REVjet: Electric Jetski Project
Investigation and proposal of thermal management system and auxiliary mounting assembly

Rowan D. Clark
20253616
School of Mechanical and Chemical Engineering
University of Western Australia

Supervisor: Prof. Thomas Bräunl
School of Electrical and Electronic Computer Engineering
University of Western Australia

Co-Supervisor: Dr. Roshun Paurabolly
School of Mechanical and Chemical Engineering
University of Western Australia

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School of Mechanical and Chemical Engineering
University of Western Australia

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Project Summary

This project was undertaken as part of UWA's requirements for the degree of Bachelor of Engineering and has been conducted in conjunction with the REV project team. The REV project is a UWA initiative aiming to design and develop environmentally sustainable technologies for future transportation. The REVjet project involves the electric conversion of a personal water craft to demonstrate the possibilities of renewable energy use in recreational water craft.

This particular project focuses on the thermal management system and auxiliary supporting structure for various components of the REVjet. Various constraints and considerations, namely cost, time, materials and interfaces, have influenced the steps taken during the process and ultimately shaped the final result.

A thermal management system has been proposed and certain features of the system have been designed to cool the motor and motor controller. An assembly for mounting various auxiliary components within the REVjet has also been designed adhering to the same constraints and considerations as the design process for the thermal management system. Future works and recommendations on further study in the related field are also proposed.

Acknowledgements

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Contents

Nomenclature

a	Acceleration
AC	Alternating Current
BSP	British Standard Pipe
BSPP	British Standard Pipe (Parallel thread)
BSPT	British Standard Pipe (Tapered thread)
C	Discharge rate of battery
C_P	Specific heat
CFD	Computational Fluid Dynamics
CNC	Computer Numerical Control
DC	Direct Current
DE	Drive-end
EPDM	Ethylene Propylene Diene Monomer
F	Force
I	Current (Amps)
ID	Inside Diameter
k	Thermal conductivity
m	Mass
ND	Nominal Diameter
NDE	Non-drive end
OD	Outside Diameter
PWC	Personal Water Craft
Q	Heat Generation (Watts)
REV	Renewable Energy Vehicle
ROV	Remote Operated Vehicle
SME	Submersible Motor Engineering
T	Temperature
TBC	To be confirmed
TLC	Thermochromic liquid crystal
TMT	Total Marine Technology

1. Introduction

With the ever increasing push towards renewable energy use on a global scale, the use of electric powered vehicles is becoming more common and feasible. Rising fuel prices and the emphasis on reducing greenhouse gas emissions have affected many industries, encouraging the development of renewable energy technologies.

Historically Personal Water Craft (PWC) tended to be powered by 2-stroke petrol engines. The 2-stroke PWCs are associated with high pollution emissions due to the expulsion of lubricating oils with the exhaust gases. The current PWC market is mostly dominated by 4-stroke technology. The 4-stroke engines produce much less pollution than their 2-stroke counterparts, but do still emit combustion exhaust gases. The high emissions of typical jet skis pollute both the air and water, which will be addressed by the REVjet.

The internal combustion powered PWCs are often frowned upon in certain areas due to the noise produced. High noise levels can be subject to complaints, particularly when used near residential areas. The REVjet will be a zero emissions vehicle, with no exhaust gases. Noise levels will also be dramatically reduced.

The inevitable re-fuelling of gasoline PWCs intuitively poses a risk of fuel spillage. Any spill occurring while refuelling against the shore or a mooring will tend to end up in the marine environment. As the REVjet will not be subject to refuelling operations, the risk of fuel spillages will be eliminated.

While the capital outlay for electric vehicles tends to be about 1.5-3 times that of the internal combustion vehicles, costs of fuel and routine maintenance for electric vehicles are significantly lower (Chan 1993).

The REV project has been involved in numerous electric vehicle conversions. The REVjet project is significantly different, in that it aims to take renewable energy technology to the recreational watercraft field, rather than land going automobiles. To date, there have been few efforts towards making electric personal watercraft.

ECOwatercraft has been working on production of electric jet skis since 2008 (ECOwatercraft 2009).

The REVjet project aims to demonstrate that renewable energy sources are possible and potentially viable for use in recreational vehicles. It also aims to show that with further development and the advancement in technology, renewable energy vehicles will become increasingly viable. The project aims will address the noise and pollution issues currently associated with PWCs.

In working toward the overall REV project objectives, this particular dissertation investigates and proposes a thermal management system and auxiliary mounting assembly. The thermal management system is intended to prevent damage and overheating of valuable components of the REVjet and help to achieve better efficiency from the REVjet. A solution to mounting numerous components within the REVjet is also a primary objective of this particular dissertation.

2. Literature Review

Little literature exists on previous attempts at constructing electric PWCs and there have been few previous efforts towards building electric jetskis. Both commercial manufacture and private hobbyists appear to have attempted similar projects.

ECOwatercraft

ECOwatercraft is one company which was supposedly manufacturing electric jetskis. The lack of current literature and inability to contact ECOwatercraft suggests that their product development/marketing has been unsuccessful. ECOwatercraft boasted their design was capable of 50mph with a range of 3 hours, however there is no reliable source of literature to support the feats of ECOwatercraft. (ECOwatercraft 2009)

Sea-Doo

Both the Sea-Doo User and Shop Manuals (Sea-Doo 2007a; Sea-Doo 2007b) provide a wealth of information applicable to the REVski project. Due to the removal of the internal combustion engine from the Sea-Doo PWC, much of the material in the manuals can be disregarded and is inappropriate for the REV project. However, they still contain valuable information regarding safety, and several of the remaining components.

Despite the removal of the internal combustion engine, the service manual is particularly useful for identifying the functions of existing components, and previous systems arrangements. Of particular interest to this project are the sections on the cooling system and the exhaust system.

The cooling system for the internal combustion engine consists of a closed loop design. This system provides cooling to the engine through the cylinder block and also provides cooling to the lubricating oil. The closed loop engine cooling system can be represented by Figure 1.

Heat is transferred to the coolant in the cylinder block and oil cooler, and the coolant then exchanges this heat with the surrounding environment through the ride plate. The ride plate is situated on the underside of the hull near the impellor such that when in operation, water passes the plate allowing more effective heat transfer. The ride plate incorporates a drain plug which is used to drain the cooling system and will likely be beneficial to this project. (Sea-Doo 2007b)

The original cooling loop also includes a thermostat which is set to divert the coolant flow depending on its temperature. If the coolant temperature exceeds 87°C, the thermostat directs the coolant through the ride plate, otherwise it is directed back into the pump to cycle through the cylinder block again. This ensures that coolant supply to the engine is not too hot, without being detrimental to the warm up time of the engine.
A coolant temperature sensor is also installed and senses the temperature of the coolant in the cylinder block. This sensor activates an alarm if the coolant temperature exceeds 100°C. (Sea-Doo 2007b)

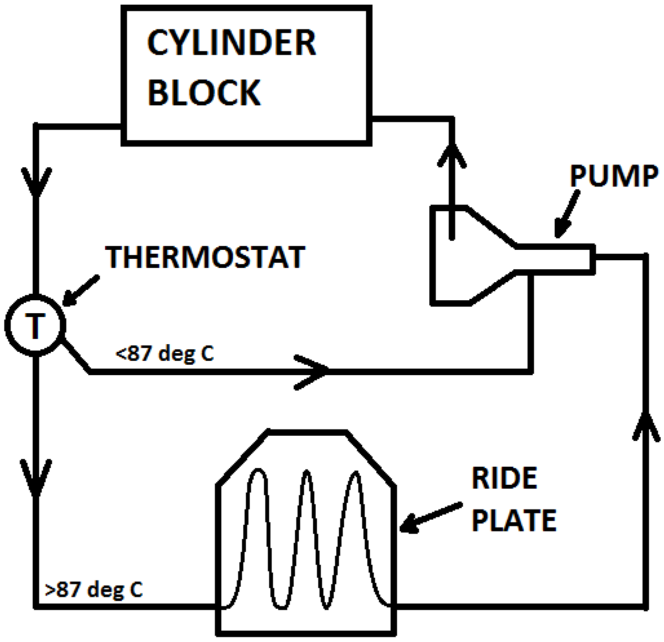

Figure 1: Existing cooling system for the internal combustion engine on the Sea-Doo jetski

The exhaust system utilises a separate open loop cooling configuration to cool the exhaust system (Figure 2). Water is fed from a high pressure region near the impellor and passed through the exhaust manifold before being returned to the surrounding environment.

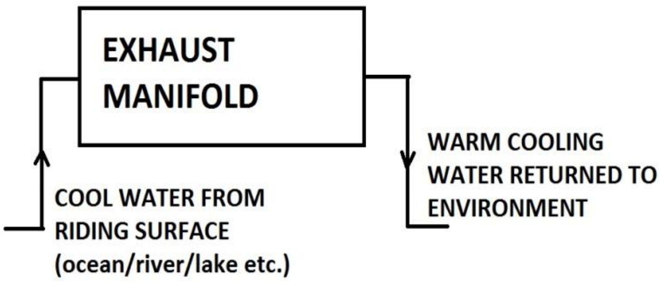

Figure 2: Representation of open loop system cooling configuration as used in the exhaust system of the Sea-Doo jetski

A reducer between the jet pump support and the jet pump on the inlet side controls the water flow to the exhaust system. Differently calibrated reducers are required for different engine models, and provide an opportunity for testing and comparison between reducers to see if a different one may be more suitable for this project.

Sea-Doo cautions the user/maintenance person that improper installation of this reducer can cause overheating and damage to the exhaust system. This should be taken into consideration if the open loop system is to be used in the revjet project.

The inlet hose for the open loop system is a ¾" diameter Goodyear SAE 20R3 heater hose, and the outlet/flushing hose is a ½" diameter hose of the same class. This hose is constructed of EPDM rubber and is intended to operate in temperature range between -40°C and 125°C, and is compatible with most available coolants (Goodyear 2013).

Using the wiring diagrams provided in the shop manual, the remaining circuitry could be analysed for potential use with the application of an electric motor.

Heat Generation and Transfer

The heat generated in electrical circuits is represented by equation 1;

$$q = I^2 R \qquad \text{(Eq. 1)}$$

(Giuliano, Advani & Prasad 2011)

For linear thermal conductivity, the heat flux (q) is given by equation 2;

$$q = -k \frac{\partial T}{\partial x} \qquad \text{(Eq. 2)}$$

(Nellis & Klein 2008)

The heat flux is dependent on the temperature gradient and the thermal conductivity of the material which is conducting the heat.

The amount of heat removed in any given component by the coolant can be determined by the following relationship;

$$Q = \dot{m} C_P (T_{outlet} - T_{inlet}) \qquad \text{(Eq. 3)}$$

(Nellis & Klein 2008)

The REVjet will be predominantly operated in the vicinity of UWA in the Swan River. Surface temperature values for the Swan River range from approximately 15 to 27°C near the Narrows Bridge region (Swan River Trust 2013). Surface temperatures in stagnant areas of the Swan River Estuary have been recorded to be as high as 29.6°C (Kristiana, Antenucci & Imberger 2012).

Taking into consideration the likelihood that the vast majority of operation of the REVjet will be conducted during the warmer periods of the year, the water temperatures for this period shall be used for calculation purposes. Utilising a warmer water temperature for calculations is also a more conservative approach than using the annual average water temperature. Warmer water temperatures will be less efficient than cooler temperature at exchanging heat with the REVjet components.

3. Design Approach

Existing Cooling System

The Sea-Doo range of personal watercraft are supplied factory fitted with a closed loop cooling system. Closed loop cooling systems provide many advantages over open loop systems. In an open loop system, water from the riding medium (sea/river/lake) is used for cooling. Often this water contains minerals and salts, and can encourage corrosion and deterioration of the engine.

The main advantage of closed loop cooling is that the engine block is not exposed to saline or dirty water. The cooling system does not have to be flushed after use, which makes the watercraft more user friendly, with less time required performing care and maintenance tasks. A closed loop system generally requires a reservoir of cooling fluid to allow for thermal expansion effects. Closed loop systems require some means of heat transfer between the coolant and the external environment, and in many cases this is achieved through a radiator where the coolant is spread into thin streams contained by a thin heat-conducting membrane. Air is passed over these membranes to cool the fluid inside.

In the case of the REVjet, the heat exchange between the coolant and the external environment occurs through the ride plate. The cooling fluid flows through the ride plate while external water passes over and under the plate transferring heat from the cooling fluid inside.

Design Considerations

The design process is often guided by limiting factors and important considerations which shape the end result. The main considerations to be taken into account for the REVjet project as a whole involve weight, financial and time aspects. Design often involves a trade-off between two desired outcomes such as weight or cost. It is important that all aspects of the project strive towards achieving the common design parameters for the REVjet, while attempting to achieve their specific function.

Weight

As with any vehicle, performance is influenced by the weight of the vehicle through the inertial effects of vehicle weight which can have a dramatic impact on vehicle performance. Not only the magnitude of the weight, but also its distribution, will affect the performance and handling characteristics of the vehicle.

In automotive applications, the addition of weight such that it is positioned internally, has little or no effect on vehicle drag. Using Newton's second law (Equation 4) it can be seen that additional mass with the same driving force will result in less acceleration (Mansfield & O'Sullivan 2012).

$$F = ma \qquad \text{(Eq. 4)}$$

In the case of a marine vessel, the weight also affects the drag. Additional weight results in the hull sitting lower in the water. The lower positioning of the hull displaces a greater volume of water and increases the hull-water contact area. The extent of this effect will depend largely on hull shape and design.

Numerous literature sources have explored the effects of weight on rowing performance. Nevill et al. (2010) went on to confirm that the body mass of rowers has a significant drag effect on water rowing speed.

Resistance is also affected by trim angle as noted by Faltinsen (2005), and there are currently a number of models of personal watercraft and boats on the market boasting trim tab features. These trim tabs allow the operator to adjust the trim of the watercraft and alter the vehicle dynamics to suit varying conditions and weight distributions. With the lack of factory fitted trim tabs, the REVjet's trim is left at the disposal of hull shape and weight distribution, highlighting the need to consider maintaining a similar weight distribution to that of the original vessel.

Budget

With limited budget and a lack of sponsorship at the date of writing, a large emphasis is placed on minimising costs. Cost restraints are common in engineering design, and can tend to place a limit on complexity of design. Important costs to be considered during design include materials costs and manufacturing costs. Materials costs depend on the type and quantity of material required, while manufacturing costs depend mainly on the manufacturing processes used and time required for fabrication.

Selection of components from external suppliers must also take into account cost considerations. Alternative components and suppliers are to be considered and approval is to be obtained for large purchases.

It is thus important that manufacturing methods and materials selection be considered throughout the design process. Obtaining quotes and discussing designs with workshop staff can also help produce more cost efficient designs.

Time

Time constraints are also a factor in the design process. It is desired for the REVjet project to be operational in the shortest time possible. Emphasis has been placed on producing a working result sooner rather than later, at the cost of less than ideal optimisation.

The time restraints are in line with the REV team objectives, in that the sooner a working prototype is developed the sooner the possibilities of REVs can be demonstrated. After a working model has been achieved, in depth testing and optimisation can be conducted. As the timeline for the REVjet project extends beyond that of a number of individual team members' projects, the testing and optimisation phases will probably be conducted by future team members.

Interfaces

With any design, the interface regions and components require particular attention to detail. Small errors in design often result in components not fitting into place due to misaligned holes, inadequate room, or inability to access bolts and other retaining devices that need to be actuated to secure a component into place.

Considerations must be given to surrounding components and how they may interact with each other. With the REVjet project, limited room is available, which is defined by the hull shape. A number of components are to be installed into this space with only a finite number of mounting points available. Interfaces with both the hull and other components are of high importance.

Materials

The marine environment in which the REVjet is intended to operate places particular importance on materials and other design considerations. Due to the corrosive nature of saline water, as reviewed by Farro, Veleva and Aguilar (2009), it is desired that materials with corrosion resistant properties are used for final designs.

The aquatic environment also poses the risk of water damage to electrical components. Steps are taken to reduce the inherent risk of water damage to components, both by preventing water entry into the hull and by applying measures to waterproof components within the hull.

Aluminium and stainless steels are commonly used metals in marine applications due to their corrosion resistant properties. The oxide coating which forms on these materials acts as a corrosion resistant barrier and protects the underlying metal (Black & Kohser

2008; Powell & Francis 2012). The 316 stainless steels are considered resistant to the corrosive environment by the American Society for Metals (1983).

Table 1 summarises a number of properties for various materials likely to be used in the REVjet project. It is noted that the most common and readily available aluminium alloy used for extrusions is the 6060 alloy, and for plate sections the 5083 alloy is the main alloy used. The 1350 and 6101 aluminium alloys are typical for electrical conductor applications. (OneSteel 2013; Tabrizian et al. 2010)

Material	Density (kg/m^3)	Elastic Modulus (GPa)	Thermal Conductivity (W/m.K)	Specific Heat Capacity (J/kg.K)	Electrical Resistivity (nΩ.m)	0.2% Yield Strength (MPa)
316	8000	193	16.2	500	74	205
1350	2705	68.9	230	900	28	28-165
6060	2700	69.5	209	896	32	55
6101	2700	68.9	218	895	32	76

Table 1: Properties for various material likely to be used in the REVjet (OneSteel 2013; American Society for Metals 1983; ASM 1990)

Incompatibility between different materials also needs to be considered, and this links to interface considerations. By taking note of the galvanic series, it is noted that aluminium (being less noble) will be subject to galvanic corrosion when in presence of carbon steels or stainless steels. Galvanic corrosion can be prevented by electrically isolating the two materials. This can be achieved by separating them with a non-conducting material such as a plastic or rubber. (Corrosion Source 2013; Powell & Francis 2012)

Motor Cooling

Motor Specifications

The motor installed in the jetski was custom built by Submersible Motor Engineering (SME) specifically for the REVjet project. SME specialise in the design, manufacture, and servicing of submersible and ROV (Remotely Operated Vehicle) motors (SME

2001). SME was able to design and manufacture an AC induction motor suitable for the REVjet's requirements.

The motor constructed for the project is a 50kW 96V alternating current induction motor. Table 2 summarises key specifications for the motor.

SPECIFICATION	VALUE
Given Output Power (kW)	50
Rated Voltage (V)	96
Number of Poles	2
Given Speed (rpm)	8000
Frequency (Hz)	135
Operating Temperature (°C)	75
Input Power (kW)	52.6265
Output Power (kW)	49.9989
Total Loss (W)	2627.59
Efficiency (%)	95.0071

Table 2: Specifications of the electric motor constructed for the REVjet project (SME 2012)

With an input power of 52.627 kW and output of 49.999 kW, the motor has an efficiency of 95% (SME 2012). Using these values the approximate value of heat generation can be determined by assuming that all power losses are dissipated though heat generation;

$$Input\ power - Output\ power = Total\ Loss = Heat\ Generated$$

$$52.627kW - 49.999kW = 2.628kW$$

Using this value is slightly conservative, and will help ensure that adequate cooling is required.

The power in the motor is lost through numerous ways, summarised Table 3;

ENERGY LOSS	AMOUNT
Copper Loss of Stator Winding (W)	647.703
Copper Loss of Rotor Winding (W)	1013.15
Iron-Core Loss (W)	421.202
Frictional and Windage Loss (W)	295.529
Stray Loss (W)	250
TOTAL LOSS (W)	**2627.59**

Table 3: Summary of power losses in the AC induction motor to be installed in the REVjet (SME 2012)

The motor has an incorporated cooling jacket (Figure 3), allowing for easy and efficient cooling, by flow of a cooling fluid. The 8mm cooling jacket is enclosed by a 2mm sheet, and is separated from the motor by a 3mm sheet. An array of baffling similar to the basic serpentine like pattern investigated by Choi et al. (2008), directs coolant flow throughout the cooling jacket. From the dimensions of these jackets, it is calculated that the motor will hold approximately 2.3L of cooling fluid.

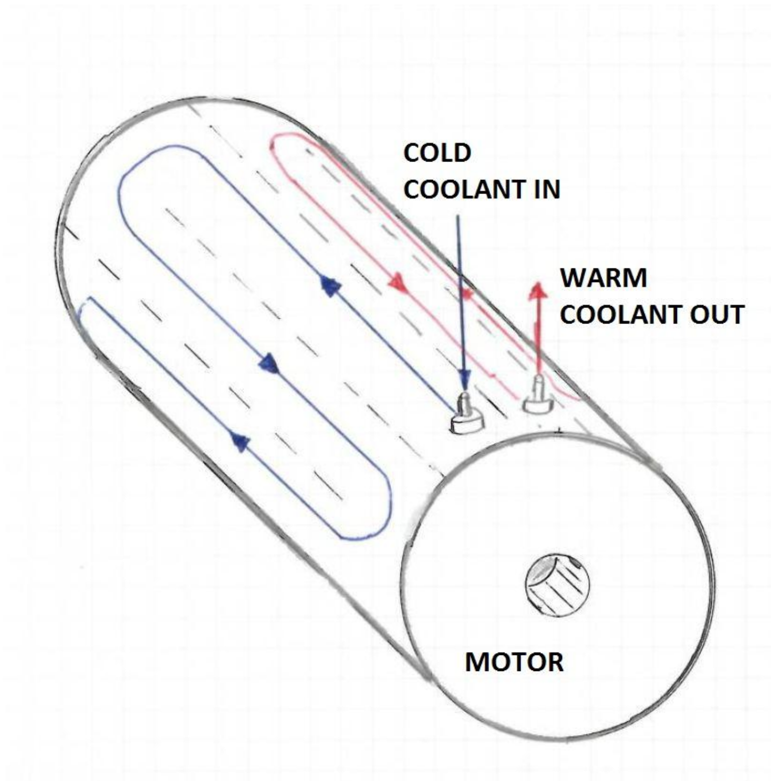

Figure 3: Illustration of the electric motor and its cooling jacket for the REVjet

For a given heat transfer, corresponding temperature changes for the coolant can be determined for specific flow rates. Taking the specific heat of water to be 4.187kJ/kgK and assuming 2.6kW of heat is transferred to the coolant, Figure 4 shows the relation between flow rate and temperature change of the coolant water.

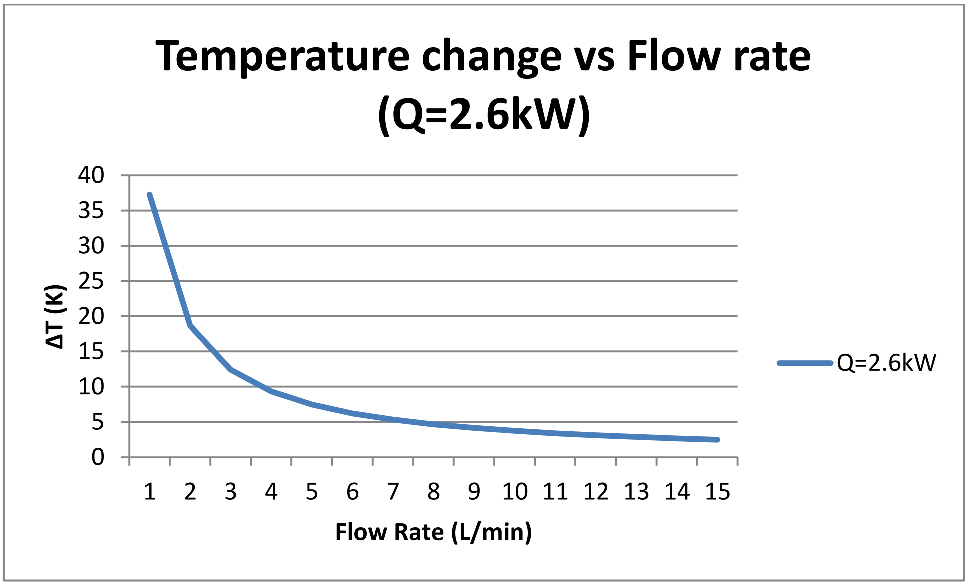

Figure 4: Relationship between flow rate and temperature change of coolant

It is noted from Figure 4 that from 5L/min onwards, increasing the flow rate only has a small effect on the temperature change of the coolant. The coolant must be supplied to the motor at a temperature significantly lower than the operating temperature of 75°C to aid heat transfer. Using the open loop system, the coolant will be supplied at approximately 25°C. This is significantly lower than the operating temperature of the motor, and even at low flow rates in the 2-3L/min region, the coolant will only reach a final temperature of about 45°C.

Controller Cooling

A motor controller is used to convert the DC power supplied from the batteries to 3-phase AC power for the induction motor. A Curtis 1238 controller was selected on the basis of its voltage capabilities and suitability to the induction motor supplied by SME.

The controller has overtemperature and undertemperature cutoffs, with linear cutback starting at 85°C and complete cutoff at 95°C. Complete cutoff also occurs at an undertemperature of -40°C (Curtis Instruments 2009). The undertemperature cutoff need not be considered for the thermal management of the REVjet project due to the extremely remote possibility of experiencing these temperatures in Australia. At low temperatures, riding of the REVjet would be less enjoyable, and at sub-zero temperatures the availability of a riding medium becomes questionable.

The controller is fitted with an aluminium heatsink from which the operating temperatures are based. The manufacturer recommends that the controller is mounted to a clean, flat metal surface with the option to use a thermal joint compound to improve heat conduction from the controller heatsink to the mounting surface (Curtis Instruments 2009). Curtis also specify that additional heatsinking or fan cooling may be necessary to meet the desired continuous ratings.

To improve the heatsinking effect, it is proposed that the controller be mounted to a heat exchanger plate which is incorporated in the cooling circuit. The controller will be mounted to the cooling plate such that the primary surface and the under face of the heatsink/baseplate are in direct contact with each other. Contact can be further aided by a thermal joint compound as suggested by Curtis Instruments (2009).

The cooling performance of several designs of cooling plates for polymer electrolyte fuel cells have been analysed in previous literature (Choi et al. 2008; Yu et al. 2009). Through the use of computational fluid dynamics (CFD) analysis, the studies show that various flow arrangements produced different cooling results.

The patterns analysed by Choi et al. (2008) are shown in Figure 5 which include 3 serpentine like configurations (A, B, C) and 3 parallel type configurations (D, E, F). Choi found that configuration C showed lower maximum surface temperatures than A & B. It was also shown that configuration C had better cooling performance than configuration F, which was the best of the parallel type configurations. Configuration C produced a lower maximum surface temperature along with a more consistent uniformity of surface temperature.

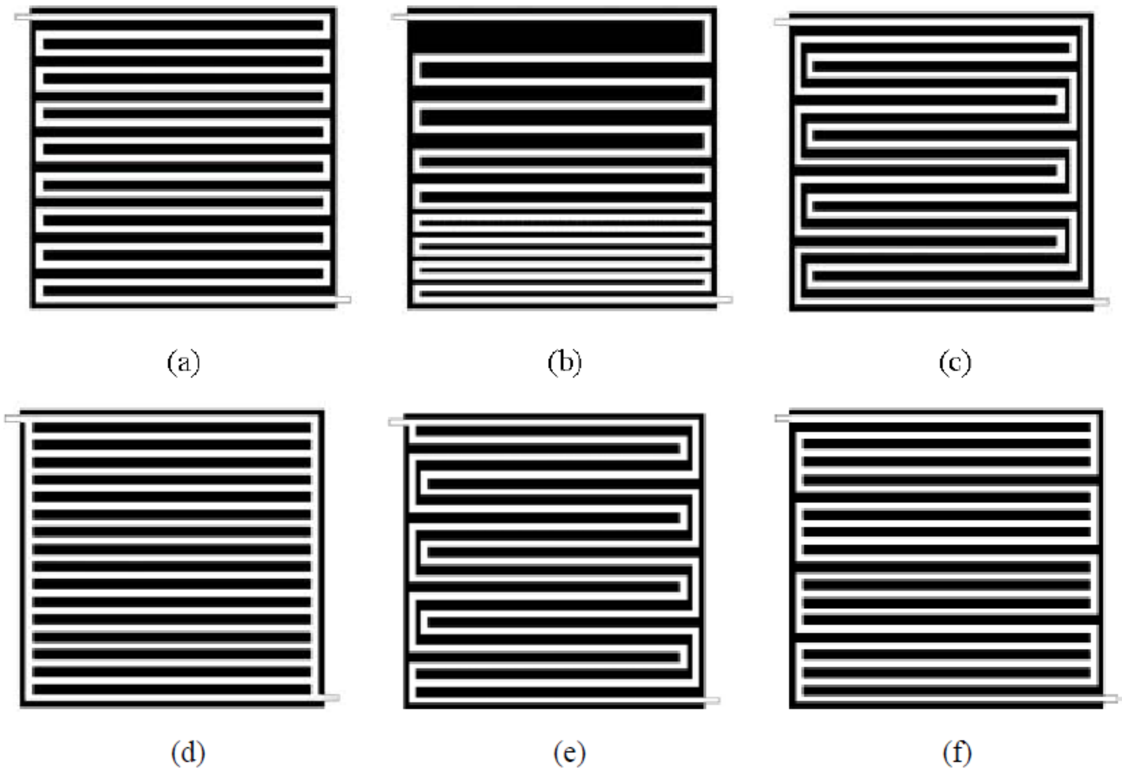

Figure 5: Cooling flow configurations investigated by Choi et al. (2008)

Yu et al. (2009) also went on to investigate the cooling performance of different flow configurations. The configurations analysed by Yu et al. (2009) are shown in Figure 6 and consists of five multipass serpentine flow fields (Models A-E) and one spiral like flow configuration (Model F).

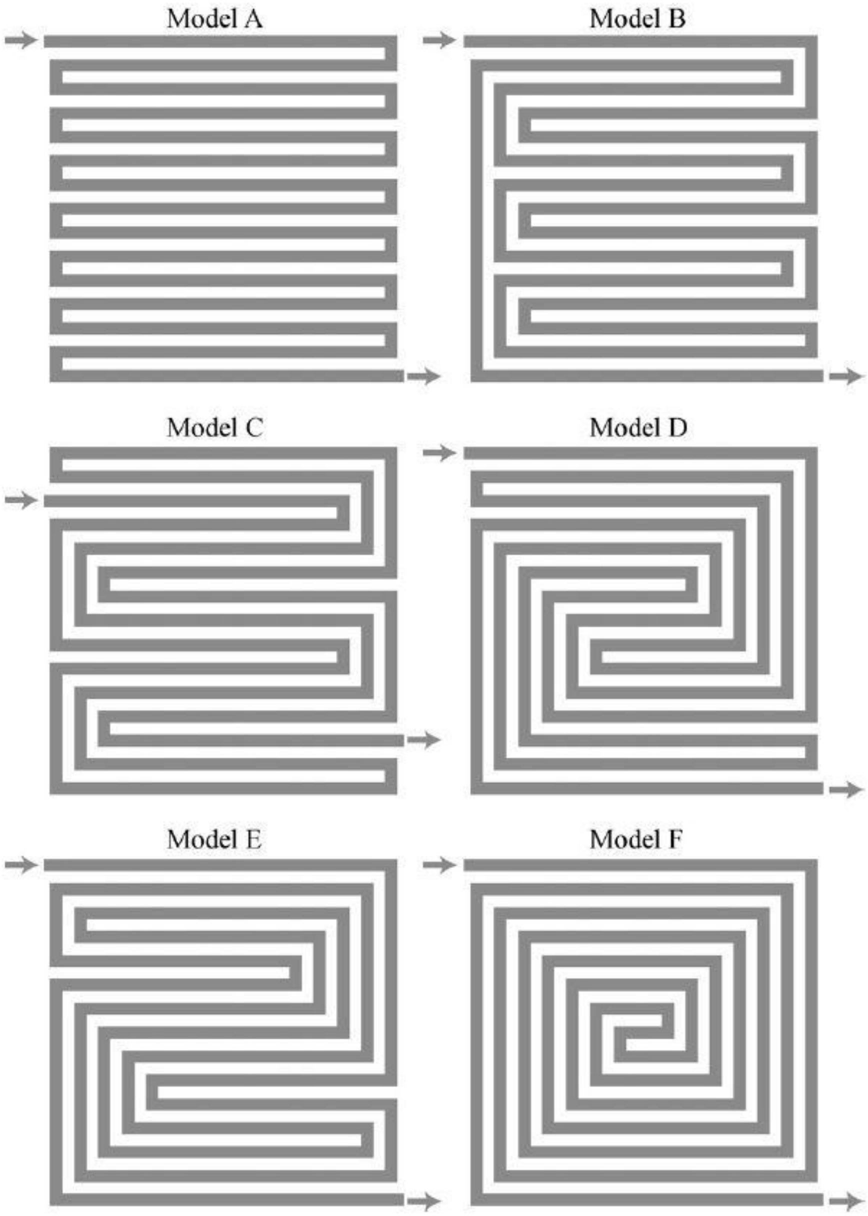

Figure 6: Configurations of flow channels in cooling plates analysed by Yu et al. (2009)

Using CFD to analyse these configurations, it was concluded by Yu et al. (2009) that Model E provided the best cooling performance whereas the simple serpentine flow pattern of Model A demonstrated the weakest cooling performance. It was also noted that Model A experienced a smaller pressure drop than the other models due to the lower number of bends. The other models exhibited greater pressure drops by about 10% (Yu et al. 2009).

These results are similar to those found by Choi et al. (2008) and suggest that the design of multipass serpentine flow patterns will produce greater cooling performance than the simple serpentine flow pattern. Yu's Model B is quite similar in design to Choi's configuration C. It was therefore inferred that of the patterns modelled by Yu et al. (2009), those that performed better than Model B provide better cooling performance than those modelled by Choi et al. (2008). A cooling flow arrangement most similar to Yu's Model E would therefore produce a more optimum cooling effect.

With significant restraints on project expenditure and high emphasis placed on creating an initial functioning REVski which can be later fine-tuned, a simple, cost effective solution is required. Taking manufacturing costs into consideration, it is proposed that a simple serpentine like exchanger plate be constructed. Simple design will dramatically reduce weld quantities and hence manufacturing costs.

The first option proposed was an exchanger plate with flow representing the basic serpentine pattern, which is the simplest of patterns analysed by Choi. This option was explored as the plate could be entirely constructed from sheetmetal with relatively uncomplicated manufacturing processes, and is similar to the cooling jacket that was fabricated for the motor. A sketch is shown in Figure 7.

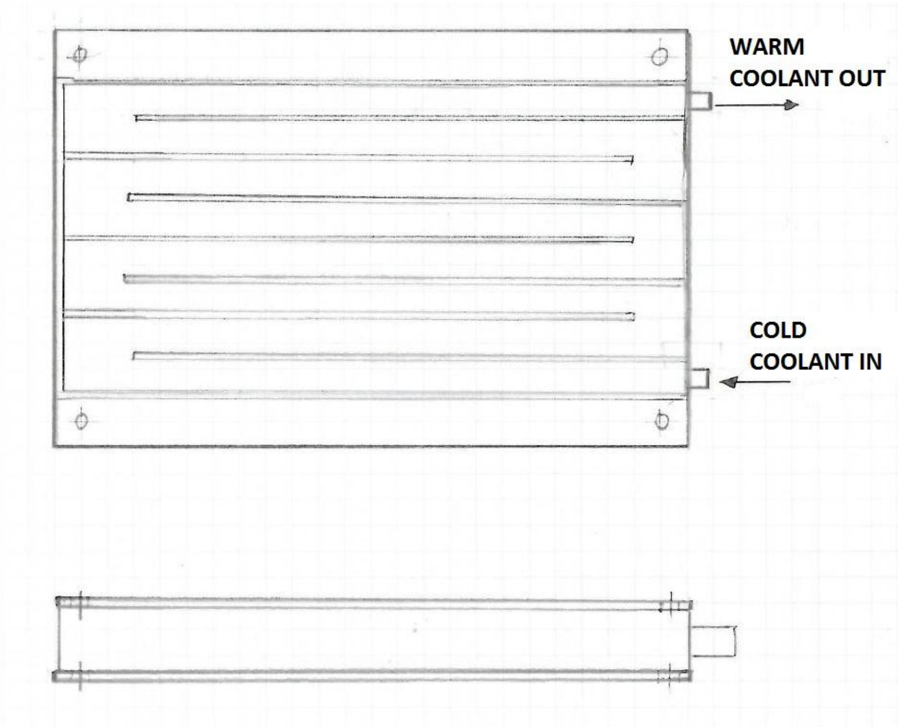

Figure 7: Sheetmetal cooling plate

An ideal solution which would have helped minimise weight and utilize less space in the REVjet involved altering the heatsink to increase its thermal cooling effect. It was considered that this could be replaced with a similar sized exchanger plate, with fluid running through it. This would have the advantage that heat would not have to be conducted through the heatsink plate before it was exchanged with the coolant. Upon investigation it was discovered that the heatsink was likely attached to the heat producing components of the controller and warranty would be voided if it was even removed. The possibility of boring holes through the heatsink was also pondered. This solution would allow coolant to flow through the heatsink, and eliminate the need for an additional exchanger plate. This option was also discounted due to the high risk of damaging the controller during the manufacturing process, and likely voiding of warranty.

Upon realising the capabilities of the UWA physics workshop and gaining advice from manufacturing professionals, a more appropriate design was found. The final design uses a thicker section of aluminium sheet (10-12mm) and uses Computer Numerically Controlled (CNC) machining processes to cut out the flow pattern. The use of the CNC machine has several advantages;

- Reduced labour time and costs
- Smooth bends in flowlines
- Possibility of more complicated flow patterns
- Less parts in final design

The use of the CNC machine makes it much more viable to use complicated flow patterns similar to those tested by Choi et al. (2008) and Yu et al. (2009). This allows a more complicated flow pattern to be designed which will provide a greater cooling effect.

By slightly modifying Yu's Model E flow arrangement, the inlet and outlet ports can be positioned on the same side. Provided enough room is left between them, this arrangement simplifies the positioning requirements of the cooling plate/controller such that hose access can be maintained. Figure 8 shows a model representation of the cooling plate with a flow pattern resembling that of Yu's Model E.

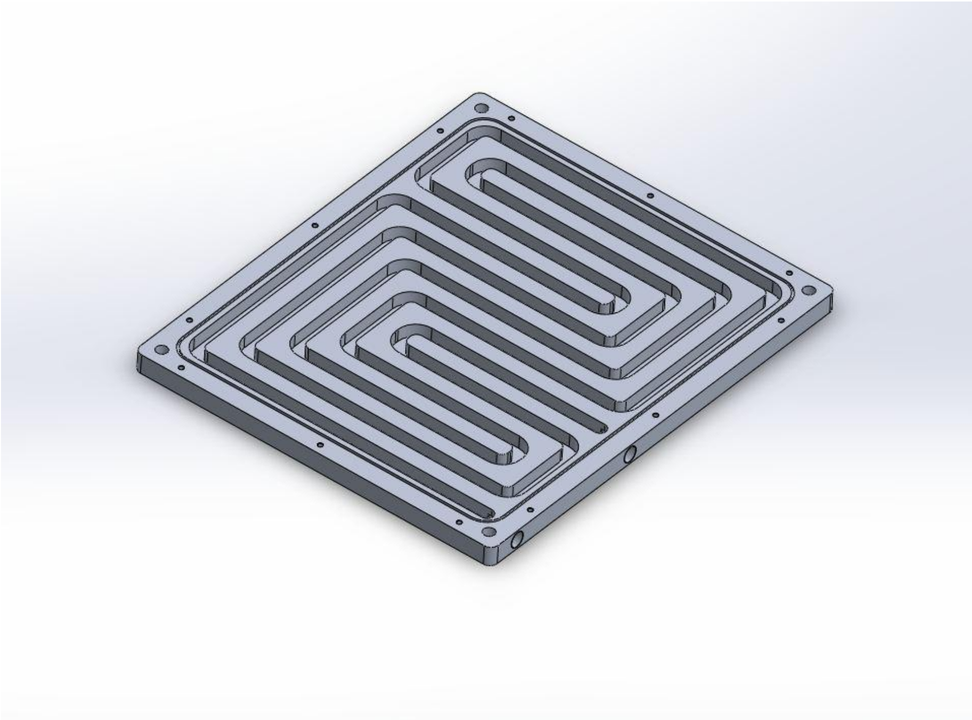

Figure 8: Model view of the controller cooling plate as designed for the REVjet, based on Model E of Yu et al. (2009)

Once the channels are removed from the aluminium plate, they must be enclosed somehow, and fittings need to be attached such that hoses can be connected. A non-permanent option was opted for, allowing the exchanger plate to be opened up and inspected if need arises. This is beneficial in the case of a blockage or scum build up, and may also be useful in future work in the case that drawing and computer models are lost.

Two options were considered for sealing the exchanger plate. It would be possible to seal the exchanger plate with either a thinner piece of aluminium sheet (2-3mm) or potentially use the lower surface of the controller's heatsink as a lid to the exchanger plate. Using the heatsink of the controller as a sealing surface has the benefit of requiring less parts and weight along with increased thermal efficiency due to direct contact with the cooling fluid. However, this solution will tend to be more difficult to seal and will possibly generate issues during installation and removal of the controller.

Using a thin section of aluminium will not add a significant amount of weight and can be semi-permanently attached such that it only needs to be removed if internal inspection is required. This option will require less re-sealing procedures and will reduce the use of consumables such as o-rings, gaskets, or sealant compounds during such processes, reducing ongoing costs associated with the likely multiple assembly and re-assemblies.

Coolant may possibly 'bridge' the channels and flow over the walls rather than through the actual channels. This will result in a poorer cooling performance as there may be large section of channel in which there is little or no fluid flow. These stagnant sections will create hot spots on the cooling plate and decrease the uniformity of surface temperature.

Bridging will occur where there are sufficient gaps between the cooling plate and the top sealing surface, allowing the coolant to 'jump' across the channels taking a shorter route through the cooling plate. Gaps may be present due to warping or an uneven surface of the top plate, or in the top faces of the cooling plate. A rough surface finish on either of the two sealing surfaces will also contribute to the possibility of this phenomenon.

Small amounts of bridging may be acceptable, provided it does not significantly reduce the flow passing through the entire length of the channel. To prevent bridging a sealing compound may be used on the contacting surfaces. Such use of a compound will prevent bridging effects, but may increase difficulties associated with servicing the cooling plate.

Fittings are to be incorporated in the design such that cooling hoses can be attached. Holes can be drilled and tapped allowing a standard BSP fitting to be screwed in. To maintain a low profile cooling plate, a smaller diameter fitting is to be used rather than continuing on the ¾" or 1" flowlines.

To maintain a low profile of 12mm, 1/8 BSP fittings were opted for. The 1/8" BSP fittings have an outside diameter of about 9.7mm. Table 4 summarises fitting sizes for

BSP threads. BSP threads come in two different types, parallel and tapered (BSPP and BSPT respectively).

Nominal Size	Outer diameter (mm)	BSPP Tapping drill size (mm)	BSPT Tapping drill size (mm)
1/8”	9.728	8.8	8.4
1/4”	13.157	11.8	11.2
3/8”	16.662	15.25	14.75
1/2”	20.955	19	18.25
3/4”	26.441	24.5	23.75
1”	33.249	30.5	30

Table 4: Sizes for BSP threads (Adaptall 2008; Newman Tools 2009)

To maintain adequate flow through the cooling system, it was then decided to use a parallel type flow configuration, in regards to the motor and motor controller cooling streams. A parallel flow configuration will result in less fluid flow through each of the parallel streams compared to that if they were in series.

However, the advantage of using parallel streams is that the coolant will enter both streams at the inlet temperature and provide a greater temperature difference for heat transfer. In a series configuration, coolant entering the downstream components will have already attained heat from the upstream components, and will have a lower ΔT, which is less favourable for heat transfer.

The final drawings sent for construction are included in Appendix1.

Hoses and connections between the cooling components should be kept to a minimum where possible. Shorter and more efficient hose routing will reduce the total amount of coolant required and help minimise the weight of the cooling system. Shorter hose lengths will also help minimise the pressure drop experienced by the fluid in the hoses.

Battery Cooling

Battery temperature affects the batteries in numerous ways and as a result plays a part in reliability and performance of the vehicle. The amount of heat generation in a battery cell is determined by the battery chemistry and kinetics (Wu, Xiao & Huang 2012). Adequate control of battery temperature greatly improves the performance of high energy battery cells (Jarrett & Kim 2011).

For the purpose of the REVjet project, 240 of the Headway H38120S batteries are to be used. These $LiFePO_4$ 10Ah cells can provide a continuous discharge rate of 3C. The 3C discharge rate implies that the 10Ah cells will provide 30Ah with a 20 minute discharge time (Headway Headquarters 2013).

A summary of specified work and store temperatures for the Headway H38120S batteries is shown in Table 5.

Work Temperature	Charge	0 - 45°C
	Discharge	-20 - 60°C
Store Temperature	In one month	-20 - 45°C
	In six months	-20 - 35°C

Table 5: Thermal specification of the batteries used in the REVjet (Headway Headquarters 2013)

The Headway batteries are cylindrical in shape and have been provided with retaining brackets, such that they can be arranged into packs. The structure of these packs leaves minimal room between the battery cells, making it difficult for air or cooling pipes to flow between the cells. In other applications, a paste has been used between battery cells to help disperse heat. These pastes are expensive, and not very suitable to the REVjet project due to the possible need for removal and reinstalling of the batteries.

New coolants have being specifically designed for battery cooling applications (Fraunhofer 2012). The CryoSolplus coolant is capable of absorbing three times as much heat as water.

Auxiliary Mounting Bridge

The addition of the numerous components required for the electric conversion of the jetski requires consideration of how and where to mount such components. Through spatial and visual analysis it was proposed that specifically designed mounting bracket be added to the jetski such that components could be attached to it and positioned relatively centrally above the motor.

The main function of the bracket is to secure the components to the hull. Components will be secured to the bracket assembly which will be mounted to the jetski hull. The original mounting points which were used for the internal combustion engine provide a suitable location to mount the bracket. The electric motor will also be mounted to these mounting points and must be kept in mind when considering the mounting of the auxiliary bridge.

The three mounting points are orientated asymmetrically and were difficult to accurately measure. With no success in contacting the Sea-Doo engineering department, nor access to 3D image capturing technology, difficulties arose in determining the relative positions of the mounting points.

Components which require mounting considerations include the motor controller and its associated cooling plate, contactors, DC/DC converter, fuses, etc. Components and their approximate weights and dimensions are shown in Table 6.

Component	Weight	No. of mounting points	Size of mounting points	Approx. Dimensions
Motor Controller	6.82kg	4	7mm	275x232x85
Cooling plate for Motor Controller	~2kg	4*	7mm	275x232x12
DC-DC converter	2.5kg	4	5mm	180x140x70
Contactors (x2)	0.6kg	2	6.35mm	78x59x107
Allowance for miscellaneous items (cable, connectors etc.)	~5kg	TBC	TBC	TBC
Total	**~20kg**			

*Cooling plate uses same mounting points and bolts as motor controller.

TBC – To be confirmed

Table 6: Components to consider for mounting above the motor in the REVjet, with their weights, details of mounting points, and approximate dimensions (Curtis Instruments 2009)

The total weight of the components which the mounting bridge assembly will be required to support is approximately 15-20kg. The static and any live loading effects of these components are to be taken by the three mounting points which were previously used for the internal combustion motor.

Taking into account the design considerations, a simple, lightweight, easily manufactured structure is required. Aluminium was the obvious choice due to its light weight and corrosion resistant properties. The softness allows for easy cutting and drilling procedures. During the design process a number of different options were explored as outlined below.

To minimise costs it is preferred that the structure be designed from one section of aluminium. Suppliers such as OneSteel offer a large variety of aluminium sections, however the lengths of sections not typically cut to suit individual orders and are generally only available in about 6m lengths (OneSteel 2013). To minimise wastage due to offcuts and make the most of the lengths of aluminium it was preferred that the structure be designed from only one section, and eliminate the need to purchase multiple lengths of aluminium.

Initially a simple bridge constructed of flat bar and similar to that in Figure 9. This solution required only aluminium flat bar sections between the gauges of 40x4 to 60x10 and would only require relatively simple cutting, bending and welding manufacturing processes. The flat bar structure can be of either bent or welded construction.

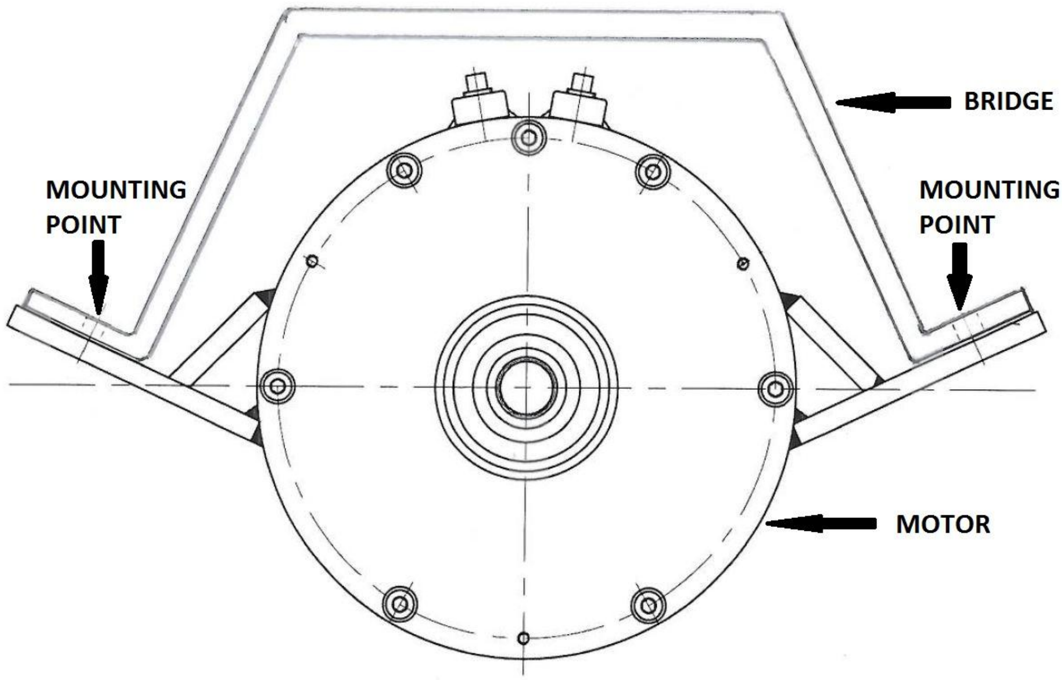

Figure 9: Simple flat bar bridge for mounting components above the motor in the REVjet

It was noted that this design appeared prone to flexing in the port/starboard direction and may fail as a consequence. To reduce the possibility of such failure, the additional use of stiffeners or gussets was then considered as shown in Figure 10.

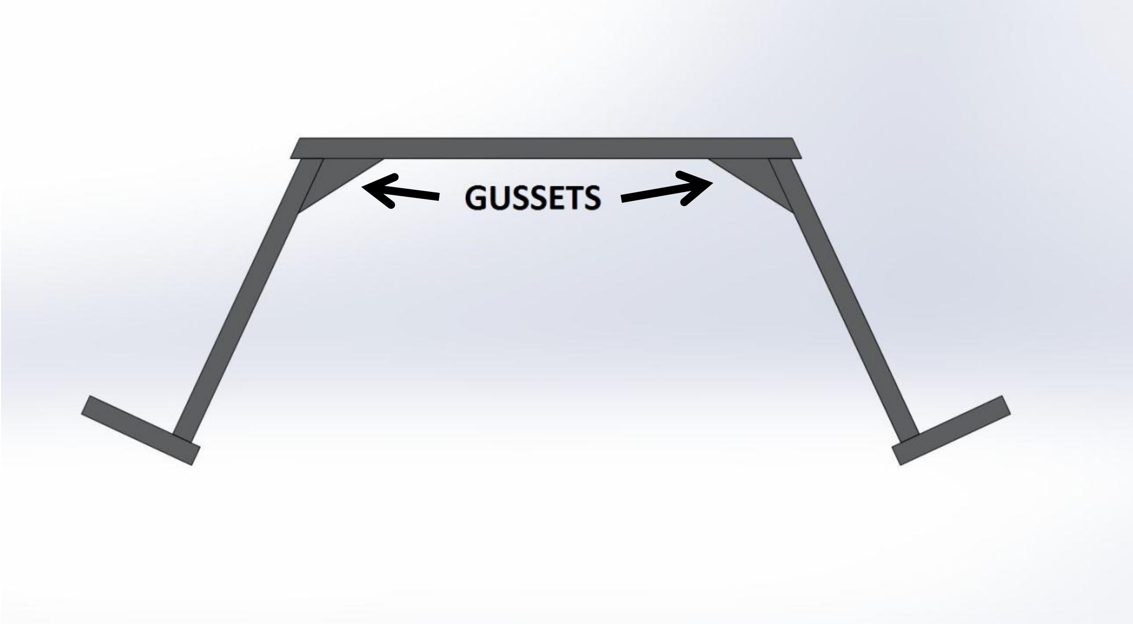

Figure 10: Flat bar bridge with gussets to increase stiffness

A similar design (Figure 11) which utilised channel sections in place of the flat bar was also considered as it would provide a much more rigid structure while still allowing adequate access to the mounting bolts. With the use of channel sections, it soon became obvious that more complicated cutting and welding patterns would be required.

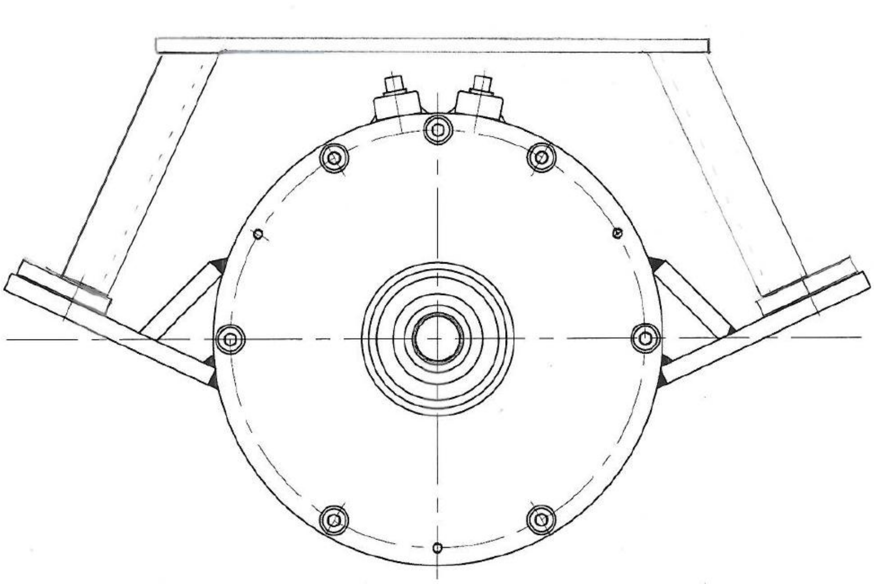

Figure 11: Bridge with channel sections for mounting components above the motor in the REVjet

Another option involved using the mounting plate as the actual bridging structure, and then simply supporting it with three different supports originating from the engine mounts. This design would require a strong and rigid mounting plate, and if not attached securely would compromise the whole structure and risk damage to the supported components.

Further investigation of potential interfacing issues found that the inlet and outlet ports for the motor cooling jacket were located at the drive end of the motor. When the motor is installed in the hull, these ports would be positioned along the line of the bridging structure. The vertical orientation of these ports also requires additional clearance above to allow for hose connections to be made. Allowing adequate clearance between the lower surface of the bridging structure and the motor's cooling ports, would significantly raise the height of the mounting platform.

Lower positioning of the mounting platform is preferable as it will aid in maintaining a lower centre of gravity. This will also allow more clearance between the top surface of the mounting platform and the lower surface of the seat, reducing possible interfacing issues between the seat and the components which are to be mounted on the platform. It was noted that this could be achieved by leaving a void in the mounting platform such the hose connections could protrude through the platform.

The design approach then returned to the option where the mounting plate is used as the bridging structure and is supported from each of the three mounting points. A small hole or slot is incorporated into the platform to allow clearance for the hose connections to the motor, enabling the mounting plate to be situated in a lower position.

To support the mounting plate from the rear mounting points, two identical supports are proposed. These supports are constructed from aluminium channel section with flat bar or plate sections welded to the ends to allow for bolting. The support members are represented by Figure 12.

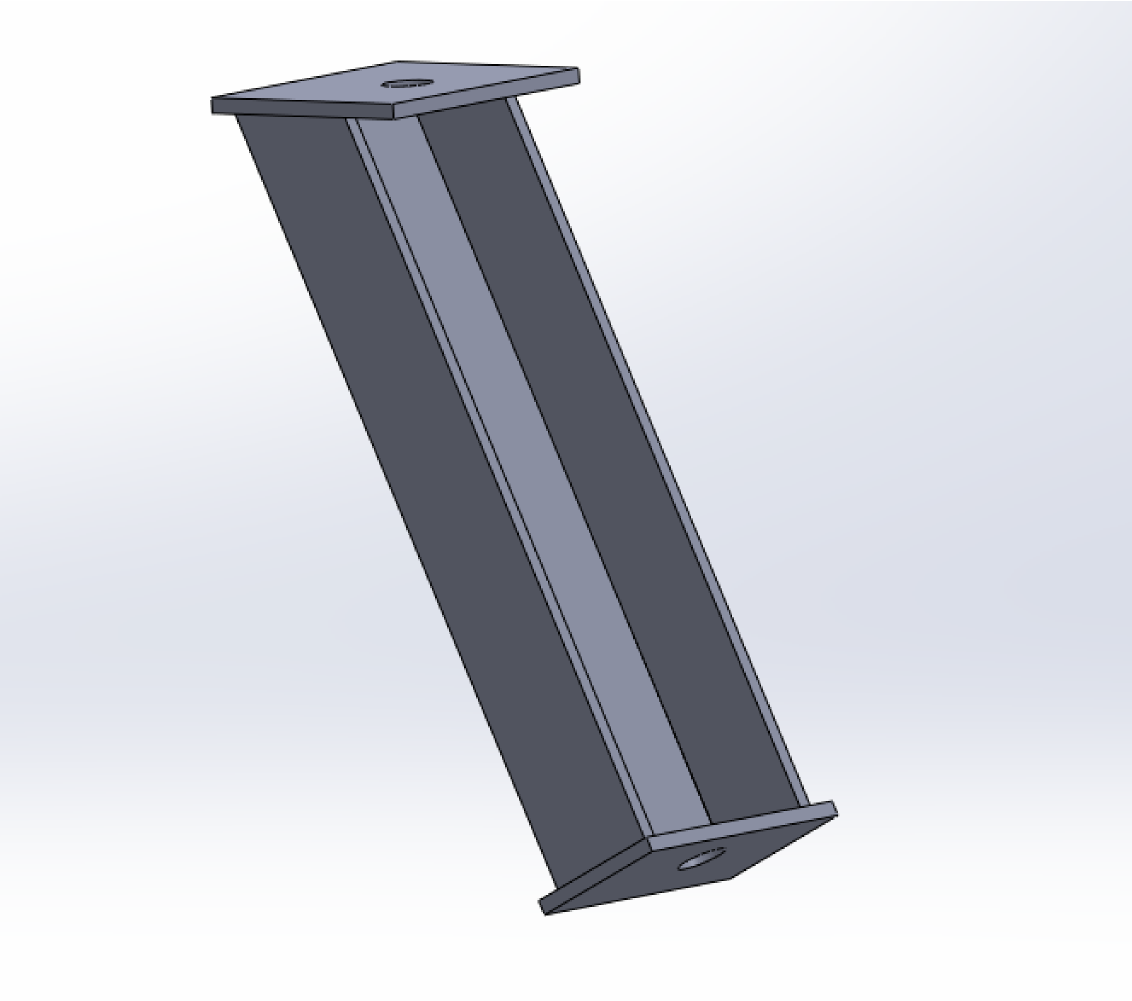

Figure 12: Support for auxiliary mounting platform for mounting components within the REVjet

As this design only needed a relatively small amount of channel section (about 400mm) it would not be a cost effective solution to purchase a length of aluminium solely for this purpose. Investigation took place to determine whether aluminium sections used for other components such as the battery box could be utilised in the support design and material orders be consolidated. The possibility of utilising offcuts from other sources was also investigated, and a section of 50x25x3mm aluminium channel was attained from TMT. This material was considered as scrap to TMT and was provided at no additional cost to the REVjet project.

To ensure that the 50x25x3mm channel section would be sufficient for the support design, a stress analysis was performed. The software program ANSYS was utilised for the stress analysis stage of the design, and the results are summarised in the Results section of this dissertation.

The design uses either a polycarbonate or polyvinyl chloride (PVC) sheet as the mounting plate. Poly-carbonate sheet was chosen over other alternatives such as steel or aluminium plate due to several considerations. The poly-carbonate sheet is light weight and non-corrosive, and also cheaper than the steel and aluminium alternatives.

Poly-carbonate is easy to work with in regards to cutting and shaping, and future alterations to the platform can be easily made by future REV team members. Polycarbonate sheet can be cold formed if the thickness and desired radii are compatible with each other, or can alternatively be thermoformed (Dotmar 2012). With the final layout of components to be mounted to the platform yet to be decided, the poly-carbonate sheet will allow future workers to easily drill holes or glue additional brackets to once final mounting locations are determined.

Due to the thermoforming capabilities of the polycarbonate sheets, vertical sections on the edges of the platform can easily be incorporated in the final design. Additional vertical surfaces can provide extra surface area for mounting additional small components if required and utilise the limited space with the REVjet hull more efficiently.

To attach the front of the mounting plate to the forward mounting point, it was proposed that a spacer be used between the mounting point and the mounting plate. As the forward mounting point is orientated horizontally, the forward supporting structure can be simplified. The spacer is to be drilled out such that a threaded rod can be inserted through it and fastened to the female thread of the mounting point. This rod can then protrude through the mounting plate which can be secured by a nut and washer, see Figure 13.

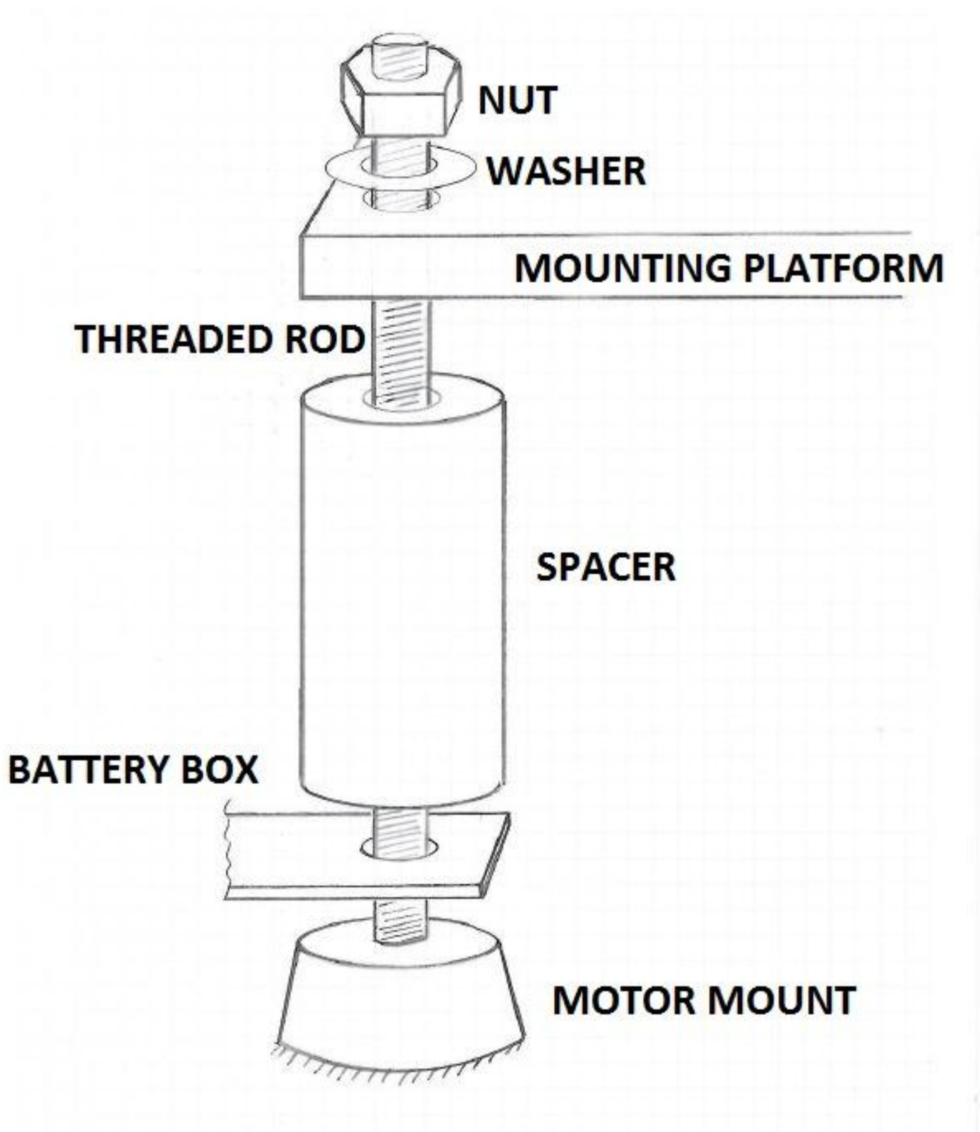

Figure 13: Schematic of the forward supporting point of the auxiliary mounting platform for the REVjet

Due to the angle of the two rear mounting points, the hole locations on the mounting plate are dependent on the thickness of the motor mounting tabs. It was thus important to verify what section of steel was to be used for these tabs. If the exact section thickness is unknown, a slot may be cut to allow for a range of values.

The design of the battery box also utilises the forward mounting point, which will interface with the auxiliary mounting bridge. The battery box design is to be mounted to the forward engine mount with a 4.8mm section of aluminium (Jayamanna 2013), and also needs to be taken into consideration.

4. Results & Discussion

Through a series of logical steps, designs have been proposed for a number of components of the REVjet project.

A cooling system for the motor and motor controller has been proposed. It utilises the existing open loop circuit and cools the motor and the motor controller in a parallel configuration. The cooling system proposed addresses the design considerations of cost, time, weight and interfaces. It is considered to be a light weight, low cost design that has taken interfacing issues into account while being functional at the same time.

The cooling circuit makes use of the water jacket which is being constructed as part of the motor and cools the motor controller with a specially designed cooling plate. The cooling plate assembly is shown in Figure 14. An o-ring is used to seal the aluminium cooling plate and tapped holes allow threaded pipe fitting to be attached for easy interface connections. The flow pattern was based on previous studies found in literature.

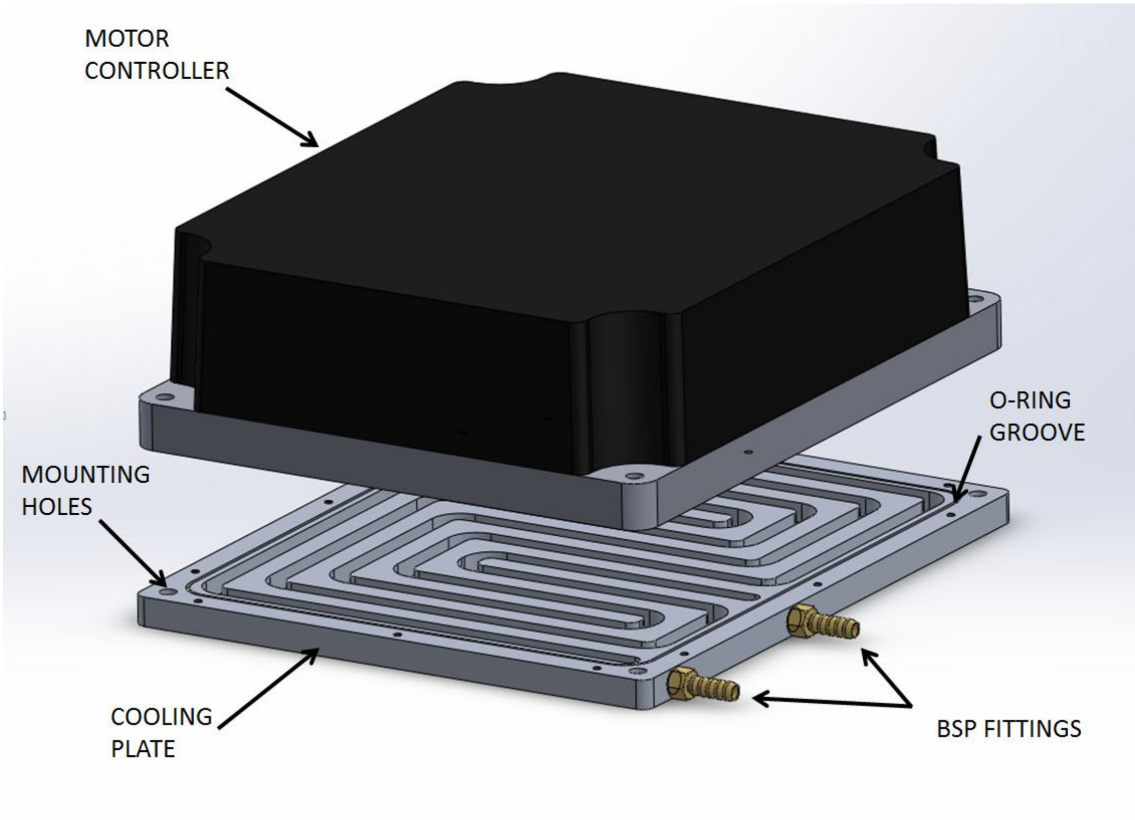

Figure 14: Motor controller and cooling plate assembly designed for the REVjet

The design for the auxiliary mounting bridge support was analysed using ANSYS software. The design was analysed for safety factor and deflection criteria. For the analysis the material was modelled as an aluminium alloy. Material properties used in the analysis are show in Table 7.

Aluminium Alloy	
Density	2770 kg/m^3
Young's Modulus	7.1 x10^{10} GPa
Poisson's Ratio	0.33
Bulk Modulus	6.9608 x10^{10} Pa
Shear Modulus	2.6692 x10^{10} Pa
Tensile Yield Strength	2.8 x10^8 Pa
Compressive Yield Strength	2.8 x10^8 Pa
Tensile Ultimate Strength	3.1 x10^8 Pa

Table 7: Properties of aluminium alloy used in stress analysis of the auxiliary mounting platform supports

The analysis was undertaken in a very conservative manner. It was assumed that each support would bear 25kg and be subject to an accelerating force equal to 10 times the normal gravitational force. The auxiliary mounting assembly is likely to be supporting less than 25kg total, which will be distributed amongst the three supports, thus by analysing the effects of the total load being applied to one individual support, a conservative result is achieved.

For the analysis it was assumed that the support was constrained in all directions at the lower surface and the inner surface of the bolt hole. These surfaces were chosen as the constraining points as this is where the supports are attached to the hull of the jetski. Figure 15 shows the force and constraint conditions used for the stress analysis.

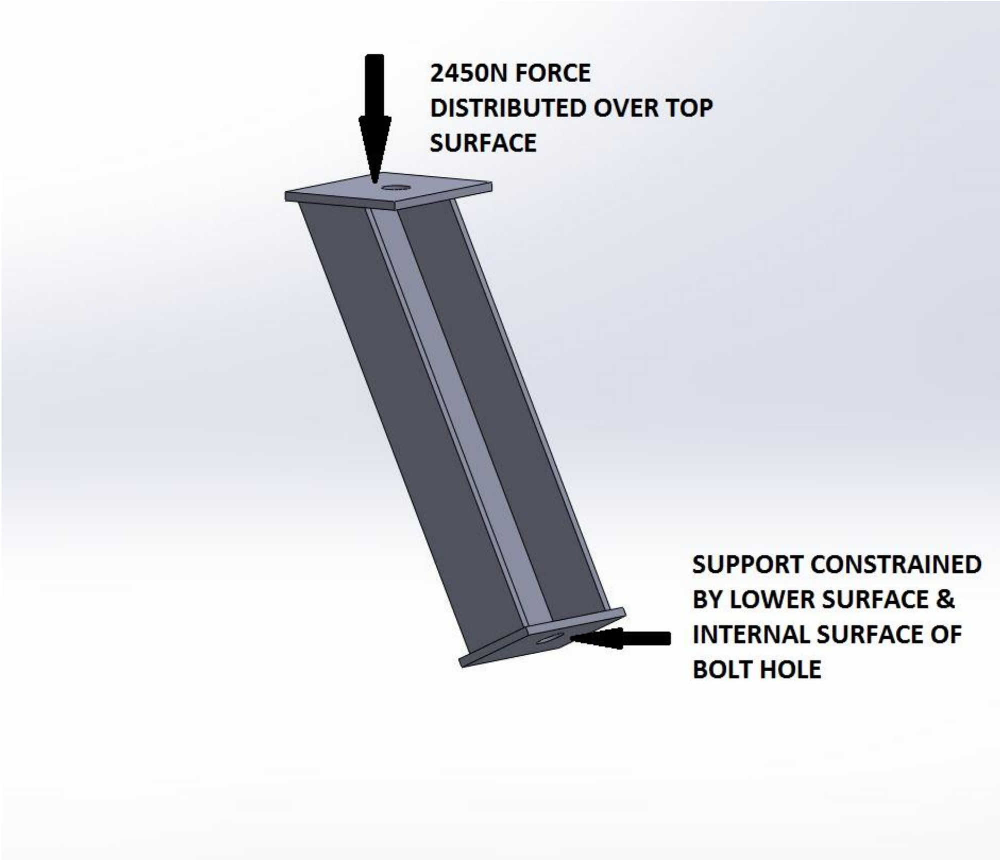

Figure 15: Force and constraint conditions applied during stress analysis of the auxiliary mounting platform supports

The results from the stress analysis indicate a minimum safety factor of about 1.36 as shown in Figure 16. This is a favourable result indicating that even with the conservative force assumptions used in the analysis, the structure is capable of supporting the load.

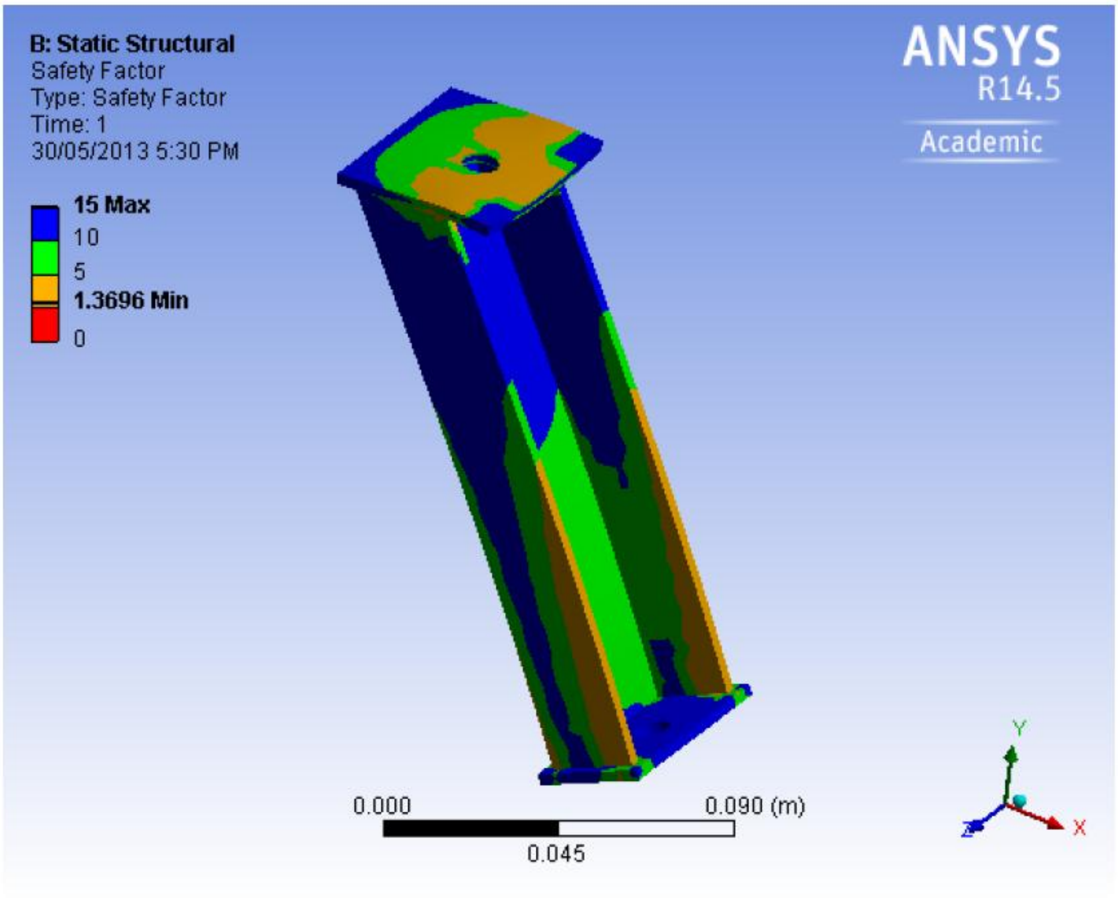

Figure 16: Safety factor analysis for the auxiliary mounting platform supports.

The results from the stress analysis also indicated that the maximum deformation in the bridge support is less than 0.4mm as indicated in Figure 17. This deformation is very minimal, and combined with the safety factor results, indicates a well-designed support capable of bearing more than the required loads. Drawings sent for manufacture of the supports are included in Appendix 2.

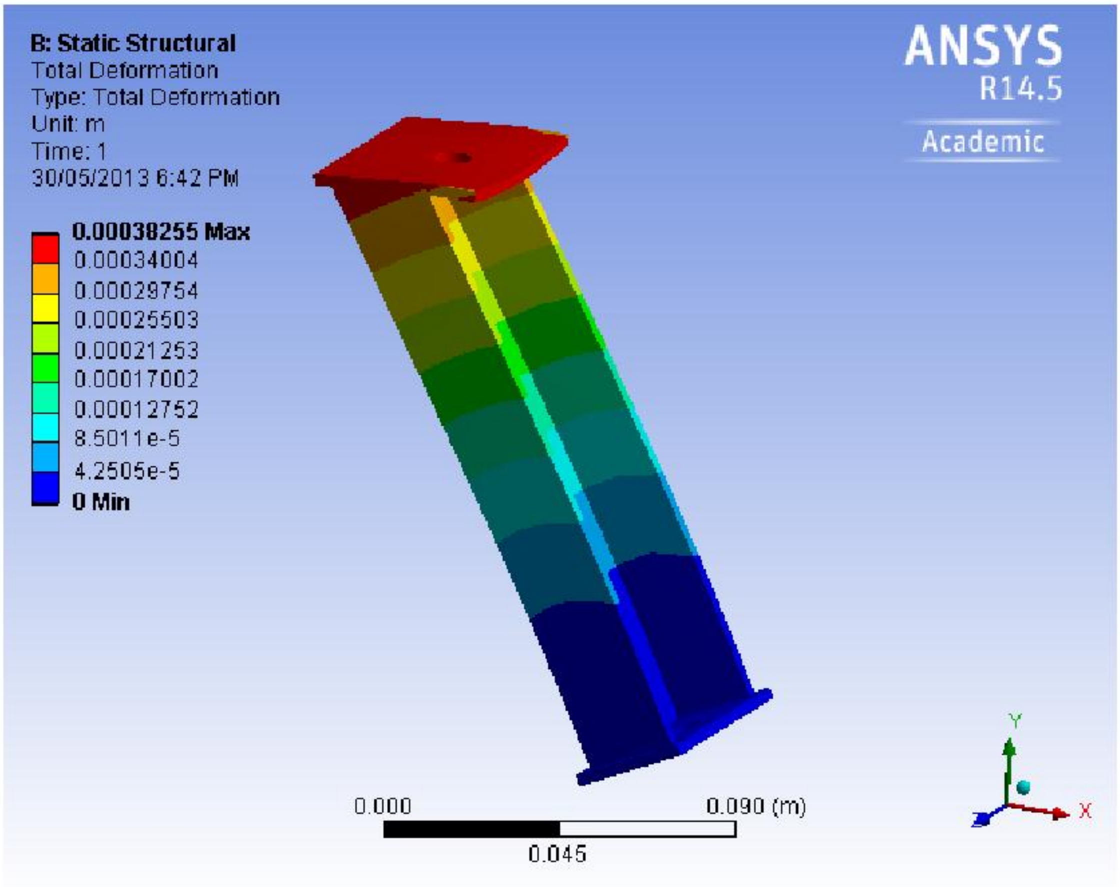

Figure 17: Results of deformation analysis performed on supporting members for the auxiliary mounting platform

A model view of the auxiliary mounting system that was designed is represented in Figure 18. This shows the mounting platform and the three supporting points. Final dimensions and locations of the mounting holes in the platform are to be confirmed with the electrical engineering students once optimal layout has been determined.

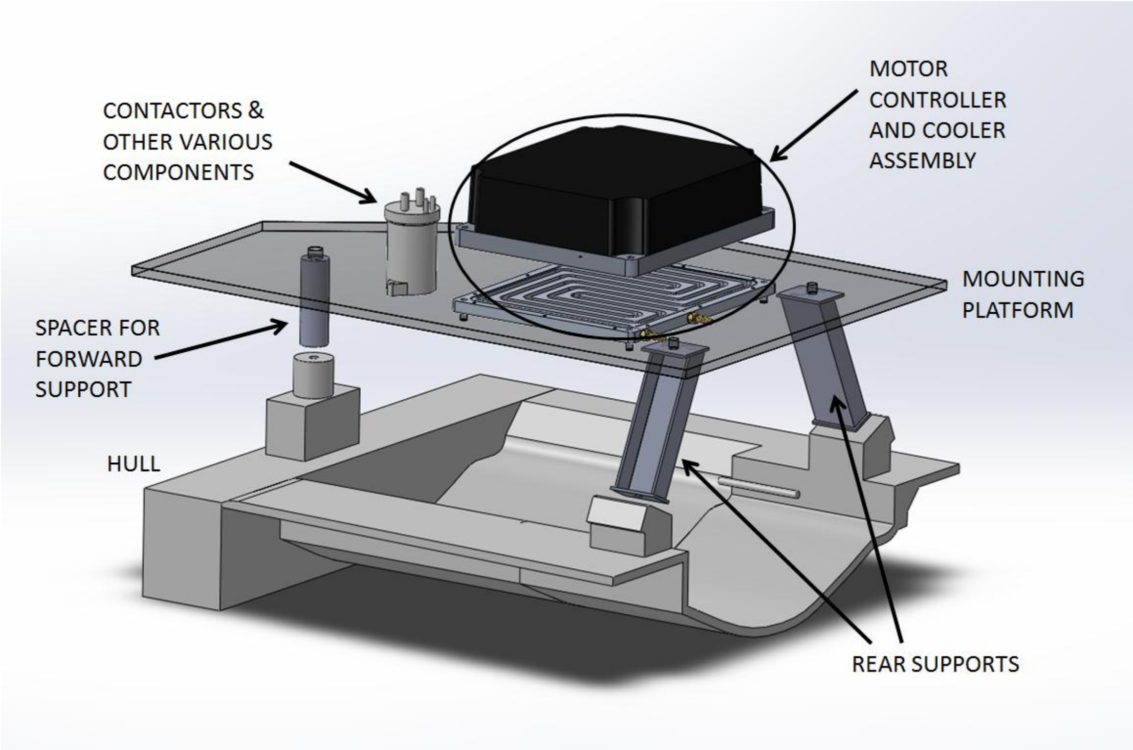

Figure 18: Model image of the auxiliary mounting system designed for the REVjet

5. Safety and Operation of Cooling System

A number of safety considerations are relevant to the cooling system of the REVjet. Some of the previous safety precautions for the Sea-Doo jetski are still relevant, along with additional considerations.

Considerations which must be taken into account with the use of the proposed open-loop cooling system include:

- Ensuring hose fittings are securely attached. Failure to do so may result in damage to components and flooding of the hull.
- After use the cooling system should be flushed with fresh water. This is done by connecting a hose to the outlet. Water should flow out of the inlet grate near the impellor.
- If the motor is to be run out of the water no coolant will be present. A hose should be connected to the outlet as done during the flushing process to provide a flow of coolant and prevent possible damage to the components.

If during future works, the closed loop system is utilised, several other precautions also need to be considered.

- Check ride plate for damage, inspect for any possible coolant leak. (Sea-Doo 2007a)
- When operating the engine while the watercraft is out of the water, the heat exchanger may become very hot. Avoid any contact with ride plate as burns may occur. (Sea-Doo 2007a)
- Ensure that the coolant level is adequate.
- If the REVski is going to be operated at temperatures below freezing point, make sure coolant is not frozen.
- When filling or replacing coolant, run the motor for a short period of time and then re-check level.

6. Conclusions and Future Work

A thermal management system has been proposed for the REVjet, utilising the remnants of a previously designed open loop cooling system, and provides cooling to both the AC motor and the motor controller. These are considered to be the two components in most need of cooling.

An auxiliary mounting assembly was designed for mounting components within the REVjet. This assembly was designed using conservative force assumptions and serves as an interface between numerous components and the hull of the jetski.

Upon final construction of the cooling plate components, the interacting faces shall be checked for variations in surface levels. Any surface roughness should be removed by sanding and if there is significant deviations in surface levels or warping of components, re-manufacturing may be required. Analysing the surfaces of the mating faces, shall determine the necessity for use of a sealing compound.

Upon completion of construction of the project, future work should focus on testing and optimisation of the thermal management system. With the possibility of future funding, more efficient options and designs may become viable.

Testing can be conducted to determine the heat generation of the batteries, both during charging and discharging. Methods of testing heat generation in battery arrangements are discussed by Giuliano, Advani and Prasad (2011). The literature discusses taking temperature measurements by the use of an infrared camera, attaching thermocouples, and the use of thermochromic liquid crystal (TLC) thermography.

In determining the heat generated by the batteries the necessity for a battery cooling solution should be determined. Depending on the outcome of such testing, an appropriate cooling system for the batteries can then be investigated and designed.

Upon installation of the motor, testing can be conducted to determine the flow rate and pressure of the water supply to the open loop system. This testing could possibly be done by detaching the outlet flow line and diverting the flow into a suitable container. If the motor is then run for a certain period of time, the amount of water in the container can then be measured to determine a flow rate.

Different models of Sea-Doo PWCs use different sized reducers to restrict the flow of water for the open loop system (Sea-Doo 2007b). Upon testing of the flow rate produced with the currently installed reducer, it will be worthwhile investigating the flow rate and pressure provided when different reducers are fitted to the REVski. Exploration of this possibility could potentially increase the effectiveness of the cooling system.

As the REVjet also has the option to use a closed loop cooling system, further investigation into the potential performance of the closed loop system can be conducted. A performance comparison can be undertaken to investigate the possibility of utilising the closed loop circuit. Further analysis may show that components will require cooling for a period of time after shutoff.

Computational fluid dynamics analysis may enable future work to refine the cooling system, and tweak it to optimise the operating performance.

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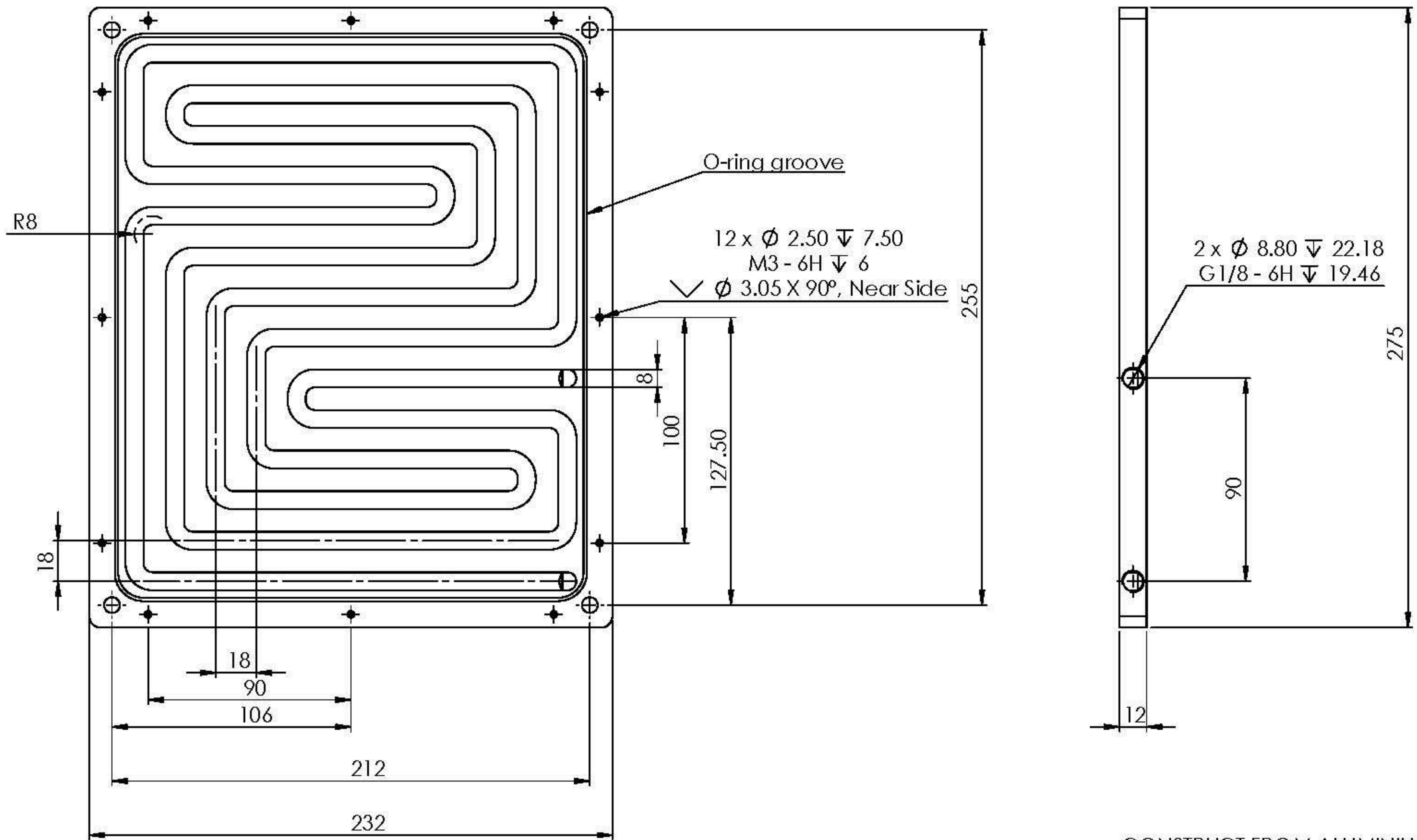
8. Appendices

Appendix 1: Manufacturing drawing for motor controller cooling plate

Appendix 2: Manufacturing drawing of auxiliary mounting platform supports



CONSTRUCT FROM ALUMINIUM SHEET
CHANNELS TO BE SPACED 18MM APART (CENTRES)
8MM WIDTH
8MM DEPTH

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

UNIVERSITY OF WA

	NAME	SIGNATURE	DATE
DRAWN	R. CLARK		
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: ALUMINIUM

WEIGHT:

TITLE: COOLING PLATE

DWG NO. **APPENDIX 1**

A3

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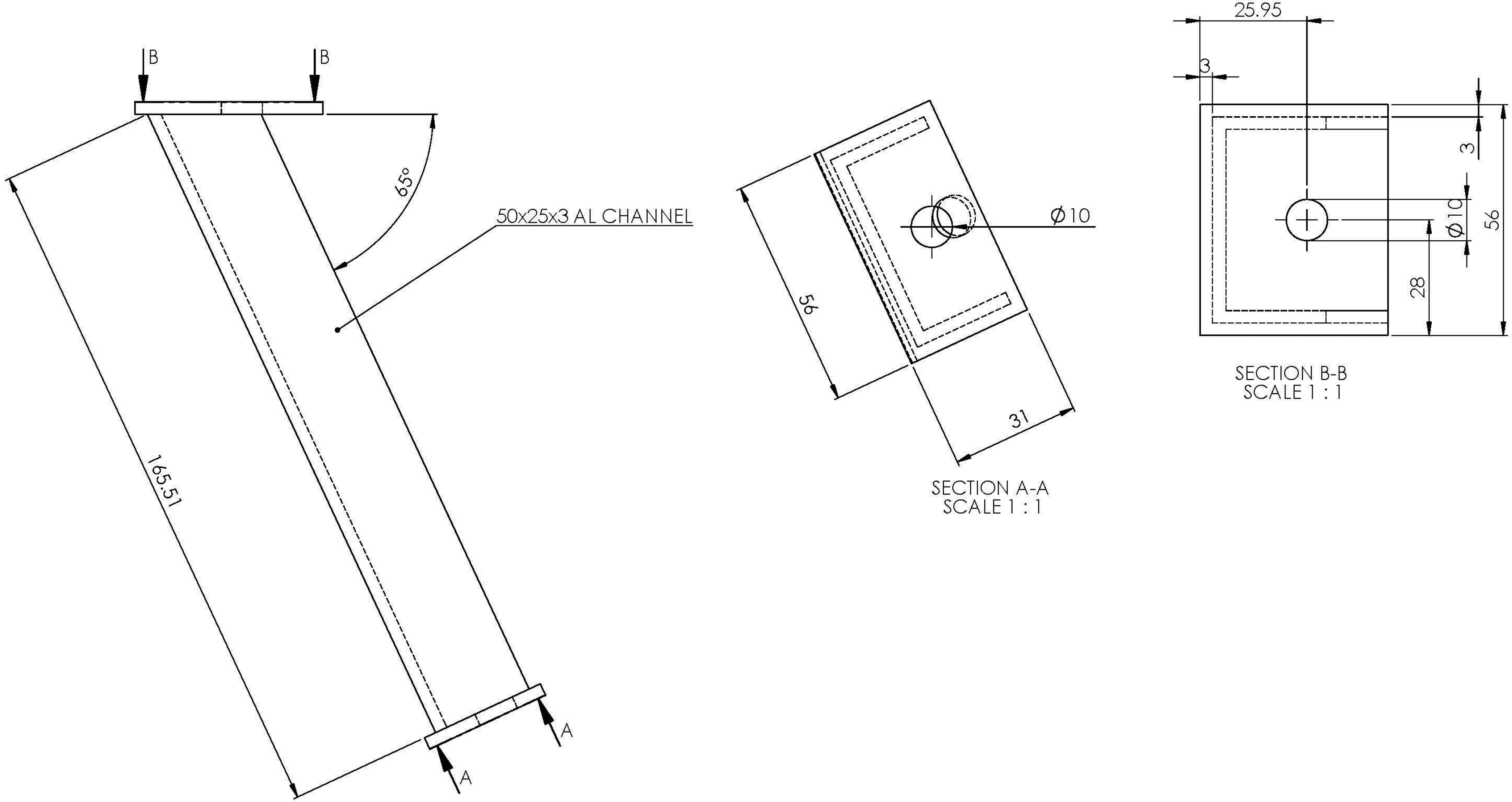
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
			University of WA	

	NAME	SIGNATURE	DATE
DRAWN	R. CLARK		
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: ALUMINIUM

WEIGHT:

TITLE: 2x SUPPORT FOR AUXILIARY MOUNTING PLATFORM

DWG NO. **APPENDIX 2** A3

SCALE:1:2 SHEET 1 OF 1