DESIGN AND DEVELOPMENT OF A CENTRIFUGAL CASTING MACHINE AND INVESTMENT CASTING PROCESS FOR HSRW

A Thesis

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ABSTRACT

Introduction

The Enspire Lab at HSRW has grown steadily for years. Presently, the lab is fairly well equipped for doing large projects, especially from steel or aluminum, and with the addition of the recently set-up CNC machine, the new 3D printer, and the imminent arrival of a new laser cutter, the lab is equipped to provide students access to a number of manufacturing methods and options. However, there isn't much equipment available for doing small projects with high degrees of accuracy, and one manufacturing method that is still conspicuously missing, is casting. The purpose of this thesis was to provide that option and the expertise that goes along with it.

Problem

Create a centrifugal casting machine that meets or exceeds the industry standards set by commercially available machines. Additionally, create a robust safe operating procedure manual that outlines the investment casting process as it specifically applies to the Enspire lab and HSRW.

Procedure

Research was done to evaluate existing commercially available centrifugal casting machines. This included research about material selections, design decisions and consumer validation. Analyzing pros and cons of different designs allowed the best options to be chosen as well as allowing for improvement on existing designs. After the research phase, computer simulation was used to design the machine. This was followed by fabrication and construction in the Enspire Lab.

Results

The casting machine is completed and should be functional. The fabrication and assembly went according to spec, but due to delays from COVID19, it is still missing a power supply and the electronic controller for the motor and micro-switch is still being programmed and fine-tuned. The investment casting procedure has been completed, but the process has yet to be tested since the machine is not yet operational and there is no burnout kiln yet available.

Conclusions

Although still untested, this thesis has provided future generations of HSRW students with an introduction to investment casting as well as access to proper, safe equipment for doing it. Due to time delays, some of the more technical objectives such as finite element analysis and condition monitoring were not possible, but the practical objectives for the machine have been met. The parts are all made to specifications; the fit and finish is acceptable; and the intended dynamics of the machine are functional.

CHAPTER 1. DESCRIPTION

Background and History

Centrifugal casting is used as a means of casting small batches of relatively small parts at very high resolution. Simple gravity pouring is insufficient for jewelry-type investment molds. This possibility is precluded by the combination of unvented molds and the desire to reproduce intricate detail together with the comparatively small volume of molten material and the consequent low hydrostatic head and low thermal capacity of the metal. Thus, some form of casting machine is used to cast the metal into the mold [Gainsbury, P. E]. One commonly used option is known as centrifugal casting.

Centrifugal casting is a means of casting small detailed parts or jewelry. A balanced, horizontally oriented, arm is driven around a vertical axis by an electric motor or torsional spring. A single-use mold and a ceramic crucible for melting the raw material are arranged together on one extremity of the arm and heated with a torch. When the raw material is molten, the arm is released, and the centrifugal force from the spin forces the liquid metal into the mold [Sias, F. R., Jr.].

The mold is made using a technique that has been practiced for thousands of years known as investment casting or lost-wax casting. Dating back to beeswax patterns from 3000 BC, it is one of the oldest known metal forming techniques. Moving the molten material into the mold by means of centrifugal force is a relatively recent development. There are patents from the early 1800s for horizontally rotating casting machines that used centrifugal forces to cast pipes (also called spin-casting), but the vertical casting process, such as that on which this thesis project is focused, did not emerge until almost 100 years later in the dental industry where highly accurate, repeatable castings of small components was necessary. Since World War II, substantial progress in the process has been made, particularly in the art world (metal-craft and jewelry-making). However, most of that progress has come as a result of material science. High technology waxes, refractory materials and specialized alloys have made the process almost infinitely customizable; while the centrifugal casting process and the machines used to achieve it remain much the same as 120 years ago.

Literature Review

Similar resolution advantages may be obtained with alternatives like pressure casting or vacuum casting and each technology has its loyal patrons [Gainsbury, P. E]. However, the centrifugal casting process is straightforward and the machines are relatively simple to construct and operate.

Investment casting is the most widely used technique for producing jewelry so it is important that a casting machine used for jewelry investment casting should meet the efficiency and quality standards expected of manufacturing equipment. Centrifugal casting is a well-established process, so the machine will need to accommodate certain standard components such as melting crucibles and flasks for the molds [Sias, F. R., Jr.]. Investment flasks are generally stainless steel cylinders, sold in sets, with diameters from two to four inches, in half-inch increments. The melting crucibles used for centrifugal casting are generally a clay-infused silica material designed to fit one of two standard retaining systems (based on two popular casting machines, Neycraft and Kerr). Neycraft crucibles fit in Kerr machines, but the inverse is not true. Since the Neycraft design is more widely applicable, and thus easier to acquire, it has been chosen as the standard for this project as well.

The most significant differentiating feature between centrifugal casting machines is the choice between a rigid rotating arm and an articulated rotating arm. The articulated arm requires additional manufacturing steps, but it offers the advantage of ensuring that the forces are always applied in the appropriate direction (moving molten material into the mold cavity). The rotation begins from rest so initially the acceleration of the crucible and mold is purely in the tangential direction. The jointed connection in the arm allows the crucible and mold to swivel freely as the direction of the acceleration changes from purely tangential to purely normal [Sias, F. R., Jr.]. Consequently, the arm can be driven at much higher torques because jerk and jounce do not have to be considered. This means the molten material spends less time in the crucible, which is desirable for maintaining melting temperatures during casting. Rigid arms must be accelerated slowly to prevent molten material from spilling over the side of the crucible. For this reason, most commercially available centrifugal casting machines have articulated rotating arms.

This project also required a fair amount of research outside the realm of scholarly articles and textbooks. Various jewelry-making forums and YouTube channels were consulted both for practical knowledge about the casting process as well as discussion about the successes and failures of other commercially available centrifugal casting machines and a host of "homemade" alternatives that are not commercially available. These sources provided a great look at what not to do, but they also offered insight into the practical use of these machines. Table 1.1 includes several examples of such sources.

Table 1.1: Example sources of folk wisdom and what not to do

https://www.youtube.com/channel/UC3u2Bnwf-959Wako0Dk93TA Supply retailer that provides tons of expert support about everything involving making jewelry. This channel features several videos about investment casting and centrifugal casting, including high-speed videos of the dynamics.
https://www.youtube.com/channel/UC3VmPL7Gq4bGEYVOZ9aGB5g Substantial practical knowledge about mold making, investment casting and finishing can be found on this channel.
https://www.youtube.com/watch?v=4HTuYa1BxEE Simple video of centrifugal casting in a casting machine with a rotating tub design
https://www.youtube.com/watch?v=j-I0l5Rh0wg Simple video of centrifugal casting in a casting machine with an open top enclosure
https://www.youtube.com/watch?v=58psqQQz7rc Overview of the pro's and con's of centrifugal casting as well as dispelling some common myths
https://www.instructables.com/Lost-Wax-Casting/

Instructions for investment casting, with pictures, and a useful comments thread.
https://www.toytowngermany.com/forum/topic/226202-where-to-purchase-jewelry-making-materials/ Useful forum about jewelry casting and finding suppliers specifically in Germany
https://www.superbmelt.com/jewelry-casting-line-solution/ Great source of information about casting metal and advice for equipment selection.
https://orchid.ganoksin.com/t/centrifugal-casting-problem/17417/13 Good discussion about the Neycraft casting machine including pros and con’s from users.
https://www.cooksongold.com/forum/showthread.php?t=5933 Folk wisdom about DIY centrifugal casting systems
https://www.youtube.com/watch?v=9ZeLn7BT3qc How NOT to bring this idea to industrial scale. This is definitely not the German way.

Relevance to HSRW

Because the process only requires an arm spinning with sufficient centrifugal force, numerous machines are commercially available spanning a wide range of prices and offering a variety of features for different applications. This thesis project will focus on designing and developing a centrifugal casting machine optimized for casting jewelry and other small parts made of soft metals. This will be applicable to a variety of student projects in the HSRW Enspire lab. The workshop is already suited to making large components with low tolerances, but is in need of equipment and processes that offer precision. Hopefully, this machine will join the new CNC machine and laser cutter as a step in that direction.

Machine Specifications

Centrifugal casting is used as a means of casting small, high-resolution parts in small batches. This thesis is focused on designing and constructing a centrifugal casting machine as well as developing a process and procedure for investment casting in the workshop of HSRW.

Desires and Constraints

Design and construct a centrifugal casting machine capable of:

- Casting soft metals with melting temperatures up to 1080°C
- Casting a range of materials with densities from Al (2560 kg/m^3) to fine Au (19320 kg/m^3)
- Casting parts with intricate detail (up to 25 μm)
- Being used safely by students
- Fitting standard COTS components used for centrifugal casting

Casting Crucible[1]

Neycraft Standard

Suitable for melting temperatures up to 1371°C

Weight: 266.5 g

Capacity: 13.2 ml (9 Oz gold or 5 Oz silver)

Investment Flasks[2]

Stainless steel, solid wall flasks

(2" – 4" diameters, in 1.2" increments)

76.2 mm (b) • 76.2 mm (h) • 1.63 mm (t)

50.8 mm (b) • 63.5 mm (h) • 1.63 mm (t)

Basic Idea

A balanced, horizontally oriented, arm is driven around a vertical axis by an electric motor or torsional spring. A single-use mold and a ceramic crucible for melting the raw material are arranged together on one extremity of the arm and heated. When the raw material is molten, the arm is released,

[1] https://www.stuller.com/products/22-4620/23798/?groupId=13348

[2] https://www.stuller.com/products/55-2410/15738962/?groupId=201441&recommendationSource=productpage& recommendationType=recommendation&recommendationId=13330

and the centrifugal force from the spin forces the liquid metal into the mold. The components and material flow during casting can be seen in figures 2.1 and 2.2.

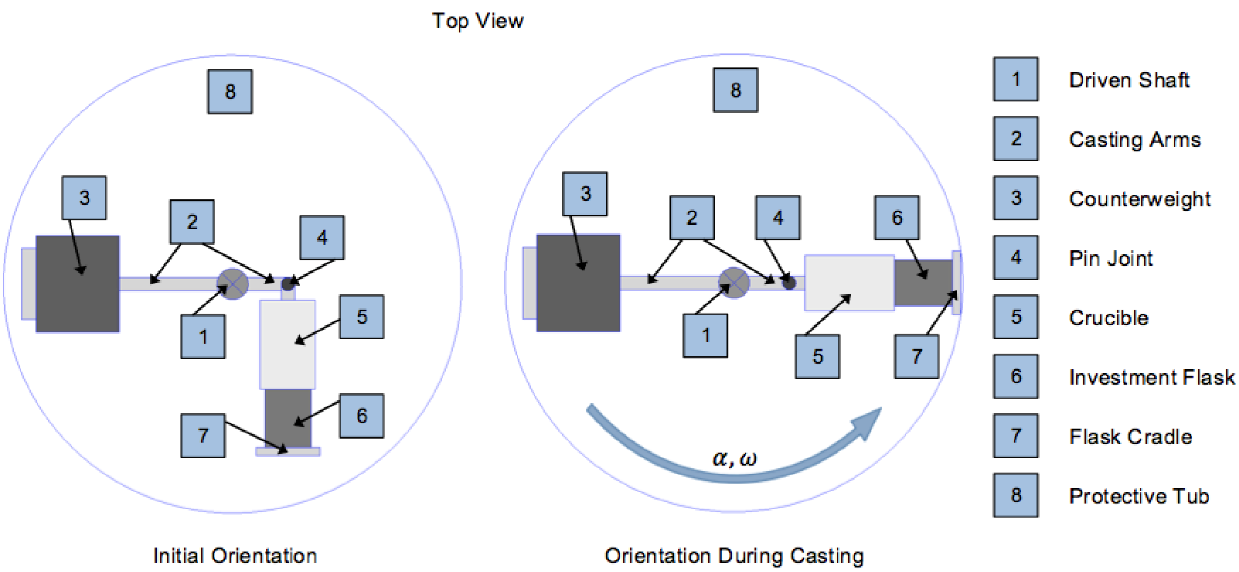

Figure 2.1: Schematic (top view) of a centrifugal casting machine and its components

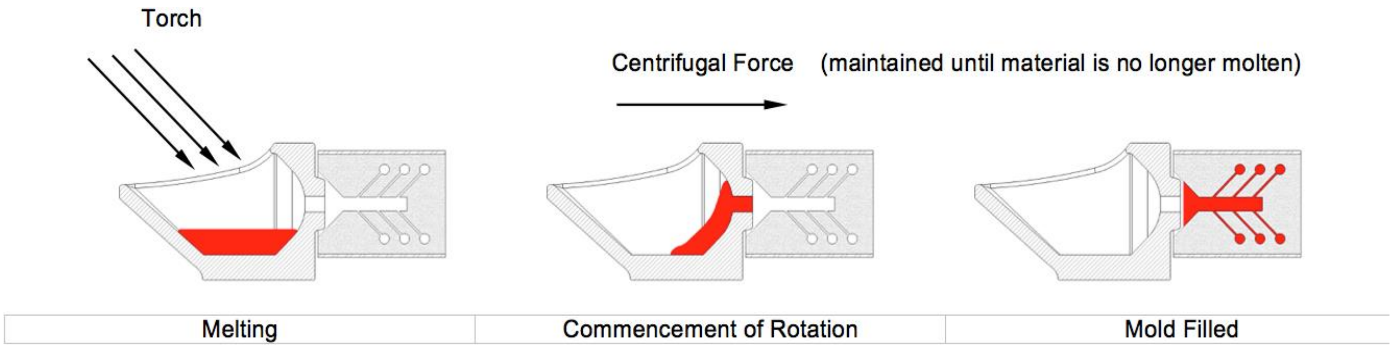

Figure 2.2: Schematic representation of casting in a centrifugal machine using a torch. The axis of rotation is vertical and is to the left of the illustration, so the centrifugal force is oriented to the right, as shown.

Timeline

Table 2.1: Proposed Gantt chart for the project

Activity	Month 1				Month 2				Month 3			
	Wk.1	Wk. 2	Wk. 3	Wk. 4	Wk. 5	Wk. 6	Wk. 7	Wk. 8	Wk. 9	Wk. 10	Wk. 11	Wk. 12
Product Research												
• Market Competition Evaluation												
• Process Standards and Constraints												
Functional Design												
Conceptual Design												
Detailed Design												
• Slide Assembly												
• Counterweight Assembly												
• Spring/ Motor Assembly												
Structural Analysis												
• Analytical Calculations												
• FEA												
Optimization of Design												
Construction												
• Buy COTS items												
• Double Check Design												
• Fabrication of Unique Components												
• Final Assembly												
Testing and Validation												
• Test of Casting Machine												
• Test of Actual Casting Process												
Documentation and Report												
• Outline												
• Design												
• Analysis												
• Construction												
• Testing and Validation												
• Rough Draft												
• Final Draft												
• Presentation												

Casting Process

Design and develop an investment casting process that:

- Is specifically applicable to the workshop at HSRW
- Is informative about the relevant variables in casting
- Is clear, easy to understand and easy to follow
- Conforms to relevant safety standards
- Can be completed concurrently with designing and building machine

The aforementioned objectives will be achieved through a series of nearly sequential steps. Preliminary research will be done to evaluate existing centrifugal casting machines. This will involve background research of material selections, design decisions and consumer validation. Analyzing pros and cons of different designs will allow for improvement. After the research phase, computer simulation will be used to design the machine. This will be followed by fabrication, construction and testing of both the machine and the casting process in the Enspire Lab at HSRW Kleve.

I) Specifications and functional design

In this stage, the set of technical requirements to be satisfied by the machine will be chosen and the physics concerning the necessary torques and forces will be performed. The goal here is to begin developing the parameters and constraints that will define the functionality of the machine.

II) Conceptual design

This stage focuses on evaluating available options to make comprehensive design choices concerning functionality, usability and aesthetics. A morphological box will be populated with relevant sub-problems and the various conceptual solution options for those problems. From this matrix of small design decisions, should emerge the best overall combined solution.

III) Detailed design

Once the parameters have been analyzed and the overall concept for the machine has been chosen, the detailed design stage can begin. The CAD model of the casting machine will be created using Solidworks, since the 3D modeling environment is ideal for assembly simulations and shape optimization without the need for expensive and time consuming iterative prototyping. In this stage, all components needed for the machine and casting process will be designed and make-or-buy decisions will be made.

IV) Structural analysis

In this stage, the primary flow of forces will be analyzed and operational stresses will be compared to allowable stresses (according to materials and geometry) to prove the components can withstand the loads required of them, including a safety factor. Analytical stress calculations will be compared to stresses obtained by finite element analysis to ensure that the theory of the continuous system closely matches the simulation of the discrete one.

V) Optimization and Refinement

Once stress analyses have been done and COTS components have been received, the design can be optimized to ensure proper fit and efficient material usage. In this stage, the design is finalized.

VI) Fabrication and Construction

The finalization of the design prompts the creation of a fabrication plan for the unique components. In this stage, a plan for fabricating each component will be created and executed using the existing tools and equipment in the workshop at HSRW. As components are being fabricated, they will be fitted and assembled with COTS components into the final casting machine.

VII) Adaptation of Casting Process

Here, the investment casting process will be made suitable for the Enspire Lab at HSRW. Relevant safety standards will be consulted and a robust process guide will be written up for students endeavoring to use the centrifugal casting machine properly. Strict adherence to this guide will ensure safe handling and operation of all equipment used in the casting process.

VIII) Testing and Validation

Once the machine has been designed and constructed and the casting process has been formalized, the testing and validation stage can begin. Here, the machine and the casting guide will be tested to ensure that a safe and proper procedure has been laid out and to evaluate the quality of one or two casted parts.

Rotation Speed

The following analysis is done to provide some insight into the physics involved and to calculate the rotation speed that is necessary to generate sufficient centrifugal force required to meet the desired level of detail in the finished cast. This begins with calculating a critical flow velocity, as outlined by John Campbell in the Complete Casting Handbook (Campbell J.). The inertial pressure is the pressure that tends to disturb the surface during flow. This pressure is defined as $\rho V^2/2$ with ρ as the density of the molten material and V being the local flow velocity. By definition, the surface tension γ acts to counter these disturbances at the surface of the melt, flattening it. The maximum pressure the surface tension can contain occurs when the surface is deformed into a hemisphere of radius r, meaning the pressure from the surface tension resisting the inertial pressure is equal to $2\gamma/r$. Therefore, to find the limit such that the velocity is sufficiently high to push the surface beyond the hemisphere, and thus exceed the maximum resistance from the surface tension, yields $\rho V^2/2 = 2\gamma/r$. The critical velocity can therefore be defined as

$$V_{\text{crit}} = 2\left(\frac{\gamma}{r_{\text{d}} \bullet \rho}\right)^{\frac{1}{2}}$$

With r_{d} as the desired detail radius of the cast and V_{crit} as the minimum flow velocity required to penetrate mold crevices of that radius. Choose $r_{\text{d}} = 25\,\mu m$ (industry standard for fine models and jewelry) and empirical measurements for γ and ρ.

Table 4.1: *Surface tensions*[3], *densities*[4] *and critical flow velocities for common jewelry materials*

Pure Metal	γ (N/m)	ρ (kg/m^3)	V_{crit} (m/s)
Ag	0.914	10490	3.734
Al	0.896	2560*	7.483
Au	1.162	19320	3.102
Cu	1.339	8940	4.895

Because the surface tensions are similar in numerical value, the densities dominate the calculation. The lower the density of the molten material, the higher flow velocity is required to penetrate the fine details of the mold. Since a minimum flow velocity is being calculated, the largest

* Metal densities decrease with increasing temperatures. Since density dominates the calculation, the lowest measured value for Al has been chosen from the literature. This density corresponds with much higher temperatures than will be used with this machine, so the error is on the safe side.

[3] (Egry, I., Ricci, E., Novakovic, R., & Ozawa, S.)

[4] (www.engineeringtoolbox.com)

numerical value must be chosen to ensure proper flow of any material used in the casting machine. As such, the values for liquid aluminum will be used for the remainder of this analysis.

It can be seen from kinematics that ${V_{\mathrm{crit}}}^2 = 2 \bullet a_{\mathrm{crit}} \bullet \Delta x$ with Δx equal to the distance from the meting part of the crucible to the mold (11 cm). So,

$$a_{\mathrm{crit}} = \frac{{V_{\mathrm{crit}}}^2}{2 \bullet \Delta x}$$

The centrifugal force on the molten material is defined according to Newton's second law as $F_{\mathrm{c}} = m \bullet a_{\mathrm{c}}$ with m as the mass of material, and the centrifugal acceleration $a_{\mathrm{c}} = r \bullet \omega^2$ with r as the distance from the molten material to the axis of rotation and ω as the angular velocity. Setting the centrifugal acceleration equal to the critical acceleration gives

$$a_{\mathrm{crit}} = \frac{{V_{\mathrm{crit}}}^2}{2 \bullet \Delta x} = r \bullet \omega^2 = a_{\mathrm{c}}$$

so,

$$\omega_{\mathrm{crit}} = \left(\frac{{V_{\mathrm{crit}}}^2}{2 \bullet r \bullet \Delta x}\right)^{\frac{1}{2}} = 36.515\ \frac{\mathrm{rad}}{\mathrm{s}}$$

$\omega = 2 \bullet \pi \bullet n$ so,

$$n_{\mathrm{minimum}} = \frac{\omega_{\mathrm{crit}}}{2 \bullet \pi} = 348.691\ \mathrm{RPM}$$

This calculation is in line with most commercially available units (200 – 1000 RPM) and these predictions are likely to be all the more accurate for parts casted from noble metals such as gold and silver since, at least in principle, they will remain free of surface oxides and carbon films that pollute the cast (alloyed components will detract from this benefit) (Campbell J.).

Angular Acceleration and Spin Duration

Intuitively, both of these parameters are linked to the amount of time the molten material spends in the crucible, the time it spends traveling from the crucible to the mold and the amount of time the molten material needs to solidify inside the mold. In other words, these parameters will be determined by the amount of time between the end of heating and the end of casting as well as the cooling properties for the various metals that will be casted. The fastest cooling rate will determine how quickly the molten material must move from the crucible to the mold; this will lead to the calculation of the angular acceleration. The slowest solidification rate will determine the length of time the cast must spin in the casting machine before stopping in order to ensure a fully solidified cast.

A cooling curve is a line graph that represents the change of phase of a material. For the purposes of casting, the transition of metals from liquid to solid is the focus. A typical qualitative cooling curve for a pure metal is shown in figure 4.1. Cooling curves for alloyed metals are similar but exhibit a range of solidification temperatures, instead of a constant temperature (sloped solidification line, instead of horizontal).

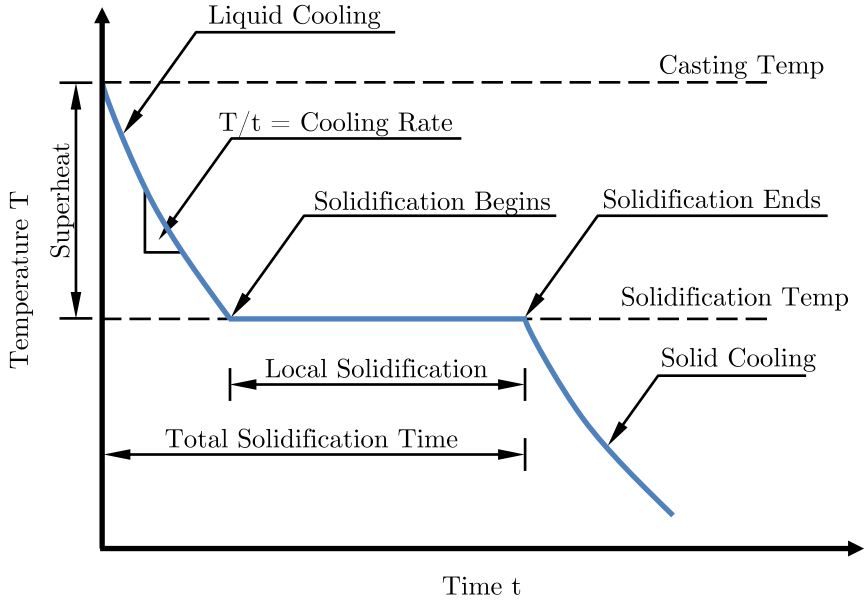

Figure 4.1: Typical cooling curve for a pure metal. The molten material must entirely fill the mold before solidification begins and the spinning process cannot end until solidification is sufficiently completed.

A graphical analysis from the literature[5][6] of cooling curves for several relevant jewelry-casting metals showed that the material with the highest cooling rate is 18K Ni white gold. This material took 1.2 seconds to cool from casting temperature to the beginning of solidification. Assuming it takes the operator 0.8 seconds[*] to remove the torch and initiate the casting process, this means the molten material must be entirely pushed into the mold by the machine within 0.4 seconds.

Kinematics gives $\Delta x = 1/2 \bullet a \bullet t^2$ with Δx equal to the distance from the meting part of the crucible to the mold (11 cm) and t being the calculated time. Since the casting process begins from rest with the articulated casting arm bent to the purely tangential direction, the acceleration experienced by the molten material will begin as tangential acceleration.

$$a_{\mathrm{T}} = \frac{2 \bullet \Delta x}{t^2} = 1.375\ \frac{\mathrm{m}}{\mathrm{s}^2}$$

By definition, $a_{\mathrm{T}} = \alpha \bullet r$ with r as the radial distance from the pin joint to the rotation axis. Therefore, the minimum angular acceleration of the casting arm is calculated to be

$$\alpha = \frac{a_{\mathrm{T}}}{r} = \frac{2 \bullet \Delta x}{r \bullet t^2} = 27.5\ \frac{\mathrm{rad}}{\mathrm{s}^2}$$

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[5] (Samuel, A. M., Mohamed, S. S., Doty, H. W., Valtierra, S., & Samuel, F. H.)
[6] (Fischer-Bühner, J.)
[*] This value was estimated by analyzing countless videos of centrifugal casting. The slowest value was chosen as representative so the error remains on the safe side.

The slowest solidification rate of the analyzed materials was pure aluminum, which took 121 seconds to fully solidify. Since all other materials took much less time to solidify, two minutes was selected as the spin duration. $\theta = \alpha \bullet t^2$, so the casting arm should reach its full angular velocity within 0.7 rotations. Once again, this seems to be in line with most commercially available units, which offer full rotation speeds within 1-2 full rotations.

Morphological Box				
Sub-challenges	Potential Solutions +Advantages -Disadvantages			Chosen
Retaining cup / flask size	2.5” diameter + Easy to manufacture - Restricted to casting small parts	3” diameter + Easy to manufacture - Restricted to casting small parts or wasting investment material for small parts	Conical-shape for range of diameters + Allows for range of flask sizes - Makes investment process more difficult - Complicated to manufacture	Stepped-shape for range of diameters + Allows for several flask sizes without making investment process harder - Stepped-shape requires additional manufacturing steps (lathe, mill)
Crucible standard	Kerr + Common (easy to purchase) - Restricted to Kerr machines	Neycraft + Most widely used (easy to purchase and inexpensive) - Work in Kerr and Neycraft machines	UltraFlex - Restricted to UltraFlex machines - Not even standard to all UltraFlex machines	
Heating option	Casting torch + Inexpensive + Easy to operate - Higher risk	Electrical induction + Easy to operate + Safer to operate - More expensive - Complicates system significantly (electronics and user interface required)	Electrical resistance + Easy to operate + Safer to operate - More expensive - Complicates system significantly (electronics and user interface)	
Rigid or articulated arm	Rigid arm + Easy to manufacture - Arm must accelerate much slower to prevent material spilling over side of crucible	Articulated arm + Allows forces to always point in the desired direction for material flow (no risk of spilling => higher torques) - More manufacturing steps (pin joint or bearing arrangement)		
Hinge for arm articulation	Pin joint + Inexpensive + Easy to manufacture - May cause too much friction to allow arm to swing freely	Slide bearing + Relatively inexpensive + Easy to manufacture + Friction should be low enough to allow arm to swing freely	Coupled rolling bearings + Friction definitely low enough to allow arm to swing freely - More expensive - More difficult to design bearing arrangement - More complicated fabrication of joint (mill, CNC, tolerance considerations, etc.)	
Force generation	Manually driven + Inexpensive - More difficult to manufacture (- crank system with very small radius means high stresses)	Spiral flat spring + Reasonably inexpensive + Could potentially use replacement spring for Neycraft machine - More difficult to design - May not be able to meet torque requirements if steel is used for slide assembly and tub (larger inertia) - May not be able to meet minimum spin duration requirements	Electric motor + Can be tailored to exact force/ torque requirements + Easy to model and design around COTS product - More expensive - May require electronics and user interface	
Motor/Machine arrangement	Machine sits on top of motor and machine	Machine sits on fixed enclosure and is driven by	Machine sits on fixed enclosure	Machine sits on fixed enclosure

	weight is axial load on motor shaft + Easiest option to design + Least expensive option - Axial load may cause longevity concerns for motor - May be more expensive	motor via spur gears + No axial load on motor - More complicated to design (housing and gear arrangement)	and is driven by motor via belt + No axial load on motor - More complicated to design (belt and pulley arrangement with bearings)	and is driven by motor via chain + No axial load on motor - More complicated to design (chain and sprocket arrangement with bearings)
Material for slide assembly	S235 Structural Steel + Inexpensive and readily available + Relatively easy to machine + Can be welded easily + High melting temperature (1480°C) - Could corrode over time	304 Stainless steel + Can be welded easily + No risk of corrosion + High melting temperature (1400°C) - More expensive - More difficult to machine	Aluminum + Inexpensive and readily available + Easy to machine + No risk of corrosion - More difficult to weld (for me) - Could corrode over time - Low melting temperature (660°C)	Combination of whatever is available in the lab + Cheapest option - Will need additional treatment (oil quench or zinc sink) to prevent corrosion
Shape of slider bars (cross-section)	Round - More difficult to manufacture (tapping ends or cotter pin arrangement)	Rectangular + Easy to manufacture and assemble - More difficult to calculate - Will require additional hardware	I-Beam - More difficult to manufacture (welding) - Unnecessary because bending loads are small - Inertia payoff is for wrong axis	
Material for tub	S235 Structural Steel + Inexpensive and readily available + Relatively easy to machine + Can be welded easily + High melting temperature (1480°C) - Could corrode over time	304 Stainless steel + Can be welded easily + No risk of corrosion + High melting temperature (1400°C) - More expensive - More difficult to machine	Aluminum + Inexpensive and readily available + Easy to machine + No risk of corrosion - More difficult to weld (for me) - Low melting temperature (660°C)	Thermoset Plastic + Lightweight (smaller inertia) + Easy to machine + No risk of corrosion -+ Difficult to cast but may be easy to purchase COTS - Brittle (less durable than metal)
Tub	Rotating + Safer in the event of a catastrophic failure of the mold or crucible, since spilled molten metal can only spill onto surface with no relative motion - More difficult to manufacture (mechanism for locking arm to tub) - Additional rotating mass means additional torque required from spring/ motor	Stationary + Easier to manufacture (possibly even COTS) - Higher risk of splashing molten metal in the event of a catastrophic failure of the mold or crucible (could be solved by adding a protective lip to the inner wall)	Stationary solid upper ring around full enclosure + Easier to manufacture - Higher risk of splashing molten metal in the event of a catastrophic failure of the mold or crucible (could be solved by adding a protective lip to the inner wall)	
Tub shape	Vertical walls + Easy to manufacture (weld) - Provides less safety in the event of a catastrophic failure of the mold or crucible	Concave walls + Safer since spilled molten material would be directed downward (into tub) instead of upward - More difficult to manufacture (cone shape) and weld		
Tub Fabrication	Deep-drawing/ pressing + Lowest mass/inertia option	Welded seams + Low mass/inertia - Long welds, difficult to manufacture. - Difficult to calculate	Bolted seams + Easy to manufacture + Relatively easy to calculate	No seams + Easiest to manufacture + Requires fewest components

	- Difficult to manufacture - May not have access to equipment	- Welding creates local brittle areas	- Highest mass/inertia -Requires more components	+ Inertia doesn't matter for stationary design inside enclosure
Enclosure Definition: Top -------- Upper lip of tub Bottom	Fully enclosed + Provides illusion of safety even in the event of a catastrophic failure - Most difficult to design and manufacture - Most expensive - May actually increase risk because of safety components interfering with casting	Open top, enclosed bottom + Allows for easy access to crucible and flask during casting - More difficult to design and manufacture (especially if a rotating tub is chosen) - More expensive - Would create possibility to get fingers between fixed enclosure and spinning tub (less safe)	Open bottom, enclosed top + Hinged, closing top may add safety in the event of a catastrophic failure of the mold or crucible - Even more difficult to design and manufacture (need a way to be able to release the arm from outside - May actually increase risk because of safety components interfering with casting	Fully open + Least expensive + Easiest to manufacture + Most commonly used option - Provides less illusion of safety in the event of catastrophic failure of the mold or crucible

For the purposes of classical rational analysis, the casting machine may be divided into hierarchies by means of its component assemblies and by means of its functions.

Component Hierarchy

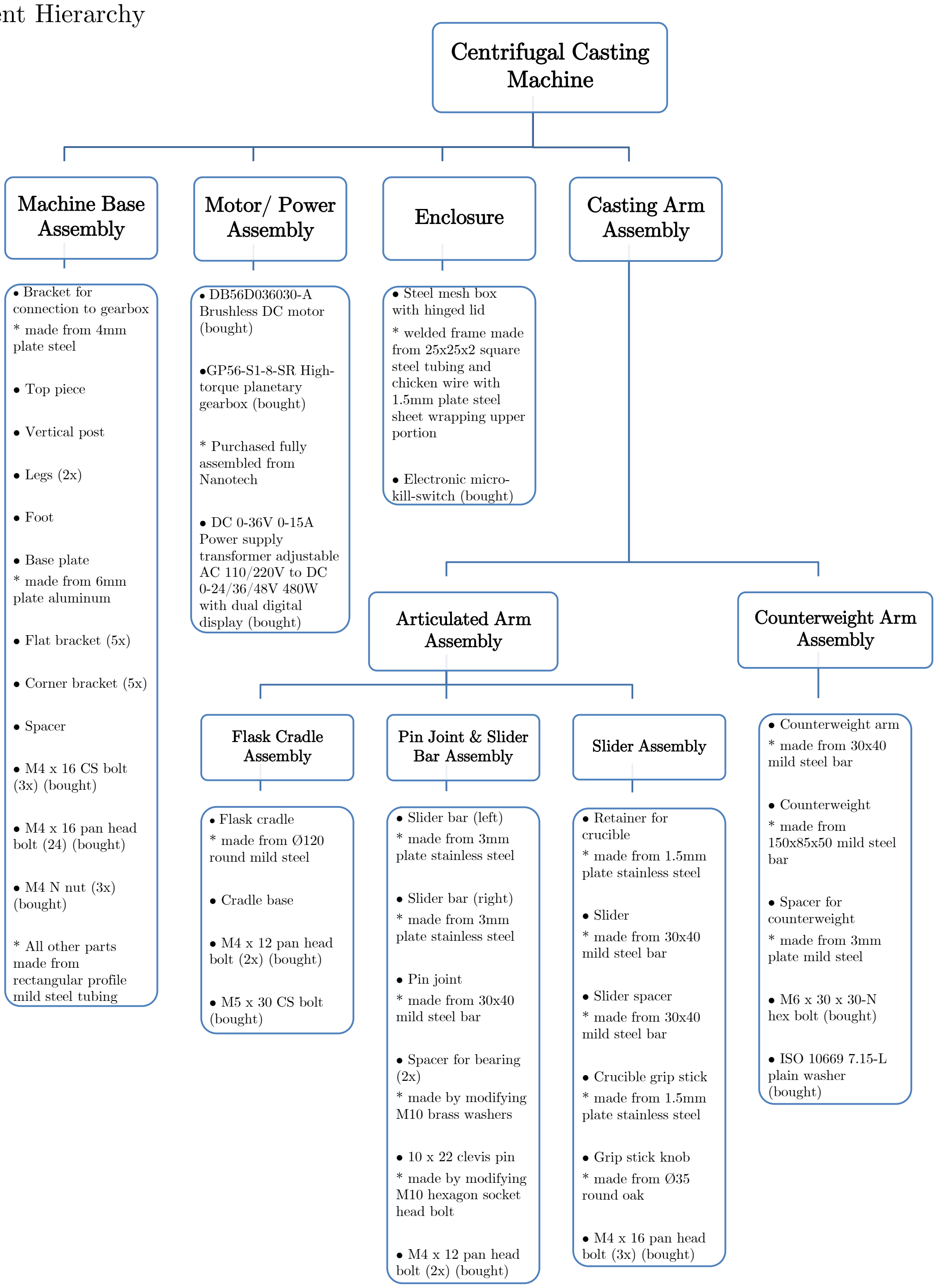


Figure 6.1: Component hierarchy diagram showing all parts and materials for final design

Functional Hierarchy

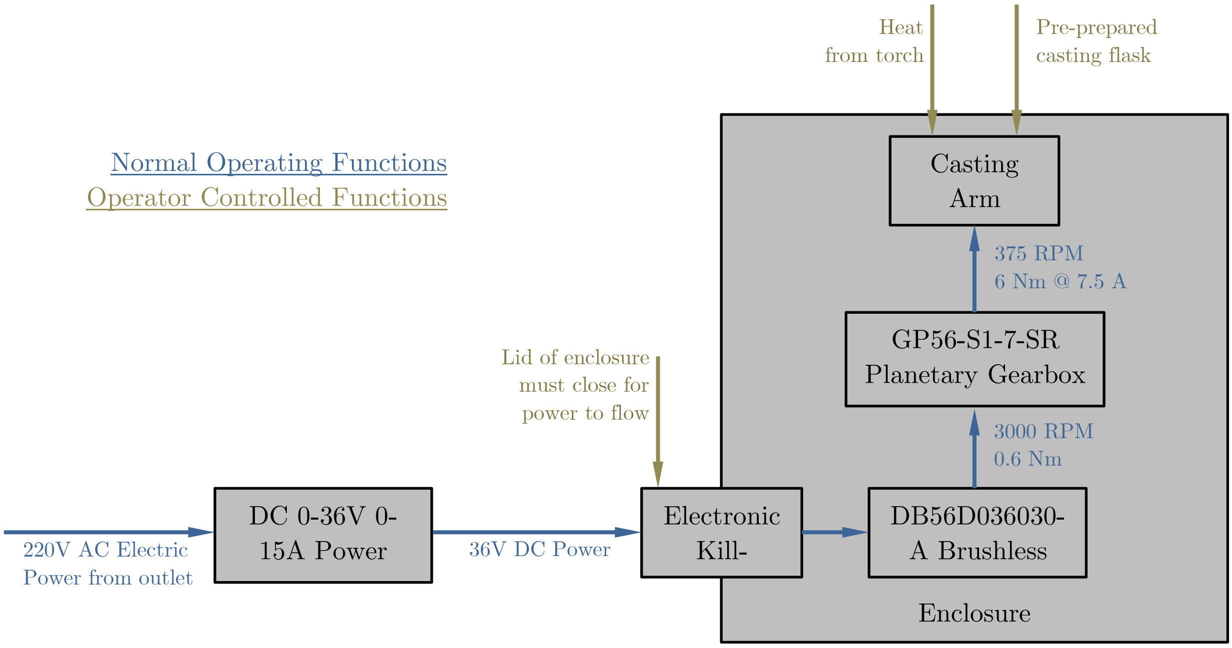
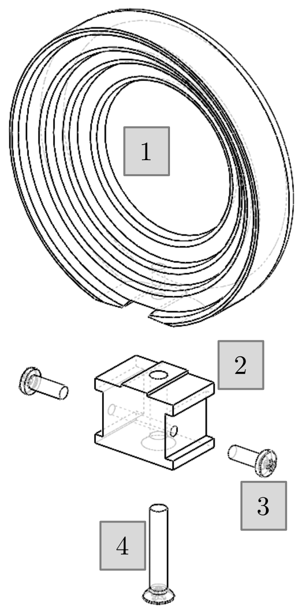
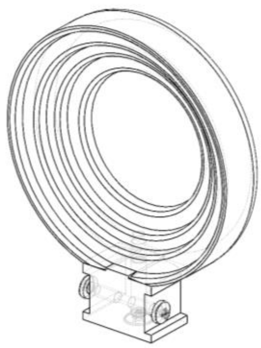


Figure 6.2: Functional hierarchy diagram showing normal operating functions and operator controlled functions

Casting Arm Sub-Assemblies

Flask Cradle Assembly

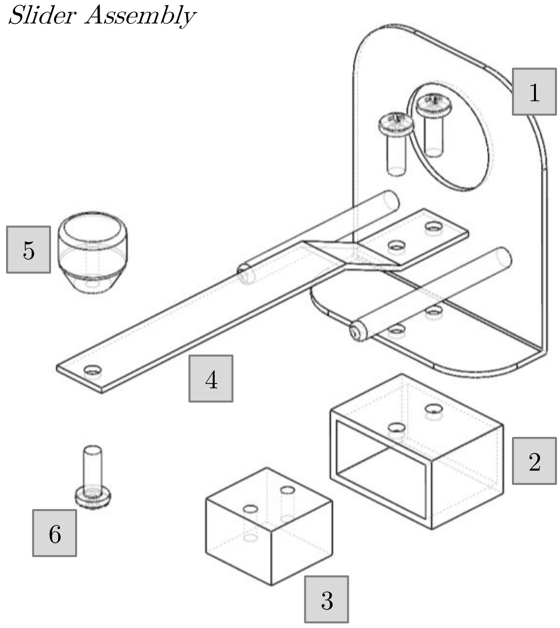


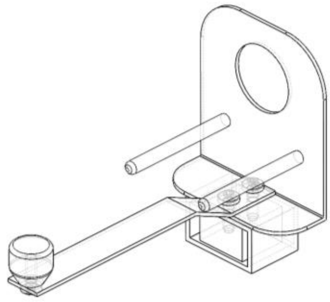


#	Part Name	Qty	Material	M or B
1	Flask Cradle	1	S235 Structural	Make
2	Cradle Base	1	S235 Structural	Make
3	ISO 7045–M4x12–Z–12N	2	304 Stainless	Buy
4	ISO 7046-1–M5x30–Z–30N	1	304 Stainless	Buy

Figure 6.3: Isometric views of exploded and assembled flask cradle assembly with bill of materials

Slider Assembly

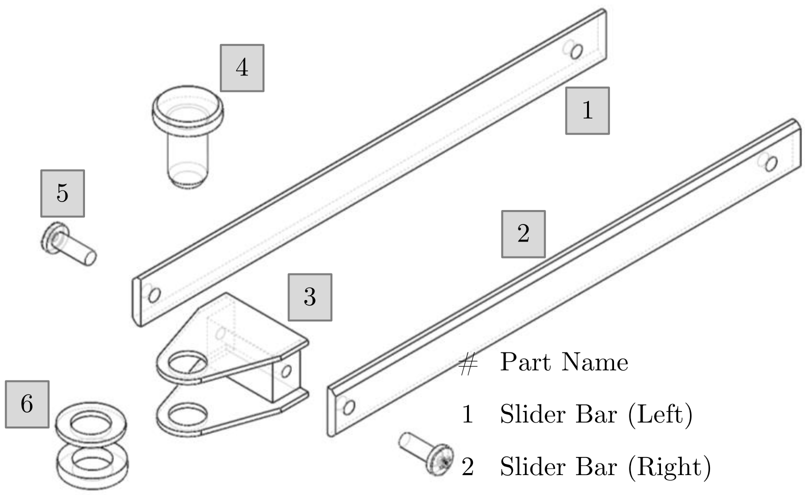


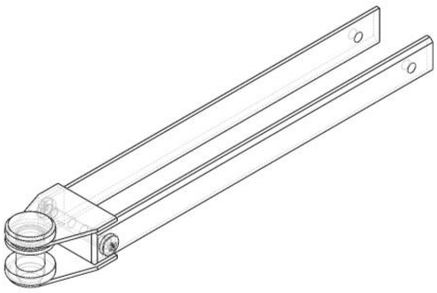


#	Part Name	Qty	Material	M or B
1	Retainer for Crucible	1	304 Stainless	Make
2	Slider	1	S235 Structural	Make
3	Slider Spacer	1	S235 Structural	Make
4	Crucible Grip Stick	1	304 Stainless	Make
5	Grip Stick Knob	1	Oak	Make
6	ISO 7045–M4x12–12N	3	304 Stainless	Buy

Figure 6.4: Isometric views of exploded and assembled slider assembly with bill of materials

Pin joint and Slider Bar Assembly





#	Part Name	Qty	Material	M or B
1	Slider Bar (Left)	1	304 Stainless	Make
2	Slider Bar (Right)	1	304 Stainless	Make
3	Pin Joint	1	S235 Structural	Make
4	ISO 2341–A–10x20	1	304 Stainless	Buy
5	ISO 7045–M4x12–Z–12N	2	304 Stainless	Buy
6	Spacer for Bearing	2	Brass	Make

Figure 6.5: Isometric views of exploded and assembled pin joint assembly with bill of materials

Full-Articulated Arm Assembly

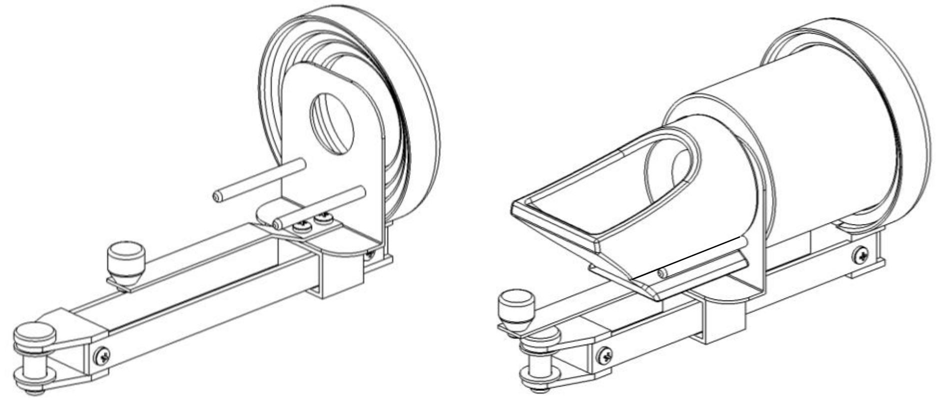
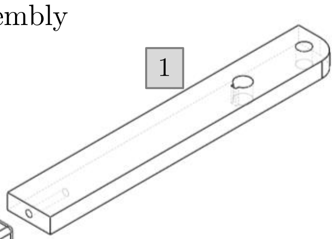
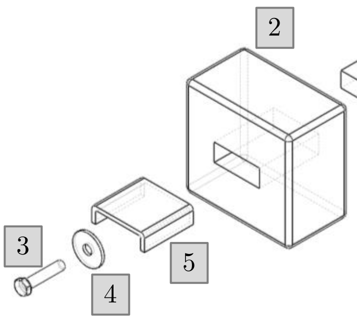
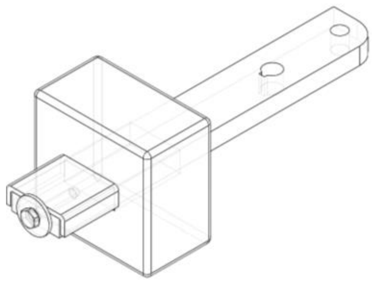


Figure 6.6: Isometric views of assembled articulated arm, shown with (right) and without (left) crucible and casting flask

Counterweight Arm Assembly







#	Part Name	Qty	Material	M or B
1	Counterweight Arm	1	S235 Structural	Make
2	Counterweight	1	S235 Structural	Make
3	ISO 4014 – M6 x 30 x 30-N	1	S235 Structural	Buy
4	ISO 10669-7.15-L	1	S235 Structural	Buy
5	Spacer for Counterweight	1	S235 Structural	Make

Figure 6.7: Isometric views of exploded and assembled counterweight assembly with bill of materials

Full Casting Arm Assembly

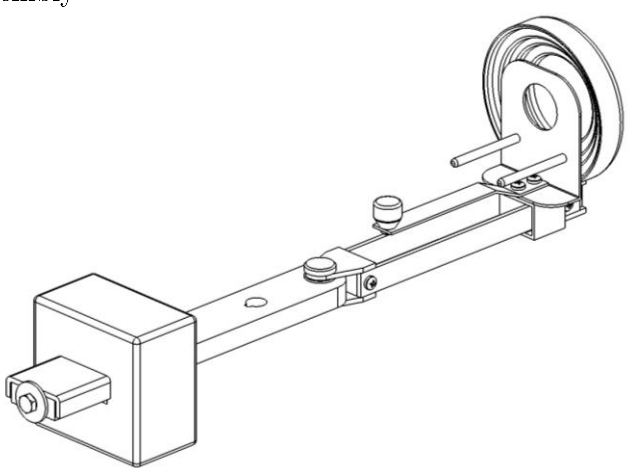


Figure 6.8: Isometric view of full assembled casting arm, shown without crucible or casting flask

Motor and Machine Base Assembly

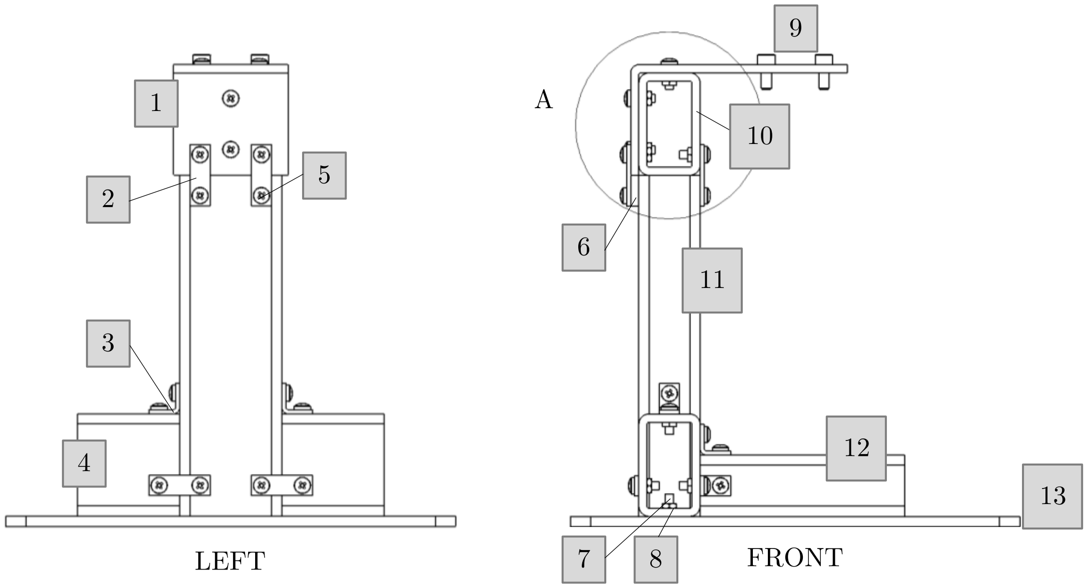


Figure 6.9: Select cardinal views of assembled motor and machine base assembly

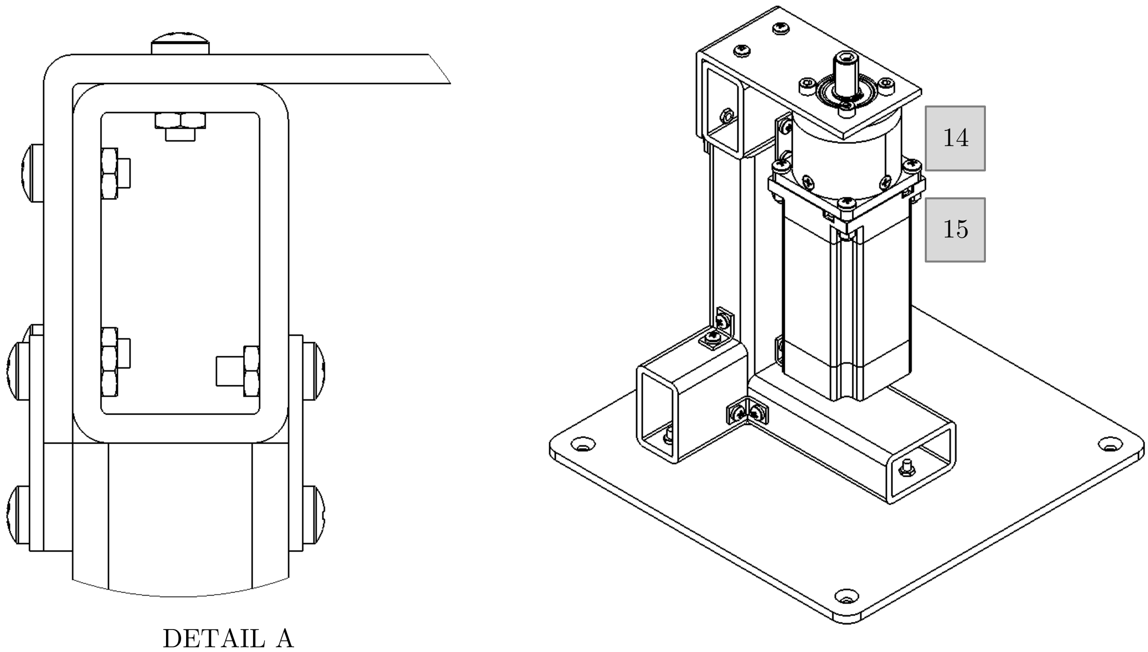


Figure 6.10: Detail A and isometric view of motor and machine base assembly showing gearbox and motor placement

Table 6.1: Bill of materials for machine base assembly

#	Part Name	Qty	Material	M or B
1	Bracket for Connection to Gearbox	1	S235 Structural	Make
2	Flat Bracket	5	S235 Structural	Make
3	Corner Bracket	5	S235 Structural	Make
4	Legs	2	S235 Structural	Make
5	ISO 7045 – M4 x 12 – Z – 12N	24	S235 Structural	Buy
6	Spacer	2	S235 Structural	Make
7	ISO 7046-1 – M4 x 16 – Z – 16N	3	S235 Structural	Buy
8	ISO – 4035 – M4 – N	30	S235 Structural	Buy
9	ISO 4762 M5 x 12 – 12N	4	S235 Structural	Buy
10	Top Piece	1	S235 Structural	Make
11	Vertical Post	1	S235 Structural	Make
12	Foot	1	S235 Structural	Make
13	Base Plate	1	1050A Aluminum	Make
14	GP56-1-S1-XX-SRS Planetary Gearbox	1	---	Buy
15	DB56D036030-A Brushless DC Motor	1	---	Buy

Enclosure

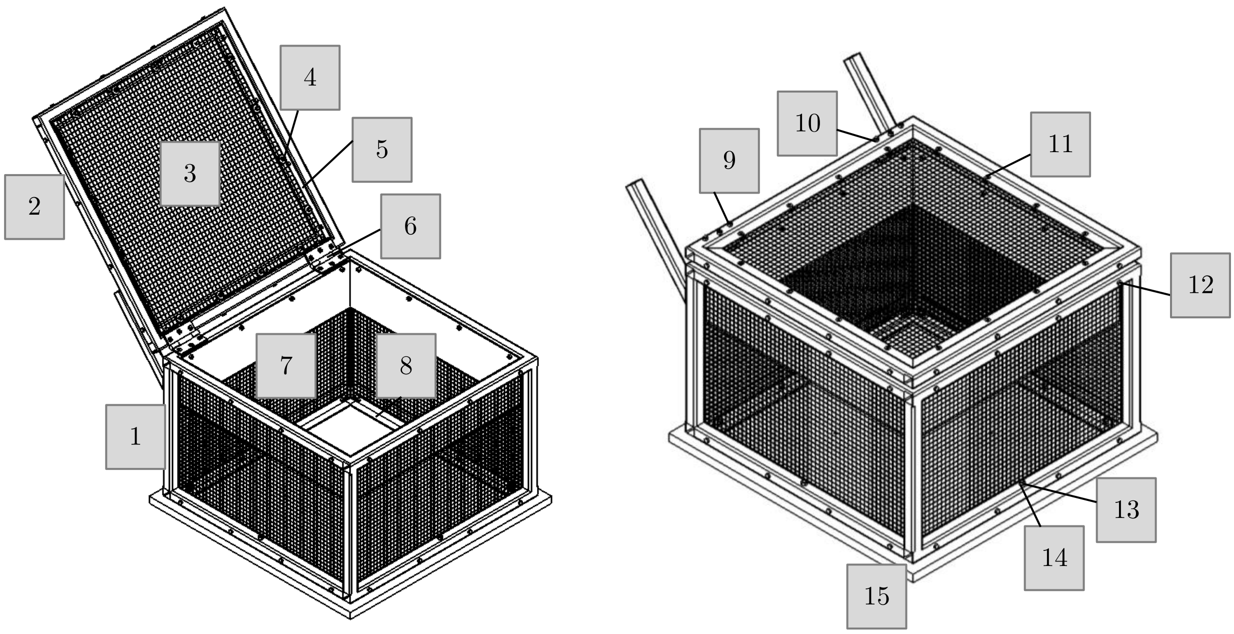


Figure 6.11: Open (left) and closed (right) isometric views of enclosure showing components

Table 6.2: Bill of materials for enclosure assembly

#	Part Name	Qty	Material	M or B
1	Welded Frame	1	S235 Structural	Make
2	Lid	1	S235 Structural	Make
3	Chicken Wire (5 pieces cut to inner dimensions of frame)	5	---	B/M
4	ISO 7094 - 5 (large M5 washers)	16	S235 Structural	Buy
5	Al L-Profile (lid)	4	1050A Aluminum	Make
6	25 x 80 mm CS Hinge	2	S235 Structural	Buy
7	1.5 mm Sheet	4	S235 Structural	Make
8	Al L-Profile (bottom)	4	1050A Aluminum	Make
9	ISO 7046-1 M5 x 35 – Z – 35N (CS bolt for hinges)	12	S235 Structural	Buy
10	ISO – 4032 – M5 – D – N (M5 nuts)	74	S235 Structural	Buy
11	ISO 7046-1 M5 x 8 – Z – 8N (CS bolt for lid)	16	S235 Structural	Buy
12	ISO 4014 M5 x 35 x 35-N (35mm M5 hex bolt)	48	S235 Structural	Buy
13	ISO 7046-1 M6 x 50 – Z – 50N (CS for frame to base)	4	S235 Structural	Buy
14	ISO – 4034 – M6 – N (M6 nuts)	4	S235 Structural	Buy
15	Base Board	1	¾ Inch Plywood	Make

Full Assembly of Casting Machine

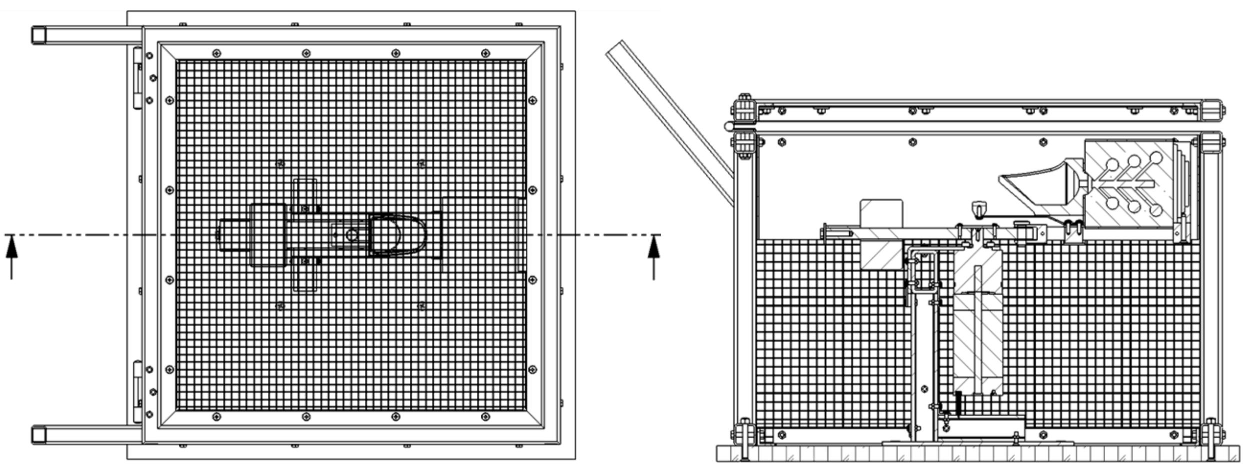


Figure 6.12: Top and right section view of full assembly of entire centrifugal casting machine, shown with crucible and flask assembly

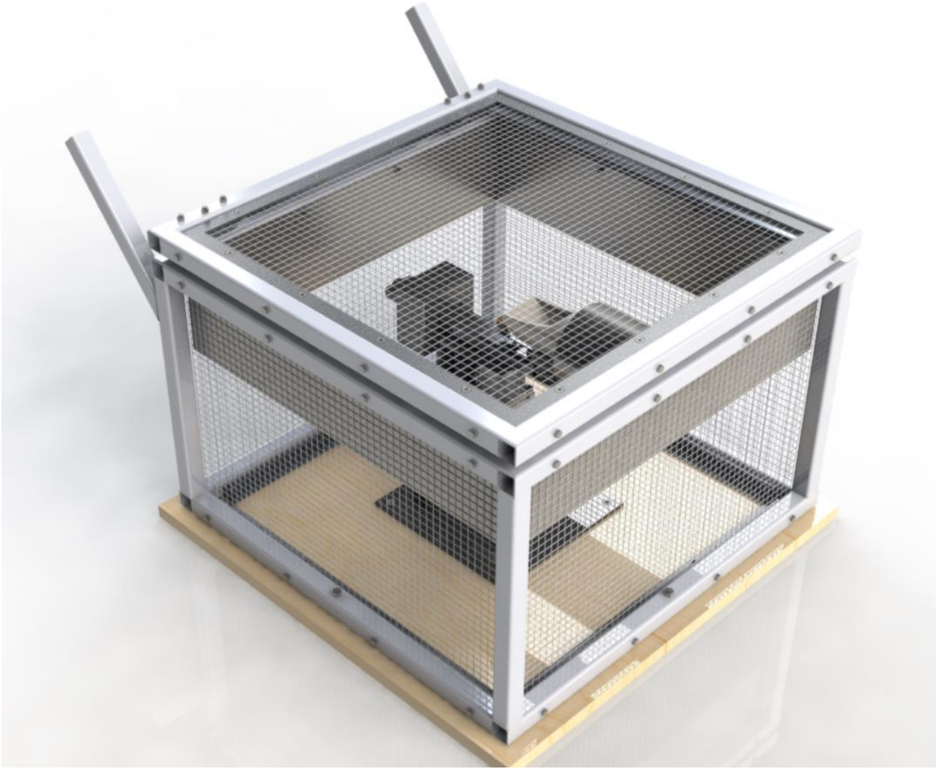


Figure 6.13: Isometric view of 3D rendering of final CAD model

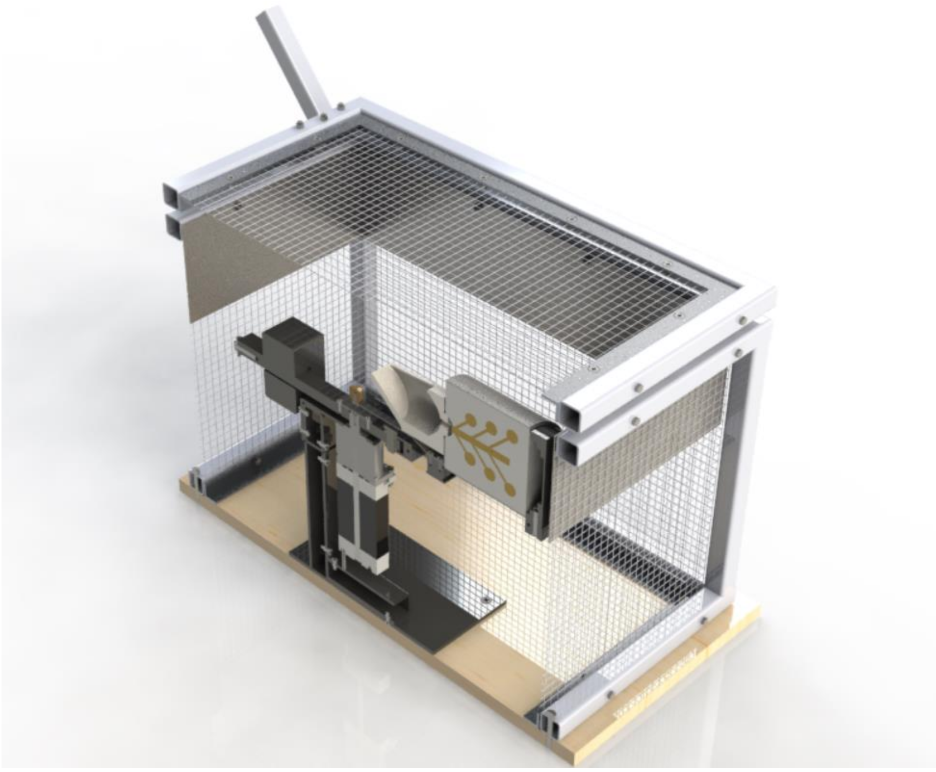


Figure 6.14: Isometric section view of 3D rendering of final CAD model

Motor Selection

Electrical power is the product of current I and voltage V:

$$P = I \bullet V$$

Mechanical power is the product of torque τ and angular velocity ω:

$$P = \tau \bullet \omega$$

An electric motor is a converter of electrical power into mechanical power. The output mechanical power of the power transmission system equals the electrical power of the motor minus some losses due to inefficiency in the drivetrain. When more current is applied to the motor, the magnetic field inside becomes stronger. Consequently, the attraction between the poles increases. This means that the current to the motor is directly proportional to the output torque. Similarly, the faster the rotor spins through the stator field, the greater the counter-electromotive force it will generate, in accordance with Faraday's law of induction. This means, as expected from the equations describing electrical and mechanical power, voltage and rotation speed are also directly proportional. In other words: to change the rotation speed of an electric motor, adjust the supplied voltage; to change the output torque, adjust the supplied current.

The output torque and rotation speed can also be affected by reduction systems like gearboxes. Commonly, planetary gearboxes are used since the relationships are straightforward. The output torque of the gearbox τ_{out} equals the product of the input torque τ_{in} and the reduction ratio of the gearbox i, times the efficiency of the gearbox η. The output rotation speed n_{out} equals the input speed n_{in} divided by the reduction ratio, again times the efficiency. In mathematical form:

$$\tau_{\text{out}} = \tau_{\text{in}} \bullet i \bullet \eta$$

$$n_{\text{out}} = \frac{n_{\text{in}}}{i} \bullet \eta$$

Similarly, output torque and rotation speed can also be affected by power transmission systems like belt drives. The relationships are the same but the reduction ratio i is the ratio of the driving pulley to the driven pulley and the efficiency η is the efficiency of the belt and pulleys.

The selection of a motor and drivetrain is a delicate dance between the requirements of the design and the standard components that are available for purchase, as well as their interfacing options. The required torque τ_{req} is calculated using the minimum angular acceleration α from the preliminary calculations and the machine's moment of inertia[7] I about the rotation axis:

$$\tau_{\text{req}} = I \bullet \alpha = (0.1605\ \text{kg} \bullet \text{m}^2) \bullet \left(27.5\ \frac{\text{rad}}{\text{s}^2}\right) = 4.414\ \text{Nm}$$

The required power P_{req} is calculated using the required torque and the minimum angular velocity ω from the preliminary calculations:

---

[7] Sum of moments of inertias of all rotating components about rotation axis, taken from CAD model
Final mass = 6.594 kg

$$P_{\text{req}} = \tau_{\text{req}} \bullet \omega = (4.414\ \text{Nm}) \bullet \left(36.515\ \frac{\text{rad}}{\text{s}}\right) = 156.755\ \text{W}$$

Given these values and the aforementioned relationships, a suitable motor and gearbox configuration was chosen.

Motor:

DB56D036030–A – Brushless DC Motor

Motor size	Nema 23
Rated power	188 W
Rated torque	60 Ncm
Rated current	7.5 A
Rated speed	3000 RPM
Rated voltage	36 V

Figure 6.15: DB56D036030–A – Brushless DC Motor and relevant technical data

Gearbox:

GP56–S1–7–SR – High-Torque Planetary Gearbox

For motor size	Nema 23, Nema 24
Efficiency	92%
Rated output torque	12.1 Nm
Reduction ratio	7
Max axial shaft load	1302 N
Max radial shaft load	516 N

Figure 6.16: GP56–S1–7–SR – High-Torque Planetary Gearbox and relevant technical data

Check of axial shaft load

In this design, the weight of the casting arm is the axial shaft load. Since the max axial load is 1302 N, the 6.6 kg mass of the machine is significantly less than the maximum admissible mass of 132.7 kg.

Check of radial shaft load

Any imbalance in the casting arm will result in a radial load on the gearbox shaft due to the centrifugal forces. The maximum mass that can be out of balance on the casting arm can be calculated using the permissible radial shaft load.

$$m_{\text{imbalance,max}} = \frac{F_{\text{per}}}{\omega^2 \bullet L} = 2.20\ kg$$

Articulated Arm Assembly

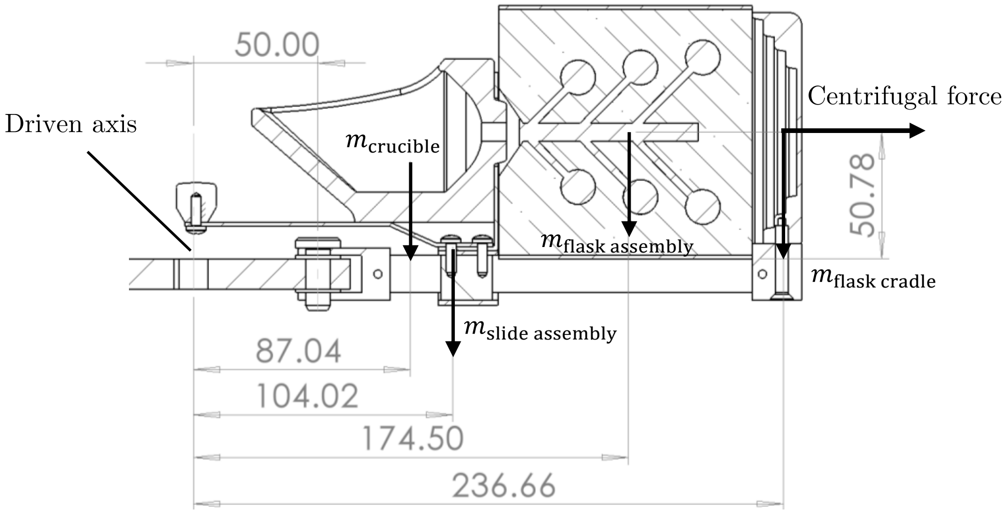


Figure 7.1: Schematic of slide assembly showing components and forces relevant for calculations

Pre-tension loads for bolts

Table 7.1: Maximum loads and minimum pretension calculations for bolts in slide assembly

Dynamic pulsating load $0 \leq \text{load} \leq F_{\text{centrifugal}}$ Maximum centrifugal load ($\alpha = 0\,\frac{\text{m}}{\text{s}}$) $$F_{\text{N,max}} = m \bullet a_{\text{N}} = m \bullet \omega^2 \bullet L$$ m: Relevant mass a_{N}: Normal acceleration L: Relevant distance from rotation axis ω: Rotational velocity from gearbox ($375\text{ RPM} = 39.27\,\frac{\text{rad}}{\text{s}}$)		
Bolted Connection:		
Flask cradle to flask cradle base	Flask base to slider bars	Slider bars to pin joint
Masses:		
Full slide assembly: 209.53 g Full flask assembly: 1070.94 g Crucible: 266.51 g Flask cradle: 522.13 g	Full slide assembly: 209.53 g Full flask assembly: 1070.94 g Crucible: 266.51 g Flask cradle: 522.13 g Cradle base: 83.04 g	Full slide assembly: 209.53 g Full flask assembly: 1070.94 g Full flask cradle assembly: 610 g Crucible: 266.51 g Slider bars: 122.29 g
Maximum transverse loads (for pre-tensioning): $$F_{\text{T}} = \omega^2 \bullet \sum m \bullet L$$		
$F_{\text{T}} = 548.131\text{ N}$	$F_{\text{T}} = 578.437\text{ N}$	$F_{\text{T}} = 607.34\text{ N}$

Minimum pretension loads for bolts in slide assembly:

$$F_\mathrm{v} \geq \frac{F_\mathrm{T}}{\mu \bullet n}$$

μ: Coefficient of static friction for stainless steel on stainless steel = 0.5

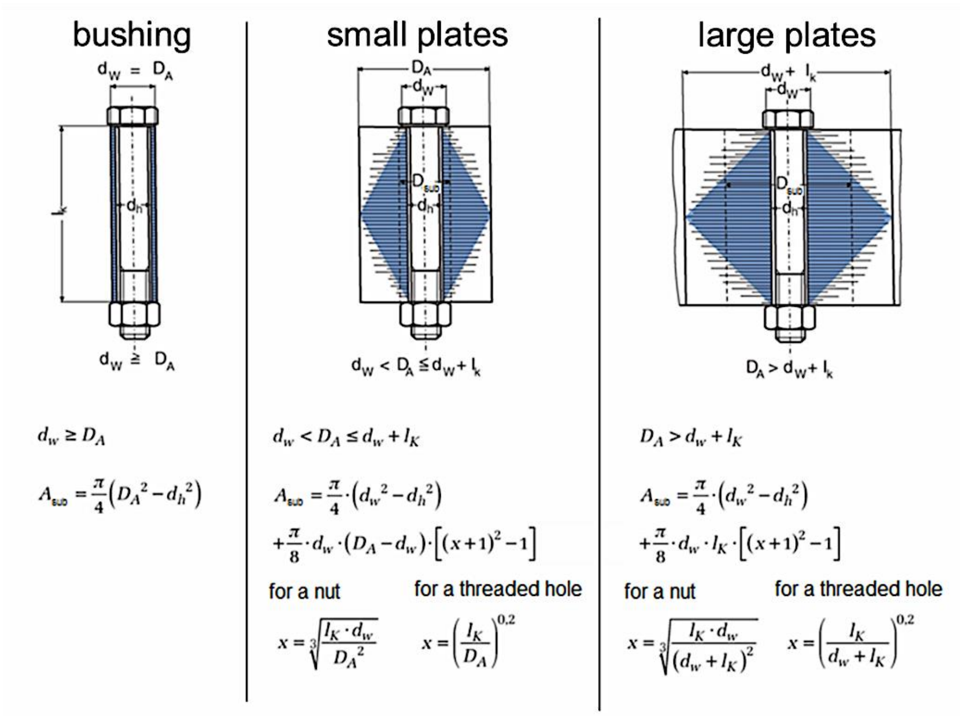
n: Number of bolts sharing the load

n=1	n=2	n=2
$F_\mathrm{v} = 1096.26\ \mathrm{N}$	$F_\mathrm{v} = 578.437\ \mathrm{N}$	$F_\mathrm{v} = 607.34\ \mathrm{N}$

Deformation of plates at pretension

Table 7.2: Plate deformation calculations for bolts in slide assembly

Based on the approach created by German engineer, Felix Rötscher [Kisters].



Bolted connection:		
Flask cradle to cradle base	Cradle base to slider bars	Slider bars to pin joint
Dimensions:		
$D_\mathrm{A} = 16\ \mathrm{mm}$	$D_\mathrm{A} = 12\ \mathrm{mm}$	$D_\mathrm{A} = 12\ \mathrm{mm}$
$d_\mathrm{w} = 9.3\ \mathrm{mm}$	$d_\mathrm{w} = 8\ \mathrm{mm}$	$d_\mathrm{w} = 8\ \mathrm{mm}$
$d_\mathrm{h} = 5.5\ \mathrm{mm}$	$d_\mathrm{h} = 4\ \mathrm{mm}$	$d_\mathrm{h} = 4\ \mathrm{mm}$
$L_\mathrm{k} = 19.53\ \mathrm{mm}$	$L_\mathrm{k} = 3\ \mathrm{mm}$	$L_\mathrm{k} = 3\ \mathrm{mm}$
Formula selection:		
$d_\mathrm{w} < D_\mathrm{A} \leq d_\mathrm{w} + L_\mathrm{k}$	$D_\mathrm{A} > d_\mathrm{w} + L_\mathrm{k}$	$D_\mathrm{A} > d_\mathrm{w} + L_\mathrm{k}$
Formula for small plates is chosen	Formula for large plates is chosen	Formula for large plates is chosen

Area of the substituting cylinder A_{sub} for a threaded hole:		
$A_{\mathrm{sub}} = 121.6\ \mathrm{mm}^2$	$A_{\mathrm{sub}} = 57.84\ \mathrm{mm}^2$	$A_{\mathrm{sub}} = 57.84\ \mathrm{mm}^2$
Elastic resilience of the plates: $\delta_{\mathrm{p}} = \frac{L_k}{A_{\mathrm{sub}} \bullet E_{\mathrm{p}}}$		
$\delta_{\mathrm{p}} = 7.648 \bullet 10^{-7}\ \frac{\mathrm{mm}}{\mathrm{N}}$	$\delta_p = 2.730 \bullet 10^{-7}\ \frac{\mathrm{mm}}{\mathrm{N}}$	$\delta_p = 2.730 \bullet 10^{-7}\ \frac{\mathrm{mm}}{\mathrm{N}}$
Deflection of the plates due to the pre-tension: $f_{\mathrm{p}} = \frac{F_{\mathrm{v}} \bullet L_k}{A_{sub} \bullet E_{\mathrm{p}}}$		
$f_{\mathrm{p}} = 0.838\ \mu\mathrm{m}$	$f_{\mathrm{p}} = 0.158\ \mu\mathrm{m}$	$f_{\mathrm{p}} = 0.166\ \mu\mathrm{m}$

Settling forces [Kisters]

Table 7.3: Settling losses and minimum assembly force calculations for bolts in slide assembly

Bolted connection:		
Flask cradle to cradle base	Cradle base to slider bars	Slider bars to pin joint
Settling losses f_{z} for the real clamping length (bolted joints according to DIN 24014): $f_{\mathrm{z}} \approx 3.29 \bullet \left(\frac{L_{\mathrm{k}}}{d}\right)^{0.34} \bullet 10^{-3}$		
$f_{\mathrm{z}} \approx 5.229\ \mu\mathrm{m}$	$f_{\mathrm{z}} \approx 2.983\ \mu\mathrm{m}$	$f_{\mathrm{z}} \approx 2.983\ \mu\mathrm{m}$
Dimensions :		
$L_{\mathrm{H}} = 3.4\ \mathrm{mm}$	$L_{\mathrm{H}} = 2.035\ \mathrm{mm}$	$L_{\mathrm{H}} = 2.035\ \mathrm{mm}$
$L_{\mathrm{S}} = 1.6\ \mathrm{mm}$	$L_{\mathrm{S}} = 0.927\ \mathrm{mm}$	$L_{\mathrm{S}} = 0.927\ \mathrm{mm}$
$L_{\mathrm{T}} = 19.53\ \mathrm{mm}$	$L_{\mathrm{T}} = 3\ \mathrm{mm}$	$L_{\mathrm{T}} = 3\ \mathrm{mm}$
$L_{\mathrm{N}} = 7.23\ \mathrm{mm}$	$L_{\mathrm{N}} = 9\ \mathrm{mm}$	$L_{\mathrm{N}} = 9\ \mathrm{mm}$
$d = 5\ \mathrm{mm}$	$d = 4\ \mathrm{mm}$	$d = 4\ \mathrm{mm}$
$d_{\mathrm{T}} = 4.2\ \mathrm{mm}$	$d_{\mathrm{T}} = 3.3\ \mathrm{mm}$	$d_{\mathrm{T}} = 3.3\ \mathrm{mm}$
Deflection of cylinder f: $f = \Delta L = \varepsilon \bullet L = \frac{L \bullet \sigma}{E} = \frac{F \bullet L}{E \bullet A}$		
Elastic resilience δ:		

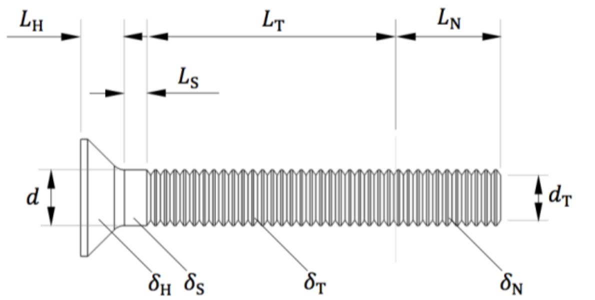


Figure 7.3: Resiliencies and dimensions of the screws in the slide assembly

$$\delta = \frac{1}{K} = \frac{f}{F} = \frac{L}{E \bullet A} = \frac{4 \bullet L}{\pi \bullet E \bullet d^2}$$

Resilience of screw head:

$$\delta_H = \frac{0.4 \bullet 4}{\pi \bullet d \bullet E}$$

Resilience of unthreaded portion:

$$\delta_S = \frac{4 \bullet L_S}{\pi \bullet E \bullet d^2}$$

Resilience of unengaged threaded portion:

$$\delta_T = \frac{4 \bullet L_T}{\pi \bullet E \bullet {d_\mathrm{T}}^2}$$

Resilience of threaded hole:

$$\delta_N = \frac{0.33 \bullet 4}{\pi \bullet d \bullet E}$$

Resilience of bolt:

$$\delta_\mathrm{B} = \delta_\mathrm{H} + \delta_\mathrm{S} + \delta_\mathrm{T} + \delta_\mathrm{N}$$

$\delta_\mathrm{B} = 7.986 \bullet 10^{-6}\ \frac{\mathrm{mm}}{\mathrm{N}}$ $\delta_\mathrm{B} = 3.128 \bullet 10^{-6}\ \frac{\mathrm{mm}}{\mathrm{N}}$ $\delta_\mathrm{B} = 3.128 \bullet 10^{-6}\ \frac{\mathrm{mm}}{\mathrm{N}}$

Loss in pretension load due to settling:

$$F_\mathrm{z} = \frac{f_\mathrm{z}}{\delta_\mathrm{P} + \delta_\mathrm{B}}$$

$F_\mathrm{z} = 597.506\ \mathrm{N}$ $F_\mathrm{z} = 877.087\ \mathrm{N}$ $F_\mathrm{z} = 877.087\ \mathrm{N}$

Minimum and maximum assembly forces:

$$F_\mathrm{v,ass,min} = F_\mathrm{v} + F_\mathrm{z}$$

$$F_\mathrm{v,ass,max} = \alpha_\mathrm{A} \bullet F_\mathrm{v,ass,min}$$

$F_\mathrm{v,ass,min} = 1693.77\ \mathrm{N}$ $F_\mathrm{v,ass,min} = 1455.52\ \mathrm{N}$ $F_\mathrm{v,ass,min} = 1484.43\ \mathrm{N}$

$F_\mathrm{v,ass,max} = 2032.52\ \mathrm{N}$ $F_\mathrm{v,ass,max} = 1746.63\ \mathrm{N}$ $F_\mathrm{v,ass,max} = 1781.31\ \mathrm{N}$

Compare maximum assembly force to permitted force $F_\mathrm{v,ass,per}$

$$F_\mathrm{v,ass,per} = 0.9 \bullet R_\mathrm{p0.2} \bullet A_s$$

$R_\mathrm{p0.2}$: 0.2% yield strength (235 MPa)

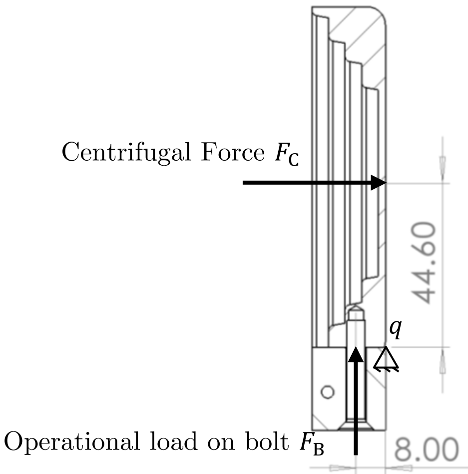
A_s: Loaded cross-sectional area

$F_\mathrm{v,ass,per} = 2930.21\ \mathrm{N}$ $F_\mathrm{v,ass,per} = 1808.96\ \mathrm{N}$ $F_\mathrm{v,ass,per} = 1808.96$

For all three bolted connections, $F_\mathrm{v,ass,max} \leq F_\mathrm{v,ass,per}$ so the bolts can take the lateral loads.

Operational Load [Kisters]

Table 7.4: Operational load calculations for the bolted connection between flask cradle and cradle base



$$\sum M_q = 0 \Leftrightarrow F_B = \frac{44.60\text{ mm}}{8.00\text{ mm}} \bullet F_c = 3055.83\text{ N}$$

Figure 7.4: Free body diagram of bolted joint and sum of moments about the assumed rotation point q

Load ratio ϕ

$$\phi = \frac{\delta_B}{\delta_B + \delta_p} = 0.0874$$

Additional load for plates due to application of operational load $F_{P,B}$

$$F_{P,B} = (1 - \phi) \bullet F_{P,B} = 2788.76\text{ N}$$

Additional load for bolt due to application of operational load $F_{S,B}$

$$F_{S,B} = \phi \bullet F_B = 267.073\text{ N}$$

Comparison of additional load on bolt to permissible load

$$F_{S,B} = 267.073\text{ N} \leq 0.1 \bullet R_{p0.2} \bullet A_s = 325.579\text{ N}$$

Since the additional load on the bolt is less than the permissible load, plastic deformation of the bolt due to the load is not to be expected with a safety factor of 1.2.

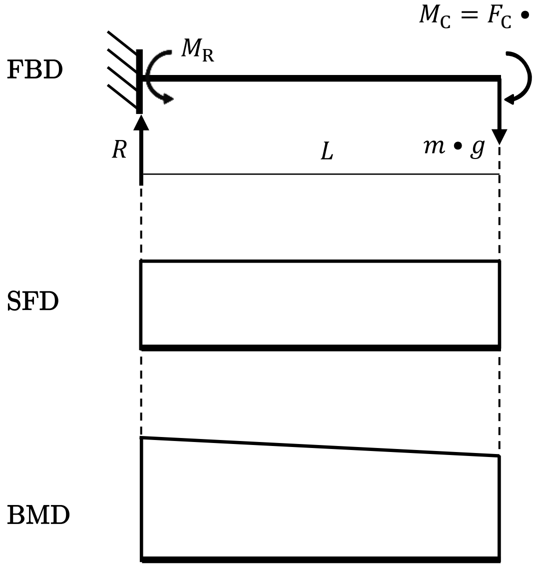
In bolted connections, the pre-tensioning friction absorbs the shear dynamic loads dynamically. With proper pre-tensioning, there is no relative motion between plates or between bolts and plates. Therefore, all wear in the bolted fastener is caused by the dynamic tensile load.

Tensile stress in slider bars

Technically, the friction between the plates should dynamically absorb the dynamic tensile load on the slider bars, and the full cross-section should be loaded. Doing the stress calculation using the reduced cross-sectional area of the hole ensures the ability of the slider bars to endure the load even if the bolted joint loosens over time.

The centrifugal load F_C acts to create a moment M_C on the slider bars at the bolted connection to the cradle base. This moment and the weight force of the flask assembly (applied at the end of the slider bars) create a bending load.

$$M_{\mathrm{C}} = F_{\mathrm{C}} \bullet h_{\mathrm{F}} = 27.83 \text{ Nmm}$$



Modulus of elasticity: 304 Stainless: 190 GPa Ultimate tensile strength $R_m = 517.017$ MPa Tensile strength at yield $R_e = 206.807$ MPa Shear strength 298.490 MPa
Mass for weight force: 2279.27 g
Rotational velocity $\omega = 39.27 \frac{\mathrm{rad}}{\mathrm{s}}$
Dimensions and second moment of area: $L = 157.25$ mm $h_{\mathrm{F}} = 50.78$ mm $I_z = 843.75 \text{ mm}^4$ (for one slider bar)

Figure 7.5: Free-body, shear force and bending moment diagrams (left), and relevant input parameters for Bernoulli-Euler beam theory (right) for slider bars

Calculated:

Max shear force: $F_{\mathrm{V,max}} = mg = 22.36 \text{ N}$

Max bending moment: $M_{\max} = M_{\mathrm{C}} + mgL = 31350.1 \text{ Nmm}$

Max bending stress: $\sigma_{\mathrm{b,max}} = \frac{M_{\max} \bullet \gamma}{I_z} = 139.334 \text{ MPa}$

The centrifugal load is transferred to the slider bars through the bolted connection, which causes an internal tensile stress. The bending load also causes an internal tensile/compressive stress. The exact dynamics of the casting process are complicated to calculate, but the maximum internal tensile stress $\sigma_{\max}$ will always be less than the sum of the stresses caused by these two loads so

$$\sigma_{\max} \leq \sigma_{\mathrm{c}} + \sigma_{\mathrm{b,max}} = \frac{F_{\mathrm{C}}}{A} + \frac{M_{\max} \bullet \gamma}{2 \bullet I_z} = 155.94 \text{ MPa}$$

A: Cross-sectional area of slider bars at the screw holes $= 33.00 \text{ mm}^2$,

γ: Distance from neutral axis to extreme fibers $= 7.5$ mm

The tensile strength of AISI 304 stainless steel is 206 MPa and the ultimate tensile strength is 517 MPa. Therefore, under normal operating conditions, failure of the slider bars due to tensile load is not to be expected with a factor of safety of at least 1.3 against plastic deformation, and a safety factor of at least 3.3 against rupture.

Pin Joint Calculations

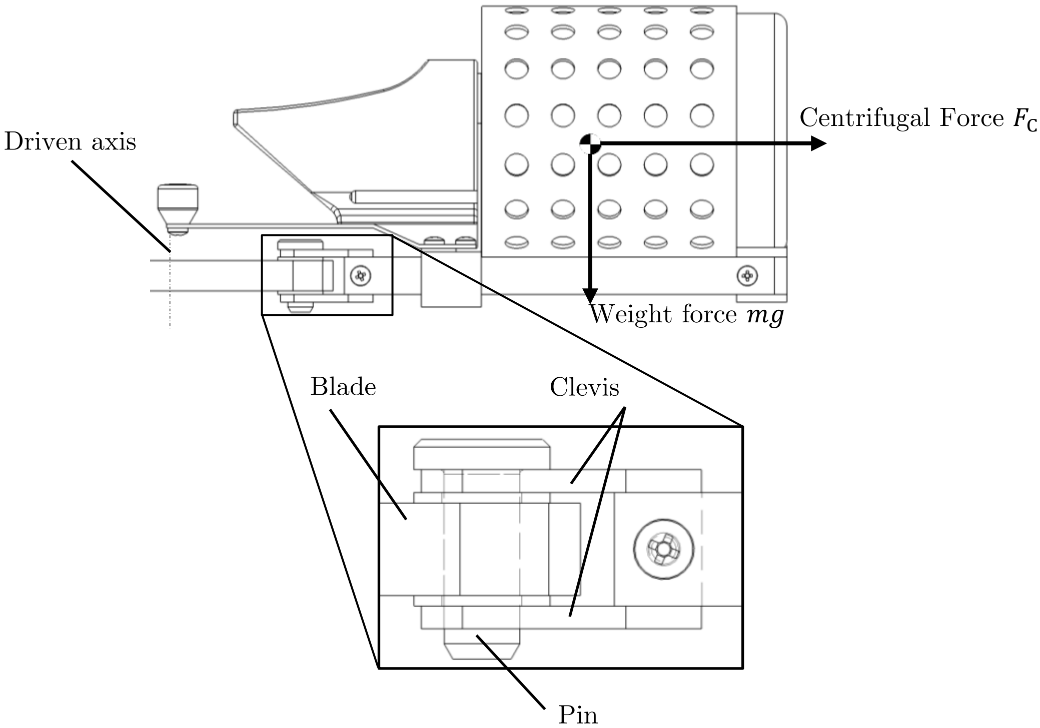
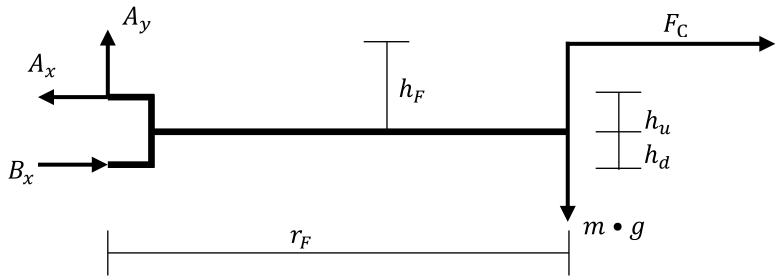


Figure 7.6: Schematic of casting arm showing components of, and forces applied to, pin joint

First, solve for reaction forces at pin joint:



$r_F = 118.78$ mm
$h_F = 50.19$ mm
$h_u = h_d = 9$ mm
$m = 2377.13$ g
$F_C = 548.131$ N

Figure 7.7: Free body diagram of casting arm with relevant dimensions

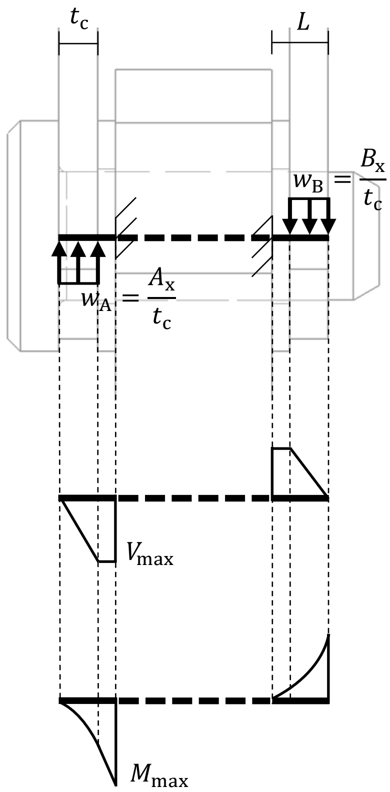
Equations of equilibrium

$$\sum M_A = 0 \Leftrightarrow m \bullet g \bullet r_F + F_C \bullet (h_F - h_u) = B_x \bullet (h_d + h_u) \Leftrightarrow B_x = 1167.87 \text{ N}$$

$$\sum F_x = 0 \Leftrightarrow A_x = F_C + B_x \Leftrightarrow A_x = 1716.00 \text{ N}$$

$$\sum F_y = 0 \Leftrightarrow A_y = m \bullet g \Leftrightarrow A_y = 23.32 \text{ N}$$

Clevis Pin



Case 3 pin joint: clearance between clevis and pin, modeled as two cantilever beams, fixed at one end, with partially distributed uniform loads applied at the free ends.

Table 7.5: Properties of clevis pin for pin joint analysis

Pin name: Form B ISO 2341 – A – 10x20 – St	
Modulus of elasticity: 304 Stainless: 190 GPa Ultimate tensile strength $R_m = 517$ MPa Tensile strength at yield $R_e = 206$ MPa Shear strength 298 MPa	
Static load: from weight force ($F_C = 0$)	
$A_S = 131.90$ N	$B_S = 131.90$ N
Pulsating load: from centrifugal force ($m \bullet g = 0$)	
$A_P = 1584.10$ N	$B_P = 1035.97$ N
Dimensions:	
$t_c = 3$ mm	$L = 4.25$ mm

Figure 7.8: Free-body, shear force and bending moment diagrams for ∅10 mm clevis pin

Table 7.6: Analysis of clevis pin for pin joint according to [Kisters]

Shear force:	
$F_{A,\mathrm{V,max}} = w_A \bullet t_c = A_x = 1716.00$ N	$F_{B,\mathrm{V,max}} = w_B \bullet t_c = B_x = 1167.87$ N
Bending moment:	
$M_A(x) = -w_A \bullet t_c\left((L-t_c)+\frac{t_c}{2}\right)$	$M_B(x) = w_B \bullet t_c\left((L-t_c)+\frac{t_c}{2}\right)$
At cantilever, $x = L$	At cantilever, $x = 0$
$M_{A,\mathrm{max,S}} = A_S \bullet \left((L-t_c)+\frac{t_c}{2}\right) = 362.73$ Nmm	$M_{B,\mathrm{max,S}} = B_S \bullet \left((L-t_c)+\frac{t_c}{2}\right) = 362.73$ Nmr
$M_{A,\mathrm{max,P}} = A_P \bullet \left((L-t_c)+\frac{t_c}{2}\right) = 4356.27$ Nmm	$M_{B,\mathrm{max,P}} = B_P \bullet \left((L-t_c)+\frac{t_c}{2}\right) = 2848.92$ Nm
$M_{A,\mathrm{max}} = A_x \bullet \left((L-t_c)+\frac{t_c}{2}\right) = 4719.00$ Nmm	$M_{B,\mathrm{max}} = B_x \bullet \left((L-t_c)+\frac{t_c}{2}\right) = 3211.63$ Nmr
Max deflection $\Delta_{max} = \frac{w(3L^4 - 4L(L-t_c)^3 + (L-t_c)^4)}{24EI}$	
At free end, $x = 0$	At free end, $x = L$
$\Delta_{A,\mathrm{max}} = 0.242$ µm	$\Delta_{B,\mathrm{max}} = 0.165$ µm

Bending stress Static load: $\sigma_{\text{per}} = 0.3R_m = 103.5\ \text{MPa}$ Pulsating load: $\sigma_{\text{per}} = 0.2R_m = 69\ \text{MPa}$ $\sigma_A = \dfrac{M_{A,\max} \bullet r}{\frac{\pi}{64}d^4} = 48.07\ \text{MPa}$ $\qquad$ $\sigma_B = \dfrac{M_{B,\max} \bullet r}{\frac{\pi}{64}d^4} = 32.72\ \text{MPa}$ Since $\sigma_{\max} \leq \sigma_{\text{per}}$, failure of the clevis pin due to bending stress is not to be expected with a safety factor against rupture of at least 1.4.
Shear stress Static load: $\tau_{\text{per}} = 0.2R_m = 69\ \text{MPa}$ Pulsating load: $\tau_{\text{per}} = 0.15R_m = 51.75\ \text{MPa}$ $\tau_A = \dfrac{2F_{A,\text{V},\max}}{\frac{3\pi}{4}d^2} = 14.57\ \text{MPa}$ $\qquad$ $\tau_B = \dfrac{2F_{B,\text{V},\max}}{\frac{3\pi}{4}d^2} = 9.92\ \text{MPa}$ Since $\tau_A \leq \tau_{\text{per}}$, failure of the clevis pin due to shear stress is not to be expected with a safety factor against rupture of at least 3.5.

Since the locations of the maximum values for bending and shear are different (shear stresses are zero when bending stresses are highest and vice versa), the calculation of an equivalent stress is unnecessary.

Clevis and blade

The largest stresses in the clevis and blades occur next to the holes. The blade takes the full force from the pin and the clevis takes a proportion of the opposing force on each arm. The maximum stresses are the sums of the nominal stresses and the additional stresses from the stress concentration caused by the hole. Both the clevis and blade were fabricated from S235 mild steel ($R_e = 235\ \text{MPa}, R_m = 360\ \text{MPa}$).

Table 7.7: Analysis of clevis for pin joint according to [Kisters]

Thickness t	
$t_A = 3.00\ \text{mm}$	$t_B = 3.00\ \text{mm}$
Loaded width c	
$c_A = 20.00\ \text{mm}$	$c_B = 20.00\ \text{mm}$
Stresses $\sigma_{\max} = \dfrac{F_{\text{V},\max}}{2 \bullet c \bullet t} + \dfrac{6 \bullet F_{\text{V},\max} \bullet (d_{\text{h}} + c)}{8 \bullet c^2 t} = \dfrac{F_{\text{V},\max}}{2 \bullet c \bullet t} \bullet \left(1 + \dfrac{3}{2}\left(\dfrac{d_{\text{h}}}{c} + 1\right)\right)$ Static load: $\sigma_{\text{per}} = 0.5R_m = 180\ \text{MPa}$ Pulsating load: $\sigma_{\text{per}} = 0.2R_m = 72\ \text{MPa}$	
$\sigma_{A,\text{static}} = 3.57\ \text{MPa}$ $\sigma_{A,\text{pulsating}} = 42.91\ \text{MPa}$	$\sigma_{B,\text{static}} = 3.57\ \text{MPa}$ $\sigma_{B,\text{pulsating}} = 28.06\ \text{MPa}$

Since $\sigma_{\text{max}} \leq \sigma_{\text{per}}$, failure of the clevis due to tensile stress is not to be expected with a safety factor against rupture of at least 1.6.

Table 7.8: Analysis of blade for pin joint according to [Kisters]

Thickness t $t = 12.50\ \text{mm}$
Loaded width c $c = 25.00\ \text{mm}$
Stresses $\sigma_{\text{static}} = 2.73\ \text{MPa}$ $\sigma_{\text{pulsating}} = 32.74\ \text{MPa}$ Since $\sigma_{\text{max}} \leq \sigma_{\text{per}}$, failure of the blade due to tensile stress is not to be expected with a safety factor against rupture of at least 2.1.

Casting Arm Assembly

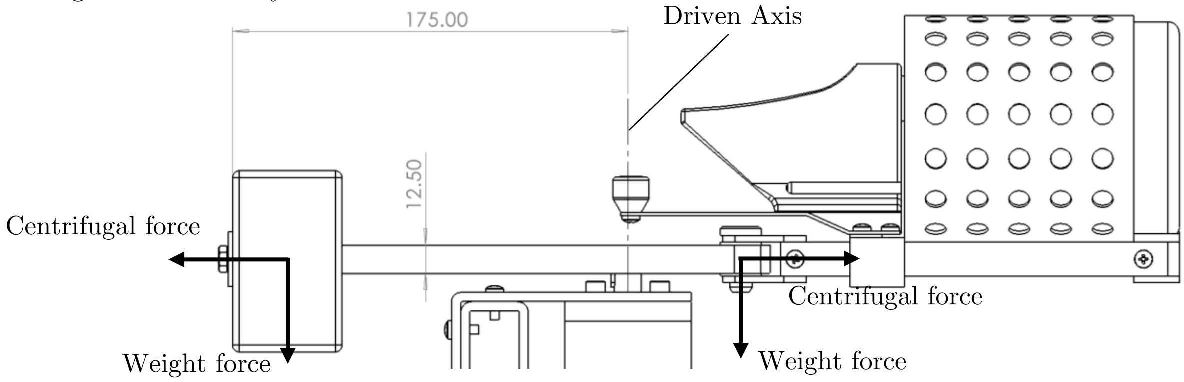


Figure 7.9: Schematic of casting arm assembly showing components and forces relevant for calculations

Counterweight arm

The moment created by the centrifugal force and the weight force of the articulated arm assembly is transferred through the pin joint to the counterweight arm. On the opposite side of the machine, the counterweight acts to keep the center of mass of the entire casting arm centered at the axis of rotation (driven axis in figure 7.9).

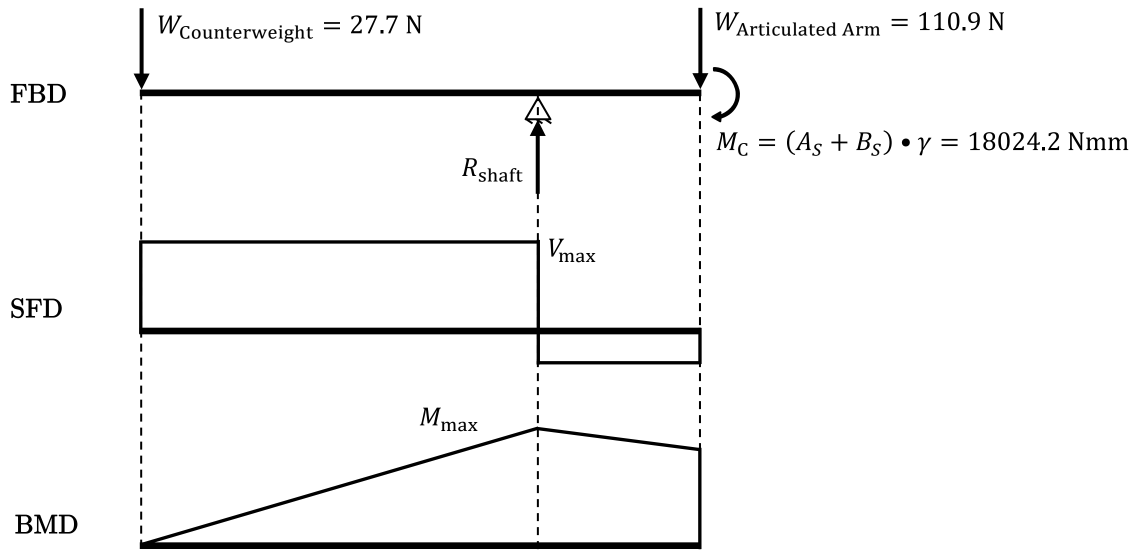


Figure 7.10: Free-body, shear force and bending moment diagrams for counterweight arm

Calculated:

Reaction force from shaft: $R_{\text{shaft}} = W_{\text{Counterweight}} + W_{\text{Articulated Arm}} = 138.66$ N

Max shear force: $F_{\text{V,max}} = W_{\text{Articulated Arm}} = 110.90$ N

Max bending moment: $M_{\text{max}} = M_{\text{C}} + mgL = 19564.8$ Nmm

Max bending stress: $\sigma_{\text{b,max}} = \frac{M_{\text{max}} \bullet \gamma}{I_z} = 21.47$ MPa

Once again, the bending load from the weight forces causes tensile stress, but there is also tensile stress caused by the centrifugal forces. The maximum internal tensile stress σ_{max} will always be less than the sum of the stresses caused by these two loads.

$$\sigma_{\text{max}} \leq \sigma_{\text{c}} + \sigma_{\text{b,max}} = \frac{F_{\text{C}}}{A} + \frac{M_{\text{max}} \bullet \gamma}{I_z} = 23.37 \text{ MPa}$$

A: Cross-sectional area of counterweight arm at the axis of rotation = 287.50 mm^2,

γ: Distance from neutral axis to extreme fibers = 6.25 mm

The tensile strength of S235 non-alloy steel is 235 MPa and the ultimate tensile strength is 360 MPa. Therefore, under normal operating conditions, failure of the counterweight arm due to tensile load is not to be expected with a factor of safety of at least 10.0 against plastic deformation, and a safety factor of at least 14.4 against rupture.

Parallel key connection

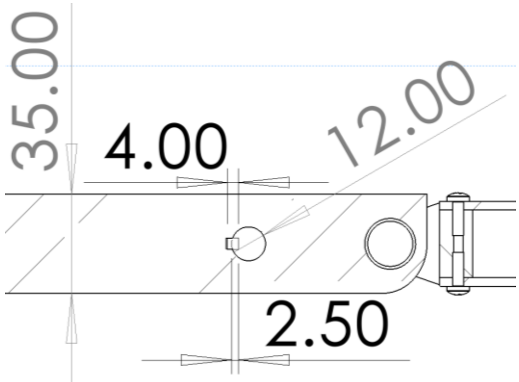


Figure 7.11: Detail view of parallel key connection

Table 7.9: Properties of shaft hub connection analysis

Feather Key: DIN 6885 – Form A - 4 x 4 x 16
Light interference fit N9/h7 to increase fatigue resistance
Hub properties Modulus of elasticity: S235 Mild Steel: 210 GPa Ultimate tensile strength $R_m = 360\ \mathrm{MPa}$ Tensile strength at yield $R_e = 235\ \mathrm{MPa}$

Damage of a key due to a shear load is very unusual for standardized parallel key connections. As such, no proof of the key is required. Furthermore, proof of the shaft for loads exceeding the design load have been provided by the manufacturer of the gear box so no proof of the shaft is provided in this document. Since the length of the key is less than 1.3 times the diameter of the shaft and since the design does not include alternating torsional moments, method C has been chosen for calculations according to DIN 6892. The calculation of the contact pressure P requires only the applied load F and the loaded area A, and proofing the hub requires only that the applied pressure is less than the permitted pressure.

$$P = \frac{F}{A} \leq P_{\mathrm{per}} = \frac{R_e}{\text{Safety Factor}}$$

Table 7.10: Analysis of parallel key connection hub according to DIN 6892

Inertia of casting arm assembly $I_z = 0.14004565\ \mathrm{kgmm}^2$
Torque required from motor $T = I\alpha = 3.85\ \mathrm{Nm}$
Force applied by key $F = \frac{T}{r} = 550.18\ \mathrm{N}$
Loaded area $A = 23\ \mathrm{mm}^2$
Stresses $P = \frac{F}{A} = 23.92\ \mathrm{MPa}$ Since $P_{\max} \leq P_{\mathrm{per}}$, failure of the counterweight arm due to the parallel key connection is not to be expected with a safety factor against plastic deformation of at least 9.8.

Bolt for retaining counterweight

During the normal casting operation, the counterweight is held onto the casting arm via an oversized steel washer and an M6 bolt. Since there is no transverse load on this bolt, beginning with a pretension calculation is unnecessary. The centrifugal force on the counterweight creates an operational load for the bolt that must be compared to its permissible load. Instead of calculating the pretension load directly, the operation load will be subtracted from the max permissible load to define the maximum pretension load for the bolt.

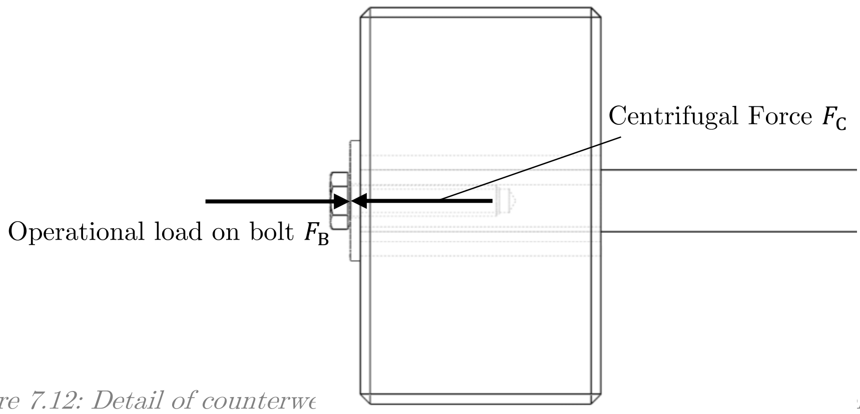


Figure 7.12: Detail of counterwe... rces

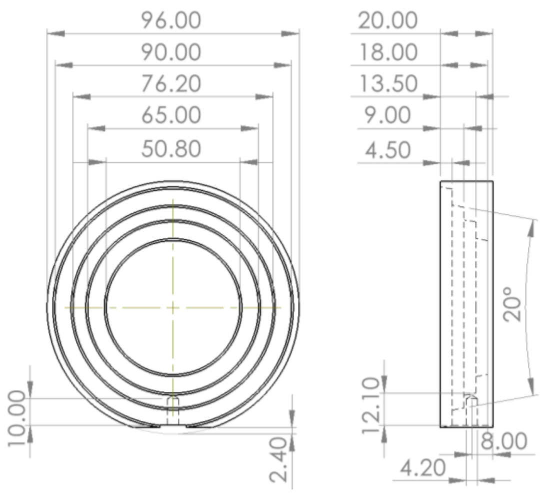
Operational Load [Kisters]

Table 7.11: Operational load calculations for the bolt that retains the counterweight

Force on bolt $$F_{\mathrm{B}} = F_{\mathrm{C}} = m\omega^2 L = 540.37\ \mathrm{N}$$ m: mass of counterweight $= 2.3244\ \mathrm{Kg}$ L: distance from axis of rotation to center of mass of counterweight $= 150.75\ \mathrm{mm}$
Cross-sectional area $$A = \pi r^2 = 75.95\ \mathrm{mm}^2$$ r: minimum diameter of M6 bolt $= 4.917\ \mathrm{mm}$
Comparison of operational load on bolt to permissible load $$F_{\mathrm{B}} = 540.37\ \mathrm{N} \leq 0.1 \bullet R_{\mathrm{p0.2}} \bullet \mathrm{A} = 1784.92\ \mathrm{N}$$ $R_{\mathrm{p0.2}}$: 0.2% yield strength (235 MPa)
Because the load on the bolt has to be less than the permissible load in order to prevent plastic deformation during operation, the pretension value for this bolt is constrained. $$F_{\mathrm{v,max}} = 0.1 \bullet R_{\mathrm{p0.2}} \bullet \mathrm{A} - F_{\mathrm{B}} = 1244.55\ \mathrm{N}$$

Flask Cradle Assembly

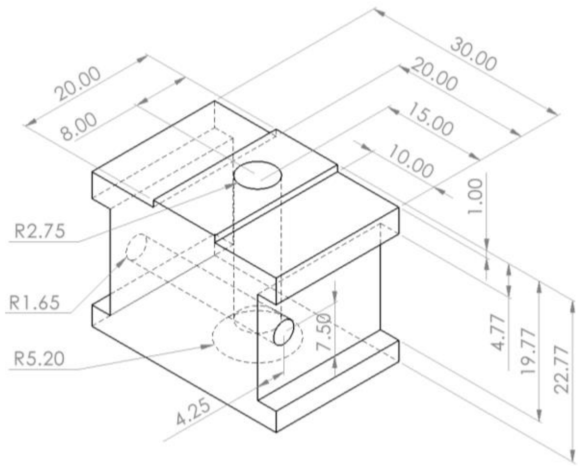
Flask Cradle



- Start with 100mm round stock and use lathe to cut outer shape and concentric rings
- Use mill to cut flat bottom and groove (no corner radius)
- Use mill to remove "corners"
- Use mill to make pilot hole
- Use M4 tap to make threads

Figure 8.1: Design and plan for flask cradle

Cradle Base

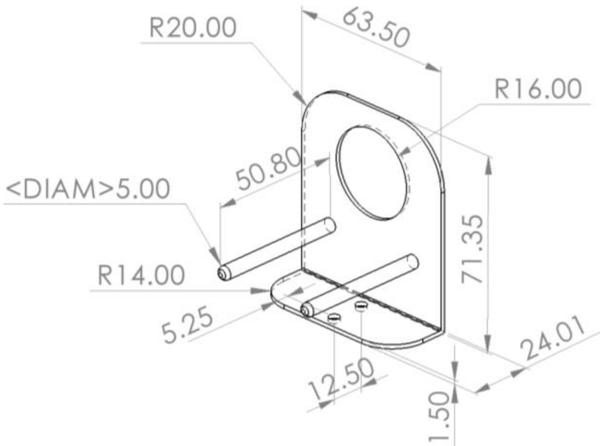


- Use mill to cut outer shape (zero corner radius for side grooves and for top notch)
- Use mill to make pilot holes for both holes and countersink for ISO 7046-1–M6x25–Z–25N (large diameter: 9.4 mm, small diameter: 4.5 mm, 90°)
- Use M4 tap to make threads in slider bar grooves

Figure 8.2: Design and plan for cradle base

Slider Assembly

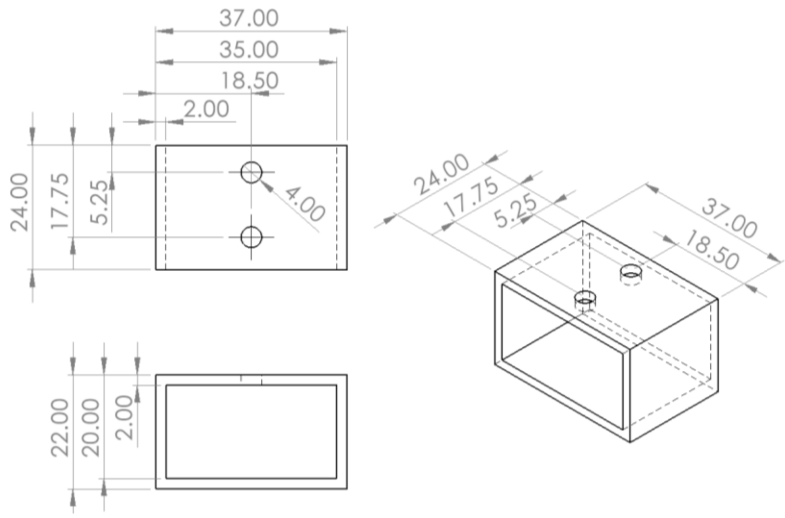
Retainer for Crucible



- Start with 1.5 mm sheet and cut rectangular shape and corner radii with band saw or angle grinder
- Use mill to drill 4 mm holes
- Bend 90° angle in metal brake or vice
- Machine support legs on lathe
- Spot weld support legs onto larger body
- Use mill to drill 27.5 mm hole (double check placement with crucible)

Figure 8.3: Design and plan for retainer for crucible

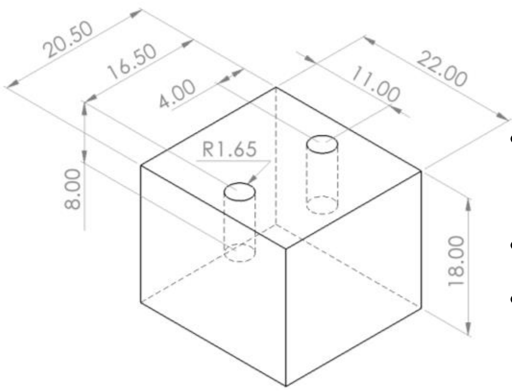
Slider



- Start with rectangular block and cut outer shape with mill
- Use mill to drill 4 mm holes (not symmetric!)
- Use mill to remove slot material (permissible corner radius: 1.5 mm)

Figure 8.4: Design and plan for slider

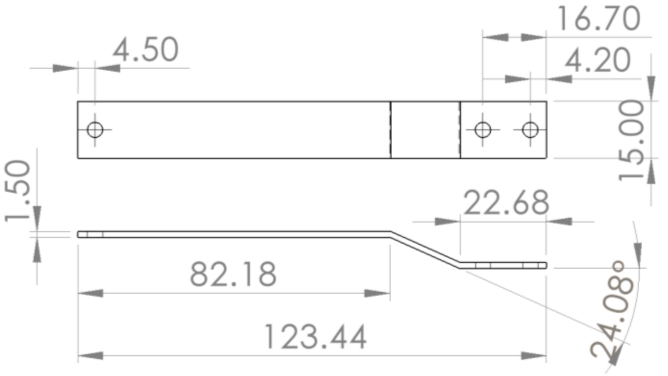
Slider Spacer



- Start with rectangular block and cut outer shape with mill
- Use mill to make pilot holes (symmetric!)
- Use M4 tap to make threads

Figure 8.5: Design and plan for slider spacer

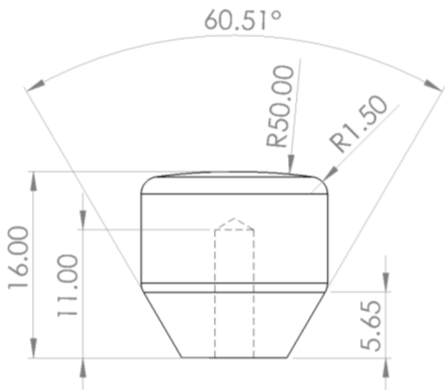
Crucible Grip Stick



- Start with 1.5 mm sheet and cut rectangular shape with band saw or angle grinder
- Use mill to drill 4 mm holes
- Bend 24.08° angles in metal brake

Figure 8.6: Design and plan for crucible grip stick

Grip Stick Knob

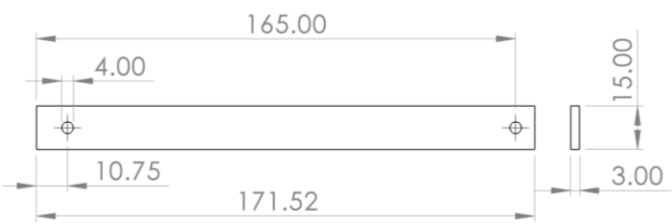


- 3D print outer shape (hopefully, if not, maybe COTS)
- Use mill to make pilot hole
- Use M4 tap to make threads
- Dimensions and angles don't really matter, just make it comfortable

Figure 8.7: Design and plan for grip stick knob

Pin Joint and Slider Bar Assembly

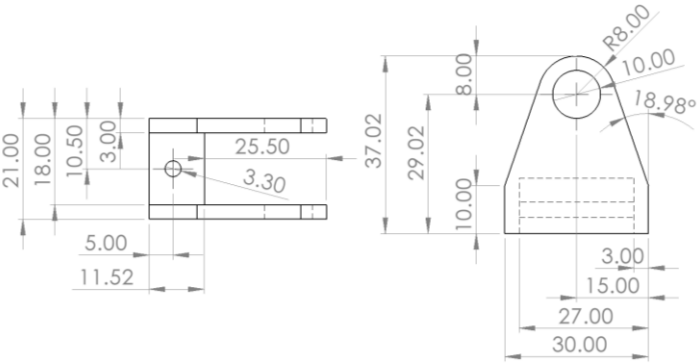
Slider Bars



- Start with 3 mm sheet and cut rectangular shape with band saw or angle grinder (try to cut both pieces at once and separate after chamfer)
- Cut 1.5 mm chamfers with mill
- Use mill to drill 4 mm holes

Figure 8.8: Design and plan for slider bars

Pin Joint

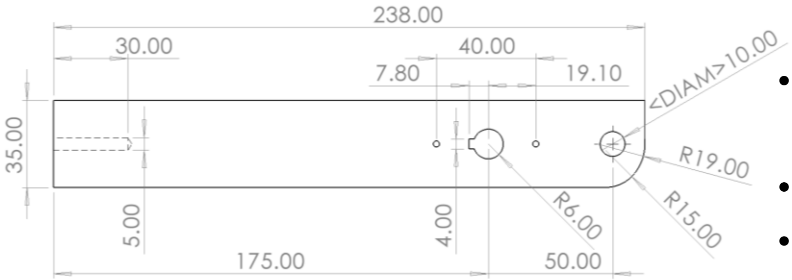


- Start with block and cut outer (top view) shape with mill
- Use mill to drill pilot hole (sides) and hole for clevis pin (top)
- Use mill to cut grooves
- Use M4 tap to make threads

Figure 8.9: Design and plan for pin joint

Counterweight Arm Assembly

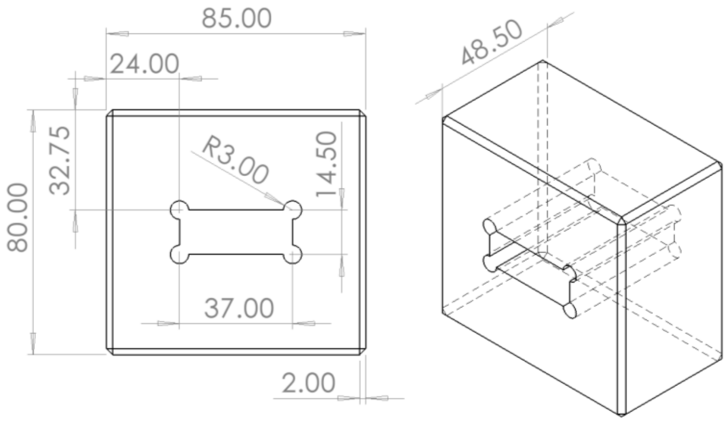
Counterweight Arm



- Start with 10mm sheet and use band saw to cut outer shape
- Use mill to make holes for shaft and pin joint and guide hole in the end
- Use M6 tap to make threads
- May have to use die filer or hand files for key groove (to avoid corner radius)

Figure 8.10: Design and plan for counterweight arm

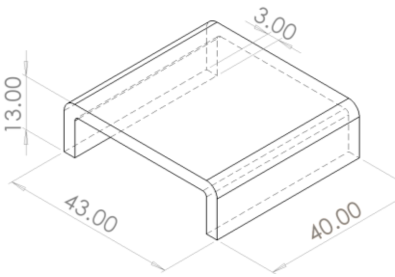
Counterweight



- Make this part(s) and spacer(s) after casting arm assembly is complete (to precisely balance)
- Use mill to make slot (actual: 10 x 35mm, adjust outward for corner radius)
- Use grinder to make chamfer (just enough to be comfortable to hold)

Figure 8.11: Design and plan for counterweight

Spacer for Counterweight

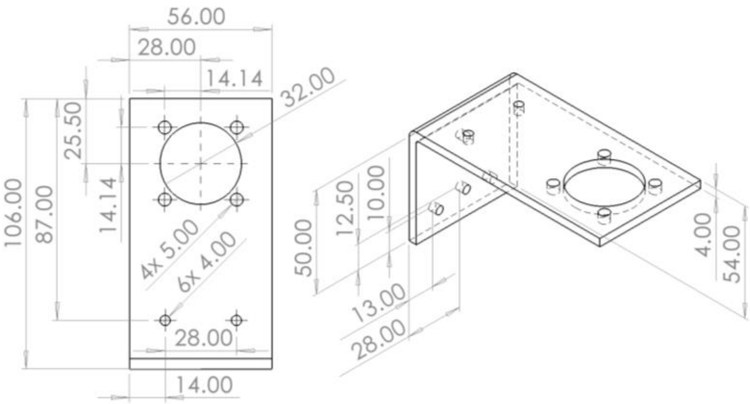


- Make this part(s) and spacer(s) after casting arm assembly is complete (to precisely balance)
- Start with 3mm sheet and use band saw or angle grinder to make outer rectangular shape
- Bend 90° angles in metal brake

Figure 8.12: Design and plan for spacer for counterweight

Motor and Machine Base Assembly

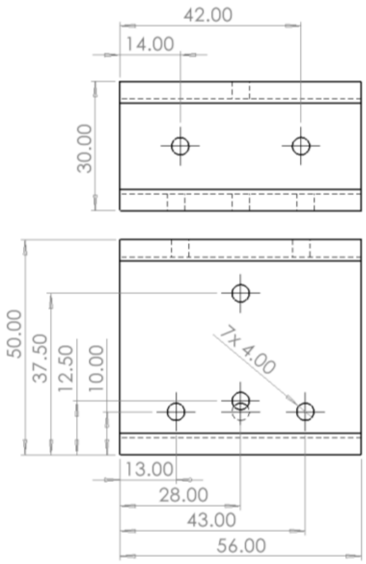
Bracket for Connection to Gearbox



- Start with 120 x 80 x 4mm square tubing and cut outer shape with band saw or angle grinder
- Use mill to make holes

Figure 8.13: Design and plan for bracket for connection to gearbox

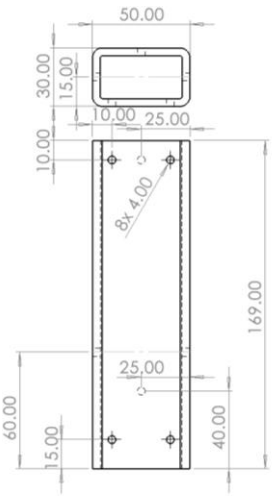
Top Piece



- Start with 30 x 50 x 4mm square tubing and cut length with band saw
- Use mill to make pilot holes (make brackets first for alignment)
- Use M4 tap to make threads

Figure 8.14: Design and plan for top piece

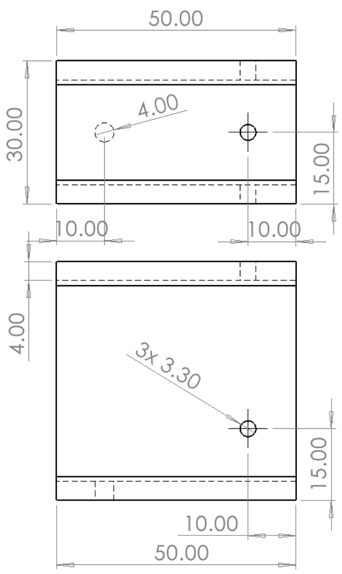
Vertical Post



- Start with 30 x 50 x 4mm square tubing and cut ~166.6mm length with band saw
- Use drill press to make guide holes (make brackets first for alignment)
- Use M4 tap to make threads

Figure 8.15: Design and plan for vertical post

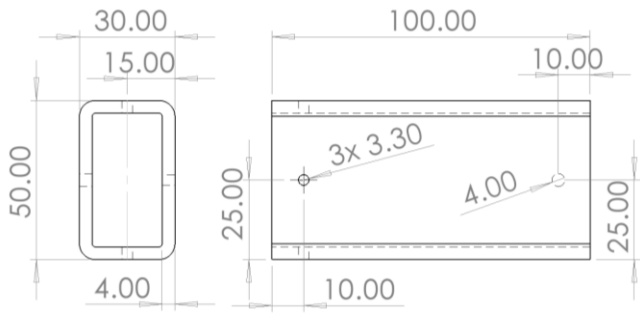
Legs



- 2x of these
- Start with 30 x 50 x 4mm square tubing and cut length with band saw
- Use mill to make bottom 4mm hole and guide holes (make brackets first for alignment)
- Use M4 tap to make threads

Figure 8.16: Design and plan for legs

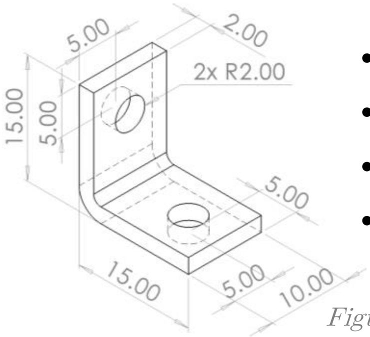
Foot



- 2x of these
- Start with 30 x 50 x 4mm square tubing and cut length with band saw
- Use mill to make bottom 4mm hole and guide holes (make brackets first for alignment)
- Use M4 tap to make threads

Figure 8.17: Design and plan for foot

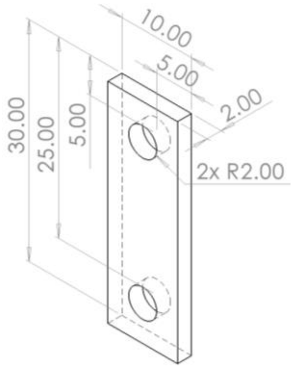
Corner Bracket



- 5x of these
- Start with 2mm sheet and use band saw to cut rectangular shape
- Bend 90° angles in metal brake
- Use mill to make holes (>4mm for clearance)

Figure 8.18: Design and plan for corner bracket

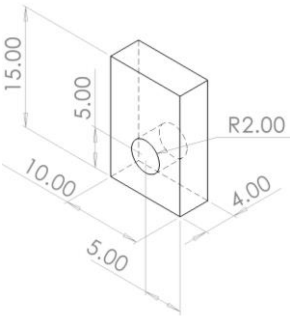
Flat Bracket



- 5x of these
- Start with 2mm sheet and use band saw or angle grinder to cut rectangular shape
- Use mill to make holes (>4mm for clearance)

Figure 8.19: Design and plan for flat bracket

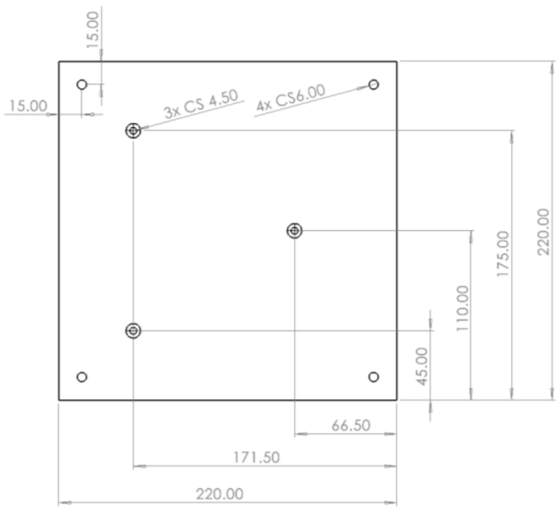
Spacer



- 2x of these
- Start with 4mm scrap and use band saw to cut rectangular shape
- Use mill to make hole (>4mm for clearance)

Figure 8.20: Design and plan for spacer

Base Plate



- Start with 5mm sheet and use band saw or angle grinder to cut square shape
- Use mill to make guide holes and countersinks for ISO 7046-1–M4x16–Z–16N (large diameter: 9.4 mm, small diameter: 4.5 mm, 90°)

Figure 8.21: Design and plan for base plate

The design for the casting machine includes 39 "make" parts plus the parts that went into the enclosure. These parts were all fabricated using the equipment and tools in the HSRW workshop. Furthermore, they were fabricated from materials and supplies from the workshop whenever possible. This meant that certain design concessions were made and minor changes became necessary to accommodate those concessions. For example, in the original design, the entire articulated arm assembly was stainless steel. However, since there was mild steel stock already readily available in the workshop, the decision was made to use mild steel for several parts. Subsequently, corrosion of the parts became more of a significant concern and it became necessary to include a corrosion resistant coating for these parts during fabrication and assembly. A combination of quenching in oil and heavy-duty acrylic paint was used to meet this need.

There were also changes to the design due to unforeseen limitations of the equipment that was available in the workshop and the skill of the operator. For example, without access to a CNC machine, the geometry of some parts needed to be simplified so they could be made on the machines that were available. The limited skill of the of the operator combined with the realities of manufacturing led to concessions such as the relaxing of irrelevant tolerances and the removal of certain features which served aesthetic functions only.

The design was also affected by the unexpected introduction of new constraints by the university or by the project supervisor. For example, the original design included a rotating tub with a second shaft hub connection between the motor and the casting arm. Thus, no enclosure was necessary. However, the designer was informed that, in order to be used in the workshop, the machine must be fully enclosed for safety with a micro-switch that only allows power to the machine when the lid of the enclosure is fully closed. With the introduction of this new full-enclosure constraint, the rotating tub featured in the original design became redundant and unnecessary, and so was removed. This saved time in the manufacturing of the rotating tub parts. However, it meant that not only was all the time designing, CAD modeling and calculating the rotating tub lost, but an enclosure needed to be designed and fabricated as well.

Finally, the entire project was heavily affected by the coronavirus epidemic. Delays in receiving some of the standard parts (such as the crucible and casting flasks) resulted in subsequent design and fabrication delays. Shipping took longer from suppliers; access to the lab was severely limited, especially early on; and there simply wasn't enough time to be able to do much of the machine testing, finite element analysis and condition monitoring that was originally planned. Furthermore, validation of the investment casting process had to wait until after the deadline.

Fabrication of Unique Components

Flask Cradle

Figure 9.1: Photos of finished flask cradle

120 mm round mild steel was chosen for the flask cradle (instead of 304 stainless) since it was available in the lab. This part also ended up with a through hole in the center since it simplified boring out the steps for the flasks and it caused no structural effect. After checking calculations and seeing the cradle base as designed, the decision was made to go with a thicker design (20 mm thick instead of 15) for this part and an M5 bolt instead of M4. This was the author's first experience turning steel on the lathe. The boring all went very well, but there was a considerable amount of difficulty trying to part the piece. After breaking the parting tool, the cut was finished with a hacksaw and then flipped in the chuck so the back side could be faced. There are a few scratches in the finished part from the failed parting, but overall it turned out pretty well. Most importantly, the geometry is correct.

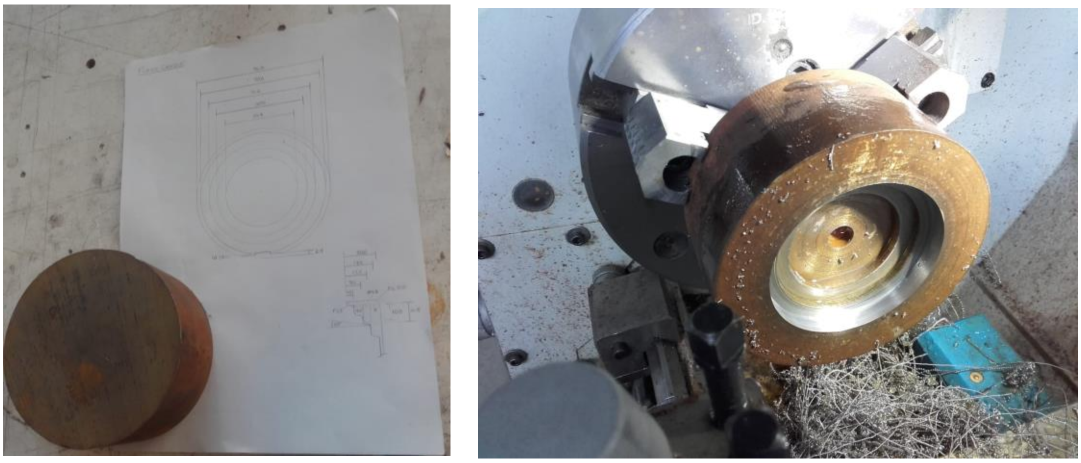


Figure 9.2: Photos of flask cradle as a work in process. Starting material with the plan (left) and boring the steps on the lathe (right)

Cradle Base

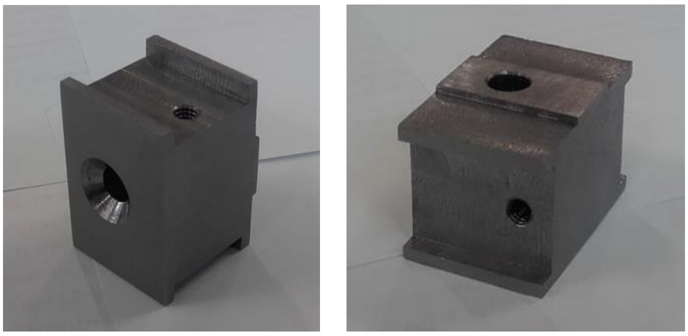


Figure 9.3: Photos of finished cradle base

30 x 40 mm bar mild steel was used to make the cradle base (instead of 304 stainless) since it was available in the shop. After making the original design, it became clear that the vertical CS hole was too close to the edge, so the part was remade, thicker (20 mm instead of 15 mm), and with an M5 bolt instead of M4 to match the change in the flask cradle.

Retainer for Crucible

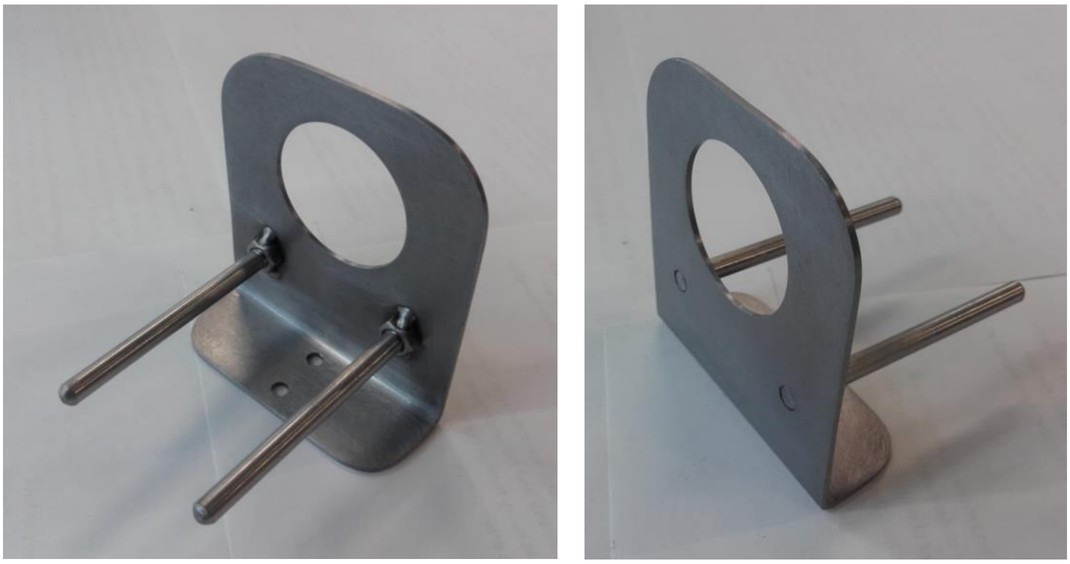


Figure 9.4: Photos of finished retainer for crucible

A piece of scrap mild steel in the lab that already had the 90° bend was used to make this part. The band saw and mill worked well to get the rectangular geometry and the bench grinder made easy work of grinding the big fillets in the top. Also found in the lab, was enough 5 mm round stainless to make the legs. Since it is not ideal to weld stainless to mild steel, the choice was made to weld two nuts to the plate and then thread the support legs. The threads on one of the arms is slightly misaligned, but the rest of the decision worked out nicely.

Slider

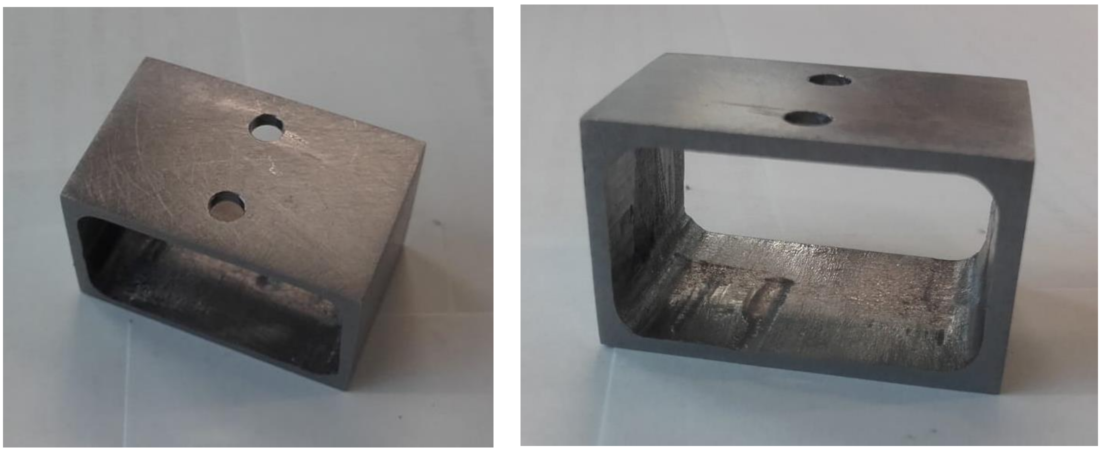


Figure 9.5: Photos of finished slider

The slider was manufactured from 30 x 40 mm bar mild steel (instead of 304 stainless) since it was available in the lab. There was no mill bit long enough to mill out the entire slot so half of it was cut from each side. The axes of the mill aren't well aligned right now so, although the part is perfectly functional, the two halves of the slot are ugly. This was also one of the first parts that was made and you can see where a few ugly mistakes were made in the mill. Since more skills have been acquired, there is a desire to remake this part sometime after the mill is serviced. It could also be made longer, and/or the slot could be made narrower from top to bottom. The weight of the crucible offsets the center of gravity of the slider assembly so it leans back on the slider bars. It shouldn't interfere with operation but it doesn't look good. Because of this dramatic aesthetic effect, this is the least pleasing part in the entire assembly.

Figure 9.6: Photos showing slider leaning back on slider bars when crucible is in place

Slider Spacer

Figure 9.7: Photo of finished slider spacer

The slider spacer was made from 30 x 40 mm bar mild steel (instead of 304 stainless) since it was available in the lab. Through holes were chosen instead of blind holes since they are easier to tap.

Crucible Grip Stick

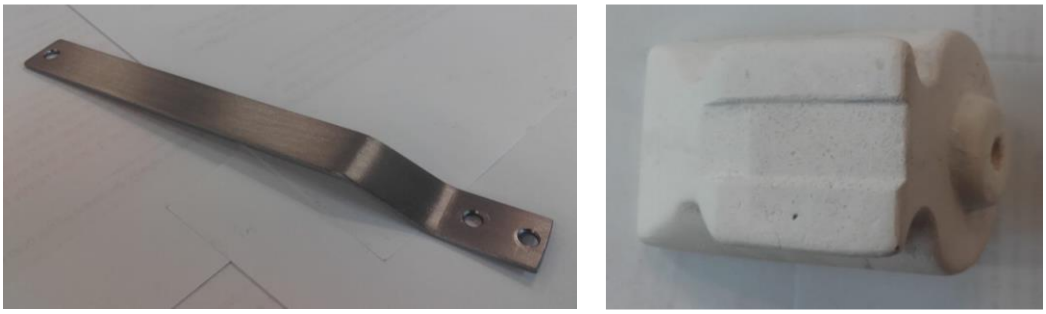


Figure 9.8: Photos of finished crucible grip stick (left) and modified crucible (right)

The crucible grip stick was fabricated from scrap 1.5 mm mild steel sheet (instead of 304 stainless) since it was available in the lab. The angles were bent in the bench vice, but it wasn't possible to bend them exactly so the decision was made to remove a small amount of material in the shape of a slot from the bottom of the crucible since it's easier to machine than steel.

Grip Stick Knob

Figure 9.9: Photos of finished grip stick knob

The grip stick knob ended up being made on the lathe out of a piece of an old oak broom handle (instead of a thermoset plastic). Fine pitch threads don't work well in wood; so two M4 nuts were glued into a slot with a two-part epoxy. The wood was finished using a few coats of cutting oil. Hopefully that will help give it a bit more heat resistance.

Slider Bars

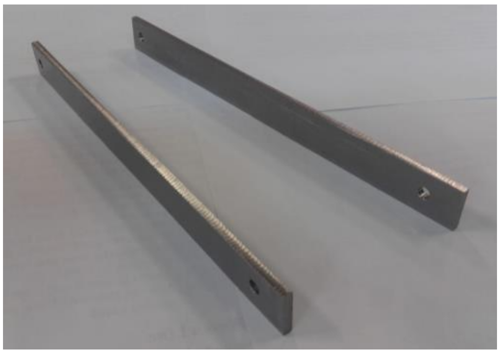


Figure 9.10: Photo of finished slider bars

The slider bars were manufactured from 3 mm sheet stainless from the lab. The decision was made to not add the chamfers since the fit is already a little bit too loose inside the slider. If the slider corrodes, the chamfers can always be added to the slider bars later to ease movement.

Pin Joint

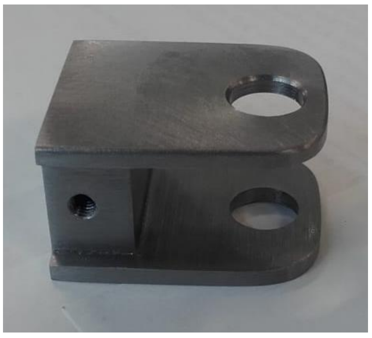
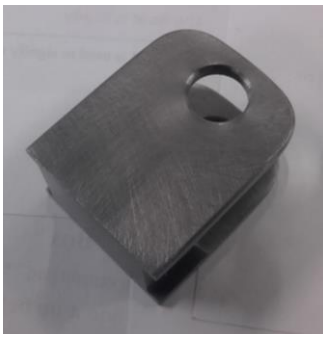



Figure 9.11: Photos of finished pin joint

The pin joint was fabricated from 30 x 40 mm bar mild steel since it was available in the lab. Technically, this part should have been called “slide bearing” since the brass spacers were used in the connection, but it looks like a pin joint so that’s what it was called. The angles in the design were unnecessary and complicated since the orientation of the spindle on the mill would have had to have been adjusted, so the part was just made rectangular and then the corners around the clevis pin hole were ground off on the bench grinder. Also, because of this part (since the calculations were a bit uncertain and the safety factor isn’t very large), the decision was made to temper all of the parts after the oil quench.

Counterweight Arm

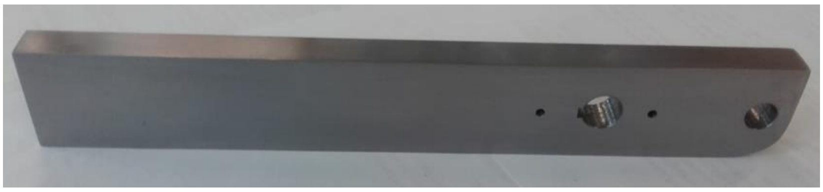
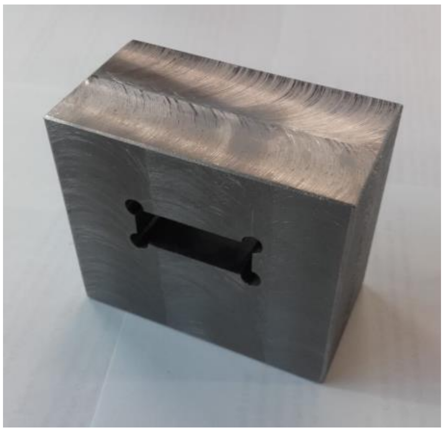


Figure 9.12: Photos of finished counterweight arm

The counterweight arm was made from 30 x 40 mm bar mild steel since it was available in the lab. The decision was also made to make it 12 mm thick (instead of 10) since it allows for a smaller counterweight and for a small groove to help with balancing. The filet was ground on the banch grinder. A long time was needed to figure out how to make the keyway since there is no access to a die filer or any small hand files in the lab. Mathias has a set of broaching tools and he was able to cut it in just a few minutes. This part took a lot of hand sanding to remove the mill marks but it turned out nice.

Counterweight



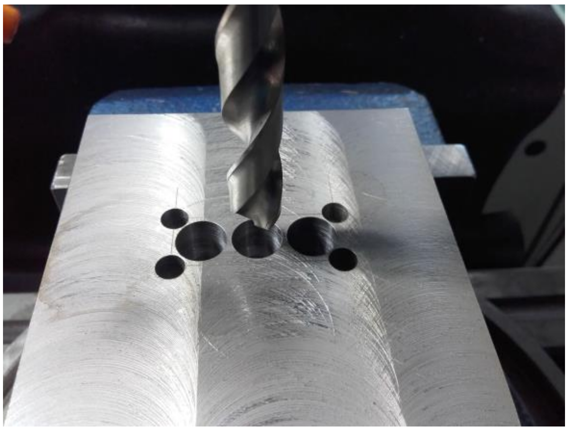


Figure 9.13: Photos of finished counterweight (left) and work in process on the mill (right)

A big piece of mild steel was found in the workshop and milled square follwed by two full days milling out the central square slot. It was brought close to the dimensions that would give the mass that had been calculated from the CAD model. However, that mass could not be relied upon to perfectly balancing the casting arm (as it could in the CAD file) since so many of the parts had been made from mystery-steel from the workshop with densities anywhere from 7500 kg/m^3 up to 8300 kg/m^3. A more practical approach was needed. When all the other parts were finished, the casting arm was completely assembled, and to the inside of the flask, was added the weight of casting metal (255 g) and the weight for the amount of investment that would fit in the largest flask (290 g). Then, material was iteratively removed from the counterweight until the casting arm was perfectly balanced at the point of rotation.

Figure 9.14: Photo of casting arm balanced on 1.5 mm sheet steel in the bench vice

Spacer for Counterweight

Once the counterweight was sized, the weight of the casting metal and investment was added to the smaller flask and the counterweight was moved inward toward the axis of rotation until it balanced once again. Then the spacer was added and played with, iteratively taking off material and re-balancing until it was perfect. If we get more flasks in the future, this process can easily be replicated so each flask has a spacer that perfectly balances it on the casting arm.

Bracket for Connection to Gearbox

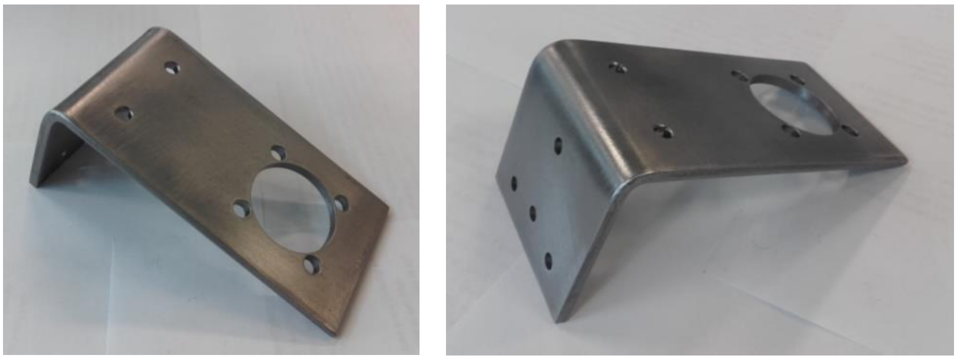


Figure 9.15: Photos of finished bracket for connection to gearbox

Mathias made the rough shape of this part by bending a piece of 4 mm plate mild steel. After some hammering and filing, it fit nicely. A tapered mill bit was used (the only bit we had with a 32 mm diameter since the boring tool is broken) so cutting the big hole was a bit sketchy, but it worked nicely in the end.

Top Piece

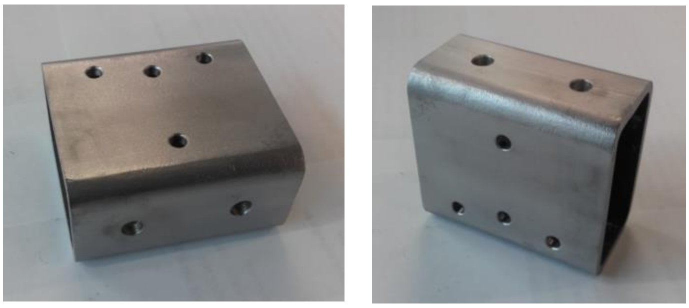


Figure 9.16: Photos of finished top piece

The decision was made to go with 3 mm thick tubing for most of the machine base assembly since it was readily available locally. This meant that the minimum thread depth could no longer be met for the M4 bolts so the threaded holes were replaced with through holes and nylon locking nuts. It's a little trickier to assemble now, but at least all those holes didn't have to be tapped.

Vertical Post

Figure 9.17: Photo of finished vertical post

Made from 3 mm thick tubing with locking nuts. There was also a bit of extra tubing so this part was made a little longer (169 mm instead of 160) to provide a bit more room for the cables coming out of the bottom of the motor. The steel tubing was all scratched up and the bluing was looking bad so all the pieces of the machine base assembly were cleaned up using a wire brush tool in the power drill. They turned out pretty well.

Figure 9.18: Before (left) and after (right) photos of old finish removal and cleanup of parts in machine base assembly

Legs

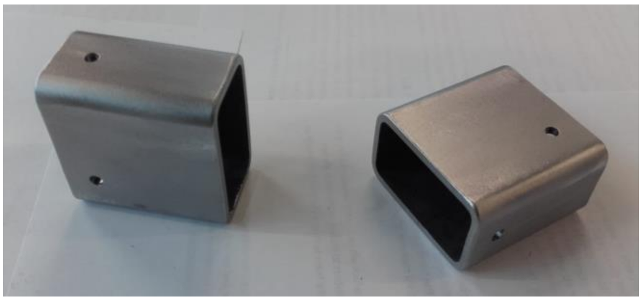


Figure 9.19: Photo of finished legs

Made from 3 mm thick tubing with locking nuts.

Foot

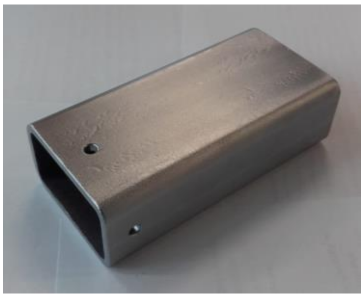


Figure 9.20: Photo of finished foot

Made from 3 mm thick tubing with locking nuts.

Corner Bracket

Figure 9.21: Photo of finished corner brackets

A piece of scap 1 inch L-bar was found in the lab. It worked perfectly for all five of these.

Flat Bracket

Figure 9.22: Photo of finished flat brackets

All five of these were made from a piece of 2 mm plate scrap from the lab.

Spacer

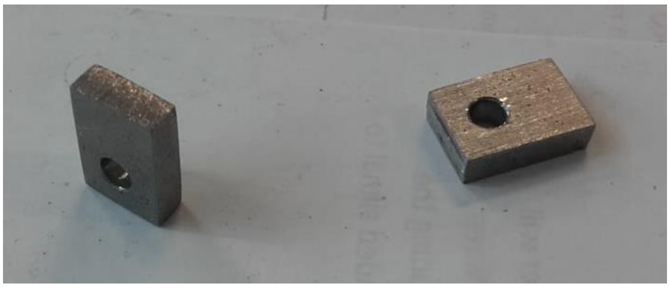


Figure 9.23: Photo of finished spacers

These were manufactured from 4 mm scrap found in the lab.

Base Plate

Figure 9.24: Photos of finished base plate. Top (left) and underside (right)

It wasn't going to be easy to get a 500 x 500 x 5 mm plate of steel, so the decision was made to make this part much smaller (220 x 220 mm) and out of 6 mm aluminum, and then attach it to a larger piece of 3/4 inch plywood for the base of the enclosure. Since there is no rotating tub in the design anymore, so much mass at the base was no longer needed and this made construction easier and meant that readily available material could be used. The scrap piece that was utilized is pretty scratched up, but this is the connection to the enclosure and will liklely take some abuse over time so the surface finish is unimportant.

Enclosure

For several weeks, the author thought the enclosure was going to be ordered and professionally made, so time was very limited when it came to designing and building it. The enclosure was designed and built on the fly, mostly using materials that were lying around in the shop. All we needed to buy were the hinges and hardware. We couldn't find decent steel mesh so we just went with chicken wire.

Initially, the plan was to hand-paint them using an acrylic paint designed to protect against corrosion. After cutting and grinding, the plates were very rusty (see figure 9.25). All the rust was painstakingly removed and the surface was taken down to a 120-grit finish with sandpaper.

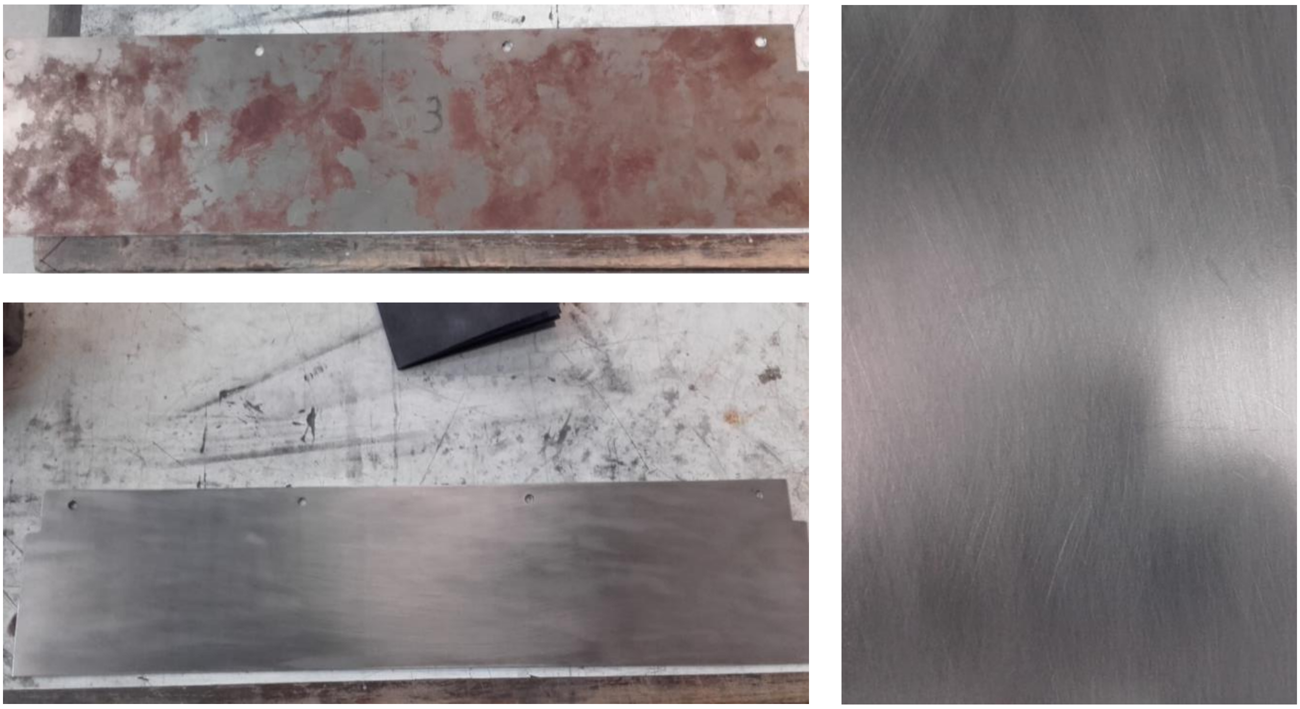


Figure 9.25: Photos of enclosure plates before (top left) and after (bottom left and right) sanding

After degreasing with acetone, the plates were painted on one side with a brush. However, within minutes of painting, spots of rust started to develop and form all over the painted surfaces.

Figure 9.26: Photos of the paint and degreaser that was used (top left) and the rusty spots after the paint dried (bottom left and right)

A few things could have gone wrong, but the most likely cause is that the paint we bought had been sitting on the shelf too long to be good anymore. A few chemistry-based options were briefly considered, but in the end, all the steel parts of the enclosure were professionally painted to prevent corrosion.

Final Assembly

Figure 9.27: Photos of assembled casting arm and machine base

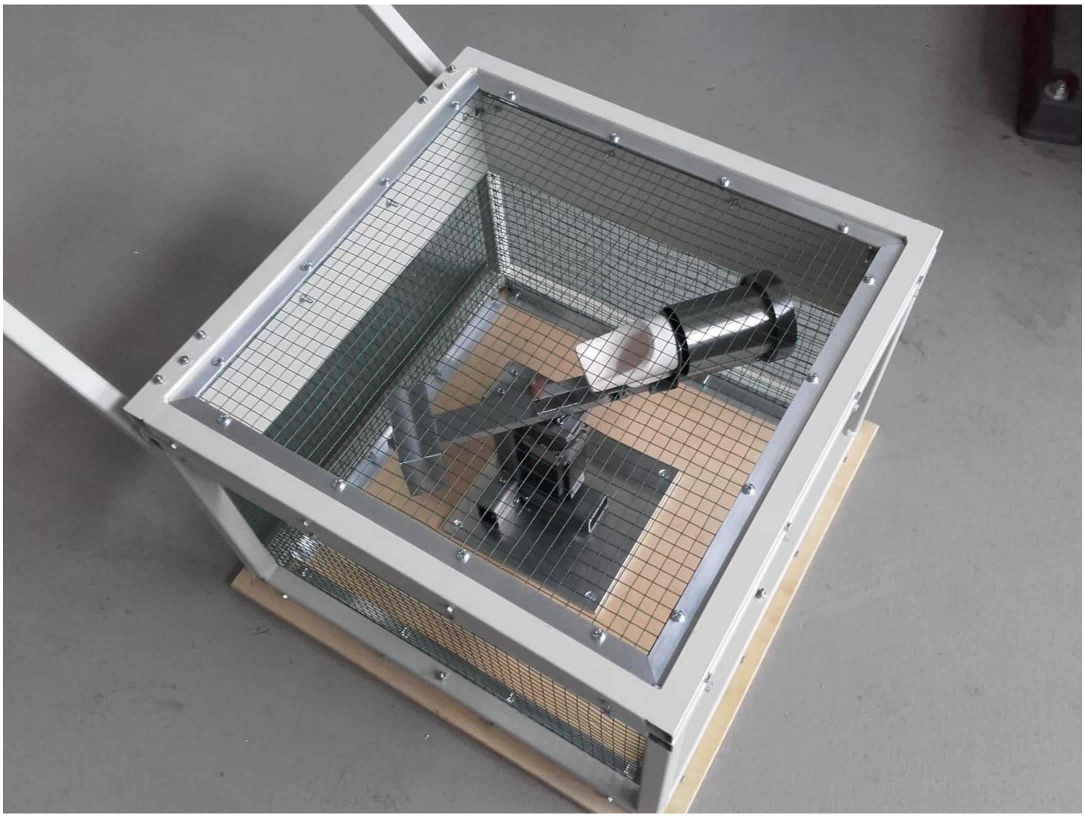


Figure 9.28: Photo of fully assembled casting machine

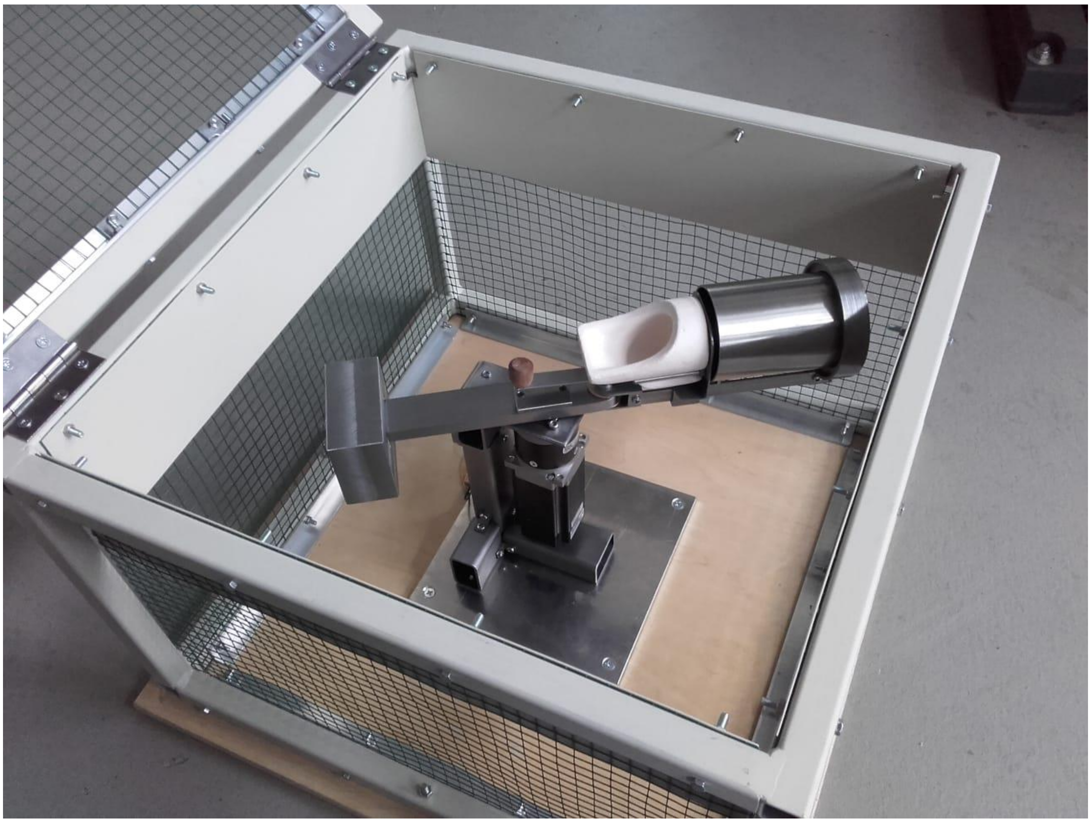


Figure 9.29: Photo of fully assembled casting machine with enclosure lid open

Overall, I think the project went well. I didn't have time to do everything I wanted, but I am satisfied with the final result and I am looking forward to the investment casting process and to finally using the casting machine.

Was the Spec met?

When creating the timeline for this project, I significantly overestimated the amount of access to the lab I would have. Because of coronavirus, I was unable to get into the lab for the first half of the project; this resulted in me doing a lot of unnecessary calculations, CAD work and documentation for parts and features that would not exist in the final iteration of the design. Furthermore, I wasn't expecting that my time in the lab would be limited by the availability of supervision or that my progress would be so slowed by my own learning curve. I was originally hoping to be able to fabricate all of my parts in two or three 60-hour weeks. Instead, the fabrication was spread out over 11 weeks and the machine was barely assembled and tested before the final deadline. Because of this, finite element analysis of the final design as well as condition monitoring of the machine itself, became impossible.

There was also a problem with the motor and gearbox configuration that we ordered. Apparently, the gearbox failed the internal quality control and so would not have been available until mid December (two and a half months after the deadline for the project). Unfortunately, this information – hidden in the fine print – was not noticed when the purchase was made, so we waited six weeks for a motor that essentially wasn't coming. Upon realizing the reality of the situation, a motor configuration with a new gearbox was immediately ordered, but the new gearbox (a 7:1 ratio rather than the original 8:1) changed the rotation speed and torque output of the drive shaft to levels outside the acceptable range. To solve this problem, a controller had to be included in the design as well. The controller allowed us to modify the pulse width, which changed the rotation speed by limiting the voltage to the motor; and to adjust the current at the new voltage so the torque requirements could be met. The ideal operating point of the casting machine was dialed in using a laser rotation counter.

Once the motor and controller are functioning properly, there may still be one final problem. Because I have made the machine out of mystery steels with varying densities and elastic moduli, I cannot trust my calculations for the natural frequency. If the natural frequency is near the driving frequency from the motor, then the machine will resonate and vibrations could increase in amplitude until the point of failure. I found a free smart phone app that does a Fast Fourier Transform of an audio signal in real time. There is a considerable amount of background noise in the lab, but I did a few small tests and according to the app, the frequency with which the machine vibrates when struck with a hammer (its natural frequency) is approximately 170 Hz. This is well above the driving frequency of only 5.83 Hz. The app may not be perfectly reliable and analyzing the audio signal is not quite as clear as analyzing the acceleration response would be, but I think we are safe enough to operate it. In case the app is completely off the mark, I may need to alter the stiffness or the mass of the machine to shift the natural frequency away from the driving frequency.

Limitations of the Design

The most significant limitation built into the design is the rotation speed. Due to the bolted connection between the flask cradle and cradle base, rotation speeds in excess of 375 RPM are not permitted. If there is sufficient demand for higher rotation speeds someday, these parts may be replaced with a casted or welded part that may increase this limit. At that time, the calculations can be rechecked to find and possibly address the next weakest link.

The next limitation is the maximum amount of metal than can be casted at once. The casting machine is limited in the size of the flasks that it can receive, the volumetric capacity of the crucible, as well as by the stresses that are induced by the spinning mass during the dynamics of casting. The maximum size of the casting flask cannot be adjusted without remaking the slider bars and the enclosure. However, the maximum mass (and subsequently the limiting stresses) could be increased as long as the rotation speed is also adjusted to accommodate the change in the centrifugal force. It is worth noting that the centrifugal force is proportional to the product of the mass and the *square* of the rotation speed. This means that a small reduction in the rotation speed would result in a relatively significant increase in mass allowance, if the centrifugal force were to be held constant.

There are also a few minor safety considerations that limit the use of the machine such as cord-management and placement in the lab (juxtaposed with the kiln) during casting. More importantly, the casting process is limited by the casting procedure document. As there are so many variables and potential dangers during casting, neither the safety of operators nor the equipment can be ensured unless there is strict adherence to the procedures and protocols that have been laid out.

Relevance to HSRW

According to DIN 8580, there are six main categories of manufacturing technologies. This project used technologies from five of those categories to create a machine designed for the sixth. *Disaggregation* is the first category and it was the main focus of the fabrication process. Several disaggregation technologies were used on nearly every part of the machine including cutting surfaces with both defined cutting edges (milling, turning, sawing, broaching, etc.) as well as undefined cutting edges (grinding, sanding, etc.). To represent the second category, *deforming*, there were the several bends of various angles that were needed for fabricating the slide assembly and the machine base assembly. *Joining* is the third category. This project includes an epoxy joint, a couple welds and almost 200 bolted connections of various sizes and for various purposes. The fourth category is *coating*. The paint on the enclosure and the oil quench for the casting arm and machine base assemblies belong in this category. One might expect the oil quench to be in the fifth category, *changing material properties*, but for this project, the quench was not a true quench since it was not done at high enough temperatures to change the properties of the materials. Technically, the type of oil quench done for this project is known as “heat coloring” or “hot bluing” even though it was done here for the purposes of corrosion prevention rather than to color the parts. However, the subsequent tempering, that was done to remove any of the residual manufacturing stresses in the parts, does in fact belong in the fifth category. And with all of those forces combined, a machine was created that will allow future students another opportunity to experience the final category, *shaping*.

This project has also included elements from a large number of the courses in my bachelor studies. The relevance of courses such as Mechanics, Manufacturing Technology, Physics and Project Management seemed obvious at the onset, but there were also unexpected aspects from courses such as Creativity and Technical Drawing that were surprisingly relevant. The approaches in my calculations were heavily dependent on my Engineering Design classes and even Thermodynamics and Drive Systems had their moments before the project was over. Of course, none of it would have been possible if I had not learned a great deal in the materials courses I have taken. Both Metallic Materials and Non-Metallic Materials were hugely helpful for this project. Finally, this project legitimately included hundreds of hours of CAD modeling and simulation and remodeling and more simulation. I think the relevance of this project with respect to the mechanical engineering curriculum at HSRW cannot be overstated.

Going Forward

The final task that must be completed before the casting process can be tested is the acquisition of a new burnout kiln. At 1000 – 1500 euro, the cost of this piece of equipment is hardly negligible. However, since the kiln requirements for burnout are relatively high, any kiln that works for casting, will also work for a large variety of potential engineering projects from normalizing and tempering metals to enameling and firing ceramics as well as functions such as sterilization and dehydration. Beyond simple safety considerations, the applications are limited only by the imaginations of the students and the willingness of their supervisors to allow exploration.

The Enspire Lab now has a centrifugal casting machine. Some decisions will need to be made in terms of how it can be safely mounted for use and stored during disuse, but the machine is built and is functional. I will be the first to test the casting machine and process (hopefully in the next month), but it should be available for other student projects immediately after that. I made a scale CAD model of a Lego man for testing. I would like to 3D print the pieces in plastic, clean them up using the various modeling waxes and tools we recently acquired, and then cast them in sterling silver. I will take pictures of the process so more of a pictorial element can then be added to the casting procedure document. Hopefully this will reduce future confusion.

One major advantage of the new machine, over other competitively priced commercially available options, is the fact that the new machine uses a motor and a controller for power rather than a spring. This means that, unlike other models, the powering of our machine can be tailored to any specific application we choose, instead of the one-size-fits-all power delivery that comes from a torsional spring. The torque and rotation speed can be adjusted to match any casting metal perfectly. This will reduce wear and fatigue in the machine, but it will also allow us to tweak the process as the successes and failures of casting become apparent over time. I have yet to see this feature on a centrifugal casting machine that retails for less than 5000 euro.

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APPENDIX A

Investment Casting Process and Procedure

Read this entire document before beginning the casting process. During casting, time is of the essence and inadequate preparation can be dangerous, so familiarity with the steps, variables and potential problems is necessary BEFORE the practical application begins. Trial runs should also be completed for each group of tasks to ensure that tools, surfaces, walkways, etc. are as they should be before introducing elements with time limits or inherent danger.

Furthermore, casting is cool and fun to watch…so the process inevitably attracts an audience. It is the responsibility of the person who is casting to regulate spectators in such a way that the casting process remains safe for everybody in the workshop.

Finally, there is a LOT to know about investment casting. The reader should not take this document as a comprehensive source of information, but rather as a guide for safe casting specifically in the Enspire Lab. There are many books and websites that discuss this topic in much higher detail and the reader is encouraged to seek them out.

Table of Contents

Equipment and Supply List

Wax forming

Materials

- Sprue wax
- Tacky/ Sticky wax
- Sculptor's wax
- Purple wax (purple buildup)

Basically any wax that is designed for lost-wax casting
*Others leave kiln-damaging carbon residues during burnout

- Several commercially available SLA, SLS, or MJP 3D printing plastics designed for no residue during burnout

  **Same problem as with wax: carbon buildup causes short-circuits that will kill the kiln over time

Tools

- Hand tools (exacto knives, dental tools, clay sculpting tools, etc.)
- 100mm (4") Depth Saw Frame
- Rubber sprue base(s) for investment flask(s)
- Hot-glue gun
- Digital scale

Investment preparation

- Rubber mixing bowl
- Investment material
- Investment flask(s)
- Latex gloves for handling the investment material (silica)
- Eye-protection for handling the investment material (silica)
- Dust mask for handling the investment material (silica)
- Measuring cup or beaker for water
- Scale to weight dry investment
- Vacuum chamber with bell jar big enough for largest flask
- Digital timer with large readout (investment material must be mixed, degassed, poured into flask and then degassed again—all within ~8 minutes)

- Wide masking tape or cellophane tape

Burnout

- Kiln capable of running at 800°C for up to 13 hours (must be near casting machine)
- Steel tray and a couple fire bricks to go under flask(s) to catch melted wax
- Some kind of ventilation to vent harmful fumes and to move oxygen through the kiln so the burned out carbon can form CO_2 and escape the kiln
- Timer and attention for burnout schedule

Casting

- A friend or colleague to assist and supervise
- Leather Gloves
- Casting safety glasses No. 5
- Iron Tongs
- Oxygen/Acetylene torch
- Rosebud torch tip
- Flint striker
- Casting material (chips or pellets small enough to fit in crucible)
- Water bucket for quenching finished part
- Toothbrush for cleaning off residual investment material

Finishing

Depends on the casted parts, but probably includes: rotary tool with metalworking accessories, jeweler's saw, metal files, grinding wheel, sandpaper of various grits, steel wool

Step-by-Step Procedure

Preparing the Mold

1. Sculpt desired parts (henceforth called “models”) from wax or 3D-print them from kiln-safe plastic. Check the models carefully for any defects and repair them if needed. The more finished the model, the less cleanup the finished casting will need. Model materials are significantly easier to work on than metal.

2. Weigh the appropriate rubber sprue base and record the weight.

3. Set the rubber sprue base on a flat surface and insert the sprue wax. Melt wax where the sprue wax and the sprue base meet. Use the alcohol lamp and a large sewing needle stuck into the end of a wooden dowel or pencil. Heat the needle and use it to melt and apply the wax.

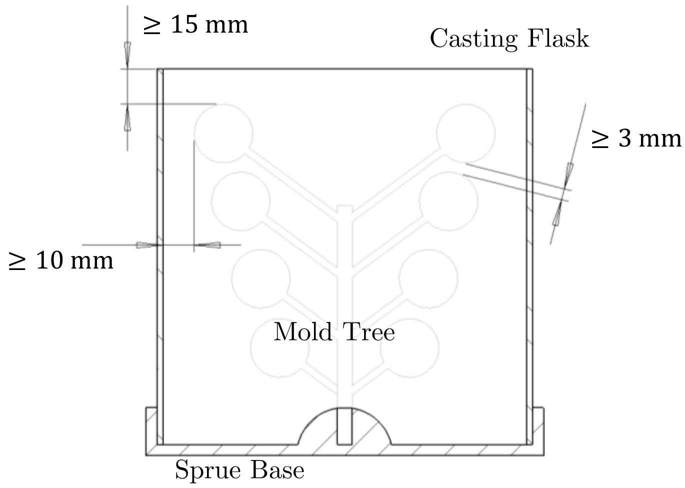
4. Mount a small sprue onto the model, preferably in a spot that won’t be problematic on the finished piece (see figure). Put a fillet of wax where the sprue is attached to the model.

Bad sprue:
sprue interferes with desired
geometry of casted component

Good sprue:
sprue does not interfere with desired
geometry and can be easily removed

5. Secure the sprued model to the tree. Keep the sprue for the model as short as possible. The sprued model can be attached with “sticky wax” or by using the hot needle again. Put a fillet of wax where the model sprue and the tree meet. When spruing multiple

models, start from the top of the tree and work toward the base. Keep the models and sprues a minimum of 3 mm apart from each other. Periodically check for at least 10 mm clearance between the models and the flask wall and always be sure there is enough room for at least 15 mm of investment material above the top of the mold tree (see figure)



Since casting is time-consuming, there is pressure to cast as many parts at once as is possible. However, if the resulting mold cavity is too large, the mold will have insufficient structural integrity and the casting will fail.

6. Now weigh the fully sprued base. Subtract the weight of the sprue base recorded in step 2 and you have the weight of your models and sprues. Weigh out the appropriate amount of casting metal while keeping in mind that the maximum mass of casting metal allowable for the casting machine is 255 g. Once the metal is weighed out, set it aside until casting. The quantity Q of metal that will be needed is:

$$Q = W \bullet G_{\mathrm{W}} \bullet G_{\mathrm{M}} + 15.55\ \mathrm{g} \ \leq 255\ \mathrm{g}$$

with

W: Weight of models and sprues in grams

G_{W}: Specific gravity of wax or other model medium

G_{M}: Specific gravity of metal being casted

15.55 g: Additional material added to fill “button” = 10 pennyweights

Note: Use metal that hasn’t been melted since leaving the refinery or metal that has only been melted once (such as old buttons and sprues), plus at least 50% by weight of new metal. Cast sprues and buttons can be recycled twice for casting material.

7. Put the flask and sprued base back together and check clearances a final time. Wrap upper lip of flask with wide masking or cellophane tape and set aside until you are ready to pour the investment material.

(Photo coming soon)

8. Instructions and proper proportions for mixing the investment material are included with the investment. Always add water to the rubber mixing-bowl first, and THEN add the investment powder to the water. Mix the investment for about 3 minutes until it's just beyond the consistency of pancake batter and it has no remaining lumps.

   Data for SRS CLASSIC™ Investment powder:

   Powder / Water Ratio: 100/38-40

   Working Time @ 22°C Slurry Temp: 8 min.

Note: Cristobalite, an ingredient in the investment material, is a known carcinogen and may also have the potential for causing reproductive damage in humans. Furthermore, chronic inhalation of cristobalite can lead to a serious lung disease known as Silicosis. Gloves, eye protection and respiratory protection are required while handling the investment material in its powdered form. See MSDS for more information.

Note: The working time of the investment material is 8 minutes and it will spend about half of that in the vacuum chamber. This means there isn't much time for pouring and there is essentially no time for mistakes. Proper attention must be paid during steps 8 – 11!

Note: Tap water should work but reverse osmosis water works better. If tap water is used, let it stand for at least one hour to allow the air to dissipate and the temperature to stabilize between 21 and 27 °C. Warmer water will accelerate the setting time of the investment.

9. Once the investment is mixed, place it on the vacuum machine. Put the bell jar over the bowl and turn on the vacuum. The investment will boil and turn frothy. Here, the

purpose of the tape that was applied to the flask in step 7 becomes apparent. Vacuum for approximately 60 seconds

(Photo coming soon)

10. While tilting the flask to ensure maximum coverage of the model, slowly pour the investment into the flask until it is full. Rotate and tap the flask to decrease the likelihood of cavities and bubbles. For very intricate models, it is a good idea to paint the investment into the details with a paintbrush before pouring.

Note: If you don't have enough mixed investment to fill a flask completely, dump it out and mix more. Do not use more than one pour to fill a flask.

11. Vacuum the filled flask the same way as the mixing bowl in step 9, but this time for 2 minutes. Once the vacuuming is complete, the flask can be set-aside on a flat surface and the 8-minute deadline for working with the investment material is over.

12. Let the filled flask set for 90 minutes and then remove the tape and sprue base by gently twisting it. Let it set for at least another 30 minutes.

13. The flask is now technically ready for burnout, but BEFORE burnout begins, the casting arm of the centrifugal casting machine must be balanced using the appropriate counterweight and spacer. The appropriate flask support spacer should also be placed on the slider bars to ensure the flask will remain level during casting.

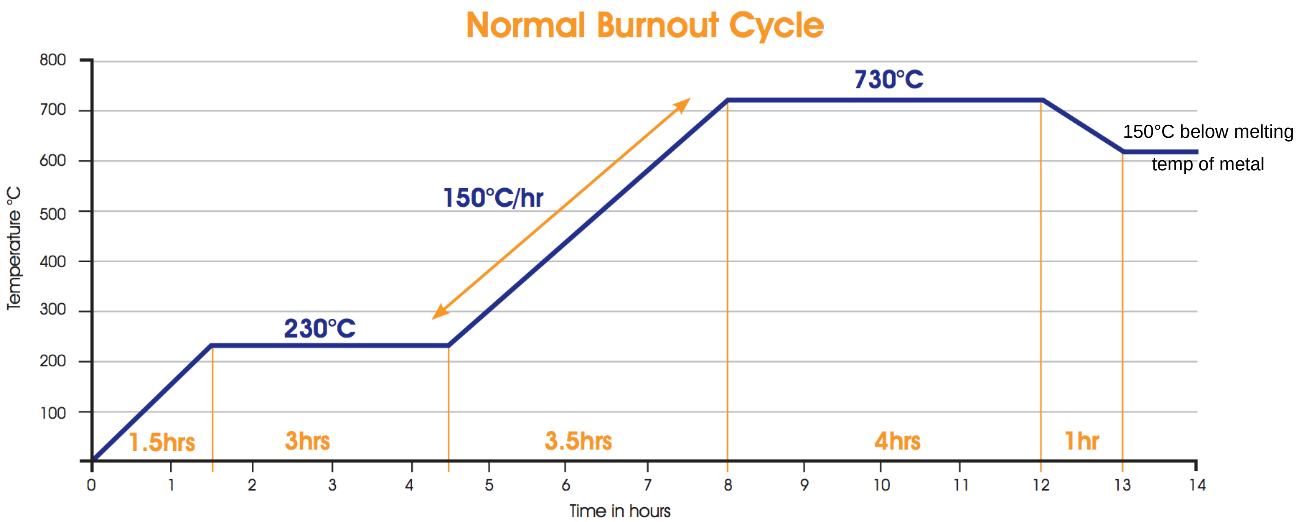
Note: this step is difficult and dangerous to do with a hot flask so make sure it is done before the flask goes into the kiln!

Burnout

Burnout is the process through which all traces of the wax are eliminated from the kiln, but it also gradually removes the chemical moisture from the investment material and brings the temperature of the mold up to the proper level to receive the molten metal. This part of the procedure is time consuming and can damage the kiln if not done properly, so attention is necessary.

14. Before putting the flask into the kiln, make sure the bottom of the kiln is protected by a steel tray or by ceramic tiles with grooves to catch and hold the wax until it vaporizes. Do NOT let the wax melt directly onto the bottom of the kiln!

15. Put the flask into the cold kiln and follow the burnout schedule provided with the investment material. The burnout schedule for SRS CLASSIC™ Investment powder is as follows:



Note: For the first 1.5 hours, the sprue should be pointing downward to allow wax to escape. Then, flip the flask every couple hours for the rest of the burnout cycle.

16. Do NOT remove the flask from the kiln to cast until it has been held at the casting temperature (150°C below melting temp of metal) for a minimum of 1 hour. If held for less than 1 hour, the core of the flask will be at a higher temperature than the readout on the kiln says and this can result in metal-mold reaction (failed casting).

17. When you are ready to begin casting, turn off the kiln. This way you won't have to think about it in a few minutes when you remove the hot flask.

Casting

Before beginning, visually inspect the casting machine for damage or corrosion that may impact its functionality. Make sure the machine is clean (with nothing stacked on top or inside of the enclosure) and free of debris. Make sure moving parts rotate or slide easily and make sure that bolted connections are tight. Securely clamp or bolt the casting machine to the workbench and, with the power supply OFF, plug the power supply into the wall. With the lid of the enclosure OPEN, turn on the power supply and make sure it is set to the appropriate settings for voltage and current and then turn it off again until you are ready to cast.

18. Light the torch with the rosebud tip while following the torch's SOP and taking all relevant safety precautions.

19. With the articulated arm of the casting machine bent to the 90° position. Add some borax flux powder to the crucible and heat the crucible until flux starts to glaze (about 30 seconds) and then add the casting metal weighed out in step 6.

(Photo coming soon)

20. Continue heating the casting metal while moving the torch around and occasionally stirring/ flipping the chunks with a carbon or ceramic stirring rod.
21. When the casting metal is nearly melted, set the torch safely aside. Take the hot flask from the kiln using steel tongs and place it into the flask cradle of the casting machine. Make sure the flask is aligned in the appropriate hole in the flask cradle in the back, and resting on the appropriate flask support spacer (chosen in step 13) in the front. Then slide the crucible up to the flask opening.

(Photo coming soon)

22. With the lid of the enclosure still open, turn on the power supply. Now the machine is "armed" so to speak. Simply closing the lid will now trigger the motor to rotate.

23. Continue heating the casting metal with the torch while stirring regularly and checking for lumps. Slide any impurities to the side of the crucible farthest from the flask mouth. Do NOT boil the metal. If the melt begins to boil, add a bit of flux and back off with the torch until the melt cools down some.

24. When the metal is liquid, make sure once again that the machine is free of all debris, fingers or tools; remove the torch and immediately close the lid of the enclosure to activate the rotation of the motor. Let the motor run for 2 minutes and then turn off the power supply. Do NOT open the lid of the enclosure until the casting arm has stopped rotating.

25. The casting flask and crucible are still very hot. Do NOT touch the flask or any part of the machine. Let the flask sit in the casting machine until the button cools down to a dull red color.

(Photo coming soon)

26. Using the iron tongs once again, remove the flask from the casting machine and quench it in the bucket of water, sloshing it back and forth. The water will remove the investment from the casting, but wait to retrieve the casting from the bucket, as it will still be hot.

27. You now have an ugly chunk of metal covered with investment and black oxidation. Scrub the remaining investment material off with a toothbrush, cut the sprues off of the model(s) and finish the piece(s) by pickling, soldering, filing, and polishing.

(Photo coming soon)

Melting Temperatures and Specific Gravities of Common Casting Metals

Metal / Alloy	Melting Range $T_{sol} - T_{liq}$ °C	Specific Gravity
Aluminum		
Pure Aluminum	660	2.55
Aluminum Alloy	463 – 671	2.8
Aluminum Bronze	600 – 655	7.7
Babbitt	249	7.27
Beryllium Copper	865 – 955	8.25
Bismuth	271	9.79
Brass		
Red Brass	990 – 1025	8.7
Yellow Brass	905 – 932	8.4
Cadmium	321	
Copper	1084	8.95
Gold		
18K yellow Gold	900 – 930	17.2
18K red Gold	890 – 900	17.18
18K Ni white Gold	910 – 940	19.25
Fine Gold	1064	19.35
Lead	327.5	11.34
Magnesium		
Pure Magnesium	650	1.738
Magnesium Alloy	349 – 649	1.74
Manganese Bronze	865 – 890	7.44
Selenium	217	4.28
Silver		
Fine Silver	962	10.6
930 Silver	780 – 900	10.4
Sterling Silver	893	10.5
Tin	232	7.5

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Campbell, J. (2015, 2011). *Complete casting handbook: Metal casting processes, metallurgy, techniques and design* (2nd ed.). Waltham, MA: Elsevier.

Fischer-Bühner, J. (2007). *Advances in the Prevention of Investment Casting Defects Assisted by Computer Simulation*. Schwaaäbisch Gmünd, Germany: The Research Institute for Precious Metals (FEM).

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Erstellt am:
20.10.2020
Erstellt von:
Ocean Tech **Lab**

SAFE OPERATING PROCEDURE

Institution: Hochschule Rhein Waal

Machine / Device

Workplace / -area:

Job type: **CENTRIFUGAL CASTING MACHINE**

Risks for Personnel and Environment

- Injury due to clothing or hair getting entangled in spinning casting arm
- Eye or body injury due to ejected materials
- Hand injury due to fingers in enclosure while casting arm is spinning
- Heat injury due to molten materials or heated casting flask
- Spinning molten material can be a fire hazard
- Gaseous metal inhalation hazard if casting metal is boiled
- Work pieces, crucible and flask will be very hot – risk of burns
- Other people could be endangered if enclosure is opened while casting arm is spinning

Risk Minimization Procedures

- Follow instructions in casting procedure manual
- Wear eye-protection and heat resistant gloves
- As appropriate for the material, wear respiratory protection
- Before first usage, obtain appropriate training
- Always cast with a partner or supervisor
- Balancing of casting arm to be assisted by qualified personnel
- Wear tight fitting clothing made of natural fibres while using torch
- Long haired operators must wear hair nets
- Warn bystanders of dangers
- Inform Management immediately of breakages

Breakdown Procedures

- In case of breakdown, stop all work and inform Management
- Ensure broken tools cannot be operated until repaired

First Aid

First Aider: __Prof Megill______________________

- In case of accident, shut off the machine
- Keep calm
- Call for First Aid
- Report the accident

First Aid:
x 299
Ambulance:
0 - 112

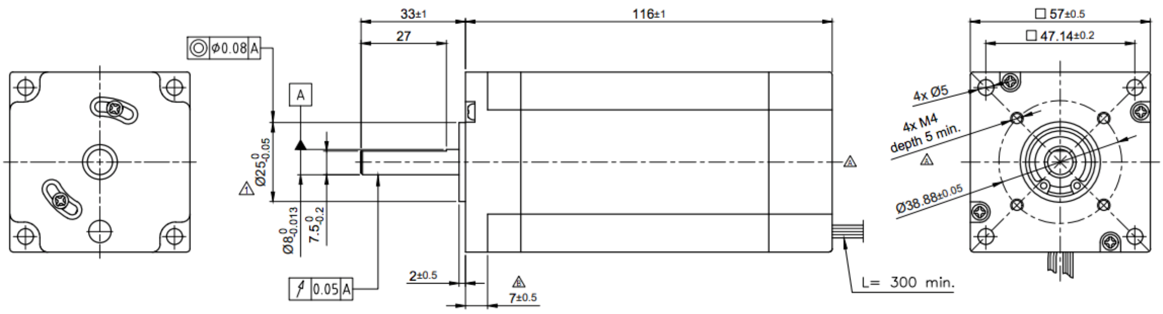
Maintenance Procedures

- Maintenance and repair are only to be undertaken by qualified personnel or companies.
- Annual electrical inspections (PAT) to be completed by qualified personnel.

Supervisor signature:

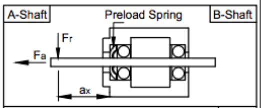
APPENDIX B

Motor Dimensioning

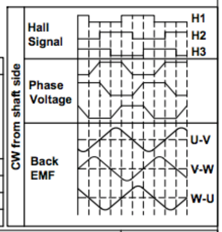


MOTOR SPECIFICATION		
No. of Poles		8
Rated Voltage	V DC	36
Current - Rated / Peak	A	7.5 / 22.5
Resistance Line to Line	±10% Ω	0.53
Inductance Line to Line (1kHz)	±20% mH	0.58
Torque - Rated / Peak	Nm	0.6 /1.8
Torque Constant	Nm/A	0.08
Back-EMF Constant	V_{rms}/krpm	5.7
Rated Power	W	188
Speed - No Load / Rated	±10% rpm	4400 / 3000
Rotor Inertia	kg m²	46 $\times 10^{-6}$

WIRING DIAGRAM			
	Colour	Function	Lead Gauge
Motor	Ye	U	UL1430 AWG18
	Rd	V	
	Bk	W	
Hall -- Impl. per Rev.	Rd	+5V	UL3265 AWG28
	Bu	H1	
	Gn	H2	
	Wh	H3	
	Bk	GND	



Max. Axial Force Fa		N	15
Max. Radial Force Fr (a2 = 20 mm)		N	75
Axial Play	Fa = 40 N	mm	0.03
Radial Play	Fr = 4.6 N	mm	0.03



GENERAL MOTOR SPECIFICATION		
Ambient Temperature	°C	-10 ...50
Max. Temperature Rise (at standstill)	°C	80
Max. Ambient Humidity (non condensing)	%	85
Insulation Class		B
Insulation Resistance	MΩ	100
Dielectric Strength (for 1 min - coil to case)	V AC	500

ISO 8015	ISO 1302	ISO 2768 cK	ISO 13715	Weight: 1.2 kg

					Date	Name
				Drawn	04.12.2017	Import
				Checked	06.09.2018	Knoll-Admin
				Approved	06.09.2018	Schneid_A
01	change diameter fl. sp.	Schneid_A	06.09.2018	Nanotec® PLUG & DRIVE		
REV	Rev. Text	Name	Rel. Date			

DB56D036030-A			
03000077			-
			A4-Q
State: Released	Rev: 01	P	

DB56

Brushless DC Motor

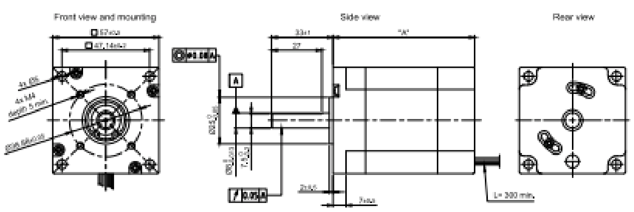
OPTIONS

VERSIONS

Type	Rated Power W	Rated Torque Ncm	Rated Current A	Peak Current A	Rated Voltage V	Rated Speed rpm	Torque Constant Ncm/A	Rotor Inertia gcm²	Length „A" mm	Weight kg
DB56L036030-A	94	30	4	12	36	3000	7.3	260	76	1
DB56C036030-A	141	45	5.4	16.2	36	3000	8	360	96	1.1
DB56D036030-A	188	60	7.5	22.5	36	3000	8	460	116	1.2

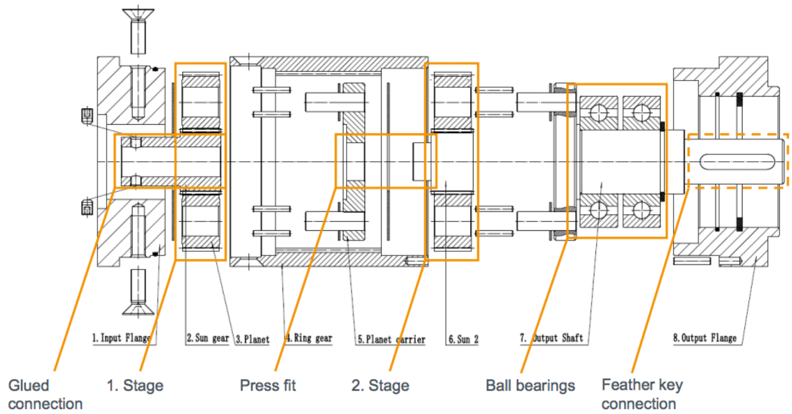
DIMENSIONS (IN MM)

DB56-A



Dimensioning of Gearboxes

Dimensioning



2

Dimensioning

Glued connection of the first sun gear (Henkel, technical books)

- Safety factor: $S = C \cdot \frac{\tau_{zul}}{\tau_T}$
- τ_{zul}: permitted torsional stress (26.5 N/mm^2, Loctite 648)
- τ_T: working torsional stress
- C: constant factor (clearance, temperature, materials, alternating stress,…)

→ Datasheet: max. torque for one-stage gearboxes

Failed motor shaft connection

Press fit of the second sun gear (KISSsoft, DIN 7190)

- Definition of the tolerances
- Dimensioning for plastic deformation of shaft and hub
  - Tightest fit: smallest hole of the carrier and biggest shaft diameter
  - Calculation of the safety factors for both parts
- Dimensioning for slide through
  - Loosest fit: biggest hole of the carrier and smallest shaft diameter
  - Calculation of the safety factor

→ Datasheet: max. torque of two-stage gearboxes

Failed press fit

3

Dimensioning

Lifetime calculation of ball bearings (KISSsys, ISO 281)

Known:

- Radial load: $F_r = 306$ N
- Speed of output shaft: n = 100 rpm
- Distance between ball bearings: a = 8 mm
- Distance between ball bearing A and radial load: b = 14 mm
- Ball bearing NSK 608 DU:
  - dynamic load rating C = 3300 N
  - static load rating $C_0 = 1370$ N

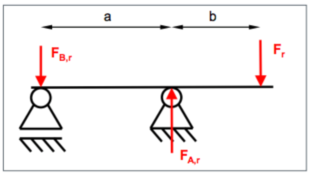
Unknown:

- Lifetime L_{10h}

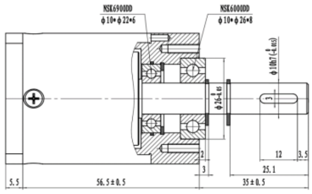
Calculation:

- Radial load @ A: $F_{A,r} = F_r \cdot (a+b)/a = 306 \cdot 22/8 = 841.5$ N
- Equivalent load: $P = F_{A,r} = 841{,}5$ N
- Lifetime: $L_{h10} = (C/P)^3 \cdot 10^6/n/60 = (3300/841{,}5)^3 \cdot 10^6/100/60 = \underline{10.000\ h}$

→ Datasheet: max. radial load F_r



Sketch for lifetime calculation (GP42)



Custom solution (GP42)

Nanotec PLUG & DRIVE

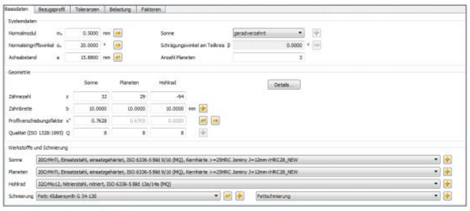
4

Dimensioning

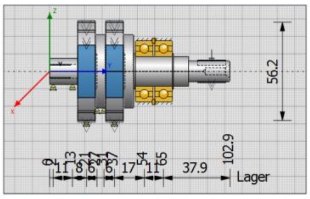
Calculations in KISSsys

- Set structure of gearbox and define calculations
- Optimisation of gear parameters

→ Datasheet: efficiency, ratios, inertia, backlash, rated torque (for given lifetime and speed)



Planetary stage calculation



Shaft calculation

GEARBOX SPECIFICATION				Speed / rpm	Torque / Nm	Lifetime for Planetary_calc1 / h	Lifetime for Planetary_calc2 / h	Lifetime for max. torque calc. / h
Reduction Ratio	-	15.504	Input	3500	1.85			
No. of Stages	-	2	Output	225.75	24.605	10000	10000	5.168
Rated Output Torque	Nm	24.6						
Max. Output Torque	Nm	39.4		Root Safety	Flank Safety	Radial Forces / N	Axial Forces / N	Position / mm
Rated Input Speed	rpm	3500	2. Sun Gear	2.2488	1.0772	430	0	50.5
Max. Input Speed	rpm	5968	2. Planet Gear	1.5177	1.092			
Backlash	°	0.52186	2. Ring Gear	1.7659	1.0053		Lifetime / h	
Efficiency	%	0.94483	1. Sun Gear	3.4305	1.2898	Bearing B1	40320.83332	
Lifetime	h	10000	1. Planet Gear	2.3244	1.3075	Bearing B2	10110.684	
Max. Axial Forces	N	430	1. Ring Gear	2.7046	1.223			
Max. Radial Forces	N	1080						
Gearbox Inertia	kg mm^2	5.4002						
Ambient Temperature	°C	-15...+90						
Protection Class	-	IP40						

User interface

Nanotec PLUG & DRIVE

5

High-torque Planetary Gearboxes

Nanotec PLUG & DRIVE

GP56

High-Torque Planetary Gearbox

Nanotec®

TECHNICAL DATA

IP Protection (Except Shaft Output)	IP54
Service Life*	10000
For Motor Size	NEMA 23, NEMA 24
Operating Temperature	-15 °C - 90 °C

*The estimated service life is an approximate value based on the listed nominal torques and an ambient temperature of 30 °C. There are no data available for differing conditions as the environmental factors and operating conditions may vary greatly.

VERSIONS

Type	Reduction Ratio	Rated Output Torque Nm	Max. Output Torque Nm	Max. Input Speed rpm	Max. Backlash ´(arc minutes)	Efficiency %	Moment of Inertia kg mm²	Admissible Axial Shaft Load N	Admissible Radial Shaft Load N	Length „L" mm	Weight kg
GP56-S1-3-SR	3	17.5	24.7	4658	29	92	8.5	1302	516	44.6	0.57
GP56-S1-7-SR	7	12.1	26.1	8988	34	92	3.7	1302	516	44.6	0.58
GP56-S1-10-SR	10	3.6	38.2	13000	35	91	3.2	1302	516	44.6	0.59
GP56-S2-11-SR	11	19.2	32.9	4658	31	89	8.4	1302	516	61.8	0.8
GP56-S2-16-SR	16	24.6	39.4	5968	32	89	6.2	1302	516	61.8	0.84
GP56-S2-62-SR	62	18.3	26.1	13000	33	86	3.1	1302	516	61.8	0.82
GP56-T1-3-HR	3	17.5	24.7	4658	29	95	9.6	1532	564	48.8	0.67
GP56-T1-7-HR	7	12.1	26.1	8988	34	95	4	1532	564	48.8	0.67
GP56-T1-10-HR	10	3.6	38.2	13000	35	94	3.3	1532	564	48.8	0.68
GP56-T2-11-HR	11	19.2	32.9	4658	31	94	8.4	1532	564	66	0.89
GP56-T2-16-HR	16	24.6	39.4	5968	32	94	6.3	1532	564	66	0.93
GP56-T2-62-HR	62	18.3	26.1	13000	33	92	3.2	1532	564	66	0.91

ORDER IDENTIFIER

GP56-
Sx-... = with standard bearing
Tx-... = with reinforced bearing

WARNHINWEIS

Please note that the GP gearboxes are only available together with a motor.

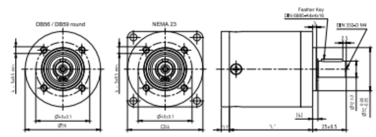
GP56

High-Torque Planetary Gearbox

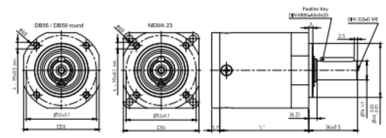
Nanotec®

DIMENSIONS (IN MM)

GP56-S



GP56-T



SRS UK Classic Investment Powder Safety Data Sheet

1. IDENTIFICATION OF THE SUBSTANCE/MIXTURE AND OF THE COMPANY UNDERTAKING

1.1 Product Identifier

Product Name:	Investment Casting Powder
REACH Registration No:	Exempted in accordance with Annex V.7
Synonyms:	n/a
Trade Names:	Classic, Stonecast (White/ Blue), Brasscast, Eurovest, Artcast, Cobra, Sculpture, Global, Silk, Cadcast, Silk Pro, 116, 117, Silk Neo

1.2 Relevant identified uses of the substance or mixture and uses advised against:
Main Applications (non exhaustive list):
Casting of Jewelry and Industrial products

1.3 Details of the supplier of the Safety Data Sheet

Company Name:	Specialist refractory services ltd.
Address:	Spencroft Road, Holditch Industrial Estate Newcastle under Lyme, Staffordshire, ST5 9JE, UK
Phone No.	+44 (0)1782 663600
Fax No.	+44 (0)1782 663611
Email address:	sales@srs-ltd.co.uk

1.4 Emergency telephone number:
Emergency Telephone No. +44 (0)1782 663600
Available outside office hours? No

2. HAZARDS IDENTIFICATION

2.1 Classification of the substance or mixture:

This product contains respirable crystalline silica (RCS). The quantity of RCS powder that is composed of particle sizes of less than 10 µm is less than 10% therefore making this product a STOT RE 2 according to criteria defined in the regulation EC 1272/2008 and harmful according to criteria defined in Directive 67/548/EEC due to the potential for generation of airborne respirable crystalline.

Airborne respirable crystalline silica may be generated during the handling and use of the product. Prolonged inhalation of high levels of respirable crystalline silica dust has been shown to cause silicosis, a nodular pulmonary fibrosis.

Workplace exposure to respirable crystalline silica dust should be monitored and controlled.

2.2 Label elements:
Classification Regulation EC 1272/2008:
Specific Target Organ Toxicant- *STOT RE 2—This product contains less than 10% respirable crystalline silica.*

H373: May cause damage to lungs through prolonged or repeated exposure via Inhalation.

Signal Word: Warning

Hazard Statements:

H373: May cause damage to lungs through prolonged or repeated exposure via Inhalation.

Precautionary Statements:

P260: Do not breathe dust.
P284: Wear respiratory protection.
P501: Dispose of contents/containers in accordance with local regulations.

2.3 Other Hazards:
This product is an inorganic substance and does not meet the criteria for PBT or vPvB in accordance with Annex XIII of REACH.

This product is exempt from REACH Registration.

3. COMPOSITION / INFORMATION ON INGREDIENTS

3.1 Mixture

	CAS #	%
Cristobalite	14464-46-1	20 - 50
Quartz	14808-60-7	20 - 60
Gypsum	7778-18-9	20 - 30

3.2 Impurities
Contains between 1 and 10% of respirable crystalline silica and is classified as STOT RE 2.

4. FIRST AID MEASURES

4.1 Description of first aid measures:

Eye Contact:	Rinse thoroughly with plenty of water for at least 15 minutes. If irritation persists seek medical advice.
Inhalation:	Move exposed person to fresh air immediately and seek medical advice.
Ingestion:	No first aid measures required.
Skin Contact:	No first aid measures required.

4.2 Most important symptoms and effects both acute and delayed
No acute and delayed symptoms and effects are observed.

4.3 Indication of any immediate medical attention and special treatment needed:
No specific actions are required.

5. FIRE FIGHTING MEASURES

5.1 Extinguishing media:
No specific extinguishing media is needed.

5.2 Special hazards arising from the substance or mixture:
Non combustible. No hazardous thermal decomposition.

5.3 Advice for firefighters:
No specific fire fighting protection is required.

6. ACCIDENTAL RELEASE MEASURES

6.1 Personal precautions, protective and emergency procedures:
Avoid airborne dust generation, wear personal protective equipment in compliance with national legislation.

6.2 Environmental precautions:
No special requirements.

6.3 Methods and material for containment and cleaning up:
Avoid dry sweeping and use water spraying or vacuum cleaning systems to prevent airborne dust generation. Wear personal protective equipment in compliance with national legislation (see section 8.2.2 for specific details).

6.4 Reference for other sections:
See sections 8 and 13.

7. HANDLING AND STORAGE

7.1 Precautions for safe handling:
Avoid airborne dust generation. Provide appropriate ventilation at places where airborne dust is generated. In case of insufficient ventilation,(10-15 air changes per hour recommended) wear suitable respiratory protective equipment (see section 8.2.2 for specific details). Where 10-15 air changes per hour is not achieved, suitable local exhaust ventilation is recommended. Handle packaged products carefully to prevent accidental bursting. If you require advice on safe handling techniques, please contact your supplier or check the good practice guide referred to in section 16.

7.2 Conditions for safe storage, including any incompatibilities:
Minimise airborne dust generation and prevent wind dispersal during loading and unloading. Keep containers closed and store packaged products so as to prevent accidental bursting.

7.3 Specific end use(s) :
If you require advice on specific uses, please contact your supplier or check the good practice guide referred to in section 16.

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

8.1 Control parameters:
Follow workplace regulatory exposure limits for all types of airborne dust (e.g. total dust, respirable dust, respirable crystalline silica dust)

The WEL (Workplace Exposure Limit) for respirable crystalline dust is 0.1 mg/m^{-3} in the UK, measured as an 8 hour TWA (Time Weighted Average).
For the equivalent limits in other countries consult your local regulatory authority.

8.2 Exposure controls:

8.2.1 Appropriate engineering controls:
Minimise airborne dust generation. Use process enclosures, local exhaust ventilation or other engineering control methods to keep airborne levels below the specified exposure limits. If user operations generate dust, fumes or mist, use ventilation to keep exposure to airborne particles below the exposure limit. Apply organistional measures, e.g. by isolating personal from dusty areas. Wash hands before breaks and at the end of the day. Remove and wash soiled clothing.

8.2.2 Individual protection measures such as personal protective equipment

Eye / face protection: Safety goggles to protect the eyes against dust ingress. Conforms to EN 166.1.B.3.4.9

Skin protection: No specific requirement.

Hand protection: Wash hands at the end of each work session. Use barrier cream / pre work cream. No specific protective gloves required, however natural rubber/ latex gloves or equivalent are advised.

Respiratory protection: In case of prolonged exposure to airborne dust concentrations, wear respiratory equipment (e.g. respirator, powered air respirator) of FFP3 or APF 40 standards or equivalent.

8.2.3 Environmental exposure controls:

Avoid wind dispersal.

9. PHYISCAL AND CHEMICAL PROPERTIES

9.1 Information on basic physical and chemical properties:

Appearance:	Fine, white powder.
Odor:	Odorless
Odor threshold:	No components are considered hazardous.
pH	7- 8
Melting point/ freezing point:	No components are considered hazardous.
Initial Boiling point:	No components are considered hazardous.
Flash point:	No components are considered hazardous.
Evaporation rate:	No components are considered hazardous.
Flammability:	No components are considered hazardous.
Upper/ lower flammability exposure limit:	No components are considered hazardous.
Vapour pressure:	No components are considered hazardous.
Relative density:	No components are considered hazardous.
Water solubility:	Non soluble
Partition coefficient:	No components are considered hazardous.
Auto ignition temperature:	No components are considered hazardous.
Decomposition temperature:	No components are considered hazardous.
Viscosity:	No components are considered hazardous.
Explosive Properties:	No components are considered hazardous.
Oxidising properties:	No components are considered hazardous.

9.2 Other information:
No other information.

10. STABILITY AND REACTIVITY

10.1 Reactivity:	No data available.
10.2 Chemical Stability:	Chemically stable.
10.3 Possibility of hazardous reactions:	No hazardous reactions.
10.4 Conditions to avoid:	No data available.
10.5 Incompatible materials:	No data available.
10.6 Hazardous decomposition products:	No data available.
11.1 Information on toxicology effects:	

11. TOXICOLOGY INFORMATION

a) Acute toxicity:
Based on available data, the classification is not met.

b) Skin corrosion/irritation:
Based on available data, the classification is not met.

c) Serious eye damage/irritation:
Based on available data, the classification is not met.

d) Respiratory or skin sensation:
Based on available data, the classification is not met.

e) Germ cell mutagenicity:
Based on available data, the classification is not met.

f) Carcinogenicity:
Based on available data, the classification is not met.

g) Reproductive toxicity:
Based on available data, the classification is not met.

h) STOT-single exposure:
Based on available data, the classification is not met.

i) STOT-repeated exposure:
This product contains respirable Cristobalite and respirable quartz as an Impurity and is classified as STOT RE 2 according to criteria defined in the Regulation EC 1272/2008.

Prolonged inhalation of high levels of to respirable crystalline silica dust may cause silicosis, a nodular pulmonary fibrosis caused by deposition in the lungs of fine respirable particles.

j) Aspiration hazard: Based on available data, the classification is not met.

12. ECOLOGICAL INFORMATION

12.1 Toxicity:	No data available.
12.2 Persistence and degradability:	No data available.
12.3 Bioaccumulative potential:	No data available.
12.4 Mobility in soil:	No data available.
12.5 Results of PBT and vPvB assessment:	No data available
12.6 Other adverse effects:	No specific adverse effects known

13. DISPOSAL CONSIDERATIONS

13.1 Waste treatment methods:

Product:
Where possible, recycling is preferable to disposal. This should be carried out in compliance with local regulations.

Packaging:
Dust generation from residues in packaging should be avoided and suitable work protection assured. The re-use of packaging is not recommended. Recycle and disposal of packaging should be carried out in compliance with local regulations and authorized waste management company

14. TRANSPORT INFORMATION

14.1 UN Number:	No data available.
14.2 UN proper shipping name:	No data available.
14.3 Transport hazard class(es):	
ADR:	Not dangerous goods.
IMDG:	Not dangerous goods.
ICAO/IATA:	Not dangerous goods.
RID:	Not dangerous goods.
14.4 Packing group:	No data available.
14.5 Environmental hazards:	No data available.
14.6 Special precautions for user:	No data available.
14.7 Transport in bulk according to Annex II of MARPOL73/78 and the IBC Code:	No data available.

15. REGULATORY INFORMATION

15.1 Safety, health and environmental regulations/legislation specific for the substance or mixture:
International legislation/requirements:

Regulation (EC) No 2037/2000:	Not relevant
Regulation (EC) No 850/2004:	Not relevant
Regulation (EC) No 689/2008:	Not relevant

15.2 Chemical safety assessment:
No chemical safety assessment has been carried out by the supplier.

16. OTHER INFORMATION

Training advice:
Employees must be trained in the proper use and handling of this product as required under applicable regulations.

Guidance Books:
EH40/2005 - Workplace Exposure Information
EH44/1997 - Dust: General Principles of Protection
EH75/4 (2002) - Respirable Crystalline Silica - Phase 1
EH75/5 (2003) - Respirable Crystalline Silica - Phase 2
HSG37 - An Introduction to Local Exhaust Ventilation

Liability:
Such information given on this safety data sheet is to the best of the company's knowledge and belief, accurate and reliable as of the date indicated. However, no representation, warranty or guarantee is made as its accuracy, reliability or completeness. It is the users responsibility to satisfy itself as to the suitability and completeness of such information for their own particular use.

Indication of the changes made to the previous revision of the SDS:
25/02/2016– First Issue.
30/03/2016– Rev 5, 5 new items added.
19/04/2016– Rev 6– Ultra silk & Fifty added.
03/03/2017– Rev 7– Impurities added.
10/05/2017– Rev 8– Removal of reference to EC 453/2010.
10/10/2018– Rev 9– Document reviewed.
30/11/2018– Rev 10– Silk NEO added.
28/02/2019– Rev 11– Document review with additional information added to section 9.

Right to Know
Hazardous Substance Fact Sheet

NJ Health New Jersey Department of Health

Common Name: **SILICA, CRISTOBALITE**

Synonyms: Calcined Diatomaceous Earth; Crystalline Silicon Dioxide, Crystabolite

Chemical Name: Cristobalite

Date: April 2002 Revision: February 2010

CAS Number: 14464-46-1

RTK Substance Number: 1657

DOT Number: None

Description and Use

Silica, Cristobalite is a colorless, odorless, crystalline (sand-like) solid. It is used in making water glass, refractories, abrasives, ceramics, and enamels, and in scouring and grinding compounds.

Reasons for Citation

- **Silica, Cristobalite** is on the Right to Know Hazardous Substance List because it is cited by OSHA, ACGIH, NIOSH, NTP and IARC.
- This chemical is on the Special Health Hazard Substance List.

SEE GLOSSARY ON PAGE 5.

FIRST AID

Eye Contact
- Immediately flush with large amounts of water for at least 15 minutes, lifting upper and lower lids. Remove contact lenses, if worn, while rinsing.

Skin Contact
- Remove contaminated clothing and wash contaminated skin with soap and water.

Inhalation
- Remove the person from exposure.
- Begin rescue breathing (using universal precautions) if breathing has stopped and CPR if heart action has stopped.
- Transfer promptly to a medical facility.

EMERGENCY NUMBERS

Poison Control: 1-800-222-1222

CHEMTREC: 1-800-424-9300

NJDEP Hotline: 1-877-927-6337

National Response Center: 1-800-424-8802

EMERGENCY RESPONDERS >>>> SEE LAST PAGE

Hazard Summary

Hazard Rating	NJDOH	NFPA
HEALTH	4	-
FLAMMABILITY	0	-
REACTIVITY	0	-
CARCINOGEN DOES NOT BURN		

Hazard Rating Key: 0=minimal; 1=slight; 2=moderate; 3=serious; 4=severe

- **Silica, Cristobalite** can affect you when inhaled.
- **Silica, Cristobalite** is a CARCINOGEN. HANDLE WITH EXTREME CAUTION.
- Contact can irritate the eyes and nose.
- Exposure to high levels of **Silica, Cristobalite** can cause a very serious lung disease called *Silicosis* with cough and shortness of breath. Very high exposures can cause *Silicosis* to develop in a few weeks; with lower exposures it may occur over many years. *Silicosis* may cause death.
- If *Silicosis* develops, chances of getting Tuberculosis are increased.
- *For more information, consult the Right to Know Hazardous Substance Fact Sheets on SILICA, TRIPOLI; SILICA, QUARTZ; and SILICA, TRIDYMITE.*

Workplace Exposure Limits

OSHA: The legal airborne permissible exposure limit (PEL) is one half of the value from the formulas:

$\frac{10\ mg/m^3}{\%\ \text{Silicon Dioxide} + 2}$ (as *respirable dust*) averaged over an 8-hour workshift, and

$\frac{30\ mg/m^3}{\%\ \text{Silicon Dioxide} + 2}$ (as *total dust*) averaged over an 8-hour workshift.

NIOSH: The recommended airborne exposure limit is **0.05 mg/m^3** (as *respirable dust*) averaged over a 10-hour workshift.

ACGIH: The recommended airborne exposure limit is **0.025 mg/m^3** (as the *respirable fraction*) averaged over an 8-hour workshift.

- **Silica, Cristobalite** is a CARCINOGEN in humans. There may be no safe level of exposure to a carcinogen, so all contact should be reduced to the lowest possible level.

Determining Your Exposure

- Read the product manufacturer's Material Safety Data Sheet (MSDS) and the label to determine product ingredients and important safety and health information about the product mixture.
- For each individual hazardous ingredient, read the New Jersey Department of Health Hazardous Substance Fact Sheet, available on the RTK website (www.nj.gov/health/eoh/rtkweb) or in your facility's RTK Central File or Hazard Communication Standard file.
- You have a right to this information under the New Jersey Worker and Community Right to Know Act and the Public Employees Occupational Safety and Health (PEOSH) Act if you are a public worker in New Jersey, and under the federal Occupational Safety and Health Act (OSHA) if you are a private worker.
- The New Jersey Right to Know Act requires most employers to label chemicals in the workplace and requires public employers to provide their employees with information concerning chemical hazards and controls. The federal OSHA Hazard Communication Standard (29 CFR 1910.1200) and the PEOSH Hazard Communication Standard (N.J.A.C. 12:100-7) require employers to provide similar information and training to their employees.

This Fact Sheet is a summary of available information regarding the health hazards that may result from exposure. Duration of exposure, concentration of the substance and other factors will affect your susceptibility to any of the potential effects described below.

Health Hazard Information

Acute Health Effects

The following acute (short-term) health effects may occur immediately or shortly after exposure to **Silica, Cristobalite**:

- Contact can irritate the eyes and nose.
- Exposure to high levels of **Silica, Cristobalite** can cause a serious lung disease called *Silicosis* with cough, shortness of breath, and changes in the chest x-ray.

Chronic Health Effects

The following chronic (long-term) health effects can occur at some time after exposure to **Silica, Cristobalite** and can last for months or years:

Cancer Hazard

- **Silica, Cristobalite** is a CARCINOGEN in humans. There is evidence that *Crystalline Silica* causes lung cancer in humans.
- Many scientists believe there is no safe level of exposure to a carcinogen. Such substance may also have the potential for causing reproductive damage in humans.

Reproductive Hazard

- According to the information presently available to the New Jersey Department of Health, **Silica, Cristobalite** has not been tested for its ability to affect reproduction.

Other Effects

- Exposure to **Silica, Cristobalite** over a long period of time can cause a very serious lung disease called *Silicosis*. Simple *Silicosis* may only cause changes in the chest x-ray. Very high exposures can cause *Silicosis* to develop in a few weeks; with lower exposures it may occur over many years. *Silicosis* may cause death.
- If *Silicosis* develops, chances of getting *Tuberculosis* are increased.

Medical

Medical Testing

For frequent or potentially high exposure (half the TLV or greater), the following are recommended before beginning work and at regular times after that:

- Lung function tests
- Chest x-ray every one to three years

If abnormal chest x-ray develops, the following should be done periodically:

- Skin test for *Tuberculosis*

Any evaluation should include a careful history of past and present symptoms with an exam. Medical tests that look for damage already done are not a substitute for controlling exposure.

Request copies of your medical testing. You have a legal right to this information under the OSHA Access to Employee Exposure and Medical Records Standard (29 CFR 1910.1020).

Mixed Exposures

- Smoking can cause heart disease, lung cancer, emphysema, and other respiratory problems. It may worsen respiratory conditions caused by chemical exposure. Even if you have smoked for a long time, stopping now will reduce your risk of developing health problems.

Workplace Controls and Practices

Very toxic chemicals, or those that are reproductive hazards or sensitizers, require expert advice on control measures if a less toxic chemical cannot be substituted. Control measures include: (1) enclosing chemical processes for severely irritating and corrosive chemicals, (2) using local exhaust ventilation for chemicals that may be harmful with a single exposure, and (3) using general ventilation to control exposures to skin and eye irritants. For further information on workplace controls, consult the NIOSH document on Control Banding at www.cdc.gov/niosh/topics/ctrlbanding/.

The following work practices are also recommended:

- Label process containers.
- Provide employees with hazard information and training.
- Monitor airborne chemical concentrations.
- Use engineering controls if concentrations exceed recommended exposure levels.
- Provide eye wash fountains and emergency showers.
- Wash or shower if skin comes in contact with a hazardous material.
- Always wash at the end of the workshift.
- Change into clean clothing if clothing becomes contaminated.
- Do not take contaminated clothing home.
- Get special training to wash contaminated clothing.
- Do not eat, smoke, or drink in areas where chemicals are being handled, processed or stored.
- Wash hands carefully before eating, smoking, drinking, applying cosmetics or using the toilet.

In addition, the following may be useful or required:

- Use a vacuum or a wet method to reduce dust during clean-up. DO NOT DRY SWEEP.
- Use a high efficiency particulate air (HEPA) filter when vacuuming. Do not use a standard shop vacuum.

Personal Protective Equipment

The OSHA Personal Protective Equipment Standard (29 CFR 1910.132) requires employers to determine the appropriate personal protective equipment for each hazard and to train employees on how and when to use protective equipment.

The following recommendations are only guidelines and may not apply to every situation.

Gloves and Clothing

- Avoid skin contact with **Silica, Cristobalite**. Wear personal protective equipment made from material which can not be permeated or degraded by this substance. Safety equipment suppliers and manufacturers can provide recommendations on the most protective glove and clothing material for your operation.
- Safety equipment manufacturers recommend Nitrile and Natural Rubber for gloves, and Tyvek®, or the equivalent, as a protective clothing material.
- All protective clothing (suits, gloves, footwear, headgear) should be clean, available each day, and put on before work.

Eye Protection

- Wear eye protection with side shields or goggles.

Respiratory Protection

Improper use of respirators is dangerous. Respirators should only be used if the employer has implemented a written program that takes into account workplace conditions, requirements for worker training, respirator fit testing, and medical exams, as described in the OSHA Respiratory Protection Standard (29 CFR 1910.134).

- New Jersey Law (N.J.S.A. 34:5-182) requires that employers provide workers with full facepiece air purifying respirators when engineering controls cannot be used.
- Where the potential exists for exposure over **0.05 mg/m^3** (as *respirable dust)*, use a NIOSH approved negative pressure, air-purifying, particulate filter respirator with an N, R or P95 filter. More protection is provided by a full facepiece respirator than by a half-mask respirator, and even greater protection is provided by a powered-air purifying respirator.
- Leave the area immediately if (1) while wearing a filter or cartridge respirator you can smell, taste, or otherwise detect **Silica, Cristobalite**, (2) while wearing particulate filters abnormal resistance to breathing is experienced, or (3) eye irritation occurs while wearing a full facepiece respirator. Check to make sure the respirator-to-face seal is still good. If it is, replace the filter or cartridge. If the seal is no longer good, you may need a new respirator.
- Consider all potential sources of exposure in your workplace. You may need a combination of filters, prefilters or cartridges to protect against different forms of a chemical (such as vapor and mist) or against a mixture of chemicals.
- Where the potential exists for exposure over **0.5 mg/m^3** (as *respirable dust)*, use a NIOSH approved supplied-air respirator with a full facepiece operated in a pressure-demand or other positive-pressure mode. For increased protection use in combination with an auxiliary self-contained breathing apparatus or an emergency escape air cylinder.
- Exposure to **25 mg/m^3** is immediately dangerous to life and health. If the possibility of exposure above **25 mg/m^3** exists, use a NIOSH approved self-contained breathing apparatus with a full facepiece operated in a pressure-demand or other positive-pressure mode equipped with an emergency escape air cylinder.

Fire Hazards

If employees are expected to fight fires, they must be trained and equipped as stated in the OSHA Fire Brigades Standard (29 CFR 1910.156).

- Extinguish fire using an agent suitable for type of surrounding fire. **Silica, Cristobalite** itself does not burn.

X

Spills and Emergencies

If employees are required to clean-up spills, they must be properly trained and equipped. The OSHA Hazardous Waste Operations and Emergency Response Standard (29 CFR 1910.120) may apply.

If **Silica, Cristobalite** is spilled, take the following steps:

- Evacuate personnel and secure and control entrance to the area.
- Eliminate all ignition sources.
- Moisten spilled material first or use a HEPA-filter vacuum for clean-up and place into sealed containers for disposal.
- It may be necessary to contain and dispose of **Silica, Cristobalite** as a HAZARDOUS WASTE. Contact your state Department of Environmental Protection (DEP) or your regional office of the federal Environmental Protection Agency (EPA) for specific recommendations.

Handling and Storage

Prior to working with **Silica, Cristobalite** you should be trained on its proper handling and storage.

- A regulated, marked area should be established where **Silica, Cristobalite** is handled, used, or stored.
- **Silica, Cristobalite** is not compatible with OXIDIZING AGENTS (such as PERCHLORATES, PEROXIDES, PERMANGANATES, CHLORATES, NITRATES, CHLORINE, BROMINE and FLUORINE); ACETYLENE; and AMMONIA.
- Store in tightly closed containers in a cool, well-ventilated area.

Occupational Health Information Resources

The New Jersey Department of Health offers multiple services in occupational health. These services include providing informational resources, educational materials, public presentations, and industrial hygiene and medical investigations and evaluations.

For more information, please contact:

New Jersey Department of Health
Right to Know
PO Box 368
Trenton, NJ 08625-0368
Phone: 609-984-2202
Fax: 609-984-7407
E-mail: rtk@doh.state.nj.us
Web address: http://www.nj.gov/health/eoh/rtkweb

The Right to Know Hazardous Substance Fact Sheets are not intended to be copied and sold for commercial purposes.

GLOSSARY

ACGIH is the American Conference of Governmental Industrial Hygienists. They publish guidelines called Threshold Limit Values (TLVs) for exposure to workplace chemicals.

Acute Exposure Guideline Levels (AEGLs) are established by the EPA. They describe the risk to humans resulting from once-in-a lifetime, or rare, exposure to airborne chemicals.

Boiling point is the temperature at which a substance can change its physical state from a liquid to a gas.

A **carcinogen** is a substance that causes cancer.

The **CAS number** is unique, identifying number, assigned by the Chemical Abstracts Service, to a specific chemical.

CFR is the Code of Federal Regulations, which are the regulations of the United States government.

A **combustible** substance is a solid, liquid or gas that will burn.

A **corrosive** substance is a gas, liquid or solid that causes destruction of human skin or severe corrosion of containers.

The **critical temperature** is the temperature above which a gas cannot be liquefied, regardless of the pressure applied.

DEP is the New Jersey Department of Environmental Protection.

DOT is the Department of Transportation, the federal agency that regulates the transportation of chemicals.

EPA is the Environmental Protection Agency, the federal agency responsible for regulating environmental hazards.

ERG is the Emergency Response Guidebook. It is a guide for emergency responders for transportation emergencies involving hazardous substances.

Emergency Response Planning Guideline (ERPG) values provide estimates of concentration ranges where one reasonably might anticipate observing adverse effects.

A **fetus** is an unborn human or animal.

A **flammable** substance is a solid, liquid, vapor or gas that will ignite easily and burn rapidly.

The **flash point** is the temperature at which a liquid or solid gives off vapor that can form a flammable mixture with air.

IARC is the International Agency for Research on Cancer, a scientific group.

Ionization Potential is the amount of energy needed to remove an electron from an atom or molecule. It is measured in electron volts.

IRIS is the Integrated Risk Information System database on human health effects that may result from exposure to various chemicals, maintained by federal EPA.

LEL or **Lower Explosive Limit**, is the lowest concentration of a combustible substance (gas or vapor) in the air capable of continuing an explosion.

mg/m^3 means milligrams of a chemical in a cubic meter of air. It is a measure of concentration (weight/volume).

A **mutagen** is a substance that causes mutations. A **mutation** is a change in the genetic material in a body cell. Mutations can lead to birth defects, miscarriages, or cancer.

NFPA is the National Fire Protection Association. It classifies substances according to their fire and explosion hazard.

NIOSH is the National Institute for Occupational Safety and Health. It tests equipment, evaluates and approves respirators, conducts studies of workplace hazards, and proposes standards to OSHA.

NTP is the National Toxicology Program which tests chemicals and reviews evidence for cancer.

OSHA is the federal Occupational Safety and Health Administration, which adopts and enforces health and safety standards.

PEOSHA is the New Jersey Public Employees Occupational Safety and Health Act, which adopts and enforces health and safety standards in public workplaces.

Permeated is the movement of chemicals through protective materials.

ppm means parts of a substance per million parts of air. It is a measure of concentration by volume in air.

Protective Action Criteria (PAC) are values established by the Department of Energy and are based on AEGLs and ERPGs. They are used for emergency planning of chemical release events.

A **reactive** substance is a solid, liquid or gas that releases energy under certain conditions.

STEL is a Short Term Exposure Limit which is usually a 15-minute exposure that should not be exceeded at any time during a work day.

A **teratogen** is a substance that causes birth defects by damaging the fetus.

UEL or **Upper Explosive Limit** is the highest concentration in air above which there is too much fuel (gas or vapor) to begin a reaction or explosion.

Vapor Density is the ratio of the weight of a given volume of one gas to the weight of another (usually *Air*), at the same temperature and pressure.

The **vapor pressure** is a force exerted by the vapor in equilibrium with the solid or liquid phase of the same substance. The higher the vapor pressure the higher concentration of the substance in air.

Right to Know Hazardous Substance Fact Sheet

Emergency Responders Quick Reference

Common Name: **SILICA, CRISTOBALITE**

Synonyms: Calcined Diatomaceous Earth; Crystalline Silicon Dioxide, Crystabolite
CAS No: 14464-46-1
Molecular Formula: SiO_2
RTK Substance No: 1657
Description: Colorless, odorless, crystalline solid

HAZARD DATA

Hazard Rating	Firefighting	Reactivity
4 - Health **0 - Fire** **0 - Reactivity** **DOT#:** None **ERG Guide #:** None **Hazard Class:** None	Extinguish fire using an agent suitable for type of surrounding fire. **Silica, Cristobalite** itself does not burn.	**Silica, Cristobalite** is not compatible with OXIDIZING AGENTS (such as PERCHLORATES, PEROXIDES, PERMANGANATES, CHLORATES, NITRATES, CHLORINE, BROMINE and FLUORINE); ACETYLENE; and AMMONIA.

SPILL/LEAKS

Isolation Distance:

Spill: 25 meters (75 feet)

Moisten spilled material first or use a HEPA-filter vacuum for clean-up and place into sealed containers for disposal.

PHYSICAL PROPERTIES

Odor Threshold:	Odorless
Flash Point:	Noncombustible
Vapor Pressure:	0 mm Hg at 68°F (20°C)
Specific Gravity:	2.32 (water = 1)
Water Solubility:	Insoluble
Boiling Point:	4,046°F (2,230°C)
Melting Point:	3,133°F (1,723°C)
Molecular Weight:	60.08

EXPOSURE LIMITS

NIOSH: 0.05 mg/m^3, 10-hr TWA

ACGIH: 0.025 mg/m^3, 8-hr TWA

IDLH: 25 mg/m^3

The Protective Action Criteria values are:
PAC-1 = 0.075 mg/m^3
PAC-2 = 25 mg/m^3
PAC-3 = 25 mg/m^3

PROTECTIVE EQUIPMENT

Gloves: Nitrile and Natural Rubber

Coveralls: Tyvek®

Respirator: <0.5 mg/m^3 - Full facepiece APR with *High efficiency filter*
>0.5 mg/m^3 - SCBA

HEALTH EFFECTS

Eyes: Irritation
Skin: Irritation
Inhalation: Nose and lung irritation with cough and shortness of breath (*Silicosis*)
Chronic: *Crystalline Silica* causes cancer (lung) in humans.

FIRST AID AND DECONTAMINATION

Remove the person from exposure.
Flush eyes with large amounts of water for at least 15 minutes. Remove contact lenses if worn.
Remove contaminated clothing and wash contaminated skin with soap and water.
Begin artificial respiration if breathing has stopped and CPR if necessary.
Transfer promptly to a medical facility.

February 2010

APPENDIX C

CAD Model accompanying this document