ME338: Manufacturing Processes II
Course Project Presentation

Manufacturing Liquid Propellant Tanks for Space Vehicles

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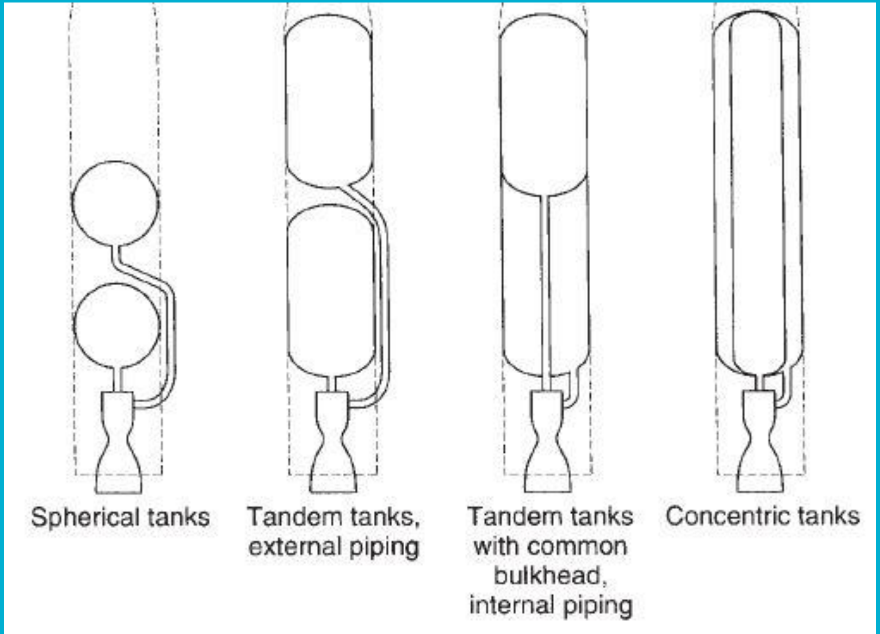
Description

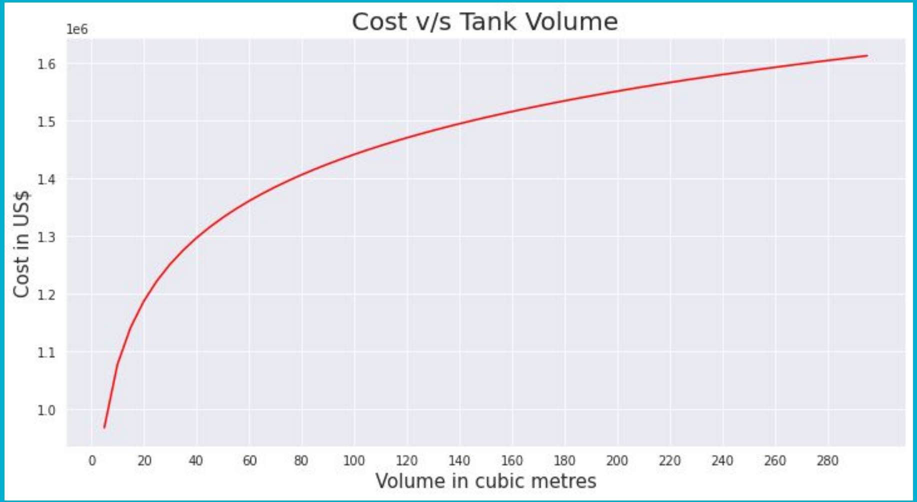


- ❖ Pressure Vessel
- ❖ Must withstand :-
- ★ high pressures; **7 bar** for normal payload and **8.5 bar** for human spaceflight certification
- ★ Cryogenic temperatures
- ★ High vibrations
- ❖ Must be inert to the propellants used such as LOX, RP-1, LH2, CH4, UDMH, NTO, etc.
- ❖ Optimized for high strength to weight ratio, and minimizing slosh and vortexing

Applications

- All advanced orbital rockets use liquid-propellant tandem tanks with common bulkhead. Examples- Atlas V, Falcon 9, Saturn V
- Propellant tanks store large quantity of cryogenic liquid propellants prior to use
- Feed propellant directly to the engines at high pressures using either autogenous pressurization or auxiliary gas tanks for pressurization system

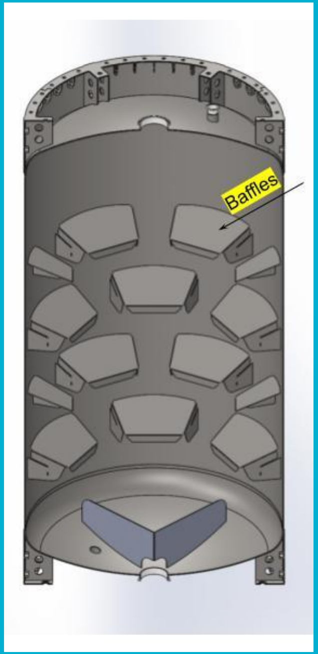
Cost Approximation



Cost = $[158112 ∗ ln(Volume) + 753943]

- Using data (indirectly) obtained from Orbital ATK Space Systems Group, and including higher fixed costs and more
- The below equation represents a functional relationship between Cost of a propellant tank and the tank's Volume
- Falcon 9 LOX tank should cost SpaceX around $1.62M
- Atlas V LOX tank should cost ULA around $1.58M

Components



Broadly, a propellant tank has 2 main components, namely:

1. Cylindrical Barrel Section
2. Ellipsoidal Bulkheads

Other minor structural components include:

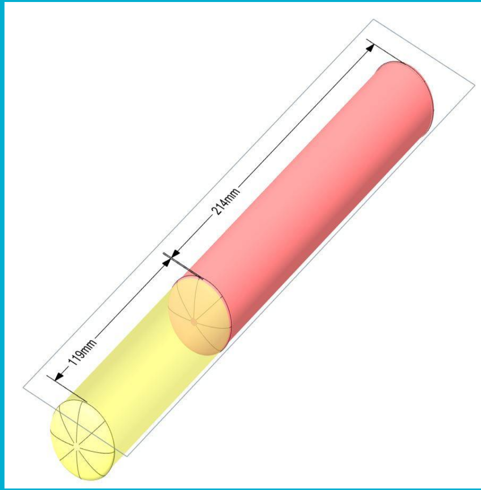
1. Baffles
2. Pressurization system supports
3. Internal and external piping to the vents and the engine thrust pucks.

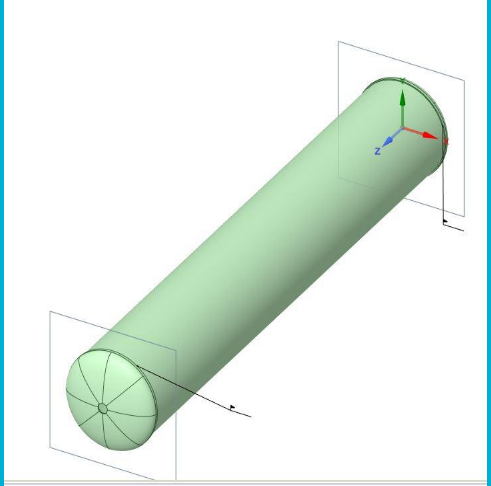
Design

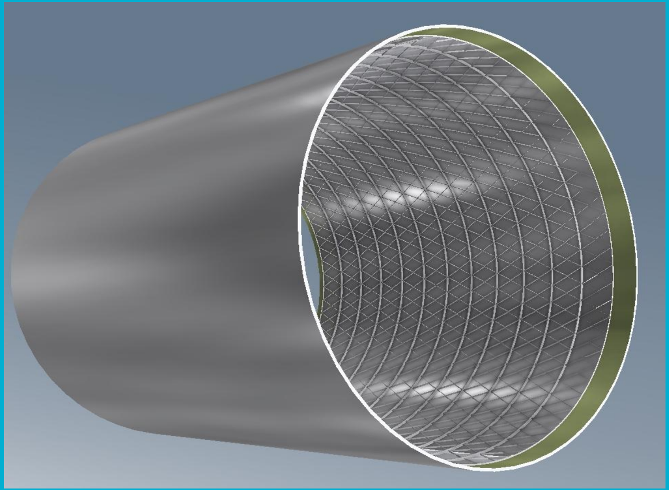
Structural Design focuses on high strength to weight ratio which heavily influences material selection. Further stiffness is achieved by either using stiffeners or by fabricating isogrid/orthogrid panels.

For Falcon 9,

- Material used- 2195 Al alloy
- Tensile Strength (Ultimate)- 590 MPa







Design (for Falcon 9)

Since wall thickness (t_{tank}) is much less than other dimensions, Plane stress can be assumed.

Hoop Stress (σ_h)

$$\sigma_h = \frac{P_{lox} r + \rho_{lox} g_{max} h}{t_{tank}}$$

where g_{max} is around **6g** and

h = Barrel length + ellipsoid height = L + c

σ_h comes out to be around **683 MPa**

Axial Stress (σ_l)

$$\sigma_l = \frac{P_{lox} r + \rho_{lox} g_{max} h}{2 t_{tank}} = \frac{\sigma_h}{2} = 341.5 MPa$$

Considering **Von Mises Criterion** for failure and using the known relations between t_{tank}, σ_h, σ_l

$$\sqrt{\sigma_h^2 + \sigma_l^2 - \sigma_h \sigma_l} \leq \sigma_{UTS}$$

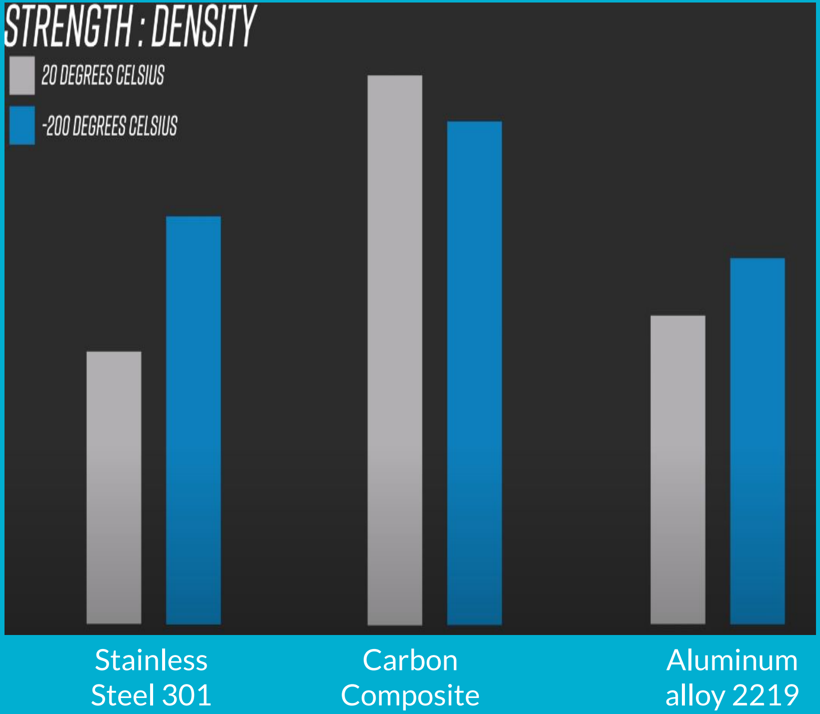
$$t_{tank} \geq \frac{\sigma_h \sqrt{3}}{2 * \sigma_{UTS}} \geq \mathbf{4.57\ mm}$$

Known-

- Peak Pressure (proof) = **8.5 bar**
- Barrel length = **21.6m**
- Tank Diameter = **3.7m**
- ***Wall thickness = 4.7mm***

Real wall thickness (4.7mm) in accordance with the minimum requirement as stated in our result

Materials



Material selection criteria:

1. Chemically inert to the fuel, oxidizer and pressurant to be used.
2. High specific tensile strength (at cryogenic temperatures)
3. Easy to fabricate and work with
4. Low per kg material cost
5. Low thermal conductivity
6. Low porosity

However, no one material has it all!

Materials (examples with grade score)

Aluminum
(2000,7000 series Al-alloys)

1. Sp. Tensile Strength - 7/10
2. Ease of fabrication and workability- 10/10
3. Low per kg material cost- 8/10

Total score = **25/30**

E.g. Falcon 9, Atlas V, SLS

Stainless steel
(300 series cold rolled)

1. Sp. Tensile Strength - 6/10
2. Ease of fabrication and workability- 8/10
3. Low per kg material cost- 9/10

Total score = **23/30**

E.g. Starship, Atlas V 2nd stage

Advanced Carbon fiber reinforced polymers

1. Sp. Tensile Strength- 10/10
2. Ease of fabrication and workability- 6/10
3. Low per kg material cost- 5/10

Total score = **21/30**

E.g. Electron, Starship (retd.)

As suggested by the total scores of the materials,

- ❖ Aluminum alloys are most widely used
- ❖ Carbon Composites are least used
- ❖ Stainless steel use is now picking up!

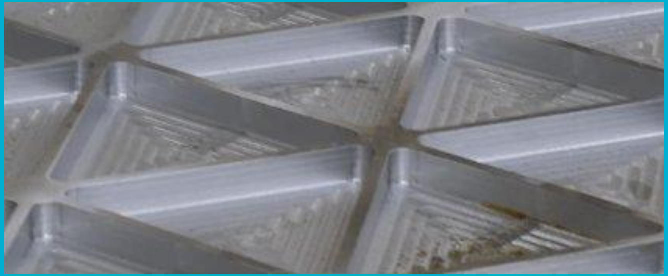
Process Selection & Manufacturing

Atlas V

- Low volume production
- Excellent quality
- Tight tolerances

Barrel Section

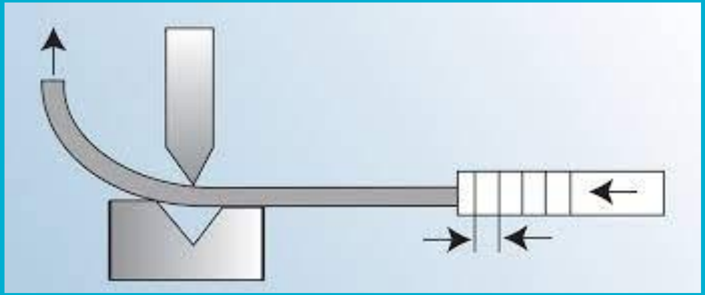
Raw Material- 6mm thick, 2.4m wide and 6.4m long sheets of 7000 series Aluminum alloy



Skin Milling-

- >66% of the material is machined out, reducing weight while maintaining strength
- First, both surfaces undergo planing to remove 0.2mm material from either side
- Iso-grid slots fabrication using **side & end-milling**
- 2-axis CNC milling machine with 12m rail length and stainless steel tool
- Coolant used is **Cimtech 310-5%**
- Whole operation to machine 2 out of the 5 panels required takes 2 days

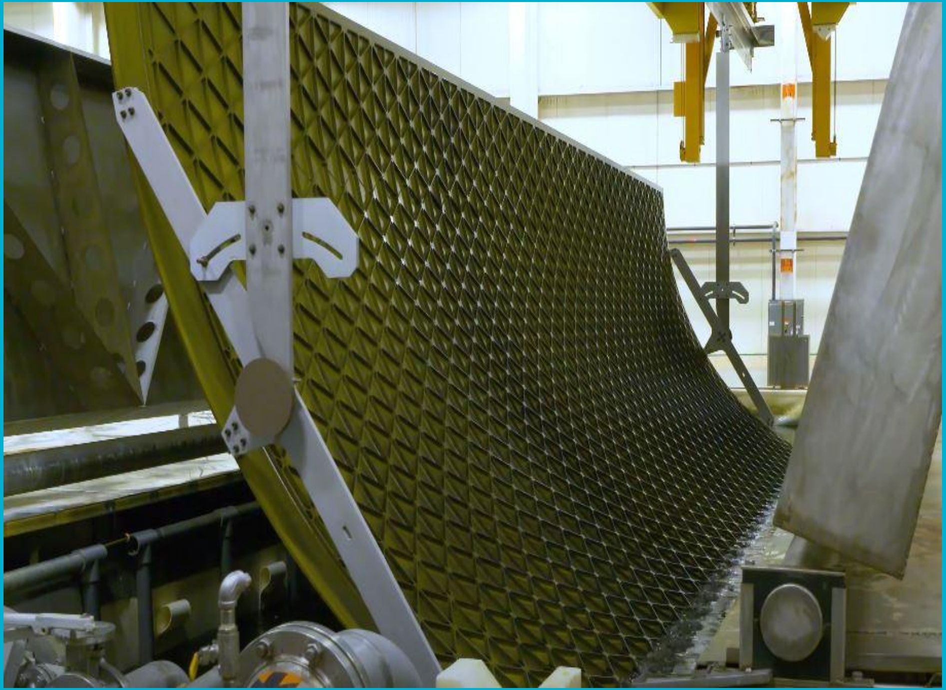
Barrel Section



Bump Bending-

- To provide the machined panels, a smooth and uniform curvature of radius 1.91m
- Manually operated 25-tons hydraulic bump presses are used
- A 2.4m wide panel requires **6 dozen bends, each 33.25 mm** apart.
- The sheet is initially positioned behind the press on a roller card
- Then it is pulled by an overhanging crane, the die is lowered and pressed against the sheet.

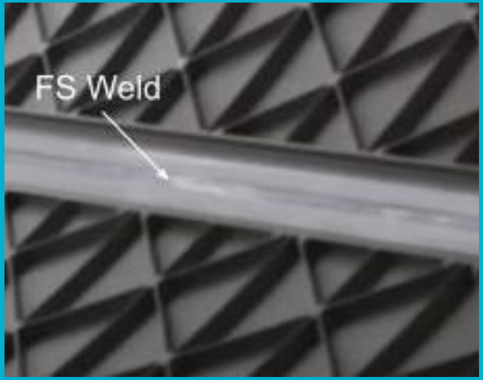
Barrel Section

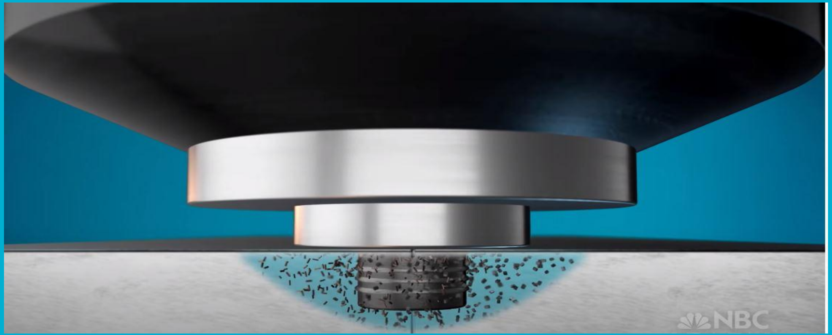


Etching & Anodizing-

- To get high quality surface finish and apply a thin layer of Oxide providing resistance to stress corrosion cracking
- The panels are first cleaned using **Turco 6849-10%** and **Ardox 157B**
- The panels are then immersed in a dip tank (>40m^3) of **10% H_2SO_4** solution
- The panels are rinsed with water and further electrolysed in a similar dip tank of **10% HNO_3** which grows the Oxide layer significantly
- Finally, the panels are cleaned using etchant cleaner **Nova EC-202L- 5-10%**

Barrel Assembly





Friction Stir Welding-

- Five of such panels are vertically tacked in a cylindrical fixture with a rotary stage
- They are joined together using friction stir welding, one seam at a time
- Friction stir welding does not melt the panel material i.e. Aluminum, so the mechanical properties are retained and there is a small heat affected zone (HAZ)
- Vertical stacking the panels together in the fixture provides reaction against the tool head and heat from the welding draws the panels together.
- Welding tool head is made of **tool steel AISI H13**

Bulkhead (for Upper Stage)

Fig. A gore of specified dimensions

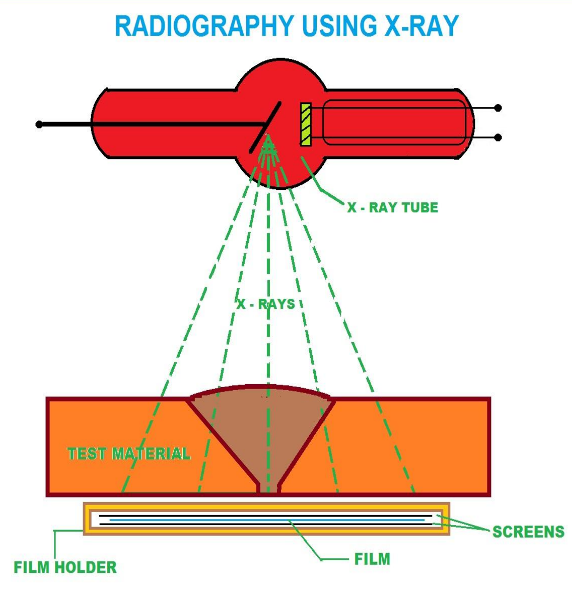
- Cold rolled **2mm** thick sheets of Stainless Steel are stretched over die of the shape as shown
- A punch shears the sheet to produce a gore of upper arc length of **0.05m** and lower arc length of **0.5m** as shown
- 24 of these gores are then welded together to make a bulkhead with a hole in the centre for plumbing
- Since these gores are too thin for friction stir welding, they are joined using resistance arc welding.
- On the booster, they are made of thick aluminum sheets and friction stir welded

Final Assembly

- The first stage barrel and the two bulkheads are horizontally set in their fixtures as shown
- They are welded together using **self-reacting friction stir welding**
- This is a relatively faster process but leaves a terminal hole that has to be filled in later
- This is achieved using clever tool and fixture design

(Much information unavailable in public domain due to **ITAR**)

Inspection



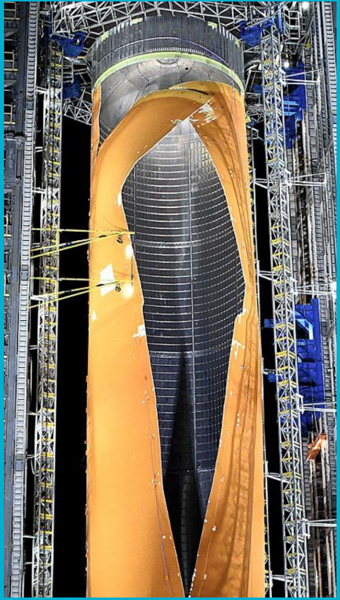


Fig. SLS Developmental Testing

All components are inspected before and after every stage of manufacturing. Some of the major inspections are as follows:-

- Bulkhead gores inspected for surface breaking defects using dye penetrant **Magnaflux ZN 60 B**
- Barrel welds and circumferential welds undergo **Radiographic testing** in an X-ray booth
- The final assembly of the propellant tank is **pressure tested** using water or liquid Nitrogen slightly above the in-flight operation pressure

(During developmental testing, the (test) tanks are pressure tested to destruction to gather data)