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ELECTRIFICATION OF MEDIUM SIZE TRACKED VEHICLE – HYDRAULIC VS ELECTRIC DESIGN AND INTEGRATION

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ABSTRACT

For medium sized combat vehicles, the traditional method for auxiliary power is hydraulics, based on proven track record of reliability, high output forces and excellent power density. With the transition to vehicle electrification, emphasis has been placed on the integration of electric motors into the overall architecture of the vehicle. Electric components generally are larger in size and weigh more for the amount of power they deliver compared to hydraulics. This paper will explore the integration of electric motors in a vehicle and the advantages and disadvantages as compared to hydraulic power.

1 INTRODUCTION

This paper compares hydraulic versus electric solutions for several functions on a medium size tracked vehicle. The key comparison factors are:

- Components required.
- Power density by volume. (kW/L)
- Power density by weight. (kW/kg)
- Efficiency and heat generation.
- Size of hydraulic lines and electric wires.

Power density factors are based on the component's rated power for its size. These factors have a large impact on component integration and vehicle weight, which significantly impacts transportability.

Out-of-scope factors include:

- Component cost.
- Development costs.
- Reliability.
- Maintainability/Serviceability.
- Noise.
- Drive train components such as engine, transmission and final drives.

Five main functions for comparison are:

- Turret.
- Ammo door.
- AC Compressor.
- Ventilation fan.
- Cooling fan.

2.0 TURRET

The main functions in the turret are gun azimuth and gun elevation.

Requirements:
Azimuth:
40° degrees per second[1] (6.67 RPM)

Estimated 40,000 Nm (29,500 ft-lbs.)
28 kW (37.5 hp)
Elevation:
-10° to +20°[1]
25° degrees per second[1]
Estimated 60,000 - 65,000 N
(13,500 - 14,600 lbs.)
13.0 kW (17.4 hp)

Turret hydraulic components.

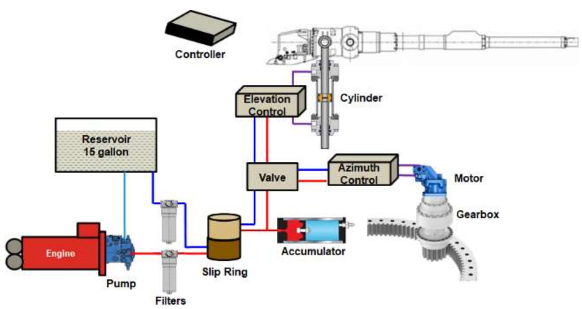

Figure 1: Gun Control – Hydraulic.

Azimuth control components:

- Hydraulic motor – Axial, piston, bent axis, fixed displacement, motor.
- Azimuth control valve.

Elevation control components:

- Hydraulic cylinder – double acting, double rod cylinder.
- Elevation control valve.

Shared hydraulic components:

- An axial piston variable pump with pressure compensated controls which provides a constant pressure to the system. This pump is also used to provide fluid to other turret and chassis functions, as described in other sections.
- Supply and return filters.
- A nitrogen charged, piston accumulator to store energy for rapid gun response.
- Turret valve to enable gun control and direct the fluid appropriately.
- A 15 gallon reservoir is required.

Also required, but assumed to be the same or equal for both solutions are:

- Azimuth slew ring gear and pinion gear.
- Azimuth gear reducer.
- Manual override.
- Slip ring to connect the fluid and electricity between the chassis and the turret.
- Gun control computer and sensors.

Turret electric components.

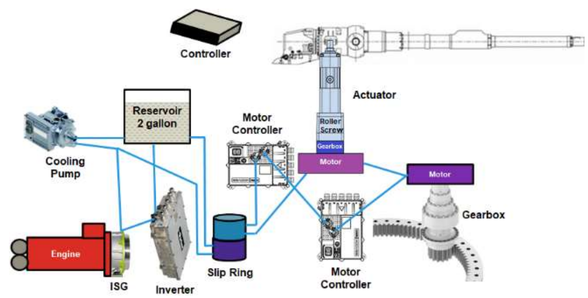

Figure 2: Gun Control – Electric.

Azimuth control components:

- Axial flux motor. (350 V)
- Motor controller.

Elevation control components:

- Roller screw actuator with a gearbox and motor.
- Motor controller.

Shared electric components:

- An Integrated Starter Generator (ISG). The generator is also used to provide power to other turret and chassis functions, as described in other sections.
- Inverter.
- An electric driven cooling pump to cool the ISG, inverter, both motor controllers and both motors.
- A 2 gallon cooling reservoir containing 50/50 water/glycol solution.

Details can be found in Appendix A.

2.1 TURRET RESULTS

Hydraulic pump and motor efficiency depends on speed, pressure and displacement, if variable. A pump and motor has a volumetric efficiency and a mechanical efficiency. For this analysis we assumed a volumetric efficiency of 95% and a mechanical efficiency of 95% for an overall efficiency of 90.3%.

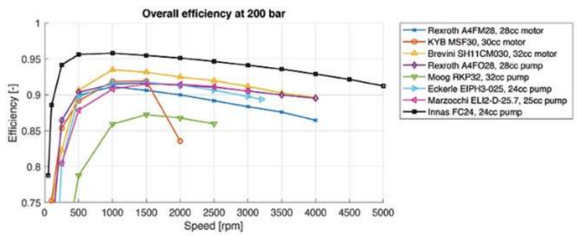

Figure 3: Typical Hydraulic Pump & Motor Efficiency.[26]

Electric motor efficiency depends on speed and torque. Different motor types will have different efficiency maps. For this analysis we used an overall efficiency of 95%. We assumed the same efficiency for the generator.

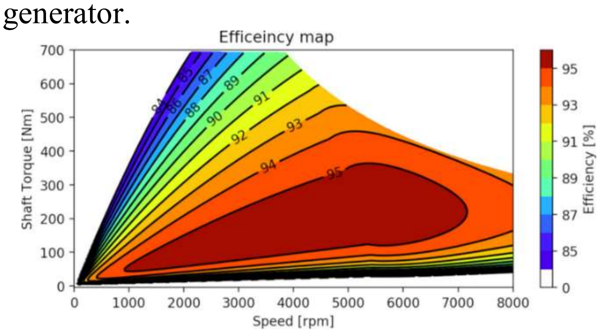

Figure 4: Typical Axial Flux Electric Motor Efficiency.[6]

High power electric components need to be cooled. We assumed all the heat due to inefficiency goes to heat the fluid. For the hydraulic system, cooling will be done with a cooling fan circuit sharing the same reservoir. The electric system needs a pump to circulate the fluid to the components. With a common reservoir, a cooling pump will also be required to circulate cooling fluid through a radiator.

For the turret system, a main difference in heat load is driven by the elevation actuator. With the hydraulic system the elevation actuator is a hydraulic cylinder with 98% efficiency. The only loss is due to friction at the piston and rod seals.

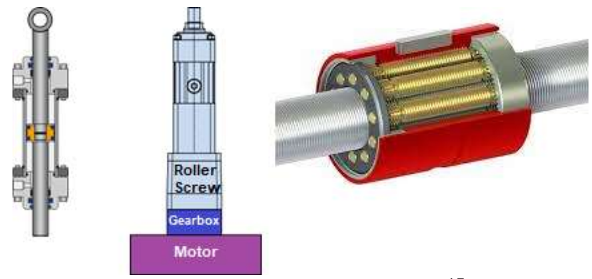

Figure 5: Elevation Actuators.[17]

The electric actuator consists of a roller screw actuator with an efficiency of 86%[19], a gearbox at 98% efficiency and a motor at 95% efficiency for an overall efficiency of 80%. At a component level, electric cannot beat the efficiency of a hydraulic cylinder, but system efficiency is the real goal and the valves to control the flow to the cylinder will dominate the power loss and this will vary with the type of system and the load.

The power loss at the hydraulic valve is given by:

$$PW_{Loss} = \Delta P_{Valve} * Q \qquad (1)$$

The pressure compensated pump maintains a constant system pressure. The load is always changing based on dynamic/inertial loads, applied loads and pressure losses through the lines and components. For the efficiency and heat load calculations, we assumed the load is one-half the system pressure and that the average pressure drop is the other half of system pressure. The flow also varies with operator's needs. Sometimes small quick motions are needed and other times more motion is needed. It would be very rare to be at max flow and max pressure drop for any length of time. For valve efficiency and heat load we assumed that the average flow is one-half the max system rated flow. For the electric components we assumed the heat load was based on supplier's stated efficiency and the power going through the component. Recommend a detailed dynamic heat load analysis be performed with varying loads, usage times, etc.

For an equivalent load, the electric system is more efficient and generates less heat compared to the hydraulic system. The main driver of this poor hydraulic efficiency results from the pressure drop across the valves. An electric system requires lower cooling heat rejection, resulting in a smaller and lighter radiator.

Figure 6 shows the peak and rated torque for a typical hydraulic and electric motor. Beyond rated speed the electric motor loses torque. The hydraulic motor can maintain torque as long as the pump and engine can provide the needed pressure, flow and power. The electric motor has a very high (240%) peak torque over rated that can be sustained for several seconds. This is a key advantage over hydraulics. The electric motor can be sized for a lower nominal torque. The peak torque can be sized for transient conditions such as acceleration and deceleration. The hydraulic motor only has a 112.5% peak torque over rated so it must be sized for full dynamic loads, not nominal loads. See Appendix B for details.

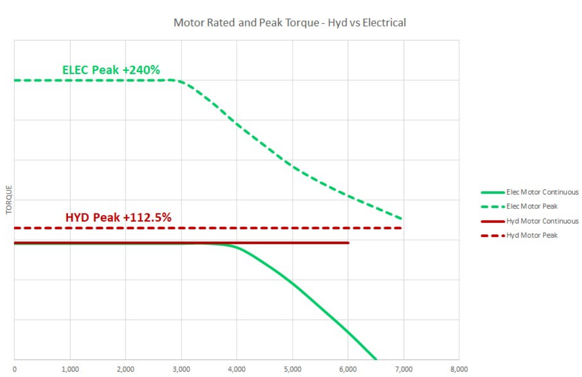

Figure 6: Motor Rated and Peak Torque.[8,29]

Advancements in motor technology and high voltage components have reduced the size and increased the power density of electrical components. However, at this time, for these turret functions, the hydraulic pump and motor are 1.2 to 2.9 times more power dense. Comparing the valves to the motor controllers, the sizes are nearly the same but the hydraulic valves are 5.5 to 6.7 times heavier.

The electric system requires a cooling pump but the hydraulic system has an accumulator.

The main hydraulic lines are -12 sized tubes and hoses for elevation and -16 size for azimuth. Hydraulic hose outside diameter (OD) and bend radius depend on the pressure rating and the supplier. Many suppliers now offer hoses with ½ the bend radius compared to the SAE standard. For these turret functions we used 3000 PSI hose with ½ SAE bend radius.

For these turret functions, wire is smaller in size and bend radius compared to hydraulic hose.

With hydraulics, for a given power, increasing the pressure will reduce the flow. But, increasing the pressure will also increase hose and tube thickness and weight. Figure 7 shows a comparison of hose OD (blue) and tube OD (green) at 3000 PSI and 6000 PSI and wire OD (red) versus power at 350 V and 480 V. Electric wire OD is about 50% smaller compared to hydraulic hose OD and 25% smaller than hydraulic tube OD.

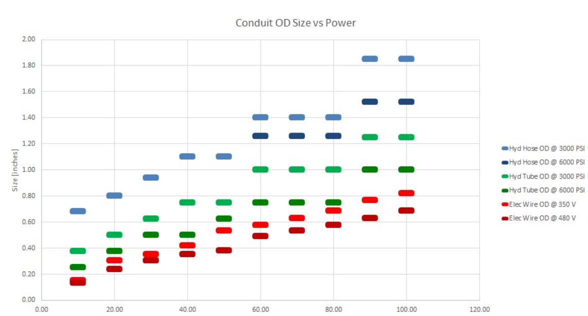

Figure 7: Hyd Hose, Tube and Wire OD vs Power.

For electric wiring we assumed a bend radius of 8 times the OD[20]. For hydraulic hose, the bend radius is given by the supplier.

Hydraulic tube bend radius was assumed to be 2 times the OD. Figure 8 shows that the electric wire (green) bend radius is less than hydraulic hose (blue). Hydraulic tube (green) has the smallest bend radius.

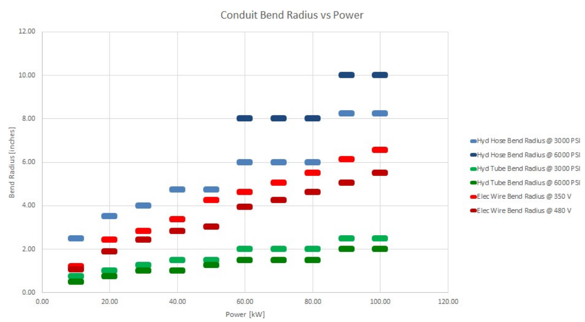

Figure 8: Hyd Hose, Tube and Wire Bend Radius vs Power.

Figure 9 shows that electric wire has the least weight for a given power. Assumption is that the connector and fitting size and weight will have similar results.

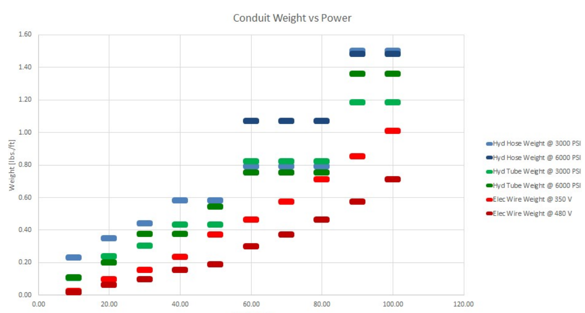

Figure 9: Hyd Hose, Tube and Wire Weight vs Power.

For electric turret control, a new slip ring needs to be developed. Existing slip ring transmits hydraulic flow and pressure, 24 volt electrical power, ground and numerous signals. A new slip ring is required with the hydraulics replaced by high voltage and high current electrics, and ability to transfer coolant.

Manual override needs to be developed.

Turret Scorecard	Hyd	Elec
Pump/Motor Power Density	+	o
Valves vs Motor Controllers	o	+
Efficiency / Heat Load	o	++
Hyd lines vs Elec wires	o	+

Key: o baseline, = equal, + better, ++ much better.

3.0 AMMO DOOR

The main function of the ammo door is to protect the crew from hits in the ammo compartment. To open the door, the loader pushes a knee switch. The door must open and close quickly. This analysis only focuses on the door actuator. Similar conclusions are assumed for the latching mechanism.

Requirements:

- Travel 610 mm 24”[2,3,4]
- Travel Time 0.8 s[2,3,4]
- Travel Speed 762.5 mm/s (610 mm / 0.8 s)
- Force Estimated 5000 N (1124 lbs.)

Ammo door hydraulic components:

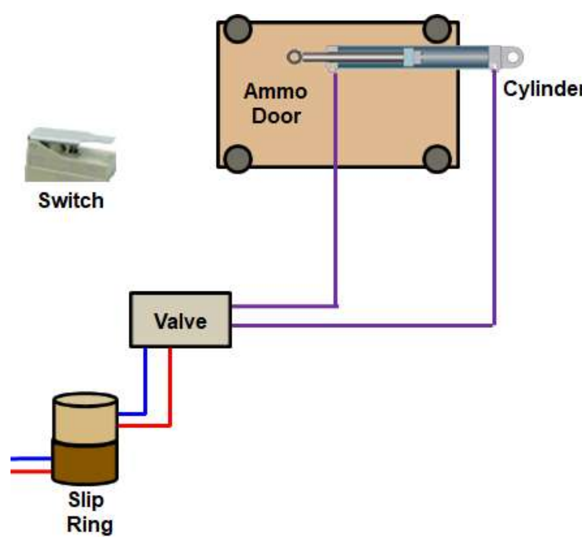

Figure 10: Ammo Door – Hydraulic.

- Hydraulic cylinder – double acting, single rod cylinder.
- Ammo door valve.

Pressurized fluid comes from the Turret pump.

Also required, but assumed to be the same or equal for both solutions are:

- Slip ring to connect the fluid and electricity between the chassis and the turret.
- Knee switch.

Ammo door electric components:

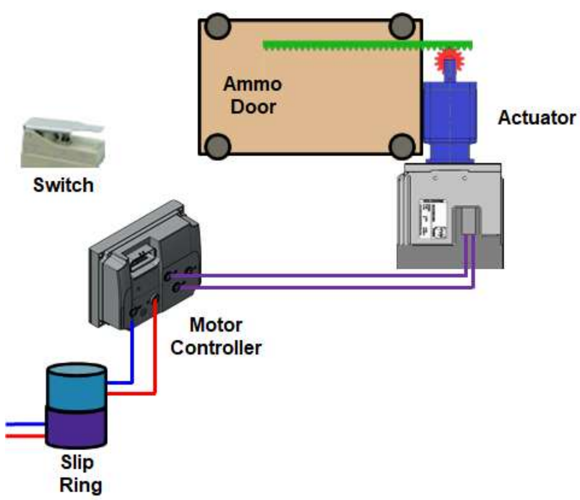

Figure 11: Ammo Door – Electric.

- Rack and pinion actuator, with an in-line planetary gearbox driven by an Interior Permanent Magnet (IPM) electric motor. (24 V)
- Motor controller.

Details can be found in Appendix C.

3.1 AMMO DOOR RESULTS

A rack-and-pinion device was selected because of its simplicity. Other mechanical and electrical solutions for actuating the ammo door are available. Power requirements would be similar for other solutions.

Hydraulic actuation has a 2.3 to 3.3 power density advantage in volume and weight. Electrical power density could be improved by using a higher voltage motor. A twenty-four volt (24 V) system was selected for this function because that is the standard vehicle voltage and an interesting comparison point. The hydraulic valve is simple and is 50% less volume but equal in weight to a motor controller. For this function, the hydraulic hose is similar in OD compared to wire but hydraulic hose has a smaller bend radius and weighs less per linear foot.

The electric motor selected is 24 volts and requires a significant amount of current at rated speed and torque. With a higher voltage motor, the electric wire would be smaller, more flexible and weigh less.

The power required to open and close the ammo door is small, the use is intermittent, and so this would not be a significant heat generator.

Ammo Door Scorecard	Hyd	Elec
Power Density	+	o
Valves vs Motor Controllers	+	o
Efficiency / Heat Load	=	o
Hyd lines vs Elec wires	+	o

Since this is only an ammo door, this function would not weigh heavily on choosing a technology solution.

4.0 AC COMPRESSOR

The main function is to provide power to the Air Conditioning (AC) compressor.

Requirements:

- Speed Estimated 5000 RPM
- Torque Estimated 20 Nm
- Power 10.5 kW (14 hp)

Hydraulic components include:

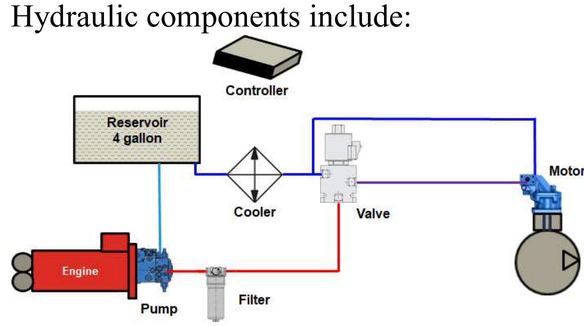

Figure 12: AC Compressor – Hydraulic.

- Axial piston variable pump with electro-hydraulic flow control to provide a desired flow to the motor.
- Filter.
- Unloading valve.
- Axial piston, bent axis, fixed displacement, motor. Pump and motor are in an open-circuit arrangement.

Shared hydraulic components:

- A cooler is required and will be combined with other cooling requirements into a single radiator.
- A 4 gallon reservoir is required and will be combined with other reservoir requirements into a single reservoir.
- Vehicle controller.

Electric components include:

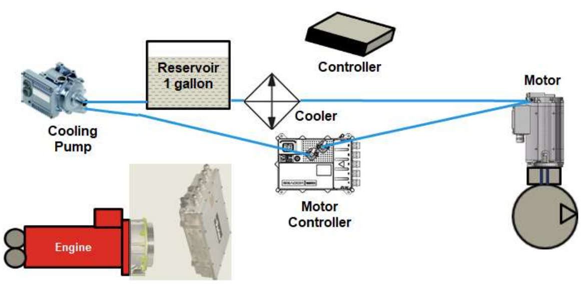

Figure 13: AC Compressor – Electric.

- Motor, Permanent Magnet (PMAC). (400 V)
- Motor controller.

Shared or combined electric components:

- Power will come from the ISG and inverter used for turret functions.
- A cooler is required and will be combined with other cooling requirements into a single radiator.
- An electric driven cooling pump to cool the motor controller and motor.
- A 1 gallon reservoir is required and will be combined with other reservoir requirements into a single reservoir.
- Vehicle controller.

Details can be found in Appendix D.

4.1 AC COMPRESSOR RESULTS

Compared to an ISG, the hydraulic pump is 1.7 times more power dense by volume and 1.8 times more power dense by weight.

The electric motor selected for this function, with comparable speed and torque, is a Permanent Magnet (PMAC) motor. Table below compares a PMAC motor to an axial flux motor and a hydraulic motor. Power density is calculated as the supplier's rated continuous or nominal power per stated volume and dry weight. This gives a good comparison of the component's power density capabilities.

Motor Type	Volume Power Density [kW/L]	Volume Ratio [-]
PMAC	2.83	1.0
Axial Flux	8.04	2.8
Hydraulic	38.81	13.7

Motor Type	Weight Power Density [kW/kg]	Weight Ratio [-]
PMAC	1.04	1.0
Axial Flux	2.38	2.3
Hydraulic	4.94	4.8

An axial flux motor is more power dense than a PMAC, but an axial motor in this size could not be found. An available larger axial flux motor, with more torque and power than required, ended up being the same size as a PMAC motor. The hydraulic motor is 13.7 times more power dense by volume and 4.8 times more power dense by weight compared to the PMAC motor.

The combined hydraulic filter and valve size is 35% smaller than the motor controller and about equal in weight.

This hydraulic system is an open-circuit hystat arrangement. The unloading valve is only used to unload the pump while the system is not in use. While in use the valve has a small pressure drop. Likewise the pressure drop across the filter is small. The hydraulic system generates 1.5 X more heat than a comparable electric system. Power requirements for the system is not that significant relative to the overall vehicle power. Even though the electric system has 32% less heat generation, the difference between the two (0.81 kW) is not significant to the overall vehicle cooling system.

Hydraulics require -12 (Ø3/4") lines which has a bend radius of 120 mm. Motor is high voltage. Wire, at nominal conditions, is 10 AWG with a size of approximately Ø4.5 mm with a bend radius of 36 mm. This function adds 4 gallons to the hydraulic tank and 1 gallon capacity is required for electric cooling. Electric system requires an electric driven cooling pump. Cooling will be shared with a common radiator.

AC Compressor Scorecard	Hyd	Elec
Power Density	++	o
Valves vs Motor Controller	+	o
Efficiency / Heat Load	=	o
Hyd lines vs Elec wires	o	++

5.0 VENTILATION FAN

One or more ventilation fans to provide cooled or heated air to the crew.

Requirements for a 1 kW fan:

- Power 1.0 kW (1.3 hp)
- Speed Estimated 5000 RPM
- Torque Estimated 1.91 Nm
- No gearbox.

Ventilation fan hydraulic components:

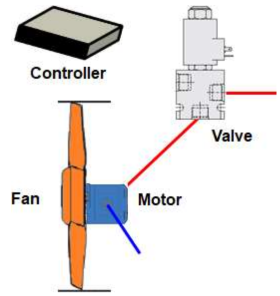

Figure 14: Ventilation Fan – Hydraulic.

- Hydraulic fixed displacement gear motor.
- Valve – flow control.

Pressurized fluid comes from the pump used for turret functions.

Also required, but assumed to be the same or equal for both solutions are:

- Vehicle controller.

Ventilation fan electric components:

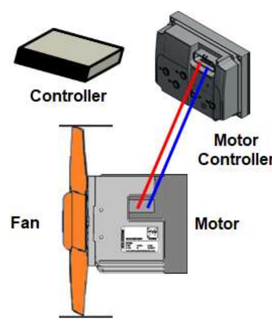

Figure 15: Ventilation Fan – Electric.

- Interior Permanent Magnet (IPM) electric motor. (24 V)
- Motor controller.

Details can be found in Appendix E.

5.1 VENTILATION FAN RESULTS

Hydraulics showed a 16 to 11 power density advantage in volume and weight. The main factor driving power density is the electric motor at 24 volts. With a high voltage motor, significant size reduction can be realized. The valve is simple and is 28% less volume and 45% less weight than a motor controller.

The power required is small and is not a significant heat generator.

Hydraulic flow only requires a -6 (Ø3/8") Ø17 mm OD hose with a bend radius of 65 mm. The 24 V electric motor requires 8 AWG wire which has an outside diameter of Ø6 mm with a bend radius of 48 mm.

Ventilation Fan Scorecard	Hyd	Elec
Power Density	++	o
Valves vs Motor Controllers	+	o
Efficiency / Heat Load	=	o
Hyd lines vs Elec wires	o	++

Since this is only a ventilation fan, this function would not weigh heavily on choosing a technology solution.

6.0 COOLING FAN

A vehicle cooling fan is required to cool fluid from the engine, transmission and the hydraulic or electric system.

Requirements for an 80 kW fan:

- Power Estimated 80 kW (107 hp)
- Speed Estimated 4200 RPM (Based on available electric motor)
- Torque Estimated 182 Nm
- No gearbox.

Cooling fan hydraulic components:

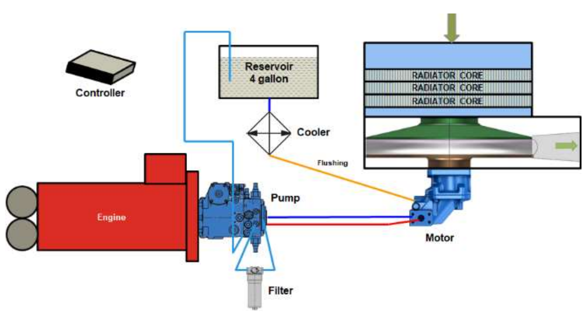

Figure 16: Cooling Fan – Hydraulic.

- Axial piston variable pump with electronic controls to provide a desired flow/pressure to the motor. A charge/cooling pump is integrated into the pump.
- Filter
- Axial piston, bent axis, fixed displacement, motor. Pump and motor are in a closed-circuit arrangement. Flushing valve is integrated into the motor.

Shared hydraulic components:

- A cooler is required and will be combined with other cooling requirements into a single radiator.
- A 4 gallon reservoir is required and will be combined with other reservoir requirements into a single reservoir.
- Vehicle controller

Cooling fan electric components:

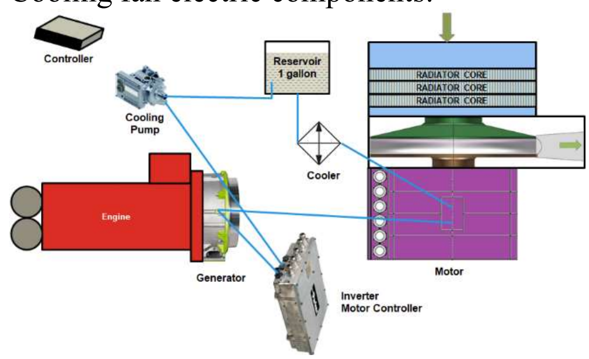

Figure 17: Cooling Fan – Electric.

- Axial flux motor. (480 V)
- Motor controller.
- A generator. For this analysis a second generator was selected. A second generator provides vehicle backup capability in case one generator fails. Starting capability is not required because it is provided by the ISG used for turret/chassis functions, unless duplication is desired. A single larger ISG is also an option.
- Inverter. This inverter is dedicated to this cooling circuit and has integrated controls for one motor.

- An electric driven cooling pump to cool the generator, the inverter, and the motor.

Shared electric components:

- A 1 gallon cooling reservoir containing 50/50 water/glycol solution.
- Vehicle controller.

Details can be found in Appendix F.

6.1 COOLING FAN RESULTS

The hydraulic motor is 5.2 times more power dense by volume and 5.7 times more power dense by weight compared to an axial flux motor. The hydraulic pump is 2.6 times more power dense by volume and 2.9 times more power dense by weight compared to an ISG.

The hydraulic pump and motor are about 90% efficient giving an overall system efficiency around 81%. The electric components are 95% efficient with an overall system efficiency of 85.7%. The electric system will reduce the heat load rejection requirement by about 6.9 kW so a smaller radiator could be used.

Hydraulic flow requires a -12 (Ø3/4") hose with an outside diameter of Ø32 mm and a bend radius of 200 mm. The high voltage electric motor requires 2/0 wire which has an outside diameter of Ø14.7 mm with a bend radius of 118 mm.

Cooling Fan Scorecard	Hyd	Elec
Power Density	++	o
Filter vs Inverter	+	o
Efficiency / Heat Load	o	+
Hyd lines vs Elec wires	o	++

7.0 CONCLUSIONS

At a component level, a hydraulic motor is more power dense than a comparable high voltage electric motor. However, the key is to evaluate this at a system level, rather than at a component level. At a system level, including all valves, controllers, lines and wires, reservoirs, etc. the systems are nearly the same.

To be competitive in power density, the electric system for the main actuators and motors needs to be at high voltage, typically around 350 V to 480 V. Electric motors are not size competitive at low voltage (24 V). A two voltage system for vehicles is recommended: 24 volts for sensors, lights, solenoids, controllers, etc. and 350 to 480 V systems for motors and actuators.

The type of motor is very important to get the power density needed to compete with hydraulics. Each motor type will have tradeoffs in performance, size, cost, and reliability. For example, the axial flux motors are larger in diameter but have less length[25]. Selecting the best motor for the application is not easy. Designer may pick a different type of motor due to size and shape differences to best integrate into the vehicle.

Since the size and shape is different from existing hydraulic components, and depends on what type of motor is chosen, it would be very difficult to fit electric components into existing design space. It would be best to start with a "clean sheet".

Also, it would make little sense to have a mixture of hydraulic and high-power electric components on the same vehicle. For example the reservoir requirements for each system is:

Reservoir	Hyd	Elec
Turret	15 gal	2 gal
AC Compressor	4 gal	1 gal
Cooling Fan	4 gal	1 gal
Total	23 gal	4 gal

If both systems were on the same vehicle then we would need two reservoirs of some capacity. For cooling we would need two radiators – one for hydraulic and one for cooling. There is no space for both, so it would be best to go all hydraulic or all electric.

Electric is more fuel efficient, so the fuel tank can be reduced in size and weight or the vehicle range could be increased.

As seen in other industries, electric solutions provide improved reliability. Service could be faster with improved diagnostics but possibly more expensive as service people are just replacing "black boxes". Rework of electric components can be difficult.

For medium sized tracked vehicles, new actuators for gun control need to be developed. A new slip ring will also need to be developed. This development should start now.

Also need to reevaluate the whole vehicle design to find the best integration of electric components into the vehicle.

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APPENDIX A – TURRET = AZIMUTH + ELEVATION

Azimuth		
Speed	40° degrees per second[1] = 6.67 RPM	
Torque	Estimated 40,000 Nm	
Power	Estimated 28 kW (37.5 hp)	
	Hydraulic	**Electric**
	Hydraulic Motor	**Electric Motor**
Type	Axial Piston Bent Axis	Axial Flux
Nominal Speed	Proprietary	5000 RPM
Pressure/Voltage	110.3 bar 1600 PSI	350 Vdc
Shaft Power	30.0 kW	52.4 kW
Volume	2592 cc	6516 cc
Weight (dry)	10.7 kg (Estimated)	22.0 kg
Power Density	30.0/2,592 = 11.57E-3 kW/cc	52.4/6516 = 8.04E-3 kW/cc
Volume Ratio	1.4 X more Power Dense by Volume	1.0
Power Density	30.0/10.7 = 2.80 kW/kg	52.4/22.0 = 2.38 kW/kg
Weight Ratio	1.2 X more Power Dense by Weight	1.0
	Gear Box	
Size	Similar	Similar
	Azimuth Controller	
Model	Proprietary Valve	Motor Controller
Volume	10,000 cc	10,106 cc
Weight	33 kg	6.0 kg
Volume Ratio	1.0	1
Weight Ratio	5.5 X more Weight	1
	Azimuth Heat Generation (1/2 Load, 1/2 Speed)	
Pressure - Load	55.2 bar 800 PSI (1/2 of Max Pressure)	-
Pressure Drop at Valve	55.2 bar 800 PSI	-
Flow - Operating	23.9 GPM (1/2 of Max Flow)	-
Motor Power Average	8.31 kw Hyd Input Power 7.50 kW Shaft Output Power	7.89 kW Input Power Same 7.50 kW Shaft Power
Motor Heat Generation Average	0.81 kW (@ 95% Vol * 95% Mech Eff)	0.39 kW (7.89 kW @ 95% Motor)
Valve Heat Generation	8.31 kW (Valve: 800 PSI, 23.9 GPM)	0.39 kW (Controller: 7.89 kW @ 95%)
Total Heat Generation @ 1/2 Load	9.12 kW = 0.81 Motor + 8.31 Valve	0.78 kW = 0.39 kW Motor + 0.39 kW Controller
	Azimuth Conduit	
Source Conduit	Hydraulic Hose SAE J517 100R17 -16 3000 PSI 207 bar	Copper 75°C 1/0
Source Conduit OD	Ø1.40" Ø35 mm	Ø0.532" Ø13.5mm
Bend Radius	6" 150 mm	8X OD 4.25" 108 mm
Source Conduit Weight	0.79 lbs./ft. 1.17 kg/m	0.372 lbs./ft.
ELEVATION		
Elevation Range	-10° to +20°[1]	

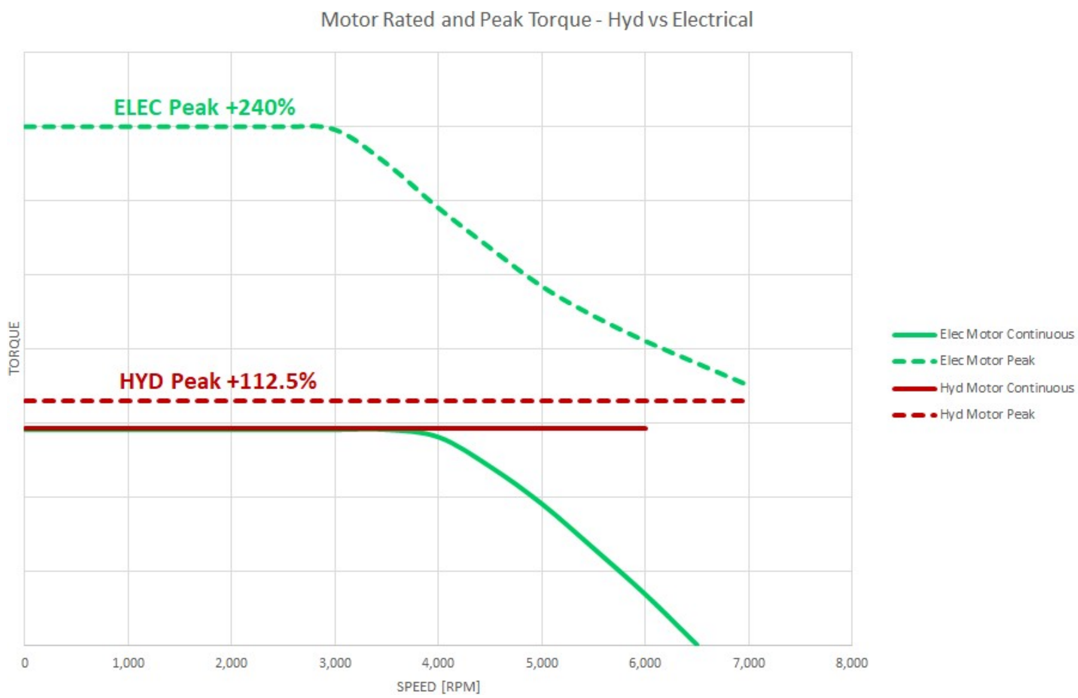
Elevation Speed	25° degrees per second[1]	
Force	Estimated 60,000 to 65,000 N (13,500 to 14,600 lbs.)	
Power	Estimated 13 kW (17.4 hp)	
	Hydraulic	**Electric**
	Elevation Cylinder	**Roller Screw**
Type	Double rod cylinder	Roller Screw
Flow/Current	69.9 LPM 18.5 GPM	145 Arms Continuous
Pressure/voltage	110.3 bar 1600 PSI	350 v
Force	64283 N 14,451 lbs. @ 1600 PSI	66,193 N 14,881 lbs (System)
Power Output	12.86 kW 17.2 hp	13.24 kw 17.8 hp
Volume	8,267 cc	24,961 cc
Weight (dry)	8,267*7.850E-3*0.8 fill factor = 52 kg	82.9 kg
Power Density	12.86/8267 = 1.56E-3 kW/cc	13.24/24961 = 0.53E-3 kW/cc
Volume Ratio	2.9 X more Power Dense by Volume	1
Power Density	12.86/52 = 0.25 kW/kg	13.24/82.9 = 0.16 kW/kg
Weight Ratio	1.6 X more Power Dense by Weight	1
	Elevation Controller	
Model	Proprietary Valve	Motor Controller
Volume	12,000 cc	10,106 cc
Weight	40 kg	6.0 kg
Volume Ratio	1.2 X more Volume	1
Weight Ratio	6.7 X more Weight	1
	Elevation Heat Generation (1/2 Load, 1/2 Speed)	
Actuator Power Average	3.28 kw Hyd Input Power 3.21 kW 4.3 hp (800 PSI @ 100mm/s)	4.01 kW Input Power Same 3.21 kW Output Power
Actuator Heat Generation Average	0.07 kW (3.28 @ 98% Overall Eff)	0.80 kW (4.01 kW @ 80% Actuator)
Valve Heat Generation	3.22 kW (Valve: 800 PSI, 9.25 GPM)	0.20 kW (Controller: 4.01 kW @ 95%)
Total Heat Generation	3.29 kW = 0.07 kW Cyl + 3.22 kW Valve	1.00 kW = 0.80 kW Act + 0.20 kW Controller
	Elevation Conduit	
Flow/Current	69.9 LPM 18.5 GPM	145 Arms Continuous
Source Conduit	Hydraulic Hose SAE J517 100R17 -12 3000 PSI 207 bar	Copper 75°C 1/0
Source Conduit OD	Ø1.10” Ø28 mm	Ø0.532” Ø13.5mm
Bend Radius	4.75” 120 mm	8X OD 4.25” 108 mm
Source Conduit Weight	0.58 lbs./ft. 0.86 kg/m	0.372 lbs./ft.
	Hydraulic Source	**Electric Source**
	Pump	**Integrated Starter Generator**
Type	Pump, Axial Piston, Variable	Integrated Starter Generator
Press/Voltage Capable	250 bar 3600 PSI	-
Flow/Current Capable	212 LPM 56.0 GPM (100%)	-
Cont. Power Capable	79.7 kW (250 bar, 90% Overall Eff)	145 kW
Volume	11,412 cc	43,852 cc

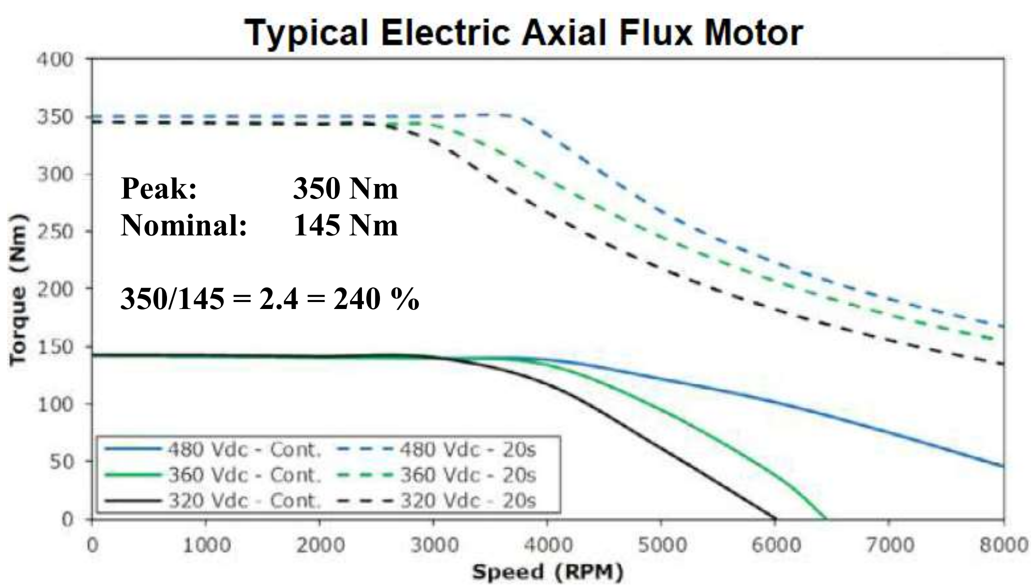
Weight (dry)	45 kg (with through drive)	119 kg
Power Density (Volume)	79.7/11412 = 6.98E-3 kW/cc	145/43852 = 3.31E-3 kW/cc
Volume Ratio	2.1 X more Power Dense by Volume	1.0
Power Density	79.7/45 = 1.77 kW/kg	145/119 = 1.22 kW/kg
Weight Ratio	1.5 X more Power Dense by Weight	1.0
Controls	Pump controls included in main pump	See inverter
	Source Heat Generation (Azimuth and Elevation @ 1/2 Load, 1/2 Speed)	
Pump Power Average	12.82 kw Shaft Input Power 11.54 kW (800 PSI @ 33.15 GPM)	12.15 kW Input Power Same 11.54 kW Output Power
Source Heat Generation Average	1.28 kW (12.82 @ 90% Pump Overall Eff)	0.61 kW (12.15 kW @ 95% ISG Eff)
	Energy Storage	
	Accumulator	**Battery (Not needed)**
Type	Accumulator, Piston	-
Capacity	2.0 Gallon, 4" Bore, 3000 PSI	-
Volume	13,142 cc	-
Weight (dry)	36 kg (dry)	-
	Additional Items	
Item	**Filter**	**Inverter**
Supply & Return Filter	4,218 cc each 2 x 4218 = 8,436 cc	24,442 cc
Weight (dry)	3.9 kg each 2 x 3.9 = 7.8 kg	25 kg
Heat Generation	0.58 kW	0.60 kW
	Turret Valve	**None**
Volume	6,000 cc	-
Weight	20 kg	-
Heat Generation	1.44 kW	-
Total Volume	8,436 + 6,000 = 14,436 cc	24,442 cc
Total Weight	7.8 + 20 = 27.8 kg	25 kg
Volume Ratio	1.7 X Less Volume	1
Weight Ratio	1.1 X More Weight	1
Total Heat Generation	2.02 kW = (0.58 kW + 1.44 kW)	0.60 kW
	No additional cooling pump required	**Electric Cooling Pump**
Cooling/Charge/Boost	-	50/50 water-glycol
Charge/Cooling Pump	-	4,256 cc 6.7 lbs 3.03 kg
Pump Controls	Included in main pump	Included on cooling pump
	Reservoir & Fluid	
Fluid	Hydraulic Oil MIL-PRF-46170	50/50 water-glycol
Reservoir/Cooling	15 gal 56,781 cc	2 gal 7,751 cc
Volume Ratio	7.5 X More Volume	1
Density of fluid	859 kg/m^3	1050 kg/m^3
Weight	48.8 kg	8.1 kg
Weight Ratio	6.0 X More Weight	1

	Controller	
Vehicle Controller	Same	Same
	Heat Generation (1/2 Load, 1/2 Speed)	
	Hydraulic	**Electric**
Az Motor	0.81 kW	0.39 kW
Az Valve/Controller	8.31 kW	0.39 kW
Elev Actuator / Motor	0.07 kW	0.80 kW
Elev Valve/Controller	3.22 kW	0.20 kW
Pump / ISG	1.28 kW	0.61 kW
Filter & Valve / Inverter	0.58 kW	0.60 kW
Turret Valve	1.44 kW	-
Total	**15.71 kW**	**2.99 kW**
Heat Ratio	5.3 X More Heat Generated	1

Contact authors at Waltonen for additional details.

APPENDIX B – MOTOR RATED AND PEAK TORQUE
Motor Rated and Peak Torque – Hydraulic vs Electrical





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$$\textbf{Hydraulic Toruqe} \quad M = \frac{V_g \, \Delta P \, \eta_{hm}}{20\,\pi}$$

$$Normial\ Pressure\ 400\ bar \quad M = \frac{32\ 400\ 100\%}{20\,\pi} = 203.7\ Nm$$

$$Maximum\ Pressure\ 450\ bar \quad M = \frac{32\ 450\ 100\%}{20\,\pi} = 229.2\ Nm$$

$$\frac{Peak}{Nominal} \quad \frac{229.2\ Nm}{203.7\ Nm} = 1.125 = 112.5\%$$

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APPENDIX C – AMMO DOOR

Ammo Door		
Travel	610 mm 24” [2,3,4]	
Travel Time	0.8 s[2,3,4]	
Travel Speed	762.5 mm/s = (610 mm / 0.8s)	
Force	Estimated 5000 N (1124 lbs) Peak	
	Hydraulic	**Electric**
	Cylinder – Single Rod Double Acting	**Rack and Pinion**
Travel	610 mm 24”	610 mm 24”
Power Output	3.81 kW 5.1 hp	3.81 kW 5.11 hp
Pressure/voltage	78 bar 1131 PSI under load	-
Flow/Current	29.34 LPM 7.8 GPM	-
Power Input	3.89 kW (98% Overall Eff)	3.89 kW (98% Overall Eff)
Volume	1853 cc	807 cc
Weight (dry)	5 kg (estimated)	Rack + Pinion = Total 5.5 kg + 0.8 kg = 6.3 kg
	Use Turret Pump	**Motor**
Type	-	Interior Permanent Magnet
Press/Voltage Capable	-	24 V to 96 V
Flow/Current Capable		200 Arms
Rated Torque & Speed	-	5 Nm @ 3000 RPM
Rated Power	-	1.6 kW (91% Eff)
Volume	-	2295 cc
Weight (dry)	-	7 kg
	Not applicable	**Gearbox**
Type	-	Inline Planetary 10:1 97%
Volume & Weight	-	1,104 cc, 3 kg
	Cylinder	**Rack & Pinion, GB, Motor**
Total Size	1853 cc	4,206 cc
Total Weight	5 kg (estimated)	16.3 kg
Power Density	3.81/1853 = 2.056E-3 kW/cc	3.81/4206 = 0.906E-3 kW/cc
Volume Ratio	2.3 X more Power Dense by Volume	1.0
Power Density	3.81/5 = 0.762 kW/kg	3.81/16.3 = 0.234 kW/kg
Weight Ratio	3.3 X more Power Dense by Weight	1.0
Control	**Control Valve**	**Motor Controller**
Supplier	Proprietary	Motor Controller
Volume	1024 cc	2139 cc
Weight (dry)	2.5 kg 5.51 lbs. (Estimated)	2.3 kg 5 lbs.
	Conduit	
	Hydraulic Hose SAE J517 100R17 -6 3000 PSI 207 bar ½ Bend Radius	Copper 75°C 3/0 AWG Assume 24 V system
Conduit OD	Ø0.68” Ø17 mm	Ø0.630” Ø16.0mm
Conduit Bend Radius	2-1/2” 65 mm	8X OD 5.04” 128 mm
Conduit Weight	0.23 lbs./ft. 0.34 kg/m	0.575 lbs./ft.

Contact authors at Waltonen for additional details.

APPENDIX D – AC COMPRESSOR

AC Compressor		
Speed	Estimated 5000 RPM	
Torque	Estimated 20 Nm	
Power	10.5 kW 14 hp	
	Hydraulic	**Electric**
	Motor	**Motor**
Type	Motor, Fixed Displacement, Bent Axis	Permanent Magnet (PMAC)
Press/Voltage Capable	350 bar 4351 PSI	400 VDC
Flow/Current Capable	61 LPM 16.1 GPM	48.9 Arms Continuous
Cont. Torque Capable	31.8 Nm (350 bar 95% Mech Eff)	27.5 Nm
Cont Shaft PW Capable	32.1 kW (350 bar 95% Mech Eff)	19.3 kW
Shaft Power Operating	10.47 kW (3198 PSI at 8.34 GPM)	10.47 kW (5000 RPM at 20)
Input Power Operating	11.6 kW	11.02 kW
Flow/Current - Op	31.6 LPM 8.34 GPM (5000 RPM, 95% Vol Eff)	31.5 Arms (95% Eff)
Heat Generation -Op	1.13 kW (10.47 kW at 90.3% Overall Eff)	0.55 kW (95% Motor)
Volume	827 cc	6,816 cc
Weight (dry)	6.5 kg	18.5 kg
Power Density	32.1/827 = 38.8E-3 kW/cc	19.3/6816 = 2.83E-3 kW/cc
Volume Ratio	13.7 X more Power Dense by Volume	1.0
Power Density	32.1/6.5 = 4.94 kW/kg	19.3/18.5 = 1.04 kW/kg
Weight Ratio	4.7 X more Power Dense by Weight	1.0
		Alternate Motor
Type	-	Axial Flux
Size	-	AXM 125 4 Turn motor
Nominal Speed	-	5000 RPM
Press/Voltage Capable	-	350 VDC
Flow/Current Capable	-	145 Arms Continuous
Cont. Torque Capable	-	100 Nm
Cont Shaft PW Capable	-	52.4 kW (5000 RPM, 100 Nm)
Volume	-	6516 cc
Weight	-	22 kg
Power Density	-	52.4/6516 = 8.04E-3 kW/cc
Power Density	-	52.4/22 = 2.38 kW/kg
	Hydraulic Source	**Electric Source**
Type	Pump, Axial, Piston, Variable	Integrated Starter Generator
Press/Voltage Capable	250 bar 3600 PSI	-
Flow/Current Capable	84 LPM 22.2 GPM (100%)	-
Cont. Power Capable	33.3 kW (250 bar, 90.3% Overall Eff)	145 kW
Flow/Current -Op	31.58 LPM 8.34 GPM (5000 RPM, 95% Vol Eff)	31.5 Arms (95% Eff)
Output Power - Op	11.61 kW (3198 PSI at 8.34 GPM)	11.02 kW (Motor Input PW)
Input Power - Op	12.86 kW (3198 PSI at 8.34 GPM)	11.60 kW (95% Eff)
Heat Generation - Op	1.25 kW (90.3% Overall Eff)	0.58 kW (95% Overall Eff)

Volume	6,061 cc	43,852 cc
Weight (dry)	15 kg (no through drive)	119 kg
Power Density	33.3/6061 = 5.49E-3 kW/cc	145/43852 = 3.31E-3 kW/cc
Volume Ratio	1.7 X more Power Dense by Volume	1.0
Power Density	33.3/15 = 2.22 kW/kg	145/119 = 1.22 kW/kg
Weight Ratio	1.8 X more Power Dense by Weight	1.0
	Source & Motor Conduit	
	SAE -12 Ports	35 amps Continuous
Source Conduit	Hydraulic Hose SAE J517 100R19 -12 4000 PSI 276 bar	Copper 75°C 10 AWG
Source Conduit OD	Ø1.09" Ø28 mm	Ø0.176" Ø4.5mm
Source Conduit Bend Radius	4-3/4" 120 mm	8X OD 1.4" 36 mm
Source Conduit Weight	0.58 lbs./ft. 0.86 kg/m	0.038 lbs./ft.
	Additional Items	
Item	**Filter**	**Inverter**
Filter & Valve /Inverter	Required. External to pump	Inverter
Volume	14,870 cc	24,442 cc
Weight	25.4 kg	25 kg
Heat Generation	0.01 kW (2 PSI at 8.34 GPM)	0.58 kW (95% Overall Eff)
	Unloading Valve	**None**
Heat Generation	0.13 kW (35 PSI at 8.34 GPM)	-
Volume	1,149 cc	-
Weight	0.39 kg	-
	No additional cooling pump required	**Electric Cooling Pump**
Cooling/Charge/Boost	-	50/50 water-glycol
Charge/Cooling Pump	-	10 GPM @ 25 PSI 4,256 cc 6.7 lbs 3.03 kg
Pump Controls	Included in main pump	Included on cooling pump
	Reservoir & Fluid	
Fluid	Hydraulic Oil MIL-PRF-46170	50/50 water-glycol
Reservoir/Cooling	4 gal 15,142 cc	1 gal 3,785 cc
Volume Ratio	4.0 X more Volume	1
Density of fluid	859 kg/m^3	1050 kg/m^3
Weight of fluid	13.0 kg	4.0 kg
Weight Ratio	3.3 X more Weight	
	Heat Generation (Operating Load)	
	Hydraulic	**Electric**
Motor	1.13 kW	0.55 kW
Pump/ISG	1.25 kW	0.58 kW
Filter/Inverter	0.01 kW	0.58 kW
Unloading Valve	0.13 kW	-
Total	**2.52 kW**	**1.71 kW**
Heat Ratio	1.5 X More Heat Generated	1

Contact authors at Waltonen for additional details.

APPENDIX E – VENTILATION FAN

Ventilation Fan		
Speed	Estimated 5000 RPM	
Torque	Estimated 1.91 Nm	
Power	1.00 kW	
Item	No gearbox	
	Hydraulic	**Electric**
	Hydraulic Motor	**Electric Motor**
Type	Gear Motor	Interior Permanent Magnet
Nominal Speed	5000 RPM	5000 RPM
Press/Voltage Capable	240 bar 3481 PSI	24 V to 96 V
Flow/Current Capable	14.4 lpm 3.8 GPM	200 Arms
Shaft Torque Capable	8.0 Nm 5.9 ft-lbs (75% Mech Eff)	2.2 Nm
Shaft Power Capable	4.20 kW (240 bar, 71.3% Eff)	1.19 KW
Speed - Operating	5000 RPM	5000 RPM
Press/Voltage - Op	57.1 bar 829 PSI under load	24 V
Flow/Current - Op	14.74 LPM 3.9 GPM (95% Vol Eff)	52.1 Amps (80% Motor Eff)
Torque - Operating	1.91 Nm (57.1 bar 75% Mech Eff)	1.91 Nm
Shaft Power - Op	1.00 kW (5000 RPM, 1.91 Nm)	1.00 kW (5000 RPM, 1.91 Nm)
Input Power - Op	1.40 kW (71.3 % Overall Eff)	1.25 kW (24 V * 52.1 amps)
Heat Generation - Op	0.39 kW (71.3% Overall Eff)	0.25 kW (80% Eff)
Volume	497 cc	2295 cc
Weight (dry)	2.2 kg (Estimated)	7 kg
Power Density	4.2/497 = 8.45E-3 kW/cc	1.2/2295 = 0.523E-3 kW/cc
Volume Ratio	16 X more Power Dense by Volume	1.0
Power Density	4.2/2.2 = 1.91 kW/kg	1.2/7 = 0.171 kW/kg
Weight Ratio	11.2 X more Power Dense by Weight	1.0
	Hydraulic Source	**Electric Source**
Source	Use same turret pump.	Use turret electrical power
	Source & Motor Conduit	
Conduit	Hydraulic Hose SAE J517 100R17 -6 3000 PSI 207 bar 1/2 Bend Radius	Copper 75°C 8 AWG Assume 24 V system 52 amp load 1.25 kW
Conduit OD	Ø0.68” Ø17 mm	Ø0.236” Ø6.0mm
Conduit Bend Radius	2-1/2” 65 mm	8X OD 1.9” 48 mm
Conduit Weight	0.23 lbs./ft. 0.34 kg/m	0.05 lbs./ft.
	Additional Items	
Item	**Valve**	**Controller**
Control	Control valve external to motor	Motor Controller
Volume	1,537 cc	2139 cc
Volume Ratio	72% 1.4 X Less Volume	100%
Density (Volume)	20%	100%
Weight (dry)	1 kg 2.2 lbs.	2.3 kg 5 lbs.

Contact authors at Waltonen for additional details.

APPENDIX F – COOLING FAN

Cooling Fan		
Power	80 kW 107 hp	
Speed	Estimated 4200 RPM	
Torque	Estimated 182 Nm	
Item	No gearbox	
	Hydraulic	**Electric**
	Hydraulic Motor	**Electric Motor**
Type	Axial, Piston, Bent Axis	Axial Flux
Nominal Speed	6300 RPM	4200 RPM
Rated Pressure/voltage	400 bar 5800 PSI	480 VDC
Peak Pressure/voltage	450 bar 6527 PSI	-
Rated Flow/Current	202 LPM 53.3 GPM	270 Arms Continuous
Rated Torque	204 Nm (400 bar 100% Mech Eff)	290 Nm
Rated Power	134.41 kW (400 bar 6300 RPM 100%)	128 kW (100% Eff)
Flow/Current - Operating	141.5 LPM 37.4 GPM (4200 RPM, 95% Vol Eff)	175.5 Arms (4200 RPM, 182 Nm, 95% Eff)
Press/Voltage - Op	376.0 bar 5456 PSI (95% Mech Eff)	480 VDC
Torque - Operating	182.0 Nm (95% Mech Eff)	182.0 Nm
Shaft Power - Operating	80.05 kW (4200 RPM, 182 Nm)	80.05 kW (4200, 182 Nm)
Input Power	88.70 kW	84.26 kW
Heat Generation - Op	8.65 kW (90.3% Overall Eff)	4.21 kW (95% Overall Eff)
Volume	3,296 cc	16,338 cc
Weight (dry)	10.7 kg	57.5 kg
Power Density	134.41/3296 = 40.8E-3 kW/cc	128/16338 = 7.83E-3 kW/cc
Volume Ratio	5.2 X more Power Dense by Volume	1.0
Power Density	134.41/10.7 = 12.6 kW/kg	128/57.5 = 2.23 kW/kg
Weight Ratio	5.7 X more Power Dense by Weight	1.0
	Hydraulic Source	**Electric Source**
Type	Pump, Axial, Piston, Variable	Integrated Generator
Nominal Speed	3600 RPM	
Rated Pressure/Voltage	400 bar 5800 PSI Nominal	
Rated Flow/Current	202 lpm 53.4 GPM (100%)	
Rated Torque	356.5 Nm	
Rated Power	134.4 kW (400 bar, 3600 RPM, Max)	145 kW
Flow/Current - Operating	141.5 LPM 37.4 GPM (41.37cc 74% disp. 95% Vol Eff)	
Pressure/Voltage - Op	376 bar 5456 PSI	
Torque - Operating	260.7 Nm (95% Mech Eff)	
Input Power - Operating	98.30 kW	88.69 kW (95% Eff)
Output Power - Op	88.72 kW	84.26 kW (Motor Input PW)
Heat Generation - Op	9.58 kW	4.43 kW (95% Eff)
Volume	15,492 cc	43,852 cc
Weight (dry)	38 kg	119 kg
Power Density	134.4/15492 = 8.68E-3 kW/cc	145/43852 = 3.31E-3 kW/cc

Volume Ratio	2.6 X more Power Dense by Volume	1.0
Power Density	134.4/38 = 3.54 kW/kg	145/119 = 1.22 kW/kg
Weight Ratio	2.9 X more Power Dense by Weight	1.0
	Source & Motor Conduit	
Working Conduit	Hydraulic Hose SAE J517 100R15 -12 6000 PSI 414 bar	Copper 75°C 174 Arms Operating 2/0
Working Conduit OD	Ø1.26" Ø32 mm	Ø0.578" Ø14.7mm
Conduit Bend Radius	8" 200 mm	8X OD 4.62" 117.6 mm
Working Conduit Weight	1.07 lbs./ft. 1.59 kg/m	0.462 lbs./ft.
	Additional Items	
Item	**Valve**	**Controller**
Flushing Valve	Integrated in motor	Not applicable
Anti-Cavitation Valve	Integrated in motor	Not applicable
Controls	Pump controls integrated in pump	Integrated in Inverter
Item	**Filter**	**Controller**
Filter/Inverter	External to pump	Inverter
Volume	2,005 cc	24,442 cc
Weight	1.4 kg	25 kg
	No additional cooling pump required	**Electric Cooling Pump**
Cooling/Charge/Boost	25 bar 365 PSI	50/50 water-glycol
Charge/Cooling Pump	Included in main pump	10 GPM @ 25 PSI 4,256 cc 6.7 lbs 3.03 kg
Pump Controls	Included in main pump	Included on cooling pump
	Reservoir & Fluid	
Fluid	Hydraulic Oil MIL-PRF-46170	50/50 water-glycol
Reservoir/Cooling Tank	4 gal 15,142 cc	1 gal 3,785 cc
Volume Ratio	4.0 X more Volume	1
Density of fluid	859 kg/m^3	1050 kg/m^3
Weight of fluid	13.0 kg	4.0 kg
Weight Ratio	3.3 X more Weight	1
Coolant/Flushing/Charge	**Hydraulic Fluid**	**50/50 Water-glycol**
Conduit	Hydraulic Hose SAE J517 100R1AT -8 2500 PSI 172 bar ½ Bend Radius	Hose SAE J517 100R6 -8 400 PSI 25.6 bar
Conduit OD	Ø0.82" Ø21 mm	Ø0.75" Ø19 mm
Conduit Bend Radius	3.5" 90 mm	4" 100 mm
Conduit Weight	0.29 lbs./ft 0.43 kg/m	0.18 lbs./ft 0.27 kg/m
	Heat Generation (Operating Load)	
	Hydraulic	**Electric**
Motor	8.65 kW	4.21 kW
Source	9.58 kW	4.43 kW
Charge & Flushing	1.74 kW	-
Filter/Inverter	0.01 kW(3 PSID @ 11 GPM)	4.43 kW (95% Eff)
Total	**19.98 kW**	**13.07 kW**
Heat Ratio	1.5 X More Heat Generated	1

Contact authors at Waltonen for additional details.