UNIVERSITY OF MANITOBA

DESIGN REPORT

High Precision Composite Mould Design

Composites Innovation Centre

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Submitted by Team 21: “*Fusion Designs*” on December 6, 2010

to fulfill, in part, the requirements of MECH4860: Engineering Design.

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Abstract

The purpose of this project is to design a high precision composite panel moulding system to improve the manufacturing process currently used by Composites Innovation Centre. The current method uses two flat aluminum plates sealed by disposable tacky tape to house the reinforcement fibre. The plates are adjusted to the desired height by means of set screws and feeler gauges. Resin is infused into the fibres by suction through a vacuum port, and left to cure. Problems associated with the current design include repeatability, time of set up, consumable cost, low fibre volume fractions and lack of heating ability.

This project aims to design an improved moulding system by addressing the height adjustment, sealing, and heating systems. The goal is to make the process as automated as possible to eliminate variability between users. High accuracy is achieved by incorporating feedback control to automatically adjust the mould to a specified position using a graphical interface. A mechanical screw jack actuator system is capable of providing large closing force, allowing higher fibre volume fractions to be produced. Electric strip heaters and insulation heat the specimen uniformly without interfering with other systems. Finally, a custom reciprocating seal effectively closes the mould cavity while allowing for adjustment over the range of anticipated panel thicknesses.

Analysis is conducted using both finite element techniques and hand calculations for heat transfer, plate deflection, and stresses to ensure that these values fall within an acceptable range. A break-even analysis based on possible manufacturing times was conducted and the mould is expected to pay for itself after producing between 204 and 507 panels (one and two hour manufacturing times respectively).

Recommendations for further research are to build a prototype to verify sealing system and expected accuracy, and to conduct time studies to find an exact break-even point.

1.0 Introduction

Composites Innovation Center (CIC) is a not-for-profit corporation that provides a range of services to their clients. These services vary from project management oriented tasks to laboratory testing and research activities [1]. The scope of the current project lies within the laboratory materials testing aspect of the corporation. CIC provides a variety of material testing services to their clients, and the manufacture of test panels is an integral part of this service. Currently, CIC employs a rigid mould vacuum infusion technique to manufacture flat test panels measuring approximately 20cm x 20cm. Each test panel provides an assortment of test specimens (such as dog-bone shape) which are later subjected to physical testing.

Unlike metals/alloys, plastics, and other homogenous materials, composites are made up of more than one discernable material. Due to this fact, many properties of composite materials vary according to the fraction of the material which is resin (matrix) and that which is reinforcement (fibre), a property described as a material's "fibre volume fraction". The mechanical properties of each component often vary by orders of magnitude, and the fibre volume fraction helps to predict whether the properties of the composite will be closer to that of the matrix or the reinforcement. Thus, it is extremely desirable to have a great degree of control over the fibre volume fraction when characterizing the properties of a material in a laboratory setting.

The current method developed in-house employs a flat panel rigid mould vacuum infusion technique that is similar to Lite RTM (Resin Transfer Moulding); however, unlike Lite RTM, strict control over the volume fraction is maintained. To accomplish this, the system employs a variable thickness mould cavity. By adjusting the volume of the mould cavity, the system is able to distribute more or less resin to the same reinforcing fibre layers. The current mould setup is shown below in Figure 1.

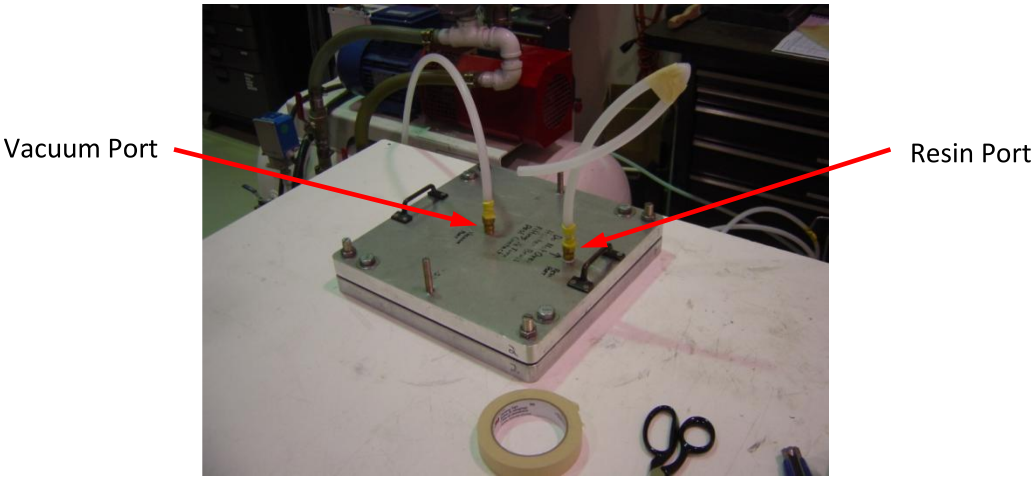


Figure 1. Current method of moulding panels, with mould closed and vacuum applied.

The mould consists of two thick aluminum plates which are set a precise distance (2-5mm) apart using four set screws and feeler gages. The space between the two plates forms the mould cavity and contains the fibre reinforcement layers. A sealant layer applied between the panels forms the outside edges of the cavity and allows for the application of vacuum pressure via a hose passing through the top plate. A second hose in the top plate pulls resin into the cavity using vacuum pressure and wets out the fibre reinforcement layers, which are shown below in Figure 2.

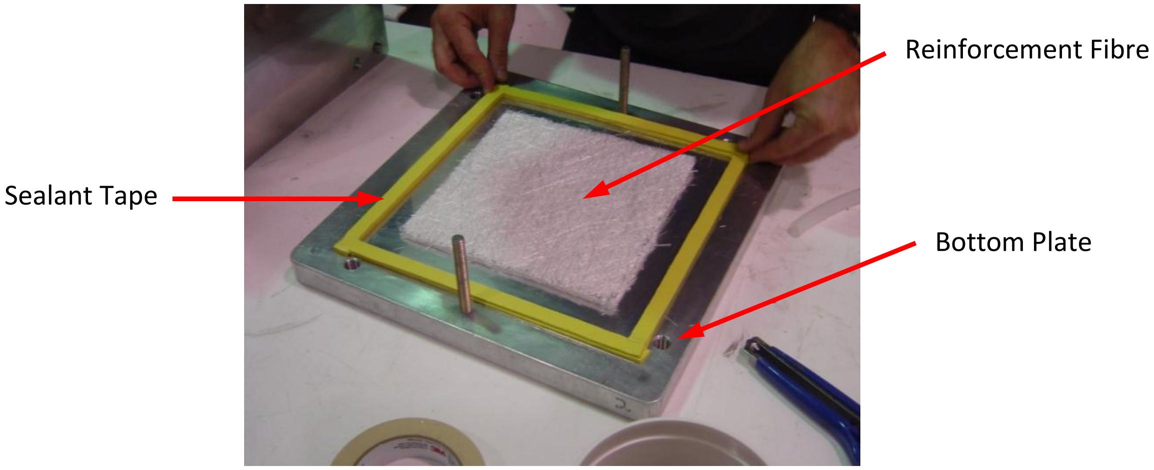


Figure 2. Open bottom plate of current mould with reinforcement in place.

Several problems exist with the current method. Firstly, the current method is tedious and time consuming to setup accurately because of the set screws, and does not provide consistent results - especially between users. Secondly, this process generates excessive waste due to the disposable seals, also shown in Figure 2. Finally, the mould must be heated using an oven in situations requiring elevated temperatures; transferring the mould between locations is inconvenient. The ideal design addresses all of these issues.

The required design must produce a flat composite panel 2-5mm in thickness while achieving a repeatability of 0.01mm with minimal variation between users. The desired panel size is 15.2cm x 45.7cm (for flammability testing, according to ASTM E162 [2]). The fibre volume fraction capability of the mould must at least match the current volume fraction of 30%; however, it would be desirable to achieve volume fractions up to 50%.

The “quality” of the panel describes the degree of wetting and presence of voids or defects. A high quality panel with good resin saturation and minimum voids or defects is absolutely critical. The panel must meet these specifications while simultaneously conforming to manufacturing specifications, namely that the manufacturing procedure should be easy to follow and faster than the current method (with a baseline of 3 panels per 8 hour shift [3]).

In order to reach the target specifications for the panels,

- The material used in the mould must be rigid enough to deflect less than 0.01mm over the mould surface during operation. This rigidity ensures that the flatness of the panel is not affected by deformation of the mould plate.
- The mould cavity must be properly sealed. An effective seal allows the mould cavity to hold vacuum pressure, which improves the quality of the panel. The seal must be compatible with the expected operating environment, including temperature and chemical exposure.
- The operating temperature of the mould is important to consider since the cure cycle for several resins occurs at elevated temperatures. The target specification for the temperature is 180°C and represents the highest temperature used in the curing cycles.
- Lastly, the cost to manufacture could be a deciding factor when choosing whether to implement the design and the design is considered feasible if the cost is kept below $10,000.

The ideal design meets all of the target specifications above, and improves the manufacturing process by producing an easy to use, consistent, and fully integrated system for the manufacture of flat composite panels.

2.0 Design Summary

The current design improves on many aspects of the current method of composite panel fabrication. The new technique is expected to reduce setup time, improve usability, produce a higher quality laminate in a larger range of volume fractions, eliminate user variability, integrate heating capabilities, and reduce consumables.

The general moulding technique draws on characteristics of both vacuum resin transfer (VaRTM) and compression moulding. The mould cavity is infused with resin through a resin port using vacuum pressure, and the mould is compressed to the final thickness using high force, squeezing out excess resin. This compression step helps to achieve the higher fibre volume fraction (50% or higher) that the client desires. The design team was unable to find any references to this particular technique, but similar processes have been used which employ positive pressure injection (instead of vacuum) with compression [4].

The image below shows the complete mould assembly. There are several important features to note before describing each section in detail. In general, the assembly consists of the two upper plates (which make up the mould cavity), guide shafts, servo-driven mechanical actuators (screw jacks), electric heaters, and an integrated control system (not shown) [5].

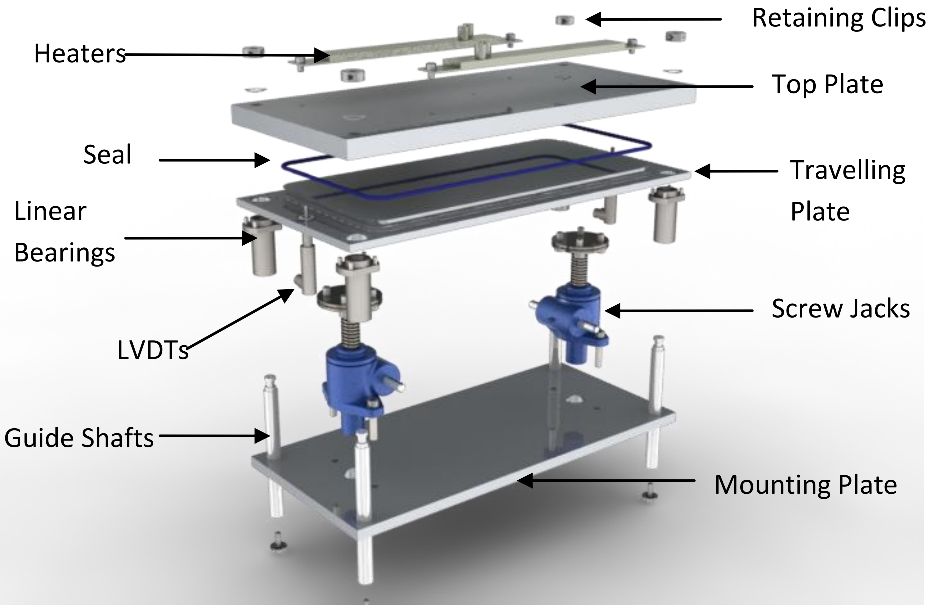


Figure 3. Exploded complete mould assembly isometric view.

An outline of the proposed procedure appears below to clarify the function of each component.

- The user places reinforcement fibre in the cavity between the two plates and closes the mould (using a graphical interface) so that the seal along the edge of the mould cavity engages.
- The air is removed from the cavity by closing the resin port and applying vacuum pressure to the vacuum port.
- Resin is infused into the mould cavity through the resin port.

Up to this point, the procedure is similar to the current method used at CIC, except that the motion of the plate is controlled using a graphical interface and feedback controlled electric motor.

- If a higher volume fraction is required, the user may close the mould using up to 18kN of force in addition to the vacuum pressure already applied (which could exert approximately 10kN over the plate surface). This additional step is optional, and provides the user with a great deal of flexibility in fibre volume fraction.

The following sections describe each of the individual components previously mentioned. Refer to Appendices B-E for detailed analysis or specification sheets for any of the components.

2.1 Mould Cavity

The mould cavity consists of sealed upper and lower dies that slide together under vacuum pressure. Details of the mould dies and sealing system follow in sections 2.1.1 and 2.1.2.

2.1.1 Upper and Lower Dies

The mould cavity shown in Figure 4 consists of a travelling plate and a top plate secured to guide shafts using retaining clips. Each plate is machined from stainless steel (alloy 410), which provides a good balance between strength, corrosion resistance, and machinability [6].

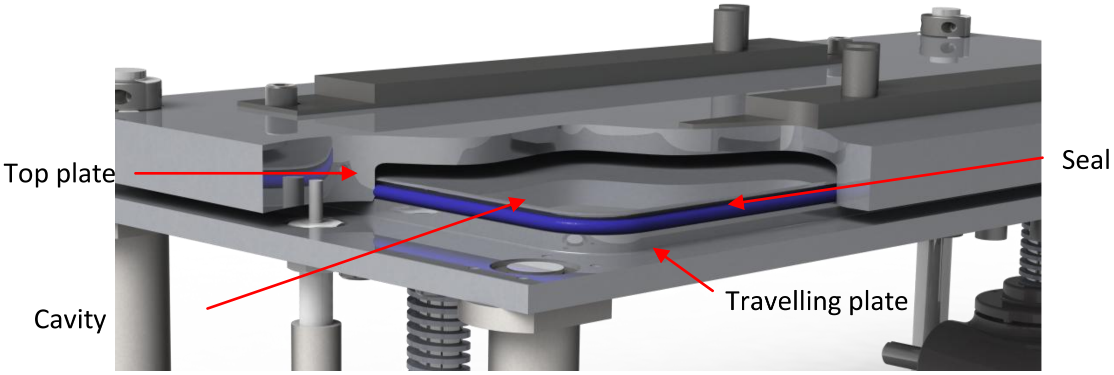


Figure 4. Mould cavity cut away view.

The travelling plate forms the bottom half of the mould and appears above in Figure 4. This plate is pushed along the guide shafts by a mechanical actuator. The four guide shafts help each corner of the mould cavity move evenly (discussed in section 2.2) to ensure the manufactured panel is flat.

The top plate provides a secure backstop for the travelling plate to push against, which allows for the production of high fibre volume fractions. An additional design feature of the top plate is the attachment method used to secure it to the mould assembly. The retaining clips, shown in Figures 3 and 4, are designed to allow for easy removal of the top plate for cleaning and surface preparation. Simplified disassembly is important since the surface of the mould cavity must be refinished (polished) periodically.

The lower die also appears in Figure 4, and consists of a 15mm raised platform on the top surface of the travelling plate. This height is specified to allow sufficient space for the seal to engage reliably over the entire range of thicknesses required (2-5mm). A groove cut laterally in the side of the platform houses the seal (refer to section 2.1.2). The corners of the rectangular platform have a large radius fillet to seat the seal effectively. The edges of the raised platform are filleted to allow for polishing, easier machining, and compatibility with the upper die cavity. The travelling plate uses linear bearings (discussed in the actuator section) to slide along the guide shafts located at the corners of the plates. The last feature of the travelling plate is for the placement of the LVDT, as discussed in section 2.2. The LVDTs are fixed to the travelling plate and allow the sensor to touch the top plate. With this design the LVDTs can be removed for easier cleaning.

The top plate also appears in Figure 4 and its primary feature is the 15mm deep rectangular cavity which acts as the upper die of the mould. The inside edge of the cavity is chamfered which allows the seal to engage smoothly. Like the travelling plate, all corners are filleted to allow for polishing, easier machining, and compatibility with the lower die's raised platform. Lastly, resin and vacuum ports are located along the centre of the width of the plate. The resin port, located in the middle, allows resin to flow into the mould effectively. The vacuum port, located near the edge, allows for even evacuation of the mould cavity.

The size of both plates is selected to be a standard size and thickness from McMaster-Carr [6]. Analysis of the deflection and stresses shows that the maximum allowable deflection occurs much sooner than the maximum allowable stress; therefore, the plates are designed primarily for deflection. The thickness is selected such that the deflection is less than the desired accuracy of 0.01mm. Refer to Appendix B for detailed analyses.

The retaining clips allow the top plate to be detached for cleaning or mould preparation, while still providing a secure and rigid connection between the top plate and guide shafts. The clips measure 30mm (diameter) x 6.35mm and are made of steel. The shoulder machined into the top of each guide shaft accepts the clips. The inside edges of the clips are chamfered to allow for the fillet radius on the shaft shoulder. A disc spring is added below the clip to pretension the shaft against the clip, holding it in place.

2.1.2 Sealing System

The sealing system is a vital part of the mould design. The design stipulates that the mould produce a high quality panel, free of voids or defects. The use of vacuum pressure during the curing stage helps to remove voids, wet out the fibres, and consolidate the laminate. Since vacuum pressure will also be used to suck the resin into the mould cavity, the sealing system impacts many aspects of the design. The general requirements for the seal are that it must be able to hold pressure (up to 1 bar) at various cavity heights. In this respect, the seal is similar to a reciprocating seal often seen in hydraulic pistons. The seal differs from a typical hydraulic piston seal in shape (non circular), operating pressure (much lower), and size (much larger). A dynamic O-ring style seal is adopted since static seals are only designed for a narrow range of compression. It would be unwise to use a static seal and simply compress it to the required height. Refer to Appendix C for design details and further discussion.

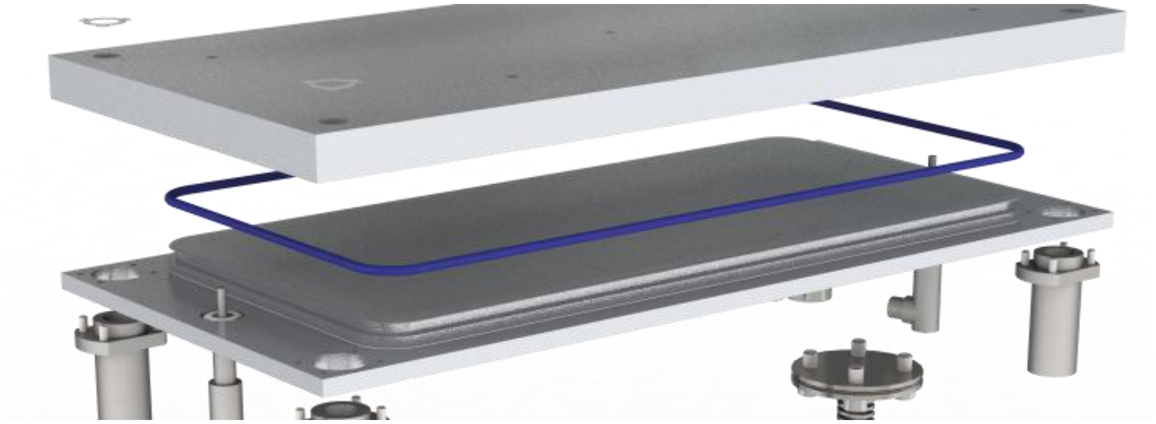


Figure 5. Suspended seal in cavity.

An image of the proposed sealing system appears in Figure 5. Note the top and bottom cavities of the mould, with the seal suspended between.

The two cavities fit together with close tolerances and seal using an O-ring. A brief overview of the seal selection, gland design, and material selection is presented below. The seal type selected is an SAE standard size AS-568-2-386 O-ring. This O-ring has a 3/16” cross section diameter and an inside diameter of approximately 17 inches (16.955 ± 0.005). Since a standard sized seal is desirable for economic reasons, the geometry of the mould cavity is adjusted to fit the seal. The adjusted mould cavity size is determined to be 20 in x 9.25 in with a fillet radius of 1.5 in.

The shape and size of the gland is a very important aspect of the seal design. O-rings operate under some initial compression that energizes the seal against the gland. When fluid pressure is applied to the gland cavity, the O-ring compresses against the side of the gland and extrudes slightly into the clearance gap. A schematic of this process appears in Figure 6.

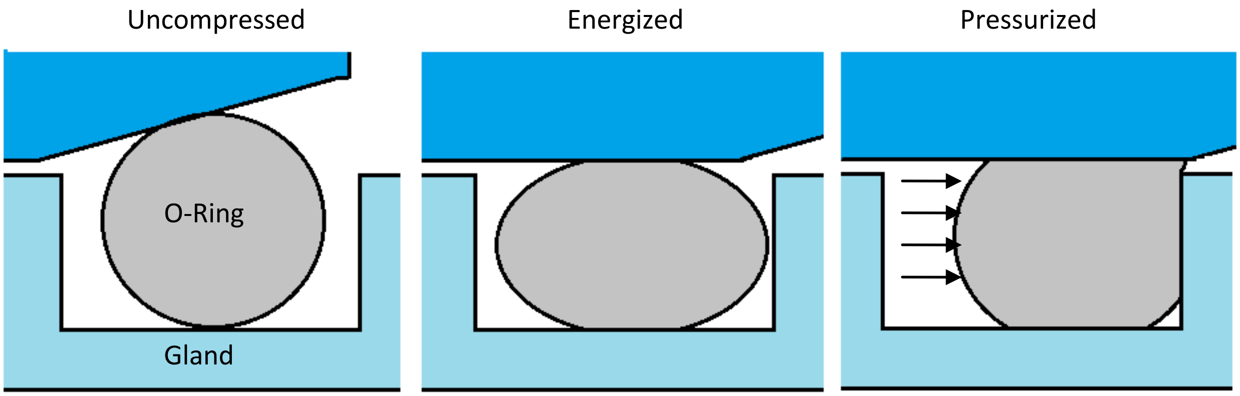


Figure 6. O-ring sealing process.

Ranges for gland dimensions from the Parker design manual are used as a guide. The specified dimensions appear in Figure 7 and TABLE I, with a brief explanation of their significance in terms of meeting the client's needs. A more detailed description of the parameter selection process and failure modes appears in Appendix C.

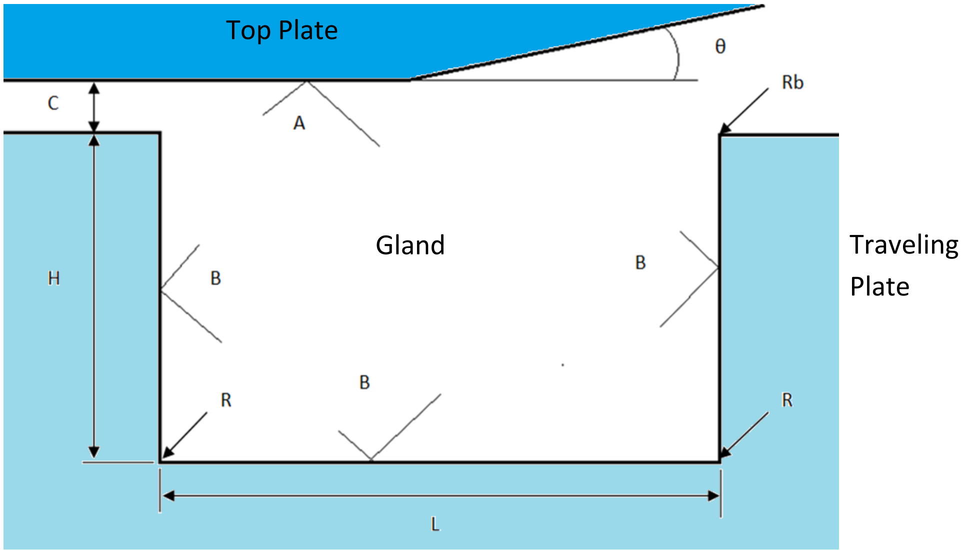


Figure 7. Gland dimensions and naming convention.

TABLE I. GLAND DIMENSIONS.

	Inches	Metric	Selection
O-ring cross section (CS)	0.210 (±0.005)	5.33 (±0.13)mm	-
Gland Length (L)	0.281 (+0.005)	7.14 (+0.13)mm	7.2 (±0.05)mm
Squeeze (%)	8-14%	-	13%
Squeeze (actual)	0.017 – 0.030	0.43-0.75mm	0.71mm
Gland Height (H)	0.185 (+0.003)	4.70 (+0.076)mm	4.7 (±0.02)mm
Radius (R)	0.020-0.035	0.51-0.89mm	0.75mm
Break edge (Rb)	0.005 (+0.005) rad	-	0.005 rad (approx)
Clearance (C)	0.0015-0.003	0.04-0.08mm	0.08mm
Surface finish (A/B max)	A -16RMS μin B -32RMS μin	A - 0.4 RMS μm B - 0.8 RMS μm	-
Insertion Chamfer (θ)	10°-20°	-	10°

Design features for the seal are generally related to meeting the client's needs in terms of an economical solution that provides the most reliable seal. Aspects of the gland design that are designed to help meet the client's needs relate to the clearance, insertion chamfer, surface finish, radius, and break edge.

Surface finish is rougher on the inside of the gland to prevent rolling of the O-ring, while the finish on the sliding surface is finer to reduce O-ring wear. Insertion chamfer is selected to be shallow, so that the O-ring is compressed uniformly and gently. This reduces the chance of spiral fracture and is less likely to damage the O-ring during mould closure. The break edge is provided to reduce the likelihood of damage during installation. All of these features extend the life of the seal and will reduce total cost.

O-ring material is selected to be highly fluorinated elastomer formulation V3819-75 from Parker. This is the most economical choice that will withstand the high temperatures and aggressive chemicals involved. Appendix C contains much more detail on the material selection.

2.2 Linear Motion System

One of the main needs of the client deals with the accuracy and user subjectivity. The accuracy of the system lies in the large gear ratio screw jacks in conjunction with LVDT feedback to the servomotors. To keep the measurements accurate over the whole plate area, the plates are kept level using the guide shafts and linear bearings.

User subjectivity is eliminated through the use of electronic controls. Each thickness is numerically entered, eliminating user error in producing thickness measurements. The design eliminates user subjectivity and increases productivity by using numerical control for the height adjustment.

2.2.1 Actuators

The actuating system is responsible for opening and closing the mould cavity and also applying pressure to the mould to compact the fibres enough to expel any excess resin from the panel. The mould is designed out of two plates, the top plate remains fixed while the travelling plate is adjusted to the proper cavity thickness.

In order to raise and lower the plate, a screw-jack is used in conjunction with an electric motor to control the input precisely. A screw jack utilizes a screw with an outer worm gear attached to a worm screw. Turning the worm screw rotates the worm gear which rotates the lead screw, raising the plate. This configuration can be shown in Figure 8.

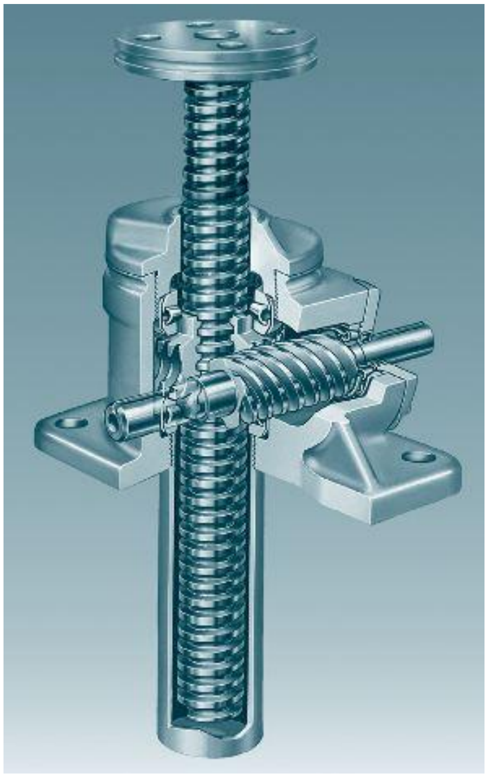


Figure 8. Screw-Jack Internals [7].

The screw style actuator relies on large gear ratios (difference between input and output rotation speed) and small leads (amount that the screw advances per rotation) to produce very small displacements of a large load. Screw jacks come in different configurations of thread pitch, gear ratios, mounting orientations and screw end conditions. The particular design uses an upright design with the mounting face on the lower edge of the jack. The jack is placed below the moving plate and pushes upwards putting the screw in compression. The end of the screw is attached to the plate with a translating load pad as shown above in Figure 8. The jack is sized appropriately for the desired loading conditions.

The design uses two jacks to provide 4000 lbs of force to compress the two plates together. This means that each jack will be contributing 2000 lbs at most. The jack chosen is a 1 ton capacity worm gear machine screw jack with a 20:1 gear ratio. This gearing ratio increases the output torque, so a less powerful and more accurate electric motor can be used to control the screw. Specifications for the chosen jack are found in Table II and Table III.

TABLE II. JACK PHYSICAL CHARACTERISTICS [7].

Jack Data	
Screw Diameter [in]	0.75
Screw Pitch [in]	0.2
Screw Lead [in]	0.2
Gear Ratio	20:01
Static Max Load [lbf]	2000
Dynamic Max Load [lbf]	2000
Rise [in.]	2
Travel Speed [in./min]	2
Max Column Load [lbf]	10198.321

TABLE III. JACK PERFORMANCE DATA [7].

Performance Data	
Input Speed [rad/min]	1.257
Screw Output Torque [in*lb]	149.413
Input Starting Torque [in*lb]	35.762
Input Running Torque [in*lb]	22.198
Input Power [HP]	0.07

2.2.2 Motor

The maximum input torque required occurs when the maximum load is being output. This input torque is split into two different cases, starting and running torque. The starting torque is when the system is stationary and begins to turn and is always higher than running torque. A motor is chosen to match this torque.

The motor of choice for this application is an AC servo motor. The motor is chosen based on the torque required on start-up of the screw. As the plates will be moving slowly, the motor output speeds are relatively low, ranging from 500-1000rpm. When choosing the motor, the stall torque is considered over maximum torque because the motor will be turning slowly and possibly pulsing on and off to reach the desired position.

The motor chosen is a brushless AC servo motor available from Baldor Electric Co. This particular motor is a BSM C-Series: part number BSM90C-2250AF. The motor has a stall torque of 46 lb-in and peak torque of 138 lb-in. This would give more than enough torque to overcome the maximum loading scenarios expected. More information about this particular motor can be found in Table IV.

TABLE IV. BSM C-SERIES: BSM90C-2250AF SERVO MOTOR SPECIFICATIONS [8].

Specification Number:	**S3P193W080**
General Parameters	
Cont. Stall Torque Lb-in (N-m):	46.00 (5.20)
Cont. Stall Current:	2.51
Peak Torque Lb-In (N-m):	138.1 (15.6)
Peak Current:	6.40
Electrical Parameters	
Torque Constant Lb-in/Amp (N-m/Amp):	21.60 (2.44)
Voltage Constant V_{pk}/KRPM (V_{RMS}/KRPM):	208.6 (147.5)
Resistance:	16
Inductance (mHy):	52.7
Mechanical Parameters	
Inertia Lb-In-s^2 (Kg-cm^2):	0.0078 (8.83)
Speed at 300 Bus Volts (RPM):	1200
Max Speed (RPM):	10000
No. of Motor Poles:	8
Feedback Device	
Encoder	
Line Count	2500ppr

2.2.3 Parallel Motion

The screw jacks and motors provide all the closing force needed, but plate levelling is still a concern. This levelling is achieved by having the plates connected by hardened steel guide shafts. The top plate is securely fastened to the shaft by the retaining clips while the moving plate slides freely. Linear bearings help the moving plate to glide effortlessly and reduce the chances of binding during movement. The bearing housings are bolted to the bottom of the travelling plate as shown in Figure 9.

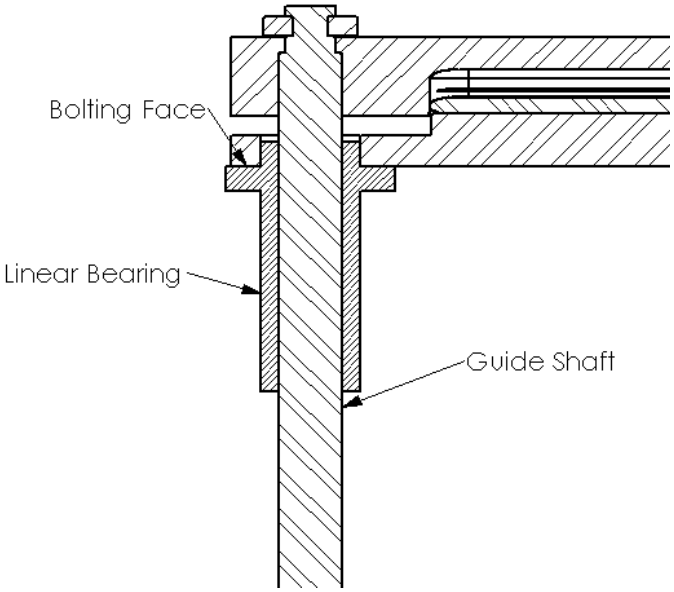


Figure 9. Bearing sleeve mounting.

The mould cavity is guided by four shafts but controlled by only two actuators. These two actuators are positioned along the length of the mould and can control the level of the cavity along this axis. It should be noted that a three screw-drive system was also considered to have control over all three degrees of freedom (two rotational and one normal); however, after consulting with an expert in the field [5], it was determined that a three drive system would not necessarily result in a higher positioning accuracy since the distance between the actuators and the plate edge would be larger, decreasing the effective accuracy in the position of each edge.

The levelling along the width of the plate is encouraged by resistance between bearings and guide shafts. The design can achieve sufficient accuracy because the maximum misalignment is proportional to the distance between supports, and the width is sufficiently small. This is clarified in Figure 10 below.

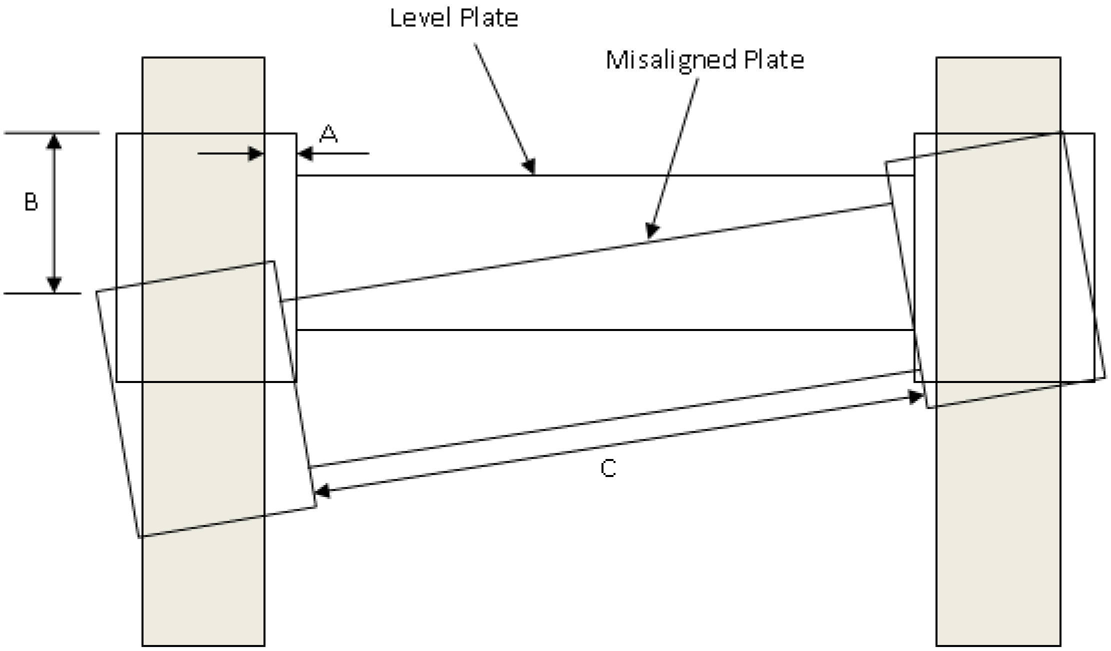


Figure 10. Plate misalignment illustration.

Figure 10 shows two scenarios, the level plate and misaligned plate. The misalignment of the plate causes a change in the height (B). If the length of the span (C) is kept short, this effect is decreased. To keep this misalignment to a minimum, the gap between the guide shaft and bearing (A) is minimized. A very small gap would limit the angle of deflection and thus, vertical misalignment (B). Bearings are selected for this design since they provide the necessary high tolerances without causing excessive friction.

2.2.4 Sensors

To be certain that the cavity is set to the proper thickness, an LVDT (Linear Variable Displacement Transducer) measures the cavity thickness at each end of the length of the plates. This information is used as feedback for the motors to control their movement. The LVDT is mounted rigidly to the travelling plate and uses a spring and plunger style core (where the plunger has a spring return that applies slight pressure to the face of the top plate without any fasteners) to facilitate removal of the top plate.

2.3 Heating

The ability to heat the mould to a surface temperature of 180◦C without interfering with the mechanical systems requires careful attention to the type of heating and insulation selected.

2.3.1 Heaters

In order to keep a constant and uniform surface temperature of 180°C with free convection on all surfaces of the mould, the un-insulated heat loss was calculated to be 194W. This value was hand calculated, and due to the limited knowledge of transient (time varying) conduction, a steady state assumption was made. Using the “SolidWorks Simulation” [9] software, a transient heat flow test with the same surface temperature was performed and the heat loss was found to be 163 W. Differences between these values are due to the transient versus steady state approaches taken. Also, there is always uncertainty involved in simulation due to the idealized nature of the problem. The actual heat loss is assumed to lie somewhere between these two values.

Omega Engineering provides a wide range of strip, finned, and ring heaters with heating capacities of 150 W and upwards [10]. An OT Series strip heater is selected (OT-1225/120) and appears below in Figure 11. This heater model has a length of 12 inches, heated length of 10.5 inches, width of 1.5 inches, thickness of 0.375 inches, and heat generation rate of 250 W [11]. The heaters are bolted down to the mould through the two slots on the ends.

Figure 11: OT Series Strip Heater from Omega (250 W) [8].

The OT series strip heaters have two offset bolt terminals at one end which are connected to a 120 V AC power source through a relay (one per plate). Each relay is controlled by the same control system as the servomotors (using thermocouples to provide feedback). The user enters a desired surface temperature and the heaters will adjust their outputs accordingly. The OT series have maximum service temperatures of 399°C (limited by the sheath material) [11], which is acceptable for the maximum expected mould temperature of approximately 200°C.

In order to keep the plate temperature as uniform as possible, two offset heaters are placed on the top of the mould and two heaters offset in the reverse manner are placed underneath (refer to Appendix E for an illustration). The four heaters have a total power of 1000 W, and since this is more than the 194 W required, the heaters can run smoothly in the low range of their capacity.

2.3.2 Insulation

Insulation added to the outside of the top and travelling plates minimizes heat loss and encourages a more uniform surface temperature. Worbo Incorporated [12] offers various high temperature protection and insulation products for household and industrial applications. They offer several possible solutions for insulating the mould, including Cool-Skin Tape or Cool-Skin Blanket, shown in Figure 12.

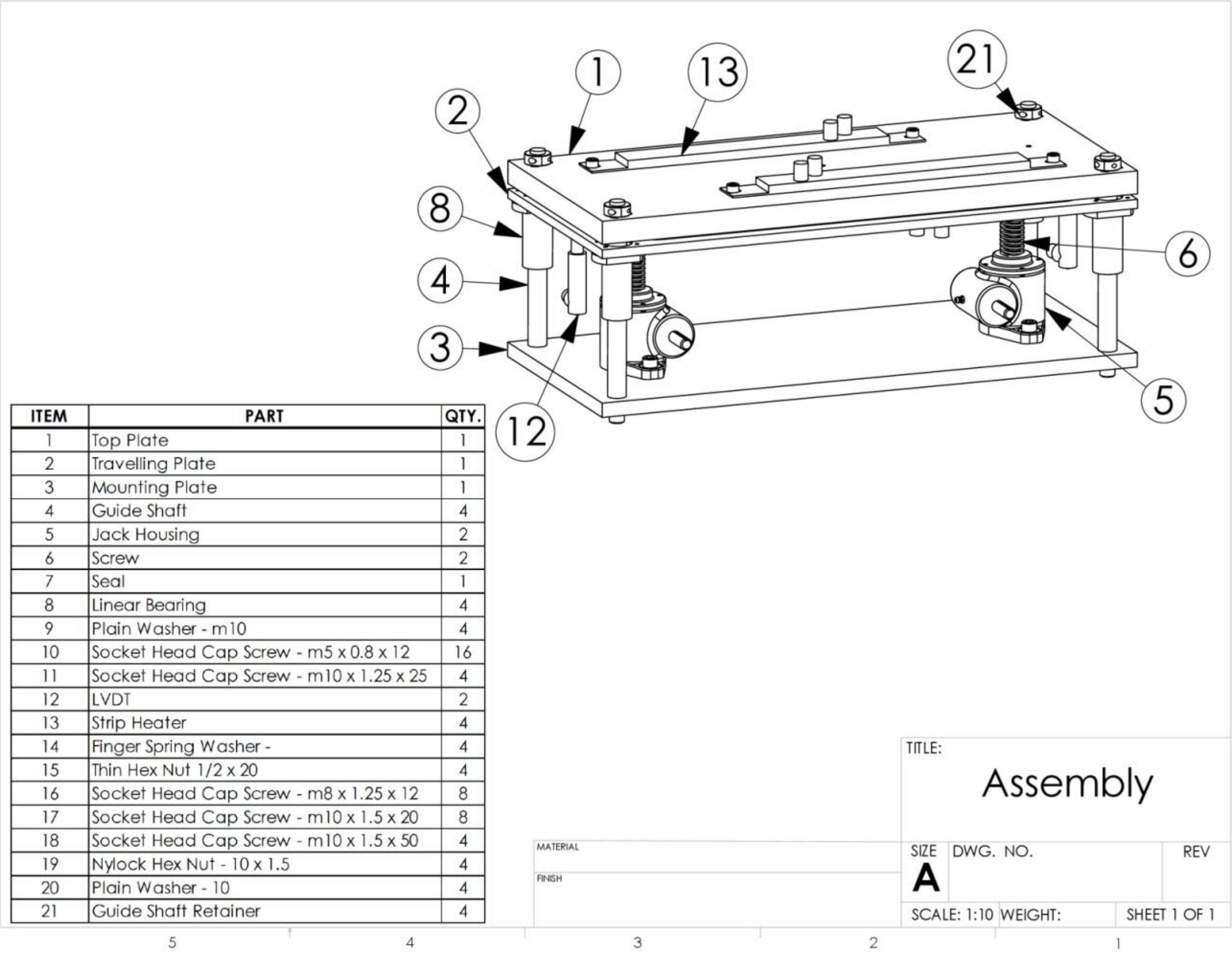
Figure 12: “Cool-Skin Blanket” from Worbo Incorporated [12].

The purpose of Cool-Skin technology is to “drastically reduce high surface temperatures to a safe touch condition” [12]. The Cool-Skin Blanket is very well suited for insulating the surfaces of the mould, since the material has a Peel and Stick Pressure Sensitive Adhesive (PSA) and is manufactured with clean non-fibrous materials. These features make the material easy to cut to the required dimensions and apply to the mould surface. The PSA insulation blanket may be applied in one or more layers to reduce the 194W heat loss. The Cool-Skin blanket is resistant to moisture, various chemicals, and shows excellent overall durability in various environments [12]. Finally, it is rated from -80 to 200°C [12], which our 180°C surface temperature falls comfortably within.

3.0 Procedure

3.1 Assembly

All parts needed to assemble the mould are listed and labelled in Figure 13. Assembly drawings for the heater, LVDT, and actuator appear in greater detail in Figures 14-16 respectively.



ITEM	PART	QTY.
1	Top Plate	1
2	Travelling Plate	1
3	Mounting Plate	1
4	Guide Shaft	4
5	Jack Housing	2
6	Screw	2
7	Seal	1
8	Linear Bearing	4
9	Plain Washer - m10	4
10	Socket Head Cap Screw - m5 x 0.8 x 12	16
11	Socket Head Cap Screw - m10 x 1.25 x 25	4
12	LVDT	2
13	Strip Heater	4
14	Finger Spring Washer -	4
15	Thin Hex Nut 1/2 x 20	4
16	Socket Head Cap Screw - m8 x 1.25 x 12	8
17	Socket Head Cap Screw - m10 x 1.5 x 20	8
18	Socket Head Cap Screw - m10 x 1.5 x 50	4
19	Nylock Hex Nut - 10 x 1.5	4
20	Plain Washer - 10	4
21	Guide Shaft Retainer	4

Figure 13. List of parts and drawing of assembled mould.

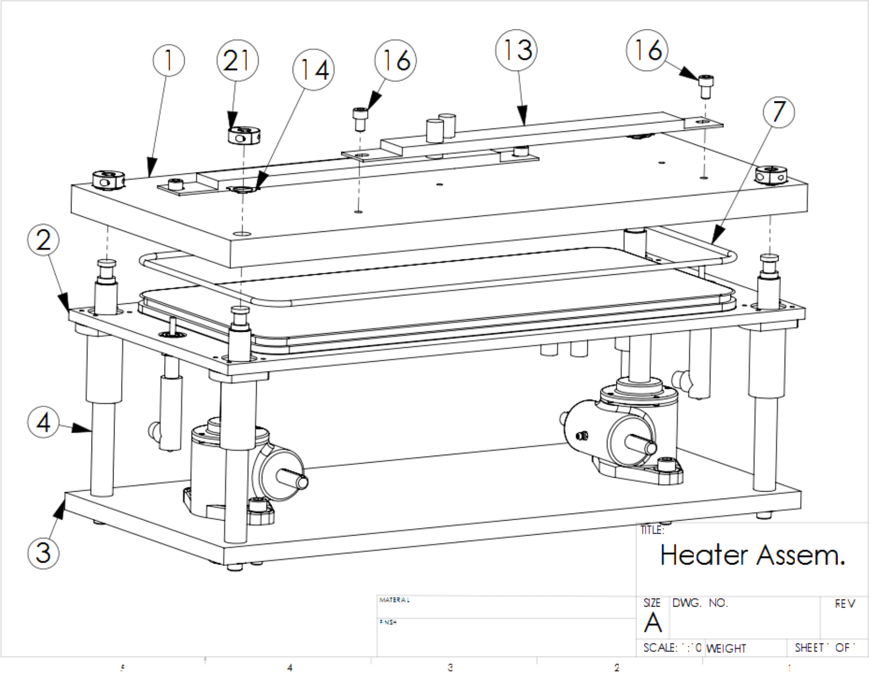


Figure 14. Heater assembly.

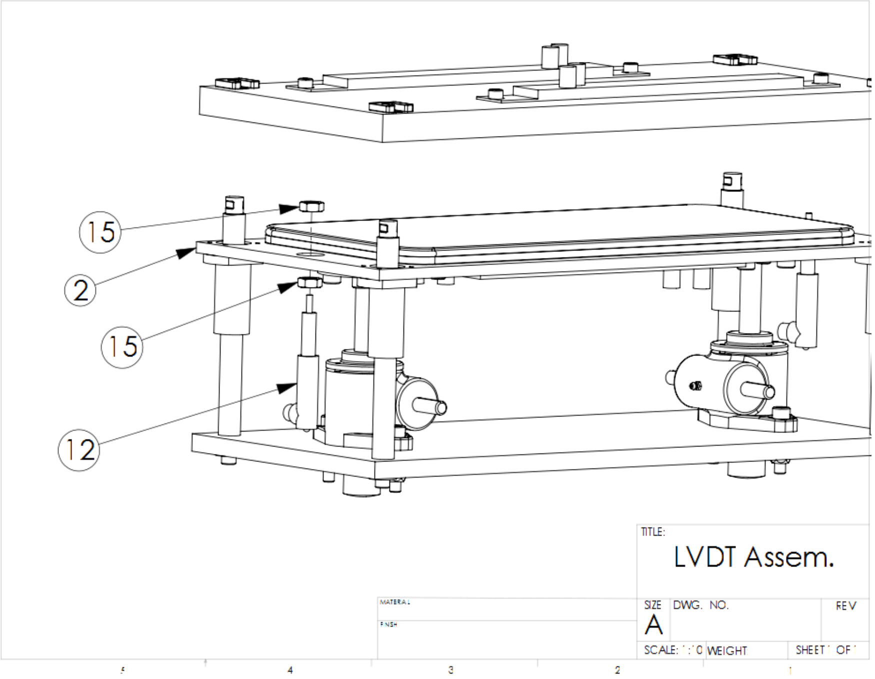


Figure 15. LVDT assembly.

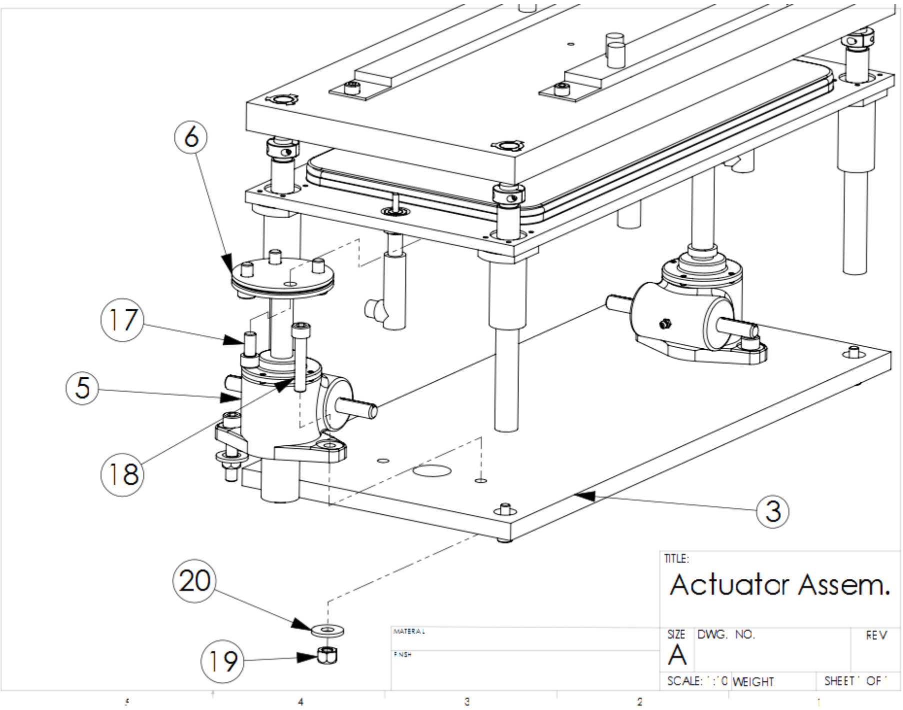


Figure 16. Actuator assembly.

3.2 Operation

The user begins by properly cleaning the entire inside of the mould with acetone and applying a release agent to the cavity surfaces. The user then places reinforcement fibre in the cavity between the two plates and closes the mould (using a graphical interface) so that the seal along the edge of the mould cavity engages. The air is removed from the cavity by closing the resin port and applying vacuum pressure to the vacuum port. Up to this point, the procedure is similar to the current method, except that the motion of the plate is controlled using a graphical interface and feedback controlled electric motor.

To achieve fibre volume fractions above the capacity of the current method, the screw jack is utilized for compression in addition to vacuum pressure. The screw jacks can close the mould using up to 18kN of force in addition to the vacuum pressure already applied (which exerts approximately 10kN over the plate surface). This additional step is optional, and provides the user with a great deal of flexibility in fibre volume fraction.

If curing at an elevated temperature is desired, the user enters the desired temperature into the interface and four electric heaters uniformly heat up the mould cavity from the top and bottom. Once the curing has completed, the user opens the mould via the graphical interface. If necessary, the screw jacks can apply force in the reverse direction so that the mould may be opened if the resin bonds the plates together. This feature should speed up the demoulding process. If the composite sticks to the top panel inside the cavity, it may either be punched out directly through the ports, or the excess flash around the perimeter may be broken away to pry the composite panel out.

4.0 Summary

The requirements related to ease-of-use, accuracy, cycle time, and consistency between users are met with the current design. The mould uses feedback controlled electro-mechanical actuators to set the height of the cavity, dynamic reciprocating O-ring seals to hold vacuum pressure over a range of cavity heights, insulation and feedback controlled electrical heaters to achieve a uniform die temperature, and linear bearings and guide shafts to precisely control the plate alignment. The mould is expected to produce panels which are free of defects and accurate to ±0.01mm. Using computer controlled systems, the user subjectivity is eliminated while also making the mould much easier to use.

The design meets these requirements while maintaining a parts cost of approximately $7,700. Including machining and assembly, the cost is still expected to fall below the budget of $10,000.

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Appendix A – Design Selection

Selection Process

Selecting a suitable design solution is never an easy task. Problems seldom have a single solution and many different designs had to be evaluated to choose the best option. In order to select an appropriate design, screening and scoring matrices were used to compare different ideas. The principal idea behind these techniques is to assign a weight to certain criteria related to the design. The different concepts were scored relative to each other and the total scores were tabulated. For the present design, concepts were divided into four different categories: process, height adjustment, measurement, and heating. These concepts and categories were selected through preliminary research into the design and early brainstorming sessions. Each category had its own list of criteria that are compared between the various design concepts.

Screening

The different categories mentioned above each have their own design options. Using the screening matrices, some conceptual designs were eliminated thus making the final design choice simpler. It was evident that certain concepts were much less suitable than others. Once certain designs were eliminated, the remaining concepts were inserted into the scoring matrix so that the value of each design could be quantified. The concepts and scoring criteria from each category are described below.

The height adjusting matrix suggested that the best design options would be a hydraulic or screw-drive system. These two systems stood out from gear train, screw-drive, piezoelectric, and electromagnetic, mainly due to their high strength and precision capabilities. Ratings were determined using carefully chosen criteria. The criteria for height adjustment included: strength, fineness of adjustment, range, cost, ease of use and supporting hardware.

The measurement matrix indicated that an LVDT or a digital indicator were the most practical choices. These two systems were selected mainly due to their ease of use and automation potential. The selection criteria for this matrix were: ease of use, cost, repeatability, automation, speed and ability to be heated.

Candidates for the heating category included heated fluid, electric heaters, and preheating. The rating was base on the criteria: cost, ease of control, supporting hardware, constant temperature, repeatability, and interference with other systems. Each design option had its own strengths depending on the criteria; therefore, all concepts were carried to the scoring matrix.

The design options selected for the moulding process were: closed mould infusion, vacuum assisted resin transfer moulding, compression moulding, and resin transfer moulding. The criteria used for ranking were: cost, volume fraction range, cycle time, ease of use, and adjustability. Closed mould infusion and compression moulding were identified as the most suitable types, and they advanced to the scoring matrix. The desirable features of these methods are their accuracy and high volume fraction capabilities respectively.

Scoring

The scoring matrices compared the design options that were carried forth from the previous screening matrices. Design options and the evaluation criteria were listed along with their relative weightings. These weightings and the design options were each scored on a scale of 1 to 5. The scores for each design were multiplied by the weighted factor, helping to understand the relative importance of each criterion.

The height adjustment was split up into two different types, automatic and manual. Both the hydraulic and screw-drive systems could be controlled automatically or manually, so it was important to consider this when making the design choice. From the scoring matrix, both the automatic hydraulic and automatic screw-drive systems provided a suitable solution for the height adjustment capability. However, upon further consideration, the hydraulic system proved to be too expensive and complicated (safety standards for pressure lines, dealing with fluid and pump integration). Thus, an automatic screw drive system was chosen.

Two possible measurement systems from the screening matrix were analyzed in their own scoring matrix. From here, an LVDT appeared to be the better device for incorporation into the design because of its high accuracy and the ease with which it can be applied to an automated system.

Since all three heating systems were carried into the scoring matrix, careful consideration had to be taken in their scoring. The scores showed that the electrical or fluid heating would be more desirable than pre-heating the mould as they would have less interference with the other systems in the design. However, the electrical strip heaters proved to be a much simpler and cheaper solution than the heating fluid of a heat exchanger.

Finally, the most suitable moulding process was determined through the scoring matrix. Upon reviewing it becomes obvious that no single technique easily satisfies the design requirements. Additionally, it is clear that the descriptions of each process are not absolute in their definition and many variations of the above techniques exist; therefore, it is better to think of these methods as families of similar techniques instead of absolute and well defined processes. A hybrid technique of the team's own design was chosen for development that includes vacuum infusion followed by compression.

Discussion

Considering the multiple parts of the design, concept integration is critical. All of the components need to function correctly and not interfere with each other. The environment in which each component operates was also considered to make sure that performance is maintained. Other design points that were considered are ease of manufacture, use, assembly, and adjustment.

Several possible design combinations were generated based on the ratings and scoring. The most promising design includes a hybrid moulding process (vacuum infused compression) with an automated screw-drive system using LVDT feedback to control the mould height. Heating is accomplished by bolt-on electric heaters. Based on the research and analysis completed, this was the design that was chosen for development.

Appendix B – Mould Cavity

Finite element analysis is completed on both plates to estimate the deflection. The total deflection should be smaller than the desired accuracy. Simulation is performed in both SolidWorks and ANSYS with various boundary conditions.

In the SolidWorks simulation, the travelling plate shown in the bottom of the figure was set as a rigid member while the top plate underwent deflection. The holes for the pins in the top plate were fixed while the remaining portions of the plate were free to move. As shown in the scale on the right side of Figure 17, the maximum displacement occurs in the middle of the top plate has a magnitude of approximately 0.001mm. This is well below the required limit on deflection of 0.01mm.

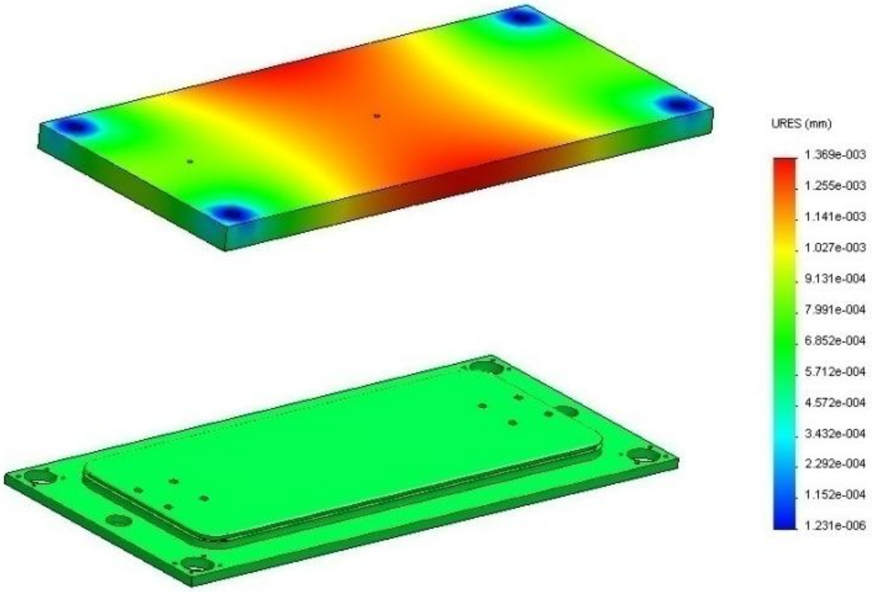


Figure 17. Deflections of the top plate (SolidWorks) [1].

Finite element modeling of the two plates was also conducted for stress. The maximum stress was determined to be well below the yield stress for type 410 stainless steel (by an order of magnitude at least), and deflection was decided to be the limiting factor.

The top and travelling plates were also modeled using the commercial finite element code ANSYS 11.0 with different boundary conditions. Due to the two planes of symmetry, only 1/4 of the plate is modeled (applying symmetry boundary conditions to symmetric planes). Geometry is imported and material elastic properties are set to those for steel E = 200 GPa and v = 0.3. Element type is “SOLID187”, which is a quadratic tetrahedral shape. Boundary conditions were applied for three cases of increasing complexity.

To help refine the solution around stress concentrations:

- Convergence set to max 5%
- Adaptive mesh refinement applied between loops
- The maximum number of loops set at 4.

Case 1: (Top Plate Only, similar to the SolidWorks case)

4500N applied to the clip bearing surface.

Fixed support along mould cavity.

Maximum deflection: 0.04mm

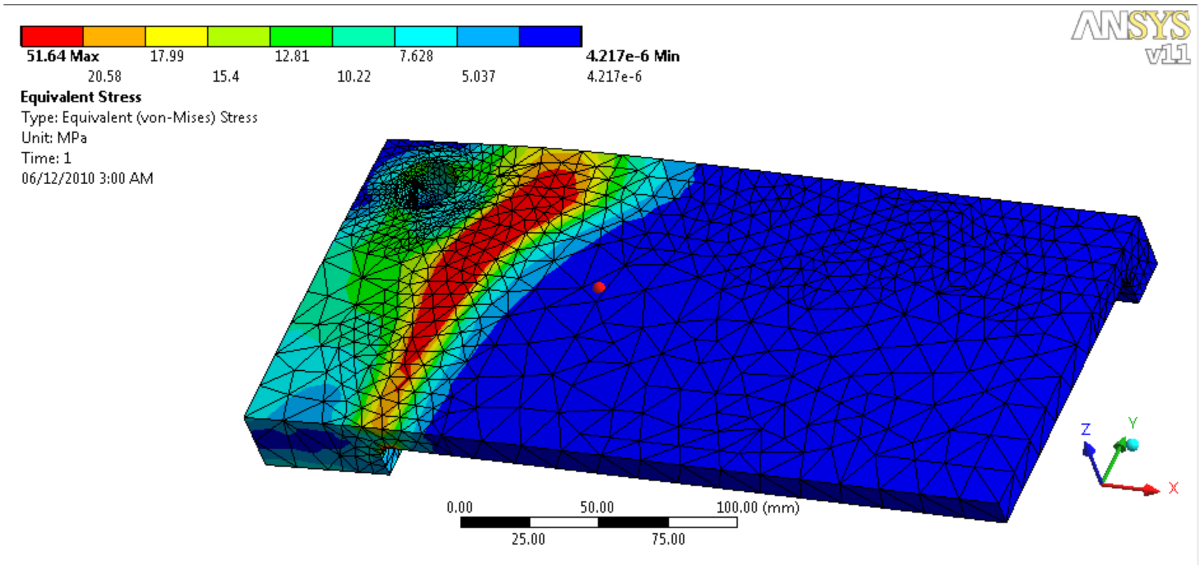


Figure 18. Stress distribution in top plate (case 1).

Case 2:

Fixed support at the clip bearing surface on top plate
4500N through actuator bearing surface on bottom plate
Contact elements applied with contact tool.
Maximum deflection: 0.03mm

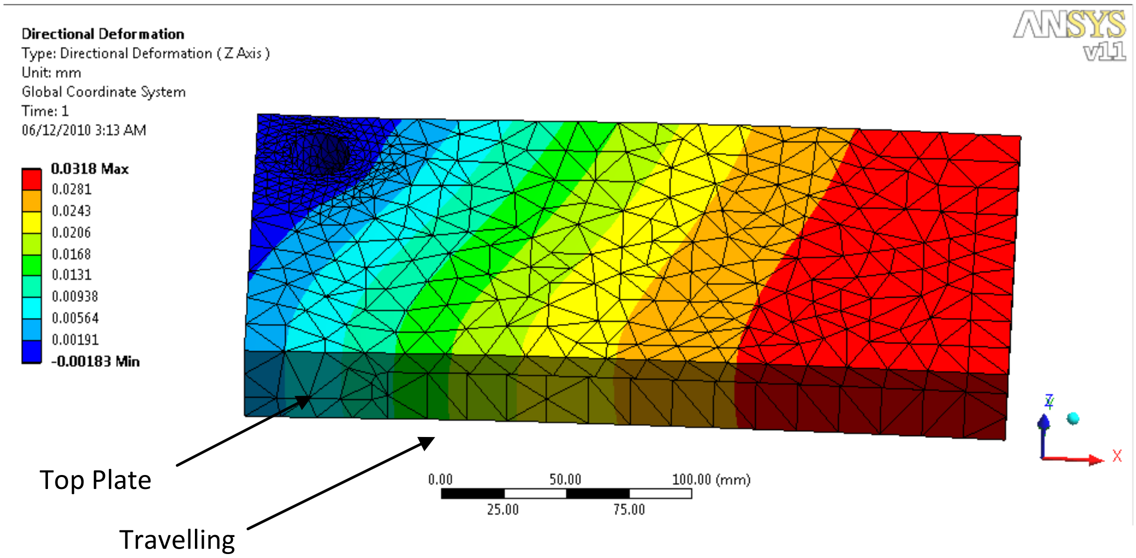


Figure 19. Deformation in the vertical direction (case 2).

Case 3:

Added cylindrical (tangential) supports to case 2 to simulate rigid guide shafts.
Maximum deflection: 0.02mm

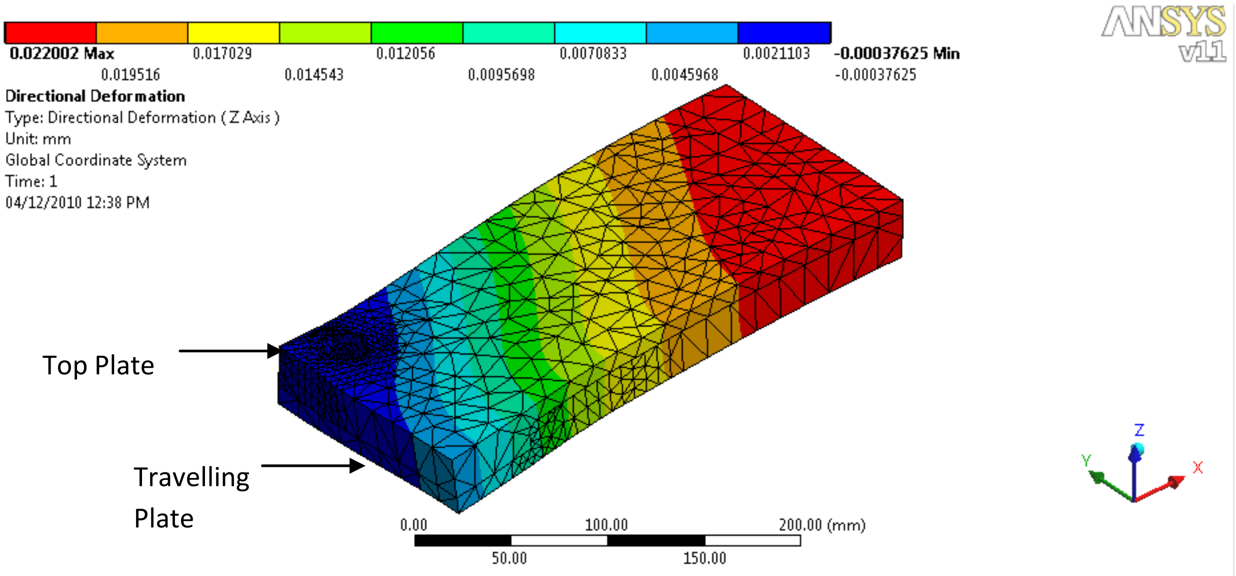


Figure 20. Deformation along the normal axis for case 3 [2].

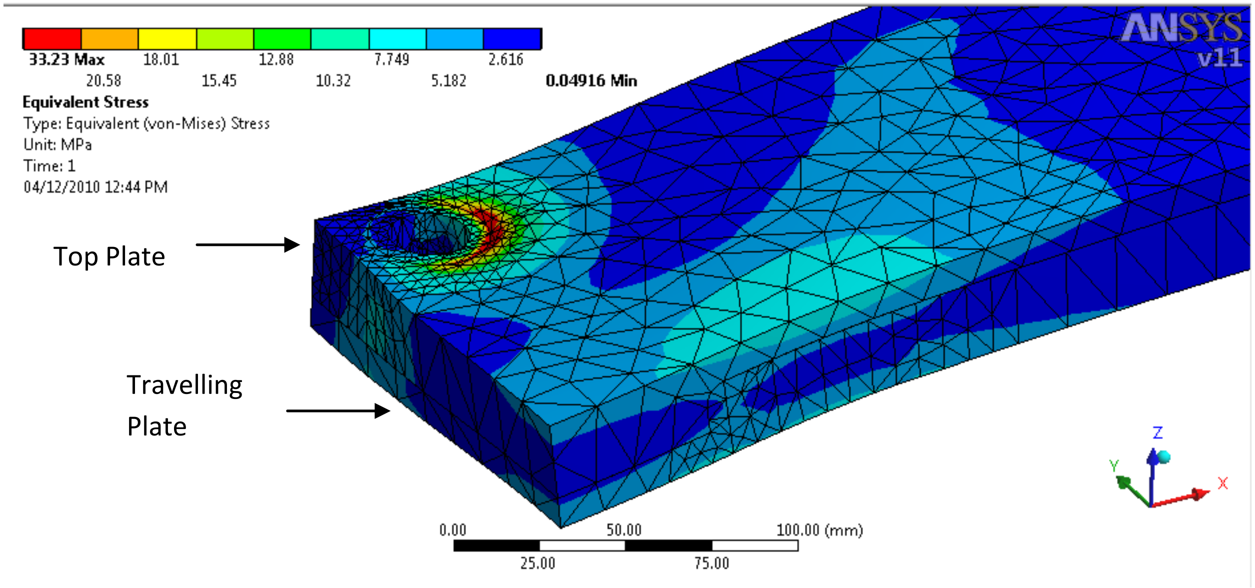
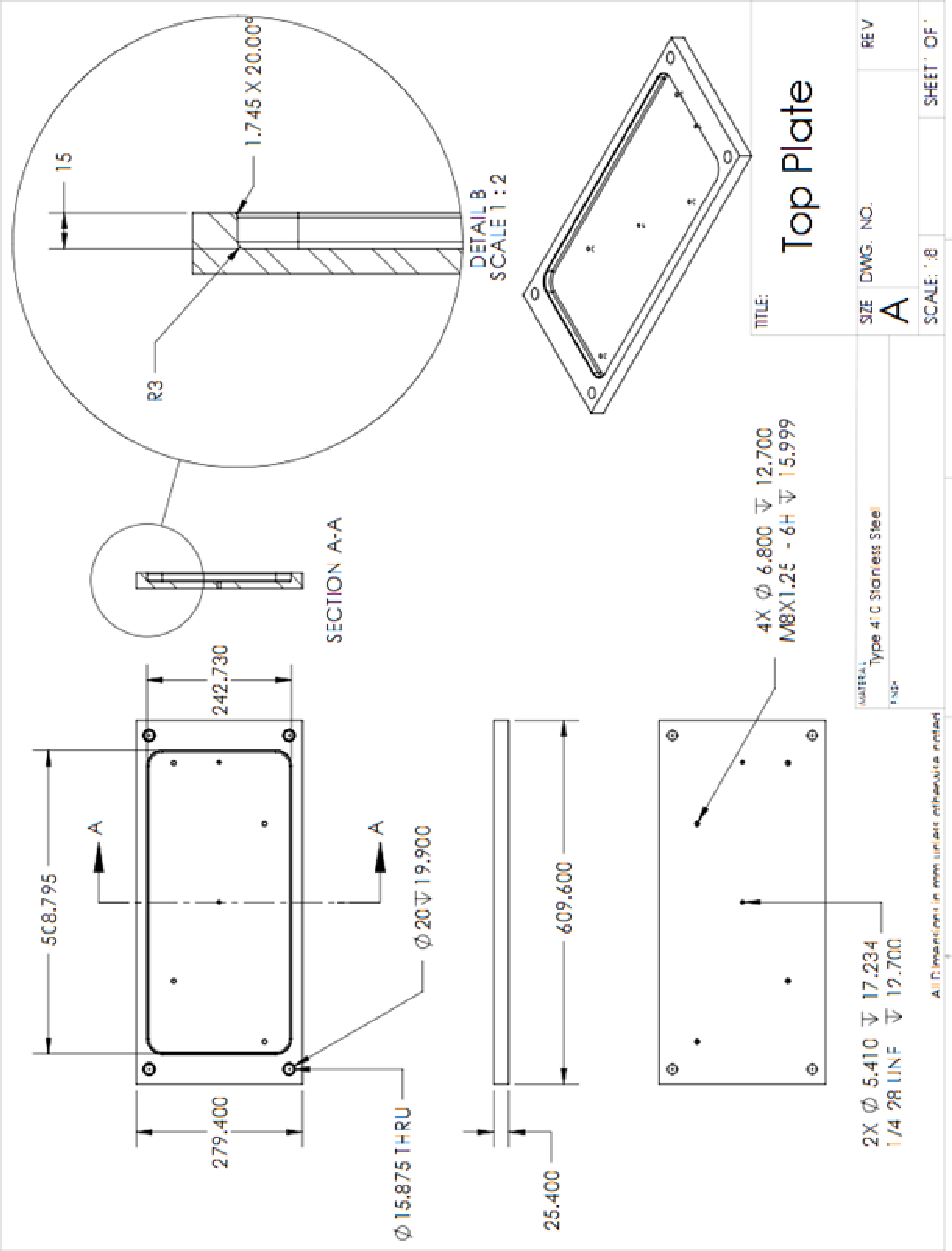
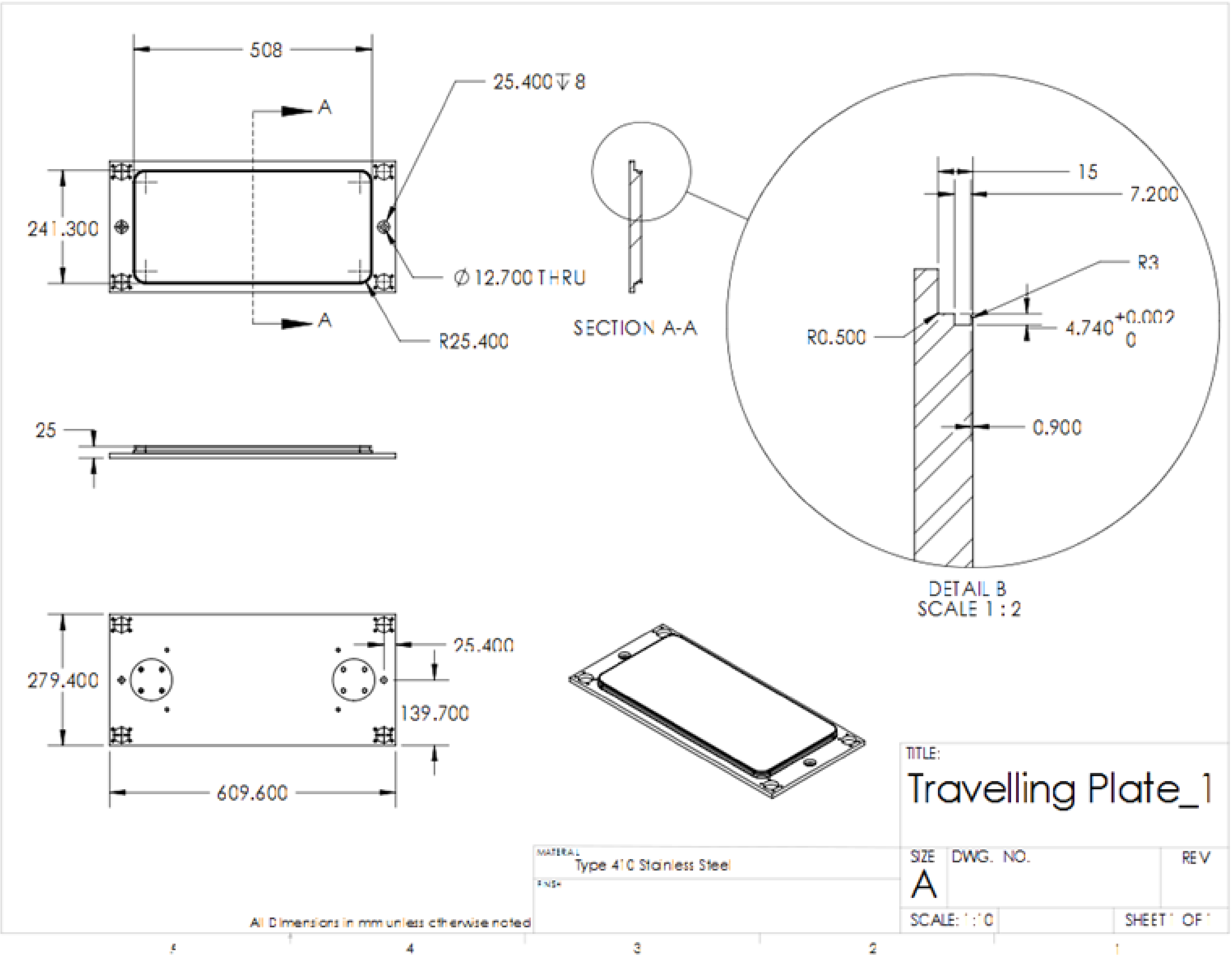


Figure 21. Equivalent stress in top and travelling plates (case 3) [2].

This problem could have been further refined by modeling contact between guide shaft and plates. Since the shafts are elastic and are expected to deform, the true deflection should lie between the values for case 2 and 3.

Maximum deflection (case 3) was estimated to be approximately 0.02mm at maximum closing force, but the variation between deflections across the panel length is only approximately 0.01mm. This is deemed to be acceptable.


1.745 X 20.00°
15
R3
DETAIL B
SCALE 1 : 2
SECTION A-A
242.730
508.795
A
A
Ø 20 ↧ 19.900
609.600
279.400
Ø 15.875 THRU
25.400
4X Ø 6.800 ↧ 12.700
M8X1.25 - 6H ↧ 15.999
2X Ø 5.410 ↧ 17.234
1/4 28 UNF ↧ 12.700
TITLE:
Top Plate
SIZE
A
DWG. NO.
REV
SCALE: 1:8
SHEET 1 OF 1
MATERIAL
Type 410 Stainless Steel
FINISH
All Dimensions in mm unless otherwise noted


508
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R3
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DETAIL B
SCALE 1 : 2
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139.700
609.600
TITLE:
Travelling Plate_1
MATERIAL
Type 410 Stainless Steel
FINISH
SIZE
A
DWG. NO.
REV
SCALE: 1:10
SHEET 1 OF 1
All Dimensions in mm unless otherwise noted
4
3
2
1

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Appendix C – Seal Design

Selection of seal type

The operating conditions for this seal are non standard. The non-circular seal must reciprocate (with a stroke of approximately 5mm) while maintaining vacuum pressure. In general, there is little information available for the design of non-circular seals. However, the Parker o-ring manual [1] indicates that "irregular chambers can be sealed [with O-rings] in both fixed and moving part installations" (1-4). The selection chart in [2] indicates that O-rings are favourable for light duty reciprocating seals (below 160 bar), while more robust reciprocating seals (U-seal or similar) are reserved for higher pressure applications (since higher pressures are required to energize the seal). Additionally, the cost to custom manufacture a traditional reciprocating U-seal or T-seal would likely be prohibitive, since the semi-rigid backing materials would need to be custom moulded in the square shape.

Equivalent diameter calculation

This size was determined by calculating an equivalent diameter from the perimeter of the cavity (offset by the gland height, h_g) and adjusting the width (H) such that the seal length would be appropriate for the standard 17 inch size O-ring. A 3% installed stretch is designed for to ensure that the seal remains well seated (as per design manual [1]). A schematic showing the required dimensions appears in Figure 22, with the equation used to calculate the equivalent diameter (derived from geometry) appearing below it.

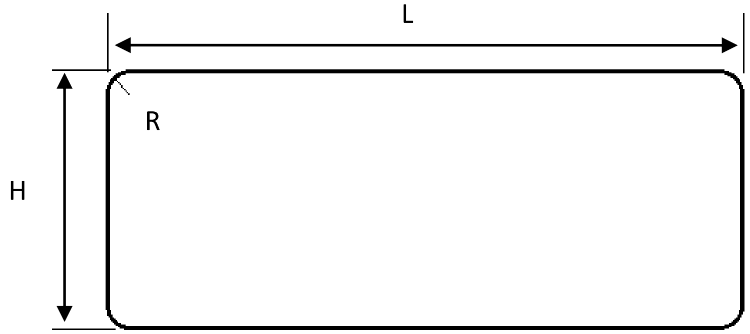


Figure 22. Geometry and nomenclature of reciprocating seal and mould cavity.

Equivalent diameter:

$$D_{eq} = \frac{2\left[L - H - 4h_g + (\pi - 4)\left(R - h_g\right)\right]}{\pi(1.03)}$$

Where L, H, and R are the length, height, and radius (as appearing in Figure 22), and h_g is the gland height.

Gland Geometry

The selection of cross sections was based on available standard sizes for this diameter (17”), which are 1/8”, 3/16”, and 1/4" nominal sizes. The 3/16” (5.33mm) diameter cross setion is selected over the other standard sizes to provide balance between flexibility (since the o-ring must wrap around a filleted rectangle instead of a circular shaft) and allowable clearance. A larger cross section would provide larger clearances and better stability (refer to the discussion on failure in the following section), but the stiffer seal would not wrap around the non-circular cavity as well. Additionally, should a larger cross section be desired at a later time, it is much easier to expand the gland than machine a new plate. By selecting the mid sized cross section, the option to expand is available.

Gland height is selected from the low end of the range to increase the compression on the seal. This is desirable since vacuum seals operate better at high squeeze [1]. The tolerance for gland height is higher than for the width since the height controls the friction and compression, which should be as even as possible.

The width is also selected to be near the low end of the range, since there is very little space available. This width provides a gland fill of approximately 65%, which is lower than the ideal fill (generally accepted to be 75%). Using larger values will only decrease the gland fill, and it is unclear why the design manual specifies gland dimensions that provide gland fill of at most 65%.

The gland fillet radius (R) of 0.75mm is selected to ease manufacture, since it is more likely that a 1.5mm round cutter is available than some non-standard size. Any radius in the range is acceptable, and this dimension may be modified to account for which sizes of ball nose cutter is available.

A shallow chamfer is desired to provide a more gradual insertion. The lower portion of the range is selected (10^{o}C).

A rougher surface inside the seal gland helps to reduce the likelihood of seal rolling, the surface finish of 32RMS (Root Mean Squared – A specification of roughness measurement) should be achievable from machining, but the finer surface finish of 16RMS on the compression side will require additional grinding or honing.

The maximum clearance gap is chosen to ease installation. The major limitation on clearance gap is seal extrusion. Since the pressures are very low (1 bar), this will not be a problem.

The amount of squeeze depends on the gland depth, clearance gap, and O-ring cross section. For this case, the squeeze is calculated to be approximately 13%, which is within the acceptable range of 8-14%.

Selection of Seal Material

The selection of a base polymer is one of the most important aspects of the seal design. There are many thousand different elastomer formulations available, and most of them are unsuitable for this particular operating environment. Temperature and chemical resistance are the two largest limitations placed on the current design. The seal must withstand relatively high temperatures that would degrade most elastomers, as well as withstand chemical attacks from a range of extremely aggressive fluids. The specific requirements for temperature and chemical resistance appear in Table V below.

TABLE V. OPERATING ENVIROMENT FOR SEAL [3-7].

Element Category	Hazard	Concentration
Temperature	20-180^{o}C	-
Cleaning	Acetone	100%
Polyester and Vinyl Ester Resins	Styrene	30-50%
	Methyl Ethyl Ketone Peroxide (MEKP)	1-2%
	Cobalt naphtenete	0.1-0.5%
Epoxy Resin	Epoxy Resin (Proprietary formulation)	-
	Hardener (Amines)	30%

The temperature requirement immediatly eliminates several elastomer families, as seen in Figure 23 below.

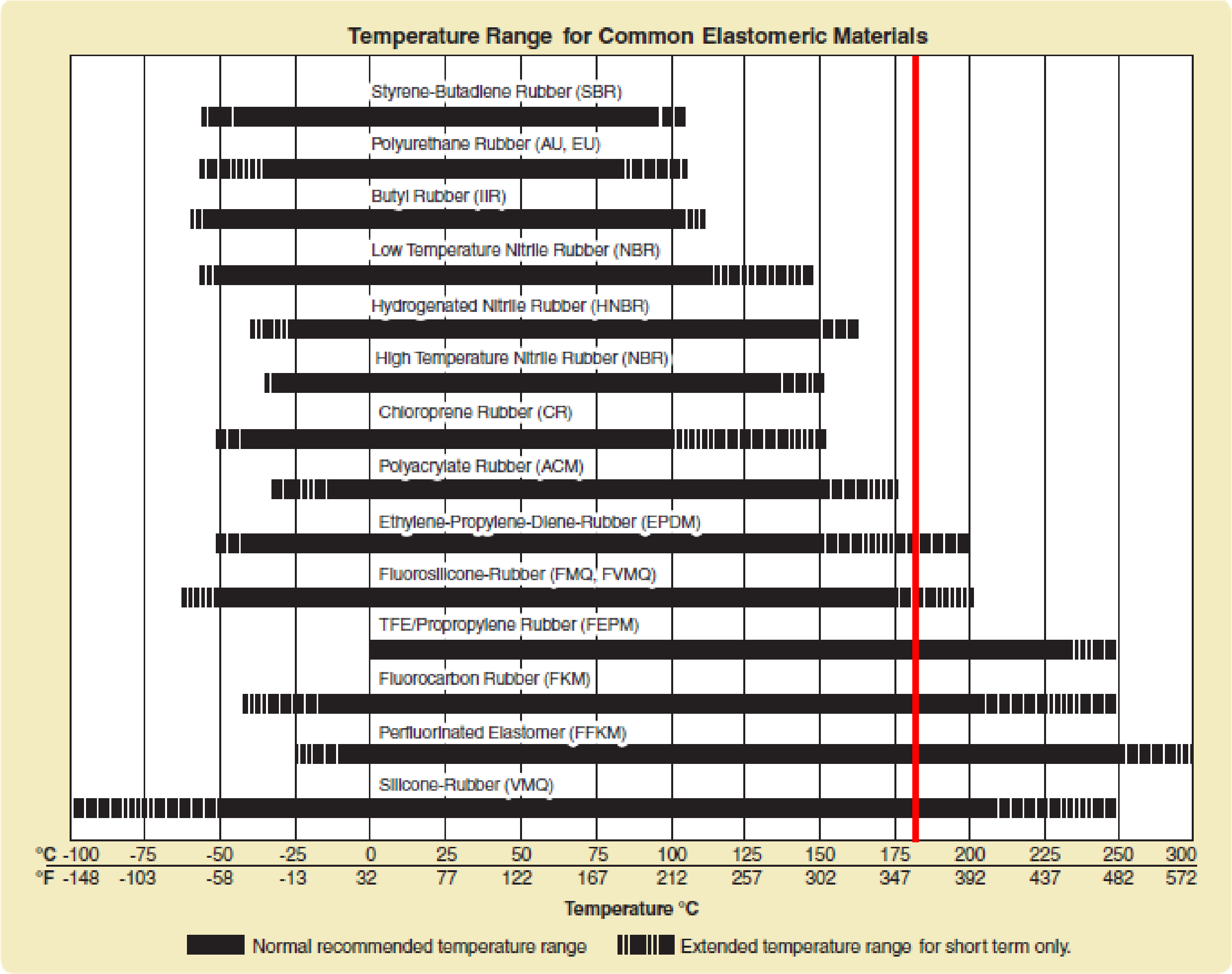
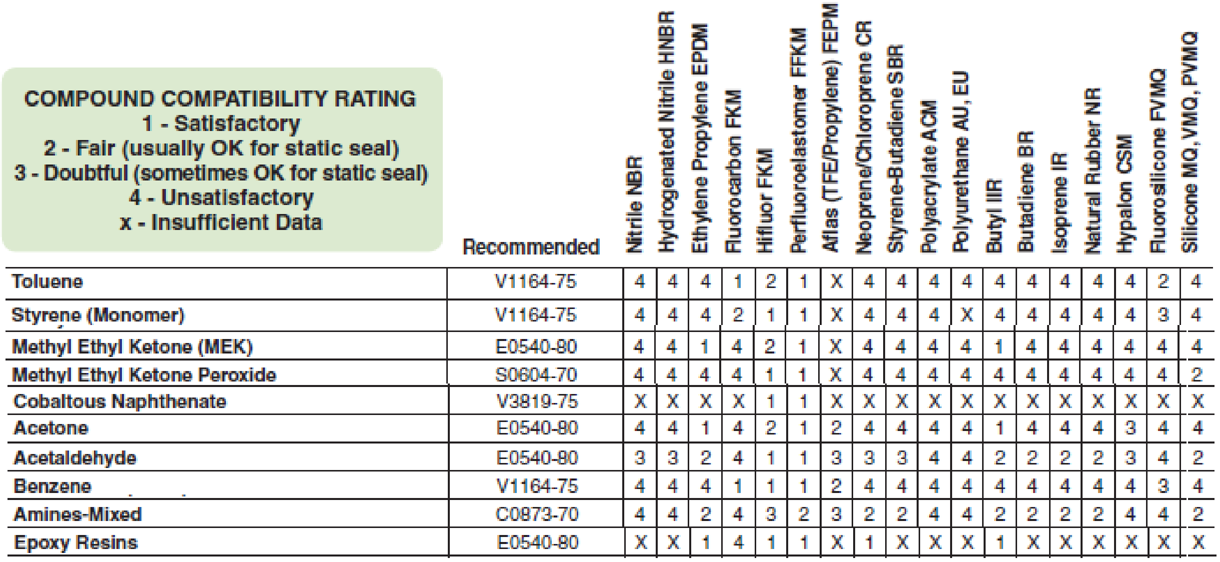


Figure 23. Comparison of the operating temperature for various elastomers [1]

From Figure 23, the red vertical line represents the highest expected temperature of 180^{o}C. The only elastomers which are able to operate at these temperatures are EPDM, FMQ, FVMQ, FEPM, FKM, FFKM, and VMQ (ASTM D1418 [8] designations).

Chemical resistance is extremely important, since many of the chemicals are very aggressive and the seal must be durable to last for several cycles. The seal must be resistant against aromatic hydrocarbons (benzene, toluene, styrene), polar solvents (MEK, acetone), amines (in the epoxy resin), as well as other specialized chemicals that fall outside of these families. TABLE VI summarizes each of the expected chemicals and the suitability of each elastomer.

TABLE VI. COMPATIBILITY OF EXPECTED FLUIDS WITH THE SEAL, ADAPTED FROM [1].



COMPOUND COMPATIBILITY RATING
1 - Satisfactory
2 - Fair (usually OK for static seal)
3 - Doubtful (sometimes OK for static seal)
4 - Unsatisfactory
x - Insufficient Data

	Recommended	Nitrile NBR	Hydrogenated Nitrile HNBR	Ethylene Propylene EPDM	Fluorocarbon FKM	Hifluor FKM	Perfluoroelastomer FFKM	Aflas (TFE/Propylene) FEPM	Neoprene/Chloroprene CR	Styrene-Butadiene SBR	Polyacrylate ACM	Polyurethane AU, EU	Butyl IIR	Butadiene BR	Isoprene IR	Natural Rubber NR	Hypalon CSM	Fluorosilicone FVMQ	Silicone MQ, VMQ, PVMQ
Toluene	V1164-75	4	4	4	1	2	1	X	4	4	4	4	4	4	4	4	4	2	4
Styrene (Monomer)	V1164-75	4	4	4	2	1	1	X	4	4	4	X	4	4	4	4	4	3	4
Methyl Ethyl Ketone (MEK)	E0540-80	4	4	1	4	2	1	X	4	4	4	4	1	4	4	4	4	4	4
Methyl Ethyl Ketone Peroxide	S0604-70	4	4	4	4	1	1	X	4	4	4	4	4	4	4	4	4	4	2
Cobaltous Naphthenate	V3819-75	X	X	X	X	1	1	X	X	X	X	X	X	X	X	X	X	X	X
Acetone	E0540-80	4	4	1	4	2	1	2	4	4	4	4	1	4	4	4	3	4	4
Acetaldehyde	E0540-80	3	3	2	4	1	1	3	3	3	4	4	2	2	2	2	3	4	2
Benzene	V1164-75	4	4	4	1	1	1	2	4	4	4	4	4	4	4	4	4	3	4
Amines-Mixed	C0873-70	4	4	2	4	3	2	3	2	2	4	4	2	2	2	2	4	4	2
Epoxy Resins	E0540-80	X	X	1	4	1	1	X	1	X	X	X	1	X	X	X	X	X	X

Fluorinated rubbers (FFKM/FKM) is the only family of elastomers that fit all of these requirements. There are two sub-categories of fluorinated elastomer that are suitable for this application:

- Perfluoroelastomers (FFKM)
    - Trade names Parofluor (Parker) or Kalrez (DuPont)
    - Approximately 75% fluorine content
- Highly fluorinated elastomer (subcategory of FKM)
    - Trade names Hifluor (Parker) or Viton ETP Extreme (DuPont)
    - Approximately 74.5% and 73.5% fluorine content respectively

These elastomers incorporate fluorine atoms into their polymer chains to resist chemical attack, much like PTFE (Teflon). The resistance to chemical attack is approximately proportional to the saturation of the chains with fluorine atoms. Perfluorinated elastomers contain approximately 75% fluorine, while Hifluor and Viton ETP contain approximately 74.5% and 73.5% respectively[9].

Perfluoroelastomers are very expensive to manufacture. A 3/16" O-ring large enough to seal the mould would cost approximately $1500 CDN. A more economical choice is the highly fluorinated FKM elastomers, costing approximately half of a comparable perfluoroelastomer for Hifluor and even less for Viton ETP.

TABLE VII summarizes the properties for the two families of material which are suitable (FKM and FFKM).

TABLE VII. PROPERTIES OF VARIOUS ELASTOMER MATERIALS, MODIFIED FROM [1].

P - Poor
F - Fair
G - Good
E - Excellent

Polymer	Abrasion Resistance	Chemical Resistance	Cold Resistance	Dynamic Properties	Heat Resistance	Impermeability	Tensile Strength	Set Resistance	Tear Resistance	Cost
FKM (eg. HiFluor)	G	E	PF	GE	E	G	GE	E	F	F
FFKM (eg. Parofluor)	P	E	PF	F	E	G	FG	G	PF	P

Weaknesses of both FKM and FFKM elastomers are tear resistance and low temperature operating conditions. Since the operating temperature is not expected to be below room temperature, the low temperature performance is not critical. The tear resistance is far more important, since the mould must be repeatedly disassembled and reassembled.

Note that the FKM is stronger, more abrasion and tear resistant (tougher), and has better dynamic properties than FFKM. This suggests that the added expense of FFKM is definitely not justified, and that the cheaper FKM base polymer should be selected.

O-Ring Failure

Spiral fracture is common in circular cross section o-rings due to the low polar moment of interia. A circular cross section is not as resistant to twisting as other shapes, such as squares or rectangles. For this reason, part of the o-ring may twist while another section remains stationary. When this partially twisted section of o-ring is under pressure and comes in contact with the edges of the gland, it may be damaged in a spiral type pattern. This is especially common for low speed applications, and can be reduced by lubricating the seal.

Other failure modes to consider include compression set, extrusion, and abrasion. Each of these topics will be touched on briefly in the following paragraphs.

Compression set occurs when a seal becomes permanently deformed and no longer exerts a sealing force against the gland and sealing surface. This shoud not be a significant concern for the current design, since the seal materials used possess good compression set properties and are not excessively compressed for long periods of time.

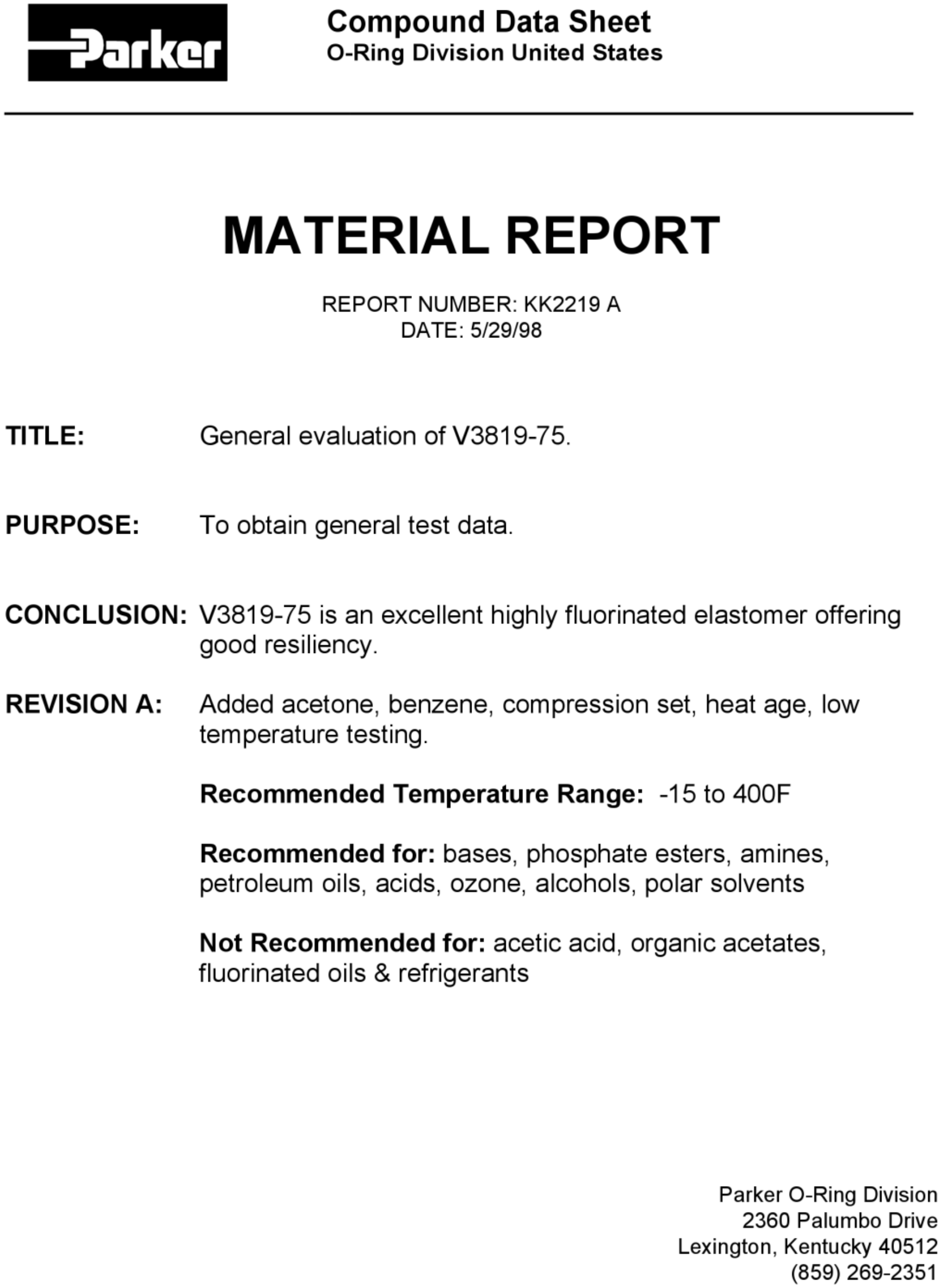
Extrusion occurs when high pressure forces the elastomer material into the clearance gap. This is not expected to occur in the current design since the pressures are far below design pressures for the specified clearance gap.

Abrasion occurs over time when rough surfaces rub against the seal. It is important to consider abrasion in the present design since the elastomer used (FKM) is not extremely abrasion resistant. The abrasion performace may be improved by ensuring a sufficiently fine surface finish and by using lubricants periodically.

In addition to proper design, the seal must be installed and used under appropriate operating conditions to reduce the possibility of failure. Some guidelines for installation and operation are provided below.

During installation, the O-ring should not be stretched more than necessary. The lead in fillet on the plate should help with installation of the O-ring. All sharp corners and metal particles should be removed to help prevent damage during installation and operation. Rolling of the o-ring should be minimized to reduce the chances of initiating a spiral fracture. During initial set up, alignment should be verified to ensure the O-ring is not loaded eccentrically.

Parker data sheet for the elastomer chosen (V3819) is available on the Parker website [10] and appears below for convenience.



Parker

Compound Data Sheet
O-Ring Division United States

MATERIAL REPORT

REPORT NUMBER: KK2219 A
DATE: 5/29/98

TITLE: General evaluation of V3819-75.

PURPOSE: To obtain general test data.

CONCLUSION: V3819-75 is an excellent highly fluorinated elastomer offering good resiliency.

REVISION A: Added acetone, benzene, compression set, heat age, low temperature testing.

Recommended Temperature Range: -15 to 400F

Recommended for: bases, phosphate esters, amines, petroleum oils, acids, ozone, alcohols, polar solvents

Not Recommended for: acetic acid, organic acetates, fluorinated oils & refrigerants

Parker O-Ring Division
2360 Palumbo Drive
Lexington, Kentucky 40512
(859) 269-2351

REPORT DATA

Report Number: KK2219 A

	V3819-75
Base Polymer	Hifluor
Original Physical Properties	
Hardness (Shore A) pts	78
Tensile Strength, psi	2030
Elongation, %	145
Modulus @ 100%, psi	1464
Specific Gravity	2.01
Low Temperature Properties	
TR-10, °F	+6
Compression Set	
70 Hours @ 392 °F	22.4
70 Hours @ 445 °F	33.1
Heat Resistance, Hardness Change (pts)	
24 Hours @ 536 °F	0
70 Hours @ 563 °F	+4
168 Hours @ 536 °F	+5
Immersion in Acetone, 24 Hrs @ 73 °F	
Hardness Change, pst	-5
Volume Change, %	+11.4
Immersion in Benzene, 168 Hrs @ 100 °F	
Hardness Change, pts	-3
Volume Change, %	+5.8

[1] Parker. (2007). *Parker O-Ring Handbook* [Online]. Available: http://www.parker.com/literature/ORD%205700%20Parker_O-Ring_Handbook.pdf. [November 20,2010].

[2] R. Flitney. (2007). *Seals and Sealing Handbook* (Fifth Edition) [Online]. Available: Elsevier [November 18, 2010].

[3] Fibre Glast. (2010, Mar). “*PART #77 – MOLDING RESIN*” [Online]. Available: http://cdn.fibreglast.com/downloads/PDCT-MSDS-00023-B.pdf [November 19, 2010].

[4] Fibre Glast. (2009, May). “*#69 – MEKP*” [Online]. Available: http://cdn.fibreglast.com/downloads/PDCT-MSDS-00019.pdf [November 19, 2010].

[5] Fibre Glast. (2009, Jun). “*PART ##1110 Vinyl Ester Resin*” [Online]. Available: http://cdn.fibreglast.com/downloads/PDCT-MSDS-00119.pdf [November 19, 2010].

[6] Fibre Glast. (2009, Jun). “*PART #*2000 VARIABLE CURE EPOXY RESIN” [Online]. Available: http://cdn.fibreglast.com/downloads/PDCT-MSDS-00130.pdf [November 19, 2010].

[7] Fibre Glast. (2009, Jun). “*PART #*2060, 60 MINUTE EPOXY CURE” [Online]. Available: http://cdn.fibreglast.com/downloads/PDCT-MSDS-00132.pdf [November 19, 2010].

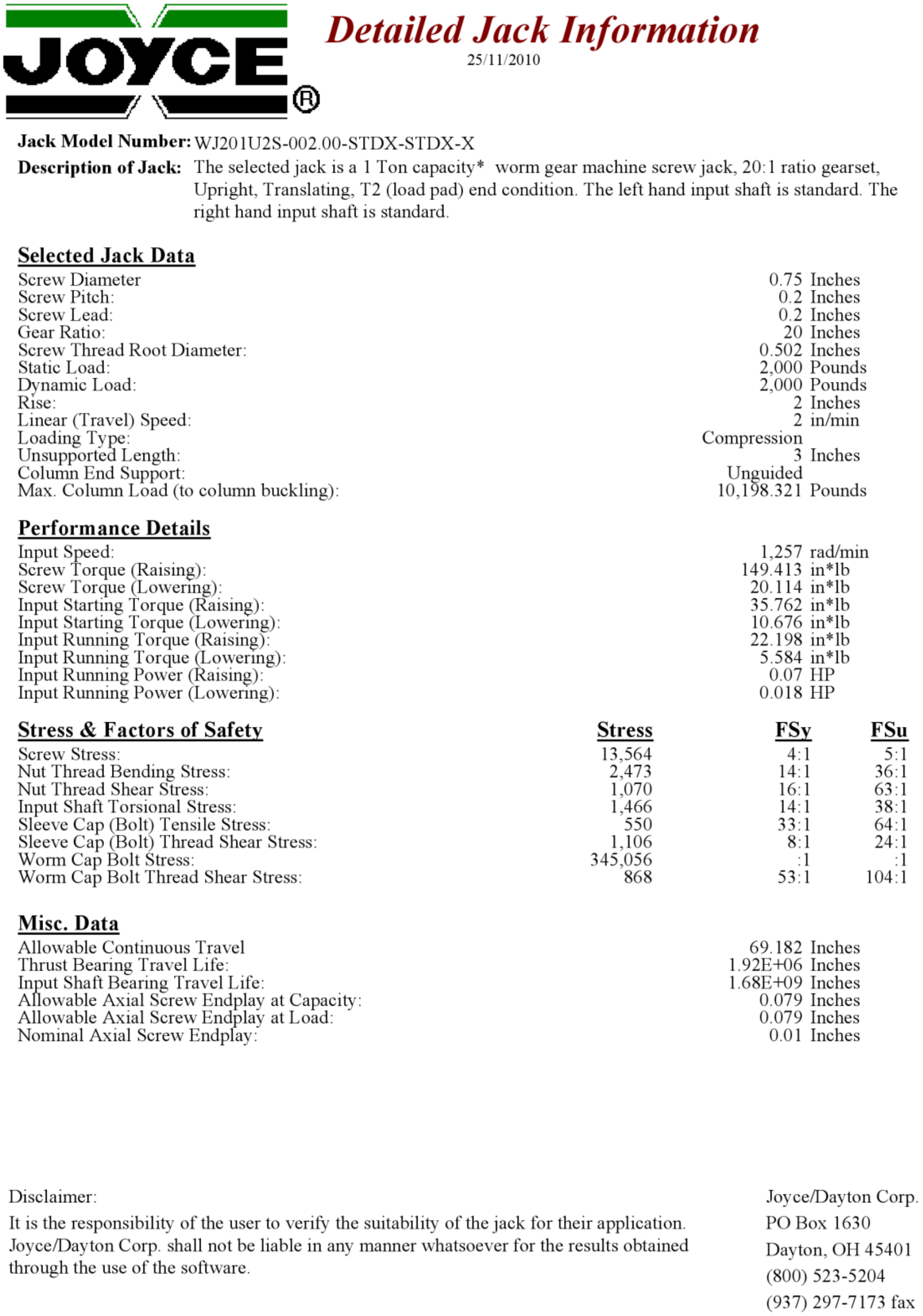
[8] Standard Practice for Rubber and Rubber Latices – Nomenclature, ASTM D1418-10a, 2010.

[9] S. Jagels. (2009). *Types of Fluorinated Elastomers* [Online]. Available: http://www.swjagels.com/uploads/Types_of_Fluorinated_Elastomers.pdf [November 20, 2010].

[10] Parker. (2009). *V3819 2-386* [Online]. Available: http://www.parker.com/portal/site/PARKER [November 17, 2010].

Appendix D – Linear Motion Systems

This appendix contains detailed manufacturers' specification sheets for the screw jack [1], PLC [2], LVDT [3], servomotor [4], and linear bearings [5], and drawings created in SolidWorks [6] for the guide shaft and mounting plate.



JOYCE®

Detailed Jack Information

25/11/2010

Jack Model Number: WJ201U2S-002.00-STDX-STDX-X

Description of Jack: The selected jack is a 1 Ton capacity* worm gear machine screw jack, 20:1 ratio gearset, Upright, Translating, T2 (load pad) end condition. The left hand input shaft is standard. The right hand input shaft is standard.

Selected Jack Data

Screw Diameter	0.75	Inches
Screw Pitch:	0.2	Inches
Screw Lead:	0.2	Inches
Gear Ratio:	20	Inches
Screw Thread Root Diameter:	0.502	Inches
Static Load:	2,000	Pounds
Dynamic Load:	2,000	Pounds
Rise:	2	Inches
Linear (Travel) Speed:	2	in/min
Loading Type:	Compression	
Unsupported Length:	3	Inches
Column End Support:	Unguided	
Max. Column Load (to column buckling):	10,198.321	Pounds

Performance Details

Input Speed:	1,257	rad/min
Screw Torque (Raising):	149.413	in*lb
Screw Torque (Lowering):	20.114	in*lb
Input Starting Torque (Raising):	35.762	in*lb
Input Starting Torque (Lowering):	10.676	in*lb
Input Running Torque (Raising):	22.198	in*lb
Input Running Torque (Lowering):	5.584	in*lb
Input Running Power (Raising):	0.07	HP
Input Running Power (Lowering):	0.018	HP

Stress & Factors of Safety	**Stress**	**FSy**	**FSu**
Screw Stress:	13,564	4:1	5:1
Nut Thread Bending Stress:	2,473	14:1	36:1
Nut Thread Shear Stress:	1,070	16:1	63:1
Input Shaft Torsional Stress:	1,466	14:1	38:1
Sleeve Cap (Bolt) Tensile Stress:	550	33:1	64:1
Sleeve Cap (Bolt) Thread Shear Stress:	1,106	8:1	24:1
Worm Cap Bolt Stress:	345,056	:1	:1
Worm Cap Bolt Thread Shear Stress:	868	53:1	104:1

Misc. Data

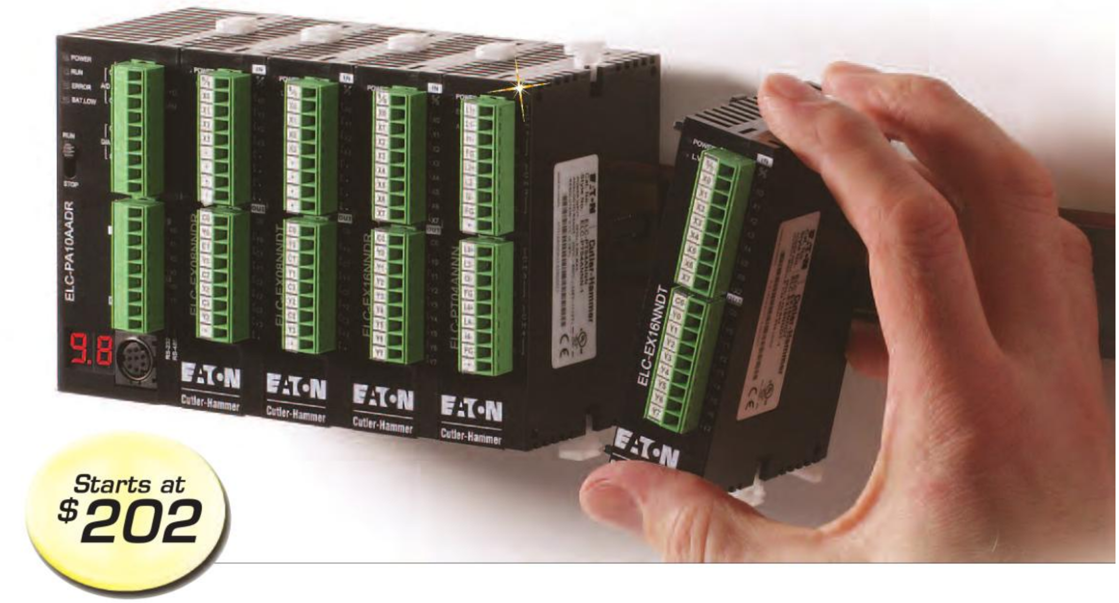
Allowable Continuous Travel	69.182	Inches
Thrust Bearing Travel Life:	1.92E+06	Inches
Input Shaft Bearing Travel Life:	1.68E+09	Inches
Allowable Axial Screw Endplay at Capacity:	0.079	Inches
Allowable Axial Screw Endplay at Load:	0.079	Inches
Nominal Axial Screw Endplay:	0.01	Inches

Disclaimer:
It is the responsibility of the user to verify the suitability of the jack for their application. Joyce/Dayton Corp. shall not be liable in any manner whatsoever for the results obtained through the use of the software.

Joyce/Dayton Corp.
PO Box 1630
Dayton, OH 45401
(800) 523-5204
(937) 297-7173 fax

NEW

ELC PROGRAMMABLE LOGIC CONTROLLERS AND MODULES



Starts at $202

1 YEAR WARRANTY CE RoHS

- **Base Models with 10 to 14 I/O, Expandable to 256**
- **Half the Size of Most PLCs**
- **1-, 4-, 8-, 16-and 32-Bit Instructions**
- **DIN Rail Mountable, No Rack Required**
- **Built-in Integral LED Display**
- **High-level Network Access - Modbus, DeviceNet and Profibus**
- **Remote Analog Modules for Analog I/O, Thermocouples and RTDs**

The Eaton Logic Controller (ELC) is Eaton Cutler-Hammer's latest offering into the PLC (Programmable Logic Controller) market. Using the latest technology this reduced-sized ELC, with its abundant module selection provides a "just right" concept, for delivering only what you want for the price you desire.

The Right Amount of I/O

Why pay for functionality you'll never need? Why be trapped with functionality that you can't scale to meet changing needs? Eaton is changing everything with the ELC. At less than half the size of most PLCs, the Cutler-Hammer ELC is an ideal solution when space is at a premium and specialized I/O needs present themselves.

ELC's Value Added Differences

4 Controller Styles:

- Basic—14 I/O (8I/6O) Over 130 instructions provide all the power you need; 2 serial ports for master/slave communications
- Clock/Calendar—Same features as the basic model plus clock/calendar, remote I/O and retentive data storage
- Analog—Same features as clock/calendar plus analog in and out
- High Speed—All the features of clock/calendar with the ability to capture or output 100 Khz pulses

A Wealth of Features

The ELC family offers four styles of controllers. These controllers offer combinations of the following features:

- High speed pulse capture and high speed pulse output on all controllers
- Interrupts
- Large module selection AC/DC in, relay/transistor out
- Large analog selection of analog in, out, combined, thermocouple, RTD platinum
- Over 200 instructions to choose from: Floating point math, communications, hex, decimal, octal, BCD, ASCII conversion, 1, 4, 8, 16, 32, bit manipulations, logical, block move, block compare, retentive data storage, time base from clock/calendar
- 2 Modbus (ASCII or RTU) serial ports: 1 slave only, 1 master/slave
- ELC controller can be wired for remote I/O communications (except the PB model)

Space Saving, Cost Saving

This space-saving design perfectly fits at home in small machine control stations as well as other enclosed applications where space is critical.

While the ELC is perfectly suited for applications with 40 I/O and less, it can also be expanded to 256 I/O. That means there's no need to change to a different controller as I/O needs expand. Furthermore, the ELC's 2 communication ports can provide any networking task. In remote mode, the ELC exchanges and shares information with up to 16 other devices, in normal mode, the ELC can communicate with up to 32 other devices. Its small size allows for reduced panel size, and saves valuable machine space.

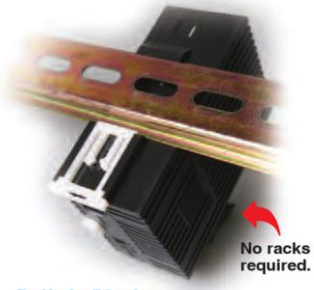
Capability

The ELC provides the instruction set of a large PLC in a small package. It is capable of 1-, 4-, 8-, 16- and 32-bit instructions, block compare, block move, communications, interrupts, clock/calendar and logic, over 240 instructions in all (except PB).

No Racks Required

A DIN rail lets you add as many modules as desired. Just snap on, and slide into place. All connections are done automatically.

ELC-PA10AADR, $440, shown larger than actual size.



Built-In Display

An integral LED display provides user-assigned process monitoring, error messages, alarms, display counts and more.

Large PLC Features

Multiple communication ports, remote I/O ability, data storage, high speed counters, high speed pulse outputs, interrupts, timer resolution to 10 ms, PIDs, plus much more.

Easy Connectivity to Drives

ELC communicates easily to MVX drives, eliminating the need to operate drives by analog voltage/current or digital I/O. ELC can access all of the parameters in the MVX by serial communications, saving money.

Remote Communication

All ELC analog type modules are capable of stand-alone operation. Mounted remotely, the ELC communicates to the analog module through its communications port. The ELC also lets you read parameters, set parameters, use scale, offset, and average values.

Software

ELCSoft programs in standard ladder, sequential function chart programming or instruction.

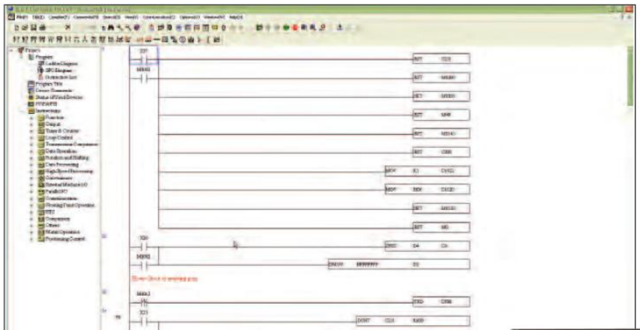
ELC Modules

ELC Expansion Modules

ELC expansion modules provide the correct amount of I/O for application solutions. Choose 8 or 16 I/O expansion modules added to the ELC processor 256 I/O (128 Inputs and 128 maximum).

ELC Specialty Modules

In addition to the expansion specialty modules like analog in, out, Platinum temperature, thermocouple, DeviceNet, PROFIBUS, and simulator switch module; can be added. The ELC-485APTR easily connects the RS485 port of MVX drive, controllers and other devices.



ELC SOFTWARE

- Display registers “in use” and modules attached to the ELC
- Monitor runtime applications; force (except basic), and enter/modify register values
- Wizards aid programming of remote I/O, standard communications, high speed counters, pulse outputs, ELC Link, positioning, interrupts, PIDs, and extension module setup

ELCSoft, software, $277.

ELC-GP02, $281.

GRAPHIC PANELS

ELC Graphic Panels are simple to program and easily connect to ELC products. ELC graphic panels make modifying an application quick and easy. ELC graphic panels also connect to Cutler-Hammer® MVX drives, IQMODBUS meters and many other devices. With over 30 objects that can be placed anywhere on the display, these tough panels also communicate with other major controllers. These graphic panels have two serial ports which can be used simultaneously to communicate. Transfer applications to or from these graphic panels using the handy transfer module (ELC-GPXFERMOD). Ten programmable functions keys provide easy to change pages, input numeric values, enter alpha-numeric passwords, set, reset and more. Create alarms, password protect, import bitmaps, and use many different fonts.

ELC-GP04, $420.

SPECIFICATIONS

ELECTRICAL/EMC

ESD Immunity: 8 kV air discharge

EFT Immunity:
  Power Line: 2 kV
  Digital I/O: 1 kV
  Analog and Communication I/O: 250 V

Damped-Oscillatory Wave:
  Power Line: 1 kV
  Digital I/O: 1 kV

RS Immunity: 26 MHz to 1 GHz, 10 V/m

OTHER APPROVALS

Agency Certifications: UL 508, cUL, CE, Class 1, Div 2

ENVIRONMENTAL RATINGS

TRANSPORTATION AND STORAGE

Temperature: -25 to 70°C (-13 to 158°F)

Humidity: 5 to 95%

OPERATING

Temperature: 32 to 131°F (0 to 55°C)

Humidity: 50 to 95%

Power Supply Voltage:
  ELC: 24 Vdc (-15 to 20%) with DC input reverse polarity protection
  Expansion Unit: Supplied by the ELC

Power Consumption: 3 to 6 W

Insulation Resistance: >5 M @ 500 Vdc, between all inputs/outputs and earth

Grounding: The diameter of the grounding wire cannot be smaller than the wire diameter of terminals L and N (all ELC units should be grounded directly to the ground pole)

Vibration/Shock Resistance:
  Standard: IEC1131-2, IEC 68-2-6 (TEST Fc)/IEC1131-2 and IEC 68-2-27 (TEST Ea)

Approx. Weight: 0.158 kg (0.348 lb)

DC INPUT POINT ELECTRICAL

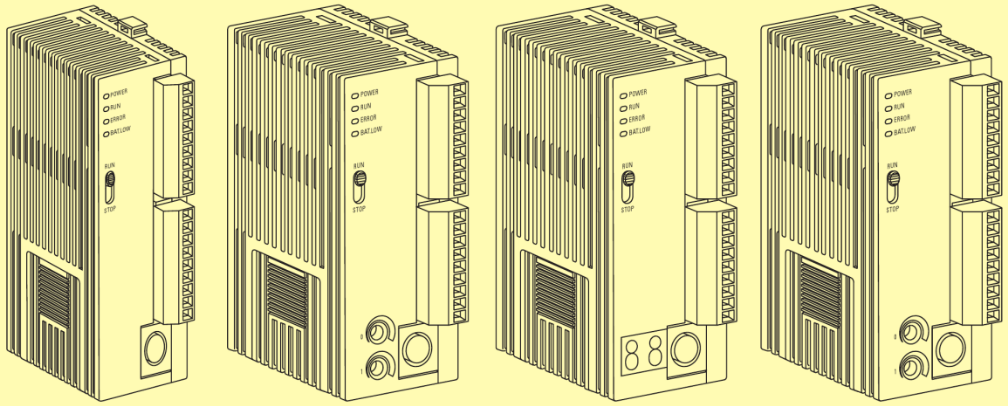
Input Type: DC (SINK or SOURCE)

Input Current: 24 Vdc 5 mA

Active Level:
  OFF/ON: Above 16 Vdc
  ON/OFF: Below 14.4 Vdc

Response Time: About 10 mS; an adjustment range of 0 to 10,000 mS could be selected through D1020 and D1021

NEW



ELC-PB14 Series ELC-PC12 Series ELC-PA10 Series ELC-PH12NNDT

SPECIFICATIONS (CONTINUED)

Maximum I/O: 256 (128 In / 128 out); any number of modules

I/O Type:
- **ELC-PB14 Series:** 14 (8 in/6 out, digital)
- **ELC-PC12 Series:** 12 (8 in/4 out, digital)
- **ELC-PA10 Series:** 10 (4 in/2 out, digital; 2 in/2 out, analog)
- **ELC-PH12NNDT:** 12 (8 in/4 out, digital)

DC In Sink/Source: Yes

Execution Speed: Basic commands—2 µ seconds min

Program Language: Boolean + ladder logic + SFC

Program Capacity:
- **ELC-PB14 Series:** 3792 Steps
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT:** 7920 Steps

Data Memory Capacity (bits):
- **ELC-PB14 Series:** 1280 Bits
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT:** 4096 Bits

Data Memory Capacity (words):
- **ELC-PB14 Series:** 744 Words
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT:** 5000 Words

Index Registers:
- **ELC-PB14 Series:** 2 Words
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT:** 8 Words

File Memory Capacity:
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT Only:** 1600 Words

Commands:
- **ELC-PB14 Series:** 32 Basic/107 advanced
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT:** 32 Basic/168 advanced

Floating Point: Yes

SFC Commands:
- **ELC-PB14 Series:** 128 Steps
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT:** 1024 Steps

Timers:
- **ELC-PB14 Series:** 128 (1 to 100 ms)
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT:** 256 (1 to 100 ms)

Counters:
- **ELC-PB14 Series:** 128 (16 bit/32 bit/up/down)
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT:** 250 (16 bit/32 bit/up/down)

High Speed Counters:
- **ELC-PB14 Series:** 1 (14 modes) 10 K max
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT:** 1 (14 modes) 20 kHz for PA/PC; 100 kHz for PH

Pulse Output:
- **ELC-PB14 Series:** 2 channels 10 kHz max
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT:** 2 channels, 40 kHz max for PC/PA, 100 kHz for PH

Master Control Loop:
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT Only:** 8 Loops

Subroutines:
- **ELC-PB14 Series:** 64 subroutines
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT:** 256 subroutines

Interrupts:
- **ELC-PB14 Series:** 6
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT:** 15 (external/time base/HS CNTR /comm)

Real-time Clock/Calendar:
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT Only:** Built-in

Specialty Expansions Modules: 8 (analog in/analog out/TC/RTD/PT); modules do not count in total I/O

Serial Ports: 2 (one RS232, one RS485)

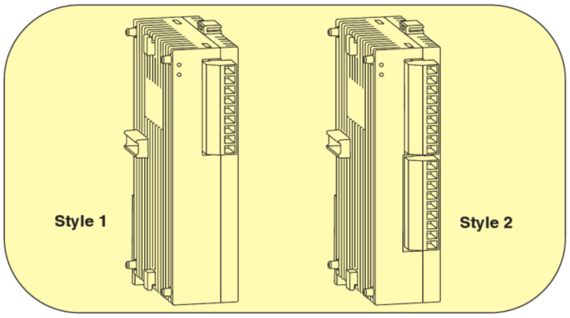
Remote I/O:
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT Only:** With 16 other devices

Run Time Editing:
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT Only:** Yes, also includes PB

Run/Stop Switch:
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT Only:** Yes, also includes PB

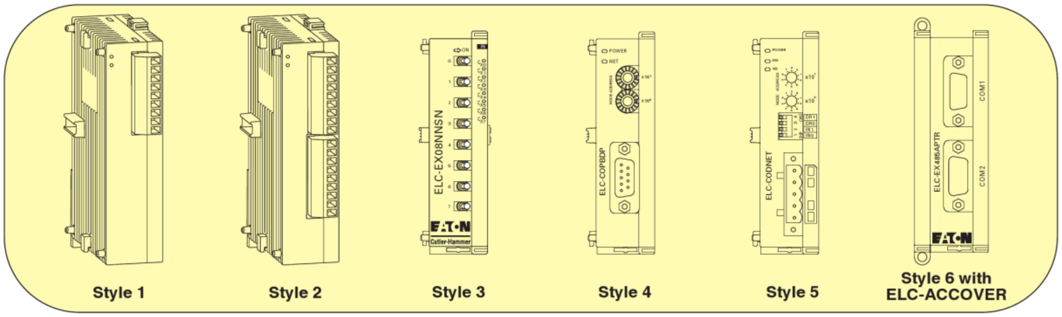
Removable Terminal Strips:
- **ELC-PC12 Series, ELC-PA10 Series, ELC-PH12NNDT Only:** Yes, also includes PB

Special Features:
- **ELC-PC12 Series:** 2 potentiometers
- **ELC-PA10 Series:** Two 7-segment displays
- **ELC-PH12NNDT:** 2 potentiometers



ELC EXPANSION MODULES

MODEL	TYPE	STYLE	INPUTS		OUTPUTS	
			POINTS	TYPE	POINTS	TYPE
ELC-EX08NNAN	AC IN	1	8	120 Vac	0	—
ELC-EX08NNDN	DC IN	1	8	DC Sink or Source	0	—
ELC-EX08NNNR	Relay OUT	1	0	—	8	Relay
ELC-EX08NNDT	IN/OUT Combo	2	4	DC Sink or Source	4	Transistor
ELC-EX08NNNT	Transistor OUT	1	0	—	8	Transistor
ELC-EX06NNNI	High Current Relay OUT	2	0	—	6	Relay (6 A)
ELC-EX08NNDR	IN/OUT Combo	2	4	DC Sink or Source	4	Relay
ELC-EX16NNDR	IN/OUT Combo	2	8	DC Sink or Source	8	Relay
ELC-EX16NNDT	IN/OUT Combo	2	8	DC Sink or Source	8	Transistor



ELC SPECIALTY MODULES

MODEL	TYPE	POWER	STYLE	INPUTS		OUTPUTS	
				POINTS	TYPE	POINTS	TYPE
ELC-AN02NANN	Analog OUT	24 Vdc	1	0	-20 mA~20 mA	2 (12 bits)	0 to 20 mA, 4 to 20 mA 0 to 10V, 2 to 10V
ELC-AN04NANN	Analog OUT		2	0	-10V ~ +10V	4 (12 bits)	
ELC-AN06AANN	Analog Combo		2	4	±10V, ±20 mA	2 (12 bits)	0 to 20 mA, 0 to 10V
ELC-AN04ANNN	Analog IN		2	4 (V = 14 bits, I = 11 bits)	±10V, ±20 mA	0	—
ELC-PT04ANNN	PT100		2	4 (V = 14 bits, I = 13 bits)	PT100	0	
ELC-TC04ANNN	Thermocouple		2	4	J, K, R, S, T	0	
ELC-EX08NNSN	Switch Input	24 Vdc	3	8	Switch	0	
ELC-COPBDP	PROFIBUS DP	24 Vdc	4	32	Digital	32	Digital
ELC-CODNET	DeviceNet	24 Vdc	5	32	Digital	32	Digital
ELC-485APTR	RS485 Easy Connect	N/A	6	0	—	0	—

To Order *(Specify Model Number)*

MOST POPULAR MODELS HIGHLIGHTED!

MODEL NO.	PRICE	DESCRIPTION	INPUT AC	INPUT DC	INPUT ANALOG	OUTPUT RELAY	OUTPUT TRANSISTOR	OUTPUT ANALOG
ELC-PB14NNDR	$202	14 I/O PB Series		8		6		
ELC-PB14NNDT	202	14 I/O PB Series		8			6	
ELC-PC12NNAR	256	12 I/O PC Series	8			4		
ELC-PC12NNDR	256	12 I/O PC Series		8		4		
ELC-PH12NNDT	266	12 I/O PH Series		8			4	
ELC-PA10AADR	440	10 I/O PA Series		4	2	2		2

DIGITAL I/O EXPANSION MODULES

MODEL NO.	PRICE	DESCRIPTION	TYPE	INPUT AC	INPUT DC	OUTPUT RELAY	OUTPUT TRANSISTOR
ELC-EX06NNNI	$143	6 I/O expansion	6 A outputs			6	
ELC-EX08NNAN	97	8 I/O expansion	AC in	8			
ELC-EX08NNDN	82	8 I/O expansion	DC in		8		
ELC-EX08NNNR	127	8 I/O expansion	Relay out			8	
ELC-EX08NNDR	127	8 I/O expansion	in/out combo		4	4	
ELC-EX16NNDR	143	16 I/O expansion	in/out combo		8	8	
ELC-EX08NNDT	119	8 I/O expansion	in/out combo		4		4
ELC-EX08NNNT	127	8 I/O expansion	Transistor out				8
ELC-EX16NNDT	143	16 I/O expansion	in/out combo		8		8
ELC-EX08NNSN	97	8 I/O expansion	Switch in		8		

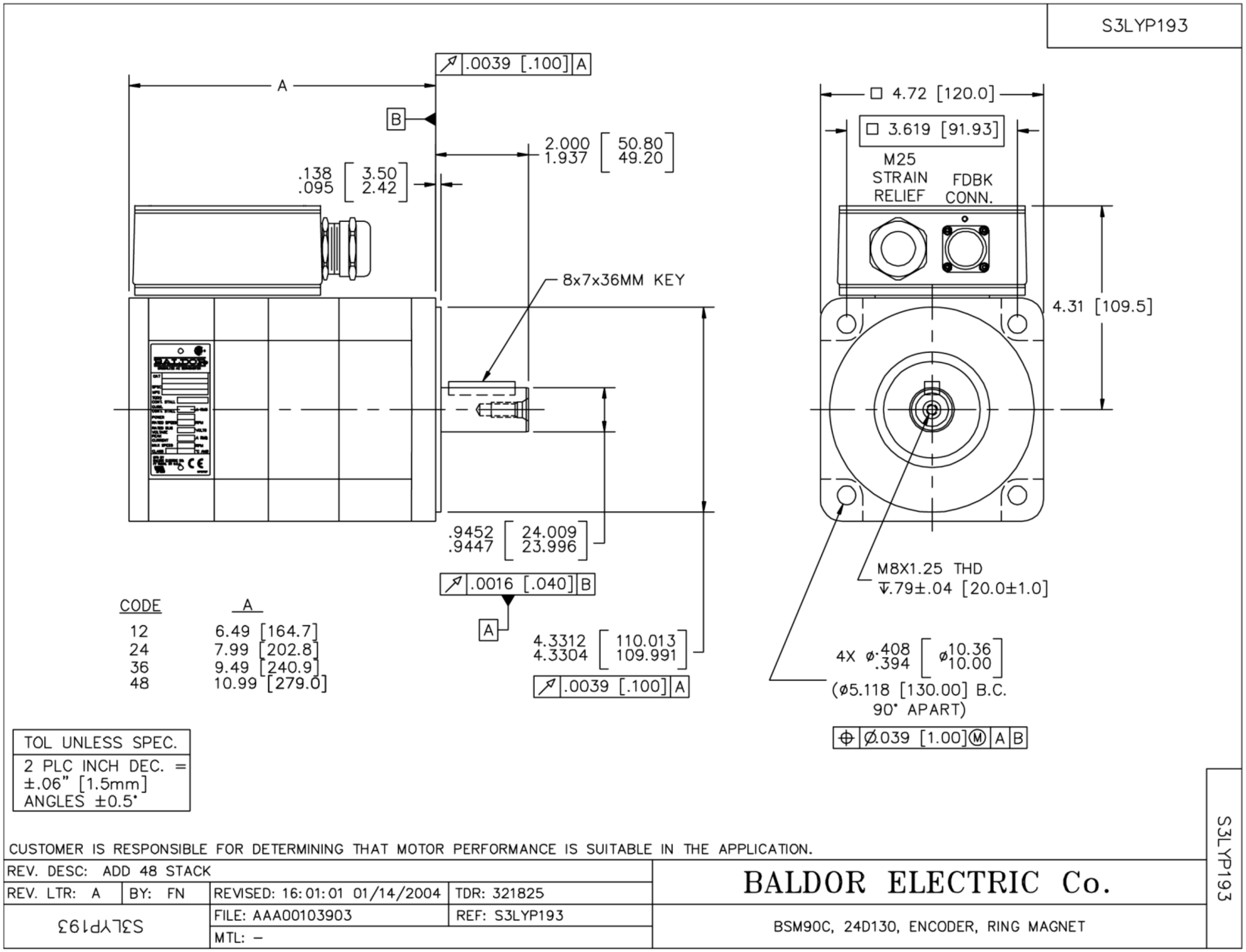
ANALOG I/O MODULES

MODEL NO.	PRICE	DESCRIPTION	ANALOG IN	ANALOG OUT
ELC-AN04ANNN	$260	4 I/O analog in	4	
ELC-AN02NANN	245	2 I/O analog out		2
ELC-AN04NANN	340	4 I/O analog out		4
ELC-AN06AANN	355	6 I/O analog in/out	4	2
ELC-TC04ANNN	370	4 I/O thermocouple J, K, R, S, T	4	
ELC-PT04ANNN	326	4 I/O platinum RTD, PT100	4	

ACCESSORIES

MODEL NO.	PRICE	DESCRIPTION
ELC-CODNET	$340	ELC expansion module for DeviceNet e
ELC-COPBDP	480	ELC expansion module for ProfibusDP slave
ELC-MC01	450	ELC motion control for 1 axis, use with ELC-PHNNDT
ELC-ACPGMXFR	143	Program transfer module for ELC controllers
ELC-GP02	281	ELC graphics panel, monochrome, 160x32 pixels, 10 keys
ELC-GP04	420	ELC graphics panel, monochrome, 128x64 pixels, 10 keys
ELC-GPXFERMOD	93	ELC graphics panel transfer module
ELC-PS01	67	ELC power supply, 24 W, 1 A
ELC-PS02	97	ELC power supply, 48 W, 2 A
ELCSOFT	277	ELC programming software for ELC controllers
ELCSOFTGP	289	ELC programming software for ELC graphics panels
ELC-CBPCELC1	43	Cable to connect a PC or a GP unit to ELC, 1 m (3.3') (DB9 pin female to 8 pin DIN)
ELC-CBPCELC3	46	Cable to connect a PC or a GP unit to ELC, 3 m (9.8') (DB9 pin female to 8 pin DIN)

Ordering Example: ELC-PB14NNDR, ELCSOFT,** $202 + 277 = **$479.


S3LYP193
.0039 [.100] A
A
B
2.000 1.937 [50.80 49.20]
.138 .095 [3.50 2.42]
8x7x36MM KEY
.9452 .9447 [24.009 23.996]
.0016 [.040] B
A
4.3312 4.3304 [110.013 109.991]
.0039 [.100] A
CODE
A
12
24
36
48
6.49 [164.7]
7.99 [202.8]
9.49 [240.9]
10.99 [279.0]
□ 4.72 [120.0]
□ 3.619 [91.93]
M25 STRAIN RELIEF
FDBK CONN.
4.31 [109.5]
M8X1.25 THD
↧.79±.04 [20.0±1.0]
4X ø.408 .394 [ø10.36 10.00]
(ø5.118 [130.00] B.C. 90° APART)
⌖ Ø.039 [1.00] Ⓜ A B
TOL UNLESS SPEC.
2 PLC INCH DEC. = ±.06" [1.5mm]
ANGLES ±0.5°
CUSTOMER IS RESPONSIBLE FOR DETERMINING THAT MOTOR PERFORMANCE IS SUITABLE IN THE APPLICATION.
REV. DESC: ADD 48 STACK
REV. LTR: A
BY: FN
REVISED: 16:01:01 01/14/2004
TDR: 321825
S3LYP193
FILE: AAA00103903
REF: S3LYP193
MTL: –
BALDOR ELECTRIC Co.
BSM90C, 24D130, ENCODER, RING MAGNET
S3LYP193

SMT-W-E TYPE

— Two Side Cut Double-Wide Flange Pilot End Type —

part number structure

example SMST 25 G W UU - E - SK

specification
SMT: standard
SMST: anti-corrosion

inner contact diameter (dr)

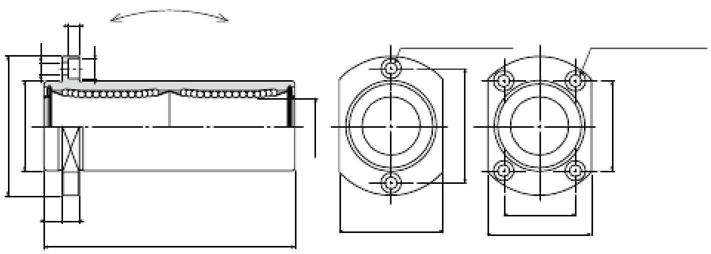
retainer material
blank: standard/steel
anti-corrosion/stainless steel
G: resin

double-wide type

seals on both sides

with pilot end

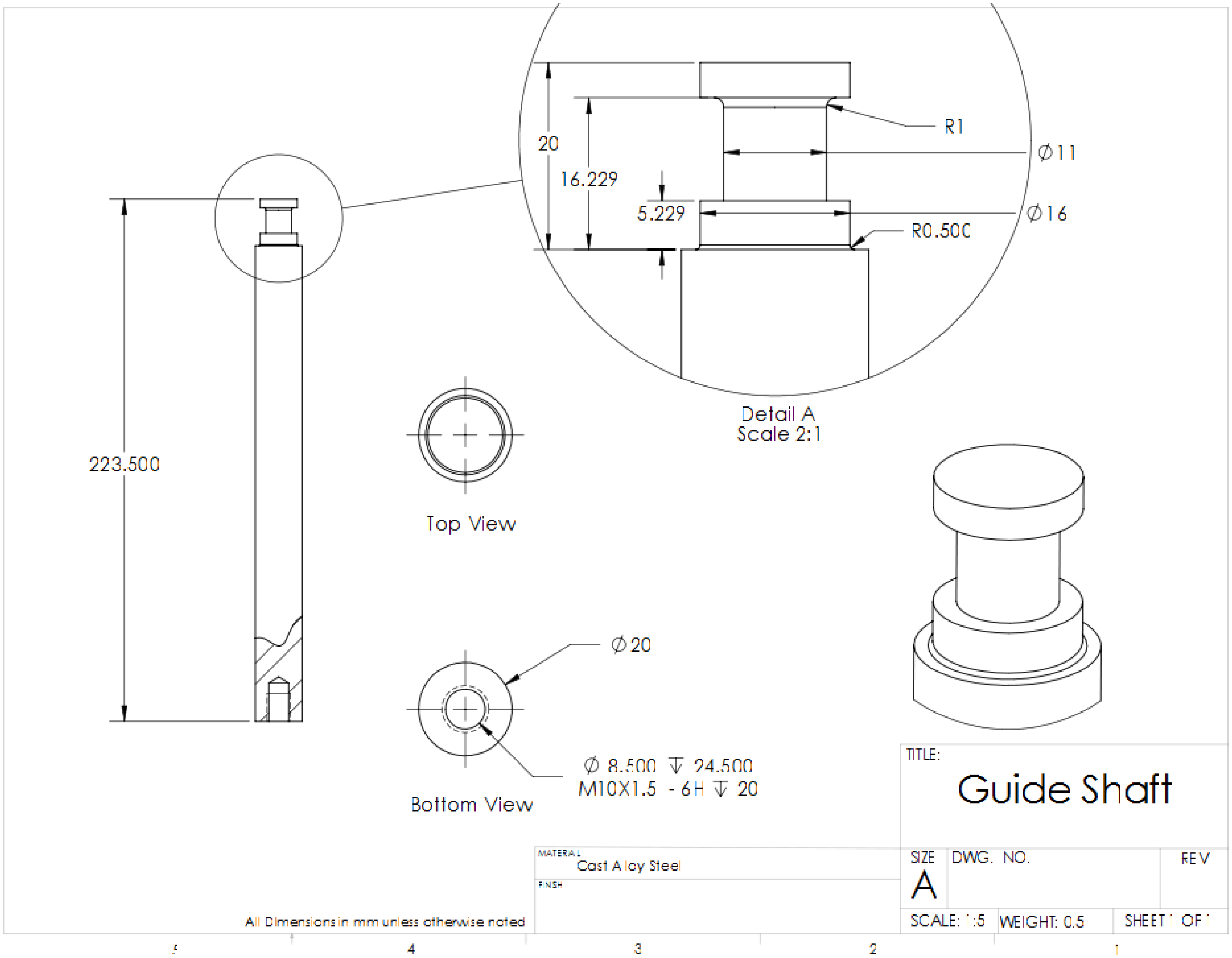
outer cylinder
surface treatment
blank: no surface treatment
SK: electroless nickel plating
LF: low temperature black chrome treatment with fluoride coating
SB: black oxide (not available on anti-corrosion type)
SC: industrial chrome plating

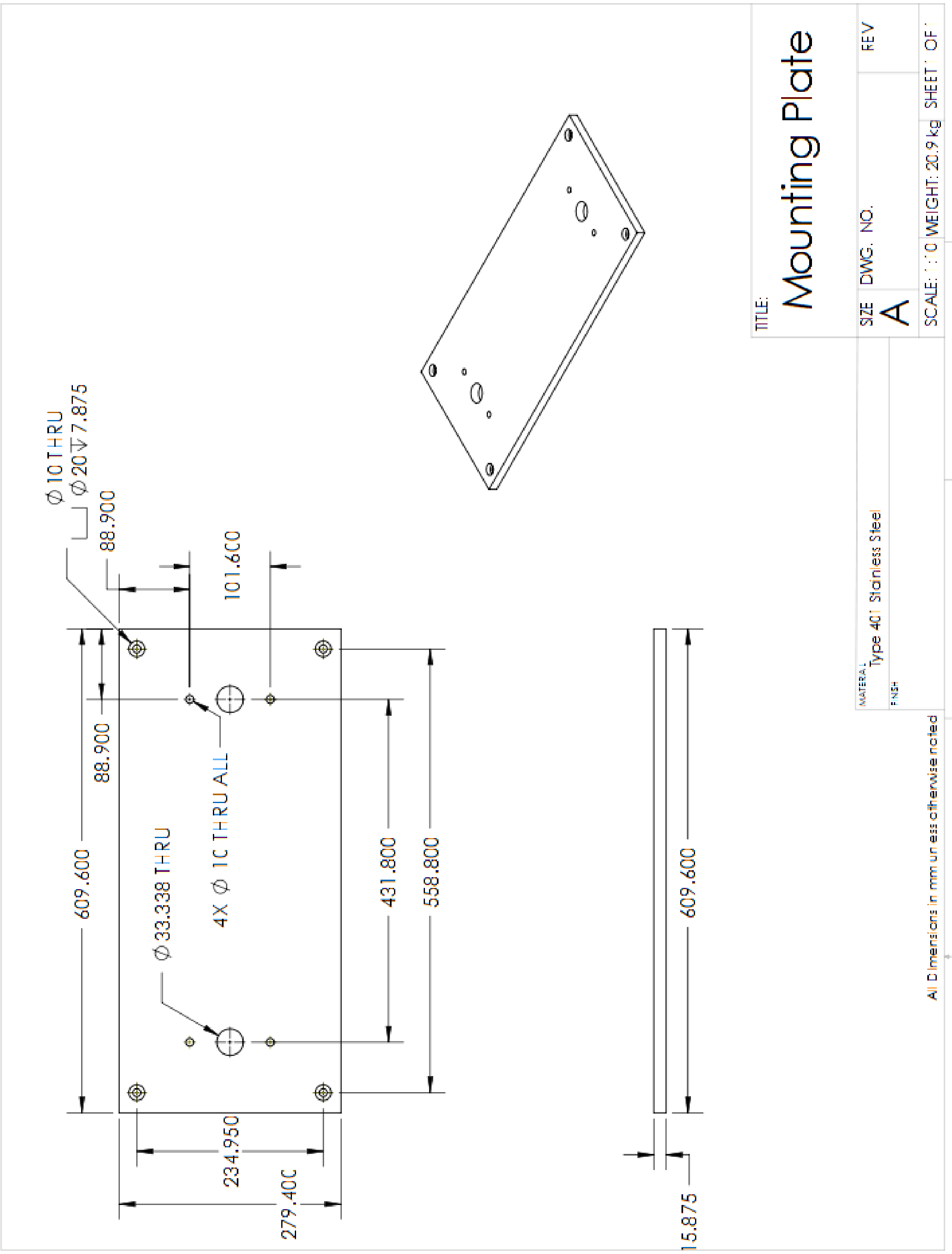


part number *				number of ball circuits	major dimensions														basic load rating		allowable static moment	mass	shaft diameter
standard		anti-corrosion			dr		D		L		flange						eccentricity	perpendicularity	dynamic	static			
steel retainer	resin retainer	stainless retainer	resin retainer		mm	tolerance µm	mm	tolerance µm	±0.3 mm	ℓ mm	Df mm	W mm	t mm	A mm	F mm	X×Y×Z mm	µm	µm	C N	Co N	Mo N・m	g	mm
SMT 6WUU-E	SMT 6GWUU-E	SMST 6WUU-E	SMST 6GWUU-E	4	6	0 −10	12	0 −13	35	5	28	18	5	20	—	3.5×6×3.1	15	15	323	530	2.18	28	6
SMT 8WUU-E	SMT 8GWUU-E	SMST 8WUU-E	SMST 8GWUU-E	4	8		15		45	5	32	21	5	24	—	3.5×6×3.1			431	784	4.31	47	8
SMT10WUU-E	SMT10GWUU-E	SMST10WUU-E	SMST10GWUU-E	4	10		19	0 −16	55	6	40	25	6	29	—	4.5×7.5×4.1			588	1,100	7.24	90	10
SMT12WUU-E	SMT12GWUU-E	SMST12WUU-E	SMST12GWUU-E	4	12		21		57	6	42	27	6	32	—	4.5×7.5×4.1			813	1,570	10.9	102	12
SMT13WUU-E	SMT13GWUU-E	SMST13WUU-E	SMST13GWUU-E	4	13		23		61	6	43	29	6	33	—	4.5×7.5×4.1			813	1,570	11.6	123	13
SMT16WUU-E	SMT16GWUU-E	SMST16WUU-E	SMST16GWUU-E	4	16		28		70	6	48	34	6	31	22	4.5×7.5×4.1			1,230	2,350	19.7	182	16
SMT20WUU-E	SMT20GWUU-E	SMST20WUU-E	SMST20GWUU-E	5	20	0 −12	32	0 −19	80	8	54	38	8	36	24	5.5×9×5.1	20	20	1,400	2,740	26.8	247	20
SMT25WUU-E	SMT25GWUU-E	SMST25WUU-E	SMST25GWUU-E	6	25		40		112	8	62	46	8	40	32	5.5×9×5.1			1,560	3,140	43.4	525	25
SMT30WUU-E	SMT30GWUU-E	SMST30WUU-E	SMST30GWUU-E	6	30		45		123	10	74	51	10	49	35	6.6×11×6.1			2,490	5,490	82.8	645	30

* UU type is standard.

1N≒0.102kgf 1N・m≒0.102kgf・m


20
16.229
5.229
R1
Ø11
Ø16
R0.500
223.500
Detail A
Scale 2:1
Top View
Bottom View
Ø20
Ø 8.500 ↧ 24.500
M10X1.5 - 6H ↧ 20
TITLE:
Guide Shaft
MATERIAL
Cast Alloy Steel
FINISH
SIZE
A
DWG. NO.
REV
SCALE: 1:5
WEIGHT: 0.5
SHEET 1 OF 1
All Dimensions in mm unless otherwise noted
5
4
3
2
1


Ø 10 THRU
⌴ Ø 20 ↧ 7.875
88.900
101.600
88.900
609.600
Ø 33.338 THRU
4X Ø 10 THRU ALL
431.800
558.800
234.950
279.400
609.600
15.875
TITLE:
Mounting Plate
SIZE
A
DWG. NO.
REV
SCALE: 1:10 WEIGHT: 20.9 kg SHEET 1 OF 1
MATERIAL
Type 401 Stainless Steel
FINISH
All Dimensions in mm unless otherwise noted
1
2
3
4
5

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Appendix E – Heating System

Heat Loss Calculations

The majority of the heat loss from the mould will be by means of convection with the surrounding air. More specifically, since the air is said to be quiescent or still, heat transfer will occur by means of free convection. In free convection, velocity has little involvement because the principles are based on the plates not moving. The first step in determining the heat loss is to calculate of value of a quantity known as the Rayleigh number [1].

$$Ra = \frac{g\beta(T_s - T_\infty)x^3}{\upsilon\alpha}$$

Where x is the length of the plate, g is the acceleration due to gravity, υ is the kinematic viscosity of the air, α is the thermal diffusivity of the air, and β is the inverse of the film temperature. The film temperature is the average of the surface temperature and the ambient temperature. The surface temperature is assumed to be 180°C and the ambient temperature is 25°C. This gives a film temperature of 102.5°C or 375.5 K. At this temperature, β is 0.002663 K^{-1}, υ is 2.372 x 10^{-5} m^2/s, α is 3.4184 x 10^{-5} m^2/s, and k is 0.031938 W/m*K. The Prandtl number at this film temperature is 0.6949. These values yield a Rayleigh number of:

$$Ra = \frac{(9.81)(0.002663)(180-25)(0.05)^3}{(2.372\ x\ 10^{-5})(3.4184\ x\ 10^{-5})} = 623{,}750$$

Since different surface conditions exist for different surfaces of the plate, they must be treated as separate orientations. Thus, separate values of the heat transfer coefficient must be calculated for the top, bottom, and sides of the mould. Treating the sides of the mould like a vertical plate, the Nusselt number for laminar flow is calculated using the following formula [1]:

$$Nu_1 = 0.68 + \frac{0.67Ra^3}{\left[1 + \left({}^{0.492}/_{Pr}\right)^{9/16}\right]^{4/7}}$$

$$Nu_1 = 0.68 + \frac{0.67(623{,}750)^3}{\left[1 + \left({}^{0.492}/_{0.6949}\right)^{9/16}\right]^{4/7}} = 14.04$$

The heat transfer coefficient can be found for the sides of the plate based on this Nusselt number. L is taken to be the height of the mould plates:

$$h_1 = \frac{Nu * k}{L} = \frac{(14.04) * (0.031938)}{(0.05)} = 8.9682\ W/m^2K$$

A different heat transfer coefficient must be calculated for the top and bottom of the plate. The Nusselt number for the top of a hot plate or the bottom of a cold plate is:

$$Nu_2 = 0.54Ra^{\frac{1}{4}} = 15.176$$

For the heat transfer coefficient, L is taken to be the minimum length of the plate as this would give the highest value and thus worst case scenario heat loss.

$$h_2 = \frac{(15.176)(0.031938)}{0.375} = 1.29\, W/m^2K$$

The Nusselt number for the bottom of a hot plate or the top of a cold plate is:

$$Nu_3 = 0.27Ra^{\frac{1}{4}} = 7.59$$

Once again, L is taken as the minimum length of the plate for the heat transfer coefficient:

$$h_3 = \frac{(7.59)(0.031938)}{0.375} = 0.646\, W/m^2K$$

The surface area of the mould was simplified to be a cube of dimensions 0.575m x 0.375m x 0.05m. Thus the total surface area of the sides of the mould is:

$$A_1 = 2(0.575 * 0.05) + 2(0.375 * 0.05) = \ 0.095\, m^2$$

The areas of the top and bottom of the plate are:

$$A_2 = A_3 = (0.575 * 0375) = 0.215625\, m^2$$

The total heat loss is equal to the heat loss through the sides, top, and bottom of the mould.

$$q = hA(T_s - T_\infty)$$

$$q_s = (8.9682)(0.095)(180 - 25) = 132.06\, W$$

$$q_t = (1.29)(0.215625)(180 - 25) = 40.11\, W$$

$$q_b = (0.646)(0.215625)(180 - 25) = 21.59\, W$$

Therefore the total heat loss in the mould is:

$$q_{total} \ = q_s + q_t + q_b = 193.76\, W$$

The preceding analysis makes some assumptions regarding the environment and heat loss characteristics. The effects of radiation were neglected since the mould will be at relatively low temperature for major radiation effects to occur. The forced convection effects from inside drafts are neglected, since they cannot be predicted. These assumptions should provide an acceptable prediction for general sizing of the heater.

The total heat loss was also calculated using simulation within SolidWorks software. This process gave a total heat loss of 163 W. This differs from the hand calculations due to the fact that it was treated as a transient problem rather than a steady state one, and also the hand calculations were taken as worst case scenarios.

The SolidWorks analysis used thermostats points to keep the temperature at roughly 180°C. The four 250 W heaters were turned on, and once the temperature reached the upper limit it would be shut off. The temperature distribution after 2 minutes is shown below in Figure 24. At this time, the elements directly underneath the strip heaters are at 88°C, and the outer areas of the plate are at room temperature of 20°C.

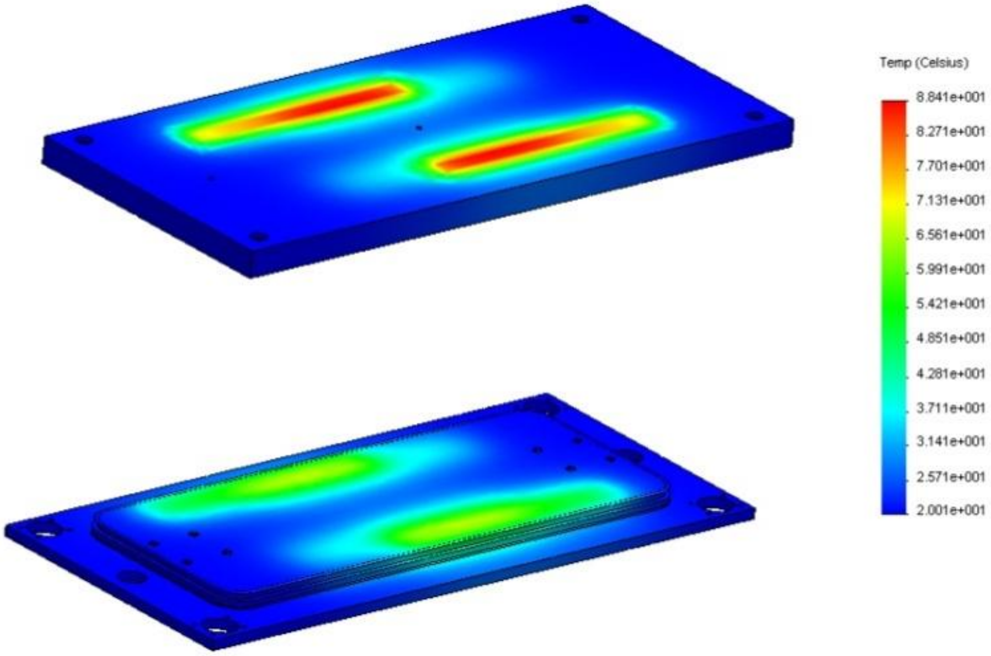


Figure 24: Heat distribution after 2 minutes.

After sufficient time had passed they would be turned back on and the procedure is repeated until the plate is at a uniform temperature. A graph of the center temperature of the plate versus time is shown in Figure 25.

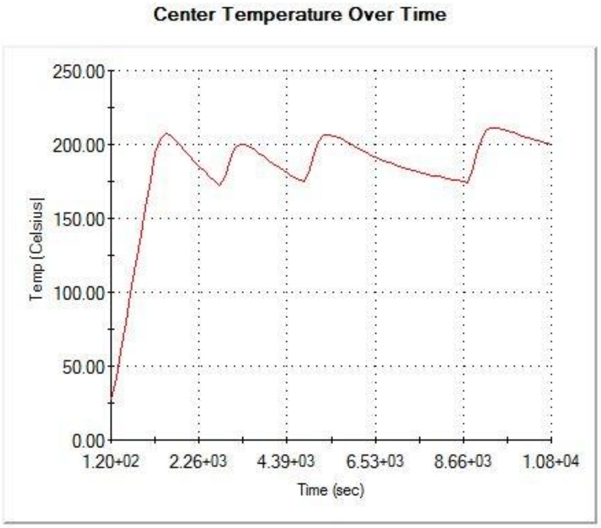


Figure 25: Graph of center temperature over time.

The graph shows that the desired temperature is initially overshot, and then self corrected in an iterative manner. To get this temperature to rest closer to 180°C, proportional or integral controllers can be used to decrease overshoot. The first instant that the center of the plate reaches 180°C is roughly 20 minutes. Figure 26 shows the heat distribution in the plate shortly after this instant. It is noted that at this time, the center of the plate is at roughly 200°C and the outer edge of the panel is at roughly 80°C.

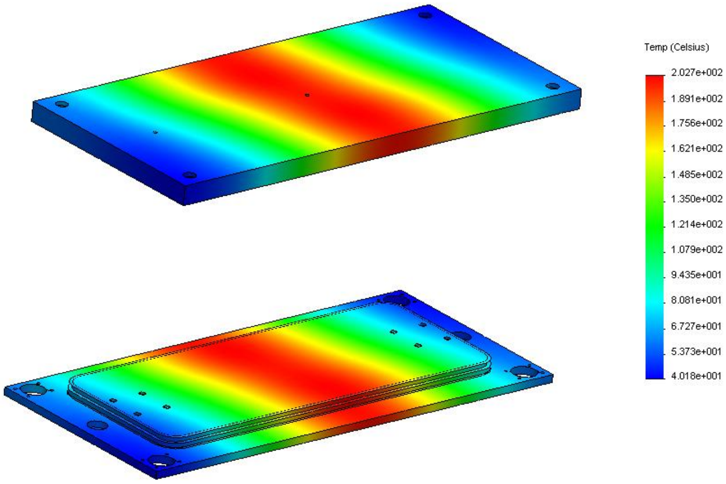


Figure 26: Heat distribution after 30 minutes.

After initially overshooting the desired temperature, the center of the plate returns to this value at roughly 35 minutes. Now undershot, the temperature increases and next reaches 180^{o}C at just over one hour of heating. Figure 27 shows the temperature distribution in the plate just before this instant. Note that the center of the plate is at 198^{o}C, and the outer edge of the plate is at roughly 120^{o}C.

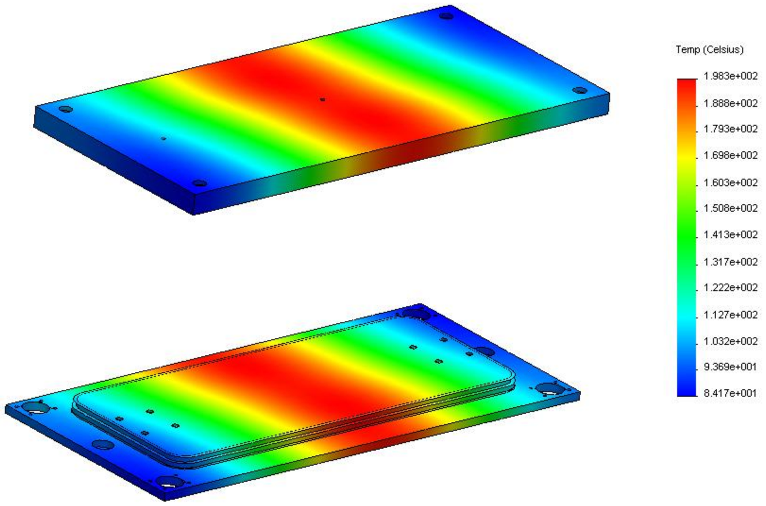


Figure 27: Heat distribution after 1 hour.

If more uniformity is desired, the process after three hours is shown below in Figure 28. At this instant the center of the plate is at 200^{o}C and the outer edges of the plate are at 175^{o}C.

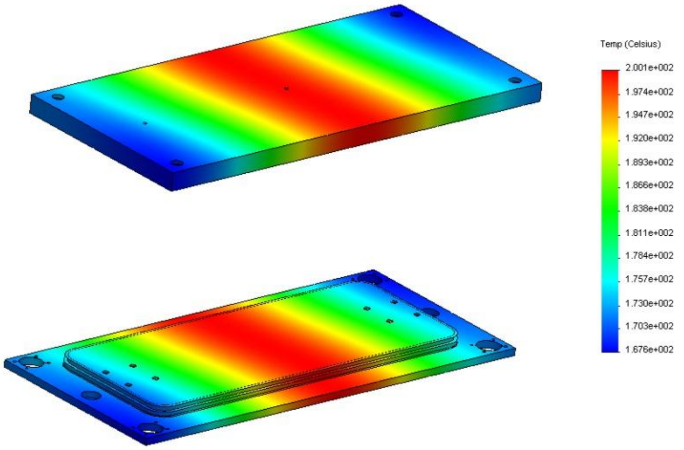


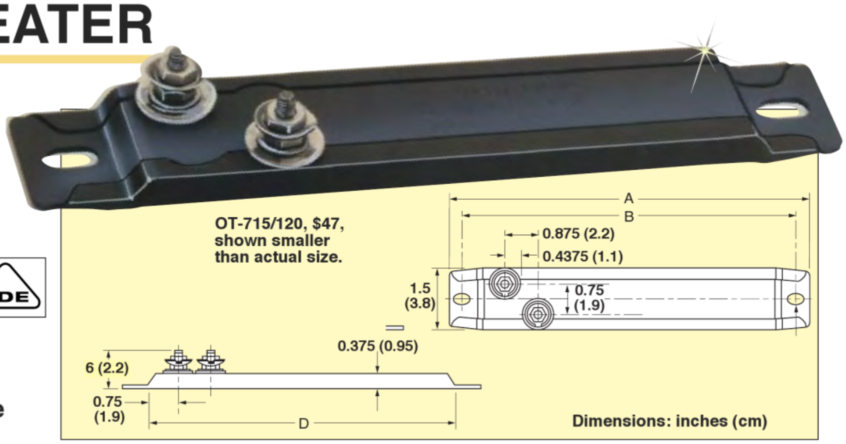
Figure 28: Heat distribution after 3 hours.

The reliability of the above results is uncertain due to the limitations on simulating free convection with the software used. Realistically, there should be a much more uniform heat distribution due to the high thermal conductivity of steel and the insulation around the outside of the mould.

Specification sheets from the manufacturers for the heater [2] and insulation [3] appear on the following two pages.

STRIP HEATER

OT Series
Starts at
$47



OT-715/120, $47, shown smaller than actual size.

- **1½" (3.8 cm) Wide**
- **2 Offset Bolt Terminals at One End**
- **Rugged, Reliable, Premium Quality**
- **UL Component Recognized and CSA Certified**

OMEGALUX® strip heaters are used principally for convection-type air heating and clamp-on installations. When selecting strip heaters for either, two important factors must be considered:

1. The proper sheath material for resisting any rusting and oxidizing inherent in the process or environment and for withstanding the sheath temperature required.

2. The watt density of the element, or watts per square inch of heated area. This should be low for heating asphalt, molasses and other thick substances with low heat transferability; it can be higher for heating air, metals and other heat-conducting materials.

SPECIFICATIONS

Max Sheath Temperature:
Iron: 399°C (750°F)
Chrome Steel: 649°C (1200°F)
Sheath Material:
Iron or chrome steel
Wattage Power: Iron sheath, 150 to 1250 watts; Chrome steel sheath, 200 to 2250 watts
Power Voltage: 120 or 240 Vac

▭ ***MOST POPULAR MODELS HIGHLIGHTED!***

To Order *(Specify Model Number)*

Dimensions: In (cm)			Rust-Resisting Iron Sheath				Chrome Steel Sheath				
A	B	D	Watts	W/In^2†	Model No.	Price	Watts	W/In^2†	Model No.	Price	Wt. lb (kg)
7½ (19)	6½ (17)	6 (15)	150	11	**OT-715/***	**$47**	200	15	**OT-702/***	**$61**	0.5 (.2)
8 (20)	7 (18)	6½ (17)	150	10	**OT-815/***	**49**	250	17	**OT-802/***	**63**	0.56 (.25)
8 (20)	7 (18)	6½ (17)	175	12	**OT-817/***	**49**	400	27	**OT-804/***	**63**	0.56 (.25)
10½ (27)	9½ (24)	9 (23)	250	10	**OT-1025/***	**50**	350	15	**OT-1003/***	**67**	0.75 (.34)
10½ (27)	9½ (24)	9 (23)	—	—	—	—	400	17	**OT-1004/***	**67**	0.88 (.40)
12 (30)	11 (28)	10½ (27)	250	8	**OT-1225/***	**50**	250	8	**OT-1202/***	**68**	0.88 (.40)
12 (30)	11 (28)	10½ (27)	—	—	—	—	350	14	**OT-1203/***	**68**	0.88 (.40)
12 (30)	11 (28)	10½ (27)	—	—	—	—	500	17	**OT-1205/***	**68**	0.88 (.40)
14 (36)	13 (33)	12½ (32)	300	8	**OT-1430/***	**54**	500	14	**OT-1405/***	**72**	1.0 (.45)
15¼ (39)	14¼ (36)	13¾ (35)	325	8	**OT-1532/***	**56**	500	12	**OT-1505/***	**73**	1.13 (.51)
17⅞ (45)	16⅞ (43)	16⅜ (42)	350	6.5	**OT-1835/***	**56**	500	10	**OT-1805/***	**78**	1.38 (.63)
17⅞ (45)	16⅞ (43)	16⅜ (42)	375	7	**OT-1837/***	**56**	750	15	**OT-1807/***	**78**	1.38 (.63)
17⅞ (45)	16⅞ (43)	16⅜ (42)	500	10	**OT-1850/***	**56**	1000	19	**OT-1801/***	**78**	1.38 (.63)
19½ (50)	18½ (47)	18 (46)	350	6	**OT-1935/***	**56**	500	9	**OT-1905/***	**82**	1.5 (.68)
19½ (50)	18½ (47)	18 (46)	500	8	**OT-1950/***	**56**	750	13.5	**OT-1907/***	**82**	1.5 (.68)
19½ (50)	18½ (47)	18 (46)	—	—	—	—	1000	18	**OT-1901/***	**82**	1.5 (.68)
21 (53)	20 (51)	19½ (50)	500	8	**OT-2150/***	**59**	750	12	**OT-2107/***	**86**	1.63 (.74)
23¾ (60)	22¾ (58)	22¼ (57)	500	7	**OT-2450/***	**61**	500	7	**OT-2405/***	**90**	1.81 (.82)
23¾ (60)	22¾ (58)	22¼ (57)	750	10	**OT-2475/***	**61**	750	10	**OT-2407/***	**90**	1.81 (.82)
23¾ (60)	22¾ (58)	22¼ (57)	—	—	—	—	1000	14	**OT-2401/***	**90**	1.81 (.82)
23¾ (60)	22¾ (58)	22¼ (57)	—	—	—	—	1500	19	**OT-2415/***	**90**	1.81 (.82)
25½ (65)	24½ (62)	24 (61)	500	6	**OT-2550/***	**63**	750	9	**OT-2507/***	**91**	2.06 (.93)
25½ (65)	24½ (62)	24 (61)	750	9	**OT-2575/***	**63**	1000	13	**OT-2501/***	**91**	2.0 (.91)
26¾ (68)	25¾ (65)	25¼ (64)	700	8	**OT-2670/***	**65**	1000	12	**OT-2601/***	**93**	2.19 (.99)
26¾ (68)	25¾ (65)	25¼ (64)	750	9	**OT-2675/***	**67**	—	—	—	—	
30½ (77)	29⅜ (75)	28 (71)	750	8	**OT-3075/***	**74**	750	8	**OT-3007/***	**100**	2.38 (1.1)
30½ (77)	29⅜ (75)	28 (71)	—	—	—	—	1000	11	**OT-3001/***	**100**	2.38 (1.1)
30½ (77)	29⅜ (75)	28 (71)	—	—	—	—	1250	13	**OT-3012/240**	**100**	2.38 (1.1)
33½ (85)	32⅜ (82)	31 (79)	750	7	**OT-3375/***	**81**	750	7	**OT-3307/***	**109**	2.69 (1.2)
35⅞ (91)	34¾ (88)	33½ (85)	1000	9	**OT-3610/***	**85**	1500	13	**OT-3601/***	**118**	2.88 (1.3)
38½ (98)	37½ (95)	36 (92)	800	6	**OT-3880/***	**92**	1000	8	**OT-3801/***	**122**	3.19 (1.4)
38½ (98)	37½ (95)	36 (92)	1000	8	**OT-3810/***	**92**	1500	12	**OT-3815/***	**122**	3.19 (1.4)
42½ (108)	41⅜ (105)	40 (102)	1250	9	**OT-4312/***	**101**	1500	11	**OT-4315/***	**134**	3.38 (1.5)
47⅞ (122)	46¾ (119)	45⅝ (115)	—	—	—	—	1350	9	**OT-4813/240**	**181**	3.75 (1.7)
47⅞ (122)	46¾ (119)	45⅝ (115)	—	—	—	—	2250	14	**OT-4822/240**	**181**	3.75 (1.7)

** Designate voltage, i.e., 120 or 240 Vac. Insert "**120**" for 120 Vac, "**240**" for 240 Vac. Model numbers containing /240 are only available in that voltage. Additional strip heater models available with other widths and bolt configurations.*

† To determine maximum allowable watt density, see figures C-8 or C-9 (page 80).

Ordering Examples: OT-815/120,** strip heater with rust resisting iron sheath, 150 W, **$49.
OT-4312/240,** strip heater with rust resisting iron sheath, 1250 W, **$101.

WORBO INC.
Thermal Protection Technology

Cool-Skin™ Blanket

...

Designed to drastically reduce high surface temperatures to a safe touch condition, Cool-skin™ is an ideal safety solution for a variety of high temperature applications. *Cool-Skin*™ Blanket is an excellent product for protecting large areas including cylindrical, rectangular or irregular shaped tanks, large diameter pipes, valves and other equipment.

Cool-Skin™ Technology

- Leading the way in user friendly thermal safety protection, Worbo's *Cool-Skin*™ products are manufactured using flexible, clean, non-fibrous materials that do not contain fiberglass or release airborne particulates. Perfect for use in a variety of environments from heavy industrial applications to clean-room and laboratory settings.
- *Cool-Skin*™ Blanket is supplied with a "peel and stick" sacrificial PSA (pressure sensitive adhesive) on one side for easy installation.
- *Cool-Skin*™ Blanket can be used in multiple layers or in conjunction with other materials to achieve the desired degree of protection to meet your criteria.
- Unlike traditional dated technologies that use glass as the insulating medium, *Cool-Skin*™ Blanket is easily cut to length in the field using an ordinary pair of scissors without "end fray" or releasing irritable fiber particulates.
- *Cool-Skin*™ Blanket is resistant to moisture, UV, corona, ozone, oxidation, cosmic radiation, ionizing radiation, chemicals, etc. and exhibits considerable overall durability in a variety of environments.

Dimensional Data	Available in standard 33ft (10m) continuous length rolls; 1/4" (6mm) thick x 39.37" (1000mm). Other sizes can be manufactured to your specification.
Temperature	Rated from -112°F (-80°C) to 392°F (200°C) continuous.
Environmental Resistance	Excellent resistance to ozone, oxidization, UV, corona, cosmic radiation, ionising radiation and weathering in general.
Flammability	Meet the flammability requirements of FAR 25.853 (a) (1) (IV) and (a) (1) (v) horizontal flammability tests.

Radiation resistance	> 10^5 Grays (10^7 Rads) Typical
Dielectric Strength	23kV.mm^{-1}
Dissipation Factor @ 50 c/s	3 x 10^{-4}
Volume Resistivity	3 x 10^{15} Ω.cm
Density	250+/- 40 kg/mtr^3
Compression Stress 40% Strain	90kPa
Tensile Strength	1.2N/mm^2
Elongation to failure	200%

...

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[2] Omega. (2010). *OT SERIES STRIP HEATER* [Online]. Available: http://www.omega.com/Heaters/pdf/OT_HEATER.pdf [November 5, 2010].

[3] Worbo. (2010). *WORBO INC. Thermal Protection Technology* [Online]. Available: http://www.worbo.com/product_overview/Burn_Protection/product_info_pdfs/Cool Skin%20Blanket%20Data%20Sheet.pdf [November 12, 2010].

Appendix F – Cost Analysis

Bill of Materials

Table VIII lists all the parts, their source, and total price.

Table VIII. BILL OF MATERIALS

ITEM NO.	PART	Source	Part Number	Price/unit	QTY.	Total Price
1	Top Plate	McMaster-Carr	1316T66	$431.95	1	$431.95
2	Travelling Plate	McMaster-Carr	1316T66	$431.95	1	$431.95
3	Mounting Plate	McMaster-Carr	9524K467	$471.90	1	$471.90
4	Guide Shaft	VXB	Kit7704	$39.00	1	$39.00
5	Jack Housing	Motion Industries - Joyce Dayton	WJ201U2S	$508.77	2	$1,017.54
6	Screw	Motion Industries - Joyce Dayton	WJ201U2S	$0.00	2	$0.00
7	Seal	(Company) - Parker	V3819 2-386	$700.00	1	$700.00
8	Linear Bearing	VXB - Nippon	SMST20WUU-E	$53.00	4	$212.00
9	Plain Washer -10	McMaster-Carr	97725A200	$7.61	1	$7.61
10	Socket Head Cap Screw - 5 x 0.8 x 12	McMaster-Carr	91290A228	$6.44	1	$6.44
11	Socket Head Cap Screw - 8 x 1.25 x 25	McMaster-Carr	91290A432	$9.26	1	$9.26
12	LVDT	Macro Sensors	GHSAR 750-A-125	$350.00	2	$700.00
13	Strip Heater	Omega	OT-1225-120V	$54.00	4	$216.00
14	Finger Spring Washer	McMaster-Carr	717K63	$10.36	1	$10.36
15	Thin Hex Nut 1/2 x 20	McMaster-Carr	94846A525	$6.76	1	$6.76
16	Socket Head Cap Screw - 8 x 1.25 x 12	McMaster-Carr	91290A416	$6.53	1	$6.53
17	Socket Head Cap Screw - 10 x 1.5 x 20	McMaster-Carr	91290A416	$8.47	1	$8.47
18	Socket Head Cap Screw - 10 x 1.5 x 50	McMaster-Carr	91290A532	$12.85	1	$12.85
19	Nylock Hex Nut - 10 x 1.5	McMaster-Carr	94645A220	$8.84	1	$8.84
20	Plain Washer - 10	McMaster-Carr	93162A330	$9.67	1	$9.67
21	Guide Shaft Clip	McMaster-Carr	3369K16	$13.33	4	$53.32
22	Insulation	Worbo Coolskin Blanket	CSB-04	$32.32	4	$129.28
23	Control System Starter Kit	Omega	ELCSTARTKIT1	$865.00	1	$865.00
24	Thermocouple Input	Omega	ELC-TC04ANNN	$396.00	1	$396.00
25	Relays	Omega	SSRDC100VDC12	$49.00	2	$98.00
26	Servo Motors	Baldor AC Brushless Servo Motors	BSM90C-2250AF	$939.00	2	$1,878.00
				Total:		**$7,726.73**

Machining

Another aspect of cost analysis is machining time. Machining time has already been minimized by selecting many factory standard dimensions. This includes choosing standard plate thicknesses, lengths and guide shaft diameters. However, most of these parts still need machining for their specific geometries.

Machining precisely and efficiently requires proper selection of spindle speed, feed rate, coolant, and type of material. Many of these factors can be determined based on the machine and tools available. The machine must be numerically controlled and is recommended to have a very stiff spindle with flood coolant if possible. This will ensure high precision with minimal chattering. Carbide steel tools are also recommended for faster spindle speeds and therefore increased feed rates. This will help decrease machining time and cost.

CIC has requested stainless steel for the plates. Different stainless steels are classified based on machinability in TABLE IX [1]. Stainless steel 410 was chosen because it has adequate strength and good machinability.

TABLE IX. MACHINABILITY [1].

Machinability	Excellent	Good	Fair	Poor
Stainless Steel Alloy	303, 416	304, 316, 410, 430	301, 302, 309, 321, 420	420V, 440C, 15-5 PH, 17-4 PH, Nitronic 60, A286

Sample Calculation

Machine time can vary depending on the machining company; however, CIC has in-house manufacturing capabilities. A sample calculation of the machine time for the mounting plate cavity can be estimated if some assumptions are made. Firstly, a 4 tooth, half inch diameter, carbide steel, 15mm deep end-mill is available. Secondly, the machine is a Haas CNC machine with flood coolant capable of a 250 surface feet per minute cutting speed. Lastly, there is 70% overlap per pass[2].

With these assumptions the spindle speed is found to be 2387rpm.

$$SpindleSpeed = \frac{CuttingSpeed * 12}{(\pi * ToolDiameter)}$$

When machining stainless steel each tooth pass should only remove 0.002 inch, known as the "ChipLoad". The feed rate is then found to be 19.096inch/min or 485mm/min.

$$Feedrate = ChipLoad * Number\ of\ Teeth * SpindleSpeed$$

The top plate shown in Figure 4 will require 54 lengthwise passes to cover the cavity area. This is using a 70% overlap on each 509mm length pass. As a rule of thumb the depth per milling cut for stainless steel should be an eighth of the tools diameter. Therefore, the maximum depth per cut is 1.6mm and the 54 passes will have to be repeated 10 times to achieve the cavities depth. At a feed rate of 485mm/min the cavity will take approximately 9.5 hours to complete [3].

Using similar calculations on all manufacturing tasks, it is estimated that no more than one thousand dollars will have to be spent on in-house manufacturing.

Break Even Analysis

The old method of manufacturing produced a maximum of 3 panels per 8 hour work day. This happened only if the operator was skilled and had gone through the learning curve of the process. Due to the time limitations of this project, a prototype was not built. For future studies, a prototype should be built and have time studies conducted on it. Once the operator has gone through the learning curve, the number of panels produced in an average 8 hour day would be compared to the total of 3 panels that can currently be produced.

Since the initial cost of the new machine is estimated to be $8500 (assuming manufacturing cost of approximately $700), and the current method of moulding takes 2.67 hours to produce each panel, the amount of time to produce a panel with the new system and the wage for a machine operator will give us the breakeven point.

Three different scenarios were tested. The first is where the new method takes 2 hours per panel, the second is 1.5 hours per panel, and the third is 1 hour per panel. We assume that the lab technician is a recent engineering graduate who is making a wage of approximately $25.00/hr. The breakeven point will be modeled with the following equation.

$$\left(\frac{\$25.00}{hr} * \frac{2.67\ hrs}{panel}\right) * x\ panels = \left(\frac{\$25.00}{hr} * \frac{A\ hrs}{panel}\right) * x\ panels + \$8{,}500$$

Where A is either 2 hours, 1.5 hours, or 1 hour.

The number of panels produced (x) until the breakeven point occurs at the intersection of these two lines. The line for each scenario and the intersection points can be seen in Figure 29.

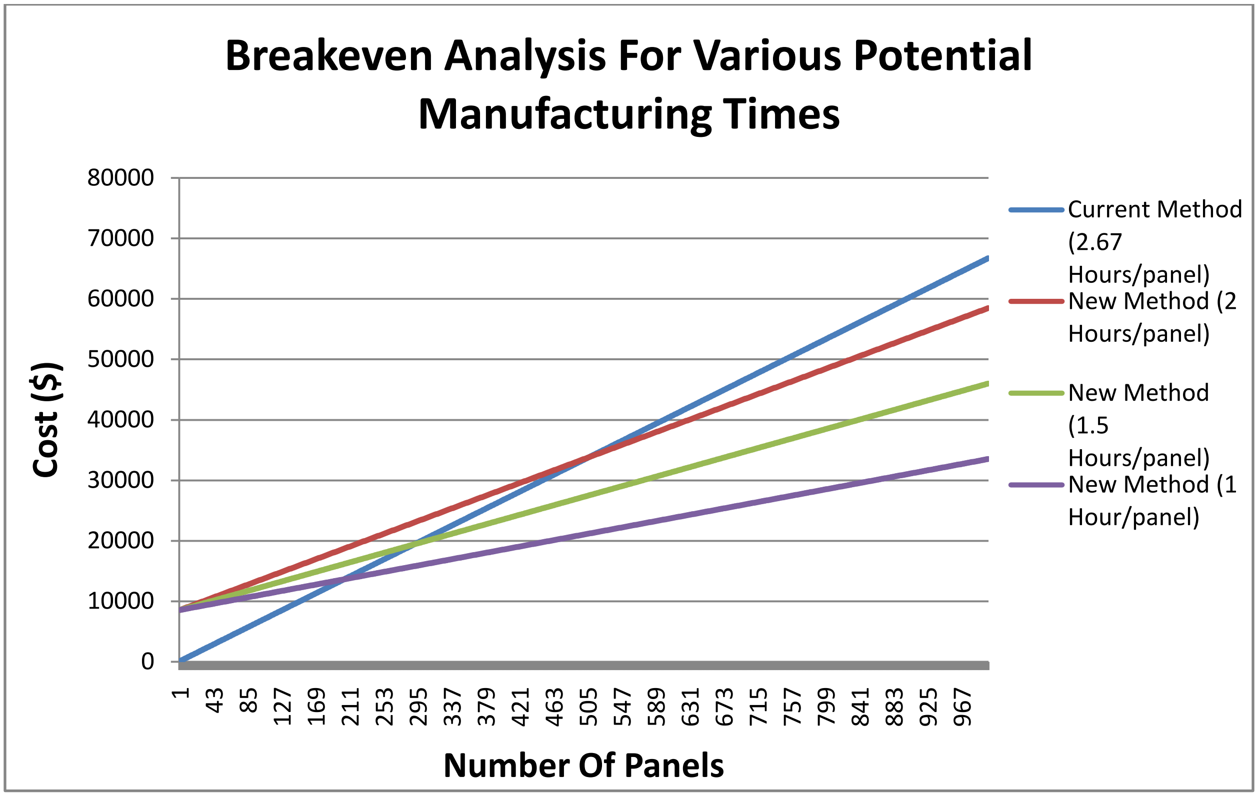

Figure 29: Breakeven analysis for various potential manufacturing times.

TABLE X below shows the breakeven points for each scenario and a summary of the breakeven analysis.

TABLE X. SUMMARY OF BREAKEVEN ANALYSIS.

Scenario	Time per Panel (Hours)	Cost per Panel ($)	Breakeven Point (# of panels)
1	2	50	508
2	1.5	37.5	291
3	1	25	204

[1] McMaster-Carr. (n.d.). *Stainless Steels* [Online]. Available: http://www.mcmaster.com/#stainless-steel [November 30, 2010].

[2] Standford University. (1997, September). *Milling Stainless Steels* [Online]. Available: http://www.stanford.edu/group/prl/documents/pdf/millss.pdf [November 30, 2010].

[3] S. Balakrishnan (private communication), Nov. 30th, 2010.