



Elements of Material Sciences
MSE 250
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Design Project

FUEL CANISTER FOR AN AUTOMOBILE

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1. Design Objective:

The objective of this design project is to create and analyze a new container that will be used to hold and dispense gasoline for an automobile. This project entails the basic formation of a simple gasoline tank, with an emphasis on the tank's material composition. The need for new gasoline tanks results from the ever-changing technology found in the automobile industry. As new vehicles are created with the intent of being more fuel efficient and while remaining cost effective, new innovations and designs are needed to keep production costs low, while also maintaining a balance in performance and strength. The goal of this design is to focus on this principle; maintaining a balance between the efficiency and strength of the tank. The tank in question will also be created with an attention to adaptability; meaning the tank will be designed in a way that it may be used for various types of automobiles, and can be easily tweaked to fit specific needs of other vehicles.

2. Design Strategy and Approach:

The first course of action needed for this design, is the determination of vehicle type and fuel capacity the tank will need to hold. Knowing the fuel size, the tank's volume and shape can be constructed in a way to effectively hold the fuel. After a shape has been established, the internal pressure of the tank should be calculated as a factor of the fuel, air, and residual water that may be found in the tank. The internal pressure will give a sense of what kind of stress the tank will be subjected to, giving the opportunity to determine a material and thickness that can successfully withstand the pressure caused by internal fluids. The residual water in the tank should also cooperate with the tank's material, to ensure no degradation or buildup of rust occurs in the tank. Once the tank has been cleared for internal pressure conditions, an attention to temperature of both the fluid and the tank should be analyzed, to ensure no unwanted reactions result from the temperature change seen in the tank. The final steps of the tank's development should be towards how easily it can be manufactured, as well as taking measures to keep the tank cost effective.

Fuel Amount Consideration:

In order for the gasoline tank to be sufficient, it must first be appropriately sized to accommodate a proper volume of fuel that can be used for all vehicles. In the U.S., the current average for tank size is between 12-17 gallons. Since large vehicles generally need larger tanks due to increase vehicle weight and size, the size of the designed fuel tank should be closer to the large end; ensuring its compatibility with both small and large vehicles. Due to this specification, the tank will be established as an average 15-gallon tank; allowing for manufactures to either reduce or increase the size of the tank to fit their specific cars needs. The fuel volume will therefore be set and analyzed at 56.5 Liters, which is just below 15 gallons. While the fuel is set at 56.5 Liters, the tank itself will need to be a little larger to accommodate for residual water and air that will be found in the tank, and help reduce the internal pressure. The tank will therefore be set at an internal volume of 62 Liters for the main chamber.

Material Consideration:

Perhaps the largest factor of this design, is the material choice used for the tank. Starting with the broad classes of materials; a choice must be made between glass, metal, polymer, ceramic, or semiconductor. Glass seems like a promising material due to its resistivity to temperature deformation, but is risky due to the atomic structure of the material. Because of their amorphous structure, glass materials are prone to fractures and can shatter. Plastics also serve as a promising material due to their ease of manufacturing and cost, but when paired with the gasoline, prove dangerous knowing that gasoline tends to dissolve simple polyethylene materials. The best choice in this case will therefore be a metal tank

due to its cheap cost combined with strength and resistance to load force, creating an elastic behavior. The biggest problem with metals is the thermal conductivity combined with the oxidation that some metals can experience. A high thermal conductivity means the tank's material can easily be influenced by hotter temperatures, leading to an increase in the fluid temperature which will cause an increase in volume and increase the pressure within the tank. A metal with a lower thermal conductivity would therefore be ideal, allowing for the convection felt at the bottom of the vehicle as it moves to have a bigger impact on keeping the tank cool and minimizing internal pressure. In addition, metals that oxidize easily like iron can lead to internal rust, contaminating the quality of the gasoline. For this reason, either Aluminum or Steel would be the best choice. Aluminum is more ductile, which would simplify manufacturing, but would also lead to a weaker tank shell that will dent easily to fast moving objects under the vehicle. For all the listed reasons above, Steel appears to be the best choice. Steel has a very high tensile strength, a low thermal conductivity, and a resistance to oxidation. The biggest downside for steel; however, is its weight, which won't matter for larger vehicles but can have an impact on smaller more fuel-efficient vehicles. This project will focus on determining a specific steel alloy that will be lighter while still maintaining all the required prerequisites noted above. The type of steel will be determined later on in the project, after fluid pressure, shell thickness, and material cost have been considered.

3. Design Visualization

The overall shape for this tank needs to be small enough to easily fit into any vehicle and allow for other equipment to easily move around the tank fuselage. A spherical tank would be a good approach due to its compact circular surface area with respect to its cross section. The spherical tank will be composed of a cylinder with two domed ends of equivalent size. The radius of each dome will be the same as the cylinder, simplifying stress and surface area calculations. The specific dimensions will be calculated in section 4a of this report. The tank will also include an inlet and outlet spout for the transition of the gasoline into the engine.



Figure 1: The conceptual design for this fuel tank. The tank is composed of a main cylindrical body with two spherical caps. Four bolt points allow for safe securement of the tank to the underside of the vehicle. An entry and exit valve allow for the transfer of gasoline throughout the vehicle.

4. Design Criterion and Implementation

a) Shape of Container

For the sake of calculations, the inlet and outlet spouts are going to be ignored for volume calculations and pressure calculations. This is due to their small overall areas that will not experience any major sort of pressure for the level of this course. Knowing the internal tank volume is set at 62 Liters, the radius and length of the capsule can be calculated using equations for total internal volume and total internal surface area. Since the tank needs to be cost effective, the ideal radius and length should produce a smaller internal surface area. Converting the 62 Liter tank into cubic meters, we find that:

$$V_i = 62 \text{ L} * \frac{1000 \text{ mL}}{1 \text{ L}} * \frac{1 \text{ cm}^3}{\text{mL}} * \frac{1 \text{ m}^3}{(100 \text{ cm})^3} = 0.062 \text{ m}^3$$

The volume and surface area of the tank can be calculated by adding the two properties for a cylinder and a sphere:

$$V = \frac{4}{3}\pi r^3 + \pi r^2 L \quad (\text{Eqn. 1})$$

$$A_s = 4\pi r^2 + 2\pi r L \quad (\text{Eqn. 2})$$

With Equations 1 and 2, and knowing the volume may not exceed 0.062 m^3 , A table can be created to showing the dimensions of the tank at various radiuses. The best possible choice will minimize surface area, therefore also reducing cost of the material.

Table 1: The inner surface area of the gasoline tank at different radius and corresponding lengths.

Volume, V [m ³]	Radius, r [m]	Length, L [m]	Surface Area, A _s [m ²]
0.062	0.010	197.339	0.1252
0.062	0.020	49.311	0.1290
0.062	0.030	21.888	0.1351
0.062	0.040	12.281	0.1436
0.062	0.050	7.827	0.1544
0.062	0.060	5.402	0.1674
0.062	0.070	3.934	0.1827
0.062	0.080	2.977	0.2001
0.062	0.090	2.316	0.2197
0.062	0.100	1.840	0.2413
0.062	0.110	1.484	0.2649
0.062	0.120	1.211	0.2905
0.062	0.130	0.994	0.3180
0.062	0.140	0.820	0.3473
0.062	0.150	0.677	0.3785
0.062	0.160	0.558	0.4114
0.062	0.170	0.456	0.4460
0.062	0.180	0.369	0.4823

From Table 1, it is clear that the surface area of the container will continue to increase as the radius increases, showing that there is no clear optimized sizing for this tank. Because there is no clear optimization, a tank should be chosen based off of reasonable size while also maintaining a low surface area. While a radius of 1 cm would provide an optimally low surface area, a tank length of 197.3 m is impossible to construct for the purpose of a vehicle. For this reason, an average choice at a radius of 15 cm and length of 67.7 cm will be used to keep surface area low while also making a reasonable size that can be attached to the bottom of the car.

b) Fluid Calculations and Analysis

Now that a container size has been chosen, the next important step is to analyze the state of the fluid, in this case gasoline, and how the fluid will affect the container. The most important consideration of the fluid, is the pressure this fluid will exert on the tank. Pressure on the tank will cause a certain extent of stress on the material which could lead to the tank fracturing and failing. The pressure will change for a container that is opened to the atmosphere compared to a closed pressurized vessel. For the sake of this design, the tank will be analyzed as an open vessel due to the entry and exit ports that will depressurize the container to atmospheric air. For an open pressure vessel, the fluid pressure is calculated by analyzing the density of the fluid at a certain height from the pressure surface, described by the equation below:

$$P = \rho * g * h \quad (\text{Eqn. 3})$$

The density of the fluid will change as a function of temperature, leading to a decrease in density while subsequently volume of the fluid increases. Since both volume and density affect the pressure the fluid in the tank. The fluid will need to be analyzed at the two observed extremes for temperature to determine where the pressure will be greater. At an average temperature of 15 °C, the density of gasoline is reported as 738 kg/m³.^[1] Using this density and the known fluid volume of 56.5 liters, we can determine the mass of the fluid when the tank is full.

$$m_{fluid} = 56.5 \text{ L} * \frac{1 \text{ m}^3}{1000 \text{ L}} * \frac{738 \text{ kg}}{1 \text{ m}^3} = 41.77 \text{ kg}$$

With the known mass of the gasoline, the volume of the fluid can be calculated at the low and high temperature that can be seen in the tank. On a cold day, the temperature of the fluid can reach an average low of -5 °C while the car is idle, while on a particularly hot day, the tank may reach an average high of 40 °C while the engine is running and radiating heat back through the car's systems. At -5 °C the density of gasoline is found to be 763 kg/m³, while the density is around 720 kg/m³ at 40 °C.^[1] With this given info, we are able to calculate the fluid volume:

$$V_{i,-5^{\circ}\text{C}} = 41.77 \text{ kg} * \frac{1 \text{ m}^3}{763 \text{ kg}} * \frac{1000 \text{ L}}{1 \text{ m}^3} = 54.7 \text{ L}$$

$$V_{i,40^{\circ}\text{C}} = 41.77 \text{ kg} * \frac{1 \text{ m}^3}{720 \text{ kg}} * \frac{1000 \text{ L}}{1 \text{ m}^3} = 58.0 \text{ L}$$

For a spherical pressure vessel, the max stress in the material is described as:

$$\sigma_{max,sphere} = \frac{Pr}{2t} \quad (\text{Eqn. 4})$$

Where t is the thickness of the vessel, r is the inner radius of the vessel, and P is the internal gage pressure acting on the vessel. A cylindrical pressure vessel experiences max stress along its length, which is equivalent to:

$$\sigma_{max,cylinder} = \frac{Pr}{t} \quad (\text{Eqn. 5})$$

Since the cylindrical base of the vessel experiences a larger amount of stress than the spherical caps, design of the tank's thickness should be centered around the fluid's internal pressure on the cylindrical base alone. Equation 3 shows that the fluid height and the density are needed to find internal pressure. We know density, but still need to find the height of the fluid. One method of finding this height is by analyzing the cylinder's cross-sectional area as an integral, and finding the point at which the area under the cross section is identical to the fraction of volume taken from the fluid compared to the total volume of the tank. Since the cross section of the cylinder is a circle, the function that correlates to the cross-sectional shape is:

$$y = \sqrt{r^2 - (x - r)^2} \quad (\text{Eqn. 6})$$

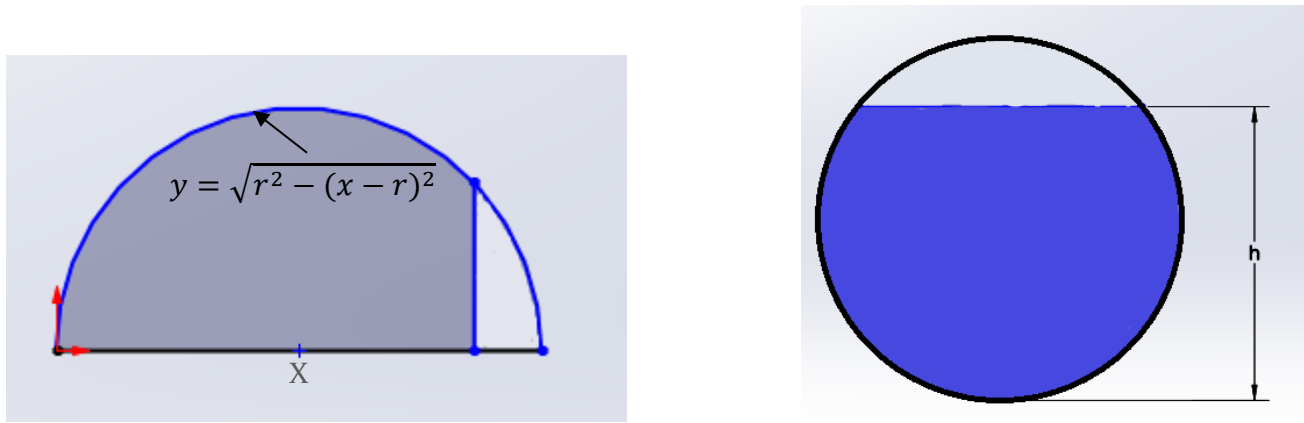


Figure 2: The cross section is split in half, then integrated using the function for a circle, the h is determined after the area under the circle is proportionate to the ratio areas determined below.

Integrating this function for the full diameter of the circle, we find that:

$$A_{function} = \int_0^{0.3\text{ m}} \sqrt{(0.15\text{ m})^2 - (x - 0.15\text{ m})^2} dx = 0.03534\text{ m}^2$$

For each temperature, there exists a volume ratio for which:

$$\text{Ratio} = \frac{V_{i,fluid}}{V_{i,tank}} \quad \text{Ratio}_{-5^\circ\text{C}} = \frac{54.7\text{ L}}{62\text{ L}} = 0.882 \quad \text{Ratio}_{40^\circ\text{C}} = \frac{58\text{ L}}{62\text{ L}} = 0.935$$

Multiplying our function's area with each ratio will give us a new area of integration that will allow us to determine the height that each fluid will rest at:

$$A_{f,-5^\circ\text{C}} = 0.882 * 0.03534\text{ m}^2 = 0.03118\text{ m}^2$$

$$A_{f,40^\circ\text{C}} = 0.935 * 0.03534\text{ m}^2 = 0.03306\text{ m}^2$$

$$0.03118 \text{ m}^2 = \int_0^{h_{-5}^{\circ\text{C}}} \sqrt{(0.15 \text{ m})^2 - (x - 0.15 \text{ m})^2} dx \quad h_{-5}^{\circ\text{C}} = 0.247 \text{ m}$$

$$0.03306 \text{ m}^2 = \int_0^{h_{40}^{\circ\text{C}}} \sqrt{(0.15 \text{ m})^2 - (x - 0.15 \text{ m})^2} dx \quad h_{40}^{\circ\text{C}} = 0.265 \text{ m}$$

Now that the resting height has been determined at each temperature, the pressure can be calculated using Equation 3.

$$P_{-5}^{\circ\text{C}} = 763 \frac{\text{kg}}{\text{m}^3} * \frac{9.81 \text{ m}}{\text{s}^2} * 0.247 \text{ m} = 1848.8 \text{ Pa}$$

$$P_{40}^{\circ\text{C}} = 720 \frac{\text{kg}}{\text{m}^3} * \frac{9.81 \text{ m}}{\text{s}^2} * 0.265 \text{ m} = 1871.8 \text{ Pa}$$

From the two calculations, we can conclude that at a higher temperature, the gasoline will exhibit a larger pressure on the tank. The internal fluid pressure should be increased to 2000 Pa to allow more realistic expectations with increased internal pressure caused from additional residual water and air that is also present in small amounts in the tank. Since the fuel tank is not pressurized, it will be exposed to ambient air, which is generally no more than 101.3 kPa. This will set the total internal pressure of the tank equal to around 103.3 kPa.

c) Engineering Calculations

Material Thickness:

Earlier in the report, Equation 5 was presented and showed that the stress was calculated as a function of the radius, the internal gage pressure, and the thickness of the pressure vessel. In the case of our design, both the radius and pressure are known, while the stress and thickness both remain unknown. The stress; however, can be calculated in a sense by analyzing the physical properties of the chosen material. When put under pressure, a material experiences strain which deforms a material. For many materials like metal, there exists a region known as the elastic region under which the deformation of the material remains only temporary, and will return to its original shape once the load is removed. Once the metal hits a specific yield point, this elastic behavior converts to a plastic behavior that leads to permanent deformation and subsequently degradation of the material. In order to minimize material failure, the design should be centered around the yield strength. For general carbon steel, the yield strength is around 250 MPa, which we can plug into Equation 5 to determine the minimum thickness needed for this fuel tank.

$$t = \frac{P * r}{\sigma} = \frac{103.3 \text{ kPa} * 0.15 \text{ m}}{250 \text{ MPa}} = 0.062 \text{ mm}$$

From this we learn that the smallest allowable diameter is 0.062 mm, which is very small compared to the radius and length of the fuel tank. This small of a minimum diameter means a couple things, the material does not have to be particularly thick, and the material does not need to be as strong as steel. Because of this, a change should be made to the second-best material outlined in section 2, which is Aluminum. Common aluminum like 6000 series aluminum has a yield strength at around 270 MPa.^[2] Using this value, we find a new minimum thickness of:

$$t = \frac{P * r}{\sigma} = \frac{103.3 \text{ kPa} * 0.15 \text{ m}}{270 \text{ MPa}} = 0.057 \text{ mm}$$

Although the minimum thickness is technically strong enough to withstand the internal pressure of the tank, this is still very thin and susceptible to outside influences like thermal deformation, dynamic

fluid pressure, and external forces that may come into contact with the tank's exterior. For this reason, the thickness should be modified to a degree of safety. Comparing the tensile stress of the tank at different thicknesses can help select a more suitable thickness for our tank.

Table 2: Stress of the tank as a function of thickness.

Internal Pressure, P_i [kPa]	Radius, r [m]	Thickness, t [mm]	Stress, σ [Mpa]
103.3	0.15	0.057	271.8
103.3	0.15	0.10	155.0
103.3	0.15	0.15	103.3
103.3	0.15	0.20	77.5
103.3	0.15	0.25	62.0
103.3	0.15	0.30	51.7
103.3	0.15	0.35	44.3
103.3	0.15	0.40	38.7
103.3	0.15	0.45	34.4
103.3	0.15	0.50	31.0
103.3	0.15	0.55	28.2
103.3	0.15	0.60	25.8
103.3	0.15	0.65	23.8
103.3	0.15	0.70	22.1
103.3	0.15	0.75	20.7
103.3	0.15	0.80	19.4
103.3	0.15	0.85	18.2
103.3	0.15	0.90	17.2
103.3	0.15	0.95	16.3
103.3	0.15	1.00	15.5

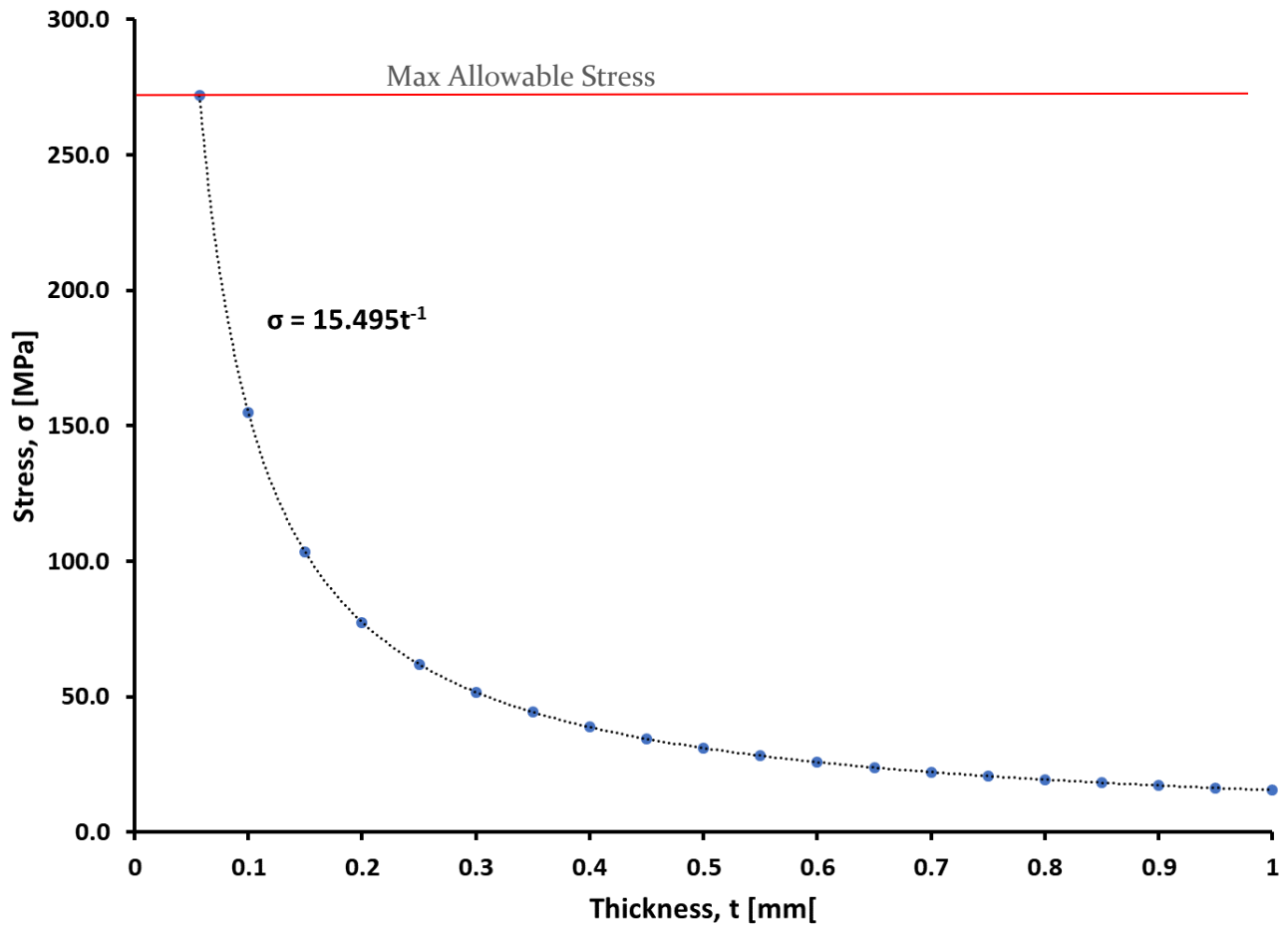


Figure 2: The stress seen in the tank follows a power fit relationship defined by $\sigma = 15.495 * t^{-1}$.

As the thickness of the tank's shell increases, the stress approaches about 10 MPa. Choosing a thickness of 1mm provides a large factor of safety in regards to the static fluid pressure seen inside the tank. However, 1 mm still remains very small for other factors such as thermal expansion and external forces. A separate factor of safety should also be applied to ensure external forces like loose projectiles under the vehicle will not pierce the shell. For these reasons, the thickness should be set at 7.5 mm to improve performance without drastically increasing cost.

Thermal Expansion:

Just like expansion of fluids in a container, solid materials will also expand in higher temperatures due to increased densities. For aluminum materials, the linear thermal expansion coefficient is $\alpha = 22 * 10^{-6} \frac{m}{m * K}$. This is a very low thermal expansion, so even at a high temperature change of 100 K, the thermal expansion of the tank's length will only be:

$$\delta_{T,L} = \left(22 * 10^{-6} \frac{m}{m * K} \right) * 100 K * 0.677 m = 1.5 mm$$

Using Poisson's ratio, this thermal expansion in length can be used to find deflection in the thickness. Poisson's ratio states:

$$\nu = -\frac{\varepsilon_{Lateral}}{\varepsilon_{Longitudinal}} \quad (\text{Eqn. 7})$$

For common metals like aluminum, Poisson's ratio is generally around 0.31, meaning the max deflection in thickness that will be seen is:

$$\delta_{T,t} = 0.31 * \frac{1.5 \text{ mm}}{677 \text{ mm}} * 7.5 \text{ mm} = 0.005 \text{ mm}$$

Because the max deflection in thickness is so small, there is no major concern for the aluminum casing becoming weak and thin enough to break.

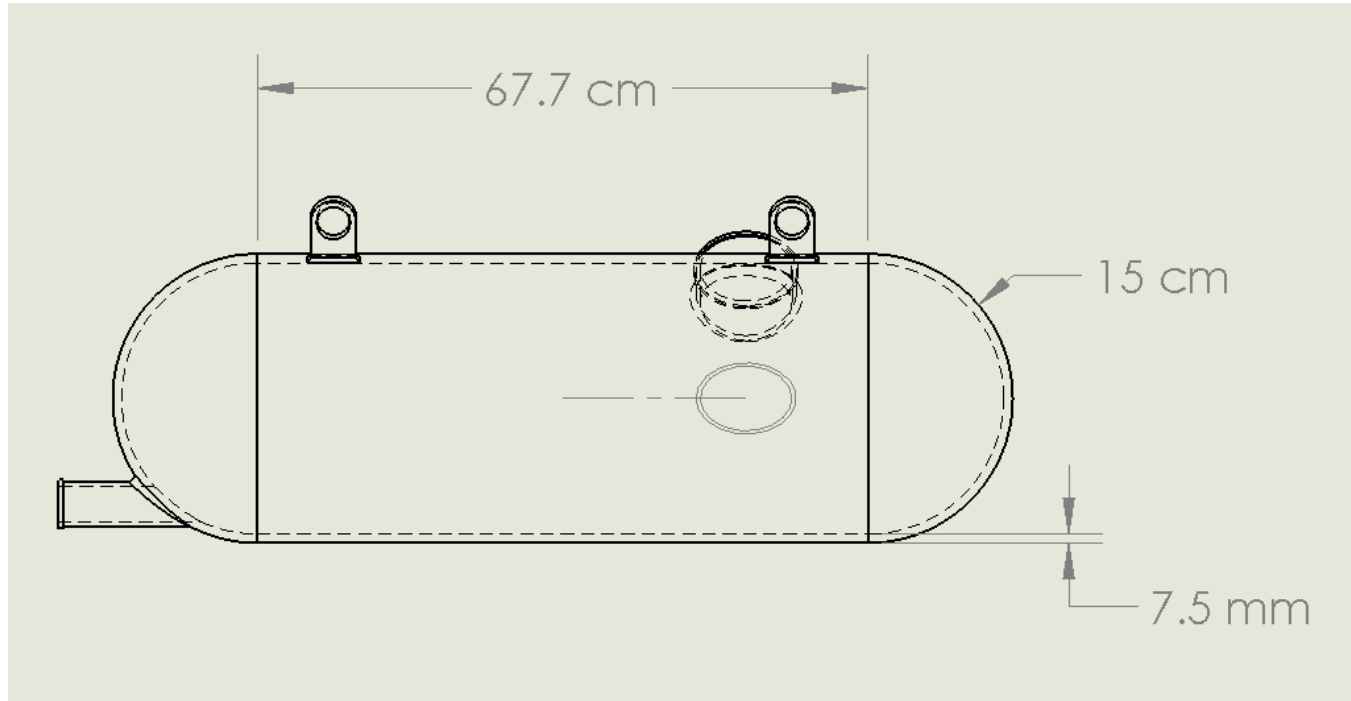


Figure 3: Final Dimensions of Tank

d) Material Selection

As stated above, the best choice for material has been narrowed down to aluminum. Aluminum is a strong metal which is resistant to temperature change, able to withstand fluid pressure, and is resilient to oxidation in the tank. The fatigue strength for a metal like aluminum is around $\frac{1}{2}$ to $\frac{1}{4}$ the yield strength, meaning that the fatigue strength for our particular case is around 60 MPa, which is still very strong compared to the stress of around 8 MPa seen in the aluminum shell. One problem that aluminum faces is that it corrodes under the presence of water. Since the tank holds a small amount of residual water, this corrosion can wear down the shell and weaken it. Since the aluminum will always be in contact with fluid, the aluminum should be anodized to help prevent oxidation of the material. The anodizing process extracts oxygen from the aluminum and creates a layer of aluminum oxide over the shell allowing for prevention of oxidation.

e) Selection of Specific Alloy

In terms of specific alloy, the best choice will be an alloy that is highly corrosion resistant, lightweight, and will be easy to manufacture to allow for swifter and easier processing for vehicles. A

good choice for these criteria would be the 6061 alloy. 6061 Aluminum is highly available, being the second most extruded alloy while providing high weldability with inert gas welding methods that lead to strong welds. Using 6061 aluminum will simplify the process for the tank's production and serve as strong resistor to physical presences like impact and temperature.

g) Material Processing

Now that a specific alloy has been selected, a material treatment process will need to be determined for the sake of knowing how tough the material can be. Calculations done in previous sections were done knowing that the yield strength of aluminum is around 270 MPa for a 6000 series alloy. In order to maintain this consistency, the aluminum can be heat treated to a T6 Temper. At this temper, the aluminum has a yield strength of at least 240 MPa, with a fatigue limit at around 97 MPa which is well above the stress threshold calculated in part 4b.^[3] This T6 temper also provides a higher resistance to impact while increasing the impact energy of the material as well.

Machining Process

The machining process for the tank is fairly straightforward due to the tanks cylindrical and spherical components. Flat plates of Aluminum 6061-T6 will be extracted from a source, and trimmed down to the appropriate thickness of 7.5 mm. Once the plates have been obtained, they will undergo and anodizing process in a tank of fluid. Following the anodization, the plates can be wrapped corner to corner, creating a natural cylindrical shape, secured together using tungsten inert gas welding. The spherical caps can also be wrapped into shape and attached via TIG welding as well. Holes can be bored for the entry and exit valves, allowing for the attachment of these valves via machine bolts and welds. Creating the final tank. The tank includes 4 attachment points to secure to the bottom of the vehicle on the backside, in a compact regime.

Estimation of Cost

In order to determine the cost of the tank, the volume of aluminum used will need to be calculated. For this tank, the main cylindrical shell and spherical caps have a volume defined by:

$$V_{Al} = ((A_{0,cylinder} - A_{i,cylinder}) * L) + (V_{o,sphere} - V_{i,sphere}) \quad (\text{Eqn. 8})$$

Using Equation 8, we find that the cylinder's volume is:

$$V_{Al,cylinder} = ((\pi(0.15 \text{ m} + 0.0075 \text{ m})^2 - \pi(0.15 \text{ m})^2) * 0.677 \text{ m}) = 0.0049 \text{ m}^3$$

Using Equation 8 again, the volume of the two spherical caps is:

$$V_{Al,sphere} = \frac{4}{3}\pi((0.15 \text{ m} + 0.0075 \text{ m})^3 - (0.15 \text{ m})^3) = 0.0022 \text{ m}^3$$

Combining the two volumes together gives that the tank's total volume is:

$$V_{Al} = 0.0049 \text{ m}^3 + 0.0022 \text{ m}^3 = 0.0071 \text{ m}^3$$

If we assume that there will be an additional 25% of material leftover as both waste and material used for the entry and exit valves to the tank, we will get a larger volume that is more accurate of cost. This 25% will also account for the price of welding and manipulating the aluminum to our specific alloy and processing.

$$V_{Al} = 1.25 * 0.0071 \text{ m}^3 = 0.0089 \text{ m}^3$$

Currently in the U.S., the price of aluminum is at around \$0.87 for a pound.^[4] Finding the weight of our tank, then converting this weight into pounds will allow for us to find the final price. Knowing that the density of our aluminum alloy is 2.7 g/cm^3 ^[3], we find the mass of our tank to be:

$$m_{Al} = 0.0089 \text{ m}^3 * \frac{(100 \text{ cm})^3}{(1 \text{ m})^3} * \frac{2.7 \text{ g}}{1 \text{ cm}^3} * \frac{0.0022 \text{ lb}}{1 \text{ g}} = 52.93 \text{ lb}$$

Giving a final cost of about:

$$C = 52.93 \text{ lb} * \frac{0.87 \text{ USD}}{1 \text{ lb}} = \$46.05$$

\$46.05 is well below the total cost of a vehicle, and will remain a good price for the tank's production.

Final Design

The goal of this project was to design a fuel tank that would be cost efficient, adaptable, and overall effective in fulfilling its purpose. The tank needed to withstand both external forces and internal pressures, while safely allowing for the transportation of fuel to the vehicle's engine. Although simple in design, there is still more that should be considered for a higher level project, including how fuel is transported from the tank, and how the tank will hold up to dynamic flows and chemical compositions of materials.

The final design specs can be summarized below, and outline all major features that were considered during the design process.

Tank Material:	Material Alloy:	Material Processing:
Aluminum	6061	Temper T6
Internal Tank Radius:	Tank Cylindrical Length:	Tank Thickness
15 cm	67.7 cm	7.5 mm
Tank Weight:	Tank Cost of Production:	Tank Gasoline Capacity:
52.93 lb	\$46.05	56.5 L

Future projects should be focused around specific vehicles, allowing for more customized fuel tanks that will be ideal for the specific vehicle, not as a general design for all vehicle types.

References

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