Mechanical Design 2 (EML 4501)

Pressure Gauge

Design Report 1 | Fall 2017

Flores,Andres D
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Introduction

The stick pressure gauge is a compact analog device used to measure a system’s air pressure via a Schrader valve. A common use for the pressure gauge is measuring air pressure in vehicle tires, like those found on buses, cars, and bicycles. Following the labels shown in Fig. 1, Table I lists the parts comprising a standard pressure gauge.

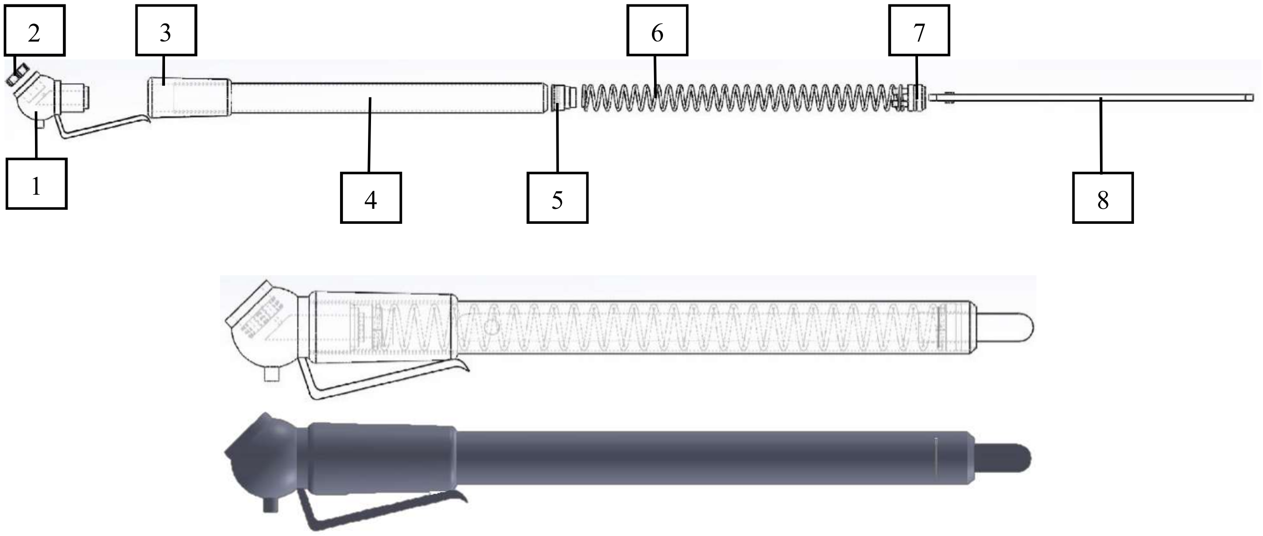


Fig. 1. Labeled diagram of a pressure gauge, transparent view of assembled pressure gauge, and external view of assembled pressure gauge.

TABLE I
Pressure Gauge Parts

Label	Part Name	Abbreviation
1	Cap	C
2	Washer	W
3	Grip	G
4	Barrel	B
5	Plunger	P
6	Spring	S
7	Keeper	K
8	Ruler	R

How a Pressure Gauge Works

A user begins by removing the cap from the Schrader valve. For proper use when measuring the air pressure in a tire, a user should position the gauge’s cap opening with the tire’s Schrader valve concentrically. The pin in the middle of the cap’s opening should align with the pin in the Schrader valve, as shown in Fig. 2. A washer press-fit into the cap’s opening prevents air from leaking when the gauge engages the Schrader valve. Once a secure seal is established between the pressure gauge and the Schrader valve, the user applies force to press the gauge cap’s pin against the valve system, releasing pressurized air from the tire and into the pressure gauge. After pressurized air enters the pressure gauge, the user removes releases the applied force. The Schrader valve's spring-loaded pin will seal the system's passage way, ending all air flow.

Fig. 2. Detailed view of the pressure gauge interacting with a Schrader valve

As the pressurized air flows through a small pinhole and a hollowed passage way in the gauge cap, it enters the barrel containing a series of mechanisms that measure the tire's pressure. As the pressurized air enters the barrel, it interacts with a rubber plunger. The interaction applies a pressure along the plunger's top surface area, causing a push along the barrel's axis. The barrel walls are smooth and lubricated with light oil to allow the plunger to slide along the barrel's length. While the plunger slides, however, the gauge's design provides an interference between the plunger and the barrel wall to prevent air from slipping past the plunger, which could potentially yield inaccurate pressure readings.

The pressurized air pushes against the plunger, which then pushes against an attached spring and a ruler, simultaneously. Depending on the amount of pressure pushing the plunger, the spring compresses along the barrel's length as the ruler gets pushed a distance equal to the plunger's displacement, dictated by the flowing air's pressure. Once the ruler is pushed to its maximum distance, relative to the air pressure, the spring stops compressing and restores itself, thereby pushing the plunger back to its original position.

After the plunger pushes the ruler its maximum distance, the user can read the ruler to determine the tire's air pressure. A keeper at the bottom of the barrel guides the calibrated ruler as the plunger pushes it out the bottom end of the pressure gauge. The keeper also provides a 'pinch' to ensure that the ruler does not slip at any point during air pressure measurement. The pinch also causes friction between the keeper and the ruler, which is accounted for in the pressure gauge's calibration. After an air pressure reading is recorded, a user can reset the pressure gauge by manually pushing the ruler back into the barrel through the keeper.

The stick pressure gauge offers valid pressure readings with ease of use. Its efficient design also allows users to comfortably store and transport the instruments in pockets, bags, and cars. While the design is efficient and the use is simple, the physics and design dictation the pressure gauge's performance is sophisticated and thorough, as different parts in the device influence one another.

Cap

Functional Parts and Requirements

- Cap houses washer
- Clips to user for secure mobility
- Gauge engages Schrader valve
- Cap press-fits with barrel

Part Description

The pressure gauge's cap is located at the top of the device and is press-fit into the barrel's larger-diameter end. The cap is where the pressure gauge engages the Schrader valve and allows pressurized air to enter the pressure gauge via hollowed passages within the gauge cap. A pin is located inside the cap, as indicated with the red circle in Fig. 3, and is designed to depress the spring-loaded Schrader valve. When the pin depresses the valve, the valve opens and allows pressurized air to flow out of the system and into the pressure gauge.

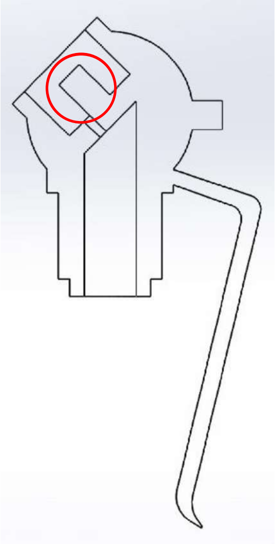


Fig. 3. Cross-sectional view of the pressure gauge cap, detailing internal features.

To prevent air leakage during engagement, the cap houses a rubber washer that is press-fit with the cap along the washer's outer diameter and clears a pinhole that allows pressurized air to enter the pressure gauge along the inner diameter. This relationship is shown in Fig. 4.

Once the pressurized air flows past the washer and through the pinhole, it enters a hollowed chamber down the cap's neck to begin interacting with the barrel's contents. The cap also features a pressure release nob along its outer curvature, which releases excess pressure from the pressure gauge when conducting measurement.

Along the cap's neck, a clip provides a means for portability, enabling users to comfortably secure the pressure gauge in carrying mechanisms including, but not limited to, pockets, a tool belt, and tool bags. When the pressure gauge is fully assembled, the cap clip experiences an interference at a single point with the grip, thereby sealing any gaps between the two parts for secure mobility.

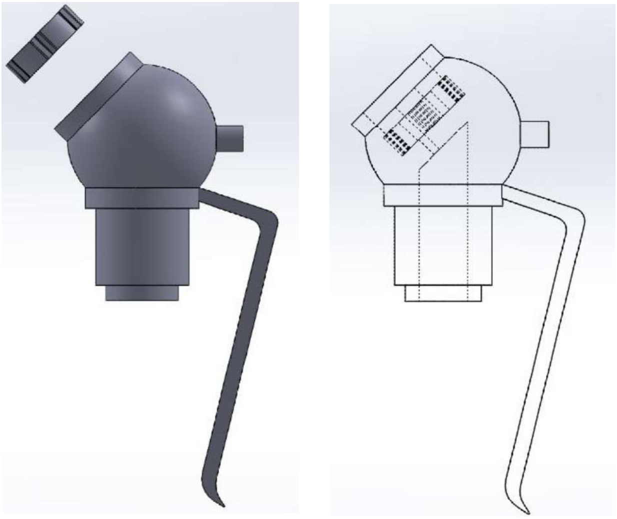


Fig. 4. Pressure gauge cap interacting with the washer.

Material Analysis

The material from which the cap was made was determined with a material burning test. A solder iron was first placed on the cap's surface to determine that that the material was a thermoplastic, since the cap melted and deformed at the solder iron's touch. Afterwards, a lighter was held to the cap and it sustained an orange flame. As the part burned, it released a black smoke, soot, and an odor comparable to burning rubber. The cap was then submerged in water and sunk. Observing the cap's responses to the material tests, recorded in Table II, Polyester was identified as the material with which the cap was produced.

TABLE II
Material Test Observations

Characterization	**Observation**
Plastic or Elastomer	Plastic
Melt or Burn	Melt
Float or Sink	Sink
Flame or No Flame	Flame
Flame Color	Orange
Smoke Color	Black
Soot	Yes
Smell	Burned Rubber
Final Material	***Polyester***

Polyester was used to manufacture the pressure gauge cap because the material classifies as a durable plastic. The material contains strong fibers, and so can withstand repetitive movement without compromising the part's integrity. The material is also hydrophobic, so liquids will not damage parts made from polyester, nor deter functionality. This plastic is also affordable and can adopt any molded shape while sustaining its functionality properties. These material properties make polyester a reliable choice for reliable pressure gauge use as the cap repeatedly engages Schrader valves.

Manufacturing

The process by which the pressure gauge cap is manufactured is injection molding, demonstrated in Fig. 5. During injection molding, material pellets are stored in a hopper that feed into a chamber surrounded by heaters. The material pellets are heated, melted and pushed through the chamber via an extruder. Once melted, the melted pellets flow into a tightly sealed mold (labeled 'mould' in Fig. 5) through injector pins and adopt the mold's hollow space's form. The melted pellets then settle inside the mold and solidify, enabling the mold to pull apart via tie bar and release the part.

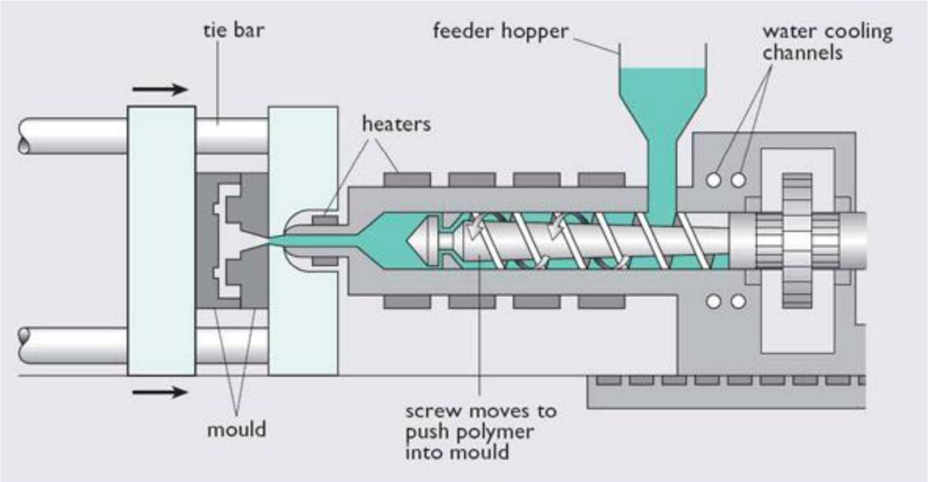


Fig. 5. Injection molding process used to manufacture the pressure gauge cap.

This manufacturing process was identified for the pressure gauge cap by observation. A seam can be located along the center of the cap's outer surface in Fig. 6, indicating where the two molds pulled apart after the melted pellets settled. Since the cap also contains internal details, one can assess that additional molds were inserted into the cap prior to the pellets settling, thereby hollowing the cap.

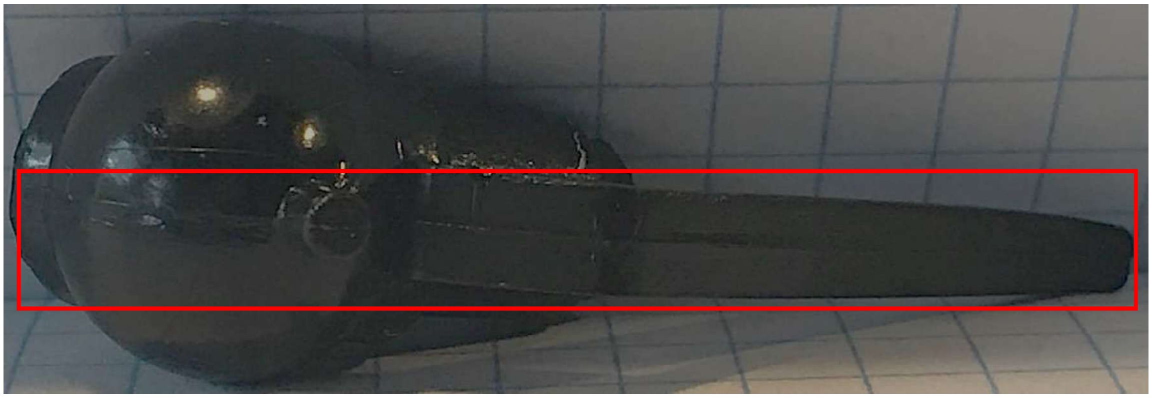
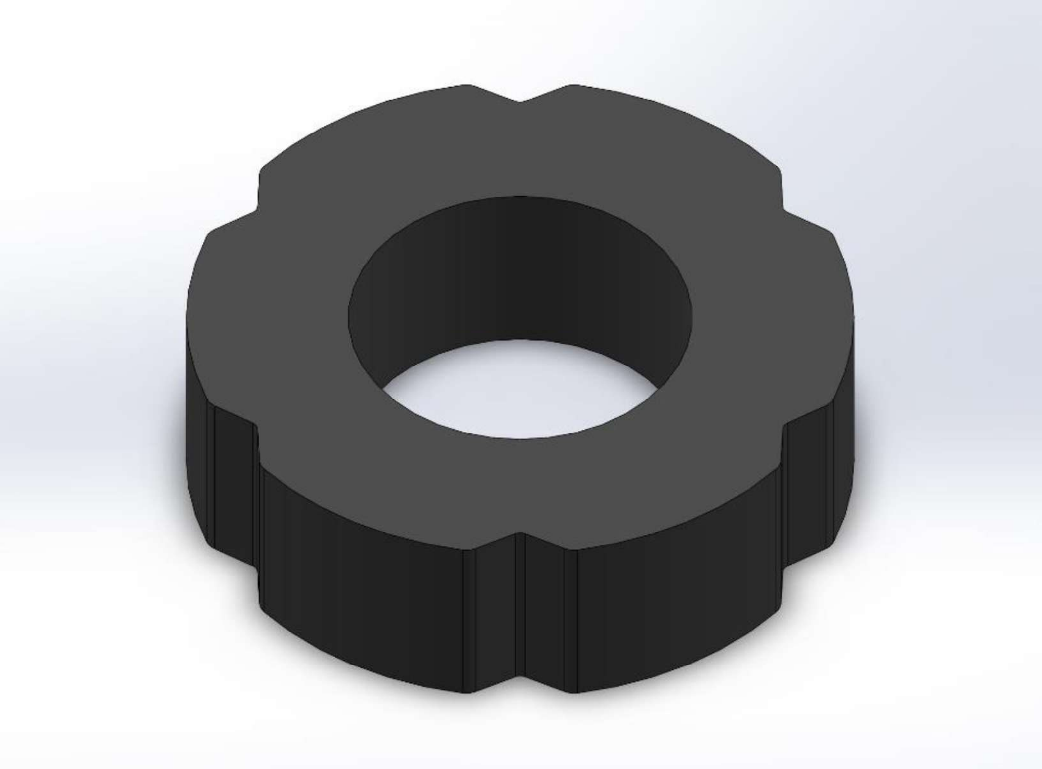


Fig. 6. Seam along the cap's outer surface indicating where the mold halves pulled apart.

Washer



Functional Parts and Requirements

- Compresses when engaging a Schrader valve
- Press-fits with Cap while clearing the pinhole

Part Description

The washer is housed inside of the cap's open end, where the pressure gauge engages the Schrader valve. It mates with cap via press-fit along the washer's outer diameter and clears the cap's pin and pinhole along its inner diameter, as shown in Fig. 7. When the washer press-fits with the cap, it compresses radially and its inner diameter decreases, thereby decreasing the clearance between the pinhole and the washer.

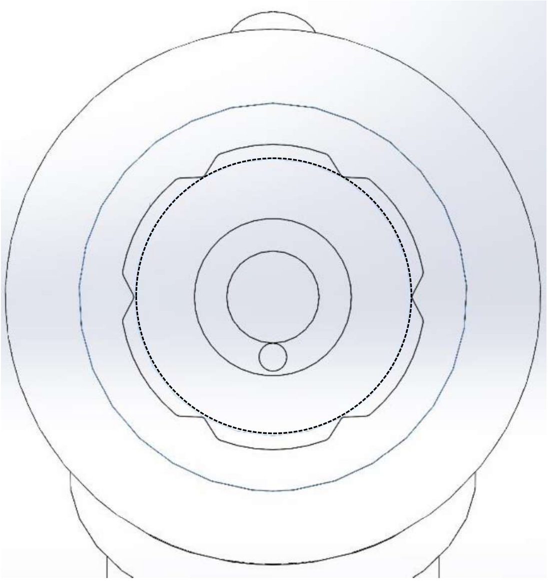


Fig. 7. Detailed view of the washer over the gauge cap prior to press-fitting.

As the cap presses against the Schrader valve during air pressure measurement, the valve axially compresses the rubber washer inside the cap and influences the amount of pressurized air flowing into the cap's pinhole. In other words, the Schrader valve makes direct contact with the washer inside the cap. The washer seals the contact via elastic deformation along the valve's diameter, and directs all pressurized air toward the pinhole for accurate pressure reading. Without the rubber washer, the pressure gauge risks leakage when the Schrader valve opens to release pressurized air from a given system.

Another function that the washer serves while the pressure gauge contacts the Schrader valve is influencing the valve the shut when the user's applied force is released. To release pressurized air from a given system into a pressure gauge, a user aligns the gauge cap with the Schrader valve concentrically and applies a force on the cap. The applied force presses the cap pin against the valve's spring-loaded pin, thereby elastically deforming the washer to seal any leakage and releasing pressurized air through the now-opened valve. After the user releases any applied force from the pressure gauge, the washer restores its shape from any elastic deformation and pushes the Schrader valve away from the pressure gauge's cap pin, thereby allowing the spring-loaded pin to shut the air passageway.

The washer's deformation is demonstrated in Fig. 8, where P is the load exerted on the washer as it interacts with the Schrader valve, and A is the washer's cross-sectional area over which the applied pressure, P, is applied, and L represents the length of the side along which an axial load is applied, which is the washer's thickness.

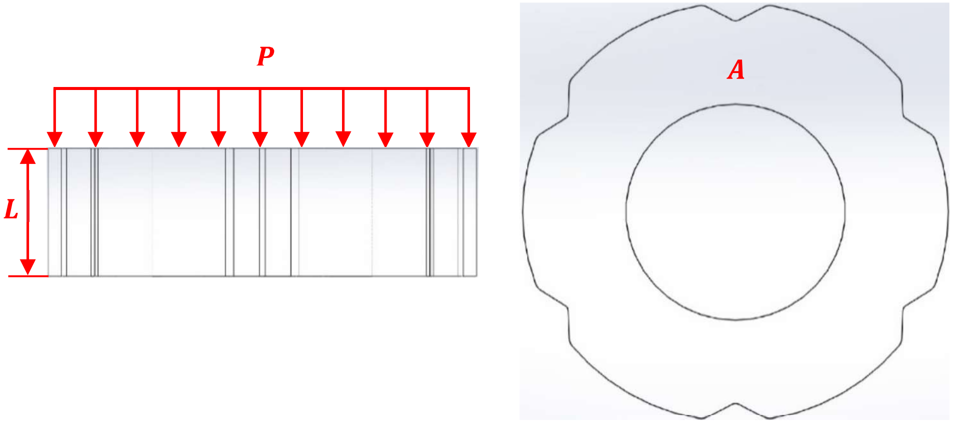


Fig. 8. View of washer detailing an applied load.

When a load is applied to the rubber washer, the it deforms axially depending on its geometry and material properties. The loaded washer's deformation, δ, can be quantified using (1), for which P, L, and A are defined in Fig. 8, and E represents the material's modulus of elasticity. The Cap to Schrader Valve closure analysis is used to determine that the washer will need to deform at least 0.014 in. to sufficiently depress the Schrader valve for pressurized air release.

$$\boldsymbol{\delta = \frac{PL}{EA}} \tag{1}$$

$$P = \frac{\delta EA}{L}$$

$$P = \frac{(0.014\ in.)\times(0.070\ in.^2)\times(5\times10^3)}{0.105\ in.}$$

$$P \approx 40\ lb.$$

While the required load for sufficiently depressing the Schrader valve, one can assess that applying a 40 lb. load is unreasonable. However, the calculation is off by one order of magnitude because the valve only engages the washer locally. The washer's surface area is also influenced by minor cut details along the washer's outer diameter, thereby decreasing the applied load value.

Material Analysis

Material identification tests were performed on the washer and Table III lists the material's behavioral responses to the tests. When a solder iron was pressed against the washer's surface, the material burned but did not melt. The material also managed to maintain a yellow and orange flame and released black smoke while burning. When extinguished, the material released an odor comparable to burned rubber and white smoke, but no soot. The washer was also submerged in water and sunk. The material's performance was then compared to the criteria set in the material identification resources (Appendix A) and used to identify styrene rubber as the washer's material.

TABLE III
Material Test Observations

Characterization	Observation
Melt or Burn	Burn
Plastic or Elastomer	Elastomer
Float or Sink	Sink
Flame or No Flame	Flame
Flame Color	Yellow and Orange
Smoke Color	Black when burned | White when extinguished
Soot	No
Smell	Burned Rubber
Final Material	***Styrene Rubber***

Styrene rubber outperforms natural rubbers in elongation, resilience, and tensile strength. These material properties are specifically crucial to the washer's performance because it repeatedly interfaces with Schrader valves. Styrene's resilience to applied loads and heightened tensile strength makes the material mechanically reliable as users continually apply a load to the washer when pressing the gauge cap against the Schrader valve. Styrene rubber also undergoes heat aging, which enables the washer to withstand a wider valve temperature range.

Manufacturing

Observing a completed rubber washer, one can assess that it was manufactured using a punching process. During a punching process, a punch featuring a desired shape vertically impacts a material's surface and shears a desired 'scrap', as shown in Fig. 9. For the washer, a washer-shaped punch with a concentric hole in the middle sheared a styrene sheet of thickness L. After punching the styrene sheet, the 'scrap' is used as the washer. Punches can also perform multiple punches at once, thereby making this process economically favorable to the manufacturer.

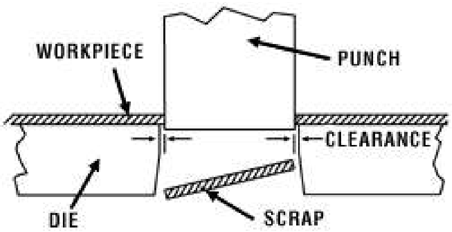


Fig. 9. Punching process in which the styrene rubber is the workpiece and the finished washer is the scrap.

Punching was identified as the manufacturing process because the finished washer in Fig. 10 had excess material along its edges, which can be attributed to the punching process. Fig. 9 indicates a clearance between the shaped punch and its appropriate hole through which the punch produces the scrap. However, the clearance can also cause excess material along the punched product's edges as the punch shears the sheet material and the scrap tears away.

Fig. 10. A completed pressure gauge washer with red circles identifying excess material along the edges.

Grip

Functional Parts and Requirements

- Press-fits with the barrel's outer diameter
- Coincident with cap neck's bottom
- Facilitates ergonomic interaction between the pressure gauge and user

Part Description

The grip is a rubber part that press-fits along the barrel's outer diameter, and is coincident with the bottom of the bottom of the cap, where it meets the barrel's larger diameter. The interactions among the grip, cap, and barrel are shown in Fig. 11. To properly mate the grip with the barrel and cap, the grip's side with a larger outer diameter must touch the bottom of the cap directly.

If the grip is placed on the barrel before the cap is press-fit, then the grip can be installed from either end on the barrel. However, the grip's small outer diameter must always be on the same side as the barrel's small diameter opening. When sliding the grip onto the barrel, it evidently exhibits strong friction between its inner surface and the barrel's outer surface.

By observation, the part is flexible to allow for elastic deformation as it press-fits with the barrel, thereby providing the ability to fit with the barrel despite the number of times it is removed. It also features an ergonomically textured surface to enhance contact between the pressure gauge and the user, thereby minimizing any pressure gauge slip during use. The grip also interacts with the cap's clip at one point of contact. This interaction secures the clip shut by implementing a 'pinch' where the user clips the pressure gauge, be it a pocket or a tool bag.

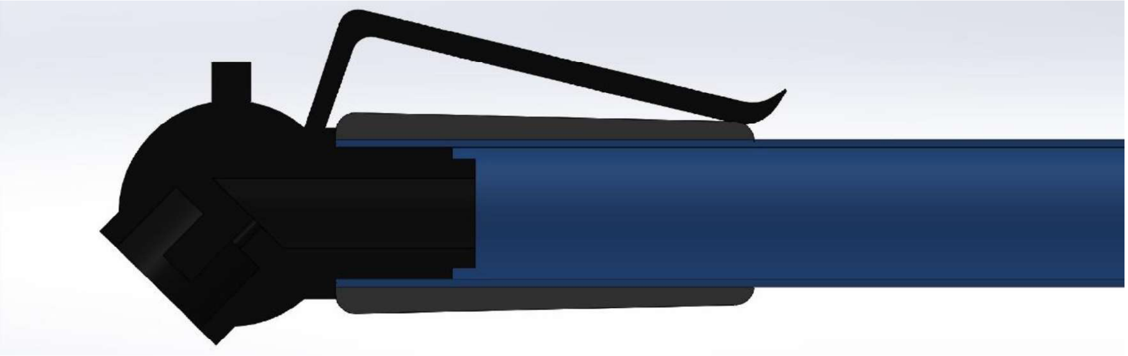


Fig. 11. Cross-sectional view of the grip interacting with the barrel and cap.

Material Analysis

Various material tests were performed to determine the material from which the grip was manufactured. When a soldering iron was held to the grip, it simply burned without melting. The grip also sustained a yellow and orange flame that released a black smoke. The grip also self-extinguished, after which it released a grey smoke but no soot. The odor that the burning grip released was similar to burning rubber. When submerged in water, the grip sunk. While no material directly matches the grip's property responses to the material test, the recorded properties listed in Table IV most closely resemble a styrene rubber.

TABLE IV
Material Test Observations

Characterization	Observation
Melt or Burn	Burn
Plastic or Elastomer	Elastomer
Float or Sink	Sink
Flame or No Flame	Flame
Flame Color	Yellow and Orange
Smoke Color	Black when burned | Grey when extinguished
Soot	No
Smell	Burned Rubber
Final Material	***Styrene Rubber***

Styrene rubber exhibits resilience and tensile strength, which are specifically crucial to the grip's performance because it repeatedly interfaces with users' hands. Styrene's resilience to applied loads and heightened tensile strength makes the material mechanically reliable as users continually grasp the grip. Styrene rubber also undergoes heat aging, which enables the grip to withstand a wider temperature range. This is specifically useful to the grip because it minimizes the chances of the rubber grip melting should the pressure gauge be placed on a hot surface.

Manufacturing

The process by which the gauge's rubber grip is manufactured is injection molding. This was determined by observing the flash from the molding die along the grip's outer surface. The injection molding manufacturing process is elaborated upon in the *Cap* section, and follows the manufacturing diagram shown in Fig. 5.

Fig. 12. Detailed view of flash along the grip's outer surface from the injection molding process.

Barrel

Functional Parts and Requirements

- Press-fits with cap
- Press-fits with grip
- Houses the plunger
- Houses the spring
- Houses the ruler
- Houses the keeper

Part Description

The barrel encompasses the pressure gauge's body and houses the all the other parts that comprise the device, as shown in Fig. 13. Observing the barrel's geometry, one notes that the openings at either end of the barrel have different diameters to properly secure the cap and keeper. The cap is press-fit into the larger of the two diameters, causing the barrel to plastically deform during assembly. The keeper slides into the barrel through the larger diameter before the cap is press-fit, and it sits concentrically on the inside of the barrel with the keeper's prongs facing inward to guide the ruler. A rubber grip is also press-fit along the barrel's outer surface, just below the cap.

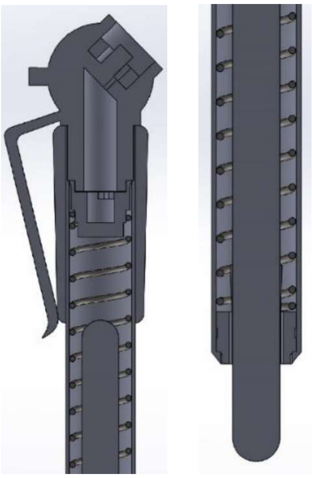


Fig. 13. Cross-sectional view of assembled pressure gauge with all fits about the barrel

In order to properly secure the cap at the barrel's larger diameter opening, the cap's mating surface has to exceed the barrel's undeformed inner diameter. When the cap enters the barrel, its outer surface pushes outward along the barrel's inner diameter (along its points of of direct contact with the cap), thereby deforming the barrel plastically to create the mating press-fit. The barrel's deformation from the cap insertion can be observed in Fig. 14.

Fig. 14. Plastically deformed barrel at the larger diameter end, where the cap press-fits.

That cap's press-fit with the barrel requires a certain amount of applied force to be removed, and so (2) and (3) can be used to perform the appropriate calculations. In the calculations, a normal force along the cap's interaction face with the barrel is calculated by multiplying a pressure and the surface area of the interacting cap face. That force is then multiplied by an average friction coefficient (between 0.3 and 0.4) to approximate the force required to remove the cap from the barrel.

$$\boldsymbol{F_N = PA = P(\pi L d)} \tag{2}$$

$$F_N = (1600\ psi)(\pi \times 0.3 \times 0.36)$$

$$F_N \approx 175\ lb$$

$$\boldsymbol{F = \mu N} \tag{3}$$

$$F = 0.35 \times 175$$

$$F = 60\ lb$$

After performing the appropriate calculations, the approximated force to pull the cap from the barrel is 60 lb. When the cap is removed from the barrel, however, one should note the plastic deformation that results from the interference fit between the two parts.

Parts not always visible to the user, but still housed within the barrel, include the plunger, spring, and ruler. The plunger is housed at the barrel's wider-diameter end and shares an interference fit with the barrel, which ensures that no air leaks past the plunger when pressurized air enters the barrel. When pressurized air exerts force on the plunger, the plunger's lip slides along the barrel's lightly lubricated inner surface. The barrel's lubricated inner surface allows the plunger to slide with minimal frictional resistance while preventing any air from slipping past the plunger.

The barrel also undergoes hoop stress, σ_n, as pressure travels through the inner components. This phenomenon is demonstrated in Fig. 15, where t is the barrel's thickness, r is the barrel's mean radius, and P is the pressure inside the barrel.

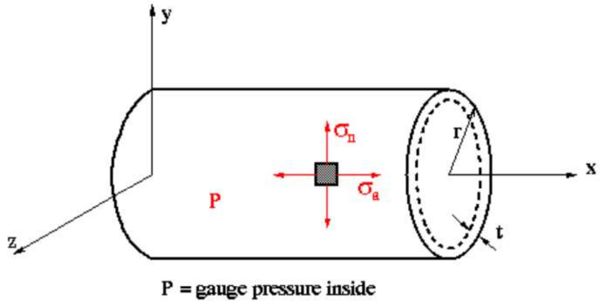


Fig. 15. Hoop stress acting on the barrel as pressured air flows through the system.

Pressurized air will flow through the barrel and push outward along the barrel's inner walls. Consequently, an infinitesimal region, shown as the dark square in Fig. 3, will be analyzed as the barrel undergoes hoop stress. This is a normal stress in the tangential direction, and can be calculated following (4). The P value parallels the average yield stress for aluminum, r and t are values recorded from the barrel's geometry.

$$\boldsymbol{\sigma_n = \frac{Pr}{t}} \tag{4}$$

$$\sigma_n = \frac{(30\ ksi)(0.18\ in.)}{0.010\ in.}$$

$$\sigma_n = 540\ ksi$$

The spring mates with the barrel concentrically and press-fits with the plunger. As pressurized air flows through the system and pushes down on the plunger, the spring compresses and restores the plunger to its original position, causing the plunger slide along the barrel's inner surface once more, but under the influence of the spring's restorative force.

A keeper sits along a filleted edge at the barrel's smaller-diameter end and fits concentrically with the opening, as shown in Fig. 16. The keeper's prongs are positioned inward, which guide the ruler as it slides in and out of the barrel. Since the keeper sits freely in the barrel's smaller-diameter opening, it is secured by the spring inside the barrel (opposite the plunger) and can rotate in place; however, the gauge's functionality is not affected by the keeper's rotation.

Fig. 16. Barrel's filleted edge along its smaller diameter, housing the keeper and the ruler.

Although not serving any functional purposes, the barrel features a metallic blue coating and white print along its outer service, spelling "Gator Mechanical Design." The barrel's surface is smooth for user comfort, and securely houses all gauge components crucial to measuring air pressure.

Material Analysis

The material identification process for the metal barrel began with determining if the material was ferrous or non-ferrous. After holding a magnet to the barrel, it classified as non-ferrous which confirms that no iron-containing material was used. The barrel was then placed in an Instron machine and underwent a tensile load until the barrel ruptured. Analyzing the data collected from the tensile load test, the material's estimated yield strength was approximately 31ksi.Based on the material's estimated property values, aluminum 6063-T6 closely matches the barrel's performance data from the Instron. Aluminum 6063-T6 material properties are listed in Table V.

TABLE V
Aluminum 6063-T6 Material Properties

Tensile Yield Strength	214 MPa = 31 ksi
Ultimate Tensile Strength	241 MPa = 35 ksi
Modulus of Elasticity	68.9 GPa = 10,000 ksi

Aluminum 6063-T6 is an ideal material for the gauge's barrel because it is a durable and lightweight material. Since the pressure gauge will likely be used around heavy pressurized machinery, durability is important to implement in the gauge's design for internal design protection and continued reliable use. The barrel's light weight makes the pressure gauge ideal for user mobility, as it can comfortably sit in a user's pocket or tool bag.

Manufacturing

The barrel's surface was observed to determine the manufacturing process by which it was made. Since the surface does not appear to contain any seams or rough edges, one can conclude that the barrel was cold-drawn. During a cold-drawing process for pipes, stock pipe is pressed through a die with an opening equivalent to a desired diameter. The stock pipe first enters the die and is secured with a gripper, which pulls the stock pipe through the die. A mandrel is a round bar around which the stock pipe is forged to a desired size, and is placed inside of the stock pipe where the die forges the inserted material. As demonstrated in Fig. 17, the stock pipe is then continuously drawn through the system until a desired pipe product is achieved.

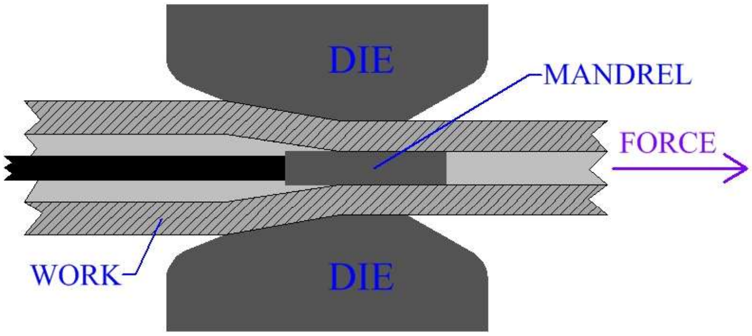
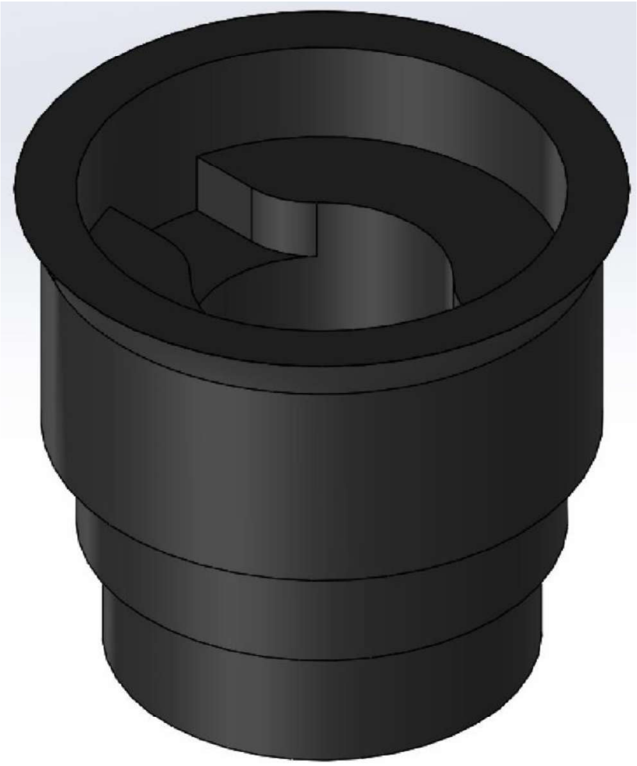


Fig. 17. Cold-drawing process by which the pressure gauge's barrel is produced.

Plunger



Functional Parts and Requirements

- Slides along the barrel while press-fit with the barrel's inner diameter
- Compresses the spring
- Pushes the ruler through the keeper

Part Description

The plunger is housed inside of the barrel and is press-fit with the spring. While the plunger is also press-fit with the barrel's inside diameter, it slides linearly along the barrel's length with some friction. An interference fit between the plunger's lip and the barrel's inner surface is crucial to the gauge's design, because as pressurized air enters the gauge, it needs to fully interact with the plunger's surface to accurately exert a compressive force on the spring and ruler. The interference fit ensures that no air entering the gauge slips past the plunger.

When pressurized air enters the barrel via the cap pinhole, it interacts with the plunger and creates a force that pushes the plunger toward the keeper, thereby compressing the attached spring. As the spring compresses, the plunger also pushes the ruler through the keeper to show a pressure reading.

The forces acting on the plunger's top surface are due to the pressurized air, acting upon the faces denoted by the blue dotted lines in Fig. 18. The green dotted lines indicate a radial deflection along the plunger's lip, which further seals the space between the plunger and barrel, thereby minimizing any air slipping past the plunger during pressure measurement. All force variables relevant to Fig. 1 and subsequent force calculations are defined in Table VI.

TABLE VI
Force Variables

Force	Variable
Force of Air Pressure	F_A
Force of Spring	F_S
Force of Barrel	F_B
Force of Ruler	F_R

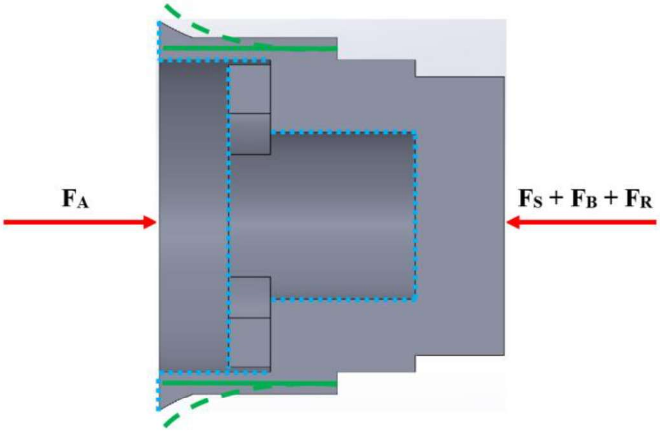


Fig. 18. Cross-sectional view of the plunger as external forces act on the plunger body.

As the pressurized air creates a force in one direction, the spring force, barrel force, and ruler force, sum to a retarding force, which will stop the plunger from sliding once it matches the force due to air pressure. The forces acting on the plunger can be calculated using (5) through (8).

$$\boldsymbol{F_A = P \times A} \tag{5}$$

$$\boldsymbol{F_S} = \int \boldsymbol{k\,dx} \tag{6}$$

$$\boldsymbol{F_B} = \mu \boldsymbol{F_N} \tag{7}$$

$$F_{f_R} = 2\mu F_{k_p}$$

$$\boldsymbol{F_R = (F_A - F_S - F_B) - F_{f_R}} \tag{8}$$

The force of air pressure is calculated using the pressure exerted by the pressurized air and the area over which the pressure interacts with the plunger, denoted by the blue dots in Fig. 18. As the pressurized air encompasses the plunger's surfaces, it exerts forces along the barrel's length and perpendicular to the barrel's inner surface via plunger lip deflection, denoted by the green lines in Fig. 18.

As the force of air pressure pushes the plunger along the barrel, the interaction with the spring, barrel, and ruler forces push upward and oppose the plunger's downward motion, as shown in Fig. 19. The force of spring is calculated using Hooke's law, where k represents the spring constant and 'x' is the distance that the spring compresses. The force of barrel exerts a frictional force along the plunger-barrel interaction point opposite the plunger's direction.

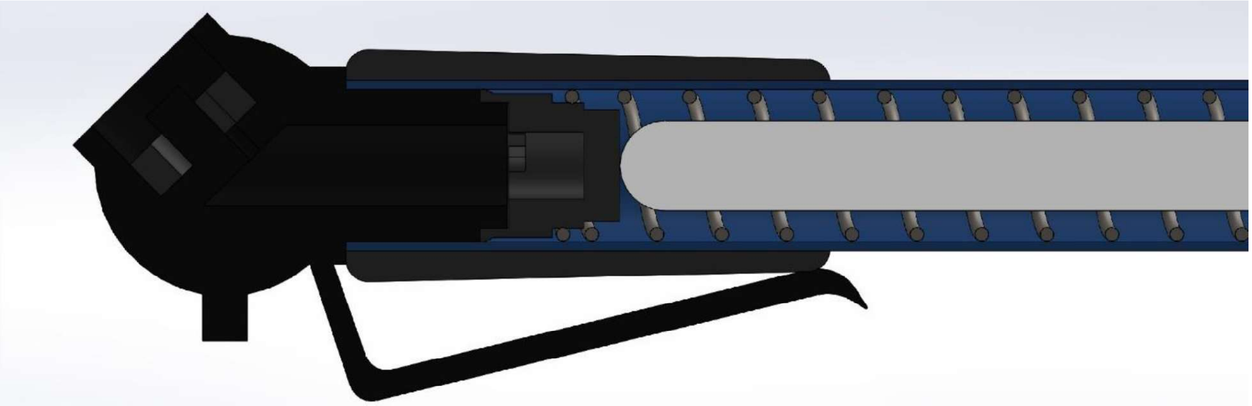


Fig. 19. Cross-sectional view of the pressure gauge, detailing part interactions with the plunger.

These forces' interactions with one another aim to exert a resultant force on the ruler from the plunger, which influences the pressure reading. However, the ruler also exerts a retarding on the plunger when the two parts interact, and is defined as the sum of the spring, barrel, and ruler frictional forces subtracted from the force of air pressure. Note that the ruler frictional force is further elaborated upon and calculated in the *Keeper* section of this report.

Material Analysis

The material from which the plunger is manufactured was determined by performing material identification tests. A soldering iron was first held to the plunger and the user observed that the plunger burned but did not melt. It sustained a yellow and orange flame, and released a black smoke while burning and a white smoke when extinguished. While no soot was released, it had an odor comparable to burned rubber. When submerged in water, the plunger sunk. Following the material's test responses in Table VII, styrene rubber was identified as the plunger's material.

TABLE VII
Material Test Observations

Characterization	Observation
Melt or Burn	Burn
Plastic or Elastomer	Elastomer
Float or Sink	Sink
Flame or No Flame	Flame
Flame Color	Yellow and Orange
Smoke Color	Black when burned | White when extinguished
Soot	No
Smell	Burned Rubber
Final Material	***Styrene Rubber***

Styrene rubber is used to manufacture the plunger because it exhibits strength and durability. The material is also cost-efficient and enables high performance. These qualities are important to consider when selecting a plunger material because this part interacts with high pressures, so a designer should aim for a material that withstands heavily applied loads. Styrene also ensures that the gauge can accept high pressures without compromising the part's performance and reliability.

Manufacturing

The manufacturing process with which the plunger was created is rubber injection molding, shown in Fig. 3. During this process, an injection press seals a heated mold and applies pressure to maintain the mold halves shut during injection and curing cycles. As an exact amount of rubber flows into the mold via runners, it fills all mold cavities to achieve internal part details and yield a desired part form. Using the rubber injection molding process allows for a short molding cycle, low unit cost, high dimensional tolerances, and flash elimination.

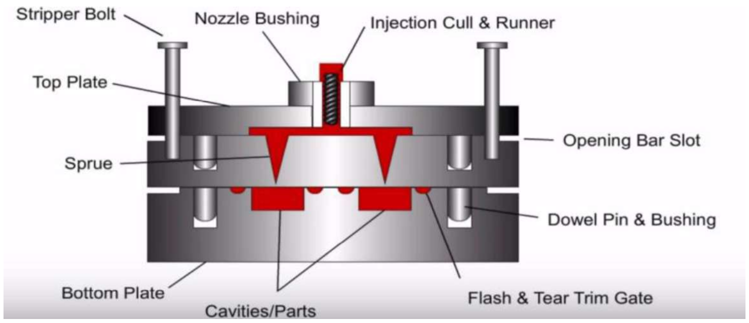
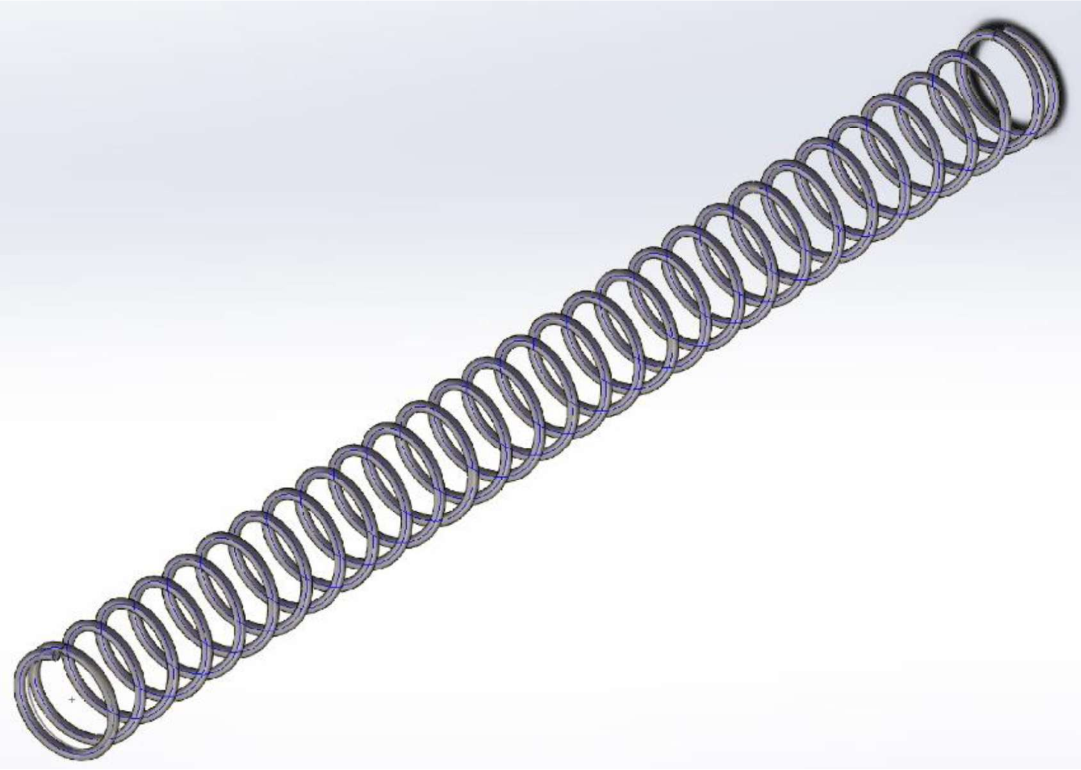


Fig. 20. Detailed diagram demonstrating the rubber injection molding process used for the plunger.

Spring



Functional Parts and Requirements

- Press-fits with plunger
- Compression along the barrel
- Secures the keeper
- Releases the ruler appropriately

Part Description

The spring is housed inside of the barrel, press-fit with the rubber plunger, and concentrically fit with the two prongs on the keeper. While the ruler does not directly mate with the spring, it is housed within the spring and secured with the keeper. During pressure measurement, the calibrated spring accurately guides pushes the ruler out a distance representative of the pressurized air flowing through the pressure gauge, and returns the plunger to its initial position.

During pressure gauge use, the spring compresses as the plunger gets pushed by the pressurized air passing through the barrel. Once the spring achieves maximum compression, as per the force acting on the plunger, the spring and attached plunger appropriately push the ruler through the keeper and the spring decompresses, restoring itself to its free length and returning the plunger to its original position.

The spring's immediate interactions are shown in Fig. 21. When observing the spring's compressive behavior, one should note that the consequent diameter change is small enough to be considered negligible. Therefore, compression should not influence how the spring interacts with the plunger and keeper.

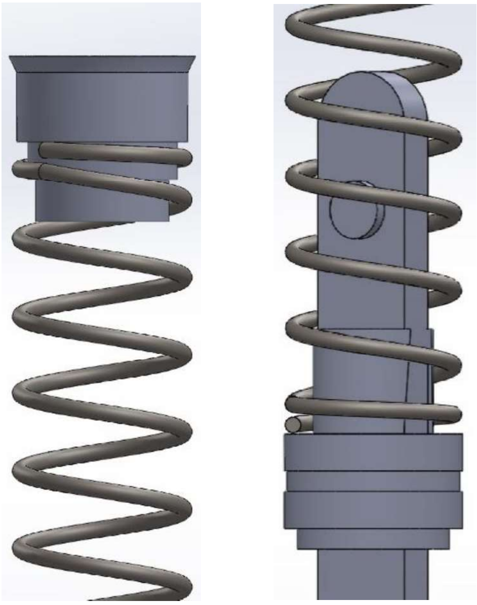
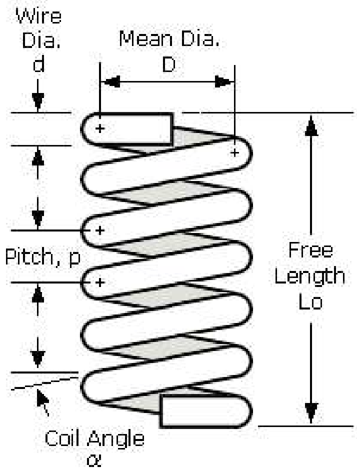


Fig. 21. Spring assembly views at relevant mates: spring to plunger (left) and spring to keeper (right)

Material Analysis

To begin determining the material from which the spring is made, the spring's geometric properties were measured using calipers and recorded in Table VIII. All measurements are related to the labeled spring diagram and used for producing a part rendering on SolidWorks.

TABLE VIII
Spring Geometry Measurements

Property	Variable	Value	Labeled Spring
Outer Diameter	n.a.	0.330 in. = 0.008382 m	
Inner Diameter	n.a.	0.260 in. = 0.006604 m	
Mean Diameter	D	0.307 in. = 0.007785 m	
Thickness	d	0.015 in. = 0.000381 m	
Free Length	L_0	4.170 in. = 0.105918 m	
Pitch	p	0.145 in. = 0.003683 m	
Space Between Coils	n.a.	0.105 in. = 0.002667 m	
Revolutions	n.a.	32 rev	
Active Revolutions	N	28 rev	
Pitch at Ends	n.a.	0.020 in. = 0.000508 m	
Revolutions at Ends	n.a.	1 rev	
Spring Mass	n.a.	2.7 g	
Spring Volume	n.a.	0.020 $\text{in}^3 = 3.277 \times 10^{-7}\ \text{m}^3$	

Once properly modeled on SolidWorks, various experimental tests were conducted to define material properties that correlated with specific materials, as specified in Table A-5 in the Appendix.

The first property defined was the spring constant, k, also known as the proportionality constant, which dictates the spring's stiffness and is used to calculate the spring's restoring force after undergoing tensile or compressive loads. The spring's theoretical restorative force is calculated using Hook's Law, which is defined in (9).

$$\boldsymbol{F = -kx = \int k\,dx} \tag{9}$$

To determine the appropriate spring constant, the spring was placed in an upright hollow cylinder to allow free compression when a load was applied. Starting with no load, masses were incrementally added to the spring and the distance that the spring compressed was recorded. Hooke's law was then used to calculate the spring constants at each incrementally recorded mass. The incremental masses, calculated forces, measured displacements, and calculated spring constants are recorded in Table IX.

TABLE IX
Spring Constant Experimental Values

Mass	Force	Displacement	Displacement	Spring Constant
0 kg	0 N	0 in.	0 m	0 N/m
0.5 kg	4.91 N	0.81 in.	0.0206 m	238.4077 N/m
1.0 kg	9.81 N	1.46 in.	0.0370 m	265.4436 N/m
1.5 kg	14.72 N	2.28 in.	0.0580 m	253.7585 N/m

Averaging the incrementally calculated spring constant values, the final spring constant was defined at 252.5 $\frac{N}{m}$. Using this calculated spring constant along with the spring's geometric measurements defined in Table I, a theoretical modulus of rigidity, G, was calculated using (10).

$$\boldsymbol{G = \frac{8kD^3N}{d^4}} \tag{10}$$

The theoretical modulus of rigidity was compared to the moduli defined for the different materials indicated in Table A-5 in the Appendix. Properties extracted from Table A-5 for materials with moduli of rigidity closest to the theoretical value were used in (11) to calculate the spring constant.

$$\boldsymbol{k = \frac{Gd^4}{8D^3N}} \tag{11}$$

This spring constant value was compared to the Hooke's Law value, and two materials satisfied performed calculations. To determine whether the spring was made from carbon steel or nickel steel, the spring's unit weight, w, was calculated with (12) using the spring's mass and volume.

$$\boldsymbol{w = \frac{Force}{Volume}} \tag{12}$$

The spring material was identified as carbon steel and the property values are listed in Table X.

TABLE X
Carbon Steel Material Properties

Properties	**Variable**	**Value**
Spring Constant	k	252.5 $\frac{N}{m}$ = 1.4 $\frac{lbf}{in.}$
Modulus of Rigidity	G	79.3 GPa = 11.5 Mpsi
Unit Weight	w	76.5 $\frac{kN}{m^3}$ = 0.282 $\frac{lbf}{in.^3}$
Modulus of Elasticity	E	207 GPa = 30 Mpsi
Poisson's Ratio	ν	0.292

Carbon steel is a metal alloy, characterized as iron alloyed with carbon. This material was selected for the spring because it features reliable strength and ductility, depending on the amount of carbon in the alloy. The material is also malleable and ductile, making it favorable for forging. Using carbon steel for the spring also introduces reliable wear resistance, which is crucial to the gauge's repeatedly dependable use.

Manufacturing

Manufacturing a spring begins with manufacturing the wire from which the spring is coiled. The spring wire is manufactured with drawing, where a stock material is drawn through a die featuring a desired shape and size, shown in Fig. 22.

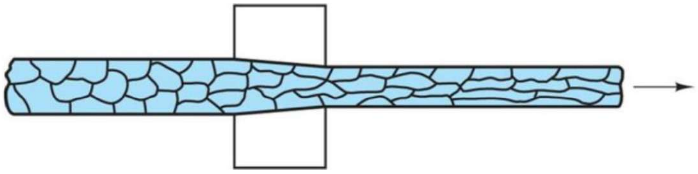


Fig. 22. Stock wire material drawn through a die during a cold-drawing wire manufacturing process

Once the wire is drawn and meets desired specifications, it is coiled using a cold winding process during which the wire is coiled at room temperature. The coiling process requires a wire to be secured with a guiding mechanism, like a lead screw, and rotated about a mandrel on a spring-winding machine or lathe, as shown in Fig. 23. The coiling process can also be completed manually, where users operate a hand-cranking winding machine.

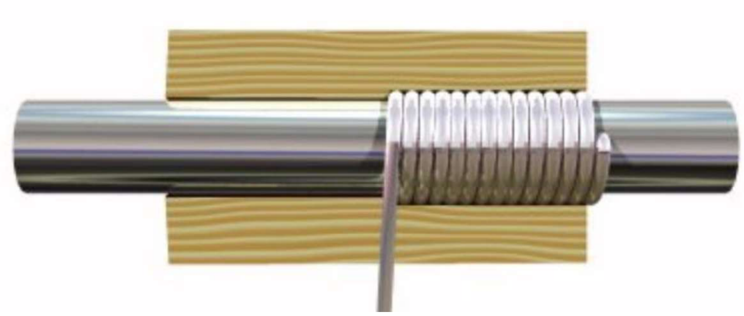
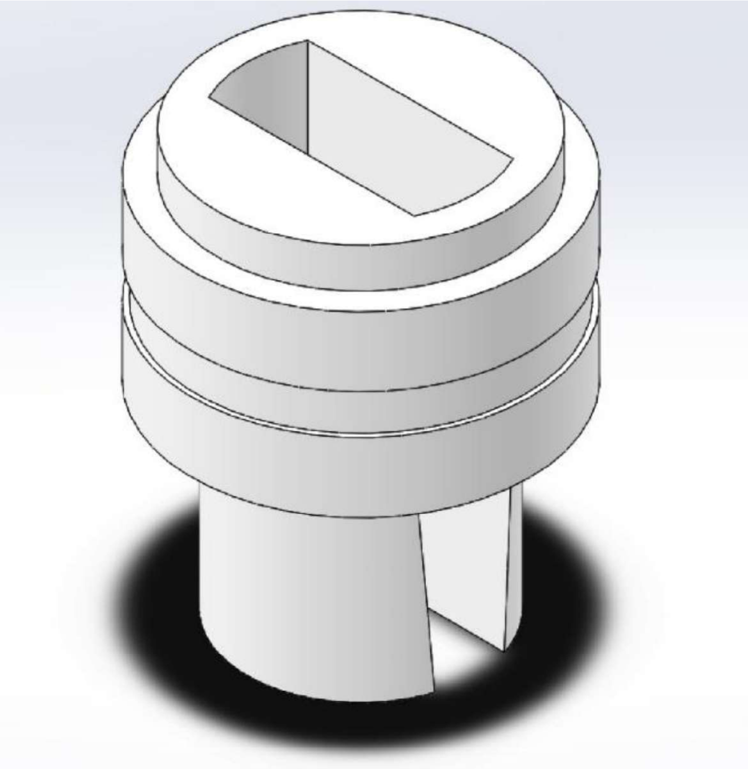


Fig. 23. A wire coiling around a mandrel during a cold coiling spring manufacturing process.

To maintain the spring's resilience and relieve the stress from coiling, the coiled wire is heat treated in an oven for a set time, then allowed to cool slowly. At this point, the spring is completed to perform its most basic functions, but the spring can undergo further finishing processes depending on design specifications, like grinding, shot preening, setting, and coating.

Keeper



Functional Parts and Requirements

- Concentrically fits with the barrel
- Secured inside a barrel with a spring
- Facilitates directional ruler sliding

Part Description

The keeper is located at the bottom of the barrel and fits concentrically with the barrel's smaller diameter and the spring. While the keeper secures the ruler, and guides it as the plunger pushes it out for a pressure reading, the two parts share a unique interaction because of the keeper prongs' shape. Observing the keeper from the side, one notes that the space between the prongs on the keeper is wider toward their interface with the rest of the part, and narrower at their free end.

As the ruler slides through the keeper slot, it is pinched by the prongs at the narrower end to prevent sliding when measuring air pressure. In other words, when the plunger pushes on the ruler, the ruler will only slide as far as the plunger pushes it. The friction caused by the prongs' pinch prevents any further ruler sliding after the spring restores the plunger, thereby minimizing any measurement error.

To begin observing how the ruler influences the keeper's geometry, Fig. 24 shows the keeper prong's cross-section with the 'r' representing the prong's radius.

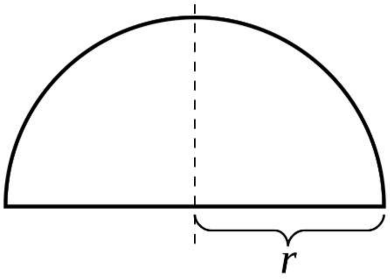


Fig. 24. Cross-sectional view of one keeper prong.

Building upon the diagram shown Fig. 24, the cross-section's area moment of inertia is calculated to define the physics influencing the prongs' geometry when the pressure gauge is in use. Table XI defines the prongs' radius and calculates the area moment of inertia at the point where the prongs interact with the ruler using (13). This note is important because the prongs' internal surfaces are angled to create a 'pinch' on the ruler's faces.

TABLE XI
Area Moment of Inertia Calculations

$$r = 0.073\ in.$$

$$\boldsymbol{I = 0.1098\, r^4} \tag{13}$$

$$I = 3.1 \times 10^{-6}\ in.^4$$

Table XII defines the dimensional (red) and force (blue) variables characterizing the keeper-ruler interaction shown in Fig. 25. As shown in Fig. 25, the ruler's thickness is greater than the prongs' smallest gap, which deflects the prongs outward when the ruler slides through.

TABLE XII
Keeper Variables Defined

Variable	**Abbreviation**
Length between keeper prongs	L_{k_p}
Ruler thickness	t_R
Difference between L_{k_p} and t_R	i
Force of keeper pinch	F_{k_p}
Force of friction	F_f
Force from of ruler	F_R

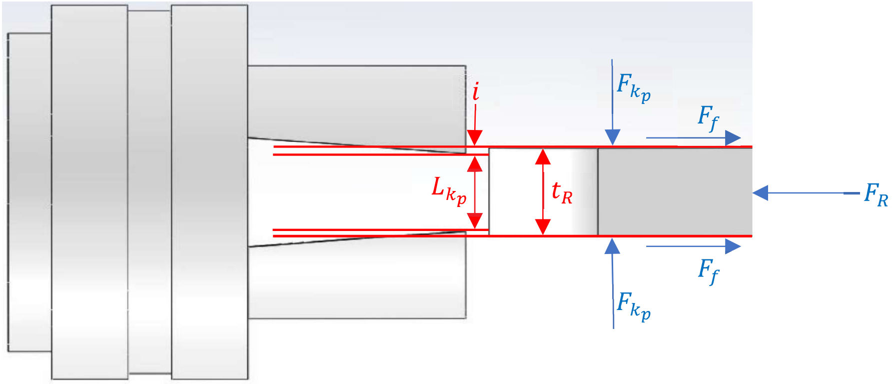


Fig. 25. Ruler and keeper prong interaction view, detailing force distributions and dimensions.

As the ruler enters the keeper, it elastically deforms the prongs to create a 'pinch' on the ruler's surface. This influences friction that allows the ruler to slide past the prongs when pushed by the plunger, but prevents additional sliding after the spring restores the plunger to its original position. The keeper prong deflection that occurs as a result of the inserted ruler is resembled in Fig. 26.

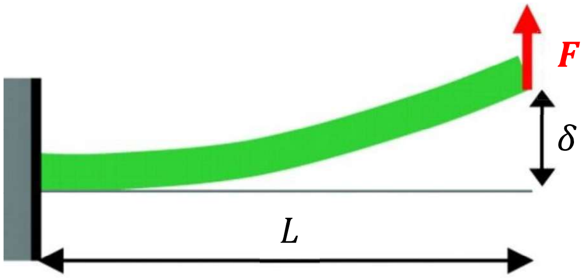


Fig. 26. Cantilever beam schematic detailing the keeper prongs' deflection from the ruler.

Following the diagram shown in Fig. 26, Table XIII performs the calculations necessary to quantify the normal force acting on the system at the keeper-ruler interface. The properties listed in Table XIII are derived from the part's geometry and material properties, and build upon (14) to determine the keeper prongs' normal load, F_{k_p}, on the ruler's surfaces.

TABLE XIII
Normal load from Keeper Prongs onto Ruler Calculations

$$\delta = 0.003\ in.$$
$$L = 0.210\ in.$$
$$E = 3 \times 10^3\ psi$$
$$\boldsymbol{\delta = \frac{F_{k_p} L^3}{3EI}} \tag{14}$$
$$F_{k_p} = \frac{3\delta EI}{L^3}$$
$$F_{k_p} = 0.090\ lbf$$

After defining F_{k_p} in terms of lbf, the load value was converted to kg, following the conversion outlined in Table XIV, to maintain all metric units.

TABLE XIV
lbf to kg Conversion

$$0.00220462262\ lbf = 1\ g \rightarrow 453.59 \frac{g}{lbf}$$
$$(0.090\ lbf) \times \left(453.59 \frac{g}{lbf}\right) = 40.08\ g \rightarrow 0.040\ kg$$
$$F_{k_p} = 0.040\ kg$$

Once all units were converted to metric units, the friction influencing the ruler's slide past the keeper prongs was calculated in Table XV using (15). The μ represents the coefficient of kinetic friction, which is the retarding force (i.e. the force of friction) that the system experiences as the ruler slides past the keeper prongs' pinch.

TABLE XV
Friction Coefficient Calculation

$$F_f = 0.016 \text{ kg}$$

$$\boldsymbol{F_f = 2\mu F_{k_p}} \tag{15}$$

$$\mu = 0.2$$

Material Analysis

Material property tests were conducted to begin determining the material from which the keeper was manufactured. A soldering iron was first held to the keeper to determine that the material melts and drips, classifying it as a thermoplastic. The keeper also managed to sustain a blue and yellow flame while releasing a white smoke. While no soot was released from the burning material, it did release an odor comparable to paraffin. When submerged in water, the keeper floated. Observing the keeper's behavioral responses to the material tests in Table XVI and using the material identification table in Appendix A, it classifies as polyethylene.

TABLE XVI
Material Test Observations

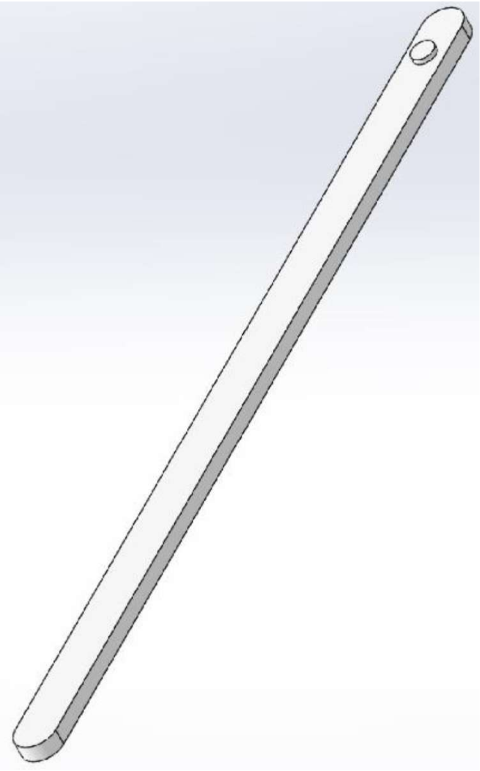
Characterization	Observation
Melt or Burn	Melt (and drips)
Plastic or Elastomer	Plastic
Float or Sink	Floats
Flame or No Flame	Flame
Flame Color	Blue and Yellow
Smoke Color	White
Soot	No
Smell	Paraffin
Final Material	***Polyethylene***

Polyethylene was used to manufacture the keeper because, while it exhibits low strength, hardness, and rigidity, it has high ductility and impact strength. These properties make polyethylene a reliable material for manufacturing a mechanically sound keeper that can withstand frequent use and exposure to impact. However, the keeper's primary function is to allow the ruler to freely slide in and out of the barrel when air pressure is being measured. Polyethylene also features low friction, which allows the ruler to slide freely and yield an accurate pressure reading without unexpected sliding.

Manufacturing

The manufacturing process with which the keeper was likely produced is injection molding. During injection molding, a mold is tightly sealed and heated to keep the mold shut during injection and curing cycles. A system of runners allows the melted polyethylene to enter the mold and fill the cavities to achieve a desired part form. This process is beneficial for manufacturing the keeper because it satisfies the keeper's internal cuts and details, offers a short molding cycle, low unit cost, high dimensional tolerances, flash elimination, and minimal scrap and/or waste.

Ruler



Functional Parts and Requirements

- Interacts with the plunger
- Interference fit with keeper prongs
- Accurately displays the air pressure measurement

Part Description

The ruler is housed inside of the barrel and directly interacts with the plunger's bottom surface and the keeper's prongs to accurately display the measured air pressure, as shown in Fig. 27. It measures pressure in two units: kg and psi, showing one of each unit scale on either side of the ruler. The ruler is able to measure pressures between 5-50 psi, or 0-3.5 kg. Observing the ruler's geometry, its two faces are flat except for one stopper peg on each flat surface (the sides that are 'pinched' by the keeper prongs), and has rounded edges at both ends.

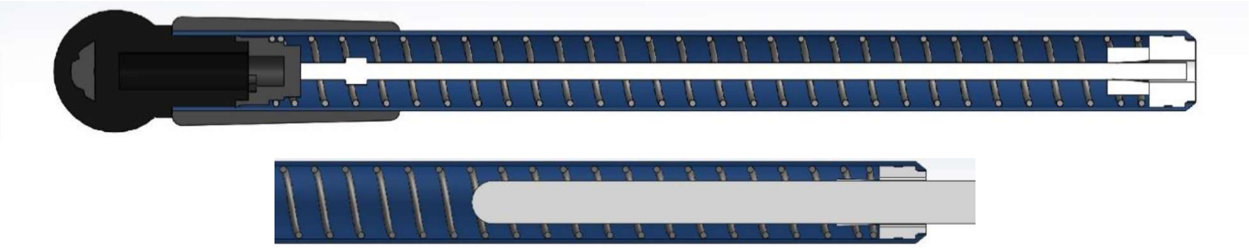


Fig. 27. Cross-sectional view of the gauge showing the ruler's interaction with the plunger and keeper prongs (top), and one of the ruler's rounded edges and flat surfaces (bottom).

As pressurized air enters the gauge barrel, it exerts a force on the plunger that pushes it down the barrel's length. The plunger compresses the spring and pushes the ruler through the keeper at the bottom of the pressure gauge. When the plunger stops sliding down the barrel, the spring decompresses and restores the plunger to its original position, leaving the ruler at the plunger's point of maximum displacement. The keeper prongs' 'pinch' hold the ruler at this point, allowing the gauge user to view the ruler's pressure reading. The keeper prongs also stop the ruler from falling out when they achieve contact with the ruler's stopper pegs at the ruler's maximum displacement.

Following the friction calculations performed in Table XI through Table XV in the *Keeper* section, the friction coefficient between the ruler and the keeper prongs is 0.2. The friction between the ruler and the keeper ensures that the ruler slides freely past the keeper when pushed by the plunger without unexpected slipping, thereby accurately measuring the air pressure in a system.

One reads a system's air pressure from a pressure gauge using the highest visible number along the ruler after the plunger pushes it out. Once a pressure is recorded, the user simply pushes the ruler back into the barrel through the keeper to reset the pressure gauge.

Material Analysis

The material from which the ruler is made was determined following the material analysis test. When a soldering iron was held to the ruler's surface, it melted. The ruler was also able to sustain an orange flame and released black smoke. As it burned, it also let off soot and an odor comparable to burning rubber. The ruler also sunk when submerged in water. Analyzing the material properties collected from the material tests in Table XVII, one can conclude that the ruler is made from polyester.

Table XVII
Material Test Observations

Characterization	Observation
Melt or Burn	Melts
Plastic or Elastomer	Plastic
Float or Sink	Sinks
Flame or No Flame	Flame
Flame Color	Orange
Smoke Color	Black
Soot	Yes
Smell	Burned Rubber
Final Material	***Polyester***

Polyester is an ideal thermoplastic material for the ruler because it is inexpensive and easy to process. This material also exhibits flexibility and a high strength to weight ratio that is practically shatterproof. Polyester also has the benefit of melting, making it ideal for injection molding and recycling. It is also widely available and economically priced, encouraging mass production of polyester parts. These material properties are crucial to the gauge's ruler because it constantly undergoes wear and tear as pressures are measured. The ruler possesses the strength to undergo high-force impacts from the plunger without shattering or deforming, and the potential to be recycled if it malfunctions. Polyester's availability and affordability is also ideal for mass production of mechanical parts.

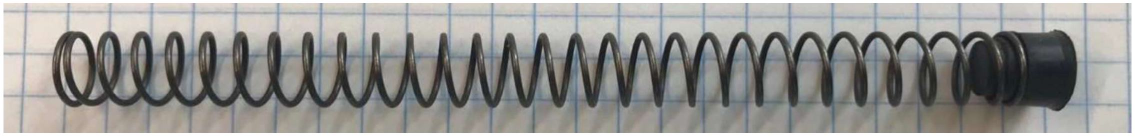
Manufacturing

The process with which the gauge ruler was manufactured is injection molding. Observation of the ruler's surface reveals meticulous details along the surface, including stopper pegs and rounded edges. The polyester from which the ruler is made also suggests that the part was manufactured using an injection molding process, since it melts easily. During this process, polyester pellets are melted and flow through injection needles into a mold. Once the liquified polyester fills all the cavities in the mold, it is left to cure and harden, adopting the ruler's shape from the injection molding dies. The complete injection molding process is elaborated upon in the *Cap* section under manufacturing, Fig. 5.

Assembly Procedure

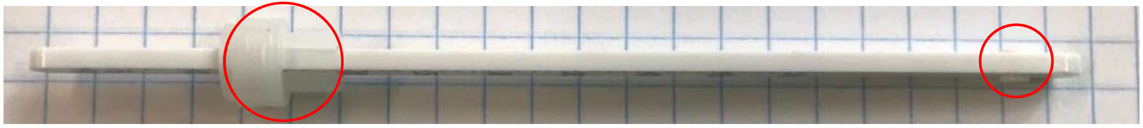
The following steps outline how the pressure gauge is assembled. This assembly process assumes that the assembler's right hand is dominant, and the images are oriented accordingly (in other words, the right parts of each image correspond to right-hand functions, and the left parts of each image correspond to left-hand functions).

1. Press fit the plunger's smallest outer diameter with any end on the spring



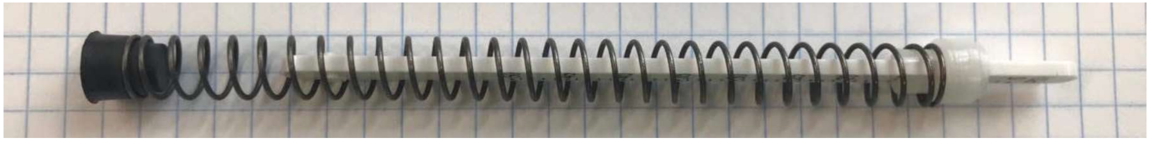
2. Rotate this step 1 assembly 180° and set aside.

3. Place the ruler inside of the keeper to ensure an interference fit between the ruler and the keeper's prongs. Note that the ruler must first be inserted through the prongs with the ruler's flatter side entering the keeper first. This ensures that the small pegs on the ruler prevent the ruler from sliding out of the keeper. Keeper prongs and ruler pegs are circled.



4. Rotate this step 3 assembly 180° and set aside.

5. Grab the subassemblies from steps 1 and 3, supporting the spring assembly with the left hand and pinching the ruler with the right hand. Insert the ruler into the spring's open end with the keeper prongs toward the spring's inside until the spring achieves contact with the keeper.



6. Rotate the step 5 assembly 180°

7. Grab the step 5 assembly, reoriented in step 6, with the left hand and align with the barrel's larger diameter opening for insertion. Slide the step 5 assembly into the barrel (keeper end of the spring slides in first) until the keeper fits concentrically with the barrel's smaller diameter opening.

8. Align the cap's smallest outer diameter with the barrel's larger diameter. Slide the smaller diameter cap end into the barrel's larger diameter end. Align the cap so the clip falls above the printed text when oriented sideways, approximately 90° from the bottom lettering.

9. Secure the cap in the barrel via press-fit using a socket and hammer. To do so, hold the step 8 assembly upright (cap side up) and secure a socket at the top of the cap. Gently tap the socket with the hammer to push the cap into the barrel and establish a secure press-fit.

10. Slide the grip up the barrel's outer surface from the end opposite the cap. The grip's larger outer diameter should enter slide onto the barrel first and slide up to the cap's base. To reach the cap's base, the grip will have to slide under the cap's clip. Note that the rubber grip will deform elastically, thus establishing a press-fit with the barrel and resisting the assembler's push as it slides (friction).

11. Holding the step 10 assembly upright (cap side up) with the cap's pin facing the user, place the washer concentrically with pin. Establish a press-fit between the washer's outer diameter and the cap by pressing the washer into the cap's opening. The washer will deform and secure itself in the cap. The cap and washer mate is circled.

Assembly Time Calculation

Designers can predict how much time assembly requires using the Boothroyd and Dewhurst method. The time calculation table considers part handling times and insertion times, based on parts' geometric and material properties. This method also considers assemblers' physical assembly nuances, like part/assembly rotations and alignments.

Considering the criteria set by the Boothroyd and Dewhurst assembly time table, α represents the angle through which a part must be rotated about an axis perpendicular to the axis of insertion to repeat its orientation. β represents the angle through which a part must be rotated about the axis of insertion to repeat its orientation. Thickness represents a part's smallest side (all part sides considered), and size represents the part's longest side (all part sides considered).

The Boothroyd and Dewhurst assembly time table is in Appendix A, and was used to estimate the time to assemble one pressure gauge in Table XVIII below. Based on the process outlined in *Assembly Procedure*, one should be able to assemble on pressure gauge in approximately 67 seconds, or 1.12 minutes.

TABLE XVIII
Boothroyd and Dewhurst Assembly Time

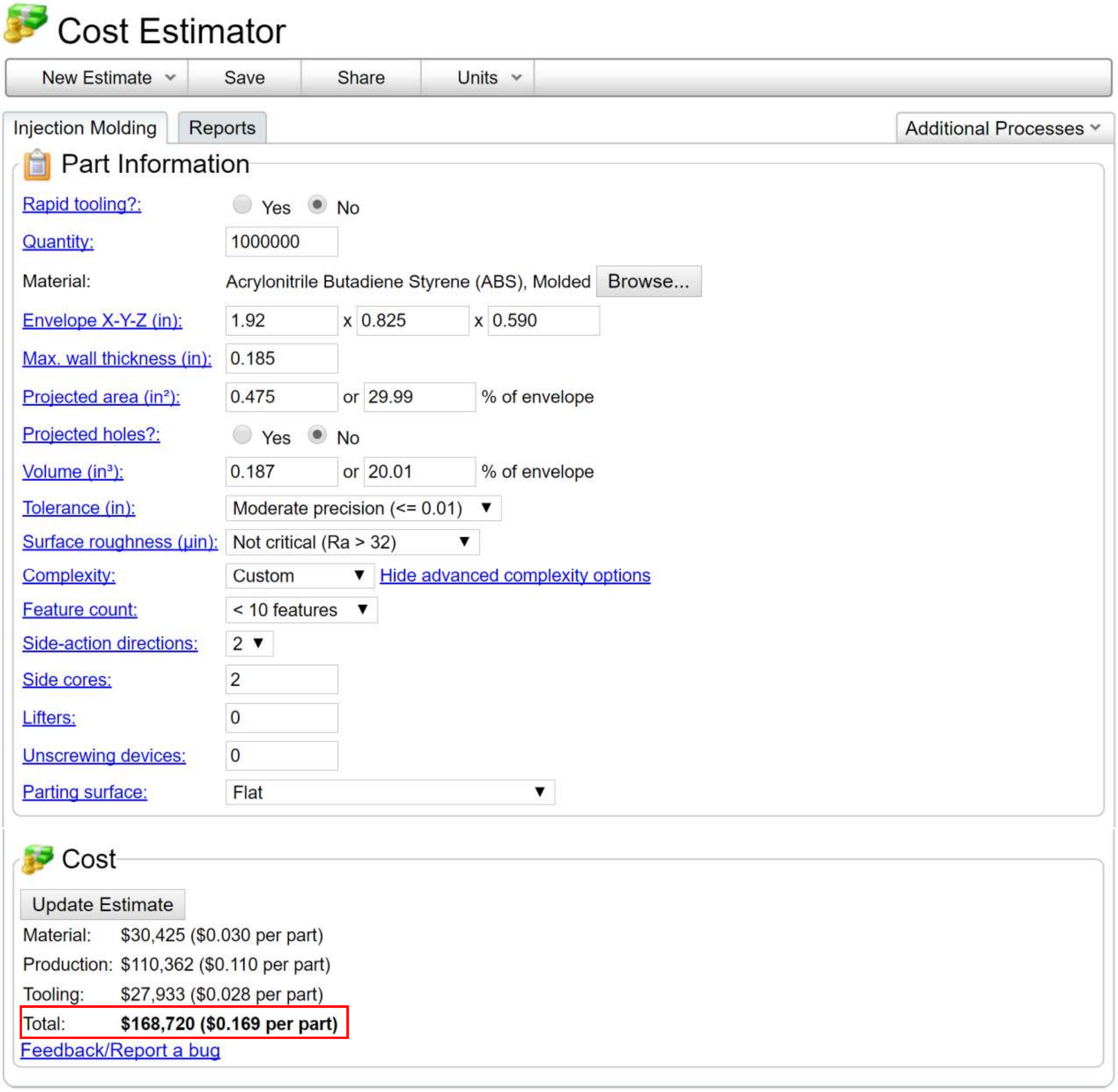
		α	**β**	**α+β**	**Handle Code**		**Handle Time (sec)**	**Insert Code**		**Insert Time (sec)**	**Total Time (sec)**
1	**Plunger**	360	0	**360**	1	1	**1.8**				**1.8**
2	**Spring**	180	0	**180**	0	3	**1.69**	0	0	**1.5**	**3.19**
3	**Rotate**	0	0	**0**	0	0	**0**	9	0	**9**	**9**
4	**Ruler**	360	180	**540**	2	3	**2.36**	0	2	**2.5**	**4.86**
5	**Keeper**	360	180	**540**	2	1	**2.1**	1	2	**5**	**7.1**
6	**Rotate**	0	0	**0**	0	0	**0**	9	0	**9**	**9**
7	**Barrel**	360	0	**360**	1	0	**1.5**	1	0	**4**	**5.5**
8	**Cap**	360	360	**720**	3	0	**1.95**	0	1	**2.5**	**4.45**
9	**Hammer**	360	360	**720**	3	0	**1.95**	9	0	**4**	**5.95**
10	**Grip**	360	0	**360**	1	0	**1.5**	3	1	**5**	**6.5**
11	**Washer**	180	0	**180**	0	1	**1.43**	4	1	**7.5**	**8.93**
										Total Time	**66.28**

Cost Analysis

Cap

The cap cost estimation considers the manufacturing process with which the cap is produced. Part material specifications and geometric properties, including dimensions and tolerances, are considered. All material specifications are determined in each part's respective section, and dimensions are defined in the part drawings located in the appendix.

This manufacturing process assumes that 1,000,000 parts are going to be manufactured. The specified manufacturing process is injection molding and a styrene material is being used. Using the cost estimator tool on *custompartnet.com*, the estimated cost for manufacturing 1 cap is $0.169, as shown in Fig. 28.



Rapid tooling?: ○ Yes ● No
Quantity: 1000000
Material: Acrylonitrile Butadiene Styrene (ABS), Molded
Envelope X-Y-Z (in): 1.92 x 0.825 x 0.590
Max. wall thickness (in): 0.185
Projected area (in²): 0.475 or 29.99 % of envelope
Projected holes?: ○ Yes ● No
Volume (in³): 0.187 or 20.01 % of envelope
Tolerance (in): Moderate precision (<= 0.01)
Surface roughness (µin): Not critical (Ra > 32)
Complexity: Custom
Feature count: < 10 features
Side-action directions: 2
Side cores: 2
Lifters: 0
Unscrewing devices: 0
Parting surface: Flat

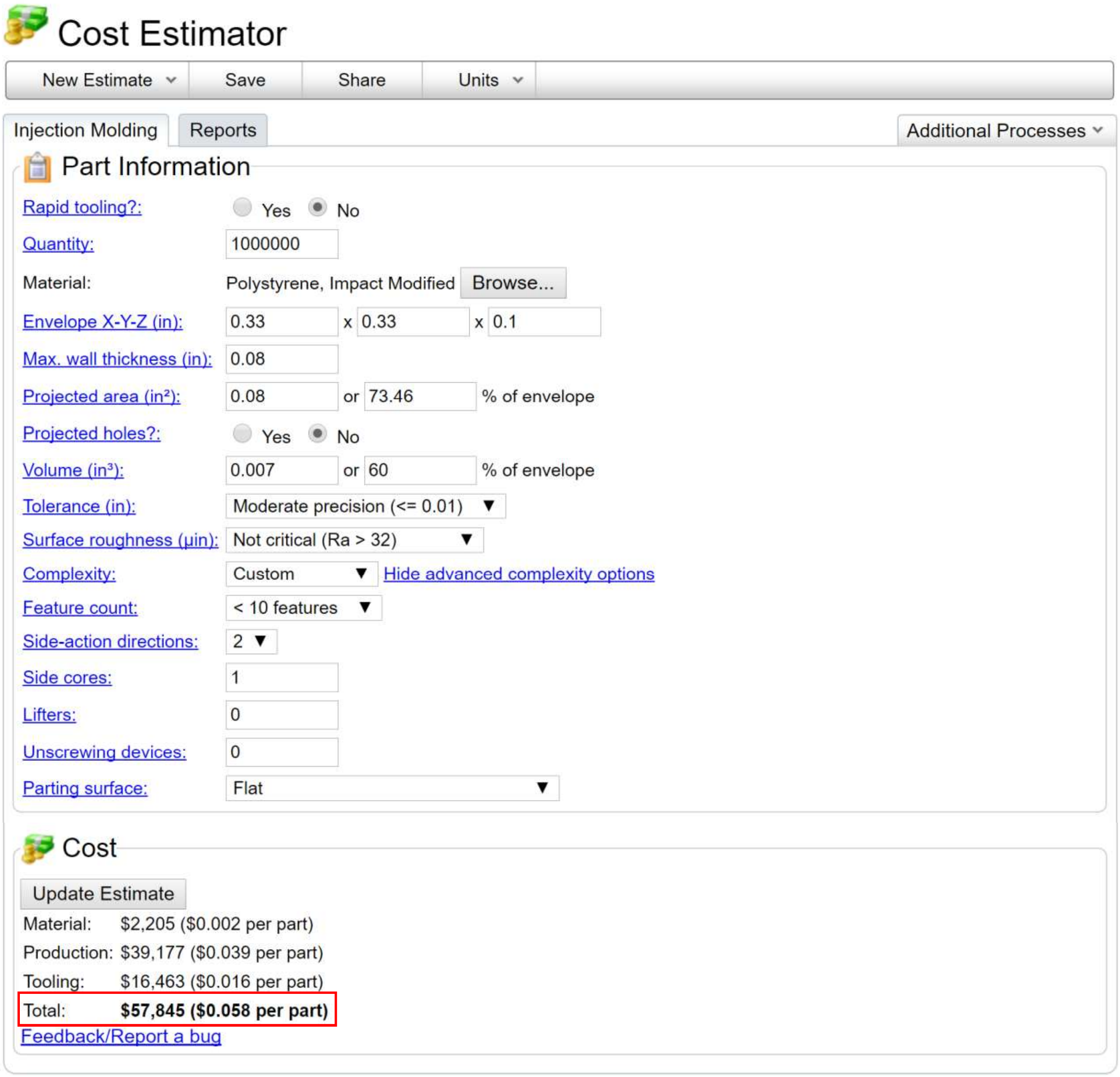
Material: $30,425 ($0.030 per part)
Production: $110,362 ($0.110 per part)
Tooling: $27,933 ($0.028 per part)
Total: **$168,720 ($0.169 per part)**

Fig. 28. Manufacturing cost estimate for the gauge cap, estimated on *custompartnet.com*.

Washer

The washer cost estimation considers the manufacturing process with which the washer is produced. Part material specifications and geometric properties, including dimensions and tolerances, are considered. All material specifications are determined in each part's respective section, and dimensions are defined in the part drawings located in the appendix.

This manufacturing process assumes that 1,000,000 parts are going to be manufactured. The specified manufacturing process is injection molding and a polystyrene material is being used. Using the cost estimator tool on *custompartnet.com*, the estimated cost for manufacturing 1 washer is $0.058, as shown in Fig. 29.



Part Information

Rapid tooling?: ○ Yes ● No
Quantity: 1000000
Material: Polystyrene, Impact Modified
Envelope X-Y-Z (in): 0.33 x 0.33 x 0.1
Max. wall thickness (in): 0.08
Projected area (in²): 0.08 or 73.46 % of envelope
Projected holes?: ○ Yes ● No
Volume (in³): 0.007 or 60 % of envelope
Tolerance (in): Moderate precision (<= 0.01)
Surface roughness (μin): Not critical (Ra > 32)
Complexity: Custom
Feature count: < 10 features
Side-action directions: 2
Side cores: 1
Lifters: 0
Unscrewing devices: 0
Parting surface: Flat

Cost

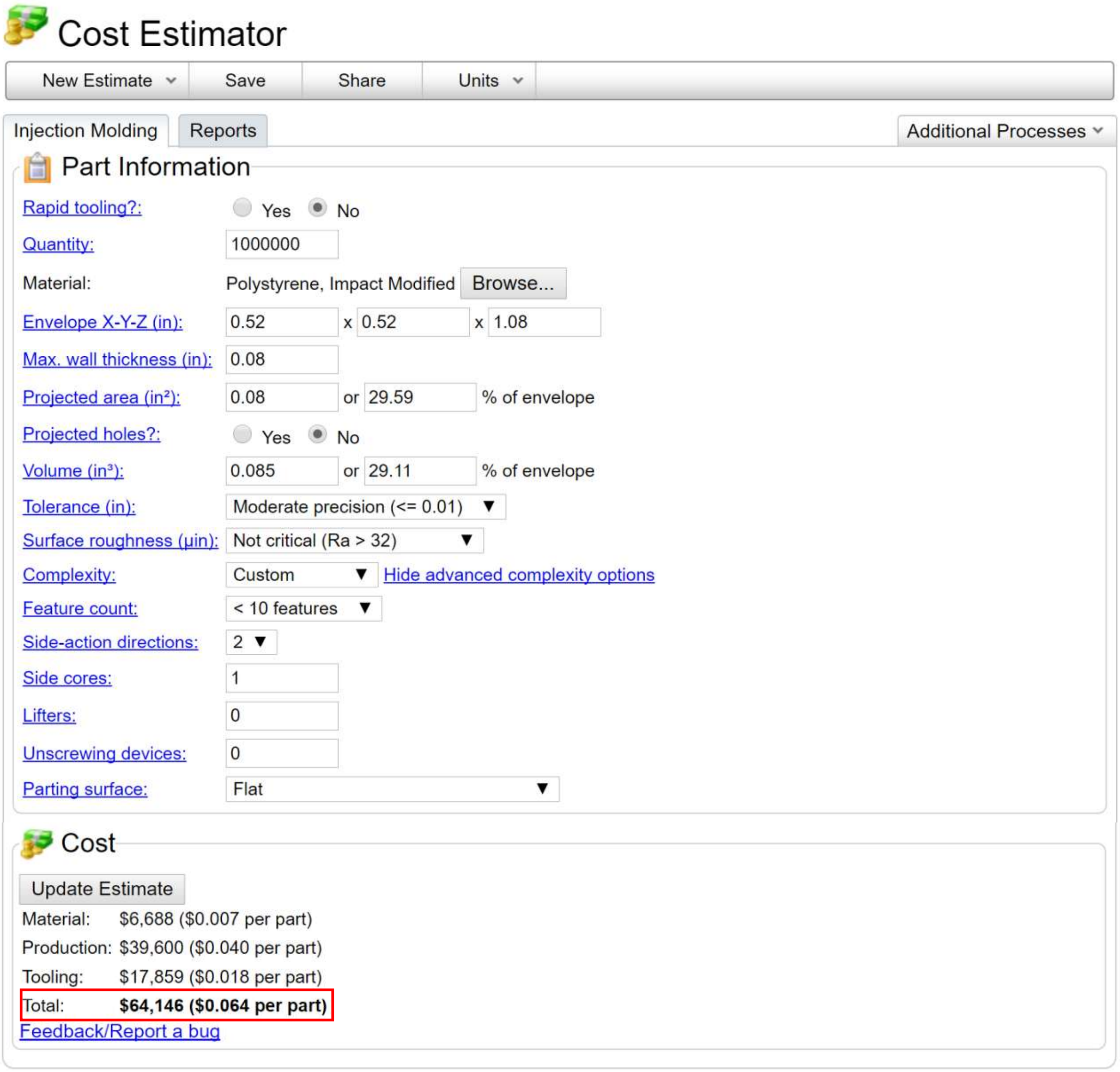
Material: $2,205 ($0.002 per part)
Production: $39,177 ($0.039 per part)
Tooling: $16,463 ($0.016 per part)
Total: **$57,845 ($0.058 per part)**

Fig. 29. Manufacturing cost estimate for the gauge washer, estimated on *custompartnet.com.*

Grip

The grip cost estimation considers the manufacturing process with which the grip is produced. Part material specifications and geometric properties, including dimensions and tolerances, are considered. All material specifications are determined in each part's respective section, and dimensions are defined in the part drawings located in the appendix.

This manufacturing process assumes that 1,000,000 parts are going to be manufactured. The specified manufacturing process is injection molding and a polystyrene material is being used. Using the cost estimator tool on *custompartnet.com*, the estimated cost for manufacturing 1 grip is $0.064, as shown in Fig. 30.



Rapid tooling?: ○ Yes ● No
Quantity: 1000000
Material: Polystyrene, Impact Modified
Envelope X-Y-Z (in): 0.52 x 0.52 x 1.08
Max. wall thickness (in): 0.08
Projected area (in²): 0.08 or 29.59 % of envelope
Projected holes?: ○ Yes ● No
Volume (in³): 0.085 or 29.11 % of envelope
Tolerance (in): Moderate precision (<= 0.01) ▼
Surface roughness (µin): Not critical (Ra > 32) ▼
Complexity: Custom ▼
Feature count: < 10 features ▼
Side-action directions: 2 ▼
Side cores: 1
Lifters: 0
Unscrewing devices: 0
Parting surface: Flat ▼

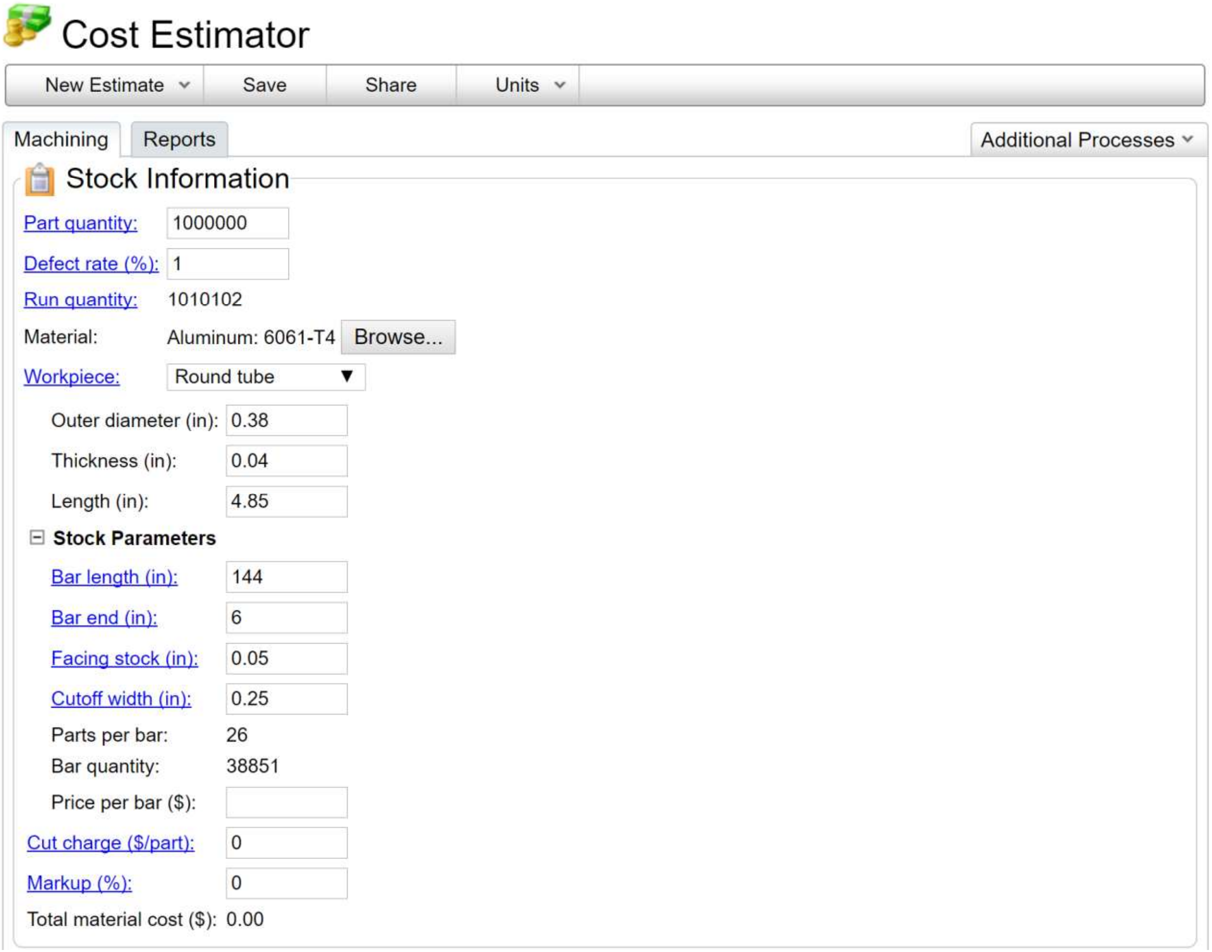
Material: $6,688 ($0.007 per part)
Production: $39,600 ($0.040 per part)
Tooling: $17,859 ($0.018 per part)
Total: **$64,146 ($0.064 per part)**

Fig. 30. Manufacturing cost estimate for the gauge grip, estimated on *custompartnet.com.*

Barrel

The barrel cost estimation considers the manufacturing process with which the barrel is produced. Part material specifications and geometric properties, including dimensions and tolerances, are considered. All material specifications are determined in each part's respective section, and dimensions are defined in the part drawings located in the appendix.

This manufacturing process assumes that 1,000,000 parts are going to be manufactured. The specified manufacturing process is machining and considers a turning process for the taper at the bottom of the barrel. An aluminum material is being used for the barrel. Using the cost estimator tool on *custompartnet.com*, the estimated cost for manufacturing 1 barrel is \$1.06, as shown in Fig. 31.

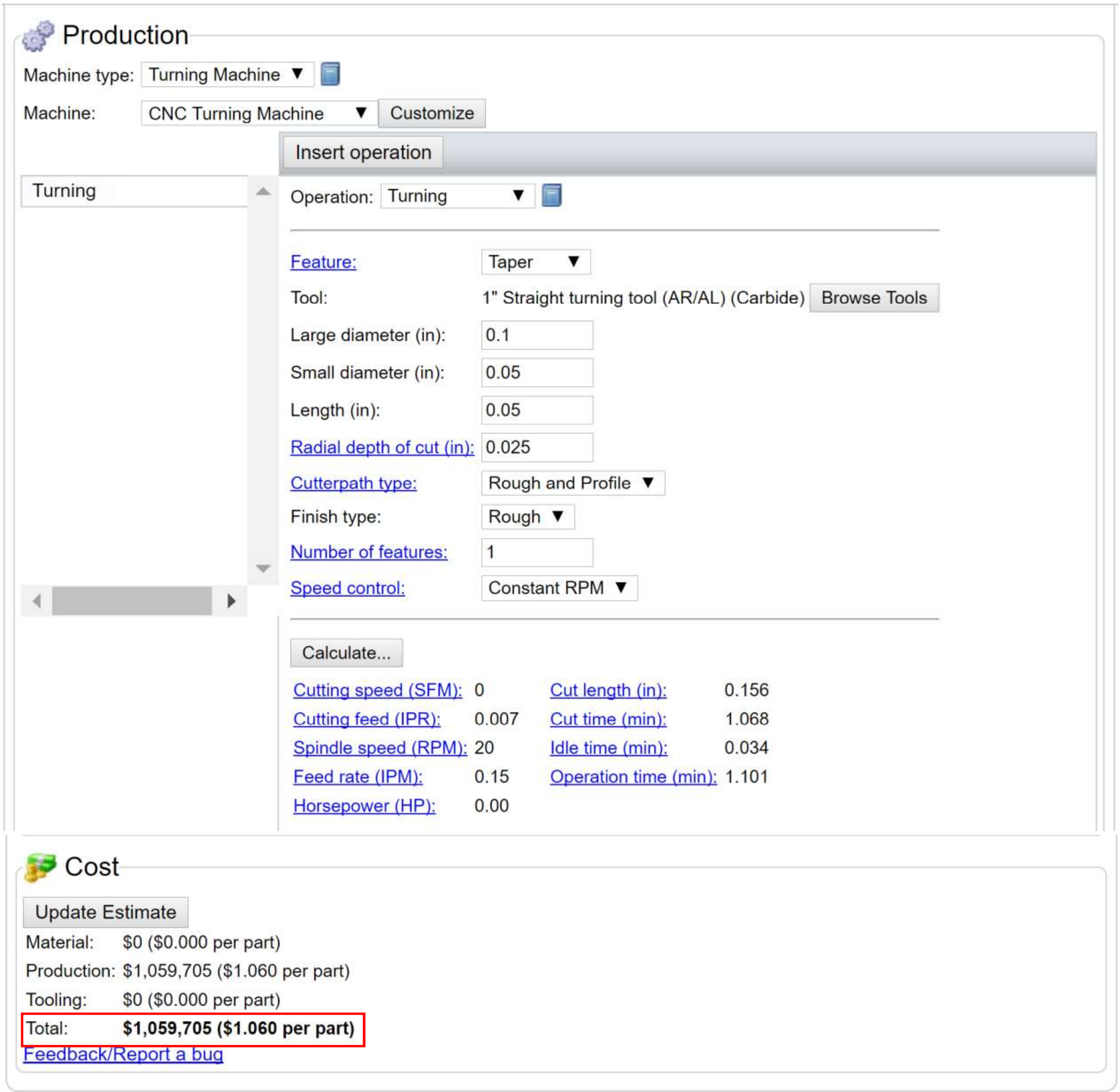


Part quantity: 1000000
Defect rate (%): 1
Run quantity: 1010102
Material: Aluminum: 6061-T4
Workpiece: Round tube
Outer diameter (in): 0.38
Thickness (in): 0.04
Length (in): 4.85

Stock Parameters

Bar length (in): 144
Bar end (in): 6
Facing stock (in): 0.05
Cutoff width (in): 0.25
Parts per bar: 26
Bar quantity: 38851
Price per bar (\$):
Cut charge (\$/part): 0
Markup (%): 0
Total material cost (\$): 0.00

Fig. 31. Manufacturing cost estimate for the gauge barrel, estimated on *custompartnet.com [Cont. on next page]*



Machine type: Turning Machine

Machine: CNC Turning Machine

Turning

Operation: Turning

Feature: Taper

Tool: 1" Straight turning tool (AR/AL) (Carbide)

Large diameter (in): 0.1

Small diameter (in): 0.05

Length (in): 0.05

Radial depth of cut (in): 0.025

Cutterpath type: Rough and Profile

Finish type: Rough

Number of features: 1

Speed control: Constant RPM

Cutting speed (SFM):	0	Cut length (in):	0.156
Cutting feed (IPR):	0.007	Cut time (min):	1.068
Spindle speed (RPM):	20	Idle time (min):	0.034
Feed rate (IPM):	0.15	Operation time (min):	1.101
Horsepower (HP):	0.00		

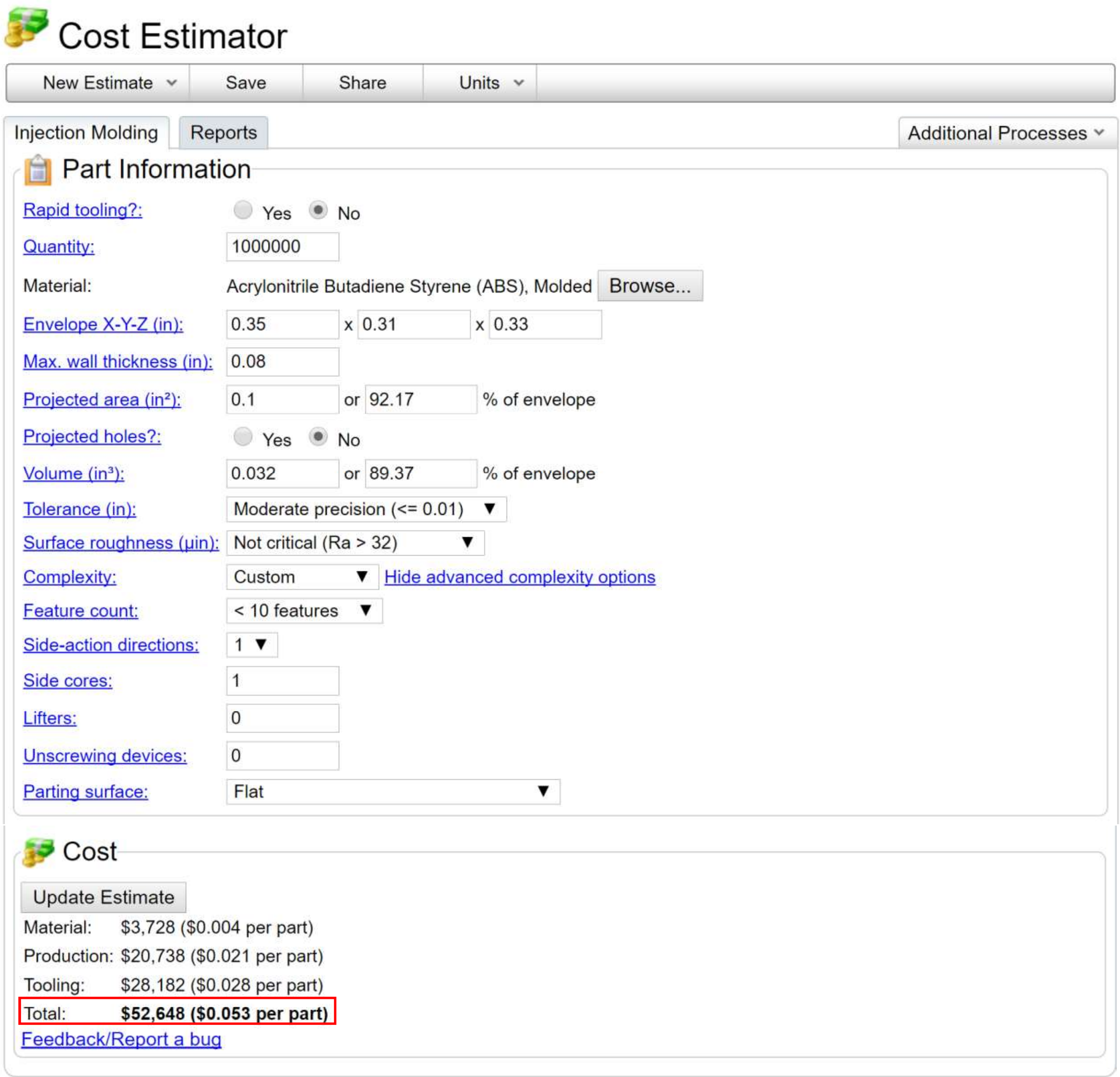
Material:	$0 ($0.000 per part)
Production:	$1,059,705 ($1.060 per part)
Tooling:	$0 ($0.000 per part)
Total:	**$1,059,705 ($1.060 per part)**

Fig. 31. Manufacturing cost estimate for the gauge barrel, estimated on *custompartnet.com.*

Plunger

The plunger cost estimation considers the manufacturing process with which the plunger is produced. Part material specifications and geometric properties, including dimensions and tolerances, are considered. All material specifications are determined in each part's respective section, and dimensions are defined in the part drawings located in the appendix.

This manufacturing process assumes that 1,000,000 parts are going to be manufactured. The specified manufacturing process is injection molding and a styrene material is being used. Using the cost estimator tool on *custompartnet.com*, the estimated cost for manufacturing 1 plunger is $0.053, as shown in Fig. 32.



Rapid tooling?:	○ Yes ● No
Quantity:	1000000
Material:	Acrylonitrile Butadiene Styrene (ABS), Molded
Envelope X-Y-Z (in):	0.35 x 0.31 x 0.33
Max. wall thickness (in):	0.08
Projected area (in²):	0.1 or 92.17 % of envelope
Projected holes?:	○ Yes ● No
Volume (in³):	0.032 or 89.37 % of envelope
Tolerance (in):	Moderate precision (<= 0.01)
Surface roughness (µin):	Not critical (Ra > 32)
Complexity:	Custom
Feature count:	< 10 features
Side-action directions:	1
Side cores:	1
Lifters:	0
Unscrewing devices:	0
Parting surface:	Flat

Material:	$3,728 ($0.004 per part)
Production:	$20,738 ($0.021 per part)
Tooling:	$28,182 ($0.028 per part)
Total:	**$52,648 ($0.053 per part)**

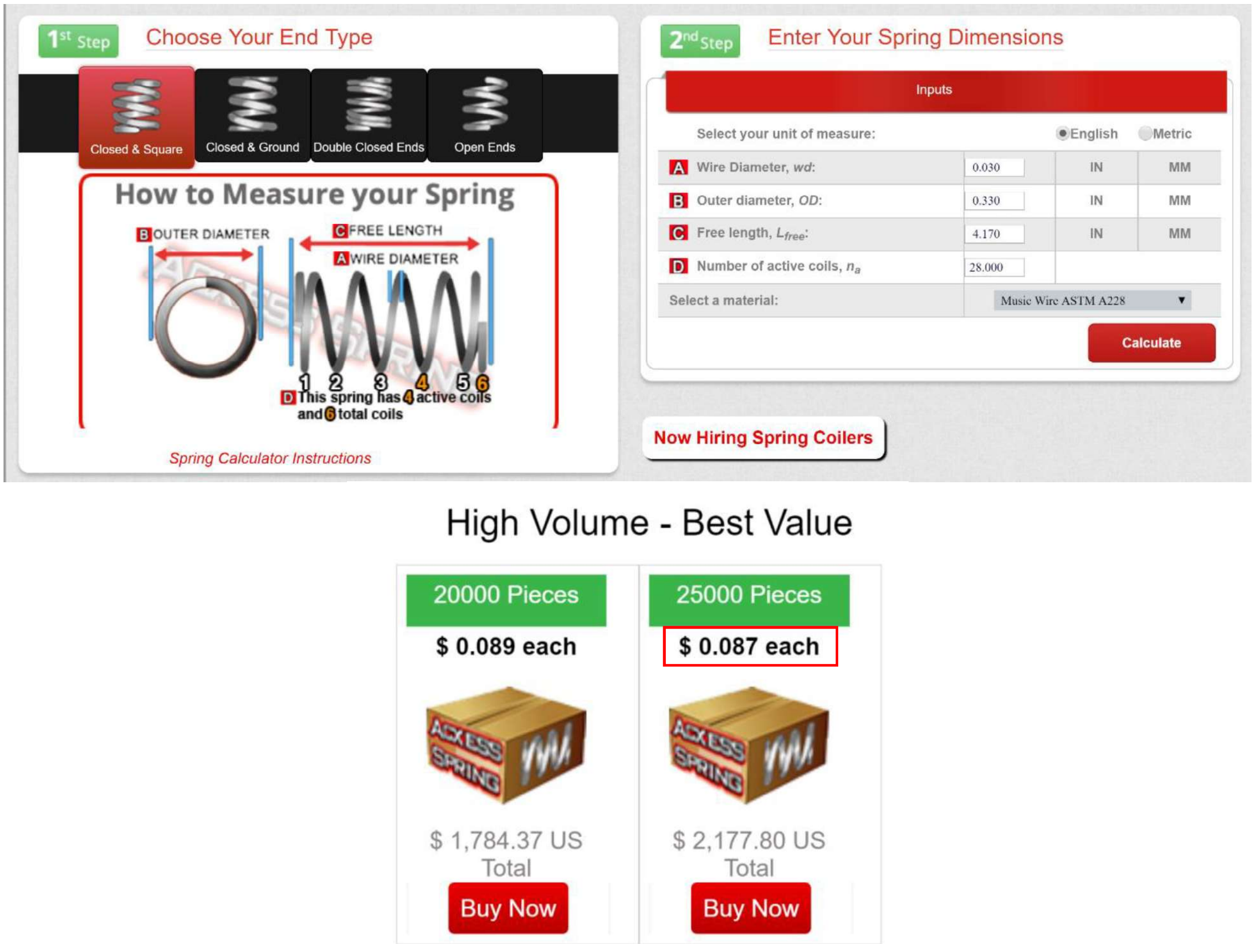
Fig. 32. Manufacturing cost estimate for the gauge plunger, estimated on *custompartnet.com.*

Spring

The spring cost estimation considers the manufacturing process with which the spring is produced. Part material specifications and geometric properties, including dimensions and tolerances, are considered. All material specifications are determined in each part's respective section, and dimensions are defined in the part drawings located in the appendix.

This manufacturing process does not consider how many parts are going to be manufactured. The specified manufacturing process is coiling and a music wire material is being used. Using the cost estimator tool on *acxesspring.com*, the estimated cost for manufacturing 1 spring is \$0.0.087, as shown in Fig. 33.

Since this estimator does not consider how many springs are being manufactured, the calculations for this report assumes that the 'best value' is determined at 25,000 parts. The associated cost per capita, as determined by the spring cost estimator, is used in the gauge's cost analysis.



Select your unit of measure: ● English ○ Metric

A Wire Diameter, wd: 0.030 IN MM

B Outer diameter, OD: 0.330 IN MM

C Free length, L_{free}: 4.170 IN MM

D Number of active coils, n_a 28.000

Select a material: Music Wire ASTM A228 ▼

High Volume - Best Value

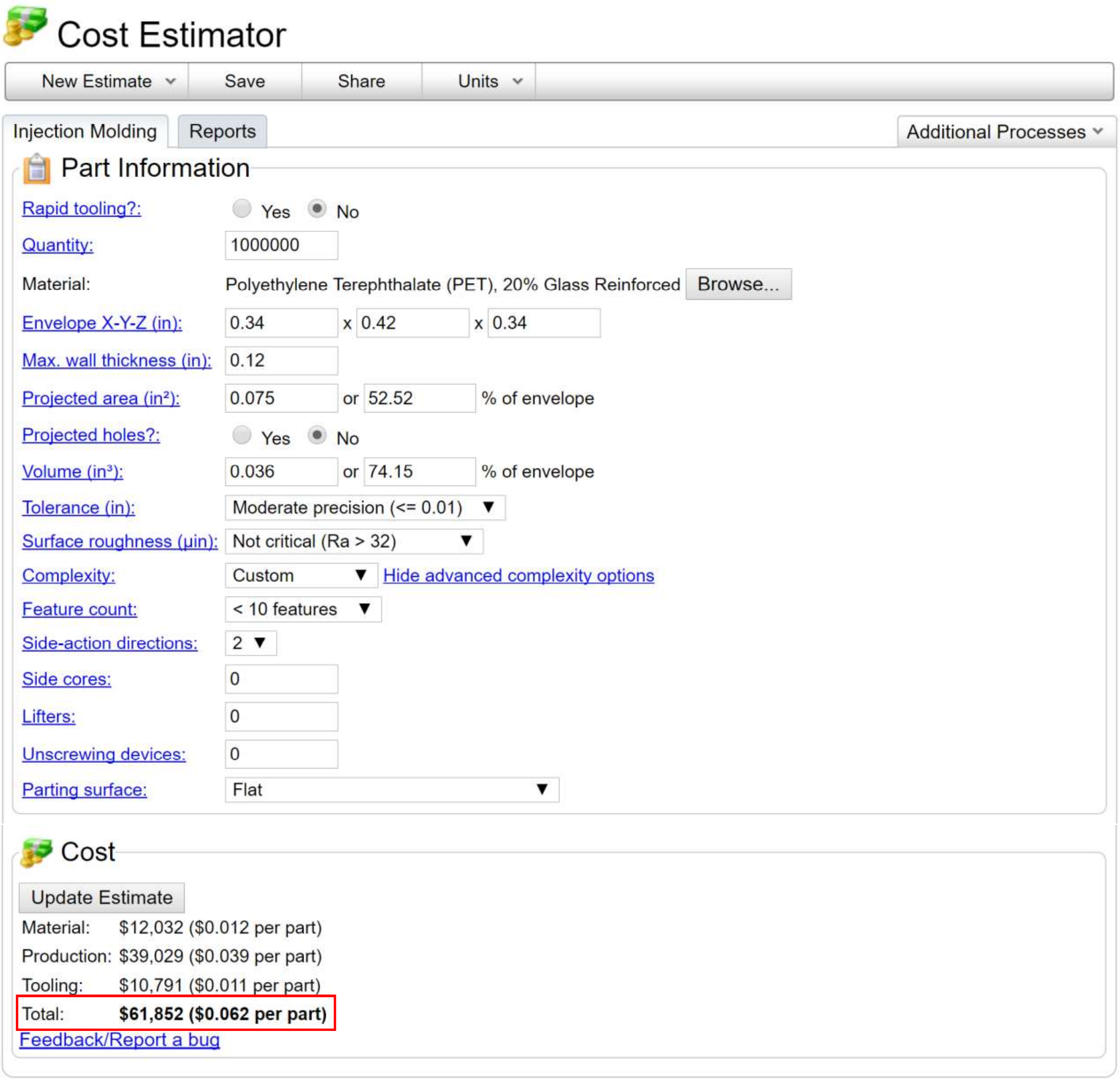
20000 Pieces	25000 Pieces
\$ 0.089 each	\$ 0.087 each
\$ 1,784.37 US Total	\$ 2,177.80 US Total

Fig. 33. Manufacturing cost estimate for the gauge spring, estimated on *acxesspring.com.*

Keeper

The keeper cost estimation considers the manufacturing process with which the keeper is produced. Part material specifications and geometric properties, including dimensions and tolerances, are considered. All material specifications are determined in each part's respective section, and dimensions are defined in the part drawings located in the appendix.

This manufacturing process assumes that 1,000,000 parts are going to be manufactured. The specified manufacturing process is injection molding and a polyethylene material is being used. Using the cost estimator tool on *custompartnet.com*, the estimated cost for manufacturing 1 cap is \$0.062, as shown in Fig. 34.



Rapid tooling?: ○ Yes ● No
Quantity: 1000000
Material: Polyethylene Terephthalate (PET), 20% Glass Reinforced
Envelope X-Y-Z (in): 0.34 x 0.42 x 0.34
Max. wall thickness (in): 0.12
Projected area (in²): 0.075 or 52.52 % of envelope
Projected holes?: ○ Yes ● No
Volume (in³): 0.036 or 74.15 % of envelope
Tolerance (in): Moderate precision (<= 0.01)
Surface roughness (µin): Not critical (Ra > 32)
Complexity: Custom
Feature count: < 10 features
Side-action directions: 2
Side cores: 0
Lifters: 0
Unscrewing devices: 0
Parting surface: Flat

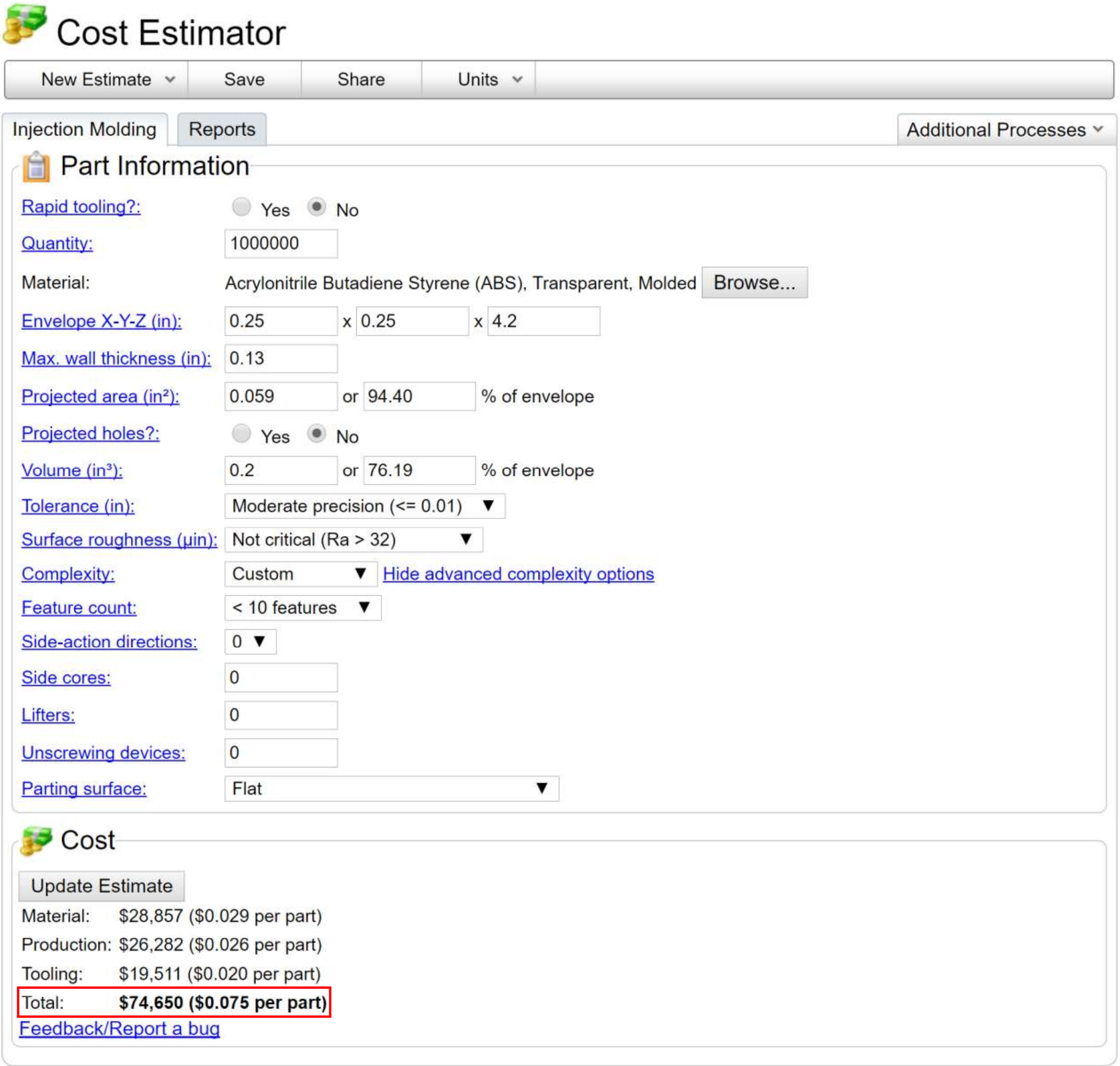
Material: \$12,032 (\$0.012 per part)
Production: \$39,029 (\$0.039 per part)
Tooling: \$10,791 (\$0.011 per part)
Total: **\$61,852 (\$0.062 per part)**

Fig. 34. Manufacturing cost estimate for the gauge keeper, estimated on *custompartnet.com.*

Ruler

The ruler cost estimation considers the manufacturing process with which the ruler is produced. Part material specifications and geometric properties, including dimensions and tolerances, are considered. All material specifications are determined in each part's respective section, and dimensions are defined in the part drawings located in the appendix.

This manufacturing process assumes that 1,000,000 parts are going to be manufactured. The specified manufacturing process is injection molding and a styrene material is being used. Using the cost estimator tool on *custompartnet.com*, the estimated cost for manufacturing 1 ruler is $0.075, as shown in Fig. 35.



Part Information

Rapid tooling?: ○ Yes ● No
Quantity: 1000000
Material: Acrylonitrile Butadiene Styrene (ABS), Transparent, Molded
Envelope X-Y-Z (in): 0.25 x 0.25 x 4.2
Max. wall thickness (in): 0.13
Projected area (in²): 0.059 or 94.40 % of envelope
Projected holes?: ○ Yes ● No
Volume (in³): 0.2 or 76.19 % of envelope
Tolerance (in): Moderate precision (<= 0.01) ▼
Surface roughness (μin): Not critical (Ra > 32) ▼
Complexity: Custom ▼
Feature count: < 10 features ▼
Side-action directions: 0 ▼
Side cores: 0
Lifters: 0
Unscrewing devices: 0
Parting surface: Flat ▼

Cost

Material: $28,857 ($0.029 per part)
Production: $26,282 ($0.026 per part)
Tooling: $19,511 ($0.020 per part)
Total: **$74,650 ($0.075 per part)**

Fig. 35. Manufacturing cost estimate for the gauge ruler, estimated on *custompartnet.com.*

Cost Per Pressure Gauge

Observing the cost to manufacture each cost, one can agree that $1.63 is a reasonable price for a pressure gauge, as shown in Table XIX. The estimates were determined using online sources and satisfy a set of criteria determined through observation, measurement, and experimentation. Each part's functional and physical requirements that were used for manufacturing estimates are elaborated upon in their respective sections throughout this report.

TABLE XIX
Pressure Gauge Material Cost

Part	Cost	Source
Cap	$0.169	*Custompartnet.com*
Washer	$0.058	*Custompartnet.com*
Grip	$0.064	*Custompartnet.com*
Barrel	$1.060	*Custompartnet.com*
Plunger	$0.053	*Custompartnet.com*
Spring	$0.087	*Acxesspring.com*
Keeper	$0.062	*Custompartnet.com*
Ruler	$0.075	*Custompartnet.com*
	Total Cost	**$1.63 / pressure gauge**

The most expensive part to manufacture is the barrel, which uses a more expensive material (aluminum) of the ones used in the pressure gauge, and undergoes two machining processes. The cap is the second-most expensive part to manufacture, which is understandable given its meticulous design containing internal cuts and required dimensional precision.

Except for the spring, the remaining parts are similarly priced, undergoing similar manufacturing processes (injection molding) and using similar materials. The spring is manufactured using coiling operation and uses a metal material (music wire), but is priced comparably with the other pressure gauge parts.

Cost Analysis

An appropriate cost analysis considers all costs associated with producing a product, from purchasing the designing and manufacturing a part to the location where a product is made. To begin understanding how costs are analyzed, *Relevant Terminology* highlights terms and variables for consideration when performing cost calculations. The variables account for desired part quantities, laborers, manufacturing facilities, and work stations.

Relevant Terminology

Monthly Quantity [Q_{mo}]: Number of a product produced within a month.

Landed Cost (Cost of Goods) [LC]: Cost to purchase each part encompassing an assembly.

Direct Labor [DL]: People who touch the product, laborers

Indirect Labor [IDL]: Indirectly support the direct labor (responsible for supplying/shipping/receiving material, support, inspection, maintenance, etc.).

Burdened Labor [BL]: Marketing, sales, web, engineer, human resources, bosses, etc.

Facilities Expense [FE]s: All business other than labor and landing cost (utilities, lease, etc.)

Work Station [WS]: Area where direct labor occurs

Fully Burdened Labor Rate [FBLR]: A company's cost for a company to have an employee, including employment benefits (does not include the employee's salary)

Overhead [OH]: Non-labor expenses required to operate a business, including rent, mortgage, depreciations on assets, liability and insurance, etc.

Variables

L = labor

W = gross (Medicare, FICA, withholding, workman's compensation, unemployment, etc.)

F = fringe

T = taxes

t = time required to complete one assembly

Calculations

The calculations necessary for performing a cost analysis are outlined in (1) through (8), along with appropriate conversion factors.

$$\boldsymbol{L = W + F + T} \tag{16}$$

$$\boldsymbol{Q_{WS}\left(\frac{widgets}{month \times WS}\right) = \frac{1}{t(\frac{min}{widget})}} \tag{17}$$

$$\boldsymbol{(Q_{ws})\frac{widgets/month}{workstation} = \frac{1}{t\,(\frac{min}{widget})} \times \frac{60\ min}{1\ hr} \times \frac{month\ work\ shift\ (hr)}{(\frac{month}{workstation})}} \tag{18}$$

$$\boldsymbol{\#WS = \frac{Q_{mo}}{Q_{ws}}} \tag{19}$$

$$\boldsymbol{Use\ rate\ (UR) = \frac{indirect\ labor\ (IDL) + burdened\ labor\ (BL) + facility\ expenses\ (FE)}{\#WS}} \tag{20}$$

$$\boldsymbol{Total = ((DL + UR) \times t) + LC} \tag{21}$$

$$\boldsymbol{Overhead = \frac{UR}{DL}} \tag{22}$$

$$\boldsymbol{FBLR = (UR + DL)} \tag{23}$$

The variables used to perform the cost analysis calculations are noted in Table XX, and a MATLAB script was written to automatically perform the calculations after a user inputs the required parameters. This program can be found in the appendix.

Table XX
Constants Used For Cost Analysis Calculations

Q_{mo}	1,000,000 pressure gauges
Shift	168 hours/month
t	66.28 seconds = 1.10 minutes
DL	$0.1853 / minute / work station
LC	$1.63
IDL	9324 / month
BL	$33,333 / month
FE	$21,012 / month
L_{Base}	$11.10

The cost analysis results listed in Table XXI were calculated by substituting the parameters listed in Table X into the cost analysis MATLAB script, located in this report's Appendix A.

Table XXI
Cost Analysis Calculation Results

Q_{WS}	9124.9 gauges / month work station
WS	110 work stations
UR	$0.0576 / minute / work station
OH	31.1044%
FBLC	$14.5762 / hour
Total	$1.90 / pressure gauge

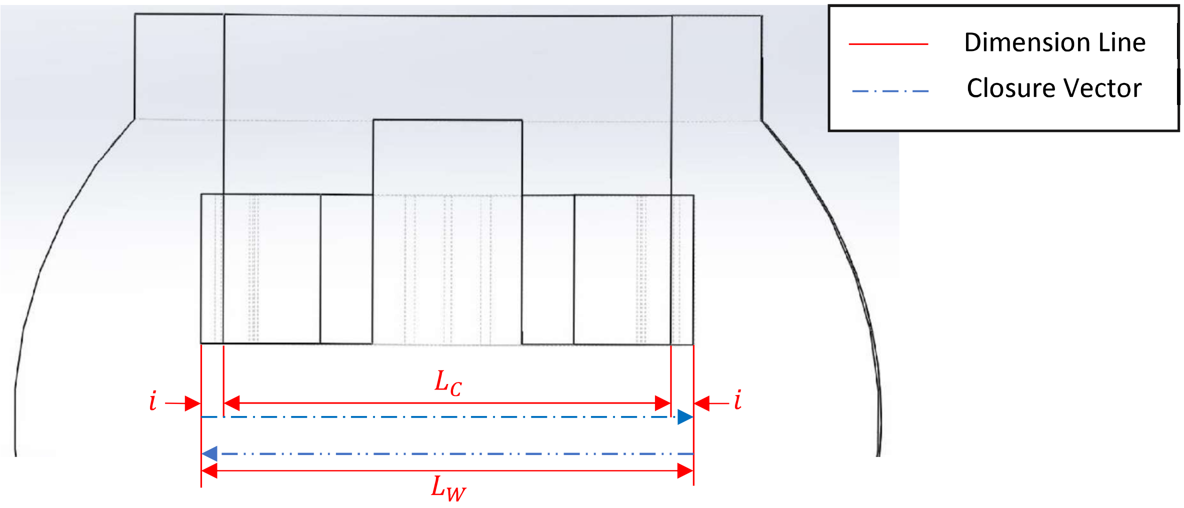
The cost analysis indicates that production will require 110 work stations, each producing 9,124.9 gauges per month. Further analysis of the overhead will account for approximately 31.1% of the company's expenses, and free burden labor cost will contribute approximately $14.57 per hour to the company's expenses. The total calculated cost of producing a pressure gauge is $1.90.

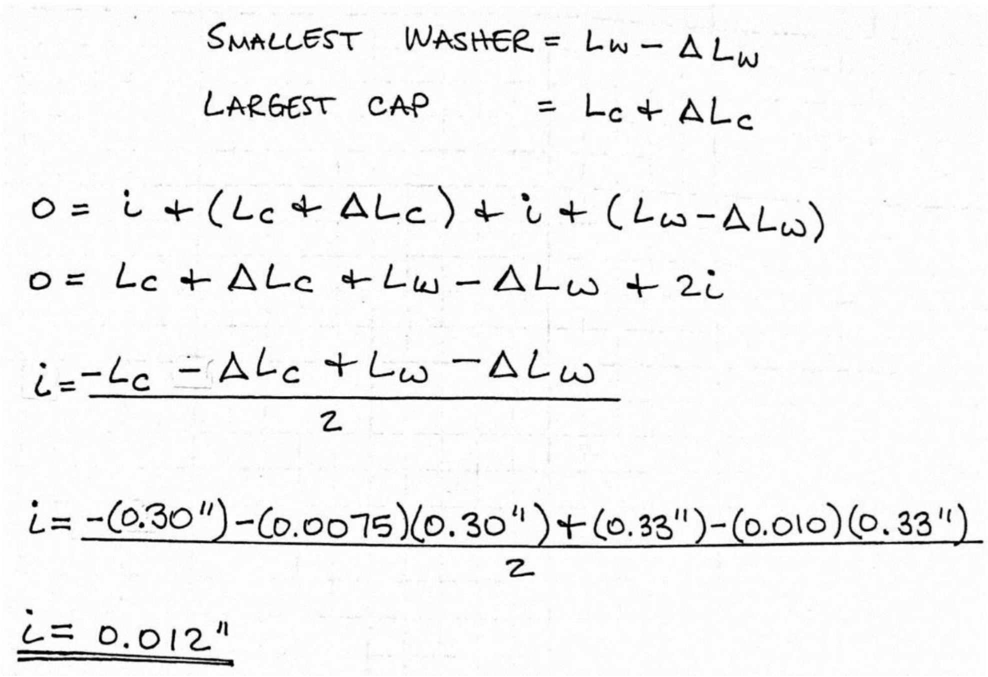
Selling the pressure gauge for approximately $2.00 will yield a $0.10 profit from every pressure gauge that is sold. Since the anticipated sale on the pressure gauge is 1,000,000 pressure gauges per month, the company is projected to earn $100,000 per month.

The MATLAB script used for performing the cost analysis calculations is available in Appendix A for users to continue exploring how different variables influence a product's production cost.

Closure Equations

Washer to Cap





SMALLEST WASHER = $L_W - \Delta L_W$

LARGEST CAP = $L_C + \Delta L_C$

$$0 = i + (L_C + \Delta L_C) + i + (L_W - \Delta L_W)$$

$$0 = L_C + \Delta L_C + L_W - \Delta L_W + 2i$$

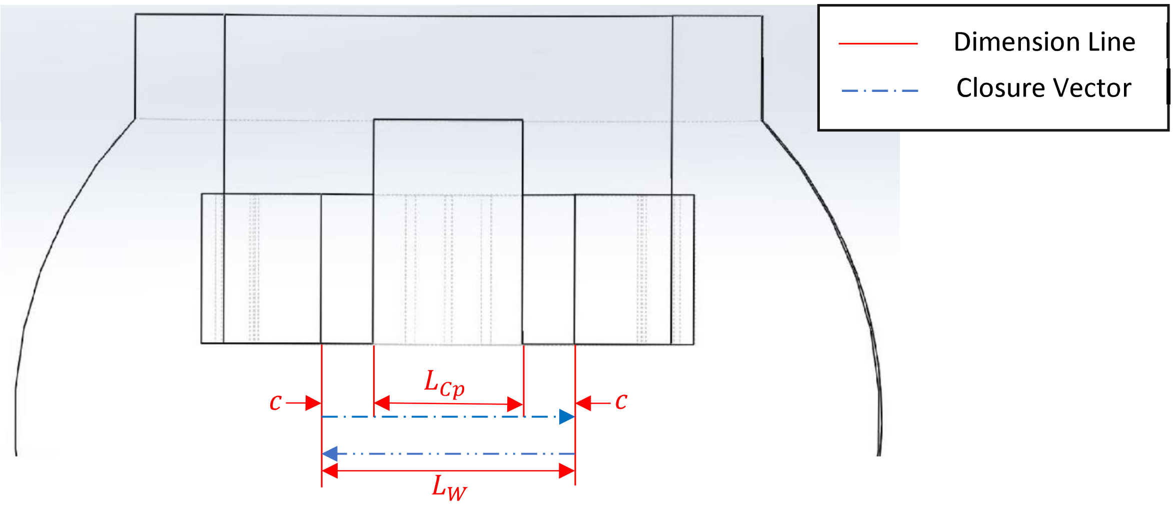
$$i = \frac{-L_C - \Delta L_C + L_W - \Delta L_W}{2}$$

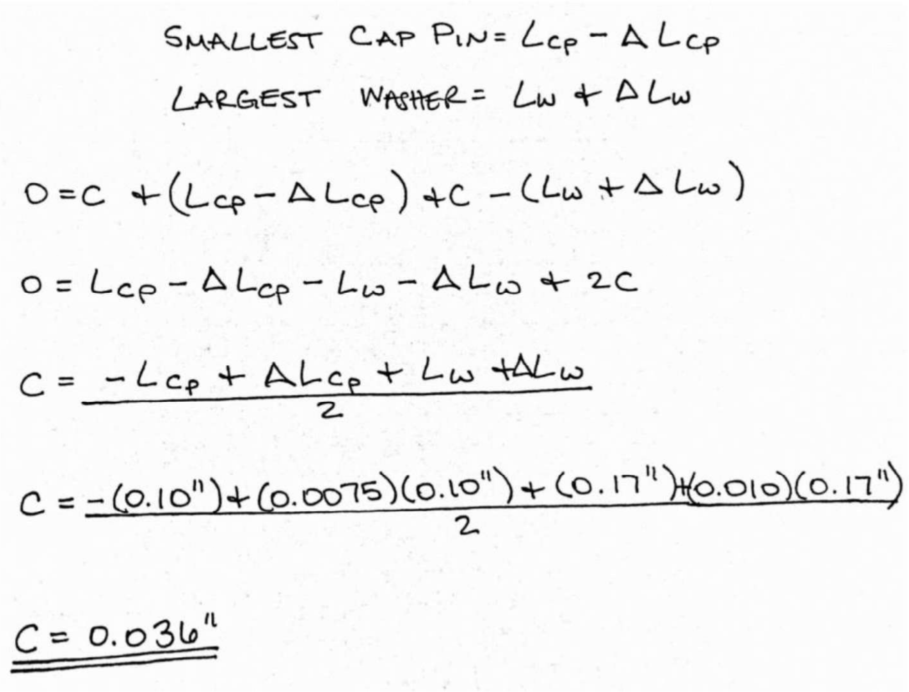
$$i = \frac{-(0.30'') - (0.0075)(0.30'') + (0.33'') - (0.010)(0.33'')}{2}$$

$$\underline{\underline{i = 0.012''}}$$

Closure Analysis: Following the closure calculations performed, the washer's outer diameter, L_W, and cap face's inner diameter, L_C, will mate with a press-fit (interference fit). Denoted by the letter 'i', the two parts have an interference of 0.012", which translates into the parts' tolerance. This interference calculation ensures that there will always be contact between the washer's surface and cap face's inner surface, thereby securing the washer in place.

Washer to Cap Pin





SMALLEST CAP PIN = $L_{cp} - \Delta L_{cp}$

LARGEST WASHER = $L_w + \Delta L_w$

$$0 = c + (L_{cp} - \Delta L_{cp}) + c - (L_w + \Delta L_w)$$

$$0 = L_{cp} - \Delta L_{cp} - L_w - \Delta L_w + 2c$$

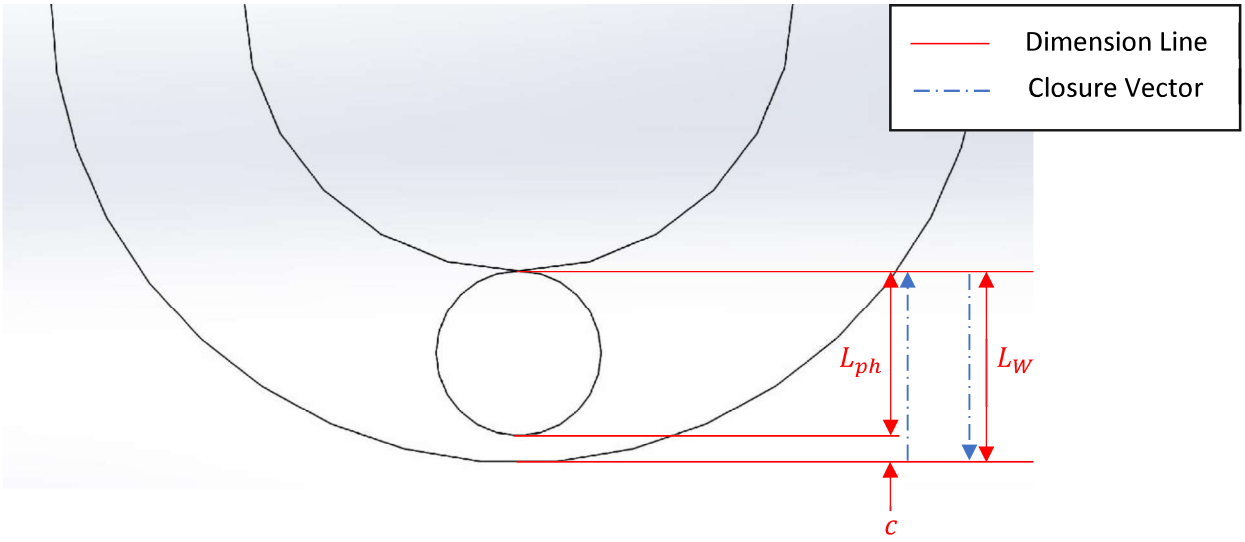
$$c = \frac{-L_{cp} + \Delta L_{cp} + L_w + \Delta L_w}{2}$$

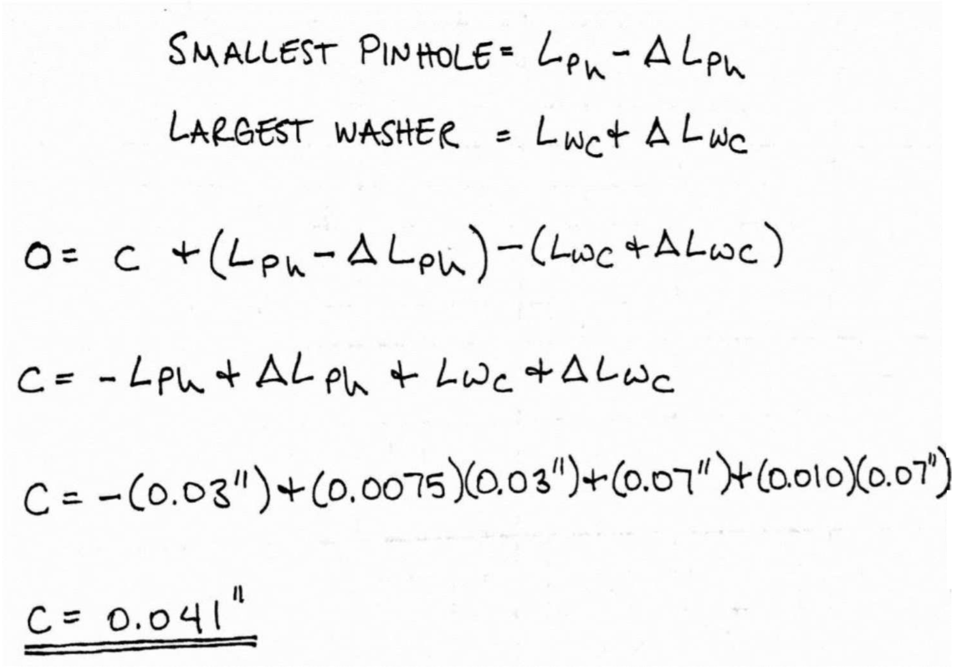
$$c = \frac{-(0.10'') + (0.0075)(0.10'') + (0.17'') + (0.010)(0.17'')}{2}$$

$$\underline{\underline{c = 0.036''}}$$

Closure Analysis: Following the closure calculations performed, the washer's inner diameter, L_W, and cap pin's outer diameter, L_{Cp}, will mate concentrically. Denoted by the letter 'c', the two parts have a clearance of 0.036", which translates into the parts' tolerance. This clearance value ensures that there is always a space between the washer's inner diameter and cap pin's outer diamemeter.

Washer to Pinhole





SMALLEST PINHOLE = $L_{ph} - \Delta L_{ph}$

LARGEST WASHER = $L_{wc} + \Delta L_{wc}$

$$0 = c + (L_{ph} - \Delta L_{ph}) - (L_{wc} + \Delta L_{wc})$$

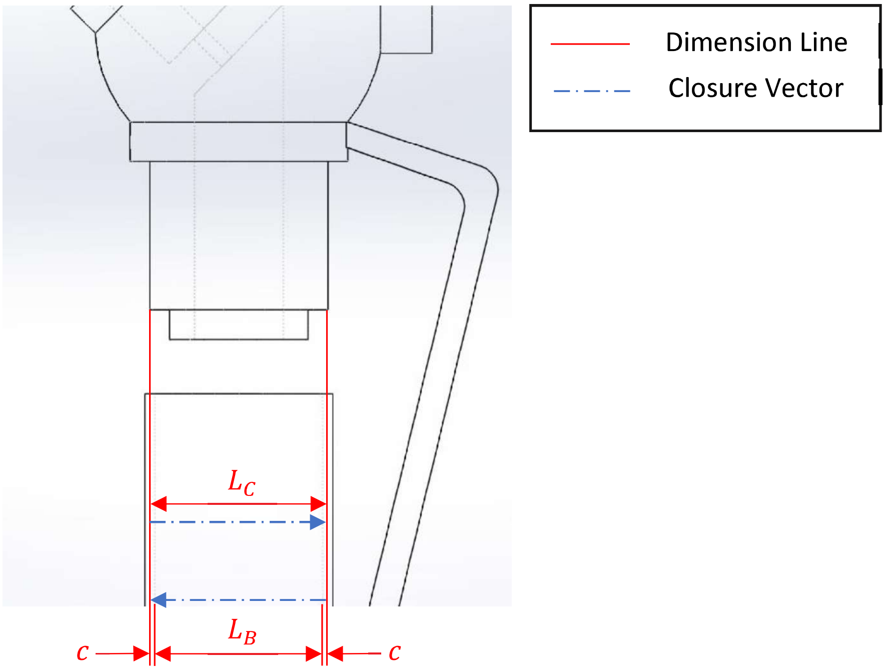
$$c = -L_{ph} + \Delta L_{ph} + L_{wc} + \Delta L_{wc}$$

$$c = -(0.03'') + (0.0075)(0.03'') + (0.07'') + (0.010)(0.07'')$$

$$\underline{\underline{c = 0.041''}}$$

Closure Analysis: Following the closure calculations performed, the washer's inner diameter, L_W, and cap pinhole's outer diameter, L_{ph}, will maintain a clearance. Denoted by the letter 'c', the two parts have a clearance of 0.041", which translates into the parts' tolerance. This clearance ensures that the washer never covers the pinhole, which would cause defective pressure gauge performance.

Cap to Barrel



SMALLEST CAP $= L_C - \Delta L_C$

LARGEST BARREL $= L_B + \Delta L_B$

$$0 = c + (L_C - \Delta L_C) + c - (L_B + \Delta L_B)$$

$$0 = L_C - \Delta L_C - L_B - \Delta L_B + 2c$$

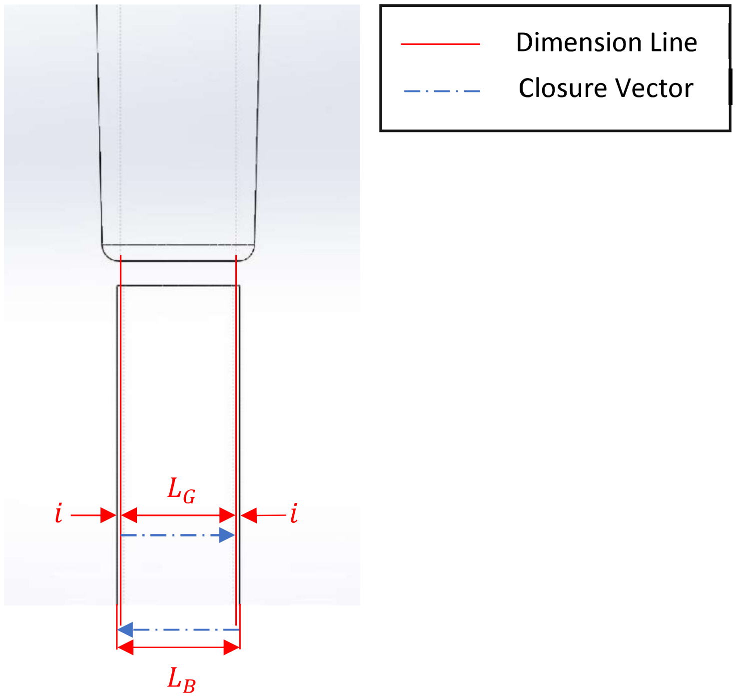
$$c = \frac{-L_C + \Delta L_C + L_B + \Delta L_B}{2}$$

$$c = \frac{-(0.36'') + (0.0075)(0.36'') + (0.34'') + (0.004)(0.34'')}{2}$$

$$\underline{\underline{c = -0.008''}}$$

Closure Analysis: Following the closure calculations performed, the barrel's inner diameter, L_B, and cap's outer diameter, L_C, will mate with an press-fit (interference fit). Denoted by the letter 'c', the two parts have a clearance of -0.008", which translates into the parts' tolerance. It is important to note the negative clearance, which translates into a positive interference value. This press-fit guarantees that the barrel and cap will securely mate and minimize slip.

Grip to Barrel



$$\text{SMALLEST BARREL} = L_B - \Delta L_B$$

$$\text{LARGEST GRIP} = L_G + \Delta L_G$$

$$0 = i + (L_G + \Delta L_G) + i - (L_B - \Delta L_B)$$

$$0 = L_G + \Delta L_G - L_B + \Delta L_B + 2i$$

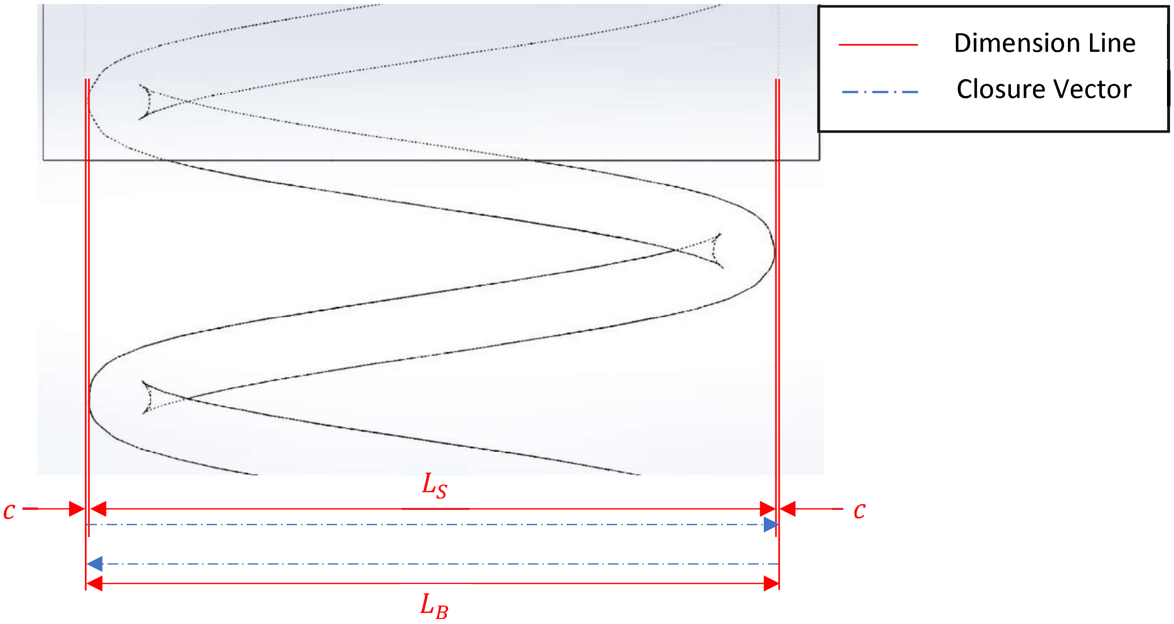
$$i = \frac{-L_G - \Delta L_G + L_B - \Delta L_B}{2}$$

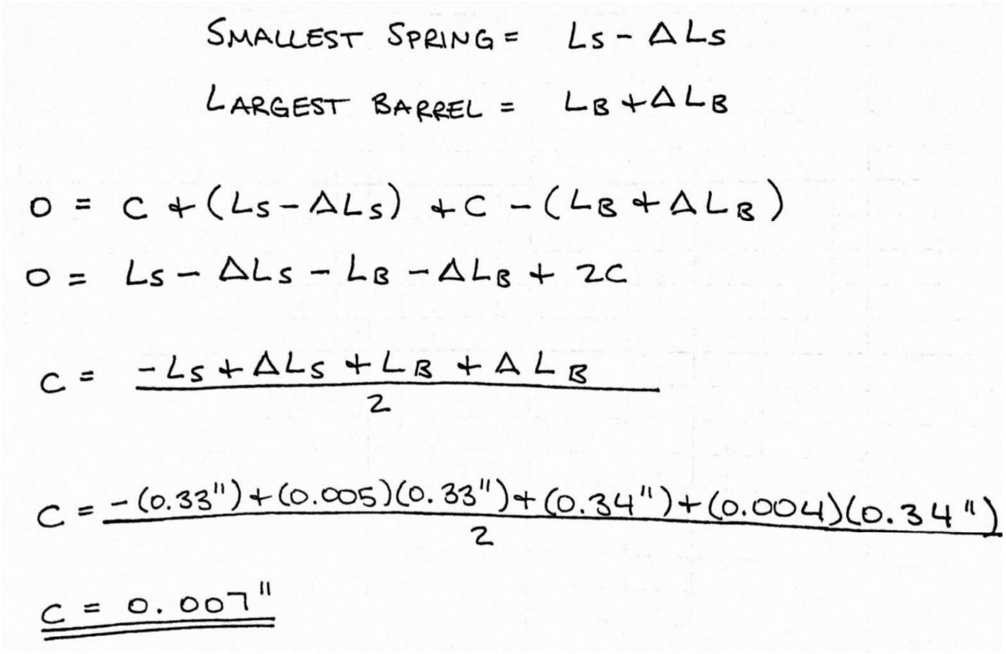
$$i = \underline{-(0.36'') - (0.0075)(0.36'') + (0.38'') - (0.004)(0.38'')}$$

$$\underline{\underline{i = 0.008''}}$$

Closure Analysis: Following the closure calculations performed, the grip's inner diameter, L_G, and barrel's outer diameter, L_B, will mate with an press-fit (interference fit). Denoted by the letter 'i', the two parts have an interference of 0.008", which translates into the parts' tolerance. This interference ensures that the grip is secured along its inner surface with the barrel's outer surface. A design benefit that the grip has for this mate is that it can deform elastically, allowing it to stretch around the barrl's surface, thus implementing compression for security.

Spring to Barrel





SMALLEST SPRING = $L_S - \Delta L_S$

LARGEST BARREL = $L_B + \Delta L_B$

$$0 = c + (L_S - \Delta L_S) + c - (L_B + \Delta L_B)$$

$$0 = L_S - \Delta L_S - L_B - \Delta L_B + 2c$$

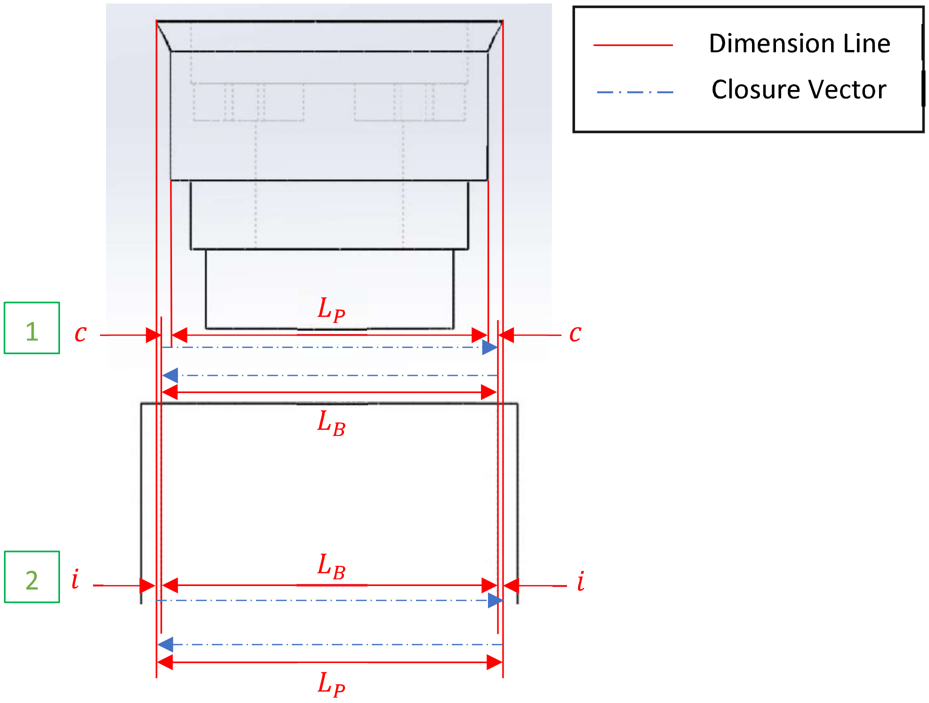
$$c = \frac{-L_S + \Delta L_S + L_B + \Delta L_B}{2}$$

$$c = \frac{-(0.33'') + (0.005)(0.33'') + (0.34'') + (0.004)(0.34'')}{2}$$

$$\underline{\underline{c = 0.007''}}$$

Closure Analysis: Following the closure calculations performed, the barrel's inner diameter, L_B, and spring's outer diameter, L_S, will mate concentrically. Denoted by the letter 'c', the two parts have a clearance of 0.007", which translates into the parts' tolerance. This clearance ensures that the spring can slide into the barrel without resistance or obstructions during assembly, and compress and expand freely when measureing air pressure. This performance is crucial to the gauge's reading because it allows the spring to appropriately compress, thereby enabling the plunger to accurately push the ruler through the keeper.

Plunger to Barrel



SMALLEST PLUNGER = $L_P - \Delta L_P$

LARGEST BARREL = $L_B + \Delta L_B$

$$0 = C + (L_P - \Delta L_P) + C - (L_B + \Delta L_B)$$

$$0 = L_P - \Delta L_P - L_B - \Delta L_B + 2C$$

$$C = \frac{-L_P + \Delta L_P + L_B + \Delta L_B}{2}$$

$$C = \frac{-(0.32'') + (0.0075)(0.32'') + (0.34'') + (0.004)(0.34'')}{2}$$

$$\underline{\underline{C = 0.012''}}$$

SMALLEST PLUNGER $= L_P - \Delta L_P$

LARGEST BARREL $= L_B + \Delta L_B$

$$0 = i + (L_B + \Delta L_B) + i - (L_P - \Delta L_P)$$

$$0 = L_B + \Delta L_B - L_P + \Delta L_P + 2i$$

$$i = \frac{-L_B - \Delta L_B + L_P - \Delta L_P}{2}$$

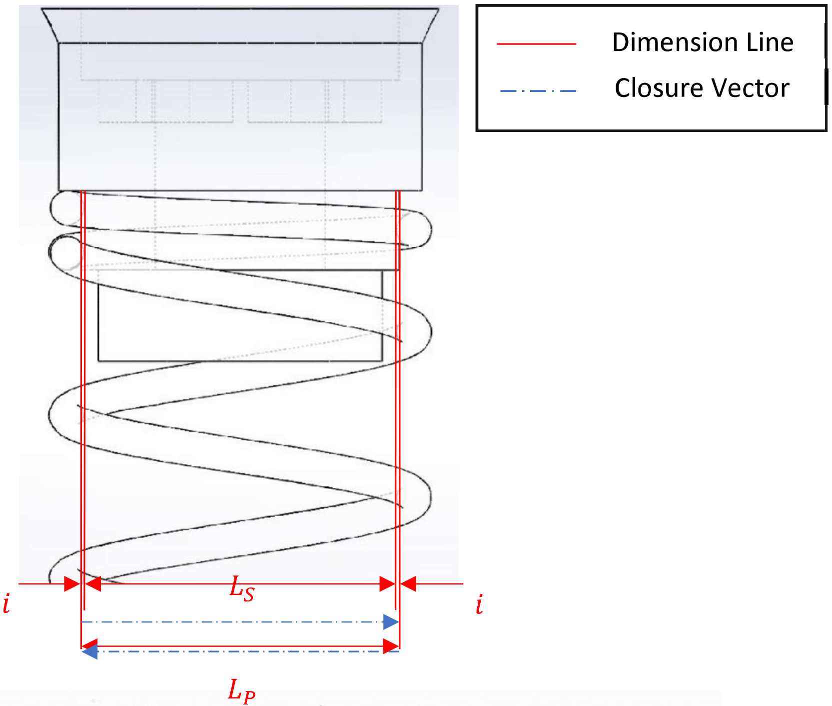
$$i = \frac{-(0.34'') - (0.004)(0.34'') + (0.35'') - (0.0075)(0.35'')}{2}$$

$$\underline{\underline{i = 0.003''}}$$

Closure Analysis: Following the closure calculations performed for labeled section 1, the barrel's inner diameter, L_B, and plunger's outer diameter, L_P, will mate concentrically. This interaction is denoted by the letter 'c', where the two parts have a clearance of 0.012". This clearance ensures that there is always a space between the the plunger's outer surface and the barrel's inner surface, thereybe ensuring the plunger's freedom to slide along the barrel's length without obstructions.

The plunger-barrel interaction uses the same variables in section 2, but the mate is different. Denoted by the letter 'i', the two parts have an interference of 0.003" which translates into the parts' tolerance. This interference is crucial to the gauge's performance because it seals the space between the barrel's inner surface and the plunger lip's out diameter. This closure is crucial to the guage's performance because it ensures that no pressurized air entering the pressure gaige slips past the plunger. The pressurized air's full interaction with the plunger is crucial to the gauge's accurace because it compresses the spring and pushes the ruler through the keeper, thereby yielding a pressure reading. However, while an interference seals the space between the barrel and the plunger, the measurement is small to minimize any discrepancies with the plunger's ability to slide along the barrel's inner walls.

Plunger to Spring



SMALLEST PLUNGER $= L_P - \Delta L_P$

LARGEST SPRING $= L_S + \Delta L_S$

$$0 = i + (L_S + \Delta L_S) + i - (L_P - \Delta L_P)$$

$$0 = L_S + \Delta L_S - L_P + \Delta L_P + 2i$$

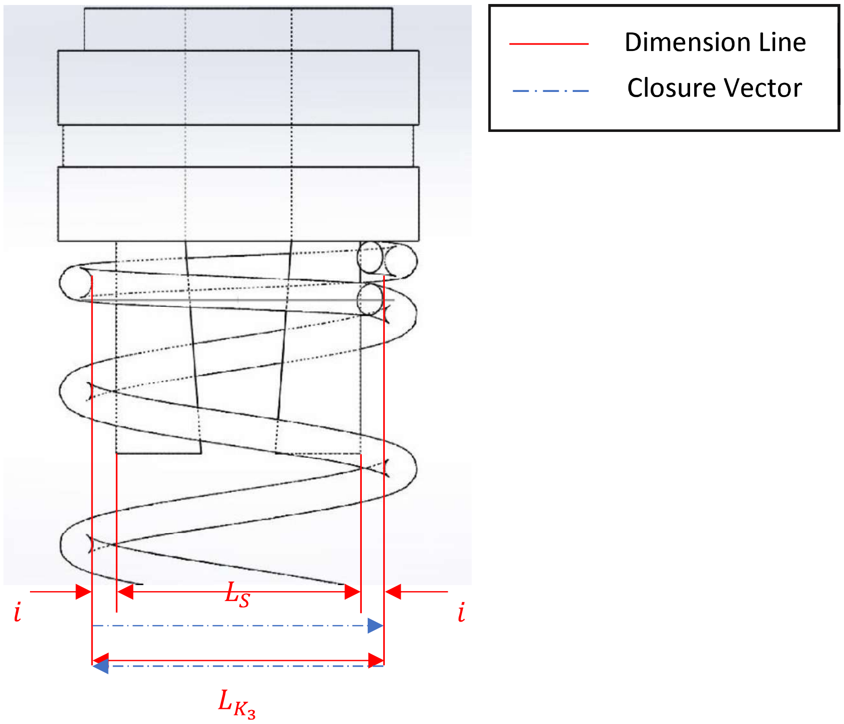
$$i = \frac{-L_S - \Delta L_S + L_P - \Delta L_P}{2}$$

$$i = \frac{-(0.260'') - (0.005)(0.260'') + (0.28'') - (0.0075)(0.28'')}{2}$$

$$\underline{\underline{i = 0.008''}}$$

Closure Analysis: Following the closure calculations performed, the spring's inner diameter, L_S, and plunger's outer diameter, L_P, will have a press-fit. Denoted by the letter 'i', the two parts have an interference of 0.008", which translates into the parts' tolerance. This interference ensures that the spring and the plunger remain intact as air pressure is measured. For the gauge to operate properly, the plunger must push down on the spring and the spring restores the plunger to its original position after reaching a maximum displacement. An interference between the parts ensures that none of the parts separate from the other during the gauge operation.

Keeper to Spring



SMALLEST KEEPER = $L_K - \Delta L_K$

LARGEST SPRING = $L_S + \Delta L_S$

$$0 = i + (L_S + \Delta L_S) + i - (L_K - \Delta L_K)$$

$$0 = L_S + \Delta L_S - L_K + \Delta L_K + 2i$$

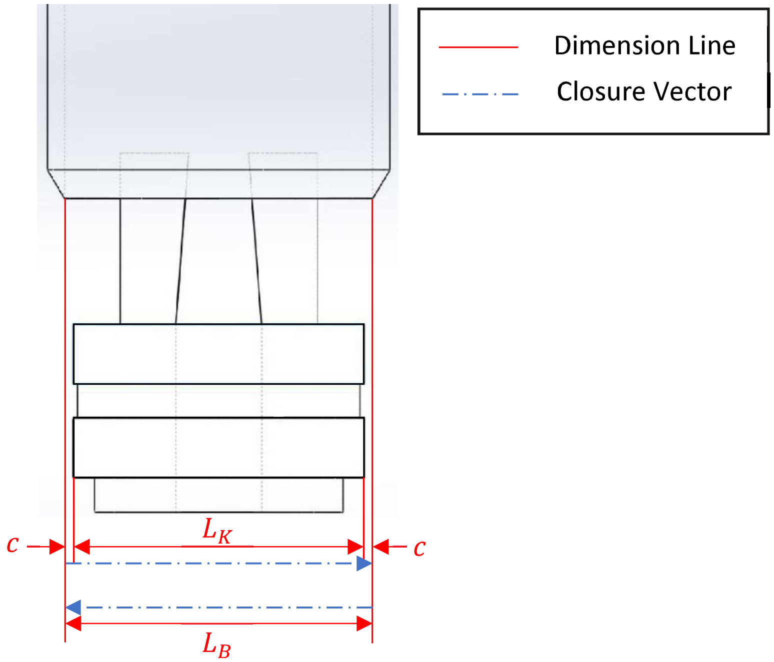
$$i = \frac{-L_S - \Delta L_S + L_K - \Delta L_K}{2}$$

$$i = \frac{-(0.260'') - (0.005)(0.260'') + (0.23'') - (0.0075)(0.23'')}{2}$$

$$\underline{\underline{i = -0.017''}}$$

Closure Analysis: Following the closure calculations performed, the spring's inner diameter, L_S, and keeper prongs' outer diameter, L_K, will mate concentrically. Denoted by the letter 'i', the two parts have an interference of -0.017", which translates into the parts' tolerance. Since the interference measurement is negative, it suggests that there is a positive clearance of 0.017". This clearance allows the spring to secure the spring in the barrel while providing the prongs freedom to deflect as the ruler slides through during air pressure measurement.

Keeper to Barrel



$$\text{SMALLEST KEEPER} = L_K - \Delta L_K$$

$$\text{LARGEST BARREL} = L_B + \Delta L_B$$

$$0 = c + (L_K - \Delta L_K) + c - (L_B + \Delta L_B)$$

$$0 = L_K - \Delta L_K - L_B - \Delta L_B + 2c$$

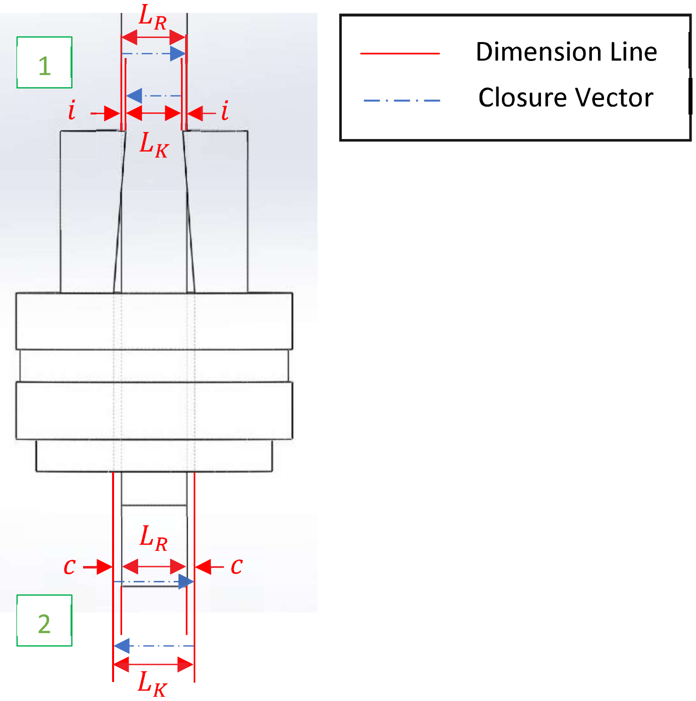
$$c = \frac{-L_K + \Delta L_K + L_B + \Delta L_B}{2}$$

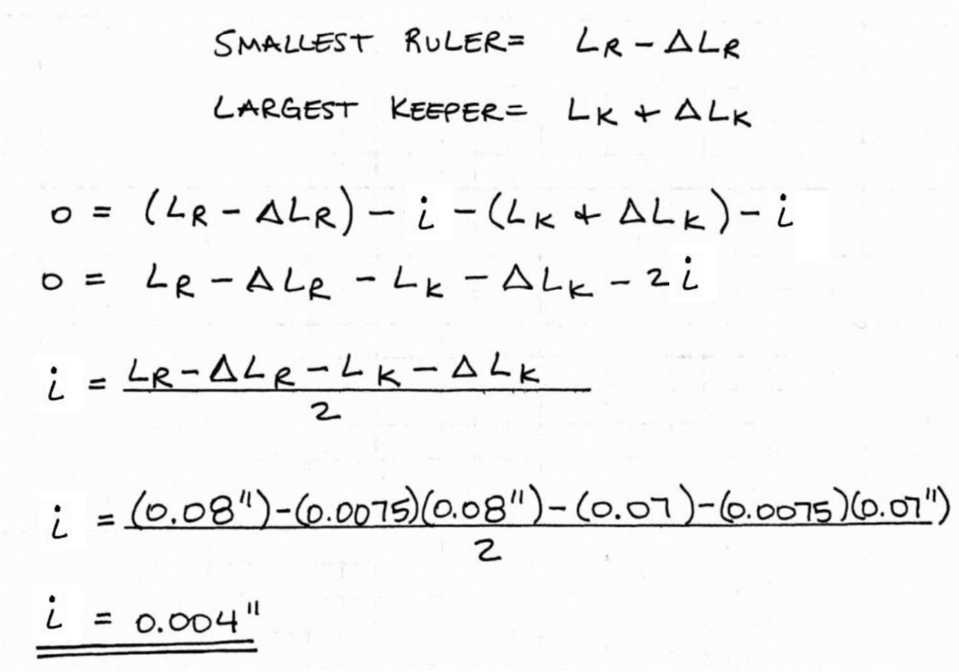
$$c = \frac{-(0.34'') + (0.0075)(0.34'') + (0.34'') + (0.004)(0.34'')}{2}$$

$$\underline{\underline{c = 0.002''}}$$

Closure Analysis: Following the closure calculations performed, the barrel's inner diameter, L_B, and keeper's outer diameter, L_K, will mate concentrically. Denoted by the letter 'c', the two parts have a clearance of 0.002", which translates into the parts' tolerance. This clearance ensures that the keeper's outer diameter fits within the barrel's inner diameter, thus allowing it to enter the barrel and slide through with no resistance or obstructions.

Ruler to Keeper





SMALLEST RULER = $L_R - \Delta L_R$

LARGEST KEEPER = $L_K + \Delta L_K$

$$0 = (L_R - \Delta L_R) - i - (L_K + \Delta L_K) - i$$

$$0 = L_R - \Delta L_R - L_K - \Delta L_K - 2i$$

$$i = \frac{L_R - \Delta L_R - L_K - \Delta L_K}{2}$$

$$i = \frac{(0.08'') - (0.0075)(0.08'') - (0.07) - (0.0075)(0.07'')}{2}$$

$$\underline{\underline{i = 0.004''}}$$

SMALLEST RULER = $L_R - \Delta L_R$

LARGEST KEEPER = $L_K + \Delta L_K$

$$0 = C + (L_R - \Delta L_R) + C - (L_K + \Delta L_K)$$

$$0 = L_R - \Delta L_R - L_K - \Delta L_K + 2C$$

$$C = \frac{-L_R + \Delta L_R + L_K + \Delta L_K}{2}$$

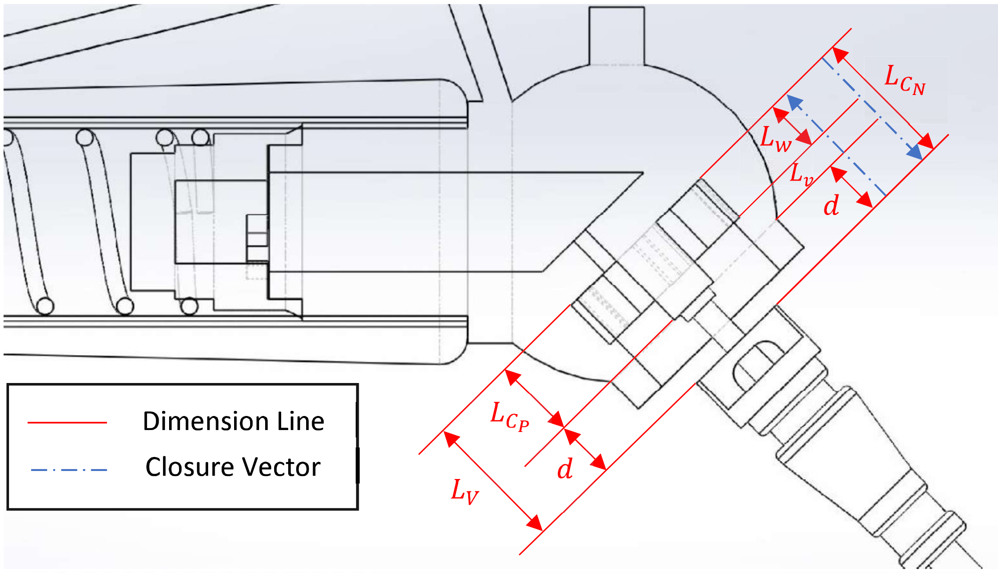
$$C = \frac{-(0.08'') + (0.0075)(0.08'') + (0.10'') + (0.0075)(0.10'')}{2}$$

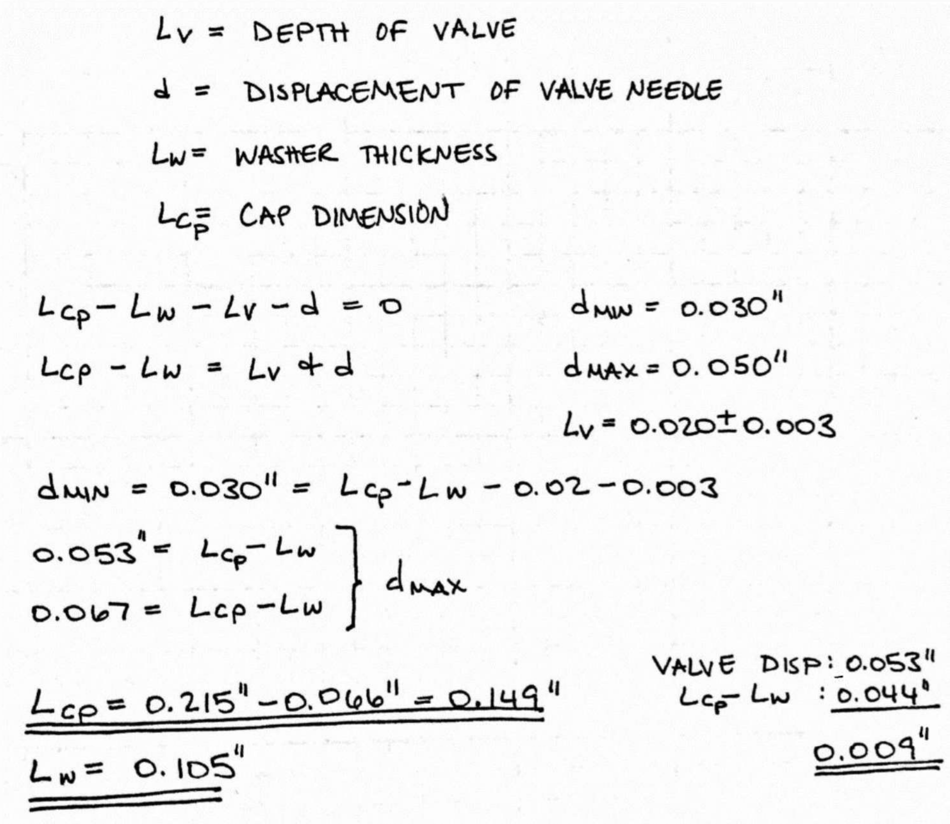
$$\underline{\underline{C = 0.021''}}$$

Closure Analysis: Following the closure calculations performed for labeled section 1, the keeper prongs' inner faces, L_K, and ruler's outer diameter, L_R, will mate with a press-fit (interference fit). Denoted by the letter 'i', the two parts have an interference of 0.004" which translates into the parts' tolerance. This interference is crucial to the gauge's performance because it guarantees a 'pinch' that keeps the ruler in place. Without this pinch from the keeper prongs, the ruler has the freedom to slide, yielding inaccurate pressure readings.

The ruler-keeper interaction uses the same variables in section 2, but the mate is different. This interaction is denoted by the letter 'c', where the two parts have a clearance of 0.021". This clearance ensures that there is always a space between the the ruler's outer surface and the keeper's inner surface to allow for free, uninterrupted sliding. This region of the keeper simply acts as a guide for the ruler to slide between the inside and outside of the barrel for appropriate aire pressure measurement / user pressure reading.

Cap to Schrader Valve





L_V = DEPTH OF VALVE

d = DISPLACEMENT OF VALVE NEEDLE

L_W = WASHER THICKNESS

L_{C_P} = CAP DIMENSION

$L_{cp} - L_w - L_v - d = 0$ $\qquad d_{MIN} = 0.030''$

$L_{cp} - L_w = L_v + d$ $\qquad d_{MAX} = 0.050''$

$L_v = 0.020 \pm 0.003$

$d_{MIN} = 0.030'' = L_{cp} - L_w - 0.02 - 0.003$

$$\left.\begin{array}{l} 0.053'' = L_{cp} - L_w \\ 0.067 = L_{cp} - L_w \end{array}\right\} d_{MAX}$$

$$\underline{\underline{L_{cp} = 0.215'' - 0.066'' = 0.149''}}$$

$$\underline{\underline{L_w = 0.105''}}$$

VALVE DISP: $0.053''$

$L_{cp} - L_w$: $\underline{0.044''}$

$\underline{\underline{0.009''}}$

Closure Analysis: The shown calculations demonstrate the Schrader valve interacting with the pressure gauge's cap. The calculations suggest that air will not leak out of a system when the gauge fully engages the valve without an applied load. In other words, the user will have to apply a force to the pressure gauge to release air from the valve. The cap dimension has a closure of 0.149", the washer has a closure of 0.105", and the valve has a closure of 0.009", all paralleling their respective tolerances.

Functional Closure Equations

To calculate the functional closures of the given pressure gauge, Fig. 36 and its labeled variable parts will be used in (24) through (32). These calculations aim to determine an error between the pressure measured by the gauge, P, and the actual air pressure inside of the pressure gauge, P*. All calculations performed in this section were completed using a MATLAB script available in Appendix A.

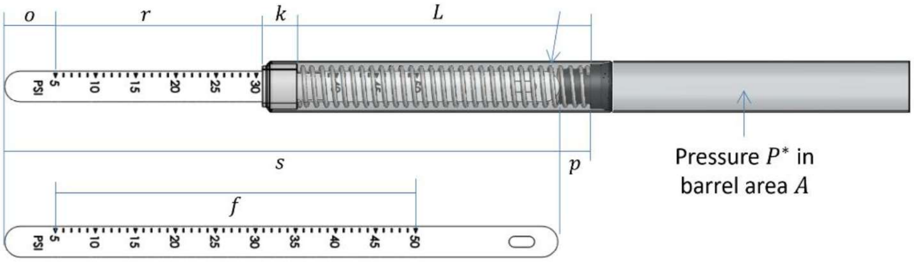


Fig. 36. Pressure gauge assembly for functional closure calculations.

The calculations begin in Table XXII, in which maximum and minimum dimensions, x, are used to determine relative tolerances, ρ_x. This calculation requires users to have access to nominal dimensions, x’, and absolute tolerances, Δx. These variables are used in (24) through (27) to define the general functional closure equations for each part interaction.

TABLE XXII
General Functional Closure Equations

$$\boldsymbol{x_{min} = x' - \Delta x = x'(1 - \rho_x)} \tag{24}$$

$$\boldsymbol{x_{max} = x' + \Delta x = x'(1 + \rho_x)} \tag{25}$$

$$\boldsymbol{\rho_x = \frac{\Delta x}{x'} = \frac{x_{max} - x_{min}}{x_{max} + x_{min}}} \tag{26}$$

$$\boldsymbol{x' = \frac{x_{max} + x_{min}}{2}} \tag{27}$$

The user begins with conducting the appropriate calculations for the spring’s length. The spring’s dimensions and relevant tolerances can be collected from the part drawings. Table XXIII builds upon (28), detailing the calculation for a relative tolerance and nominal dimension.

TABLE XXIII
Spring Length Functional Closure Equations

$$\boldsymbol{L = L_o - \frac{PA}{K}} \tag{28}$$

$$L_{min} = L_{o_{min}} - \frac{PA_{max}}{K_{min}} = L'_o\left(1 - \rho_{L_o}\right) - \frac{PA'(1 + \rho_A)}{K'(1 - \rho_K)}$$

$$L_{min} = L_{o_{min}} - \frac{PA_{min}}{K_{max}} = L'_o\left(1 + \rho_{L_o}\right) - \frac{PA'(1 - \rho_A)}{K'(1 + \rho_K)}$$

$$\rho_L = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

$$L' = \frac{L_{max} + L_{min}}{2}$$

Afterwards, the same process is followed to calculate the relative tolerance and nominal area in the barrel's cross-section. This calculation is demonstrated in Table XXIV, building upon (29).

TABLE XXIV
Barrel Area Functional Closure Equations

$$\boldsymbol{A = \frac{\pi d^2}{4}} \qquad (29)$$

$$A_{min} = \frac{\pi(d'_B\left(1-\rho_{d'_B}\right))^2}{4}$$

$$A_{max} = \frac{\pi(d'_B\left(1+\rho_{d'_B}\right))^2}{4}$$

$$\rho_A = \frac{A_{max} - A_{min}}{A_{max} + A_{min}}$$

$$A' = \frac{A_{max} + A_{min}}{2}$$

The relative tolerance and nominal 'dimensions' are calculated using the step process in Table XXV, building upon (30).

TABLE XXV
Spring Constant Functional Closure Equations

$$\boldsymbol{K = \frac{d^2 G}{8D'^3 N}} \qquad (30)$$

$$K_{min} = \frac{\left(d'(1-\rho_d)\right)^4 G'(1-\rho_G)}{8(D'(1+\rho_D))^3 N'(1+\rho_N)}$$

$$K_{max} = \frac{\left(d'(1+\rho_d)\right)^4 G'(1+\rho_G)}{8(D'(1-\rho_D))^3 N'(1-\rho_N)}$$

$$\rho_K = \frac{K_{max} - K_{min}}{K_{max} + K_{min}}$$

$$K' = \frac{K_{max} + K_{min}}{2}$$

The ruler calculation is outlined in Table XXVI, building upon (31), and considers various dimensions. This allows the functional closure to appropriately calibrate to the ruler's tick marks to the functional closures.

TABLE XXVI
Ruler Functional Closure Equations

$$\boldsymbol{o + r + k + L - p - s = 0} \qquad (31)$$

$$r = p + s - o - k - L = p + s - (o + k + L)$$

$$r_{min} = \left(p\left(1-\rho_p\right)\right) + \left(s(1-\rho_s)\right) - \left(\left(o(1+\rho_0)\right) + \left(k(1+\rho_k)\right)\left(L(1+\rho_L)\right)\right)$$

$$r_{max} = \left(p\left(1+\rho_p\right)\right) + \left(s(1+\rho_s)\right) - \left(\left(o(1-\rho_0)\right) + \left(k(1-\rho_k)\right)\left(L(1-\rho_L)\right)\right)$$

$$\rho_r = \frac{r_{max} - r_{min}}{r_{max} + r_{min}}$$

$$r' = \frac{r_{max} + r_{min}}{2}$$

After all functional closures are calculated for the relevant gauge parts, pressure calculations are performed following the specified steps in Table XXVII, building upon (32).

TABLE XXVII
Gauge Pressure Functional Closure Equations

$$\boldsymbol{\frac{P-5}{50-5}=\frac{r}{f}} \tag{32}$$

$$P = 5 + 45\frac{r}{f}$$

$$P_{min} = 5 + 45\frac{r_{min}}{f_{max}}$$

$$P_{max} = 5 + 45\frac{r_{max}}{f_{min}}$$

$$\rho_P = \frac{P_{max} - P_{min}}{P_{max} + P_{min}}$$

$$P' = \frac{P_{max} + P_{min}}{2}$$

This calculation process was completed using the dimensions and tolerances specified in the pressure gauge's part drawings and the results are available in Table XXVIII. This procedure yielded a maximum pressure of approximately 34 psi and the actual pressure inside of the pressure gauge was 30 psi. Using (33), the user determined that the pressure reading has a 13% error.

TABLE XXVIII
Final Functional Closure Calculations With Gauge Dimensions

ρ_L	0.0710
L'	2.2713 in
ρ_A	0.0080
A'	0.0908 in^2
ρ_K	0.0080
K'	1.4396 lb / in
ρ_r	0.1326
r'	1.5187 in
ρ_P	0.1191
P'	30.5367 psi

While the part dimensions are specific to the pressure gauge design, the user can apply finer tolerances to the calculations to explore how they influence the gauge's performance. Strictly to observe a trend, the MATLAB script was re-run with a 0.001 tolerance for all dimensioned component interactions. While this trend is not likely to occur in manufacturing, the script predicts that the new maximum air pressure will be approximately 31 psi, decreasing the error to 3.33%.

The functional tolerance MATLAB script is available in Appendix A for users to explore how tolerancing affects the pressure gauge's performance.

Pros and Cons

The pressure gauge is a useful tool for measuring air pressure in a system through a Schrader valve. While there are various tools for measuring air pressure, the stick pressure gauge offers its own unique set of pros and cons. The stick pressure gauge is an analog tire gauge, and is comprised of a Schrader valve attachment, a cylindrical casing, a ruler for displaying air pressure measurements, and the appropriate internal mechanisms for performing the air pressure measurement.

The primary benefit of the stick pressure gauge is that it offers efficiency. This tool is usually compact, making it easy to store in a pocket, drawer, or vehicle. Its size and light weight also offer portability, so users can access the pressure gauge nearly anywhere. The stick pressure gauge is also the least expensive pressure gauge, which makes it available to a larger consumer market.

As the stick pressure gauge circulates through a broader consumer market, it also offers user simplicity. The tool measures air pressure mechanically, bypassing complicated electrical systems requiring potentially confusing digital interfaces. Consequently, users may feel more inclined to opt for the less intimidating stick pressure gauge's that still achieves air pressure measurement. One does not have to conduct extensive research to understand how to use a stick pressure gauge, so the design is also very user-friendly.

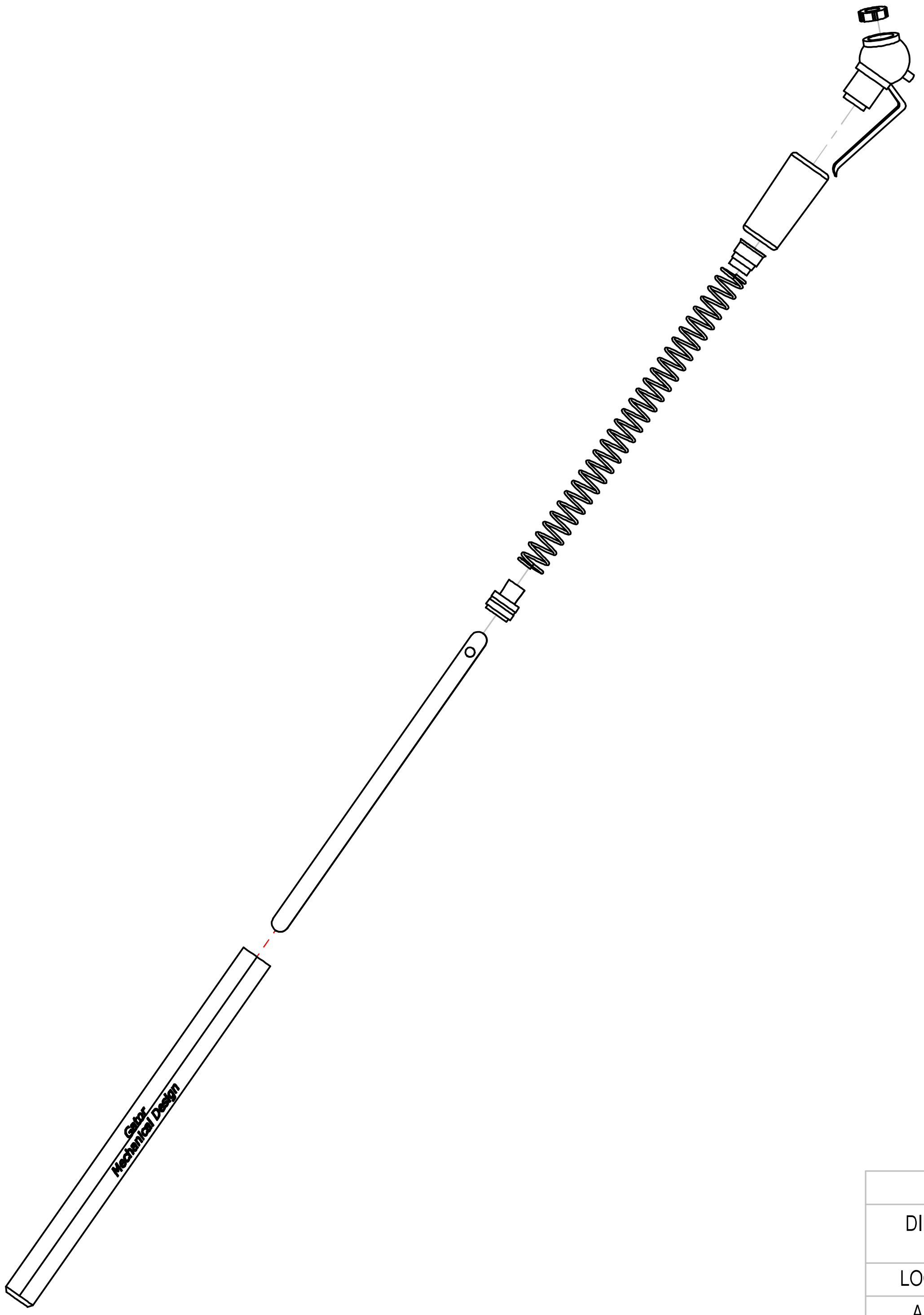
While the stick pressure gauge boasts efficiency and simplicity, it does so at the expense of reliability. The stick pressure gauge is also recognized as the least reliable air pressure measurement device. It relies on a burst of pressurized air influencing its internal collective performance to yield a valid pressure reading. Its efficient geometry also contributes to its inaccuracy, because increased wear and tear decreases the tool's pressure-measuring accuracy.

Beyond the stick pressure gauge's potentially inaccurate readings, one may still find difficulty reading the gauge's analog scale. In addition to the gauge design posing measurement discrepancies, it is also prone to human error, thereby contributing to the pressure gauge's inaccuracy.

Another challenge one may experience when using the analog reading is that there is a maximum and minimum air pressure that can be measured. If the air pressure in a system exceeds the ruler's maximum air pressure, the ruler will fully eject from the barrel, but no true pressure reading will be available to the user.

While the stick pressure gauge offers a slew of benefits, one should also consider it pitfalls. The pressure gauge is designed as a simple mechanical system that is small, light-weight, and affordable. However, those benefits are offered at the expense of the instrument's reliability. As the gauge undergoes continued use, its readings become more reliable and only contribute to the human error in air pressure reading. Overall, the stick pressure gauge is a viable tool for user-friendly air pressure measurement in a system.

Part Drawings



ITEM NO.	PART NUMBER	QTY.
1	CAP	1
2	WASHER	1
3	GRIP	1
4	BARREL	1
5	PLUNGER	1
6	SPRING	1
7	KEEPER	1
8	RULER	1

TOLERANCE UNLESS NOTED

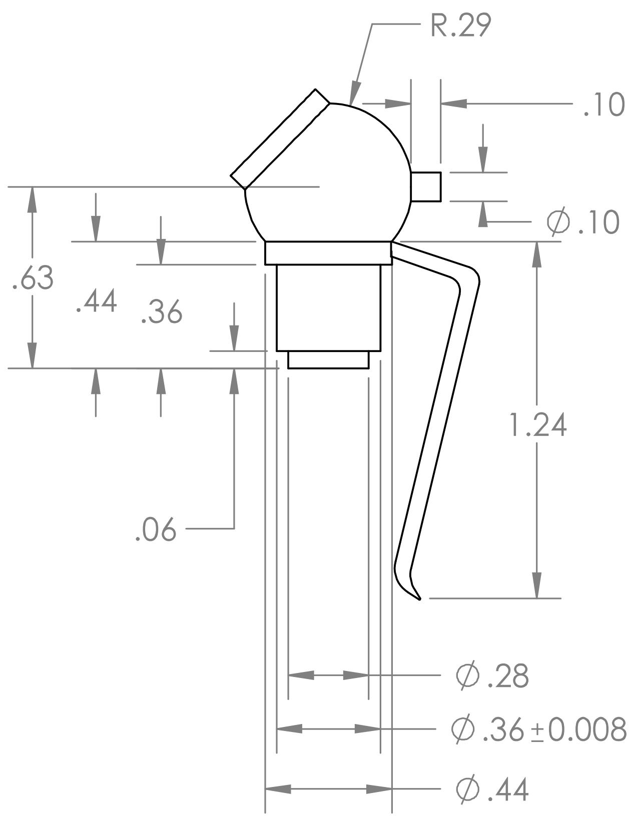
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

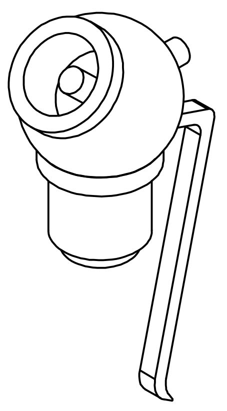
TITLE:
PRESSURE GAUGE

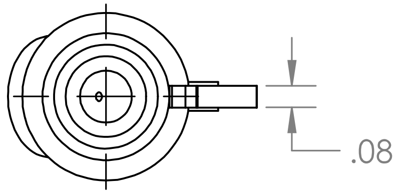
DRAWN ANDRES D. FLORES
DESIGNED ANDRES D. FLORES

SIZE	DWG. NO.	REV
A	EML 4501 - GAUGE	A
SCALE: 1:2		SHEET 1 OF 1

5 4 3 2 1



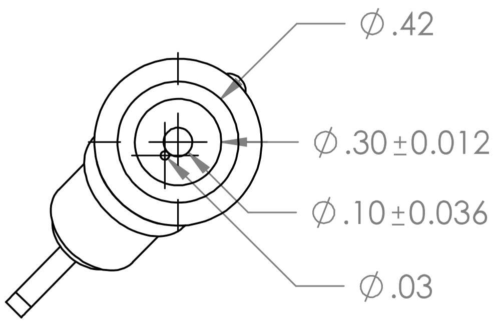




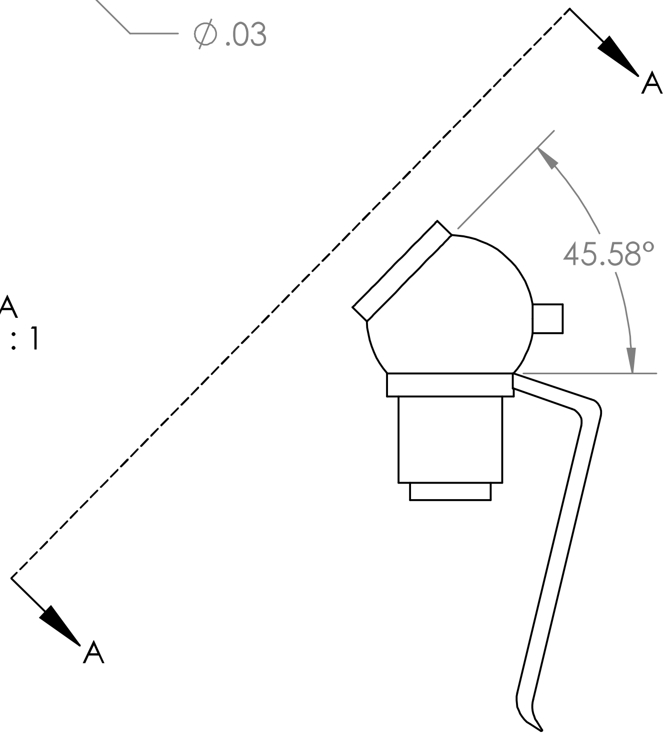
NOTES:
1. ALL DIMENSIONS IN INCHES
2. MAT'L: POLYESTER

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE:
CAP
DRAWN ANDRES D. FLORES
DESIGNED ANDRES D. FLORES
SIZE A
DWG. NO. EML 4501
REV A
SCALE: 1:1
SHEET 1 OF 3



VIEW A-A
SCALE 1.5 : 1

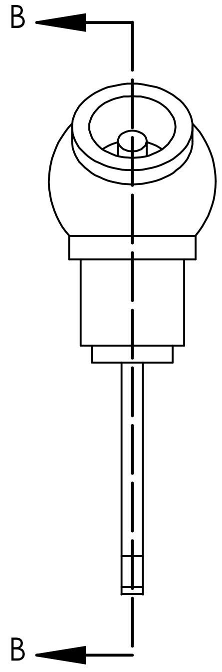


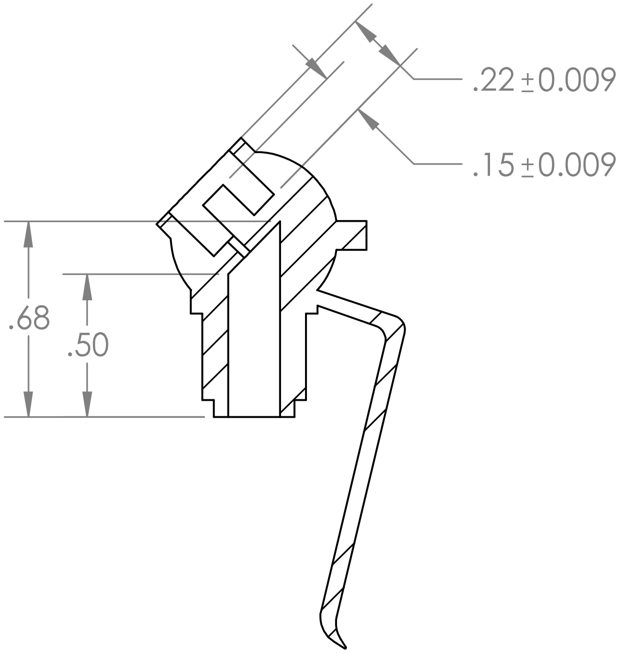
NOTES:
1. ALL DIMENSIONS IN INCHES
2. MAT'L: POLYESTER

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE: CAP		
DRAWN	ANDRES D. FLORES	
DESIGNED	ANDRES D. FLORES	
SIZE A	DWG. NO. EML 4501	REV A
SCALE: 1:1		SHEET 2 OF 3

5 4 3 2 1





SECTION B-B
SCALE 1.5 : 1

NOTES:
1. ALL DIMENSIONS IN INCHES
2. MAT'L: POLYESTER

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE: CAP			
DRAWN	ANDRES D. FLORES		
DESIGNED	ANDRES D. FLORES		
SIZE A	DWG. NO. EML 4501		REV A
SCALE: 1:1		SHEET 3 OF 3	

5 4 3 2 1

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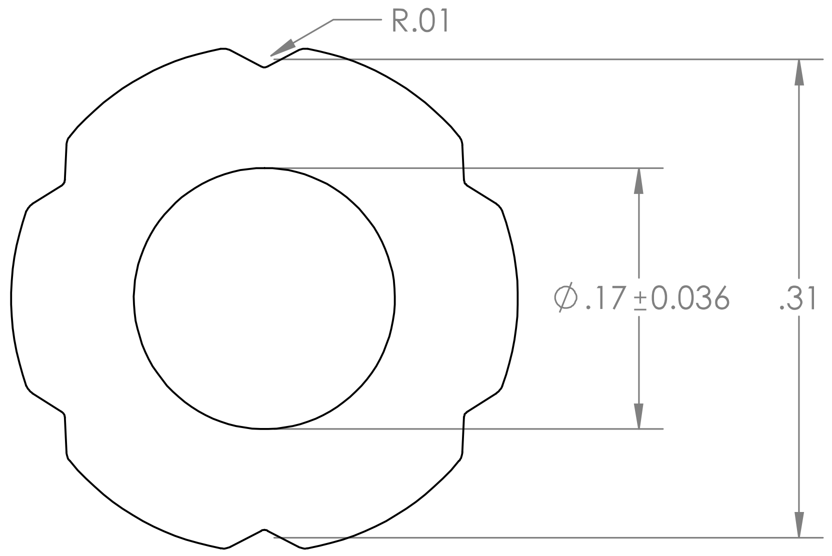
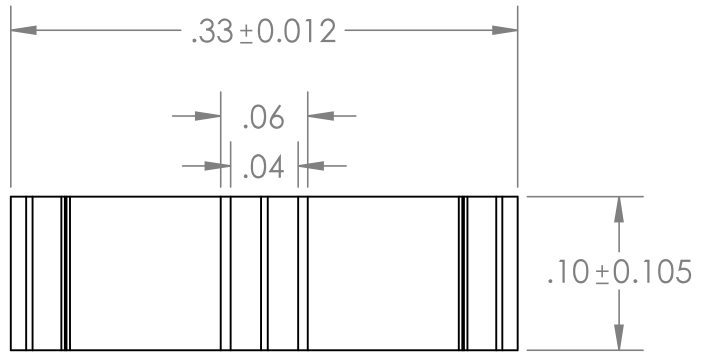
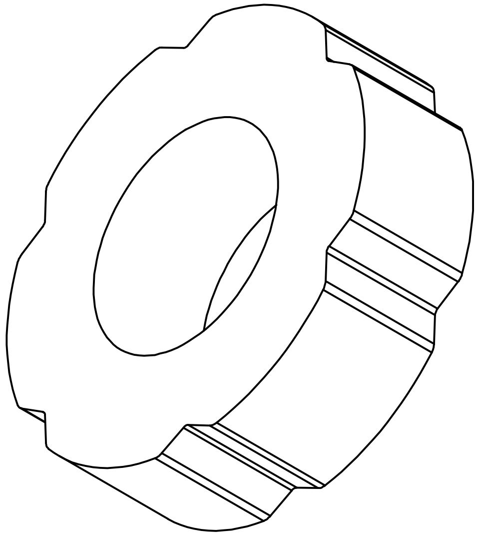


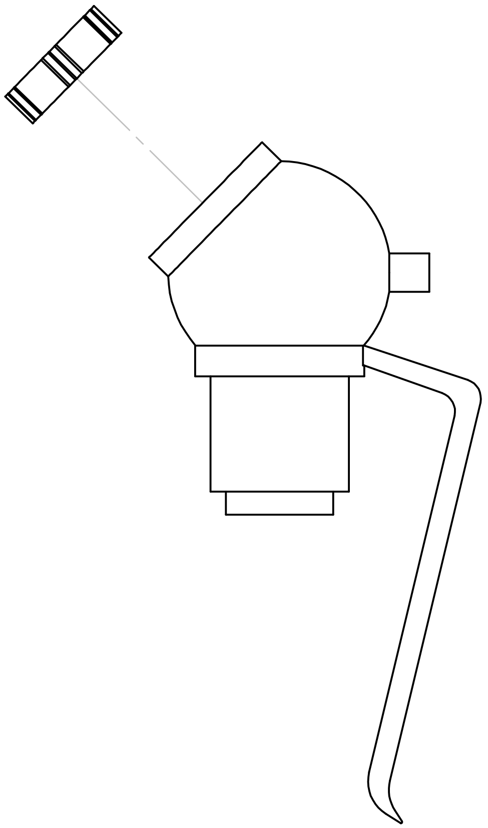




NOTES:
1. ALL DIMENSIONS IN INCHES
2. MAT'L: STYRENE RUBBER

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

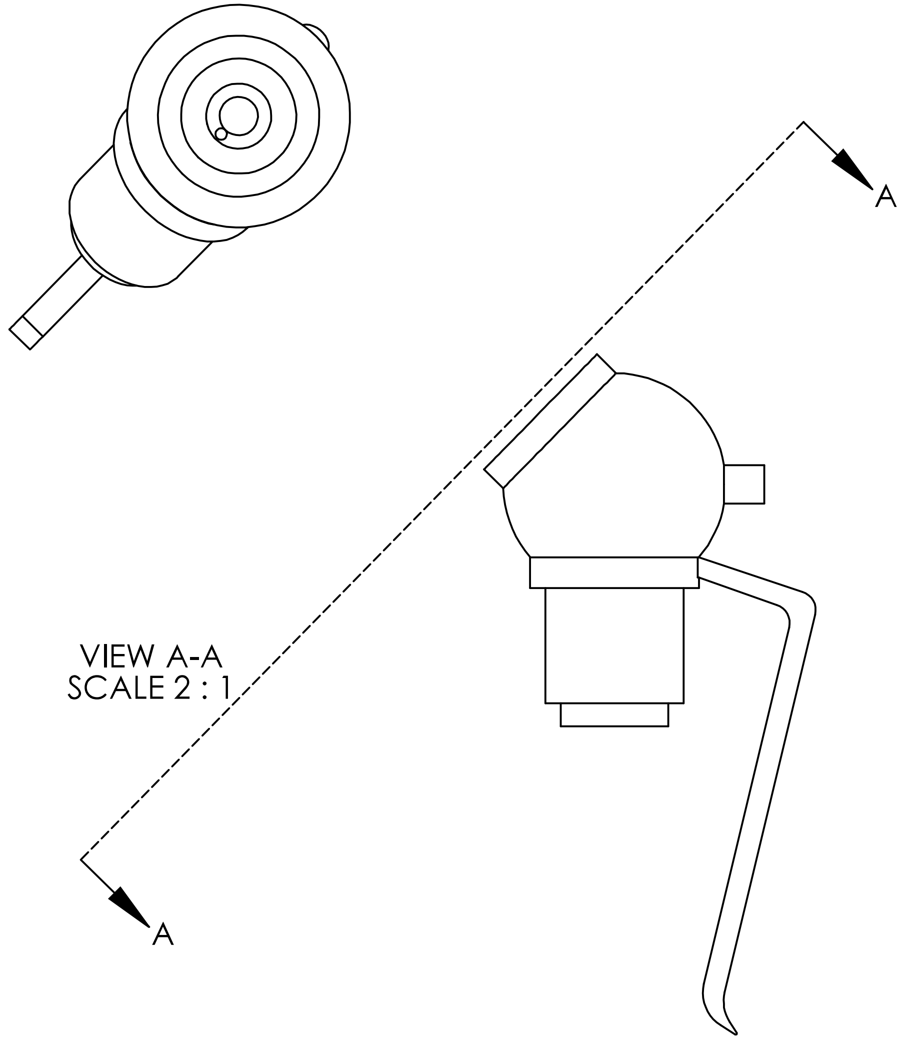
TITLE:	WASHER
DRAWN	ANDRES D. FLORES
DESIGNED	ANDRES D. FLORES
SIZE	A
DWG. NO.	EML 4501
REV	A
SCALE: 8:1	SHEET 1 OF 1



NOTES:
1. WASHER IS CONCENTRIC WITH CAP PIN
2. WASHER IS PRESS-FIT WITH CAP INNER DIAMETER

TOLERANCE UNLESS NOTED			
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

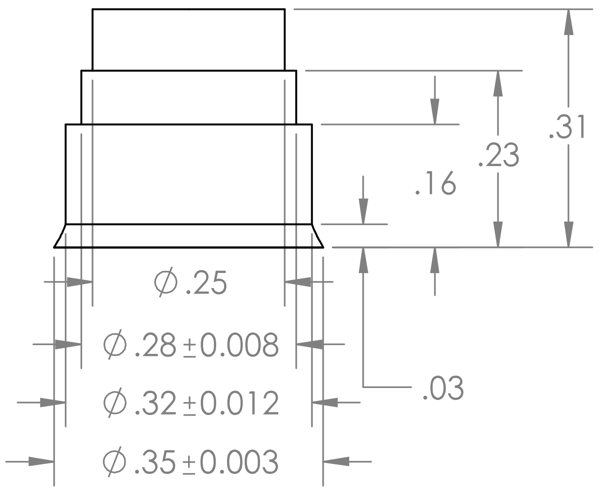
TITLE: CAP TO WASHER		
DRAWN	ANDRES D. FLORES	
DESIGNED	ANDRES D. FLORES	
SIZE A	DWG. NO. EML 4501 - CW	REV A
SCALE: 1:1		SHEET 1 OF 2

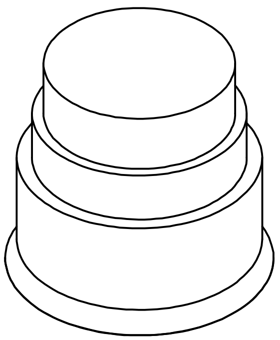


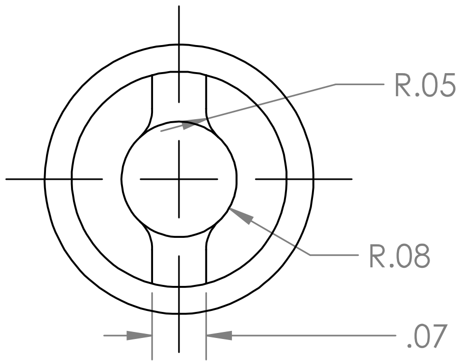
NOTES:
1. WASHER IS CONCENTRIC WITH CAP PIN
2. WASHER IS PRESS-FIT WITH CAP INNER DIAMETER

TOLERANCE UNLESS NOTED			
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

TITLE: CAP TO WASHER		
DRAWN	ANDRES D. FLORES	
DESIGNED	ANDRES D. FLORES	
SIZE A	DWG. NO. EML 4501 - CW	REV A
SCALE: 1:1		SHEET 2 OF 2



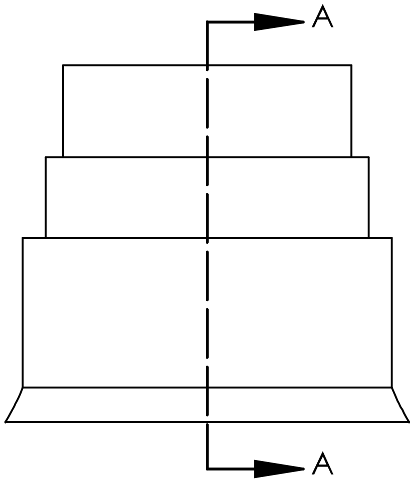


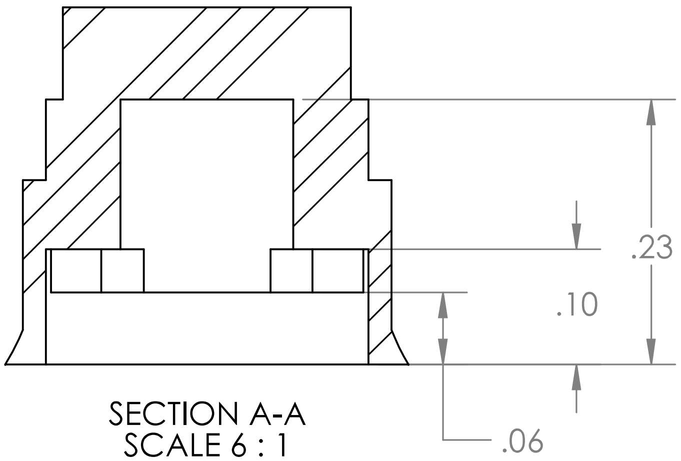


NOTES:
1. ALL DIMENSIONS IN INCHES
2. MAT'L: STYRENE RUBBER

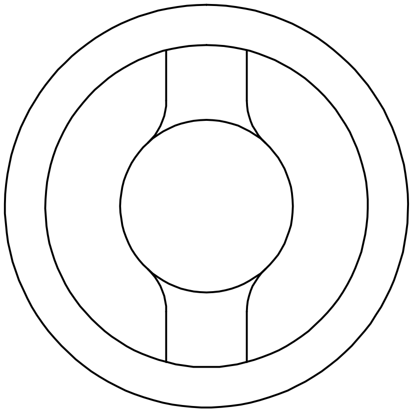
TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE: PLUNGER		
DRAWN	ANDRES D. FLORES	
DESIGNED	ANDRES D. FLORES	
SIZE A	DWG. NO. EML 4501	REV A
SCALE: 4:1		SHEET 1 OF 2





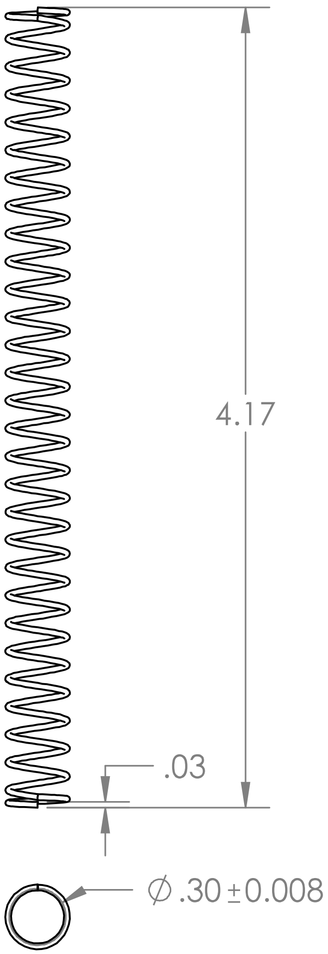
SECTION A-A
SCALE 6 : 1

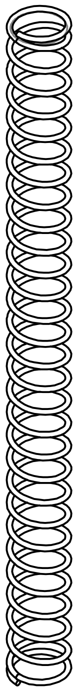


TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE: PLUNGER		
DRAWN	ANDRES D. FLORES	
DESIGNED	ANDRES D. FLORES	
SIZE A	DWG. NO. EML 4501	REV A
SCALE: 4:1		SHEET 2 OF 2

5 4 3 2 1



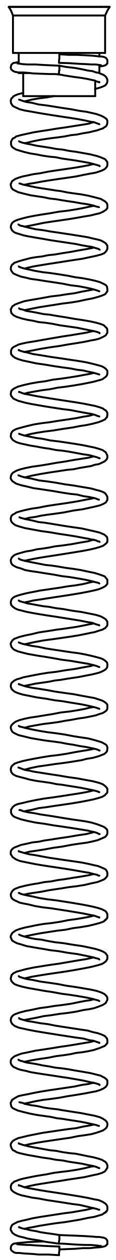


NOTES:
1. ALL DIMENSIONS IN INCHES
2. MAT'L: CARBON STEEL (MUSIC WIRE)
3. 28 ACTIVE REVOLUTIONS OF 32 REVOLUTIONS
4. PITCH: 0.145 INCHES
5. END PITCH: 0.020 INCHES

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE:
SPRING
DRAWN ANDRES D. FLORES
DESIGNED ANDRES D. FLORES
SIZE A
DWG. NO. EML 4501
REV A
SCALE: 1:1
SHEET 1 OF 1

5 4 3 2 1

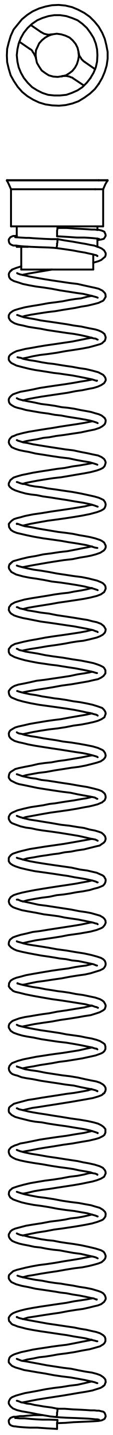


NOTES:
1. PRESS-FIT BETWEEN PLUNGER AND SPRING

TOLERANCE UNLESS NOTED			
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

TITLE: PLUNGER TO SPRING		
DRAWN	ANDRES D. FLORES	
DESIGNED	ANDRES D. FLORES	
SIZE A	DWG. NO. EML 4501 - PS	REV A
SCALE: 1:2		SHEET 1 OF 2

5 4 3 2 1

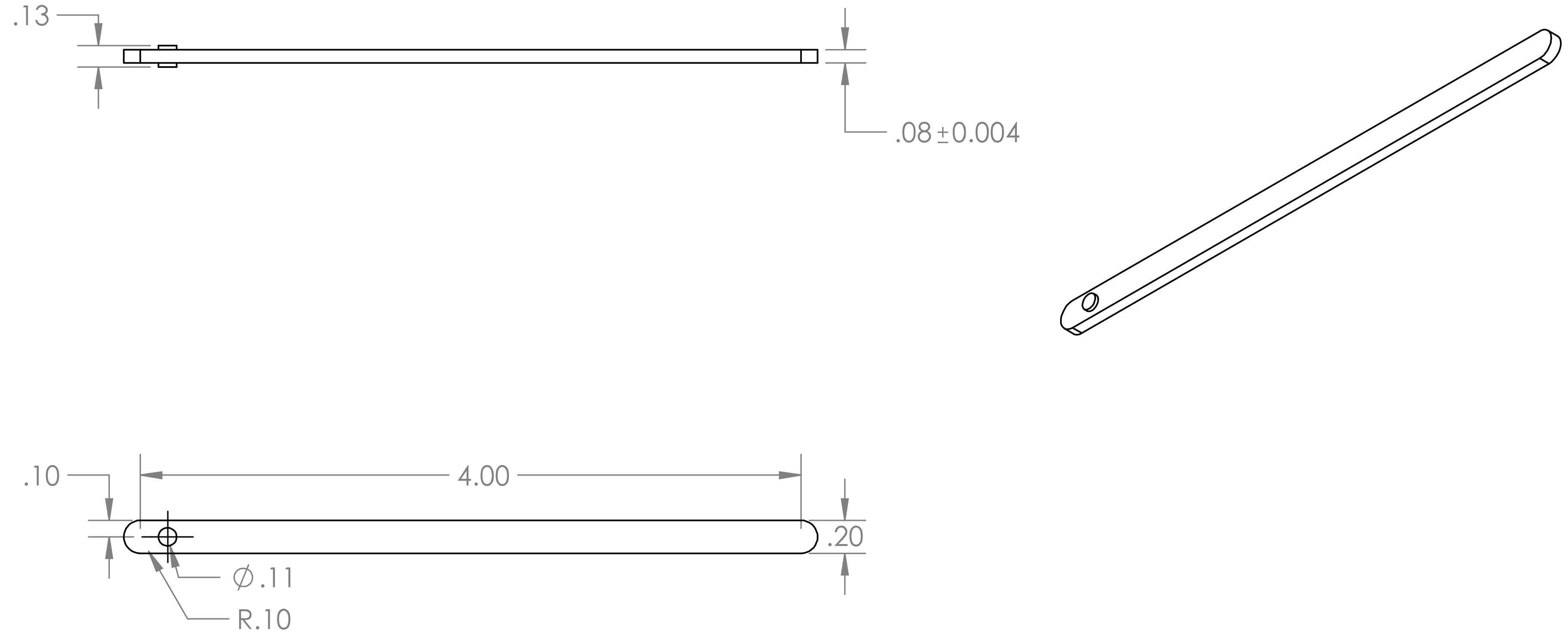


NOTES:
1. PRESS-FIT BETWEEN PLUNGER AND SPRING

TOLERANCE UNLESS NOTED			
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

TITLE:	PLUNGER TO SPRING	
DRAWN	ANDRES D. FLORES	
DESIGNED	ANDRES D. FLORES	
SIZE A	DWG. NO. EML 4501 - PS	REV A
SCALE: 1:2		SHEET 2 OF 2

5 4 3 2 1



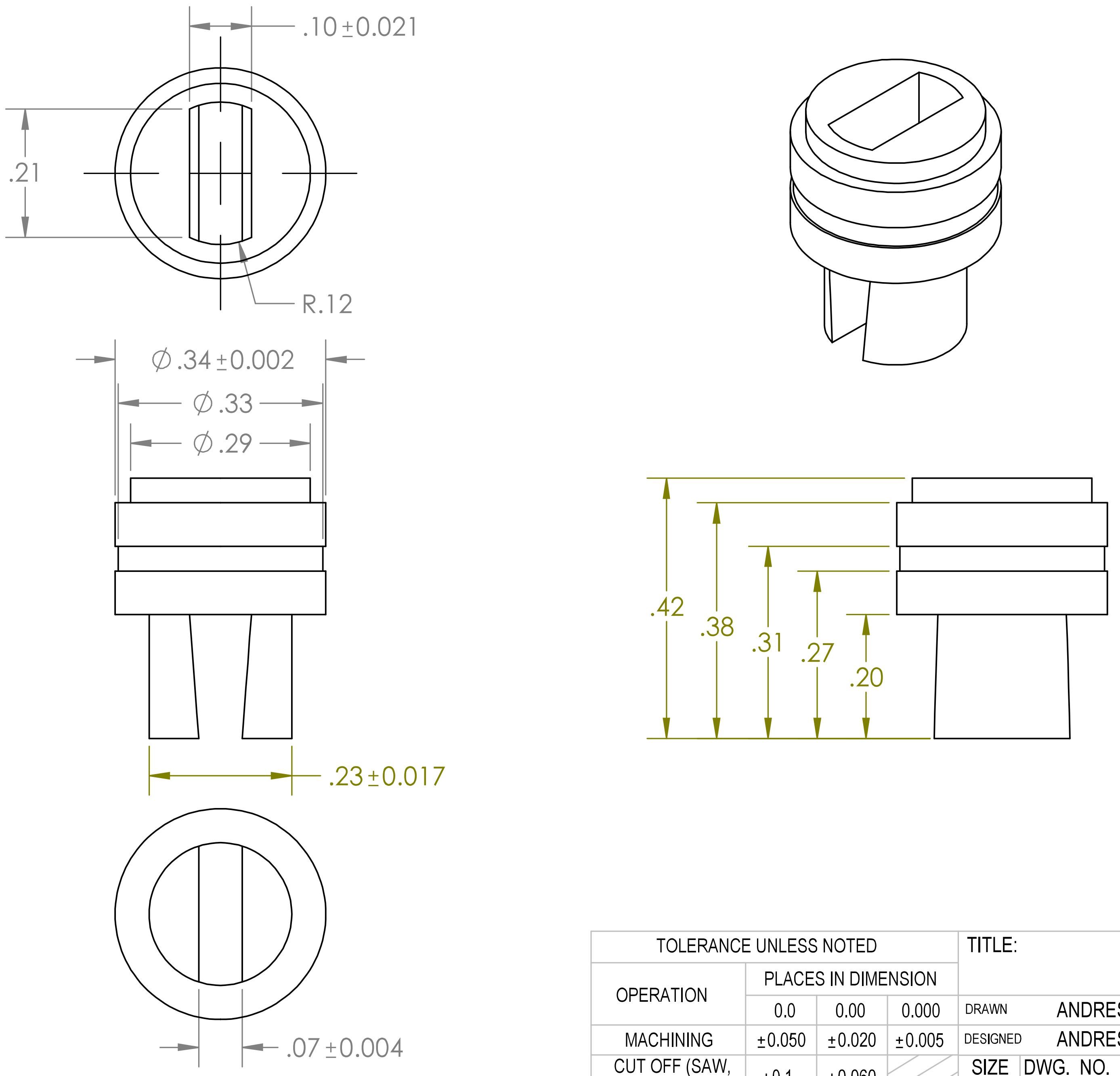
NOTES:
1. ALL DIMENSIONS IN INCHES
2. MAT'L: POLYESTER

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE:
RULER

DRAWN	ANDRES D. FLORES		
DESIGNED	ANDRES D. FLORES		
SIZE A	DWG. NO. EML 4501		REV A
SCALE: 1:2			SHEET 1 OF 1

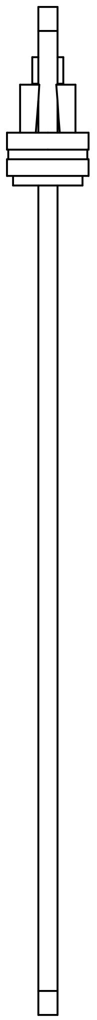
5 4 3 2 1



NOTES:
1. ALL DIMENSIONS IN INCHES
2. MAT'L: POLYETHYLENE

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE:	KEEPER		
DRAWN	ANDRES D. FLORES		
DESIGNED	ANDRES D. FLORES		
SIZE A	DWG. NO. EML 4501		REV A
SCALE: 4:1			SHEET 1 OF 1



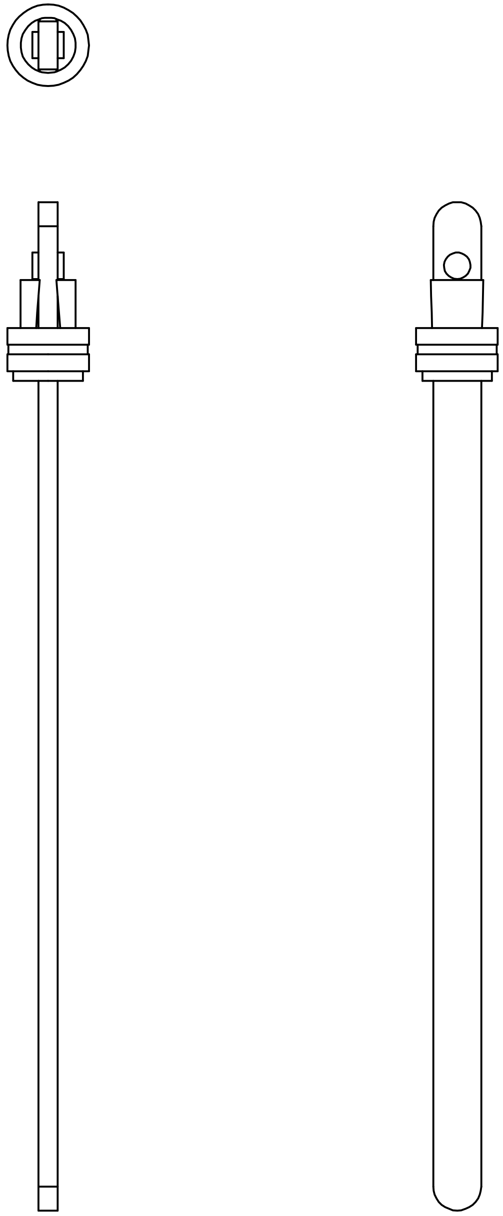
NOTES:
1. RULER PRESS-FITS WITH KEEPER PRONGS
2. RULER PEGS TOUCH KEEPER PRONG OUTER FLAT SURFACE

TOLERANCE UNLESS NOTED

DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

TITLE:
RULER TO KEEPER
DRAWN ANDRES D. FLORES
DESIGNED ANDRES D. FLORES
SIZE A
DWG. NO. EML 4501 - RK
REV A
SCALE: 1:1
SHEET 1 OF 2

5 4 3 2 1

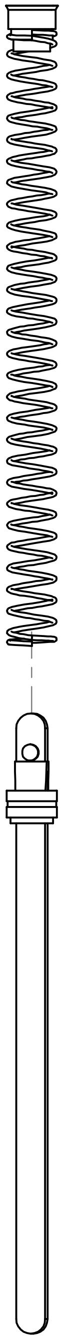


NOTES:
1. RULER PRESS-FITS WITH KEEPER PRONGS
2. RULER PEGS TOUCH KEEPER PRONG OUTER FLAT SURFACE

TOLERANCE UNLESS NOTED			
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

TITLE: RULER TO KEEPER			
DRAWN	ANDRES D. FLORES		
DESIGNED	ANDRES D. FLORES		
SIZE A	DWG. NO. EML 4501 - RK		REV A
SCALE: 1:1			SHEET 2 OF 2

5 4 3 2 1



NOTES:
1. KEEPER PRONGS FIT CONCENTRICALLY WITH SPRING
2. SPRING RESTS ON KEEPER SURFACE, PERPENDICULAR

TOLERANCE UNLESS NOTED			
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

TITLE: RK TO PS		
DRAWN	ANDRES D. FLORES	
DESIGNED	ANDRES D. FLORES	
SIZE A	DWG. NO. EML 4501 - PSKR	REV A
SCALE: 1:4		SHEET 1 OF 1

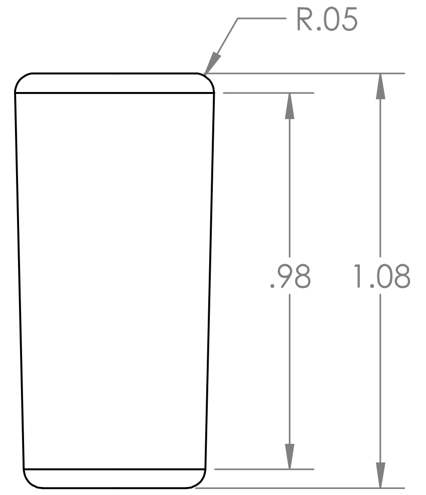
5 4 3 2 1

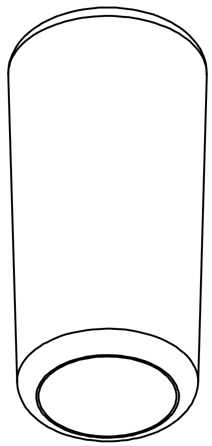
NOTES:
1. ALL DIMENSIONS IN INCHES
2. MAT'L: ALUMINUM 6063-T6
3. Blue outer surface finish
4. "Gator Mechanical Design" printed along length

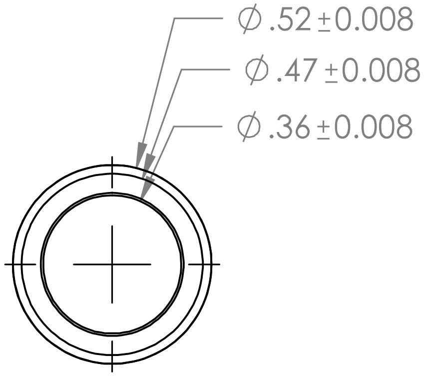
TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE:
BARREL

DRAWN	ANDRES D. FLORES	
DESIGNED	ANDRES D. FLORES	
SIZE A	DWG. NO. EML4501	REV A
SCALE: 1:2		SHEET 1 OF 1







NOTES:
1. ALL DIMENSIONS IN INCHES
2. MAT'L: STYRENE RUBBER
3. TEXTURED SURFACE

TOLERANCE UNLESS NOTED			
OPERATION	PLACES IN DIMENSION		
	0.0	0.00	0.000
MACHINING	±0.050	±0.020	±0.005
CUT OFF (SAW, BURN, SHEAR)	±0.1	±0.060	
WELDING	±0.1	±0.060	
ANGULAR DIMS	±5	±2	±0.5

TITLE:	GRIP		
DRAWN	ANDRES D. FLORES		
DESIGNED	ANDRES D. FLORES		
SIZE A	DWG. NO. EML 4501		REV A
SCALE: 2:1		SHEET 1 OF 1	

5 4 3 2 1

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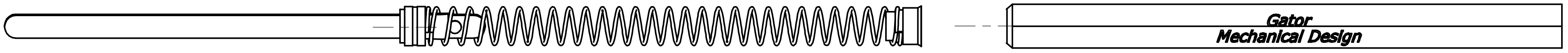
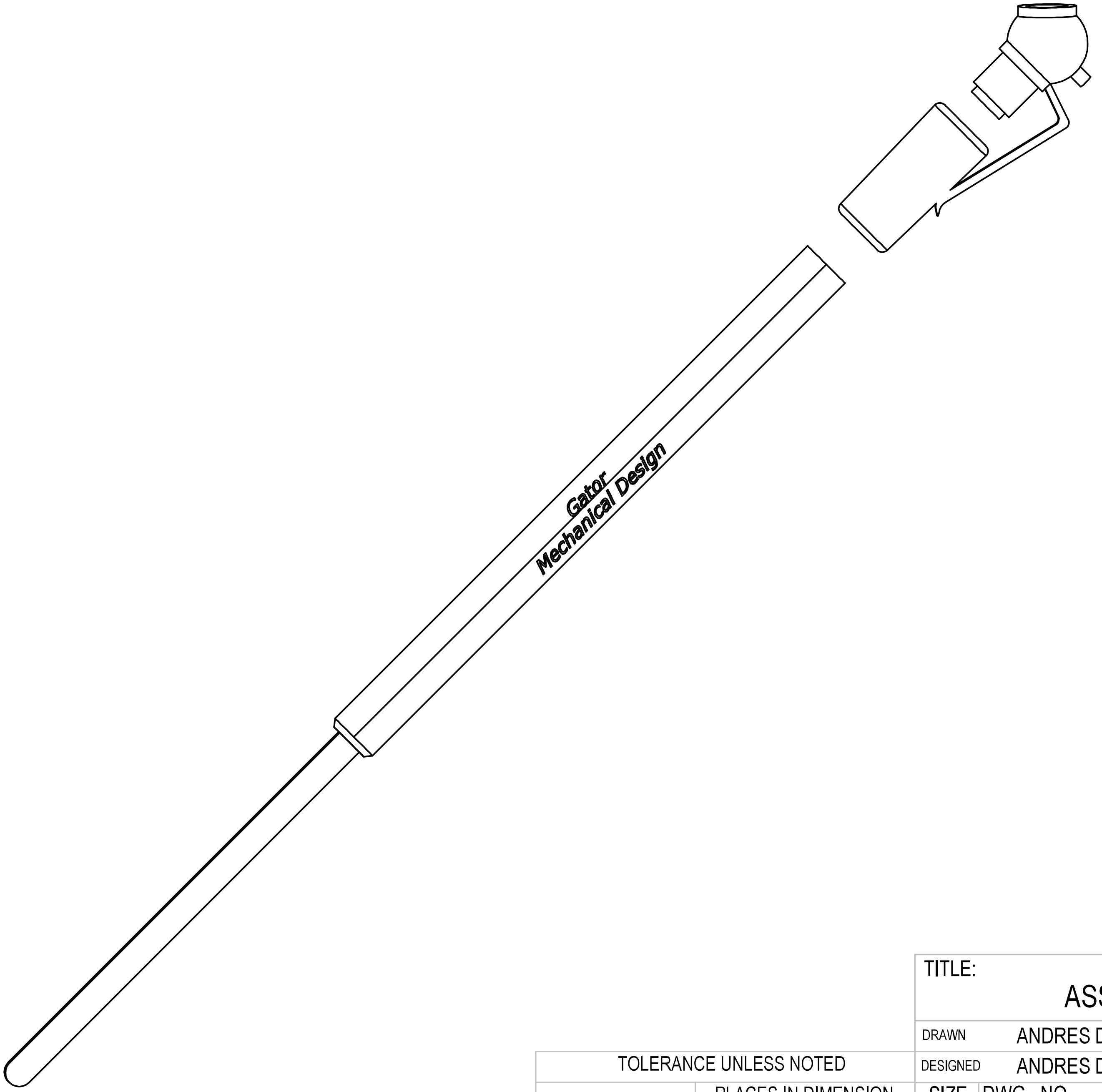


NOTES:
1. PKSR MATES WITH CONCENTRICALLY WITH THE BARREL

TOLERANCE UNLESS NOTED			
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

TITLE:
PKSR TO BARREL
DRAWN ANDRES D. FLORES
DESIGNED ANDRES D. FLORES
SIZE A
DWG. NO. EML 4501 - PKSRB
REV A
SCALE: 1:4
SHEET 1 OF 1

5 4 3 2 1

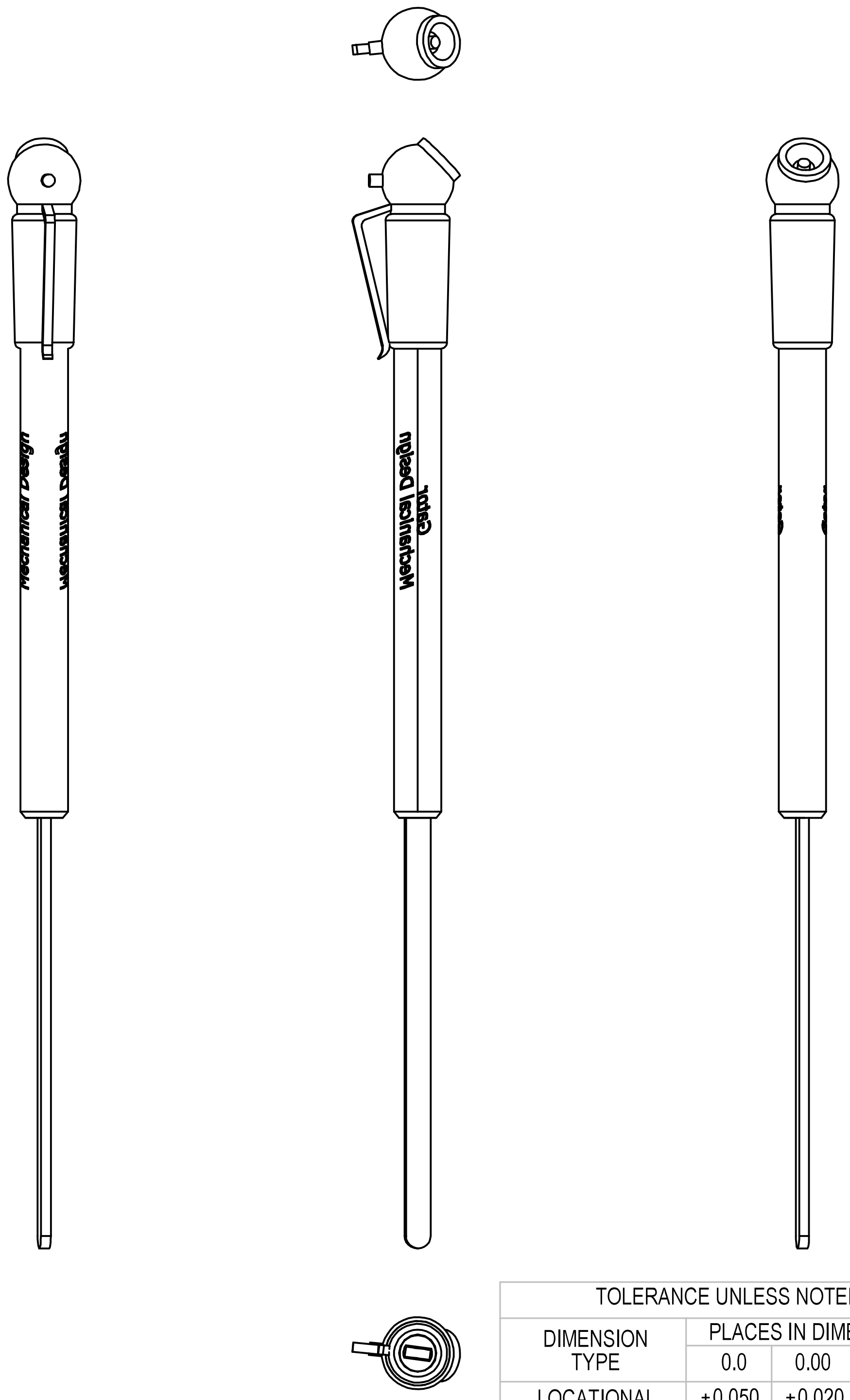


NOTES:
1. CAP PRESS-FITS WITH PSKRB AT THE LARGER DIAMETER
2. GRIP PRESS-FITS WITH PSKRB ALONG OUTER SURFACE

TOLERANCE UNLESS NOTED			
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

TITLE:
ASSEMBLED
DRAWN ANDRES D. FLORES
DESIGNED ANDRES D. FLORES
SIZE A
DWG. NO. EML 4105 - ASSEM
REV A
SCALE: 2:2.3
SHEET 1 OF 2

5 4 3 2 1



TOLERANCE UNLESS NOTED			
DIMENSION TYPE	PLACES IN DIMENSION		
	0.0	0.00	0.000
LOCATIONAL	±0.050	±0.020	±0.005
ANGULAR	±5	±2	±0.5

TITLE:
ASSEMBLED
DRAWN ANDRES D. FLORES
DESIGNED ANDRES D. FLORES
SIZE A
DWG. NO. EML 4501 - ASSEM
REV A
SCALE: 2:3
SHEET 2 OF 2

5 4 3 2 1

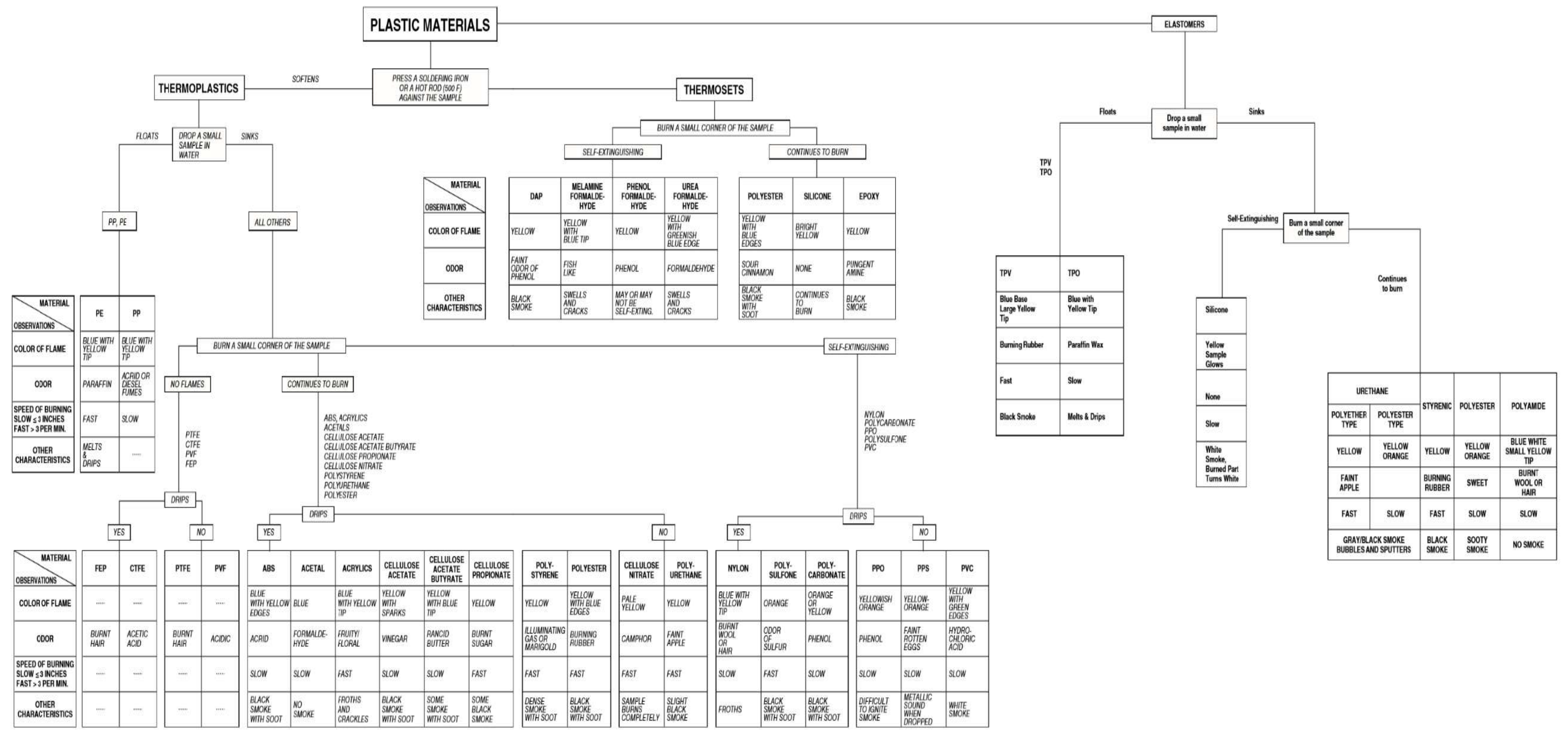
Appendix A

Table A–5

Physical Constants of Materials

Material	Modulus of Elasticity E		Modulus of Rigidity G		Poisson's Ratio ν	Unit Weight w		
	Mpsi	GPa	Mpsi	GPa		lbf/in^3	lbf/ft^3	kN/m^3
Aluminum (all alloys)	10.4	71.7	3.9	26.9	0.333	0.098	169	26.6
Beryllium copper	18.0	124.0	7.0	48.3	0.285	0.297	513	80.6
Brass	15.4	106.0	5.82	40.1	0.324	0.309	534	83.8
Carbon steel	30.0	207.0	11.5	79.3	0.292	0.282	487	76.5
Cast iron (gray)	14.5	100.0	6.0	41.4	0.211	0.260	450	70.6
Copper	17.2	119.0	6.49	44.7	0.326	0.322	556	87.3
Douglas fir	1.6	11.0	0.6	4.1	0.33	0.016	28	4.3
Glass	6.7	46.2	2.7	18.6	0.245	0.094	162	25.4
Inconel	31.0	214.0	11.0	75.8	0.290	0.307	530	83.3
Lead	5.3	36.5	1.9	13.1	0.425	0.411	710	111.5
Magnesium	6.5	44.8	2.4	16.5	0.350	0.065	112	17.6
Molybdenum	48.0	331.0	17.0	117.0	0.307	0.368	636	100.0
Monel metal	26.0	179.0	9.5	65.5	0.320	0.319	551	86.6
Nickel silver	18.5	127.0	7.0	48.3	0.322	0.316	546	85.8
Nickel steel	30.0	207.0	11.5	79.3	0.291	0.280	484	76.0
Phosphor bronze	16.1	111.0	6.0	41.4	0.349	0.295	510	80.1
Stainless steel (18-8)	27.6	190.0	10.6	73.1	0.305	0.280	484	76.0
Titanium alloys	16.5	114.0	6.2	42.4	0.340	0.160	276	43.4

PLASTICS AND ELASTOMERS IDENTIFICATION CHART



MATERIAL / OBSERVATIONS	PE	PP
COLOR OF FLAME	BLUE WITH YELLOW TIP	BLUE WITH YELLOW TIP
ODOR	PARAFFIN	ACRID OR DIESEL FUMES
SPEED OF BURNING SLOW ≤ 3 INCHES FAST > 3 PER MIN.	FAST	SLOW
OTHER CHARACTERISTICS	MELTS & DRIPS	.....

MATERIAL / OBSERVATIONS	DAP	MELAMINE FORMALDE-HYDE	PHENOL FORMALDE-HYDE	UREA FORMALDE-HYDE	POLYESTER	SILICONE	EPOXY
COLOR OF FLAME	YELLOW	YELLOW WITH BLUE TIP	YELLOW	YELLOW WITH GREENISH BLUE EDGE	YELLOW WITH BLUE EDGES	BRIGHT YELLOW	YELLOW
ODOR	FAINT ODOR OF PHENOL	FISH LIKE	PHENOL	FORMALDEHYDE	SOUR CINNAMON	NONE	PUNGENT AMINE
OTHER CHARACTERISTICS	BLACK SMOKE	SWELLS AND CRACKS	MAY OR MAY NOT BE SELF-EXTING.	SWELLS AND CRACKS	BLACK SMOKE WITH SOOT	CONTINUES TO BURN	BLACK SMOKE

MATERIAL / OBSERVATIONS	FEP	CTFE	PTFE	PVF	ABS	ACETAL	ACRYLICS	CELLULOSE ACETATE	CELLULOSE ACETATE BUTYRATE	CELLULOSE PROPIONATE
COLOR OF FLAME	.....	.....	.....	.....	BLUE WITH YELLOW EDGES	BLUE	BLUE WITH YELLOW TIP	YELLOW WITH SPARKS	YELLOW WITH BLUE TIP	YELLOW
ODOR	BURNT HAIR	ACETIC ACID	BURNT HAIR	ACIDIC	ACRID	FORMALDE-HYDE	FRUITY/ FLORAL	VINEGAR	RANCID BUTTER	BURNT SUGAR
SPEED OF BURNING SLOW ≤ 3 INCHES FAST > 3 PER MIN.	.....	.....	.....	.....	SLOW	SLOW	FAST	SLOW	SLOW	FAST
OTHER CHARACTERISTICS	.....	.....	.....	.....	BLACK SMOKE WITH SOOT	NO SMOKE	FROTHS AND CRACKLES	BLACK SMOKE WITH SOOT	SOME SMOKE WITH SOOT	SOME BLACK SMOKE

MATERIAL / OBSERVATIONS	POLY-STYRENE	POLYESTER	CELLULOSE NITRATE	POLY-URETHANE	NYLON	POLY-SULFONE	POLY-CARBONATE	PPO	PPS	PVC
COLOR OF FLAME	YELLOW	YELLOW WITH BLUE EDGES	PALE YELLOW	YELLOW	BLUE WITH YELLOW TIP	ORANGE	ORANGE OR YELLOW	YELLOWISH ORANGE	YELLOW-ORANGE	YELLOW WITH GREEN EDGES
ODOR	ILLUMINATING GAS OR MARIGOLD	BURNING RUBBER	CAMPHOR	FAINT APPLE	BURNT WOOL OR HAIR	ODOR OF SULFUR	PHENOL	PHENOL	FAINT ROTTEN EGGS	HYDRO-CHLORIC ACID
SPEED OF BURNING SLOW ≤ 3 INCHES FAST > 3 PER MIN.	FAST	FAST	FAST	FAST	SLOW	FAST	SLOW	SLOW	SLOW	SLOW
OTHER CHARACTERISTICS	DENSE SMOKE WITH SOOT	BLACK SMOKE WITH SOOT	SAMPLE BURNS COMPLETELY	SLIGHT BLACK SMOKE	FROTHS	BLACK SMOKE WITH SOOT	BLACK SMOKE WITH SOOT	DIFFICULT TO IGNITE SMOKE	METALLIC SOUND WHEN DROPPED	WHITE SMOKE

TPV	TPO
Blue Base Large Yellow Tip	Blue with Yellow Tip
Burning Rubber	Paraffin Wax
Fast	Slow
Black Smoke	Melts & Drips

Silicone
Yellow Sample Glows
None
Slow
White Smoke, Burned Part Turns White

URETHANE		STYRENIC	POLYESTER	POLYAMIDE
POLYETHER TYPE	POLYESTER TYPE			
YELLOW	YELLOW ORANGE	YELLOW	YELLOW ORANGE	BLUE WHITE SMALL YELLOW TIP
FAINT APPLE		BURNING RUBBER	SWEET	BURNT WOOL OR HAIR
FAST	SLOW	FAST	SLOW	SLOW
GRAY/BLACK SMOKE BUBBLES AND SPUTTERS		BLACK SMOKE	SOOTY SMOKE	NO SMOKE

The Plastics identification technique is laid out in flowchart for eash step-by-step identification by process of elimination. This is shown in the plastics Identification Chart. There are some basic guidelines one must follow in order to simplify the procedure. The first step is to determine whether the material is thermoplastic or thermoset. This distinction is made by simply probing the sample with a soldering iron or a hot rod heated to approximately 500°F. If the sample softens, the material is thermoplastic. If not, it is thermoset. The next step is to conduct a flame test. It is desirable to use a colorless Bunsen burner. A matchstick can also be used in place of a Bunsen burner. However, care must be taken to distinguish between the odor of the materials used in the match and the odor given off by burning plastic materials. Before commencing the burning test, it is advisable to be prepared to write down the following observations:

1.Does the material burn? 2.color of flame 3.Odor 4.Does the material drip while burning 5.Nature of smoke and color of smoke.
6. The presence of soot in the air. 7. Self-extinguishes or continues to burn. 8. Speed of burning--fast or slow

To identify the material, compare the actual observations with the ones listed in the flowchart. The accuracy of the test can be greatly improved by performing similar tests on a known sample. While performing the identification tests, one must not overlook safety factors. The drippings from the burning plastic may be very hot and sticky. After extinguishing the flame, inhale the smoke very carefully. Certain plastics like acetals give off a toxic formaldehyde gas that may cause a severe burning sensation in the nose and chest.

MANUAL HANDLING – ESTIMATED TIMES (seconds)

Key:

ONE HAND

			parts are easy to grasp and manipulate					parts present handling difficulties (1)				
			thickness > 2 mm			thickness ≤ 2 mm		thickness > 2 mm			thickness ≤ 2 mm	
			size >15 mm	6 mm ≤ size ≤15 mm	size <6 mm	size >6 mm	size ≤6 mm	size >15 mm	6 mm ≤ size ≤15 mm	size <6 mm	size >6 mm	size ≤6 mm
			0	1	2	3	4	5	6	7	8	9
parts can be grasped and manipulated by one hand without the aid of grasping tools	$(\alpha+\beta) < 360^\circ$	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
	$360^\circ \le (\alpha+\beta) < 540^\circ$	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
	$540^\circ \le (\alpha+\beta) < 720^\circ$	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
	$(\alpha+\beta) = 720^\circ$	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

ONE HAND with GRASPING AIDS

				parts need tweezers for grasping and manipulation								parts need standard tools other than tweezers	parts need special tools for grasping and manipulation
				parts can be manipulated without optical magnification				parts require optical magnification for manipulation					
				parts are easy to grasp and manipulate		parts present handling difficulties (1)		parts are easy to grasp and manipulate		parts present handling difficulties (1)			
				thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm		
				0	1	2	3	4	5	6	7	8	9
parts can be grasped and manipulated by one hand but only with the use of grasping tools	$\alpha \le 180^\circ$	$0 \le \beta \le 180^\circ$	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
		$\beta = 360^\circ$	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
	$\alpha = 360^\circ$	$0 \le \beta \le 180^\circ$	6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9
		$\beta = 360^\circ$	7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10

TWO HANDS for MANIPULATION

		parts present no additional handling difficulties					parts present additional handling difficulties (e.g. sticky, delicate, slippery, etc.) (1)				
		$\alpha \le 180^\circ$			$\alpha = 360^\circ$		$\alpha \le 180^\circ$			$\alpha = 360^\circ$	
		size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm	size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm
		0	1	2	3	4	5	6	7	8	9
parts severely nest or tangle or are flexible but can be grasped and lifted by one hand (with the use of grasping tools if necessary) (2)	8	4.1	4.5	5.1	5.6	6.75	5	5.25	5.85	6.35	7

TWO HANDS required for LARGE SIZE

		parts can be handled by one person without mechanical assistance									two persons or mechanical assistance required for parts manipulation
		parts do not severely nest or tangle and are not flexible								parts severely nest or tangle or are flexible (2)	
		part weight < 10 lb				parts are heavy (> 10 lb)					
		parts are easy to grasp and manipulate		parts present other handling difficulties (1)		parts are easy to grasp and manipulate		parts present other handling difficulties (1)			
		$\alpha \le 180^\circ$	$\alpha = 360^\circ$	$\alpha \le 180^\circ$	$\alpha = 360^\circ$	$\alpha \le 180^\circ$	$\alpha = 360^\circ$	$\alpha \le 180^\circ$	$\alpha = 360^\circ$		
		0	1	2	3	4	5	6	7	8	9
two hands, two persons or mechanical assistance required for grasping and transporting parts	9	2	3	2	3	3	4	4	5	7	9

MANUAL INSERTION—ESTIMATED TIMES (seconds)

Key:

PART ADDED but NOT SECURED

				after assembly no holding down required to maintain orientation and location (3)				holding down required during subsequent processes to maintain orientation or location (3)			
				easy to align and position during assembly (4)		not easy to align or position during assembly		easy to align and position during assembly (4)		not easy to align or position during assembly	
				no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)
				0	1	2	3	6	7	8	9
addition of any part (1) where neither the part itself nor any other part is finally secured immediately	part and associated tool (including hands) can easily reach the desired location		0	1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5
	part and associated tool (including hands) cannot easily reach the desired location	due to obstructed access or restricted vision (2)	1	4	5	5	6	8	9	9	10
		due to obstructed access and restricted vision (2)	2	5.5	6.5	6.5	7.5	9.5	10.5	10.5	11.5

PART SECURED IMMEDIATELY

				no screwing operation or plastic deformation immediately after insertion (snap/press fits, circlips, spire nuts, etc.)		plastic deformation immediately after insertion						screw tightening immediately after insertion (6)	
						plastic bending or torsion			rivetting or similar operation				
							not easy to align or position during assembly			not easy to align or position during assembly			
				easy to align and position with no resistance to insertion (4)	not easy to align or position during assembly and/or resistance to insertion (5)	easy to align and position during assembly (4)	no resistance to insertion	resistance to insertion (5)	easy to align and position during assembly (4)	no resistance to insertion	resistance to insertion (5)	easy to align and position with no torsional resistance (4)	not easy to align or position and/or torsional resistance (5)
				0	1	2	3	4	5	6	7	8	9
addition of any part (1) where the part itself and/or other parts are being finally secured immediately	part and associated tool (including hands) can easily reach the desired location and the tool can be operated easily		3	2	5	4	5	6	7	8	9	6	8
	part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily	due to obstructed access or restricted vision (2)	4	4.5	7.5	6.5	7.5	8.5	9.5	10.5	11.5	8.5	10.5
		due to obstructed access and restricted vision (2)	5	6	9	8	9	10	11	12	13	10	12

SEPARATE OPERATION

	mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				non-mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				non-fastening processes	
	none or localized plastic deformation				metallurgical processes					
						additional material required				
	bending or similar processes	rivetting or similar processes	screw tightening (6) or other processes	bulk plastic deformation (large proportion of part is plastically deformed during fastening)	no additional material required (e.g. resistance, friction welding, etc.)	soldering processes	weld/braze processes	chemical processes (e.g. adhesive bonding, etc.)	manipulation of parts or sub-assembly (e.g. orienting, fitting or adjustment of part(s), etc.)	other processes (e.g. liquid insertion, etc.)
	0	1	2	3	4	5	6	7	8	9
assembly processes where all solid parts are in place — 9	4	7	5	3.5	7	8	12	12	9	12

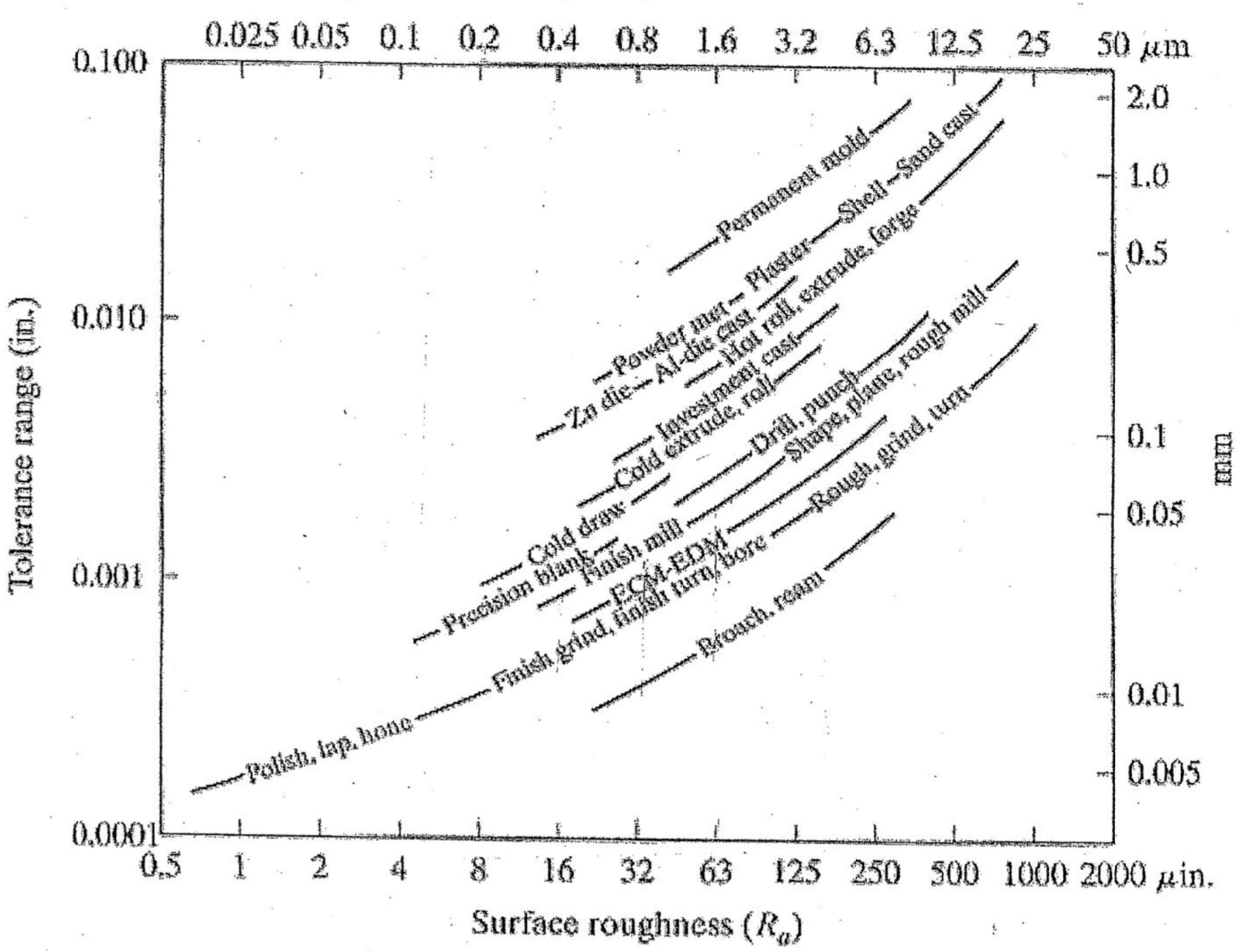


FIGURE 35.23 Tolerances and surface roughness obtained in various manufacturing processes. These tolerances apply to a 25-mm (1-in.) workpiece dimension. *Source*: J. A. Schey.

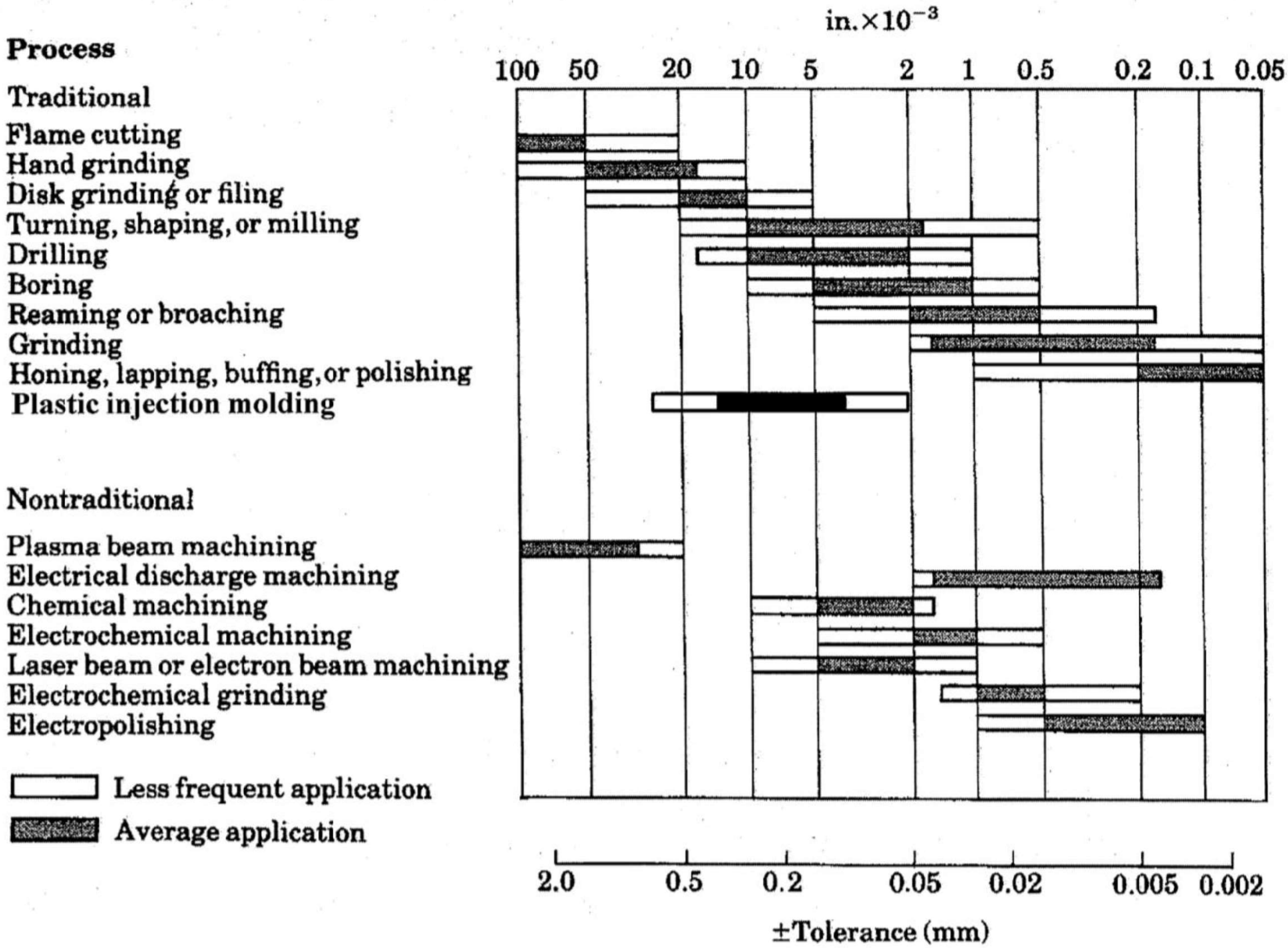


FIGURE 15.5

Tolerances produced by various processes.

MATLAB Cost Analysis

```
diary on

format compact

%INPUTS---

Q_mo = 1000000 %MonthlyQuantity
Q_mo =
     1000000
shft = 168 %hr/mo/WS
shft =
   168
t_sec = 66.28 %AssemblyTime_Seconds
t_sec =
   66.2800

% W = %Gross
% F = %Fringe
% T = %Taxes

DL = 0.1853 %DirectLabor ($/hr)
DL =
    0.1853

LC = 1.63 %LandedCost %CostOfGoods
LC =
    1.6300
IDL = 9324 %IndirectLabor
IDL =
        9324
BL = 33333 %BurdenedLabor
BL =
       33333
FE = 21012 %FacilitiesExpenses
FE =
       21012

%Calculated Variables---

t = (t_sec)/60 %AssemblyTime_Minutes
t =
    1.1047

L_base = 11.10 %$/hr/WS
L_base =
   11.1000
L = (L_base)*(1/60) %hr/60min
L =
    0.1850
% L = W + F + T %Labor ($/hr/WS)

Q_ws = (1/t)*(60)*shft
Q_ws =
```

```
   9.1249e+03
WS = (Q_mo)/(Q_ws) %WorkStations
WS =
  109.5899

UR = ((IDL + BL + FE)/WS)*(1/shft)*(1/60) %UserRate ($/min/WS)
UR =
    0.0576

OH = (UR/DL)*100 %OverHead
OH =
   31.1044
FBLC = (UR+DL)*60 %($/min)*(60min/hr); $/hr
FBLC =
   14.5762

%Cost Analysis---

one_widget = (DL+UR)*t
one_widget =
    0.2684
Total = (one_widget)+LC
Total =
    1.8984

diary off
```

MATLAB Functional Closure Equations

```
format compact
% ---BARREL---

%inputs
db = 0.34; %in
delt_db = 0.004;

%calcs
rho_db = (db*delt_db)/db
rho_db =
    0.0040

A_min = (pi)*((db)*(1-(rho_db)))^2*0.25
A_min =
    0.0901
A_max = (pi)*((db)*(1+(rho_db)))^2*0.25
A_max =
    0.0915

rho_A = (A_max-A_min)/(A_max+A_min)
rho_A =
    0.0080
A_nom = (A_max+A_min)/2
A_nom =
    0.0908


% ---SPRING---

%inputs
ds = 0.03; %in
delt_ds = 0.005;

G = 11501492.623; %psi
delt_G = 0.010;

D = 0.307; %in
delt_D = 0.005;

N = 28; %rev
delt_N = 0.010;

%calcs
rho_ds = (ds*delt_ds)/ds
rho_ds =
    0.0050
rho_G = (G*delt_G)/G
rho_G =
    0.0100
rho_D = (D*delt_D)/D
rho_D =
    0.0050
rho_N = (N*delt_N)/N
```

```
rho_N =
    0.0100

k_min = (((ds*(1-(rho_ds)))^4)*(G*(1-
rho_G)))/(8*((D*(1+rho_D))^3)*(N*(1+rho_N)))
k_min =
    1.3605
k_max = (((ds*(1+(rho_ds)))^4)*(G*(1+rho_G)))/(8*((D*(1-rho_D))^3)*(N*(1-
rho_N)))
k_max =
    1.5186

rho_k = (k_max-k_min)/(k_max+k_min)
rho_k =
    0.0549
k_nom = (k_max+k_min)/2
k_nom =
    1.4396


% ---LENGTH---

%inputs
P = 30; %lbf/in^2

L0 = 4.17; %in
delta_L0 = 0.01;

%calcs
rho_L0 = (L0*delta_L0)/L0
rho_L0 =
    0.0100

L_min = (L0*(1-rho_L0))-(P*(A_nom*(1+rho_A))/(k_min))
L_min =
    2.1102
L_max = (L0*(1+rho_L0))-(P*(A_nom*(1-rho_A))/(k_max))
L_max =
    2.4325


rho_L = (L_max-L_min)/(L_max+L_min)
rho_L =
    0.0710
L_nom = (L_max+L_min)/2
L_nom =
    2.2713

% ---RULER---

%inputs
p = 0.14; %in
delt_p = 0.01;

s = 4.21; %in
delt_s = 0.008;
```

```
o = 0.33; %in
delt_o = 0.01;

K = 0.23; %in
delt_K = 0.008;

f = 2.68; %in
delt_f = 0.01;

%calcs
rho_p = (p*delt_p)/p
rho_p =
    0.0100
rho_s = (s*delt_s)/s
rho_s =
    0.0080
rho_o = (o*delt_o)/o
rho_o =
    0.0100
rho_K = (K*delt_K)/K
rho_K =
    0.0080
rho_f = (f*delt_f)/f
rho_f =
    0.0100

r_min = (p*(1-rho_p))+(s*(1-rho_s))-((o*(1+rho_o))+(K*(1+rho_K))+(L_max))
r_min =
    1.3173
r_max = (p*(1+rho_p))+(s*(1+rho_s))-((o*(1-rho_o))+(K*(1-rho_K))+(L_min))
r_max =
    1.7201

rho_r = (r_max-r_min)/(r_max+r_min)
rho_r =
    0.1326
r_nom1 = (r_max+r_min)/2
r_nom1 =
    1.5187

% ---PRESSURE---
f_max = f*(1+(delt_f));
f_min = f*(1-(delt_f));

P_min = 5+(45*(r_min/f_max))
P_min =
   26.8999
P_max = 5+(45*(r_max/f_min))
P_max =
   34.1734

rho_P = (P_max-P_min)/(P_max+P_min)
rho_P =
    0.1191
P_nom = (P_max+P_min)/2
P_nom =
   30.5367
```