NFPA Fluid Power Vehicle Challenge

NFPA Education and Technology Foundation

NFPA Final Presentation
University of Denver
Dr. Rachel Horenstein
April 28th, 2022

1864

Agenda

- Team intro and problem statement
- Review of midway presentation
- Design modifications
- Vehicle Construction
- Initial Testing
- Final vehicle and subsystem design
- Lessons Learned

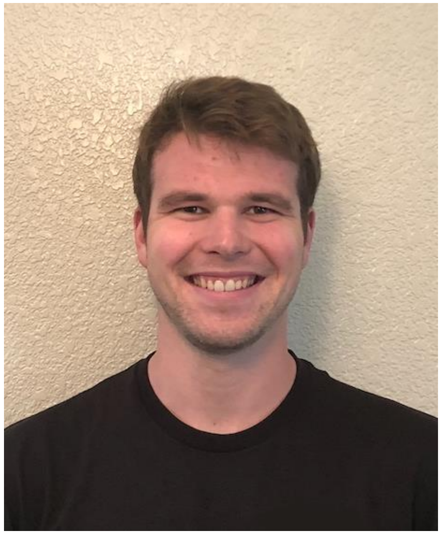
Meet the Team

Dr. Rachel Horenstein
Faculty Advisor

Jackson Harvey
Mechanical Engineer

Jonathan Katz
Mechanical Engineer

Jimmy Colfer
Mechanical Engineer



Gavin McGee
Computer Engineer

Problem Statement

- Students must design and construct a hydraulic-powered vehicle and compete in a series of test events and design competitions
- Project will be completed as part of senior design project, with little to no outside help on design or fabrication

Design Objectives

- New “from-scratch” design
  - Learn from previous DU teams' mistakes
    - 2018 – Lack of detail
    - 2019 – Unrealistically complex
- Team goal: create simple, efficient, and fast vehicle
  - Minimizing fabrication complexity and build time
  - Focusing on the sprint and endurance challenge
    - Higher rider-dependency events
    - Top design speed – 35 MPH

2018 DU Team Design

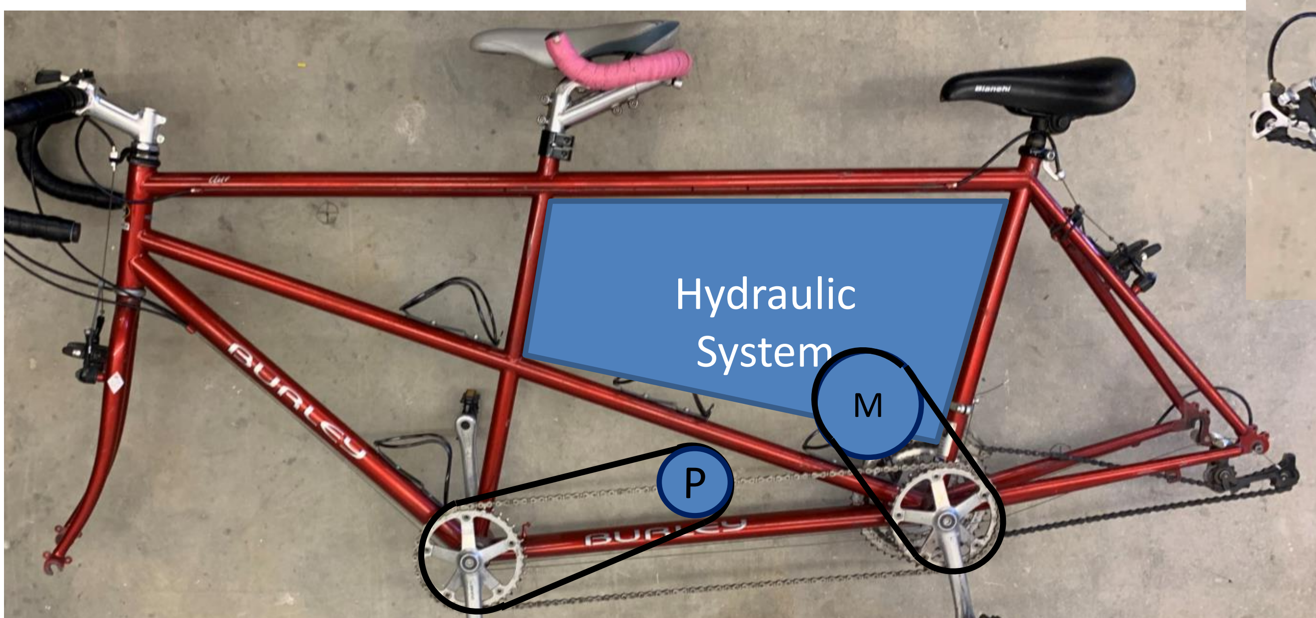
2019 DU Team Design

Midway Presentation

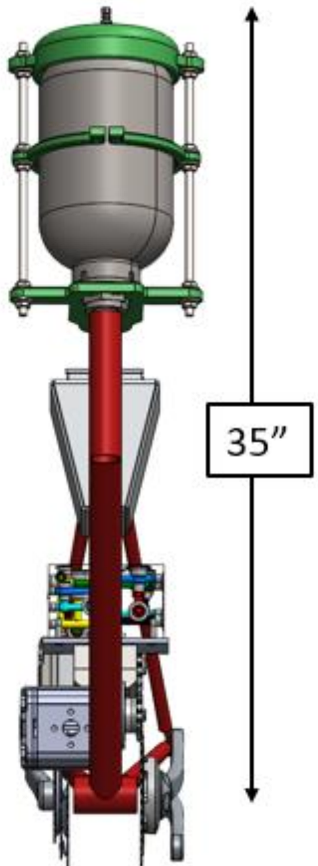
- Selected tandem bike due to separation of hydraulic and mechanical systems
- Planned to use existing derailleur for gear shifting during operation

Stoker-Drive Cassette Assembly Unaltered

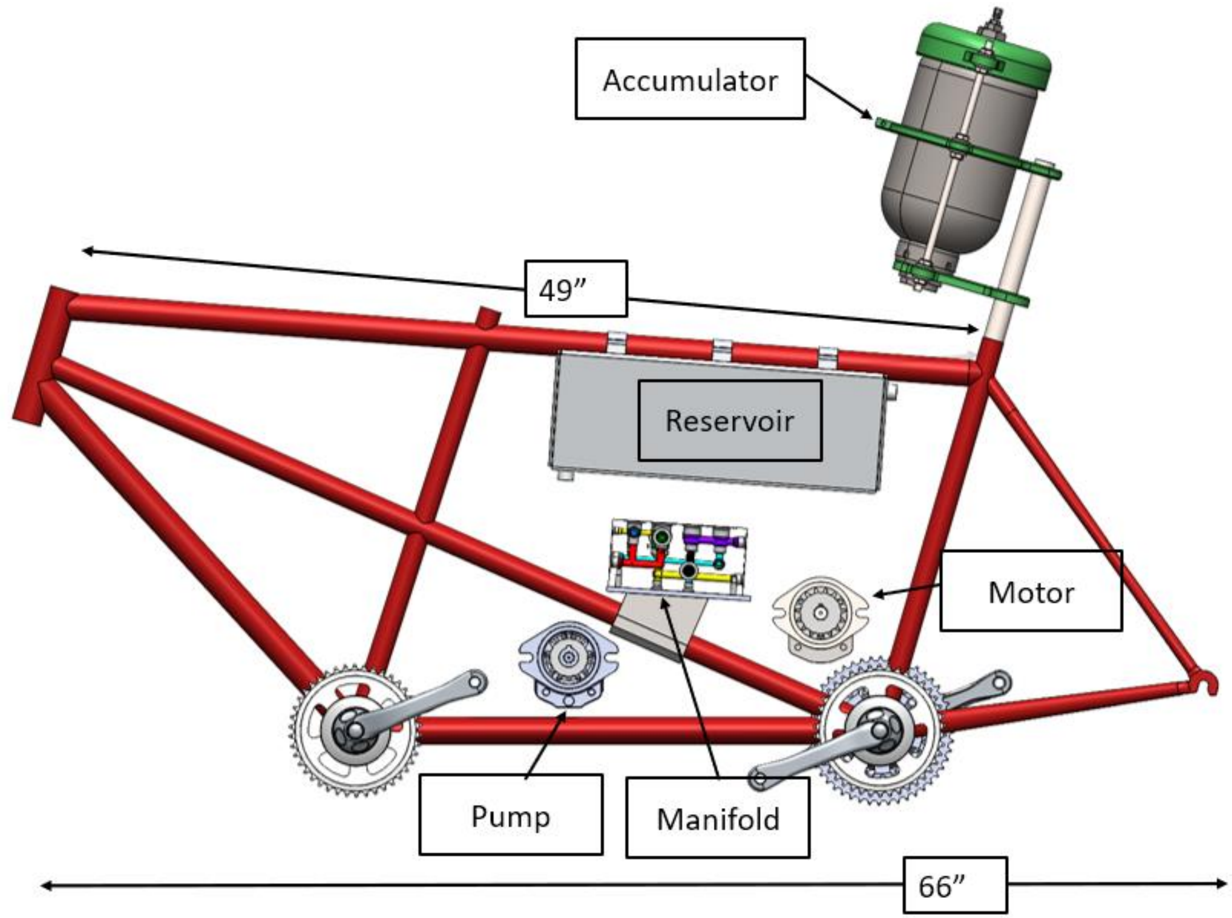
Backside



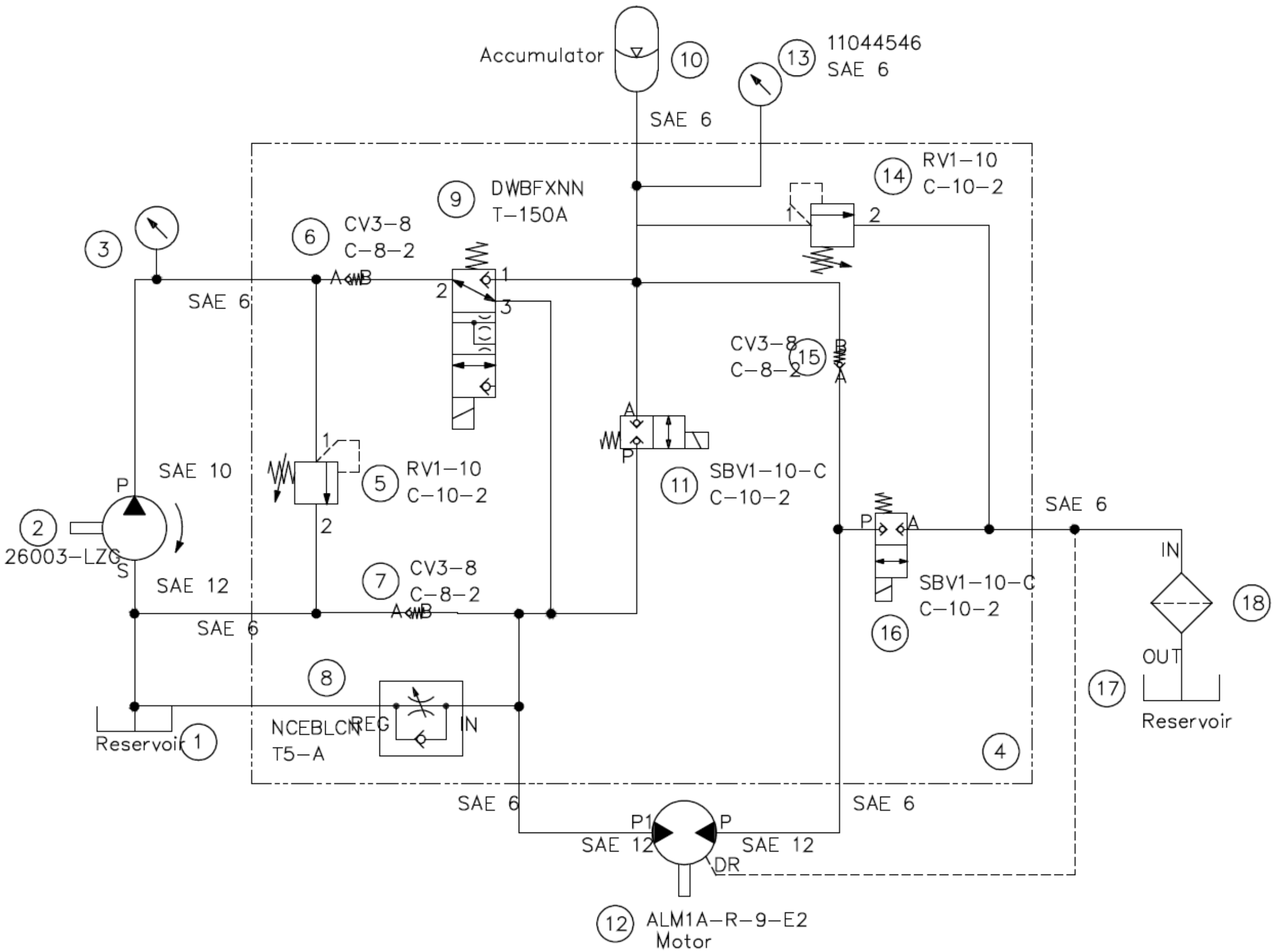
Midway Presentation



FRONT VIEW



Hydraulic Circuit



Design Updates

- Feedback from midway review highlighted regen-braking issue
- Reservoir manufacturing challenges
- Pump unavailability/replacement pump discrepancies
- Transition to fixed wheel design

Pump Change

Original component selection: Eaton 26003

SunSource was unable to supply this pump (Notified on Feb. 4)

Last minute component change to Danfoss SP2NN pump

After receiving, learned the DU machine lacked resources to machine spline coupling

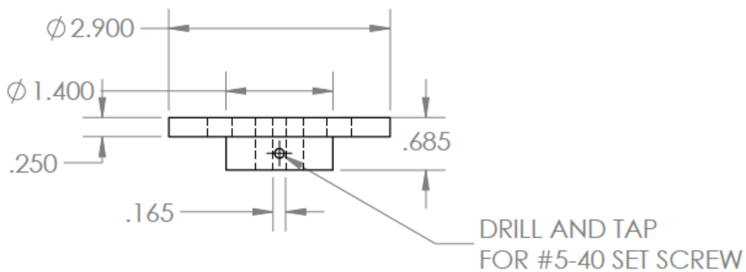
Final Decision: Re-use pump from the 2018 DU FPVC Team

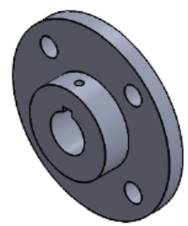
	Eaton 26003 -LZG Original Pump	Danfoss SP2NN – Selected Pump	Eaton 26702-DAB Actual Used Pump
Displacement (CID)	0.58	0.513	0.54
Direction	CCW	CCW	Bi-Directional
Shaft Type	5/8” Keyed	9 tooth spline	5/8” Keyed

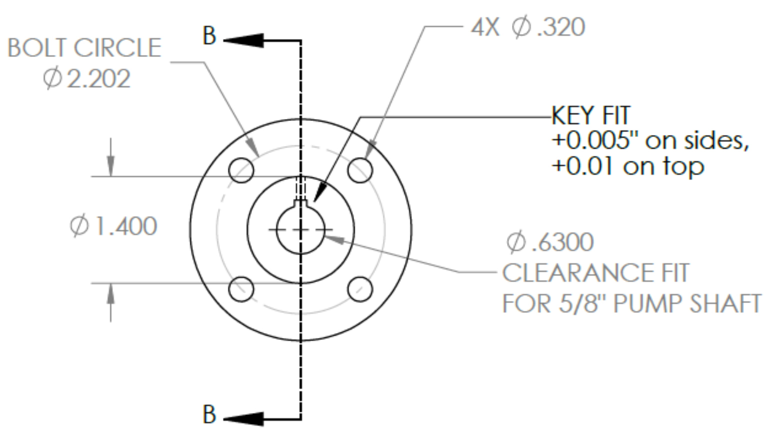
Vehicle Construction

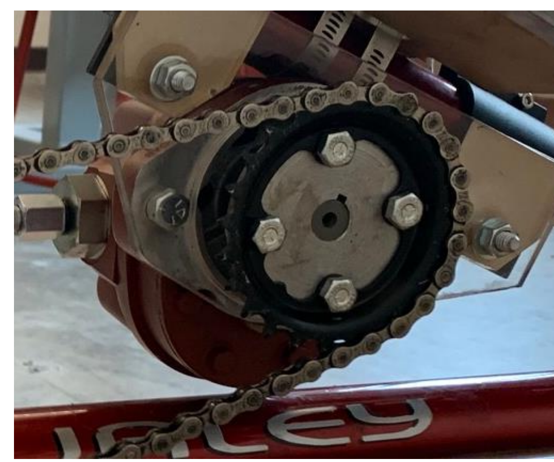
Pump and Motor Couplings

- Machined out of aluminum stock
- Designed to mate with bike sprockets







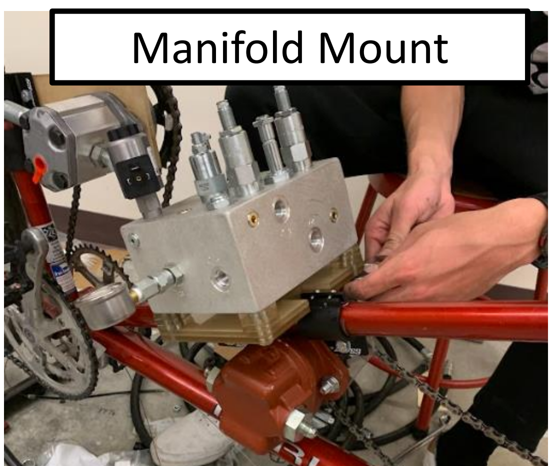


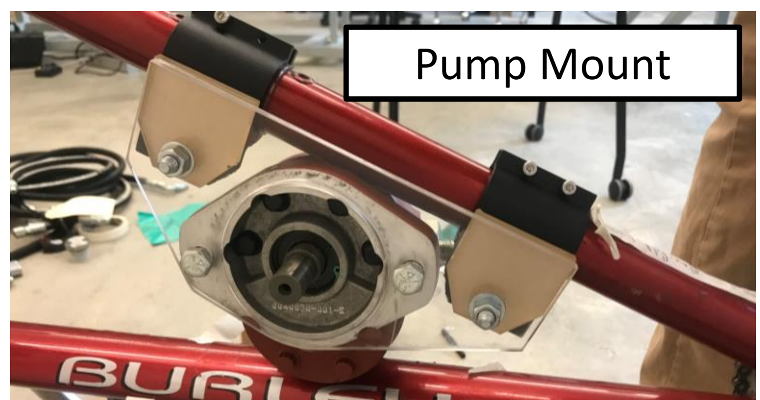
Vehicle Construction

Accumulator, Pump, and Motor mounts

- Laser cut acrylic, secured with bike frame mounts

Motor





Vehicle Construction

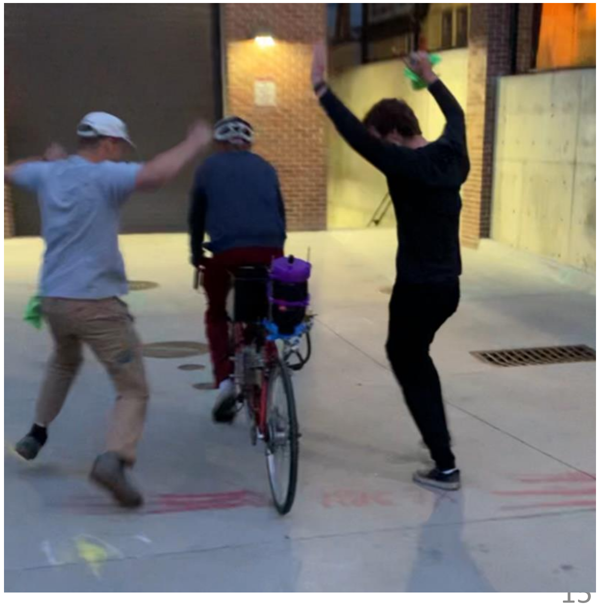
Accumulator Mount

- 3D printed to mount on stoker rider tube

Initial Build

Testing

- Stationary bike stand used for proof-of-concept tests
  - Demonstrated all drive modes worked under zero load
- Performance tests done outside
  - Demonstrated proof of working vehicle
  - Realized issues with chain tensioning, re-machined pump coupling with tighter shaft fit,
  - Remade motor mount to include chain tensioning



Final Vehicle

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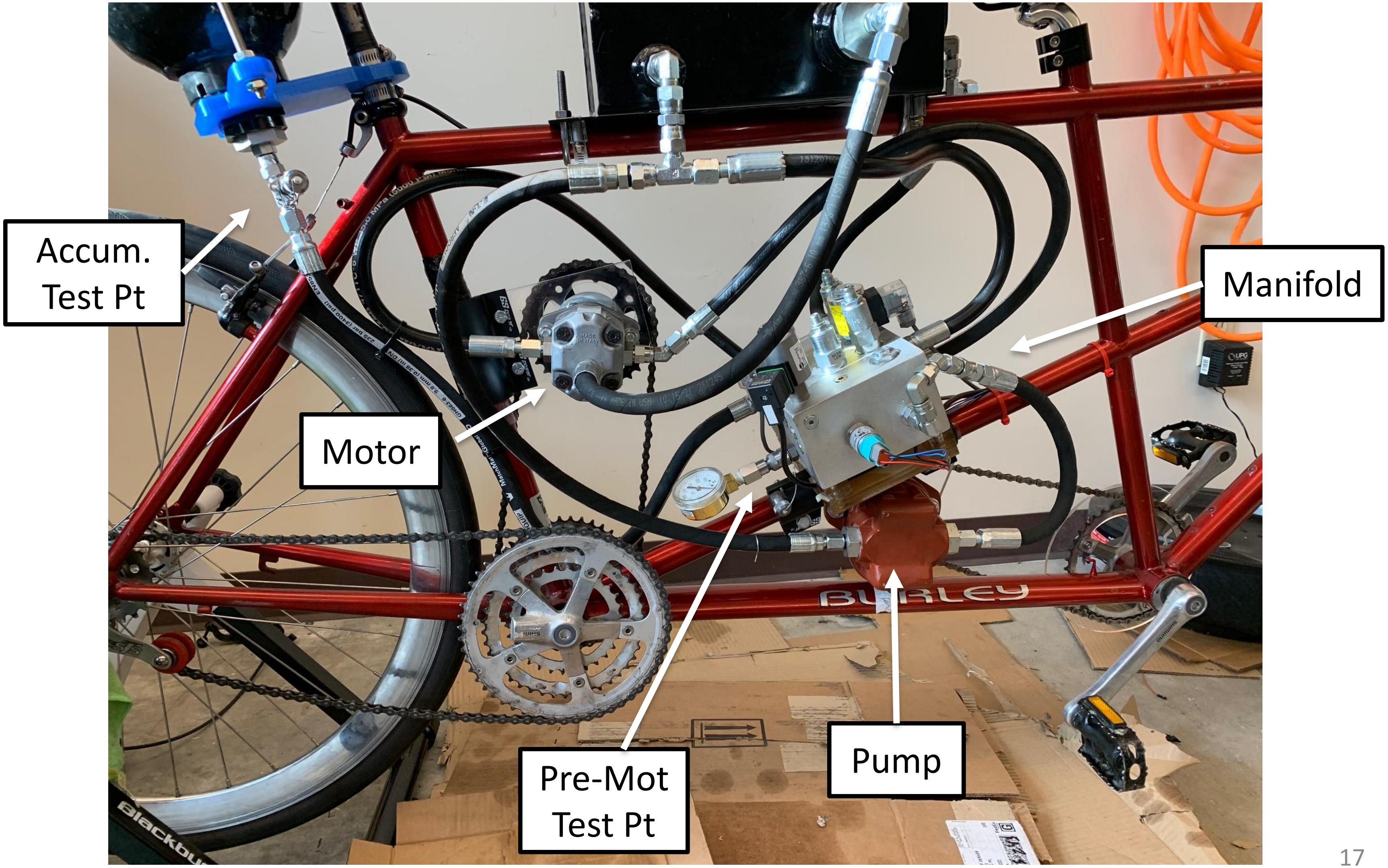
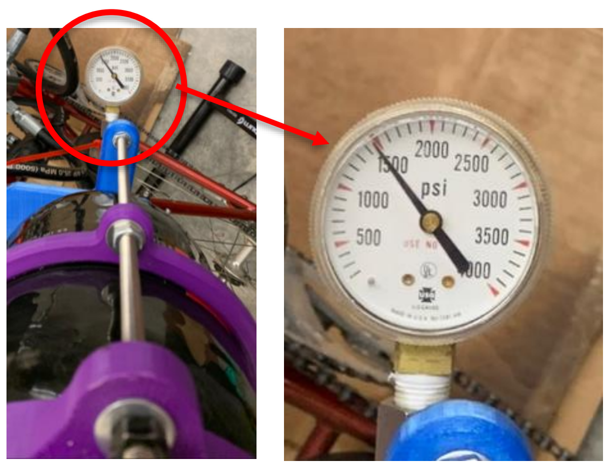
NFPA Fluid Power Vehicle Challenge

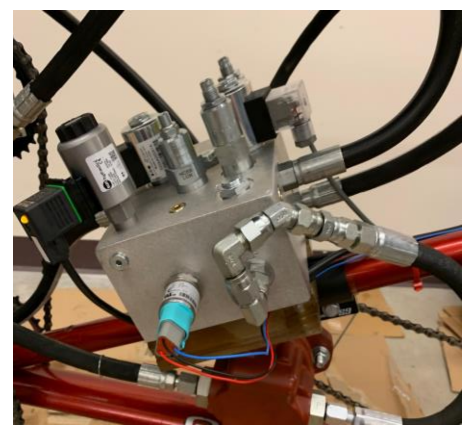
Final Vehicle -
Hydraulics

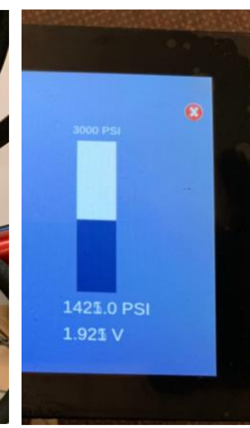


Accumulator

- Parker charging kit
- Dry N2 from DU chemistry lab
- Tested accumulator + gauges simultaneously
  - Direct charge for ~2 minutes
  - Pressure gauge @ test point and
  - Transducer in manifold



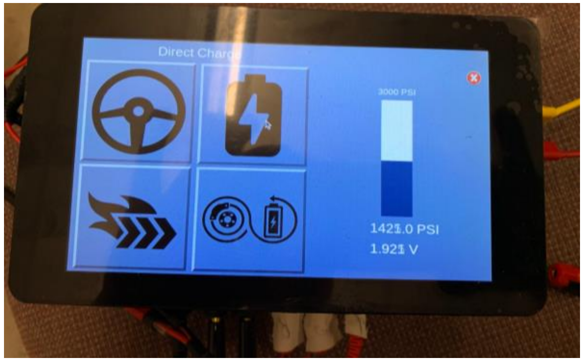


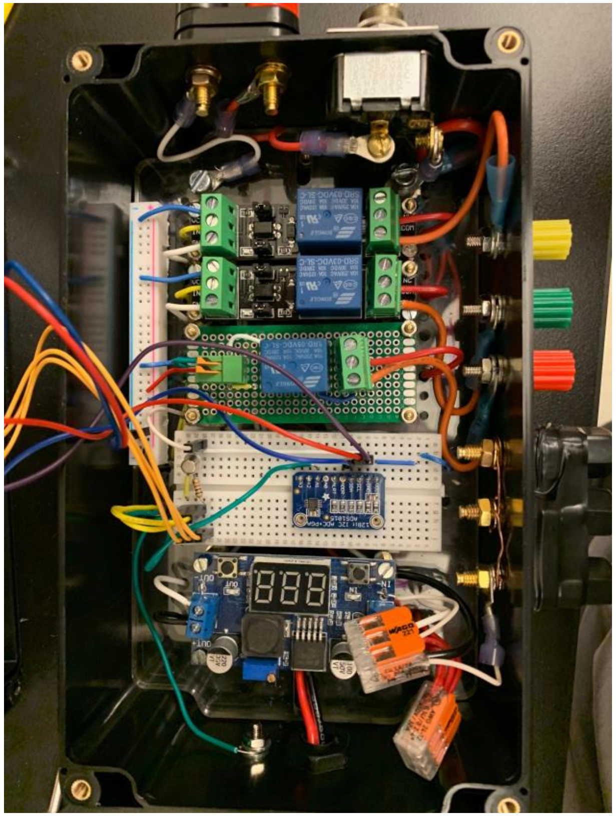


Live readout on display

Electronics

- All circuitry in housing
  - Banana plugs for all external connections
  - Main power switch
  - 3 relay circuits for solenoid control
  - Buck converter for microcontroller
  - 16-bit ADC converter for transducer
- Control
  - Raspberry PI
  - 7" Touchscreen for display and drive mode control





Gearing

- Fixed wheel design for regen
- Can modify chain to 3 different stoker cassette settings
- Testing results from motor pressure guage:
  - Cruising: 1000-1500 psi
  - Acceleration/uphill: 2500-2750 psi

Captain – Pump (40T-24T)

Motor – Stoker in (36T-40T)

Stoker out – Rear Wheel (36,42,52 -22)

Lessons Learned

- Over-estimate part lead times and anticipate component unavailability
- Have a fabrication plan in place before component selection, including fittings and adapters
- Hydraulics fittings and industry standard threads/adapters are complicated
  - Focused too much on the theoretical aspects of the design rather than practical
- Should have put more time into learning the mechanisms of bicycle components: Derailers, chain tensioners, free vs fixed wheel hubs, etc…
- Start assembly and fabrication phase as soon as possible, do not put too much responsibility on third part manufacturers or suppliers

Questions?

Backup Slides

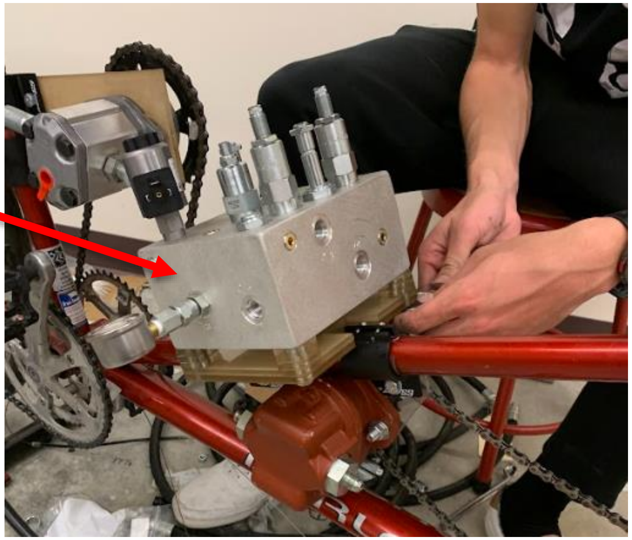
Vehicle Construction

Vehicle Construction

Initial Assembly

Pump Mount

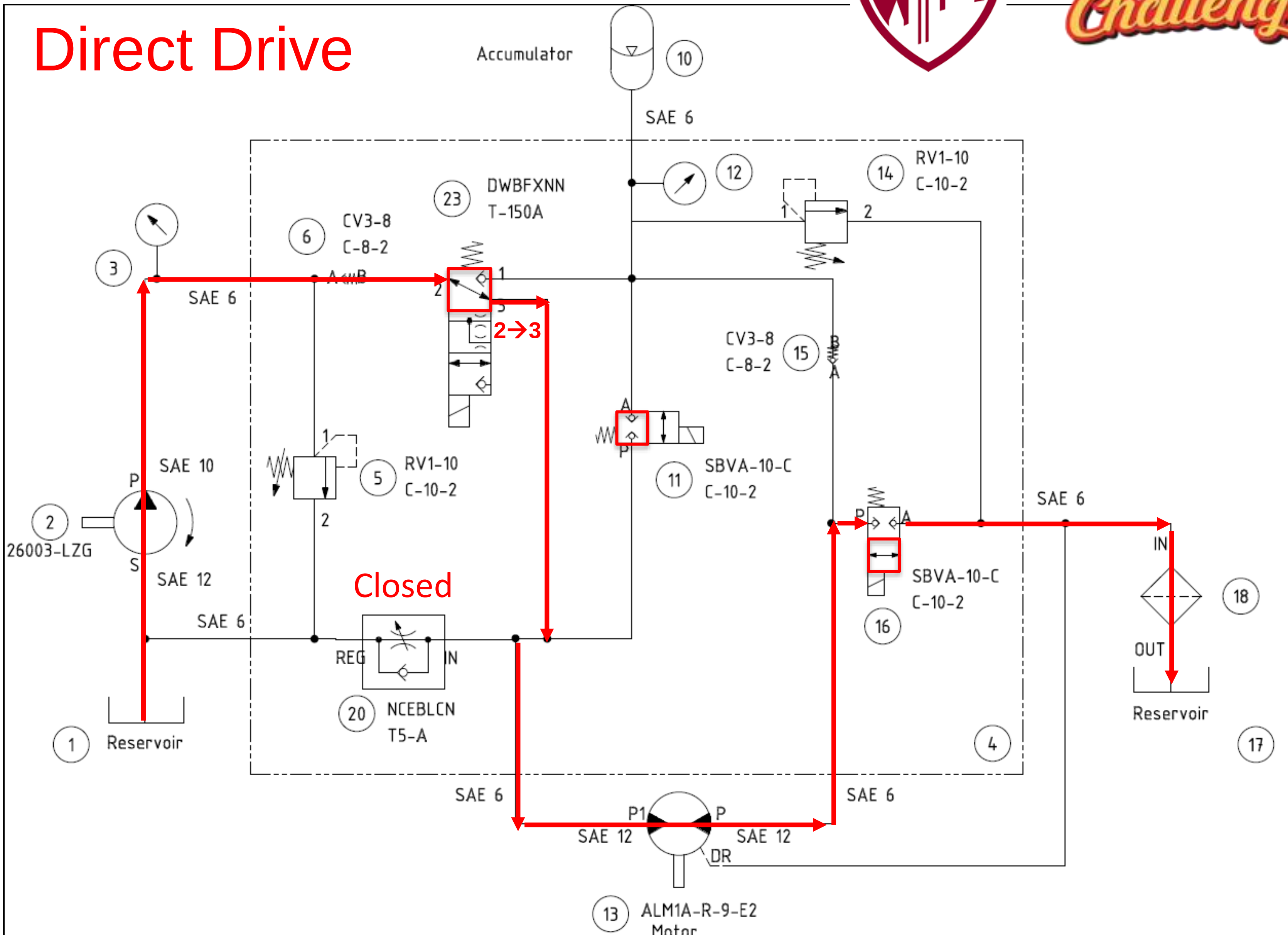
Manifold Mount



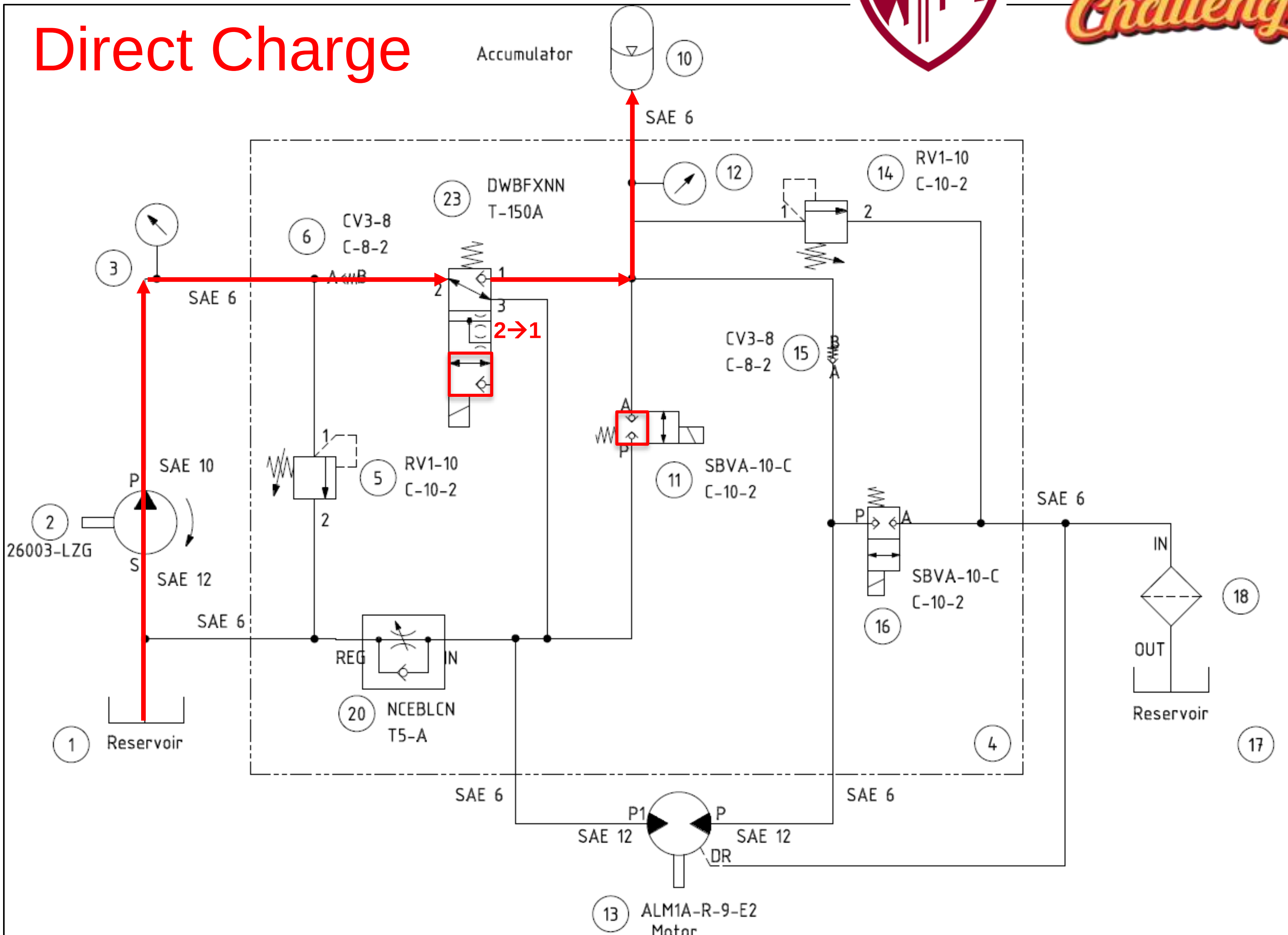
Motor Mount

Drive Modes

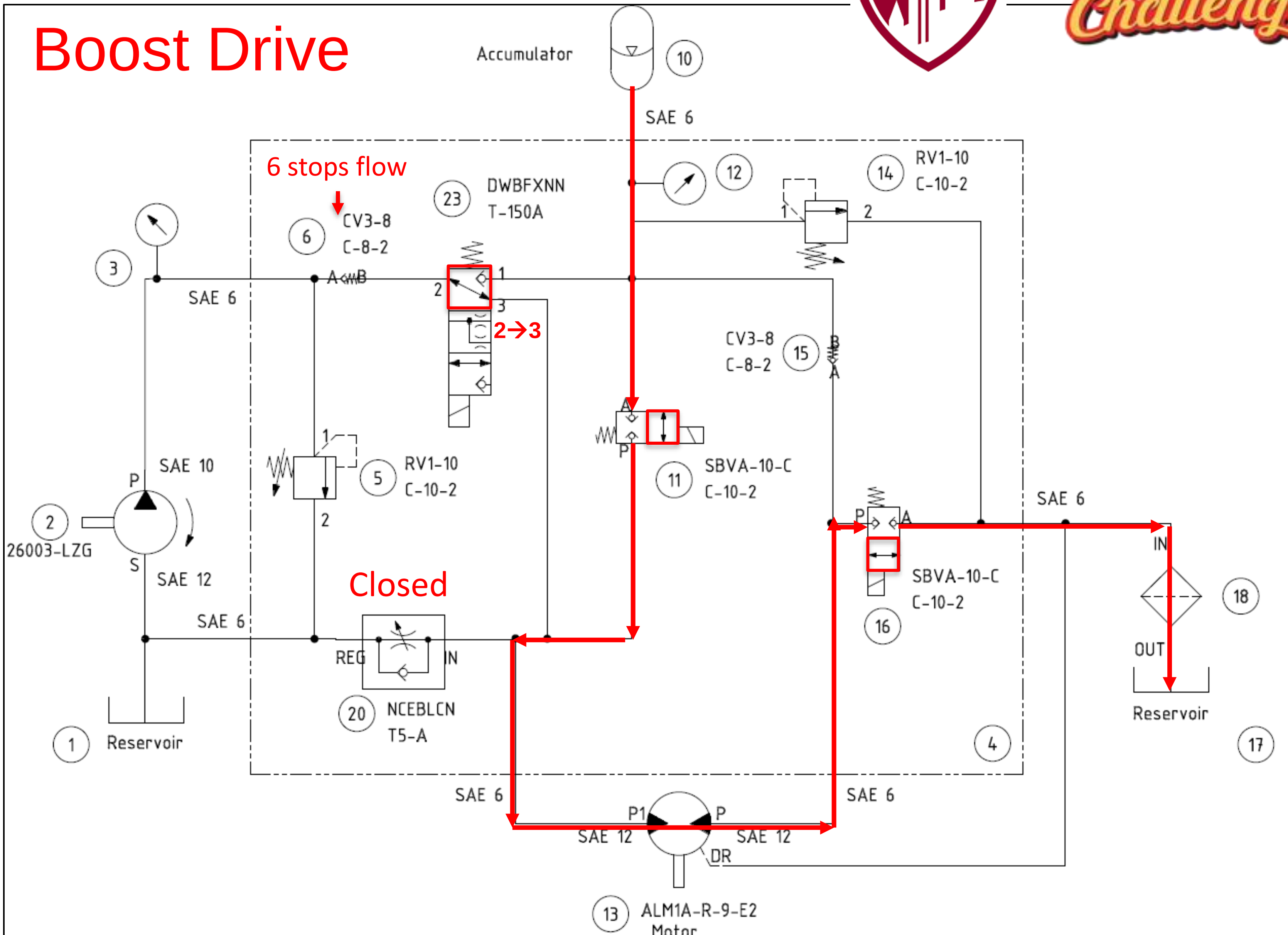
Direct Drive



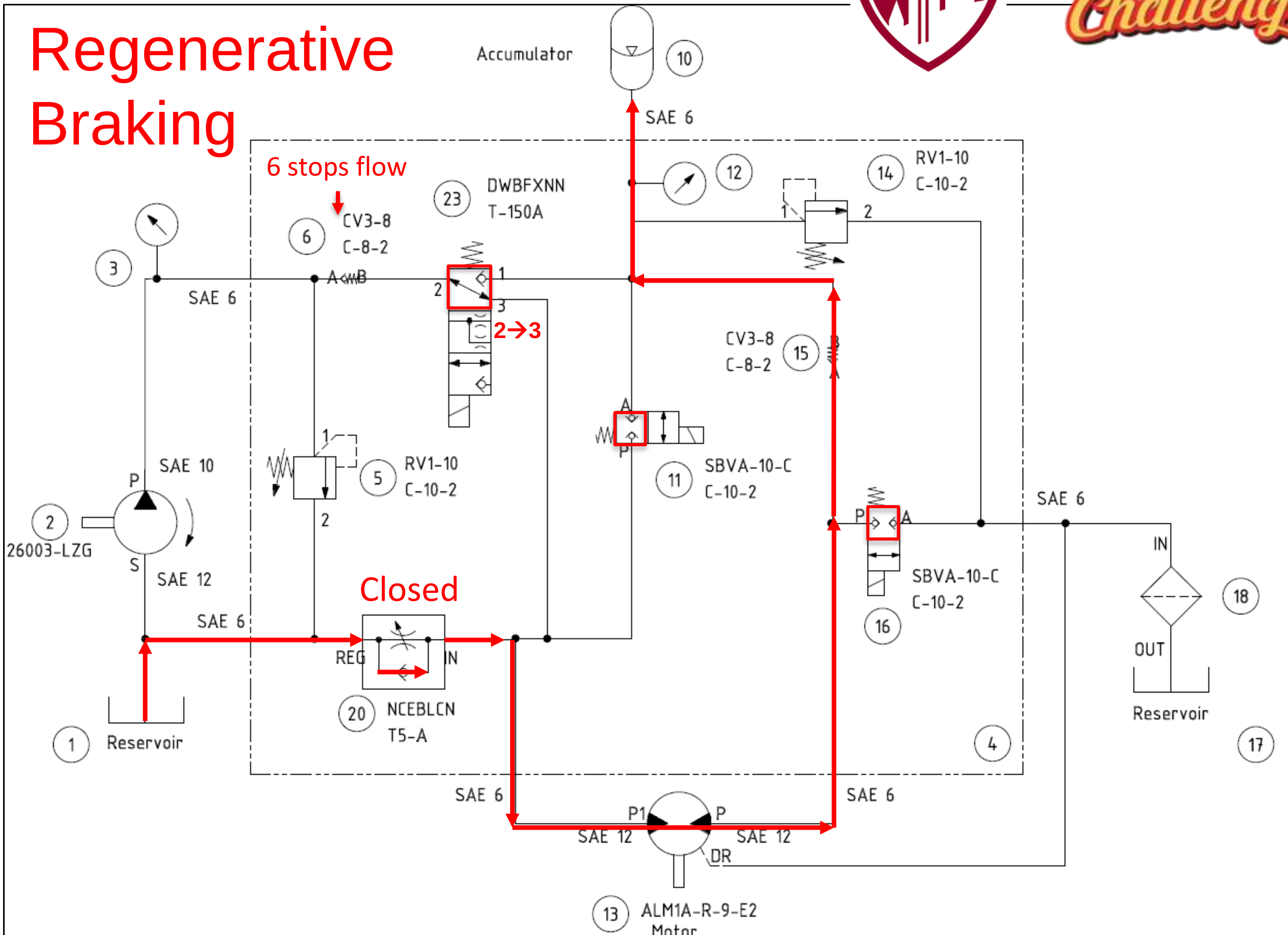
Drive Modes


Direct Charge
Accumulator
10
SAE 6
12
14
RV1-10
C-10-2
23
DWBFXNN
T-150A
6
CV3-8
C-8-2
3
SAE 6
A B
1
2
3
2→1
CV3-8
C-8-2
15
B
A
A
P
11
SBVA-10-C
C-10-2
1
2
5
RV1-10
C-10-2
SAE 10
P
2
26003-LZG
S
SAE 12
SAE 6
REG
IN
20
NCEBLCN
T5-A
SAE 6
P
A
SBVA-10-C
C-10-2
16
IN
18
OUT
Reservoir
17
4
1
Reservoir
SAE 6
SAE 6
P1
P
SAE 12
SAE 12
DR
13
ALM1A-R-9-E2
Motor

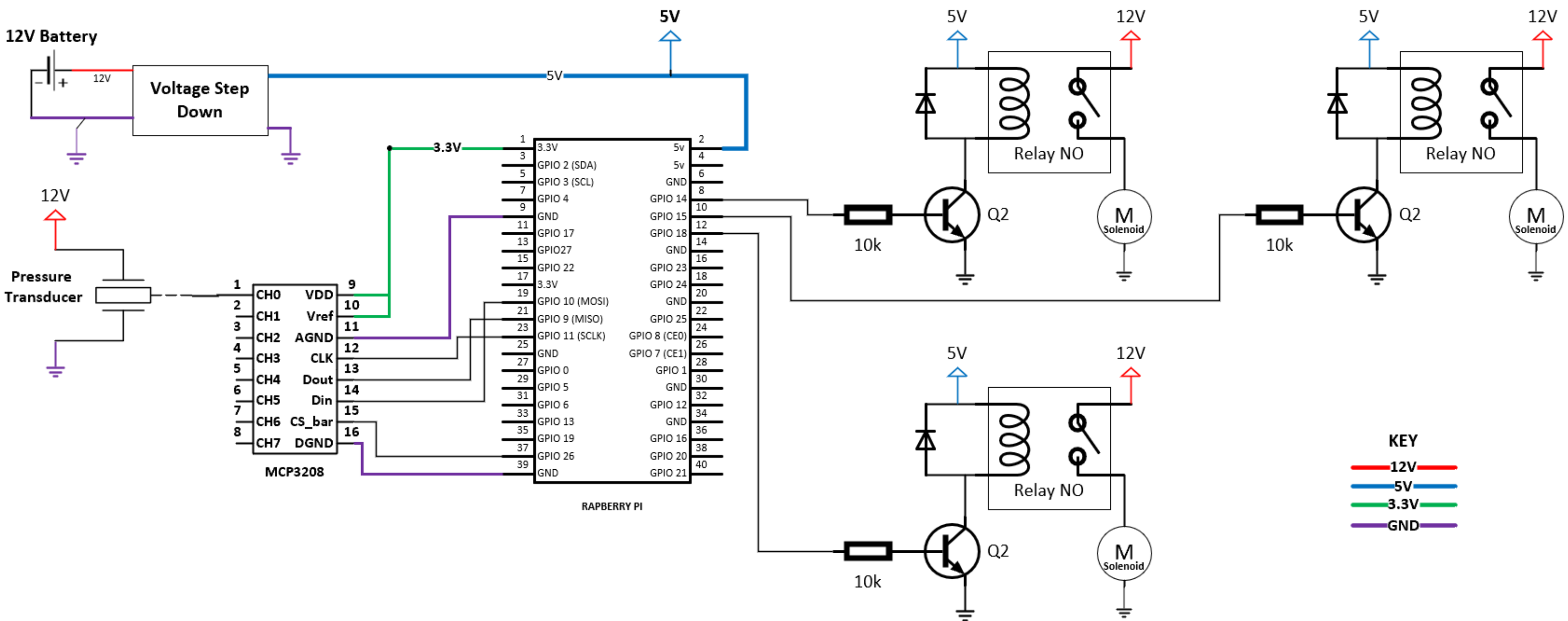
Drive Modes


Boost Drive
Accumulator
10
SAE 6
6 stops flow
23
DWBFXNN
T-150A
12
14
RV1-10
C-10-2
6
CV3-8
C-8-2
3
SAE 6
A
B
1
2
3
2→3
CV3-8
C-8-2
15
B
A
SAE 10
P
2
26003-LZG
S
SAE 12
1
5
RV1-10
C-10-2
2
11
SBVA-10-C
C-10-2
SAE 6
P
A
IN
SBVA-10-C
C-10-2
16
18
OUT
Reservoir
17
Closed
SAE 6
REG
IN
20
NCEBLCN
T5-A
1
Reservoir
4
SAE 6
SAE 6
P1
P
SAE 12
SAE 12
DR
13
ALM1A-R-9-E2
Motor

Drive Modes


Regenerative Braking
6 stops flow
Closed
2→3
Accumulator
10
SAE 6
12
14
RV1-10
C-10-2
23
DWBFXNN
T-150A
6
CV3-8
C-8-2
3
SAE 6
A B
1
2
3
CV3-8
C-8-2
15
A
P
11
SBVA-10-C
C-10-2
5
RV1-10
C-10-2
SAE 10
P
2
26003-LZG
S
SAE 12
SAE 6
REG
IN
20
NCEBLCN
T5-A
1
Reservoir
P
A
SBVA-10-C
C-10-2
16
SAE 6
IN
18
OUT
Reservoir
17
4
SAE 6
SAE 6
P1
P
SAE 12
SAE 12
DR
13
ALM1A-R-9-E2
Motor

EE Schematic



Human Performance Test

Test Goals	Determine peak and average rider output power
Methods	• A 200 ft sprint with the unmodified bicycle (1:1 captain-stoker power transmission) • Times recorded at 100 and 200 ft • Videos recorded to observe pedal speed • Several trials at different rear-cassette gear ratios to confirm power results
Results	• Avg power output 200-300 W • Peak power output 1000+ W

Pump & Motor Calculations

Assumptions

Coeff of Rolling Resistance[1]	0.005	System Pressure	2750 psi
Grade	2 %	Hydraulic Circuit Efficiency	0.9
Human Power Output	500 W	Peak Rider Speed	35 mph
System Weight	290 lb		

Results

System Flow Rate	0.42 GPM
Motor CIR	0.388
Pump CIR	0.591

Part of Summary of Midway Slides

1) "Rolling Resistance." *Engineering ToolBox*, https://www.engineeringtoolbox.com/rolling-friction-resistance-d_1303.html.

Hardware Selection

Motor

- Marzocchi ALM1A-R-9-E2
- .3878 CID bi-directional gear motor

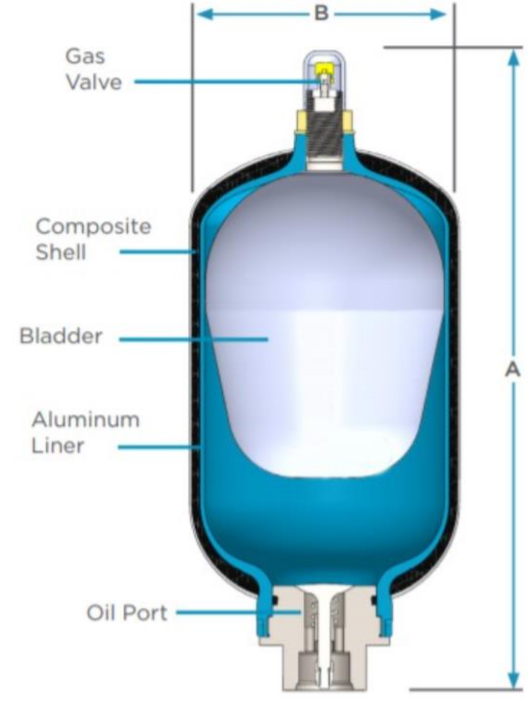
Pump

- Eaton 26003-LZG
- .58 CID CCW gear pump

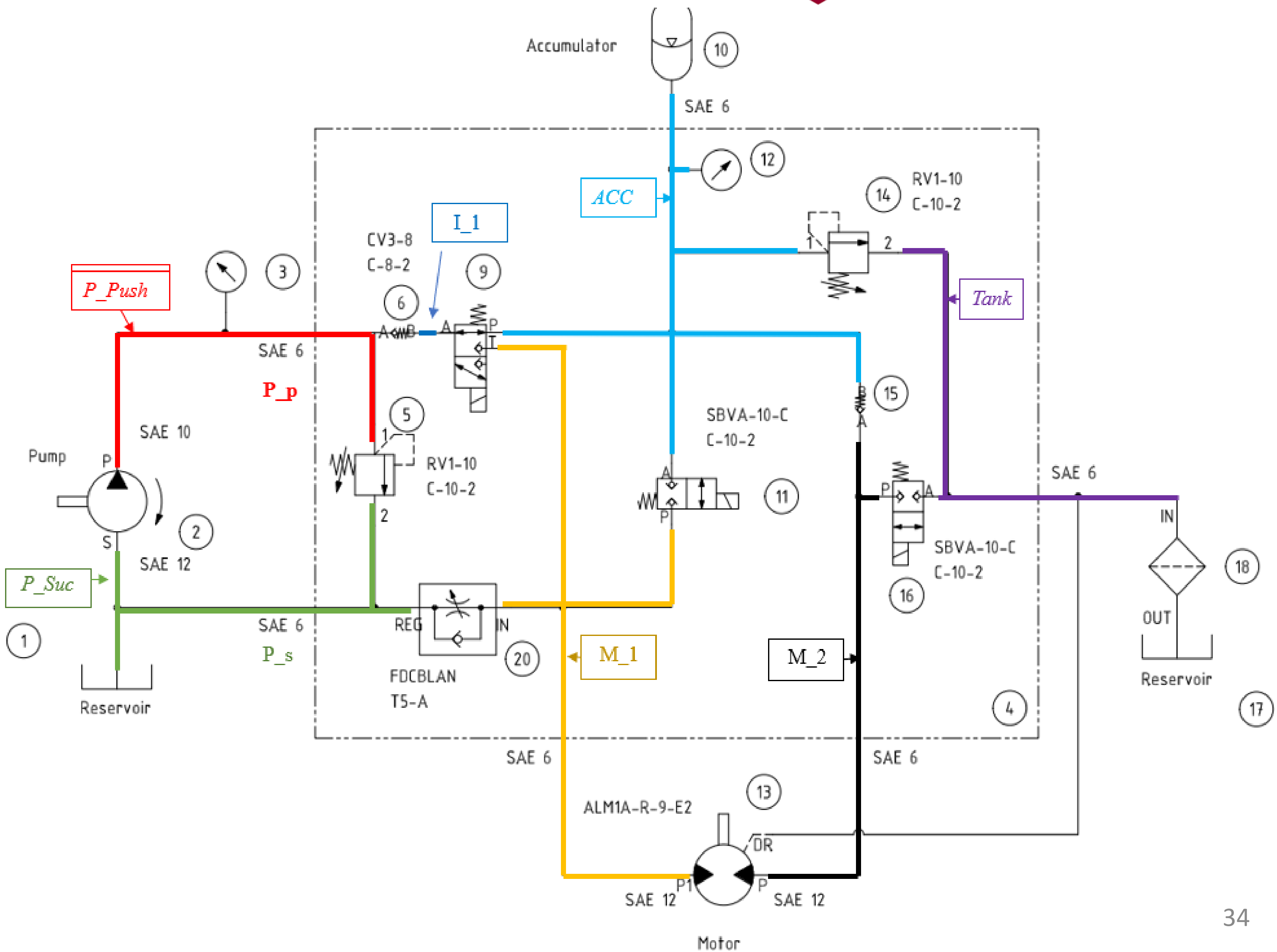
Should be Summary of Midway Slides

Accumulator

- Steelhead Composites AB30CN010G0N
- Composite 1 gal. accumulator

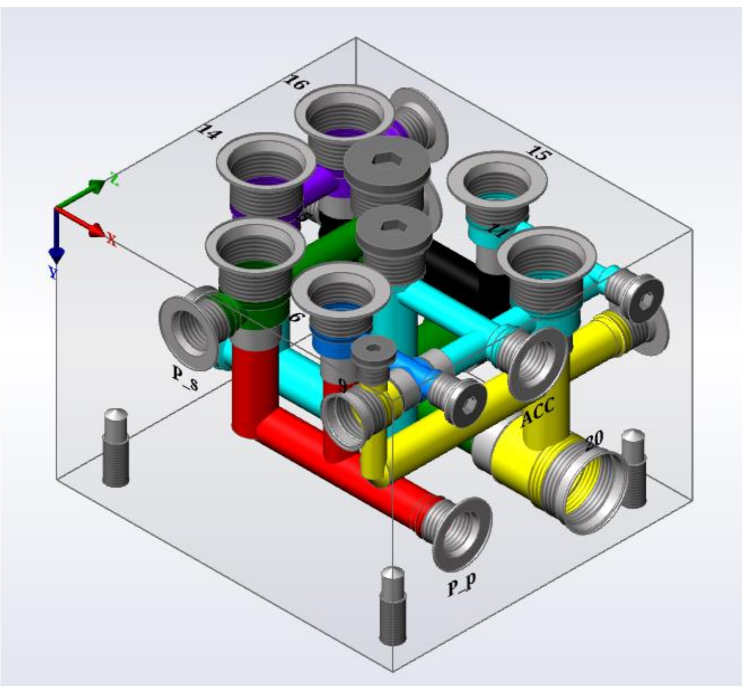


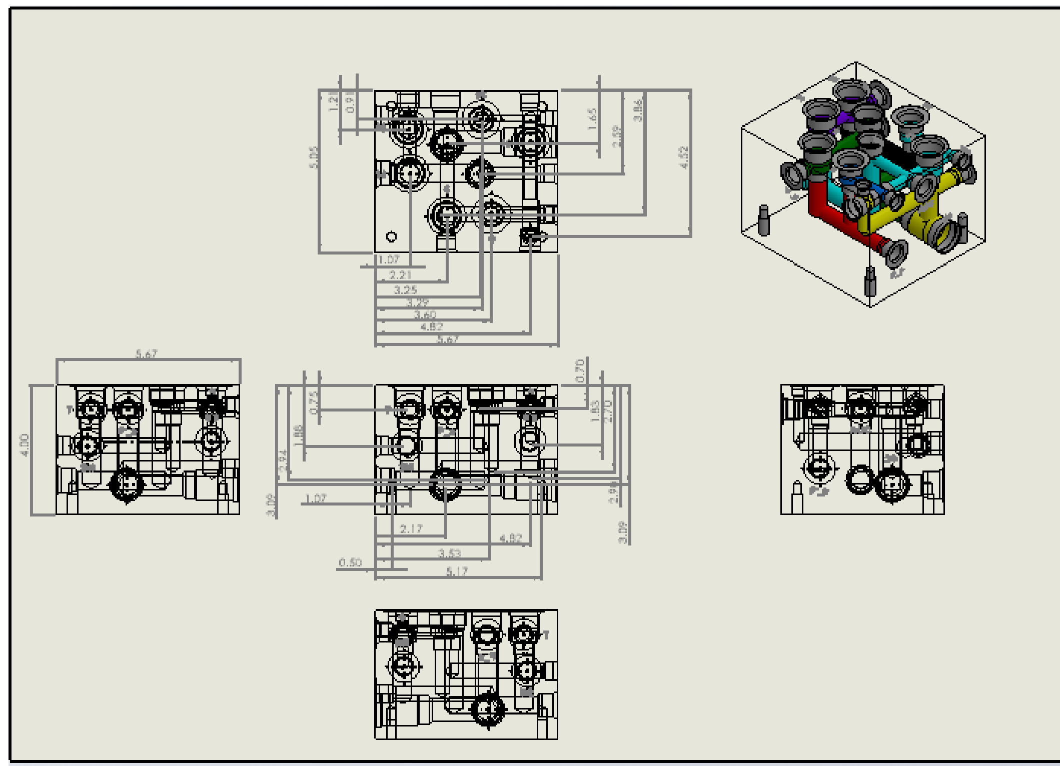
Manifold Design



Manifold Design

- Custom Designed Manifold in Solidworks with MDTools
- Expecting approval by 1/7/22





Reservoir

- Custom Designed Aluminum reservoir (~1.5 gallons)
- Interior Baffling System and Flow Diffusers
- Breather Port and quick-fill/drainage ports
- Laser cut as one sheet to reduce welds and possible failure points
- Fabricated locally in *Denver, CO* by H&H Metals

H&H METALS
Expert Fabrication Since 1980

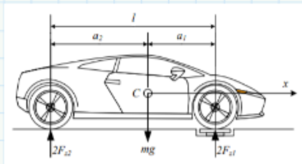
Calculations 1/2

For Reference to Testing

Wheel

$d_w := 622\ mm$

$r_w := \frac{d_w}{2} = 0.311\ m$



Frame:

Wheelbase: $L_{wb} := 69.5\ in$

Crank Height: $h_c := 10.83\ in$

Crank Length $r_c := 7\ in$

a1: $a_1 := 37.01\ in$

a2: $a_2 := L_{wb} - a_1 = 0.825\ m$

COG Height $h := 24.49\ in$

Weights:

Frame: $W_f := 35\ lbf$

Rider $W_r := 150\ lbf$

Hydr. $W_h := 100\ lbf$

Total: $W_{sys} := W_f + W_r + W_h = 285\ lbf$ $\quad m_{sys} := \frac{W_{sys}}{g} = 129.274\ kg$

Gearing

Stocker Sprocket: $N_s := 40$ $\quad$ captain Sprocket: $N_c := 40$

Stocker cassete $N_{sr} := \begin{bmatrix} 30 \\ 42 \\ 53 \end{bmatrix}$ $\quad$ pump $N_p := 20$ $\quad$ Motor $N_m := 40$

Drive cassete $N_{dr} := \begin{bmatrix} 11 \\ 12 \\ 14 \\ 16 \\ 18 \\ 21 \\ 24 \\ 28 \\ 32 \end{bmatrix}$

Rotational Characterstics

Stoker Setting $i_s := 1$ $\quad N_{cs} := N_{sr_{i_s}} = 42$

Drve Setting $i_d := 6$ $\quad N_{cd} := N_{dr_{i_d}} = 24$

Forces

$gr := \frac{2}{100}$ $\quad \alpha := \operatorname{asin}(gr) = 0.02$ $\quad F_{pull} := W_{sys} \cdot \sin(\alpha) = 25.355\ N$

Rolling resistance $\quad Crr := 0.005$ $\quad Fr := Crr \cdot W_{sys} \cdot \cos(\alpha) = 6.337\ N$

$F_t := Fr + F_{pull} = 31.692\ N$

$T_w := r_w \cdot F_t = 87.236\ lbf \cdot in$

Power

$Pkw := 500\ W$

$P_{sys} := 2750\ psi$

$Q := \frac{Pkw}{P_{sys}} = 0.418\ \frac{gal}{min}$

$\eta := 0.9$

Speed, wheel, rider rpm

$V_{max} := 35\ mph$

$\omega_w := \frac{V_{max}}{r_w} = 480.425\ rpm$

$\omega_r := 90\ rpm$

Calculations 2/2

Forces

$gr := \frac{2}{100}$ $\alpha := \mathrm{asin}(gr) = 0.02$ $F_{pull} := W_{sys} \cdot \sin(\alpha) = 25.355\ N$

Rolling resistance $Crr := 0.005$ $Fr := Crr \cdot W_{sys} \cdot \cos(\alpha) = 6.337\ N$

$F_t := Fr + F_{pull} = 31.692\ N$

$T_w := r_w \cdot F_t = 87.236\ lbf \cdot in$

Power

$Pkw := 500\ W$

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$Q := \frac{Pkw}{P_{sys}} = 0.418\ \frac{gal}{min}$

$\eta := 0.9$

Speed, wheel, rider rpm

$V_{max} := 35\ mph$

$\omega_w := \frac{V_{max}}{r_w} = 480.425\ rpm$

$\omega_r := 90\ rpm$

Stoker Cassete

$\omega_{cs} := \omega_w \cdot \frac{N_{cd}}{N_{cs}} = 274.528\ rpm$

$T_{cs} := T_w \cdot \frac{N_{cs}}{N_{cd}} = 152.662\ in \cdot lbf$

Motor

$\omega_m := \omega_{cs} \cdot \frac{N_s}{N_m} = 274.528\ rpm$

$T_m := T_{cs} \cdot \frac{N_m}{N_s} = 152.662\ in \cdot lbf$

$CIR_m := \frac{2 \cdot \pi \cdot T_m}{P_{sys} \cdot \eta} = 0.388\ in^3$

Pump

$\omega_p := \omega_r \cdot \frac{N_c}{N_p} = 180\ rpm$

$CIR_p := CIR_m \cdot \frac{\omega_m}{\omega_p} = 0.591\ in^3$

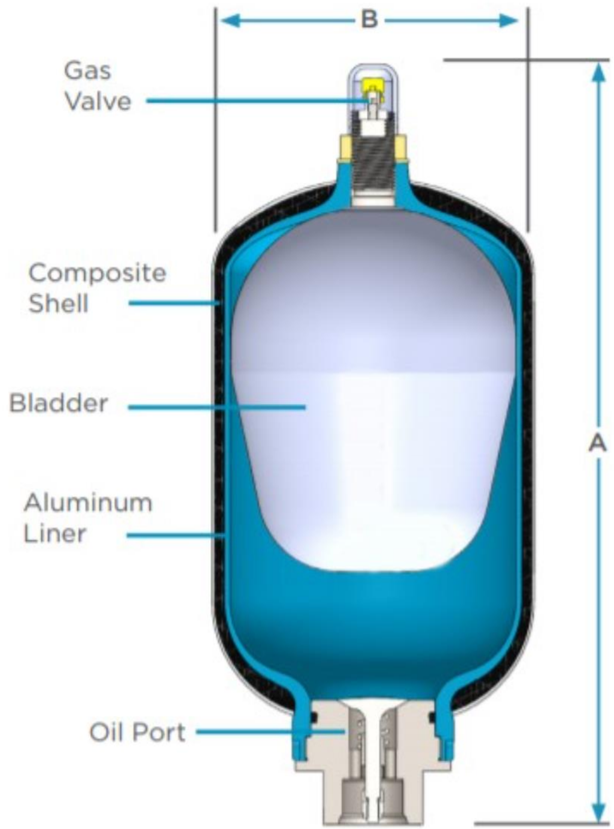
$T_p := CIR_p \cdot \frac{P_{sys}}{2 \cdot \pi} \cdot \eta = 232.834\ in \cdot lbf$

$T_r := T_p \cdot \frac{N_c}{N_p} = 465.669\ lbf \cdot in$

$T_r = 52.614\ N \cdot m$

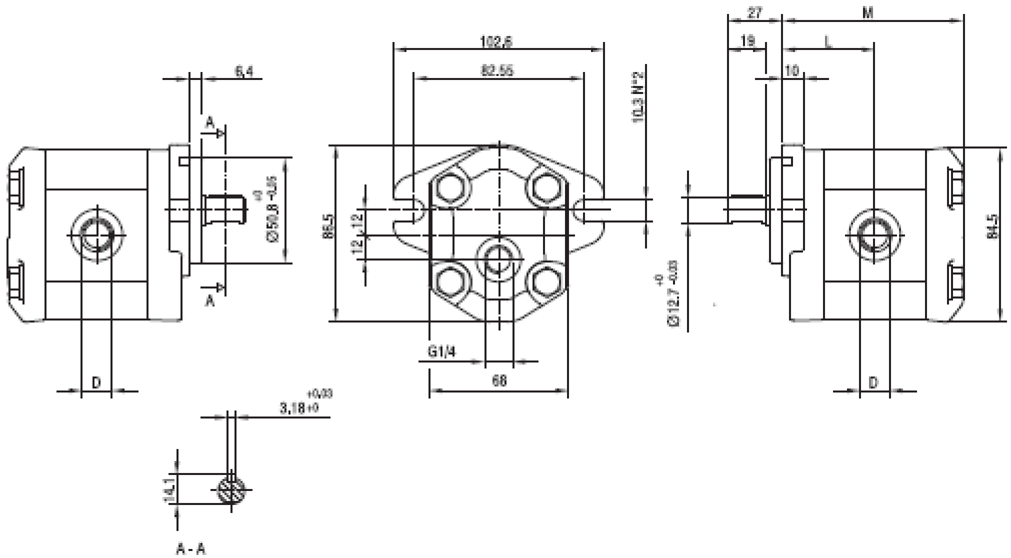
Accumulator

Nominal Volume	Operating Pressure	Dimension A	Dimension B	Weight
1 gal	3000 psi	15.7 in	6.5 in	10.8 lbs



- Carbon fiber lightweight reservoir from Steelhead Composites in Golden, CO

Pump Specs

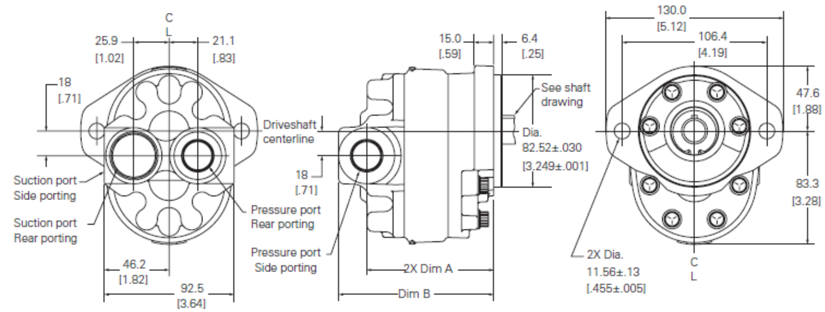


E2-means external drain

TIPO *TYPE*	CILINDRATA *DISPLACEMENT*	PORTATA a 1500 giri/min *FLOW at 1500 rev/min*	PRESSIONI MASSIME *MAX PRESSURE* P1	Pc	Pp	VELOCITÀ MASSIMA *MAX SPEED*	DIMENSIONI *DIMENSIONS* L	M	D
	cm³/giro (cm³/rev)	litri/min (litres/min)	bar	bar	bar	giri/min (rpm)	mm	mm	
AIM1A-R-4-E1	2,8	3,9	250	240	270	5000	44	86,5	3/4-16 UNF
AIM1A-R-5-E1	3,5	4,9	250	240	270	5000	45	88,5	3/4-16 UNF
AIM1A-R-6-E1	4,1	5,9	250	240	270	4000	46	90,5	3/4-16 UNF
AIM1A-R-7-E1	5,2	7,4	230	220	245	3500	47,5	93,5	3/4-16 UNF
AIM1A-R-9-E1	6,2	8,8	230	220	245	3000	49	96,5	3/4-16 UNF

Motor

Displacement cm³/r [in³/r]	6,6 [.40]	8,2 [.50]	9,5 [.58]
Max. Intermittent pressure bar [PSI]	241 [3500]	241 [3500]	241 [3500]
Rated speed (RPM)	3600	3600	3600
Minimum output flow at 207 bar [3000 PSI] and rated speed LPM [GPM]	20,1 [5.3]	25,0 [6.6]	29,5 [7.8]
Input power at 207 bar [3000 PSI] and rated speed and cont. Pressure kW [HP]	9,7 [13.0]	11,9 [15.9]	14,1 [18.9]



Model	26001	26002	26003	26004	26005	26006	26007
Displacement (cm³/r [in³/r])	6.6 [.40]	8.2 [.50]	9.5 [.58]	10.8 [.66]	13.8 [.84]	16.7 [1.02]	19.7 [1.20]
Dimension A (mm [in])	72.6 [2.86]	74.3 [2.93]	75.9 [2.99]	77.5 [3.05]	80.7 [3.18]	83.9 [3.30]	87.1 [3.43]
Dimension B (mm [in])	93.2 [3.67]	94.9 [3.74]	96.5 [3.80]	98.1 [3.86]	101.3 [3.99]	104.5 [4.11]	107.7 [4.24]

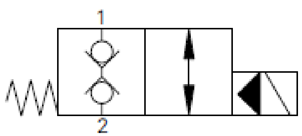
Model 26003 – 9,5 cm^3/r [.58 in^3/r] displacement

26003-RZG	26003-LZG	5/8 Keyed	Side	7/8-14 UNF-2B	1-1/16-12 UN-2B	24302-RZB/LZB
26003-RZH	26003-LZH	5/8 Keyed	Rear	7/8-14 UNF-2B	1-1/16-12 UN-2B	24302-RZC/LZD
26003-RZJ	26003-LZJ	5/8 9 T Spline	Side	7/8-14 UNF-2B	1-1/16-12 UN-2B	24302-RZA/LZA
26003-RZK	26003-LZK	5/8 9 T Spline	Rear	7/8-14 UNF-2B	1-1/16-12 UN-2B	24302-RZD/LZE

SBV1-10-C

SBV1-10-C - Solenoid Valve

2-way, 2-position, normally closed, bi-directional, poppet type solenoid valve
76 L/min (20 USgpm) • 210 bar (3000 psi)



Operation

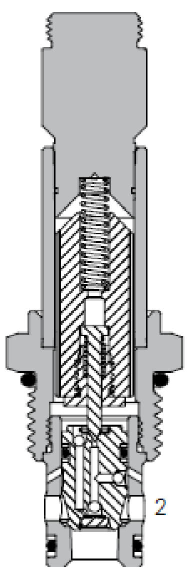
In the de-energized position the valve is blocked in both directions.

When the solenoid is energized the pilot poppet is released from the seat allowing the main poppet to open. A series of internal check valves allows full flow in both directions.

Features

Hardened and ground working parts. Lapped seat for low leakage. IP69K Tough coil compatibility. Continuously rated. Compact design with low pressure drop. 210 bar working pressure.

Sectional View



Performance Data

Ratings and Specifications

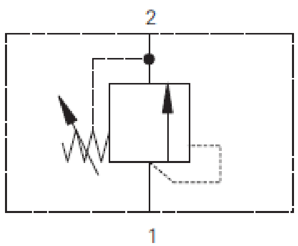
Performance data is typical with fluid at 21,8 cST (105 SUS) and 49°C (120°F)	
Typical application pressure (all ports)	210 bar (3000 psi)
Cartridge fatigue pressure (infinite life)	210 bar (3000 psi)
Rated flow	76 L/min (20 USgpm)
Internal leakage	5 drops/min, max @ 210 bar (3000 psi)
Temperature range	-40° to 100°C (-40° to 212°F)
Coil duty	Continuous from 85% to 110% of nominal voltage
Cavity	C-10-2
Fluids	All general purpose hydraulic fluids such as: MIL-H-5606, SAE 10, SAE 20 etc.
Filtration	Cleanliness code 18/16/13
Housing material (standard)	Aluminum or steel
Weight cartridge only	0,18 kg (0.39 lbs)
Seal kit	565806 (Buna-N), 889627 (Viton®)

Viton is a registered trademark of E.I. DuPont

RV1-10

RV1-10 - Relief Valve

Poppet, Direct Acting
30 L/min (8 USgpm) • 210 bar (3000 psi)



Operation

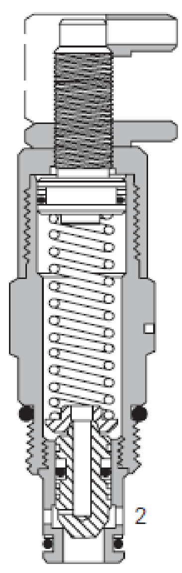
This valve remains closed from port 1 to port 2 until the predetermined setting has been reached at port 1.

The poppet is unseated and allows flow out of port 2.

Features

Fast acting, low pressure rise. Low internal leakage, high flow rate for compact design

Sectional View



Performance Data

Ratings and Specifications

Performance data is typical with fluid at 21,8 cSt (105 SUS) and 49° C (120° F)	
Typical application pressure (all ports)	210 bar (3000 psi)
Cartridge fatigue pressure (infinite life)	210 bar (3000 psi)
Rated flow	30 L/min (8 USgpm)
Internal leakage	0.3 L/min (5 drops/min) @ 85% of Pressure Setting
Cavity	C-10-2
Standard housing materials	Aluminum or steel
Temperature range	-40° to 120°C (-40° to 248°F)
Fluids	All general purpose hydraulic fluids such as: MIL-H-5606, SAE 10, SAE 20, etc.
Filtration	Cleanliness Code 18/16/13
Weight cartridge only	0,22 kg (0.48 lbs)
Seal kits	565803 Buna-N 566086 Viton*

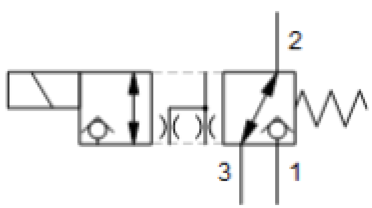
Viton is a registered trademark of E.I. DuPont

DWBFXNN

MODEL reset to default

DWBFXNN

X-Control, N-Poppet



view all

CONFIGURATION RULES

FLeX Series 3-way, direct-acting, solenoid-operated directional blocking poppet valve

Cavity	T-150A
Series	0
Capacity	6 gpm
Maximum Operating Pressure	5000 psi
Maximum Valve Leakage at 110 SUS (24 cSt)	0.004 in^3/min.@5000 psi
Response Time - Typical	50 ms
Switching Frequency	10,000 max. cycles/hr
Solenoid Tube Diameter	.63 in.
Valve Hex Size	3/4 in.
Valve Installation Torque	25 - 30 lbf ft
Model Weight	1.03 lb.
U.S. Patent #	10,302,201
Seal kit - Cartridge	Buna: 990150007
Seal kit - Cartridge	Viton: 990150006
Seal and nut kit - Coil	Viton: 990740006

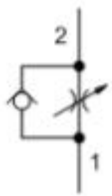
NCEBLCN

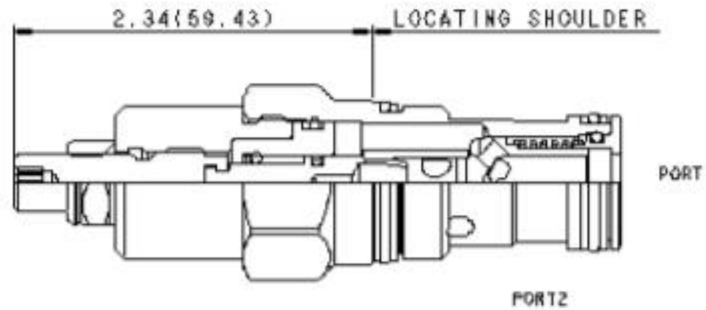
sun hydraulics

MODEL
NCEB

Fully adjustable needle valve with reverse flow check
SERIES 2 / CAPACITY: 12 gpm (.25 inch) / CAVITY: T-5A

snhy.com/NCEB





CONFIGURATION

L	Control	Standard Screw Adjustment
C	Reverse Flow Check	30 psi (2 bar)
N	Seal Material	Buna-N
(none)	Material/Coating	Standard Material/Coating

Needle valves with reverse-flow check are fully adjustable orifices used to regulate flow. They are infinitely adjustable from fully closed up to the maximum orifice diameter. An integral high-capacity check valve provides unrestricted flow from port 2 to port 1. They are not pressure compensated.

TECHNICAL DATA

NOTE: DATA MAY VARY BY CONFIGURATION. SEE CONFIGURATION SECTION.

Maximum Operating Pressure	5000 psi
Maximum Valve Leakage at 110 SUS (24 cSt)	10 drops/min.
Adjustment - No. of CCW Turns from Fully Closed to Fully Open	5
Locknut Hex Size	9/16 in.
Locknut Torque	80 - 90 lbf in.
Seal kit - Cartridge	Buna: 990203007
Seal kit - Cartridge	EPDM: 990203014
Seal kit - Cartridge	Viton: 990203006