UNIVERSITY OF AGDER

# Redesign of Utility Robot for Carbothermic Test Reactor


**Tore Meberg**

**Supervisors**
Cecilie Ødegård
John Fors


*This master's thesis is carried out as a part of the education at the University of Agder and is therefore approved as a part of this education. However, this does not imply that the University answers for the methods that are used or the conclusions that are drawn.*


University of Agder, 2015
Faculty of Engineering and Science
Department of Engineering Sciences

# Abstract

Production of aluminum based on a carbothermic reaction is an exciting field of research. It could potentially reduce the energy consumption of aluminum production drastically. Alcoa Norway Carbothermic has been involved in the field of carbothermic aluminum research since 1998. As a part of development of their newest carbothermic test reactor, the Hot Bowl reactor, Alcoa Norway Carbothermic has proposed a thesis regarding redesign of a machine used to lower different types of measuring equipment down into the reactor, called the utility robot. This thesis describe the process leading up to a new utility robot solution.

The new utility robot was designed in SolidWorks and dimensioned using calculations and FEM analyses in Abaqus. Technical drawings were composed for all fully developed components. These components were then issued for construction, and are currently being machined. Pneumatic and hydraulic cylinders, linear rails, bearings and other components were selected and ordered.

The final result is a nearly complete utility robot that fulfill the requirements and design specifications specified by Alcoa. The new solution is more automatic and is less labor intensive to operate than the old solution.

# Preface

This master's thesis is carried out as part of the education at the University of Agder Faculty of Engineering and Science, Department of Engineering Sciences, spring 2015. The goal of the thesis is to redesign a machine used for carrying out measurement on Alcoa's new carbothermic reactor currently under development.

Alcoa Norway Carbothermic has since 1998 been developing a process for producing aluminum based on a carbothermic reaction. Their last test reactor, the HEX reactor, is now decommissioned, and a new reactor is under development. Success in developing a method for carbothermic production of aluminum would revolutionize the aluminum process industry, resulting in less energy consumption and less space-consuming production facilities.

It is worth noting that this thesis has been carried out in the same period of time as the development for the rest of the reactor and its surrounding components. Some information regarding the utility robot's surroundings relevant for the design of a new utility robot was not present at the start of the semester, since they were not redesigned yet. As a consequence of this, the requirements and design specifications has been changing over the course of the semester.

I would like to give special thanks to my two supervisors, engineering manager John Fors and chief engineer Cecilie Ødegård, for countless advice throughout this semester, and for proof reading of the thesis. Their advice and insight have been essential for the final result of this thesis. I would also like to thank the employees at Alcoa Norway Carbothermic for valuable help throughout this semester.

Grimstad, 2015

Tore Meberg

Tore Meberg

# Contents

# List of Figures

# List of Tables

# Chapter 1

# Introduction

This chapter will introduce the reader to the content of the rest if this thesis.

## 1.1 Background

Alcoa Norway Carbothermic has since 1998 been developing a process for producing aluminum based on a carbothermic reaction. Up until 2006 several different reactor designs were tested and used. From 2006 to late 2013 the same reactor was used for research and gathering of data. This reactor, called the HEX reactor, is now decommissioned. A new test reactor, named the Hot Bowl reactor, and surrounding test equipment is currently under development.

## 1.2 Motivation

As the old reactor will be replaced and the surrounding machines are under revision a lot will change regarding the overall layout. The reactor and its placement will change, new machines are presented to the overall solution and so on. Consequently, new requirements and design specifications have been defined for the utility robot, requiring a new solution for mentioned robot.

The operation of the utility robot as of today is labor intensive and the operator is exposed to a somewhat demanding environment. CO-gas is likely to be present within the vicinity of the reactor, and certain areas may be subjected to extensive heat. The reactor is also prone to produce some amount of dust. It is in Alcoa's interest to make the process of operating the utility robot more automatic and simple, with less manual labor, and shorter time to do the mentioned work.

## 1.3 Problem Statement

Alcoa Norway Carbothermic requires a redesign of their utility robot used as part of their test reactor for producing aluminum based on a carbothermic reaction, and have proposed a thesis based around this. The student shall:

- Study the existing utility robot, its features and limitations
- Develop a new solution with a higher degree of automation, possibly improve the existing solution if this shows to be more suitable. The new/improved solution shall satisfy certain requirements and design criteria, listed in Chapter 3, and will contain:
  - CAD model of the solution in SolidWorks
  - Functional design specification (basis for PLC programming)

  - Work procedures for the operator
  - Safety precautions and safeguards
  - Technical drawings of developed solution
- Choose and order mechanical equipment needed for new solution
- If time allows, participate in the PLC programming of the control system

## 1.4 Scope of Work

This thesis will cover the development of a new robot used for lowering different types of probes and sensors down into Alcoa's carbothermic test reactor. The thesis will not cover redesign of the probes and sensors themselves.

## 1.5 Report Outline

**Chapter 2** provides the reader with the theoretical background needed in order to read the rest of this thesis.

**Chapter 3** presents requirements and design specifications for the new solution.

**Chapter 4** explains the concept development process leading to the final solution.

**Chapter 5** presents the final concept for the utility robot.

**Chapter 6** presents the utility robot's functional design specification.

**Chapter 7** presents calculations and analyses of critical components on the utility robot.

**Chapter 8** presents a conclusion for the thesis

# Chapter 2

# Theoretical Background

This chapter presents the theoretical background necessary to know in order to read the rest of this thesis. Firstly, the carbothermic process is discussed. Then the reader will be introduced to the reactor and the utility robot used prior to the development of the new equipment. Lastly, the new reactor and its surrounding equipment is introduced.

## 2.1 Carbothermic Reduction

A carbothermic reaction involves the reduction of a substance, often metal oxides, using carbon as a reduction agent. The final products of a carbothermic reaction is the metal in its elemental form, as well as carbon monoxide and carbon dioxide. A high temperature is needed for this process to take place at a satisfying rate [12]. One example of a carbothermic reaction is the production of iron with iron(III) oxide, $Fe_2O_3$, as a starting point. A simplified version of the chemical process mentioned above is shown i Equation 2.1.

$$2Fe_2O_3 + 3C \longrightarrow 4Fe + 3CO_2(g) \tag{2.1}$$

In Equation 2.1 iron(III) oxide reacts with carbon, resulting in elemental iron and carbon dioxide.

### 2.1.1 Carbothermic Reduction of Alumina

Alcoa's research project aims to develop a reactor suitable for full-scale production of aluminum by making use of carbothermic reduction of aluminum oxide. Aluminum oxide, $Al_2O_3$, is often called alumina, and will be addressed as so throughout this thesis. It is more difficult to reduce alumina to the elemental form of aluminum than it is to reduce iron(III) oxide to elemental iron. The reason for this is that aluminum is a very chemically reactive element which form strong bonds with oxygen [11]. The force of attraction between aluminum and oxygen is greater than that of carbon and oxygen at lower temperatures (aluminum has a stronger affinity to oxygen than carbon has), so a direct reduction of alumina to aluminum seems to be impossible.

Alcoa's experimental reactor utilizes the fact that aluminum carbide, $Al_4C_3$, is formed as an intermediate stage in the carbothermic reaction. Alumina and carbon react to form aluminum carbide and carbon monoxide, as shown i Equation 2.2. This process takes place at around 1950 °C.

$$\underbrace{2Al_2O_3}_{\text{alumina}} + 9C \longrightarrow \underbrace{Al_4C_3}_{\text{aluminum carbide}} + 6CO(g) \tag{2.2}$$

As the amount of aluminum carbide gradually builds up inside the reactor, a new process will take place, granted a sufficiently high temperature is obtainable. The newly formed aluminum carbide reacts with the remaining alumina to form carbon monoxide and, most importantly, elemental aluminum. This process requires a temperature of around 2050 °C to take place. The molten mixture of aluminum carbide and alumina is in the form of slag. The chemical equation for this reaction is shown in Equation 2.3.

$$\underbrace{Al_4C_3 + Al_2O_3}_{\text{slag}} \longrightarrow 6Al + 3CO(g) \tag{2.3}$$

The overall reaction based on the two stages in Equations 2.2 and 2.3 can be represented as shown i Equation 2.4.

$$Al_2O_3 + 3C \longrightarrow 2Al + 3CO(g) \tag{2.4}$$

## 2.2 The HEX Reactor

The last experimental reactor Alcoa developed and tested was call the HEX reactor, due to its hexagonal shape. This section will introduce the reader to the utility robot used on the HEX reactor. The HEX reactor itself will not be presented here.

## 2.3 The Utility Robot Used in HEX Reactor

The utility robot is a machine that lowers different types of measuring equipment down into the reactor. Most of this measuring equipment are used for measuring different parameters, such as temperature and metal level, but there are also lances that take samples of the alloy and slag within the reactor. The utility robot used for the HEX reactor is shown in Figure 2.1(a).

The HEX utility robot's main components are indicated in Figure 2.1(b). These components and what they are used for is explained in the next section.

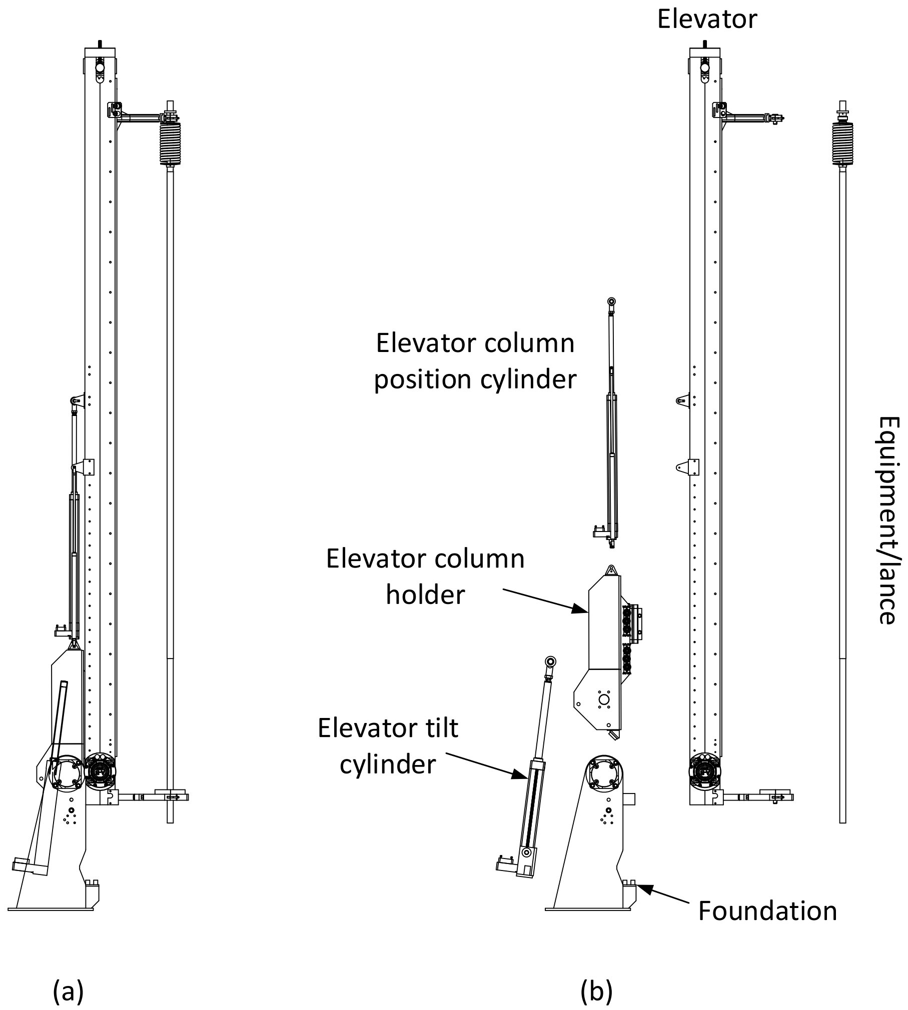



Figure 2.1: The HEX utility robot

### 2.3.1 Key Features of the HEX Utility Robot

In this section, the key features of the HEX utility robot is presented and explained.

**Elevator**

The elevator is the main feature of the utility robot. It consists of a five meter long beam called the elevator column, and a cart running in linear rails, as can be seen in Figure 2.2(a). The cart is actuated by the means of a servo motor mounted on the lower shaft of the elevator. The shaft drives a sprocket, which in turn drives a chain indicated as a blue belt in Figure 2.2(a). A second shaft is placed on the top of the elevator. The chain runs between these two shafts. The cart is fastened to the chain, and moves along with the motion of the chain, guided by the linear rails. The lance centering arm, located at the bottom of the elevator, helps keeping the horizontal displacement of the lance at a minimum, as it has to enter into a relatively narrow opening in the reactor roof (utility pipe, explained in Section 2.4).

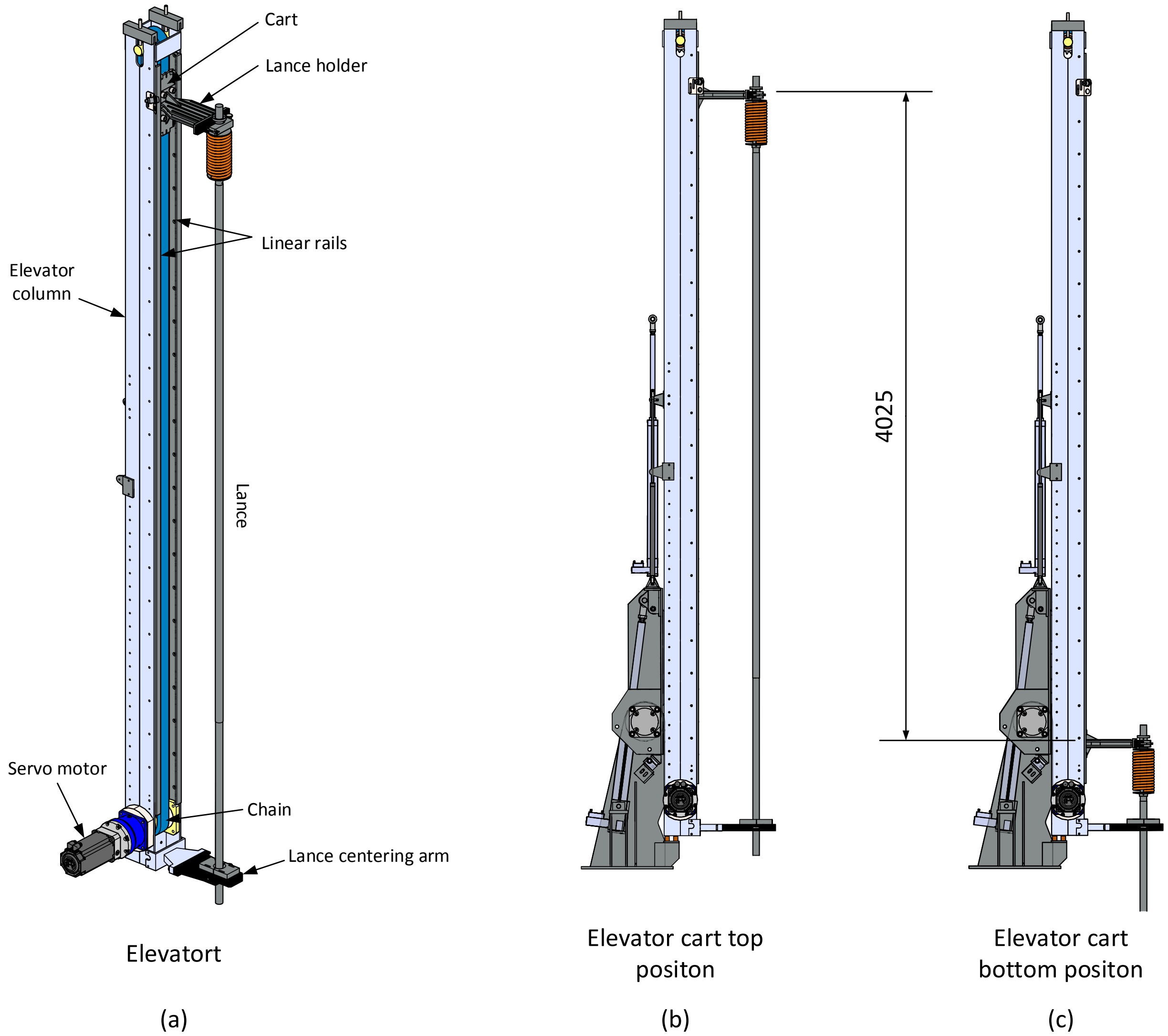



Figure 2.2: HEX elevator

Figure 2.2(b) presents the utility robot with the cart in its top position. This is the initial position prior to measurement or sampling. Figure 2.2 shows the cart in bottom position. The total travel distance of the elevator cart is 4025 mm, indicated on the figure.

The elevator cart can be seen in Figure 2.3. Four rollers are welded to the cart for guiding the cart along its path in the linear rails mounted on the elevator column. The interface between the utility robot and the lance is indicated as the lance holder in Figure 2.3. The lance holder locks the lance to the elevator cart.

The purpose of the elevator is to lower the equipment down into the reactor. The distance and velocity at which the elevator travels depends on what type of probe that is mounted on the robot.

### Elevator Column Position

The elevator column position feature is implemented in order to reach the required travel distance of the elevator, and not exceed the maximum allowable height of the utility robot, causing it to be withing collision range of the overhead crane, discussed in Section 2.6.2. This feature can be seen as a telescopic actuation of the elevator column. Figure 2.4 shows the working principle of the elevator column position feature. Figure 2.4(a) shows the robot in upper elevator column position. The total height of the HEX utility robot in this position is 5721 mm. In lower elevator column position (Figure 2.4(b)) the HEX utility robot has a total height of 5221 mm. The elevator column position feature consists of an electric cylinder and two gas springs

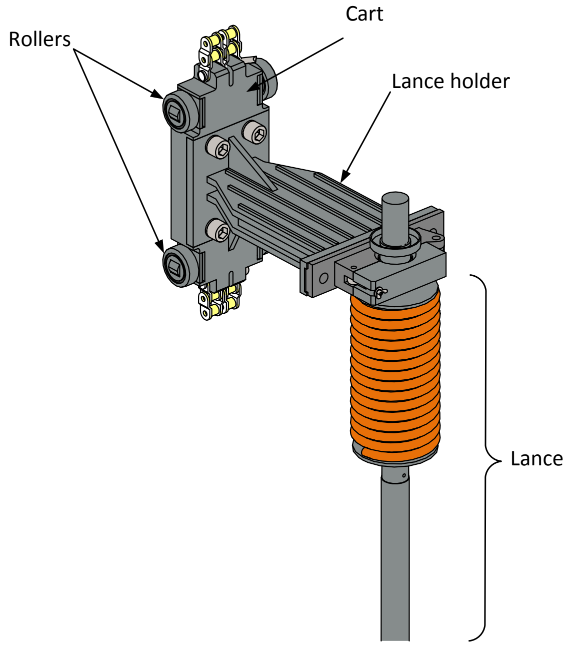



Figure 2.3: The HEX elevator cart

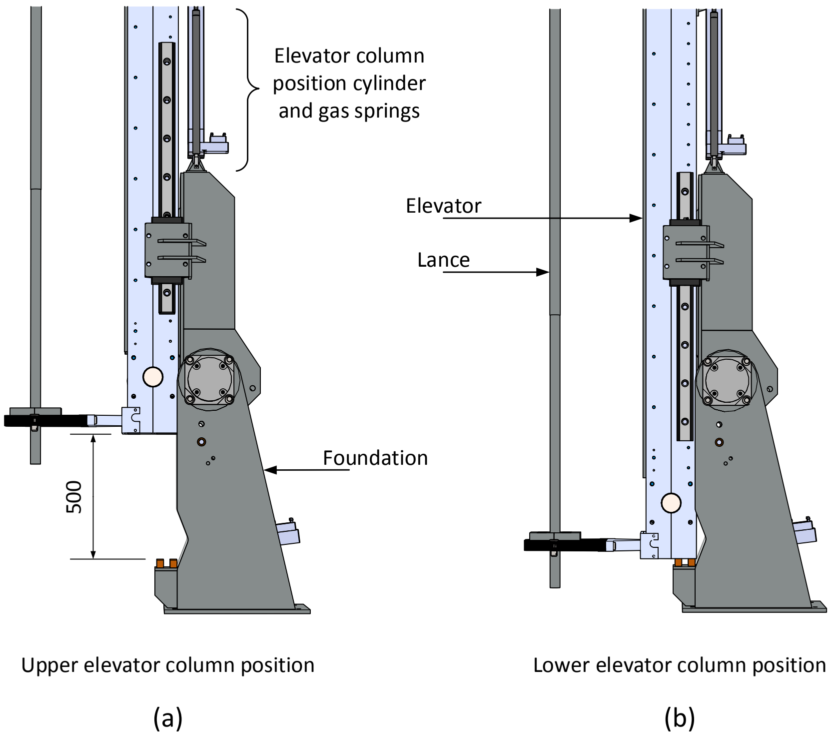



Figure 2.4: HEX utility robot elevator column position

coupled in parallel with the cylinder's axis of motion. The elevator column position feature has a travel distance of 500 mm, as indicated in Figure 2.4(a).

### Elevator Column Tilt

The elevator column tilt feature is used when changing and refitting the equipment. The utility robot is actuated from vertical to horizontal position before changing or refitting of the probe lance. The tilting motion is carried out by an electric cylinder, called elevator column cylinder in Figure 2.5. The elevator column cylinder has two gas springs coupled in parallel with the direction of the cylinder motion in order to reduce cylinder load.

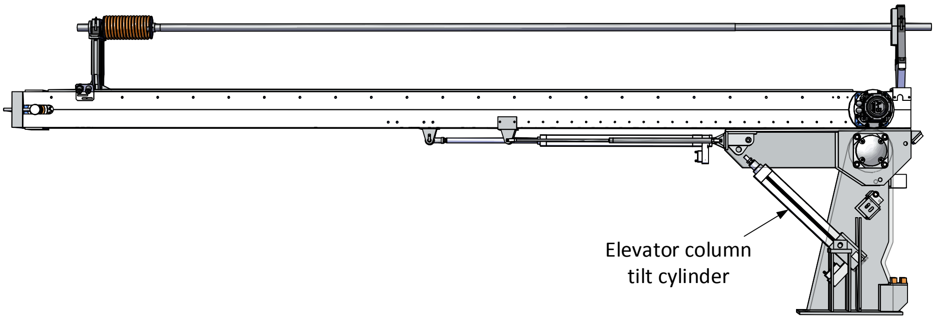



Figure 2.5: Elevator column tilt, horizontal position, HEX utility robot

In addition to being used when changing lances, the elevator column tilt feature is used to avoid collision between the utility robot and the overhead crane when the utility robot is not in use.

### Torque Release

In a carbothermic process, the reactor headspace (space between liquid and the inner ceiling of the reactor) contains different types of gases and dust. These particles will condensate on all surfaces. This is also the case with the entry hole (utility pipe) in the ceiling for the utility robot lances, even though it is continuously flushed with argon. In some cases such condensation can obstruct the entry to the headspace and hence prevent a lance from entering. As the lances are long and slender, and some of them have some sensitive graphite components at the tip, the lance may break or buckle. A torque release mechanism was introduced to the solution to cushion the impact.

All lances used by the utility robot have a spring mechanism mounted on the top part of its lance. This mechanism, shown in Figure 2.6, is called the torque release.

The main components for every lance mounted in the HEX utility robot are the torque release mechanism, the pipe and the tool, shown in Figure 2.6(a). The torque release consists of three sleeves, a spherical bearing, a spring and the top part of the lance. These components are shown in Figure 2.6(b). The two fixed sleeves in Figure 2.6(b) are fixed to the pipe. The sliding bearing and sleeve from Figure 2.6(b) are able to slide along the pipe's axial direction. When a collision occurs, the whole lance is displaced upwards referred to the elevator cart, except for the two sliding components.

All lances use the same spring and they all have the same preload. The springs used are delivered by Lesjöfors, custom produced after Alcoa's specifications. Relevant data for the chosen spring are listed in Table 2.1.

Table 2.1: Relevant data, torque release spring

| Description | Length | Force |
|---|---|---|
| $L_0$, free length | $310 \pm 5.2$ mm | 0 N |
| $L_1$, preload length | 260 mm | $1737 \pm 208$ N |
| $L_2$, fully compressed | 170 mm | $4864 \pm 255$ N |

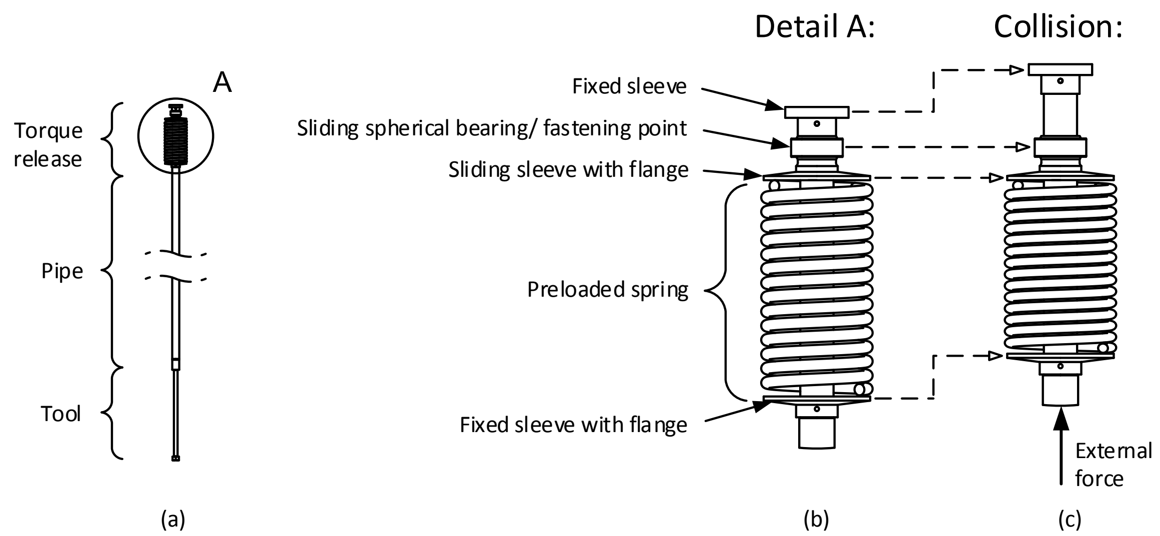



Figure 2.6: Components of the torque release mechanism used for the HEX reactor

The preload length, $L_1$ from Table 2.1, is the length at which the spring is mounted with in the torque release mechanism. The difference in lengths between the preload length $L_1$ and the fully compressed length $L_2$ is $\Delta L = 260$ mm $- 170$ mm $= 90$ mm. This distance is the total available travel distance of the torque release mechanism. The forces for the different lengths are also stated in Table 2.1. Figure 2.7 present the data in Table 2.1 as the traveled distance of the torque release with respect to the produced spring force.

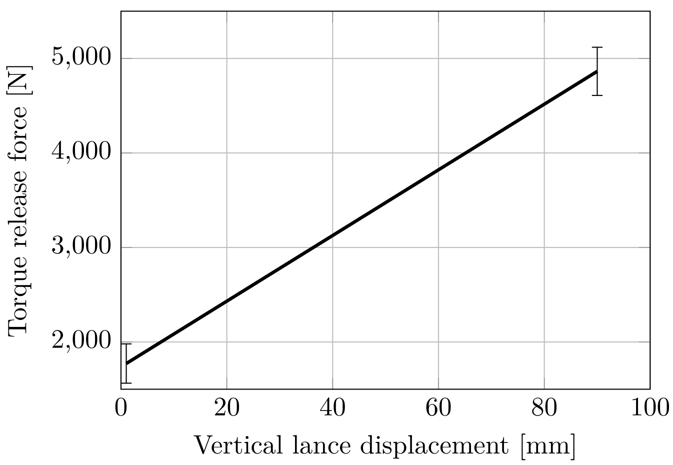



Figure 2.7: Torque release preload as a function of vertical lance displacement

## 2.3.2 HEX Utility Robot Lances

This section will explain the different probes and sensors used by the HEX utility robot.

### Agellis Probe

The Agellis probe can determine whether it is in contact with aluminum or slag. This probe is used to determine the level of molten aluminum present in the reactor. It gets its name from the company that developed it, the Agellis Group AB.

The Agellis probe is fragile and does not tolerate the high temperature for long. Because of this, the Agellis probe is covered in a paper sheath with ceramic coating for protection. The paper sheath is removed upon pulling the Agellis lance out of the reactor. This is done using a pneumatically operated clamping device. This device, called the paper sheath removal clamp, is described in Section 2.4.

#### Mechanical Level Probe

The mechanical level probe determines the total liquid level inside the reactor. The probe referred to on this lance is a simple reinforcing bar with a diameter of 10–12 mm. The probe is lowered a given distance down into the reactor. The grooves across the reinforcing bar's surface are manually inspected afterwards in order to determine the liquid level. This lance is also used for collectiong slag samples by knocking off slag fastened to the reinforcing bar.

#### Temperature Probe

The temperature lance is a type C thermocouple element encapsulated in graphite. The temperature lance measures the temperature in the reactor throughout the liquid, resulting in a temperature profile for the entire height of the reactor. The probe follows a predetermined pattern of movements to achieve as accurate measurements as possible.

#### Cleaning Lance

The cleaning lance is not a probe. It is used for keeping the utility pipe clean and free from condensate build-ups at the entry to the reactor headspace.

#### Imaging Lance

The imaging lance used for the HEX reactor was a simple webcam that was lowered into the headspace of the reactor. This was an initial test lance to establish the opacity in the headspace for future imaging of the reactor headspace.

#### Alloy Sampling Probe

The alloy sampling probe is used for taking alloy samples of the aluminum inside the reactor. It consists of a long graphite pipe with deep grooves. A metal alloy sample is obtained by collecting aluminum from the groove.

## 2.4 The Utility Pipe Used in HEX Reactor

The utility pipe, also called the utility port or sounding port, is the pipe in which the utility robot's probes are guided down through in order to access the reactor. Its main components are shown in Figure 2.8.

#### Stuffing box

For several reasons, one of the being that graphite components vaporize in contact with air at sufficiently high temperatures, the inside of the reactor and peripheral components are flushed with argon. The reactor has a slightly positive pressure, and the utility pipe is flushed with argon below the ceramic valve to prevent gas flow through the utility pipe. The stuffing box is used for maintaining the positive pressure under measurements by the means of a gasket that seals the gap between the top of the utility pipe and the lance submerged into the reactor.

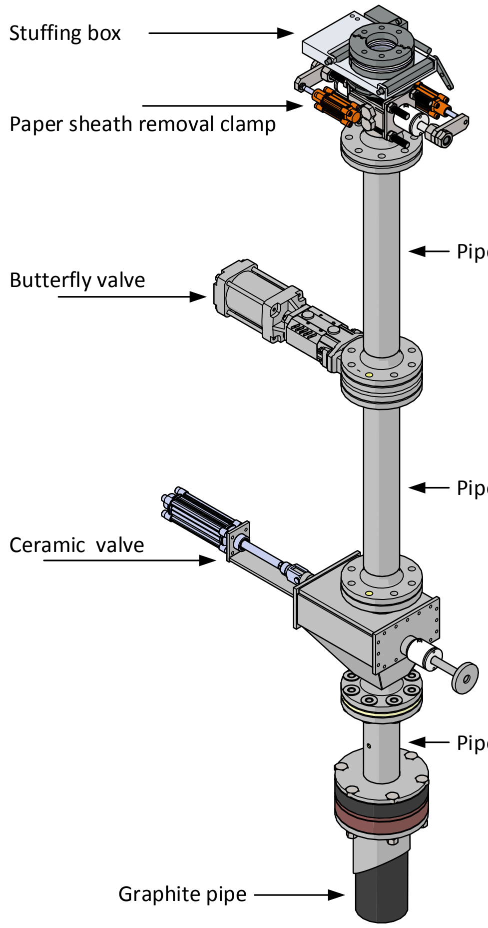



Figure 2.8: The HEX utility pipe

#### Paper Sheath Removal Clamp

The paper sheath removal clamp is used for removing the paper sheath from the Agellis lance.

#### Valves

The utility pipe includes two valves. The butterfly valve is used for isolating the utility pipe opening from the surroundings while no lance is used. The butterfly valve is gas tight. The ceramic valve's main component is a sliding ceramic plate. The ceramic plate blocks the utility pipe, protecting the rest of the pipe from radiation heating.

#### Graphite Pipe

The graphite pipe is the interface between the utility pipe and the reactor. It is used to prevent heat from the reactor to propagate to the utility pipe. The connection flange to the reactor ceiling is actively cooled.

## 2.5 The Hot Bowl Reactor

The HEX reactor has been used for around seven years. A new reactor is now under development. The new reactor, called the Hot Bowl reactor, will have many new features and auxiliary machines. This section will introduce the Hot Bowl reactor, some of its new features and the features of the Hot Bowl research facility relevant to the final design of the Hot Bowl utility robot.

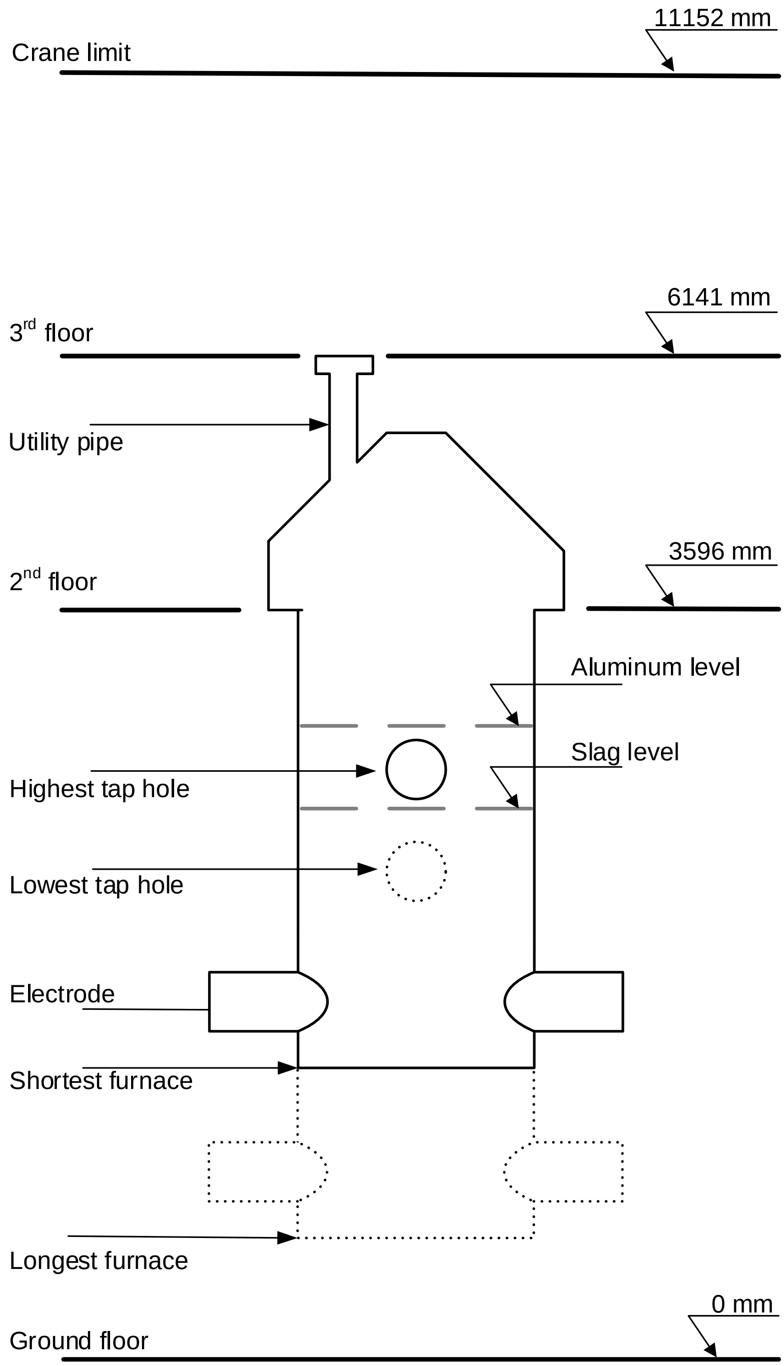



Figure 2.9: Concept sketch of the Hot Bowl reactor

As can be seen in Figure 2.9, the Hot Bowl reactor is placed in second floor. The utility pipe exits the reactor from the reactor ceiling, and extends upwards. The top of the utility pipe is flush with third floor, where the utility robot is located. Electrodes mounted at the bottom part of the reactor supplies the necessary energy to keep the carbothermic reaction going. The metal level in the reactor is above the tap hole, so that the metal can be tapped from the reactor if desired. The slag level is beneath the tap hole. Heights from ground floor and up to second and third floor is indicated in Figure 2.9.

### 2.5.1 Hot Bowl Reactor Height Adjustment

One of the new features of the Hot Bowl reactor is that it allows for adjustments of the reactor total height, and the placement of the tap hole. This allows for the team to choose the reactor size that best fits what is to be tested or measured.

The length of the reactor and the placement of the tap hole is addressed as the reactor's configuration. Figure 2.9 indicates nominal and maximal configuration (shortest reactor and longest reactor respectively) of the reactor. Nominal configuration represents the minimum reactor height. In nominal configuration, the placement of the tap hole is fixed. The difference in nominal and maximal configuration is 508 mm. This length can be arbitrarily distributed about either side of the tap hole, to be able to place the tap hole at the desired location along the reactor height.

### 2.5.2 The Hot Bowl Utility Pipe

The Hot Bowl utility pipe consist of the same components as the HEX utility robot (Figure 2.8) except that the Hot Bowl utility pipe is missing the paper sheath removal clamp, used together with the Agellis lance. The paper sheath removal clamp is moved to operate above the utility stuffing box to facilitate disposal of the paper sheath. The Hot Bowl utility pipe is presented in Figure 2.10.

All components on the Hot Bowl utility pipe works in the exact same way as for the HEX utility pipe (Section 2.4), although some of them are revised.

## 2.6 Hot Bowl Research Facility

The carbothermic research facility is located at Alcoa's facilities on Lista, Norway. The utility robot is located on third floor of the research facility. Some components surrounding the Hot Bowl reactor in the carbothermic research facility is of importance to the development of a new utility robot, and will be introduced in this section.

### 2.6.1 The Support Frame

The support frame is where the utility robot is to be mounted on. It consists of steel beams of the type HE 160B assembled in a configuration as shown in Figure 2.11.

The support frame is located in third floor, with the reactor positioned directly below it. The off-gas pipe is placed in the center of the reactor ceiling. A robot is placed above the off-gas pipe, often called the off-gas stoker. The off-gas stoker's only task is keeping the off-gas pipe free from condensate build-ups.

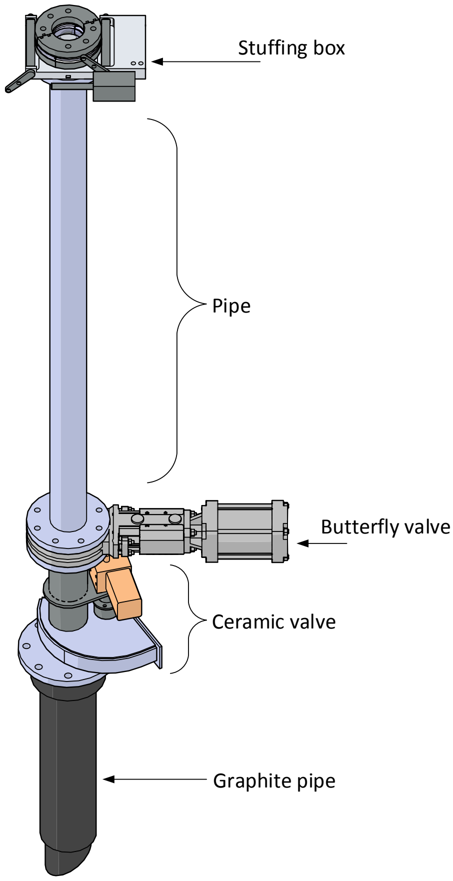



Figure 2.10: The Hot Bowl utility pipe

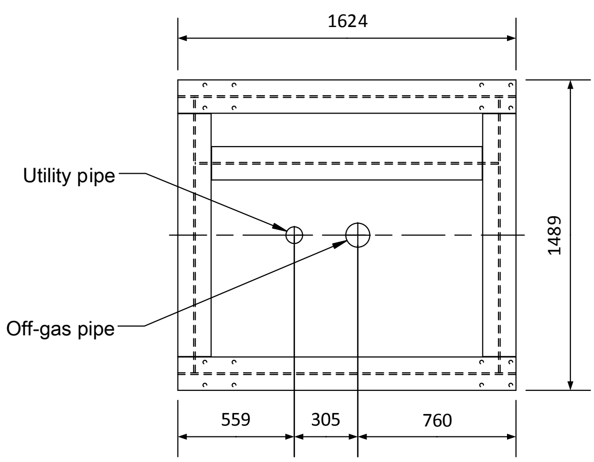



Figure 2.11: Primary dimensions and relevant length, support frame

### 2.6.2 Overhead Crane

The research facility where the experimental reactors are assembled and tested has an overhead crane, used under assembling of new equipment and general internal logistics of raw material and equipment during campaigns. A concept sketch of the crane is shown in Figure 2.12.

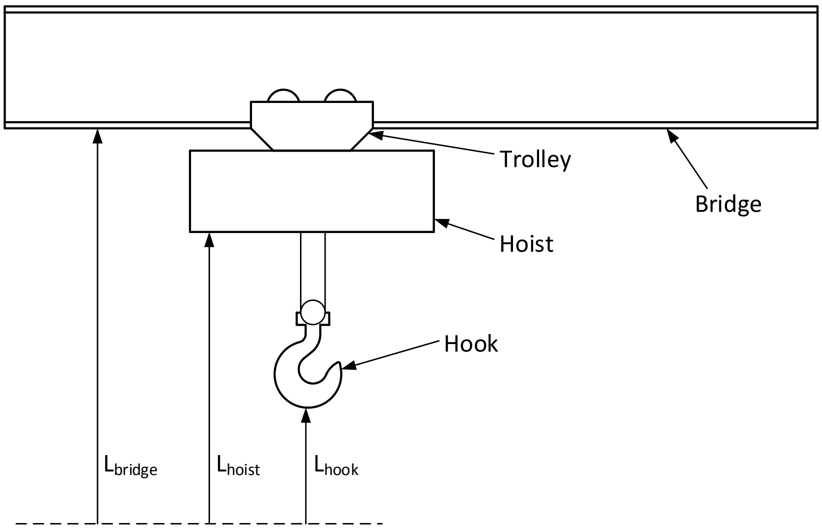



Figure 2.12: Concept sketch of the overhead crane installed in the research station ceiling

Three heights are defined in Figure 2.12; $L_{\text{hook}}$, $L_{\text{hoist}}$ and $L_{\text{bridge}}$. These heights are defined as the distance from third floor and up to selected components. The distances are shown in Table 2.2. These values were measured at the research station using a laser distance meter, so these values will probably deviate some from the real values.

Table 2.2: Lengths from third floor and up to selected crane components, Figure 2.12

| Description | Length [mm] |
|---|---|
| $L_{\text{hook}}$ | 5011 |
| $L_{\text{hoist}}$ | 5390 |
| $L_{\text{bridge}}$ | 5880 |

$L_{\text{hook}}$ is the height from third floor and up to the hook when the hook is fully hoisted.

### 2.6.3 Service Platform

The HEX utility robot had an elevator tilt feature, allowing the changing of the lances to be done from floor level. This feature is undesirable for the new solution (more about this in Section 3.2). A service platform has been developed in parallel with the development of the new utility robot. The platform, designed by Alcoa Carbothermic's layout engineer, is depicted in Figure 2.13. The service platform is used when changing the lances. The operator walks up to the top floor of the service platform and change lances by detaching the mounted lance and choosing another lance from the lance rack, indicated in Figure 2.13(b).

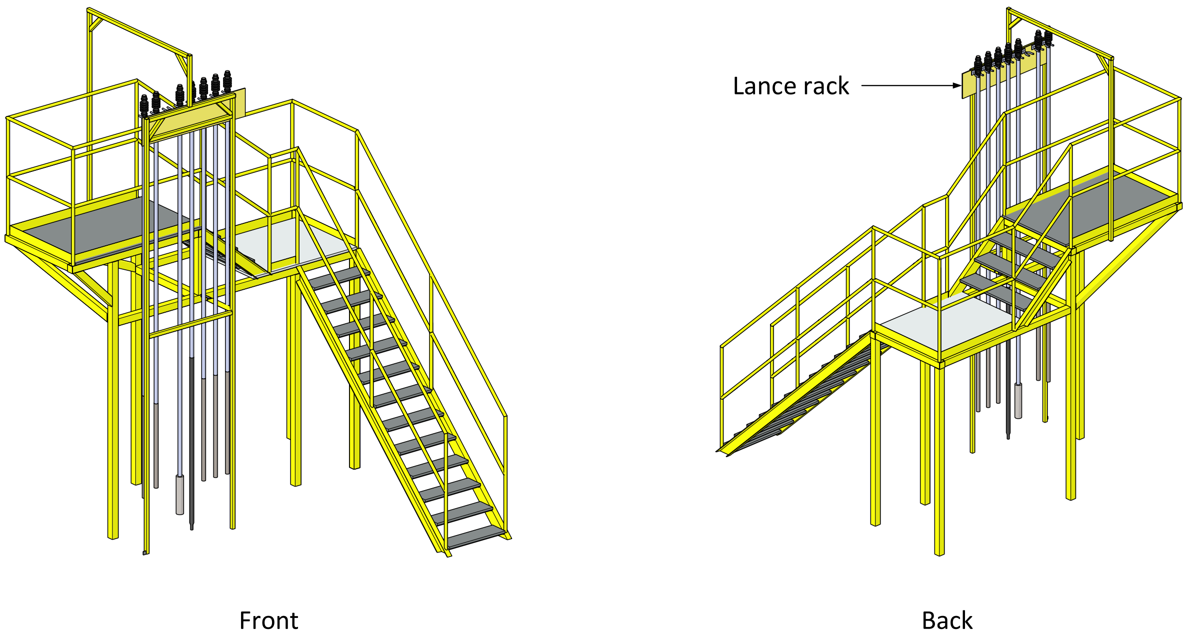



Figure 2.13: Service platform to be used together with the new utility robot

### 2.6.4 Continuous Level Measuring Probe

The continuous level measuring probe is a new machine not fully developed yet. Its purpose is to measure the aluminum level inside the reactor. It is to be installed in the vicinity of the utility pipe on third floor. The continuous level measuring probe will be placed on the top of the utility pipe whenever the utility pipe is not in use. The probe is a laser that operates with a time-of-flight principle for measuring the total liquid level of the reactor.

### 2.6.5 Lance Handler

The implementation of the continuous level measurement explained above and its high operation time requirement imposed shorter lance changing times and automatic Agellis lance paper sheath removal, as this new equipment use the utility pipe.

A new machine was proposed for automatically changing of the lances. The new robot, called the lance handler, is to take lances from the lance rack indicated in Figure 2.13 and mount them in the utility robot.

This was acknowledged rather late in the project and implementation of an automated lance handling machine and the automated removal tool for the Agellis paper sheath will be implemented during June–August this year.

# Chapter 3

# Requirements and Design Specifications

The new solution for the utility robot has to fulfill certain requirements and design specifications. This chapter explain these requirements and specifications.

## 3.1 Requirements

Regular meetings with Alcoa's supervisor has been carried out several times a week throughout the course of this semester. Requirements have been specified for the machine on demand, meaning that the requirements have been made when a question arise. Many of the questions asked during these meetings have been answered with recommendations, not requirement. Consequently, the list of requirements are a short one.

### Utility Robot Placement

The utility robot is to be mounted on the support frame located on third floor. The support frame will have other equipment mounted to it as well. The main machine apart from the utility robot to be mounted on the support frame is the off-gas stoker. Its footprint is shown in Figure 3.1. The utility robot is to be placed on the support frame without interfering with other equipment.

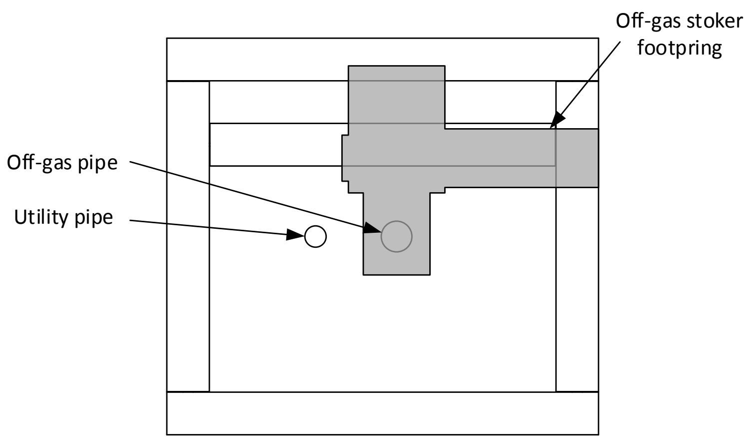



Figure 3.1: Third floor support frame

More equipment is to be mounted on the left side on the off-gas stoker, but these components are not designed yet.

#### Utility Robot Height

Maximum allowable height of the robot in initial position is determined by the height of the overhead crane presented in Section 2.6.2. It is decided that 50 mm free space between the top of the robot and the hook of the overhead crane is required. This length is measured to be $L_{\text{hook}} = 5011$ mm. From the CAD model of the HEX utility robot it is observed that this robot in lower elevator column position (see Section 2.3.1) is 5221 mm long. The HEX robot is 260 mm higher than the maximum height of the new utility robot.

#### Lance Reach

The lance lengths are determined by gathering all relevant lengths of the reactor, and define one criterion for how far down each lance needs to be able to travel. As was discussed in Section 2.5.1, the height and tap hole placement of the reactor is adjustable. Some lance length criteria are defined with respect to the tap hole, and some are defined with respect to the reactor electrodes. In order to make the lances long enough, it is needed to decide the reactor configuration which yield the longest required lance length. Some lances are independent of the reactor configuration. All lances that depend on the reactor configuration require the longest lances when the reactor has its maximum height, with the tap hole placed as far down as possible. Reactor nominal configuration and relevant lengths can be seen in Figure 3.2(a). Maximum configuration with the tap hole placed as low as possible is shown in Figure 3.2(b).

Table 3.1: Required lance lengths

| Lance | Reach criterion | Length below third floor |
|---|---|---|
| Temperature, C-element | Top of electrodes | 4343 mm |
| Temperature, pyrometer | Top of electrodes | 4343 mm |
| Agellis | As far down that one is sure to detect slag.<br>Safe to assume presence of slag 200 mm below tap hole | 3814 mm |
| Alloy sampler | To tap hole | 3614 mm |
| Mechanical level | 50 mm below tap hole | 3664 mm |
| Imaging | Inside the reactor headspace | 2705 mm |
| Cleaning | A few centimeters below utility pipe | 2605 mm |

#### Electric Conductivity Isolation

Isolation from electric conductivity between the lances and the rest of the utility robot is necessary for the final solution. This is necessary due to the fact that the content inside the reactor can have a voltage potential in relation to ground, and it is not desirable to lead this voltage to ground through the utility robot.

## 3.2 Design Specifications

#### Environment

Although the utility robot is in the vicinity of an area with CO-environment and high temperatures, these factors shall not be taken into account when choosing components for the utility robot.

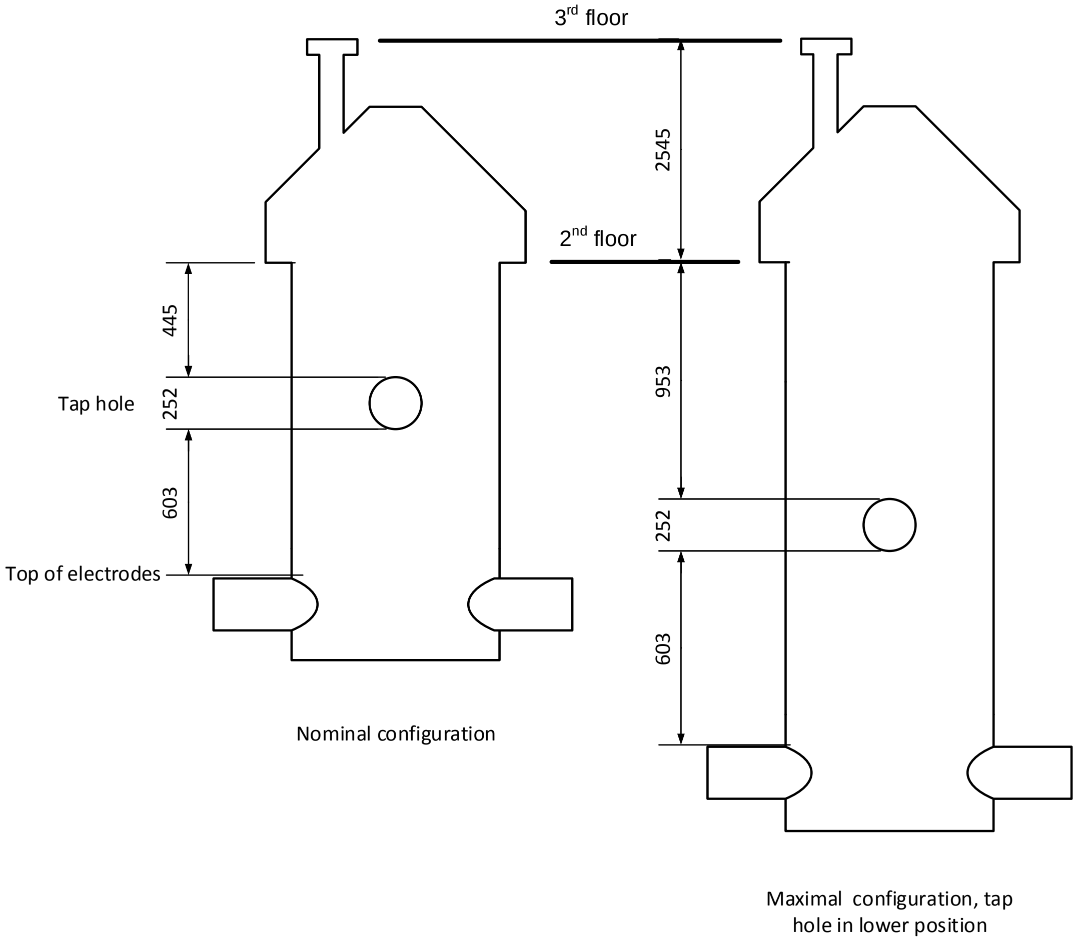



Figure 3.2: Hot Bowl reactor lengths

### Utility Robot Components Placement

The utility robot will mainly be placed in the third floor, with some parts of it going through the floor. It would be advantageous to place as much as possible of the equipment for the utility robot on the third floor, due to higher safety requirements and restricted space on the second floor. Ideally, no work is to be done on second floor while a campaign is running.

### Human Workload

The solution shall be designed with automation in mind. As little manual labor and human interaction as possible is desirable.

### Torque Release

The torque release concept from the HEX utility robot is desirable to carry on to the new utility robot. However, to make the operation of changing lances a more ergonomic experience, it is desirable to remove the old torque release solution from the lances in order to make them lighter and easier to handle. A suggested solution is to replace the springs with a pneumatic cylinder with variable pressure. This allows for the use of only one such device to produce the different reaction forces required for the different types of lances, instead of having springs of different stiffness mounted on every lance. This feature is desirable since the lances today are heavy, and it is in Alcoa's interest to improve the ergonomics of the lances.

### Elevator Column Tilt

The elevator column tilt feature is to be avoided, due to decrease in the structure stability caused by it. This is also important due to the fact that while the utility robot was tilted in the horizontal position, it blocked one of the two emergency exits on the research facility's third floor. By removing the elevator column tilt, a new solution for how the operator changes the equipment needs to be implemented.

### Lance Handler

As of March 2015 it is decided that a continuous level measuring probe is to be implemented into the solution. This probe is an independent equipment mounted on the side of the utility robot. The continuous measurement probe computes the reactor content level by using laser measurements. When in use, the probe is put on top of the utility pipe (nothing needs to be lowered down the utility pipe), and the probe sends laser pulses down into the reactor from the top of the pipe. The continuous level measurement probe will be used whenever the utility robot is not carrying out any measurements. It is desirable for the continuous measurement to start right after the utility robot has carried out measurements. Since the utility robot's lance would collide with the continuous measuring probe when the latter is placed over the utility pipe, the lance needs to be taken out of the utility robot right after measurement and put away. For an operator to do this manually, it would both increase the time for the operator at the third floor and reduce the available time for the continuous level measurement. The latter due to safety procedures for manual work with the robot. So a new machine needs to be designed and implemented for automatic removal of the lances after a measurement is carried out. Since a new robot is needed to handle lances anyway, it was decided that the new robot is to carry out the whole lance changing procedure. This robot, hereby called the lance handler, will remove the lances from the robot right after measurement and store them in a space assigned for the lances. The lance handler will not be developed in this thesis, but will have impact on the design of the utility robot.

# Chapter 4

# Concept Development

This chapter will focus on the process leading up to the final design of the utility robot.

## 4.1 Elevator Column

The elevator column is the main structure of the utility robot.

The design of the elevator column for the HEX reactor was determined by the elevator column tilt feature. This feature put emphasis on weight reduction of the elevator column. As a result, the elevator column was chosen to be made up of aluminum. In order to get the correct dimensions and strength, the elevator column for the HEX utility robot was made up of two C-beams bolted together in the web. The cross-section of the beam used for the HEX utility robot is shown in Figure 4.1(a).

The Hot Bowl utility robot shall not contain an elevator column tilt feature, so weight is not as essential this time around. The elevator column was therefore chosen to be a steel HE 200A beam. Its dimensions can be seen in Figure 4.1(b).

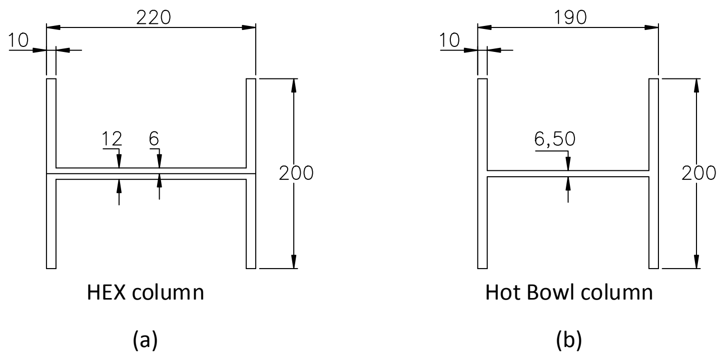



Figure 4.1: Cross-sectional area of elevator column, HEX and Hot Bowl

## 4.2 Chain Tensioner

The chain tensioner used on the utility robot for the HEX reactor was implemented in the upper shaft, as shown in Figure 4.2. The HEX driven shaft depicted has two screws going through it. These screws are entered through a block, indicated in the mentioned figure. Two nuts are fastened on the top of the screws (nuts not present in figure). The chain tension is thereby determined by the fastening torque of the nuts.

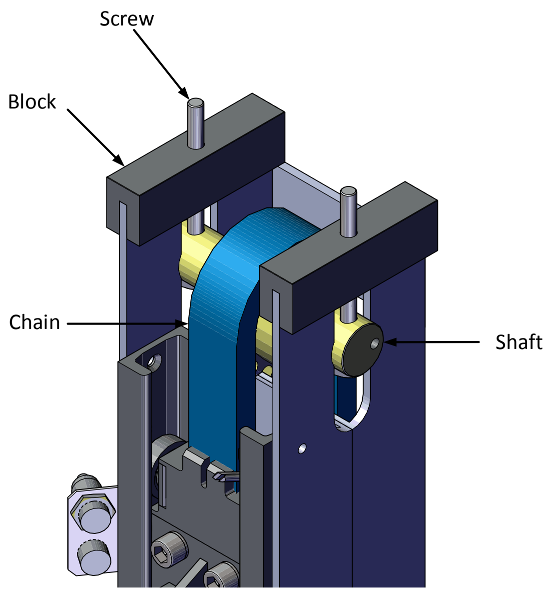



Figure 4.2: HEX driven shaft and chain tensioner

The HEX utility robot could not be lowered beneath the floor on which the robot was mounted. The redesigned robot will be able to do this due to several design aspects. If one were to use the same chain tensioner solution as was done for HEX, the chain tensioner would needed to be placed at the lower shaft, since the motor is placed on the upper shaft for the new solution (explained in Section 4.3). This is however undesirable, as the operator would need to stay on the second floor (floor below utility robot) when using the chain tensioner. In accordance with the design specifications, it is desirable to keep as little work as possible on the second floor, so a new solution is needed.

A chain tensioner was not fully developed in this thesis. From here on, it is assumed that the chain tensioner pre-tensions the chain with $F_{\text{pre}} = 10$ kN.

## 4.3 Upper Shaft and Surrounding Components

On the utility robot used for the HEX reactor, the shaft coupled to the motor (the driving shaft) was located at the bottom of the elevator column, and the driven shaft was located at the top. This is the best solution for the HEX robot. As mentioned above, the elevator column tilt feature brought with it the need for weight reduction. If the motor were to be mounted on the top end of the HEX robot, it would result in increased load on the elevator column tilt cylinder.

The Hot Bowl utility robot can be lowered beneath floor level. This feature have two important consequences for the design of the new utility robot. Firstly, if the motor were to be mounted on the lower shaft, as it was done for HEX, the motor would come closer to the reactor, and because of this be subjected to more dust particles and possibly excessive heat. Figure 4.3 shows how much further down the Hot Bowl utility robot moves as opposed to the HEX utility robot. Lastly, there is no room for the motor to move through the floor. The support frame for which the robot is to be mounted on would need to be redesigned for the motor to be able to do this.

As a consequence of this, the driving shaft was chosen to be located at the top end of the elevator column, opposite as for the HEX utility robot design.

The final solution for the assembled upper shaft can be seen in Figure 4.4. The rest of this section will explain how the upper shaft and surrounding components are designed.

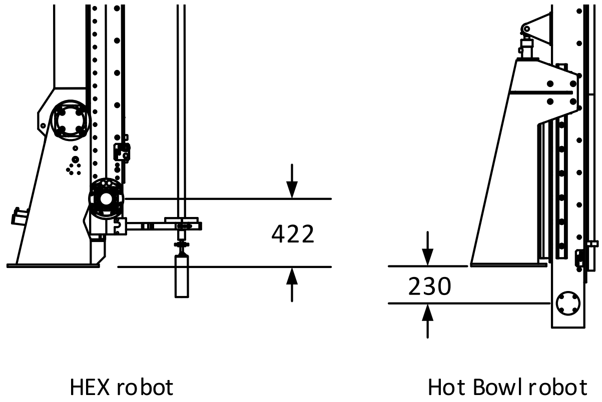



Figure 4.3: Comparison of lower elevator column position, HEX and Hot Bowl

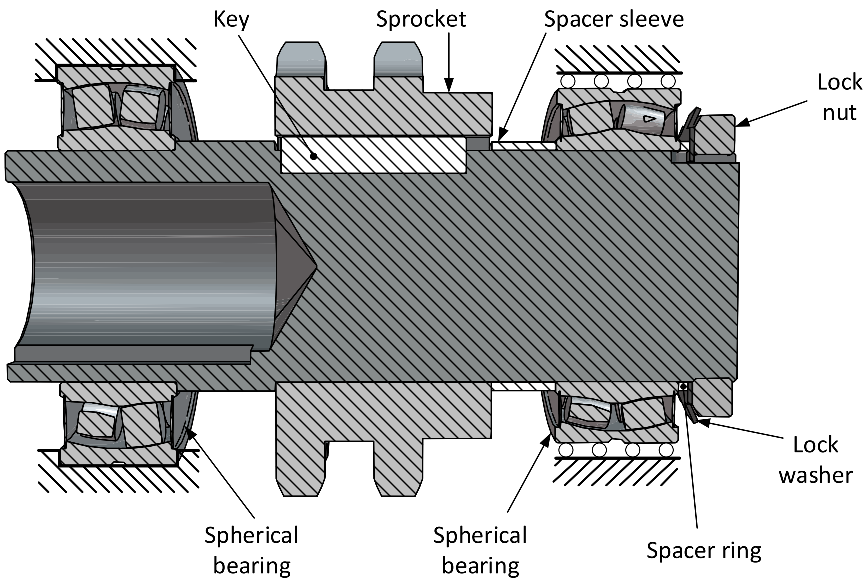



Figure 4.4: Section cut of assembled upper shaft

### 4.3.1 Upper Shaft Bearings

The bearings used for the driving (lower) shaft on the HEX utility robot is reused on the driving (upper) shaft of the Hot Bowl utility robot, since these bearings still were intact, and since they worked well last time. Relevant bearing data are given in Table 4.1. Figure 4.5 explains the dimensions mentioned in Table 4.1.

It is important to notice that the values stated in Table 4.1 are given with respect to the bearing surroundings, and not the bearing itself. This means that the maximum radius, $R_{max}$, given in the table is the maximum radius the abutment in contact with the upper ring of the bearing can have in order to ensure that the bearing's lateral surface is in contact with the lateral surface of the abutment. So $R_{max}$ as stated in the table above is in reality $R_{min}$ for the bearing itself.

It is worth noting that the bearing used for the right side, 24015-2CS2/VT143, have seals made up of the material fluoro rubber (FKM). This material gives of hazardous fumes if exposed to temperatures above 300 °C [2], and should be kept away from open fires and high temperatures. This bearing would probably be changed if it were to be mounted on the lower shaft, as the utility robot's lower end is to be lowered beneath third floor, close to the reactor.

Table 4.1: Relevant bearing data, upper shaft

| Bearing type | $d$ [mm] | $d_a$ [mm] | $D$ [mm] | $D_a$ [mm] | $B$ [mm] | $R$ [mm] | $C$ | $C_0$ |
|---|---|---|---|---|---|---|---|---|
| BS2-2215-2CS/VT143 [10] | 75 | 84 max,<br>84 min | 130 | 121 max | 38 | 1.5 max | 212 kN | 240 kN |
| 24015-2CS2/VT143 [8] | 75 | 81.5 max<br>81 min | 115 | 109 max | 40 | 1 max | 181 kN | 232 kN |

where: $d_a$ is the allowable height of the abutment for which the bearing's inner ring is to be supported against
$D_a$ is the allowable height of the abutment for which the bearing's outer ring is to be supported against
$C$ is the dynamic load rating
$C_0$ is the static load rating
$d$, $d_a$, $D$, $D_a$, $B$ and $R$ are shown in Figure 4.5

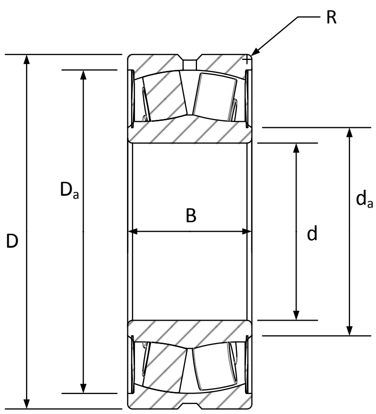



Figure 4.5: Supplementary figure, Table 4.1

#### Upper Shaft Bearing Relubrication

Both bearings used for the upper shaft are sealed spherical roller bearings with cylindrical bores. Sealed spherical roller bearings from SKF are designed to operate relubrication-free. For the bearings chosen for this application, relubrication-free conditions can be assumed if the operating conditions for the bearings lie within the green domain in the diagram taken from SKF's websites, shown in Figure 4.6. This diagram is valid for bearings in light and normal load applications, $P \leq 0.1\,C$ [2], where P is the load acting on the bearing in kN, and C is the bearing's dynamic load rating in kN.

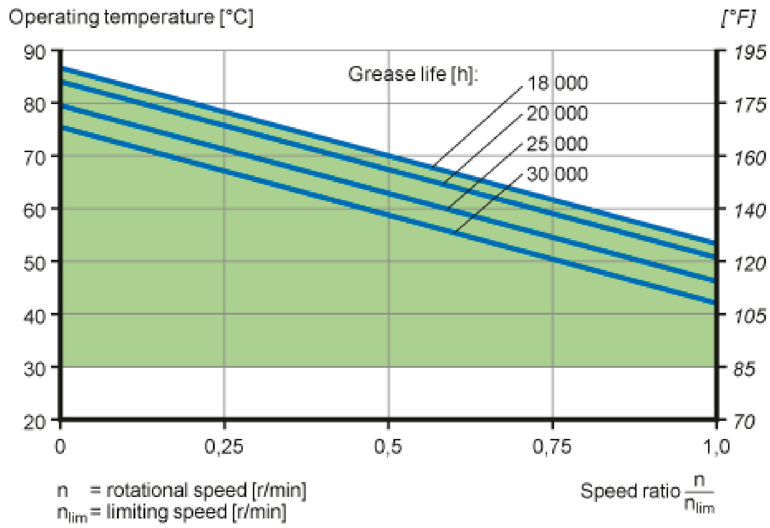



Figure 4.6: Lubrication-free operating conditions for sealed spherical roller bearings [2]

The operating temperature for the bearings of the upper shaft can be assumed as ambient temperature, well below 40 °C. Since the operating temperature is below 40 °C, the bearings of the upper shaft are relubrication-free for all speeds, as can be seen from Figure 4.6.

#### Upper Shaft Surface Roughness

SKF recommends that the surface roughness, $R_a$, of the shaft used together with their spherical roller bearings should not exceed 3.2 $\mu$m [3]. This is taken into account while designing the upper shaft.

#### Upper Shaft Diameter Tolerances

SKF recommends m6 tolerance for the shaft where cylindrical roller bearings with inner diameter from 60 mm to 140 mm are to be mounted [1]. This tolerance is used for the diameter of the whole shaft, except for the abutment.

### 4.3.2 Upper Shaft Spacers

The assembled upper shaft, depicted in Figure 4.4, consists of two spacers; one spacer sleeve and one spacer ring. These two components differ only in length; inner and outer diameter and tolerances are identical. The spacers are shown in Figure 4.7.

Tolerances are chosen i such a way that the spacers are easy to assemble on the shaft. The spacers are placed on each side of the right side bearing, SKF 24015-2CS2/VT143. From Table 4.1 the allowable height of the abutment for which the bearing's inner ring is supported against, $d_a$, is as shown in Equation 4.1.

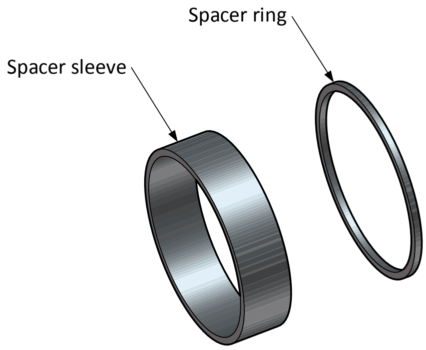



Figure 4.7: Upper shaft spacers

$$d_{\mathrm{a}} = \begin{cases} 81\ \mathrm{mm} & \mathrm{min.} \\ 81.5\ \mathrm{mm} & \mathrm{max.} \end{cases} \tag{4.1}$$

The outer diameter of the spacers are therefore chosen to be 81 mm.

Technical drawings of the upper shaft spacers are found in Appendix C. The technical drawing has item number 12 in Table C.1.

### 4.3.3 Upper Shaft

The original thought for the upper shaft for the Hot Bowl utility robot was to use the shaft from the HEX utility robot and just make it 30 mm shorter to accommodate for the 30 mm shorter elevator column, shown in Figure 4.1. It was however decided to redesign the shaft to include a lock nut and lock washer and other minor changes to get a more suitable solution for this application. The shaft designed for the Hot Bowl utility robot's driving shaft can be seen in Figure 4.8.

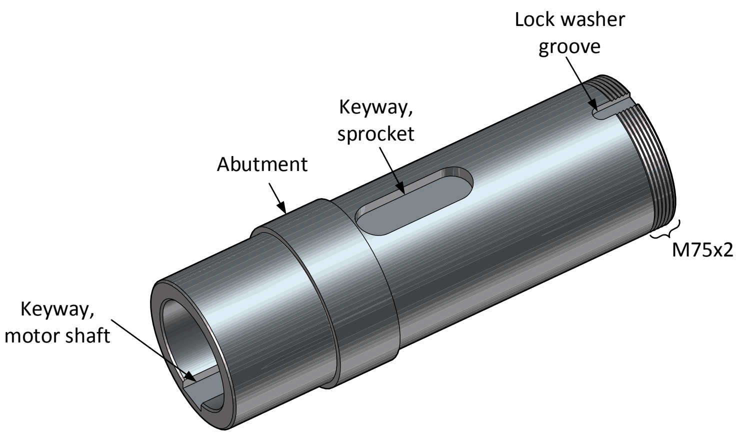



Figure 4.8: Upper shaft final design

The diameter of the abutment on the lower shaft, shown in Figure 4.8, is chosen based on recommended abutment diameter for the bearing's inner ring, $d_a$, for the shaft's left side bearing. From Table 4.1 it can be seen that the a maximum and minimum abutment diameter is specified, $\mathrm{d}_{\mathrm{a\,min}} = \mathrm{d}_{\mathrm{a\,max}} = 84$ mm. Diameter tolerances and surface roughness of the shaft is also determined by the bearings.

Technical drawings of the upper shaft is found in Appendix C. The technical drawing has item number 10 in Table C.1.

### 4.3.4 Upper Shaft Sprocket

The sprocket is used for transferring energy from the shaft to the elevator chain drive. The sprocket used for the HEX utility robot's driving shaft is reused for the new utility robot. The sprocket is a stock part triplex sprocket (sprocket for triplex chain, three chains in parallel) bought from Slettebøe AS, and is machined to fit a duplex chain (two chains in parallel) after Alcoa's specifications at Slettebøe AS before dispatching. Technical drawings of the upper shaft sprocket can be found in Appendix D.

### 4.3.5 Upper Shaft Bearing Housings

The bearing housings for the upper shaft was reused from the HEX utility robot's driving shaft. Each bearing housing has a circlip located between the bearing abutment and the allocated bearing space. These circlips lock the bearings' outer ring to the bearing housings. Since a new solution for the shaft is made, the circlip on the right bearing housing will not be used. Technical drawings of the two bearings houses are found in Appendix D.

### 4.3.6 Upper Shaft Keys and Keyways

The upper shaft has two keyways. The keyway for the motor shaft key, indicated in Figure 4.8, is reused from the HEX utility robot, and is not discussed further.

The key and keyway between the upper shaft and the sprocket is dimensioned in accordance with DIN 6880. This standard suggests width and height for the key and keyway, with accompanying tolerances. The length of the key is determined by calculations, and can be seen in Section 7.2.

Technical drawings of the upper shaft key is found in Appendix C. The technical drawing has item number 11 in Table C.1.

### 4.3.7 Upper Shaft Motor and Gearbox

The motor and gearbox are reused from the HEX utility robot.

## 4.4 Lower Shaft and Surrounding Components

The final solution for the assembled upper shaft is as depicted in Figure 4.9. The rest of this section will explain how the lower shaft and surrounding components are designed.

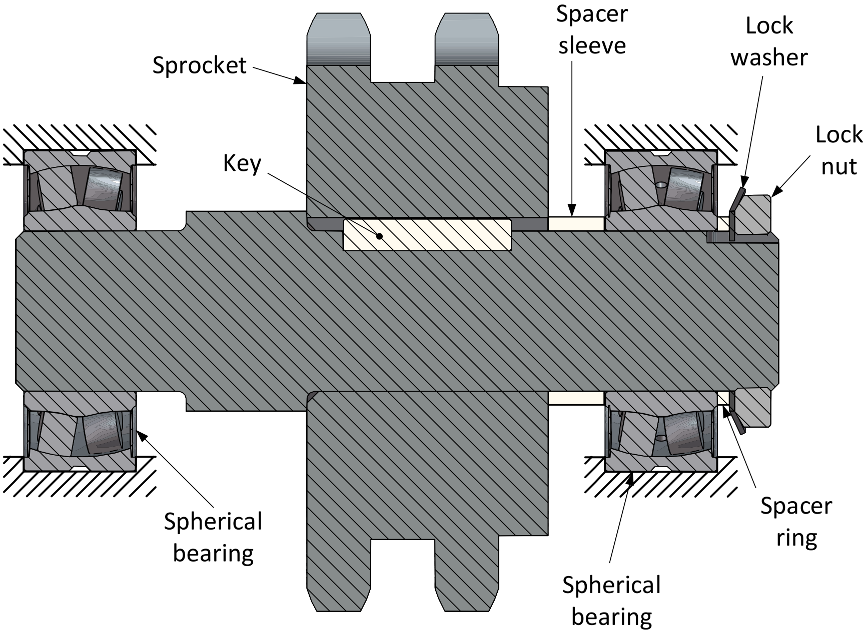



Figure 4.9: Section cut of assembled lower shaft

### 4.4.1 Lower Shaft Bearings

The bearings used for the HEX utility robot's driven shaft could not be reused in the new utility robot. Sealed spherical roller bearings with cylindrical bores were chosen for this shaft, the same type of bearings as the ones reused for the upper shaft. Spherical roller bearings were chosen to allow for radial deviation between the two bearings of the shaft, easing the machining tolerances for the machine. Two identical bearings were chosen. Relevant bearing data are given in Table 4.2. Figure 4.10 shows the dimensions mentioned in Table 4.2.

Table 4.2: Relevant bearing data, lower shaft

| Bearing type | $d$ [mm] | $d_a$ [mm] | $D$ [mm] | $D_a$ [mm] | $B$ [mm] | $R$ [mm] | $C$ | $C_0$ |
|---|---|---|---|---|---|---|---|---|
| BS2-2208-2CS/VT143 [9] | 40 | 47 max, 47 min | 80 | 73 max | 28 | 1 max | 98.5 kN | 90 kN |

where: $d_a$ is the allowable height of the abutment for which the bearing's inner ring is to be supported against
$D_a$ is the allowable height of the abutment for which the bearing's outer ring is to be supported against
$C$ is the dynamic load rating
$C_0$ is the static load rating
$d$, $d_a$, $D$, $D_a$, $B$ and $R$ are shown in Figure 4.5

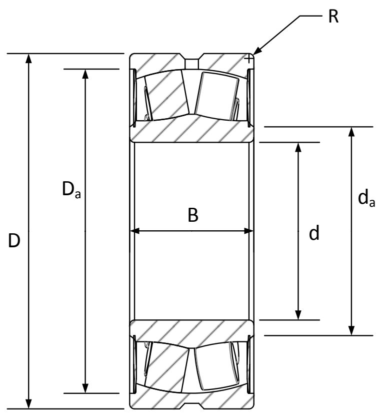



Figure 4.10: Supplementary figure, Table 4.2

Like for the bearing data given for the upper shaft, the bearing data given in Table 4.2 are given with respect to the bearing surroundings, and not the bearing itself.

### 4.4.2 Lower Shaft Bearing Calculations

#### Required Minimum Load on Bearings

SKF recommends that spherical roller bearings always should be subjected to a minimum load in order to provide satisfactory operation [26, p. 20]. An acceptable minimum load can be estimated using Equation 4.2.

$$P_m = 0.01\,C_0 \tag{4.2}$$

$$P_m = 0.01 \cdot 90\text{ kN} = \underline{900\text{ N}} \tag{4.3}$$

where: $P_m$ is the equivalent minimum load [kN]
$C_0$ is the static load rating [kN], found in Table 4.2

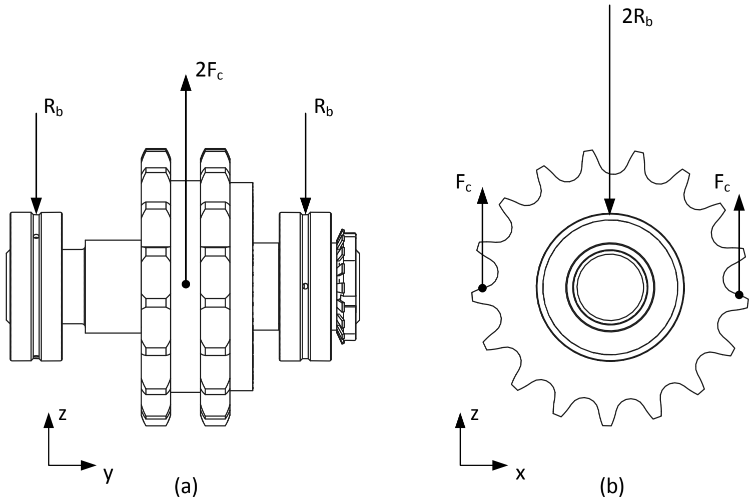



Figure 4.11: Forces acting on the lower shaft

The chain tensioner is meant to pre-tension the chain with 10 kN. This will be the situation where the bearings are subjected to minimal load. The forces acting on the shaft with this pre-tensioned chain assembled is as shown in Figure 4.11.

Equations 4.4–4.6 determines the bearing reaction force from Figure 4.11.

$$\sum F_z : \; 2F_c - 2R_b = 0 \tag{4.4}$$

$$R_b = F_c \tag{4.5}$$

$$R_b = \underline{10 \text{ kN}} \tag{4.6}$$

### Maximal Load on Bearings

The situation where the bearings are subjected to greatest load is when the lance collides with an obstacle such that the torque release exerts its maximal load.

Figure 4.11 can also be used for this calculation, but the chain force $F_c = 10 \text{ kN} + F_{\text{lance}}$, where $F_{\text{lance}}$ is the maximal force that can occur from a lance collision, $F_{\text{lance}} = 7$ kN

$$\sum F_z : \; 2F_c - 2R_b = 0 \tag{4.7}$$

$$R_b = F_c \tag{4.8}$$

$$R_b = \underline{17 \text{ kN}} \tag{4.9}$$

The maximal force is compared to the basic static load rating of the bearing, $C_0 = 90$ kN [9].

$$\underline{R_b < C_0} \tag{4.10}$$

### Lower Shaft Bearing Relubrication

Both bearings chosen for the lower shaft are sealed spherical roller bearings with cylindrical bore, like the ones used for the upper shaft. The same diagram, shown in Figure 4.6, can be used to determine whether the

where: $R_{\mathrm{b}}$ is the reaction force on the bearings
$F_{\mathrm{c}}$ is the force from the chain due to chain tensioner's preload

bearings need lubrication during their lifespan. Since the bearings chosen for this shaft endure substantially less load than the bearings for the upper shaft, the condition which needs to be fulfilled on order to make use of the diagram, $\mathrm{P} \leq 0.1\,\mathrm{C}$ [2], may not be fulfilled. However, SKF have a rule of thumb for sealed bearings [26, p. 10], stating that the bearing do not need relubrication if the following statements are true:

- Temperatures do not exceed +70 °C
- The inner ring rotates
- Speeds are not more than 50% of the limiting speeds listed in the product table

One can assume operating temperatures close to ambient for the bearings (John Fors, personal communication), even though it is possible for some amount of heat to be transferred from the reactor to the bearings. This is however more of a general design guideline than it is a requirement. Hence, item one from the list above is upheld.

The inner ring rotates, while the outer ring is fixed. The second item from the list above is upheld.

The limiting speed of the bearing chosen is $\omega_{\mathrm{b}} = 2200$ rpm [9] the servo motor's rated speed is $\omega_{\mathrm{r}} = 4000$ rpm [15, p. 3] and the gearbox's ratio is $i = 16$ [16, p. 90]. This information is used to find the maximum possible shaft speed, $\omega_{\mathrm{max}}$, shown in Equations 4.11–4.14. The criterion which has to be fulfilled is that the maximum obtainable shaft speed do not exceed 50% of the bearing limiting speed, $\omega_{\mathrm{max}} < \frac{1}{2}\,\omega_{\mathrm{b}}$.

$$\omega_{\mathrm{max}} = \frac{\omega_{\mathrm{r}}}{i} = \frac{4000\ \mathrm{rpm}}{16} \tag{4.11}$$

$$\omega_{\mathrm{max}} = 250\ \mathrm{rpm} \tag{4.12}$$

$$\frac{1}{2}\,\omega_{\mathrm{b}} = 1100\ \mathrm{rpm} \tag{4.13}$$

$$\underline{\omega_{\mathrm{max}} < \frac{1}{2}\,\omega_{\mathrm{b}}} \tag{4.14}$$

The maximum obtainable shaft speed is less than that of 50% of the bearing's limiting speed. The bearings are assumed to be relubrication-free.

#### Lower Shaft Surface Roughness

SKF recommends that the surface roughness, $\mathrm{R_a}$, of the shaft used together with their spherical roller bearings should not exceed 3.2 $\mu$m [3]. This is taken into account while designing the lower shaft.

#### Lower Shaft Diameter Tolerance

SKF recommends k6 tolerance for the shaft where cylindrical roller bearings with inner diameter from 25 mm to 60 mm are to be mounted [1]. This tolerance is used for the diameter of the right side of the abutment, where the keyway is located. The left side is set to a looser fit with a tolerance of g6. This is done to make the left-side bearing be able to slide along the shaft axial direction in case of any axial displacement of the shaft.

### 4.4.3 Lower Shaft Spacers

The assembled lower shaft, shown in Figure 4.9, consists of one spacer sleeve and one spacer ring. The spacers have identical dimensions, and differ only in length. The spacers can be seen in Figure 4.12.

The spacers are place on each side of the right side bearing. From Table 4.2 the allowable height of the abutment for which the bearing's inner ring is supported against, $d_{\mathrm{a}}$, is as shown in Equation 4.15.

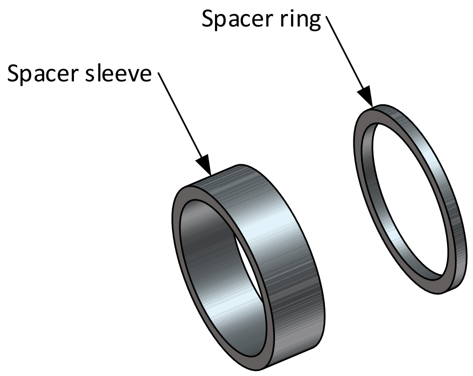



Figure 4.12: Lower shaft spacers

$$d_{\mathrm{a}} = \begin{cases} 47 \text{ mm} & \text{min.} \\ 47 \text{ mm} & \text{max.} \end{cases} \tag{4.15}$$

The outer diameter of the spacers are therefore chosen to be 47 mm.

Technical drawings of the lower shaft spacers are found in Appendix C. The technical drawing has item number 9 in Table C.1.

### 4.4.4 Lower Shaft

The lower shaft abutment diameter, surface roughness and diameter tolerances are determined by the bearings used together with the shaft. The tolerance of the left side (short side) of the abutment is set to g6 in order for this side to float axially between the bearing inner ring and the shaft.

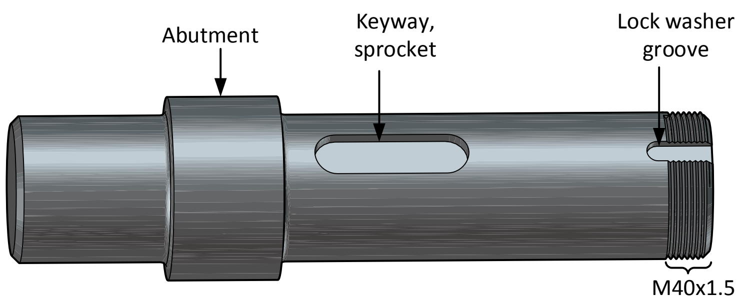



Figure 4.13: Lower shaft final design

Technical drawings of the lower shaft is found in Appendix C. The technical drawing has item number 3 in Table C.1.

### 4.4.5 Lower Shaft Sprocket

The sprocket for the lower shaft is a cylindrical duplex sprocket with the article number 16 B-2 17. The sprocket is bought from Slettebøe AS, and the bore and keyway is machined at Slettebøe before dispatching. Technical drawings of the lower shaft sprocket is found in Appendix C. The technical drawing has item number 4 in Table C.1.

### 4.4.6 Lower Shaft Key and keyway

The only torque transferred between the shaft and the sprocket on the lower shaft are made by friction in the bearings. Any calculations to determine whether the key between the shaft and the sprocket meets the torque requirements are therefore unnecessary.

The key and keyway dimensions are chosen in accordance with DIN 6880. Technical drawings of the lower shaft key is found in Appendix C. The technical drawing has item number 8 in Table C.1.

### 4.4.7 Lower Shaft Bearing Housings

The lower bearing housings both have a circlip locking the bearing outer ring i place.

The bearing housings for the lower shaft has seals for the bearing houses, as well as sealed bearings. The upper shaft does not have bearing housing seals. This is done since the lower shaft is to be lowered beneath third floor, close to the reactor, where a lot of dust is likely be produced.

Technical drawings of bearing housings and bearing housing covers are found in Appendix C. The technical drawing for the right side bearing housing has item number 5 in Table C.1, left side bearing housing has item number 6, and the bearing housing cover has item number 7.

## 4.5 Lance Centering Arm

The lance centering arm ensures that the lance coincide with the utility pipe opening so that it does not collide when lowering the lance into the pipe. The lance centering arm was not developed in this thesis due to the interface with the continuous level measurement equipment. The continuous level measurement will be placed in the same space as the lance centering arm. Since the level measurement equipment is not developed yet, the lance centering arm is put on hold for the time being.

## 4.6 Chain Drive

The chain drive is a feature carried over from the old design. Chain drives has several benefits for this application over other types of transmissions. The center-center distance between the two sprockets is chosen to be 4780 mm. It is desirable for the drive to work fast and accurate. Component wear is not a big concern, as the robot is likely not to be used for a long period of time, as it will probably be revised for the next test reactor (after the Hot Bowl) is developed.

#### Advantages of Chain Drives

- Meets the velocity requirements for the application
- Great flexibility in drive length due to splicing
- Operates effectively at high temperatures [25]

#### Disadvantages of Chain Drives

Life of chains are usually low. Correct lubrication of chain drives are critical for long service life. Unlubricated drives can wear 300 times faster than lubricated drives, and it is estimated that 90–95% of chain drives are improperly lubricated [18, p. 2]. However, this is not a big concern for this application, since the robot is probably not going to be used long enough for chain wear to occur, and since changing of chain and sprockets is not a big cost.

Belt drives would be to inaccurate to be used for this application due to slipping and dust build-ups. Belt drives also exert larger forces on the shaft bearings.

The same type of chain used for the HEX elevator will be used for the Hot Bowl elevator. This is done since this chain worked well on the HEX robot. This also eases the workload of development of a new machine, since it is known that the chain can withstand the strain put on it by operation of the utility robot. Since the chain tensioner is not developed, the total required length of the chain is still unknown. Consequently, the chain is not ordered yet.

The chain has article number 16B-2. Relevant data on the chain is shown in Table 4.3 [20, p. 23].

Table 4.3: Relevant chain data [20, p. 23]

| Art. no. | Min. tensile strength | Weight |
|---|---|---|
| 16B-2 | 106 kN | 5.42 $^{kg}/_{m}$ |

## 4.7 Lance Holder

The lance holder is the interface between the utility robot and the lances. Two concepts are presented here, where the first concept was developed before the lance handler concept was proposed, and the second concept was made after. None of these are fully developed solutions. The manually operated lance holder is the one to be used for shakedown. When the lance handler is implemented it would be desirable to close the lance holder latches without human interaction. A pneumatically actuated lance holder concept is presented, although it is in its early stages of development.

### 4.7.1 Manually Operated Lance Holder

The first concept was made for manual mounting of the lances. The operator is to stand on the service platform and manually mount the lance in the lance holder. The mounting interface of the lance for this concept consists of different rings of magnetically conductive material, such as iron. This interface is depicted in Figure 4.14.

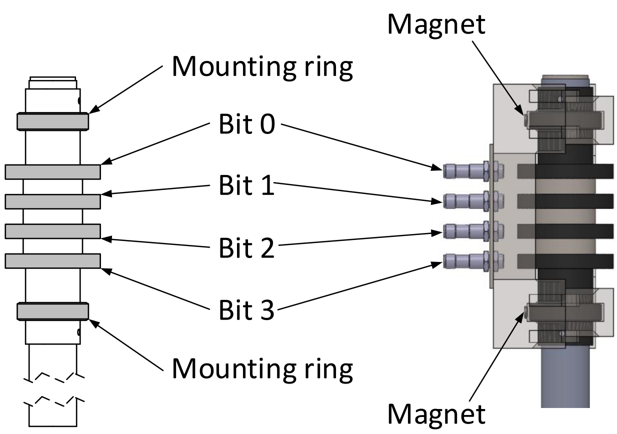



Figure 4.14: Lance and lance holder, manually operated

The lance consist of six iron ring segments, indicated in gray in the left-side illustration in Figure 4.14. The two outermost rings, called mounting rings i Figure 4.14, are used for mounting the lance in the lance holder. The mounting rings are inserted into the grooves of the front side of the lance holder. Permanent magnets are located inside these grooves, as indicated in Figure 4.15(a), keeping the lance in place until the operator has locked the lance in place with the latches.

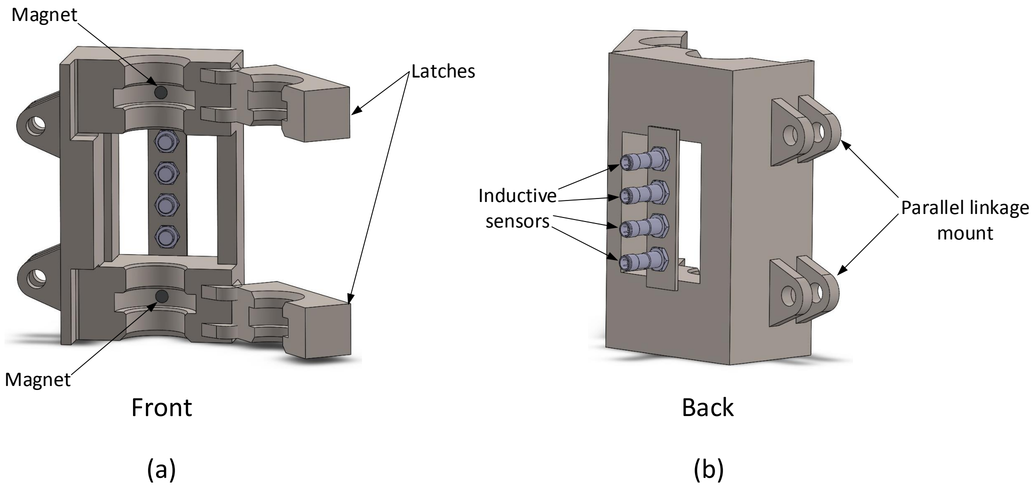



Figure 4.15: Lance holder, manually operated

The four middle rings in Figure 4.14 are used for automatic lance identification. Each iron ring represents a bit in a four digit bit pattern. The absence of a ring in the pattern represents a 'zero', and the presence of a ring represents a 'one'. Each lance is assigned its own bit pattern, presented in Table 4.4. Inductive sensors, indicated in Figure 4.15(b), are mounted at the back of the lance holder, sending the bit pattern to the control system.

Table 4.4: Tool selection bit pattern

| Equipment | Bit 3 | Bit 2 | Bit 1 | Bit 0 | Value |
|---|---|---|---|---|---|
| Empty | 0 | 0 | 0 | 0 | 0 |
| Agellis lance | 0 | 0 | 0 | 1 | 1 |
| Temperature lance | 0 | 0 | 1 | 0 | 2 |
| Pyrometer lance | 0 | 0 | 1 | 1 | 3 |
| Sampler lance | 0 | 1 | 0 | 0 | 4 |
| Mechanical level lance | 0 | 1 | 0 | 1 | 5 |
| Cleaning tool | 0 | 1 | 1 | 1 | 6 |
| Imaging lance | 1 | 0 | 0 | 0 | 7 |

The inductive sensors are spaced according to the manufacturer's recommendations: Inductive sensors mounted side by side should not be closer to each other than two times the sensing distance. The distance $e$ for the chosen sensor should be $e \geq 8$ mm [19, p. 14]. The distance between the inductive sensors is set to $e = 13$ mm.

Table 4.5: Relevant data on the inductive sensors [19, p. 3]

| Art. no | Diameter (threaded) | Sensing distance |
|---|---|---|
| XS112B3PAM12 | M12 | 4 mm |

The mounting interface between the lance holder and the parallel linkage, indicated in Figure 4.15(b), is placed in such a way that the center of the lance coincide with the parallel linkage's plane of motion, resulting in less complex forces. Between these mounting brackets and the parallel linkage, nylon bushings are placed in order to isolate the utility robot from the voltage potential in relation to ground in the molten mixture of the reactor.

### 4.7.2 Pneumatically Actuated Lance Holder

The pneumatically actuated lance holder is a concept started on for use when the lance handler is implemented into the third floor layout. Its working principle can be seen in Figure 4.16. The mounting interface on the lances consist of one fastening ring, and is indicated in Figure 4.16(b). The fastening ring is inserted into the groove of the lance holder base, shown in Figure 4.16(b). A cylinder is placed at the back of the lance holder base. The end of the cylinder rod is indicated in Figure 4.16(a). An inductive sensor tells the control system that a lance is close enough for the claws to close around the lance. The pneumatic cylinder is extracted, bringing the claws in contact with the lance pipe. The cylinder is the further extracted, moving past the point of which the linkage that the cylinder rod is mounted to are parallel. This makes the mechanism self-locking. The self-locking mechanism is explained further by the use of Figure 4.17.

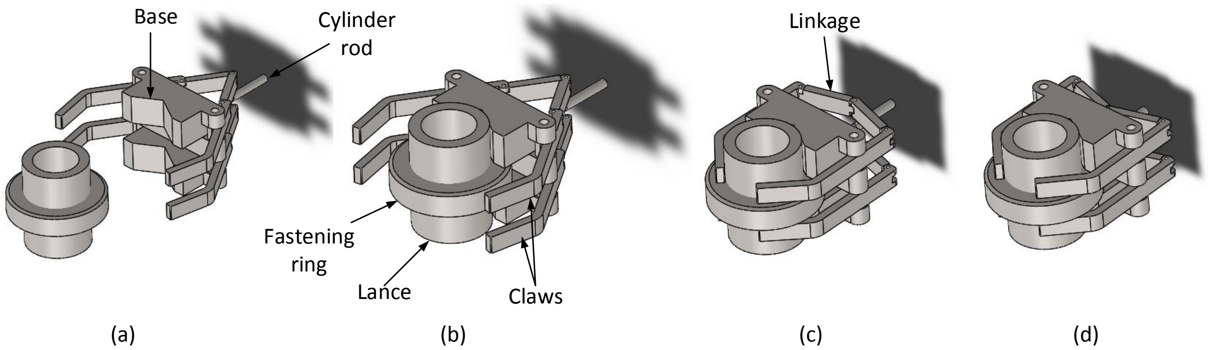



Figure 4.16: Operation sequence of pneumatically actuated lance holder

Figure 4.17 shows the same operation as the above figure. As the lance is placed in the groove of the base in Figure 4.17(b), the pneumatic cylinder exerts a force on the linkage, as shown in Figure 4.17(c). From here on and to the cylinder reaches the position shown in Figure 4.17(d), the claws will bend, producing a counter force to the pneumatic cylinder force. The cylinder keeps extracting up until it reaches the point indicated in Figure 4.17(d). Here one can observe that the claws are penetrating the lance. In practice, the claws will bend as explained above. In Figure 4.17(d) the linkages are barely past the point where the linkage members are parallel. At this point the force on the cylinder created by bending of the claws will change direction, going in the same direction as the cylinder force. From here on and out the lance holder is self-locking.

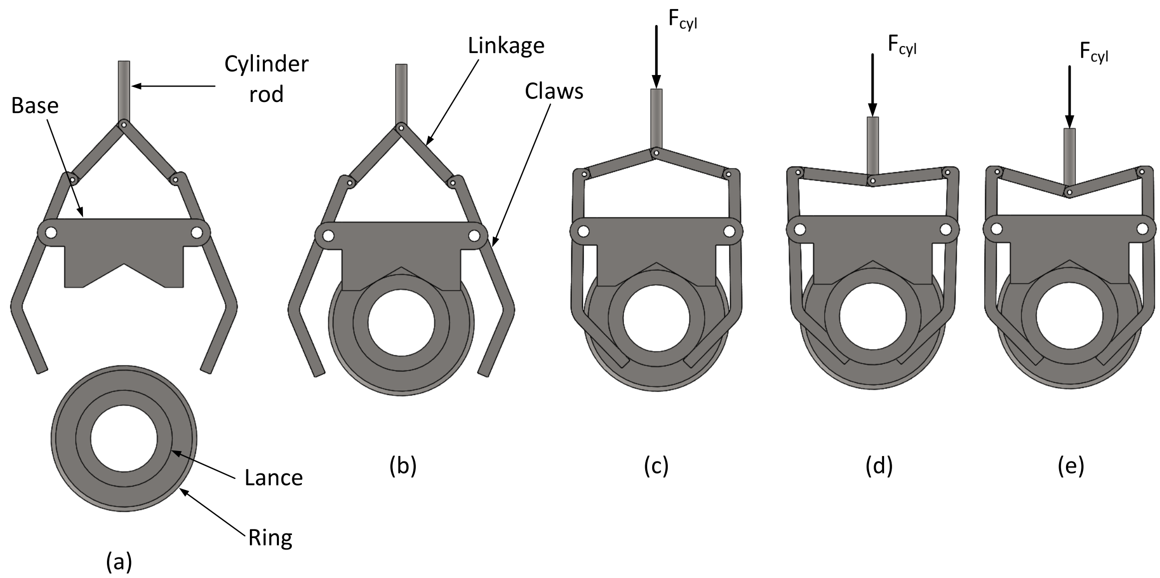



Figure 4.17: Operation sequence of pneumatically actuated lance holder

## 4.8 Torque Release

Under operation of the utility robot, the possibility exists for the lance to come into contact with an obstacle in the utility pipe while the elevator is lowering the lance. The lances are long and thin, and many of them have fragile equipment mounted at the end. The torque release is implemented in order to save the lances from damage by relieving the load on the lance during a potential lance collision.

The torque release is a feature from the HEX utility robot that Alcoa wanted to carry over to the new design. It was however desirable to redesign the concept in such a way that the torque release was not mounted directly on every lance, as it was done for the HEX reactor, explained in Section 2.3.1. Instead, a variable torque release solution mounted on the elevator cart was proposed.

Different types of solutions were tried out for this feature. The principle is the same for all concepts. The lance holder is to be suspended on a parallel linkage by hinged connections, as shown in Figure 4.18(a). The other end of the linkage is hinged to the elevator cart. Somewhere along the linkage, a pneumatic cylinder is to be mounted. The other end of the pneumatic cylinder is to be mounted to the elevator cart. The pneumatic cylinder will exert a force on the top member of the parallel linkage in the opposite direction of the force produced during a lance collision. All hinged connections in Figure 4.18 are represented as dots.

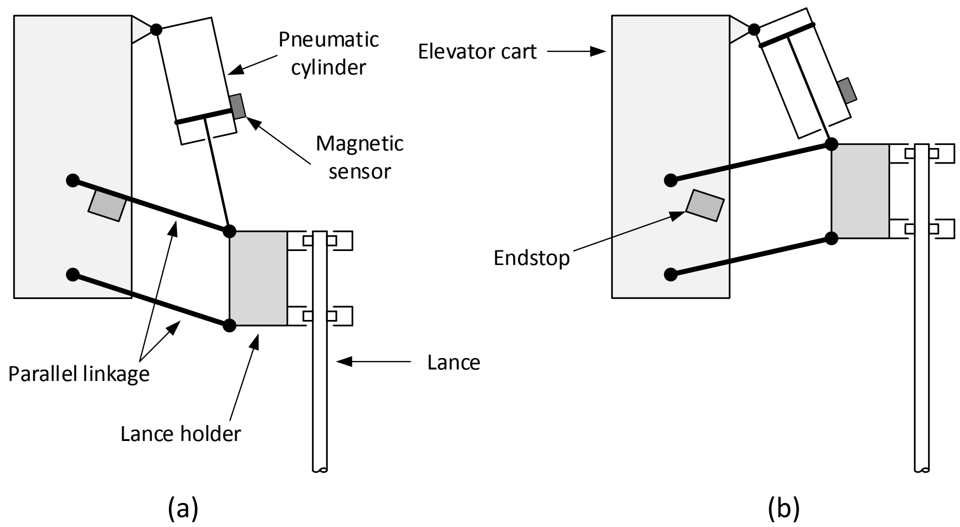



Figure 4.18: Concept sketch of the torque release feature

Figure 4.18(a) presents the torque release feature in starting position, with no collision. The pneumatic cylinder exerts a force from the piston rod to the top parallel linkage. This force, called the preload force, holds the lance in place up against the endstop, indicated in Figure 4.18(b). As the lance collides with an obstacle while the elevator cart is moving downwards, the lance will stay in the same place while the elevator cart continues in a downwards motion. The result is shown in Figure 4.18(b). As the lance moves upwards relative to the elevator cart, the pneumatic cylinder between the elevator cart and the lance will retract. The pneumatic cylinder used for this application has a magnetic core in its piston. A magnetic cylinder sensor is mounted on the cylinder, in the position for which the cylinder is fully extracted. Upon detecting a collision, the control system shall immediately abort any downwards motion of the elevator cart by cutting of the power to the servo motor and initiating the braking function of the motor.

The torque release concept sketch depicted in Figure 4.18 has an initial negative angle of the parallel linkage members in starting position. Figure 4.19 shows why this is a good idea.

Figure 4.19 shows the difference in horizontal displacement of the end of the parallel linkages depending on the initial angle. The whole traveled angle is indicated as $\alpha$. When the initial angle of starting position is 0°, the horizontal displacement is much greater than if the parallel linkage starts in a negative angle. This can be observed by comparing $\Delta x$ for the two different situations in the mentioned figure. If the parallel linkages' initial angle is set to be half of the total travel angle below 0°, the total vertical displacement of the end of the linkages, $\Delta y$ , are marginally larger than for the situation where the linkages starts in 0°. The results

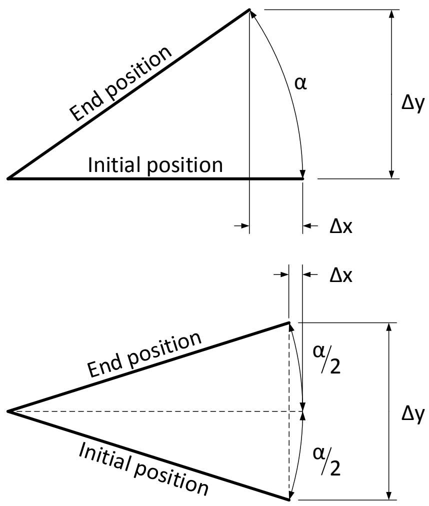



Figure 4.19: Horizontal displacement of lance due to parallel linkage initial angle

found for $\Delta x$ and $\Delta y$ both points towards having a negative initial angle. It is important to minimize $\Delta x$ such that the lance does not collide with the utility pipe inner wall if a collision occurs while the lance is inside the reactor.

### 4.8.1 First Torque Release Concept

The first concept developed had a structure very similar to the concept sketch shown in Figure 4.18. The initial torque release concept is shown in Figure 4.20. It consists of a parallel linkage system hinged to a plate called linkage bracket in Figure 4.18(b), which in turn is mounted om the elevator cart. The linkage bracket has a mechanical endstop to lock the lance holder in place in initial position (Figure 4.20(a)). The pneumatic cylinder has an initial pressure producing a force that keeps the parallel linkage's top member in contact with the endstop, locking the lance holder in initial position.

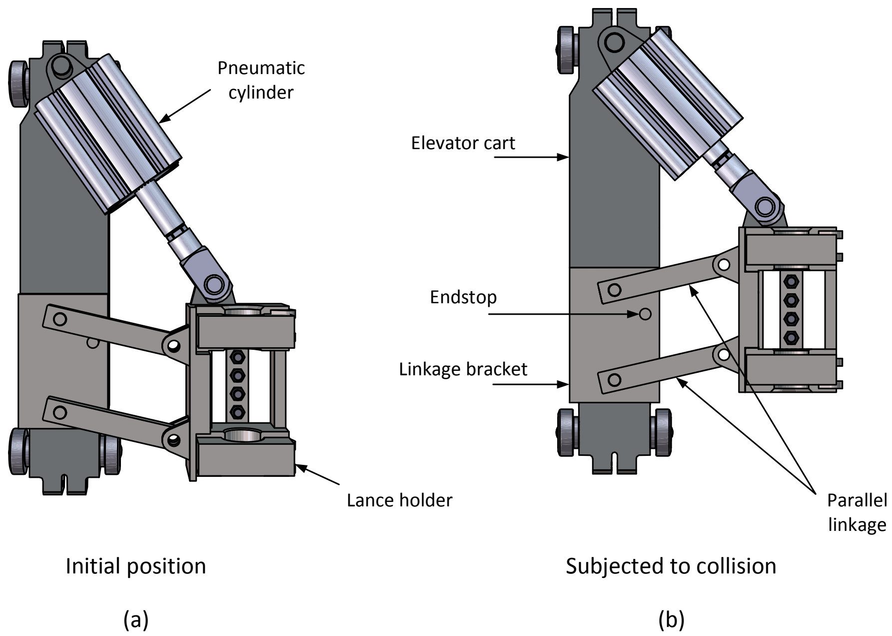



Figure 4.20: First torque release concept

As the concept is now, the cylinder collides with the elevator cart and the elevator column. This is shown in Figure 4.21. This could be possible to compensate for. It is however important to not move the lance holder to far away from the elevator cart. If the lance holder is to be placed further from the cart, that equal amount of length needs to be cut off from the foundations depth, due to restricted space assigned for mounting of the utility robot. This reduces the number of possible solutions.

Before further developing this concept, it is desirable to first investigate the possibilities of turning the whole concept upside-down, placing the cylinder–elevator cart interface on the bottom of the cart, and the parallel linkages on the top side of the cart. The reason for this is illustrated in Figure 4.21.

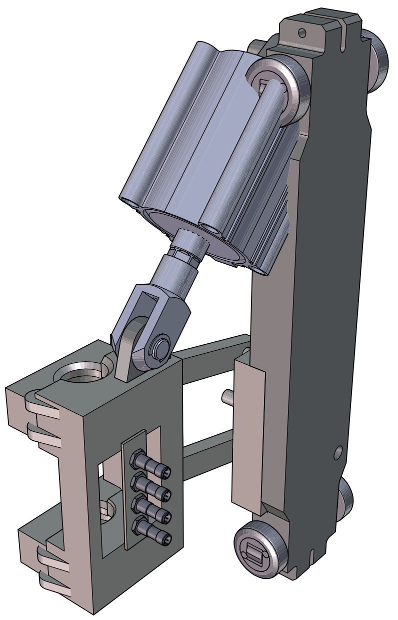


Figure 4.21: First torque release concept, back

In order for the lances to have the same range of travel distance for the two different concepts, the elevator column needs to be made differently for the two concepts. The concept for where the cylinder is mounted on the top side of the cart (first concept) requires a longer elevator column. The concept where the cylinder is mounted on the bottom of the elevator cart would need the same total length of the elevator column, but it would allow for the extra length to go down through the floor, effectively making the utility robot shorter with respect to third floor. A shorter utility robot is beneficial, since the utility robot is to avoid colliding with the overhead crane located in the research station.

### 4.8.2 Second Torque Release Concept

This section will present the second torque release concept. The torque release concept is depicted in Figure 4.22. The second torque release concept has the pneumatic cylinder mount placed at the bottom of the elevator cart. The cylinder is mounted by the means of a cylinder bracket bolted to the elevator cart, like shown in Figure 4.22. The top parallel linkage is extended the same length at the opposite side of the linkage's point of rotation. Between the two upper arms, a torsion member is placed to accommodate for the collision between the cylinder and the rest of the robot, indicated in Figure Figure 4.23(a) and (b). This concept solves the problem the first concept had regarding collision between the pneumatic cylinder and the rest of the robot, and it makes the utility robot shorter with respect to floor level. Consequently, the first concept is not further developed, and the second concept is chosen for the final solution.

The cylinder bracket, indicated in Figure 4.23(a), is bolted to the elevator cart with three bolts. Figure 4.23(b) shows the parallel linkages, linkage bracket and surrounding components. A self-lubricating bushing is placed in the hole of the cylinder linkage, where the cylinder clevis is mounted. A stiffener is added to the lower linkage for stability.

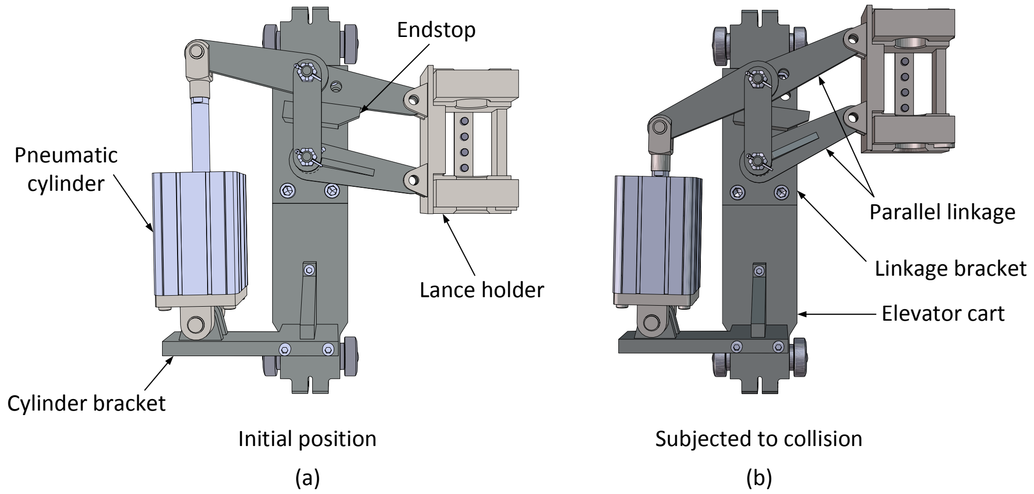



Figure 4.22: Second torque release concept in initial position and subjected to collision

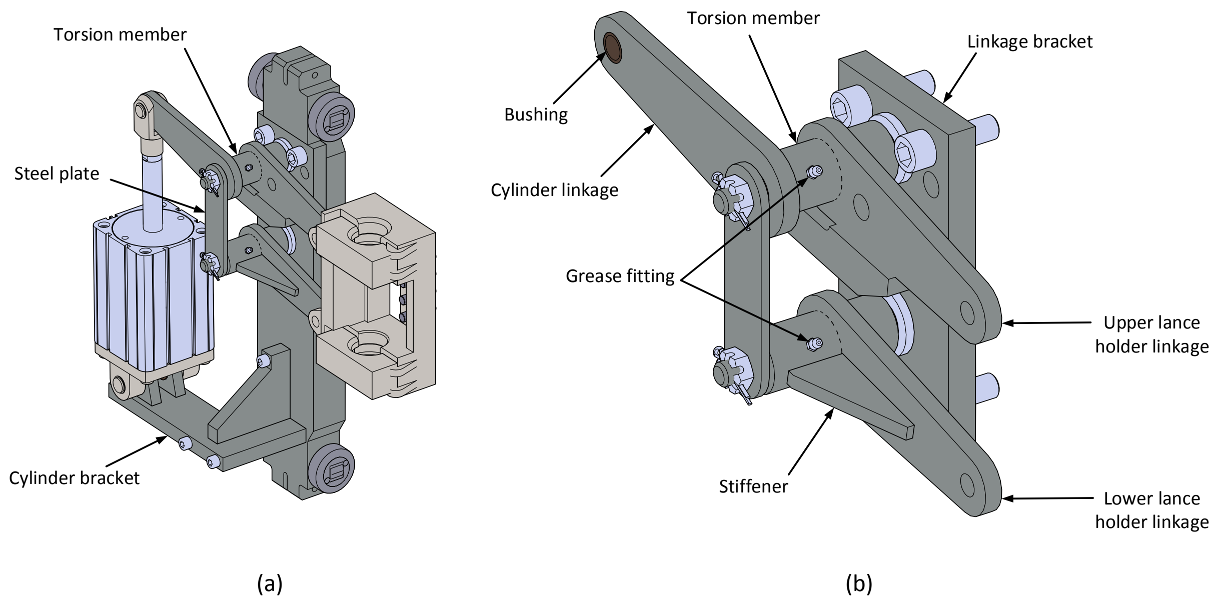
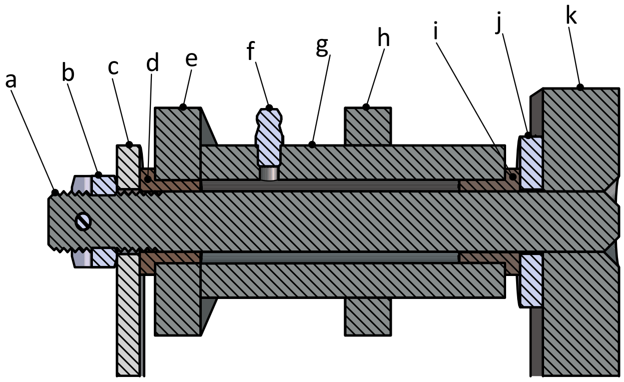
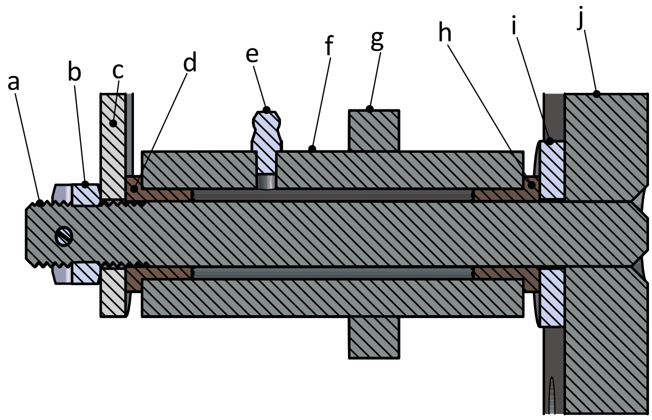



Figure 4.23: Second torque release concept




where a = threaded rod
b = castle nut
c = Steel plate
d = bronze bushing
e = arm, pneumatic cylinder
f = grease fitting
g = torsion member
h = arm, lance holder
i = bronze bushing
j = plain washer
k = linkage bracket

Figure 4.24: Upper torsion member section cut




where a = threaded rod
b = castle nut
c = Steel plate
d = bronze bushing
e = grease fitting
f = pipe
g = arm, lance holder
h = bronze bushing
i = plain washer
j = linkage bracket

Figure 4.25: Lower parallel linkage components section cut

Figure 4.23(b) indicates two grease fittings. These are used for lubrication of the bushings for which the linkages use to rotate. A section cut of the torsion member between the two upper linkages with explanations are shown in Figure 4.24.

The torsion arm shown in Figure 4.24 use two bushings (d and i in figure). The free space between the torsion member (g) and the threaded rod (a) is filled with grease for proper lubrication of the bushings. The whole assembly shown in Figure 4.24 is held together with a castle nut (b) locked in place with a split pin.

Figure 4.25 shows a section cut of the lower parallel linkage. This is not a torsion member. The working principle is the same as for the upper torsion member in Figure 4.24.

#### Torque release Endstop

The endstop is the component of the torque release mechanism that keeps the linkages in place under normal operation of the utility robot (no lance collision). A working endstop were developed in the earlier stages of the design of the utility robot. At a point, it was decided that the torque release linkages (arms) needed to be made longer, from 100 mm long to 160 mm long, to make room for the continuous level measuring probe discussed in Section 2.6.4. The endstop solution for the new torque release was not strong enough to account for the largest forces that theoretically can occur. Effort were made to try and dimension a new endstop, but the work is not finished.

The problem with designing a new endstop is the available space. It is desirable to place an endstop as far out on the linkage length as possible to prevent large forces. This were however hard to do. Several designs were tried with the new torque release lengths. The suggested solution is shown in Figure 4.26. The figure shows the elevator cart stripped of irrelevant parts, mounted in the utility robot.

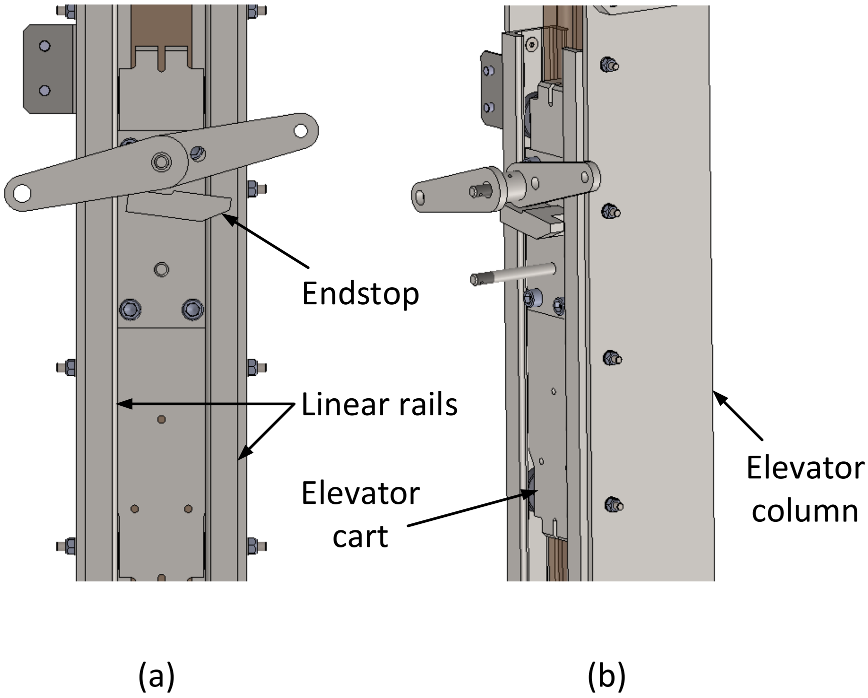



Figure 4.26: Torque release endstop

The suggested endstop solution is as large as the utility robot design allows. A groove is machined out to make room for the rotating upper linkage. The endstop is made in such a way that it is as long as the linear rails in Figure 4.26 allows, and as wide as possible without colliding with the lower parallel linkage under a lance collision. The suggested solution is not dimensioned, and will have to be investigated further before applying the suggested solution to the final design.

#### Second Torque Release Technical Drawings

Technical drawings of the component that make up the torque release are found in Appendix C. It consists of five drawings. The technical drawings for the cylinder bracket has item number 14 in Table C.1, the top parallel linkage has item number 17, the bottom parallel linkage has item number 16, the linkage bracket has item number 15, and the steel plate indicated in Figure 4.23(a) has item number 18.

### 4.8.3 Torque Release Cylinder

The air supply located at the research facility can produce between 5 and 7 bars of pressure. The preload force on the torque release, and thus for the cylinder, is chosen to be 2 kN. This is chosen in order to have about the same preload as the springs for the HEX torque release solution, explained in Section 2.3.1. To ensure that the cylinder can produce 2 kN at any given time, it is decided to determine the cylinder diameter necessary to produce 2 kN (preload) at 3 bar, well below minimum pressure of the air supply. The required cylinder piston diameter $d_{\text{cyl}}$ is determined in Equations 4.16–4.19.

$$p_{\text{cyl}} = \frac{F}{A_{\text{cyl}}} \tag{4.16}$$

$$A_{\text{cyl}} = \frac{\pi}{4}\, d_{\text{cyl}}^2 = \frac{F}{p_{\text{cyl}}} \tag{4.17}$$

$$d_{\text{cyl}} = \sqrt{\frac{4\,F}{\pi\, p_{\text{cyl}}}} = \sqrt{\frac{4 \cdot 2000 \text{ N}}{\pi \cdot 3 \cdot 10^5 \text{ Pa}}} \tag{4.18}$$

$$d_{\text{cyl}} = \underline{92 \text{ mm}} \tag{4.19}$$

As can be seen from the equations above, a cylinder with a diameter of at least 92 mm needs to be chosen. A cylinder with a piston diameter of 100 mm is chosen for the application. The stroke of the cylinder needs to be long enough to account for a lance collision. The HEX torque release had a travel distance of 90 mm. A test was carried out on the HEX utility robot, where the distance the elevator cart covered when going from maximum velocity to full stop. The distance measured was between 40 and 60 mm. To be sure, a stroke length of 100 mm is chosen.

The cylinder chosen has article number R422001240 [17, p. 2], and is produced by Bosch Rexroth. Relevant data on the cylinder can be seen in Table 4.6.

Table 4.6: Relevant pneumatic cylinder data [17]

| Art. no. | Stroke | Piston diameter | Maximum working pressure |
|---|---|---|---|
| R422001240 | 100 mm | 100 mm | 10 bar |

The cylinder chamber can theoretically obtain a pressure of 9 bar due to the type of valve chosen for the pneumatic circuit (more on this in the next section). The pneumatic cylinder chosen can withstand a pressure of 10 bar [17, p. 1], so the cylinder is dimensioned to withstand any given situation it can be subjected to.

### 4.8.4 Torque Release Cylinder Pneumatic Circuit

Different control schemes for the pneumatic circuit are possible. This section suggest one possible solution.

The air supply can deliver between 5 and 7 bars of pressure. Since the cylinder piston diameter for the pneumatic cylinder, article number R422001240, is 100 mm [17, p. 2], these pressures correspond to between 3.9 and 5.5 kN. The preload force on the cylinder is chosen to be 2 kN, as stated in Section 4.8.3. The preload pressure, $p_{\text{preload}}$, is determined in Equation 4.20.

$$p_{\text{preload}} = \frac{F_{\text{preload}}}{A_{\text{cyl}}} = \frac{2000 \text{ N}}{\frac{\pi}{4}\,(0.1 \text{ m})^2} \cdot 10^{-5} \text{ }^{\text{bar}}/_{\text{Pa}} = 2.55 \text{ bar} \tag{4.20}$$

#### Preloading the Torque Release

The preload pressure in the cylinder chamber is determined by the variable pressure relief valve (variable PRV in Figure 4.27). This valve is an electro-pneumatic regulator with a pressure range of 0.05–9 bar [22].

The variable pressure relief valve is set to a crack pressure of 3 bar. The solenoid valve between the pressure source and the variable orifice (SV1 in Figure 4.27) is then moved from closed to open. The variable orifice provide for a soft start of the air flow. When the cylinder chamber reaches 3 bar, the variable pressure relief valve starts to bleed air. The pressure transmitter (PT in Figure 4.27) tells the control system that the desired pressure is achieved. SV1 closes, and the variable PRV is set to a crack pressure corresponding to the torque release preload, 2.55 bar. Redundant pressure in the system is bled out through the variable PRV. The torque release mechanism is now ready to compensate for a lance collision.

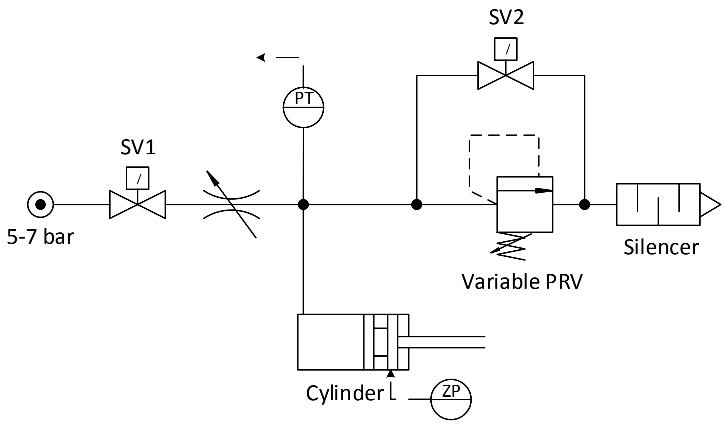



Figure 4.27: Pneumatic circuit for torque release mechanism

#### Torque Release During Lance Collision

When a lance collides as the elevator moves downwards, the cylinder in Figure 4.27 starts to retract, adding pressure to the system. Since the crack pressure of the variable pressure relief valve is in the vicinity of the initial chamber pressure, air will bleed through the valve and exit the system through the silencer. As soon as the cylinder piston starts to retract, a magnetic sensor mounted on the cylinder, indicated as ZP in Figure 4.27, tells the control system that a lance collision is being carried out, and will commence various safety precautions.

#### Removing Air From the Torque Release

If it is desired to remove all pressure from the system, the solenoid valve between the cylinder chamber and the silencer (SV2 in Figure 4.27) is moved from closed to open, allowing for the air in the circuit to exit through the silencer.

#### Summary, Torque Release Cylinder Pneumatic Circuit

The purpose of the torque release solution was to be able to adjust the pressure depending on the chosen lance. Determining these pressures are outside the scope of this thesis. The torque release pressure is set to correspond to 2 kN for all lances for the time being. Buckling calculations have been carried out to make sure that the lances can withstand the forces. The matlab-script can be seen in Appendix B.1. The results are shown in Table 4.7. Some lances have graphite parts at the tip. These components will break before the steel pipe of the lance buckle. This is however not taken into account when performing the buckling analysis. The lengths are not set in stone, but are approximations based on the utility robots height.

### 4.8.5 Torque Release Calculations

The section will present calculations of relevance done for the torque release.

Table 4.7: Buckling forces for lances

| Lance | Length | Buckling force |
|---|---|---|
| Agellis | 4280 mm | 5.4 kN |
| Mechanical level | 4210 mm | 5.6 kN |
| Cleaning lance | 3000 mm | 11.0 kN |
| Temperature lance | 4770 mm | 4.3 kN |

**Dimensioning of Torque Release Fillet Weld**

The torque release is prone to be subjected to relatively high forces. The weld between the torsion member and the parallel linkage arm of the upper parallel linkage member is investigated. When a lance collision occurs, a force corresponding to the cylinder chamber pressure is exerted on both arms of the upper parallel linkage, as shown in Figure 4.28.

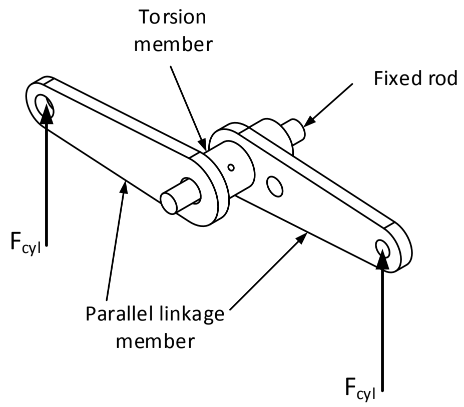



Figure 4.28: Torque release collision situation

The situation shown in Figure 4.28 can be transformed to a situation where the force only is exerted on one arm, and the torsion member is fixed, like shown in Figure 4.29.

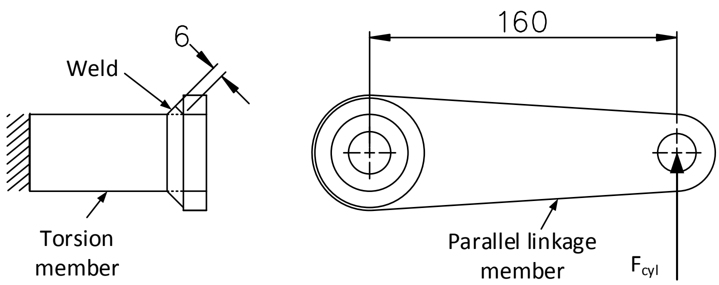



Figure 4.29: Sketch of parallel linkage subjected to a lance collision

As can be seen from Figure 4.29, a fillet weld with a throat thickness of $a = 6$ mm is chosen for this application. All equations used for the weld calculations are taken from the curriculum of the course Mechanical Design, MAS102, attended spring 2011.|

$$\tau_{\parallel} = \frac{T}{I_{\mathrm{p}}} y \tag{4.21}$$

where: $\tau_{\parallel}$ is the shear stress parallel to the weld throat length
$T$ is the torque applied to the weld
$I_\mathrm{p}$ is the polar moment of inertia
$y$ is the perpendicular distance to the neutral axis

The polar moment if inertia is found by Equation 4.22.

$$I_\mathrm{p} = \frac{\pi}{64}\left((d+2a)^4 - d^4\right) = \frac{\pi}{64}\left((40\text{ mm} + 2\cdot 6\text{ mm})^4 - (40\text{ mm})^4\right) \tag{4.22}$$

$$I_\mathrm{p} = 233244.4\text{ mm}^4 \tag{4.23}$$

The worst case scenario for the force acting on the parallel linkage is if the regulator is set to its maximum crack pressure of 9 bar by mistake. The torque generated by this situation is determined in Equation

$$T = F\cdot l = 7000\text{ N}\cdot 160\text{ mm} = 1120000\text{ Nmm} \tag{4.24}$$

$\tau_{\parallel}$ is determined in Equation

$$\tau_{\parallel} = \frac{T}{I_\mathrm{p}}\,y = \frac{T}{I_\mathrm{p}}\left(\frac{d}{2}+a\right) \tag{4.25}$$

$$\tau_{\parallel} = \frac{1120000\text{ Nmm}}{233244.4\text{ mm}^4}\left(\frac{40\text{ mm}}{2} + 6\text{ mm}\right) = \underline{124.8\text{ MPa}} \tag{4.26}$$

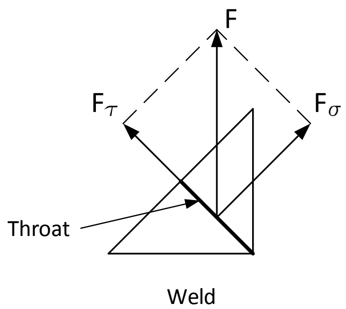



Figure 4.30: Forces acting in fillet weld

The force $F$ is decomposed to $F_\tau$ and $F_\sigma$

$$F_\tau = F_\sigma = \frac{\sqrt{2}}{2}F \tag{4.27}$$

$$F_\tau = F_\sigma = \frac{\sqrt{2}}{2}7000\text{ N} = 4950\text{ N} \tag{4.28}$$

In order to calculate the $\tau_\perp$ and $\sigma_\perp$ the area of the weld throat needs to be determined. The throat area is a conical frustum. The weld with the throat area is depicted in Figure 4.31. The weld throat silhouette is indicated in red, and the weld throat area is indicated in gray.

$$r_2 = r_1 + \sqrt{2}\,a = 20\text{ mm} + \sqrt{2}\,6\text{ mm} = 28.5\text{ mm} \tag{4.29}$$

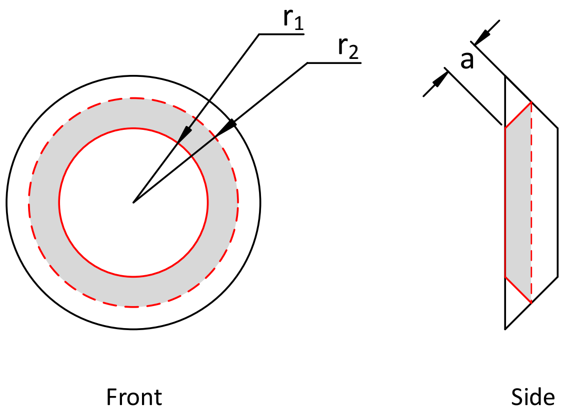



Figure 4.31: Sketch of weld with throat indicated

The formula for calculating the area of a conical frustum is shown in Equation 4.30.

$$A_{\text{weld}} = \pi\ (r_1 + r_2)\ a \tag{4.30}$$
$$A_{\text{weld}} = \pi\ (20\text{ mm} + 28.5\text{ mm})\ 6\text{ mm} = 913.9\text{ mm}^2 \tag{4.31}$$

$$\tau_\perp = \sigma_\perp = \frac{\frac{\sqrt{2}}{2}\,F}{A_{\text{weld}}} = \frac{4950\text{ N}}{913.9\text{ mm}^2} \tag{4.32}$$
$$\tau_\perp = \sigma_\perp = \underline{5.4\text{ MPa}} \tag{4.33}$$

The equivalent stress, $\sigma_e$ is determined using Equation 4.34.

$$\sigma_e = \sqrt{\sigma_\perp^2 + \sigma_\parallel^2 - \sigma_\perp\sigma_\parallel + 3\,\tau_\perp^2 + 3\,\tau_\parallel^2} \tag{4.34}$$
$$\sigma_e = \sqrt{(5.4\text{ MPa})^2 + 3\ (5.4\text{ MPa})^2 + 3\ (124.8\text{ MPa})} = \underline{216.4\text{ MPa}} \tag{4.35}$$

The equivalent stress in the weld with an applied load on the parallel linkage of $F = 7$ kN is 216.4 MPa. This is relatively high. This is however assumed to be adequate, since there is no instance where the torque release will produce 7 kN. In reality, the regulator in the torque release is set to 2.55 bar, producing 2 kN. The torque release shall never produce more force than this. If the same calculations as done above is done for $F = 2$ kN, the result is $\sigma_{e\,@\,2\text{ kN}} = 62$ kN

**Stresses in Cylinder Bracket**

$$\sigma_b = \frac{M_b}{I_{xx}}\,y \tag{4.36}$$

where: $\sigma_b$ is the stress due to bending moment
$M_b$ is the calculated bending moment
$I_{xx}$ is the area moment of inertia about a chosen neutral axis
$y$ is the perpendicular distance to the neutral axis

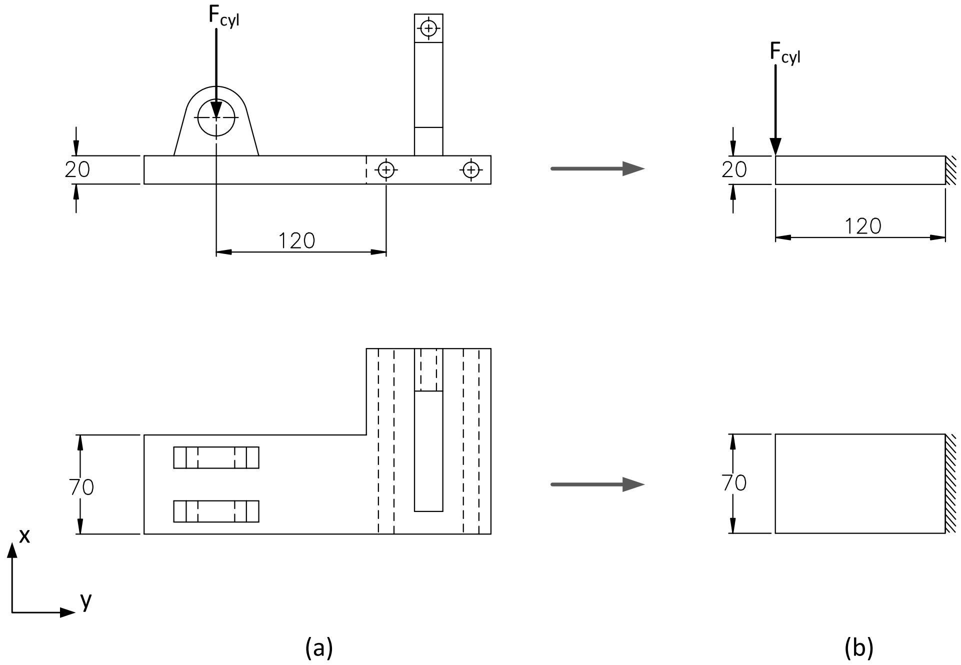



Figure 4.32: Cylinder bracket, real dimensions and simplified

The maximal cylinder force is in this case chosen to be equal to the maximal force the cylinder can produce if the pneumatic regulator is set to 9 bar, $F_{\mathrm{cyl}} = 7$ kN.

$$\sigma_{\mathrm{b}} = \frac{7000\ \mathrm{N} \cdot 120\ \mathrm{mm}}{\frac{1}{12}\, 70\ \mathrm{mm}\, (20\ \mathrm{mm})^3} \cdot 10\ \mathrm{mm} \tag{4.37}$$

$$\underline{\sigma_{\mathrm{b}} = 180\ \mathrm{MPa}} \tag{4.38}$$

The bending stress is found to be relatively high, but this is for a situation with larger-than-normal cylinder load. In reality, the cylinder load will be set to 2 kN at all times. The bending stress is therefore assumed to be acceptable.

**Lance Forces if Cylinder Chamber is Isolated**

The pneumatic cylinder used for the torque release mechanism is preloaded used a regulator. The regulator has a pressure range of 0.05–9 bar [22]. The regulator should be set to a crack pressure corresponding to 2 kN force on the lance. However, it is desirable to check how much pressure in the cylinder chamber and how much force on the lance is produced if the regulator is set to its maximum crack pressure of 9 bar under a lance collision.

It is assumed that the torque release is preloaded to correspond to 2 kN, $p_{\mathrm{preload}} = 2.55$ bar. The regulator is then set to its maximum crack pressure of 9 bar. As a collision occurs, the cylinder rod will retract, reducing the cylinder chamber volume. Boyle's law is used for calculating the pressure in the chamber as a function of present volume, and past volume and pressure. Boyle's law states that the the product of the pressure and volume is constant for a confined gas. It is assumed that the temperature of the gas is constant.

$$p_1\, V_1 = p_2\, V_2 \tag{4.39}$$

where: $p_1$ is the pressure at instance 1
$V_1$ is the gas volume at instance 1
$p_2$ is the pressure at instance 2
$V_2$ is the gas volume at instance 2

A matlab-script is composed for calculating the pressure. Boyle's law is used on the for stated in Equation 4.40.

$$p_{\mathrm{n}} = \frac{p_{\mathrm{n}-1} \cdot V_{\mathrm{n}-1}}{V_{\mathrm{n}}} \tag{4.40}$$

where: $p_{\mathrm{n}}$ is the pressure at an arbitrary instance
$V_{\mathrm{n}}$ is the gas volume at an arbitrary instance
$p_{\mathrm{n}-1}$ is the pressure at the instance before instance n
$V_{\mathrm{n}-1}$ is the gas volume at the instance before instance n

The matlab-script of this calculations is shown in Appendix B.2. The results are shown graphically in Figures 4.33 and 4.34.

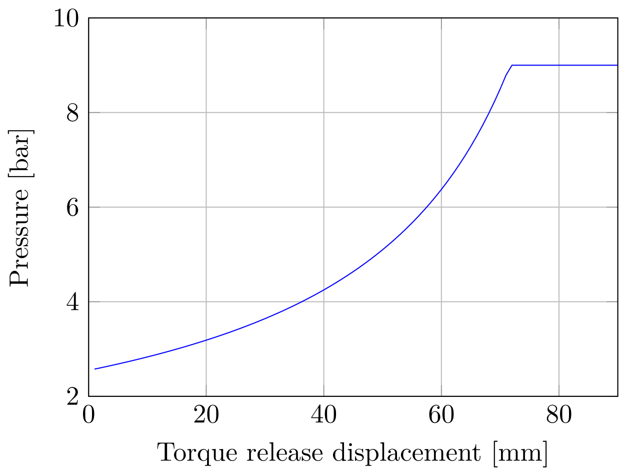



Figure 4.33: Cylinder pressure in closed cylinder chamber with respect to displacement of the torque release

Figures 4.33 shows the chamber pressure of the cylinder with respect to the torque release displacement. It can be observed that when the torque release has been displaced around 65 mm of its full travel distance of 100 mm, 9 bar is produced and the regulator release pressure. Figure 4.34 shows the force produced by the pressure shown in Figure 4.33. Figure 4.34 also shows the real Hot Bowl torque release force (constant 2 kN), and the spring force of the HEX torque release.

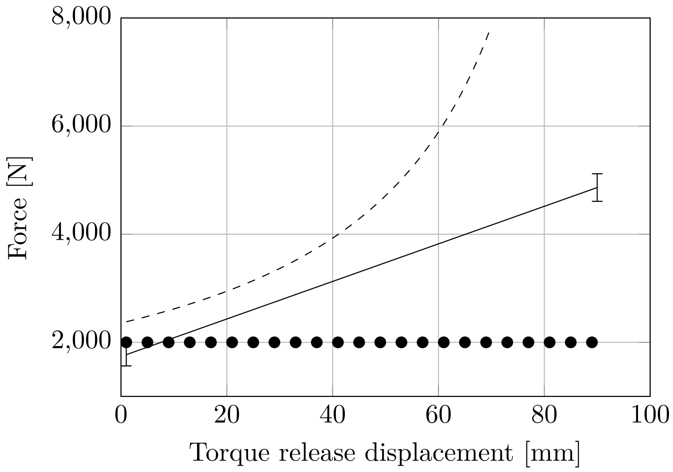



Figure 4.34: Lance forces with respect to dispalcement of torque release

where: Dotted line is the Hot Bowl torque release force as it is intended for a lance collision
Dashed line is the Hot Bowl torque release force with 2 kN preload and closed chamber
Solid line represents the torque release spring force from the HEX torque release solution

## 4.9 Elevator Cart

The elevator cart is the component that the chain actuates up and down. The equipment for mounting lances and for torque release are mounted on this cart. The cart itself consist of a machined steel block, called the cart base in Figure 4.35, and four combined rollers. The rollers move up and down the U-rails mounted on the front side of the elevator column. The u-rails are reused from the HEX utility robot. The rollers needed to be repurchased, since they were welded to the HEX cart. As the HEX linear u-rails used together with mentioned rollers were still intact, it was desirable to purchase rollers that fit the rails.

The chosen rollers have the article number TR 060.0200. Load capacities extracted from the linear rail data sheet [24, p. 17] are presented below.

- Maximum radial load, $F_{\mathrm{R\,max}}$: 8870 N
- Maximum axial load, $F_{\mathrm{A\,max}}$: 2950 N

### 4.9.1 Elevator Cart Calculations

#### Forces Acting on Rollers for Elevator Cart

The elevator cart has four rollers welded to it running in u-rails. This locks the cart position in every degree of freedom except for vertical travel.

The rollers welded to the elevator cart have the article number TR 060.0200. From the data sheet for these rollers [24, p. 17] the following load capacities are given:

- Maximum radial load, $F_{\mathrm{R\,max}}$: 8870 N
- Maximum axial load, $F_{\mathrm{A\,max}}$: 2950 N

There are no situations where the rollers are exposed to significant radial loads. It can also be seen above that the radial load capacity is high for these rollers. However, during a lance collision, significant axial loads may occur and needs to be taken into consideration. Figure 4.36 is used for the following calculations.

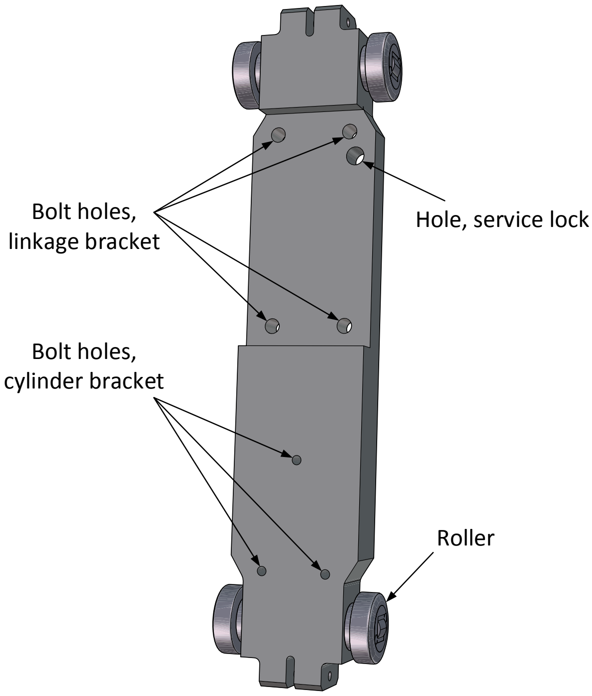



Figure 4.35: Elevator cart base

Where: $l_1 = 510$ mm
$l_2 = 156$ mm
$l_3 = 72$ mm

$$\sum F_{\text{x}} : \; F_{\text{A1}} = F_{\text{A2}} = F_{\text{A}} \tag{4.41}$$

$$F_{\text{linkage}} = 2F_{\text{cyl}} \tag{4.42}$$

$$\sum F_{\text{y}} : \; F_{\text{linkage}} - F_{\text{cyl}} - F_{\text{chain}} = 0 \tag{4.43}$$

$$F_{\text{chain}} = F_{\text{linkage}} - F_{\text{cyl}} \tag{4.44}$$

Equation 4.42 is inserted into Equation 4.44, yielding Equation 4.45.

$$F_{\text{chain}} = 2F_{\text{cyl}} - F_{\text{cyl}} \tag{4.45}$$

$$F_{\text{chain}} = F_{\text{cyl}} \tag{4.46}$$

Sum of moments defined positive counterclockwise.

$$\sum \overset{\curvearrowleft}{M}_{\text{A}}: \; \frac{l_2}{2}F_{\text{linkage}} + l_3F_{\text{cyl}} - l_1F_{\text{A2}} - \frac{l_2}{2}F_{\text{chain}} = 0 \tag{4.47}$$

In Equation 4.47, $F_{\text{A2}}$ is replaced with $F_{\text{A}}$ in accordance with Equation 4.41, resulting in Equation 4.48.

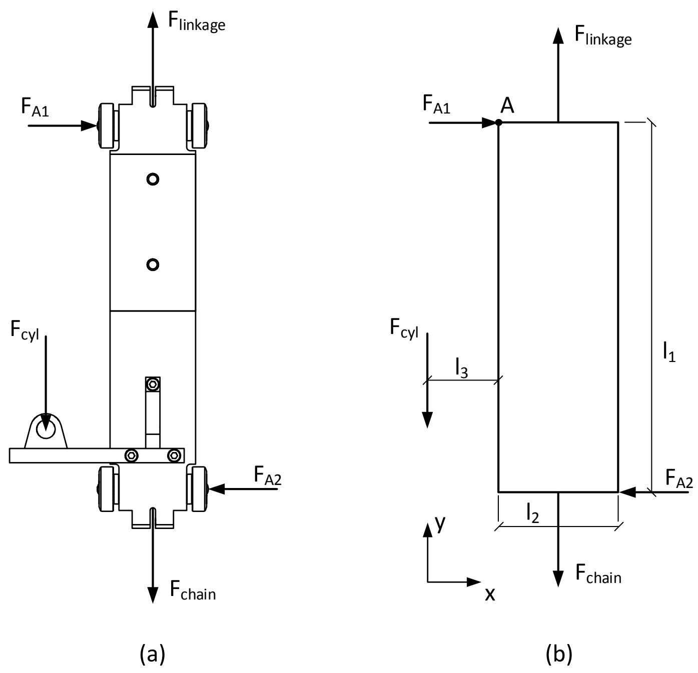



Figure 4.36: Free body diagram of elevator cart during lance collision

$$\frac{l_2}{2}F_{\text{linkage}} + l_3F_{\text{cyl}} - l_1F_{\text{A}} - \frac{l_2}{2}F_{\text{chain}} = 0 \tag{4.48}$$

In Equation 4.48, $F_{\text{chain}}$ is replaced with $F_{\text{cyl}}$ in accordance with Equation 4.46, and $F_{\text{linkage}}$ is replaced with $2\,F_{\text{cyl}}$ in accordance with Equation 4.42, resulting in Equation 4.49.

$$l_2F_{\text{cyl}} + l_3F_{\text{cyl}} - \frac{l_2}{2}F_{\text{cyl}} = l_1F_{\text{A}} \tag{4.49}$$

$$F_{\text{A}} = \frac{\frac{1}{2}l_2 + l_3}{l_1}\,F_{\text{cyl}} \tag{4.50}$$

$$F_{\text{A}} = \frac{5}{17}\,F_{\text{cyl}} \tag{4.51}$$

For determining the maximum force from the cylinder, $F_{\text{cyl}}$, one needs to take the pneumatic circuitry for the torque release cylinder into account. The pneumatic pressure source can produce between 5 and 7 bar. However, the electro-pneumatic regulator to be used in the torque release pneumatic circuitry can produce 9 bar [22]. In theory (though it is not to be used intentionally), during a lance collision, the cylinder pressure can end up at 9 bar if the regulator is set to 9 bar, and if the lance does not buckle due to the load. Consequently, it is decided to dimension the rollers for a cylinder force corresponding to $p_{\text{max}} = 9$ bar.

The cylinder piston diameter is $d_{\text{cyl}} = 100$ mm [17, p. 2].

$$F_{\text{cyl}} = p_{\text{max}}\,A_{\text{cyl}} = 9\text{ bar} \cdot 10^5\ {}^{\text{Pa}}/_{\text{bar}} \cdot \frac{\pi}{4}\ (0.1\text{ m})^2 \cdot 10^{-3}\ {}^{\text{kN}}/_{\text{N}} \tag{4.52}$$

$$F_{\text{cyl}} = 7\text{ kN} \tag{4.53}$$

The rollers' axial loads can now be determined by inserting Equation 4.53 into Equation 4.51.

$$F_A = \frac{5}{17} 7 \text{ kN} = \underline{2 \text{ kN}} \quad (4.54)$$

Although $F_A = 2$ kN lies relatively close to the maximal axial load capacity, $F_{A\,max} = 2950$ N, it is considered to be acceptable since forces of this magnitude will never occur.

## 4.10 Foundation

### 4.10.1 Elevator column position

The elevator column position feature works the same way for the new utility robot as it did for the utility robot used on the HEX reactor, explained in Section 2.3.1. The cylinder used to carry out this motion was an electric cylinder on the HEX reactor. The HEX reactor did not use any hydraulic components. The Hot Bowl reactor however will have other hydraulic components implemented, so the use of a hydraulic cylinder is a more natural choice this time around. This is further emphasized by the fact that the electric cylinder used for HEX had two gas springs coupled in parallel with the direction of the cylinder motion in order to reduce the load on the cylinder. Gas springs are not needed if a hydraulic cylinder is used.

The main components that carry out the elevator column position motion are the hydraulic cylinder and the linear rails, depicted in Figure 4.37.

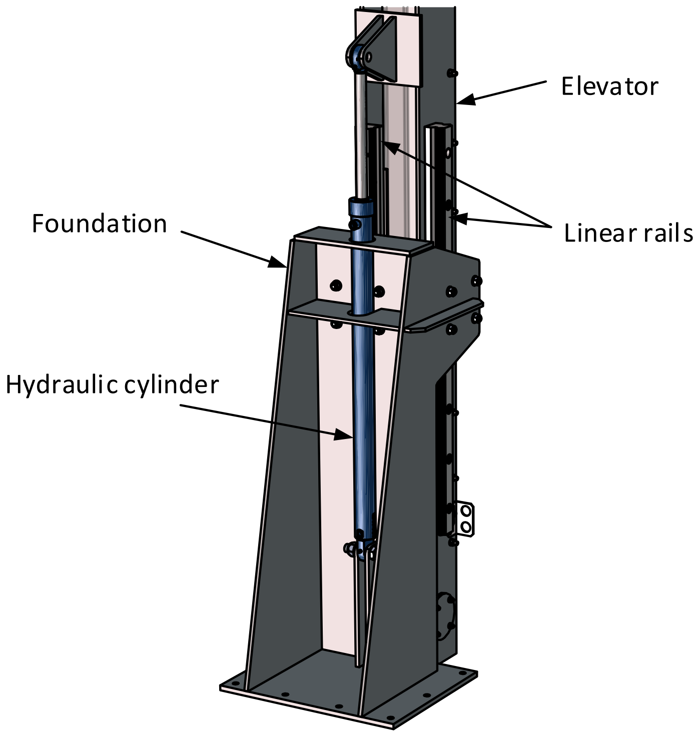



Figure 4.37: Main components of the elevator column position feature

#### Placement of Linear Rails

Two Rollco SBG linear rail systems were chosen for this application. The article number for the linear rail blocks are SBG 65FLL-K1. The linear rails to be used together with these blocks is of the type SBG 65, but the length needs to be determined before ordering. The maximum horizontal deflection of the top of the elevator column due to worst case scenario machining precision of the rail blocks is determined to be $\Delta x = 2.1$ mm. The calculations can be found in Section 7.1. A maximum horizontal deflection of the elevator column of 2.1 mm is adequate for the application.

To ensure that the chosen linear rail blocks can withstand the load from the utility robot, calculations were carried out for determining the moments acting om the rails. The calculations can be seen in Section 7.5. The moment capacities can be seen in Table 4.8, with supplementary figure shown in Figure 7.7.

Table 4.8: Extract: "Linear Rail System SBG" [23, p. 9]

| | Static moment [Nm] | | |
|---|---|---|---|
| Description | $M_{\text{R0}}$ | $M_{\text{Y0}}$ | $M_{\text{P0}}$ |
| SBG 65FLL | 8340 | 8300 | 8500 |

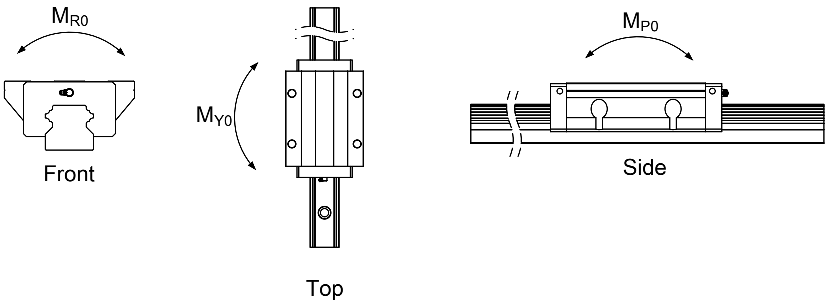



Figure 4.38: Supplementary figure, Table 4.8

The moments found acting on the linear rail blocks are as shown in Table 4.9.

Table 4.9: Calculated moments and moment capacities, SBG linear rail blocks

| Linear rail | Calculated maximum moment | Moment capacities [23, p. 9] |
|---|---|---|
| Right side | $M_{\text{Y0}} = 120$ Nm | $M_{\text{Y0}} = 8300$ Nm |
| | $M_{\text{P0}} = 1983$ Nm | $M_{\text{P0}} = 8500$ Nm |
| Left side | $M_{\text{Y0}} = 1983$ Nm | $M_{\text{Y0}} = 8300$ Nm |
| | $M_{\text{P0}} = 120$ Nm | $M_{\text{P0}} = 8500$ Nm |

As can be seen from Table 4.9, the linear rail blocks are more than strong enough to handle the load of the utility robot.

Originally, the linear rails were to be placed one on each side of the elevator column, meaning that the right side linear rail block in Figure 4.39(a) was mounted on the right side plate, just like it is done for the left side linear rail block. However, when the continuous level measuring probe was implemented, the right side linear rail needed to be placed elsewhere so that it would not collide with the new probe. The right side linear rail were therefore placed on the back of the elevator column as shown in Figure 4.39(b). Placement of the linear rail blocks for this configuration is shown in Figure 4.39(a).

The linear rails are placed as far apart on the elevator column as possible for maximum stability. As can be seen from Figure 4.40(a), there is no room for mounting of the elevator column position linear rail on the front-side of the elevator column web (front and back directions indicated on the far left side of Figure 4.40(a)). The left-side rail is therefore mounted as close to the web as possible. The bolt holes are placed in such a way that the washers do not interfere with the radius between the web and flange of the elevator column, as shown in Figure 4.40(b).

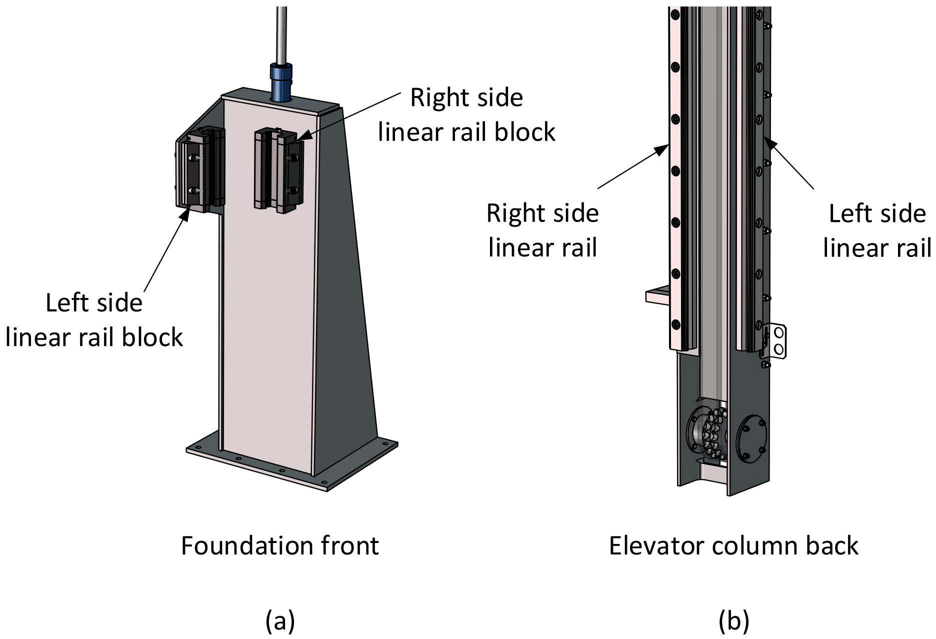



Figure 4.39: Linear rail and linear rail block placements

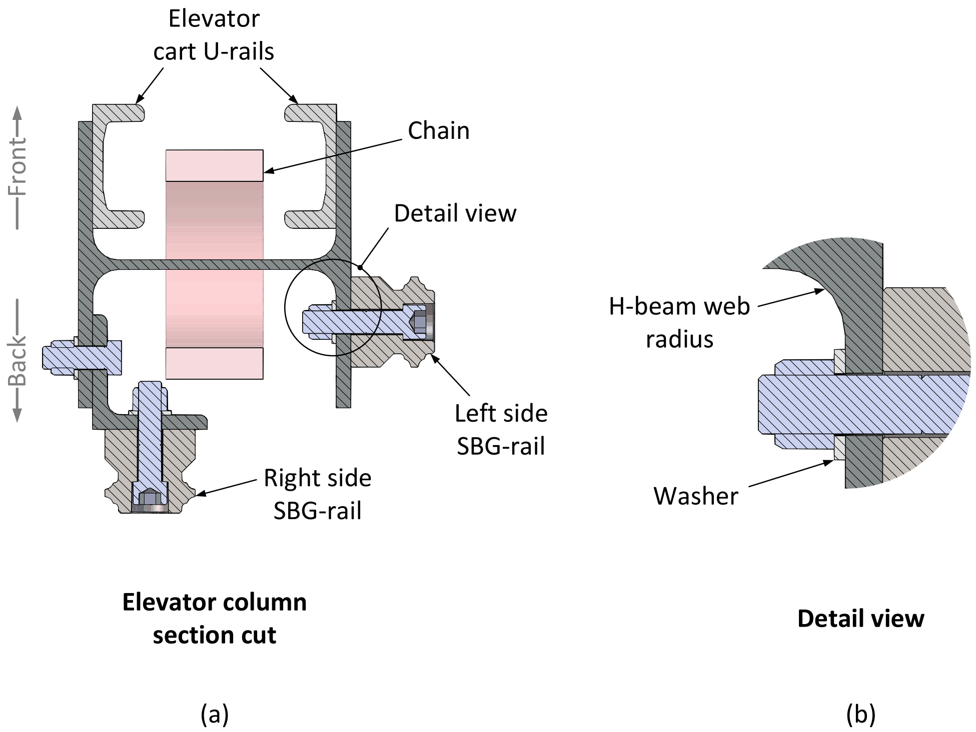



Figure 4.40: Section cut for elevator column

### Choosing Hydraulic Cylinder

The first step in choosing a cylinder is to determine the piston diameter. However, every component for the utility robot is not determined yet. If the lance handler is implemented, this will result in at least two more pneumatic cylinders on the elevator column. The imaging lance, which is not fully developed yet, will contain a motor for rotating the lance. The lance centering arm is not developed yet. These components will add extra weight to the system.

The CAD assembly of the elevator column, elevator cart and lance (everything to be held up by the hydraulic cylinder) of the robot as it is upon completion of the thesis has a weight of $m_{\text{CAD}} = 610$ kg. This includes correct weight for the pneumatic cylinder (2.5 kg), servo motor (17.6 kg, read off of motor nameplate), gearbox (36.4 kg [16, p. 90]), chain (approx. 10 meter of length, 5.42 $^{\text{kg}}/_{\text{m}}$ [4]: 55 kg), linear rails, all machined parts and so on. To be conservative, the weight is assumed to be $m = 1500$ kg. The cylinder force is determined in Equation 4.55.

$$F_{\text{cyl}} = m \cdot g = 1500 \text{ kg} \cdot 9.81 \ ^{\text{m}}/_{\text{s}^2} = 14715 \text{ N} \tag{4.55}$$

A cylinder with a piston diameter of 50 mm is chosen. The piston area is determined in Equation 4.56.

$$A_{\text{cyl}} = \frac{\pi}{4} d_{\text{cyl}}^2 = \frac{\pi}{4} (0.05 \text{ m})^2 = 1.96 \cdot 10^{-3} \text{ mm}^2 \tag{4.56}$$

The required HPU pressure is calculated in Equation 4.57.

$$p_{\text{req}} = \frac{F_{\text{cyl}}}{A_{\text{cyl}}} = \frac{14715 \text{ N}}{1.96 \cdot 10^{-3} \text{ mm}^2} \cdot 10^{-5} \ ^{\text{bar}}/_{\text{Pa}} = \underline{75 \text{ bar}} \tag{4.57}$$

A piston diameter of 50 mm seems to be adequate for this application. The next step is determining how the cylinder is to be mounted on the foundation. Two solutions were evaluated; a top mounted, fixed cylinder and a bottom mounted, hinged cylinder. The solutions can be seen in Figure 4.41(a) and 4.41(b) respectively.

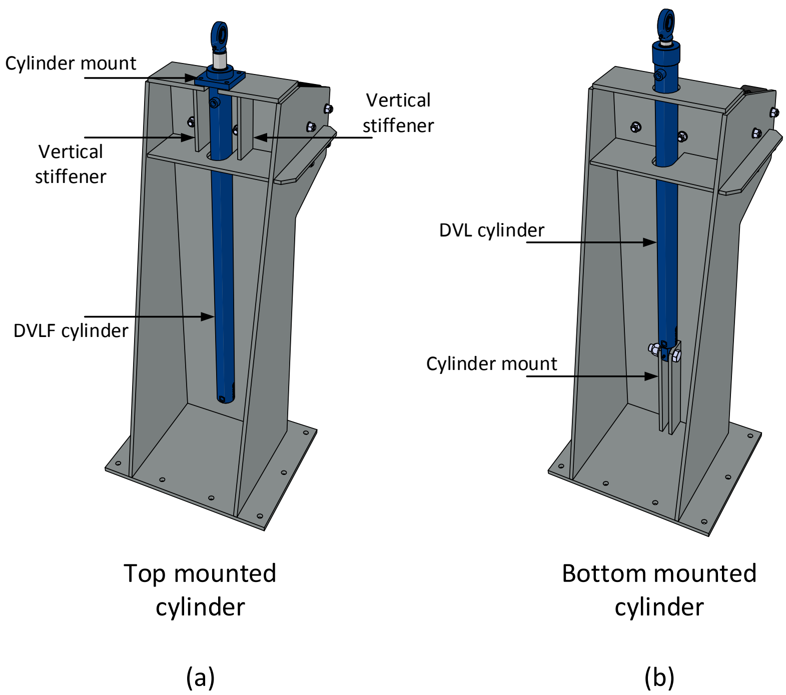



Figure 4.41: Elevator column position cylinder placement

Both solutions have the cylinders mounted as low as possible to make space on the elevator column for other components, such as a chain tensioner. The top mounted cylinder have the disadvantage of transmitting the whole force of the cylinder through the foundation, resulting in more stresses than a bottom mounted cylinder would. This is compensated for by adding two vertical stiffeners, between the two horizontal top stiffeners, depicted in Figure 4.41(a). Relevant cylinder data for the DVLF cylinder (Figure 4.41(a)) and the DVL cylinder (Figure 4.41(b)) are presented in Table 4.10. Both cylinders were found on Slettebøe's web-shop.

Table 4.10: Hydraulic cylinder data for DVL [5] and DVLF [6]

| Description | Art. no. | Piston diameter | Travel distance |
|---|---|---|---|
| Top mounted cylinder | KM DVLF 50 35 1000 | 50 mm | 1000 mm |
| Bottom mounted cylinder | KM DVL 50 30 850 | 50 mm | 850 mm |

The required travel distance of the cylinder is 680 mm. The shortest DVLF cylinder in stock that has long enough travel distance has a travel distance of 1000 mm. This is a bit much, since the linear SBG-rails for safety reasons needs to be long enough to compensate for the whole cylinder travel distance. The DVL cylinder, with its 850 mm travel distance, is a better fit.

Furthermore, the cylinder needs to be mounted relatively far away from the elevator column for which it is to be mounted to. This can result in excessive radial forces on the fixed DVLF cylinder. If one chooses the hinged DVL cylinder instead, this problem is avoided.

Based on the statements above, the DVL 50 30 850 ('**D**obbel **V**irkende sylinder med **L**ager' (double acting cylinder with bearing), piston d = **50** mm, rod d = **30** mm, travel distance = **850** mm) hydraulic cylinder is chosen. This cylinder is shipped with spherical bearing mounts on either end.

### Hydraulic Cylinder Velocity

Very little is known about the HPU to be used for the system. It is an old HPU Alcoa had in store. It is known that the motor for the HPU can produce 4 kW, and we can assume that it can produce a pressure of at least 160 bar. Since it is an old HPU, the power efficiency from the motor to the fluid, $\eta_{\mathrm{M\to F}}$, is assumed to be 80%. We end up with a maximum HPU flow as stated in Equation 4.58.

$$Q_{\text{HPU}} = \eta_{\mathrm{M\to F}} \frac{P_{\text{motor}}}{p_{\text{HPU}}} = 0.8 \cdot \frac{4\ \text{kW}}{160\ \text{bar}} = 0.8 \cdot \frac{4000\ {}^{\text{Nm}}/_{\text{s}}}{160 \cdot 10^5\ {}^{\text{N}}/_{\text{m}^2}} \cdot 60000\ \frac{{}^{\text{l}}/_{\text{min}}}{{}^{\text{m}^3}/_{\text{s}}} = \underline{12\ {}^{\text{l}}/_{\text{min}}} \tag{4.58}$$

Total required travel distance of the hydraulic cylinder, $s_{\text{cyl}} = 680$ mm. Cylinder piston diameter, $D_{\text{cyl}} =$ 50 mm.

$$v_{\text{cyl}} = \frac{s_{\text{cyl}}}{t} \tag{4.59}$$

The HPU volume flow, $Q_{\text{HPU}}$, relates to the cylinder velocity, $v_{\text{cyl}}$, like shown in Equation 4.60.

$$Q_{\text{HPU}} = v_{\text{cyl}} \cdot A_{\text{cyl}} \tag{4.60}$$

Equations 4.59 and 4.60 are merged to find the total time it takes for the elevator column position to go from initial position to top position, $t$. Note that this calculation assumes constant speed from start to finish, which is not possible. A velocity profile needs to be introduced in order to obtain the correct time.

$$v_{\text{cyl}} = \frac{Q_{\text{HPU}}}{A_{\text{cyl}}} = \frac{s_{\text{cyl}}}{t} \tag{4.61}$$

$$t = \frac{A_{\text{cyl}}}{Q_{\text{HPU}}} s_{\text{cyl}} \tag{4.62}$$

$$A_{\text{cyl}} = \frac{\pi}{4}\, D_{\text{cyl}}^2 = \frac{\pi}{4}\,(50\ \text{mm})^2 = 1963.5\ \text{mm}^2 \tag{4.63}$$

$$t = \frac{1963.5\ \text{mm}^2 \cdot \left(10^{-3}\ {}^{\text{m}}/_{\text{mm}}\right)^2}{12\ {}^{\text{l}}/_{\text{min}}} \cdot 60000\ \frac{{}^{\text{l}}/_{\text{min}}}{{}^{\text{m}^3}/_{\text{s}}} \cdot 0.68\ \text{m} = \underline{6.7\ \text{s}} \tag{4.64}$$

**Length of Linear Rails**

When the cylinder total travel distance is determined, the lengths of the linear rails can be chosen. The length of the rail needs to be the sum of the total hydraulic cylinder travel distance and the length of the linear block to be used together with the rail, as well as some free length on each side. The whole cylinder travel length will not be used, but the rails needs to be long enough for the whole cylinder travel in case something goes wrong with the control system, or the operator of the robot override the control system and extracts the cylinder from local control mode. Local control mode is an operation mode for the machine, discussed in more detail in Section 6.1.1.

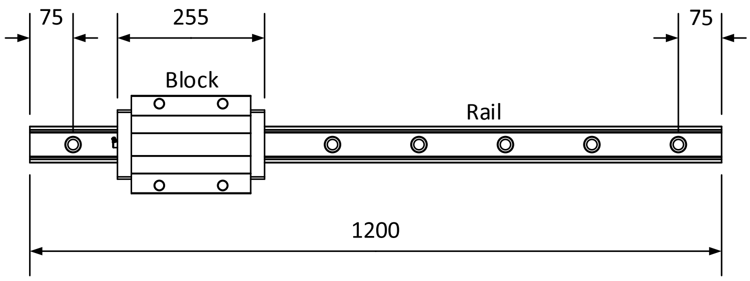



Figure 4.42: SMG linear rail system

The length of the linear rails are chosen to be 1200 mm long. The full article number is SBG 65-1200-75-75, where SBG is the type of rail, 65 is the size of the rail, 1200 is the total length in millimeters, and 75-75 is the distance from the end of the rail to center of last hole in millimeters, and the distance from the start of the rail to center of first hole in millimeters respectively.

**Height of Foundation**

Now that the linear rail lengths are determined, the placement of the linear rail blocks on the foundation, and in turn the height of the foundation, can be determined. The linear rails are to be placed at a height such that the rails never travel through the floor.

**The Hydraulic Circuit for the Elevator Column Position Feature**

Under normal operation, the elevator column position cylinder is to lower and hoist a static load (weight of elevator and lance). This is a simple operation. A proposed solution for the hydraulic circuit can be seen in Figure 4.43.

When hoisting the elevator, the the 4/3-way valve indicated in Figure 4.43 is opened in negative position (4/3-way valve moves upwards with respect to Figure 4.43). The flow runs through the check valve (CV in figure) and flows into the cylinder chamber.

When lowering the load, the 4/3-way valve opens in positive position. The flow runs through the mentioned valve and into the cylinder rod-side chamber of the cylinder. As the cylinder piston moves downwards, the flow out of the piston-side chamber runs through a counterbalance valve (CB valve in figure) that chokes the flow so that the hydraulic cylinder does not move downwards in an uncontrollable manner.

Note that the type of counterbalance valve used in Figure 4.43 (internally piloted counterbalance valve) is meant for static loads. If the load on the cylinder changes, the valve needs to be adjusted.

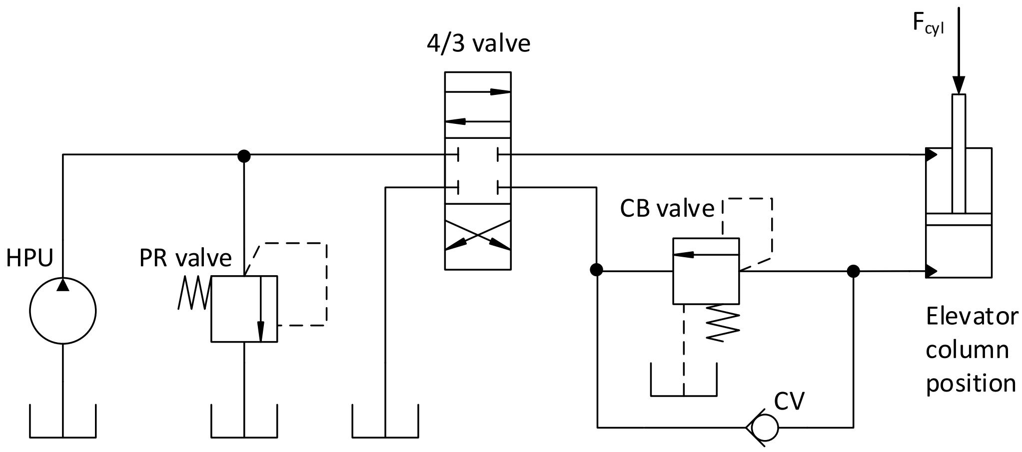



Figure 4.43: Hydraulic circuit for the elevator column position cylinder

### 4.10.2 Calculations for the Foundation

#### FEM Analysis of Foundation

A FEM analysis is carried out for the foundation. The CAD-model of the foundation was converted to a surface model with all surfaces in the mid-plane of the plates in the CAD-model. The complete process of the FEM analysis is explained in Section 7.6. The result can be seen in Figure 4.44.

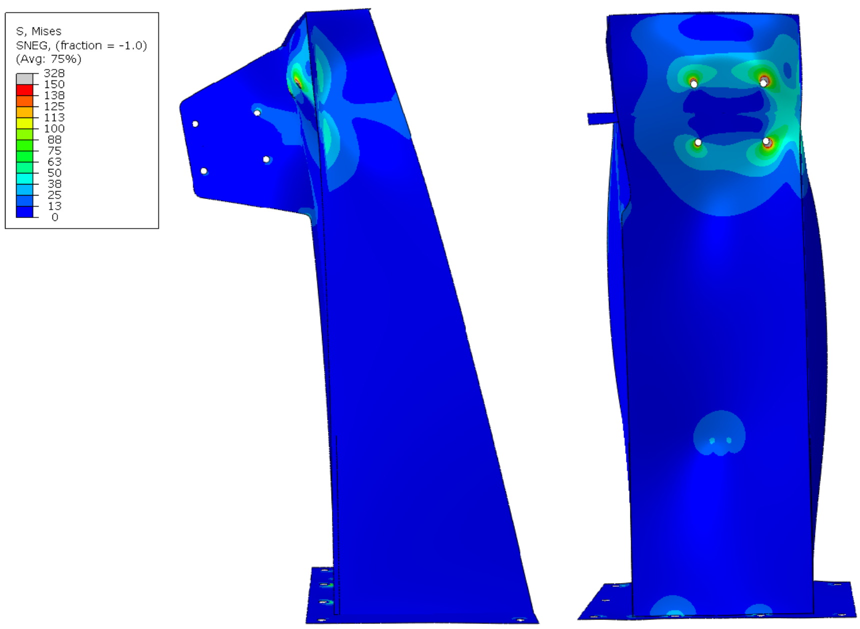



Figure 4.44: Results from FEM analysis of the foundation

#### Verification of Hole Size in Top Plate

The foundation has a hole in its top plate where the cylinder is entered into. Figure 4.45 shows the top plate.

It is desirable to determine if this hole is large enough such that the hydraulic cylinder does not collide with the top plate. It is determined that the maximum angular deviation of the hydraulic cylinder is $\Delta\phi_{\mathrm{c\,max}} = 0.02°$. The calculations can be seen in Section 7.3.

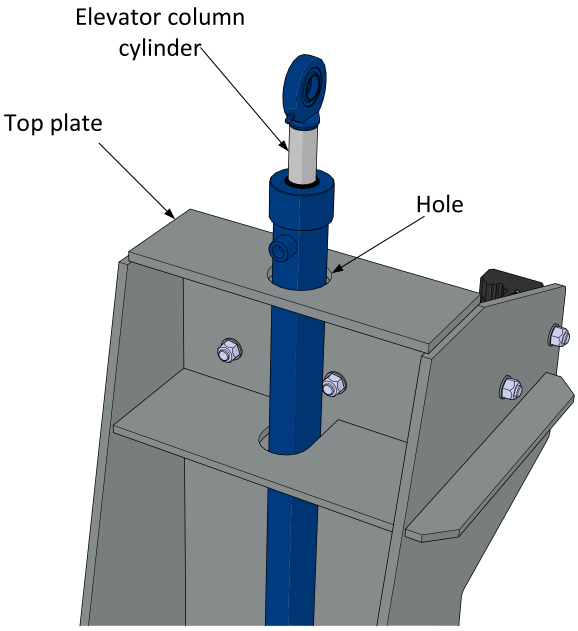



Figure 4.45: Foundation top plate

From the CAD model it is observed that the maximum possible angular deviation is $\Delta\phi_{\mathrm{c\,max\,CAD}} = 0.37°$. The hole is large enough.

## 4.11 Service Lock

The service lock was developed as a safety precaution when carrying out maintenance on the utility robot. The purpose of the service lock is to mechanically lock the parallel linkage, elevator cart and the elevator column to each other. The service lock is shown in Figure 4.46. It consists of a bent steel plate welded to a steel rod.

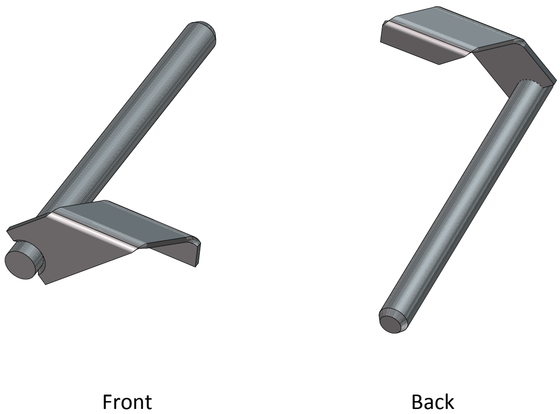



Figure 4.46: Service lock

The service lock is entered through the hole in the parallel linkage member indicated in Figure 4.47(a). Concentric holes are made through the elevator cart base and the elevator column web, such that the service lock can penetrate all these components. A inductive sensor is placed on the back of the elevator column, giving information to the control system whether the service lock is mounted or not. The control system cuts the power to the utility robot if the service lock is mounted. Figures 4.47(b) and 4.47(c) shows how the service lock is held in place. The bent plate wraps around the parallel linkage member, locking it for axial movement.

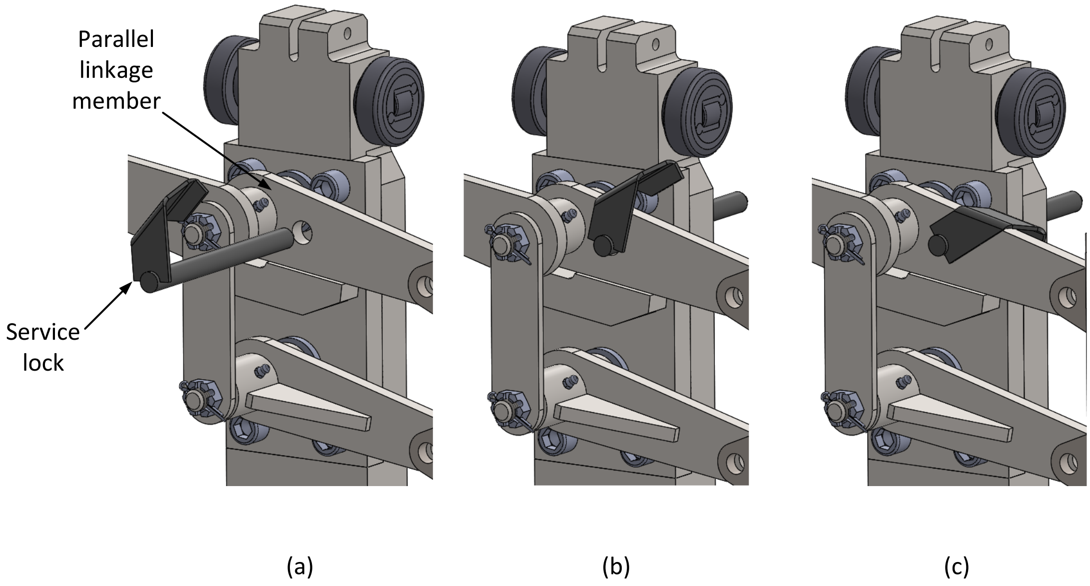



Figure 4.47: Service lock mounting sequence

Figure 4.48 shows the service lock mounted in place in the elevator cart.

The service lock has a diameter of 15 mm. The maximum shear stress that occur on the service lock is $\tau_{\text{sl}} = 63.6$ MPa. The calculations can be seen in Section 7.4.

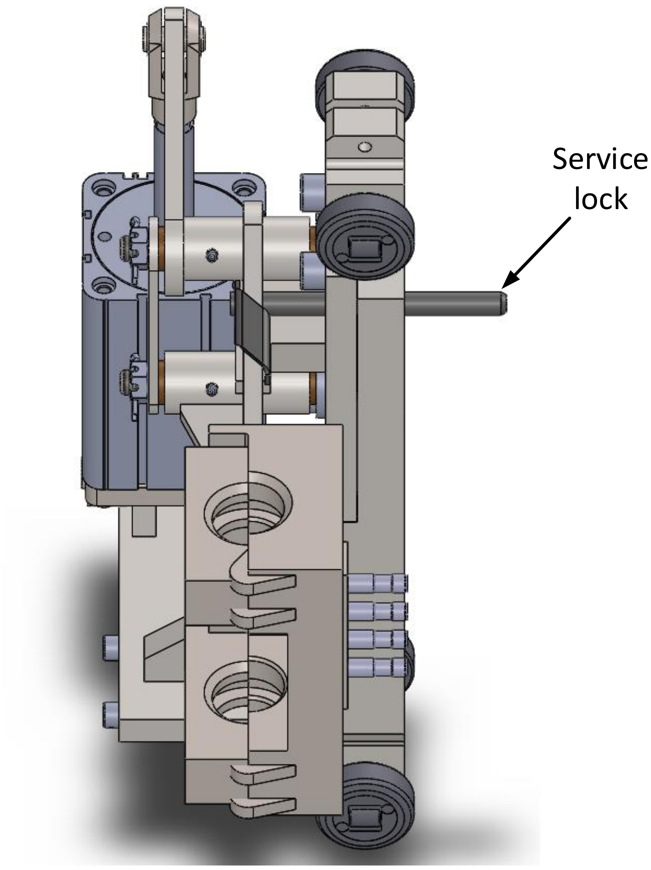


Figure 4.48: Service lock mounted on elevator cart

# Chapter 5

# Presentation of the Final Concept

This chapter presents the final concept developed as part of this thesis.

The main components of the utility robot are the foundation, elevator column, elevator cart and the lances. The mentioned components are depicted in Figure 5.1. The assembled utility robot can be seen in Figure 5.2.

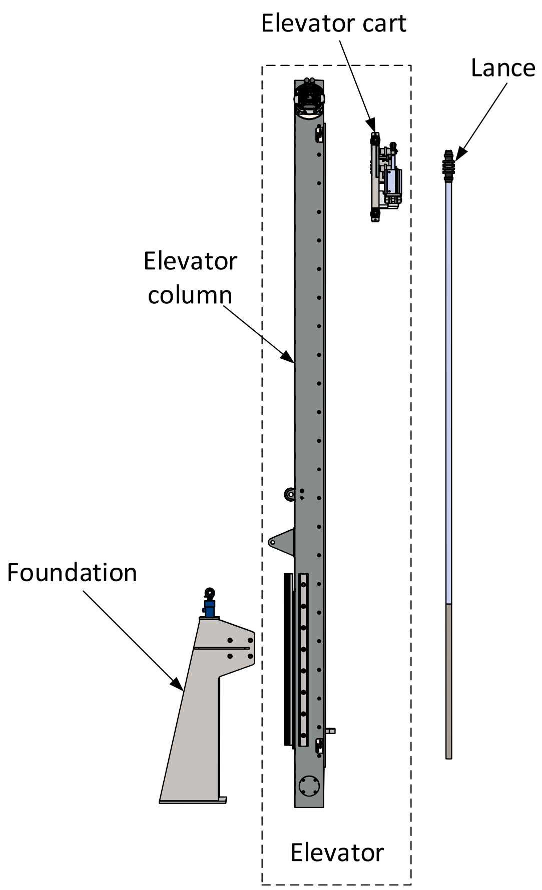



Figure 5.1: Exploded view of the Hot Bowl utility robot

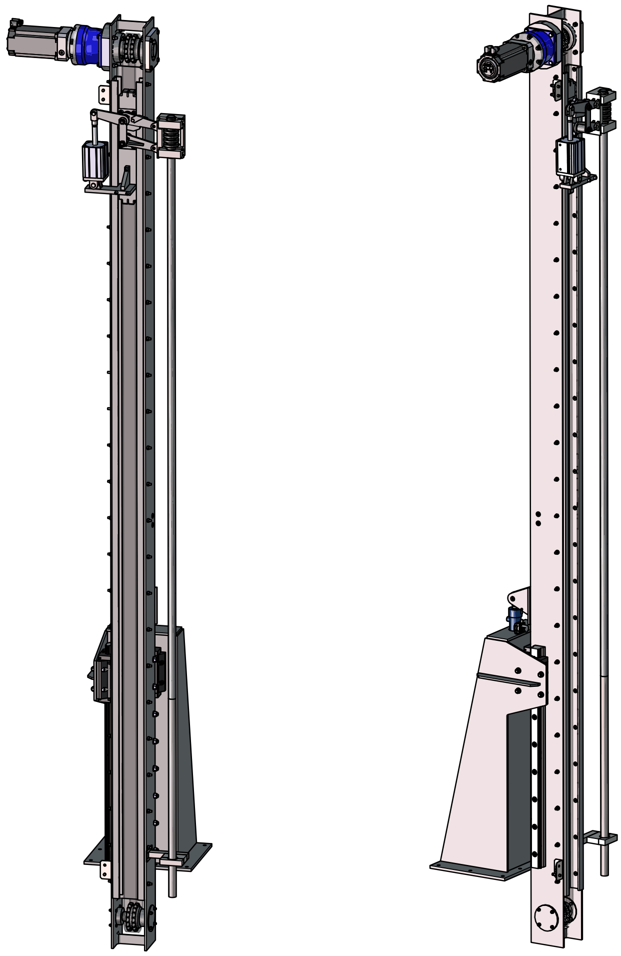


Figure 5.2: The Hot Bowl utility robot

### Foundation

The foundation is the base of the utility robot. The elevator column slides up and down the foundation by the means of linear rails. A hydraulic cylinder, indicated in Figure 5.3, actuates the elevator column up and down. This feature, called elevator column position, has a travel distance of 680 mm.

### Elevator Column

The elevator column's main member is an 5080 mm long H-profile with a chain wrapped around it. At each end a shaft is mounted with a sprocket in contact with the chain. The upper shaft has a servo motor and gearbox mounted to it, powering the actuation of the elevator cart. The elevator column is shown in Figure 5.4.

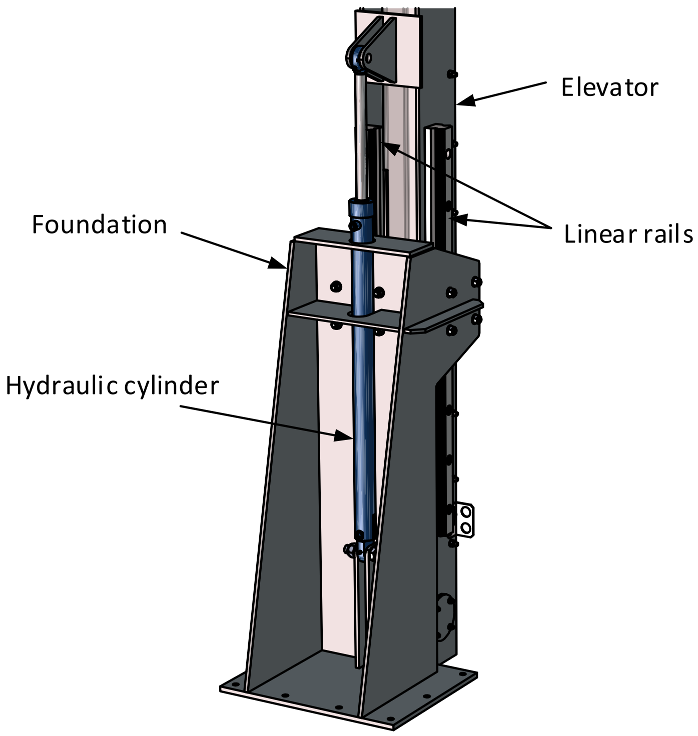



Figure 5.3: Main components of the elevator column position feature

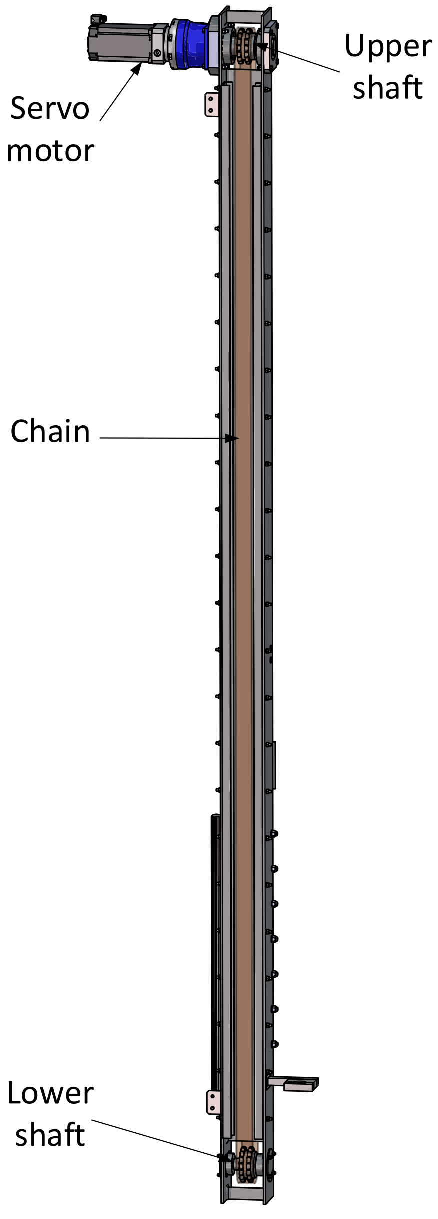



Figure 5.4: Hot Bowl elevator column

**Elevator Cart**

The elevator cart runs in linear rails along the elevator column. It is fastened to the chain, and is actuated up and down by the servo motor mounted on the elevator column's upper shaft. The elevator cart can be seen in Figure 5.5.

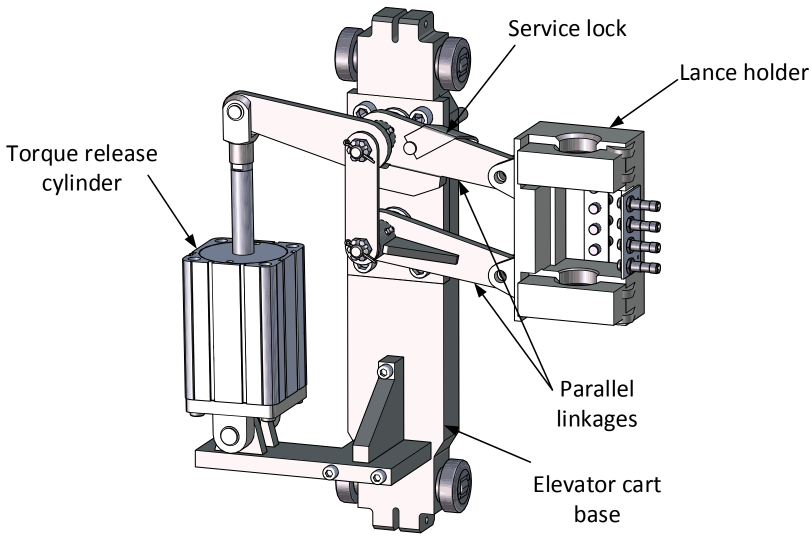



Figure 5.5: Hot Bowl elevator cart

Four u-rail rollers are welded to the elevator cart base. Lances are mounted in the lance holder. The lance holder is suspended on two parallel linkages. The parallel linkages together with the pneumatic cylinder and its bracket form the torque release mechanism.

A service lock is used for locking the elevator cart and the torque release while doing maintenance. An inductive sensor mounted on the back of the utility robot cuts the power to the system upon detecting the service lock, preventing damage on the robot due to the operator forgetting to remove the lock prior to operation of the robot.

## 5.1 Purchase List

This section presents parts that are selected and purchased throughout this semester, as well as parts supplied by the machine shop, parts not yet ordered, and parts reused from the HEX utility robot.

Table 5.1: Purchase list, Hot Bowl utility robot

| Description | Placement | No. | Article no. | Supplier |
|---|---|---|---|---|
| Pneumatic cylinder | Elevator cart | 1 | R422001240 | Bosch Rexroth |
| Cylinder sensor | Elevator cart | 2 | 0830100433 | Bosch Rexroth |
| Cylinder rod clevis | Elevator cart | 1 | 3590505000 | Bosch Rexroth |
| Cylinder rear mount | Elevator cart | 1 | 3682910590 | Bosch Rexroth |
| Lock nut | Lower shaft | 1 | KM 8 | Slettebøe |
| Lock washer | Lower shaft | 1 | MB 8 | Slettebøe |
| Lock nut | Upper shaft | 1 | KM 15 | Slettebøe |
| Lock washer | Upper shaft | 1 | MB 15 | Slettebøe |
| Self-lubricating bronze bushing | Elevator cart | 2 | 20/26X20 32X3 | Slettebøe |
| Self-lubricating bronze bushing | Elevator cart | 1 | 16/20X12 | Slettebøe |
| Bronze bushing | Elevator cart | 4 | JF 16X16 | Slettebøe |
| Sprocket | Lower shaft | 1 | 16 B-2 17 | Slettebøe |
| Hydraulic cylinder | Foundation | 1 | DVL 50 30 850 | Slettebøe |
| Linear rail | Elevator column | 2 | SBG 65-1200-75-75 | Rollco |
| Linear rail block | Elevator column | 2 | SBG 65FLL-K1 | Rollco |
| Roller for U-rail | Elevator cart | 4 | TR 060.0200 | Rollco |
| Bearing | Lower shaft | 2 | BS2-2208-2CS/VT143 | SKF |

Table 5.2: Purchase list, Hot Bowl utility robot, not yet ordered

| Description | Placement | No. | Article no. | Supplier |
|---|---|---|---|---|
| Grease fitting | Elevator cart | 2 | FET 501 A4 | Slettebøe |
| Pneumatic fitting | Pneumatic cylinders | 3 | G 1/8 | |
| Hydraulic fitting | Foundation | 2 | G 3/8 | |
| Duplex chain | Elevator column | 1 | 16 B-2 (length unknown) | Slettebøe |
| Nylon bushing | Lance holder | 2 | | |

Table 5.3: Components for the Hot Bowl utility robot supplied by machine shop

| Description | Placement | No. | Description |
|---|---|---|---|
| Screws | | | |
| Washers | | | |
| Nuts | | | |
| Circlips | | | |
| Castle nut | Elevator cart | 2 | M16 |
| H-beam | Elevator column | 1 | HE 200A L=5080 |
| Split pin | Elevator cart | 2 | Dimensions: Ø4 L40 |

Table 5.4: Re-usable components from the HEX utility robot

| Description | Placement | No. | Article no. | Supplier |
|---|---|---|---|---|
| Inductive sensor | | | XS112B3PAM12 | Schneider Electronics |
| Motor | Elevator column | 1 | MPL-B540K-MK74AA | Allen-Bradley |
| Gearbox | Elevator column | 1 | SP 180S-MF2-16-OI1-2S | Wittenstein Alpha |
| Bearing | Upper shaft | 1 | BS2-2215-2CS/VT143 | SKF |
| Bearing | Upper shaft | 1 | 24015-2CS2/VT143 | SKF |
| Sprocket | Upper shaft | 1 | 16 B-3 17 | Slettebøe |
| HPU | | 1 | Unknown | Unknown |
| U-rails | Elevator column | 2 | UP 060.0700 | Rollco |

## 5.2 Operation Manual

This section describes the manual work related to the operation of the utility robot.

### Changing of Lances

Lances are changed manually from the service platform. The top of the service platform is shown in Figure 5.6.

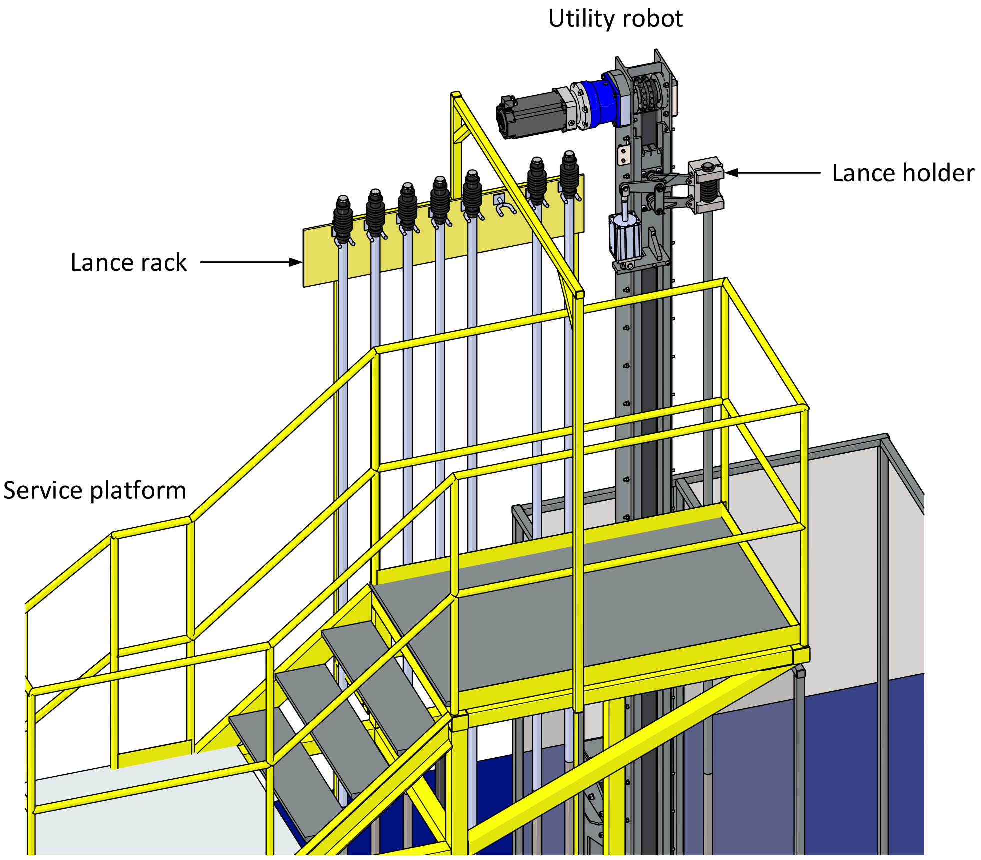



Figure 5.6: Hot Bowl service platform and utility robot

The operator will stand on the platform shown in Figure 5.6. The lance mounted on the utility robot is detached by manually opening the lance holder. The locking mechanism is not yet developed. The operator places this lance in its designated place in the lance rack and places the new lance in the lance holder. The magnets placed inside the lance holders secure the lance from falling out of the lance holder while the operator locks the lance holder latches and secures the lance in place. When the lance is secured, the lance centering arm (not within the scope of this thesis) closes around the lance by the means of pneumatic actuation.

# Chapter 6

# Control System

## 6.1 Functional Design Specification (FDS)

This section will explain how the utility robot is to be controlled by the PLC, and will be used by Alcoa's instrumentation engineers as a basis for designing a complete control scheme for the robot. This section will not include functional design specifications for components of the reactor, such as components of the utility pipe, as this is not within the scope of this thesis.

### 6.1.1 Introduction

The utility robot is the machine responsible for carrying out different types of measurements on the inside of the reactor and its molten content. The measurements are carried out by lowering a pipe with a tool at the end of it down into the reactor. These pipes with tools mounted on them are called lances. Most of the tools used are probes for measuring different parameters such as temperature, aluminum level and the composition of the aluminum, but there is also a tool used for cleaning the utility pipe, and a tool used for taking images inside the reactor. The utility robot's main components are shown in Figure 6.1.

The utility robot has three different control modes. In **operator mode** the robot is manually controlled by the operator from the control room. In **program mode** the robot is automatically controlled by the active operation mode, described in Section 6.1.10. In **local control mode** the robot is controlled manually by the operator from the local control panel.

This FDS is designed for the utility robot as it is for shakedown. The lance handler is not implemented by then, and will therefore not be described in detail in this text. The lance centering arm is also not described in this FDS, because of pending design due to undetermined design of continuous level measuring probe.

All sensors mentioned in this chapter is assigned its own number. These numbers follow the sensors throughout the whole FDS.

### 6.1.2 Elevator Cart

The elevator cart's main task is to move the lances up and down the utility pipe. The cart is fixed to a duplex chain actuated by a servo motor, and it runs in linear rails mounted on the elevator column. The elevator cart can be seen in Figure 6.2(a). Main components of the elevator cart is shown in Figure 6.2(b).

The elevator cart has three different inductive sensors along its path. Two of these sensors, called high position and low position (inductive sensor 1 and inductive sensor 3 respectively) function as endstops for the elevator cart, cutting the power to the servo motor when initiated. The third inductive sensor (inductive sensor 2) is located directly below the high position sensor (inductive sensor 1), and is used for calibrating the servo drive encoder used for determining the elevator cart position. This calibration is done every time the elevator cart passes by isensorTwoi.

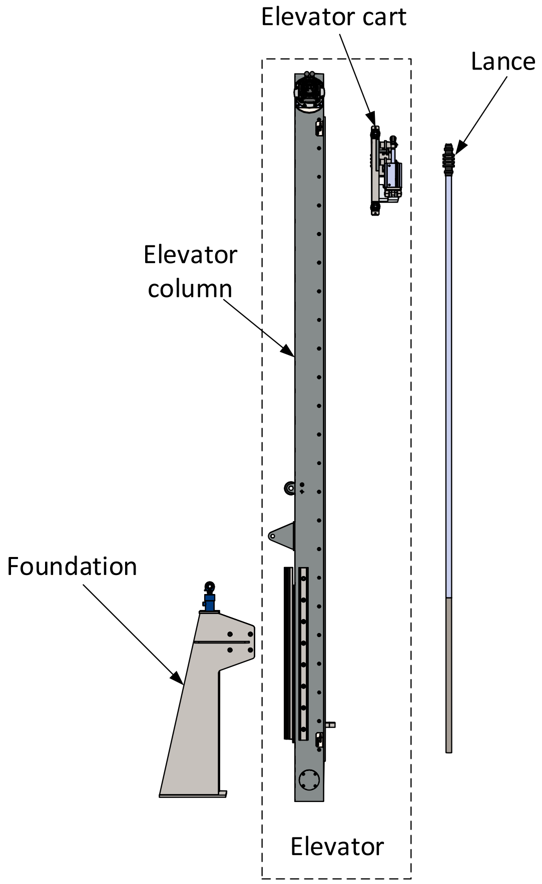



Figure 6.1: Exploded view of utility robot

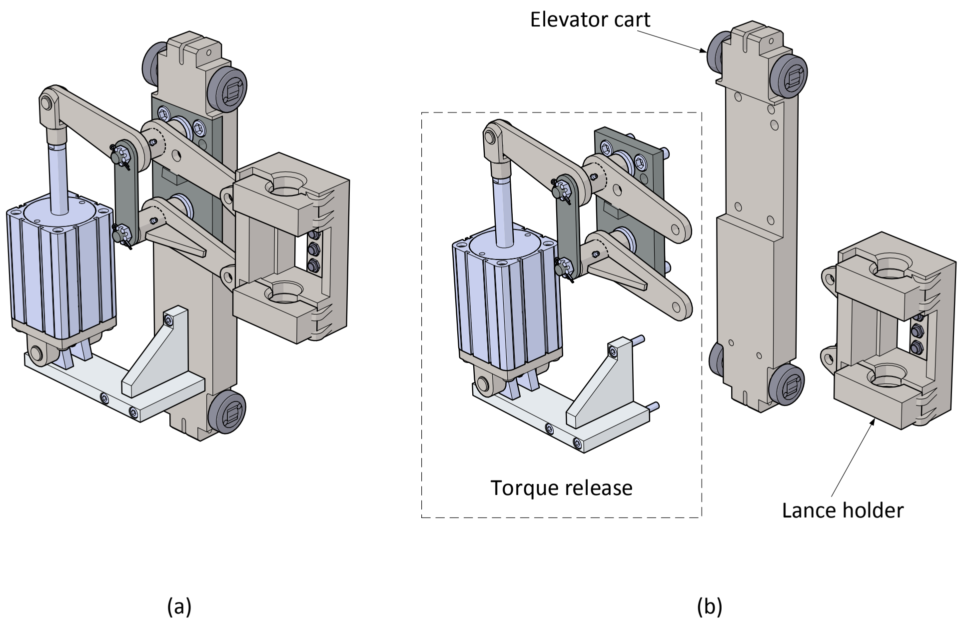



Figure 6.2: Elevator cart main components

**Operator mode**

In operator mode the elevator cart position is manually controlled by the operator from the control room. The operator is able to actuate the elevator cart up and down by the use of buttons.

#### Program mode

In program mode the elevator cart is automatically controlled by the active operation mode, described in Section 6.1.10.

#### Local control mode

In local control mode the elevator cart position is manually controlled by the operator from the local control panel.

#### Signals

The signals relating to the elevator cart are presented in Table 6.1.

Table 6.1: Elevator cart signals

| | | Mode | | |
|---|---|---|---|---|
| Description | Signal source | Operator | Program | Local |
| Elevator up | Button 1 | | | x |
| Elevator down | Button 2 | | | x |
| High position, elevator cart | Inductive sensor 1 | x | x | x |
| Calibration position, elevator cart | Inductive sensor 2 | x | x | |
| Low position, elevator cart | Inductive sensor 3 | x | x | x |
| Absolute vertical position, elevator cart | Servo drive encoder | x | x | x |

### 6.1.3 Elevator Column Position

In addition to the elevator cart's travel, the elevator column itself can also be actuated along the same axis as the elevator cart's direction of motion. This is implemented in order to be able to mount the tallest lances in the utility robot, and not collide with the overhead crane after mounting. This motion is called the elevator column position, and is actuated by a hydraulic cylinder mounted on the robot's foundation, as shown in Figure 6.3.

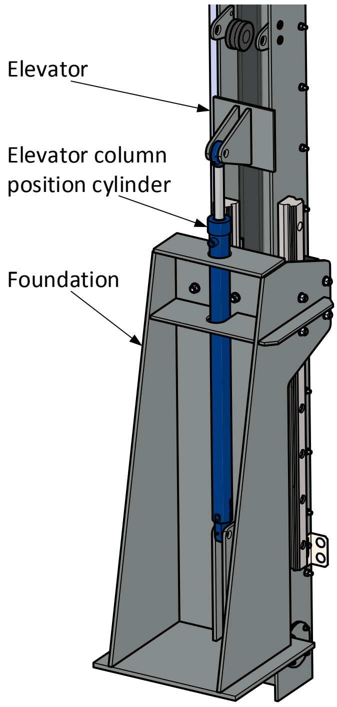



Figure 6.3: Elevator column position cylinder

The suggested solution for the hydraulic circuit is shown in Figure 6.4.

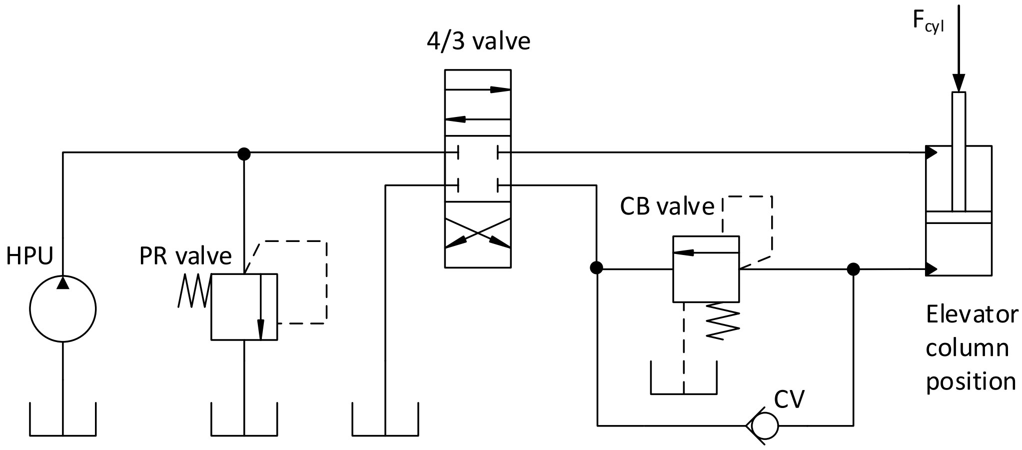



Figure 6.4: Hydraulic circuit for the elevator column position cylinder

where: HPU = hydraulic power unit
PR valve = pressure relief valve
CB valve = counter balance valve
CV = check valve

The position of the elevator column cylinder is measured with an analogue distance sensor mounted on the robot's foundation. In addition to this, an inductive sensor is mounted in top and bottom position of the cylinder. The bottom sensor (inductive sensor 4) is placed where the hydraulic cylinder is fully retracted. The top sensor (inductive sensor 5) is placed 680 mm above the bottom sensor.

#### Operator Mode

In operator mode the elevator column position is manually controlled by the operator from the control room. The operator is able to actuate the elevator column up and down by the use of buttons.

#### Program Mode

In program mode the elevator column position is automatically controlled by the active operation mode, described in Section 6.1.10.

#### Local Control Mode

In local control mode the elevator column position is manually controlled by the operator from the local control panel.

#### Signals

Table 6.2: Elevator column position signals

| | | Mode | | |
|---|---|---|---|---|
| Description | Signal source | Operator | Program | Local |
| Elevator column position up | Button 3 | | | x |
| Elevator column position down | Button 4 | | | x |
| Vertical position, elevator column | Analogue distance sensor | x | x | x |
| High position | Inductive sensor 5 | x | x | x |
| Low position | Inductive sensor 4 | x | x | x |
| Extract hydraulic cylinder | Digital output | x | x | x |
| Retract hydraulic cylinder | Digital output | x | x | x |

### 6.1.4 Lance Holder

The lance holder is the interface between the lances and the elevator cart. The lance is still in development, but its final design will likely be similar to the concept depicted in Figure 6.5. The lance holder is manually opened and closed by the means of to latches closing around the lance, locking it in place.

Four inductive sensors are mounted on a bracket at the back of the lance holder, as shown in Figure 6.5(b). These sensors detect a bit pattern attached to the lances. Each lance has its own bit pattern, presented in Table 6.3.

Table 6.3: Tool selection bit pattern

| Equipment | Bit 3 | Bit 2 | Bit 1 | Bit 0 | Value |
|---|---|---|---|---|---|
| Empty | 0 | 0 | 0 | 0 | 0 |
| Agellis lance | 0 | 0 | 0 | 1 | 1 |
| Temperature lance | 0 | 0 | 1 | 0 | 2 |
| Pyrometer lance | 0 | 0 | 1 | 1 | 3 |
| Sampler lance | 0 | 1 | 0 | 0 | 4 |
| Mechanical level lance | 0 | 1 | 0 | 1 | 5 |
| Cleaning tool | 0 | 1 | 1 | 1 | 6 |
| Imaging lance | 1 | 0 | 0 | 0 | 7 |

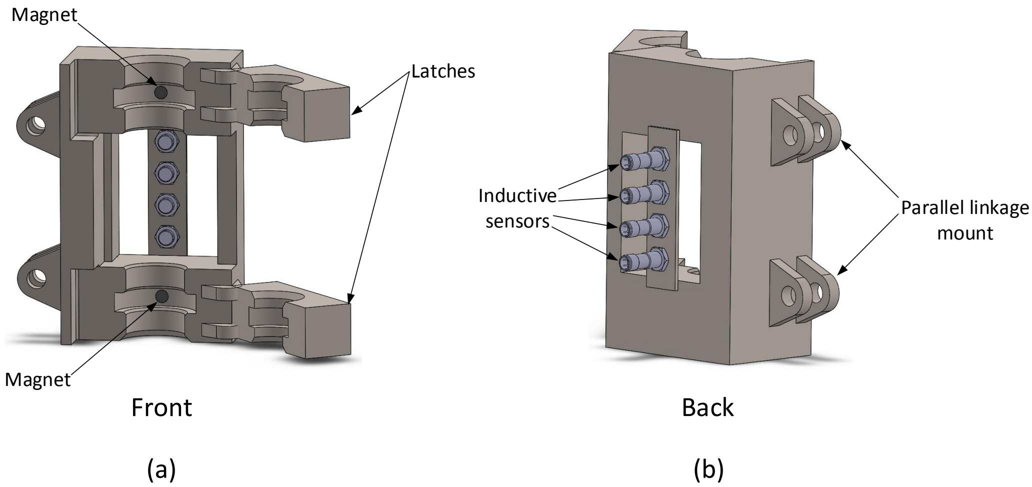



Figure 6.5: Lance holder, manually operated

#### Interlocks

Lance holder operation is interlocked when no lance is detected by the inductive sensor. The interlock is overridden when jogging from local control panel is performed.

#### Signals

The signals relating to the lance holder are presented in Table 6.4.

Table 6.4: Lance holder signals

| | | Mode | | |
|---|---|---|---|---|
| Description | Signal source | Operator | Program | Local |
| Open latches | Button 5 | | | x |
| Close latches | Button 6 | | | x |
| Latches fully open | Magnetic cylinder sensor 1 | x | x | x |
| Latches fully closed | Magnetic cylinder sensor 2 | x | x | x |
| Tool selection bit pattern, bit 0 | | x | x | x |
| Tool selection bit pattern, bit 1 | | x | x | x |
| Tool selection bit pattern, bit 2 | | x | x | x |
| Tool selection bit pattern, bit 3 | | x | x | x |

### 6.1.5 Lance Centering Arm

The lance centering arm is not within the scope of this thesis, and will not be addressed in detail in this FDS.

### 6.1.6 Fence

The utility robot will have a fence surrounding it. A door on the fence can be opened to gain access to the utility robot. An inductive sensor tells the control system whether the door is open or closed. Opening the door activates local control mode for the utility robot.

#### Signals

The signal relating to the fence is presented in Table 6.5.

Table 6.5: Fence signals

| | | Mode | | |
|---|---|---|---|---|
| Description | Signal source | Operator | Program | Local |
| Access door 1 open | Inductive sensor 7 | x | x | x |

### 6.1.7 Service Lock

When an operator is to perform any kind of service on the utility robot, the power shall be cut manually in accordance with Alcoa's internal procedures. In addition to this, the robot shall be locked with a metal rod, mechanically locking the parallel linkage, elevator cart and elevator column relative to each other. This metal rod is called the service lock. An inductive sensor (inductive sensor 6) mounted on the elevator column will function as an extra barrier, assuring no power to the system when the lock is in place.

#### Signals

The signals relating to the service lock are presented in Table 6.6.

Table 6.6: Service lock signals

| | | Mode | | |
|---|---|---|---|---|
| Description | Signal source | Operator | Program | Local |
| Service lock detected | Inductive sensor 6 | x | x | x |

### 6.1.8 Torque Release

In order to protect the lance from mechanical damage if the lance were to collide with an obstacle, a torque release mechanism is mounted on the elevator cart. The mechanism, shown in Figure 6.2, is made up of a parallel linkage mechanism and a pneumatic cylinder. A proximity sensor (magnetic cylinder sensor 5) is mounted on the pneumatic cylinder for detecting deflection from initial position of the pneumatic cylinder. Upon detecting deflection of the pneumatic cylinder, the control system shall immediately abort any downwards motion of the elevator cart by cutting of power to the servo motor and initiating the brake function of the motor. When the system has come to a complete rest, the elevator cart shall lift the equipped lance back up.

The suggested solution for the pneumatic circuit is presented in Figure 6.6.

Since the different lances used by the utility robot is of different lengths and are made of different types of materials, they all tolerate different magnitudes of force before buckling or breaking. Because of this, every lance has the possibility of having its own torque release preload. These values are not yet determined. The preloads are therefore set to be the same as the preload of the torque release for the old solution. The values are shown i Table 6.7.

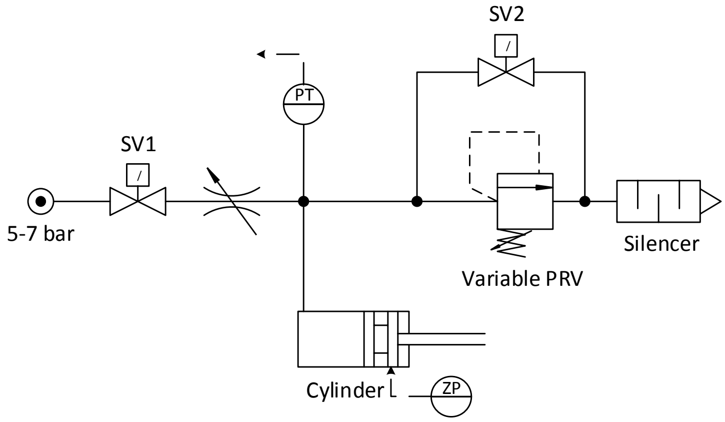



Figure 6.6: Pneumatic circuit for torque release mechanism

where: SV1 = solenoid valve
PT = pressure transmitter
ZP = magnetic sensor
SV2 = solenoid valve
Variable PRV = variable pressure relief valve

Table 6.7: Torque release preloads

| | Preload | |
|---|---|---|
| Equipment | [kN] | [bar] |
| Empty | 2 | 2.55 |
| Agellis lance | 2 | 2.55 |
| Temperature lance | 2 | 2.55 |
| Pyrometer lance | 2 | 2.55 |
| Sampler lance | 2 | 2.55 |
| Mechanical level lance | 2 | 2.55 |
| Cleaning tool/Stoker lance | 2 | 2.55 |
| Imaging lance | 2 | 2.55 |

Collision procedure:

1. Magnetic cylinder sensor 5 indicates a collision
2. Cut of power to the elevator servo motor
3. Apply maximum braking torque on servo motor brake
4. Wait until the cart's downward motion has come to a complete halt (motor encoder)
5. Move cart to top position
6. Add air to the cylinder chamber until the right preload is achieved again.
7. Wait until magnetic cylinder sensor 5 indicates that the cylinder is completely extracted again
8. An error/alarm will warn the operator of the incident, telling him/her to carry out a manual inspection of the lance
9. The system will not allow for the utility robot to run again until an operator has acknowledged that the lance has been inspected

#### Signals

The signals relating to the lance holder are presented in Table 6.8.

Table 6.8: Torque release signals

| Description | Signal source | Mode | | |
|---|---|---|---|---|
| | | Operator | Program | Local |
| Pneumatic cylinder pressure | Pressure transmitter | x | x | x |
| Pneumatic cylinder deflection | Magnetic cylinder sensor 5 | x | x | x |
| Programmable pressure relief valve | Analogue output | x | x | x |
| Add air to cylinder chamber (solenoid valve) | Digital output | x | x | x |
| Ramp down pressure (solenoid valve) | Digital output | x | x | x |

### 6.1.9 Lance Handler

The lance handler will not be implemented until after shakedown, and will not be addressed in detail in this FDS.

### 6.1.10 Operation Modes

This section describes the sequences for the operation modes for all lances. For all operations in this section that require actuation of the elevator cart/lance and no sensor is specified in parentheses, the motor absolute encoder is to be used for position control. All velocities stated in the operation modes are taken from the HEX FDS.

#### Agellis Level Measurement

The Agellis lance detects whether the probe is in contact with aluminum or slag, and can therefore be used to measure aluminum level and slag level in the reactor.

The information gathered by the Agellis probe is sent through a circuit dedicated to this specific lance. This circuit can be seen as a black box where raw data from the lance is sent in and desirable information is sent out. This circuitry is referred to as the Agellis system in the sequence below.

When the operator initiates an Agellis measurement the following sequence is carried out:

1. The Agellis system confirms that it is ready to do a measurement
2. If elevator cart is not in its top position (inductive sensor 2), move to top position
3. If elevator column position is not in upper position (analogue distance sensor), move to upper position
4. Close stuffing box if open
5. Open paper sheath removal clamp if closed
6. Move elevator column position to lower position
7. Lower the elevator cart to a position such that the tip of the lance is 200 mm above the utility pipe's lower isolation valve plate (preset position 1)
8. The utility robot is ready to carry out a measurement. Wait for the operator to activate measuring sequence
9. Open the utility pipe's lower isolation valve

10. Lower the elevator cart to a position 200 mm below the utility pipe's graphite dome (preset position 2) at a velocity of 40 m/min
11. Change the velocity to 20 m/min and continue downwards. Start sending level information to the Agellis system. Lower the elevator cart to the preset measuring depth
12. Stop sending level information to the Agellis system
13. Raise the elevator cart back up to a position such that the lower tip of the paper sheath is 100 mm above the utility pipe's isolation valve (preset position 3) at a velocity of 40 m/min
14. Close utility port isolation valve
15. Close paper sheath removal clamp
16. Raise the elevator cart to top position at a velocity of 10 m/min
17. Move the elevator column positioner to top position
18. Automatic level measurement sequence now ended

**Temperature Measurement**

The temperature measurement lance is a type C thermocouple element encapsulated in graphite.

When the operator initiates a temperature measurement the following sequence is carried out:

1. If elevator cart is not in its top position (inductive sensor 2), move to top position
2. If elevator column position not in upper position (analogue distance sensor), move to upper position
3. If paper sheath removal clamp is closed, open it
4. If stuffing box is open, close it
5. Move elevator column position to its lower position (analogue distance sensor)
6. Open upper utility pipe isolation valve
7. Lower the lance down to a position such that the tip of the lance is 200 mm above the lower utility pipe isolation valve plate
8. Ready to carry out measurement. Wait for operator to activate temperature measuring sequence
9. Open lower utility pipe isolation valve
10. Lower the lance to a position so that the tip of the lance is flush with the graphite dome at a velocity of 40 m/min. Carry out the following sub-sequence:
    (a) Wait a predefined time period for the temperature measurement to stabilize OR wait for button 9 to be pushed
    (b) If distance between tip of lance and liquid metal is more than 100 mm, lower lance 100 mm
    (c) Go to (a)
11. If full temperature measurement is selected carry out the following sub-sequence:
    (a) Lower lance to lowest position specified for this lance
    (b) Wait a predefined time period for the temperature measurement to stabilize OR wait for button 9 to be pushed
    (c) If distance between tip of lance and liquid metal is more than 100 mm, move lance 100 mm up
    (d) Go to (b)
12. Move lance up to a position where the tip of the lance is 100 mm above the utility pipe isolation valve
13. Close lower utility pipe isolation valve

14. Automatic sequence now ended

### Pyrometer Measurement

The pyrometer lance is a non-contact measuring probe that intercept and measures thermal radiation. The thermal radiation is used to determine the temperature of an object's surface [13]. The surface in this case is the graphite for which the pyrometer is encapsulated in. The pyrometer lance follows the exact same sequence as the temperature lance.

### Mechanical Level Measurement

The mechanical level probe determines the total liquid level inside the reactor. The probe referred to on this lance is a simple reinforcing bar. The probe is lowered a given distance down into the reactor. The grooves across the surface of the reinforcing bar is manually inspected afterwards in order to determine the total liquid level.

When the operator initiates a mechanical level measurement the following sequence is carried out:

1. If elevator cart is not in its top position (inductive sensor 2), move to top position
2. If elevator column position not in upper position (analogue distance sensor), move to upper position
3. If paper sheath removal clamp is closed, open it
4. If stuffing box is open, close it
5. Move elevator column position to its lower position (analogue distance sensor)
6. Open upper utility pipe isolation valve
7. Lower the lance down to a position such that the tip of the lance is 200 mm above the lower utility pipe isolation valve plate
8. Ready to carry out measurement. Wait for operator to activate mechanical level measuring sequence
9. Open lower utility pipe isolation valve
10. Lower the lance to a position where the tip of the lance is 200 mm below the the graphite dome (preset position) at a velocity of 40 m/min
11. Continue down at a velocity of 40 m/min until the preset measuring depth is reached
12. Wait a predefined period of time
13. Move lance up to a position 100 mm above the lower utility pipe isolation valve plate
14. Close lower utility pipe isolation valve
15. Wait for cool down time to finish
16. Automatic sequence now ended

The following signals are associated with the mechanical level measurement:

- Slag sample level relative to reactor bottom
- Cool down time
- Measured level on rod. Reactor metal/slag level calculated automatically

### Cleaning Mode

Cleaning mode is used to keep the utility pipe clean and free from condensate build-ups. The cleaning mode is carried out between measurements, and can either be carried out cyclic with a predefined wait time between each sequence, or it can be carried out as a single sequence.

When the operator initiates a cleaning sequence the following sequence is carried out:

1. If elevator cart is not in its top position (inductive sensor 2), move to top position
2. If elevator column position not in upper position (analogue distance sensor), move to upper position
3. If paper sheath removal clamp is closed, open it
4. If stuffing box is closed, open it
5. Lower the elevator column position to its middle position (analogue distance sensor) for operation of stuffing box
6. Open upper utility pipe isolation valve
7. Lower the elevator to a position where the tip of the cleaning lance is 200 mm above the lower utility pipe isolation valve plate
8. Close stuffing box
9. Lower elevator column position to lower position (analogue distance sensor)
10. Open lower utility pipe isolation valve
11. Lower the elevator cart to a position such that the tip of the cleaning lance is 100 mm below the graphite dome at a velocity of 40 m/min
12. Stop the elevator and reverse direction, moving the tip of the cleaning lance to a position 100 mm above the lower utility pipe isolation valve plate
13. Close lower utility pipe isolation valve
14. Move elevator column position to middle position (analogue distance sensor)
15. Open stuffing box
16. Move elevator cart up to top position (inductive sensor 2) at a velocity of 10 m/min
17. Close upper utility pipe isolation valve
18. Move elevator column position to its upper position (analogue distance sensor)
19. Close stuffing box
20. Automatic sequence now ended

### Imaging Mode

The imaging lance is not developed yet. Since the working principle of the lance is not known, no imaging sequence is composed.

# Chapter 7

# Calculations and Analyses of Critical Components

## 7.1 Maximum Horizontal Deflection of Elevator, Linear Rails

The linear rail block used for this application has the article number SBG 65FFL-K1. From the data sheet for this linear rail solution [23, p. 27] one can observe that linear rail blocks with precision class N (standard precision class) has a precision of $\Delta W_2 = \Delta H = \pm 0.1$ mm. Figure 7.1 shows where $W_2$ and $H$ are measured from.

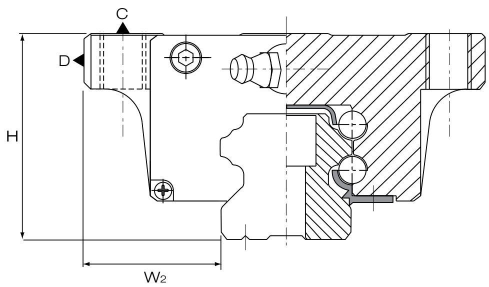



Figure 7.1: Extract from linear rail data sheet [23, p. 27]

Based on this, a worst-case-scenario is chosen for the linear rails, where maximum deviation in both ends for both rails are present. Maximum deviation on a linear rail is shown in Figure 7.2.

Maximum angle produced by deviations in the linear rail blocks is calculated in Equations 7.1–7.2.

$$\phi = \tan^{-1}\left(\frac{\Delta W_2}{L_{\text{block}}}\right) \tag{7.1}$$

$$\phi = \tan^{-1}\left(\frac{0.1\text{ mm}}{207\text{ mm}}\right) \approx 0.0277^\circ \tag{7.2}$$

When the elevator column position is in its upper position, the length between the linear rail block and the top of the elevator is $L_{\text{elevator}} = 4305$ mm. This is used together with the angle found in Equations 7.1–7.2 to determine maximum horizontal deflection of the top of the utility robot based on worst-case precision on the linear rail blocks. The result can be seen in Equation 7.5.

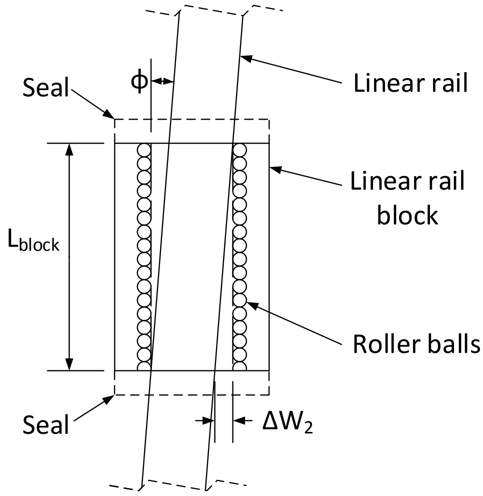



Figure 7.2: Sketch of maximum angle deflection of linear rail

$$\Delta x = L_{\text{elevator}} \sin(\phi) \tag{7.3}$$
$$\Delta x = 4305 \text{ mm} \cdot \sin(0.0277°) \tag{7.4}$$
$$\Delta x = \underline{2.1 \text{ mm}} \tag{7.5}$$

## 7.2 Forces Acting on Key for Upper Shaft

Figure 7.6 shows the chain drive and the components interacting with the chain.

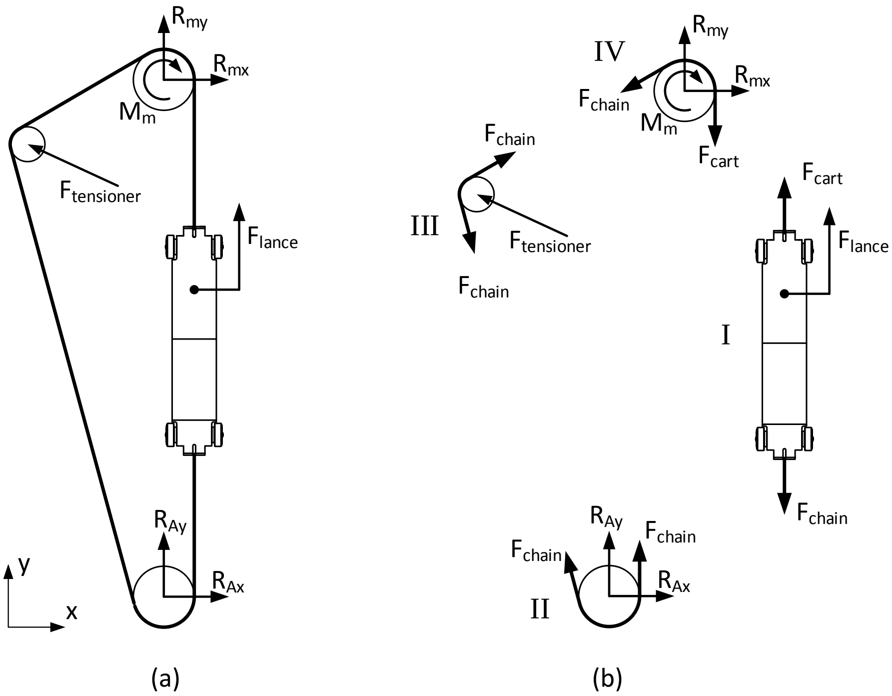



Figure 7.3: Sketch of forces acting on the chain and components interacting with the chain

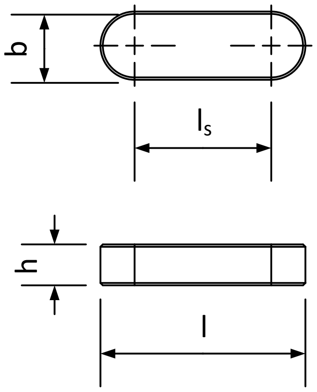



Figure 7.4: Key dimensions in accordance with DIN 6880

Table 7.1: Explanation, Figure 7.4

| Description | Length [mm] |
|---|---|
| Width, $b$ | 20 |
| Height, $h$ | 12 |
| Total length, $l$ | 60 |
| Supporting length, $l_s$ | 40 |

The chain tensioner in Figure 7.3(b), III is acting with a force on the roller, $F_{\text{tensioner}}$, in such a way that the chain is preloaded with a force $F_{\text{pre}}$. Sum of forces in y-direction for Figure 7.3(b), I is shown in Figure 7.6.

$$\sum F_{\text{I,y}} = F_{\text{lance}} + F_{\text{cart}} - F_{\text{chain}} = 0 \tag{7.6}$$

The pitch diameter of the sprockets in Figures 7.6(b), IV and 7.6(b), II is $d_{\text{p}} = 138.22$ mm [7].

$$\sum \overset{\frown}{M}_{\text{IV,m}} = r_{\text{p}} \left(F_{\text{pre}} + F_{\text{lance}}\right) - r_{\text{p}} \left(F_{\text{pre}} - F_{\text{lance}}\right) - M_m = 0 \tag{7.7}$$

$$M_m = 2\, r_{\text{p}}\, F_{\text{lance}} \tag{7.8}$$

$$M_m = 2 \cdot \frac{0.13822 \text{ m}}{2} \cdot 6000 \text{ N} = 829 \text{ Nm} \tag{7.9}$$

The shear force can now be calculated using the torque calculated in Equations 7.7–7.9, and the diameter of the shaft where the keyway is to be machined, $d_{\text{shaft}} = 75$ mm. The shear force is computed in Equation 7.10.

$$F = \frac{M_{\text{m}}}{r_{\text{shaft}}} = \frac{829 \text{ Nm}}{\frac{1}{2}\, 0.075 \text{ m}} = 22107 \text{ N} \tag{7.10}$$

The key chosen for this application is a parallel key with rounded edges, as shown in Figure 7.4. The dimensions for the key are shown in Table 7.1. The total length of the key is chosen to be $l = 40$ mm. With a width of $b = 20$ mm, the supporting length of the key becomes $l_{\text{s}} = 40$ mm.

The dimensions shown above are used together with the shear force calculated in Equation 7.10 to determine the shear stress in the key, $\tau_{\text{key}}$. The shear area of the key is the product of the key width, $b$, and the key supporting length, $l_{\text{s}}$.

$$\tau_{\text{key}} = \frac{F}{A} = \frac{F}{b \cdot l_{\text{s}}} \tag{7.11}$$

$$\tau_{\text{key}} = \frac{22107 \text{ N}}{20 \text{ mm} \cdot 40 \text{ mm}} = \underline{27.6 \text{ N/mm}^2} \tag{7.12}$$

For alloy steel, one can assume the maximum allowable shear stress, $\tau_{\text{allowed}}$, to be 58% of the material's yield strength, $\sigma_y$ [21, p. 268]. In accordance with DIN 6880, the material for the key can be assumed to have a proof stress (approximation for the yield point for materials that don't have a definite one due to their structure [14]) of $\sigma_{\text{y}^*} = 170$ N/mm². 

$$\tau_{\text{allowed}} \approx 0.58\,\sigma_{\text{y}} = 0.58 \cdot 170\ {}^{\text{N}}\!/_{\text{mm}^2} \tag{7.13}$$

$$\tau_{\text{allowed}} \approx 98\ {}^{\text{N}}\!/_{\text{mm}^2} \tag{7.14}$$

$$\tau_{\text{key}} = 27.6\ {}^{\text{N}}\!/_{\text{mm}^2} < 98\ {}^{\text{N}}\!/_{\text{mm}^2} \tag{7.15}$$

$$\underline{\tau_{\text{key}} < \tau_{\text{allowed}}} \tag{7.16}$$

## 7.3 Maximum Angular Deviation, Hydraulic Cylinder

Maximum angular deviation of the hydraulic cylinder is based on maximum angular deviation of the linear guides used for the elevator column position. This angle is found as a part of the calculations in Section 7.1, $\phi \approx 0.0277°$ (Equation 7.2). Figure 7.5 shows a sketch of the elevator column and the hydraulic cylinder, with relevant lengths.

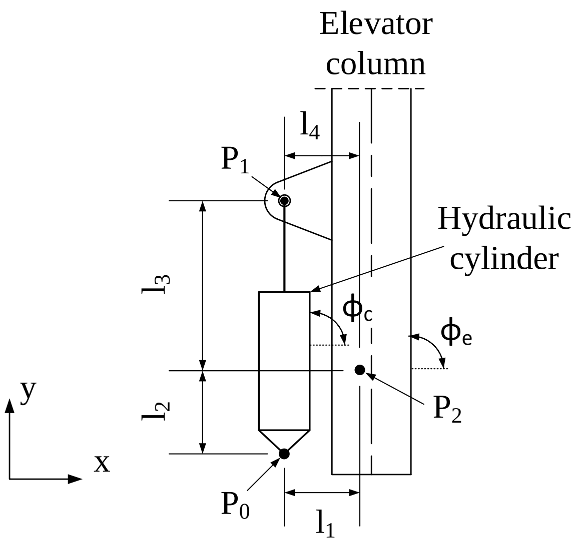



Figure 7.5: Sketch of elevator column and hydraulic cylinder

Where: $P_0$ is the position of the cylinder pivot point
$P_1$ is the position of the cylinder rod end
$P_3$ is the position of the center of the rail block where the elevator column pivots about
$l_1 = 215$ mm
$l_2 = 710$ mm
$l_3$ is the vertical distance between $P_1$ and $P_2$ referenced the elevator column
$l_4 = 215$ mm

In Figure 7.5 the positions $P_0$ and $P_2$ are both located on the foundation, and are therefore stationary points regardless of the elevator column position. Consequently, the lengths $l_1$ and $l_2$ are also constant. $l_4$ is defined as the vertical distance between $P_2$ and $P_1$ referenced the elevator column. $P_1$ and $l_3$ are dependent on the elevator column position.

$\phi$ is defined as the angle between positive y-axis and the elevator. $\phi_{\text{e}}$ is found like shown in Equation 7.17.

$$\phi_{\text{e}} = 90° - \phi = 90° - 0.0277° = 89.972° \tag{7.17}$$

The cylinder angle is determined for the elevator in both lower and upper elevator column position. The distance between the center of the linear rail and the end of the cylinder rod, $l_3$, is for the elevator column in lower and upper position $l_{3\,\mathrm{min}} = 395$ mm and $l_{3\,\mathrm{max}} = 1075$ mm respectively.

**Cylinder Angle, Lower Elevator Column Position**

With the lower end of the cylinder $P_0$ in the origin of the coordinate system, the coordinates of the end of the cylinder rod $P_1$ is determined in Equations 7.18–7.20.

$$P_1 = \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} + l_{3\,\mathrm{min}} \begin{bmatrix} \cos(\phi_\mathrm{e}) \\ \sin(\phi_\mathrm{e}) \end{bmatrix} + l_4 \begin{bmatrix} \cos(\phi_\mathrm{e} + 90°) \\ \sin(\phi_\mathrm{e} + 90°) \end{bmatrix} \tag{7.18}$$

$$P_1 = \begin{bmatrix} 215\ \mathrm{mm} \\ 710\ \mathrm{mm} \end{bmatrix} + 395\ \mathrm{mm} \begin{bmatrix} \cos(\phi_\mathrm{e}) \\ \sin(\phi_\mathrm{e}) \end{bmatrix} + 215\ \mathrm{mm} \begin{bmatrix} \cos(\phi_\mathrm{e} + 90°) \\ \sin(\phi_\mathrm{e} + 90°) \end{bmatrix} \tag{7.19}$$

$$P_1 = \begin{bmatrix} 0.2\ \mathrm{mm} \\ 1105.1\ \mathrm{mm} \end{bmatrix} \tag{7.20}$$

The angle of the cylinder, $\phi_\mathrm{c}$, is determined in Equation 7.21.

$$\phi_\mathrm{c} = \tan^{-1}\left(\frac{P_{1\,\mathrm{y}}}{P_{1\,\mathrm{x}}}\right) = \tan^{-1}\left(\frac{1105.1\ \mathrm{mm}}{0.2\ \mathrm{mm}}\right) = \underline{89.99°} \tag{7.21}$$

**Cylinder Angle, Upper Elevator Column Position**

The coordinates of the the end of the cylinder rod is determined in Equations 7.22–7.24.

$$P_1 = \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} + l_{3\,\mathrm{max}} \begin{bmatrix} \cos(\phi_\mathrm{e}) \\ \sin(\phi_\mathrm{e}) \end{bmatrix} + l_4 \begin{bmatrix} \cos(\phi_\mathrm{e} + 90°) \\ \sin(\phi_\mathrm{e} + 90°) \end{bmatrix} \tag{7.22}$$

$$P_1 = \begin{bmatrix} 215\ \mathrm{mm} \\ 710\ \mathrm{mm} \end{bmatrix} + 1075\ \mathrm{mm} \begin{bmatrix} \cos(\phi_\mathrm{e}) \\ \sin(\phi_\mathrm{e}) \end{bmatrix} + 215\ \mathrm{mm} \begin{bmatrix} \cos(\phi_\mathrm{e} + 90°) \\ \sin(\phi_\mathrm{e} + 90°) \end{bmatrix} \tag{7.23}$$

$$P_1 = \begin{bmatrix} 0.52\ \mathrm{mm} \\ 1785.1\ \mathrm{mm} \end{bmatrix} \tag{7.24}$$

The angle of the cylinder, $\phi_\mathrm{c}$ is determined in Equation 7.25.

$$\phi_\mathrm{c} = \tan^{-1}\left(\frac{P_{1\,\mathrm{y}}}{P_{1\,\mathrm{x}}}\right) = \tan^{-1}\left(\frac{1785.1\ \mathrm{mm}}{0.52\ \mathrm{mm}}\right) = \underline{89.98°} \tag{7.25}$$

As can be seen from the calculations above, the maximum angular deviation of the hydraulic cylinder due to deviations in the angular precision of the linear rail blocks are $\Delta\phi_{\mathrm{c\,max}} = 0.02°$.

## 7.4 Shear Stresses in Service Lock

- Motor peak stall torque, MPL-B540K [15, p. 3]: $T_{\mathrm{m,max}} = 48.6$ Nm
- Gearbox gear ratio, SP 180S-MF2-16-OI1-2S [16, p. 90]: $i = 16$
- Sprocket pitch diameter, [7]: $d_\mathrm{p} = 138.22$ mm

All efficiencies are disregarded. This results in a more conservative solution. Torque on sprocket, $T_\mathrm{s}$:

$$T_\mathrm{s} = T_{\mathrm{m,max}} \cdot i \tag{7.26}$$

$$T_\mathrm{s} = 48.6\ \mathrm{Nm} \cdot 16 = 778\ \mathrm{Nm} \tag{7.27}$$

Force on service lock, $F_{\mathrm{sl}}$:

$$F_{\mathrm{sl}} = \frac{T_{\mathrm{s}}}{r_{\mathrm{p}}} \tag{7.28}$$

$$F_{\mathrm{sl}} = \frac{778\ \mathrm{Nm}}{\frac{1}{2}\,138.22\ \mathrm{mm}\cdot 10^{-3}\ {}^{\mathrm{m}}/_{\mathrm{mm}}} = 11260\ \mathrm{N} \tag{7.29}$$

Service lock area, $A_{\mathrm{sl}}$:
Assume service lock diameter, $d_{\mathrm{sl}} = 15$ mm

$$A_{\mathrm{sl}} = \frac{\pi}{4}\, d_{\mathrm{sl}}^2 \tag{7.30}$$

$$A_{\mathrm{sl}} = 177\ \mathrm{mm}^2 \tag{7.31}$$

Shear stress in service lock, $\tau_{\mathrm{sl}}$:

$$\tau_{\mathrm{sl}} = \frac{F_{\mathrm{sl}}}{A_{\mathrm{sl}}} \tag{7.32}$$

$$\tau_{\mathrm{sl}} = \frac{11260\ \mathrm{N}}{177\ \mathrm{mm}^2} = \underline{63.6\ \mathrm{MPa}} \tag{7.33}$$

## 7.5 Moments Acting on Linear Rail Blocks, Elevator Column Position

Forces acting on the linear rail blocks are hard to estimate, as they are heavily influence by the center of mass of the utility robot. Since all components are not mounted on the final design (examples: pneumatic cylinders on lance centering arm, lance holder and between lance centering arm and column. Weight of the imaging lance with its own motor is unknown as it is not developed yet) it is hard to be sure if these calculations are satisfying before knowing every component of the utility robot.

where: $M_1$ and $M_2$ are moments produced between the linear rails and the rail blocks in the yz-plane
$M_{\mathrm{I}}$ and $M_{\mathrm{II}}$ are moments produced between the linear rails and the rail blocks in the xz-plane
$F_{\mathrm{hyd}}$ is the hydraulic cylinder force
$l_1 = 14.5$ mm
$l_2 = 119.5$ mm
$l_3 = 40$ mm
$l_4 = 255$ mm
$l_{\mathrm{I}} = 78.7$ mm
$l_{\mathrm{II}} = 50$ mm
$l_{\mathrm{III}} = 44.5$ mm
$l_{\mathrm{IV}} = 190$ mm

**Front:**

$$\sum F_{\mathrm{z}}:\ F_{\mathrm{hyd}} = m\cdot g = 1500\ \mathrm{kg}\cdot 9.81\ {}^{\mathrm{m}}/_{\mathrm{s}^2} = 14715\ \mathrm{N} \tag{7.34}$$

$$\sum \overset{\frown}{M}_{\mathrm{hyd}} = M_{\mathrm{I}} + M_{\mathrm{II}} + \left(\frac{l_{\mathrm{IV}}}{2} - l_{\mathrm{I}}\right) m\cdot g = 0 \tag{7.35}$$

For simplification, the moments $M_{\mathrm{I}}$ and $M_{\mathrm{II}}$ are assumed equal in magnitude, $M_{\mathrm{I}} = M_{\mathrm{II}} = M_{\mathrm{front}}$.

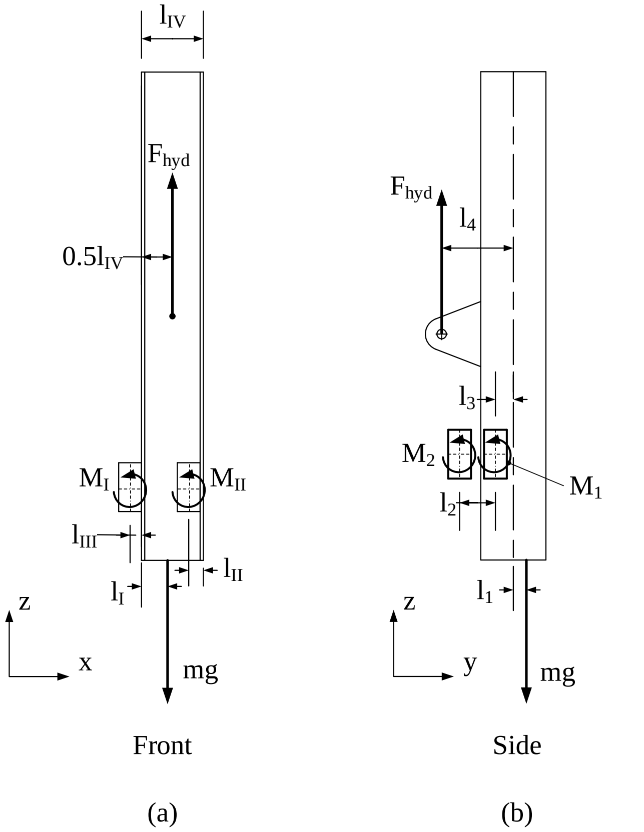



Figure 7.6: Elevator column subjected to gravity, free body diagram

$$\sum \overset{\frown}{M}_{\text{hyd}} = 2\,M_{\text{front}} + \left(\frac{l_{\text{IV}}}{2} - l_{\text{I}}\right) m \cdot g = 0 \tag{7.36}$$

$$M_{\text{front}} = -\frac{1}{2}\left(\frac{190\ \text{mm}}{2} - 78.7\ \text{mm}\right) 1500\ \text{kg} \cdot 9.81\ {}^{\text{m}}/_{\text{s}^2} \cdot 10^{-3}\ {}^{\text{m}}/_{\text{mm}} \tag{7.37}$$

$$M_{\text{front}} = M_{\text{I}} = M_{\text{II}} = \underline{-120\ \text{Nm}} \tag{7.38}$$

**Side:**

$$\sum F_{\text{z}}:\ \ F_{\text{hyd}} = m \cdot g = 1500\ \text{kg} \cdot 9.81\ {}^{\text{m}}/_{\text{s}^2} = 14715\ \text{N} \tag{7.39}$$

Sum of moments with respect to the hydraulic cylinder bracket

$$\sum \overset{\frown}{M}_{\text{hyd}} = M_1 + M_2 - (l_4 + l_1)\, m \cdot g = 0 \tag{7.40}$$

For simplification, the moments $M_1$ and $M_2$ are assumed equal in magnitude, $M_1 = M_2 = M_{\text{side}}$.

$$\sum \overset{\frown}{M}_{\text{hyd}} = 2\,M_{\text{side}} - (l_4 + l_1)\, m \cdot g = 0 \tag{7.41}$$

$$M_{\text{side}} = \frac{255\ \text{mm} + 14.5\ \text{mm}}{2} \cdot 14715\ \text{N} \cdot 10^{-3}\ {}^{\text{m}}/_{\text{mm}} \tag{7.42}$$

$$M_{\text{side}} = M_1 = M_2 = \underline{1983\ \text{Nm}} \tag{7.43}$$

### Dimensioning Linear Block

Two linear rail blocks of the type SBG 65FLL-K1, delivered by Rollco, is chosen for this application. This linear rail block is the same as one of the three linear rail systems used on the HEX utility robot. The static moment capacities in the different orientations are indicated in Table 7.2 and Figure 7.7.

Table 7.2: Extract: "Linear Rail System SBG" [23, p. 9]

| | Static moment [Nm] | | |
|---|---|---|---|
| Description | $M_{\mathrm{R0}}$ | $M_{\mathrm{Y0}}$ | $M_{\mathrm{P0}}$ |
| SBG 65FLL | 8340 | 8300 | 8500 |

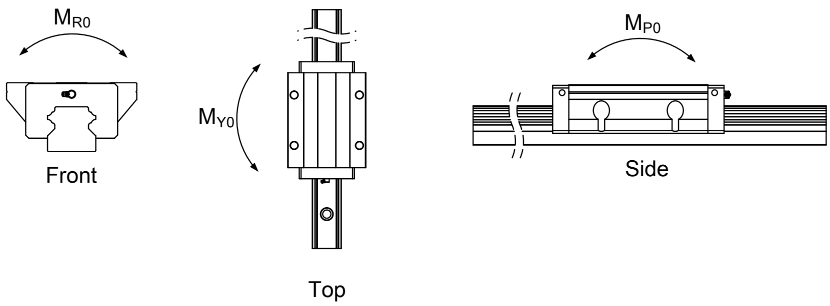



Figure 7.7: Supplementary figure, Table 7.2

## 7.6 FEM Analysis of Foundation

A FEM analysis of the foundation is carried out in Abaqus. Since the assembly is built up exclusively of plates, shell theory is applied. The foundation is converted to a surface model by redrawing it in SolidWorks. All surfaces are drawn such that the surface is in the mid-plane of all plates in the volume model (the ordinary CAD model). The surface model in imported in Abaqus as one part, so there is no need for defining interactions between the plates.

Abaqus has no built-in system of units, meaning that one has to decide which system of units one wants to use before starting to define anything on the model. Since the CAD parts are imported with millimeters by default (this is determined by measuring the same feature/line in the model in both Abaqus and SolidWorks), SI-units in millimeters are used. Relevant quantities and their units are listed i Table 7.3.

Table 7.3: Quantities and belonging units used in Abaqus for FEM analysis of the foundation

| Quantity | Unit |
|---|---|
| Length | mm |
| Force | N |
| Moment | Nmm |
| Mass | tonne ($10^3$ kg) |
| Stress | MPa $\left({}^{\mathrm{N}}/_{\mathrm{mm}^2}\right)$ |
| Density | ${}^{\mathrm{tonne}}/_{\mathrm{mm}^3}$ |

The surface model is presented in Figure 7.8, with balloons indicating the different parts. Explanations of the parts and their plate thicknesses are shown in Table 7.4. The plate thickness is used in Abaqus to assign correct section properties to the imported surface model.

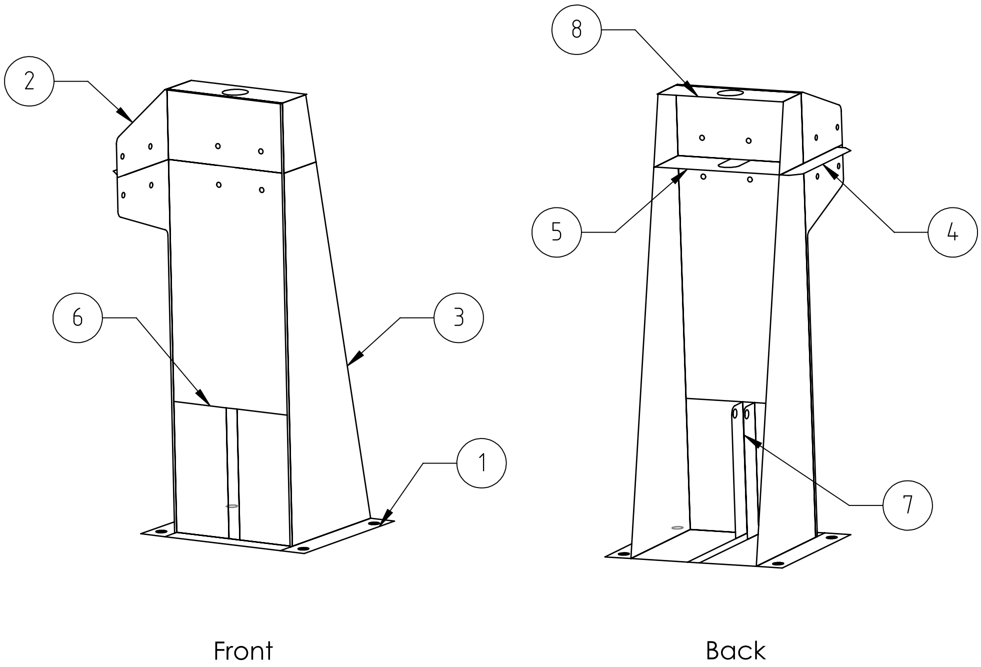



Figure 7.8: Plate model of the foundation

Table 7.4: Explanation to Figure 7.8

| No. | Description | Plate thickness |
|---|---|---|
| 1 | Floor plate | 15 mm |
| 2 | Left side plate | 12 mm |
| 3 | Right side plate | 12 mm |
| 4 | Side stiffener | 10 mm |
| 5 | Back stiffener | 10 mm |
| 6 | Front plate | 12 mm |
| 7 | Cylinder mount | 12 mm |
| 8 | Top plate | 12 mm |

It can be seen from Figure 7.8 that many of the components in the assembly contain lines running across their surfaces. These lines are called split lines, and they help Abaqus determine where on the surface to put nodes. Split lines are used everywhere to plates are in contact, to assure that nodes of the the different plates intersect, propagating the stresses in a correct manner. Figure 7.9 shows the floor plate of the foundation and its split lines as an example.

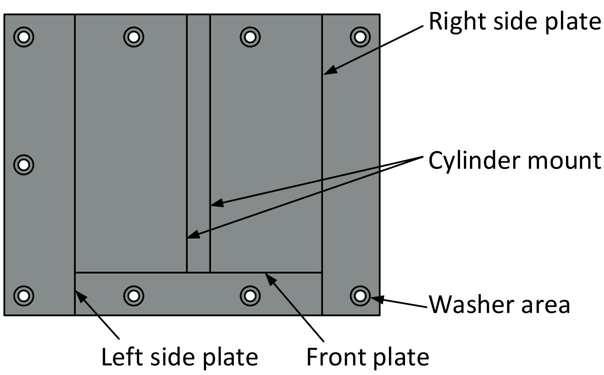



Figure 7.9: Floor plate with split lines

Figure 7.9 shows five split lines running across the plate, and nine split lines around the bolt holes. The straight split lines are used for aligning the nodes of parts in contact with each other. Figure 7.9 indicates what part is in contact with the particular split line (see Table 7.4 and Figure 7.8 for placement of parts). The split lines around the bolt holes of the floor plate are used for indicating the area of the washers for the bolts to be fastened in the holes. These areas are used to make boundary conditions later on.

**Material Properties**

The material used for the plates are S235JRG2, which is a structural steel with minimum yield strength of 235 MPa. Relevant material properties are presented in Table 7.5.

Table 7.5: Material properties used in FEM analysis of the foundation

| Description | Value |
|---|---|
| Density | $\rho = 7800\ {}^{\mathrm{kg}}/_{\mathrm{m}^3}$ |
| Young's modulus | $E = 210$ GPa |
| Possion's ratio | $\nu = 0.28$ |

### Loads on the Foundation

The moments are added to the foundation by the means of multi-point-constraints (MPCs).

MPCs binds all chosen nodes of the assembly to a chosen/created reference node by the means of rigid beams. The creation of an MPC is illustrated in Figure 7.10. Figure 7.10(a) shows a hole in a plate, with nodes equally spaced across the hole circle. Figure 7.10(b) shows the same hole with an MPC. A reference node is placed in the middle of the hole. All nodes on the hole circle is bound to this reference node by the means of rigid beams. The hole circle in Figure 7.10(b) can be seen as a rigid body, meaning that the motion of all nodes in the hole circle is governed by the reference node in the middle of the circle.

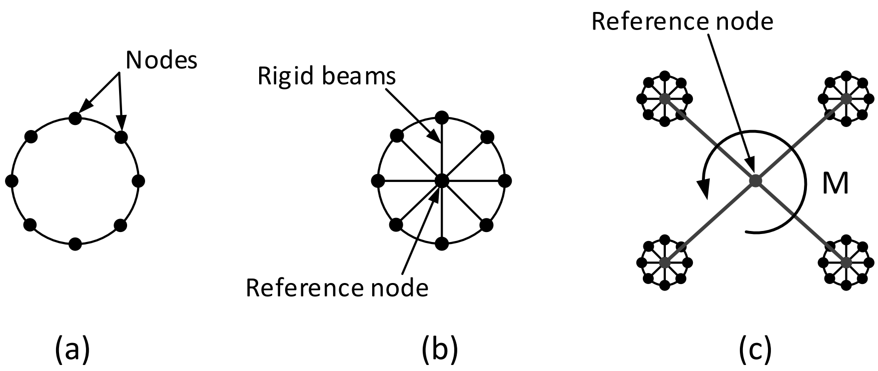



Figure 7.10: Explanatory figure, multi-point constraint

Moments on the foundation is transferred from the elevator to the foundation by the linear rails. The rail blocks are mounted to the foundation with four bolts each. Figure 7.10(c) illustrates how moments are added. This figure shows four holes with MPCs added to them (four holes identical to the hole in Figure 7.10(b)). A new reference node is added between the four existing reference points, and an MPC is added between the four existing MPC reference points and the new reference point. Lastly, the determined moment is added to the reference node.

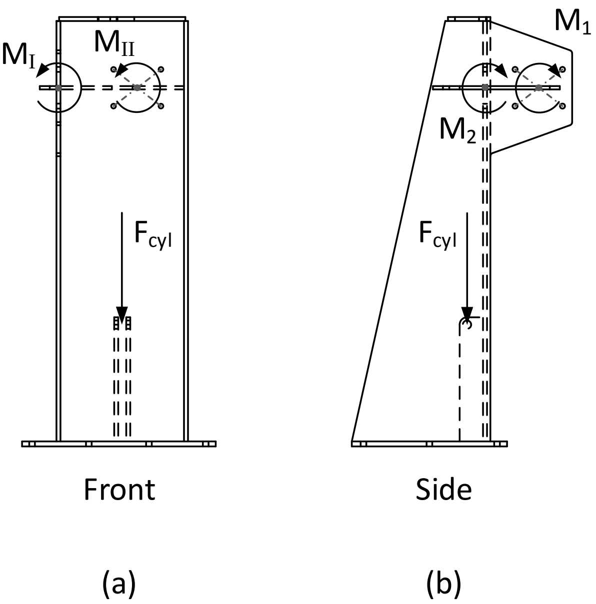



Figure 7.11: Sketch of force and moments on foundation

$M_1$ and $M_\mathrm{I}$ are placed in the same point, but in different directions. The same goes for $M_2$ and $M_\mathrm{II}$.

where: $M_{\mathrm{I}}$ is the front-plane moment on the side plate
$M_1$ is the side-plane moment on the side plate
$M_{\mathrm{II}}$ is the front-plane moment on the front plate
$M_2$ is the side-plane moment on the front plate

The values of the moments and the force are determined in Section 7.5, and are displayed in Table 7.6. The moments displayed are assumed to be equally distributed on the two rail blocks as stated in Section 7.5. The direction of the moments and the cylinder force in Table 7.6 are as indicated in Figure 7.11.

Table 7.6: Moments and force acting on the foundation

| Description | Value (Abaqus units) |
|---|---|
| $M_{\mathrm{I}}$ | 120000 Nmm |
| $M_1$ | 120000 Nmm |
| $M_{\mathrm{II}}$ | 1983000 Nmm |
| $M_2$ | 1983000 Nmm |
| $F_{\mathrm{cyl}}$ | 14715 N |

The moments are applied directly to the reference nodes discussed earlier in this chapter. The cylinder force is added as a so-called shell edge load. This is the same as pressure, but it distributes a force along a line instead of an area.

Since the cylinder mount consists of two plates, the load on each plate is half the total cylinder force, $F = \frac{1}{2}F_{\mathrm{cyl}} = 7357.5$ N. The edge of the hole is partitioned in Abaqus such that the hole consists of two half-circle edges. The edge load is applied on the lower-half of the circle. The diameter of the bolt holes are $d_{\mathrm{hole}} = 25$ mm. The edge load $p^*$ is calculated like shown in Equation 7.44.

$$p^* = \frac{F}{d_{\mathrm{hole}}} = \frac{7357.5\ \mathrm{N}}{25\ \mathrm{mm}} = 295\ {}^{\mathrm{N}}\!/_{\mathrm{mm}} \tag{7.44}$$

**Boundary Conditions**

Boundary conditions are applied to the floor plate. Every bolt hole in this plate have split lines around them, isolating a washer-formed area around each hole. M16 bolts are to be used for fastening the foundation. The inner diameter of the washer areas (hole diameter) are 17 mm. The outer diameter is 30 mm. A reference node is placed in the middle of the bolt hole, and an MPC is made with this reference point as the master node, and all nodes in the washer area as slave nodes. When this is done for every bolt hole, all the master nodes are locked in place using the boundary condition type encastré (locking all translational and rotational movement of the master nodes).

Figure 7.12 shows an MPC used around the washer area of the bolt hole. The red cross in the middle of the hole is the reference node (master node). The red area indicated the area occupied by the washer. All nodes with the red area are slave nodes to the reference node in the middle.

**Mesh**

Second order shell elements are chosen for all surfaces of the model. These elements are most suitable for bending moments. Most surfaces are assigned quadratic elements of the type S8R. These are shell elements with 8 nodes (second order element) and reduced integration. Abaqus characterizes these elements as 8-node doubly curved thick shell with reduced integration.

The surfaces assigned for washers on the floor plate (shown in Figure 7.12) are hard to fill with quadratic elements since the edges are circular. Triangular elements are assigned in these areas. The triangular elements are of the type STRI65. These are shell elements of triangular shape with 6 nodes (second order element), using 5 degrees of freedom per node.

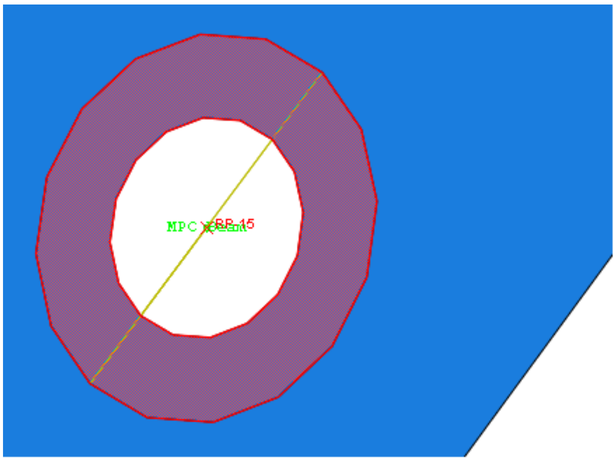



Figure 7.12: Multi-point constraint on the washer area on the floor plate

The approximate global mesh size is set to 6 mm. Local mesh control are assigned to edges where high stress concentrations are present, or where the mesh could not maintain its ideal shape. Edges assigned local mesh control are bolt holes for rail blocks (4 mm mesh), the washer area (2 mm mesh), and the holes and radiuses of the cylinder mount (4 mm mesh). The washer area with its local mesh control and triangular elements is shown in Figure 7.13.

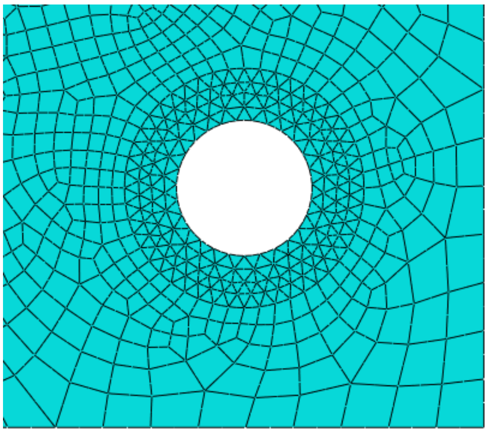


Figure 7.13: Local mesh control assigned the washer area around the bolt hole

As can be seen in Figure 7.14, the mesh used in this analysis is very fine. One could probably make the mesh much more coarse without affecting the accuracy too much. This was however decided not to change, since the simulation only took 1–2 minutes to complete.

### Results

The results presented in this section all have the same scale on the stress, meaning that the same color corresponds to the same stress in all figures below. All stress scales are set to show 150 MPa as red. All stresses displayed are Von Mises stresses.

Figure 7.15 shows the result of the finite element analysis of the foundation. The only result worth commenting on in Figure 7.15 is the stresses around the bolt holes in the front plate. These stresses are shown close-up in Figure 7.16.

The stress concentrations indicated in Figure 7.16 are probably due to the way the moment is applied to the foundations. MPCs tend to distort the results.

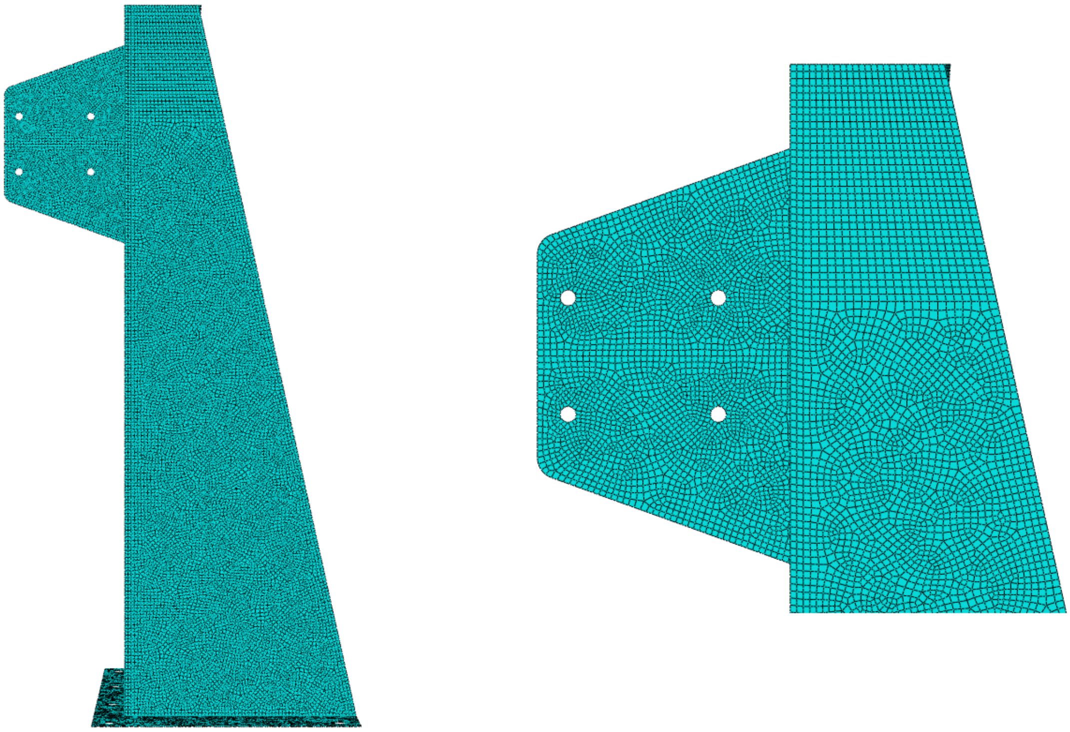


Figure 7.14: Presentation of the mesh used in the FEM analysis if the foundation

The finite element analysis was also carried out with the total moment applied to one block only, to make sure that the foundation can withstand the complete load of the elevator on one rail block. The results from applying the total load on the side-mounted rail block is shown in Figure 7.17.

The results in Figure 7.17 shows little to no stresses.

The results from applying the total load on the rail block mounted on the front plate is shown in Figure 7.18.

The results shown in Figure 7.18 indicates large stresses around the bolt holes for the front plate. These stresses are however assumed to be inaccurate because of the way the moments are applied to the edges of the holes (MPCs), creating excessive stresses. Another source of error regarding the moment applied to these holes is that the largest moment contribution is applied about an axis that coincide with the plane of the surface. Shell elements only work well on moments applied about an axis perpendicular to the surface.

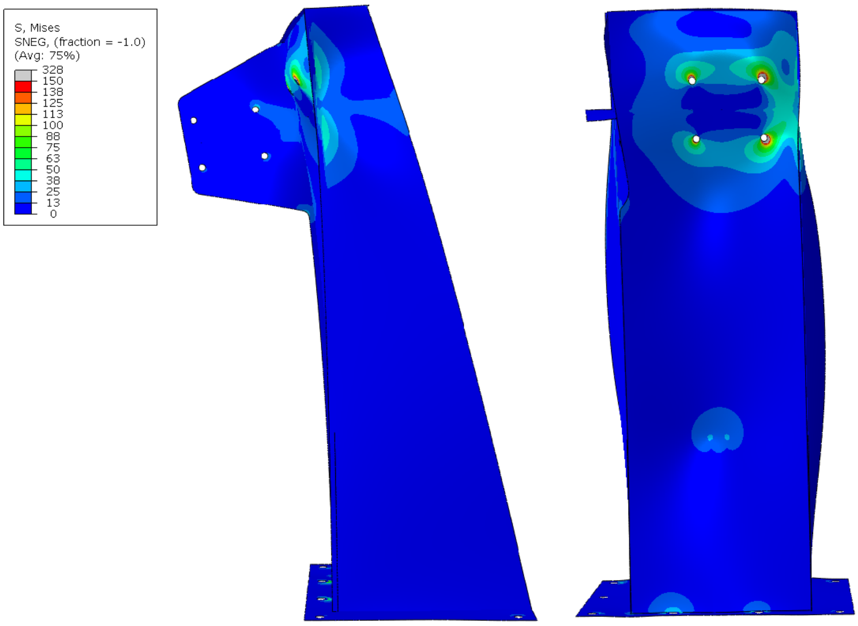



Figure 7.15: Results from distributing the moments equally on the two rail blocks

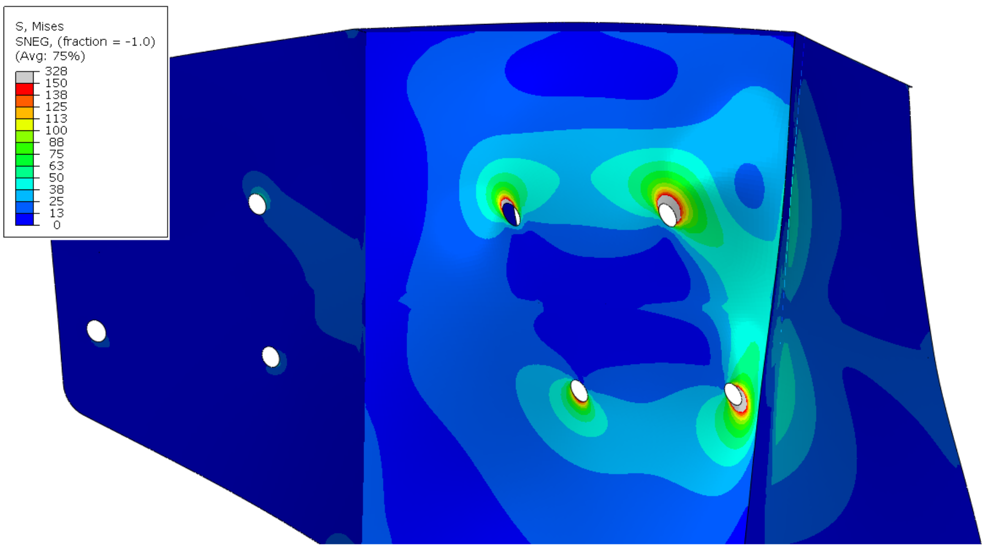



Figure 7.16: Close-up of front plate from Figure 7.15

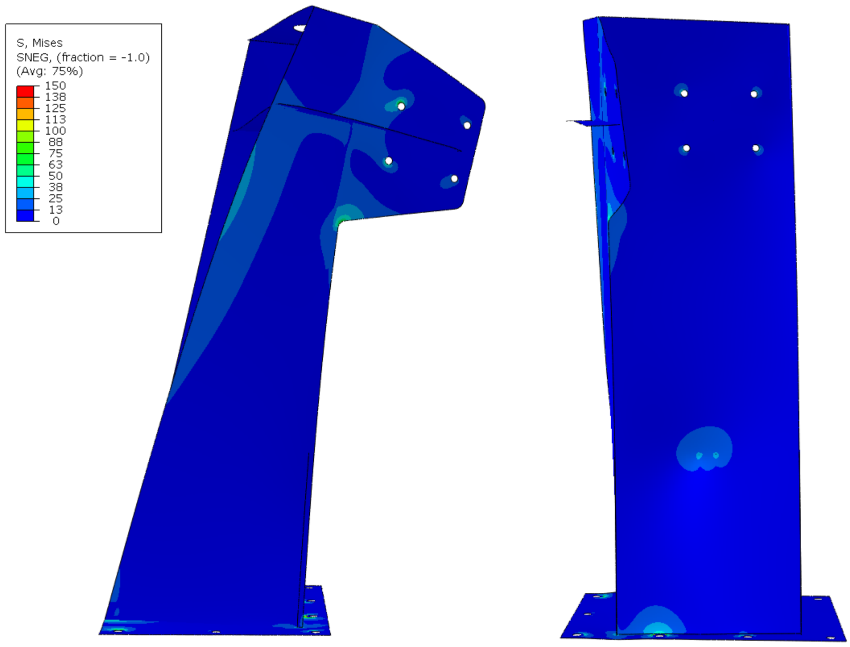



Figure 7.17: Results from applying the total moment on the rail block mounted on the side plate

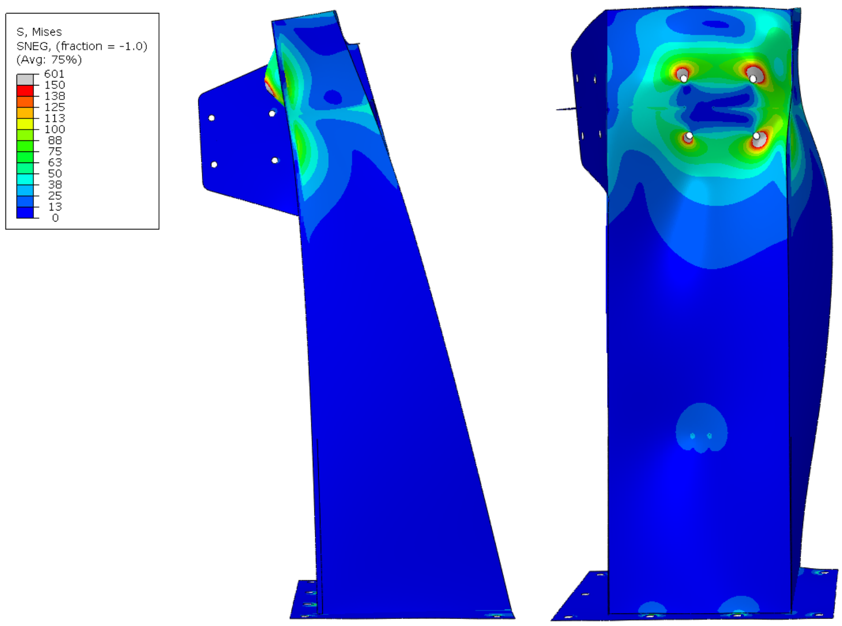



Figure 7.18: Results from applying the total moment on the rail block mounted on the front plate

# Chapter 8

# Conclusion

Throughout the course of this semester, a new solution for the utility robot is designed using SolidWorks. The parts have been dimensioned using calculations and FEM analysis. Technical drawings have been made of all developed components, and many parts have been ordered.

The result of this thesis is an almost fully developed solution for lowering probes and sensors down into the Hot Bowl reactor. Technical drawings have been issued for construction, and most components have been machined.

The new utility robot is more automatic and less labor intensive than the HEX utility robot. The lances weigh less due to torque release being implemented into the robot instead of the lances. The operator needs to move the lances a shorter distance from the utility robot and to the lance rack for the Hot Bowl utility robot than for the HEX utility robot.

## 8.1 Further Work

Although considered important, no time was found for composing assembly drawings for the technical drawings provided in Appendix C. This was of high priority, but had to be set aside in order to finish the report.

If time allowed, more effort would be made towards finishing the lance holder concept. The concept is not far from completion. The torque release endstop were not properly dimensioned, as it were shown to be more difficult than anticipated after the torque release's parallel linkages were extended from 100 mm to 160 mm. The chain tensioner were not developed as part of this thesis.

If the above items were carried out, it would be desirable to participate in the PLC programming of the utility robot.

# Bibliography


[1] Recommended fits. http://www.skf.com/group/products/bearings-units-housings/roller-bearings/principles/design-considerations/radial-location-bearings/recommended-fits/index.html. Visited: 03.05.2015.

[2] Seal materials. http://www.skf.com/group/products/bearings-units-housings/roller-bearings/principles/bearing-specifics/materials-for-rolling-bearings/seal-materials/index.html. Visited: 03.05.2015.

[3] SKF: Shaft requirements. http://www.skf.com/group/products/bearings-units-housings/bearing-units/roller-bearing-units/roller-bearing-units-general/application-of-bearing-units/shaft-requirements/index.html. Visited: 30.03.2015.

[4] Slettebøe AS: BS-2 Duplex rullekjede DIN 8187. http://www.sletteboe.no/index.php?expand=11&show=11&topmenu_2=11&PrCatNo=8210&MainPrC=8000&ProdNo=04+B-2+WEB. Visited: 26.04.2015.

[5] Slettebøe AS: KM hydraulikk sylinder, type DVL. http://www.sletteboe.no/index.php?expand=11&show=11&topmenu_2=11&PrCatNo=11870&MainPrC=11000&ProdNo=DVL+WEB. Visited: 07.05.2015.

[6] Slettebøe AS: KM hydraulikk sylinder, type DVLF. http://www.sletteboe.no/index.php?expand=11&show=11&topmenu_2=11&PrCatNo=11870&MainPrC=11000&ProdNo=DVLF+WEB. Visited: 07.05.2015.

[7] Slettebøe AS: Standard kjedehjul, duplex. http://www.sletteboe.no/index.php?expand=11&show=11&topmenu_2=11&PrCatNo=8260&MainPrC=8000&ProdNo=06+B-2+10+WEB. Visited: 26.04.2015.

[8] Spherical roller bearings, cylindrical and tapered bore, 24015-2CS2/VT143. http://www.skf.com/group/products/bearings-units-housings/roller-bearings/spherical-roller-bearings/cylindrical-and-tapered-bore/index.html?prodid=1550264015&imperial=false. Visited: 03.05.2015.

[9] Spherical roller bearings, cylindrical and tapered bore, BS2-2208-2CS/VT143. http://www.skf.com/group/products/bearings-units-housings/roller-bearings/spherical-roller-bearings/cylindrical-and-tapered-bore/index.html?prodid=1550172208&imperial=false. Visited: 29.04.2015.

[10] Spherical roller bearings, cylindrical and tapered bore, BS2-2215-2CS/VT143. http://www.skf.com/group/products/bearings-units-housings/roller-bearings/spherical-roller-bearings/cylindrical-and-tapered-bore/index.html?prodid=1550172215&imperial=false. Visited: 29.04.2015.

[11] Wikipedia: Aluminium. http://no.wikipedia.org/wiki/Aluminium. Visited: 21.01.2015.

[12] Wikipedia: Carbothermic reduction. http://en.wikipedia.org/wiki/carbothermic_reaction. Visited: 21.01.2015.

[13] Wikipedia: Pyrometer. http://en.wikipedia.org/wiki/Pyrometer. Visited: 18.04.2015.

[14] Wikipedia: Yield (engineering). http://en.wikipedia.org/wiki/Yield_%28engineering%29. Visited: 10.05.2015.

[15] Allen-Bradley. *Data sheet: MP-Series Low-Inertia Motors*. http://literature.rockwellautomation.com/idc/groups/literature/documents/pp/mp-pp001_-en-p.pdf. Visited: 03.05.2015.

[16] Wittenstein alpha. *Data sheet: General product catalogue.* http://www-alt.alphagetriebe.de/pdf/alpha_gesamtkataloge0614.pdf. Visited: 30.03.2015.

[17] Aventics. *Data sheet: Compact cylinder, ISO 21287, Series CCI.* http://www.aventics.com/pneumatics-catalog/Pdf.cfm?Language=EN&Variant=internet&file=en/pdf/PDF_p65810_en.pdf. Visited: 12.05.2015.

[18] The Gates Rubber Company. Chain - Part 5: Advantages and Disadvantages. https://ww2.gates.com/facts/documents/Gf000202.pdf. Visited: 10.05.2015.

[19] Schneider Electric. *Data sheet: Inductive proximity sensors.* http://download.schneider-electric.com/files?p_File_Id=116428608. Visited: 27.02.2015.

[20] Elite. *Data sheet: High-performance roller and conveyor chains.* http://www.iwis.de/fileadmin/user_upload/antriebssysteme/Downloads/Kataloge/ELITE_Katalog_DE_EN.pdf. Visited: 13.05.2015.

[21] Robert C. Juvinall & Kurt M. Marshek. *Fundamentals of Machine Component Design.* Wiley Global Education, 5 edition, 2011.

[22] SMC Pneumatics. *SMC ITV2050-04F3N3-Q regulator.* http://www.smcpneumatics.com/ITV2050-04F3N3-Q.html. Visited: 11.05.2015.

[23] Rollco. *Data sheet: Linear Rail System SBG.* http://rollco.no/wp-content/uploads/2012/07/Linear-Rail-System-SBG-2013-04.pdf. Visited: 05.04.2015.

[24] Rollco. *Data sheet: U-rail.* http://rollco.se/uk/wp-content/uploads/2012/07/U-Rail-2014-02.pdf. Visited: 05.04.2015.

[25] Technology Transfer Services. *Chain Drives.* https://www.techtransfer.com/blog/chain-drives/. Visited: 10.05.2015.

[26] SKF. *Data sheet: SKF spherical roller bearings.* http://www.skf.com/binary/56-29536/6100_EN.pdf. Visited: 03.05.2015.

# Appendix A

# Jargon and Definitions

**Utility robot** The robot to be developed in this thesis. Its key feature is to make measurements of different sorts on the inside content of the reactor.

**Utility pipe** The interface between the utility robot and the reactor. The utility pipe is a pipe where the equipment mounted on the utility robot is lowered through to access the reactor.

**HEX reactor** Reactor used in Alcoa's last set of campaigns. Currently under revision. It gets its name from the hexagonal shape. Used from 2006 to late 2013.

**Hot Bowl reactor** The new reactor. Currently under development.

**Support frame** The frame for which the utility robot is to be mounted. Depicted and explained in Section 2.6.1.

**Off-gas stoker** A machine installed on third floor used for keeping the off-gas pipe free from condensate build-ups

**Off-gas pipe** A pipe running through the reactor ceiling and up to third floor. Used for removing off-gases.

**Alumina** Aluminum oxide, $Al_2O_3$. Chemical compound made up of aluminum and oxygen.

**Shakedown** Testing period of the reactor after assembly.

# Appendix B

# Matlab-scripts

This appendix present matlab-scripts of interest developed as part of this thesis.

## B.1 Buckling Analysis, Lances

```
%---------------------------------------------------------------------
%Script name: Lance Buckling
%Project: Master's thesis spring 2015
%Author: Tore Meber
%Last updated: 10.05.2015
%---------------------------------------------------------------------

close all;
clear;
clc;

E=193000;   %E-modulus, material 316L [MPa, N/mm^2]
d_o=42.4;   %Outer diameter, pipe [mm]
t=2;        %Pipe thickness [mm]

r_o=d_o/2;              %Pipe outer radius
r_i=(d_o-2*t)/2;        %Pipe inner radius
I=pi/4*(r_o^4-r_i^4);   %Pipe are moment of inertia

%Calculations--------------------------------------------------------

%Lenghts, pipe only
l_agellis=3200;
l_mechlvl=3320;
l_stoker=2700;
l_temp=2940;

%Buckling force, pipe only
disp('Buckling, pipe only:')
Agellis_kN=pi^2*E*I/l_agellis^2/1000
Mechanical_level_kN=pi^2*E*I/l_mechlvl^2/1000
Stoker_kN=pi^2*E*I/l_stoker^2/1000
Temp_kN=pi^2*E*I/l_temp ^2/1000

%Lenghts, pipe and probe
l_agellis=4280;
l_mechlvl=4210;
l_stoker=3000;
l_temp=4770;

%Buckling force, pipe and probe
disp('Buckling, pipe and probe:')
Agellis_kN=pi^2*E*I/l_agellis^2/1000
```

```
Mechanical_level_kN=pi^2*E*I/l_mechlvl^2/1000
Stoker_kN=pi^2*E*I/l_stoker^2/1000
Temp_kN=pi^2*E*I/l_temp ^2/1000
```

## B.2 Calculations, Torque Release with Isolated Chamber

```
%-------------------------------------------------------------------
%Script name: Torque Release Calculations, Isolated Cylinder Chamber
%Project: Master's thesis spring 2015
%Author: Tore Meber
%Last updated: 15.05.2015
%-------------------------------------------------------------------

clear;
close all;
clc;

%Inital conditions
d=100;          %Cylinder diameter
l=100;          %Cylinder stroke

A=pi/4*d^2;     %Cylinder piston area
V1=A*l;         %Cylinder chamber initial volume
p1=2.55e5;      %Cylinder chamber initial pressure

%Calculations-------------------------------------------------------

%Hot Bowl torque release force under normal operation
HB(1:90) = 2000;    %Torque release force equal to 2 kN throughout travel distance

%Cylinder calculations, isolated chamber, Hot Bowl torque release
for(i=1:90)
    V_x(i)=A*(l-i);         %Calculate new cylinder chamber volume
    p_x(i)=p1*V1/V_x(i);    %Boyle's law, calculate new cylinder pressure
    if(p_x(i)>9e5)          %Used for HB regulator crack pressure of 9 bar
        p_x(i)=9e5;
    end;
    x(i)=i;
end;

F_x=p_x*A*10^(-6);      %Convert chamber pressure to force
p_x=p_x*10^(-5);        %Convert cylinder chamber pressure from Pa to bar


%Spring calculatios, HEX torque release
k=1737/(310-260);   %Calculate spring stiffness based on known forces and lengths
F0=1737;            %F0=1737 +/- 208 N, spring initial force

for(j=1:90)
    y(j)=j;
    F(j)=k*y(j)+F0;
end;

%Figures------------------------------------------------------------

%Comparison of cylinder forces from Hot Bowl and spring force from HEX
figure(1)
plot(x,F_x,'k--');
grid;
xlabel('Torque release displacement [mm]')
ylabel('Force [N]')
hold;
plot(y,HB,'k.');
errorbar([1 90],[F(1) F(90)],[208 255],'k');
legend('Hot Bowl, closed cylinder chamber','Hot Bowl, normal operation','HEX')

%Hot Bowl isolated chamber torque release pressure
figure(2)
plot(x,p_x)
grid;
xlabel('Torque release displacement [mm]')
ylabel('Pressure [bar]')
```

# Appendix C

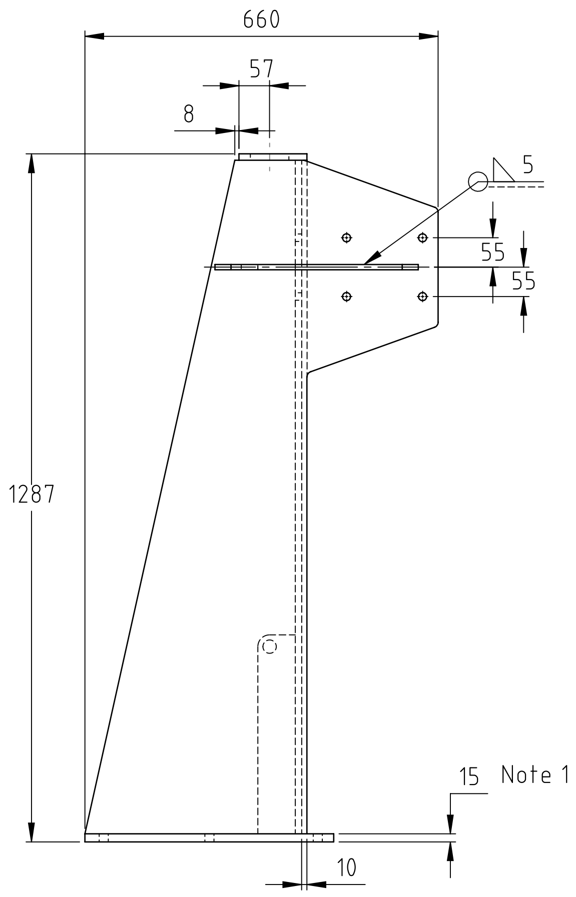
# Technical Drawings

- Most of these drawings are supposed to be printed out on A3-paper. This is specified in the title block. Some details may be hard to make out if printing these drawings out on A4-paper
- Some technical drawings consist of more than one sheet. The sheet number is specified in the title block. Number of sheets for the different technical drawings are shown in Table C.1.
- The hierarchy of the technical drawings are as following:
  - Level 1 (lowest): All parts welded together. If a part is not welded together with other parts, it gets its own drawing
  - Level 2: Functional elements. Every part that together forms a specific function of the utility robot
  - Level 3 (highest): Main assembly of the complete utility robot

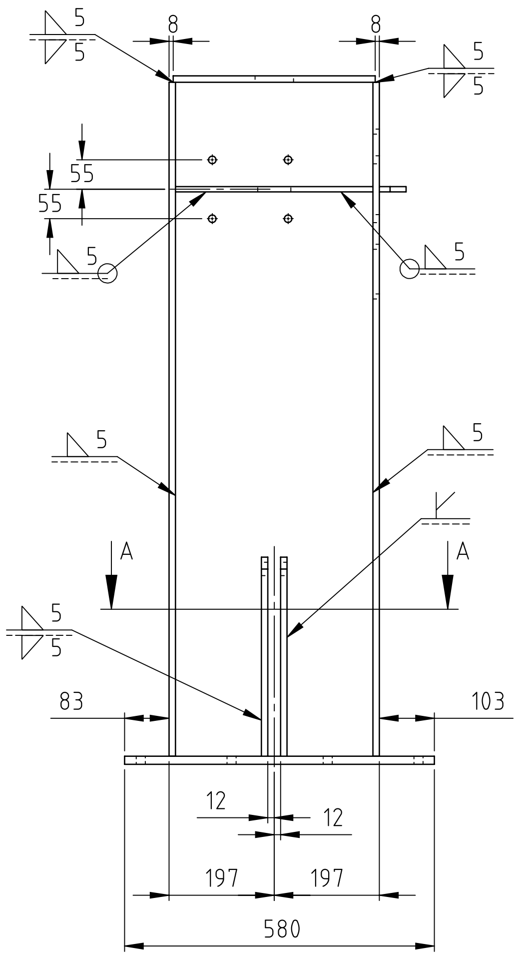
Table C.1: Technical drawings in correct order

| No. | Drawing title | Sheets | Level | Parent drawing title |
|---|---|---|---|---|
| 1 | Foundation | 2 | 1 | Foundation Assembly |
| 2 | HE 200A, L=5080 | 2 | 1 | Elevator |
| 3 | Lower Shaft | 1 | 1 | Elevator |
| 4 | Sprocket 16 B-2 17 | 1 | 1 | Elevator |
| 5 | Bearing Housing Lower Shaft, right side | 1 | 1 | Elevator |
| 6 | Bearing Housing Lower Shaft, left side | 1 | 1 | Elevator |
| 7 | Bearing Housing Cover | 1 | 1 | Elevator |
| 8 | Key, Lower Shaft | 1 | 1 | Elevator |
| 9 | Spacers, Lower Shaft | 1 | 1 | Elevator |
| 10 | Upper Shaft | 1 | 1 | Elevator |
| 11 | Key, Upper Shaft | 1 | 1 | Elevator |
| 12 | Spacers, Upper Shaft | 1 | 1 | Elevator |
| 13 | Linear Guide Bracket | 1 | 1 | Elevator |
| 14 | Cylinder Mount | 2 | 1 | Torque Release |
| 15 | Parallel Linkage Mount | 1 | 1 | Torque Release |
| 16 | Parallel Linkage, Bottom | 1 | 1 | Torque Release |
| 17 | Parallel Linkage, Top | 2 | 1 | Torque Release |
| 18 | Detail | 1 | 1 | Torque Release |

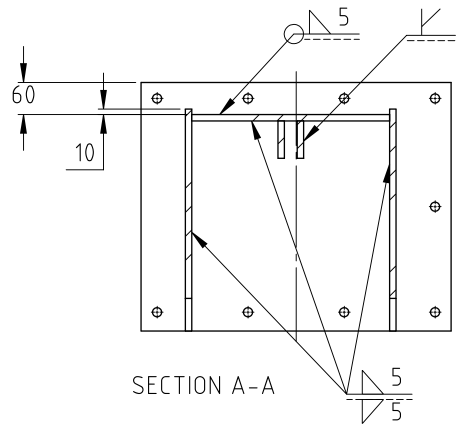
| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |
|---|---|---|---|---|---|
| A | Issued For Construction | TM | - | - | 29.04.2015 |



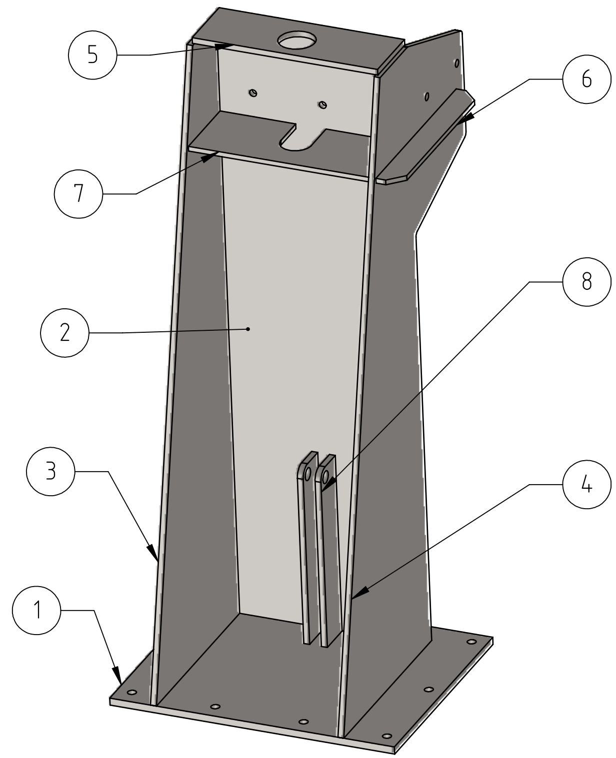

SIDE




BACK




SECTION A-A




Note 1:
Allow for post weld machining. Nominal final thickness 15 mm

| ITEM | DESCRIPTION | QTY | MATERIAL | MASS/ ITEM | MASS/ TOTAL | DRAWING | STANDARD | REV |
|---|---|---|---|---|---|---|---|---|
| 8 | PL 12x372x70 | 2 | 1.0038 (S235JRG2) | 2.38 | 4.76 | N/A | N/A | A |
| 7 | PL 10x370x150 | 1 | 1.0038 (S235JRG2) | 3.87 | 3.87 | N/A | N/A | A |
| 6 | PL 10x380x50 | 1 | 1.0038 (S235JRG2) | 1.41 | 1.41 | N/A | N/A | A |
| 5 | PL 12x378x127 | 1 | 1.0038 (S235JRG2) | 4.11 | 4.11 | N/A | N/A | A |
| 4 | PL 12x660x1260 | 1 | 1.0038 (S235JRG2) | 39.43 | 39.43 | N/A | N/A | A |
| 3 | PL 12x415x1260 | 1 | 1.0038 (S235JRG2) | 32.43 | 32.43 | N/A | N/A | A |
| 2 | PL 12x370x1100 | 1 | 1.0038 (S235JRG2) | 43.58 | 43.58 | N/A | N/A | A |
| 1 | PL 20x580x465 | 1 | 1.0038 (S235JRG2) | 31.32 | 31.32 | N/A | N/A | A |



Tolerances accepted (as stated) ISO 2768-M

Weld according to: ISO 5817-C

Total weight 160.92 kg

Projection

| | | |
|---|---|---|
| Designed | TM | - |
| Drawn | TM | - |
| Checked | - | - |
| Approved | - | - |

Break all corners and edges acc. to ISO 13715 +0,3 +0,1 -0,1 -0,3

Part/Area/Group: -
Project/No./Name: Hot Bowl

Size: A3
Sheet: 1/2



Scale 1:10

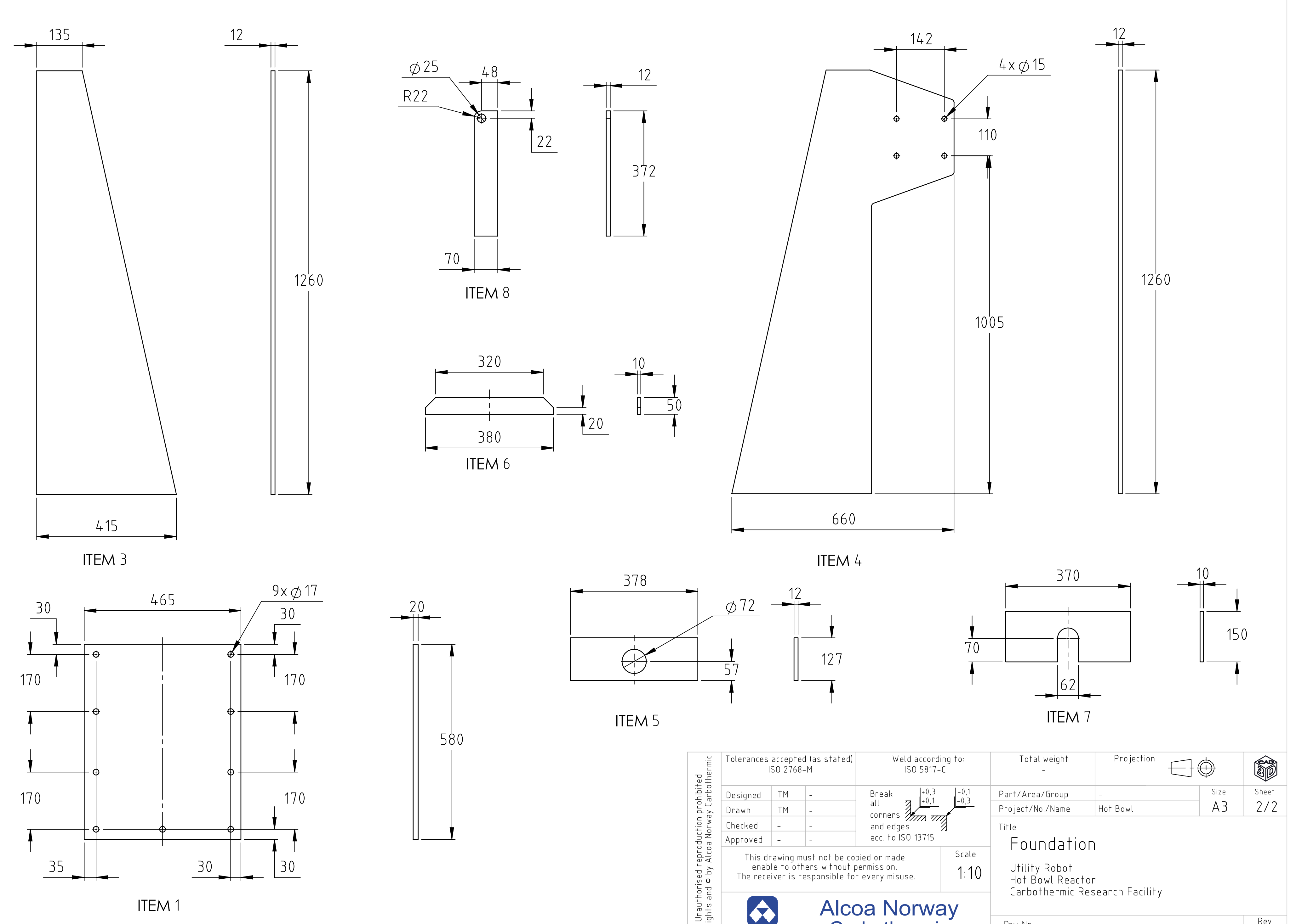
Title
# Foundation
Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

ALCOA
Alcoa Norway Carbothermic

Drw No. Foundation

Rev. A

Verify prior to construct - Do not scale






| | | | | |
|---|---|---|---|---|
| Tolerances accepted (as stated) ISO 2768-M | | | Weld according to: ISO 5817-C | |
| Designed | TM | - | Break all corners and edges acc. to ISO 13715 (+0,3 +0,1 / -0,1 -0,3) | |
| Drawn | TM | - | | |
| Checked | - | - | | |
| Approved | - | - | | |
| This drawing must not be copied or made enable to others without permission. The receiver is responsible for every misuse. | | | Scale | 1:10 |

Alcoa Norway Carbothermic

ALCOA

| Total weight | Projection | | |
|---|---|---|---|
| - | | | |
| Part/Area/Group | - | Size | Sheet |
| Project/No./Name | Hot Bowl | A3 | 2/2 |

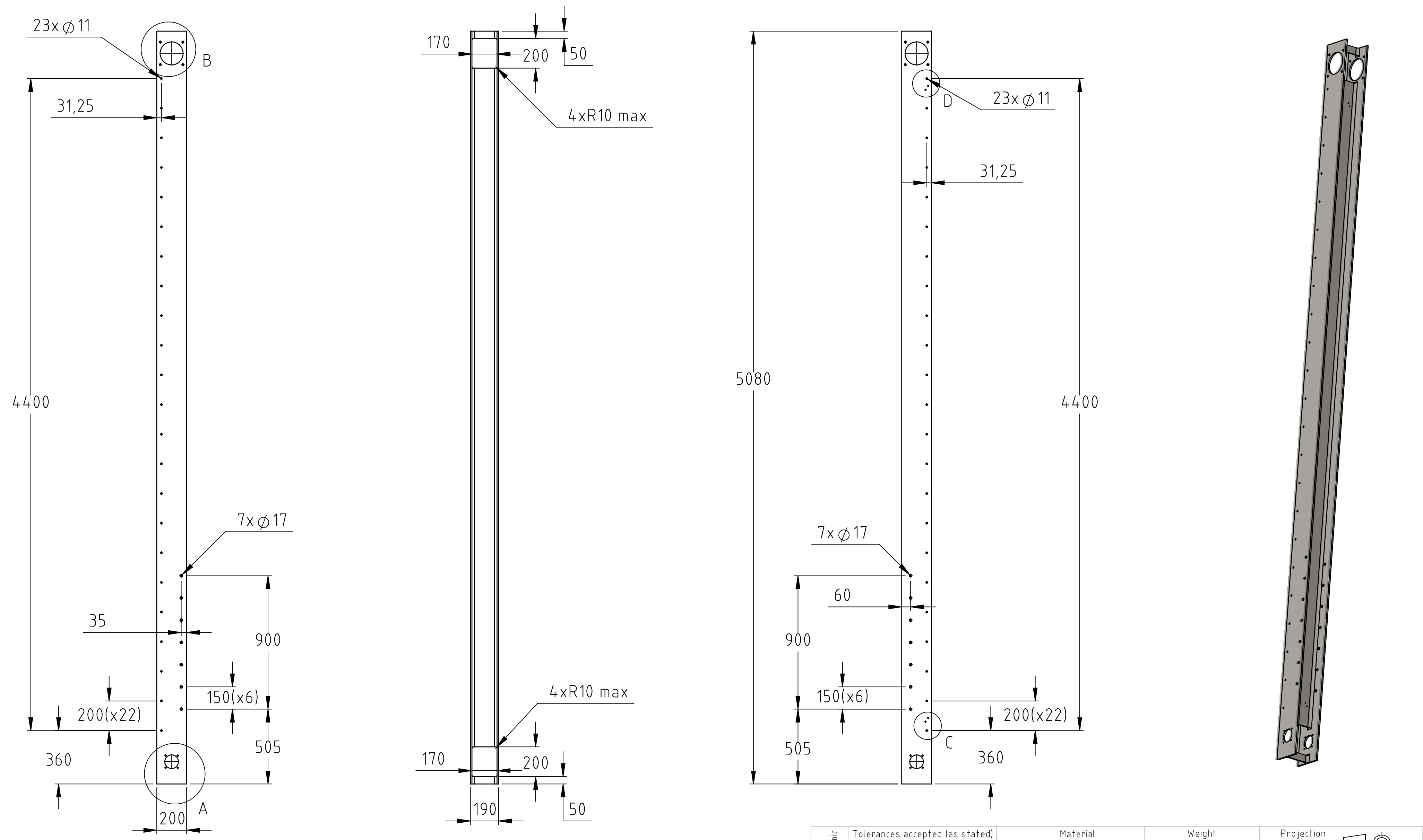
Title

Foundation

Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Drw No. Foundation

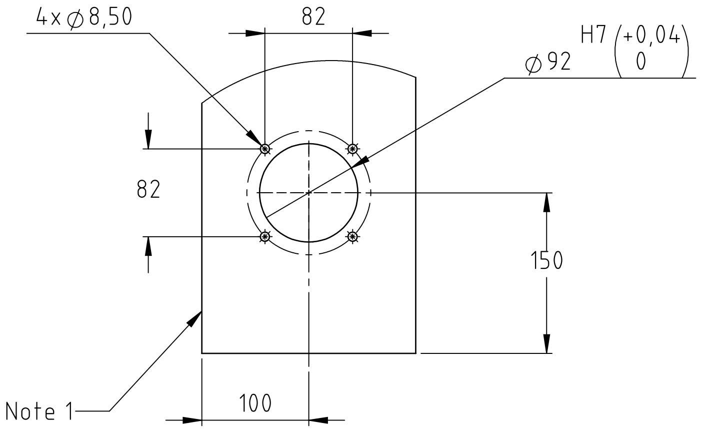
Rev. A



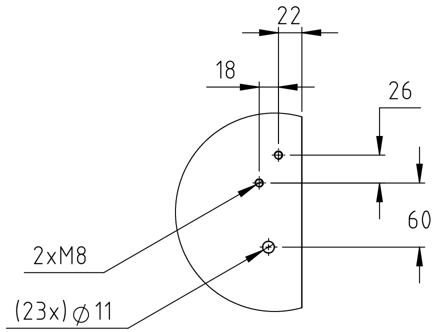



| | | | | |
|---|---|---|---|---|
| Tolerances accepted (as stated) ISO 2768-M | Material 1.0037 (S235JR) | Weight 204.32 kg | Projection | |
| Designed - - | Break all corners and edges acc. to ISO 13715 (+0,3 +0,1 / -0,1 -0,3) | Part/Area/Group - | Size A3 | Sheet 1/2 |
| Drawn - - | | Project/No./Name - | | |
| Checked - - | | Title | | |
| Approved - - | | HE 200A, L=5080 | | |
| This drawing must not be copied or made enable to others without permission. The receiver is responsible for every misuse. | Scale 1:25 | Utility Robot<br>Hot Bowl Reactor<br>Carbothermic Research Facility | | |
| ALCOA | Alcoa Norway Carbothermic | Drw No. HE__200A | | Rev. - |

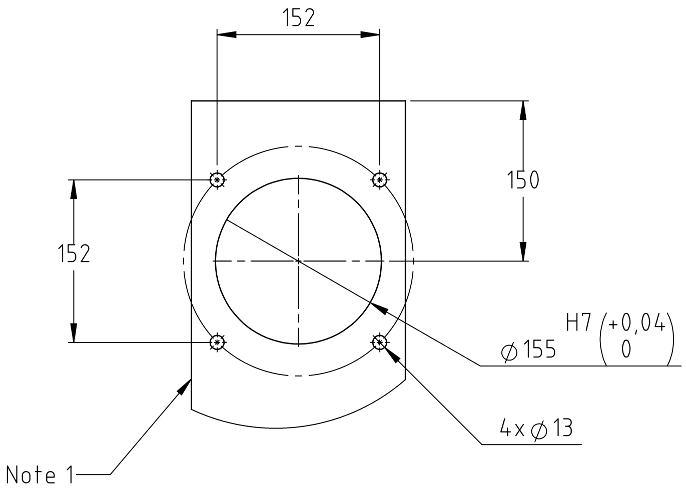
Verify prior to construction - Do not scale



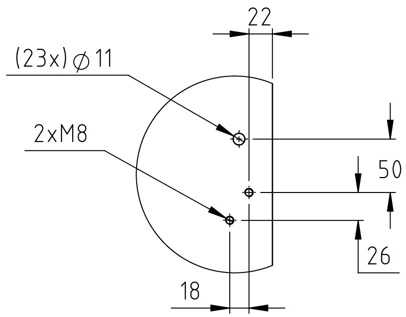

DETAIL A
SCALE 1 : 5




DETAIL C
SCALE 1 : 5




DETAIL B
SCALE 1 : 5




DETAIL D
SCALE 1 : 5

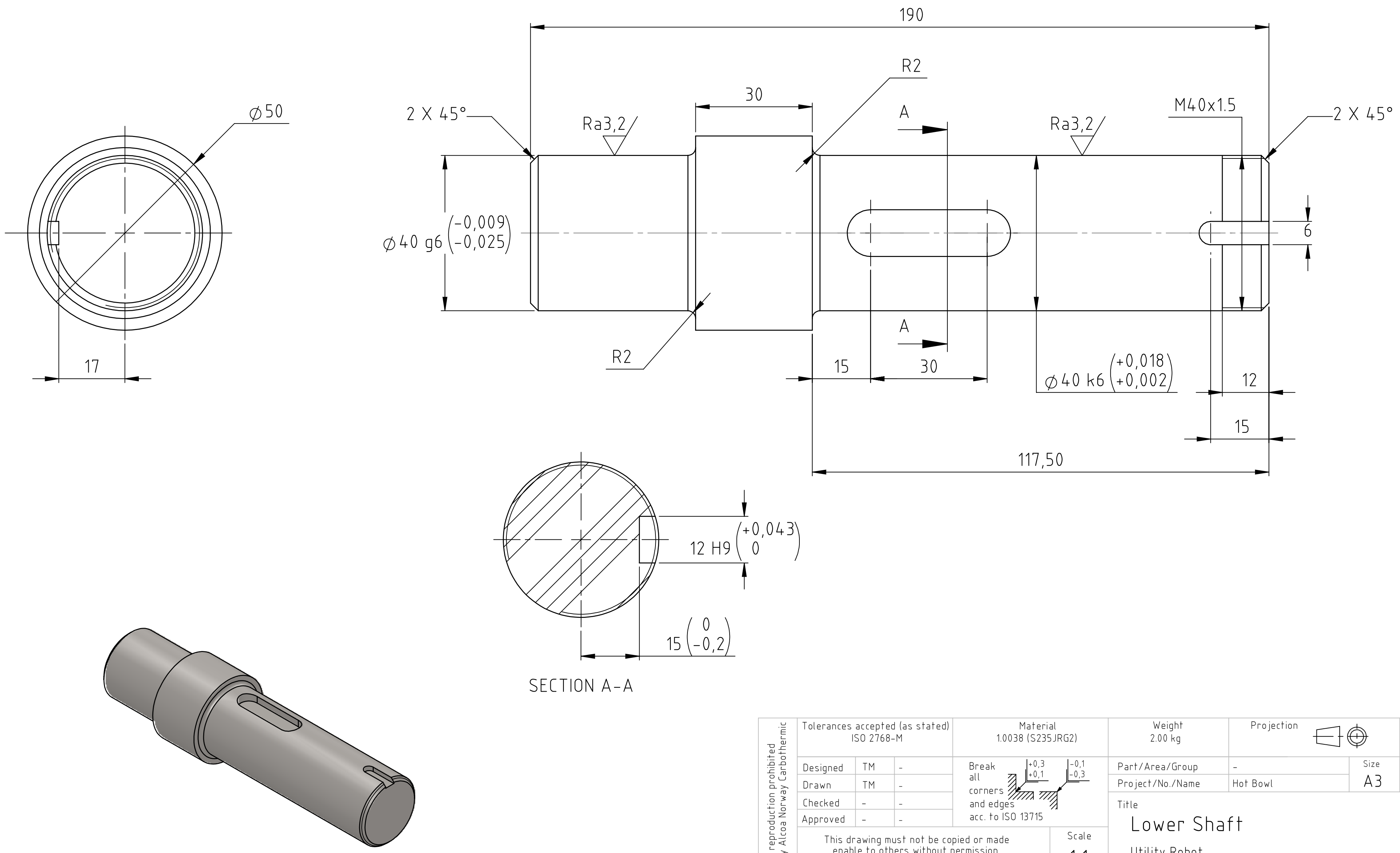
Note 1:
Alle huller og dimensjoner i denne projeksjonen er lik for begge sider av H-profil. Hullene Ø92 og Ø155 på begge sider lages i samme oppspenning (for å sikre at hullele har samme senterlinje)



| | | | | |
|---|---|---|---|---|
| Tolerances accepted (as stated) ISO 2768-M | Material 1.0037 (S235JR) | Weight 204.32 kg | Projection | |
| Designed - - | Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1; -0,1 / -0,3) | Part/Area/Group - | Size A3 | Sheet 2/2 |
| Drawn - - | | Project/No./Name - | | |
| Checked - - | | Title | | |
| Approved - - | | HE 200A, L=5080 | | |
| This drawing must not be copied or made enable to others without permission. The receiver is responsible for every misuse. | Scale 1:25 | Utility Robot<br>Hot Bowl Reactor<br>Carbothermic Research Facility | | |
| ALCOA | Alcoa Norway Carbothermic | Drw No. HE_200A | Rev. - | |

Verify prior to construction - Do not scale

| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |
|---|---|---|---|---|---|
| A | Issued For Construction | TM | - | - | 17.04.2015 |






| | | | | |
|---|---|---|---|---|
| Tolerances accepted (as stated) ISO 2768-M | | | Material 1.0038 (S235JRG2) | Weight 2.00 kg |
| Designed | TM | - | Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1; -0,1 / -0,3) | Part/Area/Group: - |
| Drawn | TM | - | | Project/No./Name: Hot Bowl |
| Checked | - | - | | |
| Approved | - | - | | |

Projection

Size: A3

Sheet: 1/1

This drawing must not be copied or made enable to others without permission.
The receiver is responsible for every misuse.

Scale: 1:1

Alcoa Norway Carbothermic

ALCOA

Title

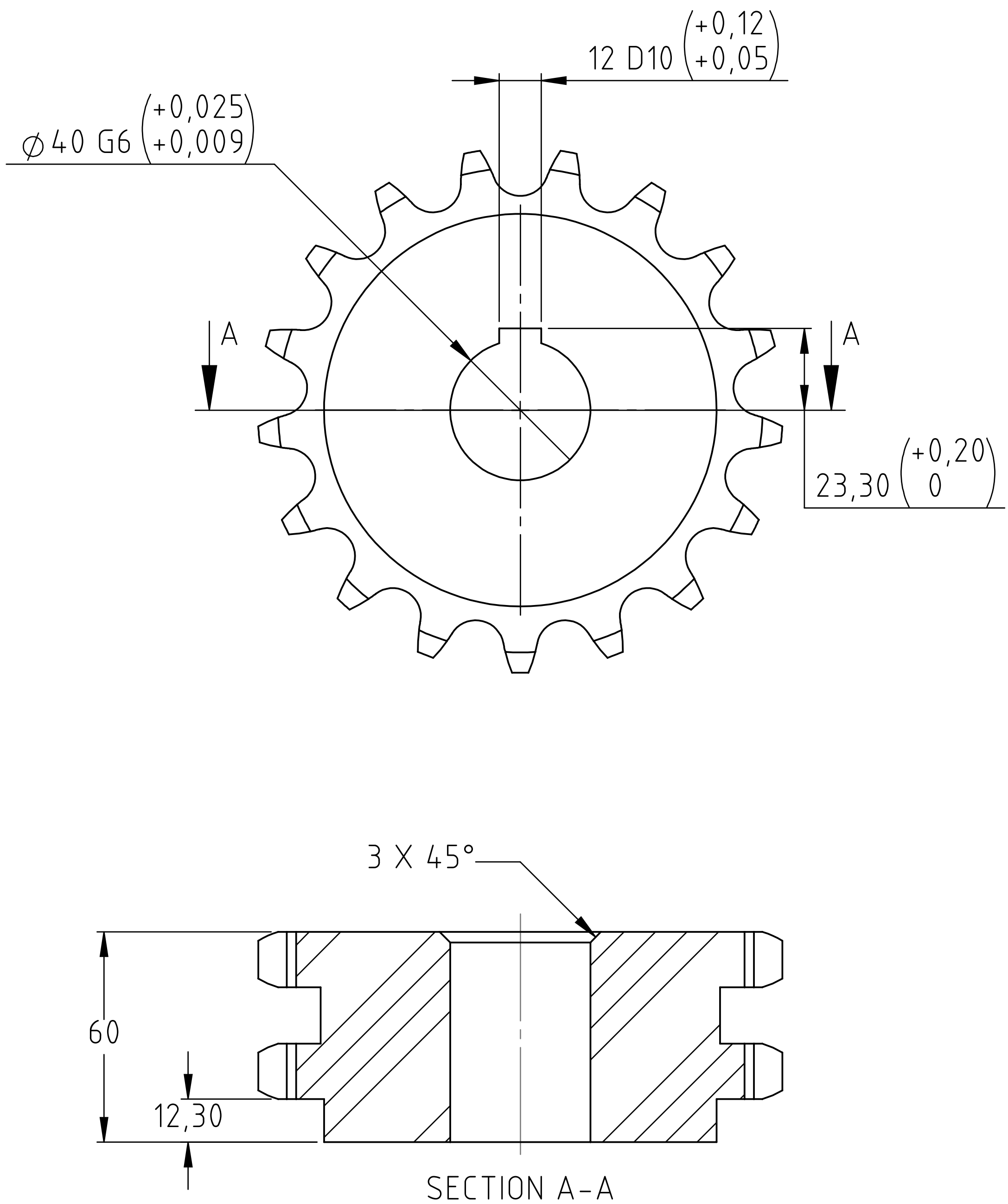
Lower Shaft

Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Drw No. Lower shaft

Rev. A

| A | Issued For Construction | TM | - | - | 17.04.2015 |
|---|---|---|---|---|---|
| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |






| | | | |
|---|---|---|---|
| Tolerances accepted (as stated) ISO 2768-M | | | Material 1.0038 (S235JRG2) |
| Designed | TM | - | Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1; -0,1 / -0,3) |
| Drawn | TM | - | |
| Checked | - | - | |
| Approved | - | - | |



Scale 1:2

Alcoa Norway Carbothermic

| | | | |
|---|---|---|---|
| Weight 5.0 kg | Projection | | |
| Part/Area/Group | - | Size A4 | Sheet 1/1 |
| Project/No./Name | Hot Bowl | | |

Title

Sprocket 16 B-2 17

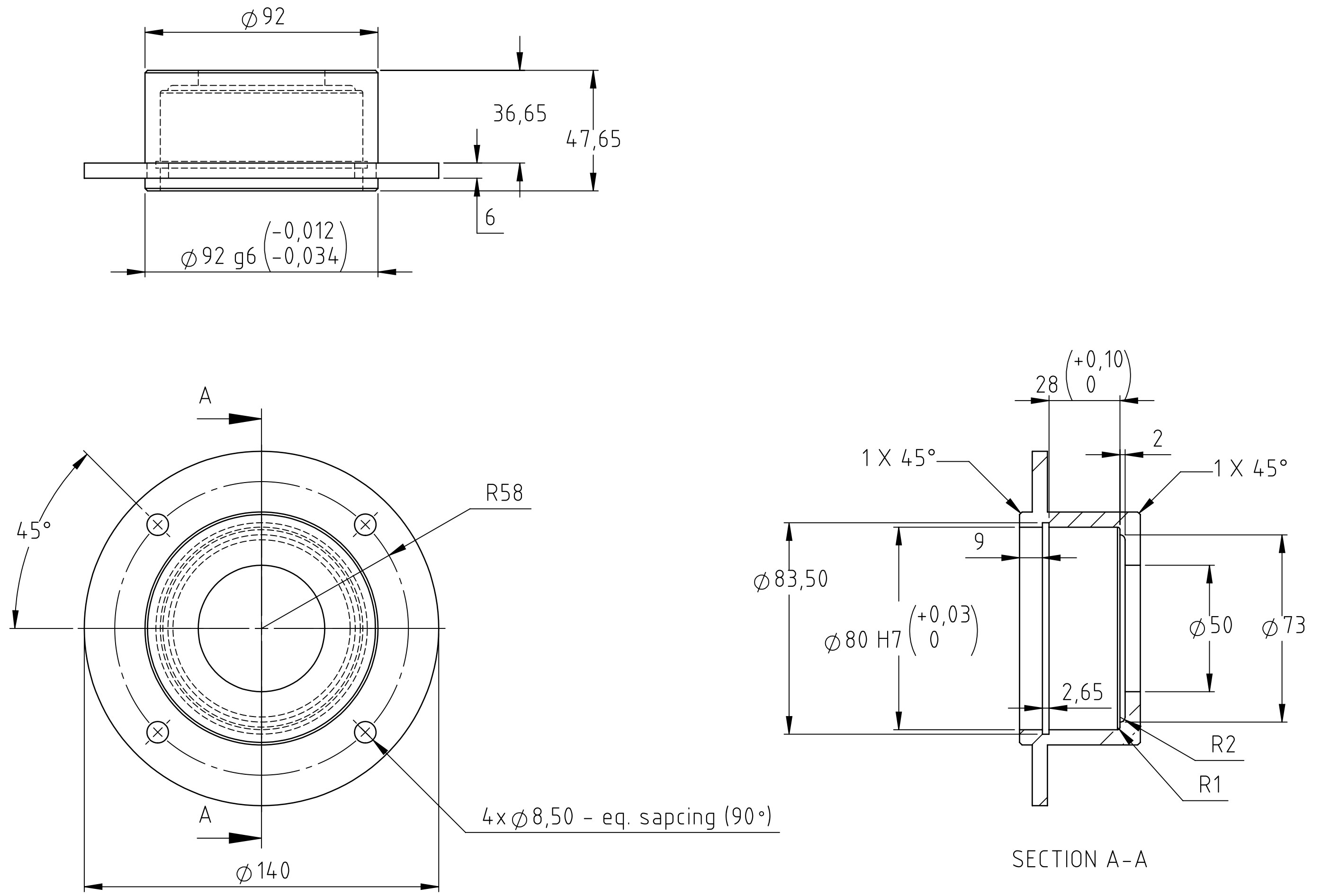
Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

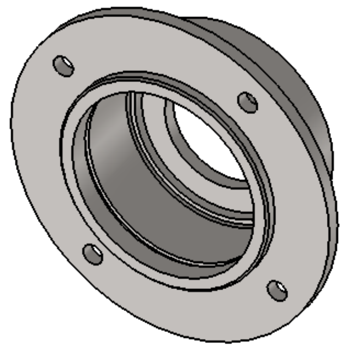
Drw No. Lower Sprocket

Rev. A

Verify prior to construction - Do not scale

| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |
|---|---|---|---|---|---|
| A | Issued For Construction | TM | - | - | 28.04.2015 |





| | | | | |
|---|---|---|---|---|
| Tolerances accepted (as stated) ISO 2768-M | Material 1.0038 (S235JRG2) | Weight 1.15 kg | Projection | |
| Designed TM - | Break all corners and edges acc. to ISO 13715 (+0,3/+0,1; -0,1/-0,3) | Part/Area/Group - | Size A3 | Sheet 1/1 |
| Drawn TM - | | Project/No./Name Hot Bowl | | |
| Checked - - | | | | |
| Approved - - | | | | |

This drawing must not be copied or made enable to others without permission.
The receiver is responsible for every misuse.

Scale 1:2

ALCOA
Alcoa Norway Carbothermic

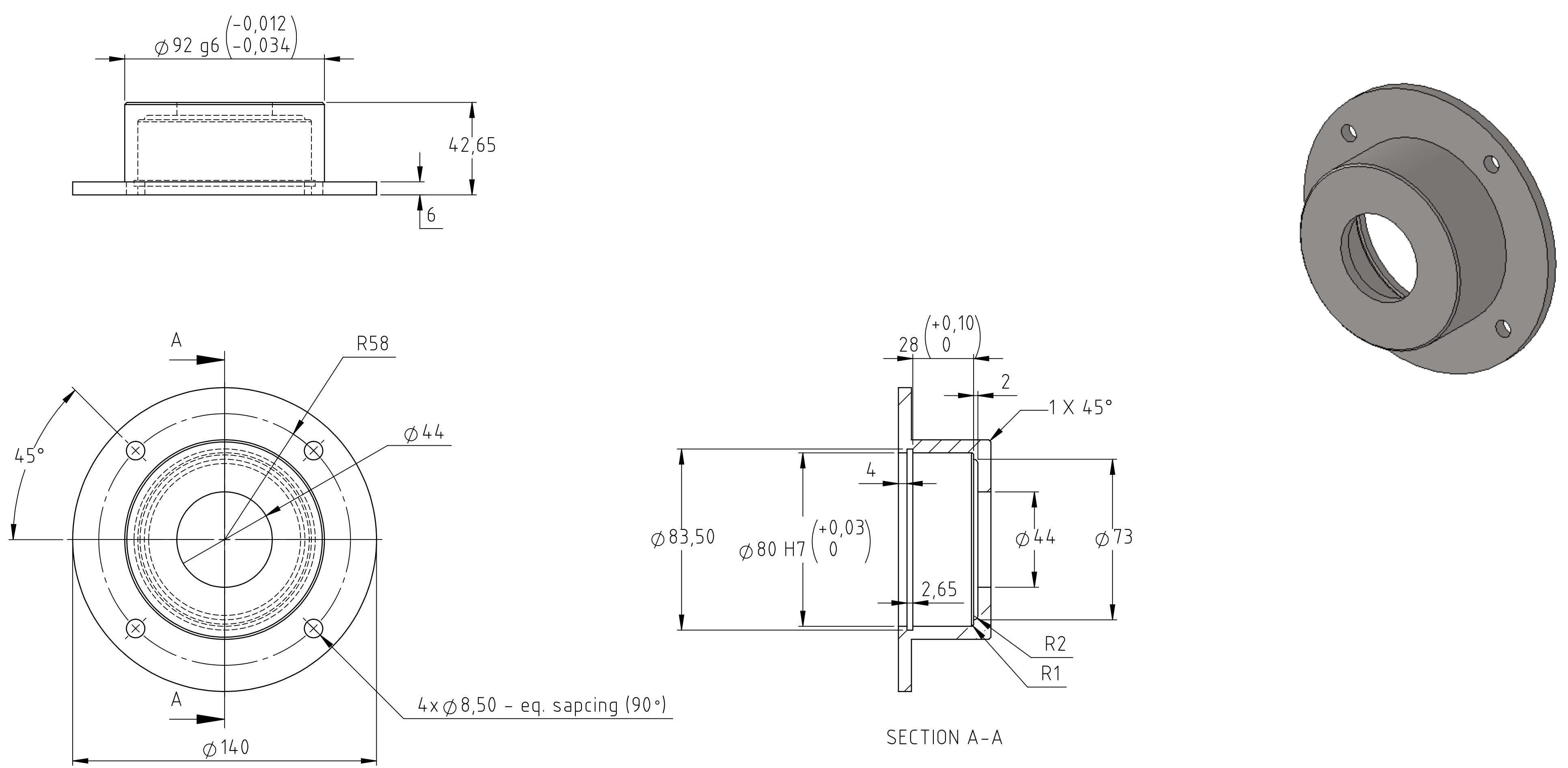
Title
Bearing Housing
Lower shaft, right side
Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Drw No. Bearing housing 1

Rev. A

Verify prior to construction - Do not scale

| A | Issued For Construction | TM | - | - | 28.04.2015 |
|---|---|---|---|---|---|
| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |






| | | | | |
|---|---|---|---|---|
| Tolerances accepted (as stated) ISO 2768-M | Material 1.0038 (S235JRG2) | Weight 1.15 kg | Projection | |
| Designed: TM - | Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1; -0,1 / -0,3) | Part/Area/Group: - | Size: A3 | Sheet: 1/1 |
| Drawn: TM - | | Project/No./Name: Hot Bowl | | |
| Checked: - - | | | | |
| Approved: - - | | | | |

This drawing must not be copied or made enable to others without permission.
The receiver is responsible for every misuse.

Scale 1:2

ALCOA
Alcoa Norway Carbothermic

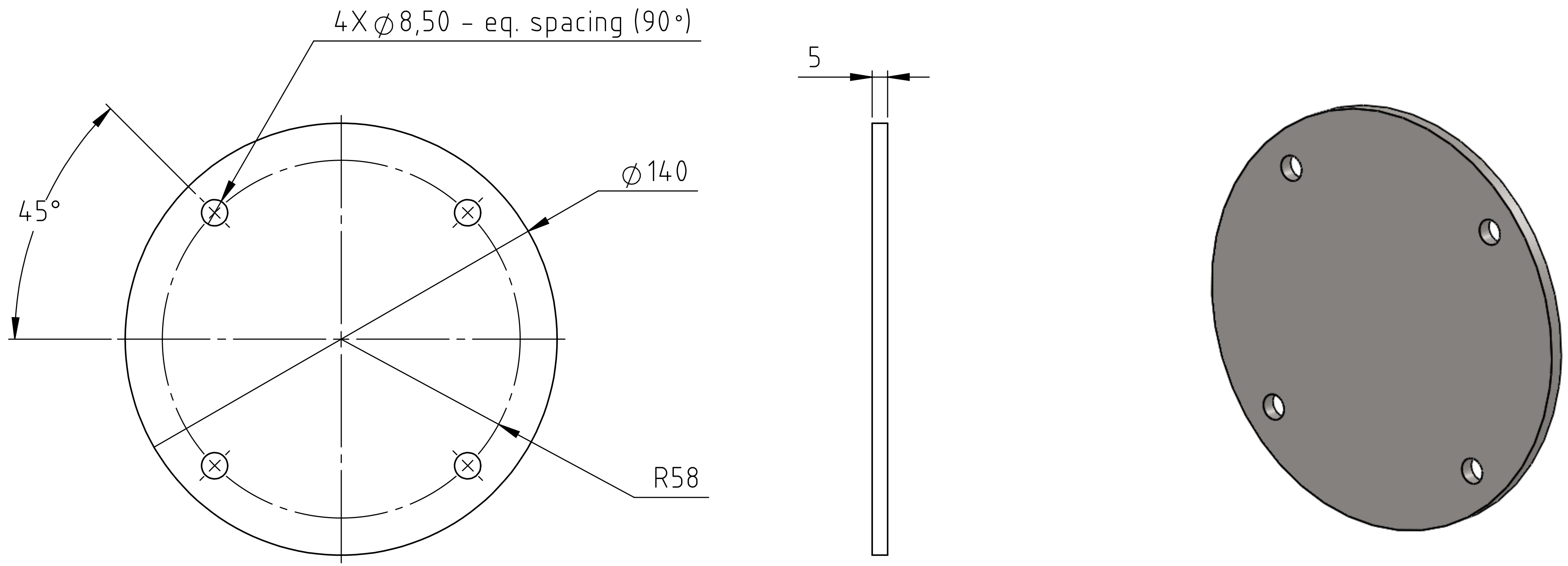
Title
Bearing Housing
Lower shaft, left side
Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Drw No. Bearing housing 2

Rev. A

Verify all dimensions prior to construction - Do not scale

| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |
|---|---|---|---|---|---|
| A | Issued For ConstructionC2 | TM | - | - | 28.04.2015 |






| | | |
|---|---|---|
| Tolerances accepted (as stated) ISO 2768-M | | |
| Designed | TM | - |
| Drawn | TM | - |
| Checked | - | - |
| Approved | - | - |

Material
1.0038 (S235JRG2)

Break all corners and edges acc. to ISO 13715 +0,3 +0,1 -0,1 -0,3

Weight
0.59 kg

Projection

This drawing must not be copied or made enable to others without permission.
The receiver is responsible for every misuse.

Scale
1:2

Alcoa Norway Carbothermic

| | | Size | Sheet |
|---|---|---|---|
| Part/Area/Group | - | A4 | 1/1 |
| Project/No./Name | Hot Bowl | | |

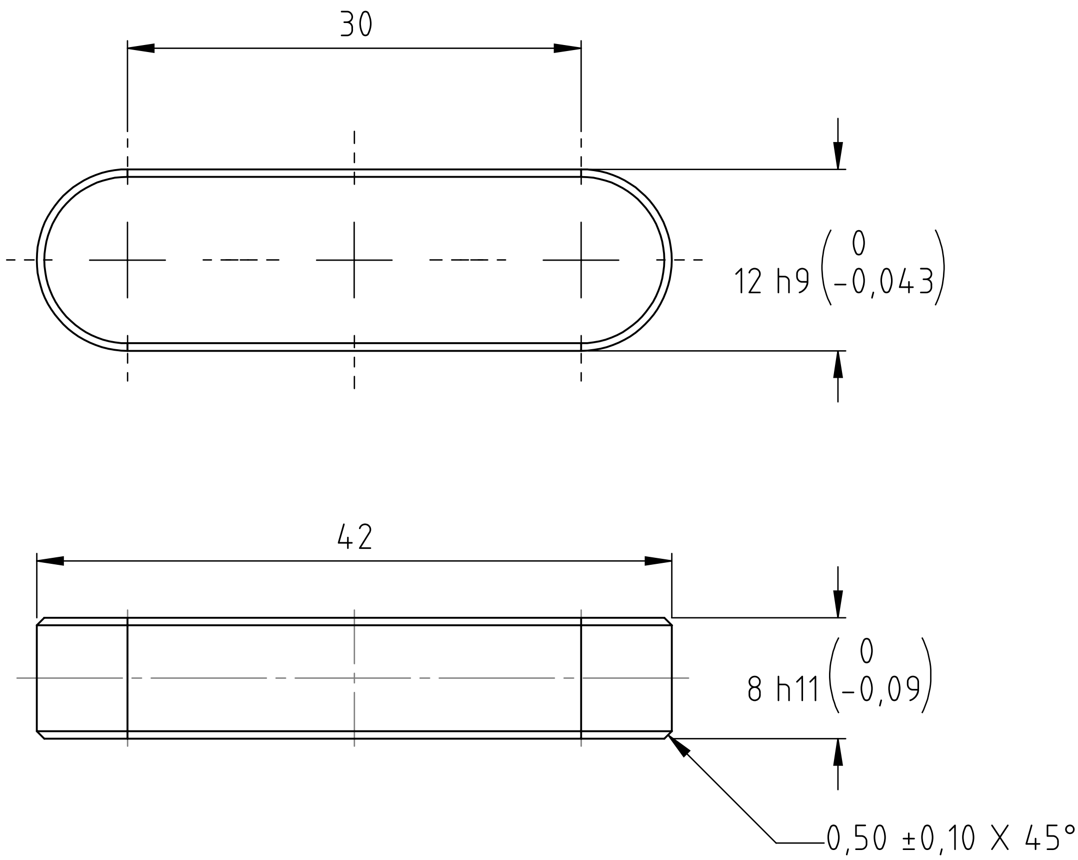
Title
Bearing Housing Cover

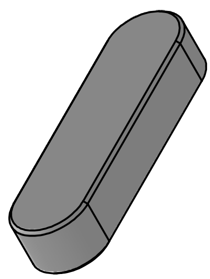
Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Drw No. Bearing Housing Cover

Rev. A

| A | Issued For Construction | TM | - | - | 17.04.2015 |
|---|---|---|---|---|---|
| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |





| | | | |
|---|---|---|---|
| Tolerances accepted (as stated) DIN 6680 | | | Material EN 10277-2 |
| Designed | TM | - | Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1; -0,1 / -0,3) |
| Drawn | TM | - | |
| Checked | - | - | |
| Approved | - | - | |



Scale 2:1

Alcoa Norway Carbothermic

| | | | |
|---|---|---|---|
| Weight 0.03 kg | Projection | | |
| Part/Area/Group | - | Size A4 | Sheet 1/1 |
| Project/No./Name | Hot Bowl | | |

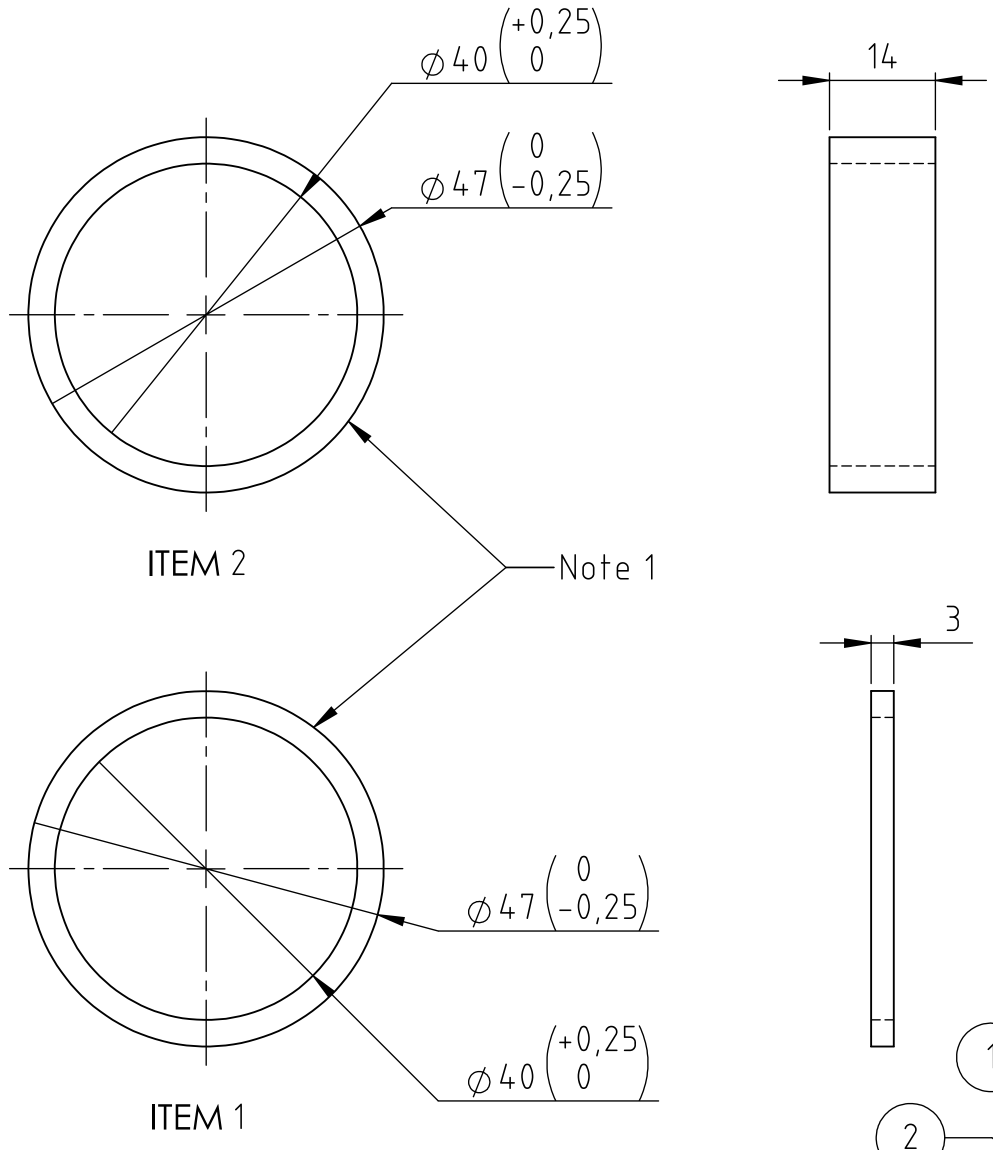
Title
Key, Lower Shaft

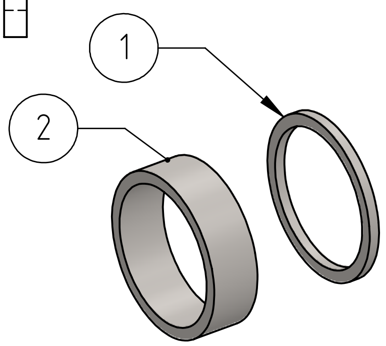
Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Drw No. Key, lower shaft

Rev. A

| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |
|---|---|---|---|---|---|
| A | Issued For Construction | TM | - | - | 30.04.2015 |




Note 1:
Parts can be cut from
same operation in the lathe

| ITEM | DESCRIPTION | QTY | MATERIAL | MASS/ ITEM | MASS/ TOTAL | DRAWING | STANDARD | REV |
|---|---|---|---|---|---|---|---|---|
| 2 | Round Bar ⌀47 L=14 | 1 | 1.0038 (S235JRG2) | 0.05 | 0.05 | N/A | N/A | A |
| 1 | Round Bar ⌀47 L=3 | 1 | 1.0038 (S235JRG2) | 0.01 | 0.01 | N/A | N/A | A |



| | | |
|---|---|---|
| Tolerances accepted (as stated) ISO 2768-M | Weld according to: ISO 5817-C | Total weight 0.06 kg |
| Projection | | |

| | | |
|---|---|---|
| Designed | TM | - |
| Drawn | TM | - |
| Checked | - | - |
| Approved | - | - |

Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1; -0,1 / -0,3)

| | | | |
|---|---|---|---|
| Part/Area/Group | - | Size | Sheet |
| Project/No./Name | Hot Bowl | A4 | 1/1 |



Scale 1:1

Alcoa Norway
Carbothermic

Title

# Spacers, Lower Shaft

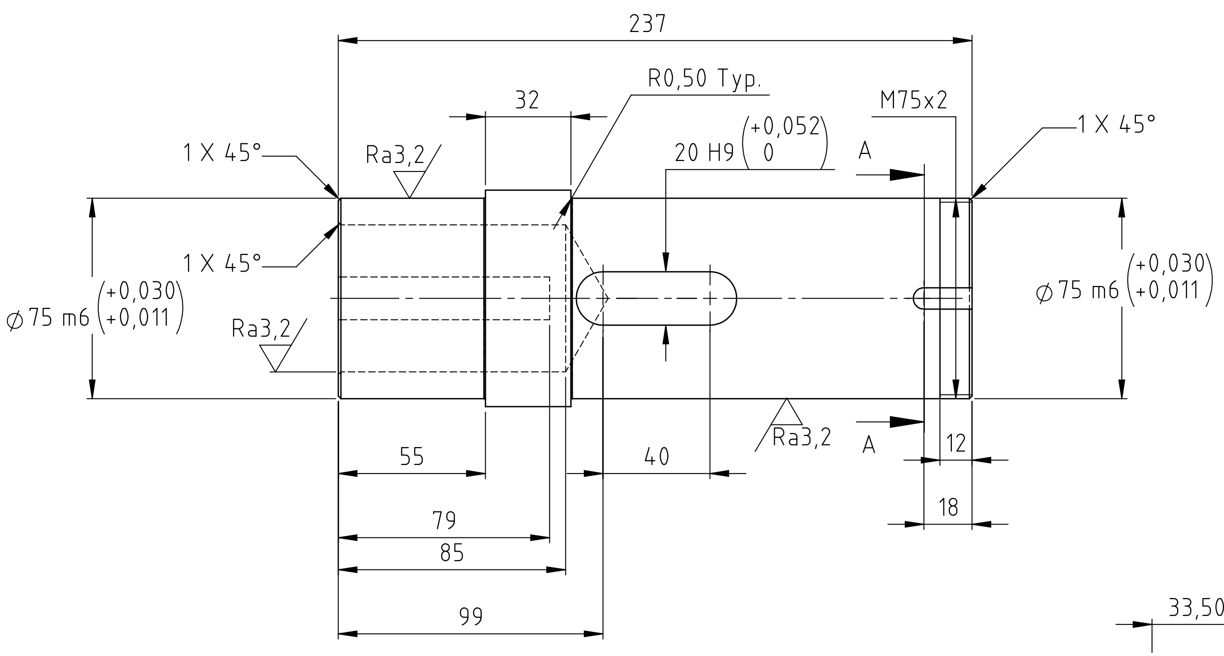
Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

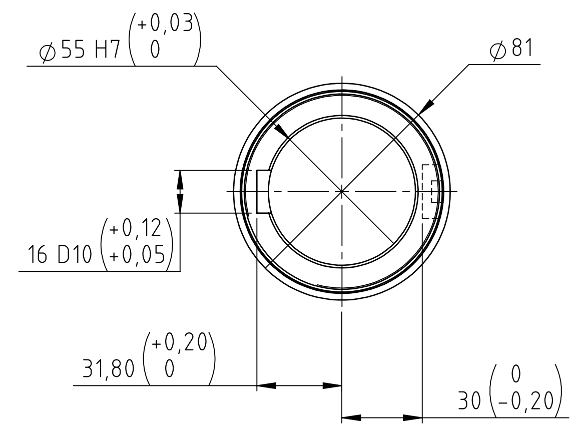
Drw No. Spacers, lower shaft

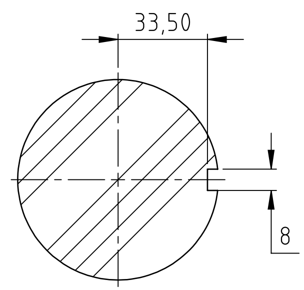
Rev. A

Verify prior to construction - Do not scale

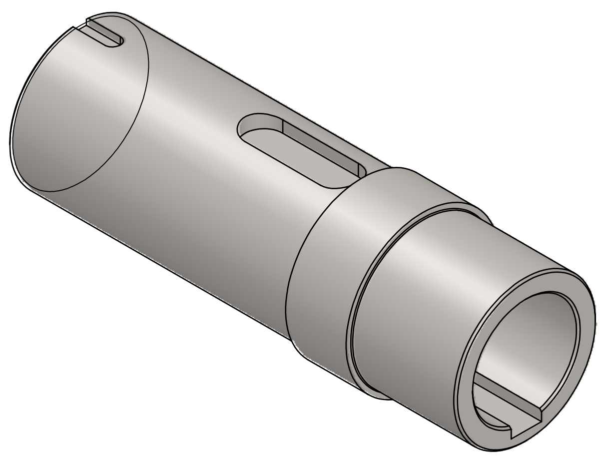
| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |
|---|---|---|---|---|---|
| B | Longer shaft, added threads to one end | TM | - | - | 17.04.2015 |
| A | Issued for construction | TM | - | - | 16.04.2015 |




SECTION A-A





| Tolerances accepted (as stated) ISO 2768-M | Material 1.0038 (S235JRG2) | Weight 6.55 kg | Projection |
|---|---|---|---|

| | | |
|---|---|---|
| Designed | TM | - |
| Drawn | TM | - |
| Checked | - | - |
| Approved | - | - |

Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1) (-0,1 / -0,3)

| | | Size | Sheet |
|---|---|---|---|
| Part/Area/Group | - | A3 | 1/1 |
| Project/No./Name | Hot Bowl | | |

This drawing must not be copied or made enable to others without permission.
The receiver is responsible for every misuse.

Scale 1:2

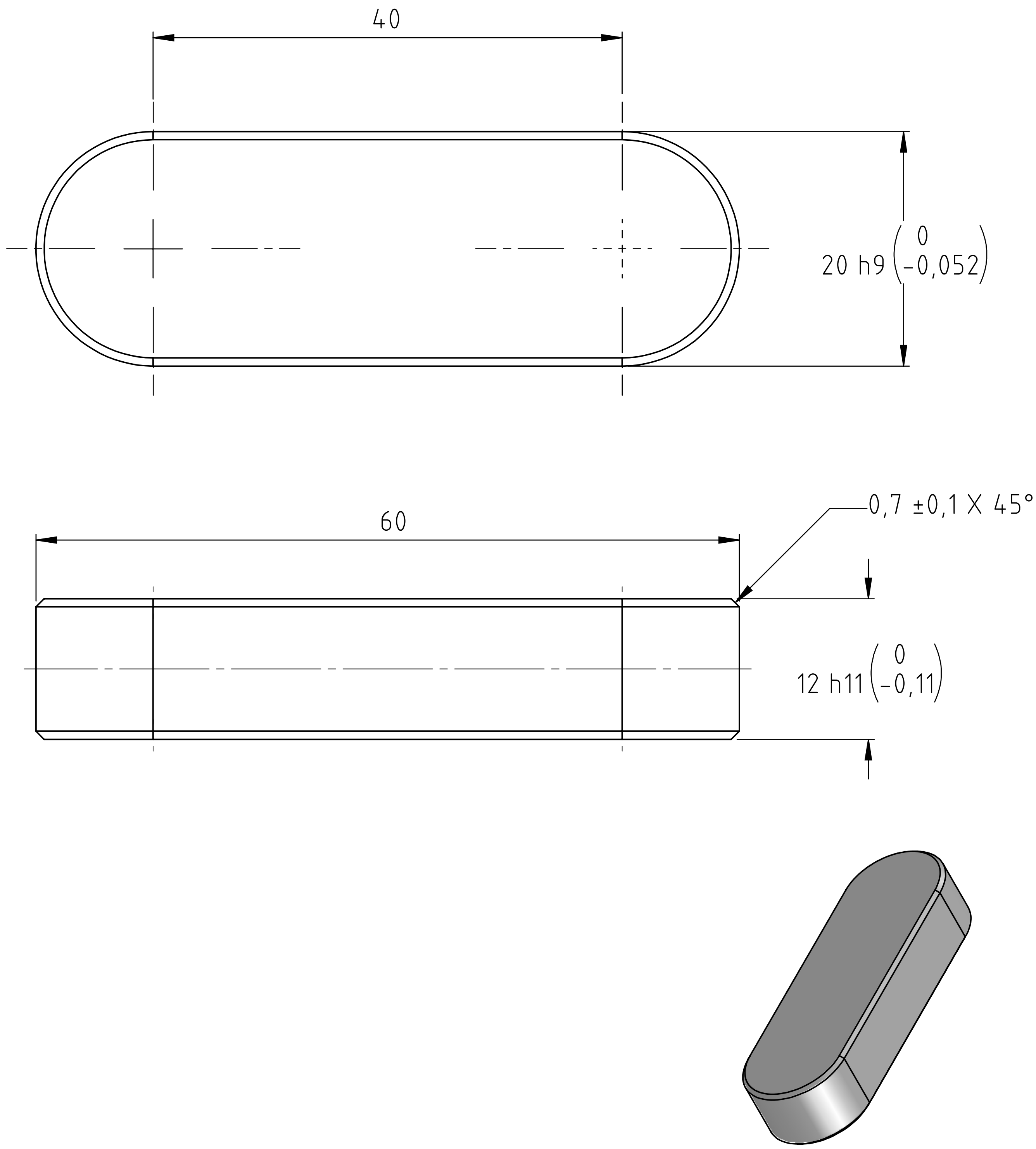
Alcoa Norway Carbothermic

ALCOA

Title
Upper Shaft
Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Drw No. Upper shaft

Rev. B




| | | | | | |
|---|---|---|---|---|---|
| Tolerances accepted (as stated) DIN 6680 | | | Material EN 10277-2 | Weight 0.10 kg | Projection |
| Designed | TM | - | Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1; -0,1 / -0,3) | Part/Area/Group | - |
| Drawn | TM | - | | Project/No./Name | Hot Bowl |
| Checked | - | - | | Size A4 | Sheet 1/1 |
| Approved | - | - | | | |

This drawing must not be copied or made enable to others without permission.
The receiver is responsible for every misuse.

Scale 2:1

Alcoa Norway Carbothermic

ALCOA

Title

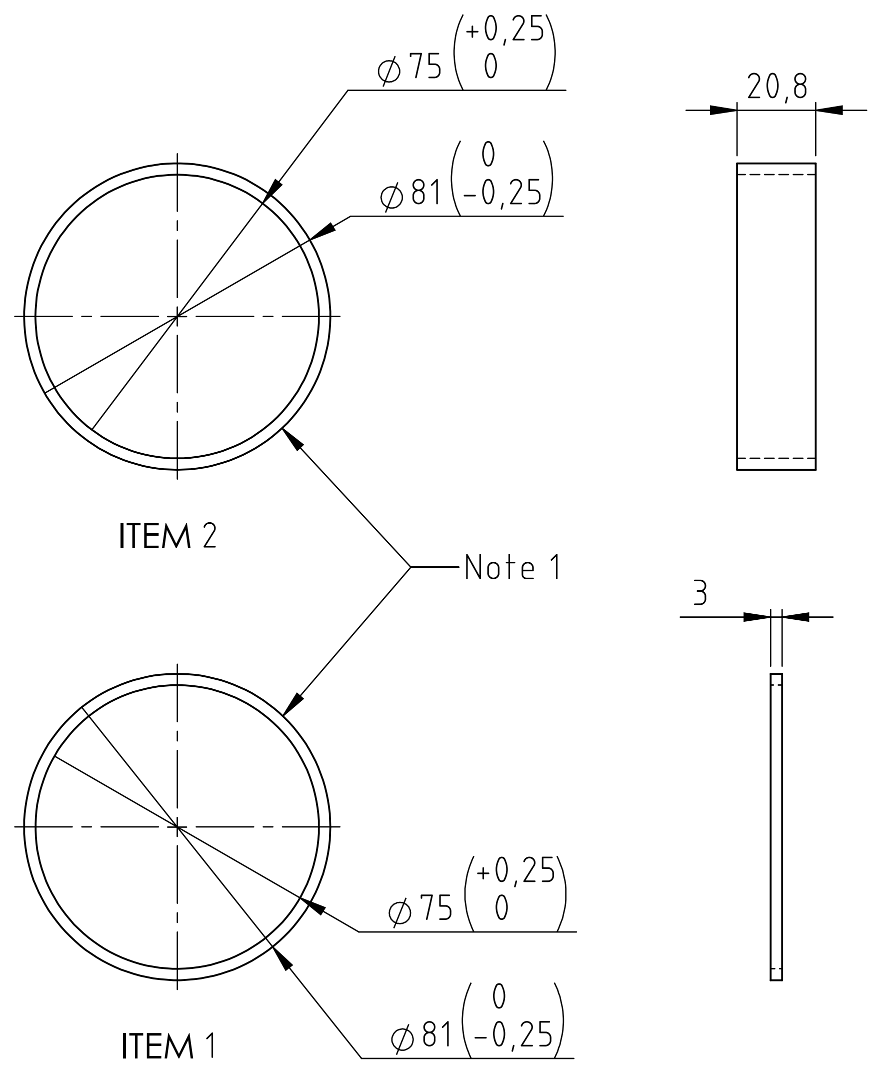
# Key, Upper Shaft

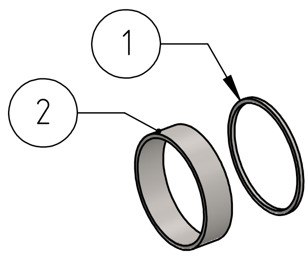
Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Drw No. Key, upper shaft

Rev. -

| A | Issued For Construction | TM | - | - | 30.04.2015 |
|---|---|---|---|---|---|
| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |




Note 1:
Parts can be cut from
same operation in the lathe

| ITEM | DESCRIPTION | QTY | MATERIAL | MASS/ ITEM | MASS/ TOTAL | DRAWING | STANDARD | REV |
|---|---|---|---|---|---|---|---|---|
| 2 | Round Bar ⌀81,5 L=18,8 | 1 | 1.0038 (S235JRG2) | 0.12 | 0.12 | N/A | N/A | A |
| 1 | Round Bar ⌀81 L=3 | 1 | 1.0038 (S235JRG2) | 0.02 | 0.02 | N/A | N/A | A |



Tolerances accepted (as stated)
ISO 2768-M

Weld according to:
ISO 5817-C

Total weight
0.14 kg

Projection

| | | |
|---|---|---|
| Designed | TM | - |
| Drawn | TM | - |
| Checked | - | - |
| Approved | - | - |

Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1) (-0,1 / -0,3)

Part/Area/Group: -

Project/No./Name: Hot Bowl

Size: A4

Sheet: 1/1



Scale
1:2

Title

# Spacers, Upper Shaft

Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

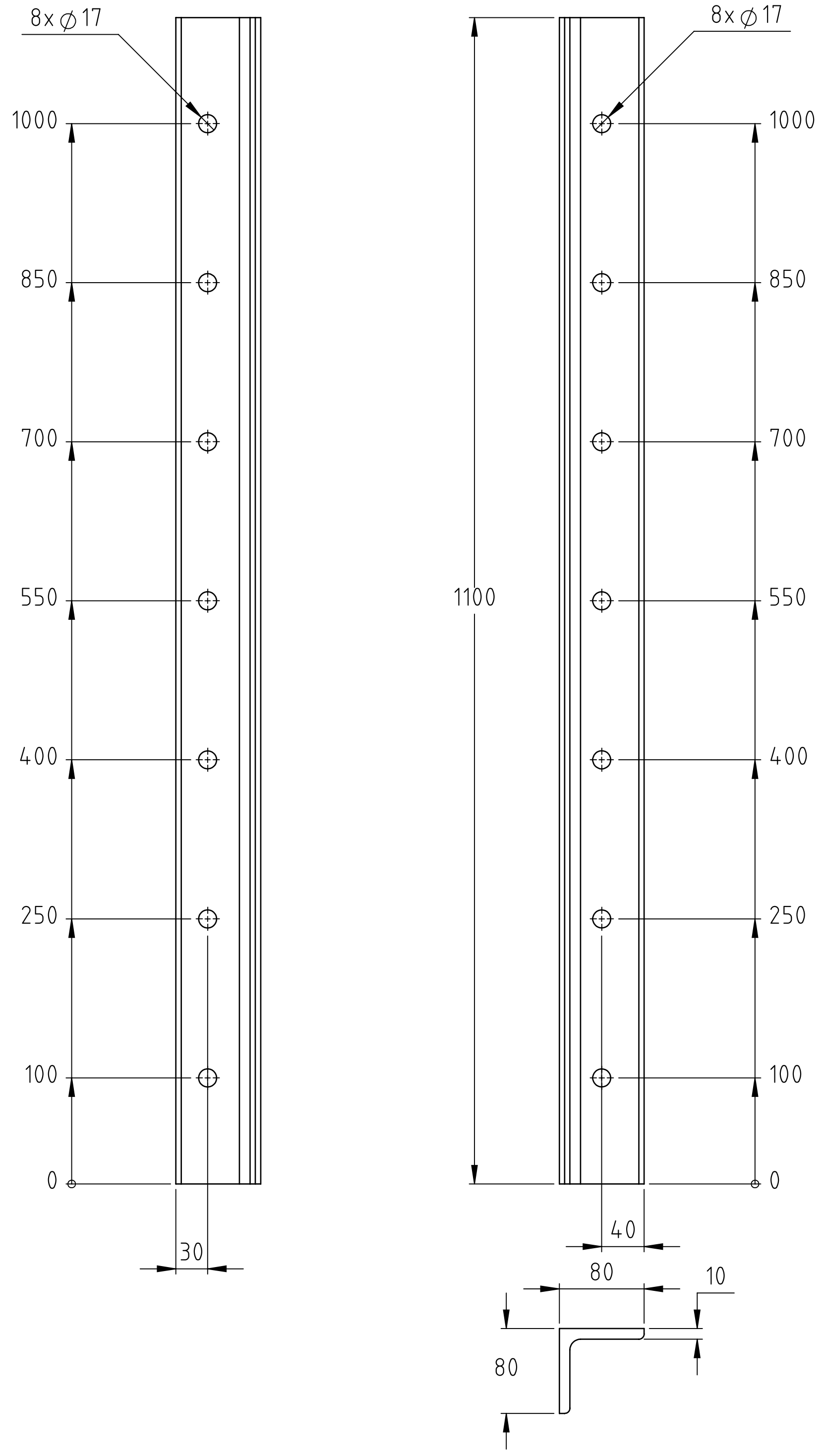
ALCOA
Alcoa Norway
Carbothermic

Drw No. Spacers, upper shaft

Rev. A

Verify prior to construction - Do not scale

| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |
| --- | --- | --- | --- | --- | --- |
| A | Issued For Construction | TM | - | - | 30.04.2015 |




| ITEM | DESCRIPTION | QTY | MATERIAL | MASS/ ITEM | MASS/ TOTAL | DRAWING | STANDARD | REV |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 1 | L 80x10 | 1 | 1.0038 (S235JRG2) | 12.71 | 12.71 | N/A | N/A | A |

Tolerances accepted (as stated) ISO 2768-M

Material 1.0038 (S235JRG2)

Weight 12.71 kg

Projection

| | | |
| --- | --- | --- |
| Designed | TM | - |
| Drawn | TM | - |
| Checked | - | - |
| Approved | - | - |

Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1; -0,1 / -0,3)

This drawing must not be copied or made enable to others without permission.
The receiver is responsible for every misuse.

Scale 1:5

Part/Area/Group: -

Project/No./Name: Hot Bowl

Size: A3

Sheet: 1/1

Title

Linear Guide Bracket

Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Alcoa Norway Carbothermic

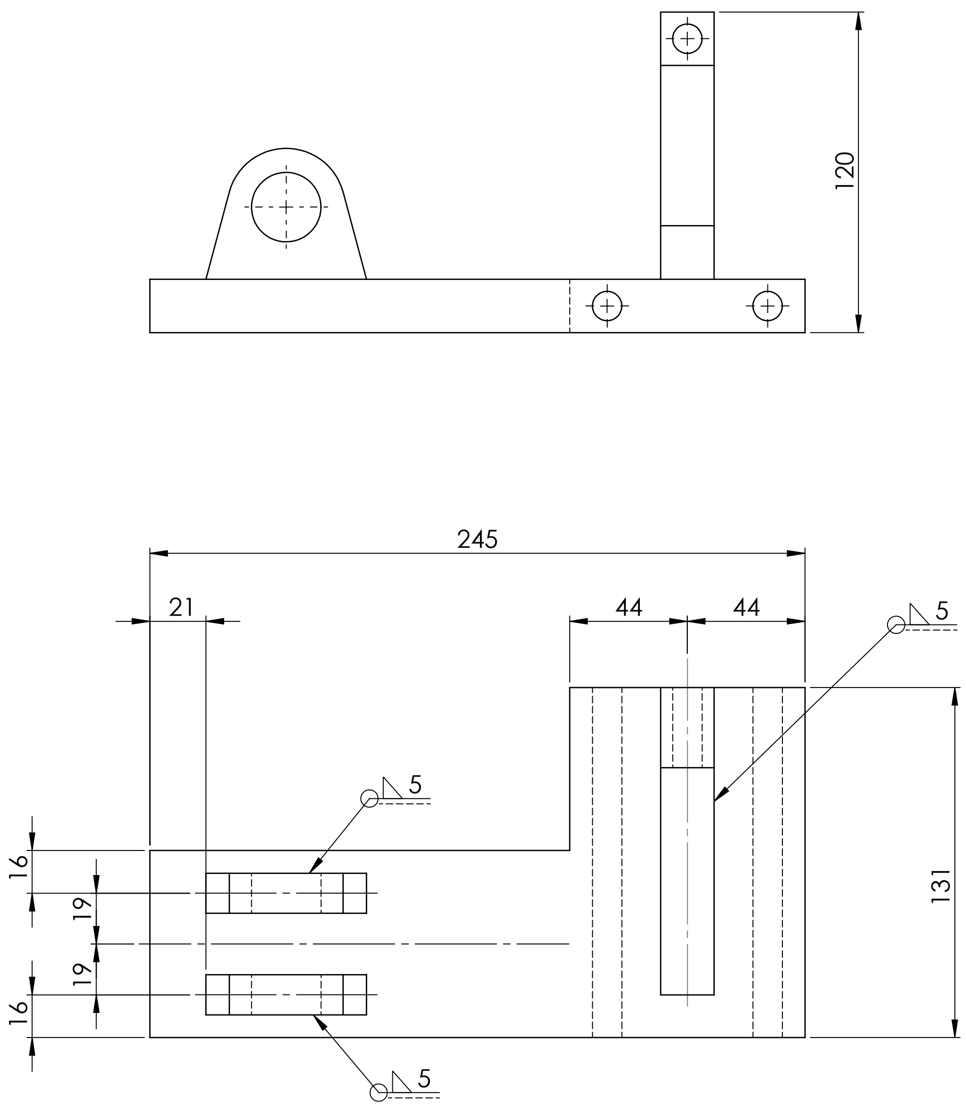
ALCOA

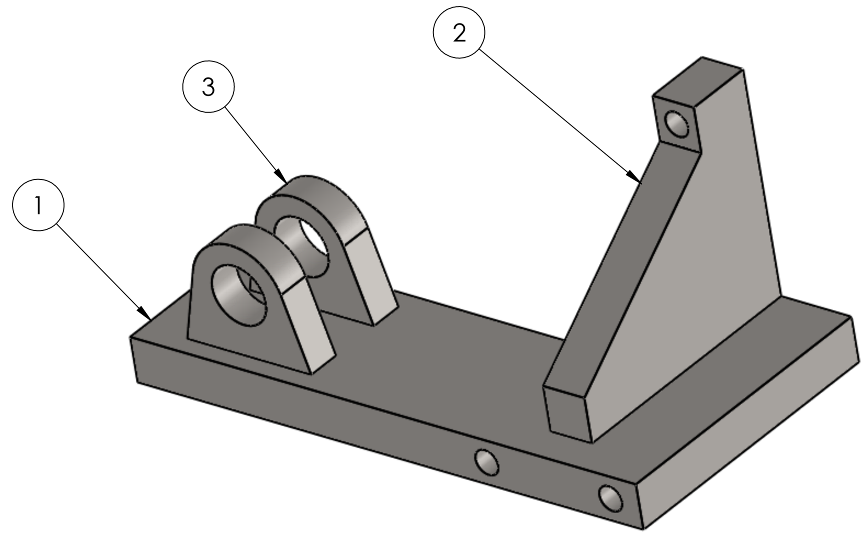
Drw No. Linear Guide Bracket

Rev. A

Verify prior to construct - Do not scale

| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |
|---|---|---|---|---|---|
| A | Issued For Construction | TM | - | - | 28.04.2015 |




| ITEM | DESCRIPTION | QTY | MATERIAL | MASS/ ITEM | MASS/ TOTAL | DRAWING | STANDARD | REV |
|---|---|---|---|---|---|---|---|---|
| 3 | PL 15x60x49 | 2 | 1.0038 (S235JRG2) | 0.19 | 0.38 | N/A | N/A | A |
| 2 | PL 20x115x100 | 1 | 1.0038 (S235JRG2) | 1.11 | 1.11 | N/A | N/A | A |
| 1 | PL 20x245x131 | 1 | 1.0038 (S235JRG2) | 3.32 | 3.32 | N/A | N/A | A |



Tolerances accepted (as stated) ISO 2768-M

Weld according to: ISO 5817-C

Total weight 4.81 kg

Projection

| | | |
|---|---|---|
| Designed | TM | 25.03.2015 |
| Drawn | TM | 30.03.2015 |
| Checked | - | - |
| Approved | - | - |

Break all corners and edges acc. to ISO 13715 +0,3 +0,1 -0,1 -0,3

Part/Area/Group: FILTER/LISTA

Project/No./Name: Hot Bowl

Size: A3

Sheet: 1/2



Scale: 1:2

Alcoa Norway Carbothermic

ALCOA

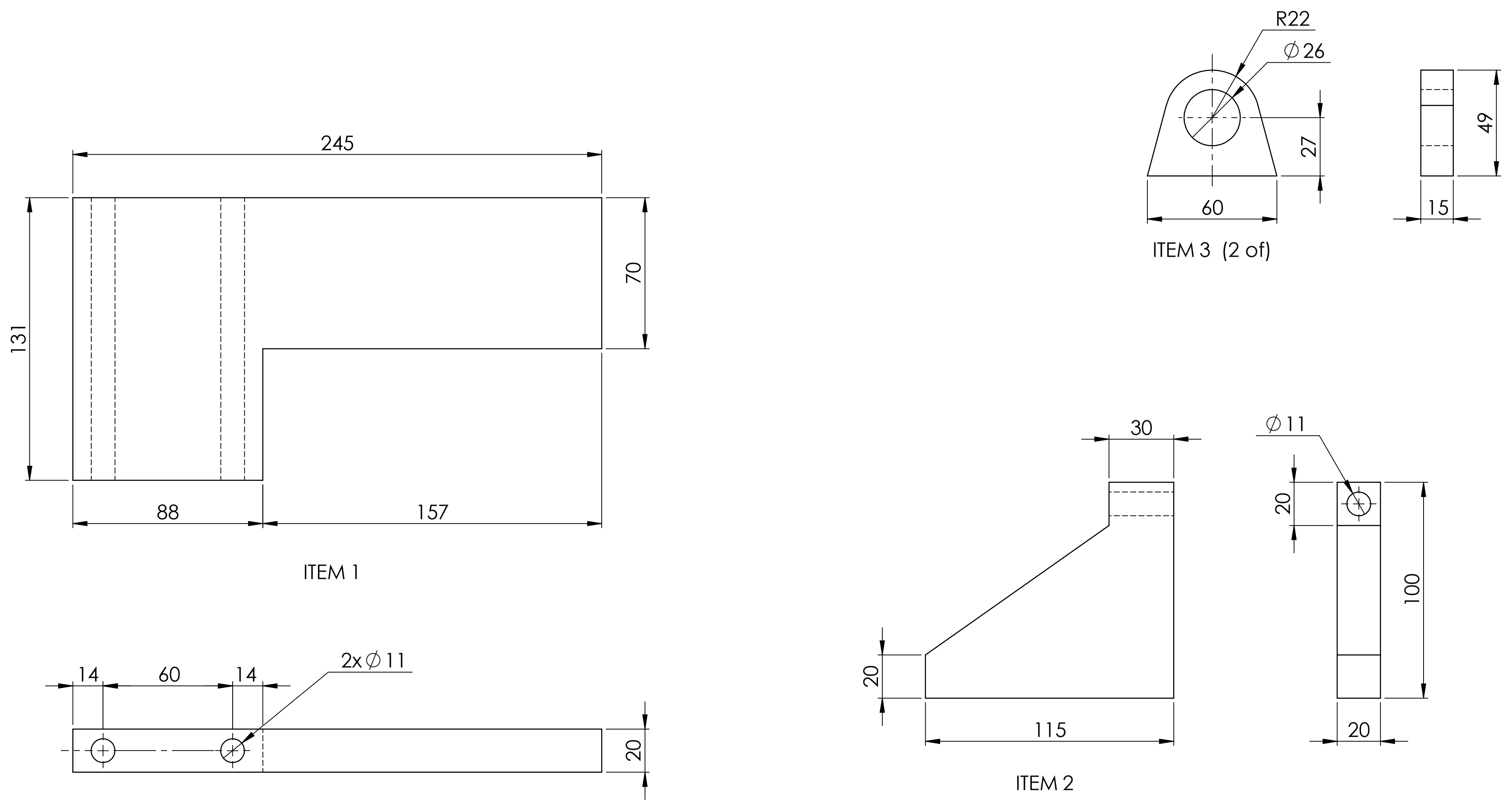
Title

Cylinder Mount

Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Drw No. Cylinder mount

Rev. A






| | | | | |
|---|---|---|---|---|
| Tolerances accepted (as stated) ISO 2768-M | | | Weld according to: ISO 5817-C | |
| Designed | TM | 25.03.2015 | Break all corners and edges acc. to ISO 13715 | +0,3 +0,1 / -0,1 -0,3 |
| Drawn | TM | 30.03.2015 | | |
| Checked | - | - | | |
| Approved | - | - | | |

This drawing must not be copied or made enable to others without permission.
The receiver is responsible for every misuse.

Scale 1:2

Alcoa Norway Carbothermic

ALCOA

| | | | |
|---|---|---|---|
| Total weight 4.81 kg | Projection | | |
| Part/Area/Group | FILTER/LISTA | Size A3 | Sheet 2/2 |
| Project/No./Name | Hot Bowl | | |

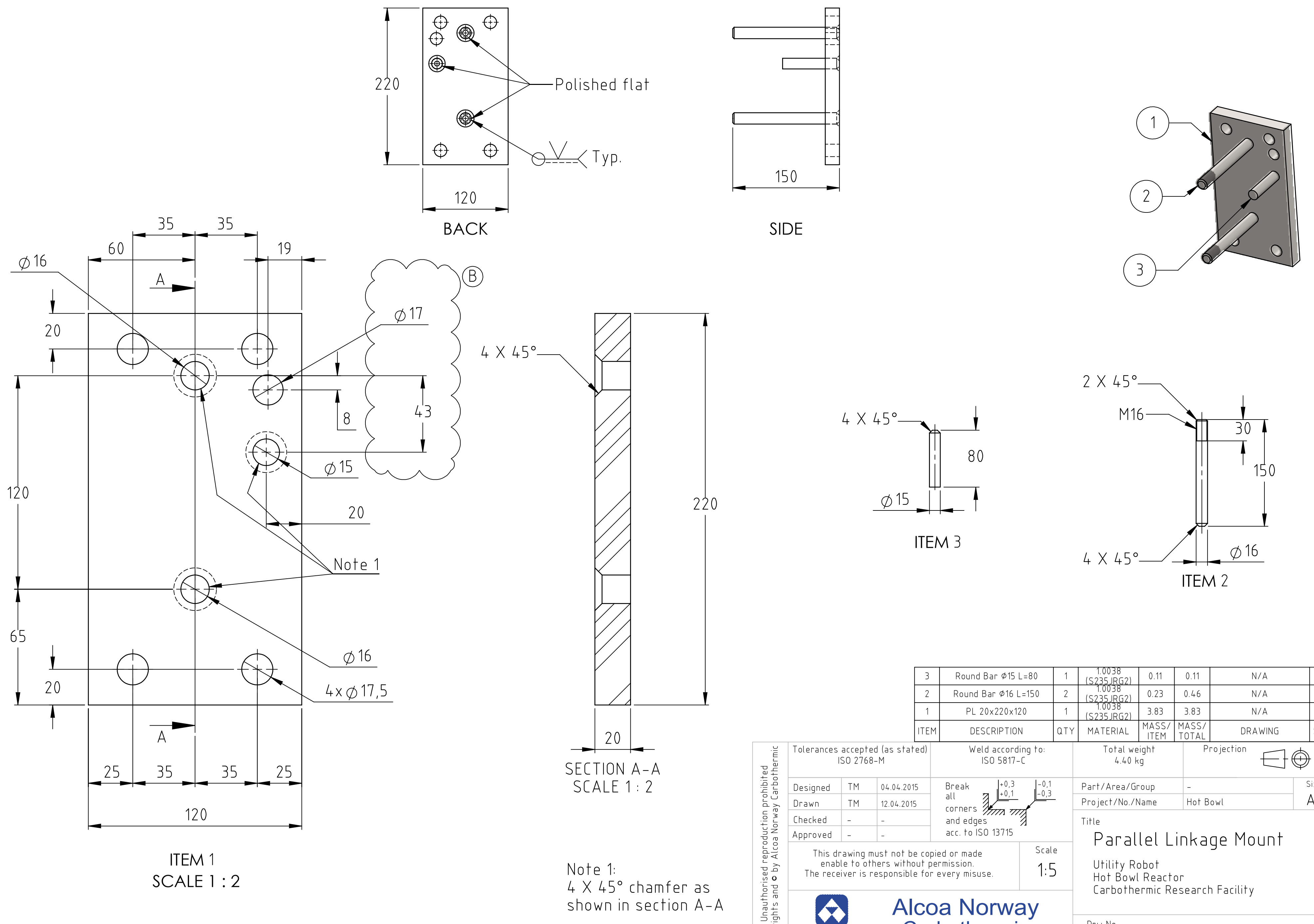
Title
Cylinder Mount
Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Drw No. Cylinder mount

Rev. A

Verify prior to construct - Do not scale

| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |
|---|---|---|---|---|---|
| B | Changed one dimension and one hole size | TM | - | - | 03.05.2015 |
| A | Issued For Construction | TM | - | - | 30.04.2015 |




Note 1:
4 X 45° chamfer as
shown in section A-A

| ITEM | DESCRIPTION | QTY | MATERIAL | MASS/ ITEM | MASS/ TOTAL | DRAWING | STANDARD | REV |
|---|---|---|---|---|---|---|---|---|
| 3 | Round Bar ⌀15 L=80 | 1 | 1.0038 (S235JRG2) | 0.11 | 0.11 | N/A | N/A | A |
| 2 | Round Bar ⌀16 L=150 | 2 | 1.0038 (S235JRG2) | 0.23 | 0.46 | N/A | N/A | A |
| 1 | PL 20x220x120 | 1 | 1.0038 (S235JRG2) | 3.83 | 3.83 | N/A | N/A | A |



Tolerances accepted (as stated) ISO 2768-M

Weld according to: ISO 5817-C

Total weight 4.40 kg

Projection

| | | |
|---|---|---|
| Designed | TM | 04.04.2015 |
| Drawn | TM | 12.04.2015 |
| Checked | - | - |
| Approved | - | - |

Break all corners and edges acc. to ISO 13715 (+0,3 +0,1 / -0,1 -0,3)

Part/Area/Group: -

Project/No./Name: Hot Bowl

Size: A3

Sheet: 1/1



Scale: 1:5

ALCOA

Alcoa Norway Carbothermic

Title

# Parallel Linkage Mount

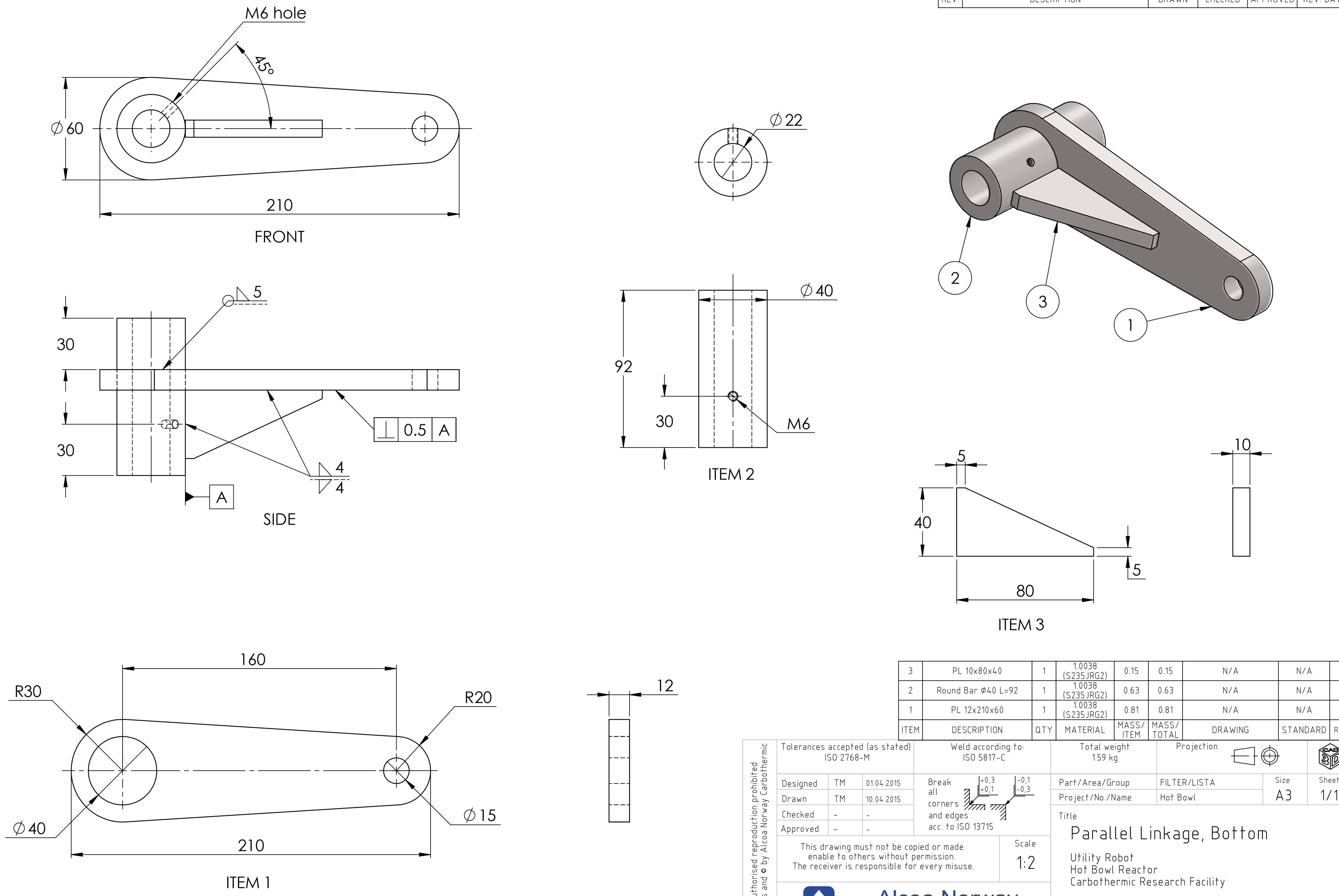
Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Drw No. Parallel linkage mount

Rev. B

Verify prior to construct - Do not scale

| A | Issued For Construction | TM | - | - | 29.04.2015 |
|---|---|---|---|---|---|
| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |




| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 3 | PL 10x80x40 | 1 | 1.0038 (S235JRG2) | 0.15 | 0.15 | N/A | N/A | A |
| 2 | Round Bar ∅40 L=92 | 1 | 1.0038 (S235JRG2) | 0.63 | 0.63 | N/A | N/A | A |
| 1 | PL 12x210x60 | 1 | 1.0038 (S235JRG2) | 0.81 | 0.81 | N/A | N/A | A |
| ITEM | DESCRIPTION | QTY | MATERIAL | MASS/ ITEM | MASS/ TOTAL | DRAWING | STANDARD | REV |



Tolerances accepted (as stated) ISO 2768-M

Weld according to: ISO 5817-C

Total weight 1.59 kg

Projection

| | | |
|---|---|---|
| Designed | TM | 01.04.2015 |
| Drawn | TM | 10.04.2015 |
| Checked | - | - |
| Approved | - | - |

Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1; -0,1 / -0,3)



Scale 1:2

Part/Area/Group: FILTER/LISTA

Project/No./Name: Hot Bowl

Size: A3

Sheet: 1/1

Title

# Parallel Linkage, Bottom

Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

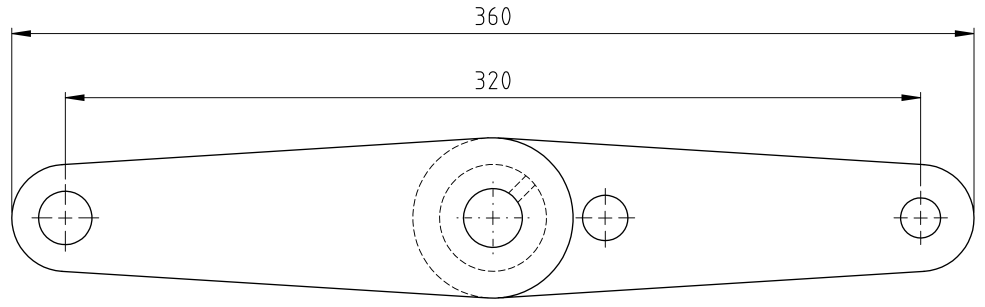
Alcoa Norway Carbothermic

Drw No. Parallel linkage 1

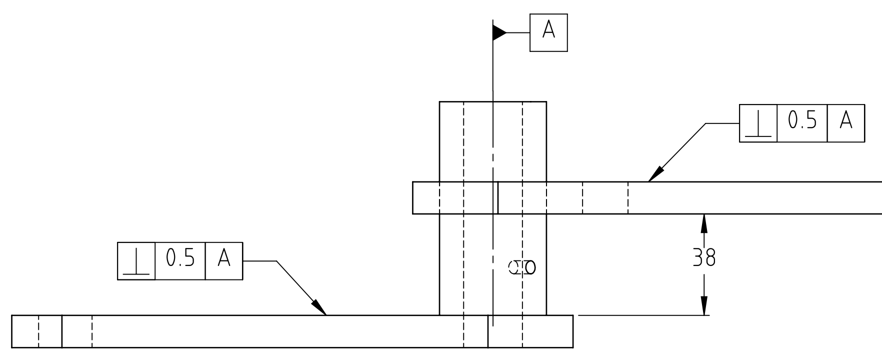
Rev. A

Verify prior to construct - Do not scale

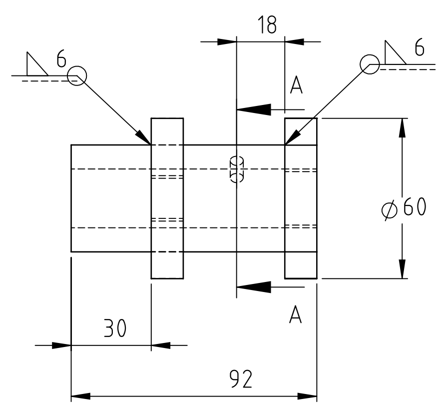
| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |
|---|---|---|---|---|---|
| A | Issued For Construction | TM | - | - | 29.04.2015 |



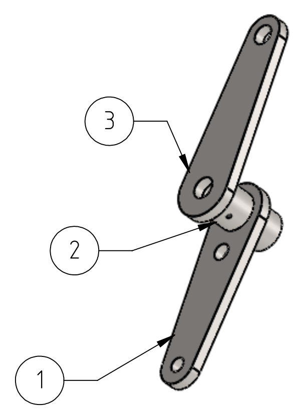
FRONT

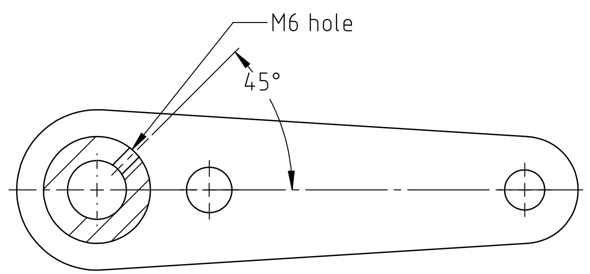


TOP



SIDE



SECTION A-A

| ITEM | DESCRIPTION | QTY | MATERIAL | MASS/ ITEM | MASS/ TOTAL | DRAWING | STANDARD | REV |
|---|---|---|---|---|---|---|---|---|
| 3 | PL 12x210x60 | 1 | 1.0038 (S235JRG2) | 0.88 | 0.88 | N/A | N/A | A |
| 2 | Round Bar ⌀40 L=80 | 1 | 1.0038 (S235JRG2) | 0.55 | 0.55 | N/A | N/A | A |
| 1 | PL 12x210x60 | 1 | 1.0038 (S235JRG2) | 0.79 | 0.79 | N/A | N/A | A |



Tolerances accepted (as stated) ISO 2768-M

Weld according to: ISO 5817-C

Total weight 2.09 kg

Projection

| | | |
|---|---|---|
| Designed | TM | 01.04.2015 |
| Drawn | TM | 10.04.2015 |
| Checked | - | - |
| Approved | - | - |

Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1; -0,1 / -0,3)



Scale 1:2

Part/Area/Group: -

Project/No./Name: Hot Bowl

Size: A3

Sheet: 1/2

ALCOA

Alcoa Norway Carbothermic

Title

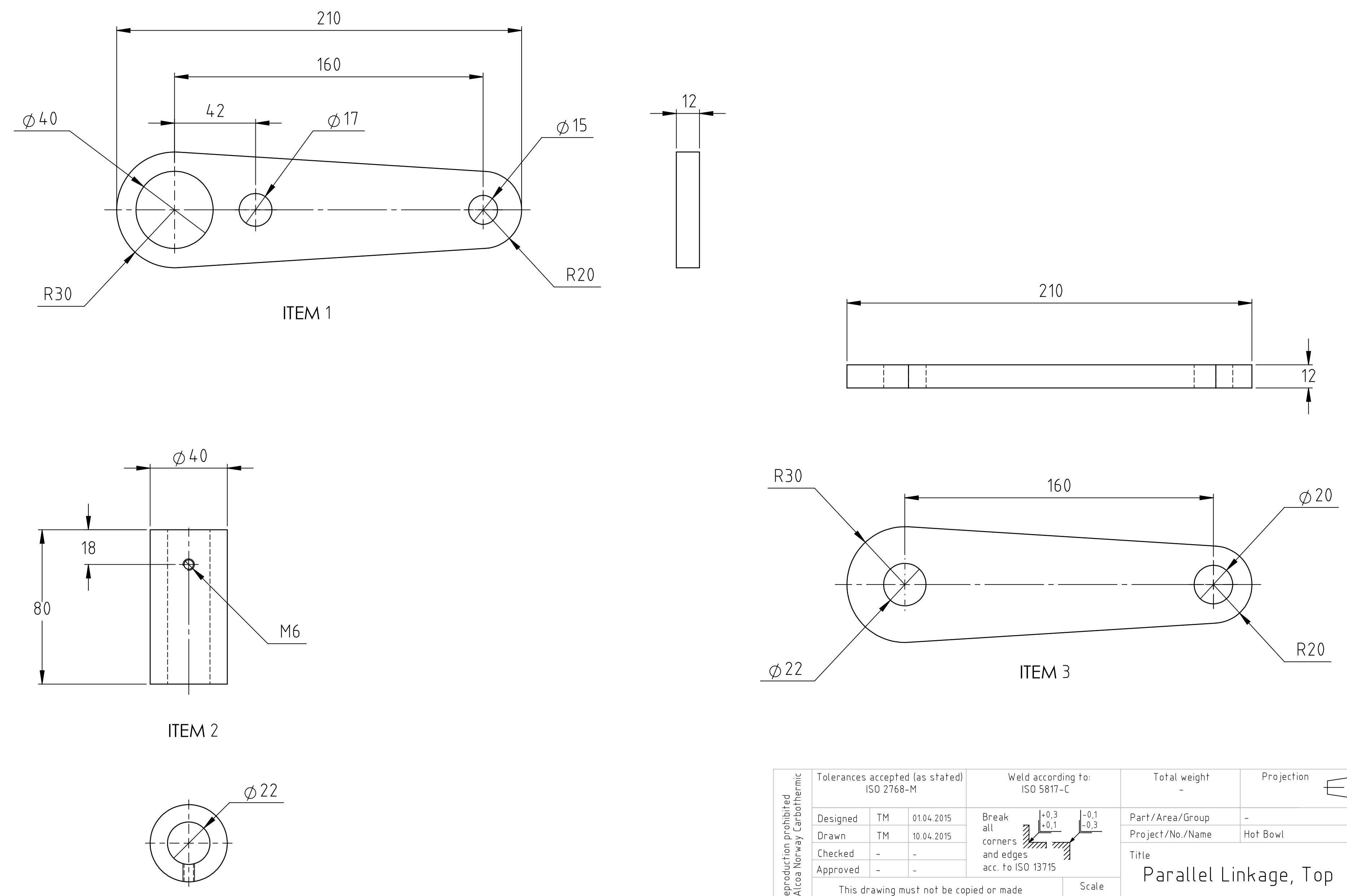
Parallel Linkage, Top

Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Drw No. Parallel linkage 2

Rev. A

Verify prior to construct - Do not scale






| | | | | |
|---|---|---|---|---|
| Tolerances accepted (as stated) ISO 2768-M | | | Weld according to: ISO 5817-C | Total weight - |
| Designed | TM | 01.04.2015 | Break all corners and edges acc. to ISO 13715 (+0,3 +0,1 / -0,1 -0,3) | Part/Area/Group: - |
| Drawn | TM | 10.04.2015 | | Project/No./Name: Hot Bowl |
| Checked | - | - | | |
| Approved | - | - | | |

Projection

Size: A3

Sheet: 2/2

This drawing must not be copied or made enable to others without permission.
The receiver is responsible for every misuse.

Scale: 1:2

ALCOA

Alcoa Norway Carbothermic

Title

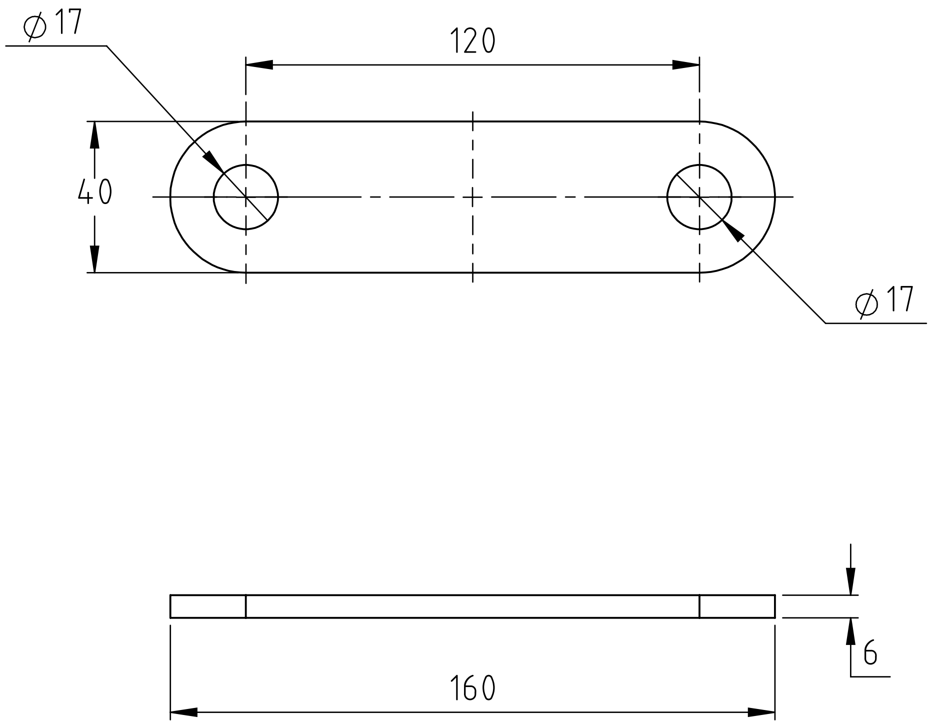
Parallel Linkage, Top

Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Drw No. Parallel linkage 2

Rev. A

| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |
|---|---|---|---|---|---|
| A | Issued For Construction | TM | - | - | 17.04.2015 |






Tolerances accepted (as stated)
ISO 2768-M

Material
1.0038 (S235JRG2)

Weight
0.26 kg

Projection

| | | |
|---|---|---|
| Designed | TM | 10.03.2015 |
| Drawn | TM | 25.03.2015 |
| Checked | - | - |
| Approved | - | - |

Break all corners and edges acc. to ISO 13715
+0,3 +0,1
-0,1 -0,3

| | | Size | Sheet |
|---|---|---|---|
| Part/Area/Group | - | A4 | 1/1 |
| Project/No./Name | - | | |



Scale
1:2

Title
Detail

Utility Robot
Hot Bowl Reactor
Carbothermic Research Facility

Alcoa Norway
Carbothermic

Drw No. Washer__alternative

Rev. A

# Appendix D

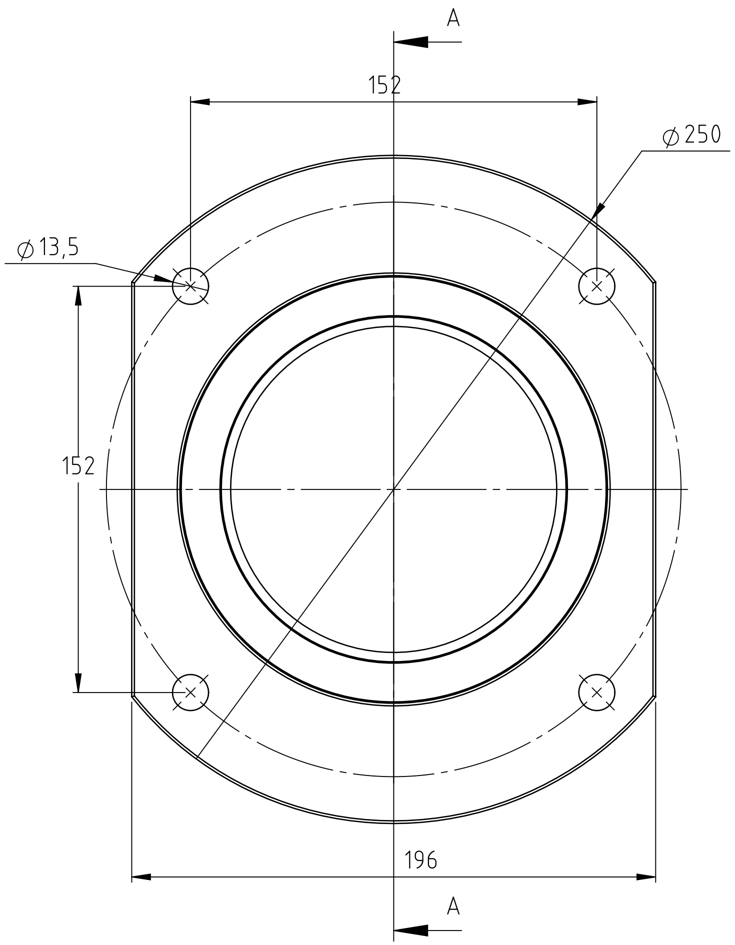
# Relevant Technical Drawings from the HEX Utility Robot

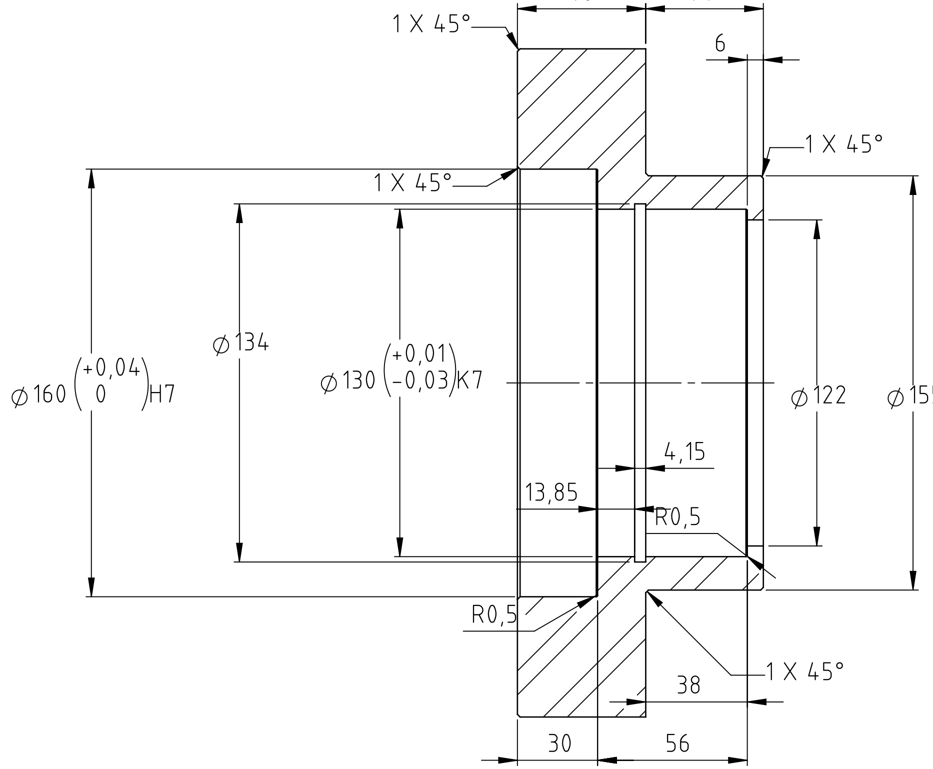
This appendix contains technical drawings of parts from the HEX utility robot that is re-used on the Hot Bowl utility robot. Table D.1 shows relevant information of the drawings, in the same way as for Appendix C.

Table D.1: Technical drawings of re-used components from the HEX utility robot

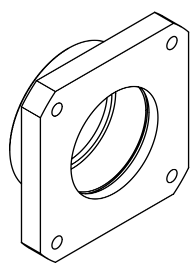
| No. | Drawing number | Description | Sheets | Level | Parent drawing title |
|---|---|---|---|---|---|
| 1 | HEX-XX-0506 | Upper shaft bearing housing, motor side | 1 | 1 | Elevator |
| 2 | HEX-XX-0507 | Upper shaft sprocket | 1 | 1 | Elevator |
| 3 | HEX-XX-0526 | Upper shaft bearing housing | 1 | 1 | Elevator |

Verify prior to construction - Do not scale




SECTION A-A



Material: S235JRG2

| A | Issued For Construction | LZ | - | - | 20.07.2012 |
|---|---|---|---|---|---|
| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |



Tolerances accepted (as stated) ISO 2768-M

Material: Alloy Steel

Weight: 7.6 kg

Projection

| | | |
|---|---|---|
| Designed | LZ | 20/06/2012 |
| Drawn | LZ | 20/07/2012 |
| Checked | - | - |
| Approved | - | - |

Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1; -0,1 / -0,3)

Part/Area/Group: SOUNDING ROBOT

Project/No./Name: HEX REACTOR

Size: A3

Sheet: 1/1



Scale: 1:2

ALCOA

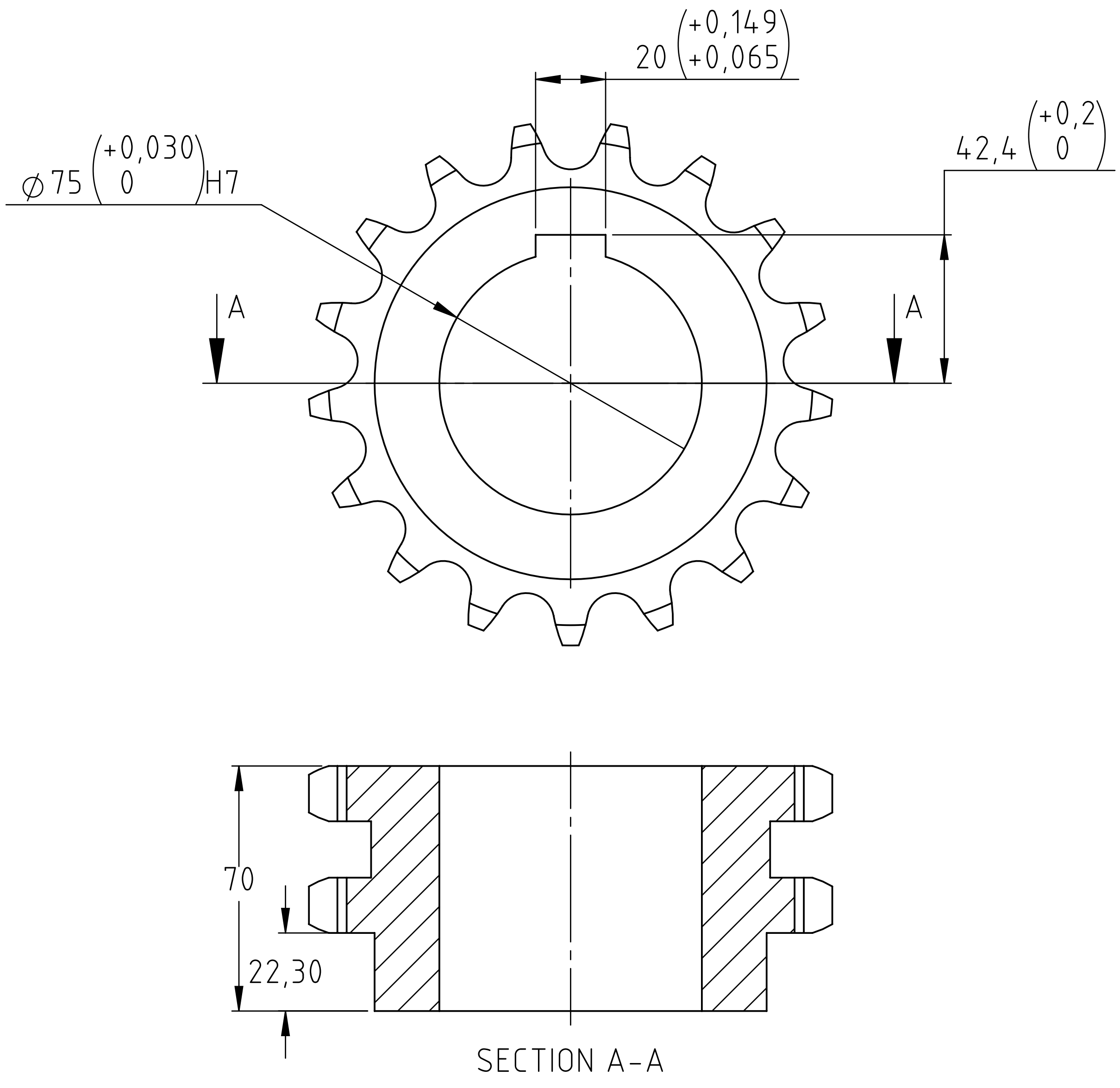
Alcoa Norway Carbothermic

Title: Distancer

Sounding Robot
HEX Reactor
Carbothermic Research Facility

Drw No. HEX-XX-0506

Rev. A+




Notes:

1. Sproket: SlettebØe art. no.16B-317
2. To be maskined out from Triplex chain wheel

| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |
|---|---|---|---|---|---|
| A | Issued For Construction | LZ | - | - | 20.07.2012 |



Tolerances accepted (as stated)
ISO 2768-M

Material: S235

Weight: 4.0 kg

Projection

| | | |
|---|---|---|
| Designed | LZ | 20/06/2012 |
| Drawn | LZ | 20/07/2012 |
| Checked | - | - |
| Approved | - | - |

Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1) (-0,1 / -0,3)

| | | Size | Sheet |
|---|---|---|---|
| Part/Area/Group | SOUNDING ROBOT | A4 | 1/1 |
| Project/No./Name | HEX REACTOR | | |



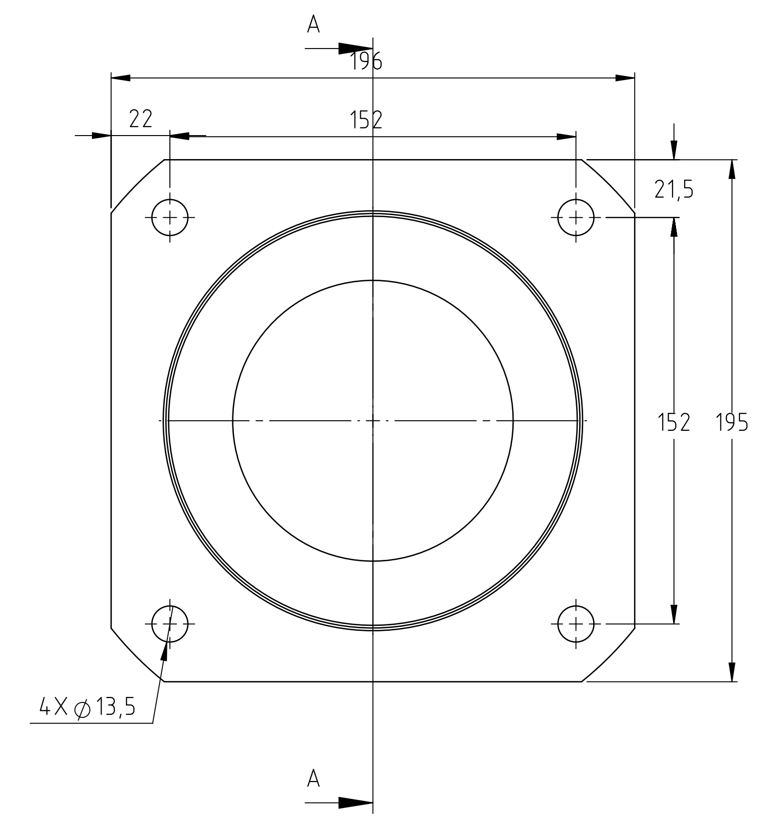
Scale 1:2

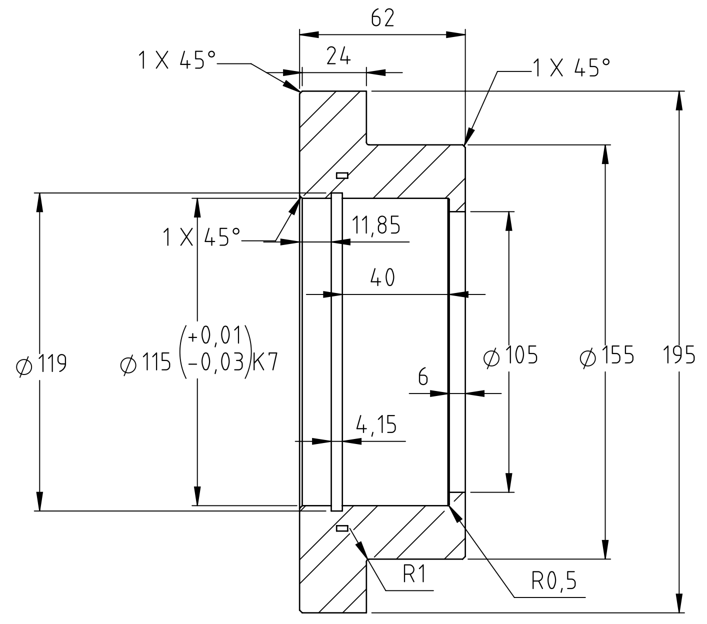
Title
## Lower Sproket
Sounding Robot
HEX Reactor
Carbothermic Research Facility

ALCOA
Alcoa Norway Carbothermic

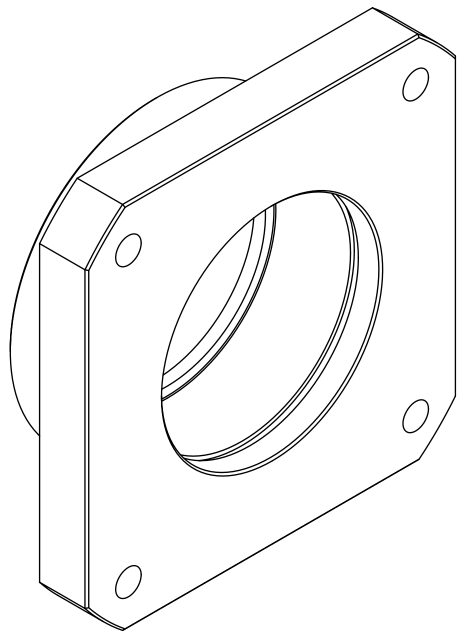
Drw No. HEX-XX-0507

Rev. A+




SECTION A-A



Notes:

1. Material: St50-2

| REV. | DESCRIPTION | DRAWN | CHECKED | APPROVED | REV. DATE |
|---|---|---|---|---|---|
| A | Issued For Construction | LZ | - | - | 25.07.2012 |

| | | | | | |
|---|---|---|---|---|---|
| Tolerances accepted (as stated) ISO 2768-M | | Material Alloy Steel | Weight 7.6 kg | Projection | |
| Designed | LZ | 24/07/2012 | Part/Area/Group | SOUNDING ROBOT | Size A3 |
| Drawn | LZ | 25/07/2012 | Project/No./Name | HEX REACTOR | Sheet 1/1 |
| Checked | - | - | | | |
| Approved | - | - | | | |

Break all corners and edges acc. to ISO 13715 (+0,3 / +0,1; -0,1 / -0,3)

This drawing must not be copied or made enable to others without permission.
The receiver is responsible for every misuse.

Scale 1:2

Title
# Bearing House

Sounding Robot
HEX Reactor
Carbothermic Research Facility

ALCOA
Alcoa Norway Carbothermic

Drw No. HEX-XX-0526

Rev. A+