University of Birmingham

School of Engineering

FINAL GROUP REPORT
Mechanical Engineering BEng

Integrated Design Project 3

Team Number	2
Group Number	2

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Feedback		
Reflecting on the feedback that I have received on previous assessments, the following issues/topics have been identified as areas for improvement:	1	Include more images to validate and reference within main body of text
	2	Be more concise when creating product design specifications.
	3	Make sure there is clear flow and structure to the report to ensure ease of reading.
In this assignment, I have attempted to act on previous feedback in the following ways:	1	Images inserted wherever possible to clearly explain written work. Labelled and referenced within main text body.
	2	PDS written concisely with quantifiable and objective requirements.
	3	Sections and sub-sections clearly labelled and each section coherently follows on from the last.
Feedback on the following aspects of this assignment (i.e. content/style/approach) would be particularly helpful to me:	1	Are the simulations we have done (Matlab, Fluent, Solidworks thermal transfer) acceptable and does it appropriately validate our results?
	2	Is the layout and fundamental design of our groups work clear?
	3	Is team integration clear and appropriate?

1. INTRODUCTION & BACKGROUND

Environmental and economic issues are compelling reasons to develop clean, efficient and sustainable domestic energy management systems. Solutions to the UK's energy crisis predominantly rely on the reduction of fossil fuel usage and improving domestic energy efficiency, as outlined by the UK's Clean Growth Strategy (CGS) [1]. The Climate Change Act 2008 committed the UK to reducing greenhouse gas emissions by at least 80% by 2050 [1], compared to 1990 levels [1]. According to the CGS, average household energy consumption has decreased by 17% since 1990. However, in order to reach this target, commercial buildings, such as university accommodations, need to significantly reduce domestic energy consumption.

Team 2 provides a combination of systems engineered to generate clean energy and reduce energy losses; hence significantly improving domestic energy efficiency. Group 2 focuses on scavenging heat energy from waste hot water, as well as using cutting-edge technology to store and supply heat energy. Our system will reduce energy wastage and costs. The system can be categorised into three subsystems: Heat Exchanger (HE), Phase Change Material (PCM) and Control & Interface.

This report begins with the Product Design Specification (PDS) and overall system schematic and information. All manufacturing and assembly processes have been included in the Appendix, including detailed BS8888 drawings and routing sheets. The technical evaluation provides a comprehensive product functionality and suitability analysis, by demonstrating the methodology and validation using simulations. These include heat and fluid flow analysis, control and power requirements, using software such as SolidWorks (Flow Simulation) and MATLAB (Simulink). A complete analysis of the wider engineering implications were conducted from health and safety risks to social and economic issues. A complete product cost analysis was conducted in section 7, suggesting a total system cost of £25,718, with a return of investment (ROI) of 6.44 years.

2. PRODUCT DESIGN

2.1 PRODUCT DESIGN SPECIFICATION

Table 1: *Product Design Specification (PDS) for the overall system.*

Product Design Specification	
Overall System	
Total floor area	2.47 m^2 (HE), 1.65 m^2 (PCM), **Total area = 4.12 m^2**
Total Cost	~ £ 25,718
Filter Maintenance	Filter must be emptied when prompted by user interface (depends on usage)
Assembly & Manufacturing	Low cost manufacturing and sub-unit assembly at manufacturing site and whole unit assembly at accommodation block
Heat Exchanger	
Dimensions	3531 mm x 700 mm x 750 mm (LWH)
Material	**Pipes**: Standard 42mm Copper pipes, **Encapsulations**: Stainless steel, austenitic, AISI 304L, annealed
Flow Type	Double bypass, counter-current flow
Layout	Shell and tube (incl. baffle plates)
Input Temperatures	7 ^oC(from main water supply)
Output Temperatures	27 ^oC (to air-sourced heat pump)
Weight	1584 kg (dry weight)
Maintenance	Inner pipes and whole unit to be checked every 18-22 months (including descaling).
Phase-Change Material Unit	
Dimensions	2550 mm x 647.5 mm x 970 mm (LWH)
Material	**Encapsulation**: Aluminum, **PCM**: PureTemp48 Ⓡ, **Pipes:** Standard 15 mm Copper Pipes, **Insulation:** Domestic Cladding, **Unit Casing:** Stainless Steel AISI 304L
Charging Duration	60 minutes
PCM Melting Point	48^o C (321 K)
PCM Heat Storage Capacity	230 KJ/kg (PureTemp48)
PCM Thermal Life cycles	+7000 melt/ solidify cycles
Pipe Flow Type	Unidirectional Flow
Unit Layout	4 x 5 PCM-copper tubing. Sandwich layout silicon heater mats.
Water Heating Capacity	3000 L can be heated in a single charge
Input Temperature	~ 27 ^oC (during operation)
Output Temperature	~ 35 ^oC (during operation)
Heaters Power Consumption	533 W each
Weight	1083 kg (dry weight)
Maintenance	PCM material requires to be replaced every 10-12 years.

2.2 SYSTEM SCHEMATIC

The simplified system schematic is shown below (Figure 1) showing the flow direction and positioning of the various components between the PCM and the Heat Exchanger (HE).

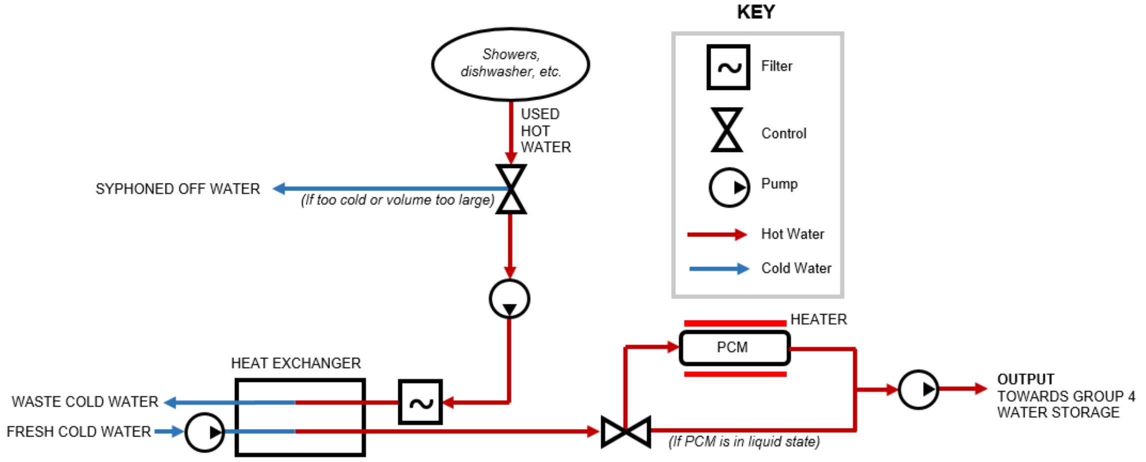


***Figure 1:** Schematic of heat exchanger and PCM system*

2.3. CAD DESIGN OF OUR SYSTEM

2.3.1. Heat Exchanger (HE)

A double bypass counter-current flow heat exchanger was designed due to its effective heat transfer properties. 50 copper alloy pipes of a standard diameter (42 mm) are encased inside a stainless-steel casing (fig 2). Pressure inside is not expected to surpass 2 bar, therefore the steel outer thickness will be adequate to contain this pressure whilst also insulating the working fluid. A rupture panel is fitted on-top of the casing as a safety measure (fig 2). Plates inside the main body encourage turbulent flow of the cool stream for improved heat transfer.

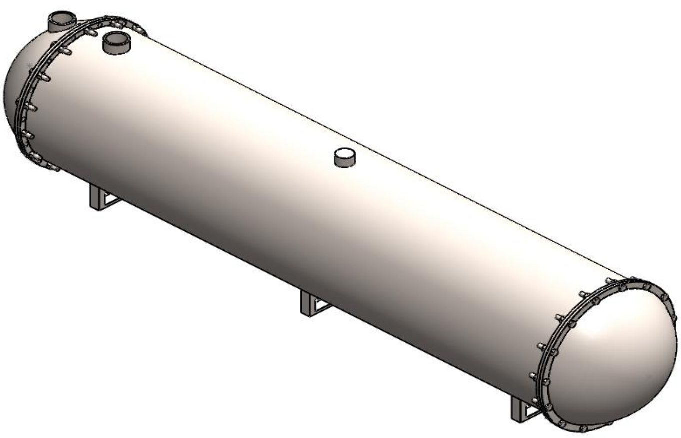


***Figure 2:** Heat exchanger CAD*

2.3.2. Phase-Change Material (PCM) Unit

The PCM unit consists of a network of copper pipes surrounded by the Phase-Change Material (fig 3). The PCM is housed by an Aluminium alloy (1050-H14) encapsulation, as this material can withstand change in air pressure and temperature. Aluminium was also chosen as the encapsulation, as it has a larger heat expansion coefficient compared to the PCM and copper tube which would prevent the encapsulation from bursting during heating. It was essential to design the capsule with a 2 mm thickness, as this was a compromise between structural integrity and thermal conductivity – which effects the thermal charging time. The heaters are "slotted" within the railings, which also support the PCM network. The casing allows for cladding, to ensure effective insulation (Fig 3). The heat exchanger is connected to the input port of the PCM using PVC pipes.

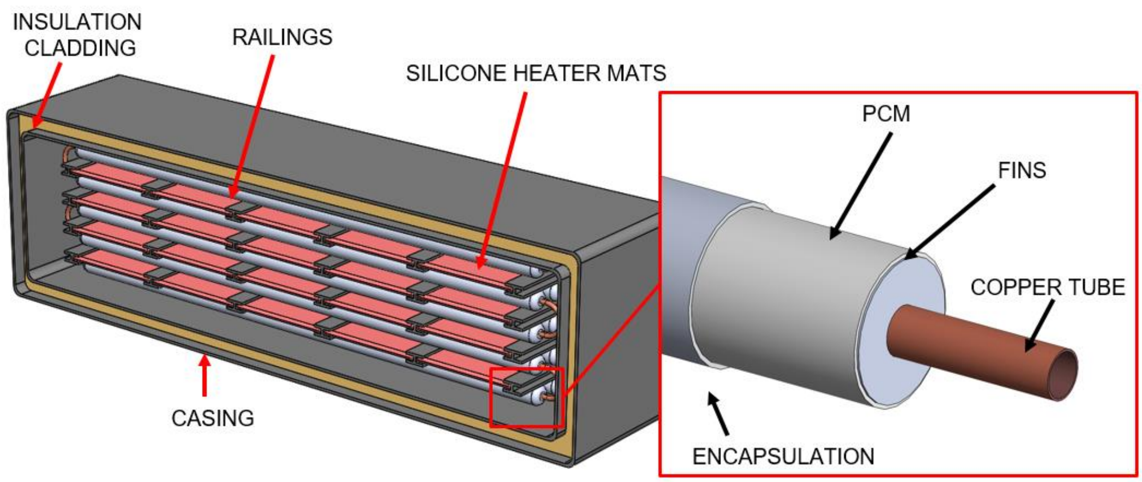


Figure 3: *Cross-section view of the PCM unit*

2.4. OUTSOURCED COMPONENTS

A combination of in-house and outsourced components were used to assemble the PCM and HE. The outsourced components predominantly include electrical and control components, such as heaters, control valves, sensors (thermistors, pressure sensors, etc.). The complete list of outsourced components can be found in **Appendix-A**.

3. DESIGN FOR MATERIALS AND MANUFACTURE

Note: *Bill of Materials, Assembly Routing Sheets, Manufacturing Routing Sheets and Detailed Operations Lists can be found in Appendix A, B, C and D*

4. TECHNICAL EVALUATION

4.1. METHODOLGY & LIMITATIONS

The main objective of the system is to increase the temperature of the incoming mains water, before entering the air-sourced heat pump (Group 4), hence reducing the amount of energy used by the air-sourced heat pump to heat up water to the desired temperature. This is to be done by scavenging heat from waste hot water.

4.1.1. Flow Temperature

The incoming temperature from the water supply is 7^o C [2][3]. The average used water temperature, of 43 ^{o}C, was calculated as a weighted average (based on the litres used) of the warm water used in showers, dishwashers, baths and hot taps [2], in a household per person and then scaled up in quantity to fit an accommodation block.

4.1.2. Heat-Exchanger Calculations

To calculate the preliminary dimensions and pipe arrangement of the heat exchanger, it was necessary to conduct heat transfer calculations. These were done to work out the heat transferred, hence the surface area of pipe required. Due to the complexity of the design criteria, multiple iterations were conducted on MATLAB to find the optimum geometry of the heat exchanger, without compromising efficiency and functionality. The first law of thermodynamics is that energy is conserved, and is governed by the following equation:

Figure 4: *Temperature nomenclature annotation*

$$(\boldsymbol{Eqn\ 1}) \qquad \dot{Q} = \dot{m}_h c_p (T_{hi} - T_{ho})$$

Where Q is the heat transferred in J/s, $\dot{m}_h$ is the hot stream mass flow rate in kg/s, c_p is the specific heat capacity of water (4200 J/kg℃ [4]) and T_{hi} and T_{ho} are the temperatures of the hot in and hot out respectively in ℃, as shown in figure 4.℃ (fig 4).

The temperature of the cold outlet stream was found by the following equation:

$$(\boldsymbol{Eqn\ 2}) \qquad T_{co} = T_{ci} + E \times (Q/\dot{m}_c \times c_p)$$

Where T_{co} and T_{ci} are the temperatures of the cold in and cold out streams, E is the effectiveness (0.7 for an average heat exchanger [4]) and $\dot{m}_c$ is the cold stream mass flow rate in kg/s.

The Log Mean Temperature Difference was calculated for a counter flow heat exchanger using the following equation 3 [5].

$$(\boldsymbol{Eqn\ 3}) \qquad LMTD = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)}$$

Where ΔT_2 is the difference in temperatures between the hot outlet and the cold inlet streams, and ΔT_1 is the difference in temperatures between the hot inlet and the cold outlet streams.
The total area of pipe needed in our heat exchanger was calculated with the following equation:

$$(\boldsymbol{Eqn\ 4}) \qquad A = \frac{Q}{(U \times LMTD)}$$

Where A is the area in m^2 and U is the overall heat transfer coefficient in W/m^2K (340 for a water-copper-water configuration [6] [7]).

From the theoretical calculations, it was evident that 50 standard diameter pipes (diameter = 42 mm) with a double bypass was suitable, to provide the required heat flux to raise the temperature of the water by 20 °C. It was calculated that the total area needed was 37.219 m^2, which would in turn require a total length of 2.802 m of pipe. The pipes were evenly distributed in a hive formation with a centre-to-centre pipe distance of 50 mm.

Note: *Equations 1 to 4 were used to model the PCM Simulink in* ***Section 4.2.4***

4.1.3. PCM Calculations

Two sets of critical calculations were conducted for the two processes: charging and discharging. Charging defines the transfer of heat from the radiator to the PCM to melt the material, and discharging refers to the transfer of heat from the PCM to the flowing water, as shown in fig 5.

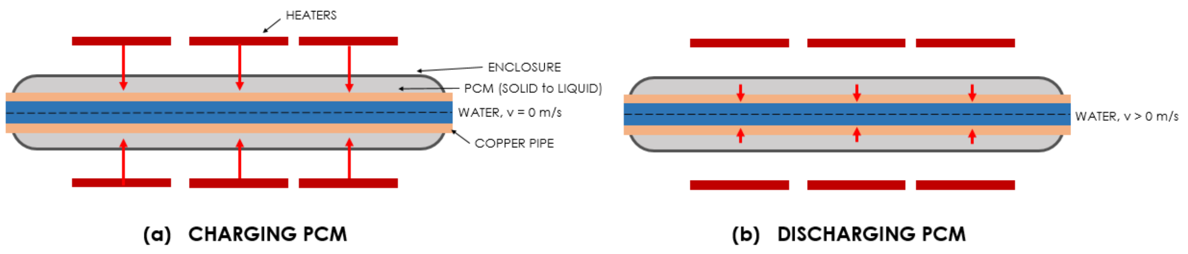


Figure 5: *Heat transfer when PCM is charging and discharging. Red arrow represents flow of heat energy.*

(A) Calculating Heater Power Requirement for Charging of PCM

The PCM charging was analysed for half the tube, whereby the line of symmetry is the dotted line in Fig 5. Equation 5 shows the amount of energy required to be supplied by the heater to melt the PCM. The mass, m, was calculated per meter, hence Equation 5 states the energy required by the heater per meter. The heat absorbed by the stagnant water was also considered.

$$(\boldsymbol{Eqn\ 5})\ Q_{HEATER} = (m_{AL} \cdot Cp_{AL} \cdot \Delta T_{AL}) + (m_{PCM} \cdot (Cp_{PCM} \cdot \Delta T_{PCM} + m \cdot \Delta h)) + (m_{WATER} \cdot Cp_{WATER} \cdot \Delta T_{WATER})$$

The power required was calculated by dividing the energy supplied by the heater, by the desired charging time of one hour (Eqn 6).

$$(\boldsymbol{Eqn\ 6})\ P_{HEATER} = \frac{Q_{HEATER}}{\Delta t}, \quad P_{HEATER} = \frac{1,887,680}{3600} = \mathbf{524\ W}\ per\ meter\ of\ PCM$$

(B) Pipe Branching - Flow Distribution Calculation using Continuity Equation

Equation 7, shows the conversion of the mass flow rate, $\dot{m}$ (kg/s), into velocity, V_1 (m/s) of the water, using the density, ρ (kg/m^3), of saturated water at 40 °C.

$$(\boldsymbol{Eqn\ 7})\quad V_1 = \frac{\dot{m}}{\rho \cdot A_1}, \quad V_1 = \frac{0.2}{(992.2).(\frac{\pi(0.02)^2}{4})} = 0.64\ m/s$$

The velocity of the water flow after being distributed into 4 pipes was calculated using the continuity equation (Eqn 8). The fluid was assumed incompressible (therefore constant density), major and minor losses were neglected, and flowing in one direction [8], as shown in fig 6a. The variable n, in Eqn 8, corresponds to the main pipe branching into 4 pipes. A_1 and A_2 represents the cross-sectional area of the pipe as shown in fig 6b.

$$(\boldsymbol{Eqn\ 8}) \quad A_1 \cdot V_1 = n \cdot A_2 \cdot V_2 \ [8]$$

$$\therefore \ V_2 = \frac{A_1 \cdot V_1}{n \cdot A_2} = \frac{(\frac{\pi(0.02)^2}{4})(2.89)}{4\ (\frac{\pi(0.013)^2}{4})} = 0.38\ m/s$$

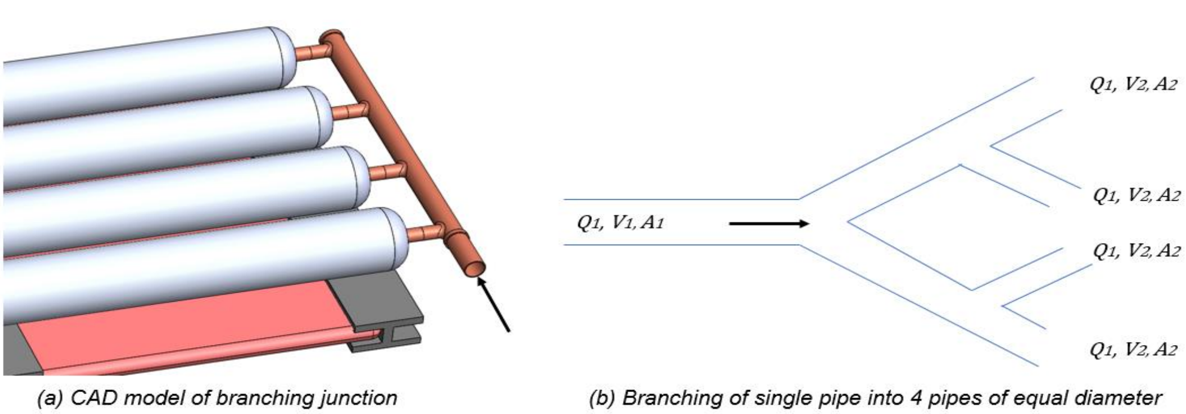


Figure 6: *Simplification of flow distribution of an incompressible fluid*

(B) Discharging PCM and minimum length calculation

The minimum length of the PCM tubes needed to be calculated to ensure the water is heated by at least 8 °C. The variables and nomenclature used in the equations are summarised in the table below:

Table 2: *Summary of key parameters and calculated values for discharging PCM*

***Thermophysical properties of saturated water at 40°C [9]**		**Other Parameters and Calculated Values**	
Parameter	Values	**Parameter**	**Values**
V, velocity of water through PCM-pipe*	0.38 m/s	k_{PCM}, thermal conductivity (PCM)	0.15
$\dot{m}$, mass flow rate main pipe*	0.2 kg/s	k_{PCM-CF}, thermal conductivity (Carbon Fiber-PCM)	16.5 W/(m.k)
$\dot{m}_{branched}$, mass flow rate per pipe*	0.05 kg/s	Re_d, Reynolds Num	**7,728**
d, diameter of pipe	0.013 m	Pr, Prandtl Num	4.19
v, kinematic viscosity*	6.387 x 10^{-7}	Nu_d, Nusselt Num	47.8
k, thermal conductivity*	0.631 W/(m.k)	α, Convective Heat Transfer Coefficient	**2320.9** W/(m^2.°C)
Cp_{313K}, specific heat*	4175 J/(kg.K)	ΔT_m, LMTD	16.7 °C
L_{PCM}, thickness of PCM	0.0435 m	Length of PCM capsule per pipe	> 7.5 m

Equation 9, 10 and 11, are used to calculate the convective heat transfer coefficient (α). The Reynold number was calculated using equation 9, to be 7734.4 therefore the flow is turbulent.

$$(\boldsymbol{Eqn\ 9}) \quad Re_d = \frac{V \cdot d}{v} \ [9], \ \ Re_d = \frac{(0.38) \cdot (0.013)}{(6.387 \times 10^{-7})} = 7734.4$$

The Nusselt number was calculated using equation 10 [9], whereby a fully developed turbulent flow (smooth circular pipe), with uniform wall temperature and uniform surface heat flux is assumed.

$$(\boldsymbol{Eqn\ 10})\quad Nu_d = (0.023)\cdot Re_d^{\frac{4}{5}}\cdot Pr^{\frac{1}{3}}\ [9],\quad Nu_d = (0.023)\cdot(7728)^{\frac{4}{5}}\cdot(4.19)^{\frac{1}{3}} = 47.8$$

The convective heat transfer coefficient calculated in equation 11 is required to find the thermal resistance for the overall heat transfer coefficient.

$$(\boldsymbol{Eqn\ 11})\quad \alpha = Nu_d\cdot\frac{k}{d}\ [9],\ \alpha = Nu_d\cdot\frac{k}{d} = (47.8)\cdot\frac{0.631}{0.013} = 2320.9\ W/(m^2\cdot{}^{o}\ C)$$

The log mean temperature difference was calculated using equation 4, as shown below:

$$(\boldsymbol{Using\ Eqn\ 4})\qquad LMTD = \frac{(48-27)-(48-35)}{\ln\left(\frac{(48-27)}{(48-35)}\right)} = 16.7\ {}^{o}C$$

Equation 12 calculates the overall heat transfer coefficient, U (W/(m^2.k), whereby the fouling and wall resistance were neglected, hence only the resistance within the water and PCM have been considered. Equation 13 shows how the PCM thermal resistance was calculated.

$$(\boldsymbol{Eqn\ 12})\quad \frac{1}{UA} = \frac{1}{\alpha A} + R_{PCM}\qquad (\boldsymbol{Eqn\ 13})\quad R_{PCM} = \frac{T}{k\cdot A}$$

Equation 14 represents the application of the steady energy flow equation, applied to the cold and hot fluid. Equation 15 is the surface area calculation.

$$(\boldsymbol{Eqn\ 14})\quad \dot{Q} = U\cdot A\cdot\Delta T_m\qquad (\boldsymbol{Eqn\ 15})\quad A = \pi\cdot d\cdot L$$

The required length, L, of the pipe can be found by combining equation 12, 13, 14 and 15, as shown in equation 16. This is essential for the design of the length of the pipe and PCM enclosure, in order to ensure the flowing water has reached the required output temperature.

$$(\boldsymbol{Derived\ Eqn\ 16})\quad L = \frac{\dot{Q}}{\pi\cdot D\cdot\Delta T_m}\cdot\left(\frac{1}{\alpha}+\frac{L_{PCM}}{k_{PCM-CF}}\right),$$

$$L = \frac{(\dot{m}_{branched}\cdot Cp_{313K}\cdot\Delta T)}{\pi\cdot D\cdot\Delta T_m}\cdot\left(\frac{1}{\alpha}+\frac{L_{PCM}}{k}\right) = \frac{(0.05)\cdot(4175)\cdot(8)}{\pi\cdot(0.013)\cdot(16.68)}\cdot\left(\frac{1}{(2320.9)}+\frac{(0.0435)}{(16.5)}\right) = \boldsymbol{7.519\ m}$$

Further calculations were conducted to investigate the effect of implementing fins, to induce further heat transfer, and reduce the length of the pipes. Equation 16 was modified to include the surface area of the fins, SA_{FINS} (m^2), and solved to find the new PCM enclosure length, shown below. The variable N, refer to the number of fins in the total unit.

$$(\boldsymbol{Derived\ Eqn\ 17})\quad L = \frac{Q}{\pi\cdot D\cdot\Delta T_m}\cdot\left(\frac{1}{\alpha}+\frac{L_{PCM}}{k}\right) - \frac{N\cdot SA_{FINS}}{\pi\cdot D},$$

$$L = (7.519) - \frac{750\cdot(2.88\ \times 10^{-6})}{\pi\cdot(0.013)} = \boldsymbol{7.466\ m}$$

Equation 17, shows that the addition of 750 fins (approximately every 10 mm), does not sufficiently reduce the length of the PCM encapsulation, hence, the cost of the fins is not justified, as the length only decreased by 0.007 %. Therefore, fins were not used in the final design.

The **thermal conductivity** of the PCM was too low for a feasible application of PCM for domestic use, hence it was necessary to research advanced methods for increasing the thermal conductivity, without compromising the thermal storage capacity and other performances. Further information on the Carbon-Fibre PCM has been discussed in **Section 6.1** of this report.

The PCM length requires to be > 7.5 m, hence each pipe in the PCM unit consists of 8 m of enclosure, separated into 4 x 2 m capsules, with curved copper pipes on either end of the 2 m pipe which results in a compact unit. The **major and minor losses** in the curved pipes were neglected (more information in **Section 6.1**).

4.2. VALIDATION & JUSTIFICATION OF METHODOLOGY

4.2.1. Heat-Exchanger Calculation Validation (Flow Simulation)

A computational fluid dynamics (CFD) simulation was completed on SolidWorks via Flow simulation to validate the calculations. These simulations worked by using the CAD model and implementing boundary conditions on the fluid domains' inputs/outputs. The boundary conditions were set at hot water inlet of 0.95 kg/s at 318 K and the hot water outlet a relative pressure of 1. The cold-water inlet was set to 0.9 kg/s at 280 K and the outlet a relative pressure of 1.

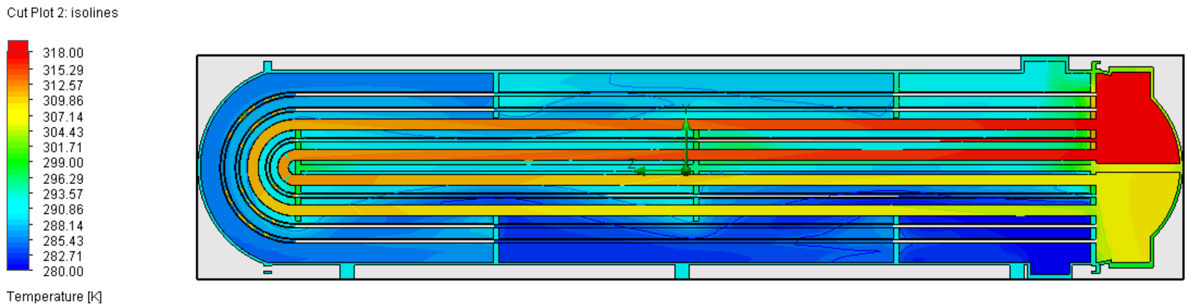


Figure 7: *Heat exchanger temperature contours*

As shown, the output cold water temperature is approximately 296.29 K, an increase of 16.29 K (fig 7). This value in kelvin correlates to a value of 23.29 °C. This value is lower than the calculated value of 27 °C. Some potential reasons for the temperature difference could be explained by a lack of outside energy transfer consider in the MATLAB script. In the MATLAB script all energy is transferred from the warm domain to the cold domain dependent on the effectiveness. This does not consider losses to the outside environment. This simulation does take this into account, with an outside environmental temperature of 20 °C. This would lower the total transfer thus reducing water output temperature.

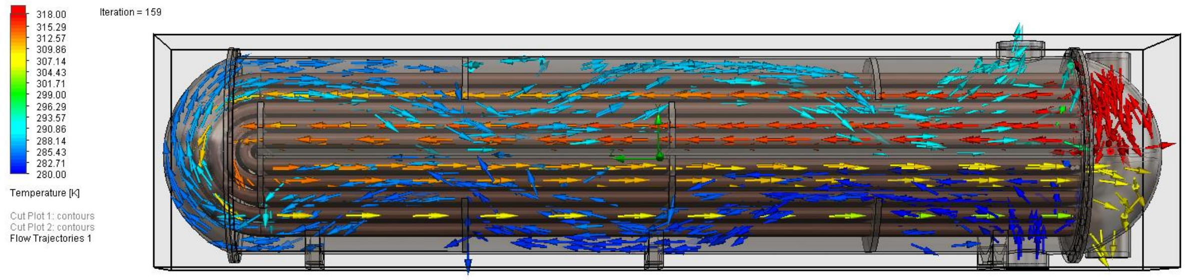


Figure 8: *Heat exchanger flow trajectories of cold and warm water domains*

A flow trajectory analysis shows that apart from some small areas of vorticity in the inlet hot domain, the fluid flows sufficiently around the heat exchanger preventing the build of stagnant water (Fig 8). This means the fresh cold water coming into the heat exchanger will flow out at the same rate as incoming. Additionally, this shows the importance of the baffles in the cold-water domain increasing turbulence and flow distance thus improving heat transfer.

4.2.2. Phase Change Material Calculation Validation (Flow Simulation)

A CFD simulation was also completed on one piping section of the PCM, this was also done on SolidWorks via Flow simulation. The boundary conditions for input water flow were 0.225 kg/s and 300 K. The justification is due to the even splitting of 0.9 kg/s into 4 simultaneous pipes. Additionally, the incoming water is the water that has exited the HE therefore has risen to an estimated temperature of 300 K. The output boundary condition was a pressure outlet with a relative pressure of 1. Additionally, to replicate the PCM discharging the material surrounding the copper pipe has been modelled as a heat source set at 321 K, 48 °C.

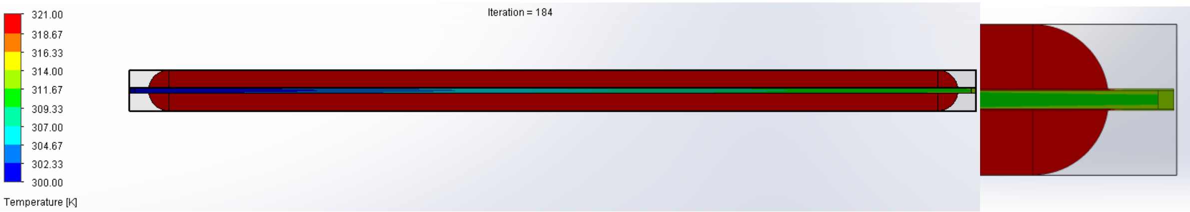


Figure 9: PCM pipe section temperature contours

As shown, the output water temperature is 311.67 K, an increase of 11.67 K (fig 9). This value in kelvin correlates to a value of 38.67 °C. This value is slightly higher than the calculated value of 8 °C. A potential reason for the increase in temperature was due to the CFD modelling limitations. The simulation could not consider the PCM temperature drop, once energy transfer occurred. This is due to the PCM being modelled as a constant temperature source. This means that the PCM always has additional energy to transfer to the water, which could account for the additional temperature increase.

4.2.3. Combined System Validation (MALAB Simulink Simulation)

A simulation was modelled (fig 10) on MATLAB Simulink to investigate the temperature behaviour of the water within our system, as well as validate the energy efficiency of our system compared to a conventional boiler.

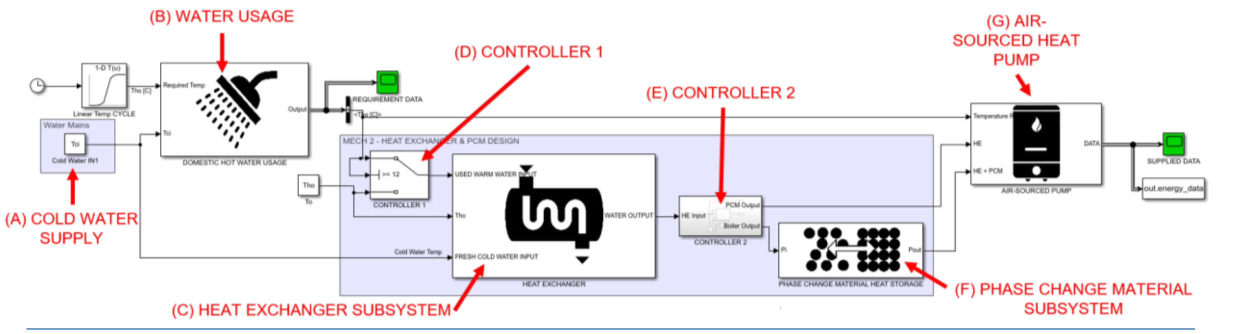


Figure 10: *Annotated MATLAB Simulink model of the combined heat exchanger and PCM system*

Each sub-system from Figure 10 are modelled as described below:

(A) **Cold water supply:** Temperature of the incoming water was 7°C (constant).
(B) **Water usage:** Temperature of the water usage was modelled as steadily increasing over time.
(C) **Heat exchanger:** Calculates the temperature of the fresh water exiting, after heat exchange, using the equations 2:
(D) **Controller 1:** A simple switch, where the incoming warm water has to be > 30 °C.
(E) **Controller 2:** Allows water to flow to through to the PCM only if the water is > 27 °C.
(F) **PCM:** An 8 °C increase in temperature of the water from the heat exchanger.
(G) **Air-sourced heat pump** calculates the work required by the air-sourced pump.

The following assumptions were made for the Simulink model:

- The heat loss during usage of water is negligible
- Mass flow rate of the water from the supply is constant throughout the model
- PCM always raises the temperature by 8° C
- This model does not consider power losses due to the filter, pump and control valve components
- Heat exchanger has a 70% heat transfer efficiency

This simulation validates that the energy required by the air-sourced pump (integrated with a HE and PCM) is significantly lower than the energy required by a conventional boiler. It is evident that the incoming temperature of water from the HE is higher than the incoming temperature from the main water supply (fig 11). Since the temperature from the main water source is always constant at 7 °C, as the desired temperature increases, the work done by the boiler increases. A conventional boiler must produce energy proportional to the desired temperature. Whereas, with a HE the work done by the air-sourced heat pump depends on both the temperature of the water from the heat exchanger and the desired temperature. The exiting water temperature of the heat exchanger increases as the desired temperature increases, since the heat is scavenged from the used water.

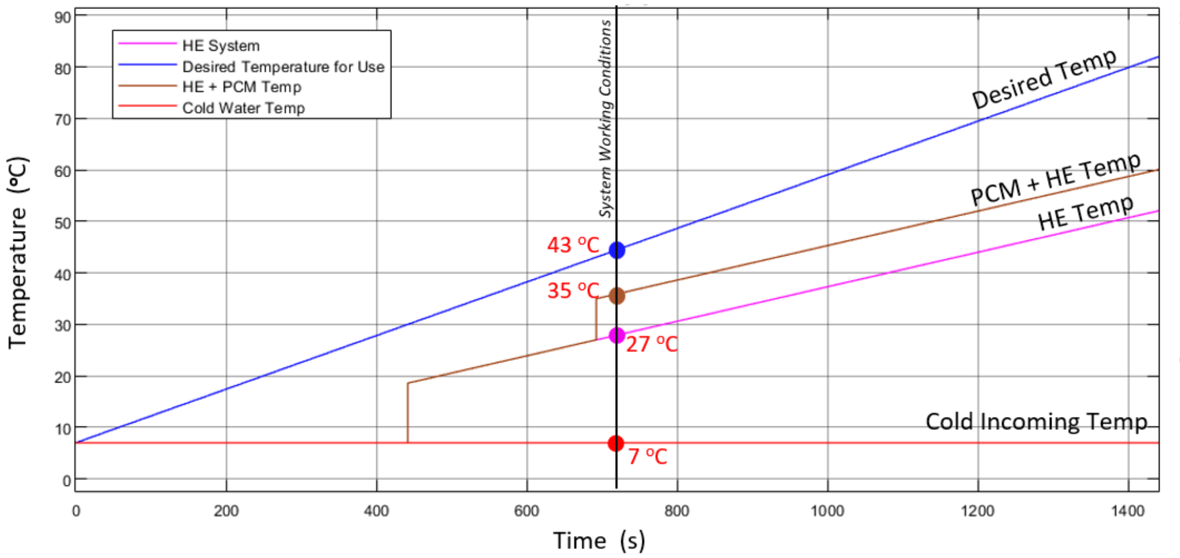


Figure 11: Simulation graph of water temperature in different systems

The difference in the desired and HE temperature depicts the heat energy losses in the system, this includes losses during the use of the water by the user. Additionally figure 11, shows that the combination of the PCM and the HE provides an even higher temperature, entering the air-sourced heat pump, hence the work produced by the air-sourced heat pump is further decreased – increasing the overall efficiency. The non-linear graph in figure 12, is due to the controllers included in the model. The HE is only active if the temperature of the incoming used water is above 30 °C, and the PCM is active if the incoming water is > 27 °C, hence before these conditions are met, the work done by the air-sourced heat pump is identical to a conventional boiler (fig 13).

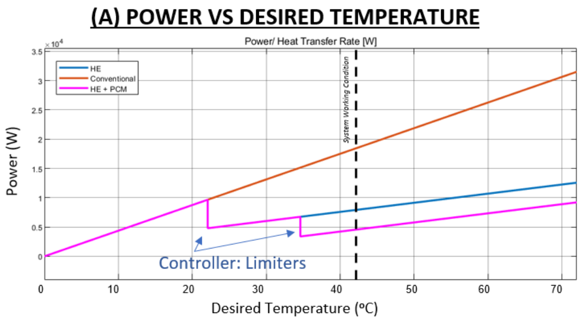


Figure 12: Energy required to heat the water to desired temperature

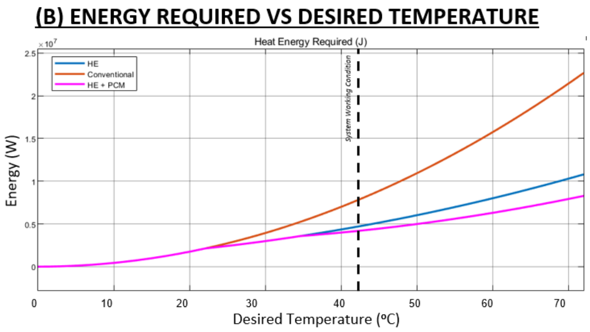


Figure 13: Power required to heat the water to desired temperature

An analysis was conducted at the system working condition (the vertical line in fig 12 and 13). At this condition, a desired temperature (for user) of 43 °C is achieved. A conventional boiler must work with a power of 17.3 kW of energy to raise the temperature from 7 °C to 43 °C (fig 12); whereas with a heat exchanger the power required by the air-sourced heat pump is 7.5 kW, because the temperature only needs to be raised from 27 °C to 43 °C (fig 12). The power required is further reduced to 4.1 kW, by using a combination of HE and PCM, as work is done to increase the temperature from 35 °C to 43 °C. Therefore, the HE and PCM system can decrease the power requirement by 76 %, however this does not consider the heater power usage. Energy efficiency increases (fig 14) as the desired temperature increases. At a desired temperature of 43 °C, the HE and PCM is 47% more efficient than a conventional system, which is heating the water from 7°C.

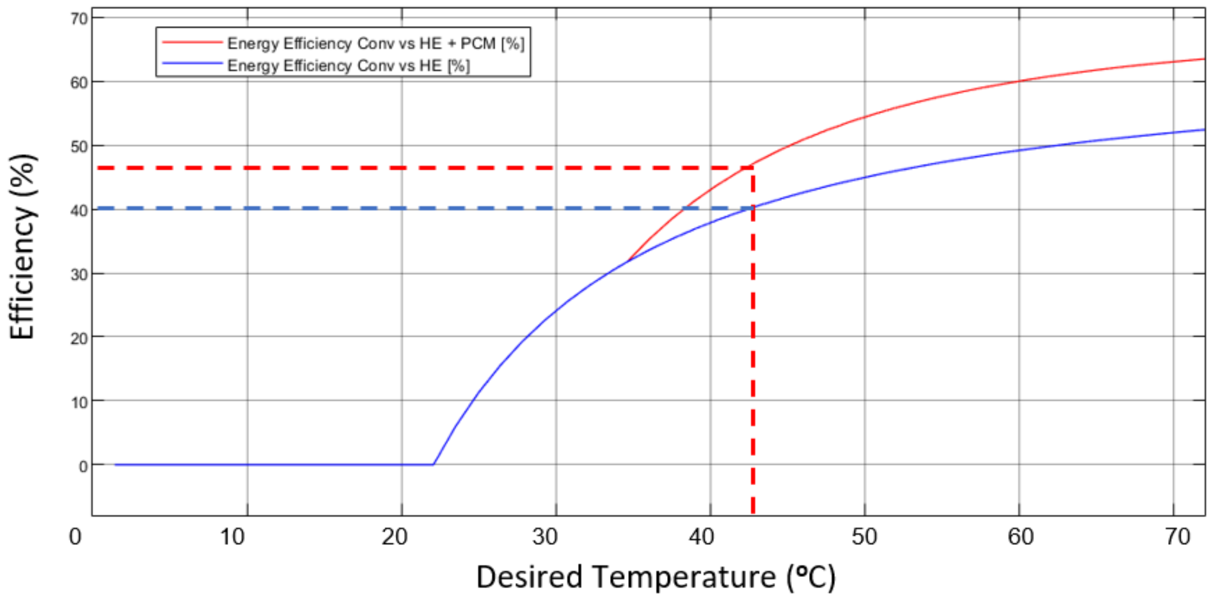


Figure 14: Energy efficiency comparing conventional boiler to HE & PCM integrated boiler

5. ENGINEERING IMPLCATIONS

5.1 Heat exchanger

The material selection was first analysed for suitability and sustainability. Copper and stainless steel both have good resistance to biofouling and water corrosion and have high strength [10]. These properties ensure longevity of use and promote the sustainability of the system. It does not require any power or harmful chemicals and thus doesn't release any pollutants, and therefore is already environmentally conscious in its design. The system is modularly designed, such that it can be partially taken apart and assembled once in the basement of the building, providing ease of manoeuvrability.

It does not pose any legal or ethical implications that contradict legislations standing to protect those interacting with this system. The vessel will not exceed 30 bar or be close to open flame and so does not breach the Simple Pressure Vessel Safety Regulations of 1991[11]. According to this legislation, it is required that the system be regularly maintained to ensure it is in good repair as to prevent danger as per Regulation 12[11].

The heat exchanger will not reach high temperatures (does not exceed 50ºC inside and 20ºC on the outside) and therefore does not pose any safety risk such a burn. To further reduce health hazards, the external pipes carrying the hot water to the system will be insulated to mitigate any further danger of injury. A rupture disk will be fitted as a means of pressure relief in case of dangerous pressure increase. To prevent this, a control valve is fitted before the hot water reaches the heat exchanger (Fig 1). This will act as a safety feature to filter off water to a run-off tank in the case of excess flowing water.

5.2 PCM

Carbon-fiber infused PCMs provides a viable sustainable solution due to its efficiency in transferring heat energy; as well as maintaining consistent temperature, therefore reducing domestic waste heat energy via heat storage. Additionally, the PCM produced by PureTemp is 100% renewable and readily biodegradable[12]. During the charging and discharging, no harmful pollutants are released, complying with SDG Goal 11[13].

Health and safety risks to humans have been significantly minimised due to the various layers. The PCM is encapsulated, and the steel casing prevents heat from being transferred to the surroundings. Insulation (cladding) ensures that the surface of the outer casing remains at room temperature. As a further precaution, warning labels will be placed on the outer casing (Fig 15). The system will be regularly maintained by accommodation staff. The modularity of the unit ensures accessibility for repair without needing to replace the whole unit (the PCM encapsulations can be individual removed and replaced).

Social implications arise from the fact that the current design is only feasible for buildings with a high domestic water usage, such as university accommodations, hotels, flats and industries. Therefore, people living in houses are unable to benefit from this technology. This is due to the reduction in efficiency when the volume of water is too low, and the dimensions of the heat exchanger and PCM unit are not feasible to be fitted in a regular UK home.

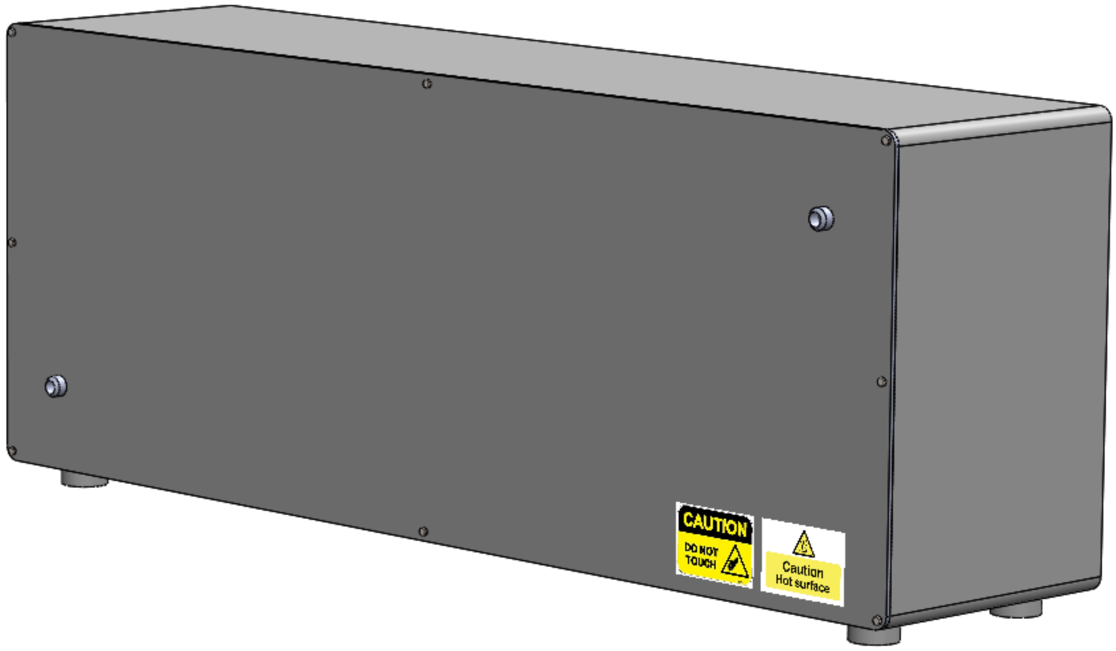


Figure 15: *Warning labels on the PCM unit*

6. FAILURE MODE, RISK EVALUATION AND MITIGATIONS

6.1. RISKS, LIMITATIONS & MITIGATION MEASURES

6.1.1. Pipe Losses Assumption

Risk/ Limitation: Neglecting major and minor head losses in pipe flow of the calculations of PCM and HE, hence the flow rate may vary.

Mitigation: Major losses in the pipes (frictional losses) can be neglected because standard copper pipes were used, with majority of fluid travel being along a straight pipe. Minor losses were avoided by having minimal components, such as control valves and bends. The bends were redesigned (fig 16), to minimise minor head losses.

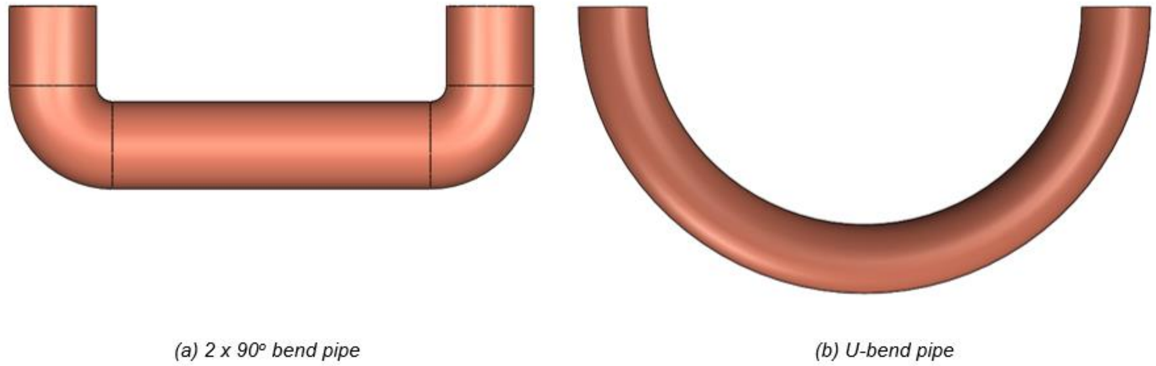


Figure 16: *Design change from 90º to U-type bend*

6.1.2. Health & Safety – Hot Surfaces

Risk/Limitation: Effective insulation and reducing health hazards due to hot surfaces.

Mitigation: Effective insulation of the PCM, via the use of cladding, is essential in achieving high efficiency during charging and discharging. The insulation also acts as a thermal barrier, preventing the external surface of the PCM unit from reaching higher temperature, hence preventing the risk of skin burn, during maintenance.

6.1.3. Functional Failure Modes

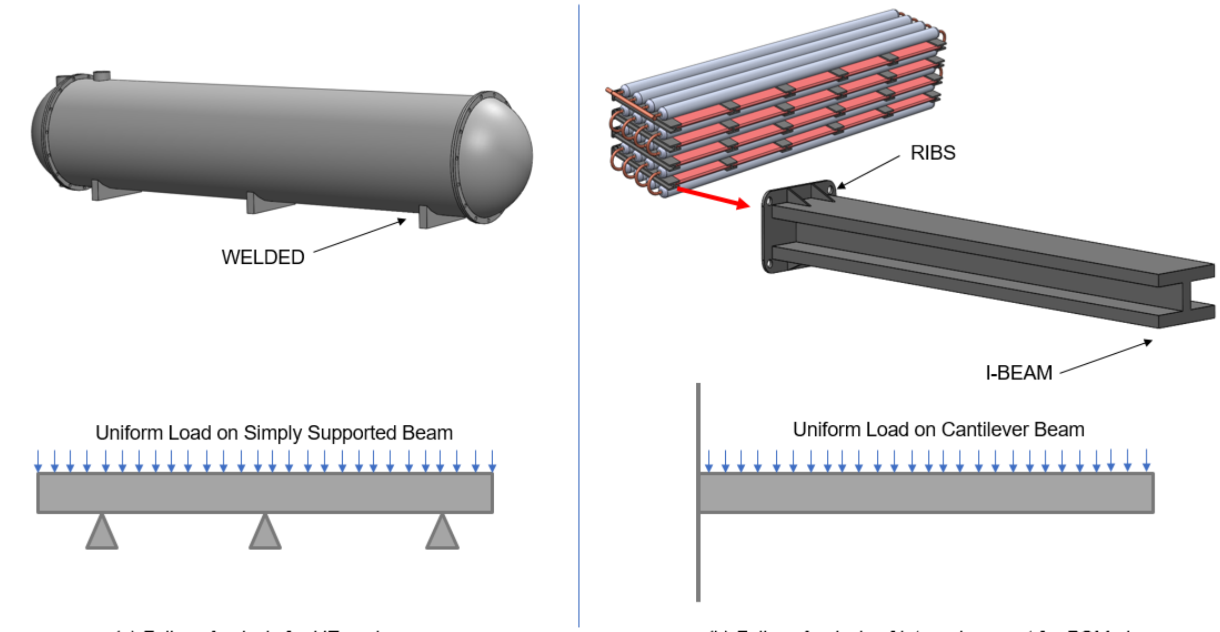
Risk/Limitation: The water usage may be higher than the HE or PCM acceptable mass flow rate thus potential pressure builds up within the pipes. There may also be a leak in the system due to damaged pipes.

Mitigation: The implemented control systems will reduce water flow using the control valve. In the event too much waste-water is flowing, it will be syphoned off to run-off tanks. If the PCM is not working or faulty, the water can bypass this and go directly to the air-sourced heat pump (Group 4).

6.1.4. Structural Failure Modes

Risk/Limitation: The heat exchanger must be supported and fitted to the ground, due to its large mass during operation, and the circular external surface. Similarly, the PCM capsules must be well supported within the casing.

Mitigation: A structural analysis was conducted (fig 17). The beams supporting the PCM capsules have ribs for further support. The HE has three support stands to reduce deflection.



(a) Failure Analysis for HE casing

(b) Failure Analysis of internal support for PCM pipes

Figure 17: *Support structure for HE casing and PCM capsules*

6.1.5. Physical Properties of PCM

Risk/Limitation: Thermal conductivity of PCM (PureTemp 48) is too low for effective heat transfer (0.15 W/(m.K)), therefore resulting in unfeasible dimensions for the PCM unit.

Mitigation: A novel phase change composite study conducted by Professor T.Nomura, suggests that lining the PCM with a percolating network of carbon fibre (CF-XN-100-Nippon Graphite Fibre) provides a significant increase in the thermal conductivity of the PCM[15][16]. The carbon fibre has a thermal conductivity 900 W/(m.K)[15]. As shown in figure 18, at 14 % volume fraction of carbon fibre, the effective thermal conductivity is 16.5 W/(m.K) when hot pressed[15]. This is an increase in thermal conductivity by a factor of 110. This implementation increases the cost of material and processing.

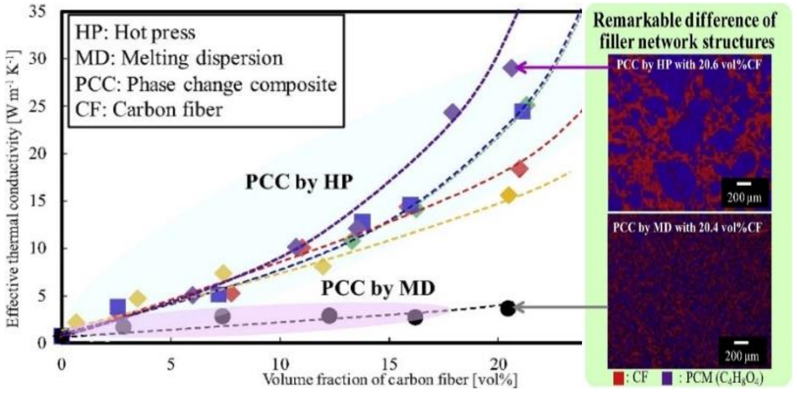


Figure 18: *The effect of volume fraction carbon fiber in PCM on thermal conductivity [15]*

6.2. BUSINESS MANAGEMENT RISKS

The wider marketing plan for the business is to sell 'STESS' as one complete unit, rather than individual elements. However, this can pose questions and implications such as what should happen if there is not a market for large investments. This is how the business management strategy of financial planning was used, before resources were spent on developing ideas, researching the market was the first task. With numbers of students looking to study at university rising each year and the overall global focus on environmental impact increasing, it can be sure that universities looking to expand student accommodation will also be looking to do so sustainably. They would therefore be interested in a product such as STESS.

The components in the heat recovery system are a combination of bought out and in-house components. Of those out-sourced, most materials are abundant and often traded within industry. This therefore mitigates any implications regarding supply chain. It is importance that we adhere to rules protecting employees involved within our business. Rules include health and safety in the workplace, fair pay with regards to equality and diversity and the Employment Rights Act (1996)[16].

7. PRODUCT COSTS

7.1 MARKET STRATEGY

Heat exchangers are not innately innovative. They have been used in commercial and industrial heat recovery applications for decades. What this means is that the technology has been developed greatly. Heat exchangers in the domestic homes are currently using predominately air to air heat transfer [17]. With up to 90% of heat produced during showers being lost down the drain [18], hence there is a dire demand for a system to recover this heat, especially whilst the world is currently in the midst of a 'Climate Change Emergency' [19]. There are some systems currently being developed which are setting out to achieve this goal, however what sets our system apart from the competition is the integration of the PCM and HE to drastically improve efficiency. PCM technology is rapidly advancing due to its extreme thermal storage properties, and current studies suggest it is nearing a technology readiness level of 9 [20], which is popular commercial use. By using these two together, we aim to reach a part of the market that is becoming increasingly popular, with technology that will change the future.

7.2 COMPONENT COSTS

This section details the cost of each component for the entire assembly. Full material information is detailed in the **Appendix-D**.

Table 3: *Costs of all raw material and outsourced components*

Part Nº	Assembly	Part name	Material/ Supplier	QTY	Price per quantity	Cost
1	Heat Exchanger	Main tube section	External Supplier	1	£1,000.00	**£1,000.00**
2	Heat Exchanger	End Shell	Material	1	£240.00	**£240.00**
3	Heat Exchanger	Input/ Output shells	Material	1	£240.00	**£240.00**
4	Heat Exchanger	Mounting Disks	External Supplier	4	£45.90	**£45.90**
5	Heat Exchanger	Shell Stands	Material	3	£88.04	**£88.04**

6	Heat Exchanger	Plates Main section	Material	1	£240.00	**£240.00**
7	Heat Exchanger	Sub Plates A	Material	1	£240.00	**£240.00**
8	Heat Exchanger	Sub plates B	Material	1	£240.00	**£240.00**
9	Heat Exchanger	Copper Pipes	External Supplier	110	£34.00	**£3,740.00**
10	Heat Exchanger	Inlets/Outlets	Material	4	£1.56	**£6.25**
11	Heat Exchanger	Nuts	External Supplier	30	£0.40	**£12.09**
12	Heat Exchanger	Bolts	External Supplier	30	£2.31	**£69.36**
13	Heat Exchanger	Rupture Disk	External Supplier	1	£1.56	**£1.56**
14	Heat Exchanger	Gasket	Material	2	£8.24	**£8.24**
15	PCM	PCM	External Supplier	1	£3,692.00	**£3,692.00**
16	PCM	Encapsulation pipe	Material	10	£165.19	**£1,651.90**
17	PCM	Encapsulation end cover	Material	40	£6.91	**£6.91**
18	PCM	Copper pipe (15mm)	External Supplier	20	£5.38	**£107.60**
19	PCM	Copper pipe bend (15 mm)	Material	1	£5.38	**£5.38**
20	PCM	Copper pipe (60mm)	Material	2	£36.78	**£73.56**
21	PCM	Stainless steel H beam	Material	1	£63.50	**£63.50**
22	PCM	Heater	External Supplier	40	£65.71	**£2,628.40**
23	PCM	Nuts	External Supplier	40	£0.40	**£16.00**
24	PCM	Bolts	External Supplier	40	£2.31	**£92.40**
25	PCM	Insulation	Material	2	£21.71	**£43.42**
26	PCM	Inner case panels (Cut into A, B, C and D)	Material	3	£375.00	**£1,125.00**
27	PCM	Outer case panels (Cut into A, B, C, D and square plate)	Material	3	£375.00	**£1,125.00**
28	General	Pump	External Supplier	3	£98.70	**£296.10**
29	General	Filter	External Supplier	1	£9.60	**£9.60**
30	General	Heat sensor	External Supplier	1	£3.50	**£3.50**
31	General	Logic controls	External Supplier	2	£74.08	**£148.16**
32	General	Control valve	External Supplier	2	£62.42	**£124.84**
Total Component Cost						**£17,800.03**

7.3 PROCESS & MANUFACTURING COSTS

This section details the manufacturing costs to manipulate the raw materials purchased into the desired final product.

Table 4: *Costs of all manufacturing processing costs*

Part No.	Assembly	Part name	Manufacturing procedure	QTY	Price per quantity	Cost (£)
2	Heat Exchanger	End Shell	Laser cutting, Stamping	1	£95.20	**£95.20**
3	Heat Exchanger	Input/ Output shells	Laser cutting, Blanking, Stamping	1	£120.90	**£120.90**
4	Heat Exchanger	Mounting Disks	Sand and resin casting, Welding	4	£94.10	**£376.40**
5	Heat Exchanger	Shell Stands	Sand and resin casting, Welding	3	£29.35	**£88.04**
6	Heat Exchanger	Plates Main section	Laser cutting	1	£97.30	**£97.30**
7	Heat Exchanger	Sub Plates A	Laser cutting	1	£25.70	**£102.80**
8	Heat Exchanger	Sub plates B	Laser cutting	1	£25.70	**£102.80**
9	Heat Exchanger	Copper Pipes	Blanking, Machine roller bending, Welding	110	£71.60	**£3,938.00**
10	Heat Exchanger	Inlets/Outlets	Casting, Welding	4	£89.10	**£356.40**
13	Heat Exchanger	Rupture Disk	Welding	1	£71.60	**£71.60**
14	Heat Exchanger	Gasket	Blanking	2	£17.50	**£35.00**
16	PCM	Encapsulation pipe	Laser cutting	10	£165.19	**£1,651.90**
17	PCM	Encapsulation end cover	Laser cutting, Stamping	40	£49.20	**£1968.00**
19	PCM	Copper pipe bend (15 mm)	Laser cutting, Machine roller bending	1	£71.60	**£71.60**
21	PCM	Stainless steel H beam	Laser cutting, welding, Hand drill	1	£411.20	**£411.20**
25	PCM	Insulation	Laser cutting	2	£21.71	**£43.42**
26	PCM	Inner case panels (Cut	Laser cutting	3	£25.70	**£77.10**

		into A, B, C and D)				
27	PCM	Outer case panels (Cut into A, B, C, D and square plate)	Laser cutting	3	£25.70	**£77.10**
Total Manufacturing Cost						**£7,918.00**

7.4 TOTAL COST EVALUATION

The total cost of this system is £25,718.03 (table 5) (C_T). Some factors that were not included are VAT and economy of scale. If the manufacturing quantity increased, this value would decrease, allowing a lower Return of investment. This value comes due to the cost of the material being used. With a large proportion coming from a single type of component, the copper pipes. This value could be reduced if a contract with a major supplier for a larger quantity could be completed.

The payback time is 6.44 years, due to an average yearly saving of £3,991.00 (table 5). This saving was calculated by summing the amount of energy saved by using system compared to a conventional boiler (eqn 18). V_A is the average water volume per person per day, U is water specific heat, ΔT is the change in temperature from incoming water to output of PCM. Once this value was calculated in KWh this value could be converted to a rough cost estimate based on energy company supply tariffs. All these values were outputted using the Simulink. This value in KWh could be converted to a rough cost estimate based on energy company supply tariffs. All these values were outputted using the Simulink.

$$(\textbf{Eqn 18}) \qquad ROI = \frac{C_T \times 3600}{V_A \times U \times \Delta T \times 365 \times 60 \times 0.15}$$

***Table 5:** Summary of costs, savings and Return on Investment (ROI)*

Area of cost	Amount
Component cost	**£17,800.03**
Manufacturing	**£7,918.00**
Total cost	**£25,718.03**
Area of saving	
Savings per Year	**£3,991.68**
ROI	**6.44 years**

8. PROJECT MANAGEMENT

Project Goals:

1. Literature review (e.g. domestic mass flow rate and UK safety regulations).
2. Preliminary design of heat exchanger: MATLAB programming and calculations
3. Designing draft Heat Exchanger CAD.
4. Preliminary design of PCM: Charging and discharging calculations on Excel
5. Designing draft PCM CAD.
6. Finalise Team integration (mass flow rate, temperature, interface, etc.).
7. Simulation on MATLAB to validate PCM-HE integration, temperature increase, efficiency, etc.
8. Conduct Solidworks Flow Simulation of water flow in HE and PCM.
9. Final CAD design of HE and PCM.

To ensure the project progression and efficient group collaboration, a project management strategy was devised. The group elected a representative to oversee deadlines and communication with other groups. Minutes were recorded after each group meeting so a summary of the progress could be easily detailed, as shown in **Appendix-E**. This ensured deadlines were met and ideas were documented for future use. The design challenge was broken down into manageable work packages. This helped make the task more approachable and helped increasing productivity. This was done by developing a Gantt chart shown in **Appendix-F**.

Within the group, the challenge was divided into two; the HE and the PCM. By doing this it allowed more focused research. It was important, however, at the meetings to explain all decisions made on each section so that those working on the HE could remain involved with the PCM advancements and vice versa.

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APPENDIX

A: BILL OF MATERIALS

A.1. Heat Exchanger Bill of Materials containing the part name, material and supplier

PART Nº	NAME	MATERIAL	SUPPLIER (CODE)	LINK/ SUPPLY	QTY
1	**Main tube section**	Stainless steel, austenitic, AISI 304L, annealed	DH Stainless (DH-B700)	https://www.dhstainless.co.uk/products/tru-bore-metric-iso/metric-pipes/metric-bore-welded-pipe/	1
2	**End Shell**	Stainless steel, austenitic, AISI 304L, annealed	Metals Warehouse (SSH-3.0)	https://www.metalswarehouse.co.uk/product/3-0mm-stainless-steel-sheet/	1
3	**Input/ Output shells**	Stainless steel, austenitic, AISI 304L, annealed	Metals Warehouse (SSH-3.0)	https://www.metalswarehouse.co.uk/product/3-0mm-stainless-steel-sheet/	1
4	**Mounting Disks**	Stainless steel, austenitic, AISI 304L, annealed	Steel Express (SSB-G304)	https://www.steelexpress.co.uk/shop/product/bespoke-blocks-grades-304/	4
5	**Shell Stands**	Stainless steel, austenitic, AISI 304L, annealed	Steel Express (SSB-G304)	https://www.steelexpress.co.uk/shop/product/bespoke-blocks-grades-304/	3
6	**Plates Main section**	Stainless steel, austenitic, AISI 304L, annealed	Metals Warehouse (SSH-3.0)	https://www.metalswarehouse.co.uk/product/3-0mm-stainless-steel-sheet/	1
7	**Sub Plates A**	Stainless steel, austenitic, AISI 304L, annealed	Metals Warehouse (SSH-3.0)	https://www.metalswarehouse.co.uk/product/3-0mm-stainless-steel-sheet/	1
8	**Sub plates B**	Stainless steel, austenitic, AISI 304L, annealed	Metals Warehouse (SSH-3.0)	https://www.metalswarehouse.co.uk/product/3-0mm-stainless-steel-sheet/	1
9	**Copper Pipes**	Copper	Monster Plumb (YORKEX42MM)	https://www.monsterplumb.co.uk/copper-pipe-tube-42mm-3m-plumbing-heating-yorkshire-yorkex42mm	110
10	**Inlets/Outlets**	Stainless steel, austenitic, AISI 304L, annealed	Steel Express (SSB-G304)	https://www.steelexpress.co.uk/shop/product/bespoke-blocks-grades-304/	4
11	**Nuts**	Stainless Steel	RS COMPONENTS (RS 276-774)	https://uk.rs-online.com/web/p/hex-nuts/0276774/	30
12	**Bolts**	Stainless Steel	RS COMPONENTS (RS 279-981)	https://uk.rs-online.com/web/p/hex-bolts/0279981/	30
13	**Rupture Disk**	Stainless steel, austenitic, AISI 304L, annealed	AssenTech	http://bursting-discs.co.uk/composite-bursting-disc-vacuum-support/	1
14	**Gasket**	Nitrile Butadiene Rubber	RS COMPONENTS (RS 796-0801)	https://uk.rs-online.com/web/p/gaskets/7960801/	2

A.2. PCM Bill of Materials containing the part name, material and supplier

PART Nº	NAME	MATERIAL	SUPPLIER (CODE)	LINK/ SUPPLY	QTY
15	**PCM**	PureTemp® 48	PureTemp (PT48)	https://www.puretemp.com/stories/puretemp-48-tds	1
16	**Encapsulation pipe**	Aluminium, Grade 6082	Metals4U (2815)	https://www.metals4u.co.uk/materials/aluminium/aluminium-tube/2815-p	20

17	**Encapsulation End Cover**	Aluminium, Grade 6082	Aalco (6082-T6-T651)	http://www.aalco.co.uk/datasheets/Aluminium-Alloy_6082-T6~T651_148.ashx	**40**
18	**Copper Pipe (15mm)**	Copper	Wickes (420002)	https://www.wickes.co.uk/Wickes-Copper-Pipe---15mm-x-2m/p/420002?utm_source=google&utm_medium=cpc&adpos=&scid=scplp420002&sc_intid=420002	**22**
19	**Copper Pipe Bend (15 mm)**	Copper	Wickes (420002)	https://www.wickes.co.uk/Wickes-Copper-Pipe---15mm-x-2m/p/420002?utm_source=google&utm_medium=cpc&adpos=&scid=scplp420002&sc_intid=420002	**16**
20	**Copper Pipe (22 mm)**	Copper	ScrewFix (77741)	https://www.screwfix.com/p/wednesbury-copper-pipe-22mm-x-3m/77741	**2**
21	**Steel Tray**	Carbon Steel BS 970 080A42	METALEX	https://www.metalex.co.uk/metal-suppliers/steel/carbon-steel/bs970-080a42-080m40/	**24**
22	**Heater**	Silicone Heater Mat	RS COMPONENTS (RS 245-685)	https://uk.rs-online.com/web/p/silicone-heater-mats/0245685/	**40**
23	**Nuts**	Stainless Steel	RS COMPONENTS (RS 527-628)	https://uk.rs-online.com/web/p/hex-nuts/0527628/	**40**
24	**Bolts**	Stainless Steel	RS COMPONENTS (RS 508-0994)	https://uk.rs-online.com/web/p/hex-bolts/5080994/	**40**
25	**Insulation Cladding**	Rigid Polyisocyanurate	Insulation Express (CELOTEX GA4000)	https://www.insulationexpress.co.uk/celotex-ga4000-insulation-board	**3**
26	**Inner case panels (Cut into A, B, C and D)**	Stainless steel, austenitic, AISI 304L, annealed	Metal Warehouse (SSH-3.0)	https://www.metalswarehouse.co.uk/product/3-0mm-stainless-steel-sheet/	**4**
27	**Outer case panels (Cut into A, B, C and D)**	Stainless steel, austenitic, AISI 304L, annealed	Metal Warehouse (SSH-3.0)	https://www.metalswarehouse.co.uk/product/3-0mm-stainless-steel-sheet/	**4**

A.3. Other Components Bill of Material containing components outside of PCM and HE

PART N^{O}	NAME	SUPPLIER (CODE)	LINK/ SUPPLY	QTY
28	**Pump**	CPS (70220020000)	https://www.completepumpsupplies.co.uk/calpeda-ct60-a-peripheral-pump-3-phase	3
29	**Filter**	Cole-Palmer (7460452)	https://www.amazon.com/3990560-Suction-Strainer-stainless-74604-52/dp/B003LZVNL6	1
30	**Thermal Sensor**	OMNI (KTC-SURFACE-5MFL)	https://www.omniinstruments.co.uk/temperature-and-humidity/surface-mount-and-pipe-mount-temperature-sensors/k-type-thermocouple-surface-mount.html	1
31	**Logic Controls**	RS COMPONENTS (RS 917-6361)	https://uk.rs-online.com/web/p/logic-modules/9176361/	2
32	**Control Valve**	Flow IT (SDV3DC12NZ5LG38)	https://www.flowfitonline.com/hydraulic-valves/diverter-valves/flowfit-3-way-hydraulic-solenoid-diverter-38-bsp-port-size-12v-dc-80-lmin-flows	2

B : ROUTING SHEETS & OPERATIONS LIST (HE)

This section contains all routing sheets for the heat exchanger components. Some of these items are bought in as standard parts but then need to be secondary manufactured for general process.

B.1. Heat Exchanger Manufacturing Routing Sheets

Routing Sheet : End Shell			
QTY: 1	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 2**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of sheet metal	Laser cutter	Fixing bed
2	Bend sheet metal cut out to hemisphere shape	Fly press	Machine bed clamp

Routing Sheet: Input/ Output shell			
QTY: 1	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 3**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of sheet metal	Laser cutter	Fixing bed
2	Blank holes out of sheet metal for piping	Break press	Machine bed fixture
3	Bend sheet metal cut out to hemisphere shape	Break press	Machine bed fixture

Routing Sheet: Mounting Disks			
QTY: 4	**Material: Stainless steel 304L**		**Part No. 4**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cast mounting disks	Foundry and die cast	Sand and resin

Routing Sheet: Shell stands			
QTY: 3	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 5**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cast Shell stands	Foundry and sand casting	Sand and resin

Routing Sheet: Plates main section			
QTY: 1	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 6**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of sheet metal	Laser cutter	Fixing bed

Routing Sheet: Sub Plates A			
QTY: 4	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 7**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of sheet metal	Laser cutter	Fixing bed
2	Cut holes out of sheet metal	Laser cutter	Fixing bed

Routing Sheet: Sub Plates B			
QTY: 4	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 8**

Op No.	Description	Machinery required	Fixture
1	**Cut shape out of sheet metal**	**Laser cutter**	**Fixing bed**
2	**Cut holes out of sheet metal**	**Laser cutter**	**Fixing bed**

Routing Sheet: Copper Pipes			
QTY: 110	**Material: Copper BS EN 1057-R250**		**Part No. 9**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Blank smaller sections of standard pipe for bending	Break press	Fixing bed
2	Bend pipes to desired specification	Machine roller	Bending Die
3	Weld pipe sections together of s	Torch welding	Mechanical vice

Routing Sheet: Inlets/Outlets			
QTY: 4	**Material: Stainless steel 304L**		**Part No. 10**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cast inlets and outlets	Foundry and sand casting	Sand and resin

Routing Sheet: Gaskets			
QTY: 2	**Material: 0.4mm Klinger statire gasket sheet**		**Part No. 14**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Blank gasket shape for	Break press	Machine bed fixture

B.2. Heat Exchanger Assembly Routing Sheet

This is the total assembly routing sheet for the Heat exchanger to be assembled. This process would mostly be done manually due to the low volumes of production and complicated design. This process also would minimise the amount of capital investment would be required for manufacturing.

Assembly Routing Sheet: Heat exchanger general assembly			
Op No.	**Description**	**Machinery required**	**Fixture**
1	Weld shell stands to main tube section	Torch welding	Mechanical vice
2	Weld mounting disk to end shell	Torch welding	Local fit
3	Weld mounting disk to Input/ Output shell	Torch welding	Local fit
4	Weld mounting disks to main tube section	Torch welding	Local fit
5	Weld copper pipe sections together	Torch welding	Mechanical vice
6	Weld sub plates A to Plates main section	Torch welding	Mechanical Vice
7	Weld Inlets/Outlets onto Main tube section and input/output sell	Torch welding	General assembly
8	Weld rupture gasket onto main tube section	Torch welding	General assembly

9	Feed copper pipes through Sub plates sub assembly and Sub plates B	Mallet	Mechanical Vice
10	Place pipes sub assembly into main tube section	Bridge crane and press	Bed
11	Places Bolts into end shell		Bed
12	Place gasket onto end shell bolts		Bed
13	Place end shell sub assembly onto Main tube, aligning bolts into holes	Bridge crane	
14	Fasten nuts onto end shell sub assembly bolts	M20 Spanner	General assembly
15	Place gasket onto end shell bolts		Bed
16	Place Input/ Output shell sub assembly onto Main tube, aligning bolts into holes	Bridge crane	
17	Faster nuts onto end shell sub assembly bolts	M20 Spanner	General assembly

B.3. Heat Exchanger Operations List

Here is a list of the operations used to manufacture and assemble the heat exchanger.

Operations Sheet: Heat exchanger				
Op No.	**Description**	**Machinery required**	**Remarks**	**Fixture**
1	Casting	Foundry and sand casting	Compress sand to standard	Sand and resin
2	Laser cutting sheet metal	Laser cutter	0.05m/s cutting speed	Fixing bed
3	Blanking metal parts from sheet metal	Break Press	Correct tooling for each assembly	Fixing bed
4	Welding metal parts	Torch welding	MMA/SMA welding	Mechanical vice/ General assembly
5	Bending parts to shape	Machine roller	Correct die for pipe bending	Bending die
6	Feeding parts into Assembly	Mallet		Mechanical Vice
7	Place gasket and end shells	Bridge crane		Bed
8	Fasten nuts onto shell assembly bolts	M20 Spanner		General assembly

C : ROUTING SHEETS & OPERATIONS LIST (PCM)

C.1. PCM Manufacturing Routing Sheets

This section includes all the routing sheets for the PCM. It includes the manufacturing process of certain parts that need to be manufactured after purchasing it's raw material.

Routing Sheet: Inner case plate A			
QTY: 1	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 1**
Op No.	**Description**	**Machinery required**	**Fixture**
1	**Cut shape out of sheet metal**	**Laser cutter**	**Fixing bed**
2	**Drill holes for placement of nuts and bolts**	**Hand drill**	**Local fit**

Routing Sheet: Inner case plate B			
QTY: 1	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 2**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of sheet metal	Laser cutter	Fixing bed
2	Drill holes for placement of nuts and bolts	Hand drill	Local fit

Routing sheet: Inner case plate C			
QTY: 1	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 3**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of sheet metal	Laser cutter	Fixing bed
2	Drill holes for placement of nuts and bolts	Hand drill	Local fit

Routing sheet: Inner case plate D			
QTY: 1	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 4**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of metal	Lazer cutter	Fixing bed
2	Drill holes for placement of nuts and bolts	Hand drill	Local fit

Routing Sheet: Outer case plate A			
QTY: 1	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 5**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of sheet metal	Lazer cutter	Fixing bed
2	Bend corners of sheet metal	Break press	Machine bed fixture

Routing Sheet: Outer case plate B			
QTY: 1	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 6**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of sheet metal	Laser cutter	Fixing bed
2	Bend corners of sheet metal	Break press	Machine bed fixture

Routing sheet: Outer case plate C			
QTY: 1	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 7**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of sheet metal	Laser cutter	Fixing bed
2	Bend corners of sheet metal	Break press	Machine bed fixture

Routing sheet: Outer case plate D			
QTY: 1	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 8**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of metal	Lazer cutter	Fixing bed
2	Bend corners of sheet metal	Break press	Machine bed fixture

Routing sheet: Square plate			
QTY: 1	**Material: Stainless steel 304L sheet material 3mm**		**Part No. 9**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of metal	laser cutter	Fixing bed
2	Bend corners of sheet metal	Break press	Machine bed fixture

Routing Sheet: Encapsulation pipe			
QTY: 20	**Material: Aluminium, commercial purity, 1-0 sheet metal 2mm**		**Part No. 10**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of sheet metal	laser cutter	Fixing bed
2	Bend sheet metal cut out to cylindrical shape	Machine roller	Bending die
3	Weld the cylindrical shape so that it forms a pipe	Torch welding	Mechanical vice

Routing Sheet: Encapsulation end cover			
QTY: 40	**Material: Material: Aluminium, commercial purity, 1-0 sheet metal 2mm**		**Part No. 11**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of sheet metal	Lazer cutter	Fixing bed
2	Bend sheet metal cut out to half a hemisphere shape	Fly press	Machine bed clamp

Routing Sheet: Copper pipe			
QTY: 1	**Material: Copper BS EN 1057-R250**		**Part No. 12**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut length of 15mm copper pipe to specification	Laser cutter	Fixing bed

Routing Sheet: Copper Pipes Bend			
QTY: 16	**Material: Copper BS EN 1057-R250**		**Part No. 13**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Blank smaller sections of 16mm pipe for bending	Break press	Fixing bed

2	Bend pipes to desired specification	Machine roller	Bending Die

Routing Sheet: H beam			
QTY: 24	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 14**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut smaller sections of standard steel 'H beam'	Lazer cutter	Fixing bed
2	Weld square plate onto one end of H beam	Torch weld	Local fit
3	Drill holes for placement of nuts and bolts	Hand drill	Local fit

Routing Sheet: Main Copper pipe			
QTY: 2	**Material: Copper BS EN 1057-R250**		**Part No. 15**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut length of 60mm copper pipe to specification	Laser cutter	Fixing bed
2	Drill 4 holes through the copper pipe	Hand drill	Mechanical vice

Routing Sheet: I - Beam Mount			
QTY: 24	**Material: Stainless steel 304L sheet metal 3mm**		**Part No. 16**
Op No.	**Description**	**Machinery required**	**Fixture**
1	Cut shape out of sheet metal	Lazer cutter	Fixing bed
2	Drill holes for placement of nuts and bolts	Hand drill	Local fit

C.2. PCM Routing Sheet

This is the total assembly routing sheet for the PCM to be assembled.

Routing Sheet: PCM assembly			
Op No.	**Description**	**Machinery required**	**Fixture**
1	Weld an encapsulation cap on one end of the encapsulation pipe	Torch welding	Local fit
2	Put a copper pipe through the cap from op no 1 and weld the copper pipe to the cap.	Torch welding	Local fit
3	Fill the encapsulation pipe from op 2 with the PCM material	Funnel	General assembly
4	Weld the encapsulation cap to top of encapsulation pipe	Torch welding	Local fit
5	Weld copper pipe to the encapsulation cap from op no 4 to form an encapsulation sub assembly	Torch welding	Local fit
6	Weld case plate sections together to form a plate sub assembly	Torch welding	Mechanical Vice

7	Fill each case plate section with insulation material.	Foam applicator	General assembly
8	Weld tray mount to H beam	Torch welding	Local fit
9	Place bolt through back plate subassembly and H beam mount		Bed
10	Fasten bolts on back plate assembly from op no 8 with nuts.	Spanner M20	Bed
11	Weld plate sub-assemblies together to form a case sub assembly	Torch welding	Mechanical Vice
12	Weld copper pipe bends to encapsulation sub-assembly	Torch welding	Local fit
13	Weld 60mm copper pipe to encapsulation sub assembly	Torch welding	Local fit
14	Feed encapsulation sub-assemblies into the case sub assembly		Bed
15	Feed heater into H beam tray		Bed
16	Place gasket onto end shell bolts		Bed

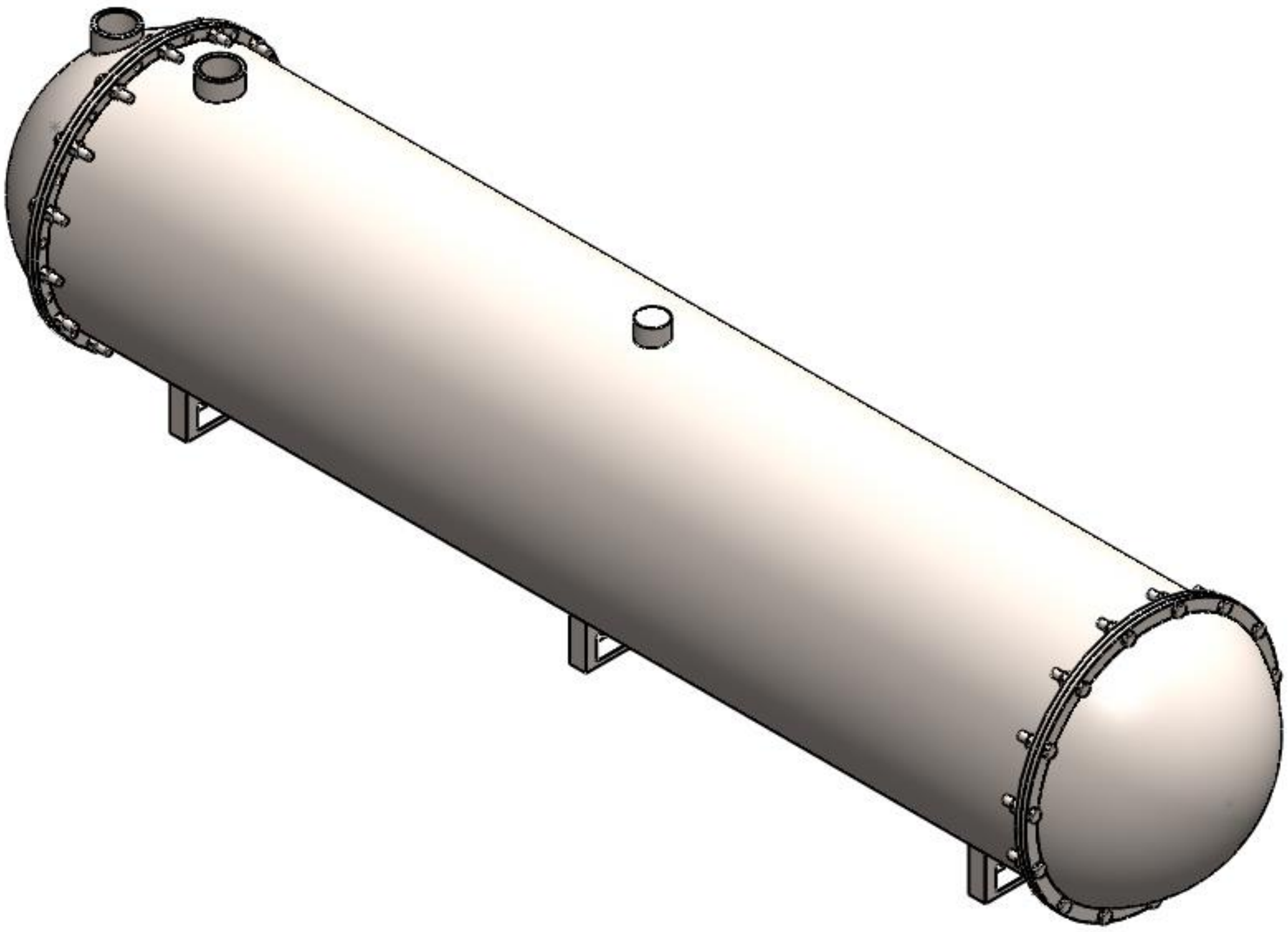
C.3. PCM Operations List

Here is a list of the operations used to manufacture and assemble the PCM.

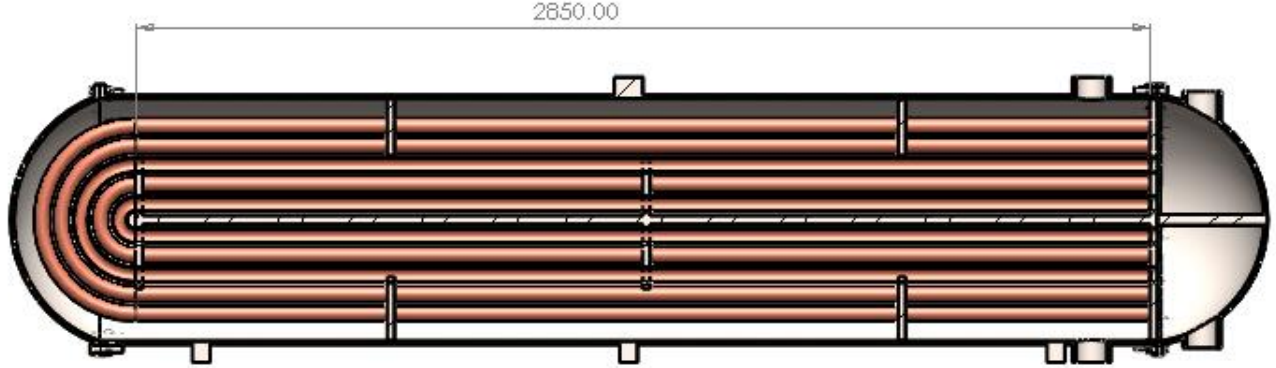
Operations sheet: Heat exchanger				
Op No.	**Description**	**Machinery required**	**Remarks**	**Fixture**
1	Laser cutting sheet metal	Laser cutter	0.05m/s cutting speed	Fixing bed
2	Blanking metal parts from sheet metal	Break Press	Correct tooling for each assembly	Fixing bed
3	Welding metal parts	Torch welding	MMA/SMA welding	Mechanical vice/ General assembly
4	Bending parts to shape	Machine roller	Correct die for pipe bending	Bending die
5	Feeding parts into Assembly	Mallet		Mechanical Vice
6	Fasten nuts onto H beam and back plate bolts	M20 Spanner		Bed

D: PARTS & ASSEMBLY DRAWINGS

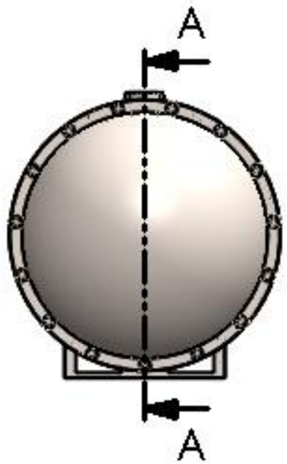
On the following pages a number of parts and assembly drawings will be presented.

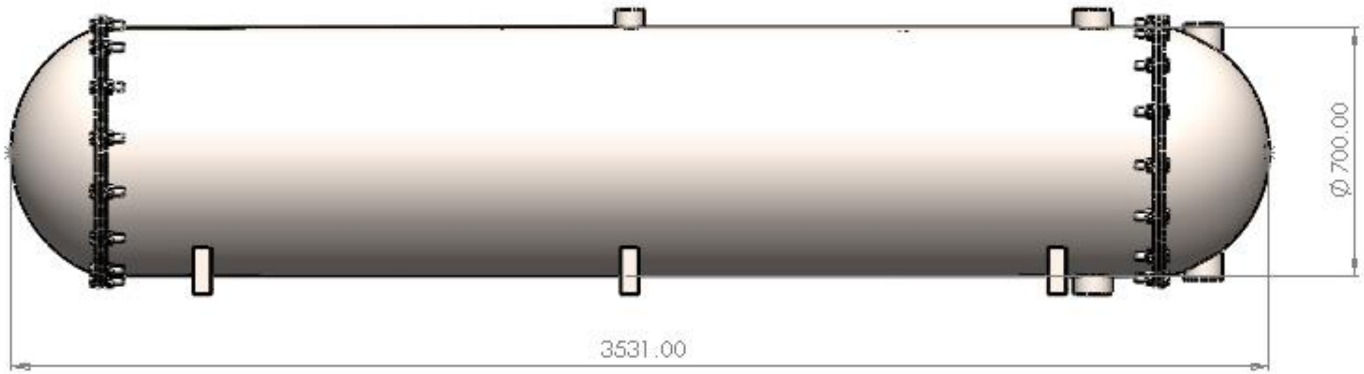


FINISH TO BS 1134: ALL OVER UNLESS WHERE STATED THREADS TO BS 3692	TOLERANCE DIMENSIONAL: ±0.25 mm ANGULAR: ±0.10 ° UNLESS OTHERWISE STATED	MATERIAL SHEET NO: 1 of 1 STANDARD : BS 8888	PROJECTION	DRAWN: Peter Thomas DATE: 27/02/2020 CHECKED: EN DATE: 05/03/2020	ORIGINAL SCALE 1:10	ALL DIMENSIONS IN mm General Assembly Heat exchanger	DRG NO. 1 WEIGHT: 1584 kg

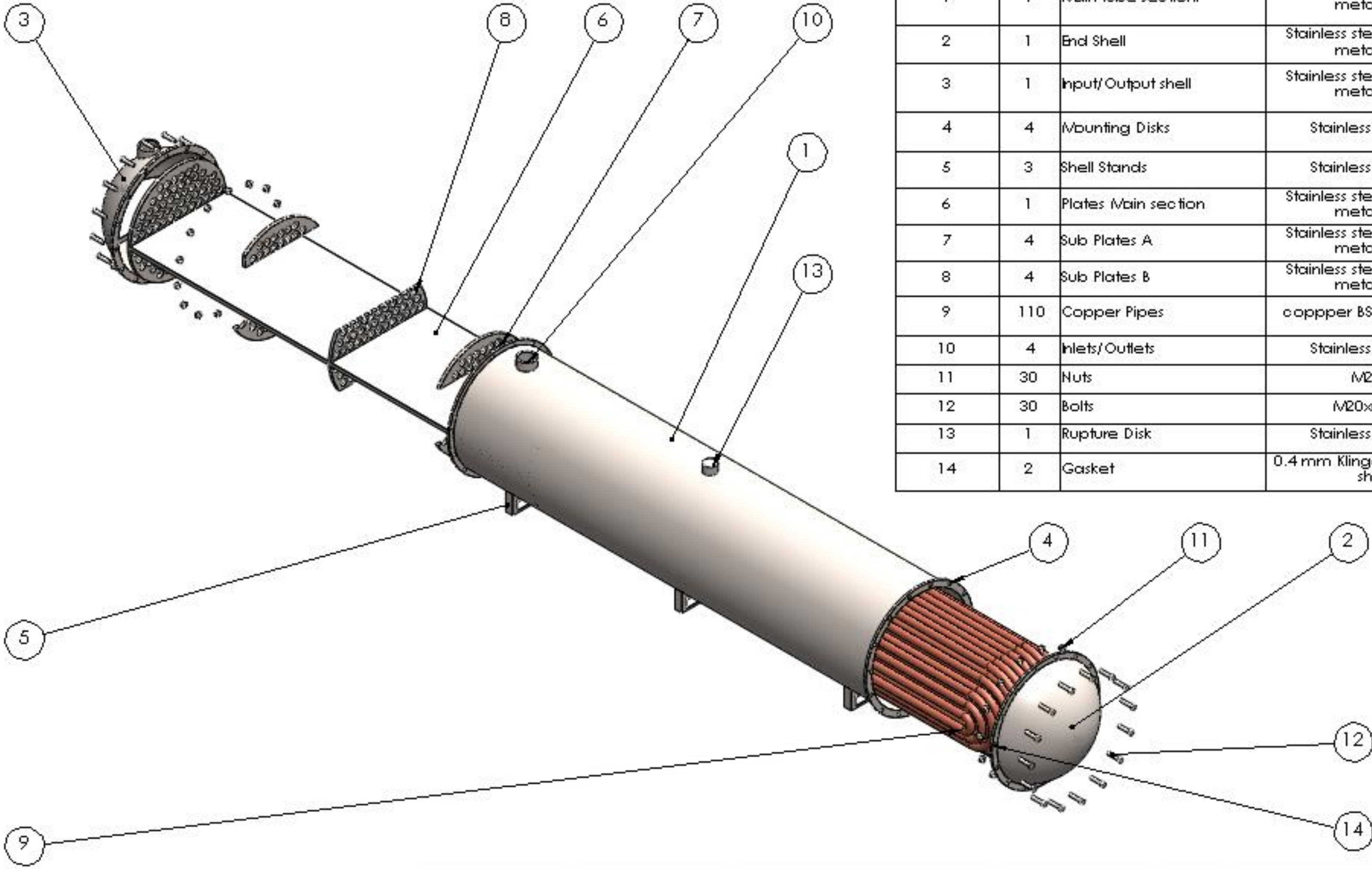


SECTION A-A



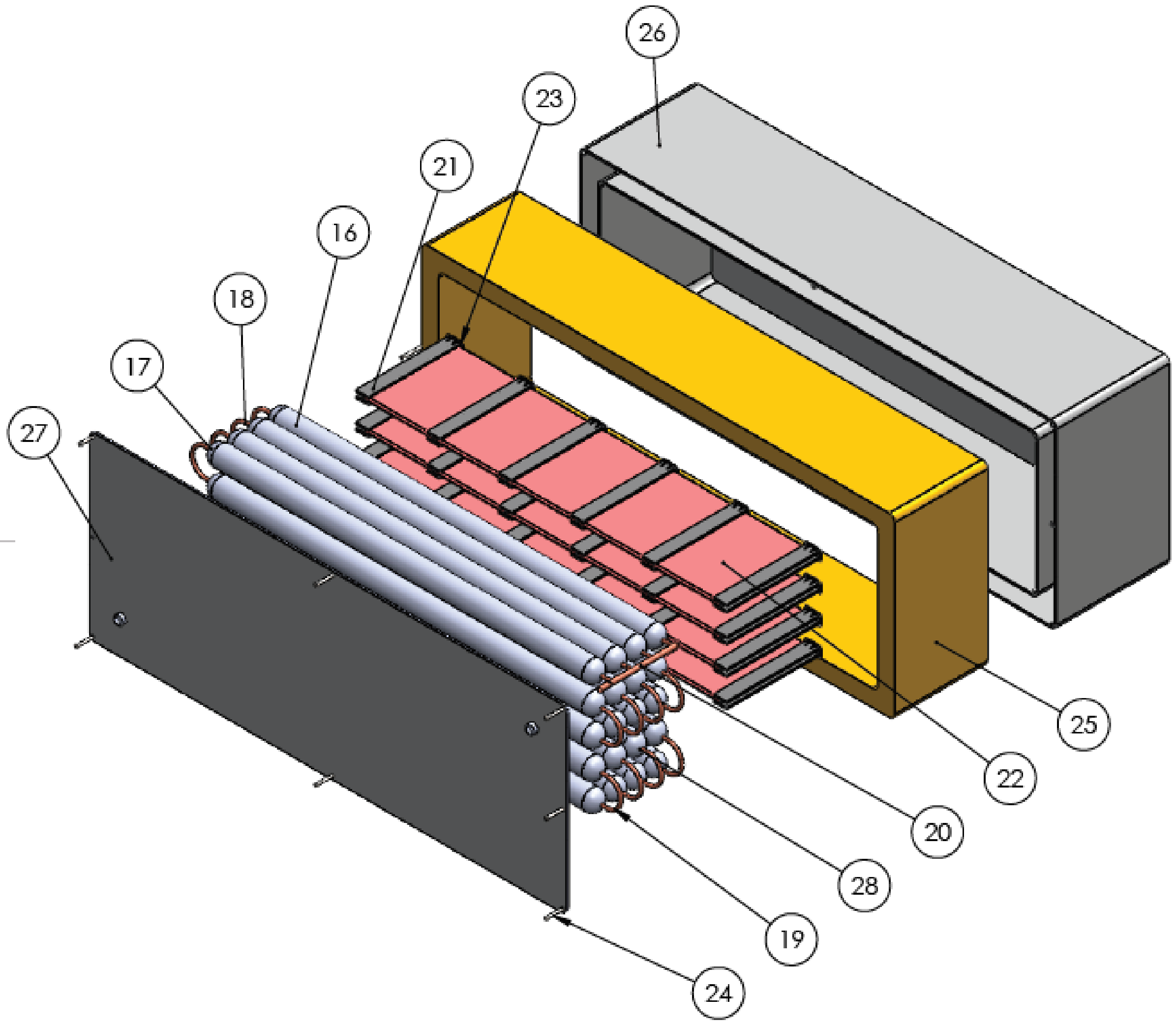


FINISH TO BS 1134: ALL OVER UNLESS WHERE STATED THREADS TO BS 3692	TOLERANCE DIMENSIONAL: ±0.25 mm ANGULAR: ±0.10 ° UNLESS OTHERWISE STATED	MATERIAL SHEET NO: 1 of 1 STANDARD : BS 8888	PROJECTION	DRAWN: Peter Thomas DATE: 27/02/2020 CHECKED: EN DATE: 05/03/2020	ORIGINAL SCALE 1:15	ALL DIMENSIONS IN mm General drawing | DRG NO. 1 Heat exchanger | WEIGHT: 1584 kg



ITEM NO.	Quantity	PART Name	Material/description
1	1	Main tube sectionl	Stainless steel 304L Sheet metal 3mm
2	1	End Shell	Stainless steel 304L Sheet metal 3mm
3	1	Input/ Output shell	Stainless steel 304L Sheet metal 3mm
4	4	Mounting Disks	Stainless steel 304L
5	3	Shell Stands	Stainless steel 304L
6	1	Plates Main section	Stainless steel 304L Sheet metal 3mm
7	4	Sub Plates A	Stainless steel 304L Sheet metal 3mm
8	4	Sub Plates B	Stainless steel 304L Sheet metal 3mm
9	110	Copper Pipes	coppper BS EN 1057-R250
10	4	Inlets/ Outlets	Stainless steel 304L
11	30	Nuts	M20 - N
12	30	Bolts	M20x60x60C
13	1	Rupture Disk	Stainless steel 304L
14	2	Gasket	0.4 mm Klinger statire gasket sheet

FINISH TO BS 1134: Ferror: broken Inc ALL OVER UNLESS WHERE STATED THREADS TO BS 3692	TOLERANCE DIMENSIONAL: ±0.25 mm ANGULAR: ±0.10° UNLESS OTHERWISE STATED	MATERIAL SHEET NO: 1 of 1 STANDARD : BS 8888	PROJECTION	DRAWN: Peter Thomas DATE: 27/02/2020 CHECKED: EN DATE: 06/03/2020	ORIGINAL SCALE 1:15	ALL DIMENSIONS IN mm Exploded View Heat exchanger	DRG NO. 1 WEIGHT: 1584 kg



ITEM NO.	QTY	PART NAME	DESCRIPTION (SUPPLIER CODE)
16	20	ENCAPSULATION PIPE	ALUMINIUM, 6082, T6 (METALS4U: 2815)
17	40	ENCAPSULATION END COVER	ALUMINIUM, 6082, T6 (AALCO: 6082-T6-T651)
18	20	COPPER PIPE	15 mm
19	16	COPPER PIPE BEND	15 mm
20	2	COPPER PIPE	22 mm
21	24	STEEL TRAY	CARBON STEEL BS 970 080A42
22	40	SILICONE HEATER MAT	RS COMPONENTS (RS 245-685)
23	96	M10 NUTS	RS COMPONENTS (RS 527-628)
24	104	M10 BOLTS	RS COMPONENTS (RS 508-0994)
25	1	INSULATION CLADDING	CELLOTEX (GA4000)
26	1	CASING	STAINLESS STEEL AISI 304L
27	1	COVER	STAINLESS STEEL AISI 304L
28	40	GASKETS	NITRILE BUTADIENE RUBBER

FINISH TO BS 1134:
ALL OVER UNLESS WHERE STATED

THREADS TO BS 3692

TOLERANCE
DIMENSIONAL: ±0.25 mm
ANGULAR: ±0.10°
UNLESS OTHERWISE STATED

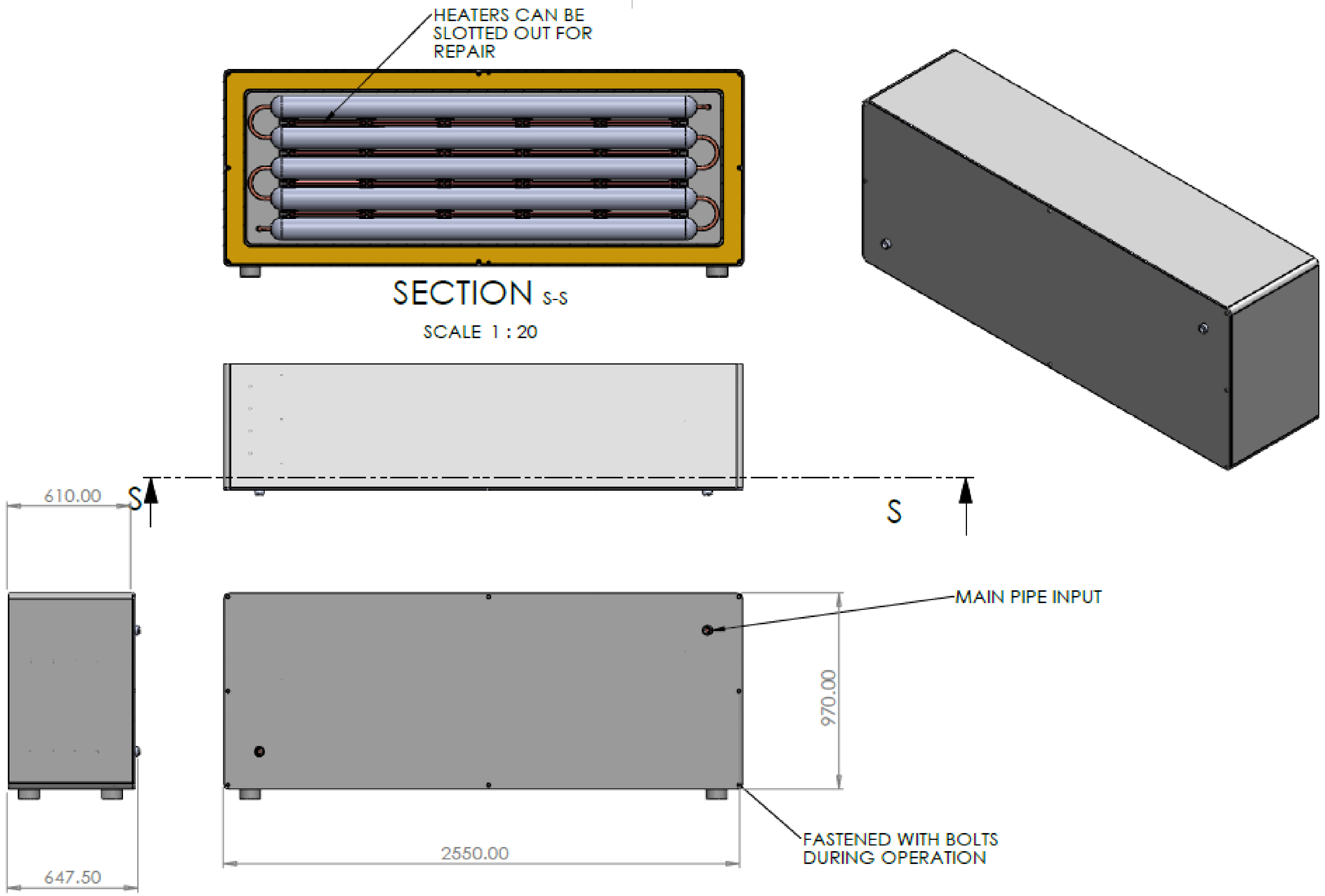
MATERIAL: -
SHEET NO: 1 of 6
STANDARD : BS 8888

PROJECTION

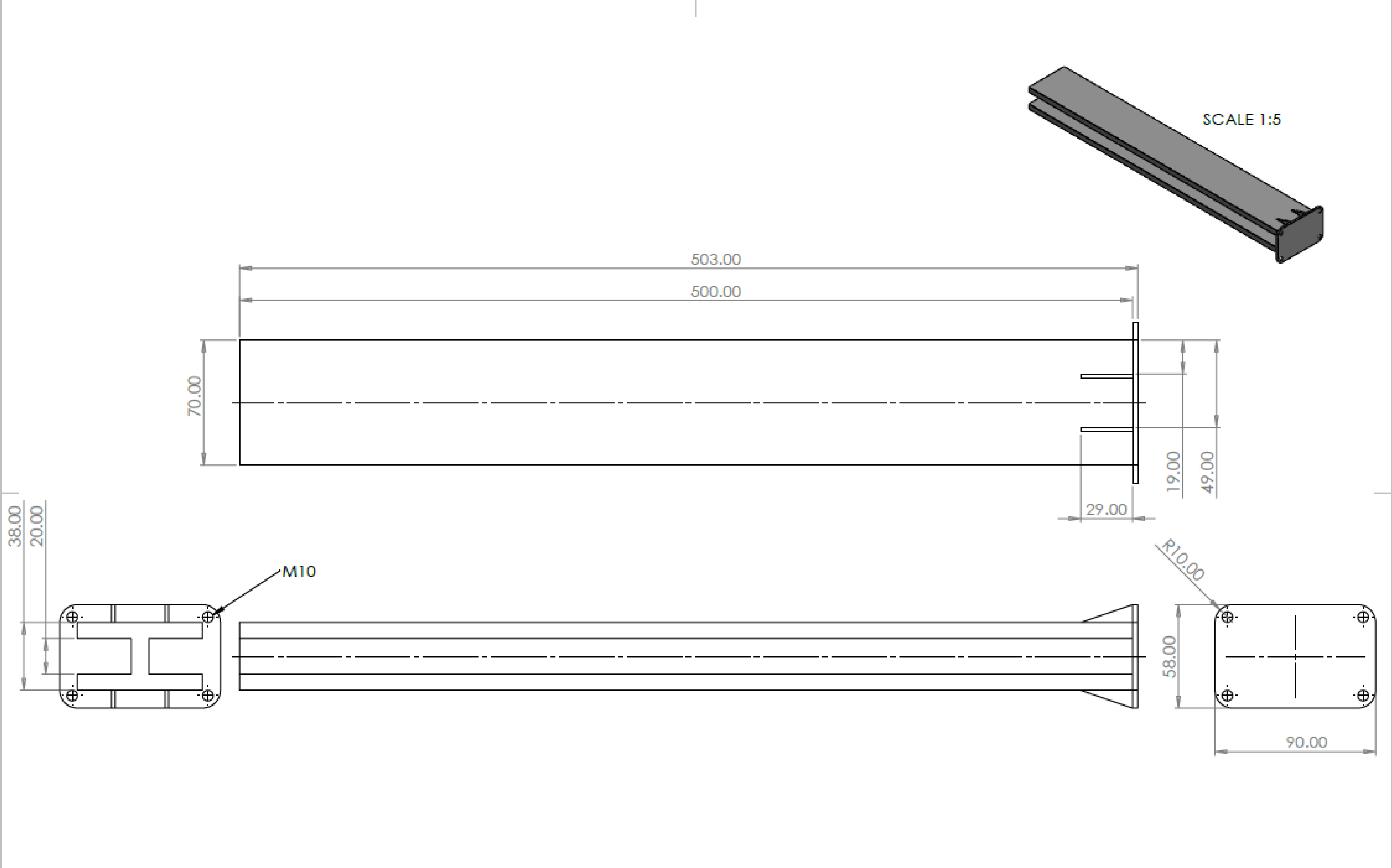
DRWN: Vinush Vigneswaran
DATE: 10/03/2020
CHECKED: EN
DO NOT SCALE DRAWING

SCALE
1:20
PAGE SIZE:
A4

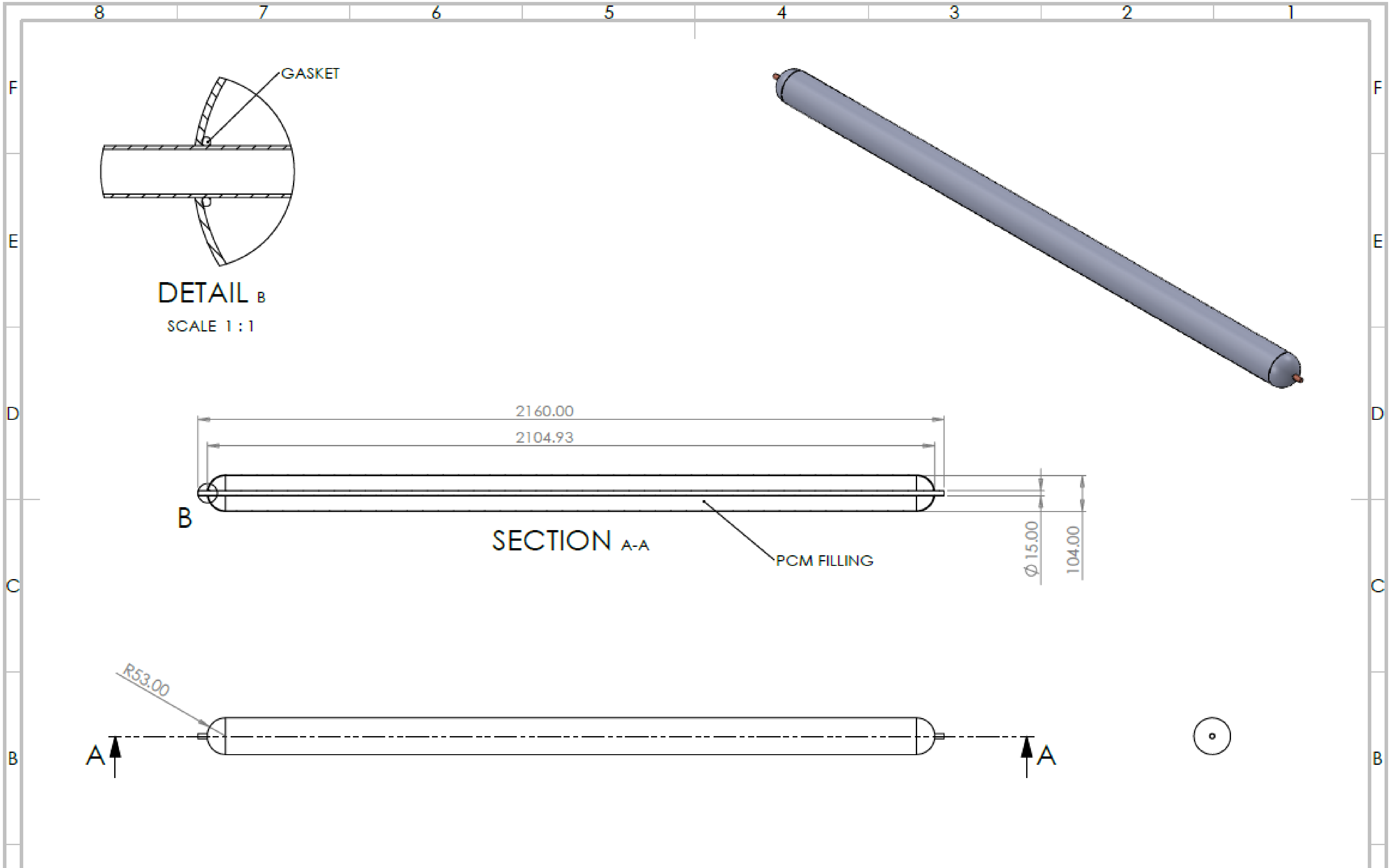
ALL DIMENSIONS IN mm
Exploded View
DRG NO.
1
PCM Unit
WEIGHT:
1083 kg



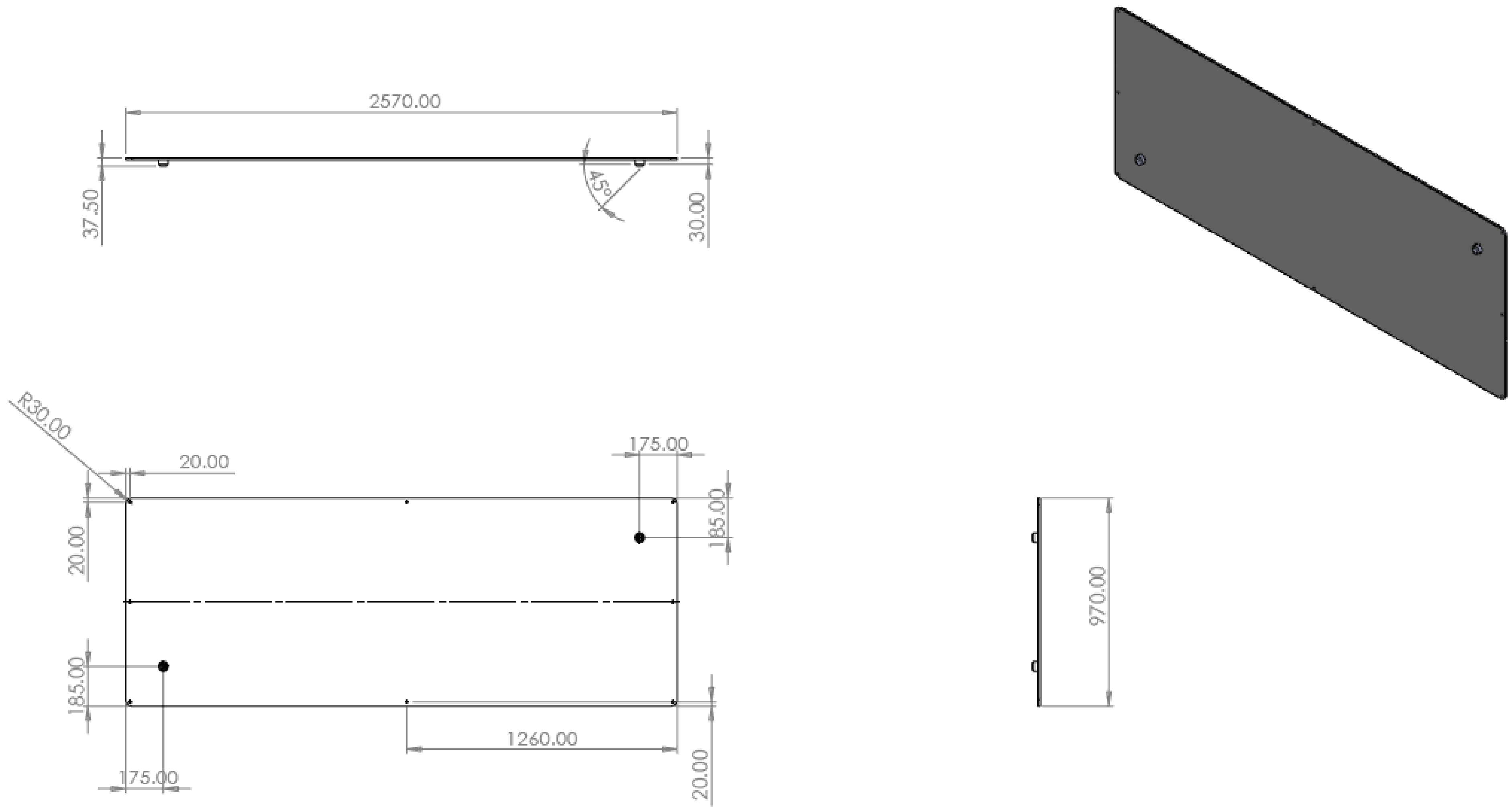
FINISH TO BS 1134: ALL OVER UNLESS WHERE STATED	TOLERANCE	MATERIAL: -	PROJECTION	DRWN: Vinush Vigneswaran	SCALE 1:20	ALL DIMENSIONS IN mm	
THREADS TO BS 3692	DIMENSIONAL: ±0.25 mm	SHEET NO: 2		DATE: 10/03/2020	PAGE SIZE: A4	General Drawing	DRG NO. 2
	ANGULAR: ±0.10°	STANDARD : BS 8888		CHECKED: EN		PCM Unit	WEIGHT: 1083 kg
	UNLESS OTHERWISE STATED			DO NOT SCALE DRAWING			



FINISH TO BS 1134: ALL OVER UNLESS WHERE STATED	TOLERANCE	MATERIAL: CARBON STEEL BS 970 080A42	PROJECTION	DRWN: Vinush Vigneswaran	SCALE 1:2	ALL DIMENSIONS IN mm	
	DIMENSIONAL: ±0.25 mm			DATE: 10/03/2020		PART 21	DRG NO. 3
THREADS TO BS 3692	ANGULAR: ±0.10°	SHEET NO: 3		CHECKED: EN	PAGE SIZE: A4		
	UNLESS OTHERWISE STATED	STANDARD : BS 8888		DO NOT SCALE DRAWING		STEEL TRAY	WEIGHT: 5.9 kg



FINISH TO BS 1134: ALL OVER UNLESS WHERE STATED	TOLERANCE	MATERIAL: -	PROJECTION	DRWN: Vinush Vigneswaran	SCALE 1:10	ALL DIMENSIONS IN mm	
	DIMENSIONAL: ±0.25 mm			DATE: 10/03/2020		GENERAL DRAWING	DRG NO. 4
THREADS TO BS 3692	ANGULAR: ±0.10°	SHEET NO: 4		CHECKED: EN	PAGE SIZE: A4	ENCAPSULATION SUBASSEMBLY	WEIGHT: 5.9 kg
	UNLESS OTHERWISE STATED	STANDARD : BS 8888		DO NOT SCALE DRAWING			



FINISH TO BS 1134: ALL OVER UNLESS WHERE STATED THREADS TO BS 3692	TOLERANCE DIMENSIONAL: ±0.25 mm ANGULAR: ±0.10° UNLESS OTHERWISE STATED	MATERIAL: STAINLESS STEEL AISI 304L SHEET NO: 6 STANDARD : BS 8888	PROJECTION	DRWN: Vinush Vigneswaran DATE: 10/03/2020 CHECKED: EN DO NOT SCALE DRAWING	SCALE 1:20 PAGE SIZE: A4	ALL DIMENSIONS IN mm PART 27 — DRG NO. 6 COVER — WEIGHT: 200 kg

E: SUMMARY OF MINUTES

	Agenda	Actions	Attendance
Group Meeting 1 & 2	• Group will be divided into sub-groups focusing on PCM, HE and integration • Gather information on water flow in UK pipes, amount of water required to be heated in university accommodation • Decisions on the type of Heat Exchanger and what values are required to start calculations	• References to journals were recorded on a shared document • Tasks were allocated to each member (two members on PCM research and development, and three members on HE) • Research on heat exchanger, flow type and LMTD was conducted	100%
Group Meeting 3 & 4	• Calculate the length of the pipes needed for the heat exchanger • Calculate the amount of water to be processed by heat exchanger and PCM • Find PCM material , and the configuration type of PCM unit • Make decisions on how to control the flow from the main supply to air-sourced heat pump	• Matlab code was written and checked by other team members, and Chemical Engineers for the HE length calculation • The length was not feasible and hence a different configuration was considered; double by-pass • PCM unit configuration of cylindrical encapsulation with heaters were finalised • Started report writing and recording calculation method	100%
Group Meeting 5 & 6	• Calculate PCM thickness and length required • Calculated heater requirement • Evaluate HE design for further turbulent flow • Start modelling HE and PCM on Simulink to validate calculations	• Discussed with our supervisor, regarding the PCM calculations and was advised to separate the calculations into two parts: Charging and Discharging. Also received more resources for calculation and validation • Simulink sub-systems were designed based on the calculations used for heat exchanger design • PCM and encapsulation material was finalised • HE CAD model was designed	100%

Group Meeting 7 & 8	• Evaluate and analyse CAD design of HE • Finish calculations for PCM charging and discharging • Complete Simulink model • Validate flow calculations and thermal conductivity using Solidworks Flow Simulation	• Further discussions with supervisor to ensure PCM calculation were correct, and to ensure design were feasible. Comments were noted and improved upon. • Simulink model were finalised and graphical results exported into the report • Flow simulation were conducted, and cross referenced with hand-calculations and iterative calculations • Thermal conductivity of PCM was too low, hence had to consider methods to increase thermal conductivity whilst maintain latent heat of PCM. • PCM unit CAD design was finalised, with calculations of charging and discharging finished	100%
Group Meeting 9 & 10	• Final draft of report to be completed • Final draft of drawings and bill of materials to be completed • Routing and operations list to be completed • Engineering implications analysed as a group and evaluated • Product costs and team integration discussed	• Exploded view, general drawing, assembly drawing and parts drawing completed by two members of the group • Calculations checked over, figures and references correctly formatted into report • Each member reviewed the full report, including costs, engineering implications, routing sheets, and technical evaluation. • Team discussion about feasibility of integration, report completion, and progress analysis.	100%

F: GANTT CHART

ID		Task Mode	Task Name	Duration	Start	Finish
1			**WP1 : Initial design phase**	**14 days**	**Mon 14/10/19**	**Thu 31/10/19**
2			Define key requirements	4 days	Mon 14/10/19	Thu 17/10/19
3			idea formation	5 days	Thu 17/10/19	Wed 23/10/19
4			Background research of ideas	7 days	Wed 23/10/19	Thu 31/10/19
5			**WP2: Presentation**	**6 days**	**Fri 01/11/19**	**Fri 08/11/19**
6			Two concept designs produced	2 days	Fri 01/11/19	Sun 03/11/19
7			Gantt chart and powerpoint creation	3 days	Fri 01/11/19	Tue 05/11/19
8			Writing script and preparation	4 days	Mon 04/11/19	Thu 07/11/19
9			Actual presentation	1 day	Fri 08/11/19	Fri 08/11/19
10			Milestone 1	0 days	Fri 08/11/19	Fri 08/11/19
11			**WP3: Development, analysis and selection of concept designs**	**11 days**	**Fri 08/11/19**	**Fri 22/11/19**
12			Key characeristics and benefits listed for both concepts	2 days	Fri 08/11/19	Sun 10/11/19
13			Calculations performed for both concepts	11 days	Sat 09/11/19	Fri 22/11/19
14			Comparison and analysis of features for both concepts	3 days	Sun 17/11/19	Tue 19/11/19
15			Selection of desired concept to move forward with	3 days	Wed 20/11/19	Fri 22/11/19
16			Milestone 2	0 days	Fri 22/11/19	Fri 22/11/19
17			**WP4: Initial report**	**16 days**	**Fri 22/11/19**	**Fri 13/12/19**
18			First draft	7 days	Fri 22/11/19	Mon 02/12/19
19			Review	3 days	Tue 03/12/19	Thu 05/12/19
20			Final version	6 days	Thu 05/12/19	Thu 12/12/19
21			Milestone 3	0 days	Thu 12/12/19	Thu 12/12/19
22			**WP5: Solidworks development**	**57 days**	**Thu 28/11/19**	**Fri 14/02/20**
23			Feedback integrated into chosen design	12 days	Thu 28/11/19	Fri 13/12/19
24			Development of design including incorporation of newfound idea	15 days	Mon 13/01/20	Fri 31/01/20
25			Review and analysis of design	6 days	Fri 31/01/20	Fri 07/02/20
26			Final changes made and cost list for parts with suppliers created	6 days	Sat 08/02/20	Fri 14/02/20
27			Milestone 4	0 days	Fri 14/02/20	Fri 14/02/20
28			**WP6: Presentation 2**	**8 days**	**Wed 12/02/20**	**Fri 21/02/20**
29			Powerpoint creation and script writing	7 days	Wed 12/02/20	Thu 20/02/20
30			Preparation	5 days	Thu 20/02/20	Wed 26/02/20
31			Actual presentation	3 days	Wed 26/02/20	Fri 28/02/20
32			Milestone 5	0 days	Fri 28/02/20	Fri 28/02/20
33			**WP7: Final report**	**49 days**	**Fri 28/02/20**	**Wed 06/05/20**
34			Write up of calculations	19 days	Fri 28/02/20	Wed 25/03/20
35			Description of requirements met	14 days	Thu 12/03/20	Tue 31/03/20
36			Team integration summary	6 days	Wed 01/04/20	Wed 08/04/20
37			Engineering drawings	26 days	Fri 20/03/20	Fri 24/04/20
38			First draft	1 day	Fri 24/04/20	Fri 24/04/20
39			Review	2 days	Fri 24/04/20	Mon 27/04/20
40			Final draft and submission	8 days	Mon 27/04/20	Wed 06/05/20
41			Milestone 6	0 days	Wed 06/05/20	Wed 06/05/20