Device to Reconfigure Wind Tunnel Floor

Final Report

April 18, 2006
ME 450
Winter 2006 Term

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Table of Contents

Table of Figures

Abstract

Behr America, Inc. currently operates a climatic wind tunnel that requires frequent reconfiguration of steel floor plates for vehicles of different wheelbases. Our project is to create a new system to accomplish this task in a safer and faster manner. The final design will be constructed and implemented at Behr's facility in Troy, Michigan.

Executive Summary

Behr America, Inc. operates a climatic wind tunnel than can test a wide range of vehicles. Its twin dynos can be adjusted for various wheel base configurations (from front wheel drive cars to tandem axle Class 8 trucks). A series of heavy steel plates are used to fill in the portions of the floor where the dyno rolls move. The floor must be reconfigured for each wheelbase.

This is currently accomplished by removing the plates with a small A-frame device. On this device, a cable is connected between a winch and a lifting magnet. This device can only lift one floor plate at a time, and each plate must be removed and placed out of the way of the dyno rolls. This process is very time consuming and dangerous to the technicians operating the device.

Through analysis of the customer requirements, we created a concept (Fig. 1, below) that would make the floor reconfiguration process quicker and safer. We chose pneumatic springs (air bags) to raise and lower the three lifting bars, on which electronically controlled permanent magnets are attached.

Our final design (Fig. 2, below) improved on this concept by doubling the number of magnets grabbing each plate. To validate our design, we used FEA to determine that the frame of the device will withstand the required loading. We performed calculations to test the stability of the device, as well as to ensure its safe reaction to certain component failures.

Behr is fabricating this device to our specifications, and should be completed in late April. Its total cost is over $17,000. However, the amount of time saved with this new device will reduce downtime in the wind tunnel and allow Behr to quickly recoup the initial cost.

Fig. 1 – Alpha Design

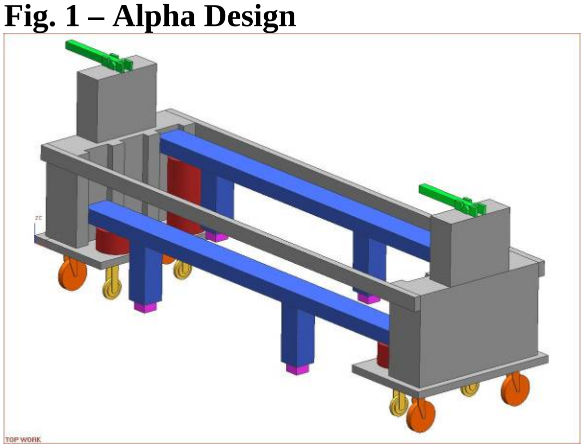
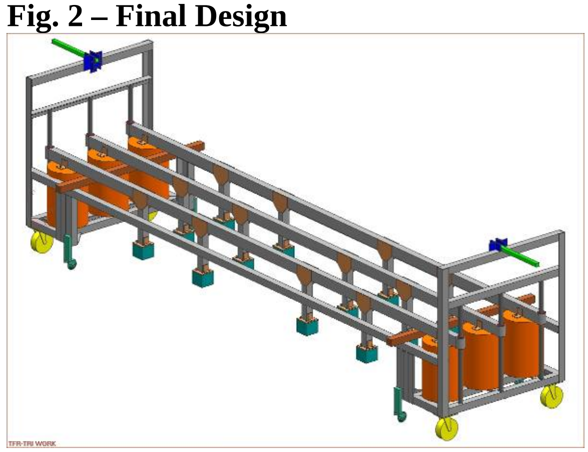


Fig. 2 – Final Design

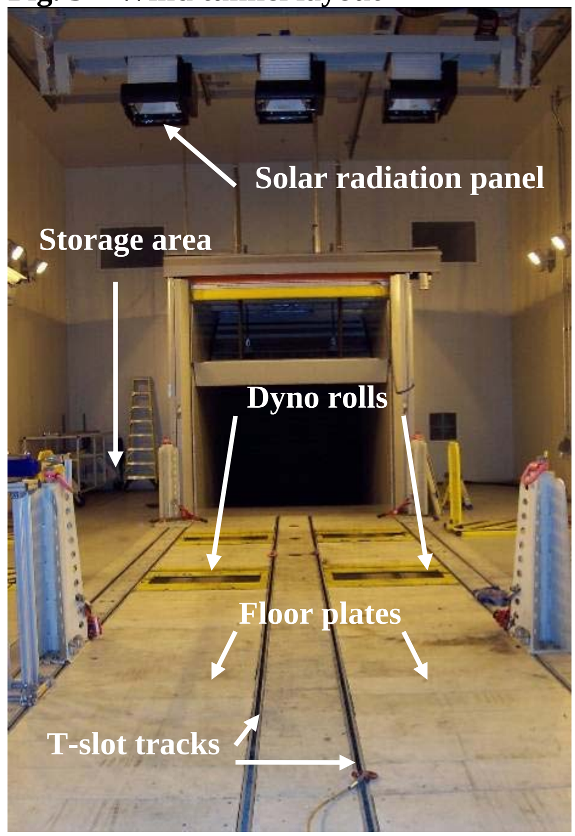


Project Overview

Problem Description

Behr America, Inc. is a company that specializes in designing and producing automotive HVAC and engine cooling components. In their technical center in Troy, Michigan, they have the most advanced wind tunnel in North America. In this wind tunnel they test their products on multiple types of vehicles. The setup of this wind tunnel includes reconfigurable floor plates (Fig. 3, right) which need to be rearranged frequently to account for vehicles with different wheelbases. Currently, they use an apparatus that lifts these heavy steel floor plates individually. During this operation, large openings are left in the floor, which is a safety hazard. Behr wants a device that can lift multiple plates, reduce hand-aligning of the plates, and provide increased safety to both the operators and the wind tunnel equipment. We plan to accomplish this by creating a new apparatus for moving these floor plates. If successful, this device will reduce the turnover time of the wind tunnel, saving money. It will also safeguard valuable equipment and ensure personnel safety.

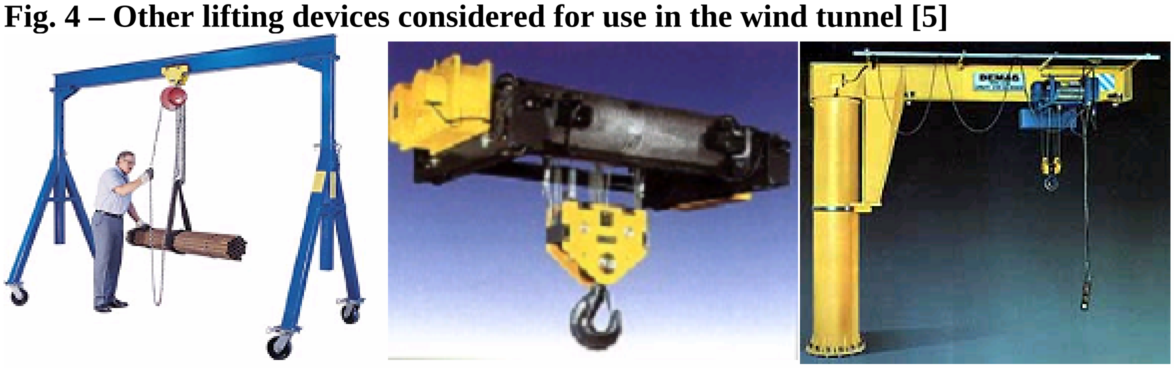
Fig. 3 – Wind tunnel layout



Information Sources

Due to the uniqueness of this project, we were unable to find any wind tunnel floor related information online or in patent documents. However, we have found several designs for similar lifting applications, shown in Fig. 4 below. Many devices are similar to the current systems (Fig. 5 and Fig. 6, page 6), and would provide no improvement. Also, the use of overhead devices is not possible due to the solar radiation panels on the ceiling of the wind tunnel (see Fig. 3, above).

Fig. 4 – Other lifting devices considered for use in the wind tunnel [5]



We have worked with our sponsors to gather as much information as possible about our project. We received a pamphlet that describes the environmental conditions of the wind tunnel, dimensional information relating to the floor layout, and specifics for the steel plates that will be lifted (see Appendix E, page 44). We have also been provided with photographs of the project area and the existing devices.

This information was provided by Behr America, Inc. employees that we have both spoken to and met with:

- Fred Pumper, Wind Tunnel Manager [3]
- Vincent Ursini, Manager, PTC & Wind Tunnel Test [6]
- Philip Stephenson, Chief Engineer – Validation [4]

Current A-frame System (CAS)

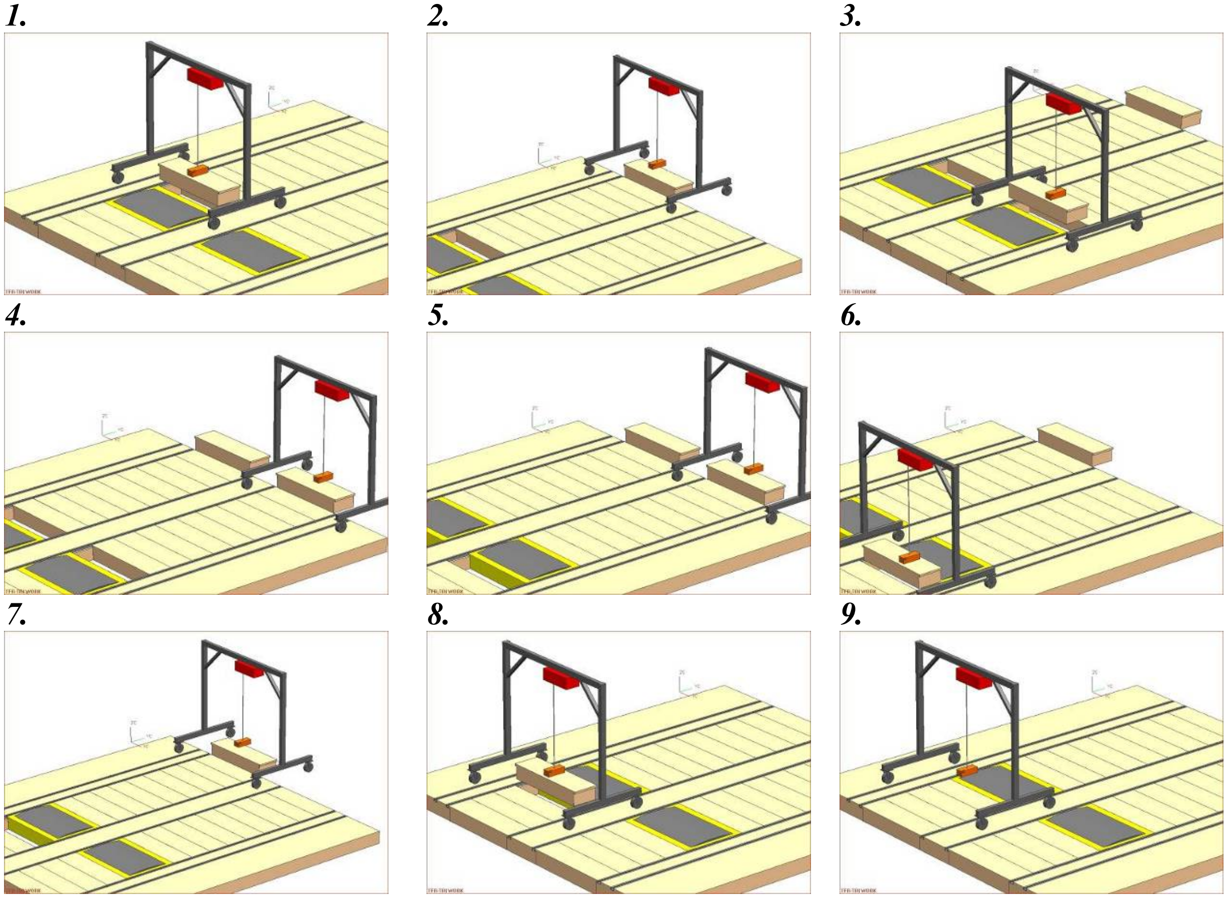
The current system, shown in Fig. 5 (below), has several limitations and shortcomings. It only lifts one plate at a time. Since the dyno rolls move as pairs (per axle), plates must be stacked off to the side, while openings are made larger on both sides. This is very time consuming. This system's small size makes it very maneuverable. However, it doesn't have an aligning device, giving it the potential to fall through the open floor. Also, due to this small size, one of the two operators must stand on the small area between the two plates. This lack of footing is a falling hazard. This device uses a motorized winch to lift the plates, which are grabbed by a magnet attached to the end of the cable. This requires the plates to be hand-aligned as they are lowered, which is a crushing and pinching hazard.

Fig. 7 on page 7 shows the procedure that Behr currently uses with the A-frame device to reconfigure the floor plates. The device is positioned above each plate that needs to be moved. The technicians then lower the magnet with the winch, engage the magnet by hand, and then lift the magnet and floor plate using the winch. This procedure is repeated for as many plates that need to be moved, with each plate needing to be stacked out of the path of the dyno rolls.

Fig. 5 – Current A-frame System

Fig. 6 – Scrapped Manufacturer's Design

Fig. 7 – Current A-Frame System operation



Scrapped Manufacturer's Design (SMD)

Behr possesses a second lifting device (Fig. 6 on page 6) which is currently not in use. It is bulky and over-designed, because the manufacturer more than likely did not want to be liable for a structural failure. Its features include the ability to lift two plates at a time (one per side), and two sets of pins to keep the device aligned over the floor opening. However, this aligning device binds frequently due to imperfections in the T-slot tracks. The pins prevent the casters from rotating 360 degrees, making the device very un-maneuverable. Also, this device does not have enough ground clearance to allow movement over vertically stacked plates. This device has a screw lifting system. It is slow lifting the plates, but it does reduce the hand-alignment needed to properly position the plates. It also uses a magnet for grabbing the plates.

Customer Requirements

We determined the customer requirements based on all gathered information on suggested improvements to the two current plate lifting devices. These customer requirements were used to develop the engineering specifications. This was done with the aid of a Quality Function Development (QFD) chart, shown in Appendix B on page 38.

Decreasing the floor turnover time is a key customer requirement. To accomplish this, the device must be able to lift multiple plates at the same time. However, it needs to have the flexibility to lift different numbers and sizes of plates. The ability to stack plates is also important. To maneuver around the wind tunnel floor, the device should be able to move and rotate in any direction, but then be locked into moving only forward or backward while lifting.

Ensuring the safety of the technicians and equipment is a major concern for our design. Eliminating the need for the operator to stand in the center is extremely important. The system for lifting the plates must be fail safe; the plates should not drop in the case of equipment or power failure. An aligning mechanism is necessary to prevent the device from physically falling into the floor opening. Improvements to the current system should also eliminate hand-aligning of the steel plates to reduce the pinching or crushing hazard. Conditions in the wind tunnel require that the new device be resistant to a wide temperature and humidity range.

Initially, we had several other customer requirements to consider. However, after discussion with Behr, they were determined to be less important than the above requirements. They include:

- The use of only one operator during the reconfiguration of the floor panels
- An automatic traversal (along the length of the floor) system
- The 200 kg unloaded weight limit proved to be too small, and was raised to 500 kg.
- The $3,000 projected cost was determined to be much too low of an estimate.

Engineering Specifications

Customer requirements are qualitative properties. To create a design, quantitative engineering specifications are needed. We used a QFD chart to relate the two. Inputs into this analytical tool include a relative weighting of the customer requirements determined during our sponsor meetings. Other inputs include engineering judgment to relate the specifications and decide whether they correlate in a negative or positive way. Outputs of the QFD consider these weights and relations, and are in the form of importance ratings.

We have decomposed these engineering specifications into categories. In these categories, the specifications are ordered by importance and have a numerical benchmark. Table 1 below lists specifications for time, capacity, and environment, while Table 2 lists specifications pertaining to operation and safety.

Table 1 – Engineering Specifications for time, capacity, and environment

	Target Value
Time to switch from Class 8 truck to FWD car configuration	
This is the benchmark we will use to measure improvement over the current design's operation time of 1.5 to 2 hours.	*1 hour*
Lifting capacity based on maximum number of plates lifted	
The structural limits of the device and the magnets must not be exceeded to ensure the safe movement of the plates. Permanent magnets are required to prevent dropping plates in the event of power loss. However, remotely actuated (by solenoid) permanent magnets are preferable (hand-operated ones would be difficult to reach). The magnets also need to be small enough to pick up the small plates (see Appendix E, page 44) without accidentally grabbing the nearby plates (3"x5" is the maximum footprint).	*500 kg*

Device weight It has an impact on its maneuverability and the number of operators required.	*less than 500 kg*
Plate lifting time We want to minimize the time lifting the plates while maintaining control.	*5 sec*
Temperature & humidity range To be stored in the wind tunnel it must withstand the conditions inside.	*-30 to 50 ºC 0 – 95 %*

Table 2 – Engineering Specifications for operation and safety

	Target Value
Ease of movement over floor The casters and push bars need to be sized to meet this target. The casters must also be able to rotate in all directions.	*moved by 2 people when loaded*
Number of plates lifted A device that picks up multiple plates is desired because it has the potential to lower the floor turnover time. However, Behr also wants us to limit the open floor space in which an operator can fall through.	*6 plates*
Number of control inputs required One operator must be able to work all the controls. We anticipate three lifting, six magnet, and one aligning controls.	*10 controls*
Device size Smaller devices are more maneuverable, but have lower lifting capacities. A smaller device is easier to store in the storage area (Fig. 3 on page 5).	*not larger than the SMD*
Number of operators To reduce interference from the safety harnesses, the operators need to be stationed on each side of the track, not in the middle.	*2 operators*
Ground clearance of machine with lifted plates We want to be able to stack two plates vertically, or allow the device to be pushed over a plate sitting on the ground.	*at least 25 cm*

Concept Generation

We used the customer requirements and engineering specifications as a basis for our concept generation. Our team strategy was to individually draft concepts to not inhibit each other's creativity and ingenuity. Each team member was required to sketch at least four concepts and afterwards the group reviewed the drawings. All sketches are attached in Appendix D (page 40).

During the first meeting with our sponsor, they suggested that an option was to redesign their existing unused device to better suit it for their needs. However, they did not want to limit us to that device, as an entirely new device could be constructed as well. This led us to generate two main concept classifications: a modification of the scrapped manufacturer's design (SMD) or a completely new system. Our five main concepts include two independent modifications to the SMD and three completely new designs.

Concept 1: SMD Redesign 1

This improvement (Fig. 8 on page 10) to the SMD would address the problems that Behr was having with pushing the device over possible floor obstructions, and with binding of the alignment pins in the T-slot tracks. This device would use existing structures to stay aligned and automatically traverse the tunnel. Another concern addressed is the safety of the operator. This concept allows one user to operate the machine without crossing the floor opening.

Fig. 8 – Concept 1

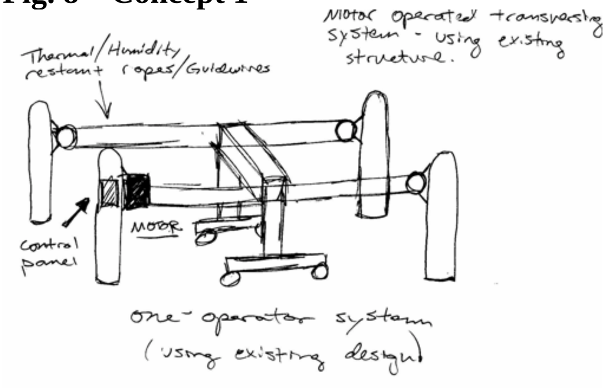
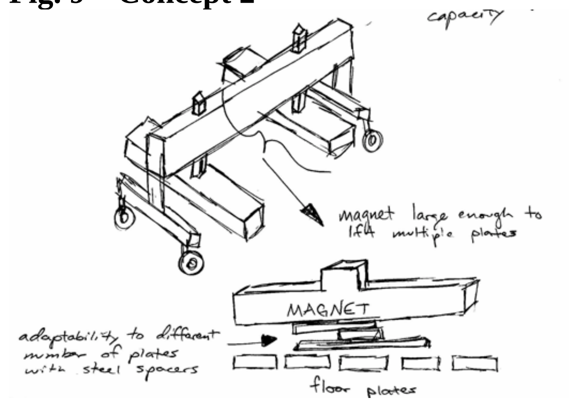


Fig. 9 – Concept 2



Concept 2: SMD Redesign 2

Another issue that our sponsor had with the unused SMD device was the limitation of only lifting two plates (one per side) at a time. This concept (Fig. 9 above) would allow for a larger magnet to be used to lift multiple plates on each side of the track, speeding up the process. It is similar to the SMD, but with larger and more powerful magnets to accommodate lifting more plates.

Concept 3: New Design 1

A completely different idea was to lift the plates up, and then set them back down on elevated rails, shown in Fig. 10 below. They then could be wheeled above the dyno rolls to their new position. This idea was meant to compliment (not replace) an existing or a new lifting device.

Fig. 10 – Concept 3

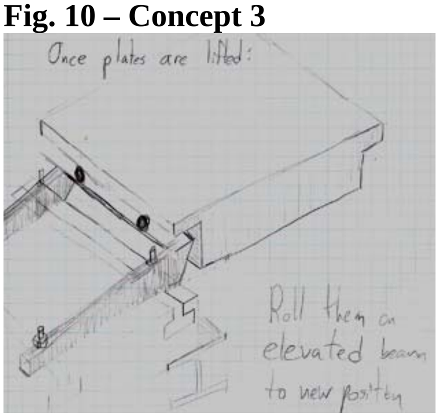
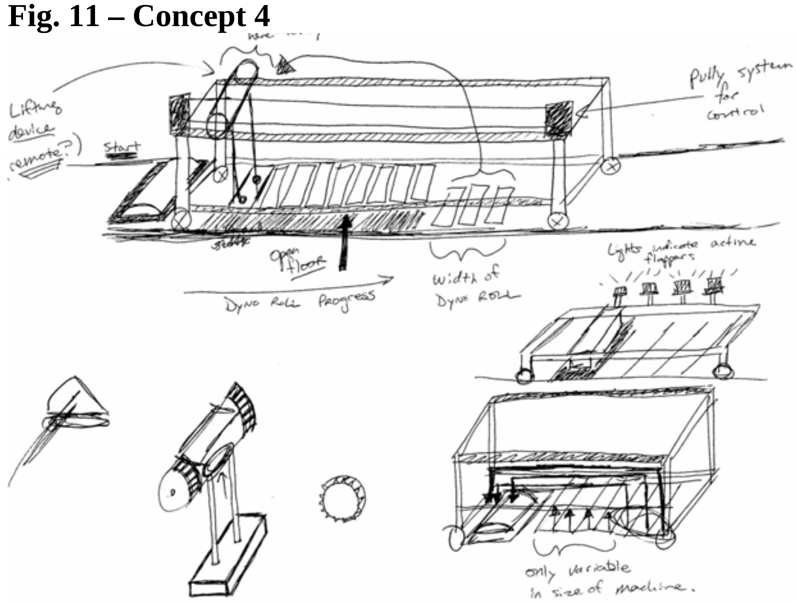


Fig. 11 – Concept 4



Concept 4: New Design 2

This concept (Fig. 11 on page 10) was designed to eliminate problems that the technicians had when they stack the plates to clear the path for the rolling of the dyno. This concept encompasses all stacking within the device. This concept was also designed to eliminate movement of the device with the extra weight of the lifted plates. The arm on the top structure of this design would mechanically lift and move plates. The procedure of this device is shown in the drawing. The plates would be lifted and held to allow movement of the dyno rolls under them. The lifting arm would then move plates at the opposite end of the device to clear a space for the dyno rolls. The entire floor opening would be enclosed during the reconfiguration of the floor. It would be remotely operated by one person.

Concept 5: New Design 3

This concept (Fig. 12 and Fig. 13 below) was created using feedback from our sponsor on previous concepts. Unlike Concept 2, it is able to lift multiple plates without one large magnet. The basis for this design is a large inner structure that the magnets would be mounted on. This structure would be lifted by a group of hydraulic or pneumatic cylinders. Once raised, the system would be moved to a new position and dyno rolls would move underneath. The sketch shows three magnets on each side of the track mounted on the rectangular inner structure. This structure would slide vertically on a base, which would be resting on swivel casters.

This concept is designed to lower the magnets to the plates, engage the magnets, and then lift the inner structure with the plates attached. Alignment would come from a 'train wheel' system that would be engaged and would roll in the existing T-slot track on the wind tunnel floor (see Fig. 13 below). All magnets would be remotely operated, along with the lifting cylinder system. This device still requires two operators to push the machine due to the weight of multiple plates.

Fig. 12 – Concept 5, several views

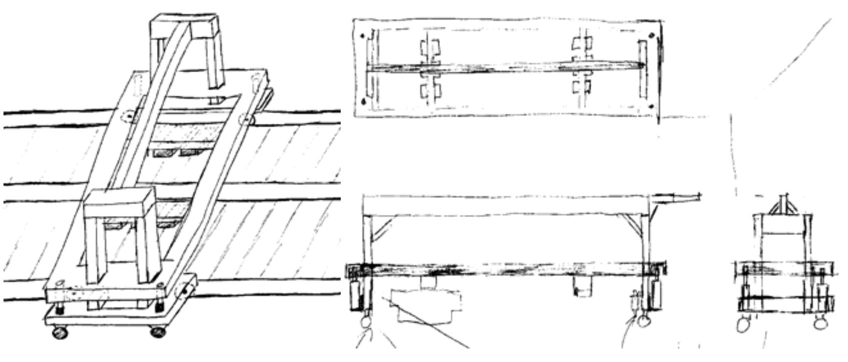
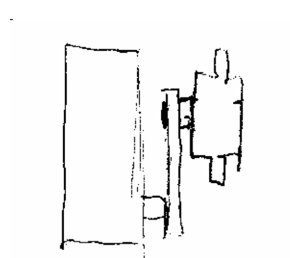


Fig. 13 – Alignment wheel



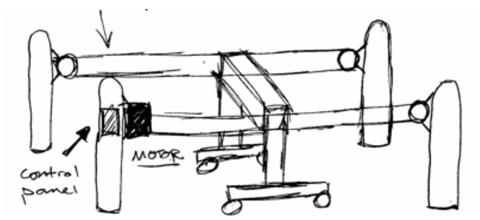
Concept Selection Process

In our initial meeting, our sponsor expressed that, in the past, the more input they gave to the student teams during the design process, the more useful the final product was to them. Considering that we have never seen the floor plate reconfiguration firsthand, we used the sponsor's responses over any type of concept scoring matrix.

During the course of concept generation we had two meetings with our sponsor. During the first we presented them Concepts 1 through 4. They told us which designs showed promise and which did not. The specific responses are listed in Table 3 below under Sponsor Comments. We proceeded to edit and improve upon these concepts with our better understanding of their requirements. Our new concept (Concept 5) was reviewed in our second concept review meeting. Comments about it are also listed in Table 3.

Table 3 – Concept Advantages, Disadvantages, and Sponsor Comments

Concept 1 – SMD Traversal Design



Advantages

This concept would use existing structures in the wind tunnel to properly align the SMD device and eliminate the current binding problems. Re-use of the current device would reduce cost. Safety would be improved due to the closing off of the opening by the cables. Motorized operation would only require one operator.

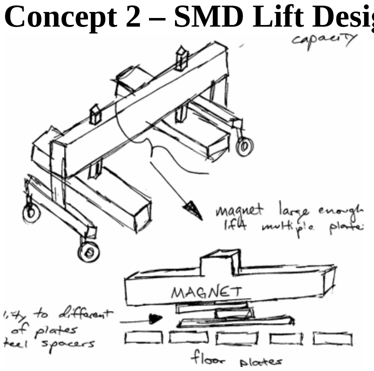
Disadvantages

The pulley system would limit the available space for other testing equipment. The cables would have to be mounted prior to reconfiguration of the floor, lengthening the procedure.

Sponsor Comments

It was found to be unfeasible due to the lack of space required for the pulley system.

Concept 2 – SMD Lift Design



Advantages

This concept would have larger magnets to lift multiple plates on each side of the track. It would use an alignment wheel system. Re-use of the SMD would reduce cost.

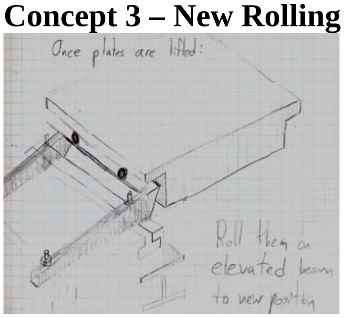
Disadvantages

This concept does not reduce the number of operators, nor does it prevent large floor openings. A major limitation of the concept would be the ability to lift an amount of plates less than the maximum capacity of the device.

Sponsor Comments

They liked the ability to lift multiple plates and the small size of the design.

Concept 3 – New Rolling Device



Advantages

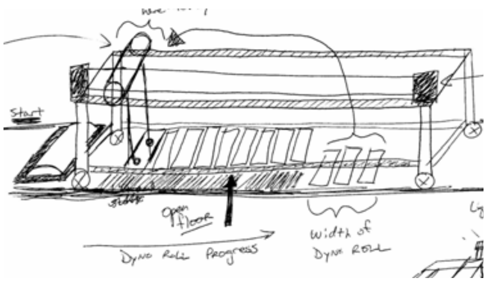
It would leave a very small opening to fall through. The dynos could travel a long distance at once. It would also compliment (not replace) existing lifting systems.

Disadvantages

We are unsure as how the device would be assembled and put under the plates. Storage of the additional parts would also be a problem.

Sponsor Comments
It was too complicated and we decided not to pursue it.

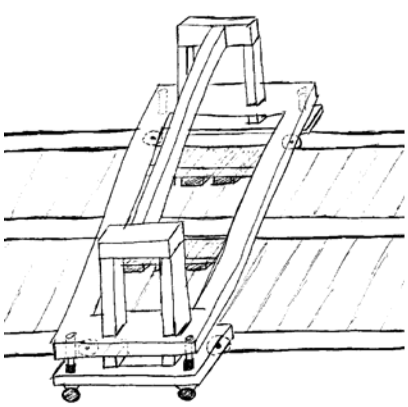
Concept 4 – New Storage Device



Advantages
All floor openings would be enclosed with this concept. It would require no movement of the device while plates were lifted. It would reduce the number of operators to one.
Disadvantages
The large size of this concept may interfere with other testing equipment still on the floor from vehicle testing. The increased complexity of the device may also be more expensive.

Sponsor Comments
The Behr technicians liked this concept and its improvements to the process. However, they were concerned that it was too large for to fit in the storage space, and that obstructions on the wind tunnel floor would make it difficult to maneuver.

Concept 5 – New Lifting Device



Advantages
This concept would be able to lift multiple plates with more stability than a cable operated system. Magnets would be remotely operated allowing different numbers of plates to be lifted. It is small enough to store in the wind tunnel and maneuver around possible obstacles.
Disadvantages
This system may be expensive due to not re-using the SMD device. This concept would also require two operators to push the device with loaded plates. Limitations in individually lifting and setting down plates may prove to be a problem in everyday use.

Sponsor Comments
The technicians and the wind tunnel manager expressed that problems would be encountered when lifting the smaller plates, a concern that was not apparent to us in the concept generation stage. Another problem is that the plates might need to be shuffled into a different order on the floor. This concept does not allow for that.

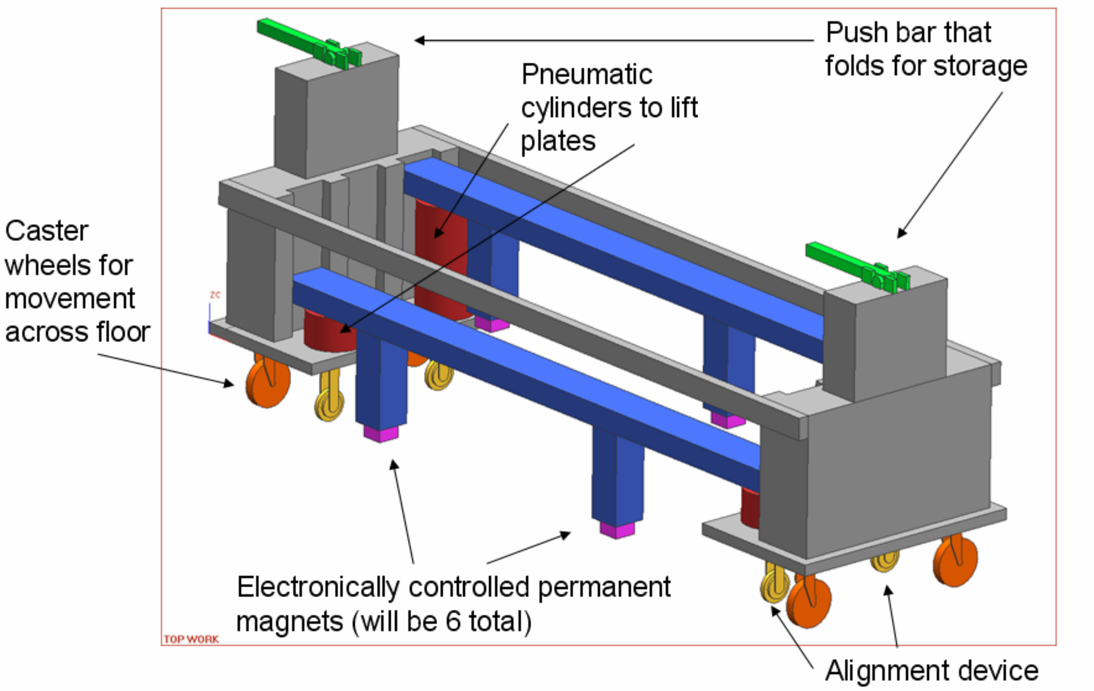
Selected Concept Description

After selecting Concept 5 as our best overall concept and reviewing it with Behr, we created our Alpha Design. It includes suggestions from both the engineers and the operating technicians and addresses their concerns with Concept 5.

This design uses a base similar to the existing SMD, and consists of casters and an alignment system to keep the device square with the T-slot tracks (Fig. 3 on page 5). The caster wheels will be selected to properly support the maximum weight. The alignment wheels will be based off of the idea in Concept 5 (Fig. 13 on page 11). We intend to either purchase or fabricate these wheels. For movement of the device, there are folding push bars for the technicians to push the device with ease.

The lifting of the plates will be done in pairs, as opposed to the connected lifting in Concept 5. The individual lifting will bring the total number of cylinders required to six (two for each bar), but will significantly reduce the weight required to be lifted by each of them. We intend to mount the individual lifting bars in tracks within the main base of our device. These tracks will be fitted with a bearing or sleeve allowing them to slide vertically during the lifting process, providing additional support to the cylinder system.

Fig. 14 – Alpha Design (omitting center lifting device)



We wish to use the smallest magnet possible to lift a large floor plate, while maintaining a proper safety factor. We will look for magnets with a small surface area, with a lifting capacity of 77 kg (plus a safety factor). If smaller magnets can be purchased, we may use a system of two magnets for each size plates, shown in Fig. 16 (on page 15). Remote electrical operation of the magnets is a high priority. The cylinder lifting system will be pneumatic or hydraulic, depending on which will fit our system best. Behr has 100 psi shop air available in the wind tunnel for use if needed.

There are several issues that must be addressed when designing the placement of our caster wheels. First, the casters must be able to support a total approximate weight of 9,800 N (2,200 lbs). Behr also was concerned about lifting plates near the ends of the tunnel. They are obstructed by the posts used to restrain test vehicles. We need to be able to lift these plates without problem. Fig. 15 on page 15 attempts to address this by placing the casters inboard of the two outside lifting bars.

Fig. 15 – Alpha Design, Sketch #1

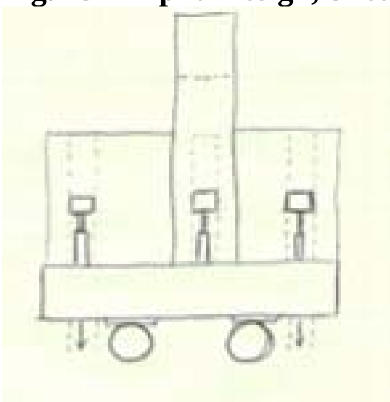


Fig. 16 – Alpha Design, Sketch #2

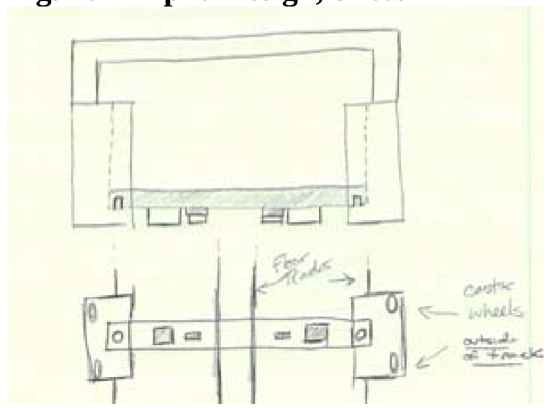
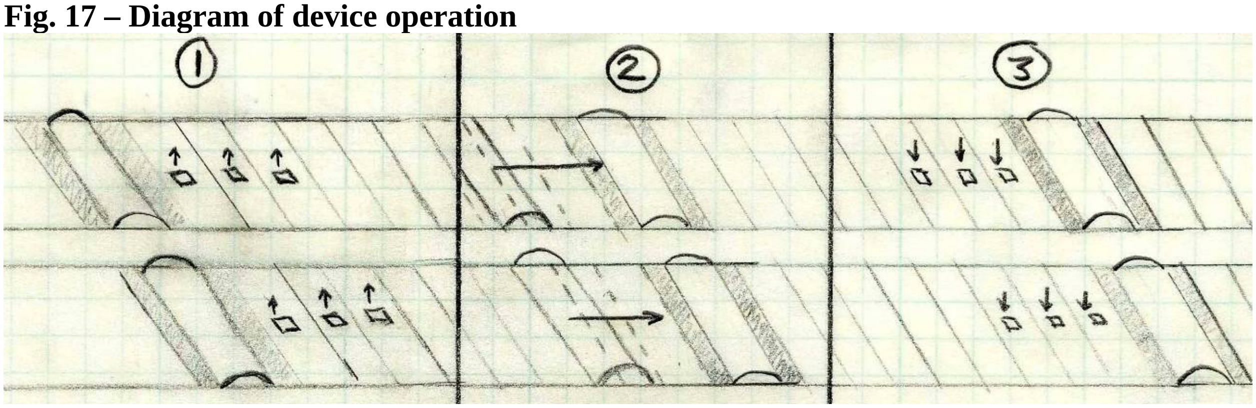


Fig. 17 below shows the intended procedure for using this device. Initially, the device will be moved out onto the floor, and the alignment wheels will be engaged into the T-slot tracks. The device will then be moved so that the magnets are directly above the plates, shown in (1). The operator will then engage the magnets and raise the lifting bars to lift the plates. Once lifted, the floor area will be open, allowing the dyno rolls to proceed forward, shown in the (2). Once moved, the device will then be placed above the opening in the floor and the operator will lower the lifting bars, shown in (3).

Fig. 17 – Diagram of device operation



Final Design

This section shows calculations for the validity and safety of our final design. Afterward, the final design and its operation are described. A summary of our design schedule is in the Gantt chart in Appendix C, page 39.

Engineering Design Parameter Analysis

The analysis of the design parameters was broken into subsections. Below, we discuss the materials used, the loading of the device, the creation and verification of the finite element (FE) model, the sizing of the magnets and air bags, and the device stability.

Materials

We chose steel as the material for our device. It is easy to work with, cheap, and will withstand the environmental conditions in the wind tunnel. We modeled it with E = 200 GPa, $\nu = 0.3$, and a yield stress of 350 MPa, properties of a general purpose steel. This device will be constructed out of steel angle, square and rectangular steel tubing, and chrome-plated solid steel rods. Table 4 below shows the general properties of the cross-sections used in our device [7], including cross-sectional area (*A*), distance to the neutral axis (*y*), moment of inertia (*I*), and polar moment of inertia (*J*). Table 5 below lists the specific properties of the materials used in our device.

Table 4 – Properties of different cross-sections

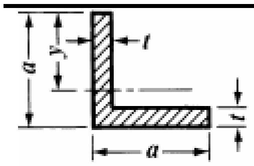
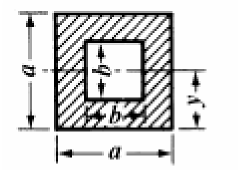
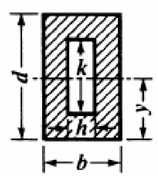
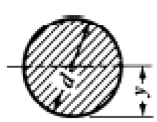
Cross-section	*A*	*Y*	*I*	*J*
	$t\cdot(2\cdot a-t)$	$a-\frac{a^2+a\cdot t-t^2}{2\cdot(2\cdot a-t)}$	$\frac{1}{3}[t\cdot y^3+a\cdot(a-y)^3-(a-t)(a-y-t)^3]$	$2\cdot I$
	a^2-b^2	$a/2$	$\frac{a^4-b^4}{12}$	$2\cdot I$
	$bd-hk$	$d/2$	$I_1=\frac{bd^3-hk^3}{12}$ $I_2=\frac{db^3-kh^3}{12}$	I_1+I_2
	$\frac{\pi d^2}{4}$	$\frac{d}{2}$	$\frac{\pi\cdot d^4}{64}$	$2\cdot I$

Table 5 – Specific cross-section properties

Cross-section	*A* (mm^2)	I_1 (mm^4)	I_2 (mm^4)	*J* (mm^4)
2”x3” rectangular tubing, 0.25” thick	1451.6	1060100	539800	1599900
2”x2” square tubing, 0.25” thick	1129.0	379400	379400	758800
1”x1” square tubing, 0.25” thick	483.9	32500	32500	65000
2”x2” angle, 0.25” thick	604.8	144700	144700	289400
1.25” dia. chrome-plated steel rods	791.7	49900	49900	99800

Loads

Table 6 below shows how we estimated the load of lifting one floor plate. The steel length is a reasonable estimate, considering the dimensions shown in Appendix F on page 45. Adding these up gives a total estimated load (for one plate) of 1042 N. No safety factor was included in this, as it is considered in later calculations.

Table 6 – Loads encountered in the lifting of one floor plate

Component	Mass (kg)
1 floor plate	76.66
2 magnets	20.72
1 meter 2”x2”, 0.25” thick steel tubing	8.87

Description of FE models

We created FE models using the geometry and steel components shown in the Appendix F on page 45. The models were created in Hypermesh and analyzed using MSC.NASTRAN 2005. All parts of our device were modeled using one-dimensional CBAR elements. Elements in the global x and global y directions (the horizontal plane) were modeled with a v-vector in the global z direction, while elements in the global z direction were modeled with a v-vector in the global y direction.

We made two conservative simplifications in our model. First, for a piece of angle or rectangular tubing, the stress recovery points are not symmetric due to the lack of symmetry in the cross-section. However, we modeled them as symmetric, but took the larger distance from the neutral axis. This would result in stresses reported back as larger than they actually are, which agrees with a conservative design basis. Second, where loads from the weight of the steel were considered, an extra 10% was added to account for additional weight from fasteners, welds, and accessories.

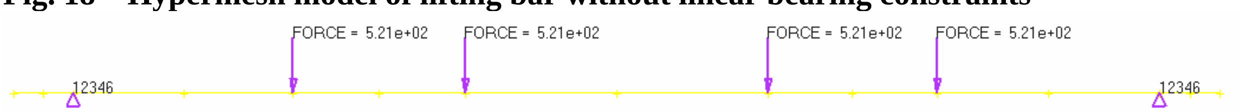
We made one non-conservative simplification. Welds, bolts, and other fasteners were not modeled. We made sure that the steel structure had a large factor of safety (discussed on page 27), so that the weaknesses from the fasteners can be neglected.

Lift bar analysis

A model of the lift bar was created, and tested with the same forces and three different sets of constraints. Since each plate is supported by two magnet assemblies, the force from each separate assembly is 521 N (half of 1042 N). This force is applied in each of the four locations where the magnet assemblies attach to the lifting bar (see dimensions in Appendix F, page 45). The first set of constraints are simple supports (no deflection, but rotation allowed) at the points where the air bags attach. This was modeled both by FE and manual beam theory. We used a comparison of the results to verify our FE model and get an upper bound on deflection of the lifting bar. The next set of constraints added the rotation constraint on each end from the linear bearing. This was done to more accurately find the deflection under typical use. Finally, we modeled the lifting bar with the end rotation constraints and only one simple support constraint. This simulates a failure of the air bag, and is used in our safety analysis.

Fig. 18 below shows the Hypermesh model of the lifting bar with the ends unconstrained. Using beam theory and singularity functions, Eqn. 1 on page 18 shows the load distribution with respect to x (the distance along the bar). The deflection (Eqn. 6) and maximum stress (Eqn. 7) are calculated using Eqn. 2 through Eqn. 5 [8]. Variables $a - f$ are dependent on the geometry. Starting from the left end, a is the distance to the 1st air bag, b is the distance to the 1st magnet assembly, c is the distance to the 2nd magnet assembly, d is the distance to the 3rd magnet assembly, e is the distance to the 4th magnet assembly, and f is the distance to the 2nd air bag.

Fig. 18 – Hypermesh model of lifting bar without linear bearing constraints



Eqn. 1

$$q(x) = P \cdot \left[< x-a >^{-1} + < x-f >^{-1} - \tfrac{1}{2}\left(< x-b >^{-1} + < x-c >^{-1} + < x-d >^{-1} + < x-e >^{-1} \right) \right]$$

Eqn. 2

$$\frac{dV}{dx} = -q$$

Eqn. 3

$$\frac{dM}{dx} = -V$$

Eqn. 4

$$EI \frac{d^2 v}{dx^2} = M$$

Eqn. 5

$$\sigma_{\max} = \left| \frac{My}{I} \right|$$

Eqn. 6

$$v_1(x) = \frac{P}{6EI} \{ < x-a >^3 + < x-f >^3 - \tfrac{1}{2}\left(< x-b >^3 + < x-c >^3 + < x-d >^3 + < x-e >^3 \right) + \frac{a-x}{f-a}\left[(f-a)^3 - \tfrac{1}{2}\left[(f-b)^3 + (f-c)^3 + (f-d)^3 + (f-e)^3 \right] \right] \}$$

Eqn. 7

$$\sigma(x)_{\max} = \left| \frac{P \cdot y_{\max}}{I} \left[< x-a >^1 + < x-f >^1 - \tfrac{1}{2}\left(< x-b >^1 + < x-c >^1 + < x-d >^1 + < x-e >^1 \right) \right] \right|$$

Eqn. 8

$$v_{\max 2} = \frac{5 \cdot w \cdot L^4}{384 \cdot E \cdot I}$$

Eqn. 9

$$w = \frac{2 \cdot P}{L}$$

Eqn. 10

$$v_{\max 3} = \frac{W \cdot L^3}{48 \cdot E \cdot I}$$

Behr used two more formulas to estimate the deflection. Eqn. 8 and Eqn. 9 model the load as a distributed load over the length of the lifting bar, while Eqn. 10 models it as a single point load (W = 2084 N) in the center of the bar. Fig. 19 below shows the deflection of the lifting bar for both manual and FE methods. Fig. 20 on page 19 shows the maximal tensile stress in the lifting bar for both manual and FE methods. The correlation between manual and FE methods is very good. Therefore, we have confidence in our FE methodology. Table 7 on page 20 summarizes the maximum deflections and stresses in the center of the lifting bar for all methods.

Fig. 19 – Unconstrained lifting bar verification of FE results

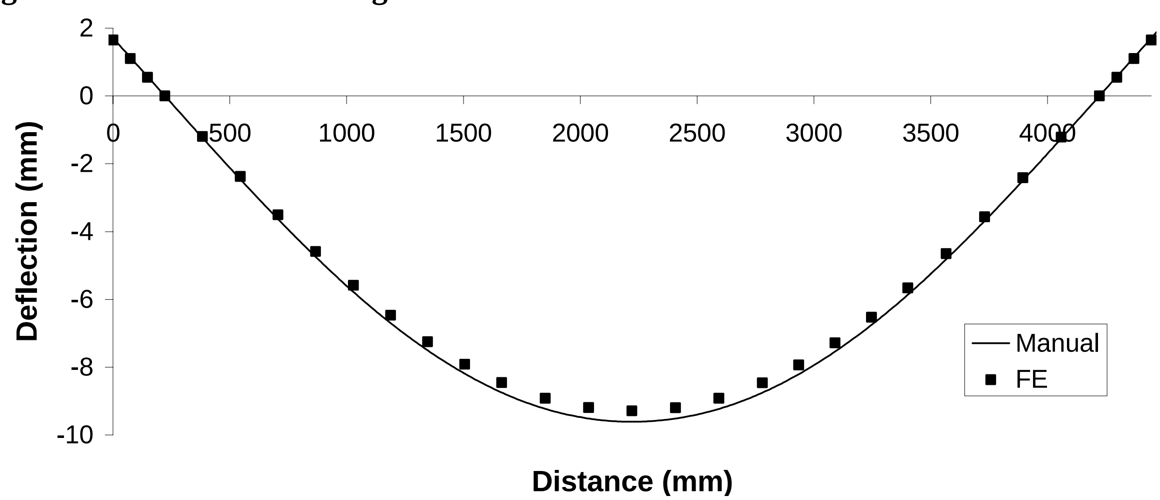


Fig. 20 – Unconstrained lifting bar stress verification of FE results

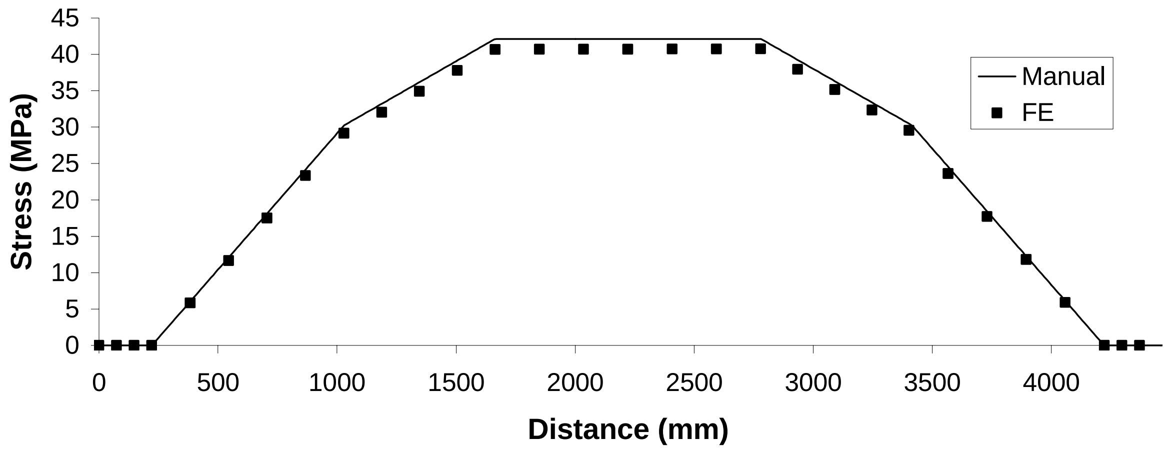


Fig. 21 below shows the addition of the end constraints that restrict rotation around an axis pointing into the page. This approximates the linear bearings. This would be the most accurate model of the deflection and stresses encountered in everyday use. Using the SPC (Single Point Constraint) output feature of NASTRAN, the moment supplied by the linear bearings can be found. Fig. 22 below shows the removal of the 2nd air bag constraint, which simulates an air bag failure. From this model, we can see if the stresses in the lifting bar and in the linear bearing are below the yield stress of steel.

Fig. 23 on page 20 shows the lifting bar deflections for both the typical and failure cases. Fig. 24 on page 20 shows the stresses in the lifting bar for both the typical and failure cases. Notice that in the event of an air bag failure, the maximum stress in the lifting bar is below the yield stress of steel. Therefore, we can conclude that the lifting bar will not fail in the event of an air bag failure. Again, Table 7 on page 20 summarizes the maximum deflections and stresses in the center of the lifting bar for all methods.

Fig. 21 – Hypermesh model of lifting bar with linear bearing constraints

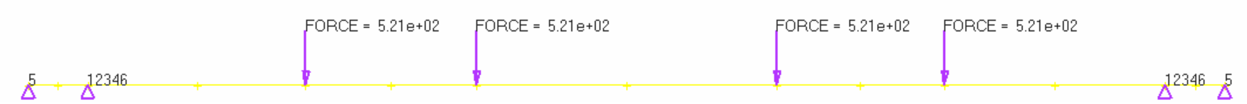


Fig. 22 – Hypermesh model of lifting bar simulating air bag failure

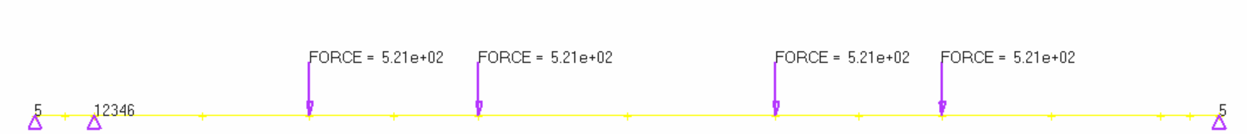


Fig. 23 – Constrained lifting bar deflections with FE model

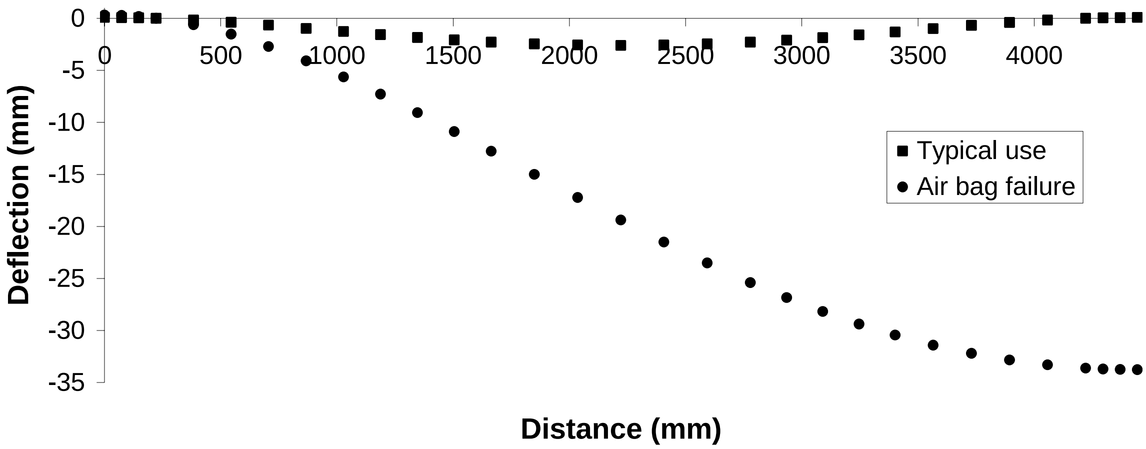


Fig. 24 – Constrained lifting bar stresses with FE model

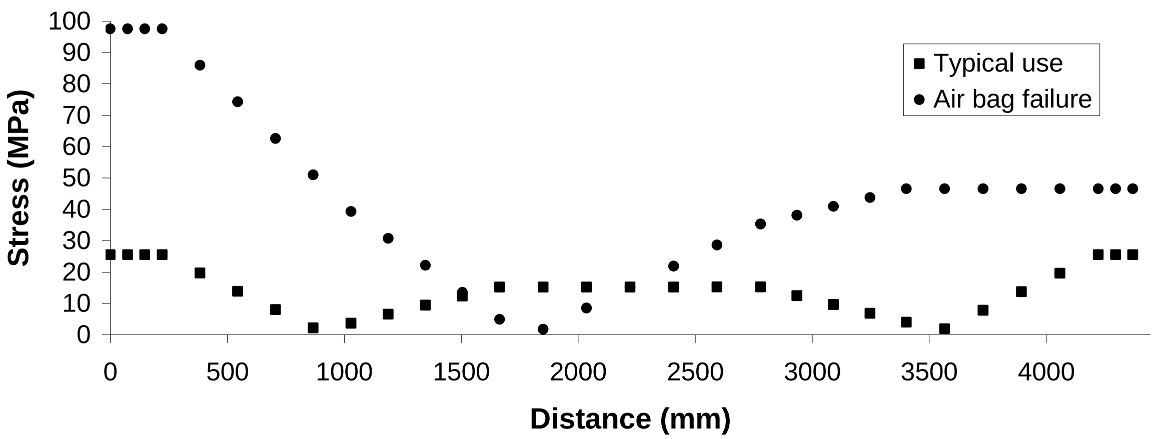


Table 7 – Maximum deflections and stresses for all methods

End constraint	Calculation Method	Deflection (mm)	Stress (MPa)
Unconstrained	FE	9.3	40.7
Unconstrained	Four point loads (v_{max1})	9.6	42.1
Unconstrained	Distributed load (v_{max2})	8.2	NA
Unconstrained	One point load (v_{max3})	13.1	NA
Rotation constrained	FE – Typical use	2.6	25.5
Rotation constrained	FE – Air bag failure	33.8	97.6

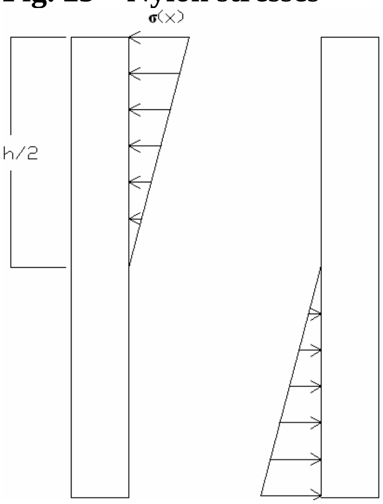
Linear bearing analysis

To laterally support our lifting bar and air bag system, we designed linear bearings from 1.25" diameter chrome-plated steel rods and 2" OD oil-impregnated nylon bushings. We needed to ensure that: the bearings would not bind, the nylon would not fail in typical use, the nylon would not fail in the case of an air bag failure, and the chrome rod would not fail in case of an air bag failure.

The coefficient of friction of the oil-impregnated nylon is 0.12. This low coefficient of friction almost ensures that the bearing would not bind [10].

The maximum allowable stress in the nylon is between 66 and 76 MPa (9,500 – 11,000 psi). We assumed a linear stress distribution in the nylon. It is shown in Fig. 25 below. Eqn. 11 below is a moment balance between the compressive stresses (σ_c) and the moment applied from the lifting bar (M_A), where *h/2* is half the length of the bearing, and *w* is the diameter of the rod. Eqn. 12 evaluates the moment balance integral and gives the maximum compressive stress in the nylon. For each case, M_A was found using the lift bar analysis above.

Fig. 25 – Nylon stresses



Eqn. 11

$$M_A = 2 \cdot w \cdot \int_0^{h/2} \sigma_c(x) \cdot x \cdot dx$$

Eqn. 12

$$\sigma_{c\max} = \frac{M_A}{w \cdot \left(h/2\right)^2}$$

Fig. 26 – FE model of chrome rod

Fig. 26 above shows the FE model of the chrome-plated steel rod. The properties of the rod are shown in Table 5 on page 16. Each end of the rod had all six degrees of freedom constrained. The linear bearing was assumed to be at the halfway point of this rod. In the center, five elements were created within the bearing's 76.2 mm (3 in.) length. These elements were connected with a rigid link, and then M_A was applied to the linked nodes.

Table 8 below shows M_A, σ_{cmax} of the nylon, and σ_{max} in the chrome-plated steel rods. The stress in the nylon never exceeds its limit, even in the failure case. The stress in the chrome-plated rods under normal use is 111 MPa, which is below the yield stress of steel. In the case of the air bag failure, the maximum stress in the rods is 420 MPa. This is over the yield stress but under the ultimate tensile stress (650 MPa) of 4140 alloy steel.

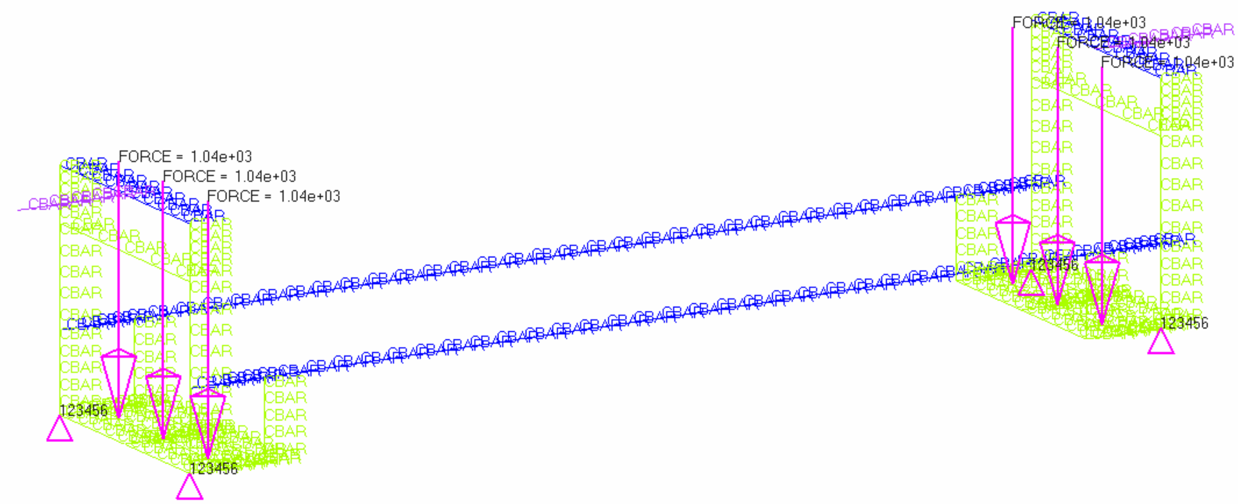
Table 8 – Linear bearing moments and stresses

Test case	Bearing	M_A (N-m)	Nylon σ_{cmax} (MPa)	Chrome σ_{max} (MPa)
Typical use	Left	736	16	111
Typical use	Right	736	16	111
Air bag failure	Left	2820	61	420
Air bag failure	Right	1340	29	195

Frame analysis

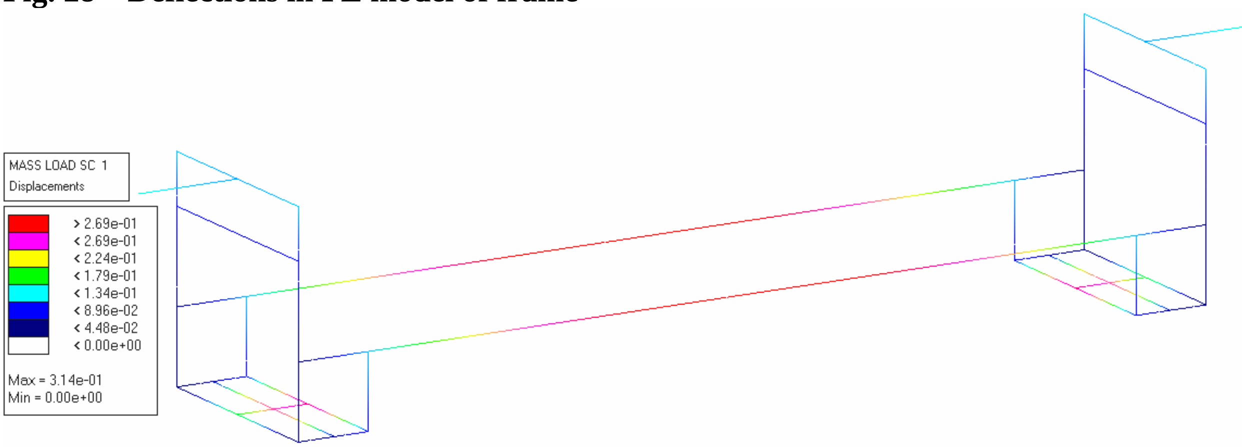
The Hypermesh model of our device frame is shown in Fig. 27 on page 22. Six nodal forces, each with a magnitude of 1042 N (see page 16), were applied to the model at the center of each air bag attachment point. One six-degree of freedom constraint per corner (four total) was added to simulate the casters.

Fig. 27 – Hypermesh model of device frame



The deflections in the frame are shown visually in Fig. 28 below. The legend shows that the largest deflection is 0.314 mm. Hypermesh does not allow visual display of the stresses when using one-dimensional elements. Inspecting the results file manually showed that the maximum tensile stress in the frame was 30 MPa, while the maximum compressive stress was 31 MPa. These stresses are an order of magnitude below the yield stress of steel. Therefore, we conclude that our frame will not fail under the applied loads.

Fig. 28 – Deflections in FE model of frame



Push bar strength

To make sure the push bar would not fail, we used two calculations. First, we used an FE model to determine the deflection and stress in the push bar while an overturning load (3500 N) was applied. Next, using the same load, we manually analyzed the hinged joint to make sure it would not fail in shear.

Fig. 29 on page 23 shows the FE model we used to find the push bar deflection. Notice the two six-degree of freedom constraints on the inboard side of the push bars. We were only interested in the push bar deflection, so the deflections and stresses in the rest of the frame were ignored.

This assumption is justifiable because the push bar assemblies are mounted to steel pieces that are much stronger than the push bars. Fig. 30 below shows the maximum deflection to be 20.5 mm. The maximum stress is 250 MPa.

Fig. 29 – Hypermesh model of device frame with push bar forces

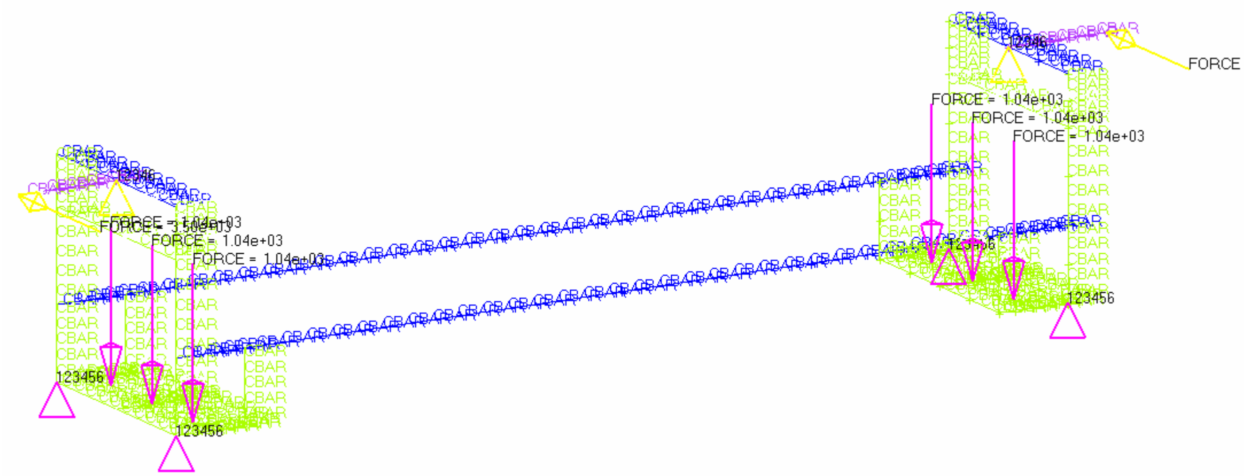


Fig. 30 – Push bar deflections in FE model of frame

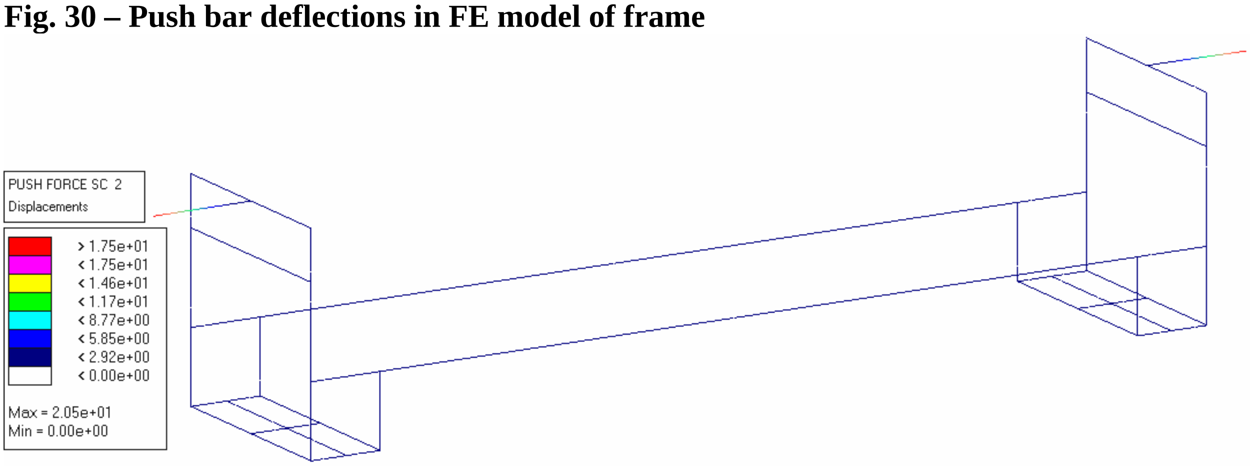
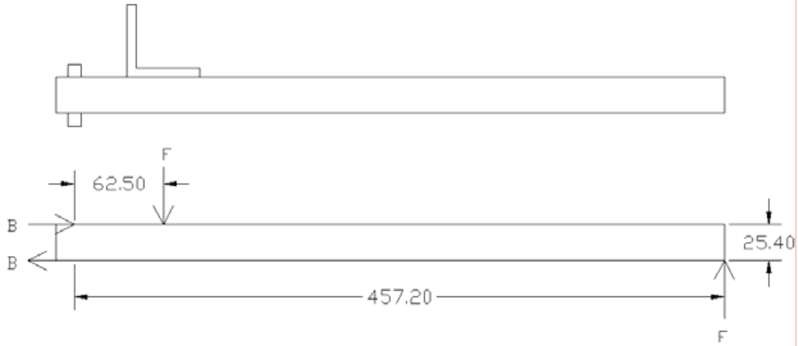


Fig. 31 on page 24 shows a top view of a push bar. When a load is applied, the left end of the bar is supported by a 5/8" pin and a piece of 2"x2" angle. Eqn. 13 is a moment balance about the top pin connection, with the applied force (F), the shear force in the angle (also F), and the shear forces in the pin (B). For F = 3,500 N (the overturning force), B = 72,000 N. Eqn. 14 gives the shear stress (τ) in terms of the shear force (V) and the cross-sectional area (A). The shear stress in the angle is 6 MPa, while the shear stress in the pin is 360 MPa.

Fig. 31 – Diagram and FBD of push bar



Eqn. 13

$$F \cdot (-62.5 + 457.2) - B \cdot 25.4 = 0$$

Eqn. 14

$$\tau = \frac{V}{A}$$

The pin shear stress is near the yield stress of steel. However, the maximum overturning load should never be applied, so failure should not occur. We conclude that, under normal operating conditions, the push bar will not fail. However, if forces near the overturning force are applied to the end of the push bar, large deflections and possible yield may occur. The noticeable deflection would provide a warning that the device is about to overturn.

Stability of device

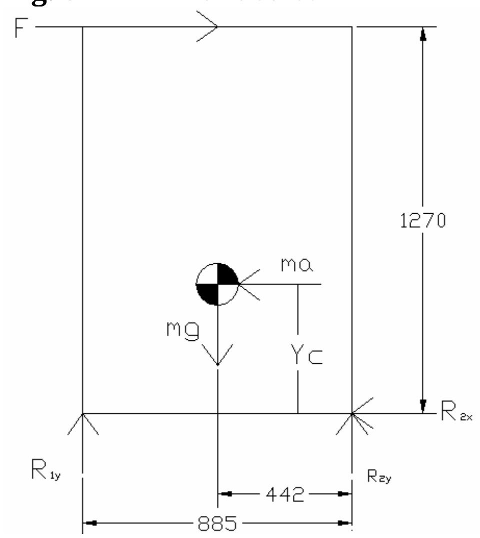
To determine the stability of the device, we first needed to estimate its center of gravity (CG). We did this for three cases: the device unloaded (no load), the device loaded but the plates not lifted (loaded low), and the device loaded and the plates lifted (loaded high). The weight of the steel components were estimated using the area properties of the steel (Table 5 on page 16), lengths from the geometry, and a steel density of 7680 kg/m^3. The individual CG heights were found by using the drawings in Appendix F on page 45. Table 9 below summarizes the CG's of the components. Components with low masses were considered negligible and left out.

Table 9 – Summary of individual CG's

			Individual CG Height (mm)		
Part	**Quantity**	**Mass (kg)**	**No load**	**Loaded low**	**Loaded high**
Lifting bar assembly	3	51	399	399	780
Floor plates and magnet assemblies	6	106	0	0	381
Stationary bars across device	2	39	550	550	550
Top bars (front to back)	2	9	1270	1270	1270
Push bars	2	2	1270	1270	1270
Outside corner posts	4	5	635	635	635
Inside corner posts	4	2	275	275	275
Chrome-plated steel rods	6	5	602	602	602
Upper front to back angles	2	5	1008	1008	1008
Lower front to back angles	6	5	196	196	196
Outside to inside angles	6	2	196	196	196

For each loading case, the composite CG (y_c) was found using Eqn. 15 on page 25, where m_t is the total mass (for each loading case), m_i is the individual mass of the components, and y_i is the individual CG height of the components. Fig. 32 on page 25 shows a schematic drawing of our device, and includes the push bar force (F), the reaction force (R_{2x}) from the device hitting an obstruction (such as a curb, or leaving the caster brakes on accidently), the two upwards reaction forces from the ground (R_{1y} and R_{2y}), the D'Alembert force (*ma*), and the force due to gravity (*mg*). The moment balance around point 2 (bottom right) is shown in Eqn. 16 below. The device starts to tip when R_{1y} is zero. Therefore, Eqn. 16 can be simplified into an expression for the overturning force (*F*) shown in Eqn. 17.

Fig. 32 – FBD of device



Eqn. 15

$$y_c = \frac{1}{m_t}\left(\sum m_i \cdot y_i\right)$$

Eqn. 16

$$\sum M_2 = -F \cdot 1270 + y_c \cdot m_t \cdot a + 442 \cdot m_t \cdot g - R_{1y} \cdot 885 = 0$$

Eqn. 17

$$F = m_t \frac{y_c \cdot a + d \cdot g}{h}$$

Under the no load and loaded high conditions, the device is most unstable when it is rolling and the casters hit an obstruction. This scenario would cause a deceleration, because the device is slowing to a halt. Since the device would never be rolling very fast, we assumed the acceleration was -1 m/s^2. When the device is loaded, but the bars lowered, it would never be moving, so we assumed the acceleration was zero. The calculations are summarized in Table 10 below.

Table 10 – Summary of overturning force (*F*) calculations

Load	*a* (m/s^2)	y_c (mm)	m_t (kg)	*F* (N)	*F* (lbs)
No load	-1	380	470	1500	340
Loaded low	0	180	1000	3400	760
Loaded high	-1	480	1000	3000	670

The lowest overturning force is 1500 N (340 lbs). Two people could exert this force, but it would take a lot of effort. We conclude that this device could be tipped over, but the operators will be instructed to avoid using excessive force (over 170 lbs per person).

Air system

Two air bags must be able to support one lifting bar and two plates, and all the accessories (including the magnets and support assemblies). Using Table 9 on page 24, the weight of the lifting bar assembly and two floor plates would be 2580 N (580 lbs). Each air bag would have to support half of that, which is 1290 N (290 lbs). The air bags we specified exert a maximum force of 2400 lbs when fully extended, which is more than enough for our application. The safety factor on lifting is 8.

To get the plates out of the floor opening and clear the dyno rolls, the minimum vertical travel required in the air bag is 250 mm. The air bags specified have a travel of 360 mm (14"). To fit in the frame of our device without the chance of puncturing the rubber, the air bags' maximum diameter cannot be more than 279 mm (11").

To ensure that the airbags did not lower too fast, we had to estimate the correct size of the flow control orifice. First, we had to estimate the volume of air in the fully inflated air bags. From their dimensions, we estimated that each air bag held 1 cubic foot of air (2 cubic feet per lifting bar). We wanted each to deflate in roughly five seconds. Eqn. 18 below shows how these numbers were computed into a cfm (cubic feet per minute) value. The diameter of the flow control orifice was then picked using the value of 24 cfm.

Eqn. 18

$$\frac{2\,cf}{5\sec}\cdot\frac{60\,s}{1\min}=24\,cfm$$

Eqn. 19

$$\sigma=\frac{F}{A}$$

Casters

The estimated total weight of the fully loaded device is 9800 N (2200 lbs). We needed four casters to take one-quarter of that load (550 lbs). We have specified casters that are rated at 1200 lbs, giving us a safety factor of 2. Each caster also has a brake to keep the device from moving, and a lock that allows the wheels to be locked in one direction. These casters are corrosion resistant and include roller bearings for ease of movement.

Magnets

In our design, two magnets lift one plate (77 kg or 170 lbs). The magnets specified can each lift a 0.25" thick (the thickness of the steel on top of the floor plate) plate with a mass of 121 kg (267 lbs) at a safety factor of 2. Behr requested that we used two magnets per plate. This results in a safety factor of 6.3 for our specific lifting operation.

These four magnets are attached to the lifting bar through a 2"x2" piece of steel tubing and a 6"x4" steel plate gusset, both 0.25" thick. Eqn. 19 above allows us to calculate the axial stress in both pieces of steel. In the tubing, with a cross-sectional area (A) of 1129 mm^2 and a force (F) of 1042 N, the axial stress (σ) is 0.9 MPa. In the gusset, with an A of 968 mm^2, σ is 1.1 MPa. These stresses are both two orders of magnitude below the yield strength of steel.

These magnets will be controlled from switches mounted on the device (one switch for all four magnets on a lifting bar). They will be powered from a central power supply mounted on the wall of the wind tunnel. The power supply requires standard 120 volt electrical power. All wiring is included with the magnets from the supplier, so no additional electrical design analysis is needed.

Other components

The alignment wheels are not weight bearing, and do not require force and stress analysis. Behr will machine the chamfer on the rubber wheels. The geometry will be determined from on-site testing.

If the device is not attached to its air line, the air bags are un-inflated, leaving the magnets touching the floor. When moving the unloaded device to and from storage, we recommend using a steel bar to support the lifting bars so the magnets do not contact the floor surface. There will be very little weight on this bar, and it will be inserted in place by the operator specifically for this purpose.

Design for manufacturability and assembly

Our project was to design and build a one of a kind device. Behr's wind tunnel is very unique, and our device is designed specifically for it. While we want to make our device as easy to build as possible, we did not have to consider mass production.

We took care to select materials and components that are readily available. This makes procurement easy, but also is important later in the device's life when maintenance is required. Behr has accounted for easy removal of the linear bearings in their fabrication of the frame. Our design is robust enough to take daily abuse and still function correctly.

The construction of our device doesn't require an extreme amount of precision. The most critical part in the respect would be the construction of the linear bearings. Even then, excessive misalignment of the chrome-plates steel rods in the linear bearing would not cause failure, only increased wear in the nylon.

Safety of final design

We used designsafe® 3.0 to assess the risk of implementing our design at Behr. The full report is in Appendix H on page 50. Our design will be used primarily by the wind tunnel technicians, but there is also some risk to managers, maintenance workers, customers, and clean-up crews. After our initial assessment of the severity, exposure, and failure probability, we found that 24 low risk procedures, while 91 posed moderate risks, and 19 were high risk.

The primary safety concern of our design was structural failure of the frame. If the lifting bars fail, the magnets and plates could fall through the floor gaps and damage equipment below, and/or cause serious injury to anybody nearby. We addressed this concern by doing a finite element analysis on the frame for both the typical loading and failure loading. Our analysis shows that all loads resulted in stresses below the ultimate tensile strength of the materials. Table 11 below summarizes the factors of safety for individual components in the design.

Table 11 – Factors of safety

Component	Failure mode	Safety factor
Frame	Yield under normal use	10*
Lift bar	Yield under normal use	10*
Lift bar	Yield with air bag failure	3
Magnet	Dropping the plate	6
Magnet support assembly	Yield	100*
Air bags	Lifting capacity	8
Casters	Collapsing	2
Chrome-plated steel rod	Ultimate failure	1.5

* order of magnitude estimation

Another possible risk is the failure of the air system. It is possible that an air line could be severed or pinched, or that an air bag may fail altogether. While we could not further safeguard the air system against damage, we were able to ensure that there would be no catastrophic failures of the frame due to a failure in the air system.

Also, there is the possibility of an electrical failure in the facility. The magnets must not drop the plates if the device loses power. This was addressed by using electronically operated permanent magnets that do not release their loads when power is removed.

Another concern was the accidental release of plates from the lifting bars. If only one plate became disengaged, the lifting bar would be unbalanced. This was addressed by only having one magnet control switch per lifting bar.

Other risks in our design focus heavily on the conduct and procedure of the person using or near the plate lifter. These include persons tripping on the electrical or air line running to the system, or being pinched or crushed in the various mechanisms. There are times when the operator will have to engage guide wheels and push the system in and out of storage. If they do not complete these tasks with care to posture and safety, it is possible they could hurt themselves from repetition or improper movement. We cannot ensure the proper conduct of people around the device, other than by recommending safety training. However, we addressed the crushing hazards by recommending sheet metal guards around all possible pinch points.

The stability of the device was also a concern. We calculated the stability of the device for both loaded and unloaded conditions. Our analysis showed that the device would not tip over unless gross negligence was exhibited by the operators.

After our safety improvements, the final assessment of the severity, exposure, and probability of actions taken by different users showed that all the high risk level had been eliminated. Also, there were 77 low risk scenarios and 57 moderate risk scenarios.

Final Design Details

This section shows all aspects of our final design, including the overall design, a schematic of the air system, and pictures of the components. More details are also located in the appendices.

Description

Fig. 33 on page 29 shows a Unigraphics model of our final design. All dimensioned engineering drawings are in Appendix F on page 45. Fig. 34 on page 29 shows a completed alignment caster, Fig. 35 shows a detail of the push bar assembly, Fig. 36 shows an air bag, and Fig. 37 shows a lifting magnet. Fig. 38 on page 30 shows a schematic of the air system.

Behr asked us to provide them with a detailed parts list to facilitate the expedient shipping of required parts through their suppliers. This was possible using common suppliers such as McMaster-Carr and others. All steel was purchased through Alro-Kurtz, a supplier that Behr frequently uses. The bill of materials is located in Appendix G, on page 45. All parts have been ordered and will be delivered to the Behr facility. The device is currently being constructed to our specifications in the Behr employees.

Fig. 33 – Final Design Trimetric View

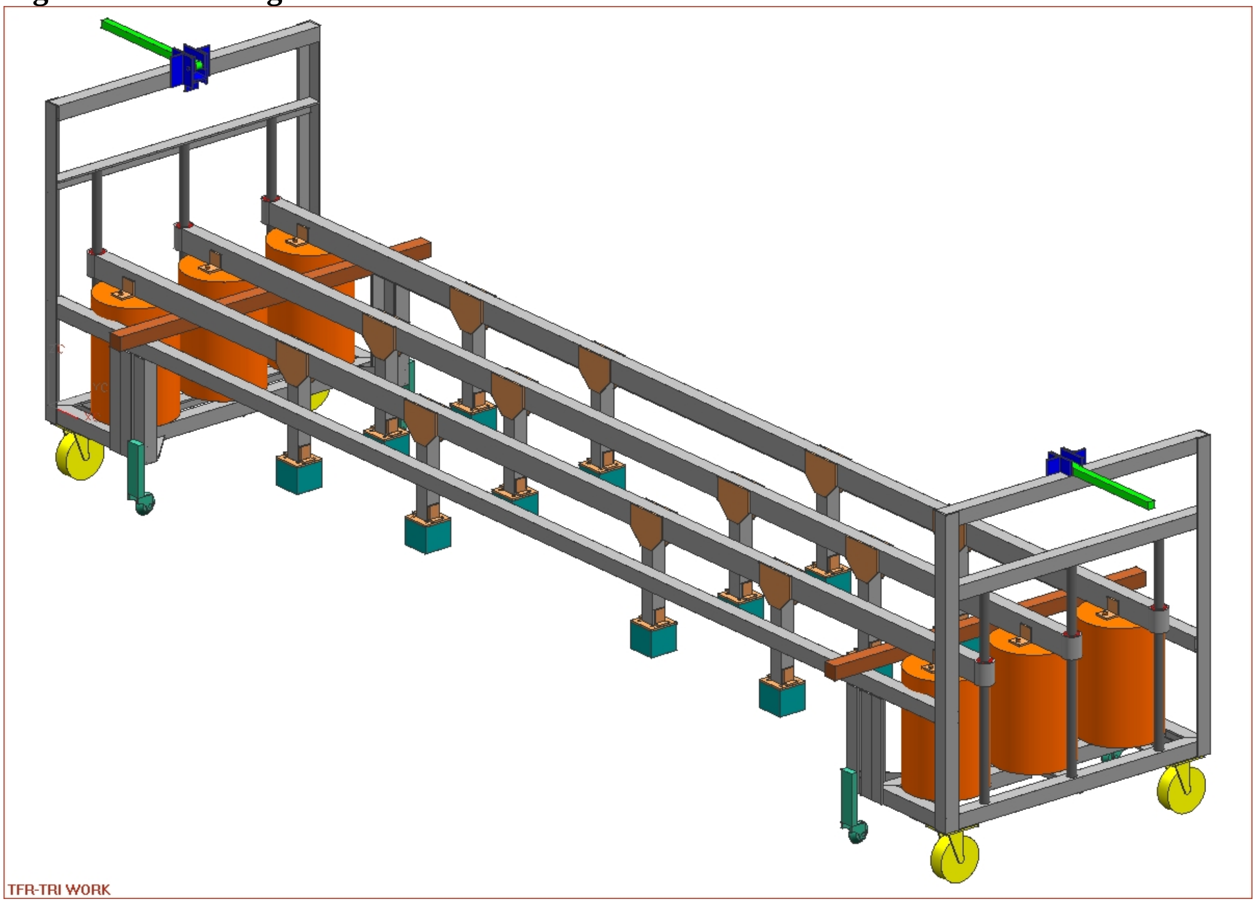


Fig. 34 – Alignment caster

Fig. 35 – Push bar

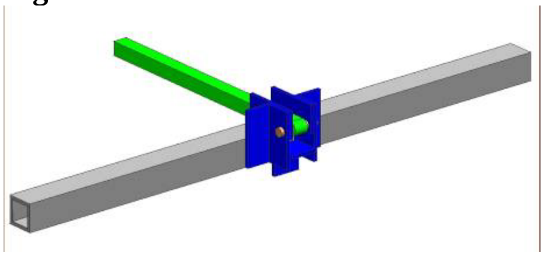
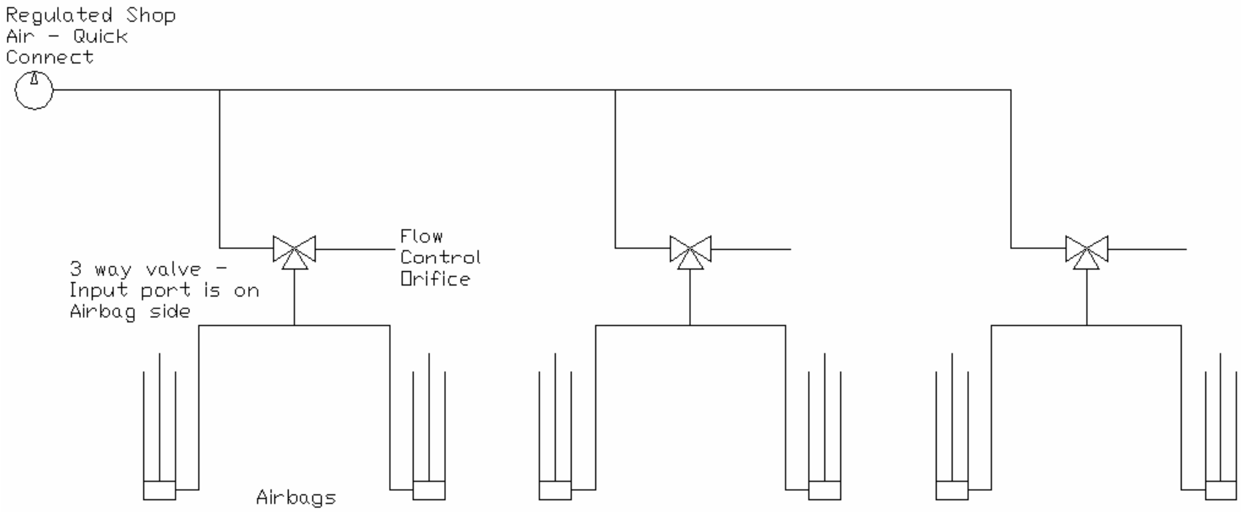


Fig. 36 – Air bag

Fig. 37 - Magnet

Fig. 38 – Schematic of air system

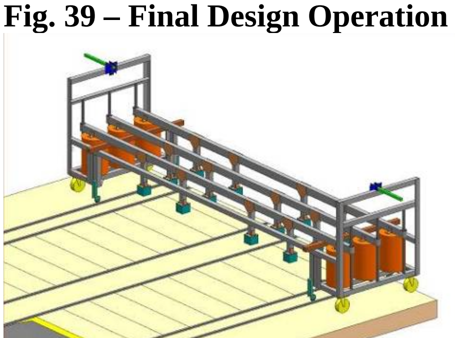


Device Operation

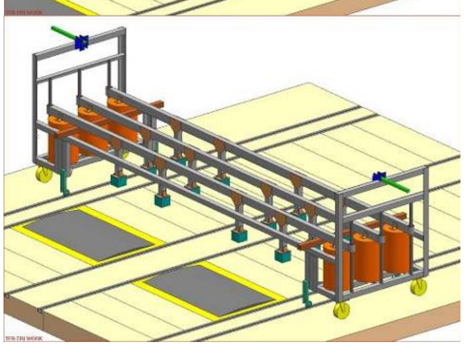
Fig. 39 below shows the procedure for use of our device when moving the maximum number of plates. Our final device will also be able to pick up, move, and set down a single pair of plates, but the most common use will be to lift and carry three plates per side to move the dyno rolls as quickly as possible. Fig. 40 on page 32 shows the controls that are operated during this time.

This device will also be operated for lifting various plates into different sized holes. The individual lifting and powering of the magnet pairs allows the user to mix and match the placement of the floor plates depending on need. This will not be the main use of the device, but it will help the technicians by eliminating the need to do any plate moving by hand.

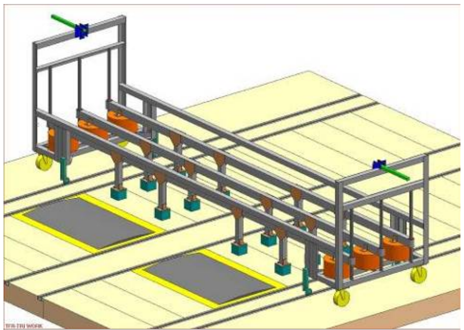
Fig. 39 – Final Design Operation



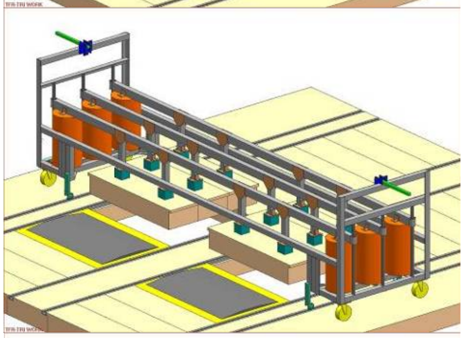
- Push bars are unfolded
- Device is rolled from storage onto track area
- Alignment wheels are engaged into the outermost T-slot tracks
- Casters are locked into moving only forward or backward



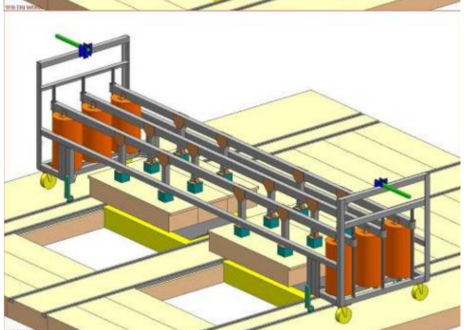
- Once aligned, the device is placed above the plates that need to be moved
- Casters are then braked for stability



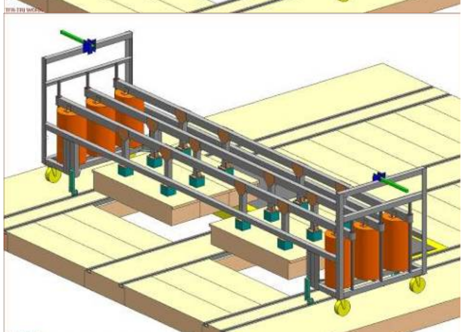
- Pressure in airbags is released slowly through flow control orifices, placing magnets on the floor plates
- Magnets are then engaged remotely



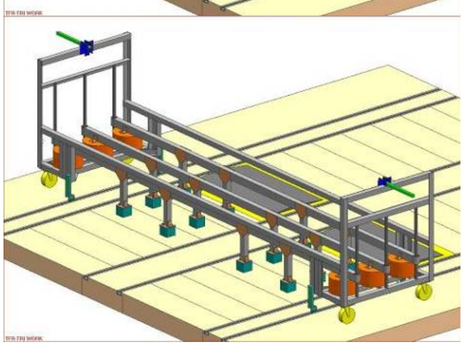
- Operator uses the air controls to fill the air bags and lift the plates



- Dyno rolls are then moved with existing hand held pendent under lifted plates

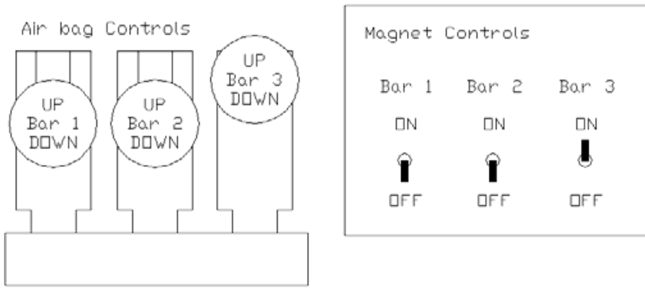


- Caster brakes are released
- Operators then use push bars to move device to new position over open floor area



- Caster brakes are set
- Air pressure in the air bags is released slowly and the plates are lowered into their new position
- Magnets are then disengaged remotely

Fig. 40 – Diagram of device controls



Design Validation

Only having a virtual prototype greatly limits validation testing that may be performed. The design operation sequence above show the soundness of the multiple plate lifting concept. All components have been sized properly. Whenever possible, all calculations were based on conservative models.

We have verified the strength of our device's frame using computer simulation of the following conditions:

- Overall strength of frame under normal and failure loading
- Overall strength of lift bars under normal and failure loading
- Linear bearing integrity due to air bag failure
- Push bar strength under normal loading

We have shown that failures under these conditions will not cause harm to any wind tunnel equipment or the operators. The device will suffer damage, but there will be no catastrophic failures.

Manufacturing Plan

As our prototype will also be used as our final design, there will be no manufacturing differences between the two. Behr will be responsible for any unforeseen problems with construction of final design.

This device was designed to require minimal high tolerance machining and fabrication. The only parts with critical dimensions are:

- The chrome rods / nylon bushings need to align correctly to prevent binding.
- The push bar assembly has a relatively small tolerance – excess movement in the joint could weaken it.

The construction and step-by-step assembly will be completed by Behr in their shop according to the prints that we provided them. Permission has been given by us to Behr to make any small changes to the design that may be needed during the construction process. Due to the one of a kind nature of this design, a repeatable process for construction is unnecessary.

Behr had not provided us many details of how they plan on constructing the device. We are aware the welding will be done using a MIG welder with a 0.25" weld fillet size.

Discussion

Overall we feel that our design process went very well. Meetings and reviews with our sponsor helped mold our design to fit their specific needs. However, when learning about their current process and the problems associated with it, it would have been helpful to see the device in operation. This was not possible due to testing being done while we were present. We based our preliminary designs off of their verbal description of the problem, but it was hard to visualize all of the problems associated with it. It would have been very beneficial to observe the relocation of the floor panels in person, or by video.

We consider our design to be a vast improvement over their current device, and also their scrapped device. Our design allows for multiple plates to be lifted on both sides of the vehicle track, individual operation of each magnet lifting bar, and a greatly improved alignment system to guide the device on the floor tracks. Safety, reduced time of operation, and ease of use have all been improved.

There are some issues that may become a problem as the device starts to be used. We are currently unsure of the durability of the nylon bushings that support the vertical movement of the airbags. This problem has been acknowledged by Behr and they have chosen to proceed as we suggested while keeping in mind other solutions if the current design becomes a problem.

At this time we are also unsure of the correct operation of the air lifting system. For example, we are unsure how quickly the air bags will lift with the weight of the plates applied. This may require an adjustment once the device is completed. We are also concerned that the air bags will not lift simultaneously. We have been given several conflicting views on this by Behr, our professors, our shop supervisors, and other less-involved engineers.

We wanted to maintain a small surface area on the magnets to lift the smallest floor plates. The smallest magnet that we were able to find is larger than the surface of the smallest plate by 2". This may cause problems if the magnet attaches itself to the adjacent plates and lifts them unintentionally. We are unable to determine if this will happen without testing. Changes may be required to the device, or the process of lifting a small plate may need to be changed.

There are several strengths to our design that haven't been covered yet. Behr chose our design over designs from several professional design firms. Also, it incorporated feedback of not just the Behr engineers, but the technicians that will operate it.

Our design also has a few weaknesses. Our solution is not simple, nor is it cheap. However, with the wind tunnel costing $1,100 an hour, it should pay for itself quickly. Plates cannot be stacked as in previous designs. We were unable to find and purchase air bags to meet our design requirement for creating enough ground clearance. We allocated room for air bags with more vertical clearance on the steel frame, should these air bags become available in the future. Validation was done using simulations, and not by actual tests on the device. It would have been nice to finish the engineering analysis sooner, so that we could have a prototype to test.

Recommendations

In meetings with Behr we have discussed maintenance of our device. They are aware that certain parts have the potential for wear. The main components that may need replacing are the nylon bushings that wear over time. They plan on constructing the device so that these parts can be replaced easily. We are unable to predict the usage of the device and therefore cannot accurately develop a maintenance timeline. After the device has been in use for some time, it may be possible to develop a maintenance schedule. The technicians are responsible for visually inspecting the device and conducting proper maintenance before using it.

We have also recommended installing a piece of sheet metal on the opposing ends of our final device. These will be put in place to prevent exposure of the operator to the moving parts of the machine. The air and magnet controls can then be mounted to this sheet metal, or the frame beneath.

Additional changes to the air lifting system may be required after testing the device with a full load. At the current time we are unable to determine if the components and controls will operate at the desired rates of lifting. We are also unsure if the two air bags per plate will lift in sync with each other. We recommend that Behr test the air system using the tee connectors specified. These tee's could be easily be replaced with more advanced regulating equipment if necessary. Behr is aware of this problem and is willing to test and change the device as needed.

We recommend that all operators be instructed to the proper use of all controls, use of alignment wheels, maximum allowable push bar force, and all safety aspects of the design.

Conclusions

Behr America operates a very advanced climatic wind tunnel. A limiting factor in the turnover time of this wind tunnel for different projects is the reconfiguration of the floor. The current setup is not only slow, but has the potential to damage equipment and cause injury to personnel.

Engineers at Behr provided us with a list of desired improvements, two existing designs that can be modified, and the use of their fabrication facilities. We have designed an improved device that increases the productivity and ensures the safety of the technicians using it.

Safety of the operation has increased in many ways with the implementation of the new design. Our design reduces fall hazards to the operators by making the opening in the floor during operation much smaller. Also, by moving both sides concurrently our design eliminates the need for the operators to stand on the narrow center permanent floor during reconfiguration.

Behr is fabricating our device for immediate use. We have provided a quality design that should drastically decrease the turnover time of the wind tunnel along with improving the safety to the operators. This device will be one of a kind and will not need to be reproduced for other uses. Yet, improvements to the design will be made over time as needed.

At this time, we are unable to determine the time improvement and monetary savings of our design. Measurements of these values can be determined after the device is completed and put to use in the wind tunnel. However, based on the design and operation improvements, we expect the savings to be significant.

Acknowledgements

We would like to thank the technicians and engineers at Behr who took time from their daily tasks to meet with us and discuss our design and its operation. Their suggestions were invaluable for recognizing potential problems. We would also like to thank Bob Coury for help with material selection and other parts of our project. His suggestions and resources were very useful to us. Finally, we would also like to thank Kazuhiro Saitou for his help and suggestions throughout the project.

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Appendix A: Team Members

Jacquie Foust
Mechanical Engineering, Senior

Jacquie Foust is from Grand Blanc, Michigan and is a 2002 graduate of Grand Blanc High School. Throughout high school Jacquie was on the Grand Blanc Varsity Swim team, the Grand Blanc Water Polo team, and the Flint YMCA Falcons swim team. She enjoyed taking technical classes, such as drafting and an engineering exploration classes. She was also a participant in the Nation Engineering and Design Competition sponsored by the Jets Corporation. Her love for drafting, problem solving, and figuring out how things worked lead her to apply to the University of Michigan Mechanical Engineering Program.

Since she has been at the University of Michigan she has been an active member of the Society of Women Engineers and held many officer positions with the society. She has been the Corporate Information Session Purchasing officer, Corporate Information Session Finance Officer, and the Membership chair. She has also had internships working with diesel engines at Cummins Inc. for the past three summers. Through her jobs she has been evolved with programming, testing, and design work. After she graduates she plans on going to graduate school to get her master degree in Mechanical Engineering. Then she hopes to get a job in a global company.

Derrick Quandt
Mechanical Engineering, Senior

Derrick Quandt hails from Shelby Township, Michigan, a Dwight D. Eisenhower High School alum who spent his time there taking a variety of courses that would lead him to his current placement at the University of Michigan. He enjoyed playing lacrosse during his days there and spent free time playing other sports and paying close attention to his studies.

Derrick has spent time working with many aspects of mechanical engineering, from the factory floor to consulting work with some of the world's biggest automotive corporations. He has had experience working in new product development for a Fortune 50 corporation. A unique experience has been had at each position and he remains undecided to which direction he wants to take during his career. His advice to everyone: Do not limit yourself to one field before you take a permanent position, experience is very necessary to decide which company you want to work for.

Kyle McGrady
Mechanical Engineering, 5th year Senior

Kyle, like Derrick, comes from Shelby Township, Michigan, where he attended Lutheran High School North and developed an interest in math and science. The natural next step for him was to seek a degree in engineering at the University of Michigan, his favorite college since the days of the Fab Five. His interests include singing and playing soccer.

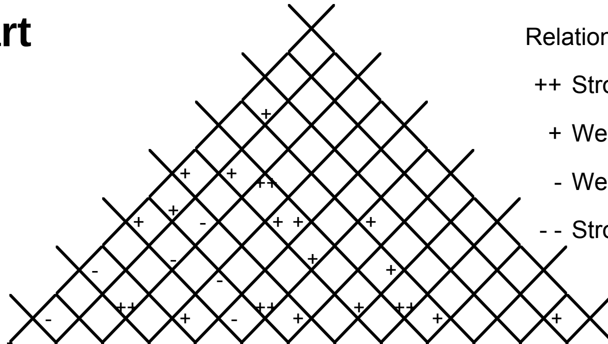
In his days at the U. of M., he has been a member of such groups as Greek Intervarsity Christian Fellowship, Chi Phi Fraternity, and lived in Alice Lloyd residence hall his senior year as Greek Affairs Advisor. Kyle has also had the great opportunity to develop a myriad of experiences and skills. Not only has he been an engineering intern at DuPont, but also spent a summer working as a quality control intern at a tiny auto supply company, Spring Design and Manufacturing, Inc. To add to his professional experience, Kyle has learned much from his positions as a mover, waiter, grocery bagger, and office assistant. He looks forward to being utilized in the future of a worthy employer, but has no work or location preference. He looks to follow his parents' advice in his future endeavors: "Bloom where you're planted."

Ryan Stevens
Mechanical Engineering, Junior

Ryan Stevens was born in Ypsilanti, but his hometown is Hubbard Lake, MI, a rural community in northern lower Michigan, about 4 hours north of Ann Arbor. It's so rural that the county only has one stoplight (and that is a half hour from Ryan's house). He played basketball and ran track in high school. Currently, he is pursuing a joint Bachelors and Master's degree in Mechanical Engineering at the University of Michigan.

Ryan spent a lot of time in high school working on cars, and someday wants to own a custom car business. He also enjoys outdoor activities. After college, he would like to work in either the automotive or commercial power fields. He had a summer internship at a nuclear power plant in Bridgman, MI. Ryan thinks being involved in the construction of new power plants would be an interesting career.

Appendix B: QFD Chart



Relationships

++ Strong positive

\+ Weak positive

\- Weak negative

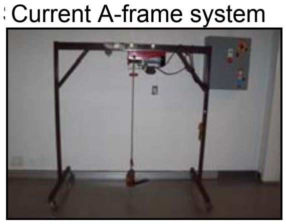
\- - Strong negative

(+) => more is better

(-) => less is better

		Weight	Device weight (-)	Lifting capacity (+)	Plate lifting time (-)	Number of plates lifted (+)	Ground clearance (+)	Device size (-)	Ease of movement over floor (+)	Number of operators (-)	Time to switch Cl. 8 truck to FWD car (-)	Number of control inputs required (-)	Purchased materials required (-)	Temperature range (+)	Humidity range (+)	Proposed Design	Current A-frame system	Scrapped manufacturers design
Engineering	Maneuverability from storage	5	3				3	9	9	3						5	5	3
Engineering	Withstand environmental cond.	10												9	9	5	5	5
Engineering	Re-use scrapped system	3		3	3							3	9	1	1	1	-	-
Engineering	Stack 2 plates per side	7					9		1		3	1				5	5	1
Engineering	Pick up multiple plates	9	1	9	3	9	1	3	1		9	1				5	1	3
Engineering	Keep device aligned over floor	10						3	9		1					5	1	2
Safety	Limit open floor space area	4				3										4	1	3
Safety	Limit open floor time	6			3	3										4	1	3
Safety	Power loss cannot drop plates	10		3												5	5	5
Safety	Ergonomics	8	3				1	3	9		1	9				4	2	2
Safety	Injury to operator	10				1		1		1						5	2	3
Operation	Minimal number of operators	8	3			1		3	9	9	3	9				3	2	2
Operation	Minimal turnover time	9		3	3	9	1		1		9					4	1	1
Operation	Automatic traversal	1	3					3	9	9	3	3	1			1	1	1
Operation	Speed of lifting	4		1	9	1					3					3	3	1
	Total		75	151	117	214	104	163	313	106	240	172	28	93	93	(1-5, 5 best)		
	Normalized		0.04	0.07	0.06	0.10	0.05	0.08	0.15	0.05	0.12	0.08	0.01	0.05	0.05			
	Importance Rating		12	6	7	3	9	5	1	8	2	4	13	10	11			
	Measurement Unit		kg	kg	sec	#	cm	m^2	peop.	#	hr	#	$	ºC	%			
	Proposed Design		500	500	5	6	25	≈4	2	2	1	3	20k	80	95			
	Current A-frame system		100	77	10	1	≈130	≈2	2	2	2	1	NA	80	95			
	Scrapped manufacturers design		300	154	20	2	<25	≈4	2	2	NA	2	NA	80	95			

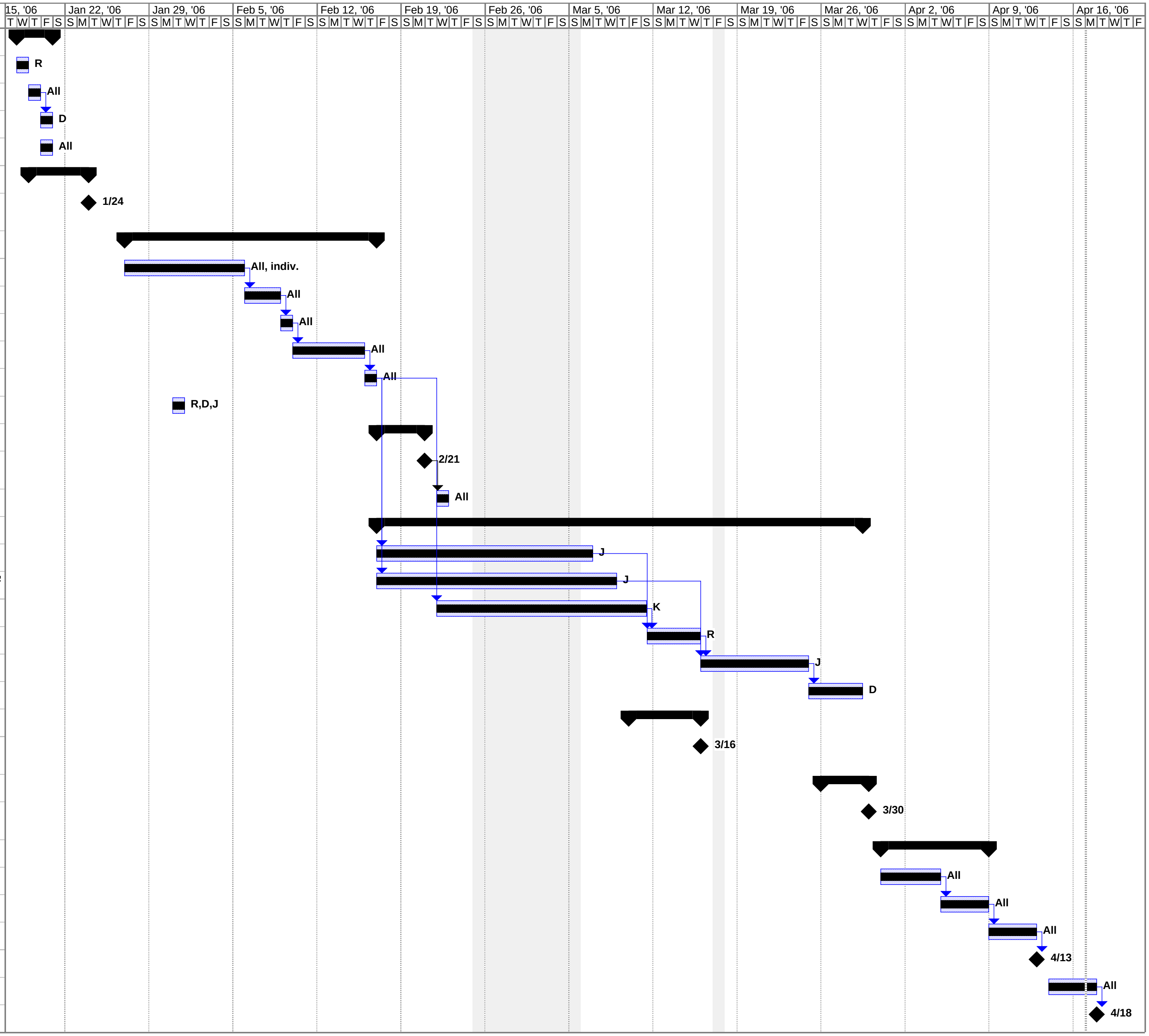
Benchmarked Designs: Current A-frame system



Scrapped manufacturers design

Appendix C: Gantt Chart

ID	Task Name
1	**Create Engineering Specifications**
2	Gantt Chart
3	Sponsor Meeting
4	Literature Review
5	QFD
6	**Write Presentation**
11	Design Review #1 - Engineering Specifications and Literature Review
12	**Generate Concept**
13	Brainstorm ideas / draw rough sketches
14	Pick best concepts
15	Sponsor Meeting - concepts need refining
16	Redo concepts with new requirements
17	Sponsor Meeting - concept approved
18	Welding training
19	**Write Presentation**
24	Design Review #2 - Concept Generation, Selection, Preliminary Engineering Analysis
25	DR #2 Feedback
26	**Design Work**
27	Create Unigraphics Model
28	Select & Evaluate Magnets & Lifting Cylinders
29	Research Structural Materials
30	FE analysis
31	Create parts list
32	Get parts list into Behr's purchasing system
33	**Write Presentation**
38	Design Review #3 - Final Design & Engineering Analysis
39	**Write Presentation**
44	Design Review #4 - Alpha Prototype Review
45	**Testing**
46	Finalize all strength calculations
47	Create animation
48	Make display for Expo
49	Design Expo
50	Report writing
51	Final Report

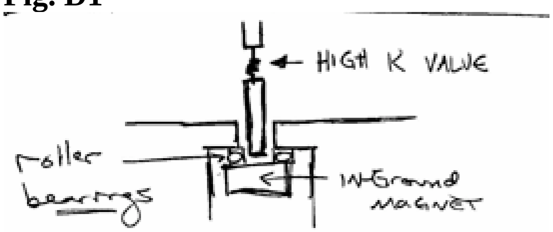


Appendix D: Additional Concepts

All of the additional concepts were grouped into alignment designs, traversal designs, storage designs, and other designs.

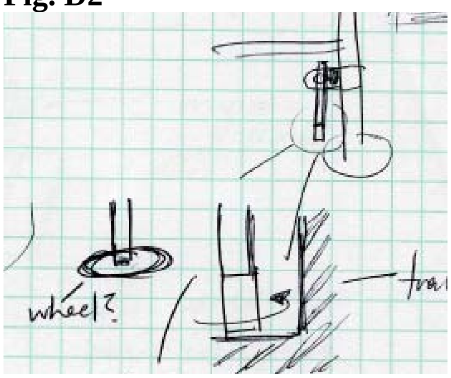
Alignment Designs

Fig. D1



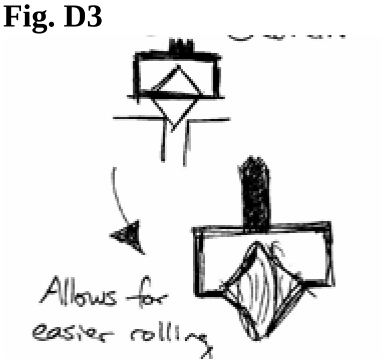
- Allows bar to slide within crooked track by utilizing attached spring.

Fig. D2



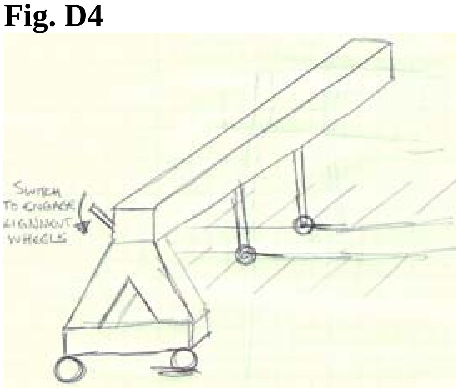
- Uses turning rod/wheel on the end of a bar kept in contact with a spring.

Fig. D3



- Utilizes curved wheel to allow movement along shifting track.
- The shape of the wheels force them to lay inside track.

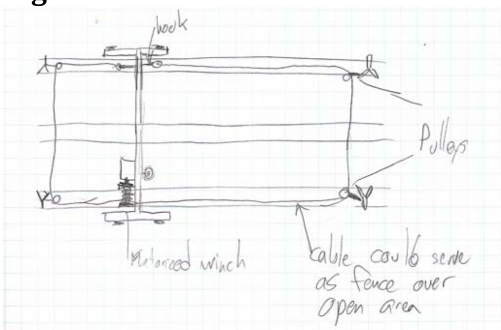
Fig. D4



- Shows swinging down of wheels to engage track and keep system straight while traversing.

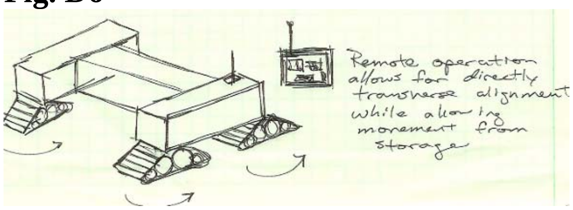
Traversal Designs

Fig. D5



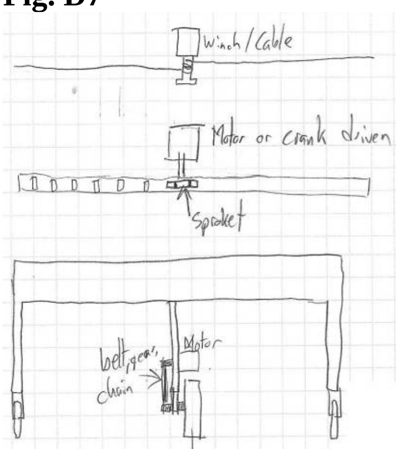
- Uses pulley system to move entire lifting mechanism up and down along tunnel.

Fig. D6



- Uses tank treads to address slipping.
- Remote control allows alignment.

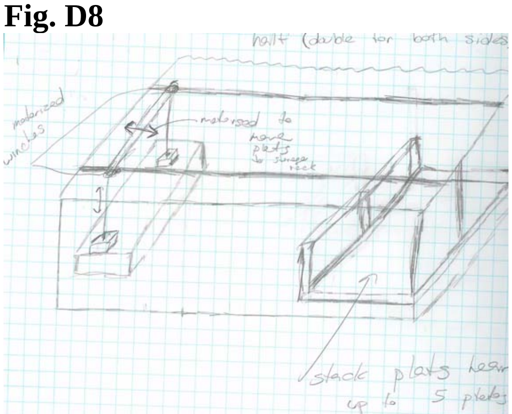
Fig. D7



- Uses a winch/cable system to drive the large lifter/magnet.
- Uses a motor and sprocket.
- Uses a wheel driven by a motor.

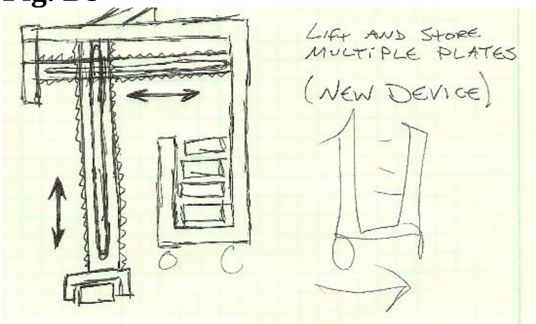
Storage Designs

Fig. D8



- Uses a side caddy to temporarily store plates for movement.

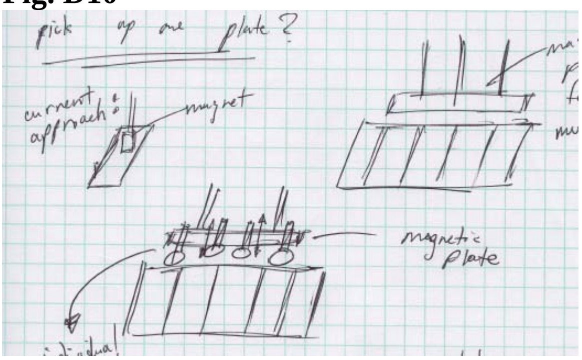
Fig. D9



- Rolling cart to store plates while apparatus moves.

Other Designs

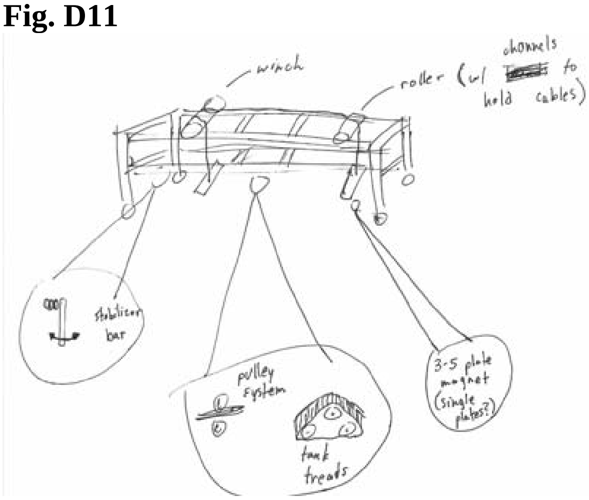
Fig. D10



Magnet mechanism

- Allows lifting of possible four plates at a time, but gives possibility to take just one or two.

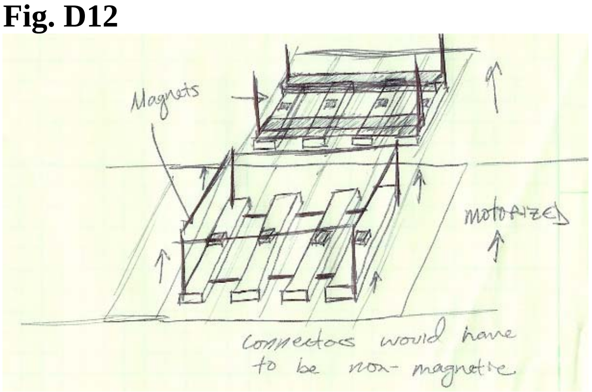
Fig. D11



Early overall system design

- Employs current winch system for plate lifting.

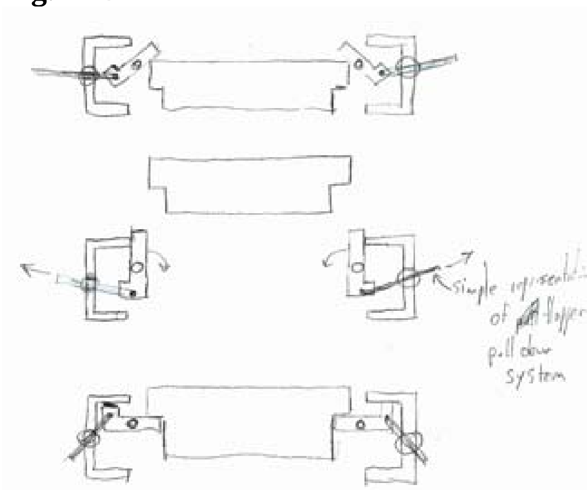
Fig. D12



Multiple plate lifting system

- Magnets actuate electronically.

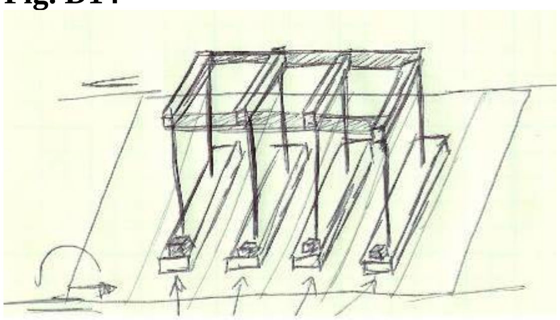
Fig. D13



Latch design

- Allows plates to be stored temporarily.
- Plates lift straight up and set upon swinging latches.
- Latches then release to allow replacement of plates after movement.

Fig. D14



Lifting design

- Shows flexibility to lift one to four plates at a time.

Appendix E: Dimensions and Weights

This appendix includes dimensions and weights of the floor plates in the wind tunnel. It also includes other miscellaneous specifications.

Table 12 – Floor Plate Dimensions

Size	Height (mm)	Width (mm)	Length (mm)	Mass (kg)
1	200	50	1210	20.00
2	200	75	1210	25.90
3	200	200	1210	47.17
4	200	350	1210	76.66

Other miscellaneous specifications:

- Safety restraint system is 9ft high. Cable diameter 3/4 inch, approximately
- Magnet, manufactured by Eriez Magnetics. Model = RPL11. Capacity = 1100 lbs
- Floor bolt size = 3/4 inch
- Power in tunnel = 480V, 100amp; 208/240V, 30amp; 110V, 20amp

Fig. 41 – Floor Dimensions

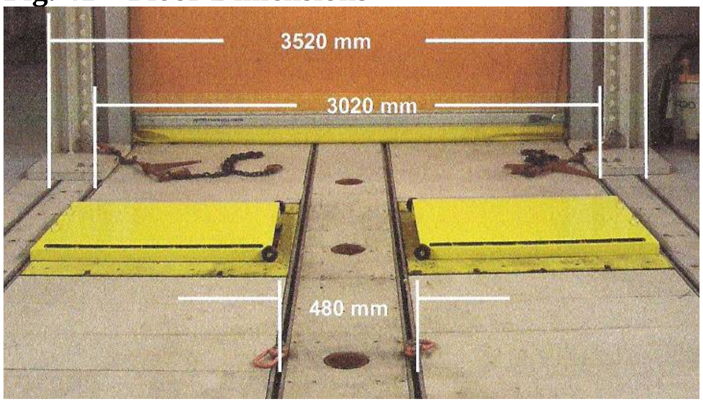
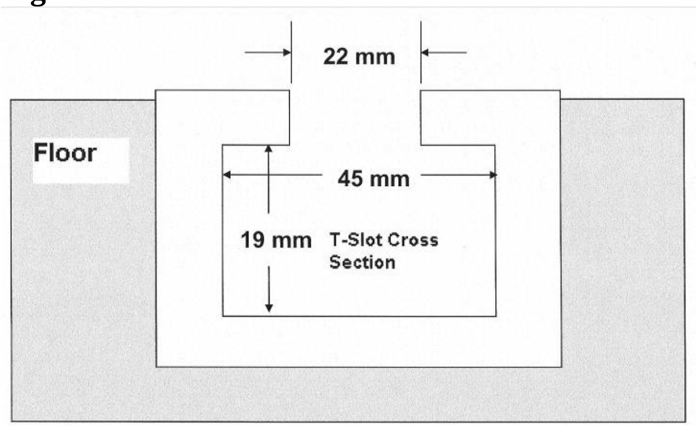
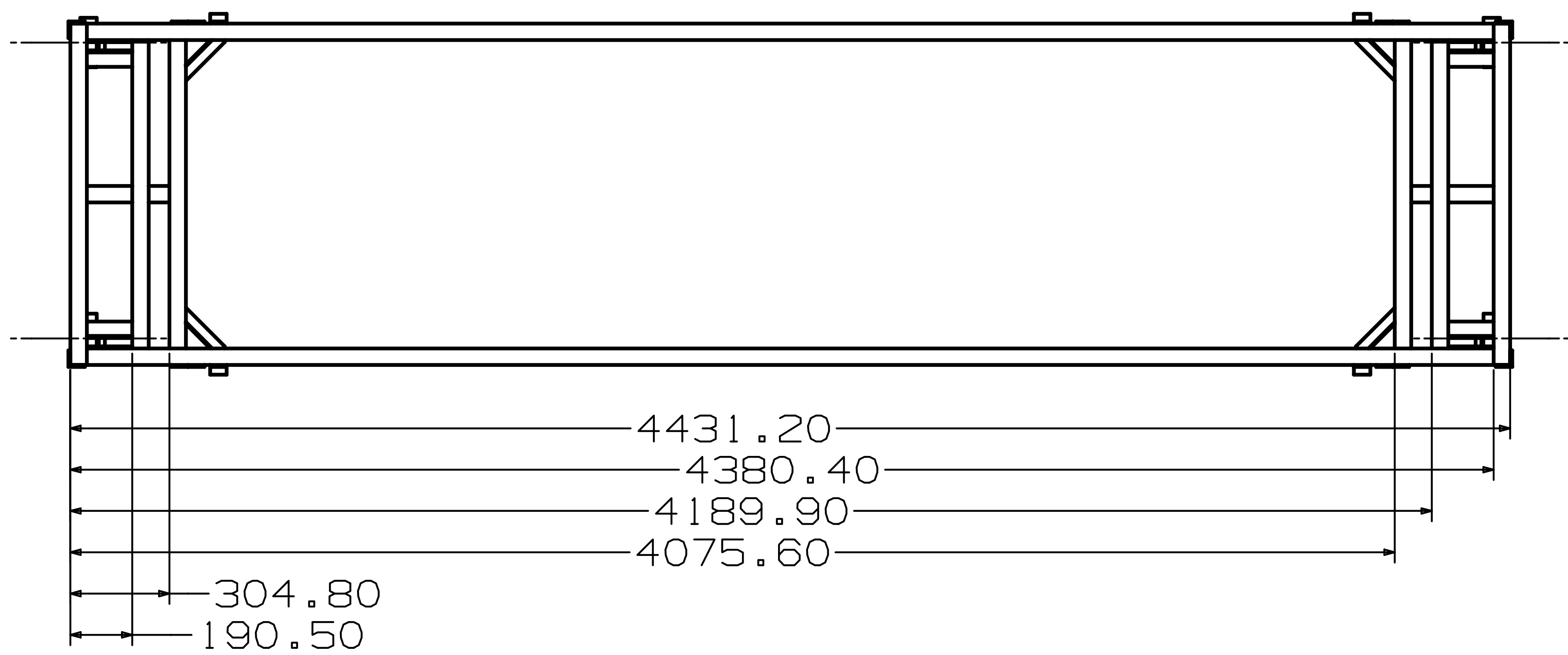
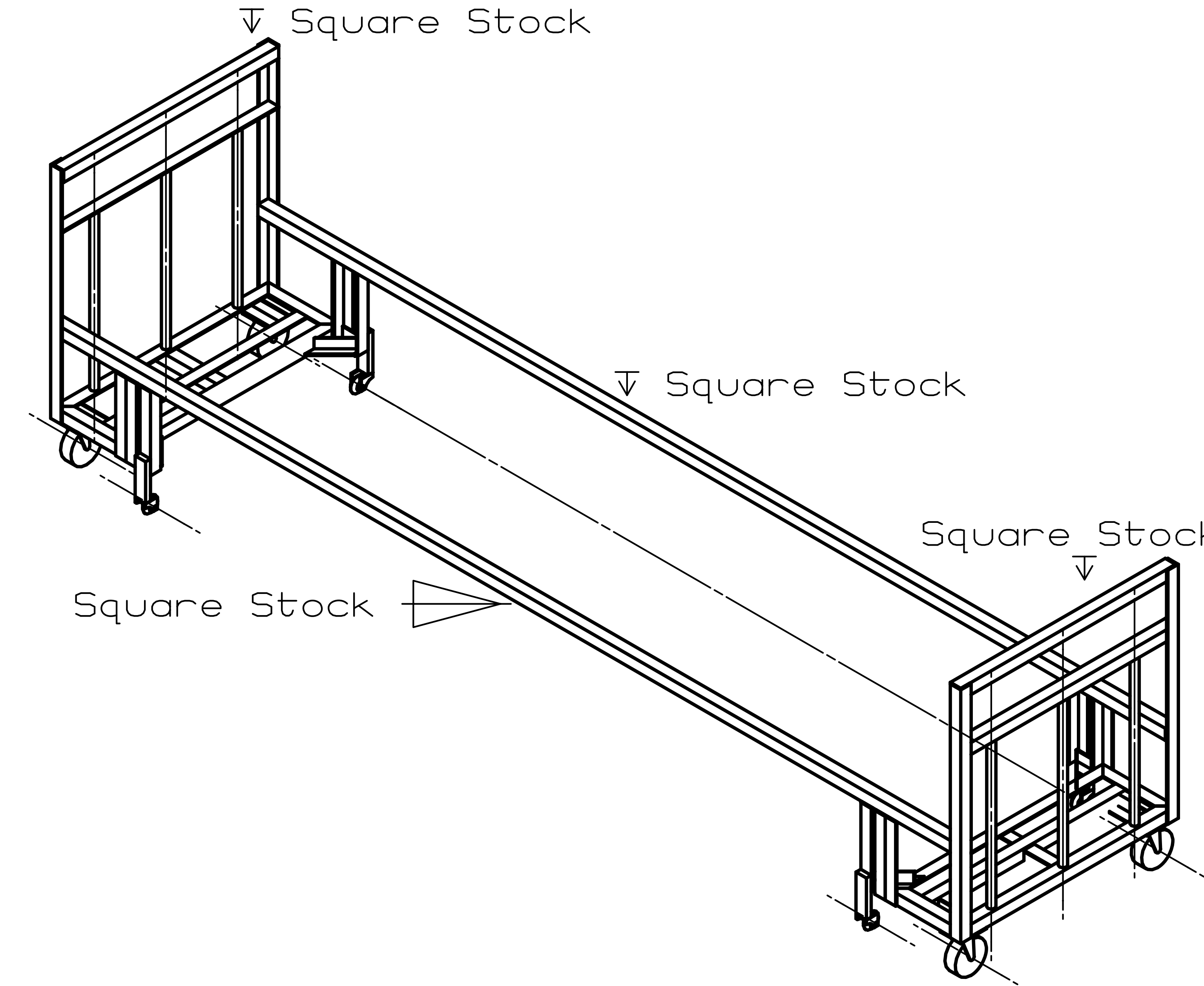
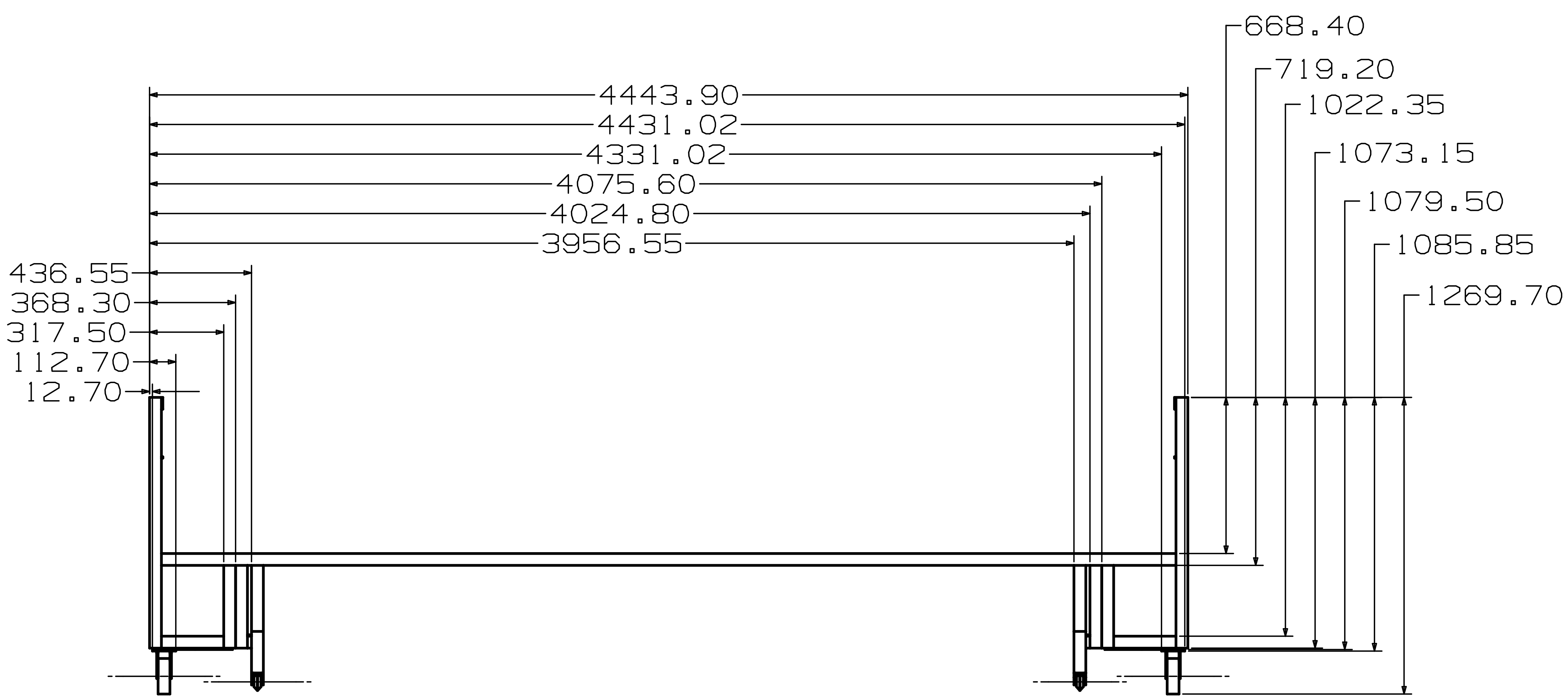


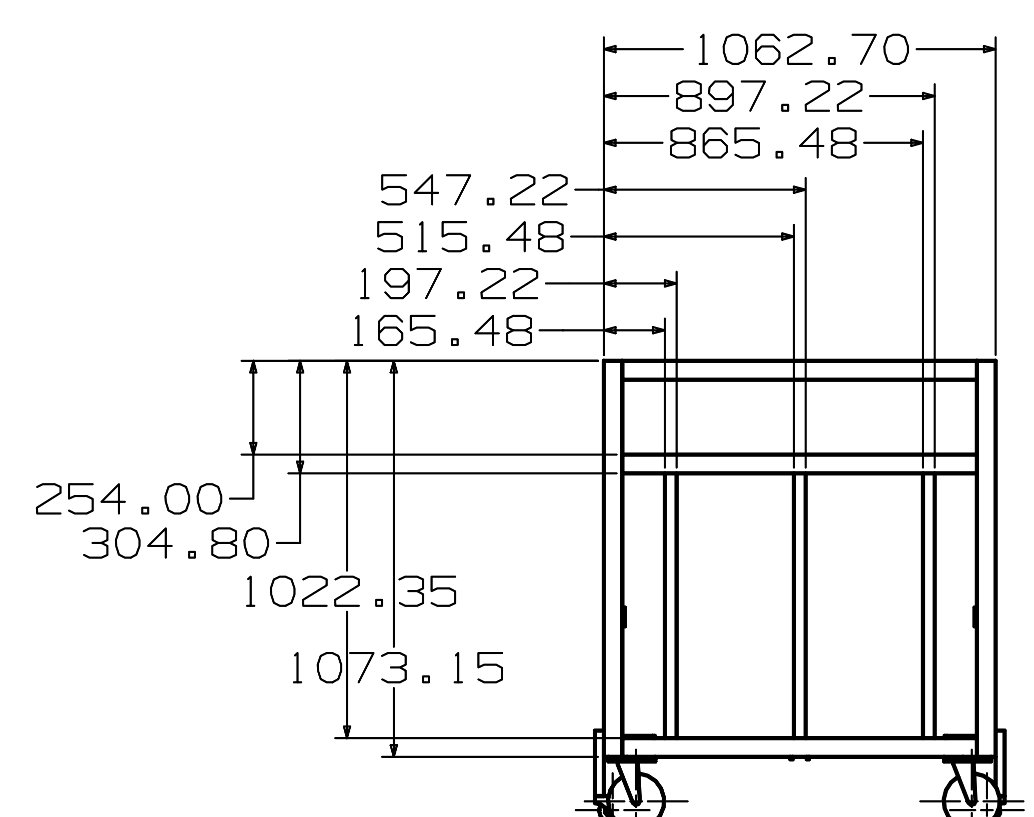
Fig. 42 – T-Slot Dimensions

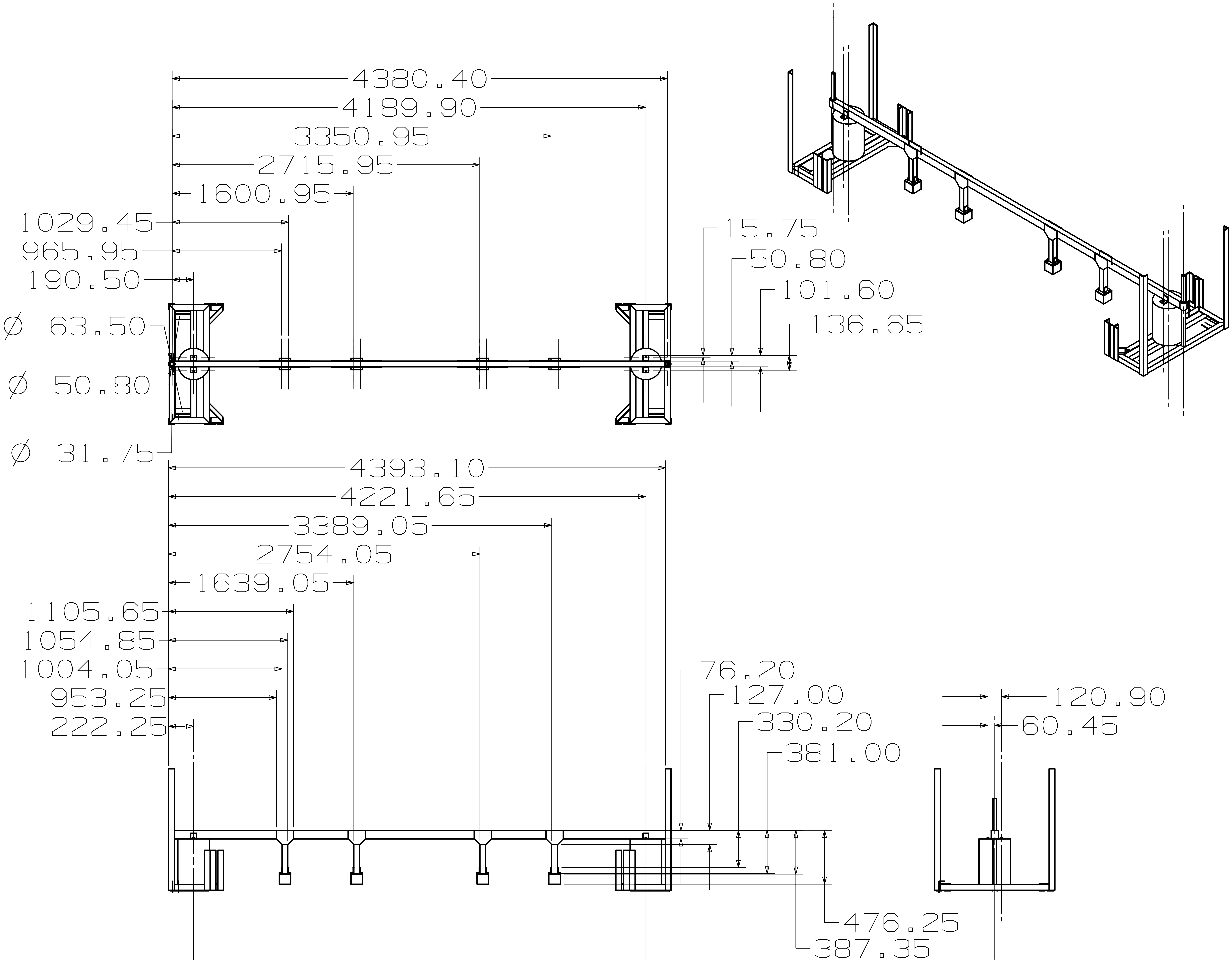


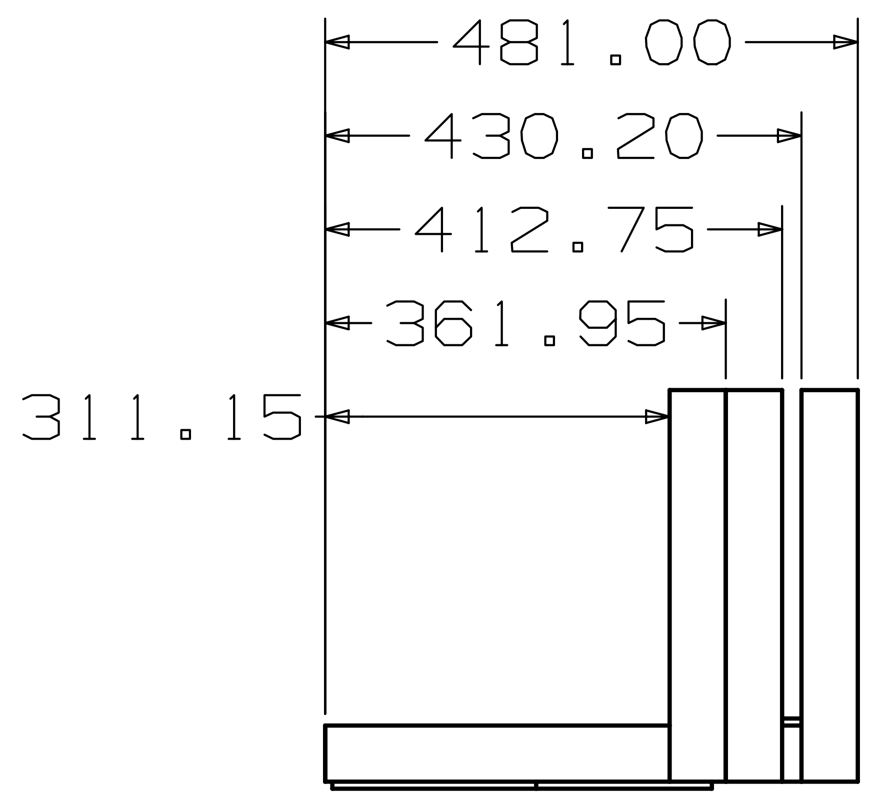

4431.20
4380.40
4189.90
4075.60
304.80
190.50

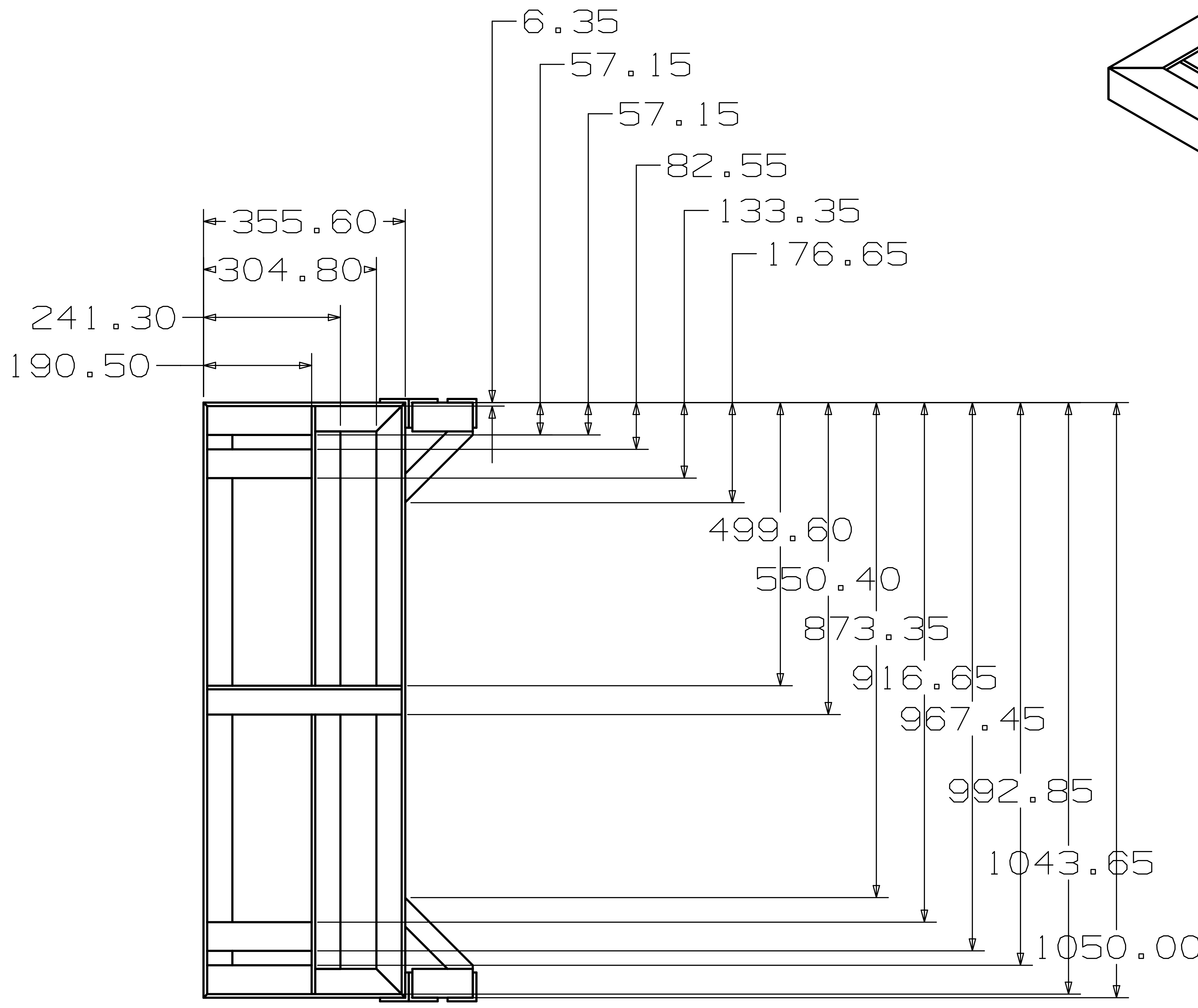

Square Stock
Square Stock
Square Stock
Square Stock

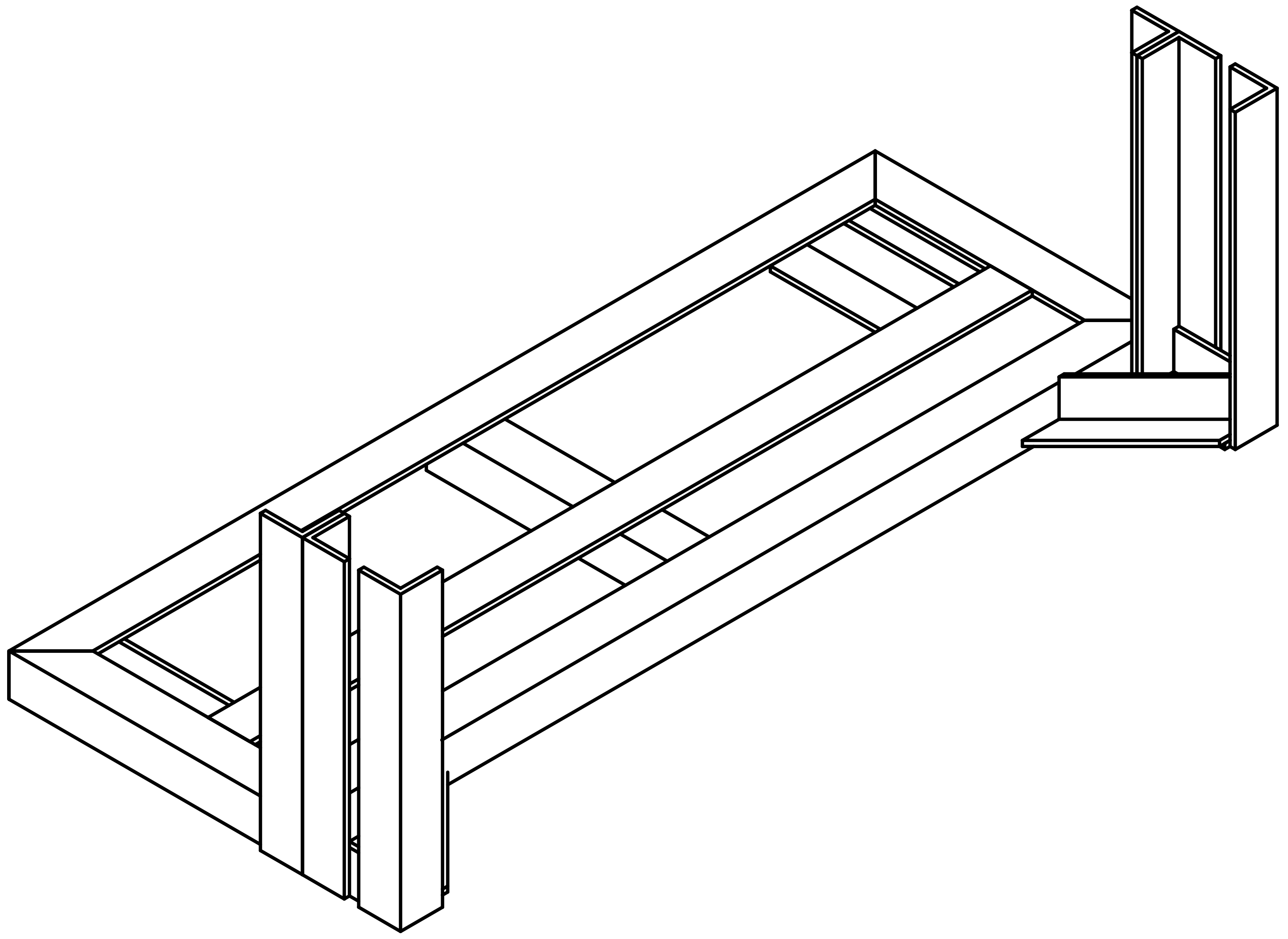

668.40
719.20
1022.35
1073.15
1079.50
1085.85
1269.70
4443.90
4431.02
4331.02
4075.60
4024.80
3956.55
436.55
368.30
317.50
112.70
12.70

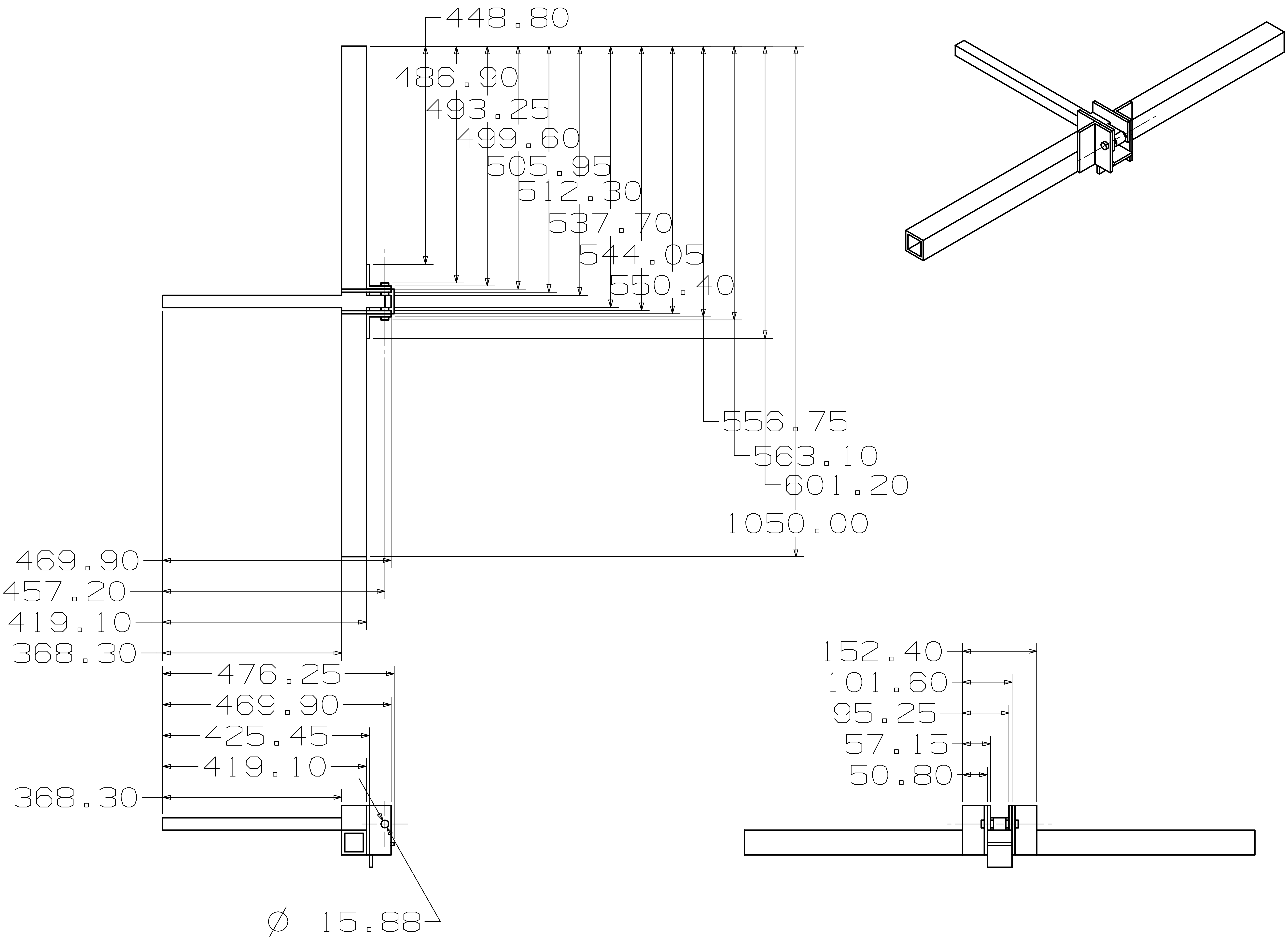

1062.70
897.22
865.48
547.22
515.48
197.22
165.48
254.00
304.80
1022.35
1073.15


4380.40
4189.90
3350.95
2715.95
1600.95
1029.45
965.95
190.50
∅ 63.50
∅ 50.80
∅ 31.75
15.75
50.80
101.60
136.65
4393.10
4221.65
3389.05
2754.05
1639.05
1105.65
1054.85
1004.05
953.25
222.25
76.20
127.00
330.20
381.00
476.25
387.35
120.90
60.45


481.00
430.20
412.75
361.95
311.15


6.35
57.15
57.15
82.55
133.35
176.65
355.60
304.80
241.30
190.50
499.60
550.40
873.35
916.65
967.45
992.85
1043.65
1050.00




448.80
486.90
493.25
499.60
505.95
512.30
537.70
544.05
550.40
556.75
563.10
601.20
1050.00
469.90
457.20
419.10
368.30
476.25
469.90
425.45
419.10
368.30
Ø 15.88
152.40
101.60
95.25
57.15
50.80

Appendix G: Bill of Materials

Legend:

MMC - McMaster-Carr (www.mcmaster.com)
IM - Industrial Magnets, Inc. (www.magnetics.com)
GC - General Caster Service, Inc. (Madison Heights, Michigan)
AK - Alro-Kurtz Steel (Detroit, Michigan)

Quan.	Cost	Subtotal	Description	Part Number
Structure Components:				
3	$ 127.16	$ 381.48	4140 Alloy Steel Hardened Chrome-Plated Rod 1.25" Diameter, 6' Length	MMC 6689T146
1	$ 33.02	$ 33.02	Oil-Impregnated Cast Nylon Hollow Rod 2" Od X 1" Id, 26" Length	MMC 84755K41
2	$ 89.08	$ 178.16	Single Wheel Caster with brake and lock 1200 pound capacity LEFT	MMC 2431T136
2	$ 89.08	$ 178.16	Single Wheel Caster with brake and lock 1200 pound capacity RIGHT	MMC 2431T121
4	$ 28.00	$ 112.00	Custom alignment casters, made out of light duty door stops and 3" HR Casters	GC
3	$ 94.10	$ 282.30	24 feet (7.3 meters) of 2”x3” square steel tubing, 0.25” thick, ASTM A-500 Grade B	AK 13026824
3	$ 71.76	$ 215.28	24 feet (7.3 meters) of 2”x2” square steel tubing, 0.25” thick, ASTM A-500 Grade B	AK 13009324
1	$ 19.04	$ 19.04	24 feet (7.3 meters) 1”x1” square steel tubing, 0.083" thick (was specified at 0.25” thick)	AK 13002124
4	$ 24.27	$ 97.08	20 feet (6 meters) 2”x2” steel A-36 angle, 0.25” thick	AK 04505520
2	$ 41.94	$ 83.88	12'x4"x0.25" steel plates (used in magnet mounting gussets)	AK 00108700
1	$ 29.72	$ 29.72	Steel Unthreaded Pipe 2" Pipe, 3' Length (for bearing)	MMC 7750K196
Magnet Components:				
14	$ 625.00	$ 8,750.00	Permatrol Lift Magnets	IM PME0404
1	$ 3,460.00	$ 3,460.00	Magnet Power Supply - 2000 Watt	IM PSB33200Axxx
3	$ 680.00	$ 2,040.00	Magnet Wiring Set	IM Wiring Set
Air System Components:				
6	$ 278.60	$ 1,671.60	Air Spring Max Force 2100lbs. @100psi. Compresed height = 6" Extended height = 20.1" Max OD. = 11" Center to Center mounting distance = 4.67" .5"-20	MMC 4324T12
3	$ 79.89	$ 239.67	Heavy Duty Pneumatic Control Valve Lever, 3-Way, 2-Position, Manual Return, 1/4" NPT	MMC 6859K34
3	$ 8.63	$ 25.89	0.021" Orifice Dia. Brass Flow-Control Orifice with Pipe Thread 1/4" Male Plug	MMC 2712T49
1	$ 7.50	$ 7.50	10 pk Brass Hose Barb, 3/16" Hose ID, 1/4" NPT	MMC 5346K12
1	$ 13.63	$ 13.63	Aluminum Distribution Manifold 3 Outlets, 3/8" NPT Inlet X 1/4" NPT Outlet	MMC 5469K113
1	$ 2.53	$ 2.53	Industrial-Shape Hose Coupling Plug, Znc-Pltd, 3/8" Nptf Male, 3/8" Cplg Size	MMC 6534K72
1	$ 12.07	$ 12.07	5pk Brass Hose Fitting Tee for 3/16" Hose Id	MMC 91355K51
100	$ -	$ -	feet of 0.25" stainless steel tubing	
	Total	**$ 17,833.01**		

Appendix H: Design Changes

Fig. 43 – Design changes between Design Review 3 and Final Report

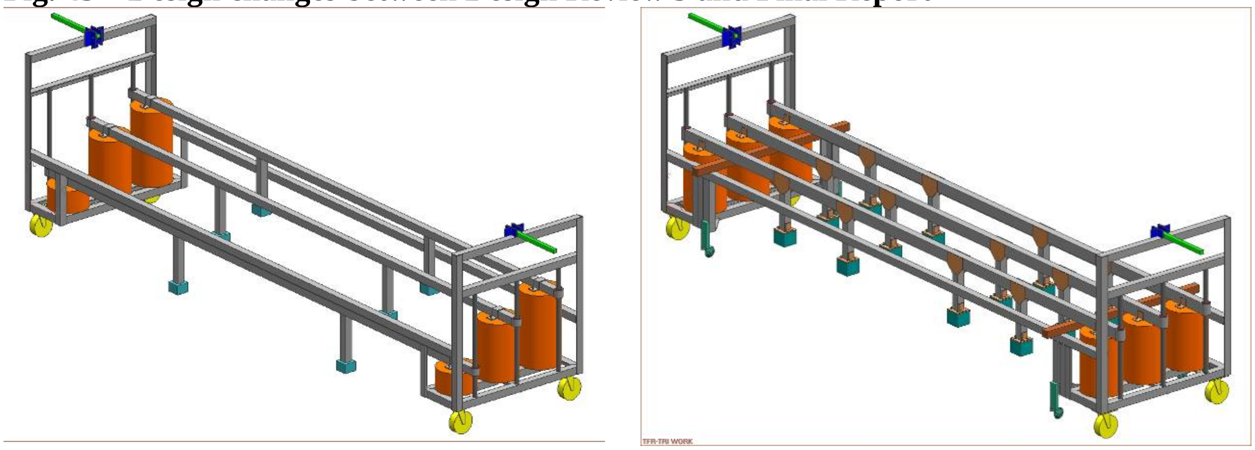


Fig. 43 above illustrates the design changes that Behr requested on March 21st, 2006. They include:

- Use two magnets per plate instead of one
- All steel tubing upgraded from 0.12" thick to 0.25" thick
- Use 2"x3" steel lifting beams instead of 2"x2"
- Air regulators removed from air system since shop air can be regulated to lower pressures
- Alignment casters finalized

In the creation of this report on April 11th, 2006, we found two errors in our previous calculations. They are listed below, with the required design change:

- Analysis showed that pin in the push bar should be upgraded from 3/8" to 5/8" in diameter
- Analysis showed that initial calculations of the flow control orifice led us to specify an orifice diameter that was much too small. We suggest drilling out the orifice to allow quicker air bag deflection.

designsafe Report

Application:	Wind Tunnel Floor Plate Reconfiguration System	Analyst Name(s):	Jacquie Foust, Kyle McGrady, Derrick Quandt, Ryan Stevens
Description:	This report will assess the risk of all persons using and moving around the plate reconfiguration system while in use and in storage.	Company:	Behr America, Corp.
Product Identifier:		Facility Location:	2700 Daley Dr Troy, MI 48083
Assessment Type:	Detailed		
Limits:	This report will assess the risk of all persons in contact with the plate reconfiguration system while completing different tasks integral to its operation and storage.		
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
operator move in/out of storage	mechanical : crushing	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator move in/out of storage	mechanical : stabbing / puncture	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator move in/out of storage	mechanical : break up during operation	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator move in/out of storage	mechanical : impact	Slight Occasional Possible	Moderate	standard procedures	Slight Occasional Unlikely	Moderate	
operator move in/out of storage	slips / trips / falls : slip	Slight Occasional Unlikely	Moderate	standard procedures	Slight Occasional Negligible	Low	
operator move in/out of storage	slips / trips / falls : trip	Slight Occasional Unlikely	Moderate	standard procedures	Slight Occasional Negligible	Low	
operator move in/out of storage	slips / trips / falls : debris	Slight Occasional Possible	Moderate	standard procedures	Slight Occasional Unlikely	Moderate	
operator move in/out of storage	slips / trips / falls : impact to / with	Minimal Occasional Unlikely	Low	standard procedures	Minimal Occasional Negligible	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
operator move in/out of storage	ergonomics / human factors : excessive force / exertion	Minimal Occasional Unlikely	Low	substitute less hazardous material / methods, standard procedures	Minimal Occasional Negligible	Low	
operator move in/out of storage	ergonomics / human factors : posture	Minimal Occasional Possible	Moderate	substitute less hazardous material / methods, standard procedures	Minimal Occasional Unlikely	Low	
operator hook up electrical/pneumatic system	mechanical : magnetic attraction / movement	Minimal Occasional Possible	Moderate	substitute less hazardous material / methods	Minimal Occasional Unlikely	Low	
operator hook up electrical/pneumatic system	electrical / electronic : insulation failure	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator hook up electrical/pneumatic system	electrical / electronic : improper wiring	Serious Occasional Unlikely	Moderate	special procedures	Serious Occasional Negligible	Moderate	
operator hook up electrical/pneumatic system	slips / trips / falls : slip	Minimal Occasional Unlikely	Low	standard procedures	Minimal Occasional Negligible	Low	
operator hook up electrical/pneumatic system	slips / trips / falls : trip	Minimal Occasional Unlikely	Low	standard procedures	Minimal Occasional Negligible	Low	
operator hook up electrical/pneumatic system	slips / trips / falls : debris	Minimal Occasional Possible	Moderate	standard procedures	Minimal Occasional Unlikely	Low	
operator position above tracks	mechanical : crushing	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator position above tracks	mechanical : break up during operation	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator position above tracks	mechanical : magnetic attraction / movement	Minimal Occasional Possible	Moderate	substitute less hazardous material / methods	Minimal Occasional Unlikely	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
operator position above tracks	slips / trips / falls : slip	Minimal Occasional Unlikely	Low	standard procedures	Minimal Occasional Negligible	Low	
operator position above tracks	slips / trips / falls : trip	Minimal Occasional Unlikely	Low	standard procedures	Minimal Occasional Negligible	Low	
operator position above tracks	ergonomics / human factors : excessive force / exertion	Minimal Occasional Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Occasional Unlikely	Low	
operator position above tracks	ergonomics / human factors : posture	Minimal Occasional Possible	Moderate	substitute less hazardous material / methods, standard procedures	Minimal Occasional Unlikely	Low	
operator position above tracks	ergonomics / human factors : repetition	Minimal Occasional Probable	Moderate	substitute less hazardous material / methods, standard procedures	Minimal Occasional Possible	Moderate	
operator position above tracks	ergonomics / human factors : lifting / bending / twisting	Minimal Occasional Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Occasional Unlikely	Low	
operator position above tracks	ergonomics / human factors : human errors / behaviors	Minimal Occasional Unlikely	Low	standard procedures	Minimal Occasional Negligible	Low	
operator lock training wheels in place	mechanical : crushing	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator lock training wheels in place	mechanical : head bump on overhead objects	Minimal Occasional Possible	Moderate	standard procedures	Minimal Occasional Unlikely	Low	
operator lock training wheels in place	mechanical : break up during operation	Serious Occasional Unlikely	Moderate	prevent energy buildup	Serious Occasional Negligible	Moderate	
operator lock training wheels in place	ergonomics / human factors : posture	Minimal Occasional Possible	Moderate	substitute less hazardous material / methods, standard procedures	Minimal Occasional Unlikely	Low	
operator lock training wheels in place	ergonomics / human factors : lifting / bending / twisting	Minimal Occasional Probable	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Occasional Possible	Moderate	
operator lock training wheels in place	ergonomics / human factors : human errors / behaviors	Minimal Occasional Unlikely	Low	special procedures	Minimal Occasional Negligible	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
operator pull down/put up push handle	mechanical : pinch point	Minimal Occasional Unlikely	Low	standard procedures, substitute less hazardous material / methods	Minimal Occasional Negligible	Low	
operator move magnet lifting bar up/down	mechanical : crushing	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator move magnet lifting bar up/down	mechanical : break up during operation	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator move magnet lifting bar up/down	mechanical : magnetic attraction / movement	Slight Occasional Possible	Moderate	standard procedures, substitute less hazardous material / methods	Slight Occasional Unlikely	Moderate	
operator move magnet lifting bar up/down	ergonomics / human factors : deviations from safe work practices	Slight Occasional Possible	Moderate	special procedures	Slight Occasional Unlikely	Moderate	
operator attach steel plate to magnet(s)	mechanical : crushing	Serious Frequent Unlikely	High	substitute less hazardous material / methods	Serious Frequent Negligible	Moderate	
operator attach steel plate to magnet(s)	mechanical : head bump on overhead objects	Minimal Frequent Possible	Moderate	standard procedures	Minimal Frequent Unlikely	Moderate	
operator attach steel plate to magnet(s)	mechanical : break up during operation	Serious Frequent Unlikely	High	substitute less hazardous material / methods	Serious Frequent Negligible	Moderate	
operator attach steel plate to magnet(s)	ergonomics / human factors : posture	Minimal Frequent Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Frequent Unlikely	Moderate	
operator attach steel plate to magnet(s)	ergonomics / human factors : lifting / bending / twisting	Minimal Frequent Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Frequent Unlikely	Moderate	
operator move system along track w/ or w/o plates	mechanical : crushing	Serious Frequent Unlikely	High	substitute less hazardous material / methods	Serious Frequent Negligible	Moderate	
operator move system along track w/ or w/o plates	mechanical : break up during operation	Serious Frequent Unlikely	High	substitute less hazardous material / methods	Serious Frequent Negligible	Moderate	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
operator move system along track w/ or w/o plates	slips / trips / falls : slip	Minimal Frequent Unlikely	Moderate	standard procedures	Minimal Frequent Negligible	Low	
operator move system along track w/ or w/o plates	slips / trips / falls : trip	Minimal Frequent Possible	Moderate	standard procedures	Minimal Frequent Unlikely	Moderate	
operator move system along track w/ or w/o plates	ergonomics / human factors : excessive force / exertion	Minimal Frequent Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Frequent Unlikely	Moderate	
operator move system along track w/ or w/o plates	ergonomics / human factors : posture	Minimal Frequent Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Frequent Negligible	Low	
operator move system along track w/ or w/o plates	ergonomics / human factors : repetition	Minimal Frequent Probable	High	standard procedures, substitute less hazardous material / methods	Minimal Frequent Possible	Moderate	
operator move system along track w/ or w/o plates	None / Other : Pneumatic Supply Failure	Slight Frequent Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Slight Frequent Negligible	Low	
operator detach steel plate(s) from magnets	mechanical : crushing	Serious Frequent Unlikely	High	substitute less hazardous material / methods	Serious Frequent Negligible	Moderate	
operator detach steel plate(s) from magnets	mechanical : cutting / severing	Serious Frequent Unlikely	High	substitute less hazardous material / methods	Serious Frequent Negligible	Moderate	
operator detach steel plate(s) from magnets	mechanical : head bump on overhead objects	Minimal Frequent Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Frequent Negligible	Low	
operator detach steel plate(s) from magnets	mechanical : break up during operation	Serious Frequent Unlikely	High	substitute less hazardous material / methods	Serious Frequent Negligible	Moderate	
operator detach steel plate(s) from magnets	mechanical : magnetic attraction / movement	Slight Frequent Possible	High	standard procedures, substitute less hazardous material / methods	Slight Frequent Unlikely	Moderate	
operator detach steel plate(s) from magnets	ergonomics / human factors : posture	Minimal Frequent Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Frequent Unlikely	Moderate	
operator detach steel plate(s) from magnets	ergonomics / human factors : lifting / bending / twisting	Minimal Frequent Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Frequent Unlikely	Moderate	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
operator stack steel plates	mechanical : crushing	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator stack steel plates	mechanical : break up during operation	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator stack steel plates	mechanical : magnetic attraction / movement	Minimal Occasional Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Occasional Unlikely	Low	
operator stack steel plates	slips / trips / falls : impact to / with	Slight Occasional Possible	Moderate	special procedures	Slight Occasional Unlikely	Moderate	
operator stack steel plates	ergonomics / human factors : posture	Minimal Occasional Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Occasional Unlikely	Low	
operator stack steel plates	ergonomics / human factors : lifting / bending / twisting	Minimal Occasional Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Occasional Unlikely	Low	
operator stack steel plates	ergonomics / human factors : deviations from safe work practices	Slight Occasional Unlikely	Moderate	special procedures	Slight Occasional Negligible	Low	
operator stack steel plates	None / Other : Pneumatic Supply Failure	Slight Occasional Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Slight Occasional Negligible	Low	
operator move system over plate(s)	mechanical : crushing	Serious Frequent Unlikely	High	substitute less hazardous material / methods	Serious Frequent		
operator move system over plate(s)	mechanical : break up during operation	Serious Frequent Unlikely	High	substitute less hazardous material / methods	Serious Frequent Negligible	Moderate	
operator move system over plate(s)	mechanical : magnetic attraction / movement	Slight Frequent Possible	High	standard procedures, substitute less hazardous material / methods	Slight Frequent Unlikely	Moderate	
operator move system over plate(s)	slips / trips / falls : slip	Minimal Frequent Unlikely	Moderate	special procedures	Minimal Frequent Negligible	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
operator move system over plate(s)	slips / trips / falls : trip	Minimal Frequent Unlikely	Moderate	special procedures	Minimal Frequent Negligible	Low	
operator move system over plate(s)	slips / trips / falls : debris	Slight Frequent Unlikely	Moderate	special procedures	Slight Frequent Negligible	Low	
operator move system over plate(s)	slips / trips / falls : impact to / with	Slight Frequent Possible	High	special procedures	Slight Frequent Unlikely	Moderate	
operator lock wheels into place/direction	mechanical : crushing	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator lock wheels into place/direction	mechanical : head bump on overhead objects	Minimal Occasional Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Occasional Unlikely	Low	
operator lock wheels into place/direction	ergonomics / human factors : posture	Minimal Occasional Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Occasional Unlikely	Low	
operator lock wheels into place/direction	ergonomics / human factors : lifting / bending / twisting	Minimal Occasional Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Occasional Unlikely	Low	
operator lift/lower various-sized magnets	mechanical : crushing	Serious Frequent Unlikely	High	substitute less hazardous material / methods	Serious Frequent Negligible	Moderate	
operator lift/lower various-sized magnets	mechanical : break up during operation	Serious Frequent Unlikely	High	substitute less hazardous material / methods	Serious Frequent Negligible	Moderate	
operator lift/lower various-sized magnets	electrical / electronic : power supply interruption	Slight Frequent Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Slight Frequent Negligible	Low	
operator lift/lower various-sized magnets	None / Other : Pneumatic Supply Failure	Slight Frequent Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Slight Frequent Negligible	Low	
operator lift/lower guide wheels into tracks	mechanical : crushing	Serious Occasional Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator lift/lower guide wheels into tracks	mechanical : cutting / severing	Serious Occasional Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
operator lift/lower guide wheels into tracks	mechanical : stabbing / puncture	Serious Occasional Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
operator lift/lower guide wheels into tracks	mechanical : head bump on overhead objects	Minimal Occasional Possible	Moderate	standard procedures	Minimal Occasional Unlikely	Low	
operator lift/lower guide wheels into tracks	ergonomics / human factors : posture	Minimal Occasional Possible	Moderate	standard procedures	Minimal Occasional Unlikely	Low	
operator lift/lower guide wheels into tracks	ergonomics / human factors : repetition	Minimal Occasional Possible	Moderate	standard procedures	Minimal Occasional Unlikely	Low	
operator lift/lower guide wheels into tracks	ergonomics / human factors : lifting / bending / twisting	Minimal Occasional Possible	Moderate	standard procedures	Minimal Occasional Unlikely	Low	
maintenance technician lubrication	mechanical : crushing	Serious Remote Unlikely	Moderate	substitute less hazardous material / methods	Serious Remote Negligible	Low	
maintenance technician lubrication	mechanical : break up during operation	Serious Remote Unlikely	Moderate	substitute less hazardous material / methods	Serious Remote Negligible	Low	
maintenance technician lubrication	ergonomics / human factors : posture	Minimal Remote Possible	Low	standard procedures, substitute less hazardous material / methods	Minimal Remote Unlikely	Low	
maintenance technician lubrication	ergonomics / human factors : lifting / bending / twisting	Minimal Remote Possible	Low	standard procedures, substitute less hazardous material / methods	Minimal Remote Unlikely	Low	
maintenance technician parts replacement	mechanical : crushing	Serious Remote Unlikely	Moderate	substitute less hazardous material / methods	Serious Remote Negligible	Low	
maintenance technician parts replacement	mechanical : break up during operation	Serious Remote Unlikely	Moderate	substitute less hazardous material / methods	Serious Remote Negligible	Low	
maintenance technician parts replacement	ergonomics / human factors : posture	Minimal Remote Possible	Low	standard procedures, substitute less hazardous material / methods	Minimal Remote Unlikely	Low	
maintenance technician parts replacement	ergonomics / human factors : lifting / bending / twisting	Minimal Remote Possible	Low	standard procedures, substitute less hazardous material / methods	Minimal Remote Unlikely	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
maintenance technician special task(s) -calibration	mechanical : crushing	Serious Remote Unlikely	Moderate	substitute less hazardous material / methods	Serious Remote Negligible	Low	
maintenance technician special task(s) -calibration	mechanical : break up during operation	Serious Remote Unlikely	Moderate	substitute less hazardous material / methods	Serious Remote Negligible	Low	
maintenance technician special task(s) -calibration	electrical / electronic : power supply interruption	Slight Remote Unlikely	Low	standard procedures, substitute less hazardous material / methods	Slight Remote Negligible	Low	
maintenance technician special task(s) -calibration	ergonomics / human factors : posture	Minimal Remote Possible	Low	standard procedures, substitute less hazardous material / methods	Minimal Remote Unlikely	Low	
maintenance technician special task(s) -calibration	ergonomics / human factors : lifting / bending / twisting	Minimal Remote Possible	Low	standard procedures, substitute less hazardous material / methods	Minimal Remote Unlikely	Low	
maintenance technician special task(s) -calibration	None / Other : Pneumatic Supply Failure	Slight Remote Unlikely	Low	standard procedures, substitute less hazardous material / methods	Slight Remote Negligible	Low	
leader / supervisor trouble-shooting / problem solving	mechanical : crushing	Serious Remote Unlikely	Moderate	substitute less hazardous material / methods	Serious Remote Negligible	Low	
leader / supervisor trouble-shooting / problem solving	mechanical : break up during operation	Serious Remote Unlikely	Moderate	substitute less hazardous material / methods	Serious Remote Negligible	Low	
leader / supervisor trouble-shooting / problem solving	electrical / electronic : power supply interruption	Slight Remote Unlikely	Low	standard procedures, substitute less hazardous material / methods	Slight Remote Negligible	Low	
leader / supervisor trouble-shooting / problem solving	ergonomics / human factors : posture	Minimal Remote Possible	Low	standard procedures, substitute less hazardous material / methods	Minimal Remote Unlikely	Low	
leader / supervisor trouble-shooting / problem solving	ergonomics / human factors : lifting / bending / twisting	Minimal Remote Possible	Low	standard procedures, substitute less hazardous material / methods	Minimal Remote Unlikely	Low	
leader / supervisor trouble-shooting / problem solving	None / Other : Pneumatic Supply Failure	Slight Remote Unlikely	Low	standard procedures, substitute less hazardous material / methods	Slight Remote Negligible	Low	
leader / supervisor inspect parts	mechanical : crushing	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
leader / supervisor inspect parts	mechanical : break up during operation	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
leader / supervisor inspect parts	ergonomics / human factors : posture	Minimal Occasional Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Occasional Unlikely	Low	
leader / supervisor inspect parts	ergonomics / human factors : lifting / bending / twisting	Minimal Occasional Possible	Moderate	standard procedures, substitute less hazardous material / methods	Minimal Occasional Unlikely	Low	
leader / supervisor walking along / by equipment	mechanical : crushing	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
leader / supervisor walking along / by equipment	mechanical : cutting / severing	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
leader / supervisor walking along / by equipment	mechanical : break up during operation	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
leader / supervisor walking along / by equipment	electrical / electronic : power supply interruption	Slight Occasional Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Slight Occasional Negligible	Low	
leader / supervisor walking along / by equipment	ergonomics / human factors : deviations from safe work practices	Minimal Occasional Possible	Moderate	special procedures	Minimal Occasional Unlikely	Low	
leader / supervisor walking along / by equipment	None / Other : Pneumatic Supply Failure	Slight Occasional Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Slight Occasional Negligible	Low	
leader / supervisor check alignment	mechanical : crushing	Serious Remote Unlikely	Moderate	substitute less hazardous material / methods	Serious Remote Negligible	Low	
leader / supervisor check alignment	mechanical : pinch point	Slight Remote Unlikely	Low	standard procedures, substitute less hazardous material / methods	Slight Remote Negligible	Low	
leader / supervisor check alignment	mechanical : break up during operation	Serious Remote Unlikely	Moderate	substitute less hazardous material / methods	Serious Remote Negligible	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
leader / supervisor check alignment	ergonomics / human factors : posture	Minimal Remote Possible	Low	standard procedures, substitute less hazardous material / methods	Minimal Remote Unlikely	Low	
leader / supervisor check alignment	ergonomics / human factors : lifting / bending / twisting	Minimal Remote Possible	Low	standard procedures, substitute less hazardous material / methods	Minimal Remote Unlikely	Low	
passer-by / non-user walk near machinery	mechanical : crushing	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
passer-by / non-user walk near machinery	mechanical : cutting / severing	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
passer-by / non-user walk near machinery	mechanical : break up during operation	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
passer-by / non-user walk near machinery	electrical / electronic : power supply interruption	Slight Occasional Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Slight Occasional Negligible	Low	
passer-by / non-user walk near machinery	ergonomics / human factors : deviations from safe work practices	Minimal Occasional Possible	Moderate	special procedures	Minimal Occasional Unlikely	Low	
passer-by / non-user walk near machinery	None / Other : Pneumatic Supply Failure	Slight Occasional Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Slight Occasional Negligible	Low	
passer-by / non-user work next to / near machinery	mechanical : crushing	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
passer-by / non-user work next to / near machinery	mechanical : cutting / severing	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
passer-by / non-user work next to / near machinery	mechanical : break up during operation	Serious Occasional Unlikely	Moderate	substitute less hazardous material / methods	Serious Occasional Negligible	Moderate	
passer-by / non-user work next to / near machinery	electrical / electronic : power supply interruption	Slight Occasional Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Slight Occasional Negligible	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
passer-by / non-user work next to / near machinery	None / Other : Pneumatic Supply Failure	Slight Occasional Unlikely	Moderate	standard procedures, substitute less hazardous material / methods	Slight Occasional Negligible	Low	