PEAPOD

Pneumatically Energized Auto-throttled Pump Operated for a Developmental Upperstage

Preliminary Design Review
18 October 2016

Team: Kelsey Aldrich, Jason Bass, Cesar Galan, Ethan Hollenbach, Tyler Roth, Alan Sanchez, Antoine Steiblen, Justin Wilmes, Scott Wurst

Customer: Tim Bulk, Chris Webber

Advisor: Josh Stamps

Overview

1. Project Overview
2. Baseline Design
3. Design Feasibility
4. Summary
5. Current Status
6. Q/A

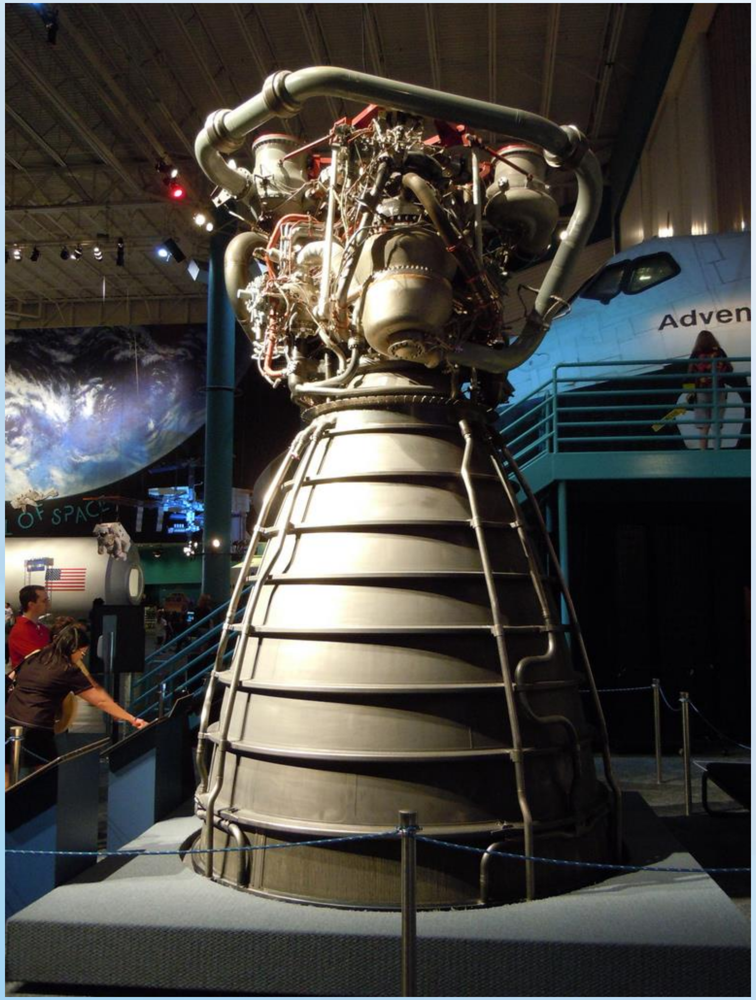
Project Overview

Project Motivation

Design and manufacture a pneumatically powered pump system for use on an upper stage rocket engine or lander.

- Proof of concept pump system for hypergolic propellants
- 10%-100% throttleability
- Pneumatically powered

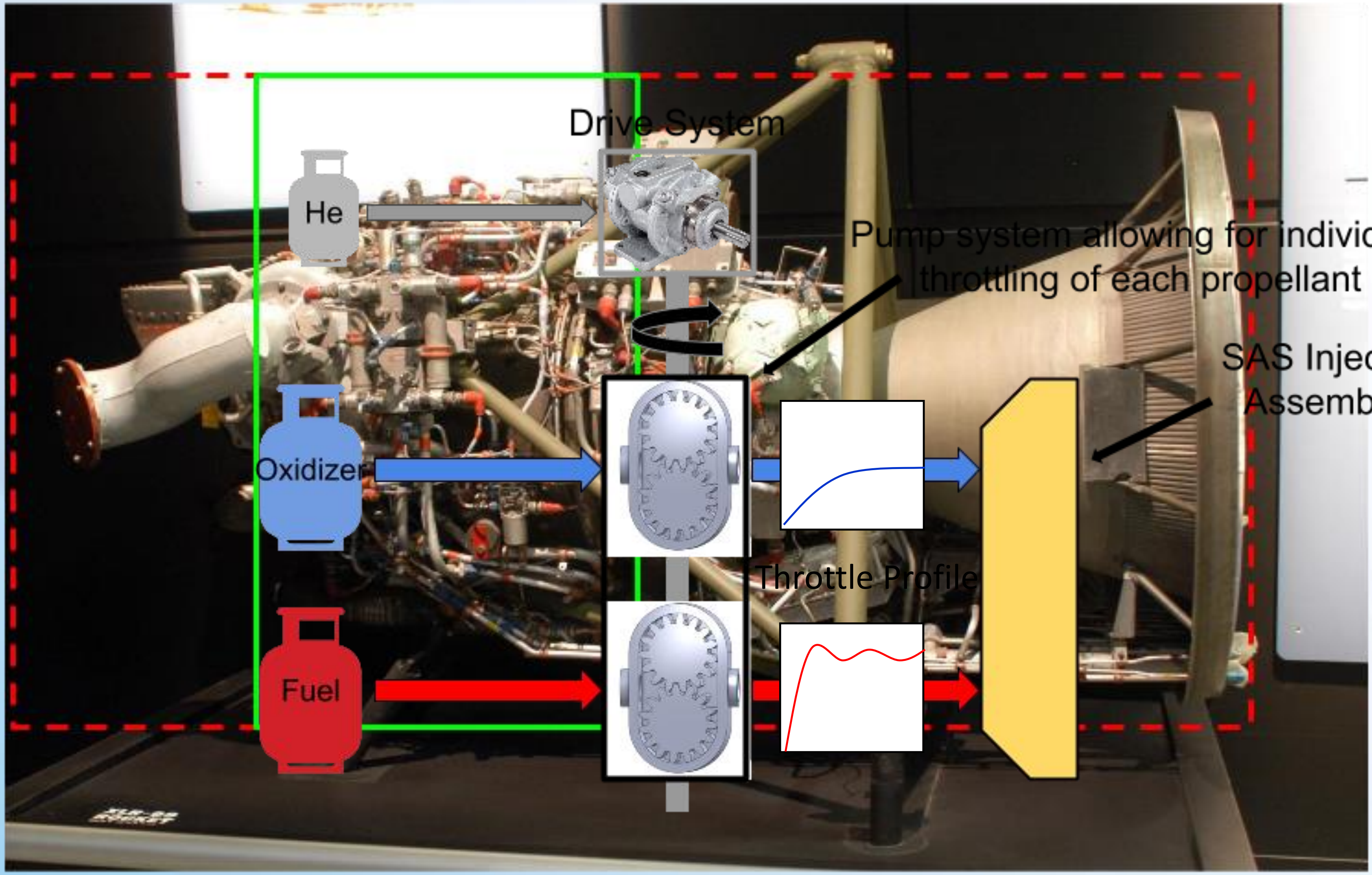
Pumps and Their Place in Rocketry



*Reference 10

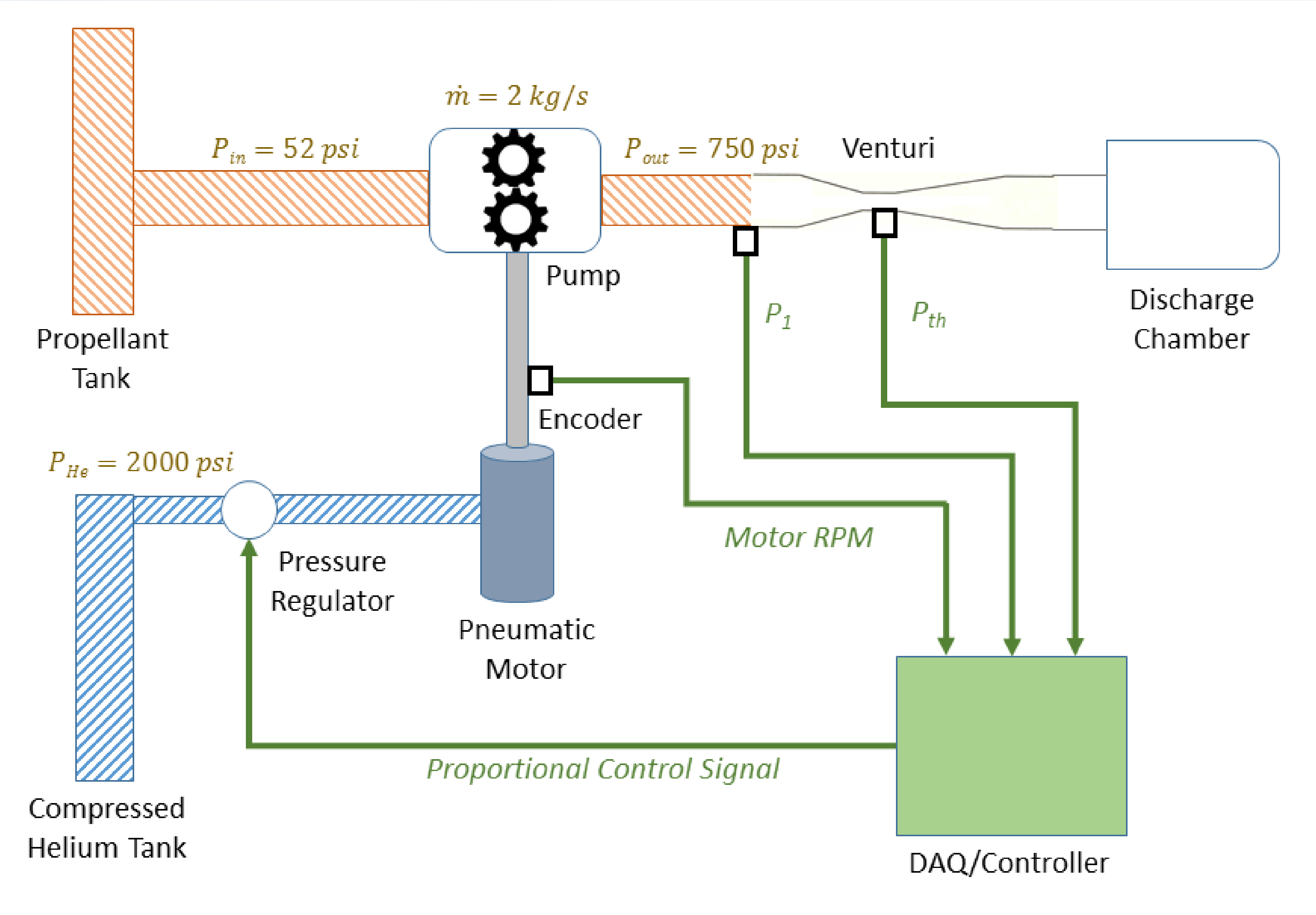
- Deliver propellants to combustor
- Low pressure fuel tanks
- Precise throttling control

Concept of Operations



*Reference 11

Functional Block Diagram



Requirements

- FR 1 – The pump shall be **pneumatically driven** using compressed helium
- FR 2 – The propellant streams shall be **individually, digitally controlled** and throttled from **10% to 100% of full throttle**
- FR 3 – The pump shall deliver a **750 ± 15 psi outlet pressure**
- FR 4 – The pump shall be able to run a provided **throttle profile** for the **full duration** of an upper stage burn

Requirements (cont.)

- FR 5 – The pump system shall have the ability to be **restarted**
- FR 6 – The pump system shall be constructed from materials that are **compatible with** the client-specified **hypergolic propellants**
- FR 7 – The pump system shall designed and manufactured such that a structural **factor of safety of 2.5** is maintained on all components
- FR 8 – The pump shall meet **75% efficiency** at maximum power/capacity

Levels of Success

Level	Functional Requirements	Performance Requirements
1	• Pneumatic power • Digital control • Meets safety requirements	• 750 ± 15 psi outlet pressure • Structural safety factor of 2.5 • 120 seconds of operation
2	• Independent propellant stream throttling • All level 1 requirements	• 10-100% throttleability • 0-100% throttle in 2 seconds • All level 1 requirements
3	• Hypergolic compatible • All level 1 and 2 requirements	• 0-100% throttle in 1 second • All level 1 and 2 requirements

Baseline Design

Positive Displacement Pumps

Positive Displacement Pump Advantages
• Positive displacement pumps can move fluids to high pressure elements (up to 5,000 psi) • Provide constant flow rates at constant pressure • Rotary PD pumps minimize pressure fluctuation

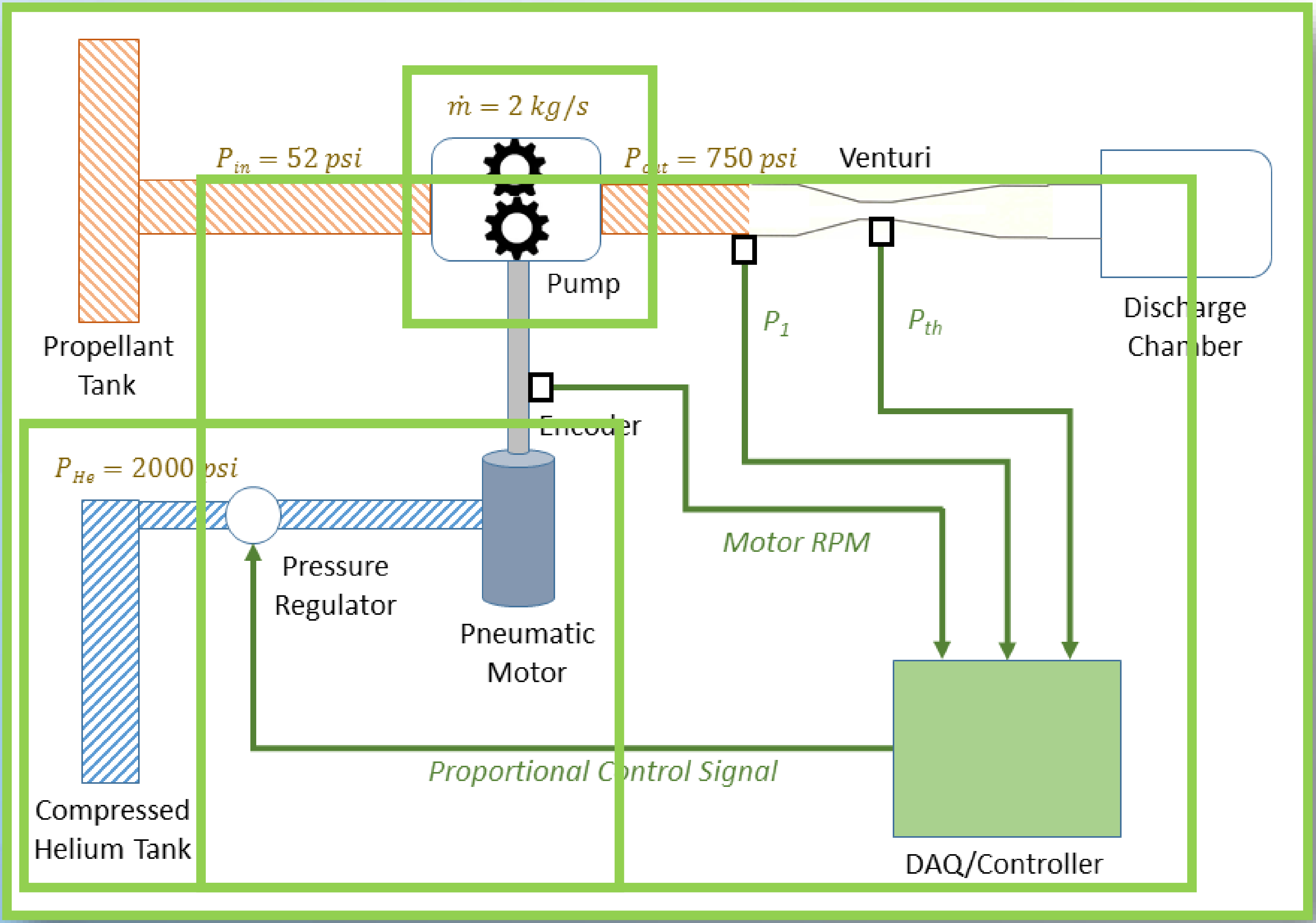
Axial Positive Displacement Pump

*Reference 13

Rotary Positive Displacement Pump

*Reference 12

Our System and Baseline Design



Key Design Elements:

1. Pump
2. Drive System
3. Throttle Control
4. Safety

Pump Selection

- Commercially available pumps are too expensive
  - Therefore it's a **design problem**
  - Trade study conducted on pump type concerning:
    - Efficiency
    - Manufacturability
    - Pressure fluctuations
    - Cost
    - Throttleability

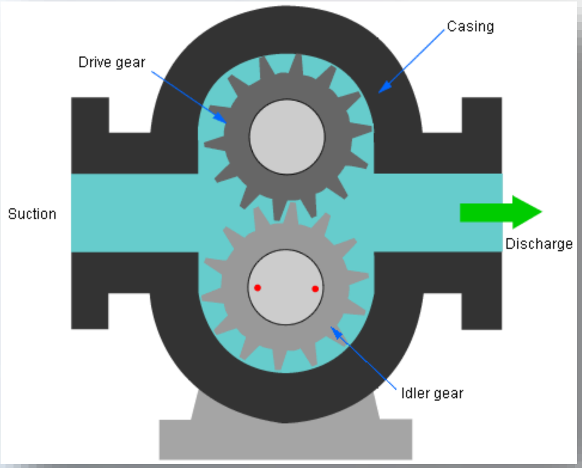
External Gear Pump

PROS

- Simple design (relative)
- Cost effective
- Self priming (helps with restartability)
- Does not pulse

CONS

- Volumetric losses
- Possible need for rotating seals
- Tight tolerances



*Reference 14

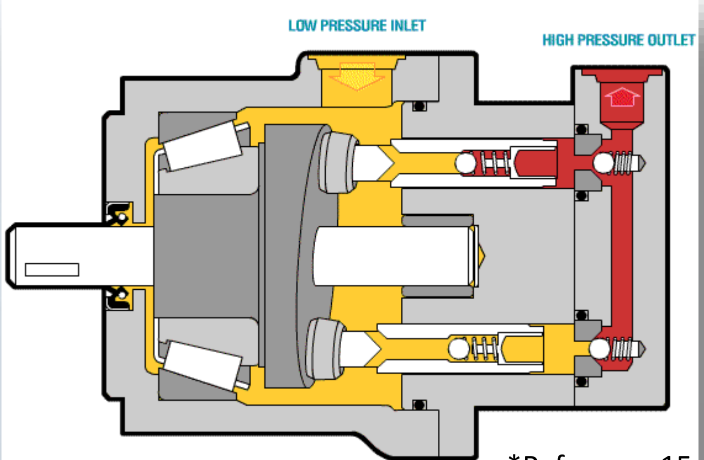
Piston Pump

PROS

- More efficient (18)
- Rotary piston pump offers two throttle methods

CONS

- Cannot run dry[7]
- Pulsing at the outlet[17]
- More complex design



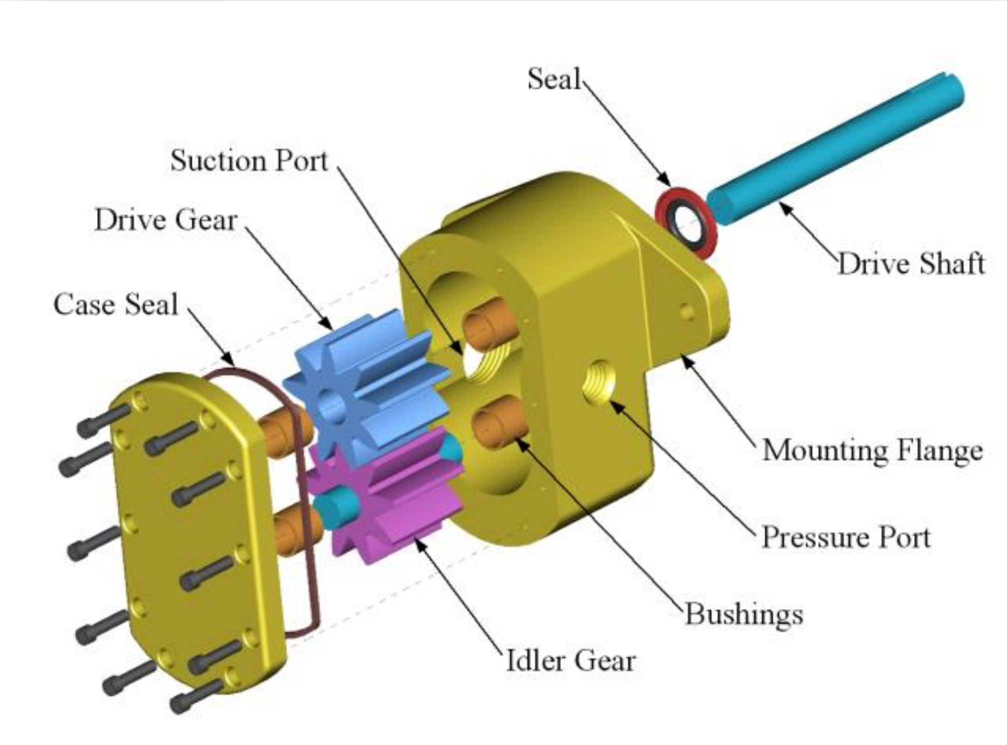
*Reference 15

Pump Trade Study

Pump Score:	Axial piston	External gear
Throttling and pressure	1.46	1.36
Efficiency and Reliability	0.61	0.57
Manufacture and design	0.89	1.46
Monetary Cost factor	0.14	0.57
Total	**3.11**	**3.96**

Selection of Baseline Pump

- **External Gear Pump**
  - Simplicity
  - Manufacturability
  - Affordability
  - Supported by both trade study and sensitivity analyses



*Reference 16

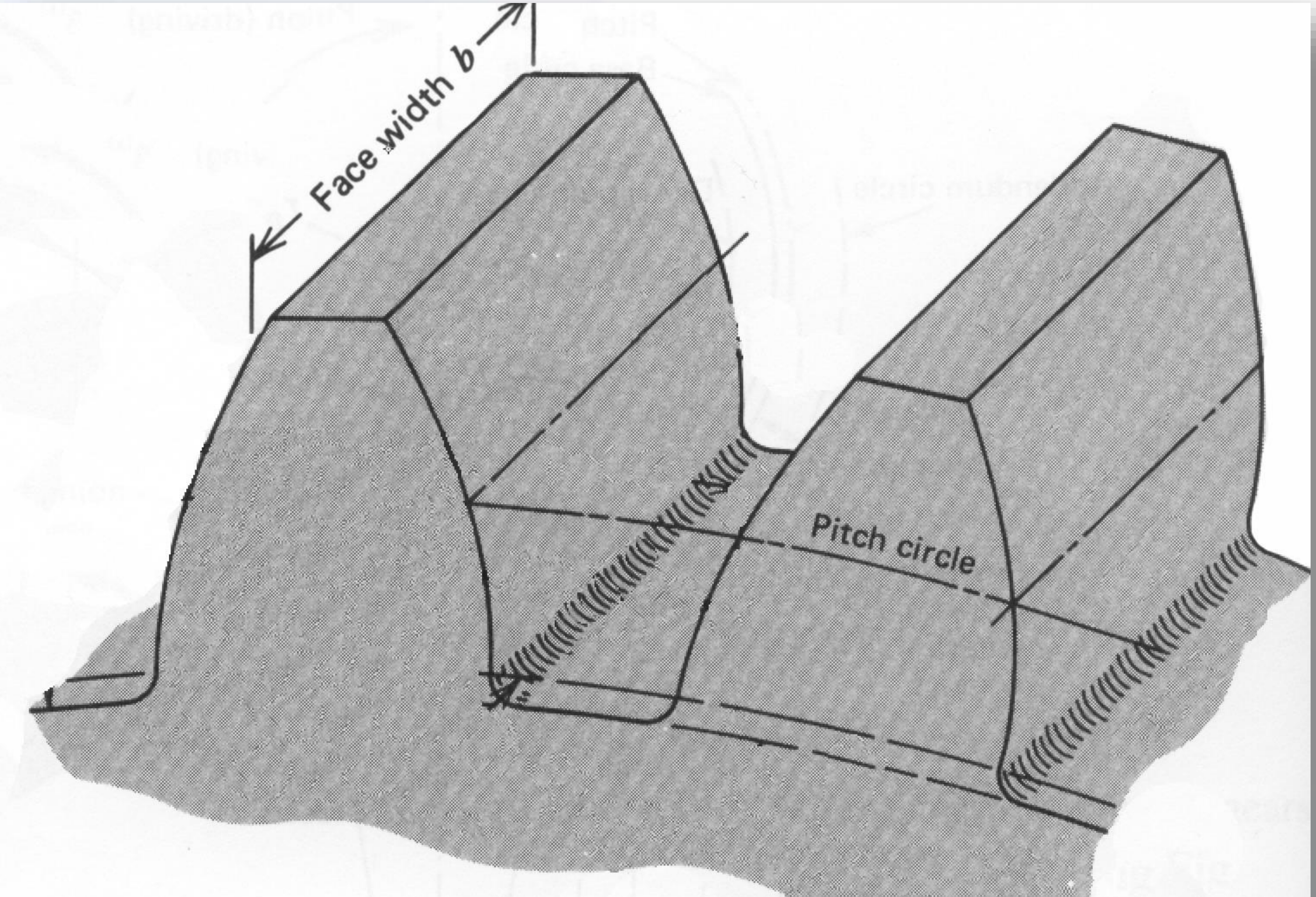
Design Feasibility

Major Concerns

- Meeting mass flow rate requirement
- Meeting efficiency requirement
- Throttling
- Integrating pumps with drive systems
- Safety

Pump Design and Analysis

- Pitch Diameter
  - Dictates other aspects of gear dimensions
- Number of Teeth
- Face Width

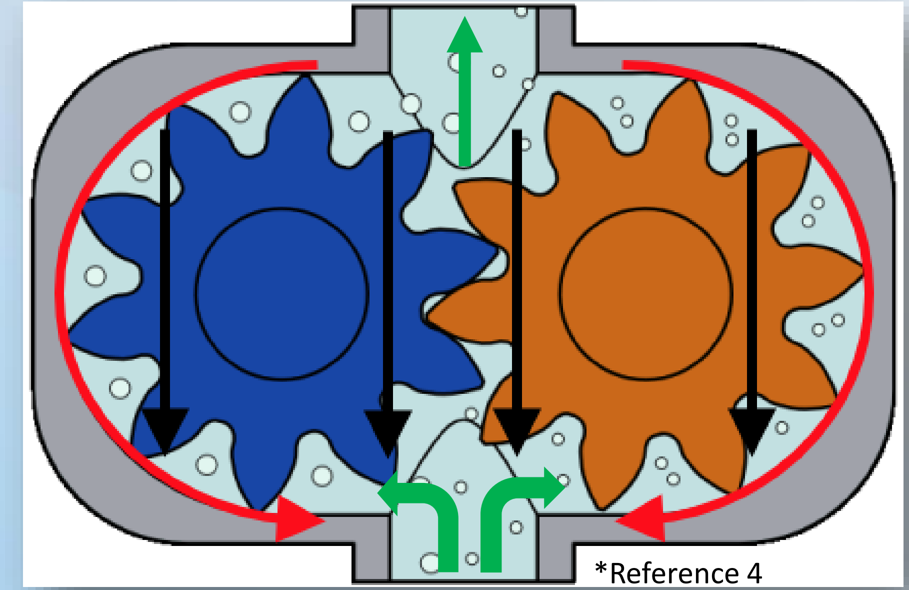


*Reference 9

Pump Design and Analysis

- Ideal mass flow rate proportional to rotational speed
- Fluid slip back through the pump, driven by higher outlet pressure
- Actual mass flow rate is ideal mass flow rate minus fluid slip back mass flow rate

$$\dot{m} = \dot{m}_{ideal} - \dot{m}_{SlipTip} - \dot{m}_{slipTop} = \left[\frac{FD^2(9n-2.35)\omega\rho}{16n^2}\right] - \left[dF\sqrt{2\Delta P_t\rho}\right] - \left[\frac{2(P_{Outlet}-P_{Inlet})}{L}\frac{d^2}{3\mu}(\rho)(2d)(4D)\right]$$

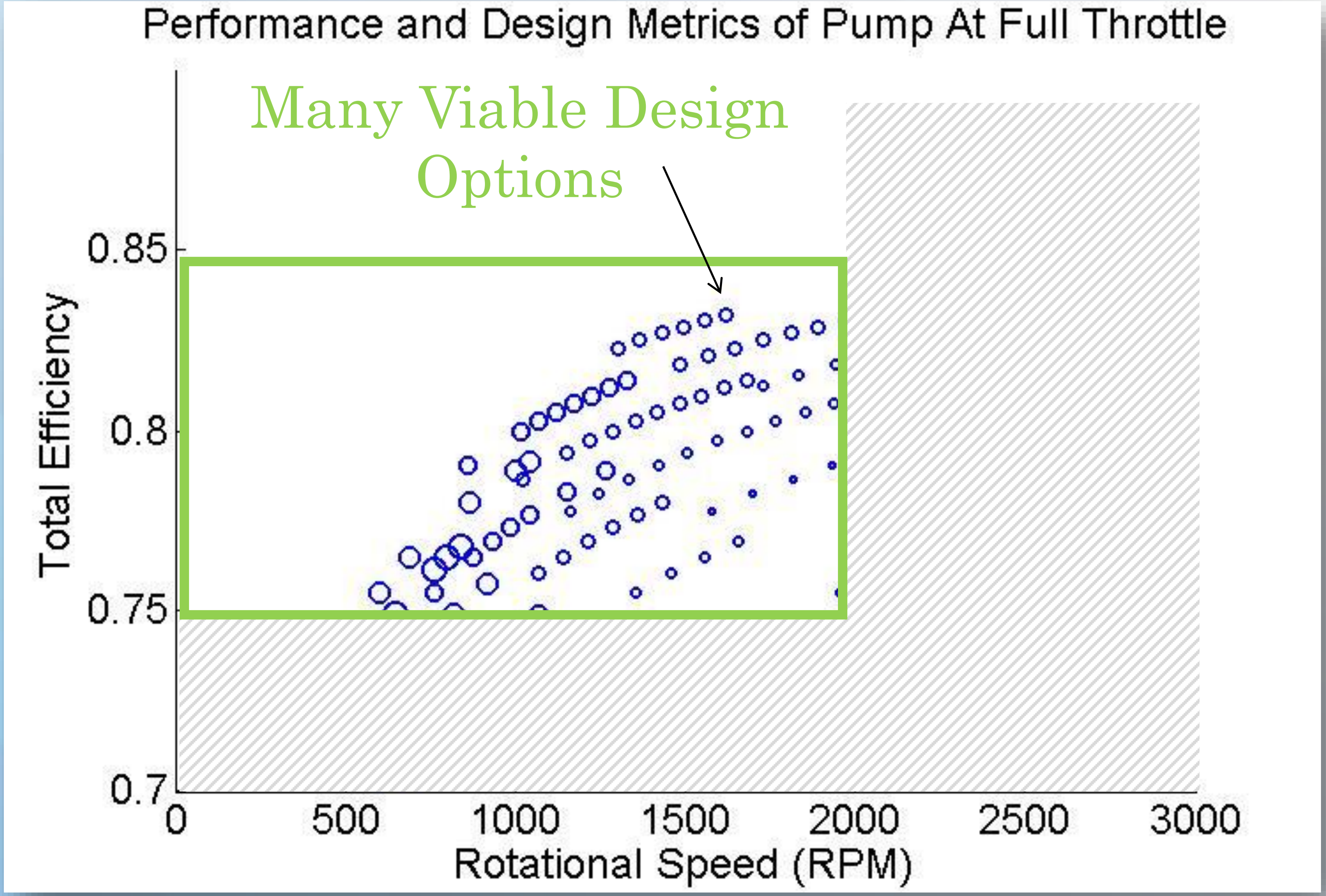


Slip-back path 1: Around outside of the gear

Ideal path of fluid travel

Slip-back path 2: Over top of the gear

Pump Design and Analysis



Design Constants

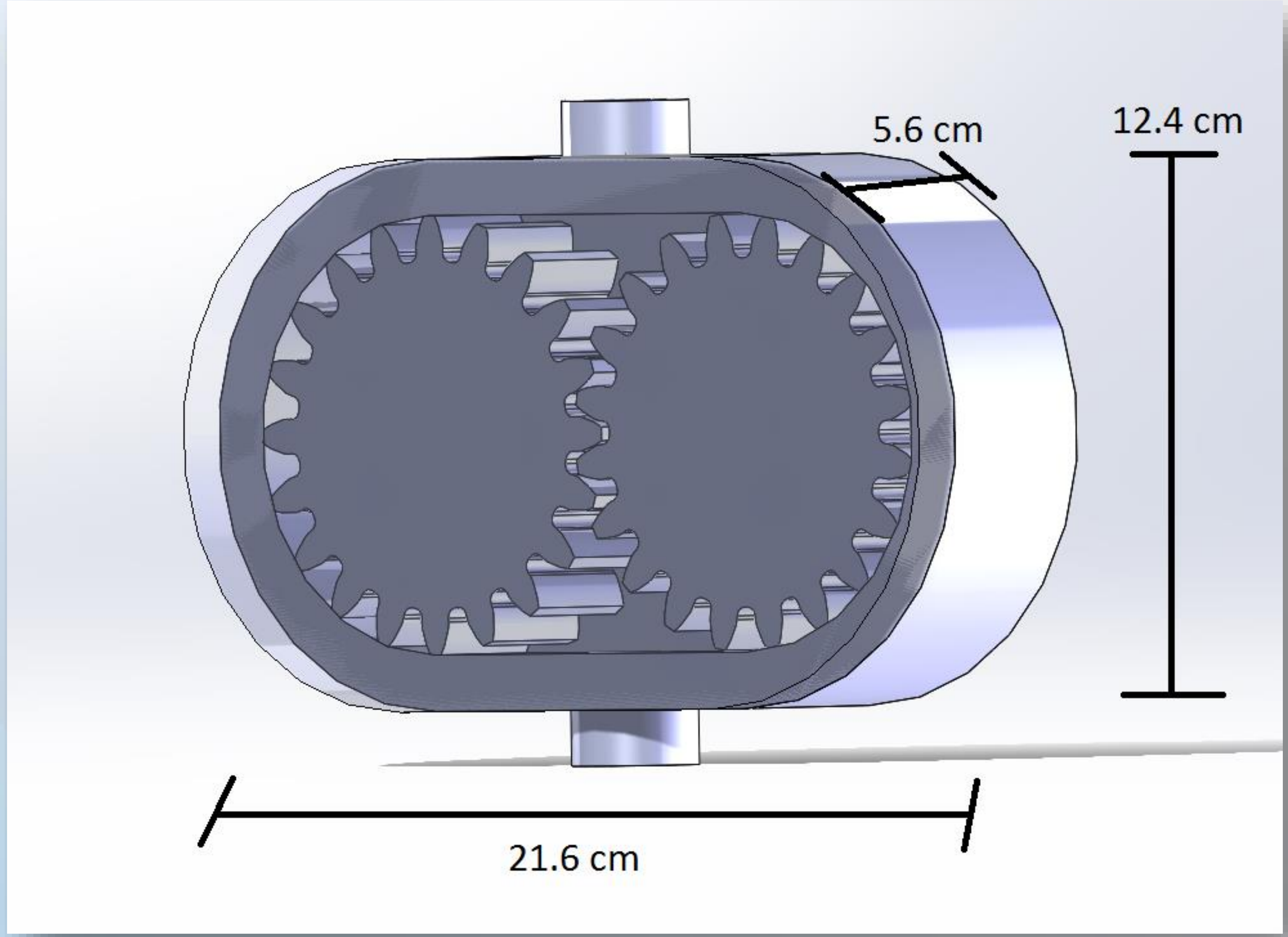
- $tip\ clearance = 0.003$“
- $\dot{m}_{margin} = 1.1$
- $\eta_{min} = 0.75$
- $RPM_{max} = 2000\ RPM$

NTO

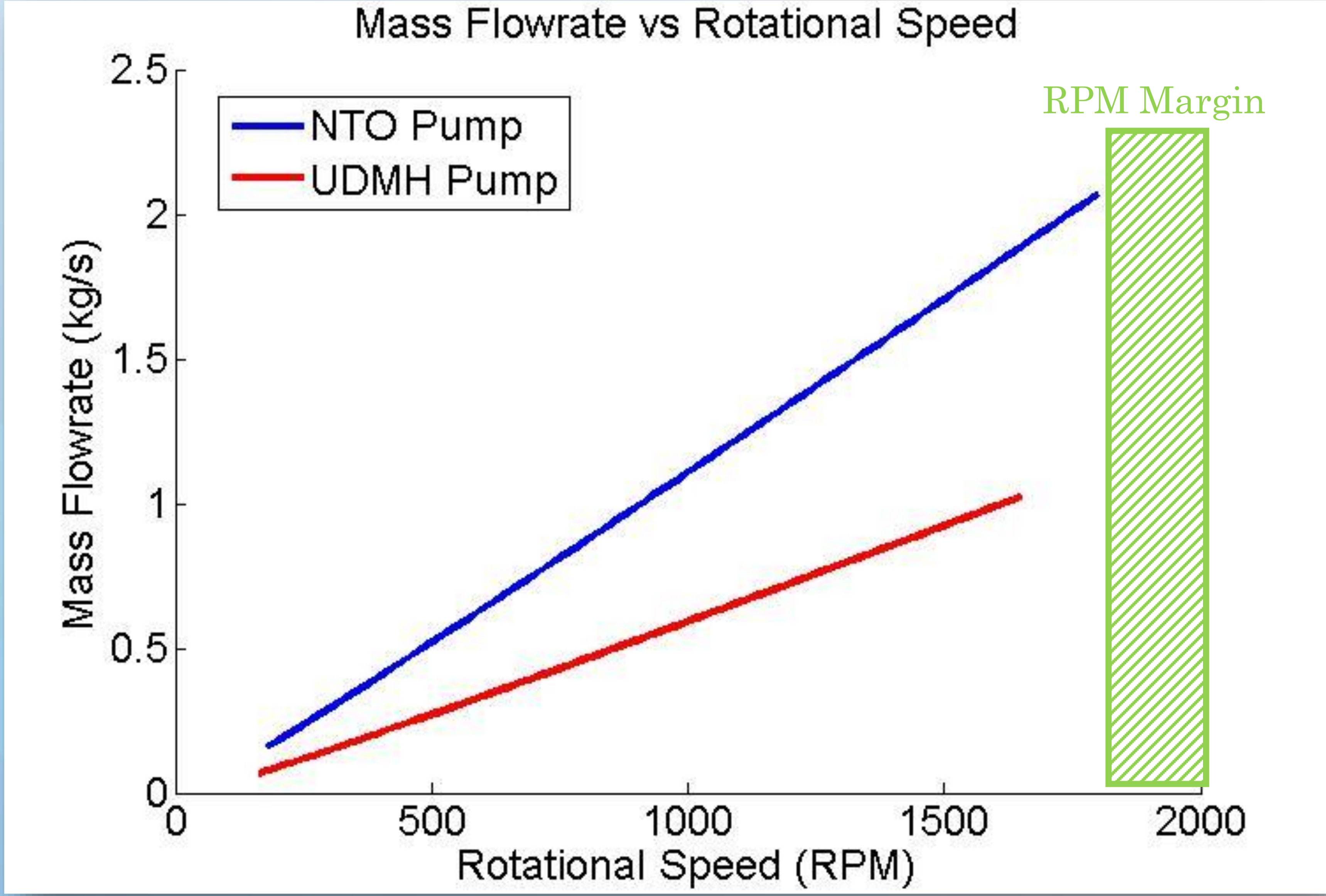
- $\rho_{NTO} = 1450\ \frac{kg}{m^3}$
- $\mu_{NTO} = 0.423\ cP$
- $\dot{m}_{NTO} = 2\frac{kg}{s}$

Gear Pump Optimized Design

- Pitch Circle: 9.0 cm
- Face Width: 3.6 cm
- Number of Teeth: 20
- Pressure Angle: 20°
- UDMH pump to use same dimensions as NTO pump



Pump Analysis



Design Constants

- $tip\ clearance = 0.003"$
- $\dot{m}_{margin} = 1.1$
- $\eta_{min} = 0.75$
- $RPM_{max} = 2000\ RPM$

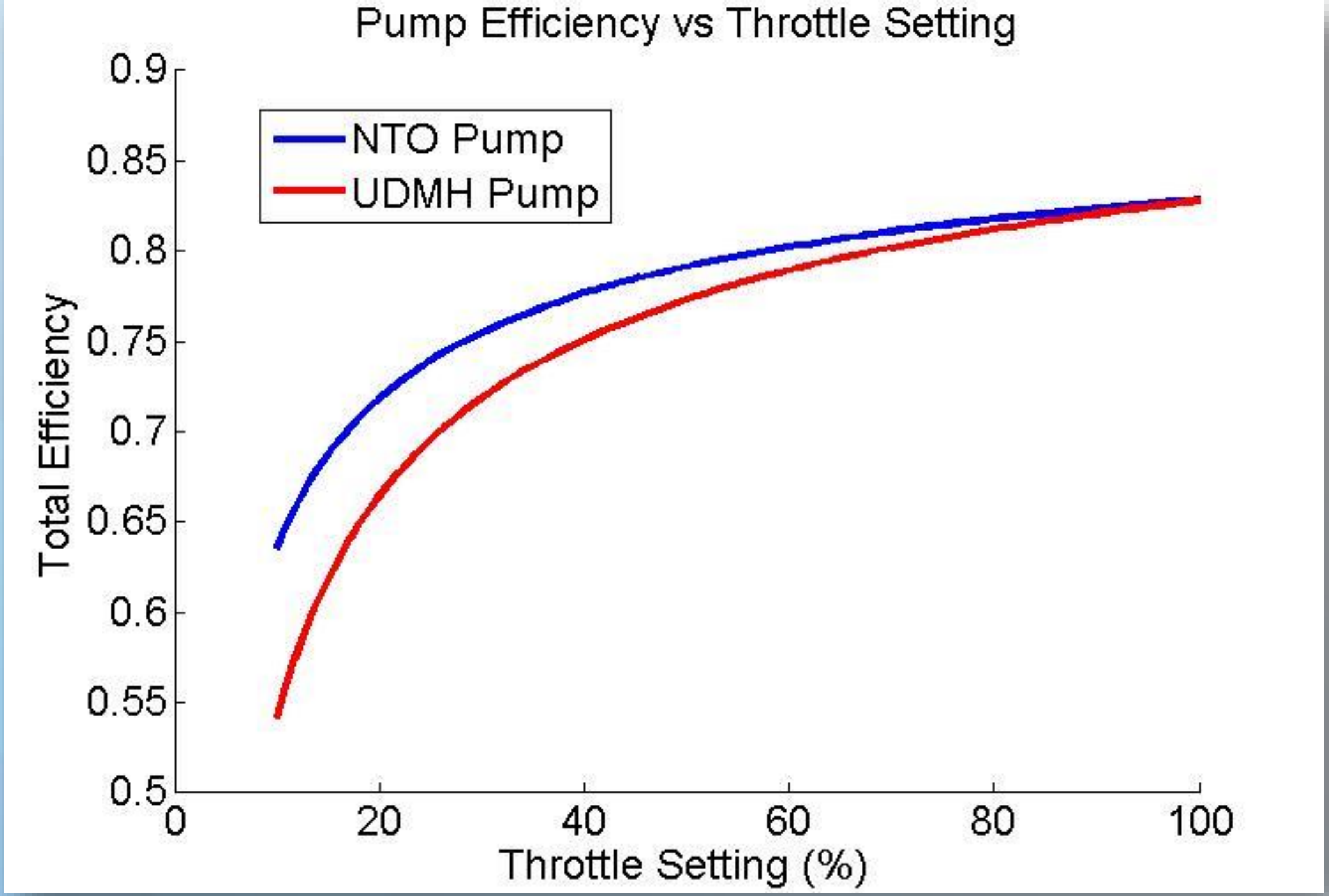
NTO

- $\rho_{NTO} = 1450\ \frac{kg}{m^3}$
- $\mu_{NTO} = 0.423\ cP$
- $\dot{m}_{NTO} = 2\frac{kg}{s}$

UDMH

- $\rho_{UDMH} = 783\ \frac{kg}{m^3}$
- $\mu_{UDMH} = 0.754\ cP$
- $\dot{m}_{UDMH} = 1\frac{kg}{s}$

Pump Analysis



Design Constants

- $tip\ clearance = 0.003$"
- $\dot{m}_{margin} = 1.1$
- $\eta_{min} = 0.75$
- $RPM_{max} = 2000\ RPM$

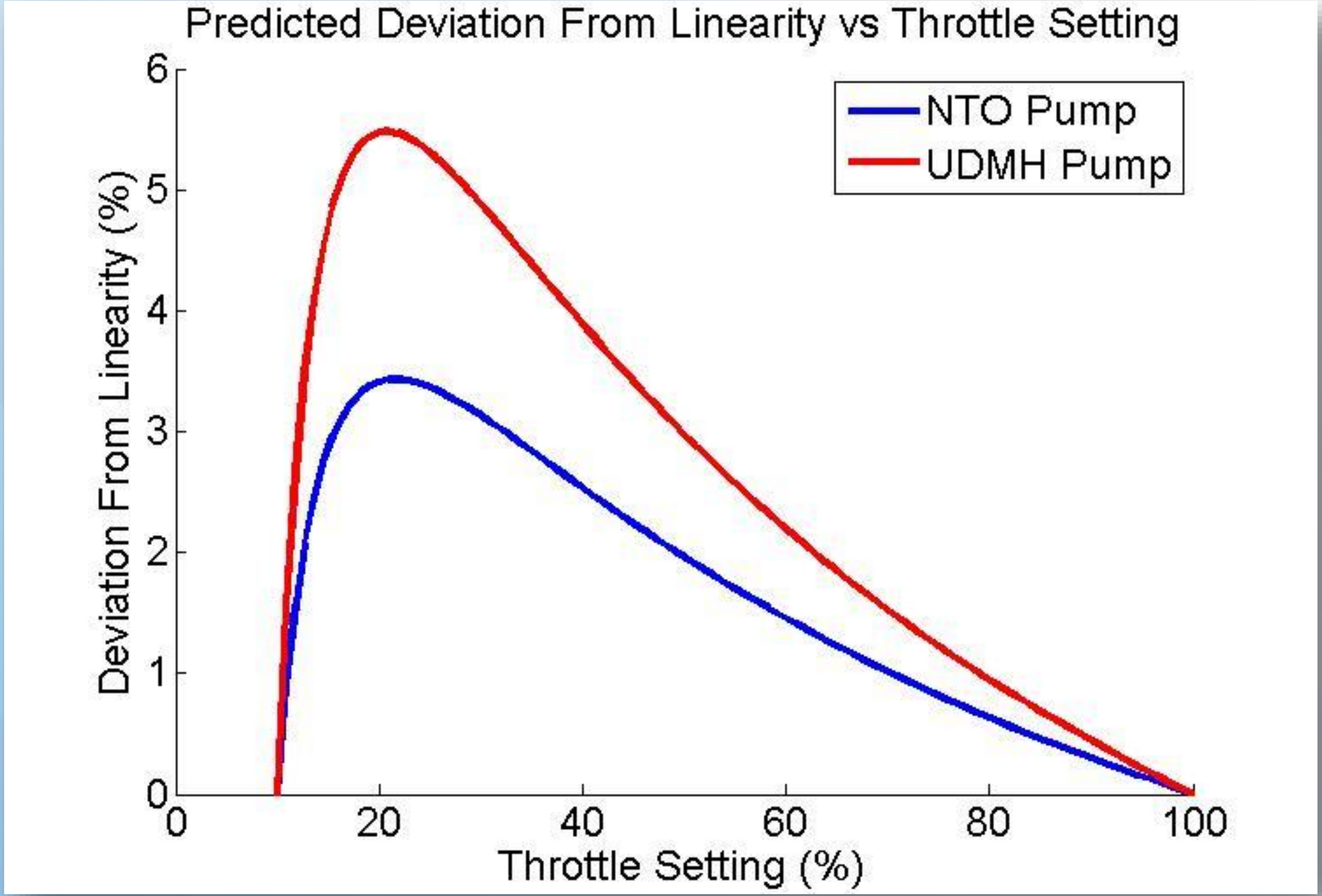
NTO

- $\rho_{NTO} = 1450\ \frac{kg}{m^3}$
- $\mu_{NTO} = 0.423\ cP$
- $\dot{m}_{NTO} = 2\ \frac{kg}{s}$

UDMH

- $\rho_{UDMH} = 783\ \frac{kg}{m^3}$
- $\mu_{UDMH} = 0.754\ cP$
- $\dot{m}_{UDMH} = 1\ \frac{kg}{s}$

Pump Analysis



Design Constants

- $tip\ clearance = 0.003$“
- $\dot{m}_{margin} = 1.1$
- $\eta_{min} = 0.75$
- $RPM_{max} = 2000\ RPM$

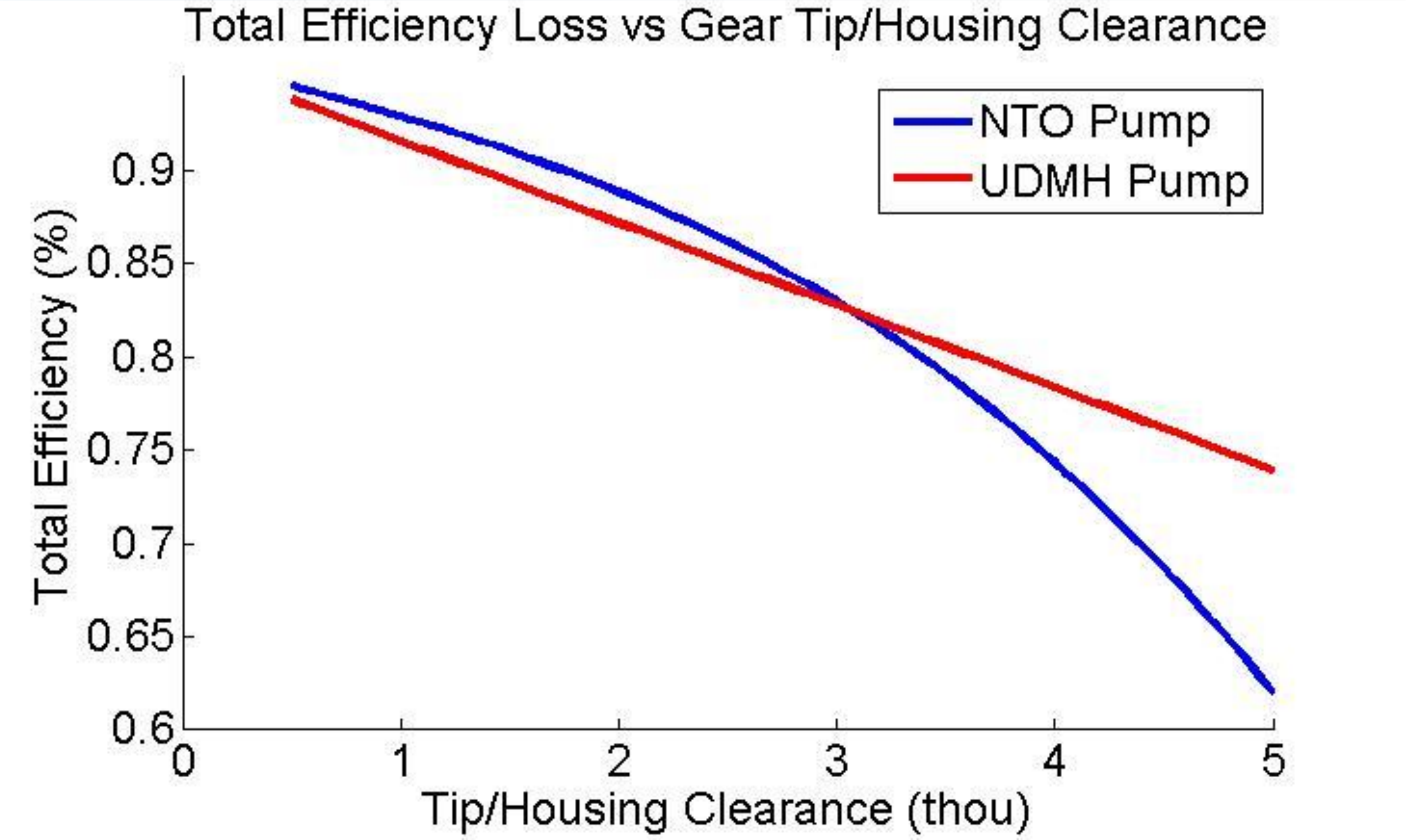
NTO

- $\rho_{NTO} = 1450\ \frac{kg}{m^3}$
- $\mu_{NTO} = 0.423\ cP$
- $\dot{m}_{NTO} = 2\frac{kg}{s}$

UDMH

- $\rho_{UDMH} = 783\ \frac{kg}{m^3}$
- $\mu_{UDMH} = 0.754\ cP$
- $\dot{m}_{UDMH} = 1\frac{kg}{s}$

Pump Analysis



Design Constants

- $\dot{m}_{margin} = 1.1$
- $\eta_{min} = 0.75$
- $RPM_{max} = 2000\ RPM$

NTO

- $\rho_{NTO} = 1450\ \frac{kg}{m^3}$
- $\mu_{NTO} = 0.423\ cP$
- $\dot{m}_{NTO} = 2\frac{kg}{s}$

UDMH

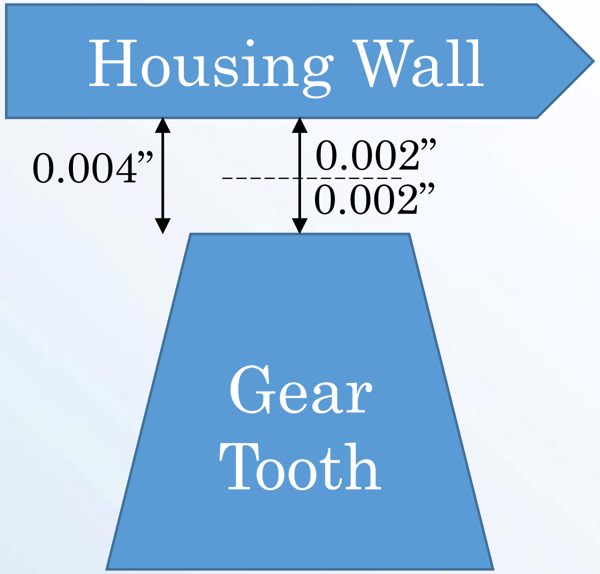
- $\rho_{UDMH} = 783\ \frac{kg}{m^3}$
- $\mu_{UDMH} = 0.754\ cP$
- $\dot{m}_{UDMH} = 1\frac{kg}{s}$

Optimized Design Loss Stack-up

Loss		NTO Pump Efficiency (%)	UDMH Efficiency (%)	Notes:
Mechanical		0.96	0.96	Agrees well with industry references.
	Rolling	0.99	0.99	
	Sliding	0.98	0.98	
	Bearing	0.99	0.99	
Volumetric		0.88	0.87	Agrees well with industry references.
	Slip at gear tips	0.93	0.89	Assumes 3 thou clearance at gear tips
	Slip over top of gears	0.95	0.97	Assumes 1 thou tolerance across top of gear.
Total Efficiency		0.84	0.84	Agrees well with industry references.

Allowable Manufacturing Tolerances

- To meet 75% efficiency
- Housing +0.002”, Gear - 0.002”
- SAS manufacturing capabilities ±0.0002”
- Provide raw materials to SAS



Hypergolic Materials

	Nitrogen Tetroxide (N_2O_4)	UDMH ($(CH_3)_2NNH_2$)
Compatible Metals	Nickel Al 1100, 2024, 5052 Stainless steel: 302, 303, 304, 316, 410, 416	Nickel Al 1100, 2024, 5052 Stainless Steel 302, 303, 304, 316, 410, 416
Compatible Non-Metals	Teflon	Teflon
Compatible Lubricants	DuPont fluorinated grease, Krytox 240, Reddy Lube	DuPont fluorinated grease, Krytox 240, Reddy Lube
Other Considerations	Depends on moisture content for selection of materials. Do Not Use Al 2024, 7075	Al may be used, but corrosive damage is found to be proportional to amount of water in the solution

Many Viable Options

Pneumatics Feasibility

Required Power	Available Drive Systems (max power)
7.87 kW(full throttle)	7.1 kW 7.5 kW 8.4 kW 9.7 kW

- Suitable pneumatic drive systems are commercially available
- Least powerful system overdriven by less than 10% to achieve required power

Drive System Integration

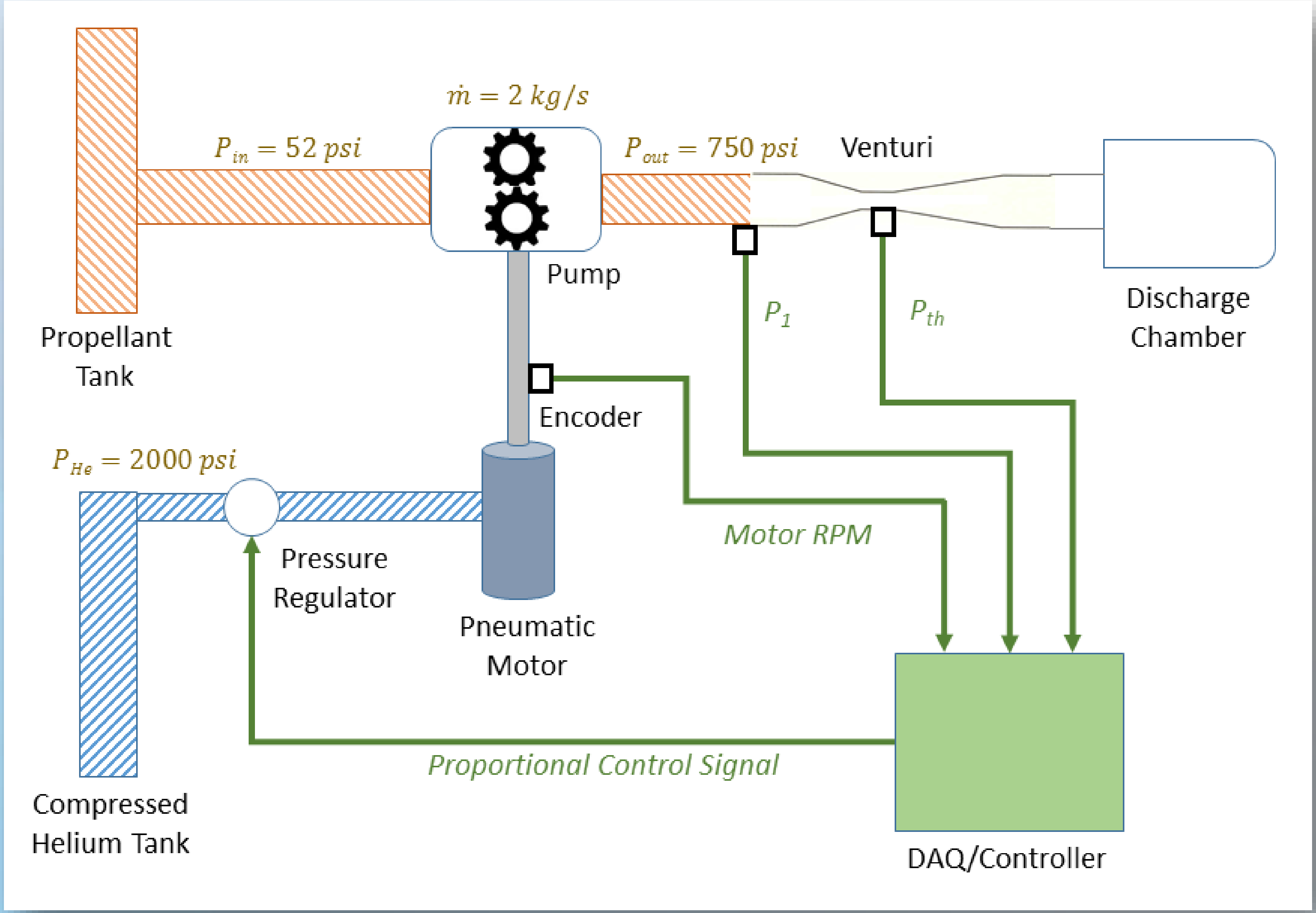
- Drive coupling
  - Geared or direct drive
  - Match motor power curve peak with max pump rpm
- Motor feed pressure
  - Regulator valve control

Selection of Throttling Method

- Three viable options
  - Vary drive system output power
  - Bypass valve
  - Combination

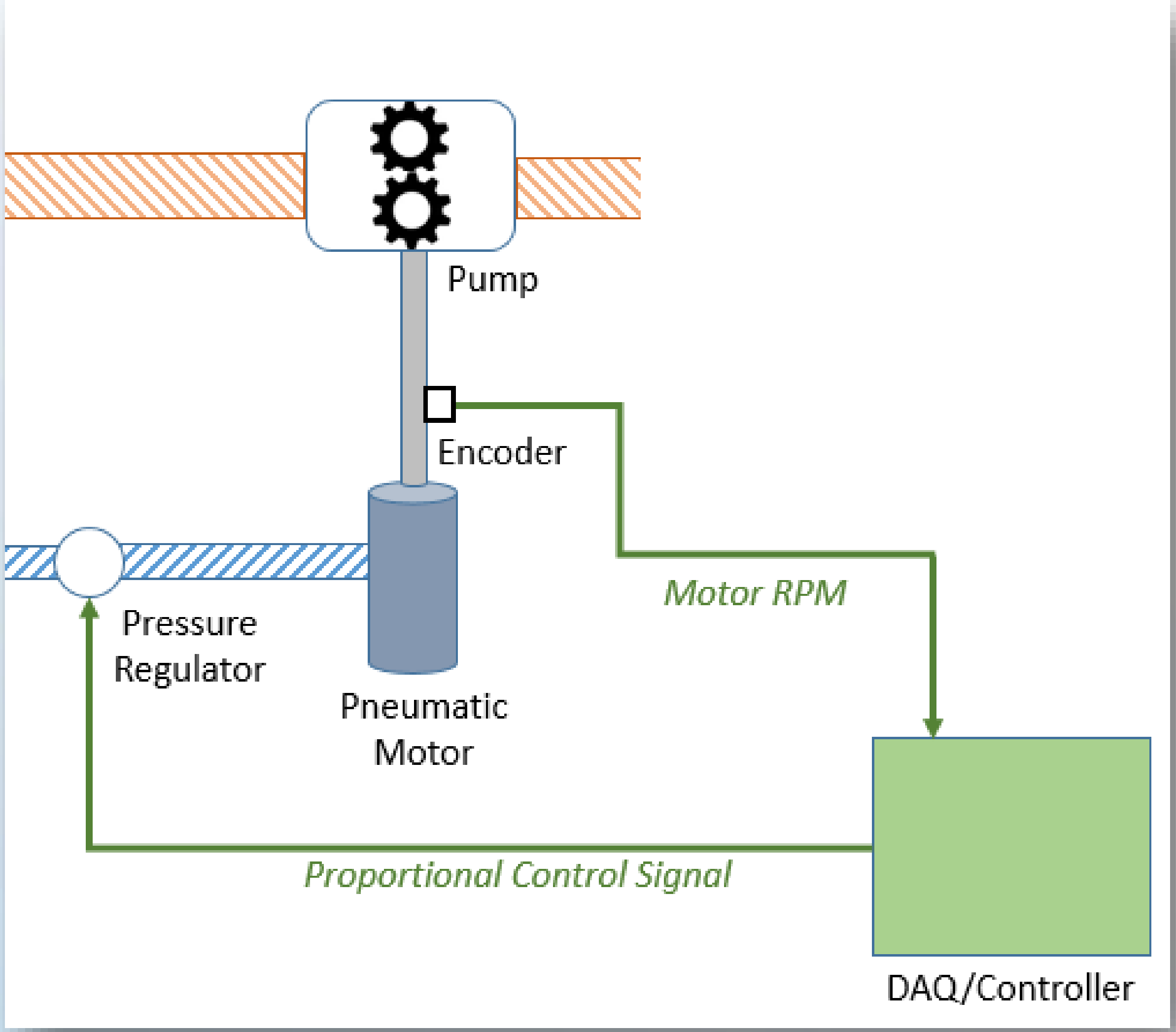
Offers highest efficiency at low throttle settings

Pump Throttling



Mass Flow Rate Controller

- Drive system RPM controlled by drive inlet pressure
- Closed loop control on desired drive system inlet pressure using a digital regulator
- Calibrated to provide a known mass flow rate for a given drive system RPM



Pressure Transducer

Off the shelf:

- Voltage output: 0V – 5V
- Time response: <1ms

Pressure Regulator

Off the shelf:

- Maximum volume flow rate: 280 cfm
- Back pressure regulated: 0 – 100 psi
- Supply pressure: 100 psi

DAQ

	Requirements	DAQ	Microcontroller
Max sampling rate	1.2 kHz	50 kHz	500 kHz
# of analog input pins	4	8	8
# of analog output pins	2	2	4
Resolution	> 8 bits	16 bits	12 bits
Voltage resolution		6 mV	50 mV
# of I/O pins	-	13	32
Input voltage	1-6 V	±10 V	

Both Options Feasible

Safety Requirement

Worst Case Failures

1. Drive system flywheel – 225 J
2. Drive system casing – 16 J
3. Pump gears – 36 J

Cinder Block Housing Strength

- Chipping - 300 J
- Cracking - 600 J
- Penetration - 800 J
- Failure - 1000 J
- Complete destruction - >1300 J

Budget

Part	Unit	Price	Quantity	Discount	Total
Wire		$ -	20	0%	$ -
NTO Gear block	8992K908	$ 47.36	2	0%	$ 94.72
NTO panel	8992K908	$ 47.36	1	0%	$ 47.36
NTO Housing	6620K41	$ 139.53	1	0%	$ 139.53
UDMH Gear Block	8983K233	$ 45.34	2	0%	$ 90.68
UDMH Panel	8983K233	$ 45.34	1	0%	$ 45.34
UDMH Housing	8983K198	$ 57.41	1	0%	$ 57.41
Nuts and Bolts	As Needed	$ 35.00	1	0%	$ 35.00
Machining Metals	As Needed	$ -	0	0%	$ -
Pressure Transducers	KG5V model	$ -	4	0%	$ -
Pressure Regulator	IP610-0120-I	$ 415.00	2	0%	$ 830.00
Accelerometers		$ -	2	0%	$ -
Line hookups	3/8" Lines	$ -	2	0%	$ -
Drive System	/-2 Air Motor	$1,181.53	1	0%	$1,181.53
Nitrogen Gas		$ 25.59	5	0%	$ 127.95
Helium Gas		$ -	1	0%	$ -
Distilled Water		$ 0.88	270	0%	$ 237.60
Regulator		$ -	1	0%	$ -
Involute Gear Cutter	10-289-044	$ 205.04	1	0%	$ 205.04
Flow Meter	MTR-304G	$ 388.75	1	0%	$ 388.75
Teflon seal	5154T31	$ 8.07	8	0%	$ 64.56
Ball Bearings	6909UU	$ 19.49	2	0%	$ 38.98
Water Drum	56W55R	$ 41.33	2	0%	$ 82.66
Krytox 240 Lubricant	240AD-2OZ	$ 230.38	1	0%	$ 230.38
Tubing	79132	$ 11.95	1	0%	$ 11.95

Legend
Electronics
Hardware
Manufacturing
Testing

Subtotal	$3,909.44
Shipping	$ 586.42
Tax	0
Total	$4,495.86

11% Financial Cushion

Stretch Budget

Part	Unit	Price	Quantity	Discount	Total
Wire		$ -	20	0%	$ -
NTO Gear block	8992K908	$ 47.36	2	0%	$ 94.72
NTO panel	8992K908	$ 47.36	1	0%	$ 47.36
NTO Housing	6620K41	$ 139.53	1	0%	$ 139.53
UDMH Gear Block	8983K233	$ 45.34	2	0%	$ 90.68
UDMH Panel	8983K233	$ 45.34	1	0%	$ 45.34
UDMH Housing	8983K198	$ 57.41	1	0%	$ 57.41
Nuts and Bolts	As Needed	$ 35.00	1	0%	$ 35.00
Machining Metals	As Needed	$ -	0	0%	$ -
Pressure Transducers	)-5KG5V model	$ -	4	0%	$ -
Pressure Regulator	IP610-0120-D	$ 415.00	2	0%	$ 830.00
Accelerometers		$ -	2	0%	$ -
Line hookups	3/8" Lines	$ -	2	0%	$ -
Drive System	Air Motor	$1,181.53	2	0%	$2,363.06
Nitrogen Gas		$ 25.59	5	0%	$ 127.95
Helium Gas		$ -	1	0%	$ -
Distilled Water		$ 0.88	270	0%	$ 237.60
Regulator		$ -	1	0%	$ -
Involute Gear Cutter	10-289-044	$ 205.04	1	0%	$ 205.04
Flow Meter	MTR-304G	$ 388.75	1	0%	$ 388.75
Teflon seal	5154T31	$ 8.07	8	0%	$ 64.56
Ball Bearings	6909UU	$ 19.49	2	0%	$ 38.98
Water Drum	56W55R	$ 41.33	2	0%	$ 82.66
Krytox 240 Lubricant	240AD-2OZ	$ 230.38	1	0%	$ 230.38
Tubing	79132	$ 11.95	1	0%	$ 11.95

Legend		
Electronics	Subtotal	$5,090.97
Hardware	Shipping	$ 763.65
Manufacturing	Tax	0
Testing	Total	$5,854.62

Summary

Summary of Design

- Two external gear pumps
- One pneumatic drive system
- Mass flow rate controlled by drive system RPM
- Drive system RPM controlled by closed-loop control of a digital pressure regulator

Current Status

Current Status

Feasibility Shown	Next Steps and Further Research
The pump can be manufactured to the correct tolerances	1. Contact SAS for shop times 2. If not, find outsourcing location
Pneumatic power is achievable	1. Choose a pump with sufficient power 2. Acquire pneumatic source
Throttleability is achievable	1. CFD and testing to decide if the drive system is the viable option 2. Design control loop
Efficiencies are met with reasonable tolerances	1. Find and secure manufacturing resources
Budget is sufficient	1. EEF Fund 2. Re-scope project to one pump

Action/Risk Items for CDR

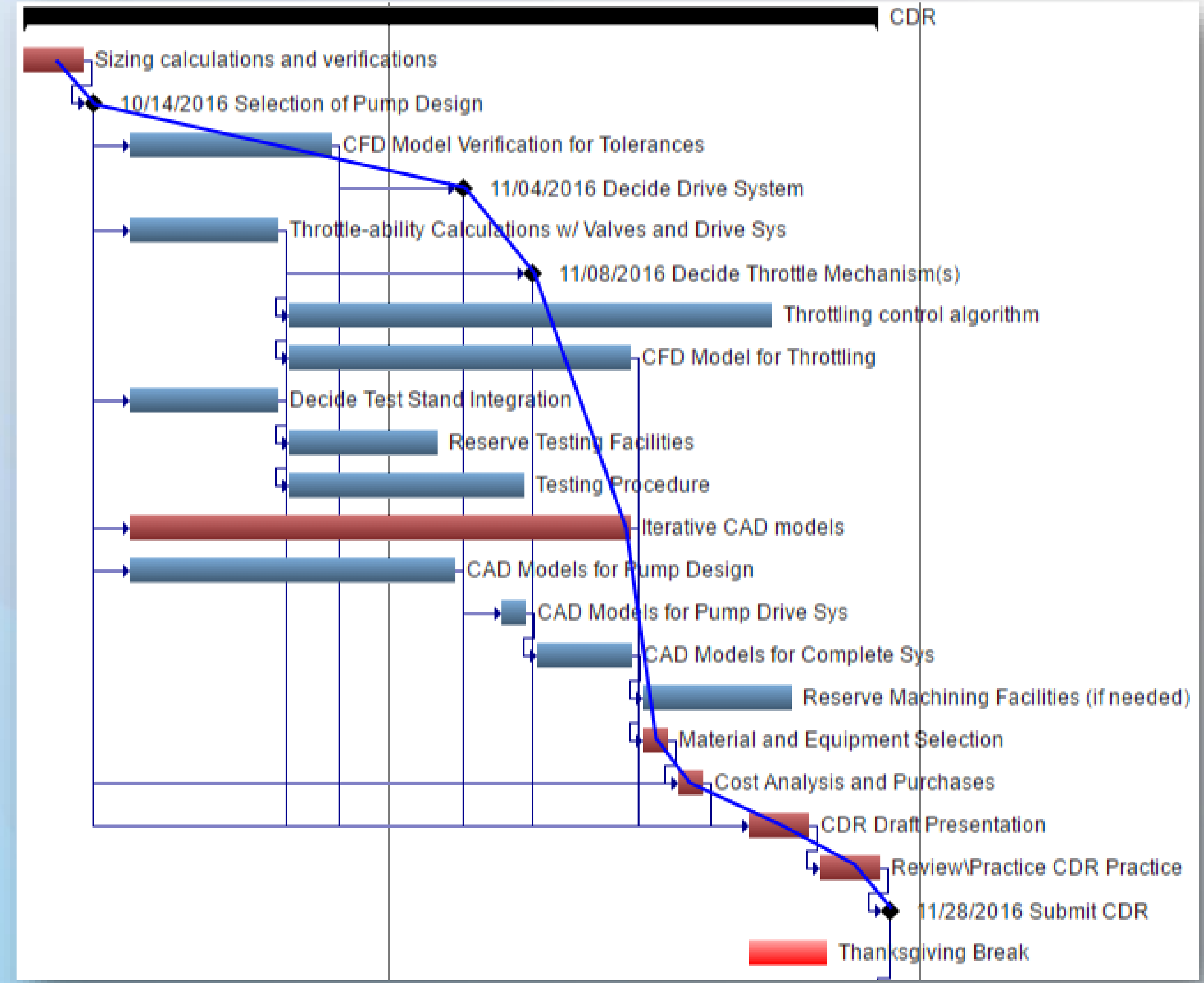
Action Items

- Complete full assembly design with bearings, seals, drive system, etc.
- Higher fidelity fluid analysis
- Structural analysis
- Further design optimization
- Throttle controller design
- Secure manufacturing resources

Risk Items

- Proper gear mating
- Proper tolerancing on drawings
- Tolerance stackup
- Full range throttleability
- Budget

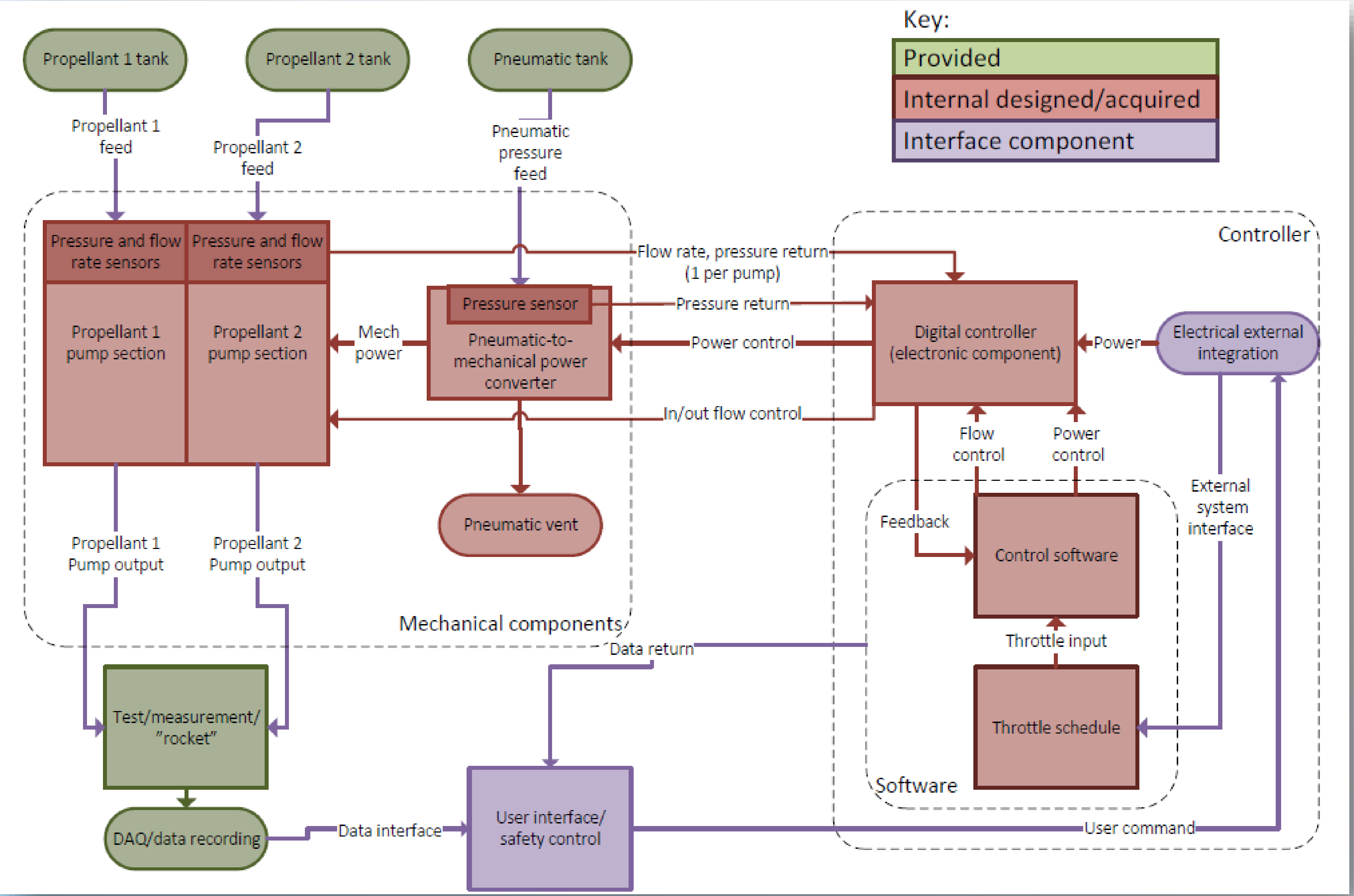
Project Timeline



Questions?

Backup Slides

FBD


Key:
Provided
Internal designed/acquired
Interface component
Propellant 1 tank
Propellant 2 tank
Pneumatic tank
Propellant 1 feed
Propellant 2 feed
Pneumatic pressure feed
Pressure and flow rate sensors
Pressure and flow rate sensors
Propellant 1 pump section
Propellant 2 pump section
Mech power
Pressure sensor
Pneumatic-to-mechanical power converter
Flow rate, pressure return (1 per pump)
Pressure return
Power control
In/out flow control
Controller
Digital controller (electronic component)
Power
Electrical external integration
Flow control
Power control
Feedback
Control software
External system interface
Throttle input
Throttle schedule
Software
Pneumatic vent
Propellant 1 Pump output
Propellant 2 Pump output
Mechanical components
Data return
Test/measurement/ "rocket"
DAQ/data recording
Data interface
User interface/ safety control
User command

Functional and Design Requirements

- FR 1 – The pump shall be pneumatically driven using compressed helium.
  - DR 1.1 – The drive system of the pump shall be powered using room temperature, compressed helium at a pressure between 2000 psi and 6000 psi.
- FR 2 – The fuel streams shall be individually, digitally controlled and throttled from 10% to 100% of full throttle
  - DR 2.1 – A digital throttle shall be implemented to individually control the mass flow rate of the propellants. The total mass flow rates of the propellants must vary from 3.0 kg/s to 0.3 kg/s.
  - DR 2.2 – The target/nominal O/F ratio shall be 2.
- FR 3 – The pump shall deliver a 750 ± 15 psi outlet pressure
  - DR 3.1 – At full throttle, the pump shall be designed to maintain an outlet pressure 750 psi. The outlet pressure of the pump shall oscillate with an amplitude of less than 15 psi at all throttle settings.

Functional and Design Requirements

- FR 4 – The pump shall be able to run a provided throttle profile for the full duration of an upper stage burn
  - DR 4.1 – The pump must be designed such that it can be run for the full duration of a 500 second burn.
- FR 5 – The pump system shall have the ability to be restarted
  - DR 5.1 – The outlet pressure and mass flow rate of the pump shall reach the desired setting within 1 second of pump start-up. If this cannot be achieved, the client has specified that a start-up transient of 2 seconds would be acceptable, although less desirable.
  - DR 5.2 – The pump must be designed such that it can be started from 0 mass flow rate.

Functional and Design Requirements

- FR 6 – The pump system shall be constructed from materials that are compatible with the client-specified hypergolic propellants
  - DR 6.1 – The pump system shall be manufactured using materials that are compatible with dinitrogen tetroxide (NTO) and unsymmetrical dimethyldydrazine (UDMH).
- FR 7 – The pump system shall designed and manufactured such that a structural factor of safety of 2.5 is maintained on all components
  - DR 7.1 – All components of the pump and pump housing shall be designed to withstand the high pressures with a structural factor of safety of 2.5 on material yield or failure.
  - DR 7.2 – All components of the pump that will experience high compressive, tensile, torque or other mechanical loads will be designed to withstand those loads with a factor of safety of 2.5 on material yield or failure.
  - DR 7.3 – All other components that will experience high stress or strain due to operation of the pump must be designed to withstand those high stresses and strains with a structural factor of safety of 2.5 on material yield or failure.
- FR 8 – The pump shall meet 75% efficiency at maximum power/capacity

Pump Trade Study Metrics

Key:	Weighting	1	2	3	4	5
Throttlability:	20	20-100%	15-100%	10-100%	5-100%	0-100%
Slew rate:	10	2 seconds	1 second	1/2 second	1/4 second	1/8 second
Pressure fluctuation	15	90+ dB	80-90 dB	70-80 dB	60-70 dB	50-60 dB
Pressure sensitivity	5	1+ atm in	0.9-1 atm in	0.75-0.9	0.5-0.75	0-0.5 atm in
Full throttle eff.	5	75-80%	80-85%	85-90%	90-95%	95-100%
Throttle eff.	5	Worse than proportional	Proportional	Large, but not proportional	Moderate	Slight
Ability to hit tolerances	5	< 0.001 mm	0.005 mm	0.01 mm	0.05 mm	0.1 mm <
Manufacture time	15	3 months	2 months	1 month	two weeks	within a week
Complexity	10	20+ moving parts	14-20 moving part	7-13 moving part	3-6 moving parts	1-2 moving parts
Pneumatic integration	10	Use something else	Build our own	Difficult	Moderate	Easy
designability	5	Difficult		Moderate		Easy
maintainability	5	Need to disassemble/ reassemble the pump	Need to remove multiple components	Need to remove another component	Need to remove a panel	simple access
outsourced machining	10	Expect $4000+	est $3000-$4000	est $2000-$3000	est $1000-$2000	est $0-$1000
off-shelf components	10	0-15%	16-25%	26-50%	51-80%	80%+
reliability	5	Major overhall after eve	Replace parts afte	Replace parts eve	Check parts every	Check if desired/non-issue
restartability	5	Leaks like a sieve	Problematic leaks	Notable leaks	Slight leaks	Negligable leaks

Full Sensitivity Study

Sensitivity factor	LPP	APP	ExGear	InGear	Screw	RV	Cent
Trade Study Results	7	4	1	2	5	3	6
Equal weightings	7	4	1	2	5	3	6
Throttlability	7	5	1	3	6	2	4
Slew Rate	7	4	1	2	5	3	6
Pressure fluctuation	7	4	1	2	5	3	6
Pressure sensitivity	7	3	1	2	5	4	5
Efficiency	7	4	1	2	5	3	6
Throttle efficiency	7	3	1	2	6	3	5
Tolerances	7	4	1	2	5	3	6
Manufacture time	7	2	1	3	5	3	6
Complexity	7	4	1	2	5	3	6
Pneumatic integration	7	3	1	2	5	4	6
Designability	7	4	1	2	5	3	6
Maintainability (easy access)	7	4	1	2	5	3	6
Outsourcing	7	4	1	2	5	3	6
Off shelf component availability	7	4	1	2	5	3	6
Reliability	7	4	1	2	5	3	6
Restartability	7	3	1	2	5	4	6

Axial Piston/Gear Pump Comparison

Sensitivity factor	Axial Piston Pump	Gear Pump	Trade Study Results	3.107142857	3.964285714
Equal weightings	57	68	Equal weightings	2	1
Throttlability	3	3.785714286	Throttlability	2	1
Slew Rate	1.928571429	3	Slew Rate	2	1
Pressure fluctuation	2.785714286	3.535714286	Pressure fluctuation	2	1
Pressure sensitivity	3.035714286	3.821428571	Pressure sensitivity	2	1
Efficiency	2.928571429	3.857142857	Efficiency	2	1
Throttle efficiency	2.964285714	3.821428571	Throttle efficiency	2	1
Tolerances	2.928571429	3.857142857	Tolerances	2	1
Manufacture time	2.892857143	3.428571429	Manufacture time	2	1
Complexity	3.035714286	3.678571429	Complexity	2	1
Pneumatic integration	2.892857143	3.75	Pneumatic integration	2	1
Designability	3.035714286	3.785714286	Designability	2	1
Maintainability (easy access)	2.964285714	3.821428571	Maintainability (easy access)	2	1
Outsourcing	3.107142857	3.964285714	Outsourcing	2	1
Off shelf component availability	3.107142857	3.964285714	Off shelf component availability	2	1
Reliability	2.928571429	3.821428571	Reliability	2	1
Restartability	3	3.785714286	Restartability	2	1

Selection of Baseline Design #2

- Axial piston pump
  - Similar applications as external gear pump
    - Favored in very high pressure applications (>1500 psi)
    - Higher efficiency
  - Lower score in trade study
  - Extra capabilities exceed scope of project
  - Larger potential for exceeding pressure differential requirement (pulsing) - mitigation methods would be very complicated and/or expensive
  - Still viable because of capability to hit requirements. Due to budgeting, compromises might have to be made on scope of project

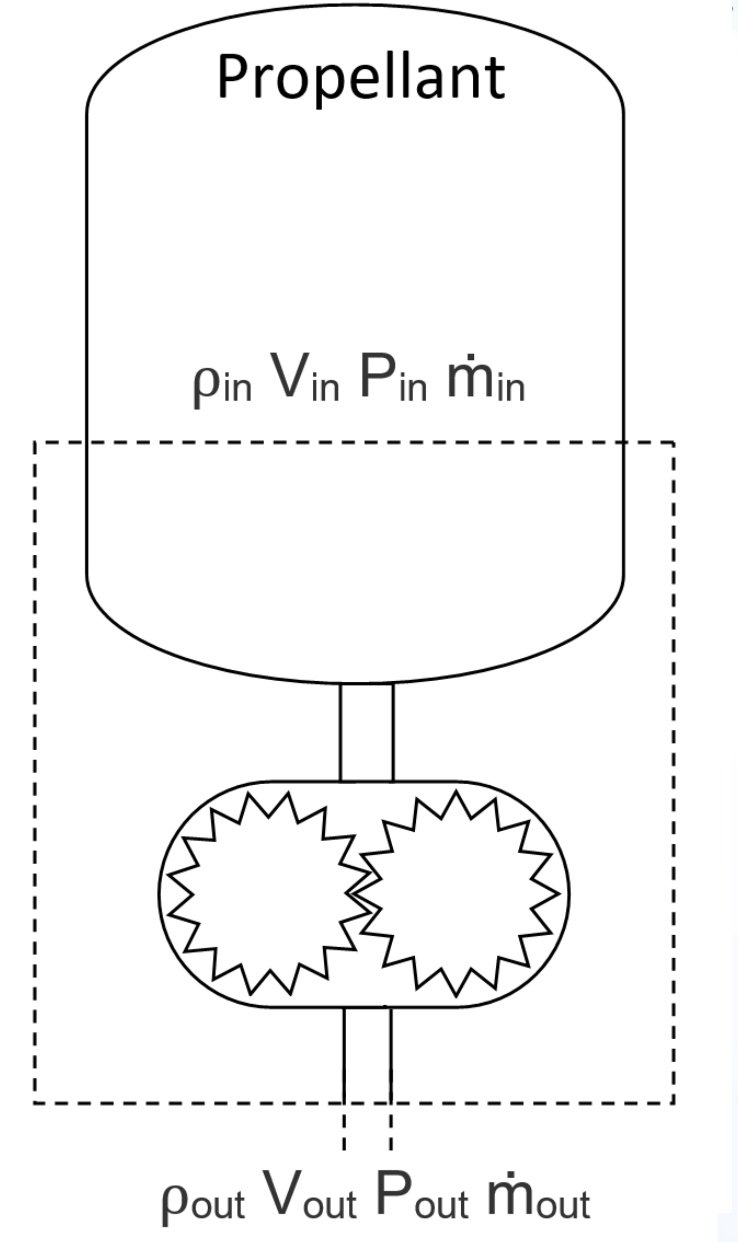
Hypergolic Propellant Properties

	Hydrogen Peroxide	Nitrogen Tetroxide	UDMH	Water
Density (g/cm^3)	1.45	1.44246	0.791	1
Viscosity (cp @ 20C)	1.245	0.396	0.56	0.890-1.0034
Oxidizer or Fuel	Ox	Ox	Fuel	Neither

	Hydrogen Peroxide	Nitrogen Tetroxide	UDMH
Compatible Metals	Al 1060, 1260, 1360, 5254, 5652 Tantalum, Zirconium	Moisture <0.1%: Carbon steel, Inconel-X, Nickel Al 1100, 2024, 5052, 6061, 6066, 356, B356, see ref. Stainless steel: 300 and 400 series Wet: 300 series stainless steel	Nickel, Monel, Stainless Steel 302, 303, 304, 321, 314, 410, 416 Al 1100, 2024, 5052 see ref. *Al may be used, but corrosive damage is found to be proportional to amount of water in the solution
Compatible Non-metals	Compatible Non-Metals Teflon, Kel-F, Aclar	Teflon, graphite, kynar, polyethylene (lim. use), pyrex glass, fluorobestos, tedlar	Teflon, Kel-F, polyethylene, Garlock Gasket 900, Nylon, Glass Pyrex
Compatible Lubricants	No Class I, Class II: Fluorolubes, Kel-flo polymers, Halocarbon oils, perfluorolube oils	Fluorolube series, Graphite (dry), Nordcoseal-147 and DC 234S Molycote Z (binderless), Teflon tape, Redel Reddy lube 100 NA 2-205-2 (Alochlor-1254), DuPont fluorinated grease, Krytox 240.	Apiezon L, Reddy Lube 200, DuPont fluorinated grease, Krytox 240.

Power Estimation

- $\rho_{in} \approx \rho_{out}$ $\dot{m}_{in} = \dot{m}_{out}$ $V_{in} \approx 0$
- $\therefore \dot{W}_{press} = (\dot{m}/\rho)(P_{out} - P_{in})(1/\eta_{pump})$
- $\dot{W}_{UDMH} = 7.16$ kW
- $\dot{W}_{N2O4} = 7.87$ kW
- $\dot{W}_{kinetic} = \dot{m}/(2\,\pi^2\,\rho^2 r^4)$
- $\dot{W}_{kinetic} < 10\%$ of $\dot{W}_{total}$ if pump outlet radius > 0.15 in
- $\dot{W}_{kinetic} \propto 1/r^4$



Efficiency

- Theoretical mass flowrate through a gear pump is given by:

$$\dot{m} = \frac{FD^2(9n - 2.35)\omega\rho}{16n^2}$$

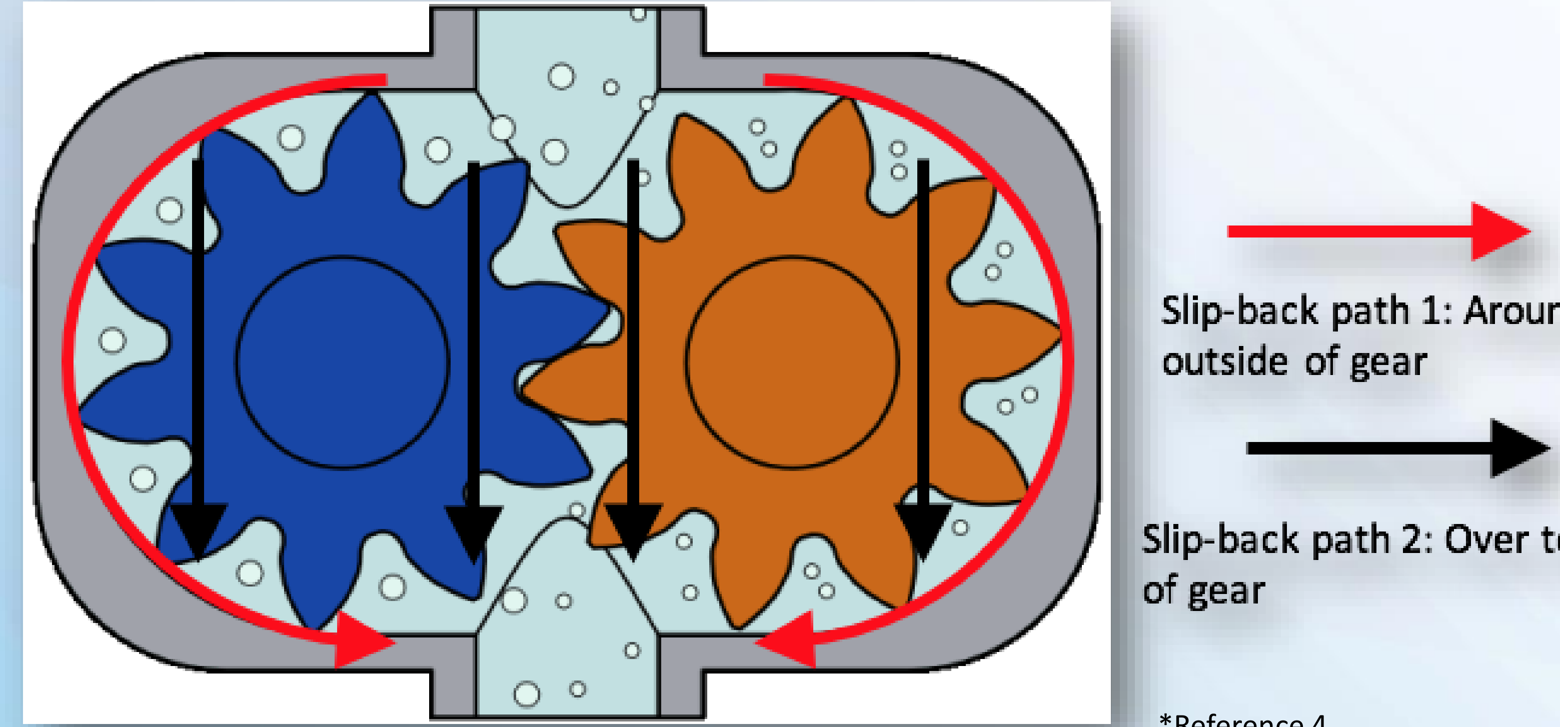
Where F is the gear face width, D is the ptich diameter of the gear, n is the number of teeth on the gear, ω is the angular velocity of the gear and ρ is the density of the fluid being pumped.

Mechanical Losses

- Can be calculated using the equations given in ref. “Spur-Gear-System Efficiency at Part and Full Load” (old NASA report)
- Losses include windage, bearing losses, and rolling/slipping losses
- Mechanical efficiencies are usually very high for spur gears

Volumetric Losses

- Caused by fluid slip-back from the outlet to the inlet
- Very dependent on manufacturing tolerances
- Usually account for 60% to 80% of the efficiency loss of a gear pump
- Slip back occurs around the tips of gears and over the top of each gear, as shown below.
- All calculations were completed assuming a clearance of 1 thousandth of an inch at the gear tips and over the top of the gears.



Slip-back path 1: Around outside of gear

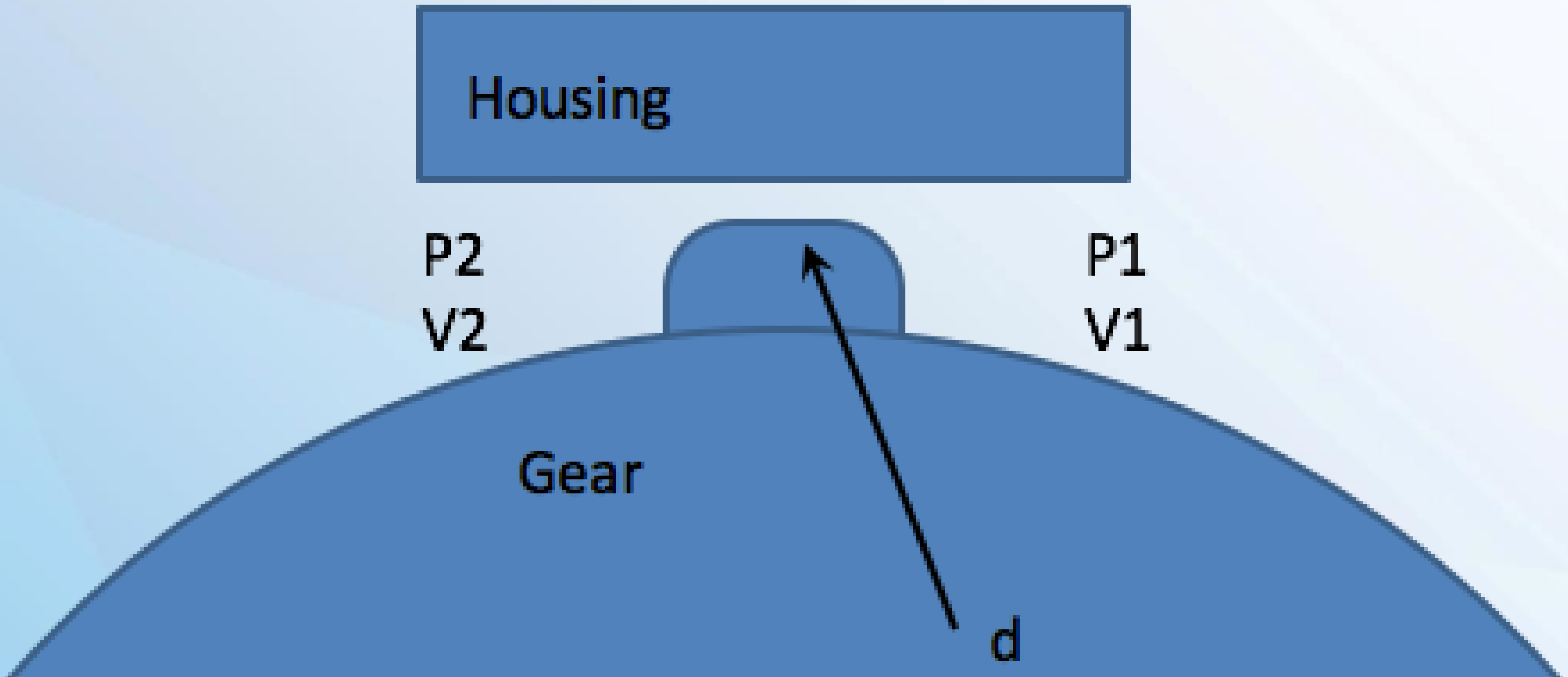
Slip-back path 2: Over top of gear

*Reference 4

Volumetric Losses

Calculating Slip-Back at Ends of Gear Teeth

The clearance between the tip of the gear and the housing can be thought of as a narrow orifice with dimensions of F (gear face width) and d (the housing clearance).



Volumetric Losses

- Calculating Slip-Back at Ends of Gear Teeth

The back-slip occurs over each tooth that is in close contact with the housing so for 15 gears, back-slip occurs over 7 teeth.

The equation for mass flux through a narrow orifice is:

$$\dot{m} = A\sqrt{2\Delta P\rho} = dF\sqrt{2\Delta P_t\rho}$$

Where d is the clearance at the tip, F is the gear face width, ΔP_t is the difference in pressure across the tooth and ρ is the density of the fluid

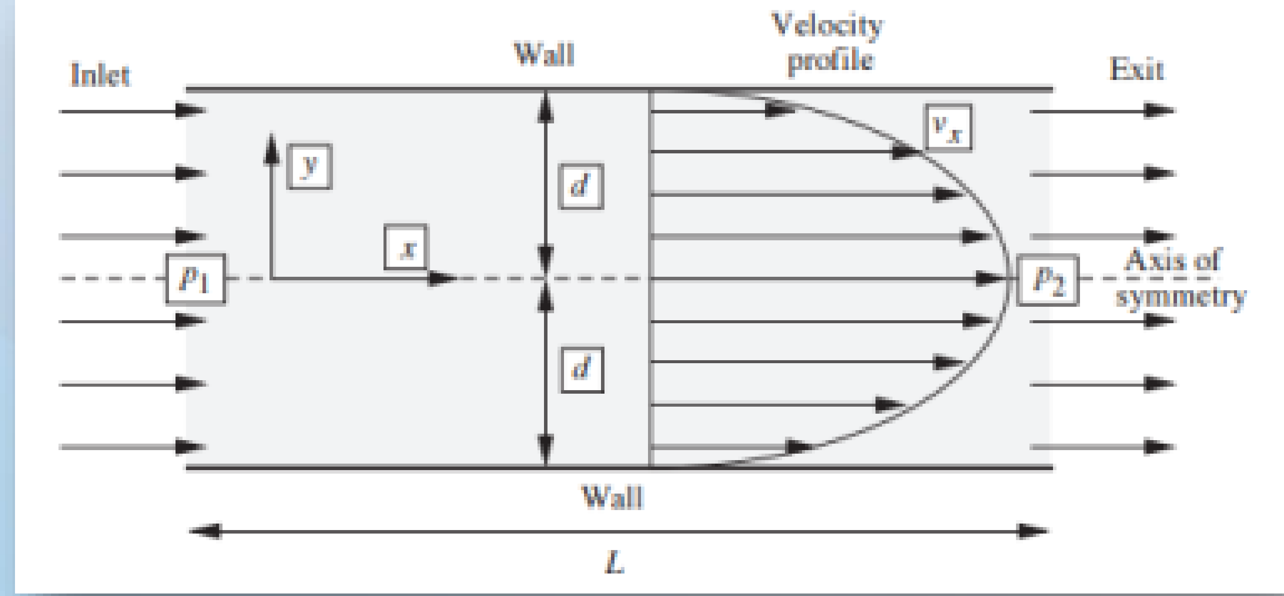
If we assume a linear drop of pressure across all 7 teeth (ie $\Delta P_t = (P_{outlet} - P_{inlet})/n$). We get a slip-back mass flow rate of 0.067 kg/s across the top of each tooth. This is the slip back around only one gear so the total slip back is 0.134 kg/s around both gears which gives an efficiency loss of about 6.7%.

The assumption of a linear pressure drop is good in this case because it satisfies the continuity equation by predicting equal mass flow rate across the top of each tooth.

Volumetric Losses

Calculating Slip-Back over the Tops of the Gears

The back-slip occurs over the top of both gears. This can best be idealized as viscous flow through a narrow channel, as shown below.



Volumetric Losses

- Calculating Slip-Back over the Tops of the Gears

The average velocity of the flow is given by the equation:

$$V_{avg} = \left(\frac{2(P_{outlet} - P_{inlet})}{L}\right)\left(\frac{d^2}{3\mu}\right)$$

Where L is the length of the channel (calculated as $L = \left(\frac{4}{3\pi}\right) D$, the average distance across a circle of diameter D), d is half of the clearance, and μ is the dynamic viscosity of the working fluid.

The mass flow rate can then be written:

$$\dot{m} = V_{avg}\rho\,(2d)\,(4D)$$

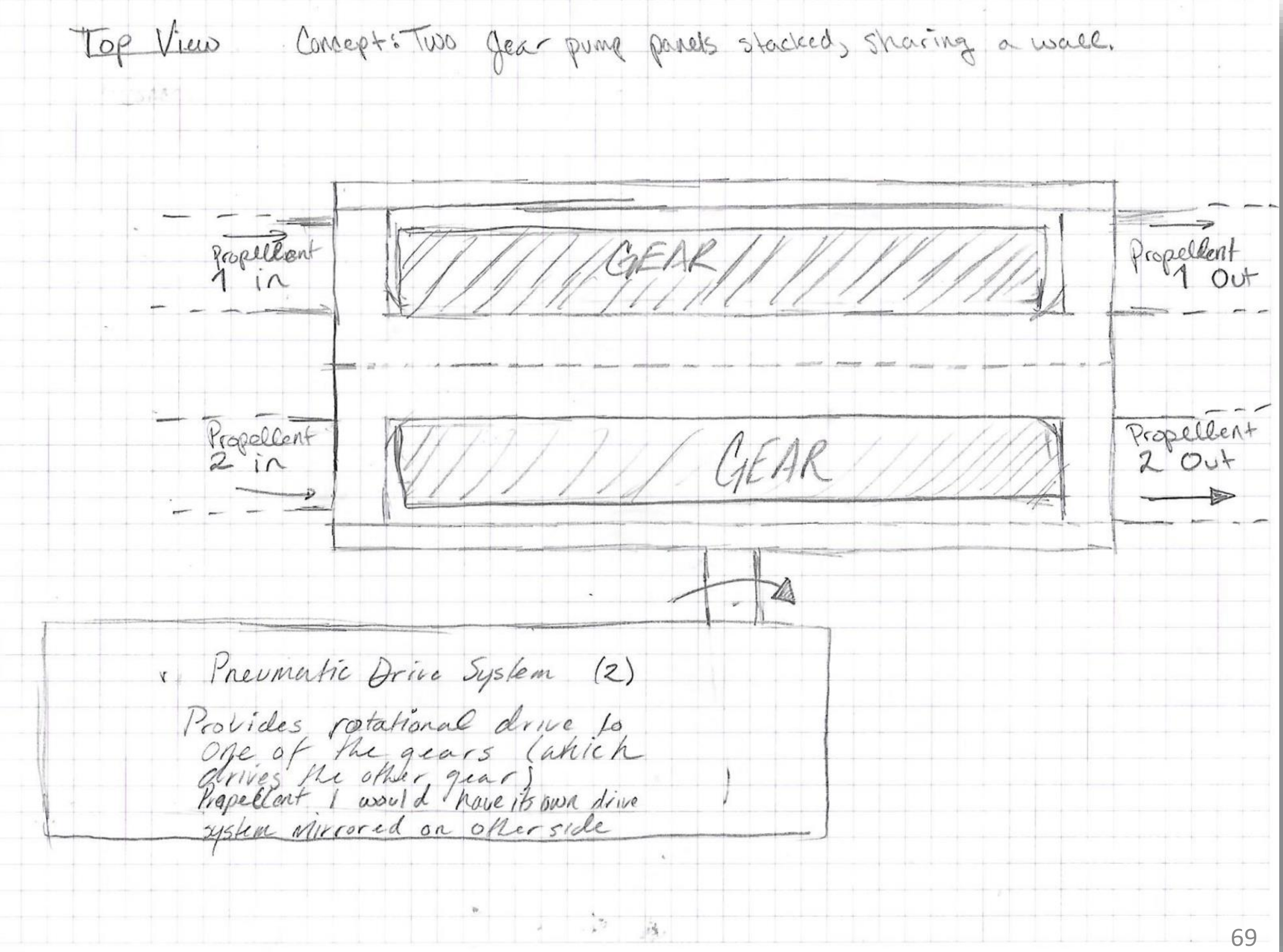
This equation yields a total back-slip mass flowrate of 0.213 kg/s and an efficiency loss of 11%.

This is a very conservative estimate because it assumes slip-back across the entire bottom and top surfaces of both gears at the maximum outlet pressure. A more realistic estimate would be to replace 4D with D in the above equation. This yields a slip-back mass flowrate of 0.0532 kg/s and an efficiency loss of 2.7%.

In order to remain conservative we will use the 2D as the slip area which results in a mass flowrate of 0.106 kg/s and an efficiency loss of 5.3%.

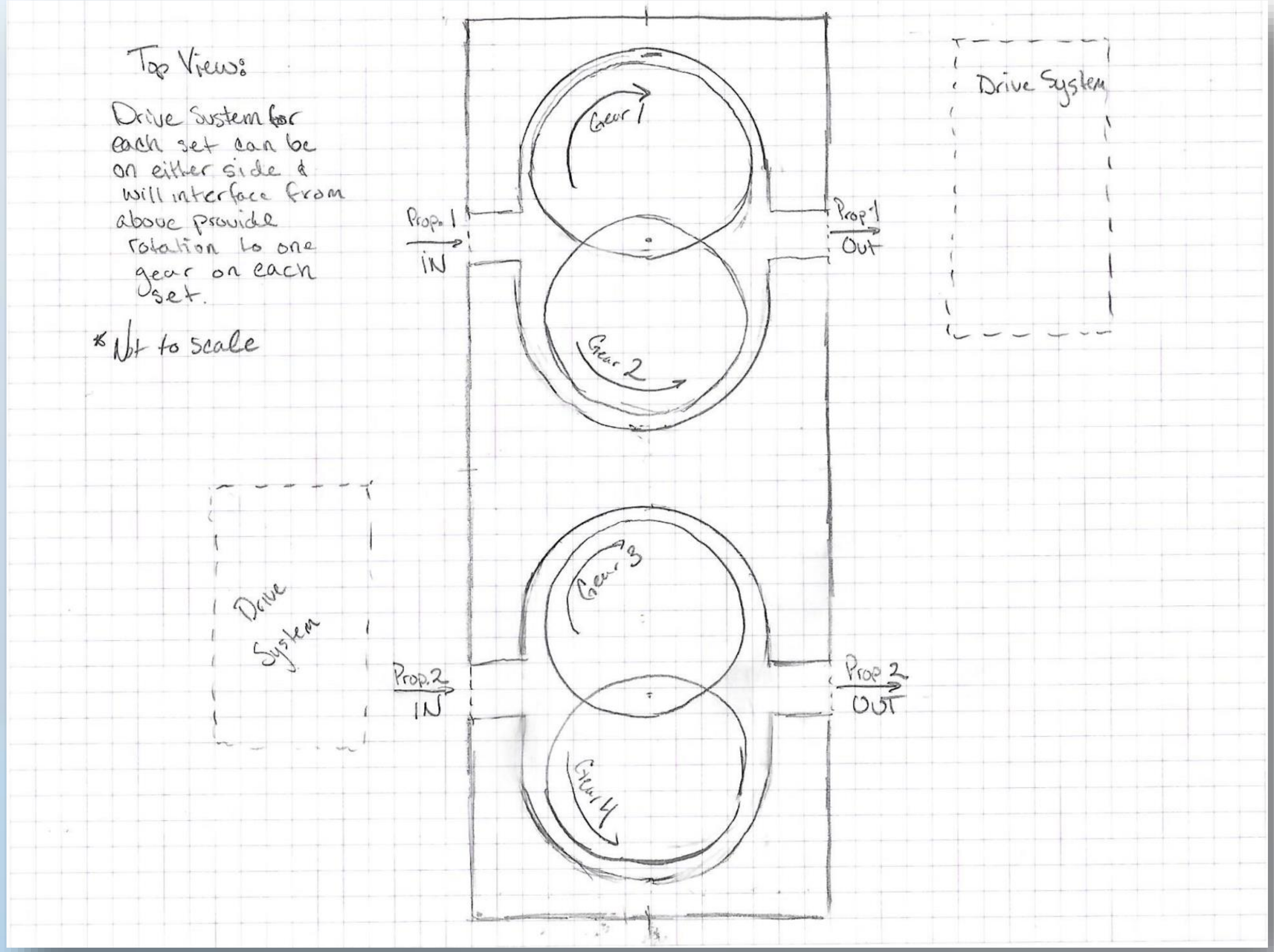
External Gear Combination 1

The two gear pumps are 'pancaked' together and run parallel to make for very compact running of both pumps. Drive systems are placed right next to the side they are driving and could have a very compact design.



External Gear Combination 2

The two propellants are placed and run parallel to one another. The drive systems can be placed opposite each other to allow for compact outside housing.



Initial Power Estimates

$\rho_{in} \approx \rho_{out}$ $\dot{m}_{in} = \dot{m}_{out}$ $V_{in} \approx 0$

$\therefore \dot{W}_{press} = (\dot{m}/\rho)(P_{out} - P_{in})(1/\eta_{pump})$

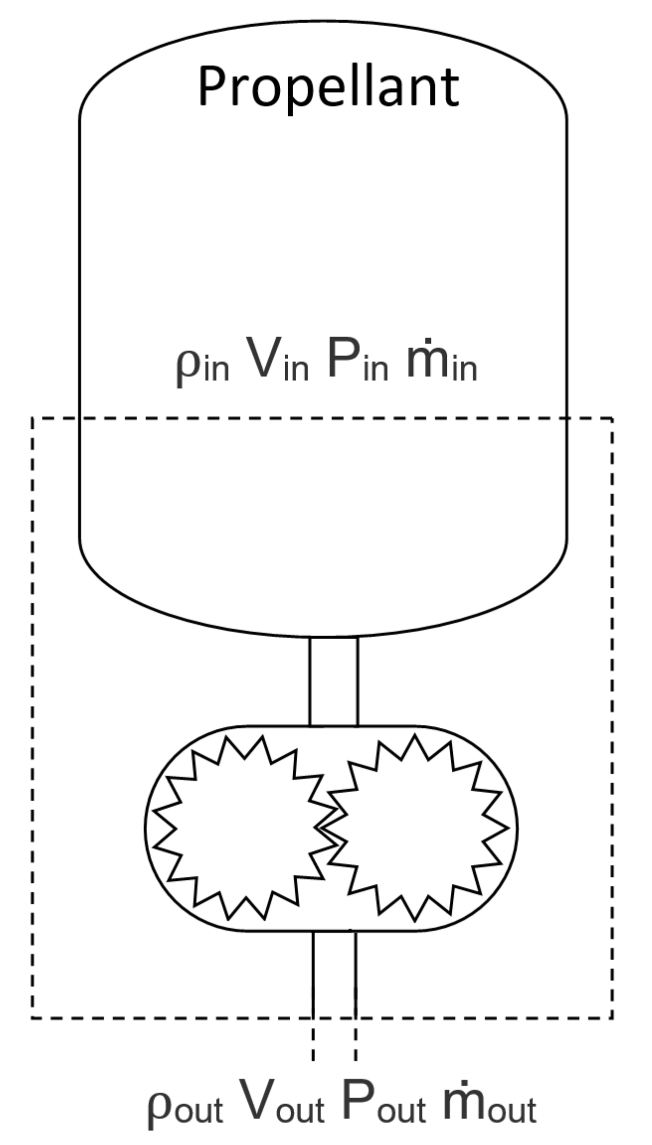
$\dot{W}_{UDMH} = 7.16$ kW

$\dot{W}_{N2O4} = 7.87$ kW

$\dot{W}_{kinetic} < 10\%$ of $\dot{W}_{total}$ if pump outlet

Radius > 0.15 inches

$\dot{W}_{kinetic} \propto 1/r4$



Theory of Cavitating Venturi

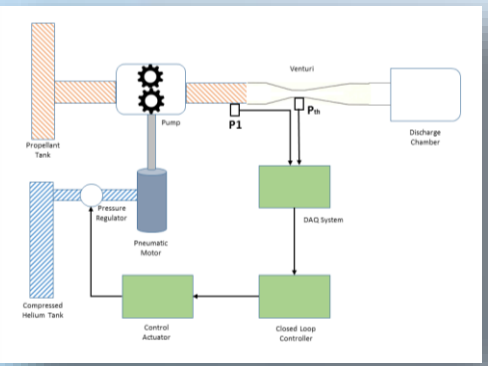
- Pressure reduction in converging section of venturi leads to static pressure at throat < vapor pressure of liquid
- Rapid partial transition from liquid to vapor (cavitation)
- Phase change causes flow to choke at throat, preventing downstream pressure change from affecting the upstream flow

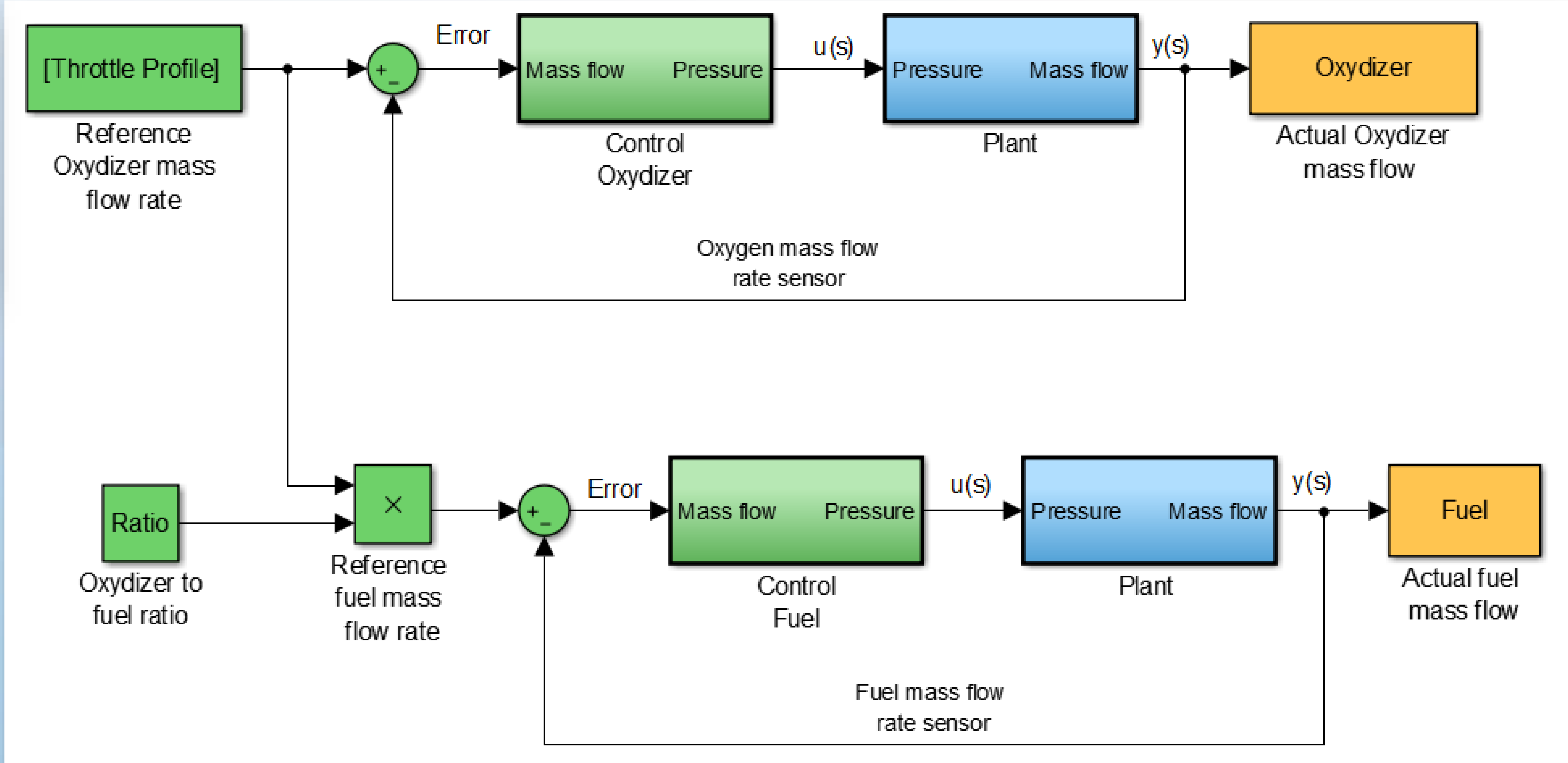
$$\dot{m} = A_{th}\sqrt{2\rho(P_1 - P_{th})}$$

A_{th} - Area at venturi throat
ρ - liquid water density at throat
P1 - Pressure at pump exit
Pth - Pressure at venturi throat

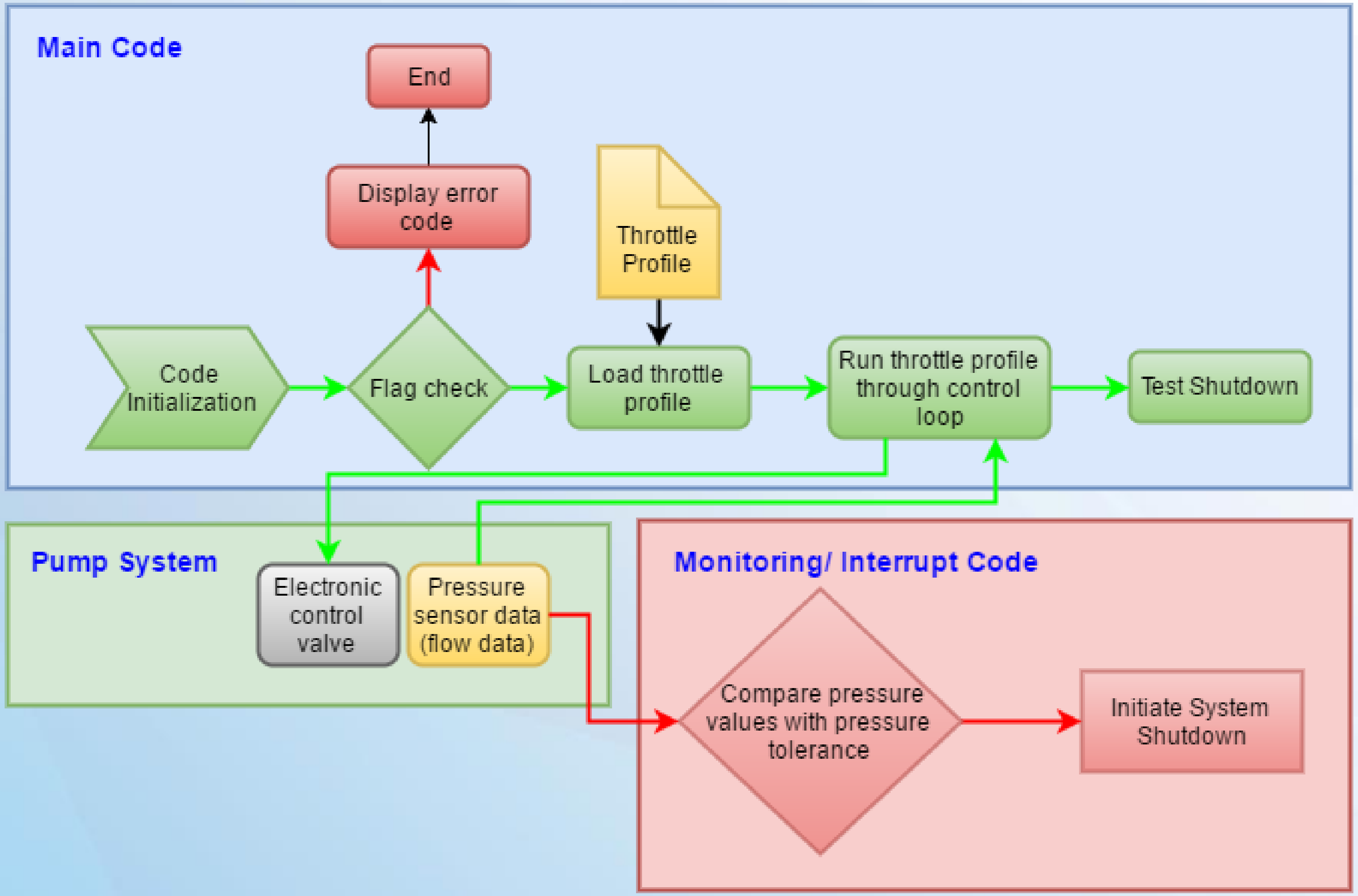
*Reference 4

Pump Control System



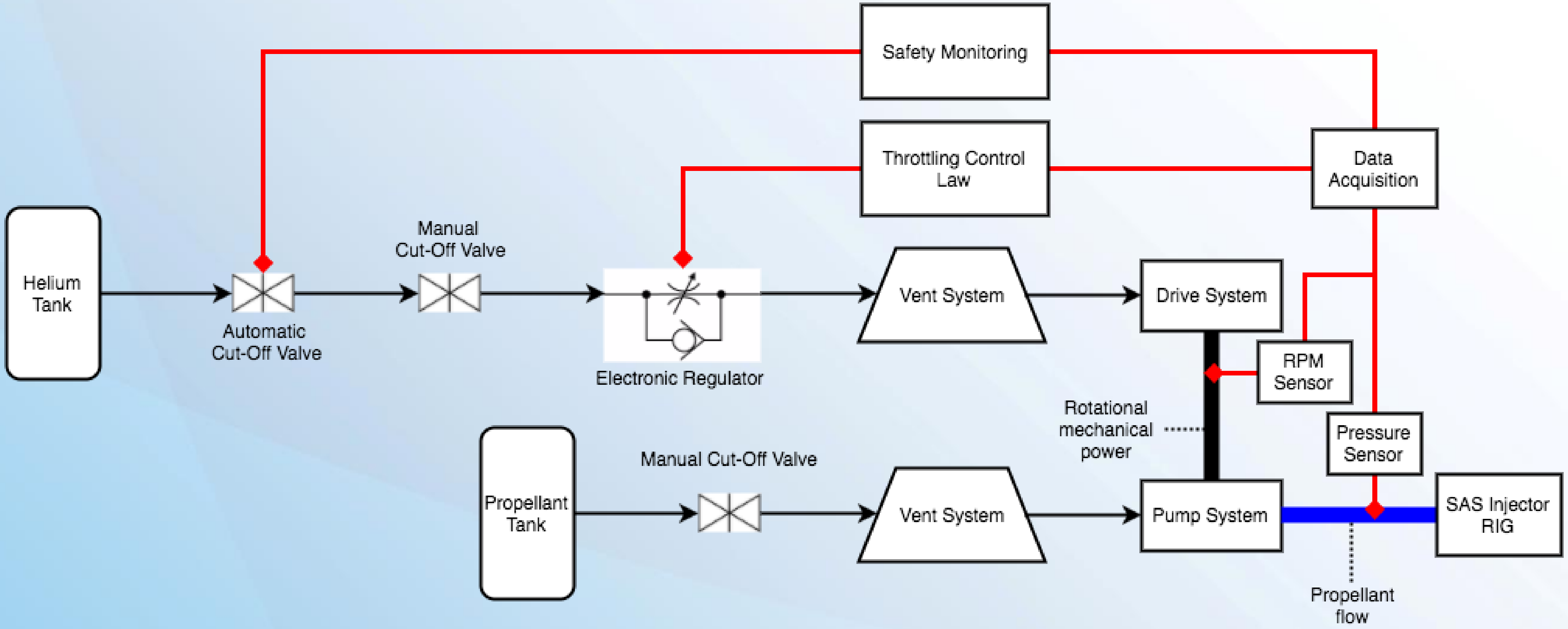


Code Flow



Main Code
End
Display error code
Throttle Profile
Code Initialization
Flag check
Load throttle profile
Run throttle profile through control loop
Test Shutdown
Pump System
Electronic control valve
Pressure sensor data (flow data)
Monitoring/ Interrupt Code
Compare pressure values with pressure tolerance
Initiate System Shutdown

Selected Design



Frequency

Maximum frequency
spike

$$f_p = \frac{\omega * N_{gear}}{30}$$

DAQ

- Max spike frequency: 1.2 kHz
- Minimum operation frequency: 2.4 kHz
- Minimum Analog Output pins: 2
- Minimum Analog Input pins: 4
- Minimum Resolution: < 0.1 or 8 bits>

DAQ

DAQ provided: NI USB – 6002

Analog Inputs pins: 8

Analog Output pins: 2

Digital I/O pins: 13

Resolution: 16 bits

Maximum Bandwidth: 300 kHz

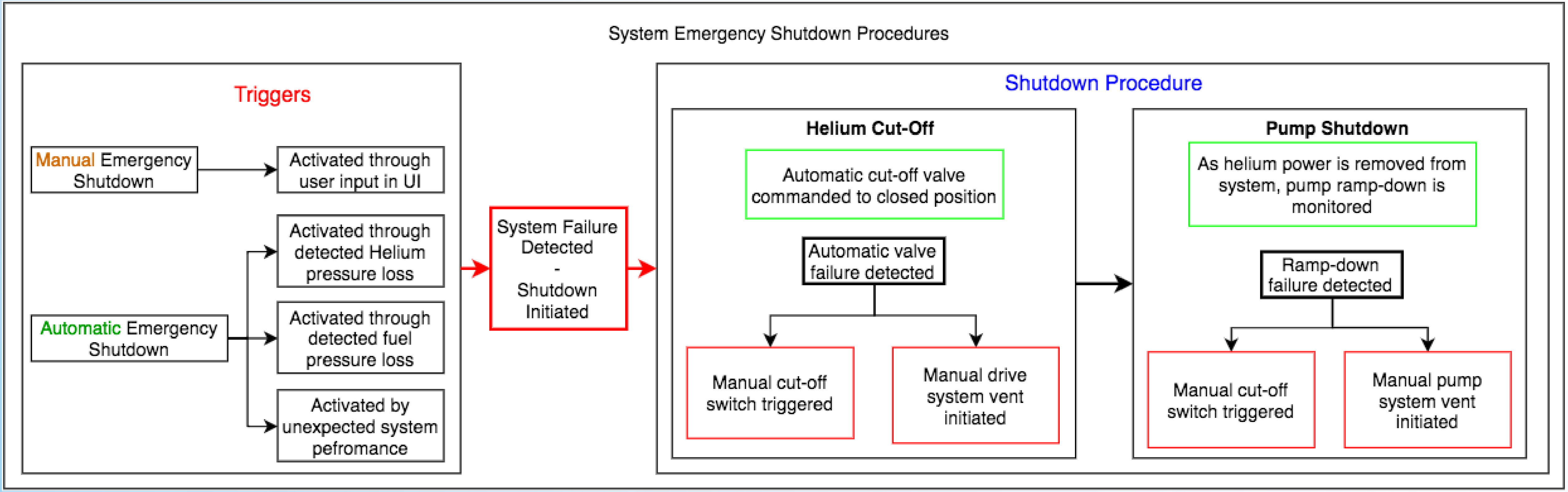
Microcontroller (if necessary)

myRIO microcontroller
Analog Inputs pins: 8
Analog Output pins: 4
Digital I/O pins: 32
Resolution: 12 bits
Maximum Bandwidth: 500 kHz

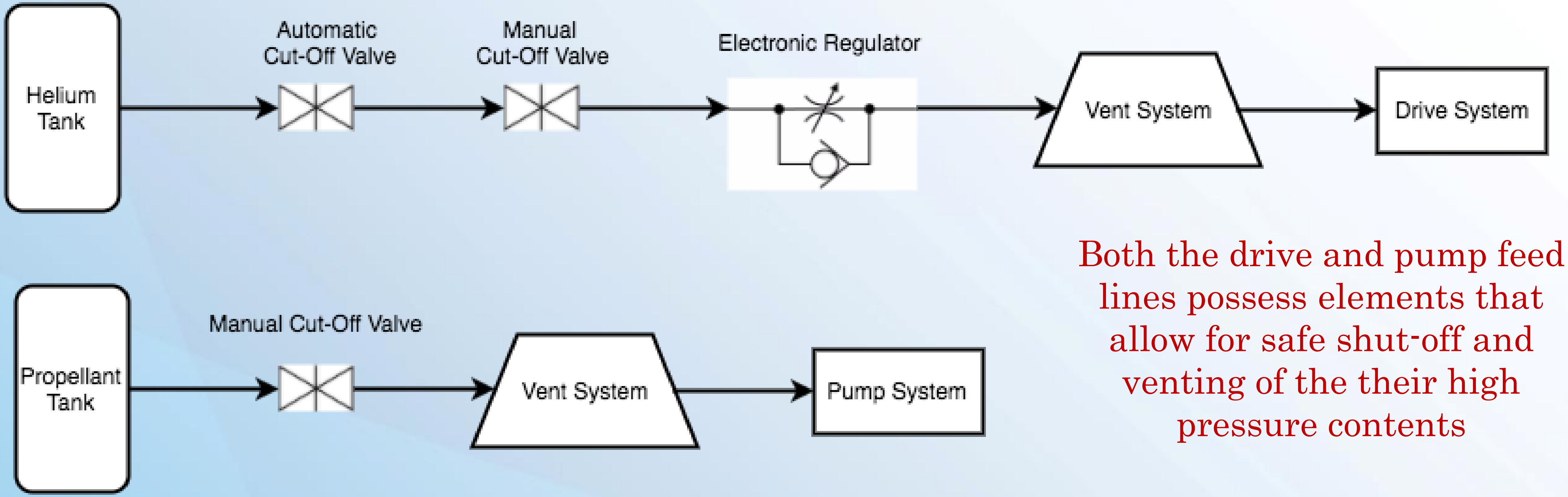
Helium and Water Required for Test

- 0.7 gallons/s for 120 seconds = 84 gallons water
  - Same volumetric flow rate as propellants
- 280 cfm @ stp for 120 seconds per propellant = 2.83 kg helium

Safety Requirement



Safety Components



Both the drive and pump feed lines possess elements that allow for safe shut-off and venting of the their high pressure contents

Budget With References

Part	Unit	Price	Quantity	Discount	Total		Reference
Wire		$ -	20	0%	$ -		Trudy's Shop. Ask before using
NTO Gear block	8992K908	$ 47.36	2	0%	$ 94.72		http://www.mcmaster.com/#standard-stainless-steel-sheets/=14gw4wo
NTO panel	8992K908	$ 47.36	1	0%	$ 47.36		http://www.mcmaster.com/#standard-stainless-steel-sheets/=14gw4wo
NTO Housing	6620K41	$ 139.53	1	0%	$ 139.53		http://www.mcmaster.com/#standard-stainless-steel-sheets/=14gw6xv
UDMH Gear Block	8983K233	$ 45.34	2	0%	$ 90.68		http://www.mcmaster.com/#standard-stainless-steel-sheets/=14gw8rl
UDMH Panel	8983K233	$ 45.34	1	0%	$ 45.34		http://www.mcmaster.com/#standard-stainless-steel-sheets/=14gw8rl
UDMH Housing	8983K198	$ 57.41	1	0%	$ 57.41		http://www.mcmaster.com/#standard-stainless-steel-sheets/=14gwanw
Nuts and Bolts	As Needed	$ 35.00	1	0%	$ 35.00		http://www.homedepot.com/p/Prime-Line-1-4-20-Carriage-Bolts-with-Nuts-GD-52103/202633663
Machining Metals	As Needed	$ -	0	0%	$ -		SAS Will Machine for us to specified tolerances. Given advanced notice
Pressure Transducers	KG5V model	$ -	4	0%	$ -		SAS Provided. http://www.omega.com/pptst/PX309-5V.html
Pressure Regulator	IP610-0120-I	$ 415.00	2	0%	$ 830.00		http://www.omega.com/pptst/ip610.html
Accelerometers		$ -	2	0%	$ -		SAS provided. http://www.pcb.com/nx/cSearch.aspx?q=357b11
Line hookups	3/8" Lines	$ -	2	0%	$ -		SAS Provided. http://www.mcmaster.com/#quick-disconnect-hose-couplings/=14gt96o
Drive System	'-2 Air Motor	$1,181.53	1	0%	$1,181.53		http://www.fergusonengineering.com/GastAirMotor_lubed_motors.html
Nitrogen Gas		$ 25.59	5	0%	$ 127.95		https://hdsupplysolutions.com/shop/p/40-cubic-feet-rr-nitrogen-refill-p135009?gclid=CJr8_fHRxM8CFQqKaQodSI4FJw
Helium Gas		$ -	1	0%	$ -		SAS Provided
Distilled Water		$ 0.88	270	0%	$ 237.60		Any at CU? https://www.walmart.com/ip/Great-Value-Distilled-Water-1-Gal/10315382
Regulator		$ -	1	0%	$ -		SAS Provided
Involute Gear Cutter	10-289-044	$ 205.04	1	0%	$ 205.04		http://www.travers.com/involute-high-speed-steel-gear-cutters/p/353135/?lite=true#diametrical_pitch=4&pressure_angle=20%C2%
Teflon seal	5154T31	$ 8.07	8	0%	$ 64.56		https://www.zoro.com/dayton-shaft-seal-58-in-ptfe-carbon-ceramic-3acf6/i/G0758633/?gclid=CPmpsv7yxM8CFYOFaQodnxINJQ
Ball Bearings	6909UU	$ 19.49	2	0%	$ 38.98		http://www.mcmaster.com/#ring-seals/=14iup14
Water Drum	56W55R	$ 41.33	2	0%	$ 82.66		http://www.thecarycompany.com/55-gallon-tight-head-plastic-drum-56w55r?utm_source=google_shopping&m=simple&gclid=CLI
Krytox 240 Lubricant	240AD-2OZ	$ 230.38	1	0%	$ 230.38		http://www.skygeek.com/dupont-lubricants-grease-240ad-2-oz-tube-240ad2oz.html?utm_source=googlebase&utm_medium=shoppi
Tubing	79132	$ 11.95	1	0%	$ 11.95		http://www.supplyhouse.com/MARS-79132-3-8-Clear-Tube-100-Ft?gclid=CMrxtqzzxM8CFYYCaQod7wMIWg

Legend							
Electronics				Subtotal	$3,520.69		
Hardware				Shipping	$ 528.10	0.15	Assume 15% Shipping cost
Manufacturing				Tax	0		Assume Tax free because university
Testing				Total	$4,048.79		

References

1. https://www.google.com/search?q=NI+USB+%E2%80%93+6002&rlz=1C1ARAB_enUS489US490&source=lnms&tbm=isch&sa=X&ved=0ahUKEwirwJrns87PAhXr6oMKHbsVC04Q_AUICSgC&biw=1600&bih=770#imgrc=QiBVYbduyPJp3M%3A

2. http://hydraulicspneumatics.com/200/TechZone/HydraulicPumpsM/Article/False/6401/TechZone-HydraulicPumpsM

3. "High Accuracy Pressure Transducer." *High Accuracy Pressure Transducer*. Omega, n.d. Web. 09 Oct. 2016.

4. https://www.google.com/search?q=external+gear+pump+diagram&biw=1427&bih=757&source=lnms&tbm=isch&sa=X&sqi=2&ved=0ahUKEwjmiLjbps_PAhXC6IMKHff7DngQ_AUIBigB#imgrc=L8shgHBQwhC9CM%3A

5. Ghassemi, Hojat, and Hamidreza Farshi Fasih. "Application of Small Size Cavitating Venturi as Flow Controller and Flow Meter." *Flow Measurement and Instrumentation* 22.5 (2011): 406-12. Web.

6. https://www.hawe.com/en-us/products/product-search-by-category/hydraulic-pumps/axial-piston-pumps/v30e/

7. https://dc-us.resource.bosch.com/media/us/products_13/product_groups_1/mobile_hydraulics_4/pdfs_6/re92650.pdf

8. http://www.researchinventy.com/papers/v3i2/A0320107.pdf

9. http://coewww.rutgers.edu/classes/mae/mae488/hw/lectures/gear/gear.htm

10. https://www.toolmex.com/CatSearch/231/involute-gear-cutters-20-degree-pressure-angle

References (cont.)

9. http://coewww.rutgers.edu/classes/mae/mae488/hw/lectures/gear/gear.htm

10. https://www.flickr.com/photos/diorama_sky/5643411308

11. https://en.wikipedia.org/wiki/Reaction_Motors_XLR99

12. http://www.visionqci.com/who-we-serve/gear-pumps/

13. http://fuell-engineering.com/double_action_pump.html

14.http://spoki.tvnet.lv/izgudrojumi/Ka-lietas-strada/699867

15. http://www.globalspec.com/learnmore/flow_transfer_control/pumps/piston_plunger_pumps

16. https://en.wikipedia.org/wiki/Gear_pump

17. Bergada, J., Kumar, S., Davies, D., & Watton, J. (2012). A complete analysis of axial piston pump leakage and output flow ripples. *Applied Mathematical Modelling, 36*(4). doi:10.1016/j.apm.2011.09.016

18. http://www.hydraulicpumps.co.uk/different_types.php