Manufacturing Liquid Propellant Tanks for Space Vehicles

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***Abstract*—In the 21st century, the extent to which our lives have become so dependent on artificial satellites is astounding. From communications and navigation to earth observation and planetary exploration, satellites have become essential for tasks as conventional as watching television to dealing with national security threats. To get the satellites to their destination orbit, we require an orbital class rocket.**
All launch vehicles require some form of propulsion to breach the Karman line and reach orbit.The most widely used one is chemical propulsion which requires chemical propellant.
The launch vehicle needs to carry its propellants, both fuel and oxidizer, through the flight safely and feed it to the engines consistently and at high pressure. In this project we dive deep into the design and manufacturing of a liquid propellant tank manufactured by the ULA.

I. Product Description

A liquid-propellant tank in space vehicles is a pressure vessel that is also a part of the vehicle. In bipropellant rocket engine systems, the propellants are stored in separate fuel and oxidizer tanks within the flying vehicle. They store the propellant while **minimizing slosh and vortexing**.Their design also depends on the propellant feed systems and the engines used.
Since the tanks are part of the vehicle itself, their dry mass needs to be low, and the material should withstand high pressures, vibrations, and cryogenic temperatures. **Balloon tanks** are the most extreme of these as they are held rigid only by internal pressurization but are incredibly lightweight. These tanks are usually shaped **spherocylinders** (capsules). Although the optimal shape for the desired properties is spherical, it doesn't utilize the vehicle's volume appropriately. While increasing volume and weight are always trimmed down, spherocylinders offer the best solution. The absence of edges makes the handling of pressure easier, allowing to produce a safer tank.

II. Product Applications

Propellant storage tanks are present in all stages of the launch vehicle and also in the spacecraft. They store the propellant used by engines and thrusters to impart thrust to drive the vehicle up or control other motions such as pitch or roll. In many cases, they also hold the pressurant tanks required to keep the propellant tanks pressurized. The Liquid propellant tanks onboard satellites store the propellant for an extended period while minimizing boil-off.

III. Cost Approximation

Due to the competitive nature of the industry and space vehicle technology coming under the purview of International Traffic in Arms Regulations (ITAR) due to its sensitiveness, much information about them is kept officially classified. So, the actual costs of launch vehicles parts such as propellant tanks are unknown.
Here, we attempt to provide an educated approximation of the costs using method of extrapolation.

Through data correlating spacecrafts' propellant tanks volume and their costs, available indirectly from Orbital ATK Space Systems Group, we have come up with a functional equation to estimate costs of launch vehicles propellant tanks through curve-fitting. However, we are mindful of the differences in tank types for spacecraft and launch vehicles. The former requires much higher standards to be met and employs sophisticated manufacturing equipment, but the latter needs a much larger developmental site and equipment. So, we have tweaked the data a bit to account for higher fixed costs.

Volume (m^3)	**Cost**
0.461	$640,000
0.432	$620,000
0.229	$520,000
0.059	$290,000
0.015	$100,000

The best-fit curve for the above data as derived using Python scripts is:

$$Cost = 158112 * ln(Volume) + 753943 \tag{1}$$

We will now use the best-fit curve to estimate the cost of **oxidizer** tanks on some well-known launch vehicles' first stages, namely **SpaceX's Falcon 9** and **ULA's Atlas V**.

- **Falcon 9**
  The Falcon 9 booster stage carries **287,400 kg** of **Liquid Oxygen** (LOX) stored at the temperature of **-207°C**. At this temperature, LOX is 10% denser than at its boiling temperature, so ρ is **1250 kg/m^3**.
  Therefore, Volume of LOX stored accounting for approximately 5% for ullage available for pressurant, pressurant tanks and baffles is **241 m^3**.
  From the curve, the total cost to company for a single

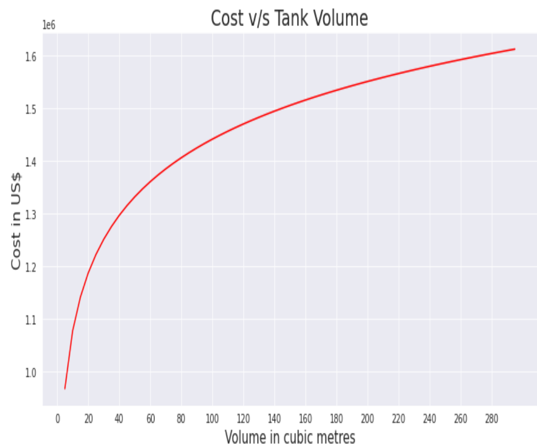

Fig. 1: Best-fit curve

Oxidizer tank on Falcon 9 booster is approximately **1.62 million USD**

- **Atlas V**
  The Atlas V first stage carries **207,385kg** of **Liquid Oxygen** (LOX) stored at the temperature of **-183°C**. At this temperature, the density of LOX ρ is **1141 kg/m**^{3}.
  Therefore, Volume of LOX stored accounting for approximately 5% for ullage available for pressurant, pressurant tanks and baffles is **191 m**^{3}.
  From the curve, the total cost to company for a single Oxidizer tank on Falcon 9 booster is approximately **1.58 million USD**

IV. Desgin, Drawing & Components

A. Design

Propellant tanks are designed to maximum hoop stress seen due to pressure loading due to internal pressure and hydrostatic pressure at maximum flight g-loading.
Here, we frame the design requirements of a propellant tank based on what NASA expects in order to certify a vehicle for Crew.

Operating pressure	7.5 bar
Proof Pressure	8.5 bar

We have attempted to back trace design considerations for the **Falcon 9** rocket's Full-Thrust Block. Some of its required specifications are:-

Inner Diameter	3.7m
Material Used	Al-Li 2195 alloy
σ_{UTS}	590 MPa
Wall Thickness	4.7mm
Dome Shape	Ellipsoidal (a=3c)
Barrel Length	21.6m
ρ_{lox}	1250 kg/m^3

Since propellant tanks have very little thickness compared to their other dimensions, **Plane stresses** can be assumed and that it remains constant in the material across the thickness, all along the length.
Stresses in the cylindrical barrel section of the tank:

- **Hoop Stress**
$$\sigma_h = \frac{P_{lox}r + \rho_{lox}g_{max}h}{t_{tank}} \tag{2}$$
  where g_{max} is around **6g** and
  h = Barrel length + ellipsoid height = L + c; *ullage=c*
  σ_h comes out to be around **683 MPa**
- **Axial Stress**
$$\begin{aligned}\sigma_l &= \frac{P_{lox}r + \rho_{lox}g_{max}h}{2t_{tank}} \\ &= \frac{\sigma_h}{2} = 341.5MPa\end{aligned} \tag{3}$$

Considering **Von Mises Failure** criteria for plane stress,
$$\sqrt{\sigma_h^2 + \sigma_l^2 - \sigma_h\sigma_l} \leq \sigma_{UTS} \tag{4}$$
Using the following relations, we obtain,
$$\begin{aligned}\sigma_l = \frac{\sigma_h}{2}, \sigma_h &= \frac{P_{lox}r + \rho_{lox}g_{max}h}{t_{tank}} \\ t_{tank} &\geq \frac{\sigma_h\sqrt{3}}{2 * \sigma_{UTS}} \\ &\geq \mathbf{4.57\ mm}\end{aligned} \tag{5}$$
And the tank thickness of Falcon 9 in practice is **4.7 mm**, very much in accordance with our result.
To design a tank shell which can endure such high stresses and still be relatively lightweight, parameters taken into consideration are- **Temperature environment, mass properties of fluid, and Material, mass properties of tank shell**
To maintain rigidity while keeping the structure strong and light-weighted, **Isogrid** structures are machined out of the Barrel sheets. Isogrid uses an array of equilateral triangle cutouts to increase the stiffness per weight of a structure. The pattern may be manufactured by machining a metallic panel, or it may be constructed using fiber composite materials. Isogrid is an efficient stiffening technique for dome structures and the work was later extended to include plates and cylinders.

B. Components

The components that make up a propellant tank are the central barrel frame, the ellipsoid bulkheads on either ends and the feed systems for the fuel, pressurizer.
For the barrel of tanks used in upper stages, the tank does not need to bear any additional weights or higher g forces, so allowing a thin and tough metal sheet to support.
The barrel is made of multiple arc pieces welded together. This helps the making of the grid patterns and keeping material properties in desired state easier. The parts are welded together using friction stir welding. As, welding by means involving heating leads to distortion in the uniformity and development of residual stresses and strains.
The ellipsoidal bulkheads of the capsule tank are made stronger and thicker than the barrel portion owing to higher stress developments. To join it to the barrel portion, friction

Fig. 2: Isogrid structure

weld is to be used again for earlier mentioned reasons. The end has to be a dome as the presence of edges of any sort would lead to enormous stresses and failure. The bulkheads are similar in role but are different in where they are positioned. Multiple Tanks that store the oxidizer, fuel etc. Are sometimes held together using mechanical supports which keep the tanks safe and intact while help dampening the vibrations caused be stirring or turbulent liquid content flows.

C. Drawing

The following drawings are sized for Falcon 9 Block 5 design. Original dimensions have been scaled down by **100**.

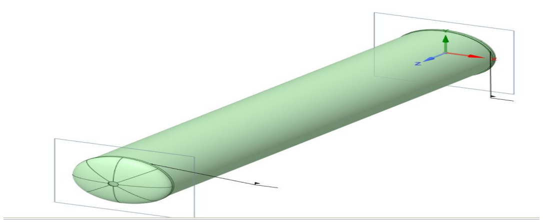

Fig. 3: General Propellant tank

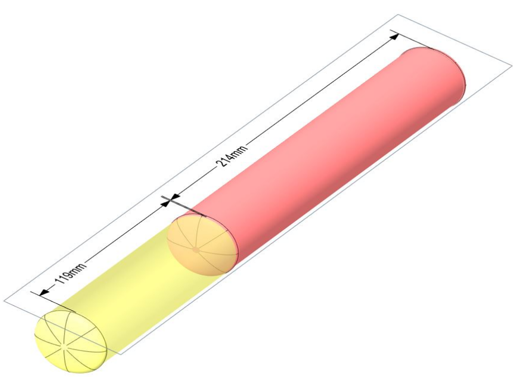

Fig. 4: LOX/RP-1 tanks assembly on Falcon 9

Fig. 5: Side view of tanks assembly on Falcon 9

V. Materials & Process Selection

A. Materials

The propellant tanks of a rocket are first supposed to not interact with the fuel or oxidant neither physically or chemically. The fuels majorly used now are cryogenic fuels, which means they are to be maintained at extremely low temperatures. The fuel or oxidants which are usually used are ones with high energy per volume. The *common* fuels are

- Liquid Methane
- Liquid Hydrogen
- Refined Kerosene
- And Liquid Oxygen is the mostly used oxidant.

Liquid hydrogen provides with the most energy density but has a major disadvantage of low density. Other fuels such as Kerosene and Methane might have a lower energy density but are dense and save space. And Hydrogen storage and handling is difficult as it disperses through many materials. Thus, making Liquid hydrocarbons the next best fuel, for both storage and operation. There are various options to chose from for making tanks for the Liquid Oxygen and Hydrocarbons.

Fuel tank materials: The limiting quantity for the tank materials is the tank weight, as in the case of any rocket component we would link to make it as light as possible for better efficiency. The fuel tank materials should have these *properties*:

- Low thermal conductivity
- High tensile strength at the low temperatures
- Practical fabrication possibilities
- Economic feasibility

As said in earlier sections, the tank is mostly under stress from the contents inside and so, never really under any compressive stresses. The best materials which satisfy the requirements are metallic such as **Titanium**, **Aluminum**, **Stainless steels**. Titanium and Aluminum are mostly used as Alloys which provide better statistics for our requirements. The other major option are carbon fiber, composite materials, epoxies and resins. Due to complicate making processes, the slight margin of improvement with these is ignored and general metallic tanks are used. The metallic tanks are made with higher grade refined raw materials than general market available products. Such as the zinc grade Aluminum, with zinc being the major alloying element, the 7000 series aluminum is a often used choice, it is seen used in the ULA's Atlas rocket for various components.

The next generation rockets such as the SpaceX starship (now retd.), the Rocket Lab Electron use carbon fiber and composite material tanks. The tanks of carbon fiber are extremely expensive in making so are only used in the recent reusable rockets. The lesser used material options are beryllium copper alloy, Duralumin. The tanks are also in cased in low conductive material coatings.

B. Processes

Since rockets are generally not made in large volumes but require tight tolerance and excellent quality, the manufacturing processes involved are high-end and machinery utilized is usually custom made for the rocket. So, the criteria for selection is **low volume and high per piece cost**. Here, we have enlisted the manufacturing processes involved for fabricating the components of a propellant tank of ULA's Atlas V.

- **Barrel Section**
  6mm thick, **2.4m** wide and **6.4m** long sheets of **7000 series** Aluminum comes in which is converted into one of the five sections that make up the barrel of a cylindrical propellant tank.
  First the sheets need to be machined to form the Isogrid pattern then they need to be given an accurate curvature which is followed by applying a coating of thin oxide layer and then the sections are finally welded together to form the barrel.
  The processes selected are-:
  1. Skin Milling: CNC end and side milling to machine out an array of inter-connected equilateral triangles. Water is used as a coolant and the chips are all collected and recycled.
  2. Bump Bending: In order to provide a smooth, wide-radius curvature in our thick high-strength plate section, dozens of bends are bumped by the brake punch a few degrees at a time.
  3. Annodizing: A thin layer of oxide is applied using a pool of sulphuric acid. It provides the barrel not just corrosion resistance but also a little bit of extra hardness which prevents stress corrosion cracking.
  4. Friction Stir Welding: To assemble the barrel, the five curved plate sections are fixed and held mechanically and welded together one seam at a time. In comparison to conventional welding in which a filler material is fused with the parent material which creates a heat-affected zone that has different mechanical properties than the parent material, friction stir-welding mechanically stirs the parent material itself which leads to a strong joint.

- **Bulkhead**
  1. Blanking: A roll of 2mm thick Aluminum sheet is stretched over an appropriately sized and gore-shaped die and subsequently punched to obtain the panel.
  2. Welding: These panels are then welded together using friction-stir welding for the first stage tanks and resistance arc welding for the Centaur stage since the panels are too thin for friction-stir welding.

- **Final Assembly**
  The bulkheads are assembled with the barrel using **self-reacting circumferential friction-stir welding**.

VI. Manufacturing, Assembly, Coatings, Machines and Inspection

Since the oxidizer-to-fuel ratio of **RD-180 engine** is **2.72** and total propellant mass is **284,089 kg**, it can be worked out that the sheets would be around 6.4m long if **5%** length is reduced while machining.
So, the raw material for the propellant tank manufacturing unit at **ULA** is **6mm** thick, **2.4m** wide, **6.4m** long, 7000-series Aluminum sheets from a company called **Arconic**.

- **Skin Milling**
  First both sides of the aluminum sheets are planed by removing about 0.2mm thick layer from either side using an automated CNC milling machine.
  Then, both sides are manually cleaned and inspected one side undergoes **end-milling and side milling** to create slots for fabricating the Iso-grid structure. Coolant used is **Cimtech 310-5%** (and water-95%) which is a low-pH synthetic fluid approved for use in the aerospace industry and provides excellent lubricity which enhances the tool life. This is supplied using a hole in the tool head. The tool head is a **square end** bit made of tool steel. The whole operation of milling and inspecting an aluminum sheet at every stage takes about 2 days.
- **Bump Bending**
  The milled sheets are then brought to the bump bending press after drying and inspecting it for sometime by hanging. Two operators manually operate both the strong-back bump press and an overhead crane which pulls the sheet up thus displacing the sheet from the die.
  A single panel is bumped around **6 dozens** times with the distance between each bump being **33.25mm**
  First the sheet is positioned behind the press on a roller card and slightly pulled over the die, then the punch is lowered and pressed against the sheet; the punch is subsequently raised and the operator pulls the sheet up by a few inches and bump presses again to create the curvature with the desired radius of curvature. Then, the segments are inspected whether or not they have the desired curvature within the tolerance bounds.
- **Blanking (for Bulkhead)**
  The bulkhead is made up of about **24** gores of upper width of about **0.05m** and lower width of about **0.5m**. The sections are produced by punching the milled sheets againt dies of the required shape and dimensions. The hole in the middle is used to attach plumbing which provides the propellant feed to the engines.
- **Surface finishing/Coatings**
  Etching & Annodizing: The curved plates are then sent to the chemical processing unit where they are etched to get a consistent high quality surface.
  First, the segments are rinsed and washed with water and alkaline cleaner such as **Turco 6849 -10% and Ardrox**

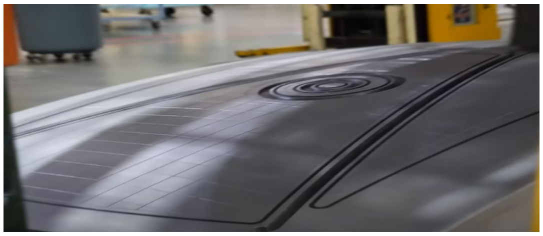

Fig. 6: Bulkhead Gore Die

157B to get rid of any chemical substance left over on the surface from machining.
Then, the segments are etched in a dip tank of **10% Sulfuric acid** solution which also gives it a thin oxide layer. The segment is then taken out of the tank and rinsed with water and then again dipped in a large tank of **10% Nitric acid** solution through which electricity is passed which gives it a **thicker oxide layer**.
Finally, the segment is taken out and cleaned using an alkaline etchant cleaner **(Nova EC-202L- 5-10%)**, dried and inspected.

- **Barrel Assembly**
These panels are now to be assembled together to form the barrel section. Five of these panels are brought together and held mechanically in a custom designed large fixture which keeps the panels **vertically stacked** so that heat from welding draws them up, also **providing a reaction** against the welding tool head so that material does not get through and this whole setup is on a rotary stage which turns the fixture so that all the five panels can be welded one seam at a time without moving the welding tool. This reduces complexity in the design of the welding machine and thus reduces cost. The Welding tool head is made of **tool steel AISI H13**.

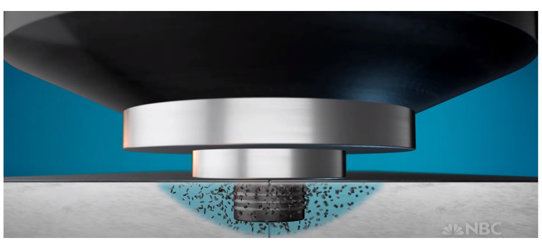

Fig. 7: Friction Stir Welding

- **Final Assembly**
For final assembly, the barrel and bulkheads are set in their respective fixtures **(horizontally)** and are welded together by **circumferential self-reacting friction stir welding** which is attained through clever design of the tool head and the fixture. However, much information about fixture design is not available in the public domain due to **ITAR**.
- **Machines**
1. 25ton hydraulic brake presses
2. 2-axis CNC milling machine with **12m** rail length

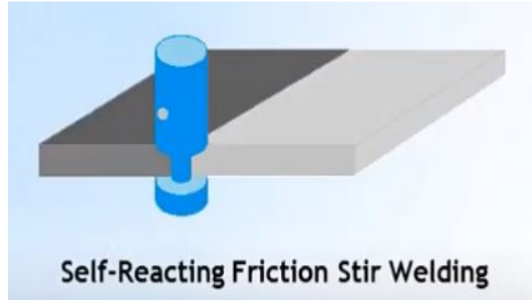

Fig. 8: Self-reacting Friction Stir Welding

3. 2-axis Friction Stir Welding Machine
4. 3-axis Self-reacting Friction Stir Welding Robot
4. Dip tanks of more than **40 cubic metres** volume capacity

Fig. 9: CNC Milling Machine

Fig. 10: Bending Press

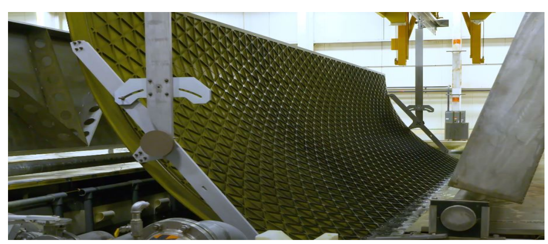

Fig. 11: Dip Tank for Annodization

- **Inspection**
  There are several manual inspections during and after every stage of manufacturing.
  Before actually milling the iso-grid, the planed sheets are **manually** inspected for any leftover chip etc.
  After bending, the panels are inspected for their curvature and after chemical processing, the panels are dried for natural ageing which also gives it a tint of bronze color which is very much a hallmark of Atlas V booster and inspected for a consistent layer of oxide.
  Bulkhead gores are inspected for surface breaking defects by using a dye penetrant such as **Magnaflux ZL 60 B**
  After assembly, the barrel welds and the circumferential welds between the barrel and the bulkheads undergo **Radiographic testing** in an **X-ray** booth. Penetrating radiation is passed through the welds which absorb part of the energy. The amount of energy absorbed by the object depends on its thickness and density. The areas which do not absorb any energy will be dark when the film is developed. This provides a permanent film record of weld quality which is inspected by a trained personnel and is rejected or approved after which the assembly either undergoes further processing or more inspection.
  The tank is finally **pressure tested** by filling the tank with an inert liquid such as **water or LN2** above the pressure the tank would see in-operation during flight. This not only checks for leaks and structural integrity but also **work hardens** the tank which marginally increases its capacity and strength.
  After this, all the required plumbing is installed on the tank and is sent along the assembly line for further integration with other hardware such as the rocket engines, avionics, etc., and the completed article is rolled out to its destination.

VII. Cost Analysis

Here we attempt to estimate the direct costs incurred by the company for producing a single propellant tank. For better understanding, we follow a particular launch vehicle here, namely **SpaceX's Falcon 9**.

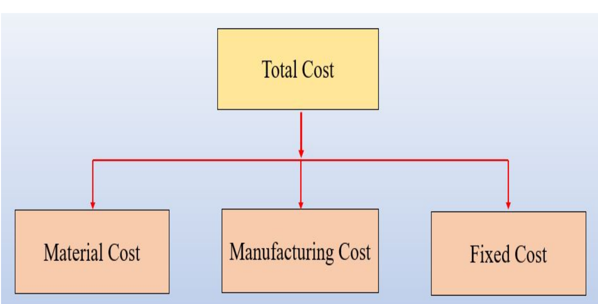

Fig. 12: Total Cost Structure

Before we delve deep into each one of them, some specifications of the Falcon 9 booster's oxidizer tank:

Inner Diameter	3.7m
Material Used	Al-Li 2195 alloy
LOX Tank Volume	241m^3
Wall Thickness	4.7mm
Dome Shape	Ellipsoidal (a=3c)
Barrel Length	21.6m
Segments in Barrel	5

Note: Some appropriate assumptions have been made based on known data, such as dome (bulkhead) shape has been approximated to be **ellipsoidal with a=3c**.

- **Material Cost**
  Al-Li 2195 Aerospace grade alloy- Cost is around **$15/kg** and density is **2.7g/cc**
  Volume of material in the LOX tank:
  $$V = \pi DLt + \frac{\pi D^2 t}{2} \quad (6)$$
  D: Inner Diameter, t: Wall Thickness, L: Barrel Length
  But since we know that around 5% more material is required for baffles, internal plumbing, etc. and **seven-tenth** of the material is lost while machining , total volume of material purchased is **4.50 m^3** which is **12,150 kg**. Therefore, total material cost is around **$183,000**.

- **Manufacturing Cost**
  Milling
  Assuming that it takes effectively **1 day** to machine the iso-grids in one panel, and the machining happens half of the day i.e. machining time per piece (tm) is **12 hours**.
  Using approximated data,
  Labour cost per hour (L_m) be **$25/hr**
  Overhead charge (B_m) of the machine that includes draining high amount of energy every hour, be **$275/hr**
  So, machining cost per piece of panel is
  $$c_m = t_m(L_m + B_m) \quad (7)$$
  Cost of machining one panel comes out to be **$3,600** so cost of machining for one tank is 5 times $3,600 which is **$18,000**
  If the set-up, loading and unloading and tool cost, all combined cost same as the machining cost per tank. Then, total cost of **milling operation** is **$36,000**

  Bump Bending
  Assuming that it takes **6 hours** to bend one panel of the barrel, Labour cost per hour (L_m) be **$25/hr** and Overhead charge (B_m) of the machine that includes draining high amount of energy every hour, be **$375/hr**
  Cost of bending all panels of a propellant tank should be around **$12,000**. If the set-up, loading and unloading and tool cost, all combined cost same as the process's cost per tank. Then, total cost of **bending operation** is **$24,000**

Annodizing
Assuming that **1 batch** of chemicals i.e. mainly sulphuric acid and nitric acid are required for annodizing all panels of a booster propellant tank, each batch being **45m**^{3}, and cost of sulphuric acid being **$0.5/kg** and cost of nitric acid being **$1/kg**.
Cost of sulphuric acid incurred is **$42,000** and cost of nitric acid incurred is **$68,000**.
Assuming all other costs of this operation is one-fourth of the total cost of the chemicals, annodization cost can be approximated to be around **$140,000**, which makes this process one of the costliest manufacturing processes involved.

Welding
Using known industry standard data:
Aluminum welding time (r): **0.6 m/hr**
Cost of welding: **$150/hr**

$$L' = 5L + 2\pi D \tag{8}$$

L': Length of weld, which is the summation of circumferential welds and longitudinal welds; ***L'* = 131.25m**
Cost of welding = 150* $\dfrac{L'}{r}$ which is almost **$33,000**.

Total Manufacturing Cost of a booster propellant tank should be around **$233,000**

- **Fixed Costs**
  Fixed costs make up the maximum portion of the costs incurred by the company but is difficult to estimate with such limited information, as is available. Fixed costs includes **Factory overheads, R&D, Distribution overheads, etc.**

VIII. Role of Team Members

Individual contribution in this report:
Abstract, Cost Approximation, Design, Engineering Drawing, Process selection, Manufacturing, Assembly, Machines, Inspection, Cost Analysis: Vishal Srivastava

Description, Applications, Components, Material selection: Nikith Veerapaneni

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