Water Flow and Fuel Loading

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ACADEMIC-INDUSTRY LIQUID ROCKET SYMPOSIUM 2023

Why Perform A Water Flow Test?

- Determine if pressurant regulator is adequate for a pressure fed system
  - Pressure during propellant flow
    - Pressure drops
      - Thrust will drop with tank pressure
      - Regulator is inadequate
      - Excessive pressure drops in plumbing
      - Use helium instead of nitrogen
    - Pressure stays constant
      - Thrust will be as expected
      - Regulator is adequate
      - Plumbing is adequate

It Is Also A Good Time To Practice a Wet-Rehearsal

- Propellant and Pressurant Loading/Unloading
- Systems Integration
  - Ground Support Equipment
  - Control Console
  - Procedures
  - Countdown

When to Perform Water Flow Testing?

- Before the propulsion team commits to a rocket engine static test firing

- This test would validate:
  - Static firing test stand pressurant subsystem
  - Static firing test stand propellant loading/unloading
  - Ground support equipment
  - Control console
  - Procedures

Water Flow Testing Must Be Performed in a Safe Area

- There is no ignition
  - No fire hazard
- The pressurant and propellant tanks will be brought to full-pressure for the first time
  - High-pressure hazard
    - Tank rupture
    - Throwing metal parts
  - Perform away from
    - Buildings
    - People
  - Perform in open field or concrete test cell
  - Make sure there is adequate drainage
  - Personnel stay safe distance away when pressurized

How To Perform the Water Flow Test?

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Calculate Water Flow Parameters

- Calculate Propellant Volume Flow Rate
- Calculate Orifice Area
- Calculate Orifice Drill Size
- Calculate Amount of Water to Load
- Calculate Initial Pressure of Pressurant Tank

Calculate Propellant Volume Flow Rate

$$F = w_t \cdot I_{sp} \qquad w_t = \frac{F}{I_{sp}} = \frac{500}{239} = 2.09\text{-lb/sec}$$

$$r = \frac{O}{F} = \frac{w_O}{w_F} \qquad w_O = \frac{r \cdot w_t}{r+1} \qquad w_F = \frac{w_t}{r+1}$$

<u>LOX/75%Ethanol & 25%Water Engine</u>

F—Thrust (500-lb_f)

r – Mixture Ratio (1.3)

I_{SP}—Specific Impulse (239-sec)

w_t– Total Propellant Flow Rate (lbs/sec)

w_o– Oxidizer Flow Rate (lbs/sec)

w_F– Fuel Flow Rate (lbs/sec)

ρ_O—Density of Liquid Oxygen (71.2-lbs/ft^3)

ρ_F—Density of 75% Ethanol & 25% Water (52.6-lbs/ft^3)

v_O—Oxidizer Volumetric Flow Rate (ft3/sec)

v_F—Fuel Volumetric Flow Rate (ft3/sec)

$$w_O = \frac{1.3 \cdot 2.09}{1.3+1} = 1.18\text{-lb/sec}$$

$$w_F = \frac{2.09}{1.3+1} = 0.91\text{-lb/sec}$$

$$v_O = \frac{w_O}{\rho_O} = \frac{1.18}{71.2} = 0.0165\text{-ft}^3\text{/sec}$$

$$v_F = \frac{w_F}{\rho_F} = \frac{0.91}{71.2} = 0.0173\text{-ft}^3\text{/sec}$$

Calculate Orifice Area

$$w_{wO} = \rho_w \cdot v_O = 62.4 \cdot 0.0165 = 1.03\ lb/sec$$

$$w_{wF} = \rho_w \cdot v_F = 62.4 \cdot 0.0173 = 1.08\ lb/sec$$

$$w_t = C_d A\sqrt{2g\rho\Delta P} \qquad A = \frac{w_w}{C_d\sqrt{2g\rho_w\Delta P}}$$

<u>LOX/75%Ethanol & 25%Water Engine</u>

ΔP—Injector Input Pressure to Atmosphere (400-psi or 57600-lbs/ft^2)

w_W– Water Flow Rate (lbs/sec)

v_O—Oxidizer Volumetric Flow Rate (ft^3/sec)

v_F—Fuel Volumetric Flow Rate (ft^3/sec)

A—Area (ft^2)

A_O—Oxidizer Orifice Area (ft^2)

A_F—Fuel Orifice Area (ft^2)

ρ_W—Density of Water (62.4-lbs/ft^3)

g—Acceleration Due to Gravity (32.2-ft/sec)

C_d—Discharge Coefficient Cavitating Orifice (0.61)

$$A_O = \frac{1.03}{0.61 \cdot \sqrt{2 \cdot 32.2 \cdot 62.4 \cdot 57600}} = 0.000111 ft^2$$

$$A_F = \frac{1.08}{0.61 \cdot \sqrt{2 \cdot 32.2 \cdot 62.4 \cdot 57600}} = 0.000116 ft^2$$

Orifice Drill Size

$$A_O = 0.000111 ft^2 \cdot 144\ in^2/ft^2 = 0.0160 in^2$$

$$A_F = 0.000116 ft^2 \cdot 144\ in^2/ft^2 = 0.0168 in^2$$

<u>LOX/75%Ethanol & 25%Water Engine</u>

A_o – Oxidizer Orifice Area (in^2)

A_F – Fuel Orifice Area (in^2)

D_o – Oxidizer Orifice Diameter (in)

D_F – Fuel Orifice Diameter (in)

$$A = \frac{\pi}{4} D^2 \qquad D = 2 \cdot \sqrt{A/\pi}$$

$$D_O = 2 \cdot \sqrt{A_O/\pi} = 2 \cdot \sqrt{0.0160/3.142} = 0.143 in$$

$$D_F = 2 \cdot \sqrt{A_F/\pi} = 2 \cdot \sqrt{0.0168/3.142} = 0.146 in$$

Calculate Amount of Water to Load

$$w_{WO} = 1.03\ lb/sec \qquad w_{WF} = 1.08\ lb/sec$$

$$w_{WOt} = \Delta t \cdot (W_{WO}) = 10 \cdot 1.03 = 10.3\ lb$$

$$w_{WFt} = \Delta t \cdot (W_{WF}) = 10 \cdot 1.08 = 10.8\ lb$$

<u>LOX/75%Ethanol & 25%Water Engine</u>

w_{WO}– Water Mass Flow Rate for Oxidizer (lbs/sec)
w_{WF}– Water Mass Flow Rate for Fuel (lbs/sec)
w_{WOt}– Water Total Mass of Oxidizer (lbs)
w_{WFt}– Water Total Mass of Fuel (lbs)
V_{WO}– Water Volume for Oxidizer (ft^3)
V_{WF}– Water Volume for Fuel (ft^3)
V_O– Water Volume for Oxidizer (gal)
V_F– Water Volume for Fuel (gal)
ρ_W—Density of Water (62.4-lbs/ft^3)
Δt—Firing Time (10-sec)

$$V_{WO} = W_{WOt} \cdot \rho_W = 10.3/62.4 = 0.165\ ft^3$$

$$V_{WF} = W_{WOFt} \cdot \rho_W = 10.8/62.4 = 0.173\ ft^3$$

$$V_O = 0.165\ ft^3 \cdot 7.48\ gal/ft^3 = 1.23\ gal$$

$$V_F = 0.173\ ft^3 \cdot 7.48 gal/ft^3 = 1.29\ gal$$

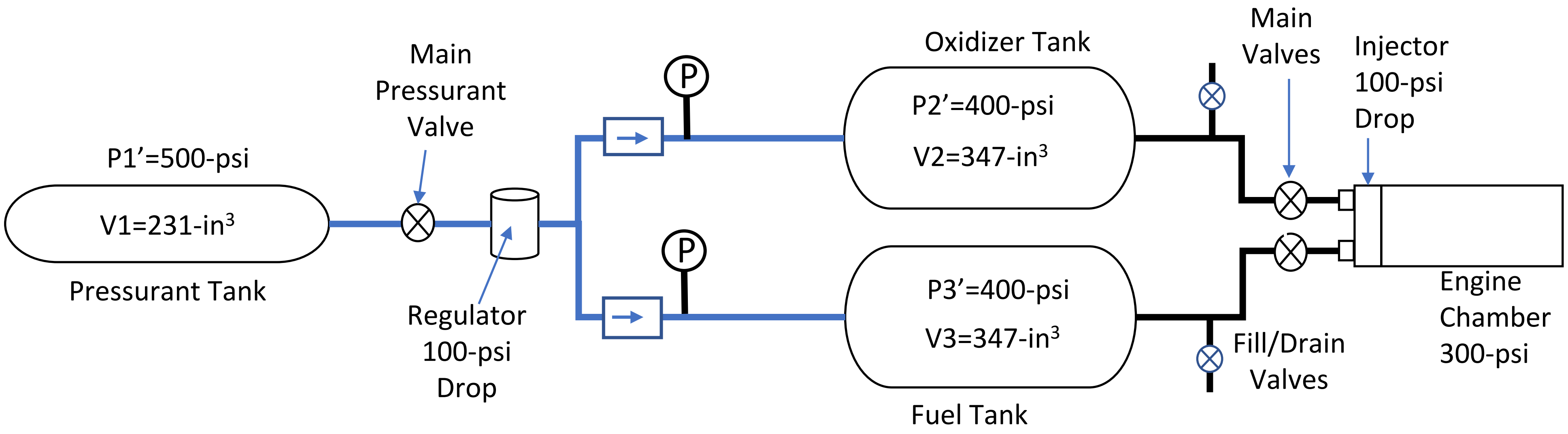
Final Pressure of Pressurant Tank

Initial P1?, P3=0, P4=0

Final P2’=500, P3’=400, P4’=400

Assumes 300-psi Chamber Pressure

Full Duration of Burn



Calculate Initial Pressure of Pressurant Tank

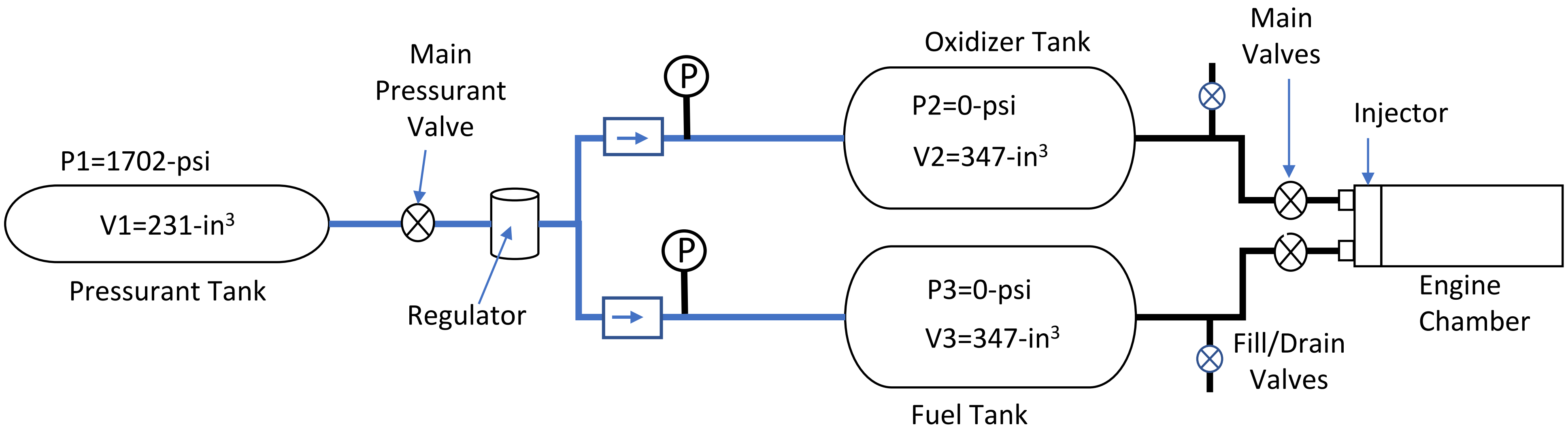
$P_i \cdot V_i = P_f \cdot V_f$ **Boyle's Law**

$P1 \cdot V1 = P1' \cdot V1 + P2' \cdot V2 + P3' \cdot V3$

$P1 \cdot 231 = 500 \cdot 231 + 400 \cdot 347 + 400 \cdot 347$

$P1 = (500 \cdot 231 + 400 \cdot 347 + 400 \cdot 347)/231$

P1 = 1702-psi



Fuel Loading Demonstration

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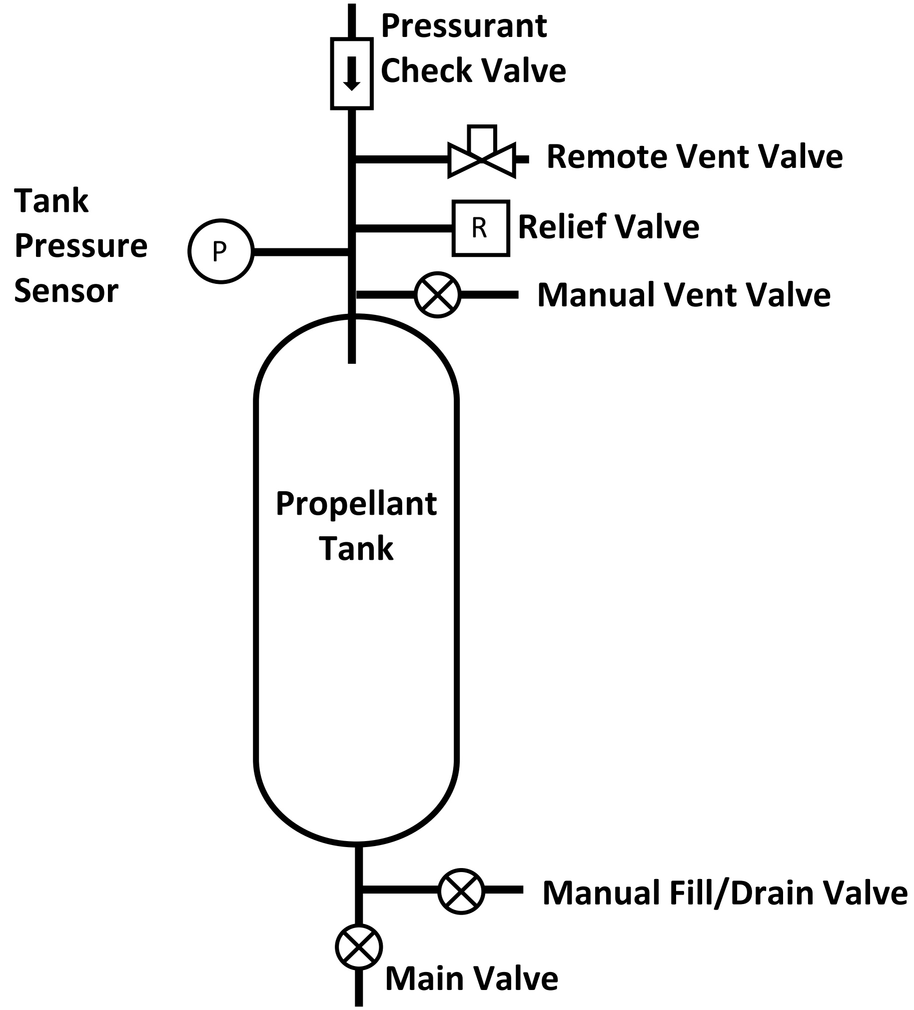
Tank Loading Features

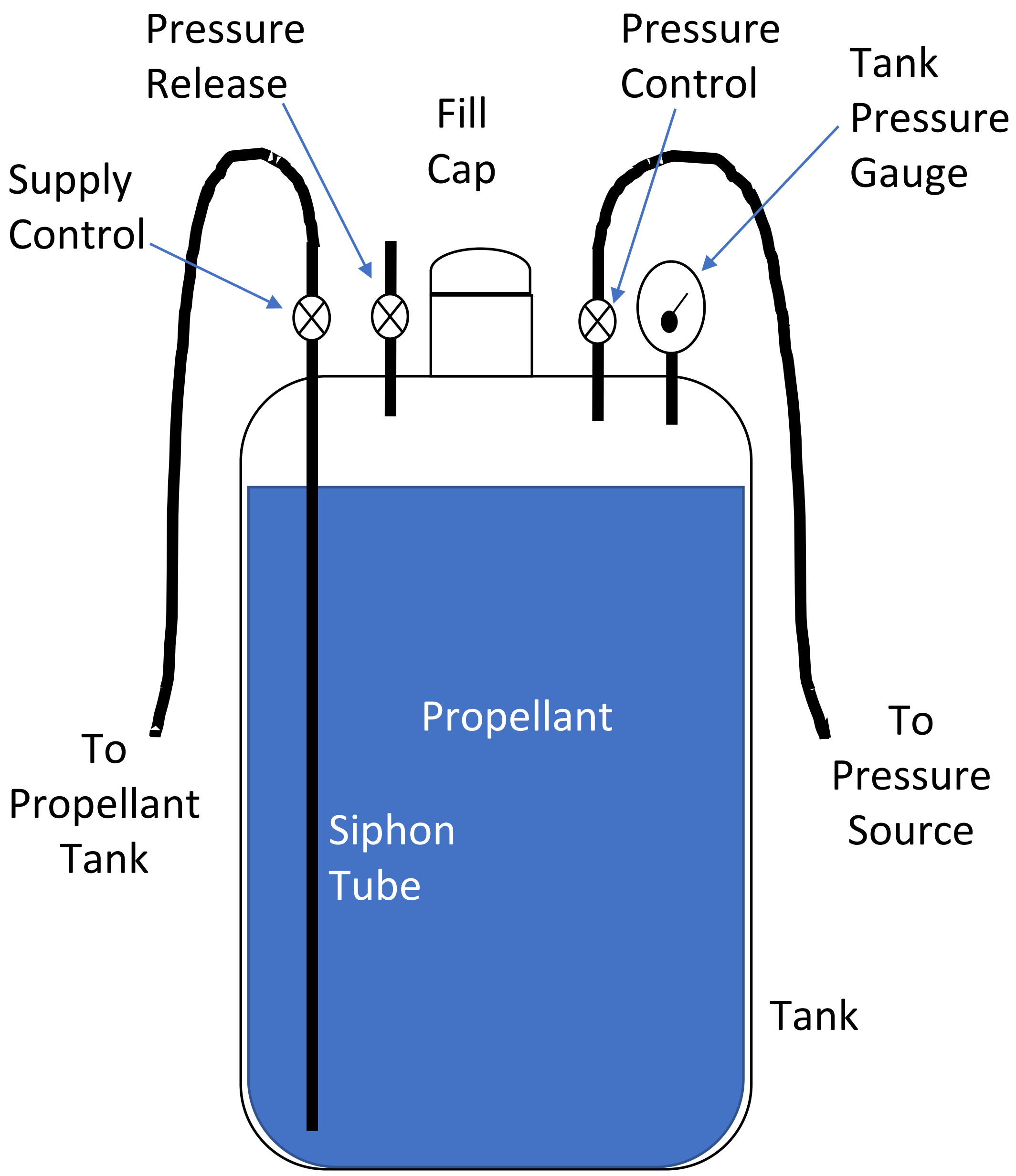
- Applies to static test stands and rockets
- Near top of tank
  - Manual vent valve
  - Remote commanded vent valve
  - Pressure transducer
  - Check valve
- Near bottom of tank
  - Fill and drain valve above main valves



Allows for manually draining the rocket/static test stand by gravity and without additional equipment

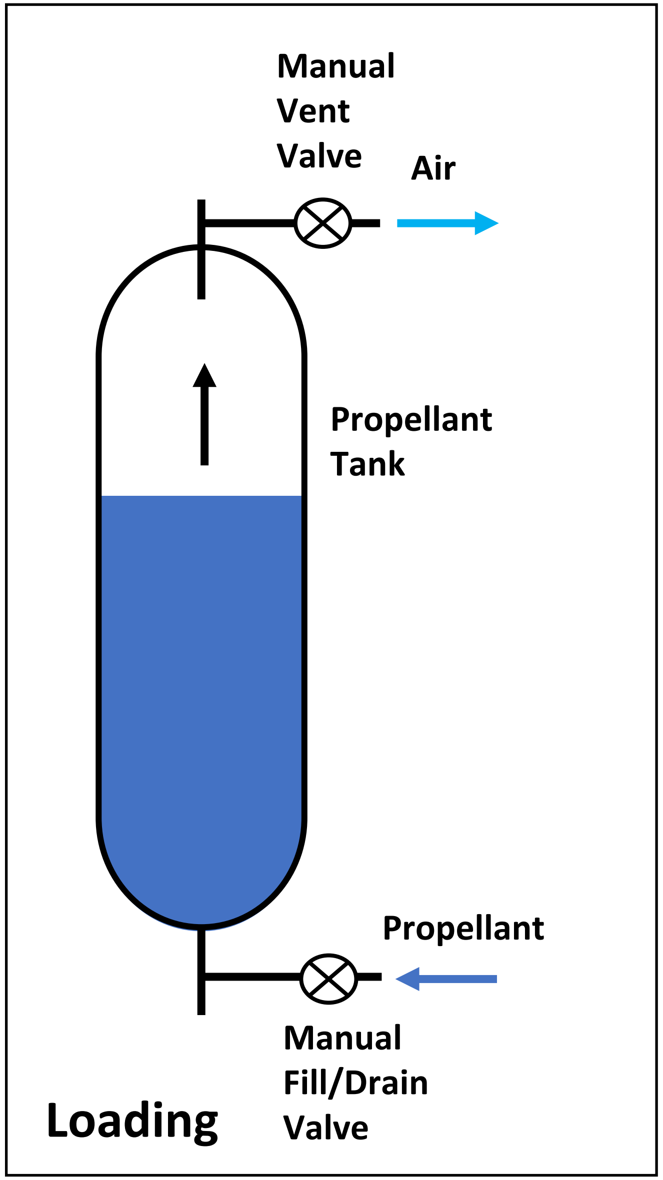
Propellant Transfer Tank

- Allows for Safe Handling of Propellant
  - Limits Exposure to Propellant
  - Limits Spillage of Propellants
- Transfer Tank Features
  - Hose to Pressure Source
  - Pressure Control Valve
  - Pressure Release Valve
  - Supply Control Valve
  - Tank Pressure Gage
  - Siphon Tube
  - Hose to Propellant Tank
- All materials compatible with the propellant



Propellant Loading

- Loading (Fill)
  - Do Not Fill from Top of Tank
  - Open Manual Vent to Vent Gas from Top of Tank
  - Fill from Bottom of Tank
    - Use Propellant Transfer Tank
    - Use Pump



Water Flow Test Demonstration

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Configure Static Firing Stand or Rocket

- Make orifices
- Remove rocket engine
- Install orifices on each propellant line
- Slowly load commercial pressurant tank to calculated pressure
- Load propellant tanks with the calculated amount of water

Perform the Water Flow Test

- Everyone needs to retreat to a safe distance or protected bunker
- Open main pressurant valve (pressurizing both propellant tanks)
- Perform countdown
- Open main valves
- Measure propellant tank pressures
  - Use data acquisition system
    - Sample 100-hz
  - Pressure should be constant (400-psi)
- Time water flow
  - Time should be as expected (10-sec)

After Test Reconfiguration

- Remove Orifices
- Dry Tanks
- Dry Plumbing
- Cryogenic Propellant
  - Replace Fill and Drain Ball Valve
  - Replace Main Ball Valve
- Install Engine