoil forces and recoil energies for various rifles and shotguns in order to compare and quantify various recoil suppression methods.

10. Acknowledgements

The team would like to take this opportunity to thank their advisor, Dr. Noori, for his guidance throughout the project. For assistance in understanding and purchasing force sensors, the team would like to thank both Professor Peter Schuster and Professor Charles Birdsong. Also, PCB Piezotronics application engineers for answering multiple questions about load cells and being a valuable resource for all aspects of the set up. Likewise, Measurement Computing for explaining how data acquisition units function and help in selecting an appropriate product. Finally, the team would like to thank Weatherby and Greg King for the opportunity to work on this project.

11. References:

British War Office. Textbook For Small Arms. N.p.: Naval and Military, 1929. Print.

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Appendix:

A - Sample Output Graph

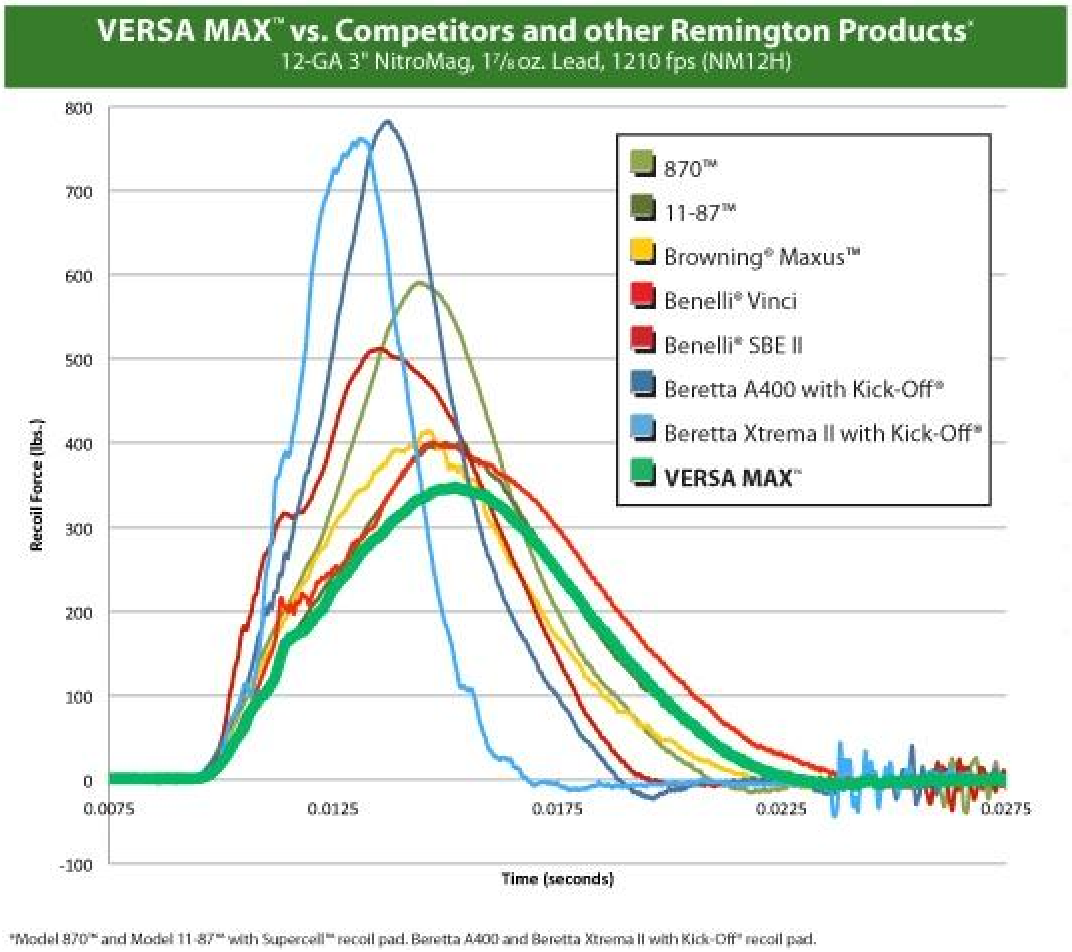


Figure 9 – Sample Force and Time Graph

This graph is an illustration of the desired force vs. time output graph that we hope to acquire from our recoil test system. This graph was found without any information about the sensor or system used to test but the resolution and output are features desired from our system.

Recoil Thrust System Weatherby, Inc.	Weighting (Total 100)	Force Sensor	USB DAQ	Material	Gun Mount	Trigger Mechanism	Table Clamps	Proof Load Firing	Universal Fixture	Instruction Labels	Impulse Calculations	Momentum Sling	Benchmarks Scale of 1 (Bad) to 5 (Good)
Customer Requirements (Step #2)		Engineering Requirements (HOWS)											
Accurate force vs. time data	15	●	●					●			0	1	
Accommodate different models of gun	5	○		Δ					●		3	5	
Keep firearm pointed downrange	10			●	●		●		●		N/A	2	
Prevents firearm from lifting off bench	10			Δ	○		●	Δ	○		N/A	1	
Attach to various firing benches	5			●	○		●				N/A	3	
Simple trigger mechanism	5					●					N/A	1	
Available materials	5			●	○		○	Δ	Δ		N/A	2	
No complex training required to use	5	Δ	○						○	●	1	1	
Portable - Move to difference ranges	5		●	●			●				N/A	1	
No damage to firearm	10	○	Δ	○	●			○	●	○	N/A	3	
Connect to laptop	10	●	●								N/A	1	
Does not require outside power (besides laptop)	5	●	●			○					N/A	5	
Will not break	10	●	Δ	●	○			●	Δ		N/A	3	
Total Weight	100												
Technical Priority		410	350	360	270	60	285	270	285	75			
Percentage of Total (%)		17	15	15	11	3	12	11	12	3			

● = 9	Strong Correlation
○ = 3	Medium Correlation
Δ = 1	Small Correlation
Blank	No Correlation

Figure 10 – QFD House of Quality

B - Quality Function Development

The QFD is a method to determine the most important engineering requirements. From the Percentage of Total line, it shows that the Force Sensor is the most important, with the USB Data Acquisition and Material selection next. Focus should also be placed on the fixture, the table clamps and proof load firing to determine accuracy

C - Concept Design Ideas

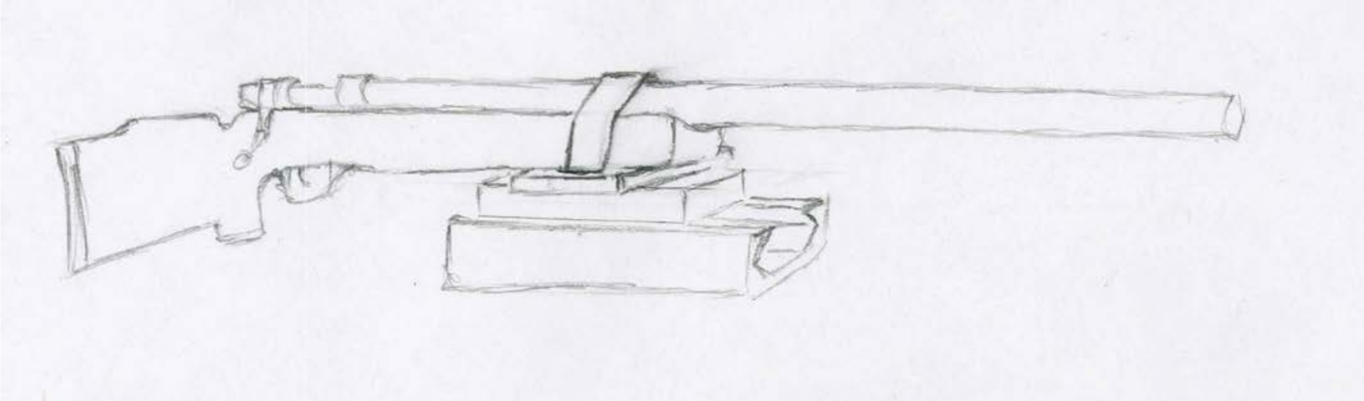


Figure 11 - Design possibility showing a rifle mounted on one of the sliding rails

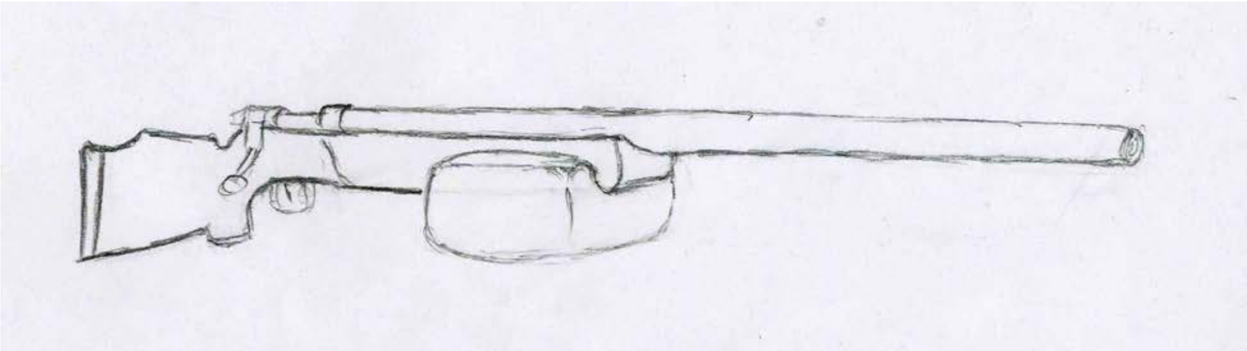


Figure 12 - Design drawing illustrating a mount without the rails, such as a leather rest

D – Prototype Production

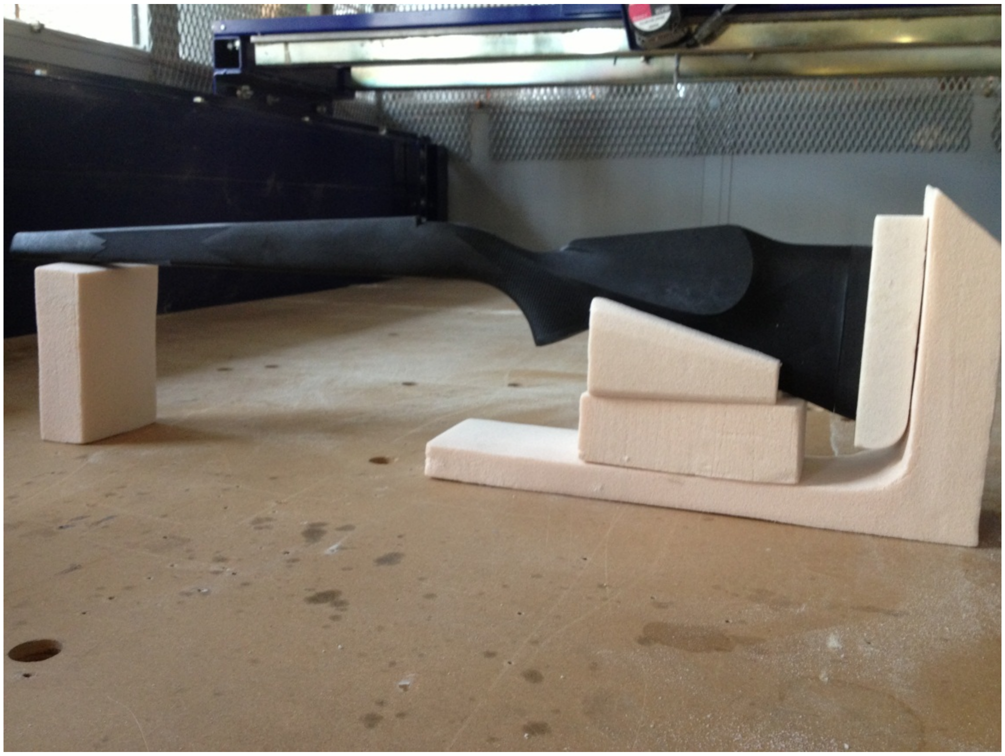


Figure 13 - Side view of foam prototype showing each component

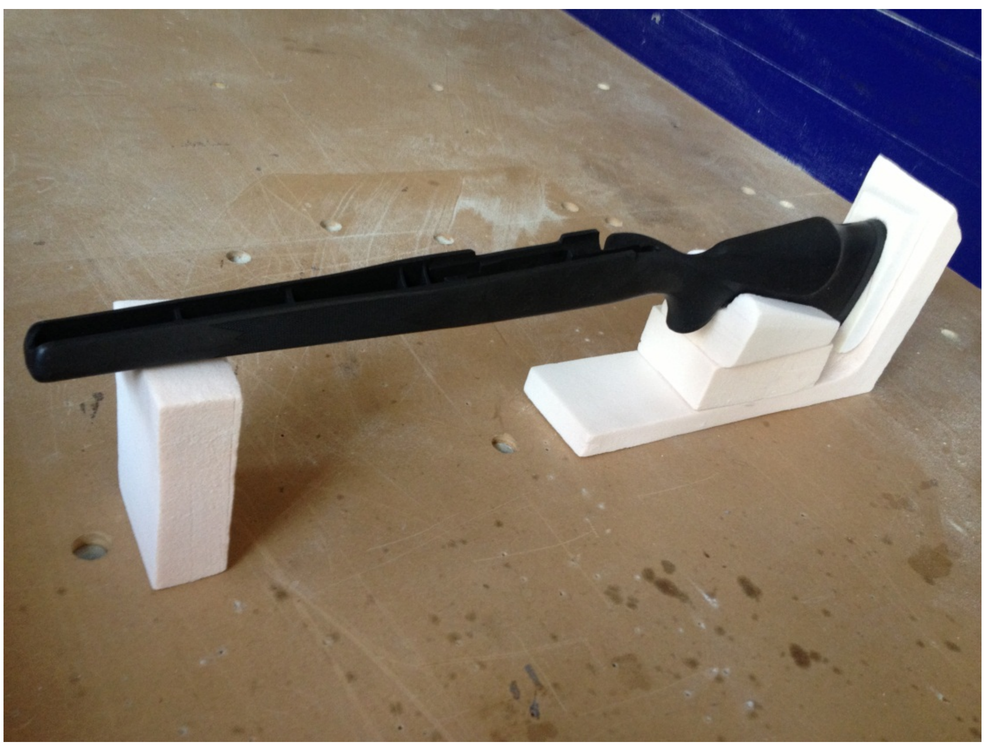


Figure 14 - Top view of the foam prototype model

E - Concept Analysis

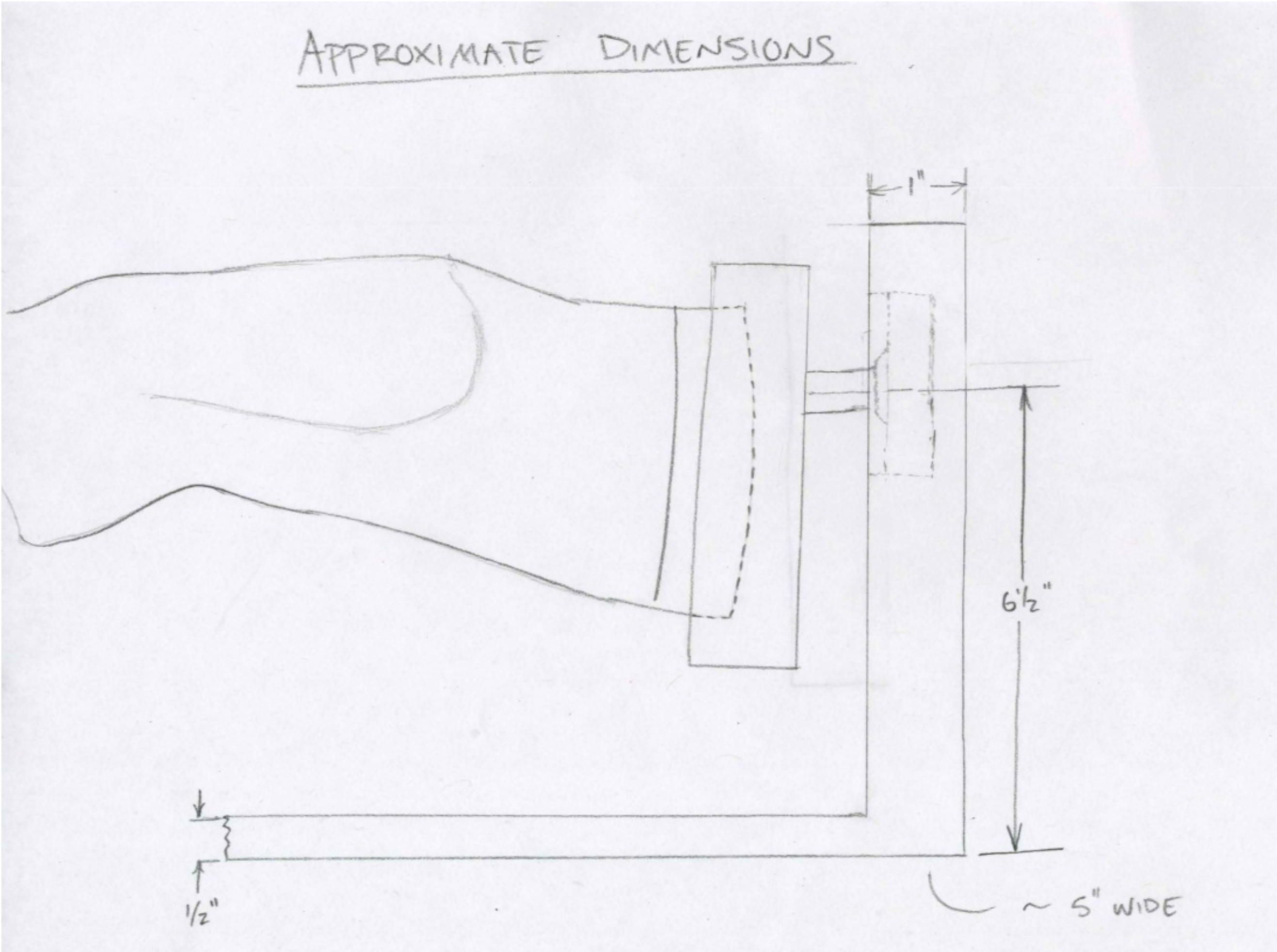


Figure 15 - Basic dimensions and schematic of top system design

The concept analysis models the back plate as a cantilever beam. This simplification is used so the analysis is simple and results in a basic understanding of how to design the complete system.

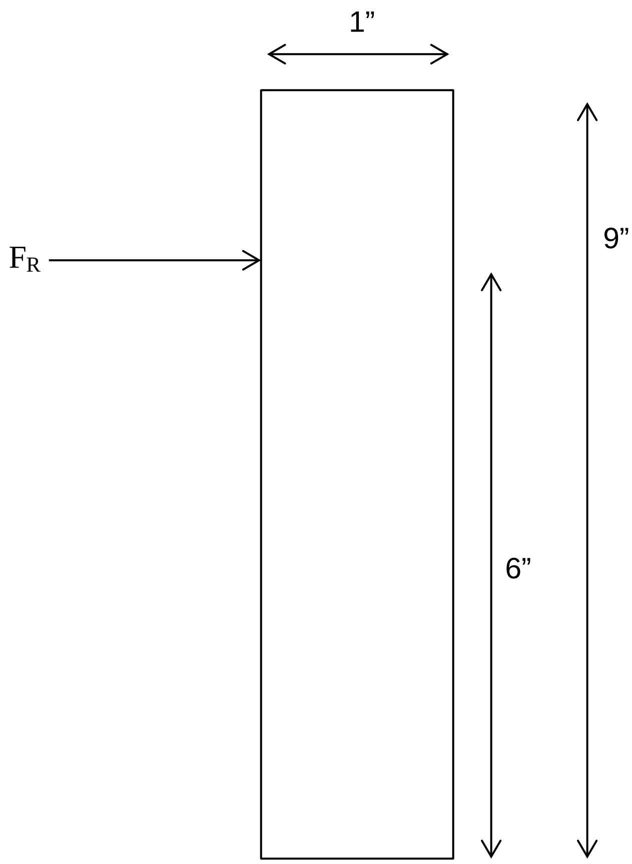


Figure 16 – Dimensions for basic deflection analysis

Estimated Recoil Force: F_R = 2000lb

Dynamic Load Factor: $k_{dynamic}$ = 2

Length to Sensor: L_{Sensor} = 6 inch

Total Length of Beam L_{total} = 9 inches

Thickness of Plate: t = 1 inch

E_{Al} = 1.04 x 10^7 lb_f/in^2

$$I = \frac{1}{12} Width * t = \frac{1}{12} * 4 * 1$$

$$I = 4/12$$

Max Deflection for Intermediate Load

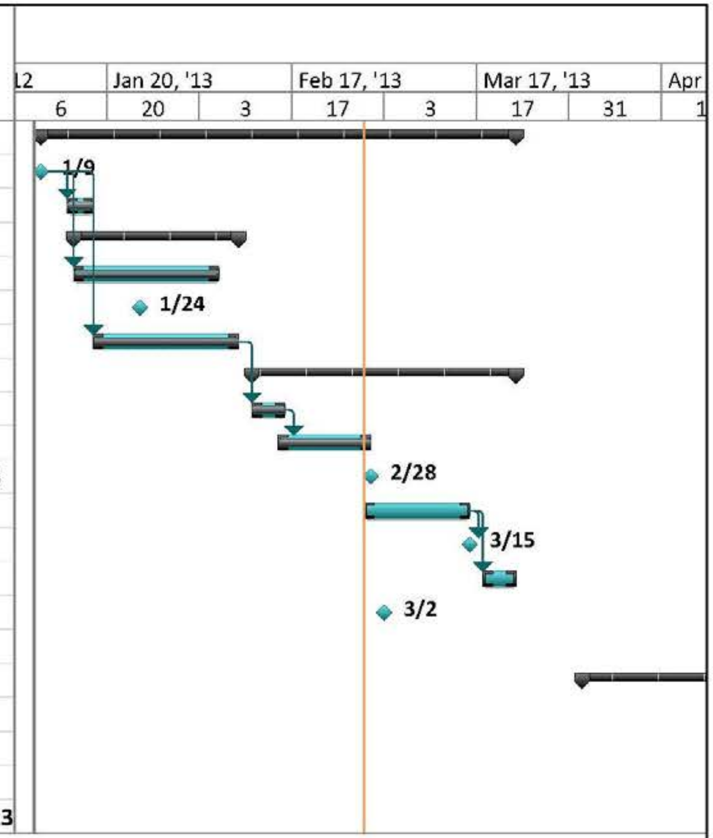
$$\delta_{back} = \frac{F_R k_{dynamic} L_{Sensor}^2}{6EI} (L_{sensor} - 3L_{total})$$

$$\delta_{back} = \frac{(2000lb)(2)(6in^2)}{(6)(1.04E7)\left(\frac{4}{12}\right)} (6 - 3(9))$$

$$\delta_{back} = -0.0485\ inch$$

F - Gantt Chart

ID		Task Mode	Task Name	Duration	Start	Finish
1			**Winter 2013**	**52 days**	**Wed 1/9/13**	**Fri 3/22/13**
2	✓		Assigned Project	0 days	Wed 1/9/13	Wed 1/9/13
3	✓		Letter to Sponsor	4 days	Mon 1/14/13	Thu 1/17/13
4	✓		**Project Proposal**	**19 days**	**Tue 1/15/13**	**Fri 2/8/13**
5	✓		Background Research	16 days	Tue 1/15/13	Tue 2/5/13
6	✓		Meet Sponsor at Weatherby	0 days	Thu 1/24/13	Thu 1/24/13
7	✓		Project Proposal	16 days	Fri 1/18/13	Fri 2/8/13
8			**Concept Design**	**30 days**	**Mon 2/11/13**	**Fri 3/22/13**
9	✓		Brainstorming	5 days	Mon 2/11/13	Fri 2/15/13
10	✓		Prototype	10 days	Fri 2/15/13	Thu 2/28/13
11	✓		Concept Design Review	0 days	Thu 2/28/13	Thu 2/28/13
12			Concept Design Report	12 days	Thu 2/28/13	Fri 3/15/13
13			Concept Design Report Due	0 days	Fri 3/15/13	Fri 3/15/13
14			Concept Design Presentation	5 days	Mon 3/18/13	Fri 3/22/13
15			Yellow Tag Test Due	0 days	Sat 3/2/13	Sat 3/2/13
16						
17			**Spring 2013**	**49 days**	**Tue 4/2/13**	**Fri 6/7/13**
29						
30			**Summer 2013**	**56 days**	**Fri 7/5/13**	**Fri 9/20/13**
32						
33			**Fall 2013**	**56 days**	**Mon 9/23/13**	**Mon 12/9/13**



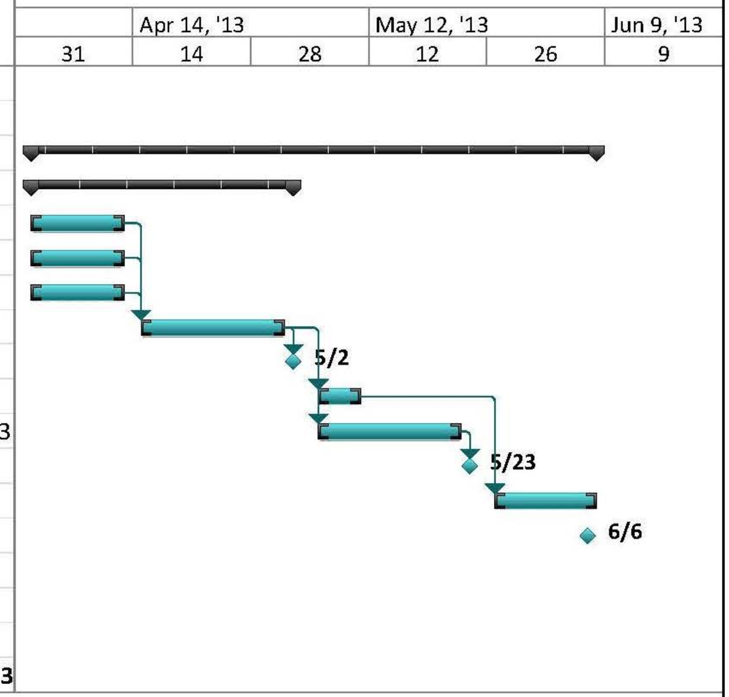
Project: ME428 Group 20 Gantt C
Date: Thu 2/28/13

Task	External Milestone	Manual Summary Rollup
Split	Inactive Task	Manual Summary
Milestone	Inactive Milestone	Start-only
Summary	Inactive Summary	Finish-only
Project Summary	Manual Task	Deadline
External Tasks	Duration-only	Progress

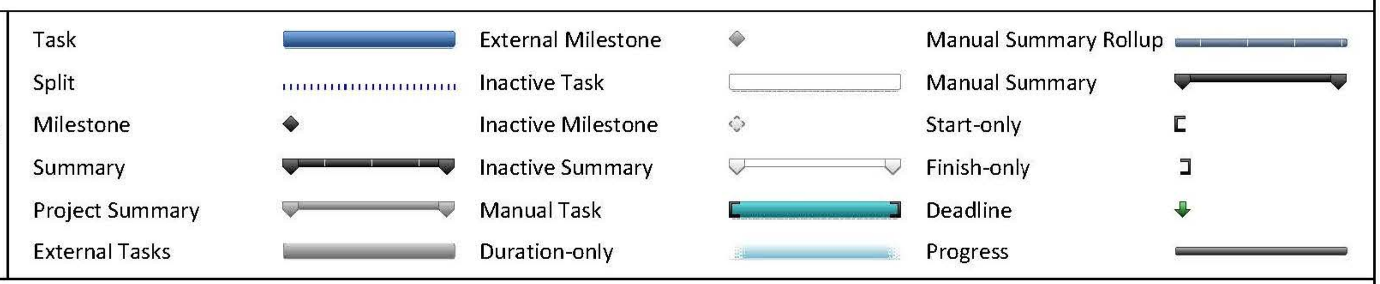
Page 1

Figure 17 – Winter 2013 Gantt Chart

ID		Task Mode	Task Name	Duration	Start	Finish
1			**Winter 2013**	**52 days**	**Wed 1/9/13**	**Fri 3/22/13**
16						
17			**Spring 2013**	**49 days**	**Tue 4/2/13**	**Fri 6/7/13**
18			**Critical Design Report**	**23 days**	**Tue 4/2/13**	**Thu 5/2/13**
19			Engineering Analysis	9 days	Tue 4/2/13	Fri 4/12/13
20			Drawing & CAD	9 days	Tue 4/2/13	Fri 4/12/13
21			BOM	9 days	Tue 4/2/13	Fri 4/12/13
22			Critical Design Report	13 days	Mon 4/15/13	Wed 5/1/13
23			Critical Design Review	0 days	Thu 5/2/13	Thu 5/2/13
24			Order Parts	5 days	Mon 5/6/13	Fri 5/10/13
25			Design of Test Experiment	13 days	Mon 5/6/13	Wed 5/22/13
26			Manufacturing and Test Review	0 days	Thu 5/23/13	Thu 5/23/13
27			Begin Manufacturing	10 days	Mon 5/27/13	Fri 6/7/13
28			End of Quarter Report	0 days	Thu 6/6/13	Thu 6/6/13
29						
30			**Summer 2013**	**56 days**	**Fri 7/5/13**	**Fri 9/20/13**
32						
33			**Fall 2013**	**56 days**	**Mon 9/23/13**	**Mon 12/9/13**



Project: ME428 Group 20 Gantt C
Date: Thu 2/28/13



Page 1

Figure 18 - Spring 2013 Gantt Chart

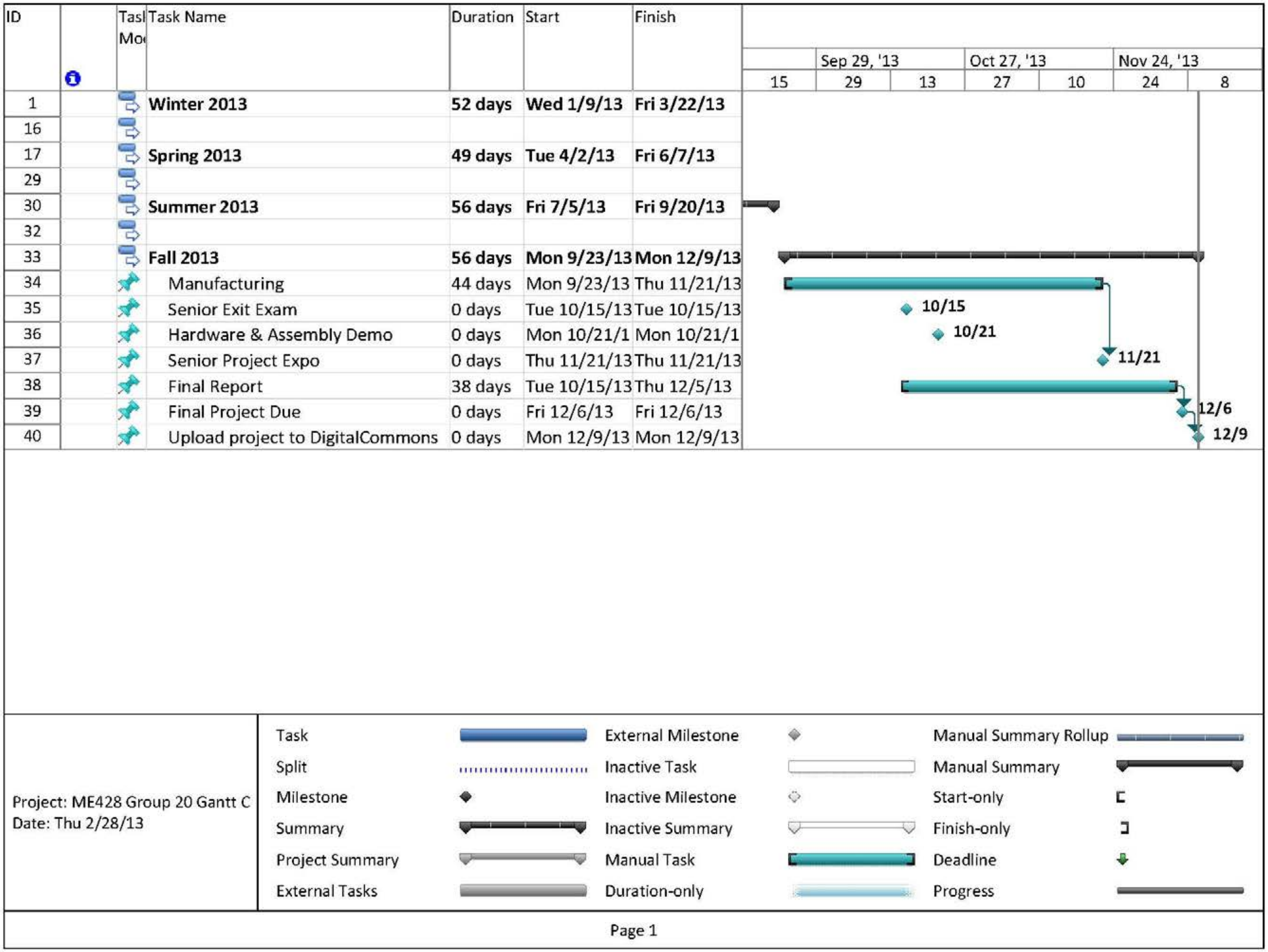


Figure 19 - Fall 2013 Gantt Chart

G – Test Data

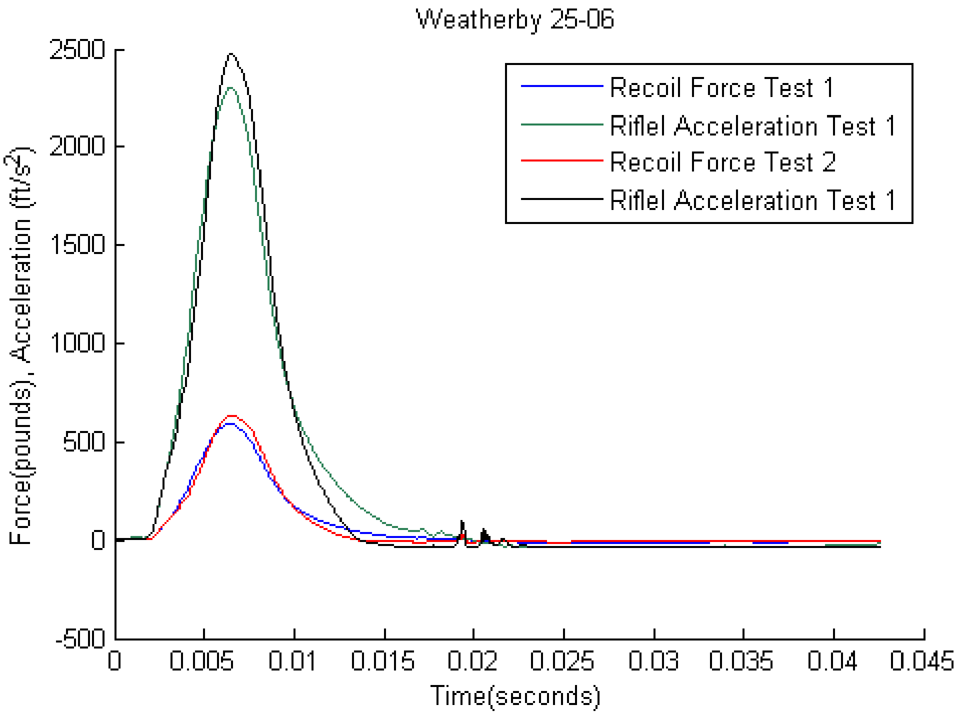


Figure 20 - Recoil Force and Acceleration for Weatherby .25-06

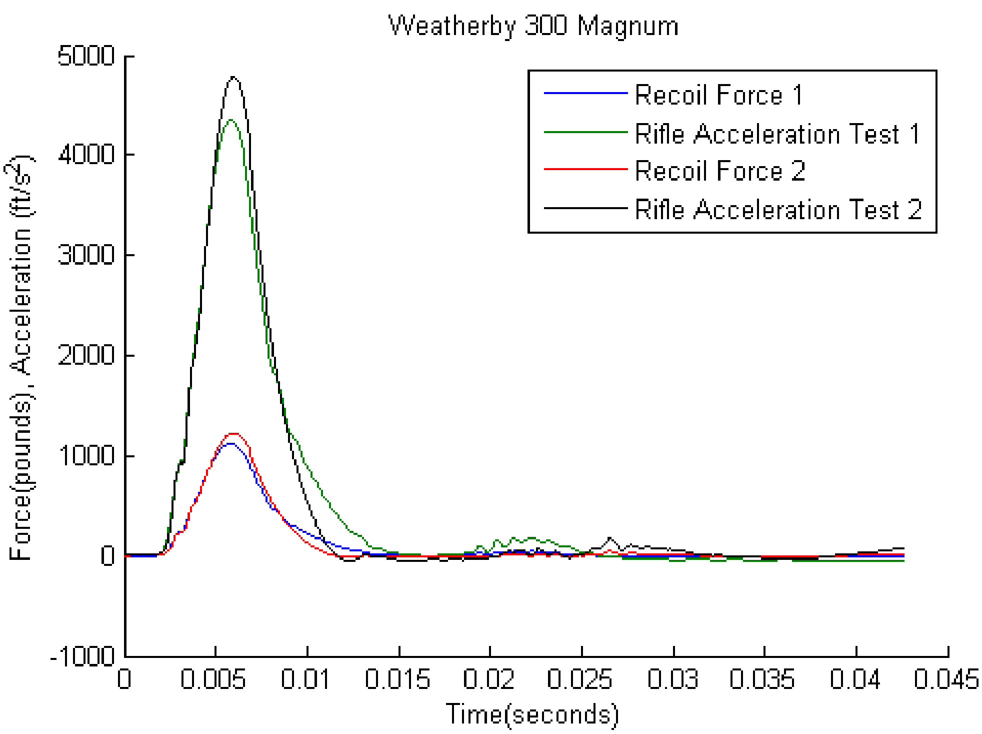


Figure 21 - Recoil Force and Acceleration for Weatherby 300 Magnum

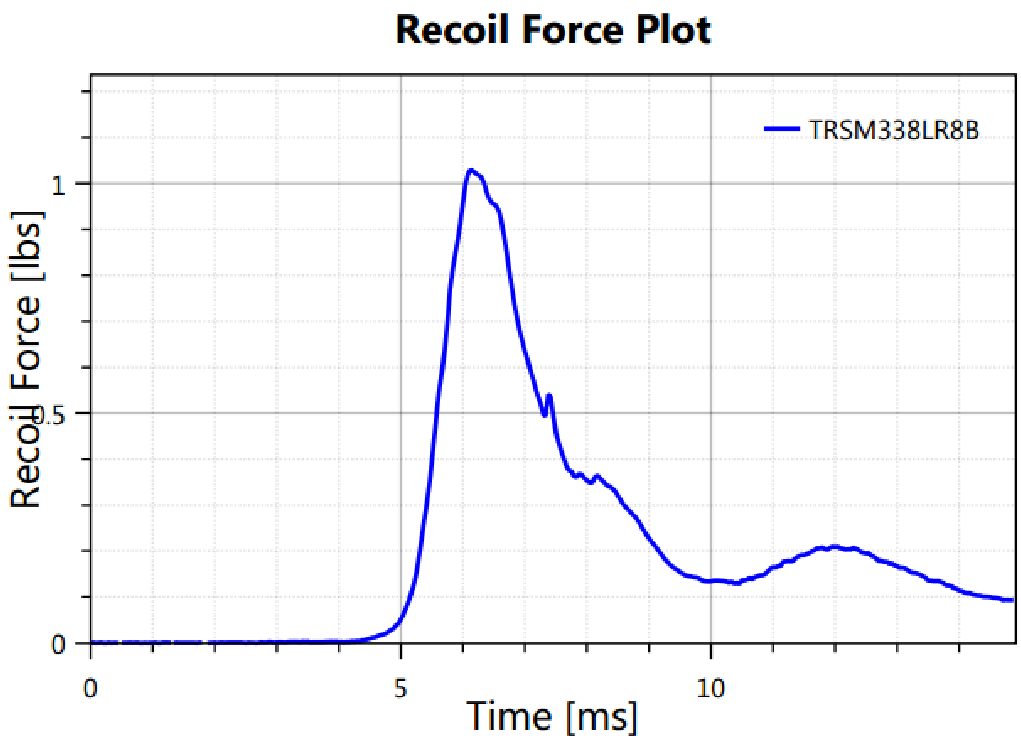


Figure 22 - Experimental data from final system for Weatherby 338, first shot

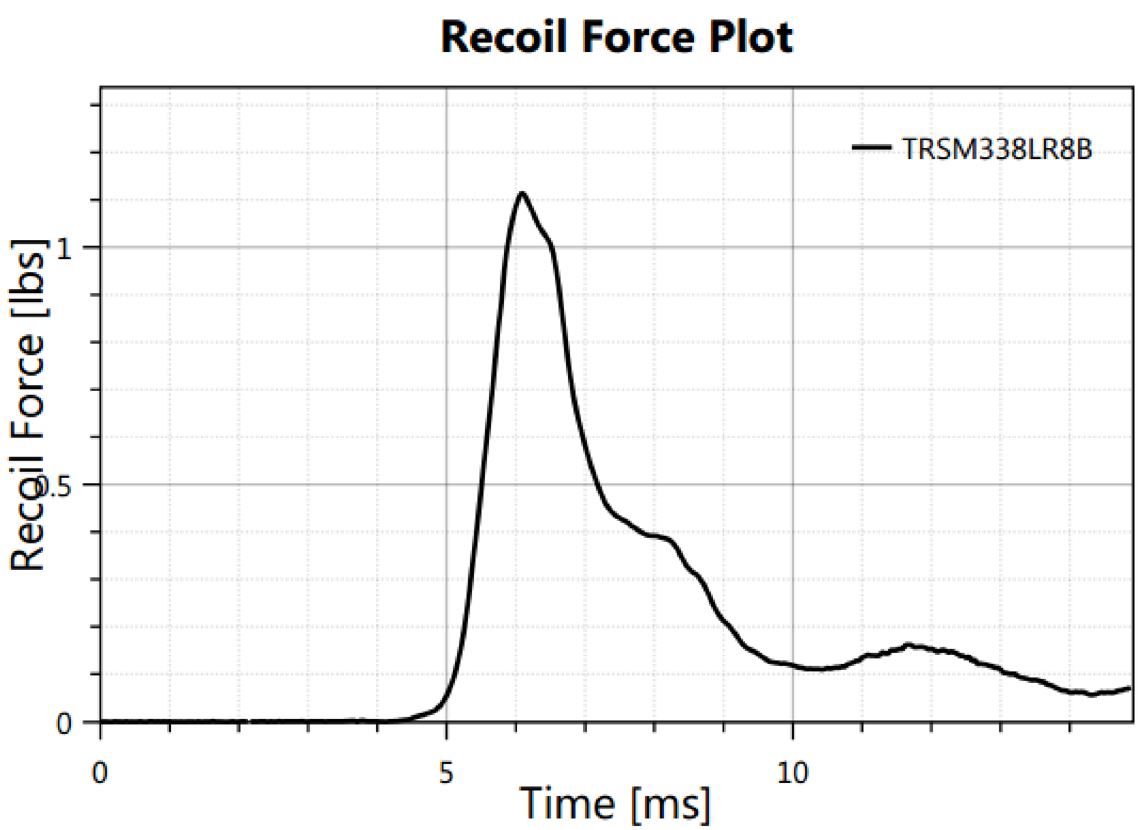


Figure 23 - Experimental data from final system for Weatherby 338, second shot

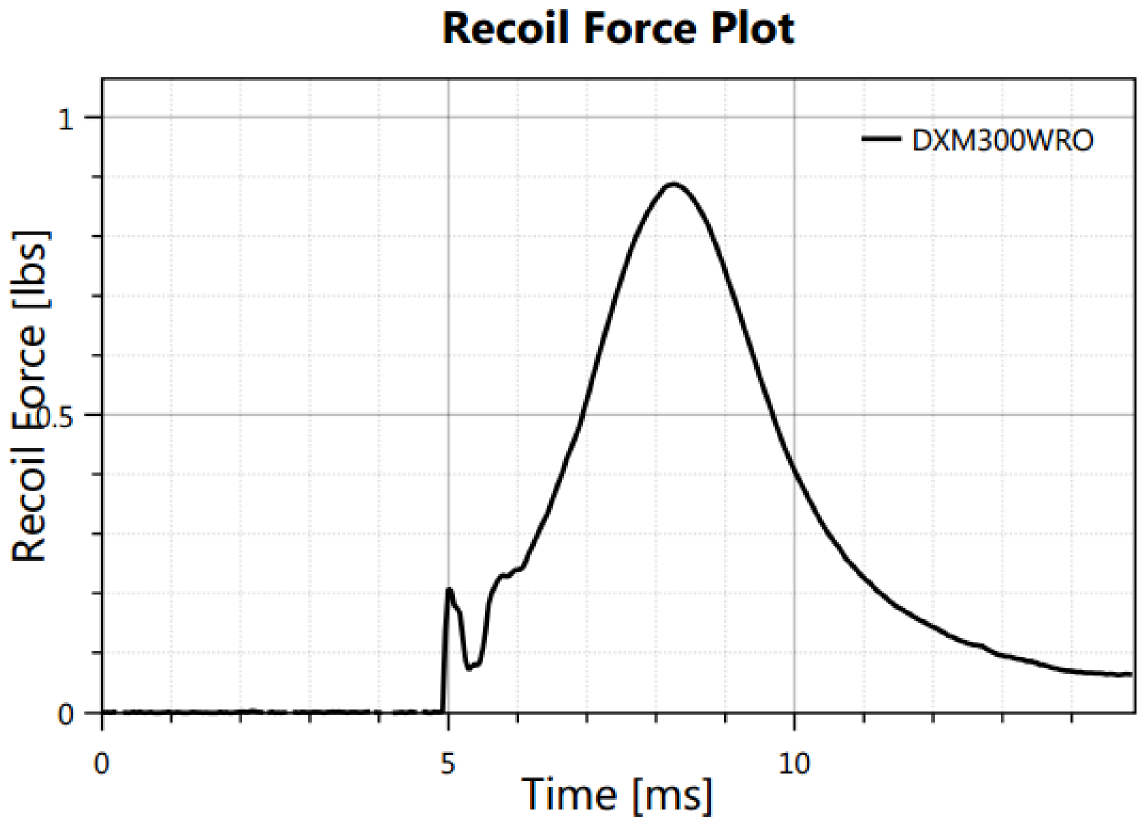


Figure 24 - Experimental data from final system for 300 Weatherby Magnum

H - EES Program for Force Analysis

Senior Project Rifle Recoil System Design
Trevor Foster, Benjamin Canfield-Hershkowitz, Wil Meijer
For: Weatherby
April 30, 2013
Cal Poly San Luis Obispo

Input Values

$W_{rifle} = 9.25$ [lbf] *INPUT weight of rifle*

$W_{FrontRest} = 6$ [lbf] *Weight of front rest*

$W_{BackRest} = 5$ [lbf] *Weight of back rest*

$W_{Rail} = 3$ [lbf] *Weight of linear rail?*

$F_{Recoil} = 3200$ [lbf] *Estimated maximum recoil force from .460*

$H_{Sensor} = 4$ [in] $+ t_{spacer}$ *Measured height of sensor from the top of the base*

Sled Dimensions

$H_{Total} = t_{base} + t_{spacer} + h_{back}$ *Total height from table top to the top of the back*

$h_{back} = 8$ [in] *Just the back plate(including the spacer)*

$t_{Back} = 3$ [in] *Thickness of back plate*

$Width_{back} = 4$ [in] *Back plate width, make sure it is easy to get around*

$t_{base} = 0.5$ [in] *Sled base thickness*

$L_{Base} = 36$ [in] *Total length, same as the one at Weatherby(3ft)*

$Width_{Base} = 6$ [in] *Width of the sled base*

$height_{TC} = 3$ [in] *Table catch height, separate from the thickness*

$Width_{TC} = 6$ [in] *Width of the table catch*

$t_{TC} = 3$ [in] *Table catch thickness, will mount with the same screws as back plate*

$Unit_{Weight,Al} = 0.098$ [lbf/in^3] *From Shigley, Table A-5*

$W_{Base} = Unit_{Weight,Al} \cdot L_{Base} \cdot Width_{Base} \cdot t_{base}$ *Sled weight without the slot cutouts*

$W_{Back} = Unit_{Weight,Al} \cdot h_{back} \cdot Width_{back} \cdot t_{Back}$ *Weight of solid back plate, no screws, spacer included*

Finding Center of gravity/mass

$$X_{Back,CG} = \frac{t_{Back}}{2}$$

$$X_{Base,CG} = \frac{L_{Base}}{2}$$

$$\overline{X}_{Sled} = \frac{W_{Base} \cdot X_{Base,CG} + W_{Back} \cdot X_{Back,CG}}{W_{Back} + W_{Base}}$$

$$W_{Sled} = W_{Back} + W_{Base}$$

$$Y_{Back,CG} = \frac{h_{back}}{2}$$

$$Y_{Base,CG} = \frac{t_{base}}{2}$$

$$\overline{Y}_{Sled} = \frac{W_{Base} \cdot Y_{Base,CG} + W_{Back} \cdot Y_{Back,CG}}{W_{Back} + W_{Base}}$$

$W_{table,catch} = height_{TC} \cdot Width_{TC} \cdot t_{TC} \cdot Unit_{Weight,Al}$ *Table catch weight, without screws*

System Dimensions

$X_{BackRest} = t_{Back} + 6$ [in] *From FBD, distance to center of back rest from far edge of back plate*

$X_{FrontRest} = 30$ [in] *From FBD, distance to center of front rest from far edge of back plate*

$X_{Rail} = X_{BackRest}$ *Center of rail from far edge of back plate*

$$\overline{X}_{System} = \frac{W_{Base} \cdot X_{Base,CG} + W_{Back} \cdot X_{Back,CG} + \left[W_{Rail} + W_{BackRest} + \frac{W_{rifle}}{2}\right] \cdot X_{BackRest} + \left[W_{FrontRest} + \frac{W_{rifle}}{2}\right] \cdot X_{FrontRes}}{W_{rifle} + W_{FrontRest} + W_{BackRest} + W_{Rail} + W_{Back} + W_{Base} + W_{table,catch}}$$

System COM

$W_{System} = W_{FrontRest} + W_{BackRest} + W_{Rail} + W_{Back} + W_{Base}$ *Weight of system, no screws added*

Deflection of Back Piece

$E_{Al} = 1.04 \times 10^7$ [lbf/in^2] *Shigley Table A-5*

$I_{back} = \frac{1}{12} \cdot Width_{back} \cdot t_{Back}^3$ *Total inertia including spacer, without screws, assuming welded*

$\delta_{back} = F_{Recoil} \cdot 2 \cdot \frac{H_{Sensor}^2}{6 \cdot E_{Al} \cdot I_{back}} \cdot [H_{Sensor} - 3 \cdot h_{back}]$ *Cantilever beam with intermediate load*

Safety and Reliability

Infinite Life

$n_f = \frac{1}{\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}}}$ *Goodman Failure criteria*

$S_{ut} = 42000$ [lbf/in^2] *For 6061 T6 Aluminum*

$Dynamic_{Load,Factor} = 2$ *Since this is a very fast impulse and not a static load, need dynamic load factor*

$\sigma_{max} = Dynamic_{Load,Factor} \cdot F_{Recoil} \cdot H_{Sensor} \cdot \frac{t_{Back}}{2 \cdot I_{back}}$ *Maximum bending moment*

$\sigma_a = \frac{\sigma_{max}}{2}$

$\sigma_m = \sigma_a$

$S_e' = 0.5 \cdot S_{ut}$

$S_e = k_a \cdot k_b \cdot k_c \cdot k_d \cdot k_e \cdot k_f \cdot S_e'$ *Need all the k's*

$k_a = 2.7 \cdot \left[\frac{S_{ut}}{1000}\right]^{-0.265}$ *Surface factor, machined, Shigley Table 6-2*

$d_e = 0.808 \cdot \sqrt{t_{Back} \cdot Width_{back}}$ *Equivalent diameter, Shigley size factor EQ 6-20*

$k_b = 0.91 \cdot d_e^{-0.157}$ *for 2< $d_{e<10}$ in*

$k_c = 1$ *bending*

$k_d = 1$ *normal temperature*

$k_e = 0.702$ *99.99% Reliability*

$k_f = 1$ *no miscellaneous effects*

Life Cycles

$\sigma_{rev} = \frac{\sigma_a}{1 - \frac{\sigma_m}{S_{ut}}}$

$f = 0.9$ *fatigue strength fraction*

$a = \frac{[f \cdot S_{ut}]^2}{S_e}$

$b = \frac{-1}{3} \cdot \log\left[f \cdot \frac{S_{ut}}{S_e}\right]$

$N = \left[\frac{\sigma_{rev}}{a}\right]^{\left[\frac{1}{b}\right]}$ *# of expected cycles*

Screw Analysis

$t_{spacer} = 1$ [in] *spacer in back plate between base and back plate*

$d = \frac{3}{4\ [in]}$ *Nominal diameter of screws*

$E_{screw} = 3 \times 10^7$ [psi] *Steel*

$A_d = \pi \cdot \frac{d^2}{4}$ *Nominal area of unthreaded portion*

$l = h + \frac{d}{2}$ *grip length*

$h = t_{base} + t_{spacer}$ *intermediate region*

$l_t = l - l_d$ *length of threaded portion of grip*

$l_d = L_{screw} - l_{threads}$ *length of unthreaded portion of grip*

$l_{threads} = 2 \cdot d + 1 / 4$ *Length of threds*

A_t=0.663$_{in2}$

1in UNF 12 TPI

A_r=0.625$_{in2}$

1 in UNF 12 TPI

$A_t = 0.373$ [in^2] *3/4in UNF 12 TPI*

$A_r = 0.351$ [in^2] *3/4in UNF 12 TPI*

$k_{screw} = A_d \cdot A_t \cdot \left[\frac{E_{screw}}{A_d \cdot l_t + A_t \cdot l_d} \right]$ *Screw stiffness*

$L_{screw} = 2.75$ [in] *total length. Try 2.75 or 3*

$K_m = E_{Al} \cdot d \cdot A_{stiff} \cdot \mathbf{exp}\left[B_{stiff} \cdot \frac{d}{l} \right]$ *Material stiffness, all aluminum*

$A_{stiff} = 0.7967$ *From Table 8-8*

$B_{stiff} = 0.63816$ *From Table 8-8*

$C = \frac{k_{screw}}{k_{screw} + K_m}$ *Stiffness constant*

$S_p = 120000$ [psi] *Proof strength for SAE grade 8, medium-carbon alloy, Q&T, Shigley Table 8-9*

$n_d = 0.577 \cdot 2 \cdot A_r \cdot \frac{S_p}{F_{Recoil} \cdot Dynamic_{Load,Factor}}$ *Design factor for bolted joints loaded in shear, bolt threads extend into shear plane*

$F_i = 0.75 \cdot A_t \cdot S_p$ *Preload*

$\tau_{shear} = F_{Recoil} \cdot \frac{Dynamic_{Load,Factor}}{2 \cdot A_r}$ *Shear stress per bolt*

Yielding Safety Factor

$$n_{load} = \frac{S_p \cdot A_t - F_i}{C \cdot F_{Recoil} \cdot \frac{Dynamic_{Load,Factor}}{2}}$$ *load factor guarding against joint separation*

$$n_{yield} = \frac{S_p \cdot A_t}{C \cdot F_{Recoil} \cdot \frac{Dynamic_{Load,Factor}}{2} + F_i}$$ *yielding factor of safety*

Fatigue

$$\sigma_{a,screw} = C \cdot \frac{F_{Recoil} \cdot Dynamic_{Load,Factor}}{2 \cdot A_t}$$

$$\sigma_{m,screw} = C \cdot \frac{F_{Recoil} \cdot Dynamic_{Load,Factor}}{2 \cdot A_t} + \frac{F_i}{A_t}$$

$$\sigma_{i,screw} = \sigma_{m,screw} - \sigma_{a,screw}$$

$$n_{f,screw} = S_{e,screw} \cdot \left[\frac{S_{ut,screw} - \sigma_{i,screw}}{\sigma_{a,screw} \cdot (S_{ut,screw} + S_{e,screw})}\right]$$ *Goodman fatigue safety factor*

$S_{e,screw}$ = 23200 [psi]

$S_{ut,screw}$ = 150000 [psi]

SOLUTION

Unit Settings: Eng F psia mass deg

a = 124842
A_r = 0.351 [in^2]
A_t = 0.373 [in^2]
B_{stiff} = 0.6382
d = 0.75 [in]
$Dynamic_{Load,Factor}$ = 2
E_{Al} = 1.040E+07 [lbf/in^2]
f = 0.9
F_{Recoil} = 3200 [lbf]
$height_{TC}$ = 3 [in]
H_{Sensor} = 5 [in]
I_{back} = 9 [in^4]
k_b = 0.7742
k_d = 1
k_f = 1
k_{screw} = 6.508E+06 [lbf/in]
L_{Base} = 36 [in]
L_{screw} = 2.75 [in]
$l_{threads}$ = 1.75 [in]
n_d = 7.595
$n_{f,screw}$ = 2.091
n_{yield} = 1.279
$\sigma_{a,screw}$ = 3843 [psi]
σ_m = 2667 [psi]

A_d = 0.4418 [in^2]
A_{stiff} = 0.7967
b = -0.173
C = 0.4479
δ_{back} = -0.005413 [in]
d_e = 2.799 [in]
E_{screw} = 3.000E+07 [psi]
F_i = 33570 [psi]
h = 1.5
h_{back} = 8 [in]
H_{Total} = 9.5 [in]
k_a = 1.003
k_c = 1
k_e = 0.702
K_m = 8.021E+06
l = 1.875 [lbf/in]
l_d = 1 [in]
l_t = 0.875 [in]
N = 3.113E+09 [Cycles]
n_f = 3.373
n_{load} = 7.807
σ_a = 2667 [psi]
$\sigma_{i,screw}$ = 90000 [psi]
σ_{max} = 5333 [psi]

$\sigma_{m,screw}$ = 93843 [psi]
S_e = 11445 [psi]
$S_{e,screw}$ = 23200 [psi]
S_{ut} = 42000 [lbf/in^2]
τ_{shear} = 9117 [psi]
t_{base} = 0.5 [in]
t_{TC} = 3 [in]
$Width_{back}$ = 4 [in]
$Width_{TC}$ = 6 [in]
$W_{BackRest}$ = 5 [lbf]
$W_{FrontRest}$ = 6 [lbf]
W_{rifle} = 9.25 [lbf]
W_{System} = 33.99 [lbf]
$X_{BackRest}$ = 9 [in]
$\overline{X}_{Sled}$ = 10.24 [in]
$X_{Base,CG}$ = 18 [in]
$X_{Rail,}$ = 9 [in]
$\overline{Y}_{Sled}$ = 2.015 [in]
σ_{rev} = 2847 [psi]
$S_{e'}$ = 21000 [psi]
S_p = 120000 [psi]
$S_{ut,screw}$ = 150000 [psi]
t_{Back} = 3 [in]
t_{spacer} = 1 [in]
$Unit_{Weight,Al}$ = 0.098 [lbf/in^3]
$Width_{Base}$ = 6 [in]
W_{Back} = 9.408 [lbf]
W_{Base} = 10.58 [lbf]
W_{Rail} = 3 [lbf]
W_{Sled} = 19.99 [lbf]
$W_{table,catch}$ = 5.292 [lbf]
$X_{Back,CG}$ = 1.5 [in]
$\overline{X}_{System}$ = 16.89 [in]
$X_{FrontRest}$ = 30 [in]
$Y_{Back,CG}$ = 4 [in]
$Y_{Base,CG}$ = 0.25 [in]

No unit problems were detected.

I - Detailed Drawings and Solid Modelling

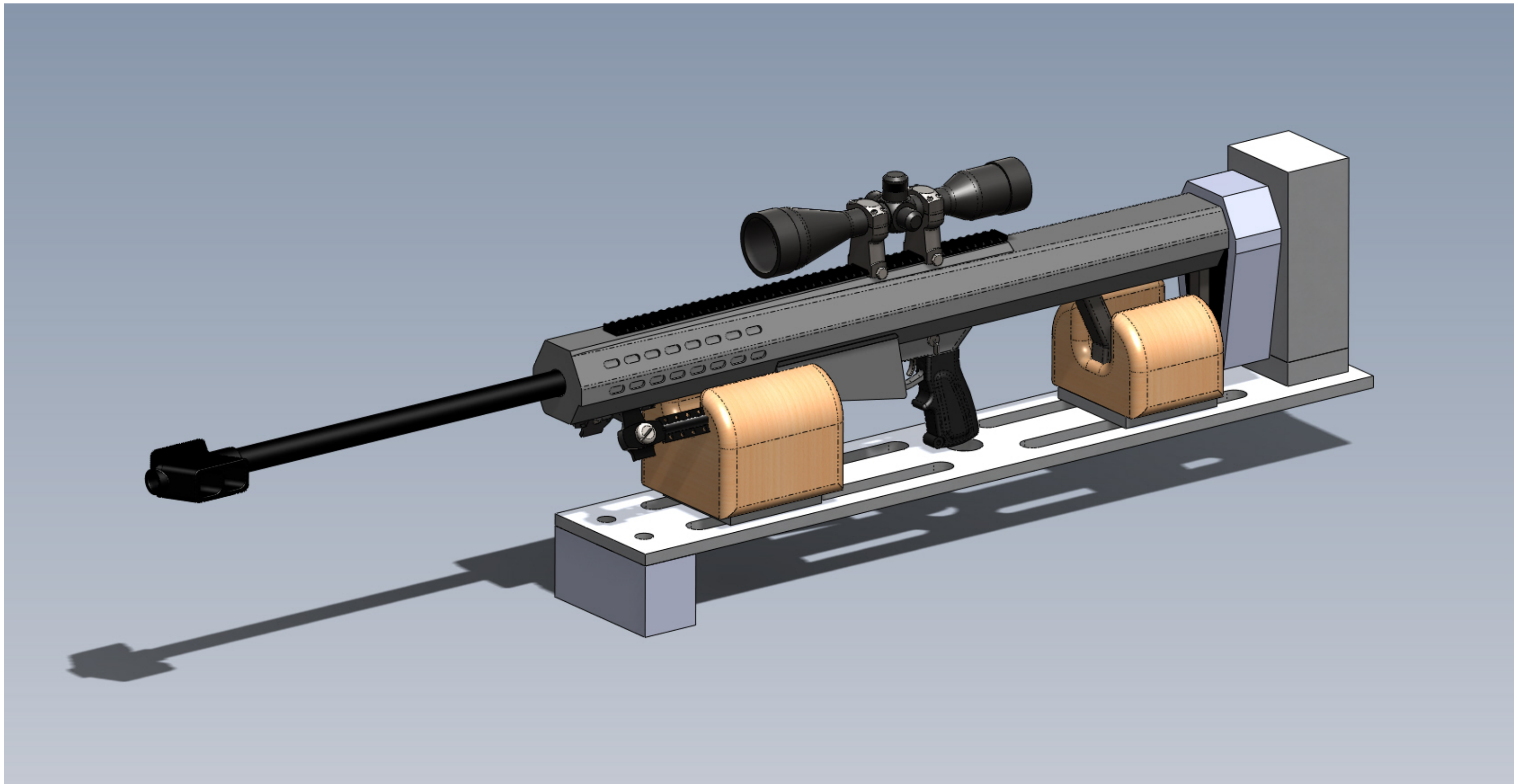


Figure 25 - Final Design Isometric View Solid Model

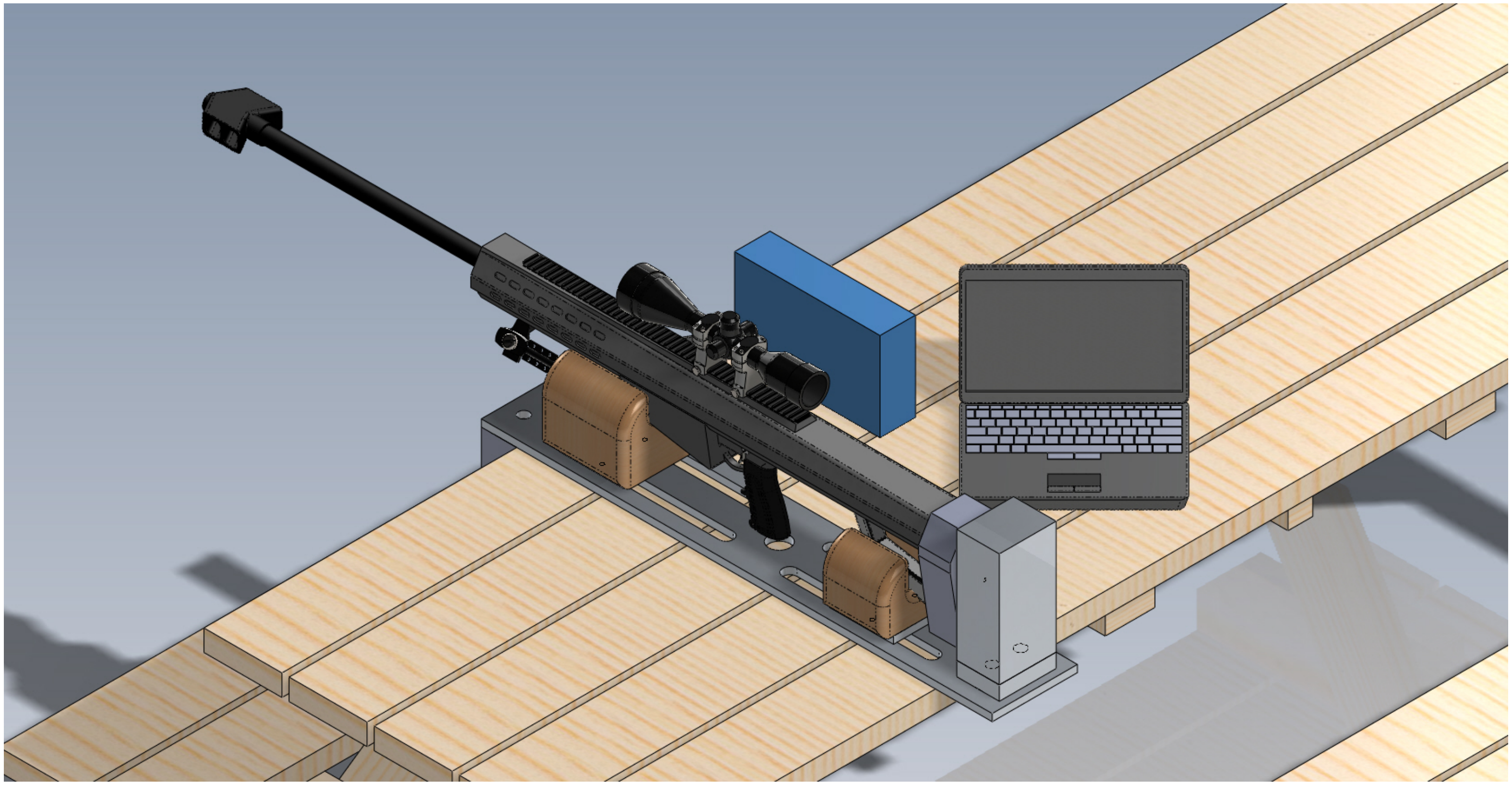


Figure 26 - Final Design modeled in testing configuration

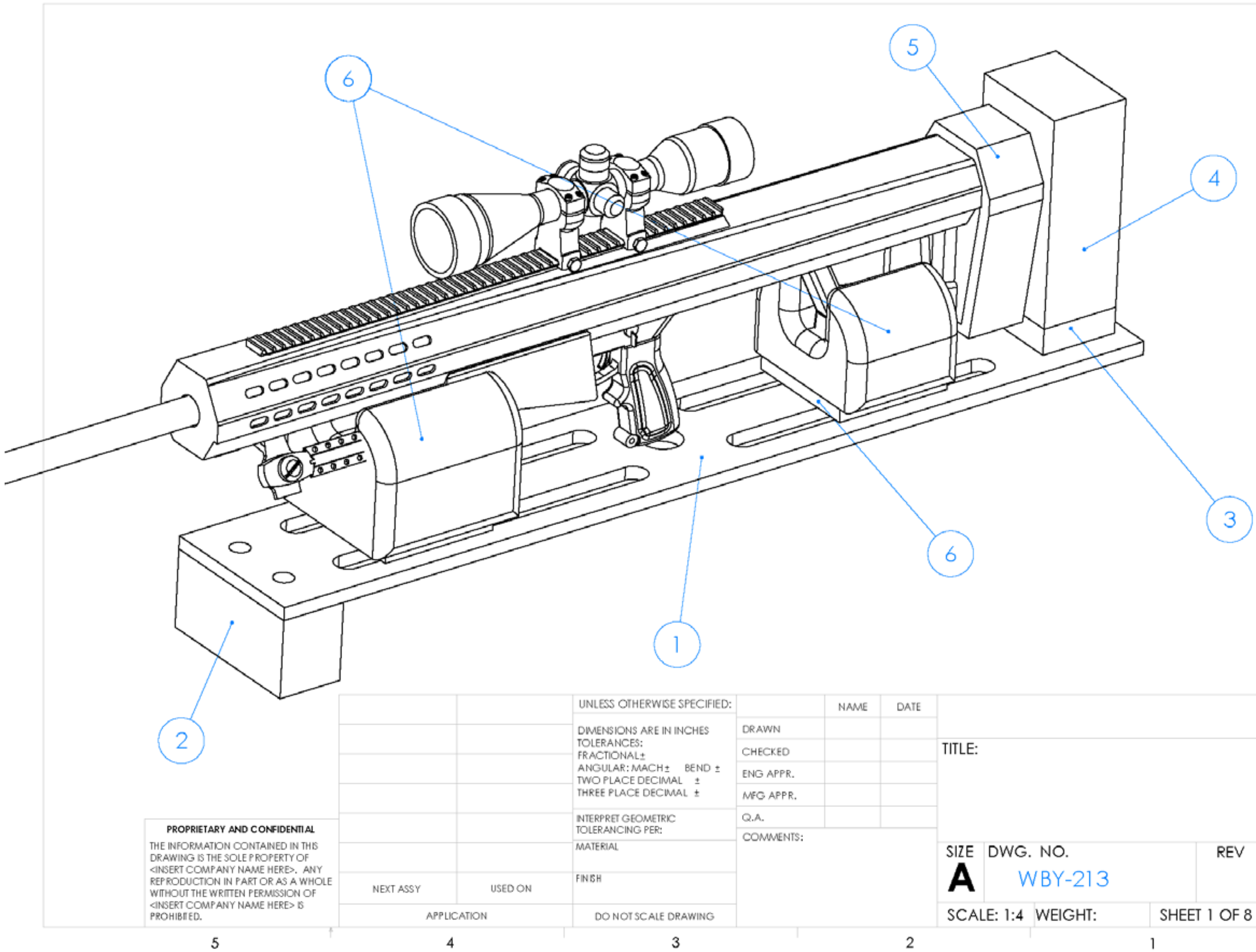


Figure 27 - Mechanical Drawing Overview

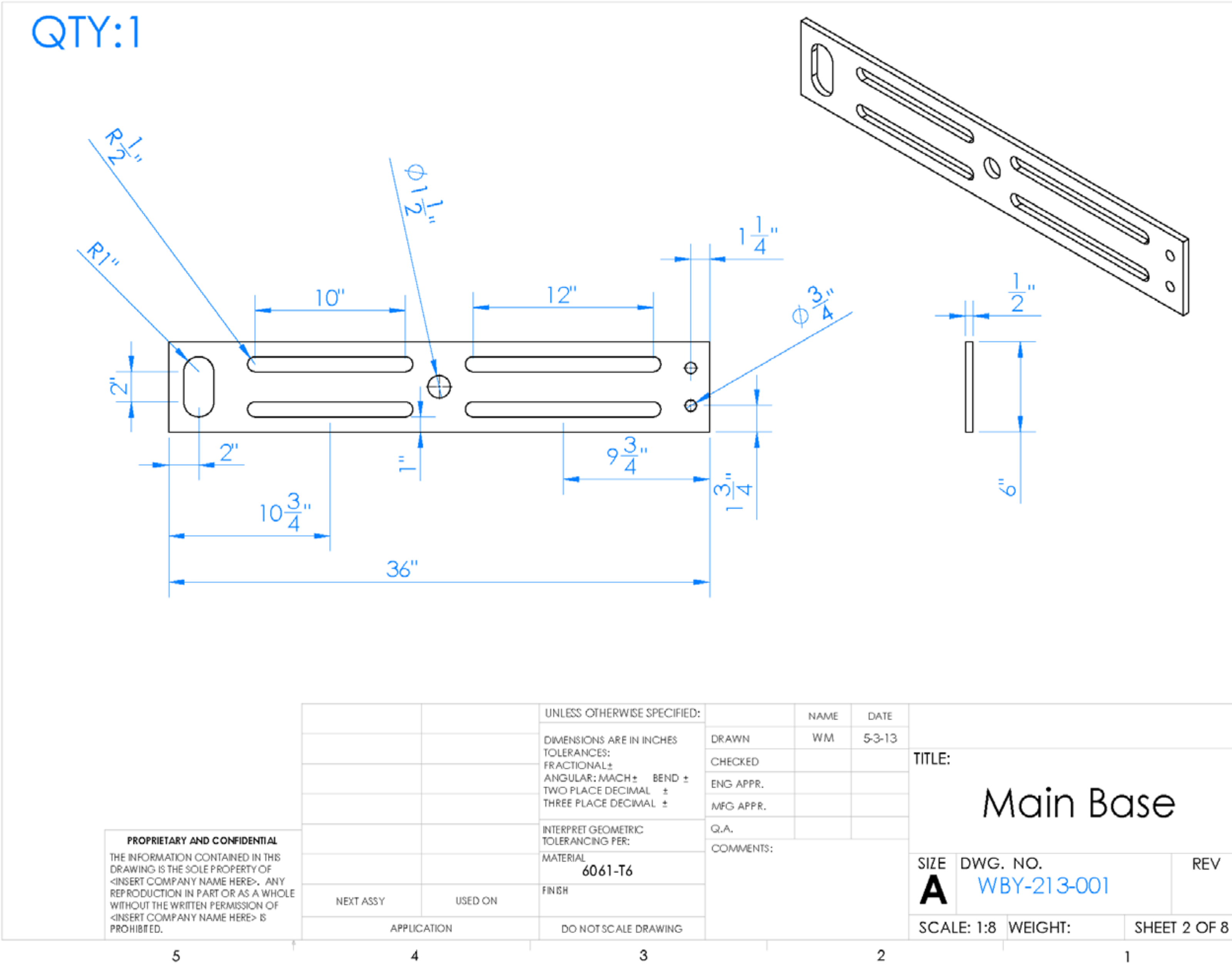


Figure 28 - Mechanical Drawing Main Base

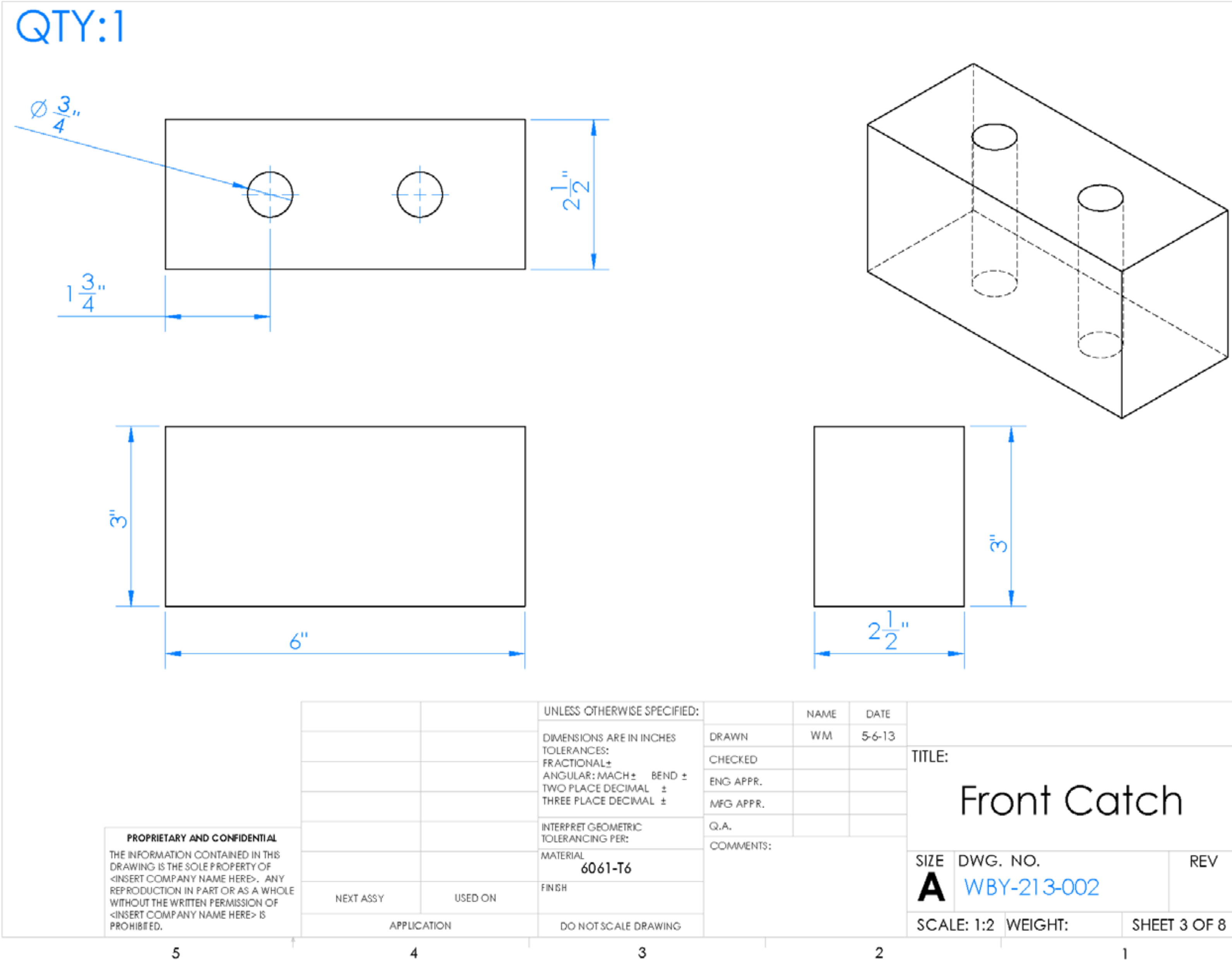


Figure 29 - Mechanical Drawing Front Catch

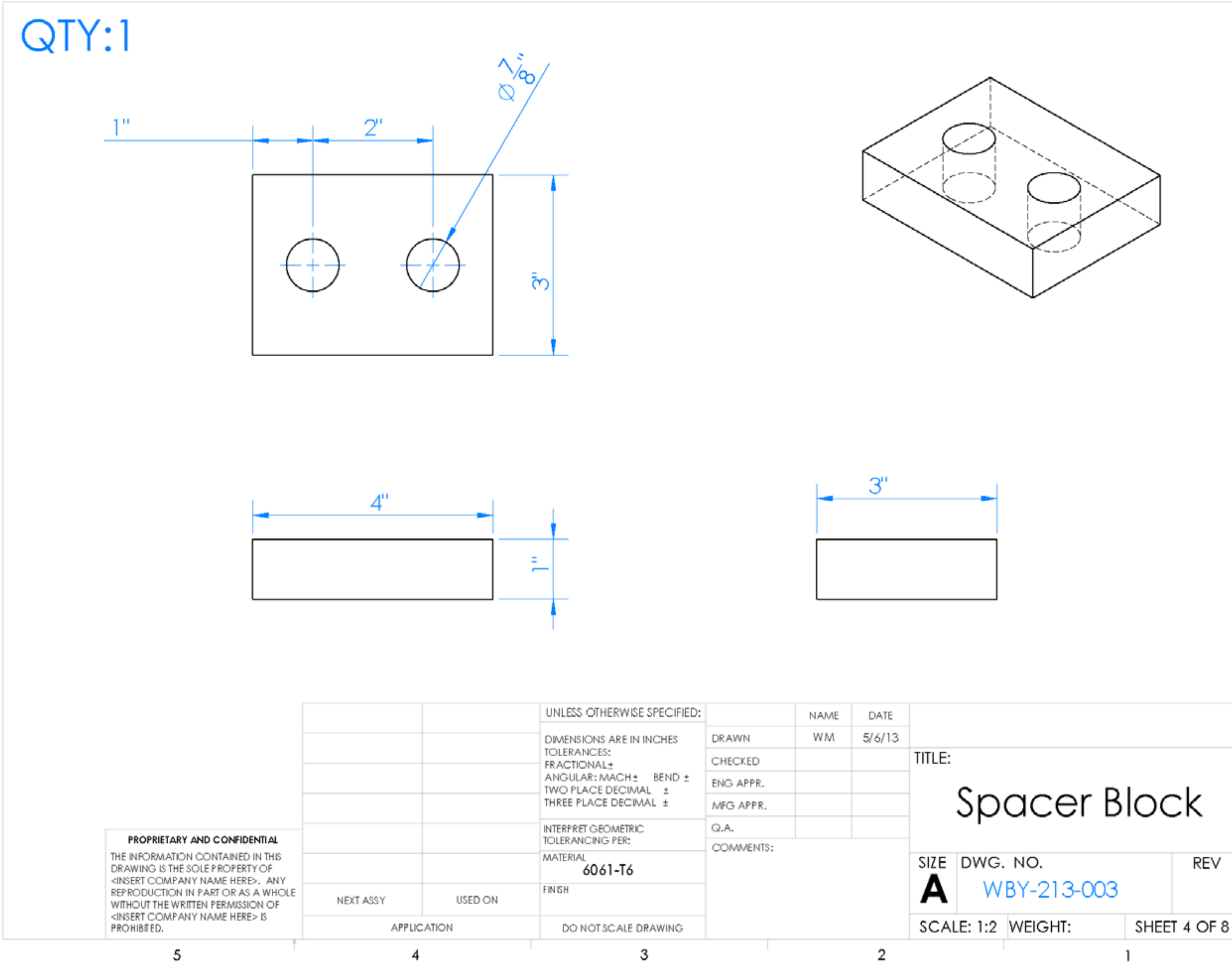


Figure 30 - Mechanical Drawing Spacer Block

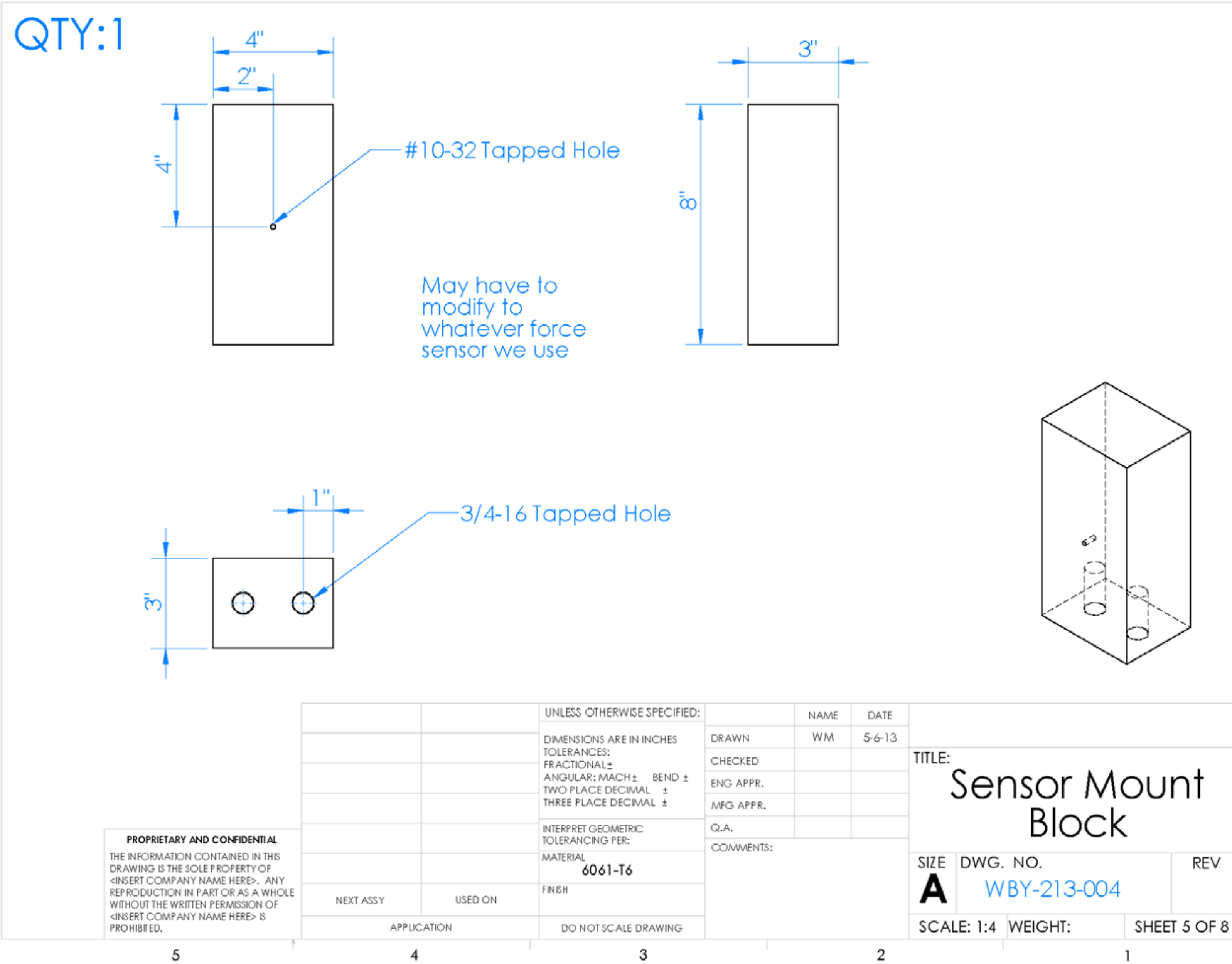


Figure 31 - Mechanical Drawing Sensor Mount

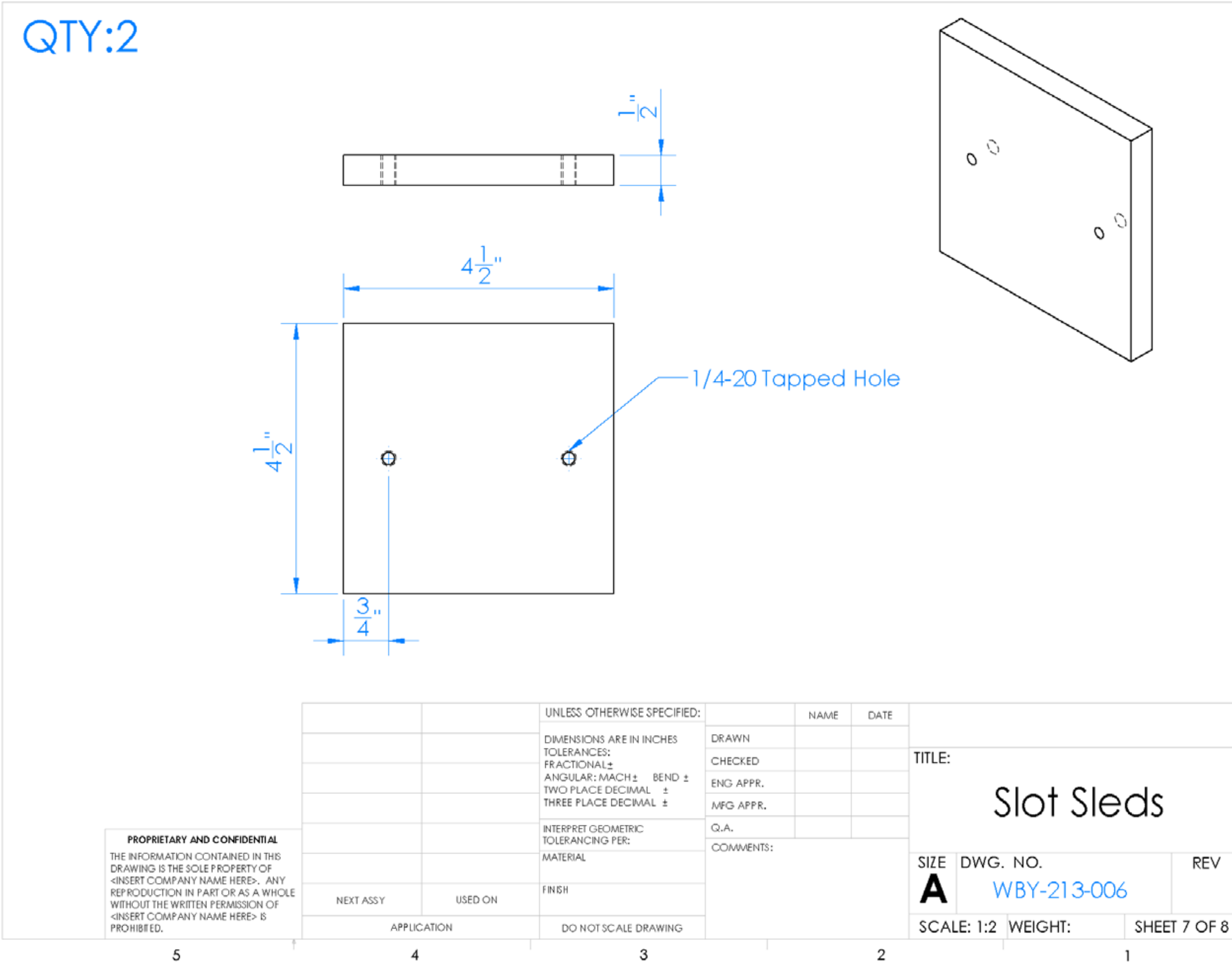


Figure 32 - Mechanical Drawing Slot Sleds

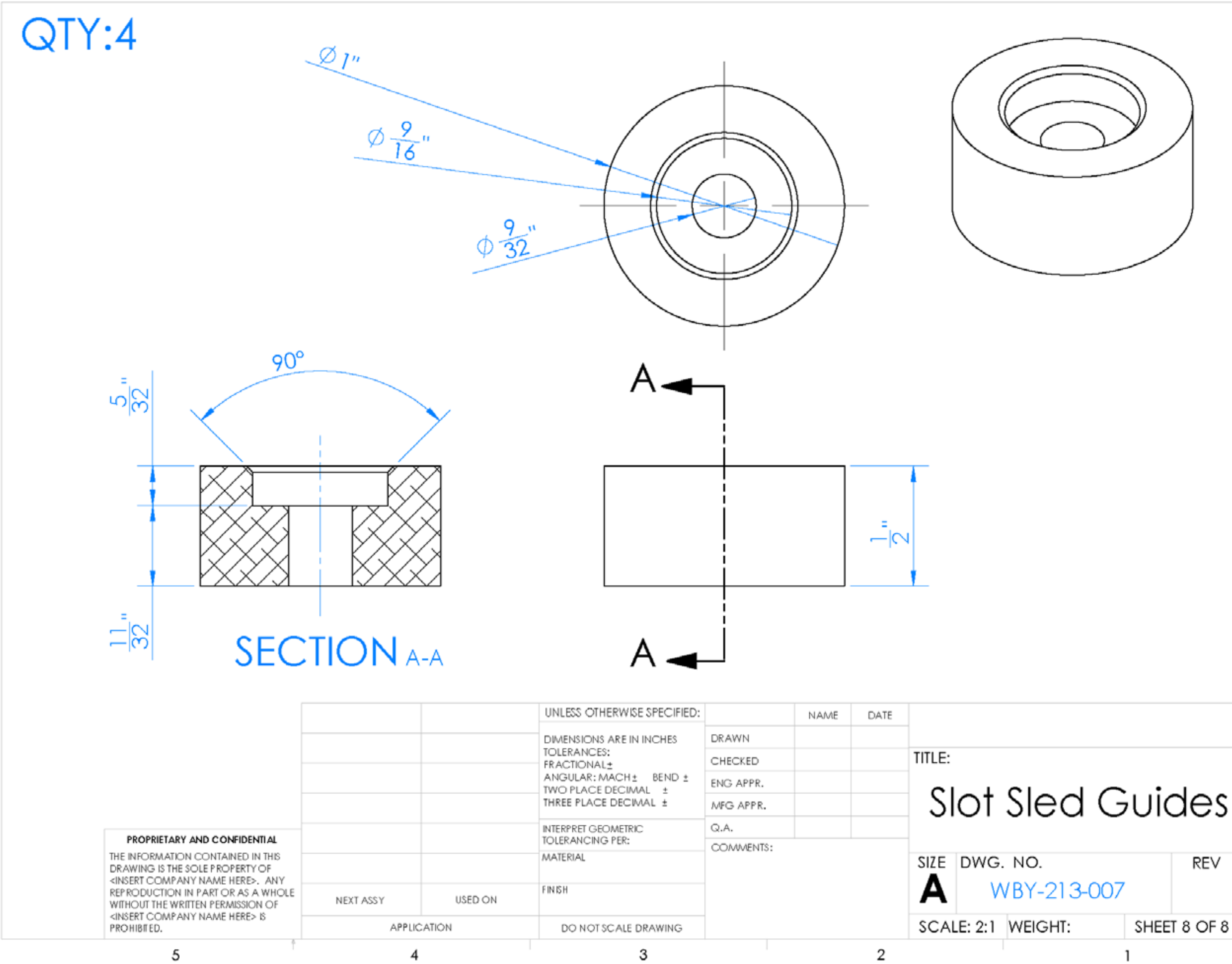
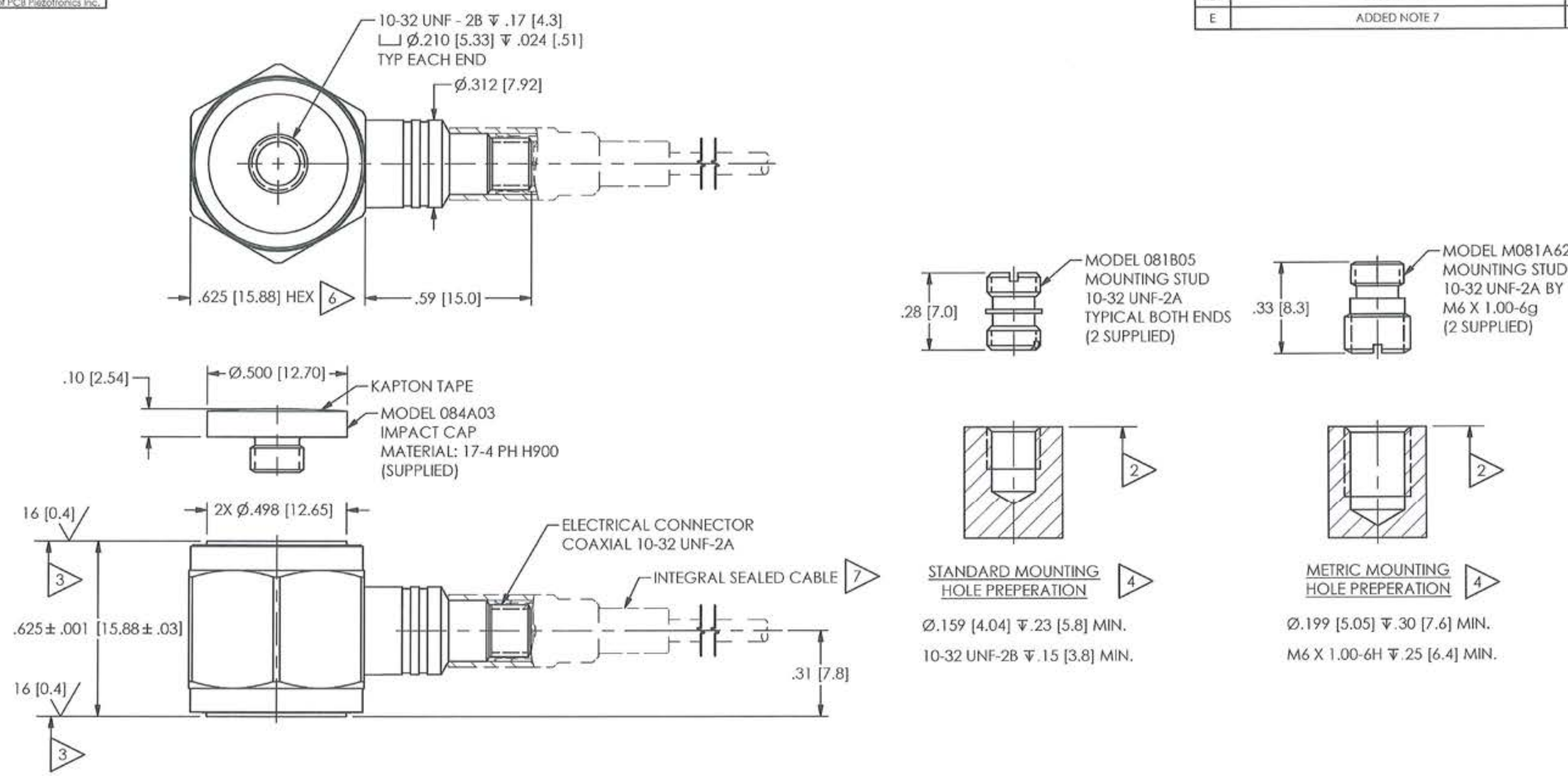


Figure 33 - Mechanical Drawing Slot Sled Guides

8561

REVISIONS		
REV	DESCRIPTION	DIN
E	ADDED NOTE 7	39128



7 ADD CABLE FOR WATER RESISTANT OPTION.

6 MOUNTING TORQUE ON .625[15.88] HEX, 16-20 IN-LBS [181-226 Ncm].

5.) COMPRESSIVE FORCE ON CELL YIELDS POSITIVE OUTPUT VOLTAGE.

4 DRILL PERPENDICULAR TO MOUNTING SURFACE TO WITHIN ±1°.

3 THESE SURFACES GROUND FLAT AND PARALLEL TO WITHIN .001[0.03] TIR.

2 MOUNTING SURFACE TO BE FLAT TO WITHIN .001[0.03] TIR WITH A MIN 125 [3.2]√

1.) CASE MATERIAL-STAINLESS STEEL.

UNLESS OTHERWISE SPECIFIED TOLERANCES ARE:	
DIMENSIONS IN INCHES	DIMENSIONS IN MILLIMETERS [IN BRACKETS]
DECIMALS XX ±.01 XXX ±.005	DECIMALS X ±0.3 XX ±0.13
ANGLES ± 2 DEGREES	ANGLES ± 2 DEGREES
FILLETS AND RADII .003 - .005	FILLETS AND RADII 0.07 - 0.13

DRAWN		CHECKED		ENGINEER	
JDM	6/5/12	EOB	6/12	JDK	6/5/12

TITLE
INSTALLATION DRAWING
GENERAL PURPOSE ICP®
FORCE SENSOR

PCB PIEZOTRONICS
3425 WALDEN AVE. DEPEW, NY 14043
(716) 684-0001 E-MAIL: sales@pcb.com

CODE IDENT. NO. 52681 | DWG. NO. 8561

SCALE: 2.5X | SHEET 1 OF 1

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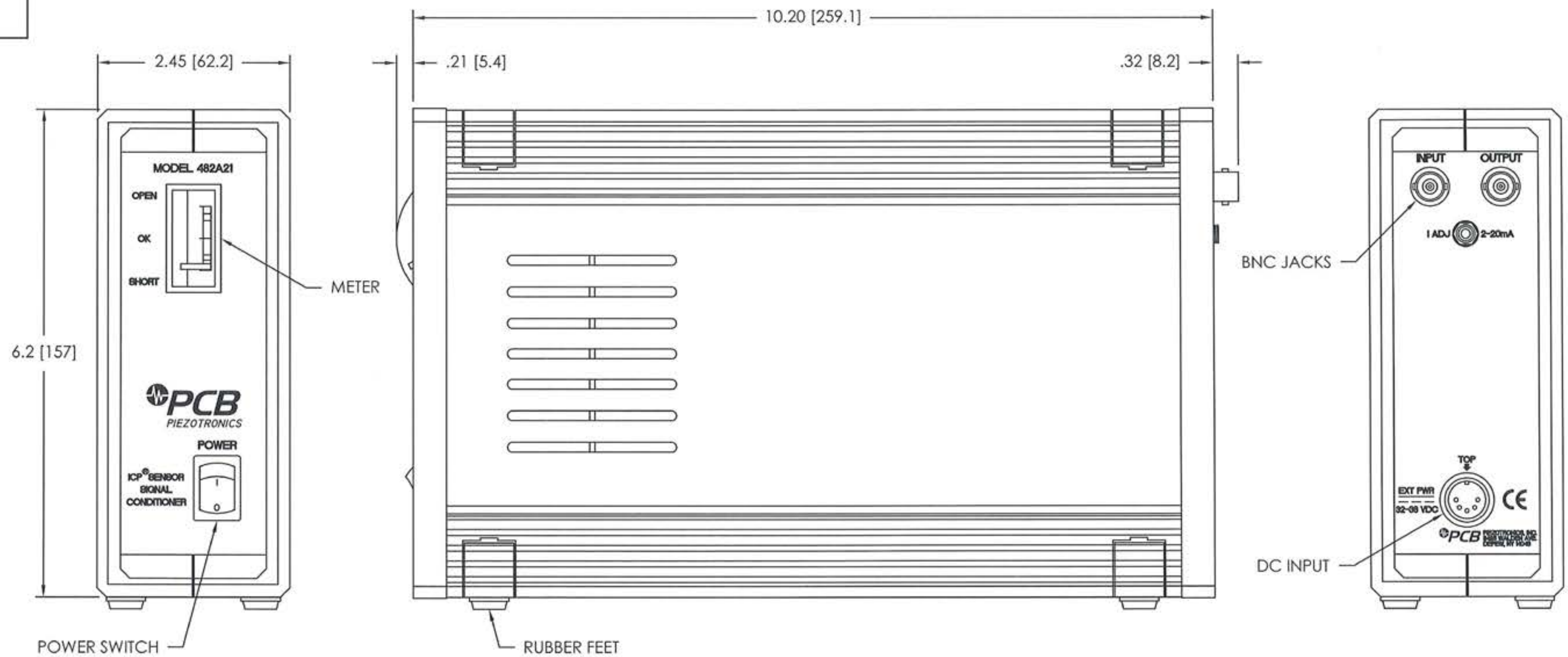
6498

REVISIONS

REV	DESCRIPTION	DIN
A	CHANGED ARTWORK	37737



UNLESS SPECIFIED TOLERANCES	
DIMENSIONS IN INCHES	DIMENSIONS IN MILLIMETERS [IN BRACKETS]
DECIMALS XX ±.03 XXX ±.010 ANGLES ±2 DEGREES	DECIMALS X ±0.8 XX ±0.25 ANGLES ±2 DEGREES
FILLETS AND RADII .003 - .005	FILLETS AND RADII [0.07 - 0.13]

DRAWN		CHECKED		ENGINEER	
SMB	12/15/11	ECB	12/16/11	KEN L	12/15/11

TITLE
OUTLINE DRAWING
MODEL 482A21
ICP® SENSOR SIGNAL CONDITIONER

PCB PIEZOTRONICS™
3425 WALDEN AVE. DEPEW, NY 14043
(716) 684-0001 EMAIL: SALES@PCB.COM

CODE IDENT. NO. 52681 | DWG. NO. 6498

SCALE: 1.5X | SHEET 1 OF 1

Mechanical drawings

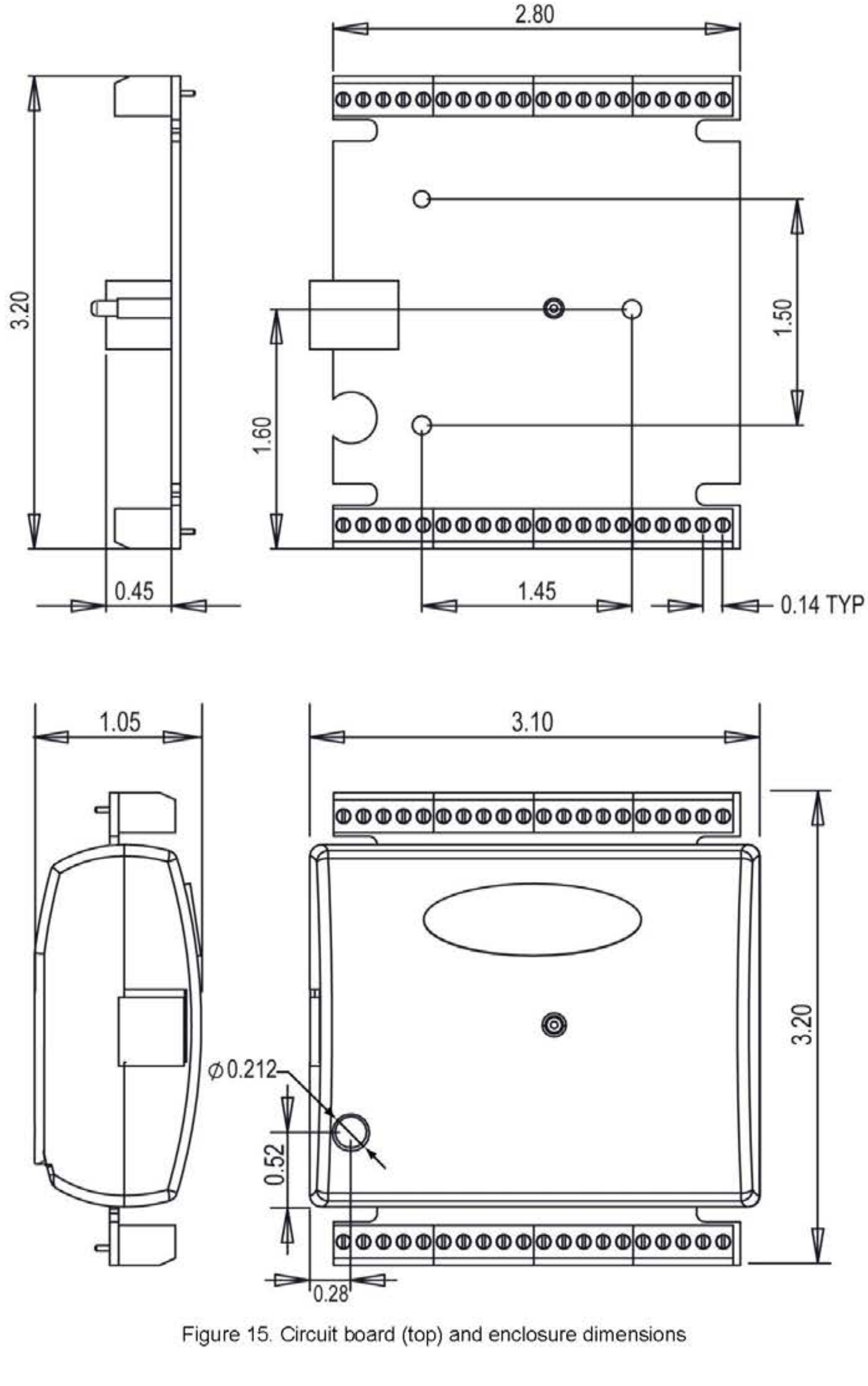


Figure 15. Circuit board (top) and enclosure dimensions

Specifications

All specifications are subject to change without notice.
Typical for 25°C unless otherwise specified.
Specifications in *italic text* are guaranteed by design.

Analog input

Table 1. Analog input specifications

Parameter	Condition	Specification
A/D converter type		Successive approximation type
Input voltage range for linear operation	CHx to GND	Single-ended mode: ±10 V max Differential mode: –10 V min, +20 V max
Absolute maximum input voltage	*CHx to GND*	*±28 V max*
Input impedance		*122 kΩ*
Input current (Note 1)	V_{in} = +10 V	70 µA typ
	V_{in} = 0 V	–12 µA typ
	V_{in} = –10 V	–94 µA typ
Number of channels		8 single-ended or 4 differential; software-selectable
Input ranges	Single-ended	±10 V, G=2
	Differential	±20 V, G=1 ±10 V, G=2 ±5 V, G=4 ±4 V, G=5 ±2.5 V, G=8 ±2.0 V, G=10 ±1.25 V, G=16 ±1.0 V, G=20 Software-selectable
Throughput (Note 2)	Software paced	250 S/s typ, PC-dependent
	Continuous scan	0.014 S/s to 48 kS/s
Channel gain queue		Software selectable. 8 elements in SE mode, 4 elements in DIFF mode. One gain element per channel. Elements must be unique and listed in ascending order.
Resolution (Note 3)	Differential	14 bits, no missing codes
	Single-ended	13 bits
Integral linearity error		±2 LSB typ
Differential linearity error		±0.5 LSB typ
Absolute accuracy long term drift (Note 4)	±20 V range	±3 LSB typ (Δt = 1000 hrs)
	±4 V range	±6 LSB typ (Δt = 1000 hrs)
	±1 V range	±8 LSB typ (Δt = 1000 hrs)
Trigger source		External digital: TRIG_IN Software-selectable

Note 1: Input current is a function of applied voltage on the analog input channels. For a given input voltage, V_{in}, the input leakage is approximately equal to (8.181 * V_{in} – 12) µA.

Note 2: Maximum throughput when scanning is machine dependent.

Note 3: The ADS7871 converter only returns 13 bits (0 to 8,192 codes) in single-ended mode.

Note 4: Extrapolating the long term drift accuracy specifications will provide the approximate long term drift of the intermediate input ranges.

Accuracy

Table 2. Accuracy, differential mode

Range	Absolute Accuracy 25 °C (±mV)	Absolute Accuracy 0 °C to 50°C (±mV)
±20 V	10.98	49.08
±10 V	7.32	33.42
±5 V	3.66	20.76
±4 V	2.92	19.02
±2.5 V	1.83	14.97
±2 V	1.70	14.29
±1.25 V	1.21	12.18
±1 V	1.09	11.63

Table 3. Accuracy, single-ended mode

Range	Absolute Accuracy 25 °C (±mV)	Absolute Accuracy 0 °C to 50 °C (±mV)
±10 V	10.98	49.08

Noise performance

Table 4. Noise performance, differential mode

Range	Typical counts	Least significant bit$_{root\ mean\ square}$ (LSB$_{rms}$)
±20 V	8	1.21
±10 V	8	1.21
±5 V	9	1.36
±4 V	10	1.51
±2.5 V	12	1.81
±2 V	14	2.12
±1.25 V	18	2.72
±1 V	22	3.33

Table 5. Noise performance, single-ended mode

Range	Typical Counts	LSB$_{rms}$
±10 V	8.0	1.21

Analog output

Table 6. Analog output specifications

Parameter	Condition	Specification
Resolution		12-bits, 1 in 4,096
Output range		*0 V to 5.0 V*
Number of channels		2
Throughput (Note 5)	Software paced	250 S/s single channel typ, PC dependent
	Hardware paced, per channel	50 kS/s max
Power on and reset voltage		0 V, ±20 mV typ; initializes to 000h code
Output drive	Each D/A OUT	5 mA, sourcing
Slew rate		0.8 V/ µs typ

Note 5: Maximum throughput when scanning is machine dependent.

Model Number 208C05	ICP® FORCE SENSOR	Revision G ECN #: 17909

Performance	ENGLISH	SI	
Sensitivity (±15 %)	1 mV/lb	224.82 mV/kN	
Measurement Range (Compression)	5000 lb	22.24 kN	
Measurement Range (Tension)	500 lb	2.224 kN	
Maximum Static Force (Compression)	8000 lb	35.59 kN	
Maximum Static Force (Tension)	500 lb	2.224 kN	
Broadband Resolution (1 to 10000 Hz)	0.05 lb-rms	0.222 N-rms	[1]
Low Frequency Response (-5 %)	0.0003 Hz	0.0003 Hz	[2]
Upper Frequency Limit	36 kHz	36 kHz	[3]
Non-Linearity	≤1 % FS	≤1 % FS	[4]
Environmental			
Temperature Range	-65 to +250 °F	-54 to +121 °C	
Temperature Coefficient of Sensitivity	≤0.05 %/°F	≤0.09 %/°C	
Electrical			
Discharge Time Constant (at room temp)	≥2000 sec	≥2000 sec	
Excitation Voltage	20 to 30 VDC	20 to 30 VDC	
Constant Current Excitation	2 to 20 mA	2 to 20 mA	
Output Impedance	≤100 Ohm	≤100 Ohm	
Output Bias Voltage	8 to 14 VDC	8 to 14 VDC	
Spectral Noise (1 Hz)	0.00168 lb/√Hz	0.00750 N/√Hz	[1]
Spectral Noise (10 Hz)	0.00112 lb/√Hz	0.00501 N/√Hz	[1]
Spectral Noise (100 Hz)	0.000459 lb/√Hz	0.00205 N/√Hz	[1]
Spectral Noise (1000 Hz)	0.000133 lb/√Hz	0.000592 N/√Hz	[1]
Output Polarity (Compression)	Positive	Positive	
Physical			
Stiffness	6 lb/µin	1.05 kN/µm	[1]
Size (Hex x Height x Sensing Surface)	0.625 in x 0.625 in x 0.500 in	15.88 mm x 15.88 mm x 12.7 mm	
Weight	0.80 oz	22.7 gm	
Housing Material	Stainless Steel	Stainless Steel	
Sealing	Hermetic	Hermetic	
Electrical Connector	10-32 Coaxial Jack	10-32 Coaxial Jack	
Electrical Connection Position	Side	Side	
Mounting Thread	10-32 Female	Not Applicable	
Mounting Torque (Recommended)	16 to 20 in-lb	181 to 226 N-cm	

CE[5]

All specifications are at room temperature unless otherwise specified.
In the interest of constant product improvement, we reserve the right to change specifications without notice.
ICP® is a registered trademark of PCB group, Inc.

Optional Versions (Optional versions have identical specifications and accessories as listed for standard model except where noted below. More than one option may be used.)

N - Negative Output Polarity

Output Polarity (Compression)	Negative	Negative

W - Water Resistant Cable

Notes

[1] Typical.
[2] Calculated from discharge time constant.
[3] Estimated using rigid body dynamics calculations.
[4] Zero-based, least-squares, straight line method.
[5] See PCB Declaration of Conformance PS023 for details.

Supplied Accessories

080A81 Thread Locker (1)
081B05 Mounting Stud (10-32 to 10-32) (2)
084A03 Impact Cap (1)
M081A62 Mounting stud, 10-32 to M6 x 1, BeCu with shoulder (2)

Entered: LAB	Engineer: LAB	Sales: JJM	Approved: JMF	Spec Number:
Date: 07/09/2003	Date: 07/09/2003	Date: 07/09/2003	Date: 07/10/2003	**8369**

PCB PIEZOTRONICS
FORCE / TORQUE DIVISION

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Depew, NY 14043
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Phone: 800-828-8840
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E-mail: info@pcb.com
Web site: www.pcb.com

Model Number 482A21	SIGNAL CONDITIONER, LINE (OR DC) POWERED	Revision J ECN #: 32514

Performance	ENGLISH	SI	
Channels	1	1	
Voltage Gain (±1 %)	1:1	1:1	
Low Frequency Response (-5 %)	<0.1 Hz	<0.1 Hz	
High Frequency Response (-5 %)	>1000 kHz	>1000 kHz	
Fault/Bias Monitor/Meter	26 V FS	26 V FS	
Environmental			
Temperature Range	32 to 120 °F	0 to 50 °C	
Electrical			
Power Required (Standard)	DC power	DC power	
Excitation Voltage (To Sensor)	25 to 27 VDC	25 to 27 VDC	
DC Offset (Maximum)	<20 mV	<20 mV	
DC Power	+32 to 38 VDC	+32 to 38 VDC	[1]
DC Power	0.12 amps	0.12 amps	[1]
Constant Current Excitation (To Sensor)	2 to 20 mA	2 to 20 mA	[2]
Discharge Time Constant (0 to +50%)	10 sec	10 sec	[3]
Spectral Noise (1 Hz)	0.71 μV/√Hz	-123 dB	[4]
Spectral Noise (10 Hz)	0.09 μV/√Hz	-142 dB	[4]
Spectral Noise (100 Hz)	0.05 μV/√Hz	-147 dB	[4]
Spectral Noise (1 kHz)	0.04 μV/√Hz	-149 dB	[4]
Spectral Noise (10 kHz)	0.03 μV/√Hz	-150 dB	[4]
Broadband Electrical Noise (1 to 10000 Hz)	3.25 μV	-110 dB	[4]
Physical			
Electrical Connector (Input, sensor)	BNC Jack	BNC Jack	
Electrical Connector (Output)	BNC Jack	BNC Jack	
Electrical Connector (DC Power Input)	DIN Jack	DIN Jack	
Size (Height x Width x Length)	6.3 in x 2.4 in x 11 in	16 cm x 6.1 cm x 28 cm	
Weight	1.51 lb	685 gm	

CE[5]

All specifications are at room temperature unless otherwise specified.
In the interest of constant product improvement, we reserve the right to change specifications without notice.
ICP ® is a registered trademark of PCB group, Inc.

Optional Versions (Optional versions have identical specifications and accessories as listed for standard model except where noted below. More than one option may be used.)

Notes

[1] Provided by supplied external DC power supply.
[2] User adjustable, factory set at 4 mA (± 0.5 mA). One control adjusts all channels.
[3] With >= 1M ohm input impedance of readout device.
[4] Typical.
[5] See PCB Declaration of Conformance PS024 for details. A low impendance connection from case to earth ground is required to maintain CE compliance.

Supplied Accessories

017AXX Power Cord ()
488B04/NC Power Convertor ()

Entered: LLH	Engineer: PLH	Sales: JJM	Approved: LLH	Spec Number:
Date: 03/12/2010	Date: 03/02/2010	Date: 03/12/2010	Date: 03/12/2010	**6528**

PCB PIEZOTRONICS ELECTRONICS DIVISION

3425 Walden Avenue
Depew, NY 14043
UNITED STATES
Phone: 800-828-8840
Fax: 716-684-0987
E-mail: info@pcb.com
Web site: www.pcb.com

K - Matlab Analysis Code

```
%%Rifle Recoil Force Calculation
%%Calculates Recoil Energy and Graphs Force and Energy vs Time

%%
close all
clear all
clc

%% Load our Data
load test1_2506
load test2_2506
load test1_300wbymag
load test2_300wbymag

%% system constants
m_rifle_2506= 8.25/32.174
m_rifle_300wbymag= 9.25/32.174

%% determine acceleration from force data
test1_2506(:,3)= test1_2506(:,2)/m_rifle_2506;
test2_2506(:,3)= test2_2506(:,2)/m_rifle_2506;
max_force1= max( test2_2506(:,3) ) %and max force

test1_300wbymag(:,3)= test1_300wbymag(:,2)/m_rifle_300wbymag;
test2_300wbymag(:,3)= test2_300wbymag(:,2)/m_rifle_300wbymag;

%% Plot data
hold on
% 25-06
plot(test1_2506(:,1),test1_2506(:,2), 'b')      %force1 vs time
plot(test2_2506(:,1),test2_2506(:,3), 'b')      %accel1 vs time
plot(test2_2506(:,1),test2_2506(:,2), 'r')      %force2 vs time
plot(test1_2506(:,1),test1_2506(:,3), 'r')      %accel2 vs time

% 300wby mag
figure(2)
hold on
plot(test1_300wbymag(:,1),test1_300wbymag(:,2), 'r')      %force3 vs time
plot(test1_300wbymag(:,1),test1_300wbymag(:,3), 'r')      %accel3 vs time
plot(test2_300wbymag(:,1),test2_300wbymag(:,2), 'b')      %force4 vs time
plot(test2_300wbymag(:,1),test2_300wbymag(:,3), 'b')      %accel4 vs time

% plot(test1_300wbymag(:,1),test1_300wbymag(:,2),'g')
% plot(test2_300wbymag(:,1),test2_300wbymag(:,2),'k')

xlabel('time(seconds)')
ylabel('force(pounds)')

legend('test 1 25-06','test 2 25-06','test 1 300 wby mag','test 2 300 wby mag')
%% Calculate Integrals
% figure(2)
% Area11 = trapz(test1_2506(:,1),test1_2506(:,2))     %area under force1 vs. time
Area111= trapz(test1_2506(:,1),test1_2506(:,3))     %area under accel1 vs. time
% Area112 = trapz(test2_2506(:,1),test2_2506(:,2))    %area under force2 vs. time
Area1112= trapz(test2_2506(:,1),test2_2506(:,3))    %area under accel2 vs. time
```

```
% 300 wby mag
Area3001= trapz(test1_300wbymag(:,1),test1_300wbymag(:,3))
Area3002= trapz(test2_300wbymag(:,1),test2_300wbymag(:,3))

%% And calculating recoil energy based on .5mv^2

RecoilEnergy1= 0.5*m_rifle_2506*Area111*Area111
RecoilEnergy2= 0.5*m_rifle_2506*Area1112*Area1112

RecoilEnergy300wbymag1= 0.5*m_rifle_300wbymag*Area3001*Area3001
RecoilEnergy300wbymag2= 0.5*m_rifle_300wbymag*Area3002*Area3002

% Area12 = trapz(test2_2506(:,1),test2_2506(:,2))
% Area21 = trapz(test1_300wbymag(:,1),test1_300wbymag(:,2))
% Area22 = trapz(test2_300wbymag(:,1),test2_300wbymag(:,2))
```

L - Matlab Sensor Code

```
%%Rifle Recoil Project
%%Effective Sensor Rate Reduction for Sensor Selection
close all
clear all
clc

%% Load our Data
load test1_2506
load test2_2506
load wby300corrected

%% Begin for loop
%n values change the effective Hz of sensor
n=[200];
%s values change the start point for recording. (initial was 200ms before
%trigger)
s=1;


for k = 1:length(n) %Run for all values of n
%% Extrapolate Data As If Recorded at Lower Refresh Rates
%Create variable name based on n, each iteration is saved as new variable
%Saves w/ end of s (shortened) from s (start), by n, to the end.
eval(['test1_2506s_' num2str(n(k)) '(:,1)=test1_2506(s:n(k):end, 1)']);
eval(['test1_2506s_' num2str(n(k)) '(:,2)=test1_2506(s:n(k):end, 2)']);
eval(['test2_2506s_' num2str(n(k)) '(:,1)=test2_2506(s:n(k):end, 1)']);
eval(['test2_2506s_' num2str(n(k)) '(:,2)=test2_2506(s:n(k):end, 2)']);
eval(['WBY300Cor1s_' num2str(n(k)) '(:,1)=WBY300Cor1(s:n(k):end, 1)']);
eval(['WBY300Cor1s_' num2str(n(k)) '(:,2)=WBY300Cor1(s:n(k):end, 2)']);
eval(['WBY300Cor2s_' num2str(n(k)) '(:,1)=WBY300Cor2(s:n(k):end, 1)']);
eval(['WBY300Cor2s_' num2str(n(k)) '(:,2)=WBY300Cor2(s:n(k):end, 2)']);


%% System constants
m_rifle_2506= 8.25/32.174;
m_rifle_300wbymag= 9.25/32.174;

%% Determine acceleration from force data
eval(['test1_2506s_' num2str(n(k)) '(:,3)=test1_2506s_' num2str(n(k))
'(:,2)/m_rifle_2506']);
eval(['test2_2506s_' num2str(n(k)) '(:,3)=test2_2506s_' num2str(n(k))
'(:,2)/m_rifle_2506']);
eval(['MaxForce1_' num2str(n(k)) '=max(test1_2506s_' num2str(n(k)) '(:,3))']); %Max Force
25-06 test 1
eval(['MaxForce2_' num2str(n(k)) '=max(test2_2506s_' num2str(n(k)) '(:,3))']);

eval(['WBY300Cor1s_' num2str(n(k)) '(:,3)=WBY300Cor1s_' num2str(n(k))
'(:,2)/m_rifle_2506']);
eval(['WBY300Cor2s_' num2str(n(k)) '(:,3)=WBY300Cor2s_' num2str(n(k))
'(:,2)/m_rifle_2506']);
eval(['MaxForce3_' num2str(n(k)) '=max(WBY300Cor1s_' num2str(n(k)) '(:,3))']); %Max force
300wby test 1
eval(['MaxForce4_' num2str(n(k)) '=max(WBY300Cor2s_' num2str(n(k)) '(:,3))']);


%% Calculate Integrals (To Get Velocity)
eval(['Vel2506_1_' num2str(n(k)) '=trapz(test1_2506s_' num2str(n(k)) '(:,1),test1_2506s_'
num2str(n(k)) '(:,3))']);  %area under accel1 vs. time
```

```
eval(['Vel2506_2_' num2str(n(k)) '=trapz(test2_2506s_' num2str(n(k)) '(:,1),test2_2506s_'
num2str(n(k)) '(:,3))']);  %area under accel2 vs. time

eval(['Vel300_1_' num2str(n(k)) '=trapz(WBY300Cor1s_' num2str(n(k)) '(:,1),WBY300Cor1s_'
num2str(n(k)) '(:,3))']);  %area under accel1 vs. time
eval(['Vel300_2_' num2str(n(k)) '=trapz(WBY300Cor2s_' num2str(n(k)) '(:,1),WBY300Cor2s_'
num2str(n(k)) '(:,3))']);  %area under accel2 vs. time


%% And calculating recoil energy based on .5mv^2
eval(['RecoilEnergy2506_1_' num2str(n(k)) '=0.5*m_rifle_2506*(Vel2506_1_' num2str(n(k))
')^2']);
eval(['RecoilEnergy2506_2_' num2str(n(k)) '=0.5*m_rifle_2506*(Vel2506_2_' num2str(n(k))
')^2']);

eval(['RecoilEnergy300_1_' num2str(n(k)) '=0.5*m_rifle_300wbymag*(Vel300_1_'
num2str(n(k)) ')^2']);
eval(['RecoilEnergy300_2_' num2str(n(k)) '=0.5*m_rifle_300wbymag*(Vel300_2_'
num2str(n(k)) ')^2']);

%% Output Variable
%Output Hz
eval(['hz_' num2str(n(k)) ' =96.153/n(k)']);
eval(['all_' num2str(n(k)) '=[n(k),hz_' num2str(n(k)) ',MaxForce1_' num2str(n(k))
',MaxForce2_' num2str(n(k)) ',MaxForce3_' num2str(n(k)) ',MaxForce4_'...
    num2str(n(k)) ',RecoilEnergy2506_1_' num2str(n(k)) ',RecoilEnergy2506_2_'
num2str(n(k)) ...
    ',RecoilEnergy300_1_' num2str(n(k)) ',RecoilEnergy300_2_' num2str(n(k)) ']']);


%% Graph Comparison
figure (1)
hold on
% 25-06
eval(['x1 = test1_2506s_' num2str(n(k)) '(:,1)']);
eval(['y1 = test1_2506s_' num2str(n(k)) '(:,2)']);
eval(['z1 = test1_2506s_' num2str(n(k)) '(:,3)']);
eval(['x2 = test2_2506s_' num2str(n(k)) '(:,1)']);
eval(['y2 = test2_2506s_' num2str(n(k)) '(:,2)']);
eval(['z2 = test2_2506s_' num2str(n(k)) '(:,3)']);

plot(x1,y1, 'b')      %force1 vs time
plot(x1,z1, 'b')      %accel1 vs time
plot(x2,y2, 'r')      %force2 vs time
plot(x2,z2, 'r')      %accel2 vs time

xlabel('time(seconds)')
ylabel('force(pounds)')

% 300wby mag
eval(['x3 = WBY300Cor1s_' num2str(n(k)) '(:,1)']);
eval(['y3 = WBY300Cor1s_' num2str(n(k)) '(:,2)']);
eval(['z3 = WBY300Cor1s_' num2str(n(k)) '(:,3)']);
eval(['x4 = WBY300Cor2s_' num2str(n(k)) '(:,1)']);
eval(['y4 = WBY300Cor2s_' num2str(n(k)) '(:,2)']);
eval(['z4 = WBY300Cor2s_' num2str(n(k)) '(:,3)']);

figure(2)
hold on
```

```
plot(x3,y3, 'b')      %force4 vs time
plot(x3,z3, 'b')      %accel4 vs time
plot(x4,y4, 'r')      %force4 vs time
plot(x4,z4, 'r')      %accel4 vs time

xlabel('time(seconds)')
ylabel('force(pounds)')

clear x1 y1 z1 x2 y2 z2 x3 y3 z3 x4 y4 z4
k=k+1;
clc
end

disp(['Program Complete. Data started at ' num2str(s)])
```

M - Bill of Materials

Table 4 – Estimated Cost Bill of Materials

Category	Part Description	Purpose	Dealer	Part Number	Price $	Quantity	Total ($)
Fasteners	Grade 8 Alloy Steel Hex Head Cap Screw Zinc Yellow Pltd, 3/4"-16 Thrd, 3" L, Fully Thrd	Back Plate Fasteners	McMaster	92620A875	7.87	4	31.48
	Grade 8 Coated Alloy Steel Hex Head Cap Screw 3/4"-16 Thread, 4" Length	Table Catch Fasteners	McMaster	91286A514	4.24	4	16.96
Washers/Nuts	3/4 in. Zinc-Plated Nuts, Washers and Lock Washers (4-Pieces)	Table Catch Fasteners	Home Depot	00694	4.86	1	4.86
Aluminum	6061 Aluminum1/2"x6"x3ft	Base	McMaster	8975K221	68.31	1	68.31
	6061 Aluminum Anodized 1.25" Dia x 1' Rod	Sleds	McMaster	8974K161	9.95	1	9.95
	6061 Aluminum 3"x4"x12"	Back Plate, Spacer	McMaster	8975K327	93.65	1	93.65
	6061 Aluminum 3"x3"x6"	Table Catch	McMaster	8975K564	44.12	1	44.12
	Multipurpose Aluminum (Alloy 6061) 1/2" Thick, 5" Width, 1' Length	Adjustable Sleds	McMaster	8975K436	21.94	1	21.94
Butt pad	Impact-Resistant UHMW Polyethylene Sheet 5" Thick, 12" X 12" (3-4 Attachments)	Butt pad	McMaster	8752K987	178.47	1	178.47
	Allen Company Shoot'N Bag, Filled Set	Front and Rear rests	Amazon	B001GXJJ84	24.18	1	24.18
	Velcro Velstretch Strap 1 X 27-Inch, 2 Pack, Black	Straps	Amazon	90441	7.00	1	7.00
	Hydraulic Trigger Release	Firing	Weatherby Provided System				
Sensor	PCB 208C05	Force Sensor	PCB	208C05	400.00	1	400.00
	PCB 428A21	Conditioner	PCB	428A21	410.00	1	410.00
	General purpose coaxial cable, white FEP jacket, 3-ft, BNC plug to BNC plug	BNC-Wire	PCB	002T03	10.00	1	10.00
	PCB 002C05	Force cable	PCB	002C05	39.00	1	39.00
	MC USB-1408FS	DAQ Unit	MC DAQ	USB-1408FS-Plus	249.00	1	249.00
	Laptop Computer	Data Analysis	Weatherby Provided System			1	0.00
Parts Subtotal (No Shipping/Tax) ($)							**1608.92**

Table 5 - Actual Cost Bill of Materials

Category	Part Description	Purpose	Dealer	Part Number	Price $	Quantity	Total ($)
Fasteners	Grade 8 Alloy Steel Hex Head Cap Screw Zinc Yellow Pltd, 3/4"-16 Thrd, 3" L, Fully Thrd	Back Plate Fasteners	McMaster	92620A875	7.87	4	31.48
	Grade 8 Coated Alloy Steel Hex Head Cap Screw 3/4"-16 Thread, 4" Length	Table Catch Fasteners	McMaster	91286A514	4.24	4	16.96
Washers/Nuts	3/4 in. Zinc-Plated Nuts, Washers and Lock Washers (4-Pieces)	Table Catch Fasteners	Fastenal		11.31	1	11.31
Aluminum	6061 Aluminum1/2"x6"x3ft	Base	McMaster	8975K221	68.31	1	68.31
	6061 Aluminum Anodized 1.25" Dia x 1' Rod	Sleds	McMaster	8974K161	9.95	1	9.95
	6061 Aluminum 3"x4"x12"	Back Plate, Spacer	McMaster	8975K327	93.65	1	93.65
	6061 Aluminum 3"x3"x6"	Table Catch	McMaster	8975K564	44.12	1	44.12
	Multipurpose Aluminum (Alloy 6061) 1/2" Thick, 5" Width, 1' Length	Adjustable Sleds	McMaster	8975K436	21.94	1	21.94
Butt pad	Impact-Resistant UHMW Polyethylene Sheet 5" Thick, 12" X 12" (3-4 Attachments)	Butt pad	McMaster	8752K987	178.47	1	178.47
	Caldwell Deadshot Shooting Bag Combo, Filled Set	Front and Rear rests	Amazon		24.99	1	24.99
	Velcro Velstretch Strap 1 X 27-Inch, 2 Pack, Black	Straps	Amazon		4.10	2	8.20
	Hydraulic Trigger Release	Firing	Weatherby Provided				
Sensor	PCB 208C05	Force Sensor	PCB	208C05	369.00	1	369.00
	PCB 428A21	Conditioner	PCB	428A21	360.00	1	360.00
	General purpose coaxial cable, white FEP jacket, 3-ft, BNC plug to BNC plug	BNC-Wire	PCB	002T03	28.80	1	28.80
	PCB 002C05	Force cable	PCB	002C05	35.10	1	35.10
	MC USB-1408FS-Plus	DAQ Unit	MC DAQ	USB-1408FS-Plus	249.00	1	249.00
	Laptop Computer	Data Analysis	Weatherby Provided			1	0.00
Additional Parts	Velcro Straps 2" x 36" 2 pack	Straps	Home Depot		5.36	2	10.73

	Velcro Straps 2" x 4"	Straps	Home Depot		2.67	2	5.35
	Washers		Home Depot				3.76
	Machine Screws	Sleds	Home Depot		1.06	3	3.19
	BNC to BNC	DAQ Set Up	Radioshack		7.19	1	7.19
	Foam Board	Poster	Art Central		9.99	1	9.99
	Mounting Spray	Poster	Art Central		7.22	1	7.22
	Tube Rolls to Protect Poster	Poster	Staples		6.99	1	6.99
	Needles (to sew velcro)	Firing Set Up	Beverly's		7.78	1	7.78
	BNC to Wire	DAQ Set Up	Digi-Key		10.92	1	10.92
Parts Subtotal (No Shipping/Tax) ($)							**1624.39**

Table 6 - Cost Overview

Estimated Cost

Dealer	Price ($)	Tax ($)	Shipping ($)	Total ($)
McMaster	$464.88	$35.12	$26.00	$526.00
Home Depot	$4.86	$0.36	$0.00	$5.22
Amazon	$31.18	$2.49	$0.00	$33.67
PCB	$859.00	$64.43	$0.00	$923.43
MC DAQ	$249.00	$0.00	$9.95	$258.95
Grand Total ($)				**$1,747.27**

Actual Cost

Dealer	Price ($)	Tax ($)	Shipping ($)	Total ($)
McMaster	$464.88	$35.12	$26.00	$526.00
Estimated. No invoice received by team for McMaster				
Home Depot	$23.03	$1.83	$0.00	$24.86
Amazon	$33.19	$2.66	$0.00	$35.85
PCB	$792.90	$59.47	$11.85	$864.22
MC DAQ	$249.00	$20.72	$9.95	$279.67
Other Merchants	$61.39	$4.91	$5.47	$71.77
Subtotal	$1,624.39	$124.71	$53.27	
Grand Total ($)				**$1,802.37**
Overage				$55.11

N - Sensor Specification Sheets

~ Calibration Certificate ~

Model Number: 482A21

Serial Number: 6381

Description: Signal Conditioner

Manufacturer: PCB

Customer:

P.O.:

Method: Comparison Method (AT104-17)

Calibration Data

Temperature: 75 °F (24 °C)

Humidity: 50%

Channel	Volts	Current (mA)	Gain X1
1	25.8	3.99	1.000

Condition of Unit

As Found: n/a

As Left: New unit, in tolerance

Notes

1. Calibration is N.I.S.T. traceable through PCB control number QC-214.
2. This certificate shall not be reproduced, except in full, without written approval from PCB Piezotronics, Inc.
3. Calibration is performed in compliance with ISO 9001, ISO 10012-1, ANSI/NCSL Z540.3 and ISO 17025
4. Measurement uncertainty (95% confidence level with a coverage factor of 2) for the sensitivity reading is +/- 0.2 %
5. See Manufacturer's Specification Sheet for a detailed listing of performance specifications.

Technician: Travis Davis TD

Date: 08/21/13

Due Date:

PCB PIEZOTRONICS™

Headquarters: 3425 Walden Avenue, Depew, NY 14043

Calibration Performed at: 10869 Highway 903, Halifax, NC 27839

TEL: 888-684-0013 FAX: 716-685-3886 www.pcb.com

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ecal98-3459944696

CALIBRATION CERTIFICATE

Model: 208C05
Serial #: LW38012
Description: Force Sensor
Type: ICP

Sensitivity*: 0.9720 mV/LBF
0.2185 mV/N

Linearity*: 0.3% FS
Uncertainty:** +/- 1 %

Date: 10/8/2013
By: Scott Skibniewski, Cal. Tech.
Station: 0-10,000 lb Load Cell (Test Procedure AT501-6)

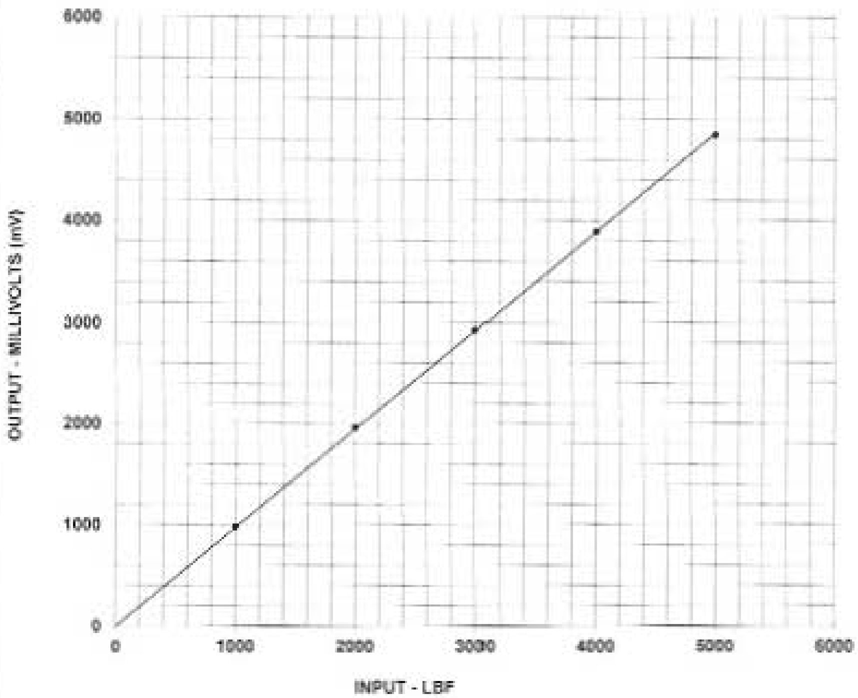
Temp: 72 deg F [22deg C]
Humidity: 48 %

Cert #: 495115

Bias: 10.19 VDC

* Zero based, least-squares straight line.
** Measurement uncertainty represented using a coverage factor of k=2 which provides a level of confidence of approximately 95 %.

Condition of Unit:
As Found: Not applicable
As Left: In tolerance, new unit



TEST DATA

INPUT (LBF)	OUTPUT (mV)
1000	981
2000	1960
3000	2925
4000	3891
5000	4844

Notes:
1 Standard calibration is supplied in compression mode.
2 Station # 41
3 This sensor is torque to 20 in-lbs prior to calibration.
4 Calibration is traceable to NIST and is accredited to ISO 17025 and ANSI/NCSL Z540.3.
5 NIST traceability through PCB control # NC014.
6 This certificate may not be reproduced, except in full, without written approval from PCB Piezotronics, Inc.

CALIBRATION CERT #1862.02

PCB PIEZOTRONICS

Tel: 888-684-0013 Fax: 716-685-3886 Email: sales@pcb.com
Headquarters: 3425 Walden Avenue, Depew, NY 14043
Manufacturing and Calibration Facility: 10869 Highway 903, Halifax, NC 27839
ISO 9001 CERTIFIED

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