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April 15, 2021

Freya Hik
Mountains of Relief
2095 Cliffwood Rd.
North Vancouver, BC
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Dear Ms. Hik,

RE: Design Phase 3 – Improved Cookstove for Rural Nepal

G1 Consulting is pleased to present this Phase 3 Report for the Improved Cookstove for Rural Nepal. The following items are enclosed in this report:

- Detailed design description and analysis
- Design compliance matrix
- Product cost and manufacturing analysis
- Engineering design drawings

In total, the number of engineering hours spent on this project was 812 junior and 10 senior hours for a total cost of $74,580, around 30% over budget. The final manufacturing cost of each stove is an estimated $ 88.

It has been the pleasure of G1 Consulting to work alongside Mountains of Relief to design an improved cookstove. The team is grateful for the experience, as well as the guidance and contributions from all of the clients and advisors. If there are any questions, please direct them to the sponsor liaison Robert Chauvet (rchauvet@ualberta.ca).

Best Regards,

G1 Consulting

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Improved Cookstove for Rural Nepal

Phase 3 Design Report

April 15, 2021

Group 1 Consulting LLC.

Executive Summary

Families in rural Nepal lack access to reliable sources of energy and are reliant on deadfall wood to meet their home cooking and heating needs. Furthermore, many of these homes lack the proper infrastructure to efficiently remove harmful fumes from indoor spaces. This has led to unsustainable wood consumption and health problems for inhabitants. In partnership with Mountains of Relief, G1 Consulting has designed a rocket stove with finned chimney to meet the required specifications. These specifications included providing 1000W of heat to cookpots, and 1050W of space heating while emitting fewer than 0.23 grams of carbon dioxide per minute per World Health Organization guidelines.

The finalized design consists of a brick-and-mortar rocket stove with a galvanized steel finned chimney. It combusts wood efficiently because of the natural draft underneath the flame, and the chimney pulls the combustion flue gases outside of the home. The combustion heats two cookpots with 1050W of heat while also generating 1070W for space heating, meeting the requirements. The stove reduces wood consumption by 57% compared to conventional fires. While the design is theoretically closed and all flue gases would exit via the chimney, leakage points were analyzed to see the potential emissions released in the home. These were well below the target specified, at 0.05 g/min. Operational requirements were met while keeping proportions, dimensions, and methods of cooking with the new stove similar to existing solutions, which makes adoption easier.

Throughout our process, G1 Consulting focused on creating something that could be adopted in Nepal as seamlessly as possible. Our design solution will be manufactured with locally available materials and equipment and is economically viable for use. A cost analysis revealed that the materials transportation and labour for the stove would cost $88 CAD per unit, less than the target $100.

Overall, the project concluded at a total of 30% over budget, with the final charges to the project being $75,000. This was due to an unreliable assessment of the scope of the project. Before implementing the design in Nepal, G1 consulting recommends a prototyping phase be carried out to verify function and manufacturability.

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List of Acronyms

Acronym	**Full Term**
WHO	World Health Organization
ICS	Improved Cook Stove
IAP	Indoor Air Pollution
CAD	Canadian Dollars
TLUD	Top Lit Updraft
AEPC	Alternative Energy Promotion Center

1. Introduction

In rural Nepal, the methods for home cooking and heating are to collect deadfall wood from nearby forests and to burn it as a 3 stone open fire inside the home as shown in Figure 1. The problem with this is that most of these homes lack the proper infrastructure to efficiently remove harmful fumes from indoor spaces, creating severe health hazards due to smoke inhalation. In addition to this, on a wider scale, these primitive stoves are inefficient and disproportionately burn through the fuel supply. This contributes to a negative impact on the environment in the form of an unsustainable deforestation rate, resulting in loss of biodiversity, soil erosion, landslides, and flooding [1].

Mountains of relief is a charity organization that was initially established to help and support the people of Nepal after a devastating earthquake in 2015. They continue to carry out humanitarian initiatives and projects there including building and repairing schools and providing financial aid to individuals and groups in need.

Figure 1: A typical example of a wood burning stove in rural Nepal [1].

Mountains of Relief has commissioned G1 Consulting to design an improved cookstove. The stove is to be constructed from locally available materials and use local wood to boil water in two pots, heat a 14 m^2 kitchen in the winter (ambient outdoor conditions of 2 degrees Celsius, in a clay walled house), be more efficient than current 3-stone fires (target burn 30% more efficiently), and reduce the amount of harmful emissions released indoors (World Health Organization Guidelines of 0.23 g/min of particulate matter). The design has to do all of these things while keeping in mind the traditional cooking practices of families in rural Nepal. This report outlines the final design solution, including simulation analysis and cost and manufacturing details.

2. Design Specifications Revisions

As the project has evolved, the understanding of necessary specifications has also evolved. G1 Consulting has constantly been updating specifications as the project progresses to ensure that the resulting design is the most accurate. Table 1 shows a comprehensive list of the specification changes, while Appendix A – Specification Matrix Changes, details the changes and rational behind them.

Table 1: Design Specification changes from Phase 2 to Phase 3.

Former Specification	Revision	Justification
Deliver medium-high heat (1500 W) to the first pot (standard 5L cooking pots or Kadhai)	Deliver medium-high heat (1000 W) to the pots (standard 5L cooking pots or Kadhai)	Revisions to the heat analysis, and stating that 5 L pots are not to be completely full
Maintain comfortable temperature (15C) for kitchen (144ft^2 minimum, 7ft high) Desired heat flux: 2040W	Maintain comfortable temperature (15C) for kitchen (144ft^2 minimum, 7ft high) Desired heat flux: 1080W	Revisions made to the thermal envelope calculations since phase 2
Meet WHO threshold for fire admissions 0.59 (g CarbonDioxide /min) [24h avg]	Meet WHO threshold for fire admissions 0.23 (g CarbonDioxide /min) [24h avg]	This was taken as the more conservative estimate of an unvented room instead of a vented room
Target thermal efficiency: 100%	Target reduction in fuel use (compared with conventional three-stone fire) while maintaining operating requirements: 30% reduction	The client originally wanted efficiency to be maximized to reduce deforestation (wood consumption). Providing a direct comparison to a 3-stone fire while meeting the performance parameters provides a more direct assessment of fuel use reductions and impact on the end-user.
Cost of locally-available materials and labor. Target $30 CAD	Cost of locally-available materials and labor. Target $100 CAD	This new price was determined after further consultations with the client about including labor and transportation costs.

3. Overall Description

The final design has changed since our decision in Phase 2, combining elements of the finned chimney and rocket stove concepts. It now features a brick-and-mortar stove that is made to have features of a rocket stove design. The brick allows for a simple, stacking constriction without the use of complex molds or manufacturing. The design also consists of a clay stovetop that is custom molded to fit a two of a family's specific pots. This flexibility in the design allows for families to keep the pots and cooking practices they already have. Having holes in the cooktop also allows for more heat to be transferred from the combustion to the pot as it is in more direct contact. A chimney removes the harmful flue gases from the combustion area of the stove and releases them outside of the home. This is done via a galvanized steel chimney with cooling fins. With the fins, the surface area of the chimney is increased to allow for more heat to be extracted from the hot flue gases to be used for space heating. Table 2, Figure 2, and Figure 3 all outline the final design with annotated features.

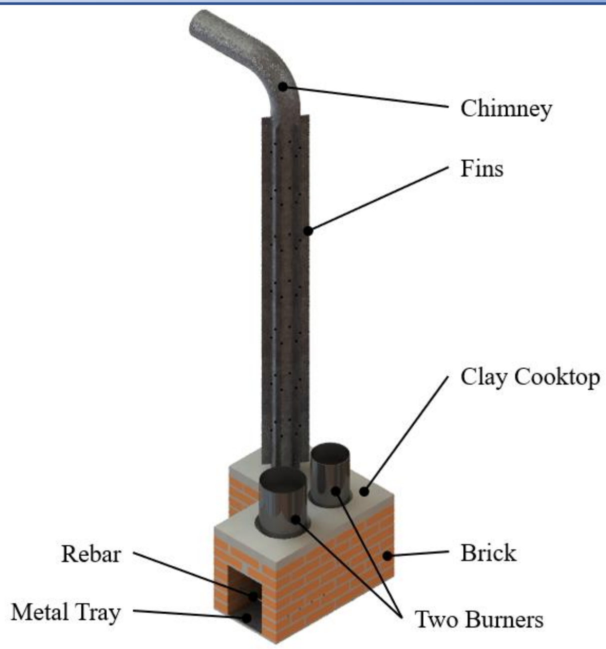


Figure 2: Overall design features with annotations.

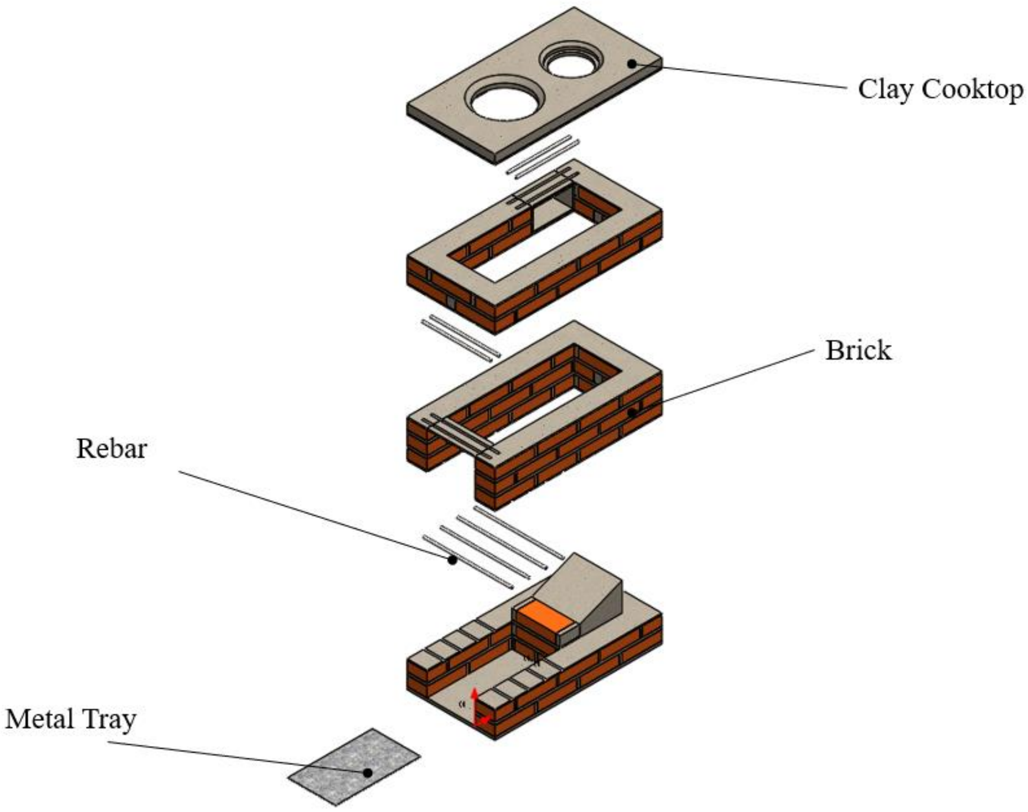


Figure 3: Annotated exploded view of the rocket stove.

Table 2: Design features of the final design.

Item	Usage
Chimney	Removes flue gases from the home to the outside. Constructed from hot dipped galvanize steel as it provides rigidity, good conduction and is locally available
Fins	Bolted to the inside & outside of chimney to provide more surface area for convection from flue gasses and thus larger heat transfer the room
Clay Cooktop	Accommodates two burners/pots and is custom molded from clay for each family's desired pots.
Rebar Supports	Provides a shelf for the wood to rest on and allow air to flow underneath. The rebar is embedded in the mortar layer between the bricks.
Metal Tray	Galvanized steel tray underneath wood to collect fallen ash for disposal
Two Burners	Two burner design accommodates two pots which is common in Nepalese cooking
Brick	Provides stove with a rigid, easy to manufacture design. Provides insulation to the combustion chamber so the stove reaches steady state operation faster.

To give a better understanding of the scale of the stove, the following diagram (Figure 4) outlines the dimensions while the table below (Table 3) summarises them.

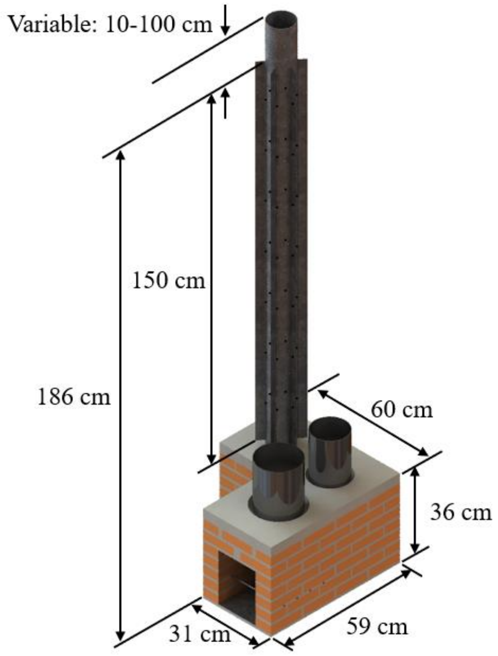


Figure 4: Stove with dimensions.

Table 3: Key dimensions of the stove.

Item	Dimension
Footprint	60 cm x 60 cm
Stove Height	36 cm
Top of Pot Height	54 cm
Finned Chimney Section	150 cm
Height of Chimney	Variable, minimum 196 cm

3.1 Combustion Chamber

The combustion chamber is where both the combustion of deadfall wood and the heating of the cooking pots occur, as shown in Figure 5. Table 4 gives a detailed explanation on the features and function of the combustion chamber. Deadfall wood from native species in Nepal is inserted in the fuel door on top of the rebar supports. This allows for the air, created by the natural draft from the chimney, to flow underneath the combustion. This phenomenon allows for a hotter and more complete combustion of the wood. This combustion then generates a flame and flue gases which help heat the pots on the stove. The flue gases heat the pots by convection, travelling over the bottom surface of the pots before the flue gases are pulled into the chimney and out of the home. The flame provides a radiation source that also heats the exposed bottom surface of the pots.

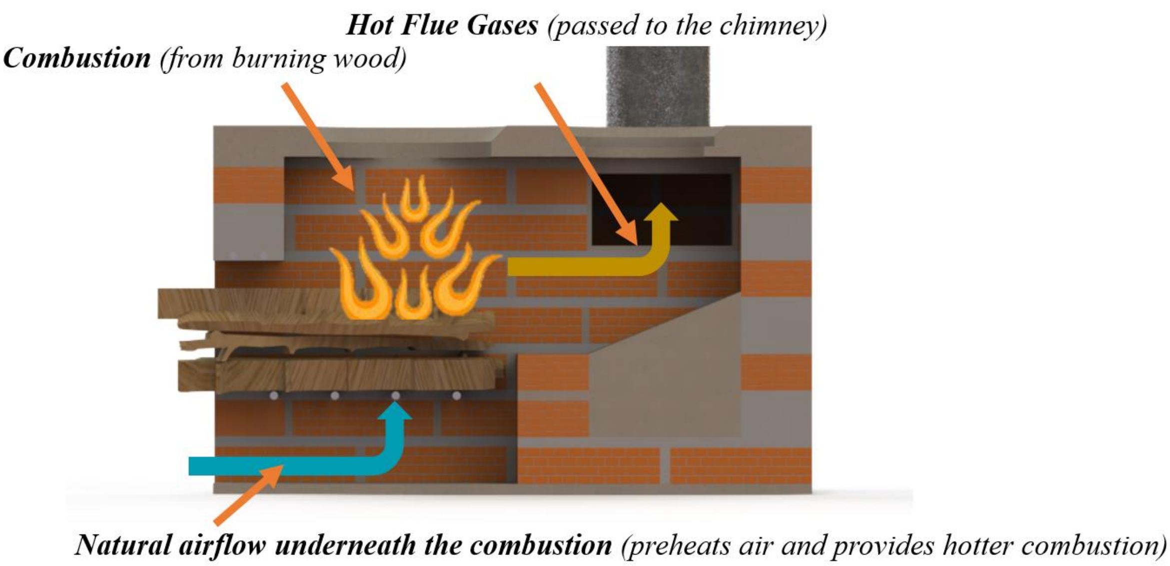


Figure 5: Combustion chamber design features.

Table 4: Design features of the combustion chamber.

Item	Usage
Natural Draft Airflow	Natural draft due to temperature differences from the stove and room provides the air and oxygen needed for combustion. This also pulls the flue gases through the chimney.
Flue Gases	From the wood combustion. Provides convection heat to the pots and flows into the chimney.
Combustion	Combustion is achieved by lighting wood and providing a sufficient oxygen supply. This combusts into flue gases, and provides heat to the pots via radiation

3.2 Chimney

The steel chimney has galvanized steel fins bolted to both its interior and exterior as seen in Figure 6. Preliminary analysis indicated that convection- particularly inside the chimney- was a limiting factor for heat transfer. The fins increase surface area and thus rate of natural and forced convection. The entire chimney extracts approximately 700W from flue gasses, 300W of which is a result of the added fins. This finned chimney allows the space heating requirements to be met with a smaller, more efficient fire. Complete calculations are given in Appendix E – Space Heating Analysis.

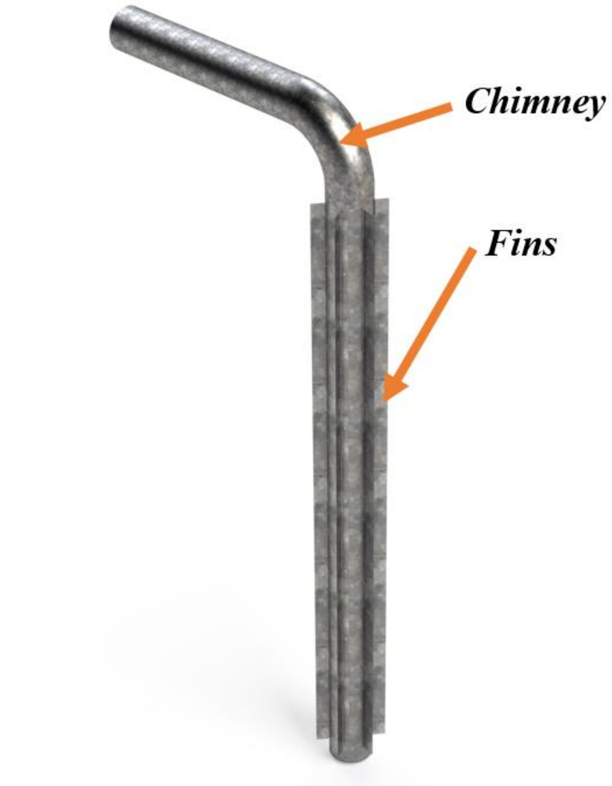


Figure 6: Annotated diagram of the chimney.

The fins and chimney are made from hot-dipped galvanized steel. This material is widely available, inexpensive, and corrosion resistant. This will extend the life of the system as hot flue gasses contain moisture and sulphur compounds from the biomass and may therefore be corrosive. Galvanized steel also has high thermal conductivity, aiding in heat transfer. Galvanized pipes are easily obtained from manufacturers in Nepal, and galvanized steel sheets are available in all villages as they are commonly used in roofing. While this design uses straight fins, corrugated sheeting is also available and offers more surface area per linear section due to its wave shape- offering improved heat transfer performance. Villagers may be able to easily build and repair fins as scraps of roofing material are often available for free.

3.3 Design Flexibility & Human Factors

Social acceptance of new cookstoves was noted by the client as a barrier to widespread adoption of improved cookstoves. Thus, the system was designed to integrate with existing techniques and adapt to constraints in different communities. This flexibility enables our design to accommodate as many communities needs as necessary while still reducing emissions and fuel consumption. Table 5 outlines the challenges and the solutions our design comes up with.

Table 5: Challenges and human factors considered in the design.

Human Considerations	Solution
Wood collection and preparation practices	Stove accommodates large pieces of wood that do not need to be cut or prepared before using
The small dwelling (144sq. ft) has limited room for a stove	The 60 cm by 60 cm footprint fits nicely in the corner of the kitchen, out of the way of other household activities
Height of the stove must be suitable for cooking while kneeling	Top of the cooking pot is 50 cm, below the NASA recommended kneeling height. [2] If a different height is needed, then the stove can be raised higher off the ground by adding a clay base.
Different communities may have differing access to materials and building supplies. Acceptance of new cookstoves may also differ in communities beyond those to whom we have spoken.	The design can be made with either just the rocket stove or the finned chimney dependant on resources and familial needs. The chimney does not need the fins attached if the village is in a warmer climate or if they lack the proper fasteners. The chimney can be retrofitted to an open fire or other improved cookstove if they currently have a solution that works. In the case of the chimney on an open fire, the chimney could be fitted to a range hood and roof hangers as demonstrated in Phase 2

4. Summary of Analysis

Analysis was performed to determine the performance of the design. The calculations done aligned with key specifications discussed within the team and with the client. This included the heat transferred to each pot, to the room, and generated from combustion and the emissions released to the room. A thorough material analysis was performed, which directly led into a cost analysis for the materials for each design. A summary of the analysis process is shown in Figure 7.

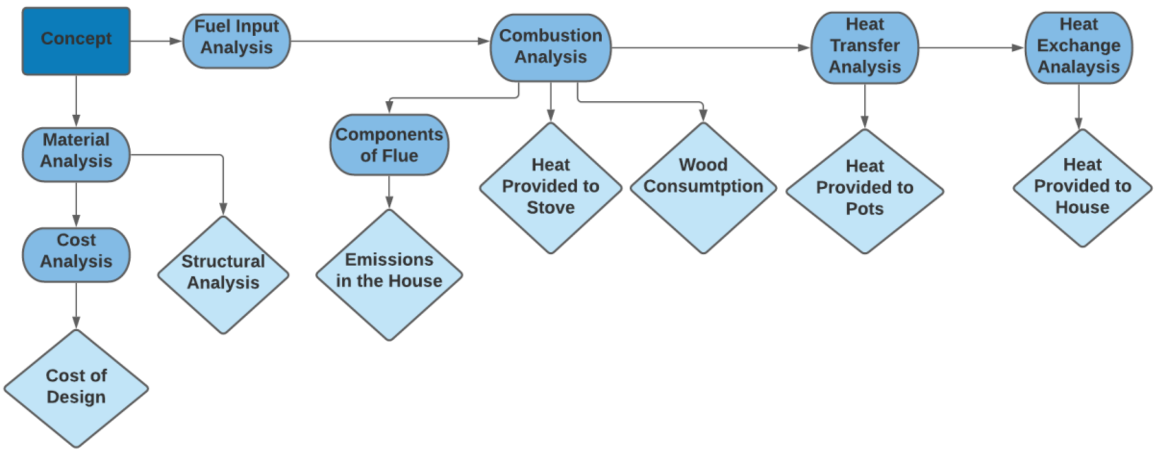


Figure 7: Summary of the Analysis.

4.1 Combustion

The components and physical properties of the flue gas was calculated by researching experimentally determined inputs for common bio-fuels found in Nepal. These values were then input to a Matlab program created by G1 Consulting to determine output parameters. The inputs and outputs of the program can be seen below as a flowchart in Figure 8. The complete Matlab program and values for inputs and outputs of the rocket stove can be seen in Appendix C – Combustion Analysis along with assumptions and methodology.

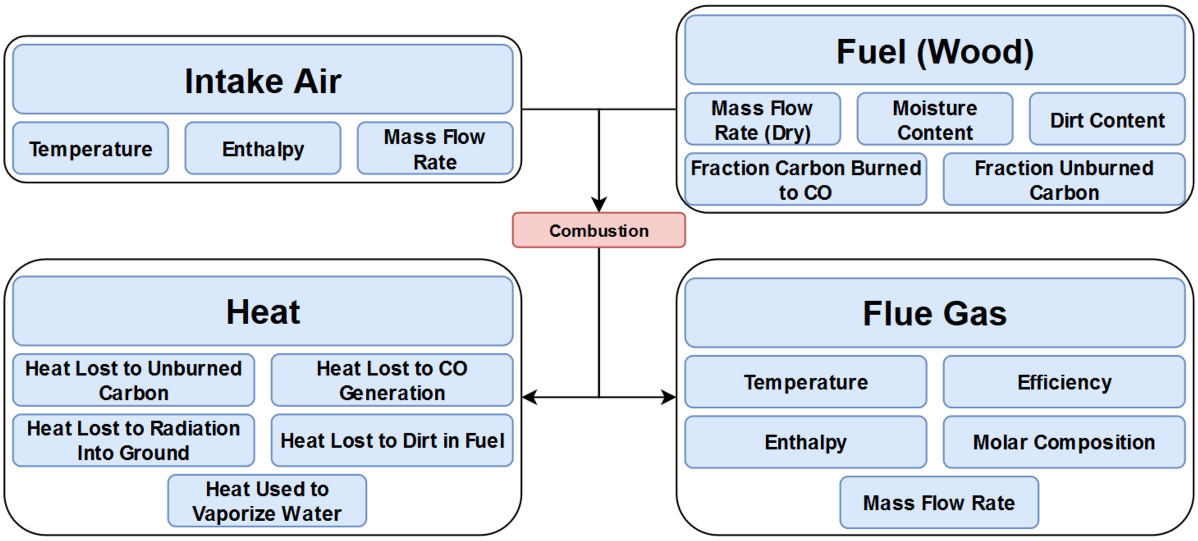


Figure 8: Flow chart of combustion analysis.

4.2 Heat Transfer to Pots

The heat transfer calculations were refined from Phase 2 to include a numerical analysis. This was done because for this complex heat transfer and geometry, hand calculations did not seem to adequately represent all of the parameters involved. For the numerical solution, SolidWorks Flow Simulation was used to perform a transient, conjugate heat transfer analysis. This involved radiation from the fire, convection of the flue gas over the pot surface and throughout the rest of the stove and chimney, and heat conduction through the stove and chimney. In the simulation, two pots were modeled with fluid subdomains containing water; the larger pot contained a volume of 2.5 L, with the smaller holding 1.7 L. The results of this can be seen below in Table 6. Note that the values shown for heat transfer rates are the sum of both pots with less radiation occurring at the second pot but a similar time to boil water due to the difference in volume. Figure 9 below shoes how the hot air from combustion interacts with the surfaces of the pots to transfer heat into the water with the visual aid of streamlines. Further details of this simulation can be found in Appendix D – Heat Transfer in the Stove Analysis.

Table 6: Heat power transferred to pots and time to boil.

Parameter	Value (Simulation)
Net incident radiation (both pots)	940 W
Convective heat transfer rate (both pots)	150 W
Time to boil water in small pot	1900 sec
Time to boil water in large pot	1880 sec

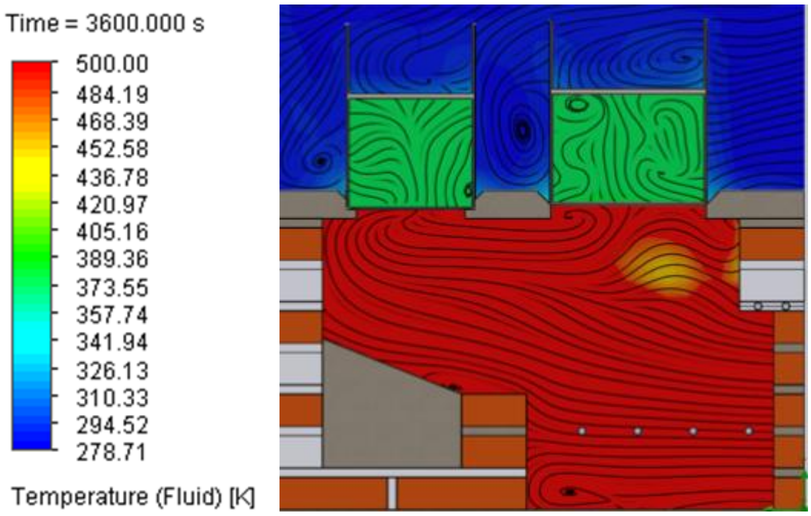


Figure 9: Heat transfer to pots.

4.3 Heat Transfer to Room

Like the heat transferred to the pots, heat transferred to the room was also solved using both analytical and numerical (simulation) methods. To sustain the required space heating for the prescribed floor area and temperatures, it was determined that at least 1050W of heating was required to compensate for the heat lost at steady-state due to both cold air infiltration and heat loss through brick walls and corrugated steel roof. This value was obtained from the most demanding conditions (15 °C inside, 2 °C outside) in winter. From this, the heat flux and airflow rate at the target conditions were obtained. The operating conditions specified by the client and average to the location are shown in Table 7.

Table 7: Parameters to calculate the thermal envelope of the room.

Variable	Value	Source
Room Dimensions (LxWxH) [m]	3.7 x 3.7 x 2.2	Client
Wall Material - Conduction rate [W/mK] - Convection rate [W/m^{2}K]	See Appendix F	[3]
Air Intake for Fire [m^3/s]	0.0045	Appendix C – Combustion Analysis
Number of Occupants	5	Client
Air Changes Per Hour	6	[4]
Internal Temperature [K]	275	Client
External Temperature [K]	293	Client

Further, a thermal network was developed as shown in Figure 10. This included the mechanisms of forced convection inside the pipe and over internal fins, plus natural convection over the cylindrical pipe and vertical fins outside the chimney. Convection from the pots and radiation from the pipe were also considered, in addition to the convection and radiation from the stove calculated from the combustion analysis. Constant surface temperatures were assumed for the 1.5m finned section and 1m finless section and checked in an iterative manner until a convergent solution was achieved. This assumption was validated using a static thermal analysis. Complete calculations can be found in Appendix E – Space Heating Analysis. It was determined that 1050W of heating would be required in the worst-case scenario, which is approximately the heating value predicted analytically (1064W) and through simulations (1190W). While these results may not be accurate to 5W due to underlying assumptions, it is reasonable to say that the required worst-case heating scenario has been met.

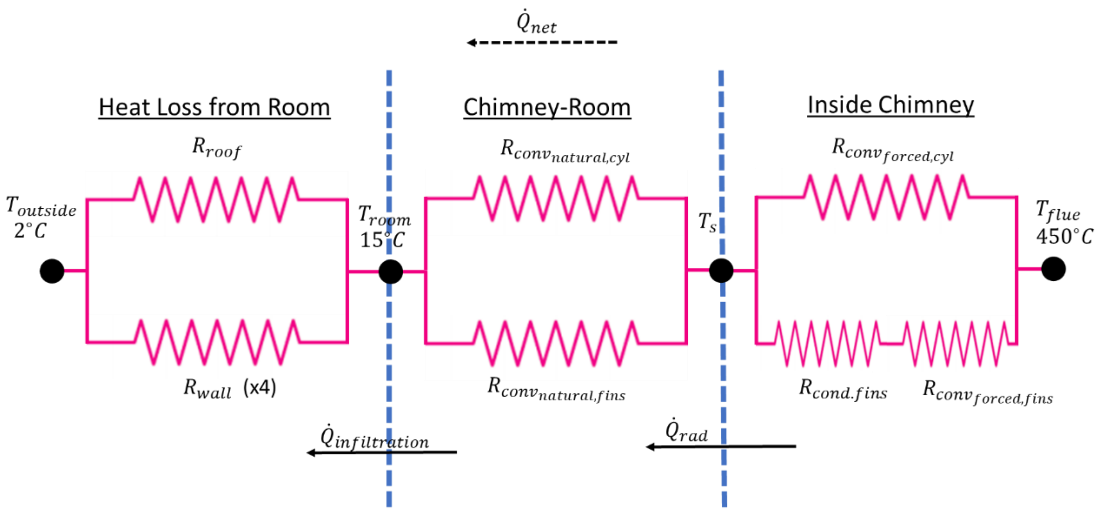


Figure 10: Thermal network diagram for the chimney-building system.

The assumption that the base of the chimney (i.e. the pipe) and the internal fins would be at a lumped average temperature for a given position on the chimney was assessed in SolidWorks. By specifying the internal and external convection coefficients as specified in Appendix E – Space Heating Analysis, the temperature gradient on the chimney was obtained, as show in Figure 11. The inside and outside walls of the pipe were within 50°C of each other, therefore this assumption was considered valid.

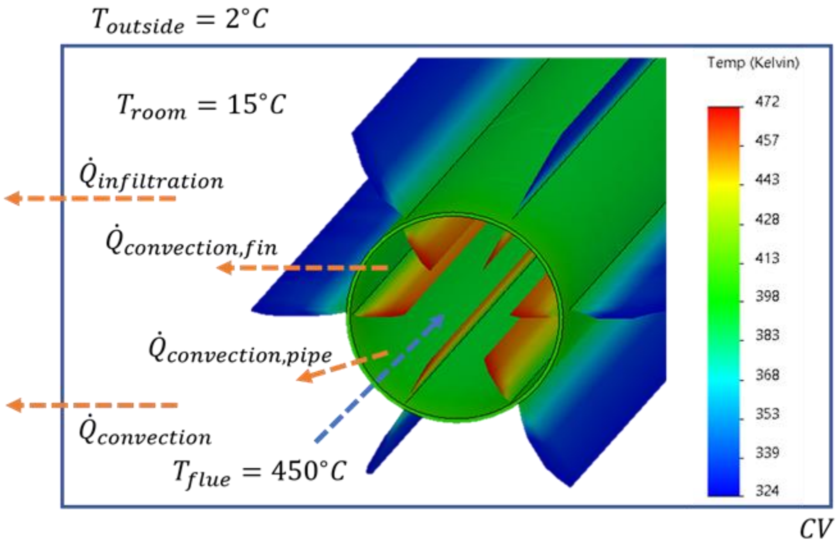


Figure 11: Temperature gradient for finned chimney with control volume (room) and methods of heat transfer shown.

A similar SolidWorks Flow Simulation described in the Heat Transferred to Pots section of this report was used to approximate the heat transferred to the room from the stove, chimney, and pots. When the stove is being used for space heating it is implied that the fire will be maintained for a minimum of 8 hours per day, due to this fact the steady state assumption is valid for space heating analysis. To obtain results for space heating, the same simulation parameters described in the previous section of this report were used with the time dependency removed. Converged goals from the analysis are shown below in Table 8. Note that this simulation includes 6 air replacements per hour of the 144 ft^2 dwelling. Figure 12 displays the temperature in the room at a certain vertical plane after a 1-hour physical time transient simulation.

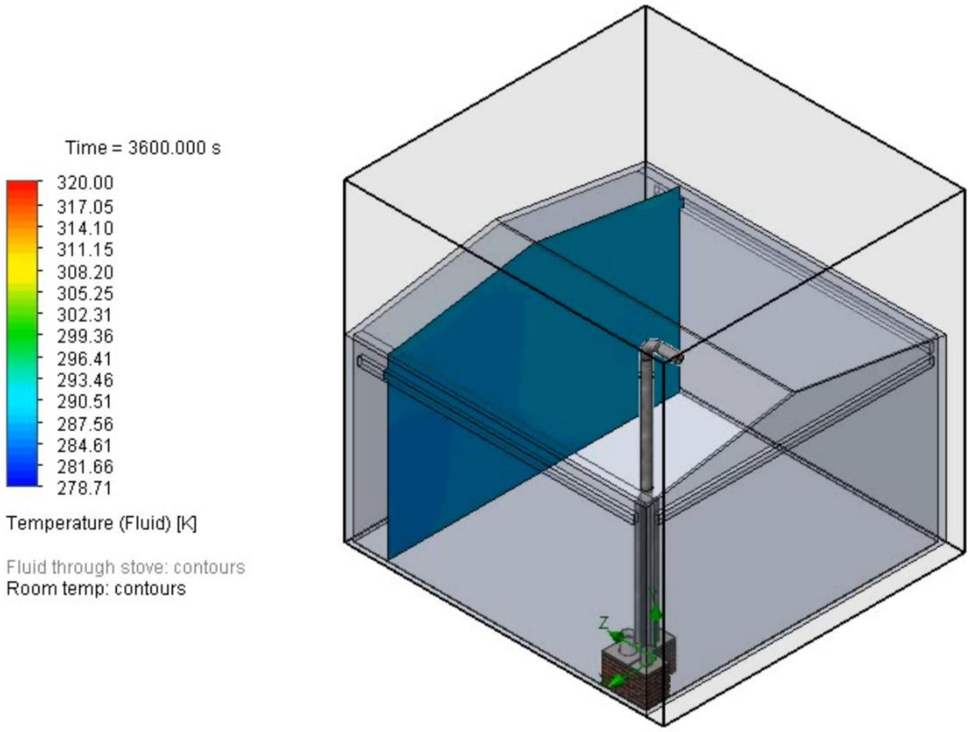


Figure 12: Cut plot of temperature in room.

Table 8: Heat transferred to room from stove, chimney, and pots obtained from analytical and numerical methods.

Parameter	**Calculated Value**	**Simulated Value**
Heat transferred from finned chimney	744 W	600 W
Heat transferred from stove	320 W	320 W (user-specified)
Heat transferred from pots (both)	N/A (Simulated only)	240 W
Average steady-state room temperature	15 °C	15 °C

4.4 Chimney Optimization

Once the thermal network, boundary conditions, and minimum operating conditions were determined, a factorial design evaluation varying the number and dimensions of fins was performed in SMath. The number of fins was varied, with the number of internal and external fins assumed equal and plotted in Figure 13. The optimal design, balancing material use and heat output, included six fins with 3cm long external fins and 2cm long internal fins.

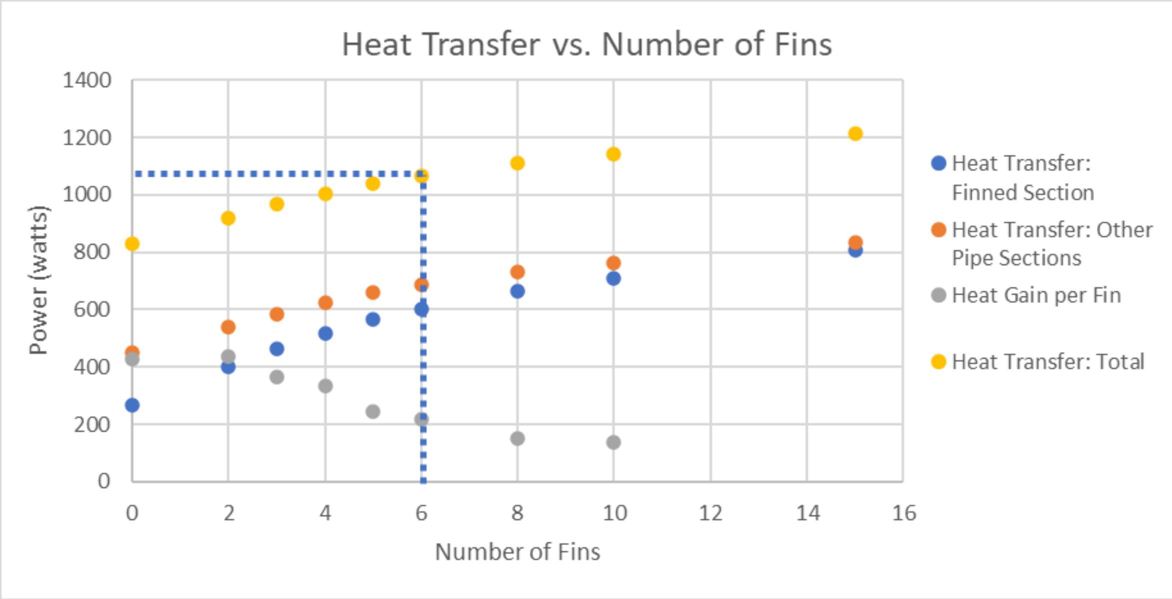


Figure 13: Heat output of Chimney and Stove System with varying fins. Final design operating point is denoted by blue line. Yellow denotes total system heat output (including stove). Orange denotes heat output from all chimney sections inside the building. Blue denotes heat extracted from finned portion of chimney. Grey denotes additional heat extracted per added fin.

This demonstrated that adding fins improves heat output by at least 30% at the operating system (1060W vs. ~800W) and is required to bring total heating above the ~1000W heating requirement. Further, the conducting chimney contributes approximately 70% of the total heating power, indicating the chimney's necessity versus conventional, highly-insulated brick chimneys.

4.5 Emissions to the Room

The emissions from the stove were calculated by determining what portion of the flue gases left the stove and made it into the kitchen. This was done by taking a simple mass balance based on area fractions. The leakage area from around a burner was compared to the area inside the stove to determine the percentage of flue gas lost to the room. The following diagram (Figure 14) shows the mass flow rate of the flue through the stove and leaking around the pots. The inputs and outputs of this analysis can be seen in Table 9, while the full analysis can be found in Appendix F – Emissions Analysis.

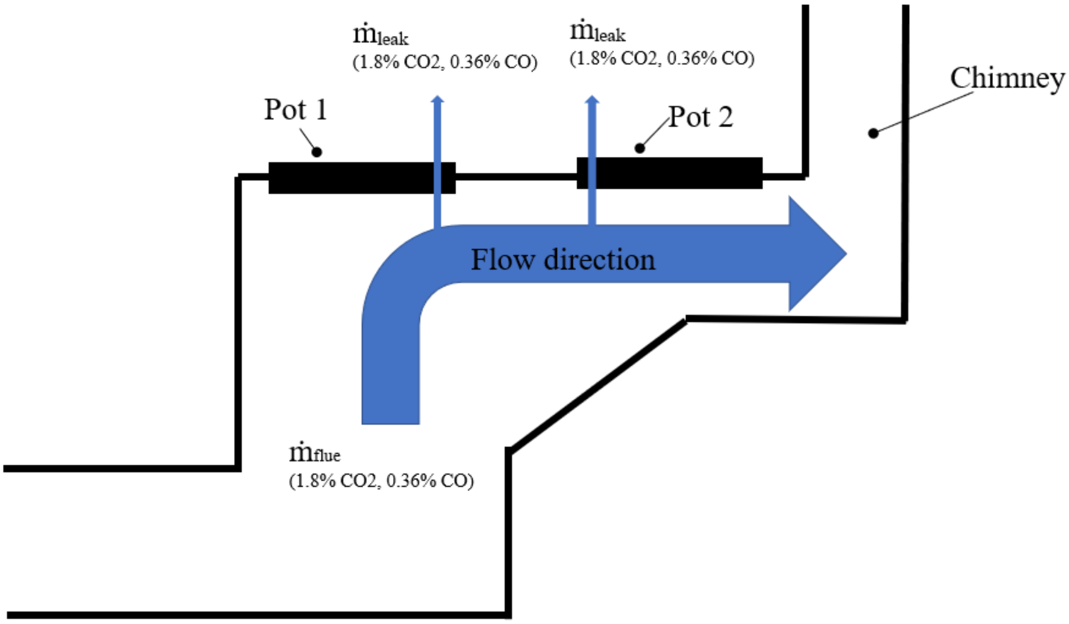


Figure 14: Diagram to show the analysis of the emissions to the room.

Table 9: Parameters to calculate the emissions to the room.

Inputs	**Outputs**
Mass flow rate of flue gas [kg/s]	Flow rate of CO into the room [g/min]
Mass fractions of CO and CO_2 in flue gas [%]	Flow rate of CO_2 into the room [g/min]
Areas of leakage and stove interior [m^2]	

An analysis was completed on the assumed leakage of the stove due to an imperfect fit around the pot and clay top. A further study was then run to determine the maximum allowable leakage area to still meet the WHO specifications for indoor air quality. As seen in Figure 15, the maximum allowable leakage area is 0.0025 m^2 (25 cm^2) which is five times larger than the estimated leakage area of 0.0005 m^2. This design point had a mass flow rate of 0.05 g/min.

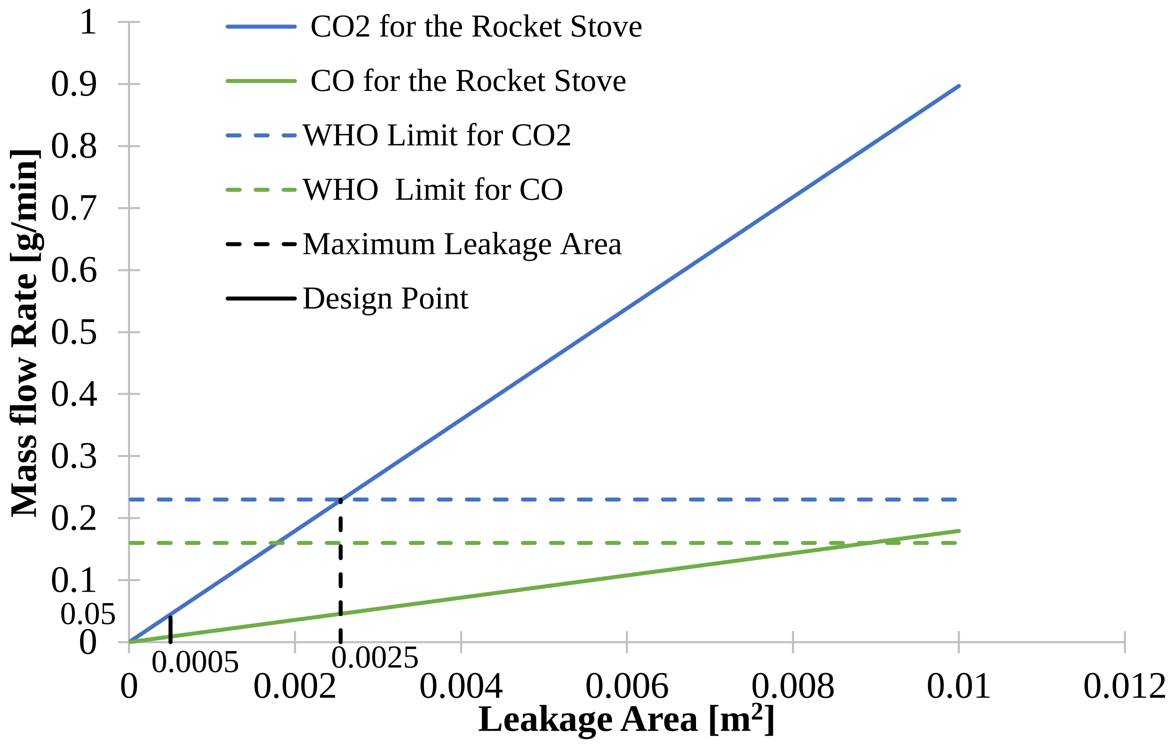


Figure 15: Emissions to the room as a function of leakage area inside of the stove. The solid lines denote the rates of CO and CO2 leakage from the rocket stove, while the WHO guidelines are shown as well as the maximum allowable leakage area and design point.

4.6 Structural

The structural analysis assesses the stresses acting on the potholes from the weight of the cookware and food to determine whether the cookware and food can be supported by the clay. This was done by using the known mass and geometries of the cookware from client communications and calculating the stress that will be exerted onto the pot skirts and comparing them to the yield strength of the supporting clay. The inputs and outputs of this analysis can be seen in Figure 16 and Table 10. Calculations can be found in Appendix G – Structural Analysis.

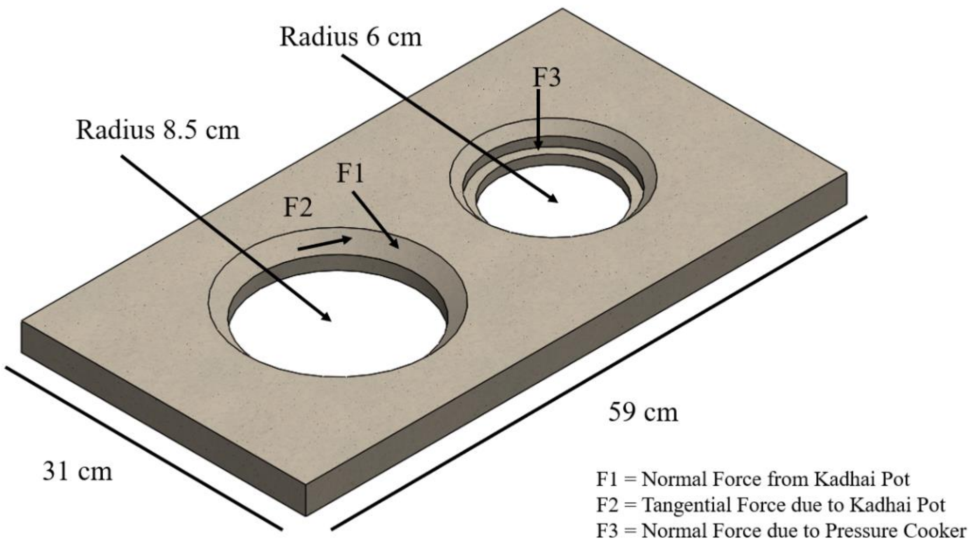


Figure 16: Diagram to show the structural analysis of the clay top.

Table 10: Parameters to calculate the structural aspects of the stove.

Inputs	Outputs
Mass of cookware [kg]	Stress acting on pot skirts [Pa]
Mass of food [kg]	Factor of Safety for the clay stovetop
Geometry of cookware [m]	
Material properties of clay [5]	

The results of this analysis proved that the clay was strong enough to support the cookware and additional loads. A summary of the results can be found in Table 11.

Table 11: Results of the structural analysis.

Item	Value
Maximum Load that the Clay can Support	89 kg
Minimum Factor of Safety	25

4.7 Safety and Human Factors

As this product is for household use, inherent safety is of utmost importance. The following hazards were found and solutions can be seen in Table 12.

Table 12: Safety analysis table.

Hazard	Solution
Chimney is hot surface to the touch	Fins provide a light barrier against users touching the core piece of chimney Chimney is set behind cookstove and thus more difficult to contact
Chimney may fall	Chimney is made of lightweight material, weighing less than 20kg. It is also anchored into either the wall or roof. The fins also provide a wide base of support against the stove. Pieces of the galvanized sheet metal may also be used as ties to anchor to the wall, if acceptable to users.
Chimney produces harmful fumes	Current design emits fumes to the room at a rate within WHO standards (<0.23g/min CO_x). By contrast, an open fire releases about 25g/min so this represents a significant reduction.

5. Cost and Manufacturing

5.1 Cost Analysis

To determine the cost of the Rocket Stove and Finned Chimney, the design was broken down into three components: the Rocket Stove, the Chimney Base, and the Finned Chimney, as shown in Figure 17, and analysed separately.

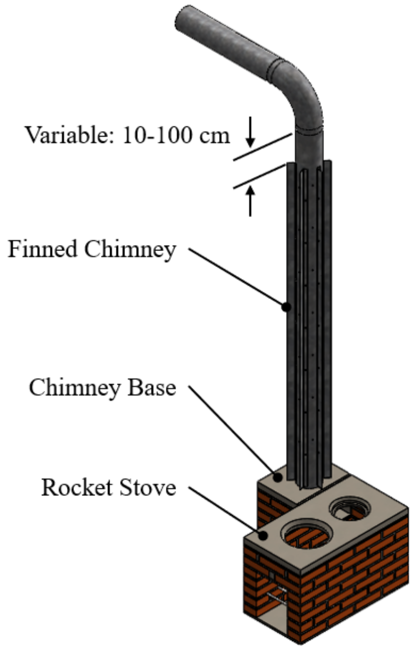


Figure 17: The three main components of the rocket stove and finned chimney.

Due to the Finned Chimney having a variable length to accommodate for varying roof heights, a range for the total cost of each unit was determined. Based on a minimum height of 2.0 m for a chimney directed out the dwelling wall (below 2.2 m roof specified by client) and maximum height of 3.0 m for a chimney directed out the roof, the lower and upper bound for the cost was determined to be $87.11 CAD and $91.86 CAD, respectively, for every 333 units produced. The lower bound cost for each component of the Rocket Stove and Finned Chimney including labour, tools, and transportation is summarized in Table 13.

Table 13: Lower bound cost for each component in the rocket stove and finned chimney per 333 units produced.

Item	**Cost (CAD)**
Rocket Stove	13.28
Chimney Base	3.93
Finned Chimney	44.79
Labour	23.00
Tools	0.39
Transportation	1.73
Total	87.11

A breakdown of these costs into materials, labour, machining, and transportation and tools is shown in Figure 18.

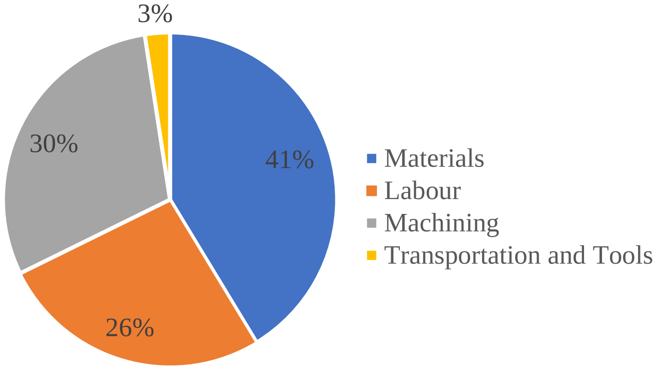


Figure 18: Lower bound cost breakdown per 333 units produced.

As shown in Figure 18, materials has the largest share of the cost per unit, mostly due to the cost of sheet metal for the Finned Chimney. However, it should be noted that leftover roofing material can be used as sheet metal for the manufacturing of the Finned Chimney. An in-depth cost analysis can be found in Appendix H – Cost Analysis.

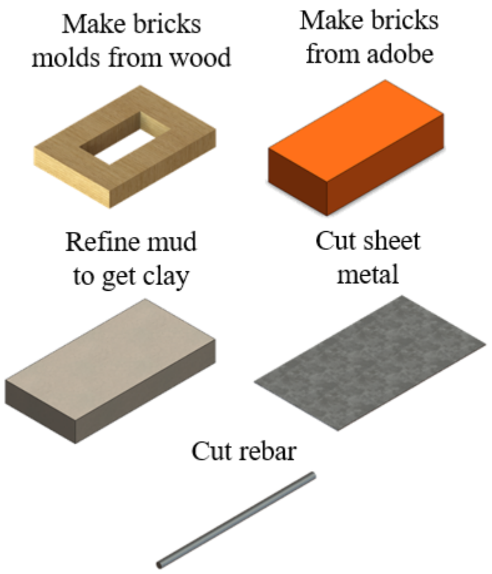
5.2 Manufacturing

The manufacturing of the Rocket Stove and Finned Chimney will take place in three steps. First is the transportation of materials and tools to the rural site. Second is the preparation of materials on site. Third is assembling the Rocket Stove, Chimney Base, and Finned Chimney. The Rocket Stove and Chimney Base are constructed together while the Finned Chimney is constructed separately. The required materials and amount including labour is shown in Figure 19. The total time for the preparation of materials and assembly is estimated to take 2 days of labour (8 hours/day). The instruction manual can be found in Appendix I – Instruction Manual.

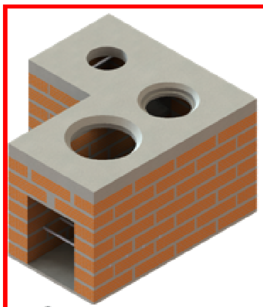
1. Transportation

Transport to Site:
- Iron Cutter
- Iron Sheet Metal
- Rebar
- Trowel
- Wood
- Fasteners
- 90° Elbow

2. Prepare materials



3. Assemble Rocket Stove, Chimney Base, and Finned Chimney



	Material	Amount
Rocket Stove and Chimney Base	Rebar	2.9 m, 11 pieces
	Brick	102 bricks, 0.033 m^3 of adobe
	Clay (mortar)	0.022 m^3
	Iron Sheet Metal	1 kg, 0.051 m^2
	1.5 days of labour	

	Material	Amount
Finned Chimney	Iron Sheet Metal	12-18 kg, 1.32-1.64 m^2
	Set of Screws and Nuts	42
	90° Elbow	1
	0.5 day of labour	

Figure 19: Overview of the process to manufacture the Rocket Stove and Finned Chimney design.

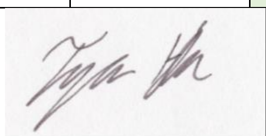
6. Design Compliance Matrix

A compliance matrix was made to compare the final design to both the Phase 2 design and the project specifications. The goal was to check the performance specifications and ensure that they met or exceeded the specifications for the Nepal Improved Cookstove. In every category, the final design of the rocket stove with finned chimney met these specifications. The results can be seen in Table 14. The client has signed off on this compliance matrix.

Table 14: Design compliance matrix.

Item	Description	Specifications	Source	Weight Factor (1-5)	Target	Units	Rocket Stove with Finned Chimney	
							Phase 2	**Final**
1	**Functionality & Operation**							
1.1	Heating Output	Maintain comfortable temperature (15C) for kitchen (144ft^2 minimum, 7ft high) Desired heat flux: 1050W	Team	4	1050	W	360	1070
1.2	Cooking	Deliver medium-high heat (1000 W) to the pots (standard 5L cooking pots or Kadhai)	Team	4	1000	W	1100	1040
1.4	Operation Time	Safe for 8h of continuous operation, year-round	Team	3	8	h	8	8
1.5	Cook Surfaces	Two cook surfaces, one sized for 3-5L pot, one sized for smaller (2L) Karai/ pressure cooker. 28cm diameter	Client	4	2	# of Surfaces	2	2
1.6	Wood Consumption	Use less wood than a traditional 3 stone fire. (1.3 kg/hr) [6]	Team	3	30	Reduction [%]	57	57
2	**Health & Safety**							
2.1	Emissions (General)	Reduce smoke and CO accumulation in house compared with open fireplace (est: 25g[C]/min) Goal to reach WHO standard of 0.59g[C]/min	Standard	5	25	CO2 [g/min]	0.17	0.05
2.2	Emissions (Legal)	Meet WHO threshold for fire admissions 0.59 (g/min) [24h avg]	Standard	3	0.59	CO2 [g/min]	0.17	0.05
3	**Dimensions & Physical Design**							
3.1	Support cookware and food	Kadhai or pot: 2kg, mass of food: (1.5kg-6kg) Maximum total load: 8kg	Client	4	8	kg	74	74
3.2	Footprint	60cm x 60cm (2' x 2')	Client	3	3600	cm^2	2400	3600
3.3	Height	Cook surface at suitable height for cooking while kneeling (55cm based on NASA anthropometric data for 50th percentile knee height)	Client	4	55	m	50	54
4	**Cost**							
4.1	Unit Cost	Cost of locally-available materials and labor	Client	5	100	$ (CAD)	25	88
5	**Materials and Assembly**							
5.1	Fuel Preparation	Changes in practice to traditional wood collection	Client	3	10	N/A	8	8
5.2	Additional fuels:	Ability to accommodate different fuels	Client	2	10	N/A	3	3
5.3	Assembly tools	Standard imperial screwdrivers, hammers, wrenches only (no specialized equipment)	Client	3	10	N/A	5	3
6	**Maintenance**							
6.1	Cleaning	Easy to clean daily (<20 min/week)	Client	4	20	minutes	15	20

Client Signature:



7. Future Work and Recommendations

While G1 Consulting has designed an improved cookstove for rural Nepal, there are some key steps required before doing a pilot project. This includes building a prototype of the model to ensure functionality and easy manufacturing. Another step is to prototype how the finned chimney can be implemented separately with a range hood.

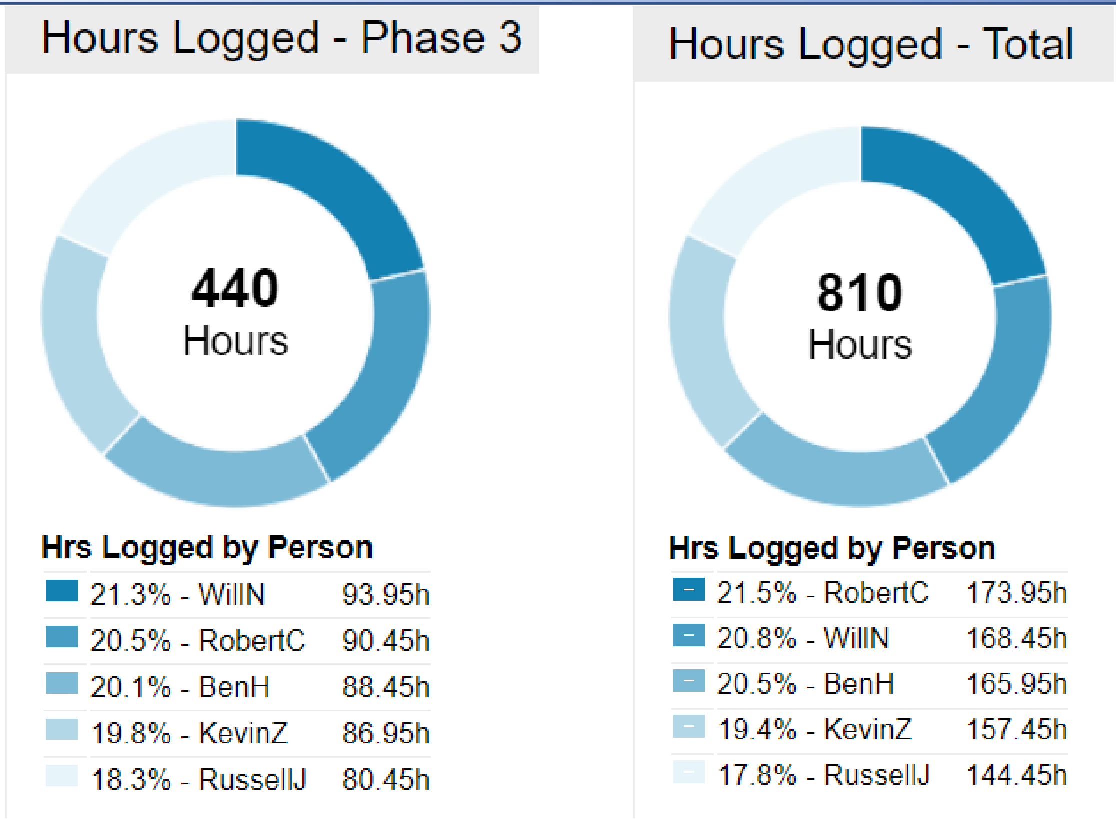
8. Project Management

The final duration for the project and associated costs, based on $90/hr for junior engineers and $150/hr for senior engineers, are outlined in Table 15. A breakdown of the allocation of these hours for each member of the team is shown in Figure 20. The amount of time that was spent by the team overall was more than was planned for by approximately 30%. This in part is due to a flawed initial assessment of the scope of work involved. The main changes to phase 3 from what was initially planned, were an increased focus on design viability calculations and drastic changes to the changes to the design of the finned chimney to improve the final product manufacturability. These changes were crucial to the overall success of the project. With reasonable assurance, the effort and time reported has been necessary and all work has been carried out with excellence.

A Gantt chart outlining all tasks and deliverables of the project is shown in Section 21.1 Project Schedule. A report of lessons learned from the project is detailed in Section 21.2 Lessons Learned.

Table 15: Engineering hours estimate and actual.

Phase	Jr. Engineer Hours		Sr. Engineer Hours		Cost	
	Estimate	Actual	Estimate	Actual	Estimate	Actual
1	114	107	3	2	$ 10,710	$ 9,930
2	222	263	4	3	$ 20,580	$ 24,300
3	253	440	5	5	$ 23,520	$ 40,350
Total	625	810	10	10	$ 57,750	**$ 74,580**



a) b)

Figure 20: Junior engineering hours logged: a) in phase 3, b) over total project life.

9. Conclusion

G1 Consulting has designed an emission reducing, efficient stove that meets the needs of families in rural Nepal. This design meets the required specifications of providing sufficient heat for cooking, sufficient heat for space heating, and reduction in emissions all without requiring cultural changes to adopt the technology. These were all proven based upon detailed analysis and the design costs less than the agreed upon $100 CAD. Before this stove gets implemented in rural Nepal, G1 Consulting recommends prototyping the stove to ensure the stove is fully operational.

10. References

[1] Alpine Club of Canada, 2020. [Online]. Available: http://acc.uberflip.com/i/1309633-acc-gazette-winter-2020/23?. [Accessed 01 02 2021].

[2] National Aeronautics and Space Administration, "ANTHROPOMETRY AND BIOMECHANICS," [Online]. Available: https://msis.jsc.nasa.gov/sections/section03.htm. [Accessed 2 March 2021].

[3] A. Mishra and A. Rai, *COMPARATIVE PERFORMANCE ASSESSMENT OF CONVENTIONAL BUILDINGS OF KATHMANDU*, International Journal of Current Research, Dec 2017.

[4] "Air Change Rates in typical Rooms and Buildings," Engineering Toolbox, [Online]. Available: https://www.engineeringtoolbox.com/air-change-rate-room-d_867.html. [Accessed 22 Feb 2021].

[5] Ministry of Physical Planning and Works, Department of Urban Development and Building Construction, "Nepal National Building Code," Government of Nepal, 7 December 1993. [Online]. Available: http://www.iibh.org/kijun/pdf/Nepal_14_NBC_109_1994_Unreinforced_Masonry.pdf. [Accessed 03 Mar 2021].

[6] K. Post, "Communitry managed forests reduce deforestation," 06 06 2019. [Online]. Available: https://kathmandupost.com/climate-environment/2019/06/06/community-managed-forests-reduce-deforestation-and-poverty-study. [Accessed 15 04 2021].

[7] E. Tools, "Calculator of Enthalpy of Moist Air," [Online]. Available: https://www.herramientasingenieria.com/onlinecalc/AirEnthalpy/AirEnthalpy.html. [Accessed 21 February 2021].

[8] JG, "The Outdoor Air Myth Exposed," Wood Heat, [Online]. Available: https://woodheat.org/the-outdoor-air-myth-exposed.html. [Accessed 24 February 2021].

[9] J. Yarde, "How Long Does a Cord of Wood Last? Preparing for Winter," Burly Beaver, 2021. [Online]. Available: https://burlybeaver.com/how-long-cord-wood/. [Accessed 24 February 2021].

[10] A. Dadkhah-Nikoo, "Analysis of Wood Combustion and Combustion Systems for a Combined Cycle Wood-Fired Power Plant," Oregon State University, Oregon, 1985.

[11] A. J. Marchese, "Achieving Tier 4 Emissions in Biomass Cookstoves," Colorado State Univerisity, Fort Collins, 2018.

[12] M. Holmgren, "X Steam, Thermodynamic properties of water and steam," 2021. [Online]. Available: https://www.mathworks.com/matlabcentral/fileexchange/9817-x-steam-thermodynamic-properties-of-water-and-steam. [Accessed 18 February 2021].

[13] M. Wallius, "gasProp," 29 April 2020. [Online]. Available: https://www.mathworks.com/matlabcentral/fileexchange/75268-gasprop. [Accessed 16 February 2021].

[14] "Stainless Steel 90 Degree Elbow," Metline Industries, [Online]. Available: https://www.metline-pipefittings.in/product/pipe-tube-fittings/stainless-steel-pipe-tube-fittings/stainless-steel-90-degree-elbow/?fbclid=IwAR1tAHYfofQ-liVB-Tp6tbzEBjhA6_dq5L9gjGEssOSuRIZfCwmic3DHk5s#. [Accessed 9 April 2021].

[15] "Phillips Rounded Head Screws for Sheet Metal," McMaster-Carr, [Online]. Available: https://www.mcmaster.com/92470A049/. [Accessed 9 April 2021].

[16] "Low-Strength Steel Hex Nut," McMaster-Carr, [Online]. Available: https://www.mcmaster.com/90480A002/?fbclid=IwAR2J0O7WhrxczBgHQ_YnZWjy2HTHxxO6IHl0r91k6noSIi3yohrnO-SUEVQ. [Accessed 10 April 2021].

[17] "Galvanized Hollow Pipe," Hulas Steel, [Online]. Available: https://hulassteel.com.np/profiles/galvanized-hollow-pipes/?fbclid=IwAR0-xNiqlPat5A3jiAwRKXP_q0pic76-s_7vQTRknjf1GhN236eX7v8jDtA#. [Accessed 10 April 2021].

[18] A. Parajuli, S. Agrawal, J. Tharu, A. Kamat, A. Jha and H. Darlami, "A simplified model for understanding the performance," *Clean Energy,* vol. 3, no. 4, pp. 288-306, 2019.

[19] A. Parajuli, "A simplified model for understanding the performance of two pot enclosed mud cookstoves," *Clean Energy,* vol. 3, no. 4, pp. 288-306, 2019.

[20] M. Kshirsagar, "A mathematical tool for predicting thermal performance of natural draft biomass cookstoves fro identification of a new operational parameter," *Energy,* vol. 93, no. 1, pp. 188-201, 2015.

[21] Pipe flow calculations, "Pipe flow calculations," [Online]. Available: https://www.pipeflowcalculations.com/tables/flue-gas.xhtml. [Accessed 01 03 2021].

[22] P. Ramen, "Improved test method fro evaluation of bio-mass cook-stove," *Energy,* vol. 71, pp. 479-495, 2014.

[23] M. Lunden, W. Delp and B. Singer, *Capture Efficiency of Cooking Related Fine and Ultrafine Particles,* 2014.

[24] Saakha Group, "TODAY'S RETAIL PRICE OF SAAKHA TOR STEEL," Saakha Group, [Online]. Available: https://titanium-stainless-steel.continentalsteel.com/viewitems/sheet-and-coil-steel/galvanized-sheets. [Accessed 01 03 2021].

[25] K. Decker, "Cooking Efficiently: 3-stone fires, biomass & hobs," *Permaculture,* 11 March 2015.

[26] Star Pipe Products, "Cast Iron Soil Pipe Products," Star Pipe Products, [Online]. Available: http://starpipeproducts.com/pdf/Soil%20Pipe/PriceList/SPPL_07_02.pdf. [Accessed 03 Mar 2021].

[27] Government of Nepal, "Department of Urban Developement and Building Construction," [Online]. Available: https://www.dudbc.gov.np/uploads/default/files/c4f2d67c03bc00d4e9a280f2223392e4.pdf. [Accessed 01 02 2021].

[28] Government of Nepal, "Department of Urban Developement and Building Construction," [Online]. Available: https://www.dudbc.gov.np/uploads/default/files/998b31e2549c235445c152204355bc90.pdf. [Accessed 01 02 2021].

[29] S. Sapkota, *Personal Communication*, 2021.

11. Appendix A – Specification Matrix Changes

This Appendix outlines the changes in our specification matrix since Phase 2. Each new specification is updated in green and old specifications are crossed off in black in Table 16.

Table 16: Changes to the specification matrix since Phase 2.

Item	Description	Specifications	Weight Factor (1-5)	Target	Units
1	**Functionality & Operation**				
~~1.1~~	~~Heating Output~~	~~Maintain comfortable temperature (15C) for kitchen (144ft^2 minimum, 7ft high) Desired heat flux: 2610W~~	~~4~~	~~2610~~	~~W~~
1.1	Heating Output	Maintain comfortable temperature (15C) for kitchen (144ft^2 minimum, 7ft high) Desired heat flux: 1050W	4	1050	W
~~1.2~~	~~Cooking~~	~~Deliver medium-high heat (1500 W) to the first pot (standard 5L cooking pots or Kadhai)~~	~~4~~	~~1500~~	~~W~~
~~1.3~~	~~Cooking~~	~~Deliver medium-high heat (1500 W) to the second pot (standard 5L cooking pots or Kadhai)~~	~~4~~	~~1500~~	~~W~~
1.2	Cooking	Deliver medium-high heat (1000 W) to both pots (boil 4L in traditional cooking pots or Kadhai)	4	1000	W
1.4	Operation Time	Safe for 8h of continuous operation, year-round	3	8	h
1.5	Cook Surfaces	Two cook surfaces, one sized for 3-5L pot, one sized for smaller (2L) Kadhai/ pressure cooker. 28cm diameter	4	2	# of Surfaces
~~1.6~~	~~Thermal Efficiency~~	~~Provide more complete combustion than open fire~~	~~3~~	~~100~~	~~Efficiency [%]~~
1.6	Fuel Use Reduction	Provide more complete combustion than open fire; minimize wood use below 1.3 kg/hr [6]	3	30	Reduction in Wood Consumption [%]
2	**Health & Safety**				
2.1	Emissions (General)	Reduce smoke and CO accumulation in house compared with open fireplace (est: 25g[CarbonDioxide]/min)	5	25	CO2 [g/min]
~~2.2~~	~~Emissions (Legal)~~	~~Meet WHO threshold for fire admissions 0.59 (g CarbonDioxide /min) [24h avg]~~	~~3~~	~~0.59~~	~~CO2 [g/min]~~
2.2	Emissions (Legal)	Meet WHO threshold for fire admissions 0.23 (g CarbonDioxide /min) [24h avg]	3	0.23	CO2 [g/min]
3	**Dimensions & Physical Design**				
3.1	Support cookware and food	Kadhai or pot: 2kg, mass of food: (1.5kg-6kg) Maximum total load: 8kg	4	8	kg
3.2	Footprint	60cm x 60cm (2' x 2')	3	3600	cm^2
3.3	Height	Cook surface at suitable height for cooking while kneeling (55cm based on NASA anthropometric data for 50th percentile knee height)	4	55	m

4	**Cost**				
~~4.1~~	~~Unit Cost~~	~~Cost of locally-available materials and labor~~	~~5~~	~~30~~	~~$ (CAD)~~
4.1	Unit Cost	Cost of locally-available materials and labor	5	100	$ (CAD)
5	**Materials and Assembly**				
5.1	Fuel Preparation	Changes in practice to traditional wood collection	3	10	N/A
5.2	Additional fuels:	Ability to accommodate different fuels	2	10	N/A
5.3	Assembly tools	Standard imperial screwdrivers, hammers, wrenches only (no specialized equipment)	3	10	N/A
6	**Maintenance**				
6.1	Cleaning	Easy to clean daily (<20 min/week)	4	20	minutes
7	**Total**				

Explanation of changes to target values:

1.1 Heating output target value changed after revised estimates of number of air changes per hour, fire air intake, and insulating properties of walls and roof.

1.2 Volume of pots changed after clarification of pot size and average pot utilization in discussions with client. Pots assumed to be approximately 80% full rather than completely full.

1.6 The client originally wanted efficiency to be maximized to reduce deforestation (wood consumption). Providing a direct comparison for 3-stone fires meeting the same performance parameters provides a more direct assessment of fuel use reductions

2.2 A range of acceptable air qualities based on CO and CO_2 are available from the sources cited. Target pollution rate was lowered to reflect most stringent standard.

4.1 Initial estimate of $30 was not specified by client, after further discussions client arrived at $100 maximum price limit based on internal organizational feasibility assessment. While the target price may ideally be lower, this higher target is a reflection of "off the shelf" price and not necessarily expected prices as materials (particularly the sheet metal) are often widely available for free or at discounted rates as they are leftover building materials.

12. Appendix B – SolidWorks Simulation Setup

This section of the appendix will outline the common SolidWorks Flow Simulation setup used between the heating of the pots and the space heating analyses. Details of the variations between these simulations will be provided in Appendix D – Heat Transfer in the Stove Analysis, and Appendix E – Space Heating Analysis.

12.1 Computational Domain

The computational domain of this analysis included a dwelling modeled around the stove and encompassed the dwelling and chimney entirely. Figure 21 below shows the domain in wireframe around the solid model and Table 17 below shows the coordinates of the computational domain.

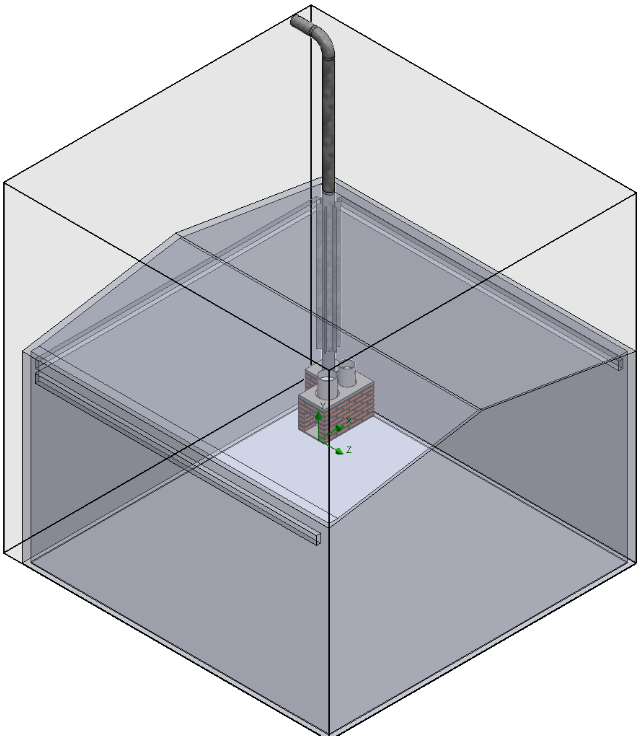


Figure 21: Computational domain of flow simulation.

Table 17: Computational domain bounds.		
Coordinate	**Bounds**	
X	-3.02 m	0.64 m
Y	-0.02 m	3.79 m
Z	-0.73 m	3.14 m

12.2 Fluid Subdomains

Three separate subdomains were created through the use of SolidWorks lids tool. The first being the interior of the dwelling filled with standard temperature and pressure air. The second domain was the interior of both pots filled with liquid water, and the third domain was the inside of the stove and chimney which contained the flue gas mixture discussed in Appendix C – Combustion Analysis.

The separation of fluid subdomains allowed for specific goals to be setup to determine parameters such as water temperature with respect to time and average air temperature in the dwelling.

12.3 Boundary Conditions

As seen above in Figure 21, there are slotted sections running the length of three sides of the dwelling. These were modelled based on pictures provided by the client. To simulate air flow through the dwelling for 6 air replacements per hour, these slots had boundary conditions attached. The two on walls opposite each other had an environmental pressure boundary condition applied with the third slot having an inlet velocity of 1 m/s ambient pressure and temperature air. The purpose of this style of modelling was to accurately simulate the natural convection that occurs throughout the dwelling to heat incoming air.

An environmental pressure boundary condition was also applied to the outlet of the chimney in order to make the system watertight.

A lid was placed over the entry to the stove and used to set a mass inlet boundary condition which had a temperature of 863 K, pressure of approximately 110 kPa (ambient pressure plus stack pressure) and gaseous composition as shown in Table 21 as per the combustion analysis results.

12.4 Heat Sources

The heat transfer that occurs in a wood stove is result of both radiation and convection. The convection occurred due to the inlet mass rate discussed in the boundary condition section. Due to limitations in the SolidWorks Flow package, radiation had to be setup as an external analysis. This was done in a separate study which had the properties shown in Figure 22. From this, we obtained the incident radiation flux that occurred on the bottom surfaces of the pots and then applied this value as a heat source to each pot in the internal simulation.

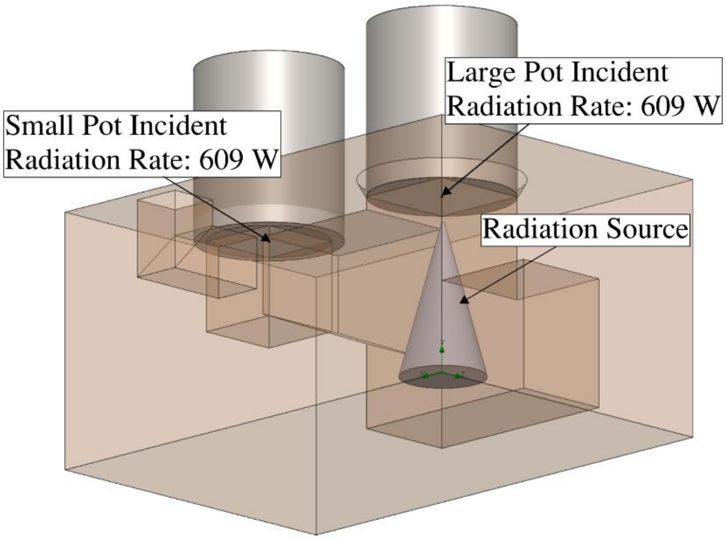


Figure 22: Incident radiation on pot surfaces.

The parameters of the radiation source are provided below in Table 18 with only the incident rates carrying over to the internal flow simulation.

Table 18: Radiation source parameters.

Parameter	**Value**
Stove Material	Brick, Fireclay 3
Radiation Source Material	Carbon, Filament 3
Pot Material	Iron, Smooth, Oxidized 3
Radiation Source Type	Diffusive Surface
Radiation Source Temperature	970 K

The values shown in Figure 22 were applied as heat sources in the internal flow simulation.

12.5 Meshing

Both a global mesh and local mesh were used in the solution for both transient and steady state cases. The global mesh was set to automatic and given a level of refinement of 3. High refinement was not necessary in this setting as it is only used to evaluate heat convection through air in the dwelling and an increased refinement would provide minimal gain to accuracy with high increase to computation time.

Two local meshes were used, one encompassing the stove and pots while the other covered the finned chimney. These can be seen below in Figure 23. Due to the decreased cavity sizes and introduction of a fluid-solid boundary within these meshes, a higher level of refinement was needed than in the global mesh. Both local meshes shared refinement levels and properties which can be seen below in Table 19. This resulted in the simulation having a total of 80,588 fluid cells and 45,691 solid cells.

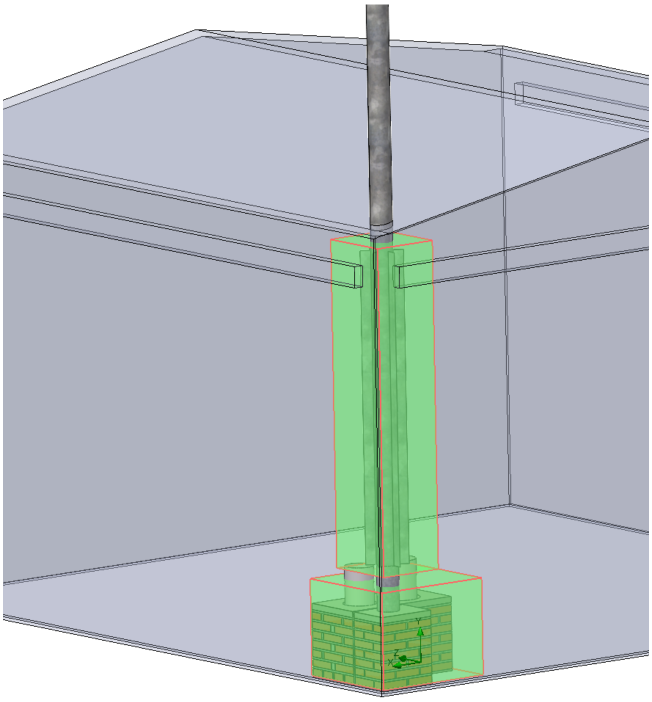


Figure 23: Local mesh domains.

Table 19: Local mesh parameters.	
Parameter	**Value**
Cell Type	Cuboid
Level of Refining Fluid Cells	4
Level of Refining Solid Cells	2
Level of Refining Cells at Fluid/Solid Boundary	2
Characteristic Number of Cells Across Channel	3
Maximum Channel Refinement Level	1
Small Solid Feature Refinement Level	4
Tolerance Level	3

13. Appendix C – Combustion Analysis

The following Matlab program was created to calculate flue gas temperature inputs from combustion. Table 20 shows the inputs for the Rocket Stove design. These values are experimentally determined through performance curves, typically by manufacturer or researcher testing, and typical values researched for each stove were used.

Table 20: Input parameters for combustion analysis.		
Parameter	Rocket Stove	Sources
Intake air temperature (K)	300	N/A
Enthalpy of intake air (kJ/kg)	50	[7]
Dead state enthalpy (kJ/kg)	0	[7]
Mass rate of air (g/s)	2	[8]
Mass rate dry wood (g/s)	0.15	[9]
Moisture content	0.5	[10]
Dirt content	0.02	[10]
Fraction C burned to CO	0.11	[11]
Fraction unburned C	0.05	[10]

The Matlab code was developed through modification of a program written in [10] for a wood fired powerplant. Nitrogen, oxygen, carbon monoxide, carbon dioxide were considered to be ideal gasses in the calculations while real properties of water vapor were used in calculating enthalpy and temperatures. This program is dependant on the functions XSteam and gasProp which can be found at [12] and [13], respectively.

With the inputs specified in Table 20, output values can be seen below in Table 21, including the mass fraction composition of the flue gas.

Table 21: Output parameters for combustion analysis.

Parameter	Rocket Stove
Energy input of wood (kW)	2.40
Energy input of air (kW)	0.10
Energy transmitted to flue gas (kW)	1.99
Heat lost to unburned carbon (kW)	0.12
Heat lost to CO generation (kW)	0.08
Heat lost to dirt in fuel (kW)	2.8 E-04
Heat lost to radiation (kW)	0.20
Heat used to vaporize water (kW)	0.58
Flue gas temperature (K)	863
Efficiency (%)	32.23
Mass rate of CO (g/s)	8.0 E-03
Mass fraction carbon dioxide (CO_2)	0.0180
Mass fraction carbon monoxide (CO)	0.0036
Mass fraction water (H_2O)	0.1628
Mass fraction nitrogen (N_2)	0. 6826
Mass fraction oxygen (O_2)	0.1329

Figure 24 below shows the control volume and location at which temperature and other parameters were calculated in this analysis. A full list of input and output parameters of the program are tabulated in Table 22.

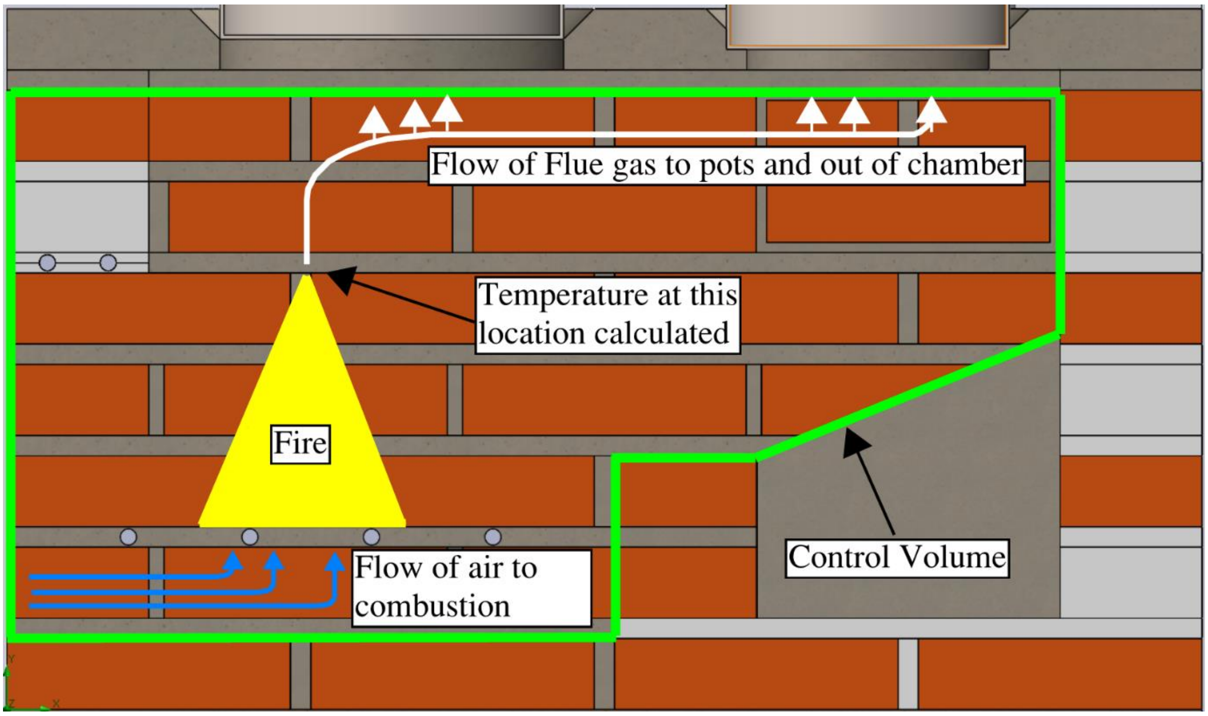


Figure 24: Control volume of combustion analysis.

Table 22: Input and outputs for combustion analysis.	
Input Parameters	**Output Parameters**
Intake air temperature [K]	Energy input of wood [kW]
Enthalpy of intake air [kJ/kg]	Energy input of air [kW]
Dead state enthalpy [kJ/kg]	Energy transmitted to flue gas [kW]
Mass rate of air [g/s]	Heat lost to unburned carbon [kW]
Mass rate dry wood [g/s]	Heat lost to CO generation [kW]
Moisture content [%]	Heat lost to dirt in fuel [kW]
Dirt content [%]	Heat lost to radiation [kW]
Fraction C burned to CO [%]	Heat used to vaporize water [kW]
Fraction unburned C [%]	Flue gas temperature [K]
	Efficiency [%]

Matlab code:

```
%Written by Will Nagge

%Edited February 28, 2021

%This code is adapted from A Dadkhah-Nikoo (1985) which is in Fortran
%User input information about wood entering combustion chamber

%Objectives: The objective of this program is to determine the composition,
%temperature and properties of flue gas from combustion of wood in a stove.

%Assumptions:
% - Steady state operation, stove wall already at max temperature
% - Ideal gas law applies
% - All carbon in fuel is available
% - Wood fiber saturation point of 23% MC
% - Dirt is present in fuel
% - All unburned carbon exits in flue gas, none in ash
% - 8% of heat is lost to radiation into the floor of the stove


clc
clear
Ta=input('Enter the ambient air temperature (deg K):');
Ha_in=input('Enter the enthalpy of intake air (kJ/kg):');
Ha_dead=input('Enter dead state air enthalpy (kJ/kg):');
HHVorLHV=input('Does flue gas condensation occur (yes=1, no=0):');
MFair=input('Enter the mass flow rate of air (g/s):');
Mbdw=input('Enter the mass rate of bone-dry clean wood (g/s):');
xH2O=input('Enter the mass fraction of wet wood/dry wood (g water/g wet
wood):');
xDirt=input('Enter the mass fraction of dirt/dry wood (g dirt/g dry wood):');
xCO=input('Enter the amount of carbon burned to carbon monoxide (g burned to
CO/g C in fuel):');
xCunb=input('Enter the amount of unburnt carbon (g unburnt C/g C in fuel:');

%Below are typical constituents of Oak, a common hard-wood tree found in
%mid-elevations of Nepal (https://www.feedipedia.org/node/108). Values are
```

```
%taken from A Dadkhah-Nikoo (?1985) Table 2.2.a.
xH=0.0609; %(fraction hydrogen of dry weight)
xC=0.4878; %(fraction carbon of dry weight)
xO2=0.4498; %(fraction oxygen of dry weight)
xASH=0.0015; %(fraction carbon of dry weight)

%Below is molecular weight for H2, O2, C, CO2, CO, N2 and H2O (g/mol)
MWH2=2.016;
MWO2=31.999;
MWC=12.011;
MWCO2=44.009;
MWCO=28.010;
MWH2O=18.015;
MWN2=28.013;

%Molecular weight of combustion air (g/mol)
MWair=28.965;

% Calculate the air-fuel ratio, mass flow rate of fuel constituents, and
% mass of fuel in combustion chamber
AFrat=MFair/Mbdw; %air fuel ratio
Mwcw=Mbdw/(1-xH2O); %Mass rate of wet clean wood
Mdirt=Mwcw*xDirt; %Mass rate of dirt in fuel (g/s)
MH2O=xH2O*Mwcw; %Mass rate of moisture in the fuel (g/s)
Mwtot=Mwcw+Mdirt; %Total mass rate of fuel entering combustion chamber
Mash=xASH*Mbdw; %Mass rate of ash
Mcbn=xC*Mbdw; %Mass rate of carbon (g/s)
MCCO=xCO*Mcbn; %Mass rate of CO produced
MCunb=xCunb*Mcbn; %Mass rate of unburnt carbon (secondary combustion?)
MCCO2=Mcbn-MCCO-MCunb; %Mass rate of carbon burned to CO2
MO2=xO2*Mbdw; %Mass rate of oxygen in the fuel
MH2=xH*Mbdw; %Mass rate of hydrogen in the fuel

%Convert to mole rate (mol/s)
MLH2=MH2/MWH2;
MLH2O=MH2O/MWH2O+MLH2;
MLC=Mcbn/MWC;
MLCO2=MCCO2/MWCO2;
MLCO=MCCO/MWCO;
MLCunb=MCunb/MWC;
MLO2=MO2/MWO2;
MLair=MFair/MWair;

%Significant combustion air constituents (mol/s). Air is constant composition
%with varying altitude and only density changes. Molar ratio source:
%https://www.engineeringtoolbox.com/air-composition-d_212.html
MLN2a=0.78084*MLair;
MLO2a=0.20946*MLair;
MLCO2a=0.000412*MLair;

%Combustion products (mol/s)
MLCOprod=MLCO;
MLCO2prod=MLCO2+MLCO2a;
MLN2prod=MLN2a;
MLH2Oprod=MLH2O;
MLO2prod=MLO2+MLO2a-(MLCO/2+MLCO2+MLH2);

%mole fraction of products

sumMLprod=MLCOprod+MLCO2prod+MLN2prod+MLH2Oprod+MLO2prod;
```

```
yH2Oprod=MLH2Oprod/sumMLprod;
yCOprod=MLCOprod/sumMLprod;
yCO2prod=MLCO2prod/sumMLprod;
yN2prod=MLN2prod/sumMLprod;
yO2prod=MLO2prod/sumMLprod;

%Molecular weight and mass rate of flue gas
MWprod=yH2Oprod*MWH2O+yCOprod*MWCO+yCO2prod*MWCO2+yN2prod*MWN2+yO2prod*MWO2
;
Mprod=sumMLprod*MWprod;

%Energy Balance (temperature in deg K)

%Initial guess for Tc (flue gas temperature)
Tc=Ta+100;

HHV=20000;
%Energy into combustion chamber, first find heating value
if HHVorLHV==1
    HV=20000; %kJ/kg higher heating value
else
    HV=16000; %kJ/kg lower heating value
end
%Energy in wood
Qwood=HV*Mbdw/1000;
%Energy in air
Qair=(Ha_in-Ha_dead)*MFair/1000;
%Total energy into combustion chamber
Qin=Qwood+Qair;

%Energy Losses

%Radiation loss
Qrad=0.08*Qin; %kJ/s (A Dadkhah-Nikoo (?1985))

%Carbon monoxide generation
QCCO=MLCO*MWCO*4340*2.326/1000;

%Unburned carbon loss (32773 kJ/kg C burned)
QunbC=MCunb*32773/1000;

%Formation of H2O from H2 (2463 kJ/kg)
QH2=MLH2*MWH2O*2463/1000;

%Vaporization of H2O
%To vaporize free water
Qfw=MH2O*2463/1000;

%Additional energy for bound water (fiber saturation point MCfsb=23%. Assume
%MCtotal>MCfsb always. Equation for Hbw adapted from A Dadkhah-Nikoo (?1985).
%Convert from btu/s to kJ/s in Qbw
MC=23; %% this is moisture content of bound water
Mbw=MC*Mwcw*10^(-3)/100;
Hbw=(1/MC)*(467.9415*MC-32.314115*(MC^2)+1.040786667*(MC^3)+4.680145*10^(-
2)*(MC^4)-6.588278*10^(-3)*(MC^5)+2.569851667*10^(-4)*(MC^6)-3.48937*10^(-
6)*(MC^7));
Qbw=Mbw*Hbw*1.05506;

%Total energy to vaporize water
```

```
Qvap=QH2+Qfw+Qbw;

%Heating of the dirt (heat capacity dirt = 0.465 kJ/kgK
Qdirt=Mdirt*0.465*(Tc-Ta)/1000;

%Total loss (QH2, Qfw, Qbw can be recovered if condensation occurs)
Qloss=Qdirt+Qvap+QunbC+Qrad+QCCO;



%Energy output enthalpy and entropy (Evaluated at Tc (K))
Hc=yH2Oprod*XSteam('h_pT',1,Tc-
273)+yCO2prod*gasProp("CO2","T","h",Tc)+yCOprod*gasProp("CO","T","h",Tc)+yO
2prod*gasProp("O2","T","h",Tc)+yN2prod*gasProp("N2","T","h",Tc);
Sc=yH2Oprod*gasProp("H2O","T","s",Tc)+yCO2prod*gasProp("CO2","T","s",Tc)+yC
Oprod*gasProp("CO","T","s",Tc)+yO2prod*gasProp("O2","T","s",Tc)+yN2prod*gas
Prop("N2","T","s",Tc);
Href=yH2Oprod*gasProp("H2O","T","h",Ta)+yCO2prod*gasProp("CO2","T","h",Ta)+
yCOprod*gasProp("CO","T","h",Ta)+yO2prod*gasProp("O2","T","h",Ta)+yN2prod*g
asProp("N2","T","h",Ta);
if Href<0
    Href=0;
else
end
Qc=MFair*(Hc-Href)/1000;

%Iterate flue gas temperature
TcNEW=0;
%Check tol
if abs((Tc-TcNEW)/Tc)>0.00001
    TcNEW=Tc;
    Hc=Href+(Qin-Qloss)*1000/Mprod;
    %Hc=yH2Oprod*XSteam('h_pT',1,Tc-
273)+yCO2prod*gasProp("CO2","T","h",Tc)+yCOprod*gasProp("CO","T","h",Tc)+yO
2prod*gasProp("O2","T","h",Tc)+yN2prod*gasProp("N2","T","h",Tc);

Tc=(yH2Oprod*(XSteam('T_ph',1,Hc)+273)+yCO2prod*gasProp("CO2","h","T",Hc)+y
COprod*gasProp("CO","h","T",Hc)+yO2prod*gasProp("O2","h","T",Hc)+yN2prod*ga
sProp("N2","h","T",Hc));
    %goto(130)
    Qc=MFair*(Hc-Href)/1000;
else
    %Tc=TcNEW;
end
%Qc=MFair*(Hc-Href)/1000;
%Total energy transfer to the flue gas
Qflue=Qc+Qvap;

%Calculate theoretical air amount and excess air amount (EA %)
MLO2th=MLC+MLH2/2-MLO2;
MLath=MLO2th/xO2;
Math=MLath*MWair;
EA=(MFair-Math)/Math*100;
AFratth=Math/Mbdw; %Theoretical air fuel ratio

%%Calculate efficiency

%Fuel availability (Exergy). Emperical formula Shieh and Fan [1982].
EXbdwHHV=Mbdw*HHV/1000;
EXbdwLHV=(Mbdw*((340.12*xC-5996.25*xH+1062.45*xO2-
51.139*xASH)*1.7997732*1.0556+HHV))/1000;
```

```
EXbw=2.326*Mbw*abs(54.3714-(2.924894*10^2-42.84346*MC+5.039131*MC^2-
0.5740694*MC^3+3.584556*10^(-2)*MC^4-8.335498*10^(-4)*MC^5-9.477914*10^(-
6)*MC^6+1.095668*10^(-6)*MC^7-4.493423*10^(-8)*MC^8+8.533094*10^(-
10)*MC^9));

%Availability of wet fuel
EXwcwHHV=EXbdwHHV+EXbw;
EXwcwLHV=EXbdwLHV+EXbw;

%Availability of air in
%Tdsabs=Ta % deg K dead state = amb temp due to outdoors conditions
Samb=gasProp("Air","T","s",Ta);
%Sds=gasProp("Air","T","s",Tds);
%Hds=gasprop("Air","T","h",Tds);
EXair=0; %dead state is where the air intakes from

%Availability of flue gas exiting (Hc and Sc already calculated)
%Assume Hds=0~Href
Hds=Href;
EXc=Mprod*((Hc-Hds)-Ta*(Sc-Samb))/1000;

%Now calculate efficiency
EFF21=100*EXc/EXwcwHHV; %Based off HHV
EFF22=100*EXc/EXwcwLHV; %Emperical equiv
EFF1=100*(Qflue-Qair)/Qwood;
%%%%%%%%EFF12=(Qflue-Qc-Qe)/Qwood need to calc exhaust properties   %This
includes the heat exhausted from the building, same as Qc but at exhaust
temp.

%Calculate solid discharge
Mdis=Mash+Mdirt+MCunb;

fprintf('Theoretical air-fuel ratio:   \t\t\t\t%.2f\n',AFratth)
fprintf('Theoretical mass rate of air (g/s):   \t\t\t%.2f\n',Math)
fprintf('Actual air-fuel ratio:   \t\t\t\t\t%.2f\n',AFrat)
fprintf('Excess air percent:   \t\t\t\t\t%.2f\n\n',EA)

fprintf('Mass rate of bone-dry fuel (g/s):   \t\t\t%.2f\n',Mbdw)
fprintf('Mass rate of wet, dirty fuel (g/s):   \t\t\t%.2f\n',Mwtot)
fprintf('Mass rate of water in fuel (g/s):   \t\t\t%.2f\n',MH2O)
fprintf('Mass rate of combustion air (g/s):   \t\t\t%.2f\n',MFair)
fprintf('Mass rate of solid discharge (g/s):   \t\t\t%.2f\n',Mdis)
fprintf('Mass rate of flue gas out (g/s):   \t\t\t\t%.2f\n\n', Mprod)

fprintf('Energy input of wood (kJ/s):   \t\t\t\t\t%.2f\n',Qwood)
fprintf('Energy input of combustion air (kJ/s):   \t\t%.2f\n',Qair)
fprintf('Energy transfered to flue gas including water vapor energy (kJ/s):
%.2f\n\n',Qflue)

fprintf('Heat loss by unburned carbon (kJ/s):   \t\t\t%.2f\n',QunbC)
fprintf('Heat loss by CO generation (kJ/s):   \t\t\t%.2f\n',QCCO)
fprintf('Heat loss by dirt in fuel (kJ/s):   \t\t\t%.2f\n',Qdirt)
fprintf('Heat loss by radiation (kJ/s):   \t\t\t\t%.2f\n',Qrad)
fprintf('Energy used to vaporize water (kJ/s):   \t\t%.2f\n\n',Qvap)

fprintf('Combustion air temperature (K):   \t\t\t\t%.2f\n',Ta)
fprintf('Flue gas temperature (K):   \t\t\t\t\t%.2f\n\n',Tc)
```

```
fprintf('First law efficiency:    \t\t\t\t\t\t%.2f\n',EFF1)
fprintf('Second law efficiency (based on HHV):    \t\t%.2f\n',EFF21)
fprintf('Second law efficiency (emperical):    \t\t\t%.2f\n',EFF22)
```

14. Appendix D – Heat Transfer in the Stove Analysis

14.1 Simulation

The general setup described in Appendix B – SolidWorks Simulation Setup was used to conduct this simulation. A time dependant study was performed with goals setup to measure the temperature of water in both pots with respect to time. Parameters for the time dependency can be seen below in Table 23 with an output plot of the fluid temperature for both pots as a function of time seen in Figure 25.

Table 23: Time dependent simulation parameters.

Parameter	Criteria
Flow freezing	Disabled
Solving time step	5 s physical time
Save full results	30 s periodic physical time
Finish Conditions	3600 s physical time

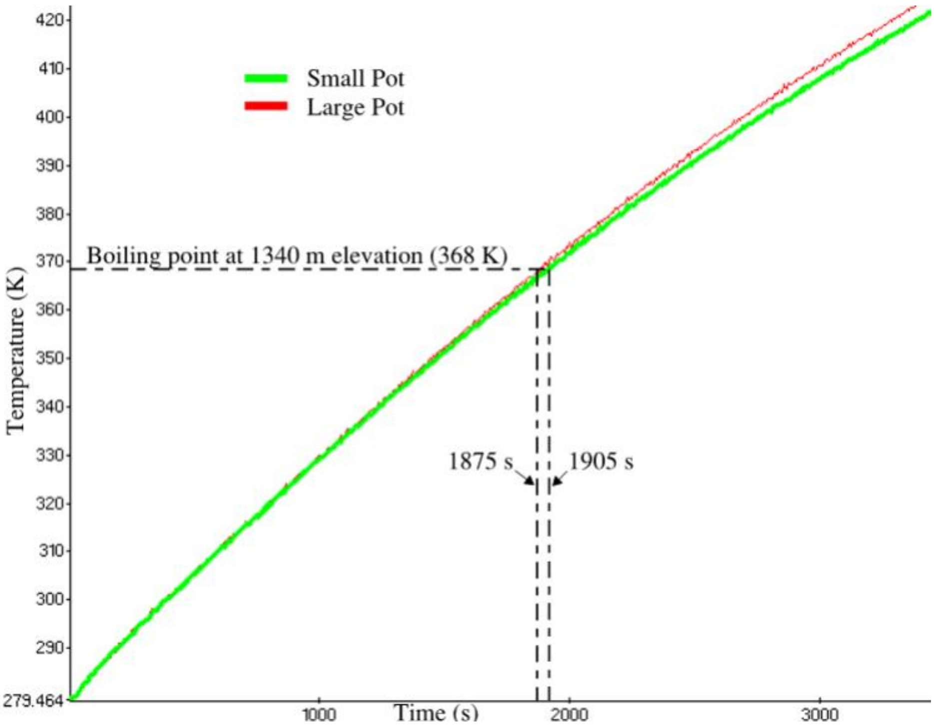


Figure 25: Fluid temperature for large and small pot as a function of time.

As we can see from the figure above the time to boil water in both pots is between 31 and 32 minutes. A graphical representation of the convective heat applied to the pots as result of combustion is shown in Figure 26 as a cut plot with streamlines.

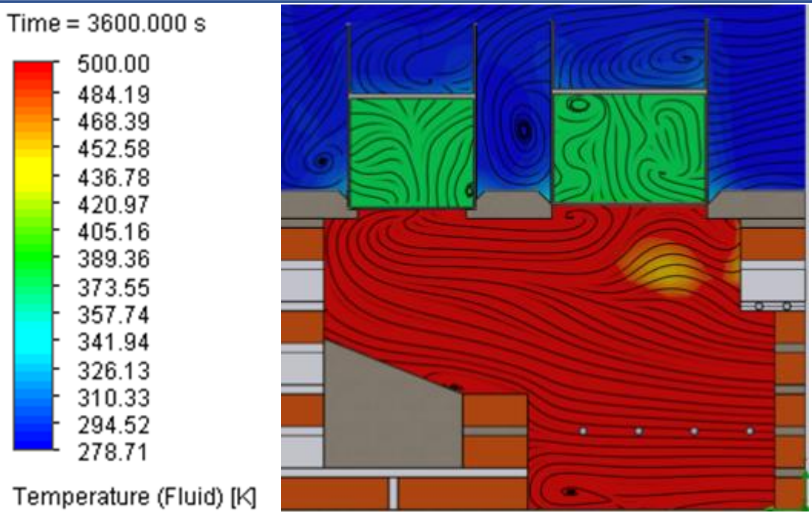


Figure 26: Cut plot of stove and water temperature inside stove and pots as water reached boiling point (green).

15. Appendix E – Space Heating Analysis

15.1 Thermal Envelope Calculations

Prepared by: Ben Hallworth Date: 04/12/2021

Chimney Friction and Heat Transfer Calculations

Objective: Determine the properties of the internal flow through a chimney. Following this, determine heat transfer rates between the flue gasses and room based on client-specified boundary conditions and using a chimney with internal and external fins.

Pipe / Plate Geometry Dimensions

$D := 4\ in$ $R := \frac{D}{2}$

$h_{chimney} := 3\ m$ Chimney height

$A_{duct} := \pi \cdot R^2 = 0.0081\ m^2$ Geometry factor for internal flow

$\varepsilon_{galv} := .15\ mm$ Surface roughness. Obtained from Introduction to Thermo-Fluid design

$n_{fin} := 6$ Number of fins (same on inside and outside, for simplicity and minimization of fasteners)

$L := 1.5\ m$ Length of finned pipe section

Air Properties

Engineering Toolbox

From literature: $T_{flue} := 720\ K$ $T_{amb} := 288\ K$ Indoor air temperature of 15C

Assume flue gasses to be Air at T.avg = 585K

$P_{amb} := 97.7\ kPa$ Pressure at 1000m elevation

$c_{p.air} := 1.04\ \frac{kJ}{kg\ K}$ $R_{air} := 287\ \frac{J}{kg\ K}$ Assume properties of air at average temperature (shown below, guess from iterations)

$\nu := 4.90 \cdot 10^{-5}\ \frac{m^2}{s}$

$\rho_{flue} := \frac{P_{amb}}{R_{air} \cdot T_{flue}} = 0.4728\ \frac{kg}{m^3}$ Density is calculated at T.flue (exit temp from flame) as this is the value specified from combustion calculations and is related to inlet air properties. Actual density used elsewhere in calculations is at T.av

Available head

$g := 9.81\ \frac{N}{kg}$

$P := 0.0342\ \frac{K}{m} \cdot P_{amb} \cdot h_{chimney} \cdot \left(\frac{1}{T_{amb}} - \frac{1}{T_{flue}}\right) = 20.8834\ Pa$ Stack effect estimate of pressure from fire

Citation 33 in clean energy paper

$\frac{P}{\rho_{flue} \cdot g} = 4.5025\ m$ Available head

Flow Rate

$m_{dot.flue} := 2.15\ \frac{g}{s}$ Flue gas mass flow rate, obtained from Rocket Stove Calculations

$Q := \frac{m_{dot.flue}}{\rho_{flue}} = 0.0045\ \frac{m^3}{s}$ $v_i := \frac{Q}{A_{duct}} = 0.5609\ \frac{m}{s}$ Flow velocity (within estimates for fire)

$R_{wall.i} := 0.14 \frac{m^2 K}{W} \cdot \frac{1}{A_{wall}}$ Thermal resistance of wall due to internal convection (valye specified in paper per unit area)

Corugated metal roofing:

$R_{wall.o} := 0.06 \frac{m^2 K}{W} \cdot \frac{1}{A_{wall}}$ Thermal resistance of wall due toe xternal convection (valye specified in paper per unit area)

Cited from: https://www.researchgate.net/publication/322253509_COMPARATIVE_PERFORMANCE_ASSESSMENT_OF_CONVENTIONAL_BUILDINGS_OF_KATHMANDU

$R_{wall} := R_{brick.cond} + R_{wall.i} + R_{wall.o} = 0.0911 \frac{K}{W}$ Heat loss in series (internal and external convection, conduction)

$U_{wall} := \frac{1}{R_{wall} \cdot A_{wall}}$ $U_{wall} = 1.4124 \frac{W}{m^2 K}$ Within range of paper above

$U_{roof} := 1.86 \frac{W}{m^2 K}$ $R_{roof} := \frac{1}{U_{roof} \cdot A_{roof}}$ Conservative estimate from [1]

$HL_{transfer} := (T_i - T_o) K \cdot \left(\frac{4}{R_{wall}} + \frac{1}{R_{roof}} \right) = 893.1465 W$ Heat flow through 4 walls, 1 roof
Heat flow through each is added (cumulative) since temperature is assumed constant and there are 5 pathways

$HL_{tot} := HL_{infiltration} + HL_{transfer} = 1055.2915 W$ Final thermal envelope heat loss

$HL_{tot} = 3600.8041 \frac{BTU}{hr}$

Conclusion: The minimum heating rate required to maintain the specified temperature is 1055W. This is somewhat conservative as it superimposes airflow rates for the fire and users on top of the expected number of air changes per minute. Further, it neglects any heating provided by solar radiation. This allows for worst-case scenatios in winter where white snow may reduce the rate of radiation absorption. This value seems somewhat reasonable given the small volume of the room.

References

https://www.researchgate.net/publication/322253509_COMPARATIVE_PERFORMANCE_ASSESSMENT_OF_CONVENTIONAL_BUILDINGS_OF_KATHMANDU

https://www.engineeringtoolbox.com/air-change-rate-room-d_867.html

https://soa.utexas.edu/heat-loss-due-infiltration-using-air-change-method

15.2 Analytical Solution for Chimney Heat Transfer

SMath was used to perform parametrized fluid flow and heat transfer analysis.

Prepared by: Ben Hallworth Date: 04/12/2021

Chimney Friction and Heat Transfer Calculations

Objective: Determine the properties of the internal flow through a chimney. Following this, determine heat transfer rates between the flue gasses and room based on client-specified boundary conditions and using a chimney with internal and external fins.

Pipe / Plate Geometry Dimensions

$D := 4\ \mathrm{in}$ $R := \frac{D}{2}$

$h_{chimney} := 3\ \mathrm{m}$ Chimney height

$A_{duct} := \pi \cdot R^2 = 0.0081\ \mathrm{m}^2$ Geometry factor for internal flow

$\varepsilon_{galv} := .15\ \mathrm{mm}$ Surface roughness. Obtained from Introduction to Thermo-Fluid design

$n_{fin} := 6$ Number of fins (same on inside and outside, for simplicity and minimization of fasteners)

$L := 1.5\ \mathrm{m}$ Length of finned pipe section

Air Properties

Engineering Toolbox From literature: $T_{flue} := 720\ \mathrm{K}$ $T_{amb} := 288\ \mathrm{K}$ Indoor air temperature of 15C

Assume flue gasses to be Air at T.avg = 585K

$P_{amb} := 97.7\ \mathrm{kPa}$ Pressure at 1000m elevation

$c_{p.air} := 1.04\ \frac{\mathrm{kJ}}{\mathrm{kg\ K}}$ $R_{air} := 287\ \frac{\mathrm{J}}{\mathrm{kg\ K}}$ Assume properties of air at average temperature (shown below, guess from iterations)

$\nu := 4.90 \cdot 10^{-5}\ \frac{\mathrm{m}^2}{\mathrm{s}}$

$\rho_{flue} := \frac{P_{amb}}{R_{air} \cdot T_{flue}} = 0.4728\ \frac{\mathrm{kg}}{\mathrm{m}^3}$ Density is calculated at T.flue (exit temp from flame) as this is the value specified from combustion calculations and is related to inlet air properties. Actual density used elsewhere in calculations is at T.av

Available head

$g := 9.81\ \frac{\mathrm{N}}{\mathrm{kg}}$

$P := 0.0342\ \frac{\mathrm{K}}{\mathrm{m}} \cdot P_{amb} \cdot h_{chimney} \cdot \left(\frac{1}{T_{amb}} - \frac{1}{T_{flue}} \right) = 20.8834\ \mathrm{Pa}$ Stack effect estimate of pressure from fire

Citation 33 in clean energy paper

$\frac{P}{\rho_{flue} \cdot g} = 4.5025\ \mathrm{m}$ Available head

Flow Rate

$m_{dot.flue} := 2.15\ \frac{\mathrm{g}}{\mathrm{s}}$ Flue gas mass flow rate, obtained from Rocket Stove Calculations

$Q := \frac{m_{dot.flue}}{\rho_{flue}} = 0.0045\ \frac{\mathrm{m}^3}{\mathrm{s}}$ $v_i := \frac{Q}{A_{duct}} = 0.5609\ \frac{\mathrm{m}}{\mathrm{s}}$ Flow velocity (within estimates for fire)

Friction Calculations

$A_{cs} := \pi \cdot R^2$ Cross section area

$H_{fin.i} := 2\ cm$ Fin height & length

$A_{WP} := \pi \cdot D + 2 \cdot n_{fin} \cdot H_{fin.i}$ Wetted perimeter (including fins)

Cross sectional Area

Wetted Perimeter

$D_h := \frac{4 \cdot A_{cs}}{A_{WP}} = 5.7994\ cm$ Hyrdaulic diameter

$Re_D := \frac{v_i \cdot D_h}{\nu} = 663.844$ Re < 2300 so Laminar

Using relations for laminar flow of unknown geometry

$f_{chimney} := \frac{96}{Re_D} = 0.1446$ c value unknown for this geometry, but maximum is 96 (thin channel) Using this is conservative for laminar flow

$L_{elbow} := 25\ ft$ Equivalent length due to 90 degree elbow. Obtained from Introduction to Thermo -Fluid design

$L_{bellmouth} := 0.1\ ft$ Equivalent length of bellmouth entrance. Assume sloped chimney entrance is similar to a bellmouth entrance

$$h_{L.chim} := \left(f_{chimney} \cdot \frac{L + (L_{bellmouth} + L_{elbow})}{D} \right) \cdot \frac{v_i^2}{2 \cdot g} = 0.2088\ m$$

Head and pressure losses through finned section

$P_{HEX} := P - \rho_{flue} \cdot g \cdot h_{L.chim} = 19.9147\ Pa$

$$L_{max} := \frac{P_{HEX} \cdot D \cdot 2}{f_{chimney} \cdot v_i^2 \cdot \rho_{flue}} = 188.1268\ m$$

Approx. Maximum length of chimney before stagnation occurs

Essentially showing adding length downstream will not lead to stagnation

Downstream (Finless) Pipe Section

For low reynold's number, f is rougly constant for a given e/D so use the same

$D_{h.pipe} := D = 10.16\ cm$ Same diamaeter pipe, no fins

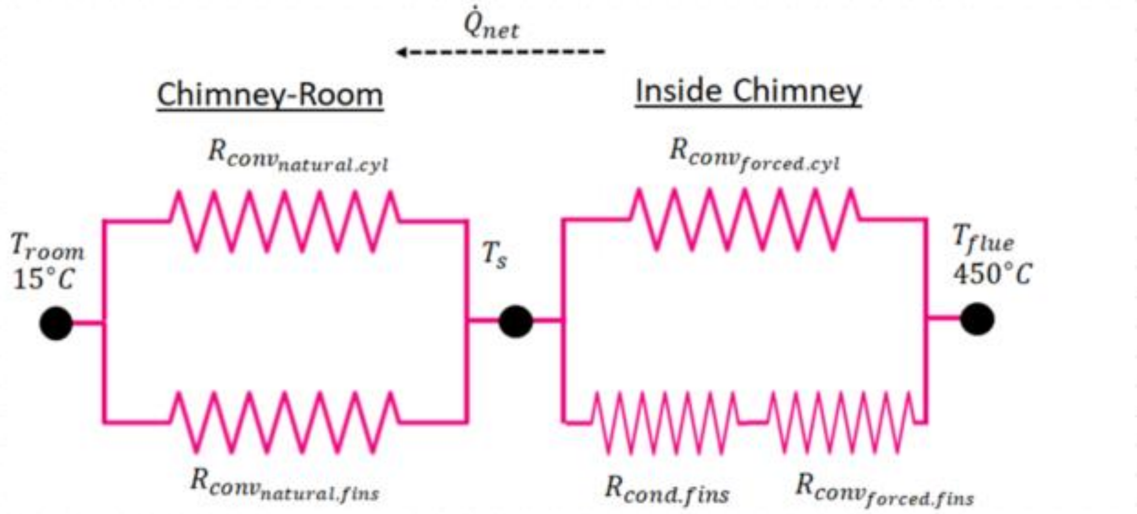
$Re_{i2} := \frac{v_i \cdot D_{h.pipe}}{\nu} = 1162.9971$ $Laminar$ $f_{pipe} := \frac{64}{Re_{i2}} = 0.055$ Circular so friction value known

$h_{loss.pipe} := f_{pipe} \cdot \frac{L}{D_{h.pipe}} \cdot \frac{v_i^2}{2 \cdot g} = 0.013\ m$ Head loss through straight pipe

$P_{loss.ds} := (h_{L.chim} + h_{loss.pipe}) \cdot \rho_{flue} \cdot g = 1.0291\ Pa$ Total pressure loss through entire chimney

Value is low due to laminar flow over 1.5m lenght

Heat Transfer Calculations



Overview of thermal network diagram for chimney illustrating heat transfer mechanisms

Heat calculations were performed iteratively (starting with guesses of surface and flue temperature). The calculations shown are from the final iteration

Iteration 1: $T_{s.1} := T_{amb} + 0.1 \cdot (T_{flue} - T_{amb})$ — Surface temperature at inside of pipe (arrived at iteratively)

$T_{f1} := \frac{T_{s.1} + T_{flue}}{2} = 525.6\ K$ — Film temperature for inside of pipe

Proprties of air at T film — Source: Engineering Toolbox

$Pr_i := 0.7 \qquad k_{air.i} := 0.05\ \frac{W}{m\ K}$

$L_{plate} := L$ — Internal fins are same length as external

<u>Internal Flow Heat Transfer Analysis</u>

<u>External flow over flat plates (fins) within pipe</u>

Plates have externnal forced convection with Ts = T pipe

$A_{plate} := 2 \cdot n_{fin} \cdot L \cdot H_{fin.i} = 0.36\ m^2$

$Re_L := \frac{v_i \cdot L_{plate}}{\nu} = 17170.2323$ — This is less than the critical value for external flow (5 E5), so laminar

$Nu_{plate} := 0.664 \cdot Re_L^{0.5} \cdot Pr_i^{\frac{1}{3}} = 77.2542$

$k_{th.galv} := 52\ \frac{W}{m\ K}$ — Conductivity of galvanized steel

$A_{c.fin} := n_{fin} \cdot (0.4\ mm \cdot L)$ — Cross-sectional Area of fins (plates)

$h_{th.plate} := \frac{k_{air.i}}{L_{plate}} \cdot Nu_{plate} = 2.5751\ \frac{W}{m^2\ K}$ — Convection coefficient of internal fins

$$R_{fins.i} := \frac{1}{h_{th.plate} \cdot A_{plate}} + \frac{H_{fin.i}}{2 \cdot A_{c.fin} \cdot k_{th.galv}} = 1.1321 \frac{K}{W}$$

Assume on average heat conducted from centre of fin to base (half length of internal fine). E.g. Convects to same temperature but on average has to travel half the length of the fin to the wall of the chimney

Total fin resistance is convection plus conduction (in series)

$$\frac{H_{fin.i}}{2 \cdot A_{c.fin} \cdot k_{th.galv}} = 0.0534 \frac{K}{W}$$

Check: conductive resistance is low

Pipe cylinder Internal heat transfer

Assume constant surface temperature

From above, all Reynolds numbers below that of the laminar value (2300) -> laminar

Thermal entrance region:

Surface area of cylindrical pipe secion

$$A_{pipe.HEX} := \pi \cdot D \cdot L = 0.4788 \, m^2$$

$$Nu := 10 \cdot D = 1.016 \, m$$

so developing flow in the finned section (L = 1.5m)

$$Nu_{pipe.i} := 3.66 + \frac{0.065 \cdot \left(\frac{D}{L}\right) \cdot Re_D \cdot Pr_i}{1 + 0.04 \cdot \left(\left(\frac{D}{L}\right) \cdot Re_D \cdot Pr_i\right)^{\frac{2}{3}}} = 5.1226$$

Developing laminar flow

$$h_{th.pipe} := \frac{k_{air.i}}{D} \cdot Nu_{pipe.i} = 2.521 \frac{W}{m^2 \, K}$$

$$R_{pipe.i} := \frac{1}{h_{th.pipe} \cdot A_{pipe.HEX}} = 0.8285 \frac{K}{W}$$

Thermal resistance of pipe

$$R_{conv.i} := \frac{1}{\frac{1}{R_{pipe.i}} + \frac{1}{R_{fins.i}}} = 0.4784 \frac{K}{W}$$

Thermal resistance of heat transfer from flue gast to chimney

External Heat Transfer

Properties of air at Tf.o

$$Pr := 0.7241$$

$$T_{f.o} := \frac{T_{s.1} + T_{amb}}{2} = 309.6 \, K$$

External film temperature (at which properties of air obtained)

$$\beta := \frac{1}{T_{f.o}}$$

Coefficient of expansion

$$k_o := 0.027 \frac{W}{m \, K}$$

Conductivity of air at film temperature

$$v_o := 1.64 \cdot 10^{-6} \frac{m^2}{s}$$

Kinematic viscosity

Pipe External Heat Transfer (Natural)

$$gr_L := \frac{g \cdot \beta \cdot \left(T_{s.1} - T_{amb}\right) \cdot D^3}{\nu_o^2} = 5.3376 \cdot 10^8$$

Grashof number for exposed pipe

$$Ra_D := gr_L \cdot Pr = 3.8649 \cdot 10^8$$

Raleigh number

$$Nu := \left(0.6 + \frac{0.386 \cdot Ra_D^{\frac{1}{6}}}{\left(1 + \left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}}\right)^2 = 85.7812$$

Nusselt number for external flow over cylinder

$$h_{o.pipe} := \frac{k_o}{D} \cdot Nu = 22.7962 \ \frac{W}{m^2 \ K}$$

external convection coefficient

$$R_{conv.o.pipe} := \frac{1}{2 \cdot \pi \cdot R \cdot h_{o.pipe} \cdot L} = 0.0916 \ \frac{K}{W}$$

Thermal resistance of pipe

External Cooling Fin Heat Transfer

Heat transfer over internal fins

$L_{fin} := L$ $\quad H_{fin} := 3 \ cm$

Length and height of fins

$t := 1 \ mm$

fin thickness

$$S := \frac{\pi \cdot D}{n_{fin}} - t = 0.0522 \ m$$

Fin Spacing

$$A_{fin} := 2 \cdot n_{fin} \cdot L_{fin} \cdot H_{fin} = 0.54 \ m^2$$

$$A_{fin.tot} := 0.5 \cdot \left(A_{plate} + A_{fin}\right) = 0.45 \ m^2$$

$$Ra_L := \frac{g \cdot \beta \cdot \left(T_{s.1} - T_{amb}\right) \cdot L_{fin}^3}{\nu^2} \cdot Pr = 1.3933 \cdot 10^9$$

$$Nu_{fin} := 0.54 \cdot Ra_L^{\frac{1}{4}} = 104.3282$$

$$h_{fin} := Nu_{fin} \cdot \frac{k_o}{S} = 53.9653 \ \frac{W}{m^2 \ K}$$

Vertical plates

$$R_{conv.o.fin} := \frac{1}{h_{fin} \cdot A_{fin}} = 0.0343 \ \frac{K}{W}$$

$$R_{conv.o} := \frac{1}{\frac{1}{R_{conv.o.fin}} + \frac{1}{R_{conv.o.pipe}}}$$

Combined system

$$R_{total} := R_{conv.i} + R_{conv.o} = 0.5034 \ \frac{K}{W}$$

$$R_{conv.i} = 0.4784 \ \frac{K}{W}$$

$$R_{conv.o} = 0.025 \ \frac{K}{W}$$

Greater resistance inside pipe

Check Assumptions :

$T_{av.est} := T_{flue} - 135\ K = 585\ K$

Estimate of average flue gas temperature in finned section. Finned section is 1 .5m long so gas temp will drop from T.flue. Simplification is that the finned section operates between T.av (Boundary condition of flue gase) and T.ambient. This value was arrived at iteratively.

$$Q_{HEX} := \frac{\left(T_{av.est} - T_{amb}\right)}{R_{total}} = 590.0291\ W$$

$Q_{HEX} = 2013.2627\ \frac{BTU}{hr}$ Total heat transferred from chimney

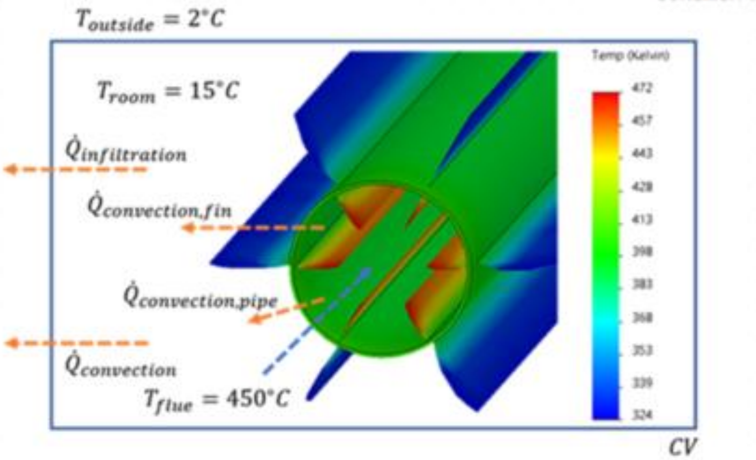
$T_{s.1.actual} := T_{av.est} - Q_{HEX} \cdot R_{conv.i} = 302.7303\ K$ Check surface temperature of pipe wall

$T_{s.1} = 331.2\ K$

There is only a 30 degree difference in the assumed energy transfer, so we can assume the solution has converged. Given the uncertainty in assumptions further iterations will likely not yeild more accurate solutions. Since limiting factor is internal convection, having actual surface temperature lower than assumed means heat transfer was underestimated

$T_{s.inlet} := T_{flue} - Q_{HEX} \cdot R_{conv.i} = 437.7303\ K$

Check lumped pipe surface temperature at inlet (will compare with thermal simulation where T.air boundary condition is equal to T.flue)



Steady state thermal simulation at inlet (with flue gasses at T.flue) show here. This shows base of fin and chimney at approximately constant temperature of around 430K which is close to the T.s.inlet value of 437K. Therefore results and lumped wall temperature assumption valid.

Evaluation: heat transfer if just bare pipe (no fins or internal plates)

$$Q_{test} := \frac{\left(T_{flue} - T_{amb}\right)}{R_{conv.o.pipe} + R_{pipe.i}} = 469.5005\ W$$

Compare with 711W below. Shows significant heat transfer increases with fins

$$T_e := T_{flue} - \frac{Q_{HEX}}{c_{p.air} \cdot m_{dot.flue}} = 456.123\ K$$

Temperature at exit of finned section

$$T_{av} := \frac{T_{flue} + T_e}{2} = 588.0615\ K$$

T.av was estimated to be average of inlet and outlet temperature of finned section. The result is checked here for convergence.

$T_{av.est} = 585\ K$ *Close*

T.av.est given in initial calculations and resultant T.average

Downstream of finned section (i.e. finless chimney portion):

$L_{pipe} := 1\ \mathrm{m}$ Length of finless chimney section inside dwelling

$$Q_{Bare.pipe} := \frac{T_e - T_{amb}}{R_{conv.o.pipe} + R_{pipe.i}} \cdot \left(\frac{L_{pipe}}{L}\right) = 121.8115\ \mathrm{W}$$

Heat transferred from 1m section down from fins

Estimate to demonstrate negligible effect of radiation:

$\epsilon_{galv.emis} := 0.23$ Emissivity of clean galvanized steel

$\sigma_{SB} := 5.67 \cdot 10^{-8} \frac{\mathrm{W}}{\mathrm{m}^2\ \mathrm{K}^4}$ Stephan-Boltzmann constant

$$Q_{rad} := \sigma_{SB} \cdot \epsilon_{galv.emis} \cdot (\pi \cdot D \cdot L) \cdot \left(T_{s.1}^{\ 4} - T_{amb}^{\ 4}\right) = 32.1737\ \mathrm{W}$$

Assume radiation only from cylinder

Fins are hottest near base and quickly decay to near-ambient temperature. Therefore, fins mostly radiate heat back to each other so their surface area is negligible in total overall heating area. This is a conservative estimate as it assumes radiation only from the cylindrical portion of the stove.

$$Q_{total} := Q_{Bare.pipe} + Q_{HEX} + Q_{rad} = 744.0142\ \mathrm{W}$$

Total heat transferred from flue gasses to outside

Is this reasonable? Well, total energy transferred to the flue gasses was 1650W (per combustion calculations); therefore,

$$\frac{Q_{total}}{1650\ \mathrm{W}} \cdot 100\ \% = 45.0918\ \%$$

43 percent of energy was extracted from flue gasses. This appears reasonable

Energy and Material Summary

$Q_{stove.rad} := 320\ \mathrm{W}$ Heat energy from stove

$A_{galv.steel} := \frac{A_{fin}}{2} + \frac{A_{plate}}{2} = 0.45\ \mathrm{m}^2$ Total fin/ plate material area (for material calculations)

$1650\ \mathrm{W} - Q_{total} = 905.9858\ \mathrm{W}$ Heat from rocket stove exhausted to the environment

$Q_{total} + Q_{stove.rad} = 1064.0142\ \mathrm{W}$ Total heat transferred from fire & chimney to room

Conclusion

The total heat output for all modes of heat transfer from the stove and chimney to the room is 1064W. This is a greater value than the amount of heating required to maintain the dwelling at 15C. While the number of assumptions made means results are likely not accurate to a single watt, the fact that assumptions are conservative (e.g. only radiation from cylindrical portion; conservative estimate of required space heating; Surface temperature assumed higher than actual when limiting factor is internal convection) indicates that the required heating is met. As simulations are in agreement with calculated values (e.g. inlet chimney temp) and assumed values converged after iterations, the final conclusion is reasonable.

15.3 Simulation

The general setup described in Appendix B – SolidWorks Simulation Setup was used to conduct this simulation. A steady state analysis was performed with a volume goal on the room air fluid subdomain to measure the average fluid temperature. Point goals were also used at various locations to probe the temperature in higher and lower heat regions which occurred due to higher or lower air velocity at different areas throughout the dwelling.

Table 24: Simulation parameters for CFD simulation of heat transfer in chimney and stove

Parameter	Criteria
Flow freezing	Disabled
Stop conditions	Goal convergence – all
Save full results	10 iterations
Iterations to stop	203

The below Figure 27 show that the heat transferred to the room from the chimney which converges to a value of 601.45 watts. Note that for this simulation the stop criteria was removed to obtain a longer data set in order to examine if there were any unexpected changes with extended iterations on the steady state analysis.

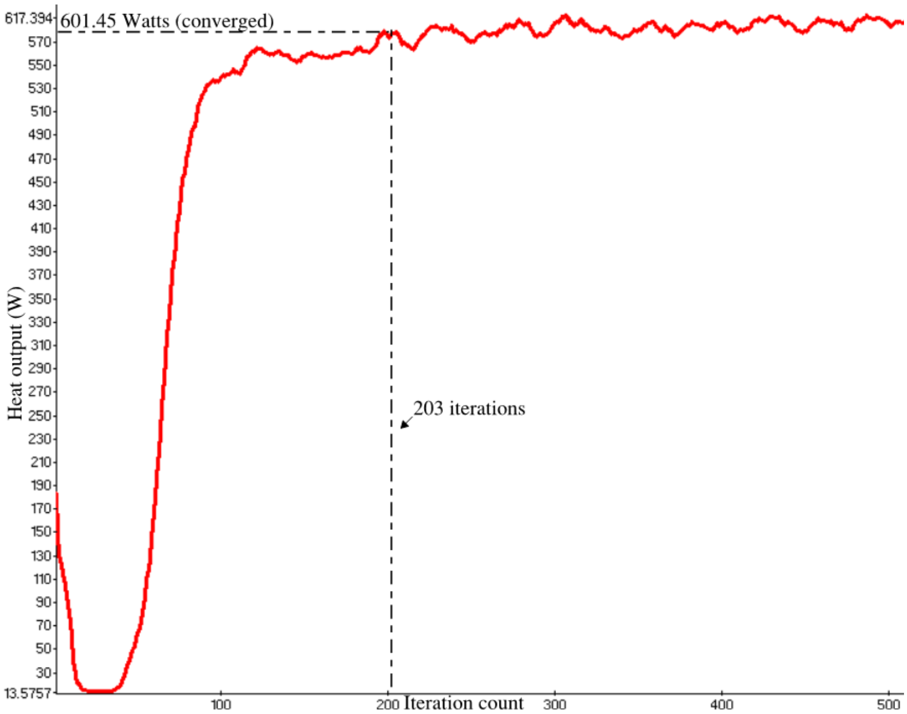


Figure 27: Heat output from chimney as a function of simulation iteration.

A cut plot showing the room temperature at a certain vertical plane within the dwelling can be seen in the main body of this report and is labelled Figure 12: Cut plot of temperature in room.

16. Appendix F – Emissions Analysis

The emissions from the stove were calculated by determining what portion of the flue gases left the stove and made it into the kitchen. This was done by taking a simple mass balance based on area fractions. The leakage area from around a burner was compared to the area inside the stove to determine the percentage of flue gas lost to the room. The following diagram shown in Figure 28, (previously shown as Figure 14 in the report body) shows the mass flow rate of the flue through the stove and leaking around the pots.

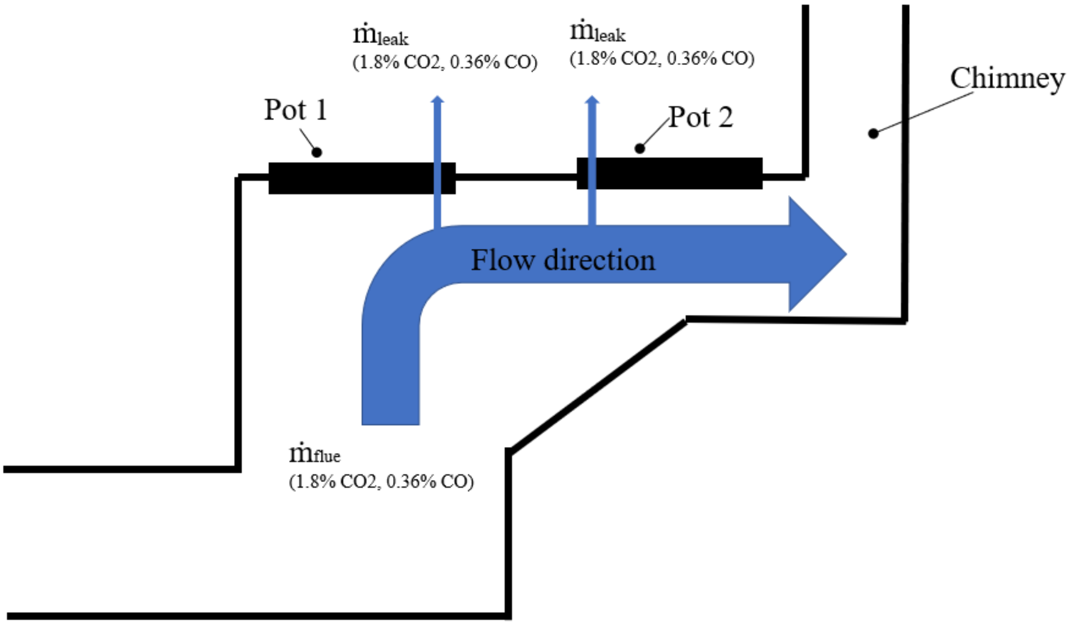


Figure 28: Diagram to show the analysis of the emissions to the room.

This analysis involved taking the outputs from the combustion analysis. Most notably the mass flow rate of the flue a gases through the stove and the composition of said flue gases. It then outputted the flow rates of both CO and CO_2 into the room. This is shown in Table 25.

Table 25: Parameters to calculate the emissions to the room.

Inputs	**Outputs**
Mass flow rate of flue gas [kg/s]	Flow rate of CO into the room [g/min]
Mass fractions of CO and CO_2 in flue gas [%]	Flow rate of CO_2 into the room [g/min]
Areas of leakage and stove interior [m^2]	

An analysis was completed on the assumed leakage of the stove due to an imperfect fit around the pot and clay top. This analysis is shown in the Figure 29 below.

Prepared By: Robert Chauvet Date: 04/05/2021

Flue Leakage:

The goal of this analysis is to determine the amount of flue gases excaping around the pot. This analysis will be done using flow rates and the area of leakage in the stove.

Assumptions

The fit around the pot was not perfect and a 1mm gap of space is around the pot

The flow rate throughout the stove is constant

The amount of flue leakage is proportional to the areas of flow (Mass Balance)

Analysis

$D_{pot} := 0.17 \ m$

$W_{combustion} := 0.17 \ m$

$$A_{leakage} := \left(\frac{(D_{pot} + 0.001)^2}{4} \cdot \pi - \frac{(D_{pot})^2}{4} \cdot \pi \right) \cdot 2 = 0.0005 \ m^2$$

Then we do a simple momentum balance across of the zone.

The area from the leakage is quite small for each pot

$$Ratio := \frac{A_{leakage}}{W_{combustion}^2} = 0.0185$$

This means that 2.7% of air could escape into the room at the pots

From the combustion calculations, we know the percent of CO and CO2 in the flue gas and the flow rate

$m_{flue} := 0.0024 \ \frac{kg}{s}$

Mass flow rate of CO2 into the room

$$m_{co2} := m_{flue} \cdot Ratio \cdot 0.018 = 8.0068 \cdot 10^{-7} \ \frac{kg}{s}$$

This value in g/min is

$$m_{co2final} := m_{co2} \cdot 60 \cdot 1000 = 0.048 \ \frac{g}{min}$$

Mass flow rate of CO into the room

$$m_{co} := m_{flue} \cdot Ratio \cdot 0.0036 = 1.6014 \cdot 10^{-7} \ \frac{kg}{s}$$

This value in g/min is

$$m_{cofinal} := m_{co} \cdot 60 \cdot 1000 = 0.0096 \ \frac{g}{min}$$

These rates seem reasonable for the smalll amount of leakage possible and meet the standards for indoor air quality

Figure 29: Emissions to the room hand calculations.

These values are then compared to the World Health Organization (WHO) guidelines for indoor air emissions. These standards are derived to give a value in g/min of the allowable emissions from an indoor stove. It gives both a vented area and unvented area value depending on the conditions the stove is in. Just to be conservative, the lower value (unvented kitchen) is assumed. This value is 0.23 g/min of CO2 (Particulate matter above 2.5 micrometres, in which CO2 is a good estimate).

A further study was then run to determine the maximum allowable leakage area to still meet the WHO specifications for indoor air quality. The formulas for leakage area and mass flow rates were compared against the limits set out by WHO.

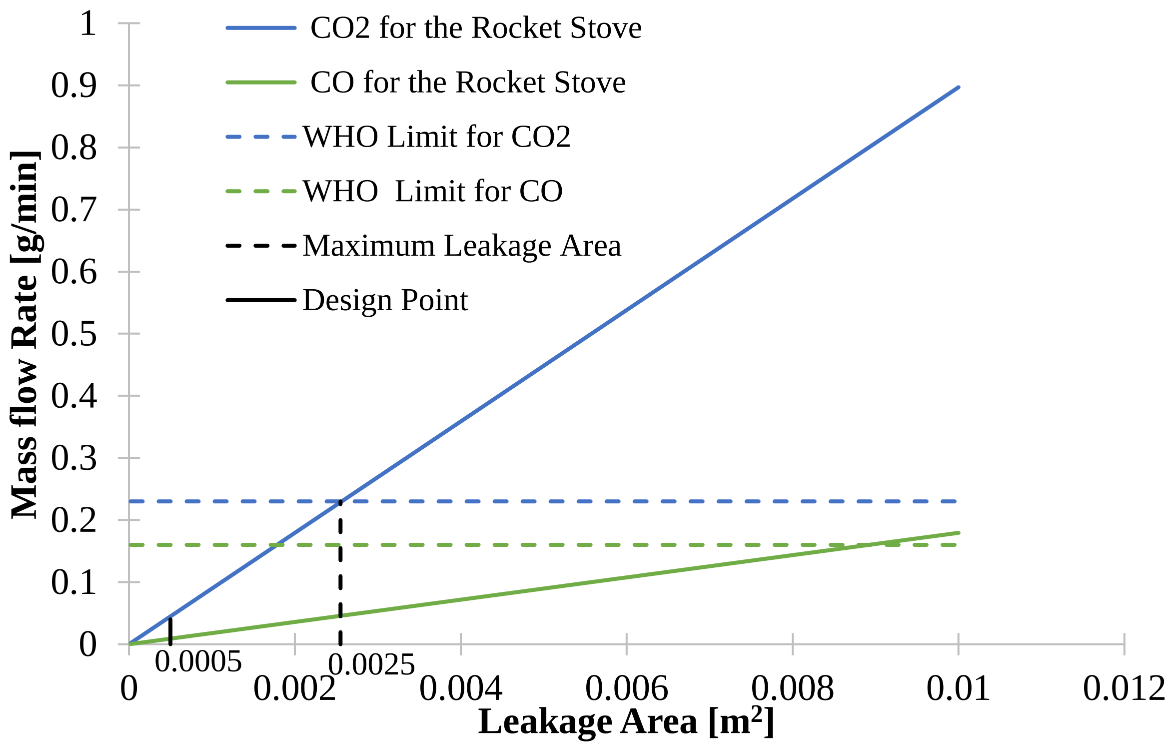


Figure 30: Emissions to the room as a function of leakage area inside of the stove.

Figure 30 shows that the mass flow rates rise linearly with the leakage areas. The CO2 rate reaches the limit first, at 0.0025 m2. This is much larger than the assumed 0.0005 m2 area that is assumed in the system G1 Consulting designed. This shows that the leakage area could be 5 times larger and meet the emissions set out by WHO as safe for indoor use. This validates our design as it shows we are well under emissions limits for the stove.

17. Appendix G – Structural Analysis

This section outlines the stress calculations on the pot skirts for the final rocket stove.

Objective

Prepared By: Kevin Zhong
Date: March 2, 2021

Determine if the pot skirts are strong enough to support cookware and food of a typical Nepalese meal.

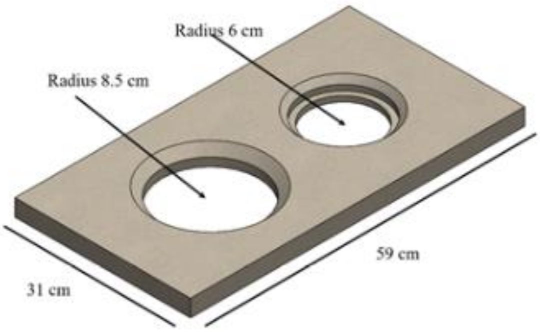
Knowns

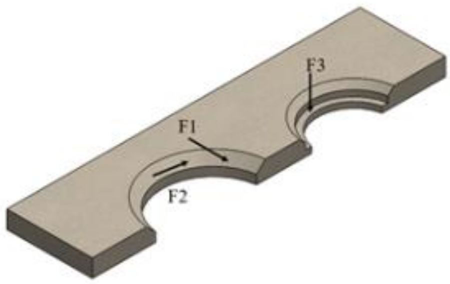
1. Pot 1 will be used to support a Kadhai (wok). Total mass of the Kadhai (2 kg) and food (1.5 kg) will weigh 3.5 kg.
2. Pot 2 will be used to support a lidded cylindrical vessel (flat bottom). Total mass of the cylindrical vessel (2 kg) and food (5 to 6 L, approx 6 kg) will weigh 8 kg.

Assumptions

1. The Kadhai and cylindrical vessel will sit perfectly in their custom-molded positions.

Sketch





Note that sketch is not drawn to scale. These are a cross-section view of pot skirts 1 and 2

F_1 is the force acting perpendicular to the surface of pot skirt 1 from the cookware and food

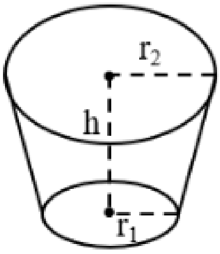
F_2 is the force acting parallel to the surface of pot skirt 1 from the cookware and food

F_3 is the pressure acting on the lip of pot skirt 2 from the cookware and food

Analysis

Prepared By: Kevin Zhong
Date: March 2, 2021

Pot 1 Analysis



$r_{1\_1} := 85\ mm$

$r_{2\_1} := 100\ mm$

$h := 20\ mm$

Note that sketch is not drawn to scale.

The inner surface area of pot skirt 1 in which F_1 and F_2 act on is given by:

$$A_1 := \pi \cdot \left(r_{1\_1} + r_{2\_1}\right) \cdot \sqrt{\left(r_{1\_1} - r_{2\_1}\right)^2 + h^2} = 0.0145\ m^2$$

The weight of the Kadhai and food is given by:

$$W_{kadhai} := 3.5\ kg \cdot 9.81\ \frac{m}{s^2} = 34.335\ N$$

The angle of the skirt is given by:

$$\theta_{skirt} := \mathrm{atan}\left(\frac{r_{2\_1} - r_{1\_1}}{h}\right) = 36.8699\ deg$$

The weight of the Kadhai and food acting parallel to the skirt is given by:

$$W_{kadhai\_parallel} := W_{kadhai} \cdot \cos\left(\theta_{skirt}\right) = 27.468\ N$$ Therefore, $F_2 := W_{kadhai\_parallel} = 27.468\ N$

The weight of the Kadhai and food acting perpendicular to the skirt is given by:

$$W_{kadhai\_perpendicular} := W_{kadhai} \cdot \sin\left(\theta_{skirt}\right) = 20.601\ N$$

Therefore, $F_1 := W_{kadhai\_perpendicular} = 20.601\ N$

The shear stress acting on the pot skirt is given by:

$$\tau := \frac{F_2}{A_1} = 1890.451\ Pa$$

The normal stress acting on the pot skirt is given by:

$$\sigma_1 := \frac{F_1}{A_1} = 1417.8383\ Pa$$

For a conservative analysis, the mud clay will be assumed to be of the lowest compressive strength of mortar as documented by the Nepal National Building Code NBC 109: 1994.

Therefore, $\sigma_{str\_compression} := 5 \cdot 10^{5}$ Pa

Source: http://www.iibh.org/kijun/pdf/Nepal_14_NBC_109_1994_Unreinforced_Masonry.pdf

The safety factor is given by:

$$SF_1 := \frac{\sigma_{str\_compression}}{\sigma_1} = 352.6495$$

Therefore, the clay will be able to support the perpendicular loading from the Kadhai.

For a conservative analysis, the cohesive (shear) strength of soft clay will be used.

Therefore, $\sigma_{str\_shear} := 48000$ Pa

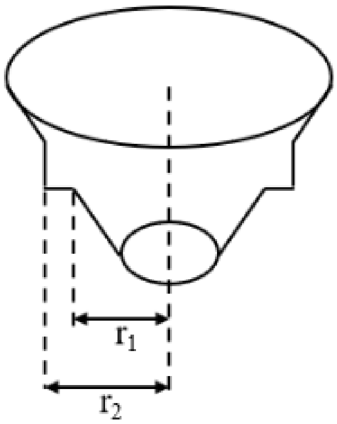
Source: https://www.jsg.utexas.edu/tyzhu/files/Some-Useful-Numbers.pdf

The safety factor is given by:

$$SF_2 := \frac{\sigma_{str\_shear}}{\tau} = 25.3908$$

Therefore, the clay will be able to support the shear loading from the Kadhai.

Pot 2 Analysis



$r_{1\_2} := 60$ mm

$r_{2\_2} := 70$ mm

Note that sketch is not drawn to scale.

The surface area of the lip is given by:

$$A_2 := \pi \cdot \left(r_{2\_2}^{\ 2} - r_{1\_2}^{\ 2}\right) = 0.0041\ \text{m}^2$$

The weight of the cylindrical vessel and food is given by:

$$W_{cv} := 8\ \text{kg} \cdot 9.81\ \frac{\text{m}}{\text{s}^2} = 78.48\ \text{N}$$

Therefore, $F_3 := W_{cv} = 78.48$ N

The normal stress acting on the lip is given by:

$\sigma_2 := \frac{F_3}{A_2} = 19216.123\ Pa$

The compressive strength of clay is $\sigma_{str\_compression} = 5 \cdot 10^5\ Pa$

The safety factor is given by:

$SF_3 := \frac{\sigma_{str\_compression}}{\sigma_2} = 26.0198$

Therefore, the clay will be able to support the cylindrical vessel.

Conclusions

For pot 1, the safety factor for perpendicular and parallel loading is $SF_1 = 352.6495$ and $SF_2 = 25.3908$, respectively. Therefore, the clay will be able to support the weight of the Kadhai and food.

For pot 1, the safety factor for loading is $SF_3 = 26.0198$. Therefore, the clay will be able to support the weight of the cylindrical vessel and food.

Maximum loading that each pot can handle without failing

Pot 1

The compression and shear strength of clay is shown below respectively.

$\sigma_{str\_compression} = 5 \cdot 10^5\ Pa$

$\sigma_{str\_shear} = 48000\ Pa$

The stresses are used to calculate the maximum compression and shear force that can be exerted on pot skirt 1.

$F_{str\_compression} := \sigma_{str\_compression} \cdot A_1 = 7264.933\ N$

$F_{str\_shear} := \sigma_{str\_shear} \cdot A_1 = 697.4336\ N$

Using these maximum values, the maximum weight (in terms of force) that the pot skirt can support is:

$F_{max\_compression} := \frac{F_{str\_compression}}{\sin\left(\theta_{skirt}\right)} = 12108.2217\ N$

$F_{max\_shear} := \frac{F_{str\_shear}}{\cos\left(\theta_{skirt}\right)} = 871.792\ N$

Since the shear stress component is the limiting factor, as calculated above, the maximum mass that can be supported by the pot skirt 1 is equivalent to $F_{max\_shear} = 871.792\ N$.

Therefore, the maximum combined mass of the Kadhai and food that pot skirt 1 can support is:

$$m_{max} := \frac{F_{max\_shear}}{9.81 \frac{m}{s^2}} = 88.8677 \text{ kg}$$

Pot 2

The compression strength of clay is shown below.

$$\sigma_{str\_compression} = 5 \cdot 10^5 \text{ Pa}$$

The compression strength of clay is used to calculate the maximum compression force that can be exerted on pot skirt 2.

$$F_{str\_compression\_2} := \sigma_{str\_compression} \cdot A_2 = 2042.0352 \text{ N}$$

This maximum compression force is the weight (in terms of force) that can be supported by pot skirt 2. Therefore, the maximum mass that pot skirt 2 can support is:

$$m_{max\_2} := \frac{F_{str\_compression\_2}}{9.81 \frac{m}{s^2}} = 208.1585 \text{ kg}$$

18. Appendix H – Cost Analysis

The detailed cost analysis for the Rocket Stove and Finned Chimney design can be found in this section.

The following information shown in Table 26 was gathered from the client and through research online.

Table 26: Costs for materials, transportation, tools, and labour.

Item	Cost
Iron Sheet Metal	1.15 CAD/kg
Rebar/Sheet Metal Cutter	115 CAD
Transportation	115 CAD
Brick	0.03 CAD per brick (labour)
Rebar (diameter = 8mm, length = 12m)	1 CAD
Rebar/Sheet Metal Cut (per part)	1 CAD
Labor	11.5 CAD/day
90° Elbow	9.5 CAD [14]
Self-tapping Screws (Quantity: 50) (McMaster-Carr Part # 92470A049)	6.50 CAD [15]
Nuts (Quantity: 50) (McMaster-Carr Part # 90480A002)	1.83 CAD [16]
Trowel	2 CAD
2 in. x 4 in. wood (l=8 ft.)	12 CAD
Clay	0 CAD

Based on this information and the solid model shown in Figure 17, the cost for materials and machining (rebar and sheet metal cuts) for each of the Rocket Stove, Chimney Base, and Finned Chimney are shown in Table 27, Table 28, and Table 29, respectively.

Table 27: Material and machining costs for the Rocket Stove.

Item	Quantity	Cost per Quantity (CAD)	Total Cost (CAD)
Bricks	71	0.03	2.13
Rebar	1	1	1
Iron Sheet Metal	1 kg	1.15	1.15
Rebar/Sheet Metal Cuts	9	1	9
Clay	0.016 m^3	0	0
		TOTAL	**13.28**

Table 28: Material and machining costs for the Chimney Base.

Item	Quantity	Cost per Quantity (CAD)	Total Cost (CAD)
Bricks	31	0.03	0.93
Rebar/Sheet Metal Cuts	3	1	3
Clay	0.006 m^3	0	0
		TOTAL	**3.93**

Note that 2.82 m of rebar is required for the Rocket Stove and Chimney Base combined while one rebar has a length of 12 m. Since the cost of the rebar is calculated with the Rocket Stove, the cost will not appear in the Chimney Base calculations.

Table 29: Lower bound material and machining costs for the Finned Chimney.

Item	Quantity	Cost per Quantity (CAD)	Total Cost (CAD)
Iron Sheet Metal	12.3 kg	1.15	14.15
Sheet Metal Cuts	14	1	14
Self-tapping Screws	42	0.13	5.46
Nuts	42	0.04	1.68
90° Elbow	1	9.5	9.5
		TOTAL	**44.79**

Note that a package of 50 screws costs $6.50 CAD, therefore, each screw costs $0.13 CAD and a package of 100 nuts costs $3.66 CAD, therefore, each nut costs $0.04 CAD.

From the cost of materials and machining for each component, the cost for 1000 stoves in the Shikhar Ambote village (population of 5000, approximately 1000 dwellings) factoring in tools, transportation, and labour is shown in Table 30 below.

Table 30: Lower bound total costs to produce 1000 stoves.

Item	Quantity	Cost per Quantity (CAD)	Total Cost (CAD)
Rocket Stove	1,000	13.28	13,280
Chimney Base	1,000	3.93	3,930
Finned Chimney	1,000	45.47	44.785
Rebar/Sheet Metal Cutter	3	115	345
Transportation	15	115	1,725
1 Worker (# of days)	2000	11.5	23,000
Trowel	10	2	20
2 in. x 4 in. wood (l=8 ft.)	2	12	24
		TOTAL	**87,109**

Based on the lower bound total costs for 1000 stoves, each unit costs $87.11 CAD per 333 units produced. It is shown that three rebar/sheet metal cutters are needed, however, it should be noted that it is more likely the blade of the cutter needs to be replaced. It is estimated that each blade costs 1/3 of the price of the machine itself (seen from local hardware stores), therefore, the total price of $345 CAD includes 1 cutter at $115 CAD and 6 additional blades at $38 CAD per blade. The total cutting time for each unit was estimated to be approximately 30 minutes. Based on these values, one blade will last approximately 143 units produced or 72 hours of total cut time. 15 transportation trips to bring materials such as wood, rebar/sheet metal cutter, trowel, sheet metal, screws, and nuts will be required. It should be noted that each transport truck is capable of carrying a load of 3000 kg. 15 trips is an overestimate based on the total amount of sheet metal required (13.3 kg/stove for 1,000 stoves = 13,300 kg). With 15 trips, this averages to approximately 900 kg per trip. This overestimate is to account for rebar, screws, nuts, rebar/sheet metal cutter, trowel, and wood. It is estimated that the Rocket Stove will take 1 day of labour and each of the Chimney Base and Finned Chimney will take 0.5 days of labour each, assuming 8 hour labour days. In total, each unit will take 2 days of labour. Trowels will be used to put clay on the bricks. Two 2 in. x 4 in. pieces of wood with length of 8 ft (2.4 m) will be used to make the brick molds, molds for the cook top, and molds for the Chimney Base top. These components are shown in Figure 31. Note that the end pipe and pipe are purchased from Hulas Steel (Serial #70) [17] and the elbow is purchased from Metline Industries [14]. As G1 Consulting was unable to get a quote for the end pipe and pipe, the parts were modelled in SolidWorks with the appropriate material and based on the mass, a cost of $1.15 CAD/kg from the client was used for the cost analysis. The fins are from leftover roofing material, which is widely available in rural Nepal and cost estimated at a price of $1.15 CAD/kg.

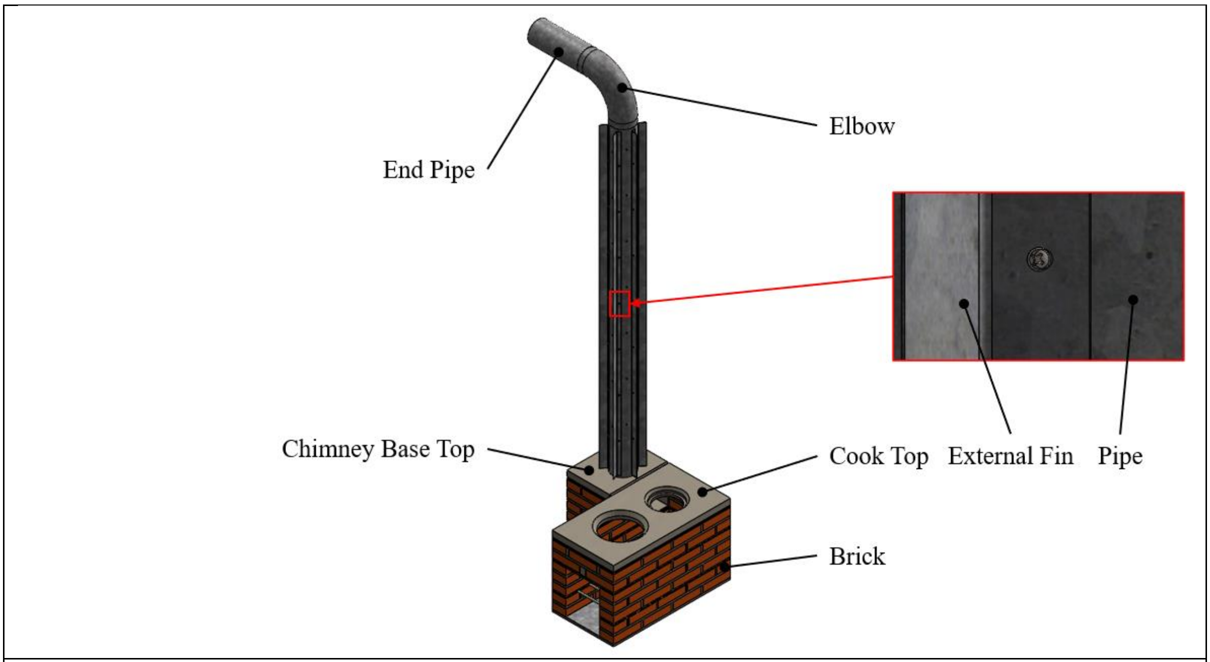


Figure 31: Annotated isometric of the Rocket Stove and Finned Chimney design.

19. Appendix I – Instruction Manual

Improved Cookstove

Manufacturing and Assembly Manual

Disclaimer

Group 1 Consulting is not responsible for any losses or injuries resulting in the manufacturing, assembly, or use of the improved cookstove.

Introduction

This manual will guide you through the steps required to build and install the improved cookstove properly in the home. It is arranged by the different sections of the structure, the combustion section of the stove and the chimney. These sections can then be chosen and built separately if only one or the other is desired.

This document is meant to supplement the engineering drawings provided.

Bill of Materials

Item	Quantity
Brick	102 (32,928 cm^3 of adobe)
Clay	21,786 cm^3
Rebar (diameter = 8 mm, length = 12 m)	1
90° Elbow	1
Self-tapping Screws	42
Nuts	42
2 in. x 4 in. wood (length = 8 ft.)	1

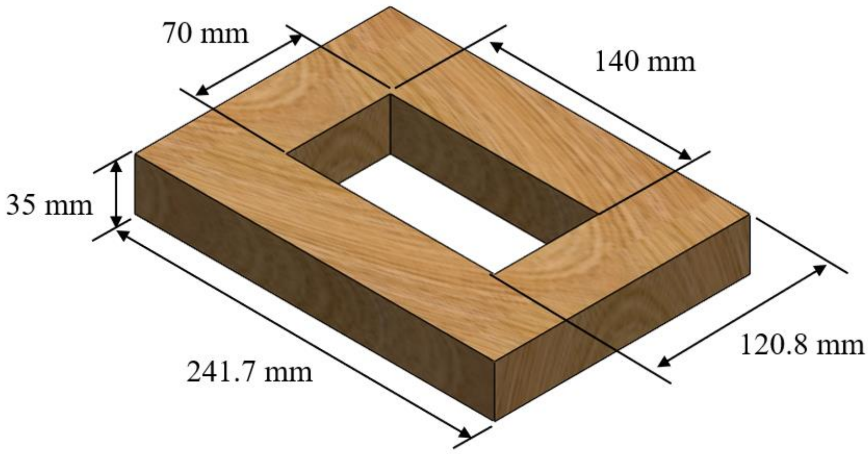
Tools Required

Item	Quantity
Rebar/Sheet Metal Cutter	1
Trowel	1

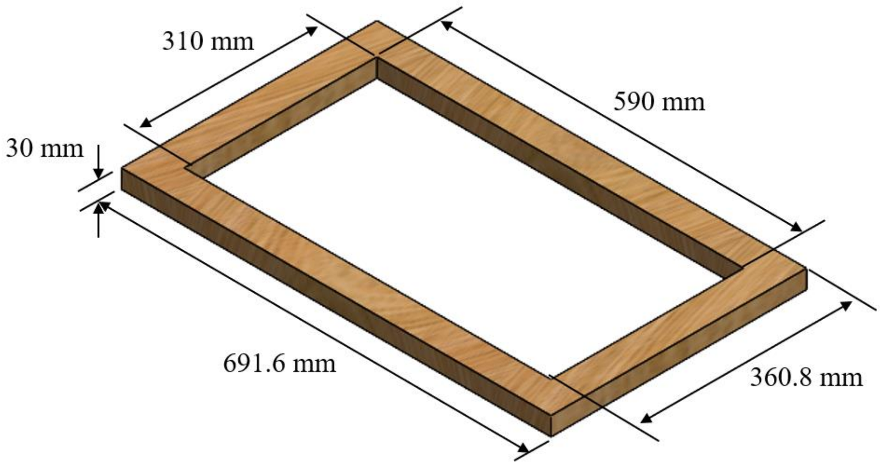
Stove and chimney base

1. Cut the 2 in. x 4 in. wood to make the a) brick mold, b) cook top mold, and c) chimney base top mold with the dimensions as shown below.

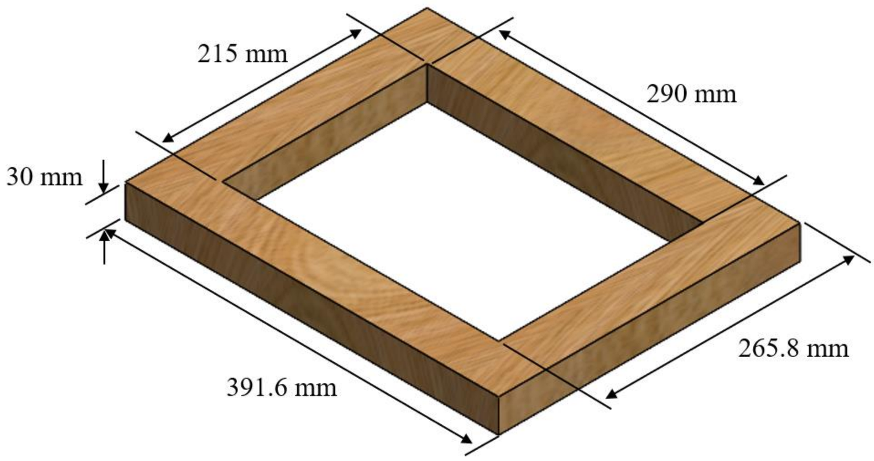
a) Brick mold



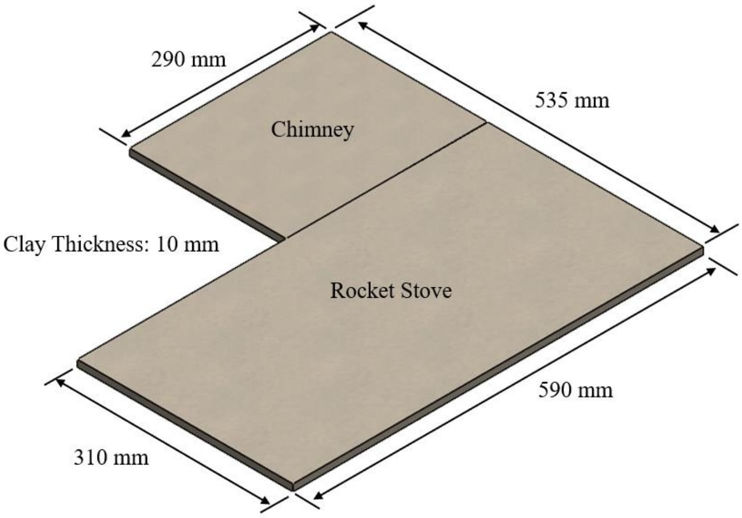
b) Cook top mold



c) Chimney base top mold



2. Lay a flat, level pad of clay at the location where the stove and chimney base are to be in the home. Allow it to cure fully before proceeding.



3. Form the top surface out of clay where the pots will be placed when cooking.

    a. Main outer dimensions must be 590 mm x 310 mm x 30 mm
    b. Holes for pots should be centered along the short edge, the centers holes should be as close as possible to 190 mm and 425 mm from the edge for the larger and smaller hole respectively to endure that they are in proper positions for the fire to heat the pots well.
    c. Ensure that the spacing between holes is sufficient that there will be good support and structural integrity of the top slab.
    d. Wrap the pots that you want to have the top fitted to in plastic wrap and add clay around them to make a tight fit. Remove the pots and allow the clay to cure.

4. Form a 290 mm x 225 mm x 10 mm layer of clay for middle of chimney base. Be careful with this as it will be fragile since it is very thin.

5. Form the top piece of clay with a hole where the Chimney will sit inside. The block should be 290 mm x 215 mm x 30 mm. Form the hole by placing a section of the pipe around where it should be and placing clay around it then remove the pipe an allow it to cure. The center of the pipe hole should be 77.5 mm in from the long edge and centered across the long edge. See figure.

6. While the clay from the previous steps is curing, cut the rebar to the required lengths. The rebar will need to be cut into the following pieces:

Item	Quantity
Rebar (diameter = 8 mm, length = 220 mm)	5
Rebar (diameter = 8 mm, length = 240 mm)	2
Rebar (diameter = 8 mm, length = 310 mm)	4

7. The following steps will go over the layers of brick that make up the stove walls. Follow the figures to see how the bricks, clay, and rebar are laid out.

8. In between the 2nd and 3rd layer of bricks, place the 4 pieces of 310 mm long rebar 60 mm from the front stove opening placed 60 mm center-to-center as shown in the figure.

9. Lay a clay infill, on an incline from the top of the bricks of layer 3 to near the bottom of the bricks of layer 5 as shown in the figure.

10. Place two 240 mm long pieces of rebar across where the opening of the stove will be, 20 mm from the front and 30 mm center-to-center, as shown in the figure.

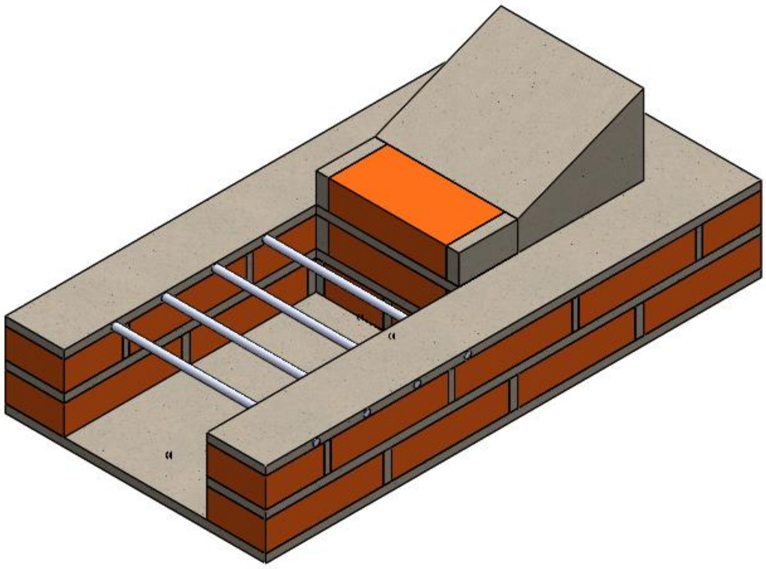
11. Place the fully cured 290 mm x 225 mm x 10 mm layer of clay in the location shown in the figure. Place some wet clay around it to ensure that there is an airtight seal.

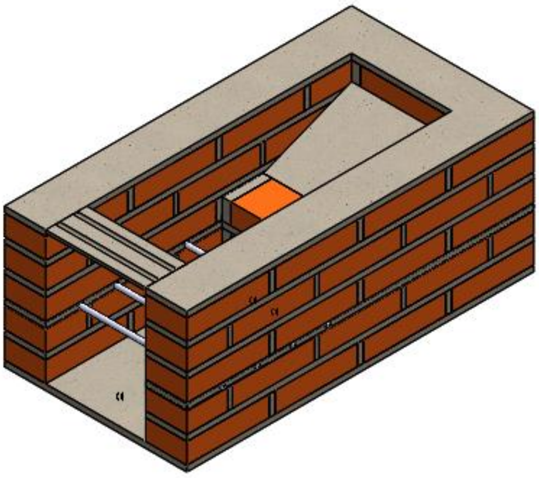
12. Place two 220 mm long pieces of rebar over the opening between the stove and the chimney base sections as shown in the figure.

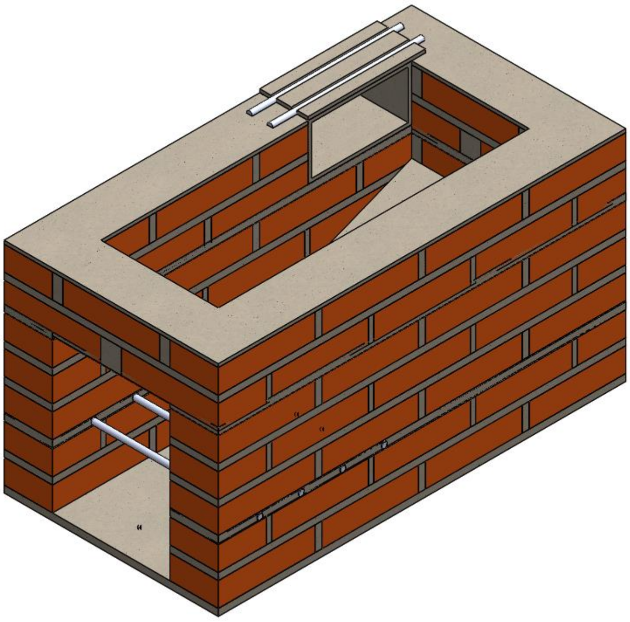
13. Place two 220 mm long pieces of rebar 65 mm apart center-to-center, 45 mm from the split between the chimney base and the stove sections. ***IMPORTANT*** Make sure that these will go across the middle of the hole for the chimney as these will be there to support the chimney.

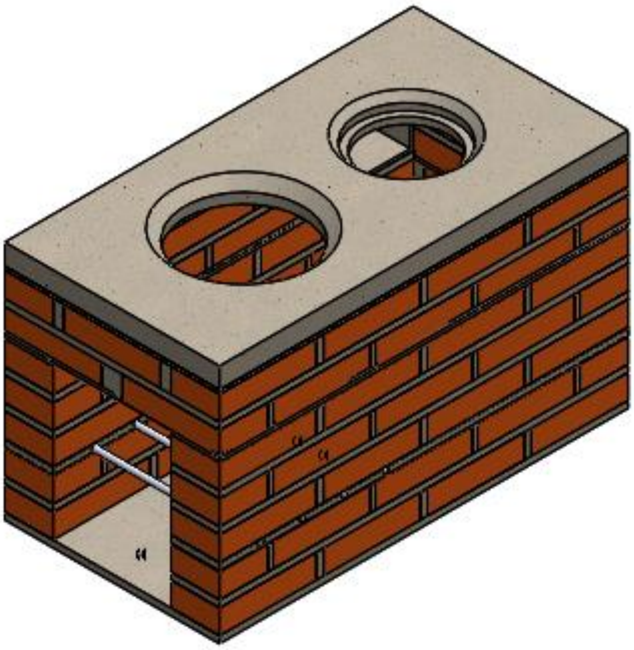
14. Place another 220 mm long piece of rebar to add support to the top that is in between the chimney and the cooking surface.

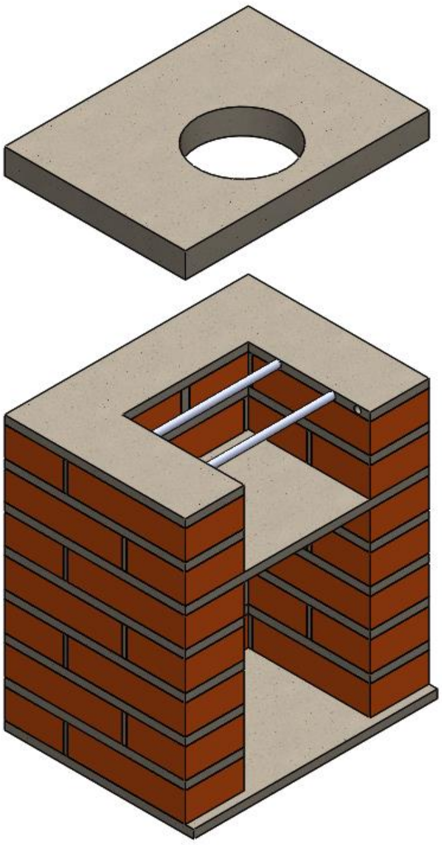
15. Place both the fully cured top pieces of clay (the cooking surface and the chimney hole) and add wet clay in necessary places to ensure that it is properly secured and sealed.











Chimney

1. Determine if chimney is to go out of roof or horizontally through wall. Cut 2mm thick 4” ID pipe to required height (either 50cm above roof height or height at which pipe will exit wall)
    - Pipe essentially rests on ground inside stove, so no other corrections are required.
    - Ensure vertical section of pipe is at least 150cm to ensure heating performance requirements met.

2. If chimney is exiting dwelling horizontally through wall, cut 50cm section for this purpose.

Chimney Fins

1. From galvanized sheet metal, cut six 4.8cm x 150cm strips and six 3.8 x 150cm strips.

2. Mark seven holes centred 0.75cm from the long edge, with the first 15cm from the long edge and spaced 20cm apart thereafter on each of the strips.

3. Stack the strips such that they are aligned along the long edge nearest to the holes (ensures holes are aligned)

4. Using a drill or, if necessary, a hammer and the sheet metal screws, punch 3mm holes through each of the markings.
    - Note: If it is difficult to punch holes through all layers, punch the holes through one set of strips and use these as a guide for the other strips.
    - Ensure that there are pairs of fins (one 4.8cm, one 3.8cm) such that one was the guide for the other. This ensures holes are aligned.

5. Align one of the strips parallel to the length of the 4in galvanized steel pipe, with the short edge offset 40cm from the edge of the pipe (i.e. bottom of the chimney)

6. Using the holes in the strip as a guide, mark 6 holes along the chimney

7. Repeat the above step five more times to mark six rows of holes evenly spaced around the circumference of the pipe, using one strip from each of the pairs of long and short strips.
    - To ensure even spacing, consider using a piece of rope cut such that it wraps around the pipe and place six evenly spaced markings on this rope. Use these to make markings evenly around the pipe.
        - Consider doing this on both ends of the pipe to ensure alignment of the rows along the long axis of the chimney.

8. Punch these holes using a hammer and the sheet metal screws, or a drill. Do not apply too much pressure to the pipe as this may crush it.

9. Check alignment of the holes between pairs of strips and holes in the pipe.

10. Mark bending point on all strips (approximately 1.5cm from long edge nearest holes, see drawing package).

11. Bend strips as shown in drawing package (one set will be bent upwards, one will be bent downwards, when viewed from holes aligned).

12. Bend the portion of the short-width strips (i.e. interior fins) along the line made by the holes, such that plane on which the holes lie becomes bent like an upside-down V when the entire fin is viewed like an L. Bend approximately 30 degrees.

13. Bend the portion of the short-width strips (i.e. interior fins) along the line made by the holes, such that plane on which the holes lie becomes bent like a right side-up V when the entire fin is viewed like an L. Bend approximately 30 degrees.

14. Screw sheet metal screws into short-width strips, such that screws enter holes from direction where strips are bent down (e.g. from the vertical end of the "L"). Ensure screws remain in place when left unsupported. If this is not the case, use adhesive to allow them to remain in holes unsupported.

15. One at a time, slide the short-width bent strips (i.e. interior fins) with screws inside the pipe and align with holes. Turns screws or support as necessary such that interior fins remain in place and screws stick out of holes in pipe.

16. Align holes of wide-width bent strips (i.e. external fins) with screws which stick out of the pipe. Align such that portions of internal and external fins sticking out radially from pipe are aligned.

17. Use hex nuts (x42) to tighten down screws. Tighten as much as possible to ensure contact between fins and pipe.

Chimney pipe (part 2.)

1. Place chimney into base in stove and through roof (if necessary)
   - In this case, cutting hole in roof and dropping vertical chimney down may be the least-invasive option. Complete step 2 before doing so.
   - After chimney is secured, use clay or any available filler to create seal between chimney stack and roof, to prevent rain leaking in.
2. Weld or, if welding is unavailable, screw elbow to vertical section of chimney
3. If chimney exits dwelling horizontally, weld or screw horizontal pipe section into other portion of elbow

20. Appendix J – Client Meeting Minutes

Below are all meeting minutes recorded between G1 Consulting and the client representative.

Meeting Minutes – Client Meeting #1

Meeting Information

Objective: Team 1 will introduce themselves to the client of Mountains of Relief and review the preliminary details regarding scope of work, design specifications, and deliverables to attain and accurate plan and schedule going forward, with special regard to the Phase 1 Report.

Date: January 22, 2021 **Location:** Remote

Time: 12:00-13:00 **Meeting Type:** Client

Minutes by: Will Nagge

Attendees: Michael Nicol-Seto, Ben Hallworth, Kevin Zhong, Robert Chauvet, Russell Johnson, Will Nagge

Agenda Items	Decisions
1. General housekeeping and meeting times • Best means of communication • Schedule regular meetings (weekly / bi-weekly) • Obtain clients preferred document sharing method for completed meeting minutes etc. • Permission to record meetings 2. Review preliminary design specifications given in the project proposal • Clarify manufacturing and material constraints 3. Obtain relevant documentation relating to current stoves and use-cases • Obtain past work/ research/ modelling • Where they're stuck? • Ask them good sources for information	1. • Google meets will be used for meetings going forward • Email is preferred for other communication • Tentative meeting schedule with client will be Friday at 11:00-12:00, weekly. Subject to change • A Google Drive folder will be shared with the client for document sharing purposes 2. There are a few contacts on the ground in Nepal • Demographic use-case is still being investigated by the client • Client to share pictures of current stove designs (in drive) • Group to schedule meeting with Nepalese founder who lives in Jasper (next week) • Rice and dal is common food • Open design criteria with two basic concepts: standalone system or physical design for built-in (mud/brick) • Insulated cooking vessel, or solar cooker could be viable option • Raj will provide additional specifications • Does not need to be just a stove, heating of dwelling is also a consideration

	• Prototype is desirable but not a hard requirement and depends on Phase 2 and Covid 3. Cheryl to provide more information regarding costing and financial role out to Nepal • Client (Raj) to provide information on typical fuel (tree type) available at next meeting • Eg: insulating shroud that can be taken away to release heat • Two burners is desirable • Michael to get in touch with Connor about any other literature available • Thermo-electric device is possibility but not required

Meeting Minutes – Client Meeting 2 / Inter-team

Meeting Information

Objective: Specifications for Stove

Date: Jan 26, 2021 **Location:** Google Meets

Time: 17:00-18:30 **Meeting Type:** Client/Inter-team

Minutes by: Will Nagge

Attendees: Michael Nicol-Seto, Ben Hallworth, Kevin Zhong, Robert Chauvet, Russell Johnson, Will Nagge, Raj Ghimire, Connor Speer, Group 4

Agenda Items	Decisions
1. Introductions • Meet the rest of the team 2. Questions for Raj/Specifications • Make sure to iterate if these questions are answered in the survey to just point us in that direction • What is the survey? Is it region specific, what are the demographics? • Other uses for stove (lighting, counter, heat, communal/familial thing) • Home size, space needed to heat • Price point, prohibitively expensive materials? • Climate, Average temperature • Home modifications (exhaust) • Portability	1. Introductions • Raj does not have engineering background; in Canada for 2 years • Motivated by earthquake • Also developing school, other charitable actions 2. Questions for Raj/Specifications • Specs document coming in next day or so • Focussed in two communities (Suresh's community and one other) ◦ 1140m and 1540m elevation ◦ Central Nepal ◦ Survey at 1220m ◦ 5000m and 8000m respectively

- Size/space limitations (height as well with seated cooking)

- Water Heating Requirement
- Materials used for stove?
- Size/Material of pots and pans
- Are both burners to be the same
- Raw material access (Clay, Brick, Rebar, Metals, Ducting)
- Corrugated roofing
- Manufacturing Methods (Hand done, Tools, Molds)
- Maintenance on stoves
- Type of wood to be burned
- What would be the target rollout quantity

3. Questions for client/sponsor, project structure
   - Two unique design (based on survey, they can meet different needs)
   - COVID restrictions on prototyping (Roommates can work at least two people to prototype, if projects overlap)
   - MecE 460 wants three designs, and prove which one is best with simulation etc. If we are using prototyping methods to prove the designs, we can't make three stove feasibly. Can we prototype and run three tests/modifications instead (Talk to prof with client?)
   - Instruction manual as last deliverable

- Stove: mainly cooking and heating
  - Not to heat whole house
  - Smoke still goes everywhere
  - Heats separate kitchen
  - 144 feet squared (Suresh)
  - 200 on upper end
  - Roof not well-sealed
  - Could close gaps if proper smoke management

- 20-30C summer, -2-12 in winter
- Propane stove: has counterspace?
- Not significantly windy (except short rainy season)
- Easy to make modifications for ventilation
- Houses are mud/stone, they have electricity for power tools to make modifications
- Ceilings 5-7ft high
- 2ft x 2ft stove, 2 burners
  - Eg 2 rocket stoves for half the height
  - Crouching is common for heating and, cooking
  - Some families have stove in middle, others in corner depending on ventilation
- Standalone stove is preferred (Suresh)
- Smoke is main priority, more than portability
- Easy to clean, durable is preferred
- Use: up to 8h/day
- Less firewood is ideal
- 2 types of pots, kagi(?) like a round bottom wok / flat bottom standard pot for rice (3-5L) / pressure cooker
- Very available material: clay, brick, rebar, iron. Sheet metal for manufactured design
- Current stoves are hand made by collecting clay and hand-making bricks.
- All stoves handmade
- Ease of use, install-ability important
- Instruction manual is a desirable deliverable.

	• Need only consider wood as biomass for scope of this project. • Clean, scrape soot, remove ash is typical maintenance. Cleaning ventilation is important parameter • Ideally applicable to thousands of people, prefer methods that are feasible for small-batch though as that would be the start (qty: 10) • Collect small pieces of unprepared deadfall wood (branches basically). Typically collected in dry season or dried first if collected in rainy season. They can cut if needed. • Heat only needed in winter (possibly have a removable insulation layer) • Leave it open for prototyping throughout the project, provided it is safe with covid. Prototype does not have to look the same as final design necessarily. If we can't prototype it is not a deal-breaker • Client does not have hard requirements / requests for simulation, see more value in experimental results

Meeting Minutes – Client Meeting 3

Meeting Information

Objective: Discuss current state of brainstorming with client.

Date: February 10, 2021 **Location:** Google Meets

Time: 18:00 – 19:00 **Meeting Type:** Client

Minutes by: Will Nagge

Attendees: Freya Hik, Ben Hallworth, Kevin Zhong, Robert Chauvet, Will Nagge

Agenda Items	Decisions
1. What is the baseline reference stove we are improving relative to? 2. Accessibility of polymer	• Discuss brainstormed ideas with Freya: Cookstove/condensing boiler: Addresses keeping head in the house, lower enthalpy exhaust exiting. ○ TLUD (two stage combustion): Reduces PM and other emissions along with increase thermal efficiency. ○ Rocket stove: Very efficient and practical, might not meet their needs though. • Raj to be emailed by group regarding material availability and cost (PVC

	specifically), also wood preparation (ask what tools they have) rkghimire@yahoo.co.in / sure.sapkota@gmail.com • Baseline: Lots of people still using chulha (traditional stove). One in Raj's home is common in those communities and chimney does not work well. • Ask Raj if there has been more success with new ICS or modification to current stove. • Cost of transportation is high (for rebuilding school, 50% of cost)

Meeting Minutes – Advisor Meeting 4

Meeting Information

Objective: Review concepts selected for Phase 2 report.

Date: February 23, 2021 **Location:** Google Meets

Time: 13:00 – 14:00 **Meeting Type:** Advisor

Minutes by: Will Nagge

Attendees: Amit Kumar, Ben Hallworth, Kevin Zhong, Robert Chauvet, Will Nagge

Agenda Items	Decisions
1. Review concept selections 2. Discuss calculation methods.	• Rocket stove concept: how is wood stacked, should there be a grill instead of rebar? Maybe add perpendicular bars as well. Concerned about adequate air flow to combustion chamber. Second combustion chamber would not work well as most of the combustion air would be CO_2 coming from the primary chamber. How much combustible gas and O_2 goes to the second chamber? Need secondary air inlet to the second chamber. Manual blower (fan/bellow) could be integrated to supply additional air. • TLUD: Good to use a bellow as a fire starter, ask client if they have liquid fuel available for fire starter as well. Is a PM filter possible for flue gas? Jute bag possibly. • Flue Gas: Dr. Andre Mcdonald would be best person to discuss Ben's calculation issues with.

	• Review report draft next Tuesday. •

Meeting Minutes – Client Meeting 5

Meeting Information

Objective: Discuss design concepts with client.

Date: February 25, 2021 **Location:** Google Meets

Time: 17:30 – 18:30 **Meeting Type:** Client

Minutes by: Will Nagge

Attendees: Freya Hik, Ben Hallworth, Kevin Zhong, Robert Chauvet, Russell Johnson, Will Nagge

Agenda Items	Decisions
1. Discuss 3 concepts	• Review final concepts ○ Brick is the decided primary material ○ Can we calculate the leakage of harmful components of flue gas? ○ Ben's concept complimentary to rocket stove and tlud ○ Email Raj about fire starting methods ○ Fire starting till natural draft starts, could they just leave door open at the start? ○ Wood inlet opposite door restricts the layout of the house. ○ No meeting next week.

Meeting Minutes – Client Meeting 6

Meeting Information

Objective: Review Phase 2 report and path forward for Phase 3.

Date: March 18, 2021 **Location:** Google Meets

Time: 17:30-18:30 **Meeting Type:** Client

Minutes by: Will Nagge

Attendees: Freya Hik, Ben Hallworth, Kevin Zhong, Robert Chauvet, Russell Johnson, Will Nagge

Agenda Items	Decisions
1. Go through report for client comments.	• Main concern is cost. No matter how well engineered, they will

	not pay $300+ for a stove in developing countries. • Can talk to Cheryl about transportation cost if further clarification is needed. • Generally, very impressed with report. • In communities where limitations are present for power availability etc, it is better to implement only the stove or only the chimney than nothing. • No newsletter but option to stay involved with organization post-project. •

Meeting Minutes – Client Meeting 7

Meeting Information

Objective: Review path forward for Phase 3.
Date: March 25, 2021 **Location:** Google Meets
Time: 17:30-18:30 **Meeting Type:** Client
Minutes by: Will Nagge
Attendees: Freya Hik, Ben Hallworth, Kevin Zhong, Robert Chauvet, Russell Johnson, Will Nagge

Agenda Items	Decisions
1. Review cost analysis 2. Review updated stove and finned chimney solid models. 3. Review phase 3 calculation updates	• Stove $14 CAD, chimney $35 CAD, 3 days labor to build both ($88 including labor for full assembly). Changes from phase 2 report are that the chimney material was vastly reduced. This price is under the assumption of large production run, cost for small batch could get up to $110/stove • Stove without a finned chimney should still have a plain pipe/clay chimney to exhaust fumes. Preferably metal to reduce construction complexity. • Design conference is submission of 10 min video and there

	is a 10-minute open house on April 8th for Q&A. • Should be able to send video for Mountains of Relief to watch.

21. Appendix K – Project Management

21.1 Project Schedule

The following chart outlines all activities carried out by the team for this project.

	Project Folders	Owners	Remaining Effort	Finish [E]	Dec-24 Jan-01 Feb-01 Mar-01 Apr-01 Apr-16
	INBOX	RussellJ	0h - 0h		
	ASAP TASKS	Unassigned	0h - 0h	2021-04-15	
	EVENTS (Out of Office)	Unassigned	0h - 0h	2021-04-15	
	ACTIVE PROJECTS	Group1	0h - 0h	2021-04-16	
	Nepal Stove for Mountains of Relief	Group1	0h - 0h	2021-04-16	
	Phase 1	Group1	0h - 0h	2021-04-15	
	Team Meetings	BenH, KevinZ, RobertC, RussellJ, WillN	0h - 0h	2021-04-15	
	Logo Design	RussellJ	0h - 0h	2021-04-15	
	Team Charter	RussellJ, RobertC	0h - 0h	2021-04-15	
	Project Schedule	RussellJ	0h - 0h	2021-04-15	
	Project Management	RussellJ, WillN	0h - 0h	2021-04-15	
	Initial Information Gathering	Group1	0h - 0h	2021-04-15	
	Determine Design Objectives	BenH, KevinZ, RussellJ, WillN, RobertC	0h - 0h	2021-04-15	
	Determine Key Specifications/ Constraints	BenH	0h - 0h	2021-04-15	
	Project Research	KevinZ, RobertC, BenH, RussellJ, WillN	0h - 0h	2021-04-15	
	Review Codes and Standards	RobertC	0h - 0h	2021-04-15	
	Market Research	WillN	0h - 0h	2021-04-15	

	Project Folders	Owners	Remaining Effort	Finish [E]	Dec-24 Jan-01 Feb-01 Mar-01 Apr-01 Apr-16
	Report Writing	Group1	0h - 0h	2021-04-15	
	• Cover Letter	RobertC	0h - 0h	2021-04-15	
	• Design Specification Matrix	BenH	0h - 0h	2021-04-15	
	• Cost and Time Estimate	WillN	0h - 0h	2021-04-15	
	• Business Case	KevinZ	0h - 0h	2021-04-15	
	• Gantt Chart	RussellJ, WillN	0h - 0h	2021-04-15	
	• Report Editing/Finalization	BenH, KevinZ, RobertC, RussellJ, WillN	0h - 0h	2021-04-15	
	Phase 2	Group1	0h - 0h	2021-04-15	
	• Team Meetings	BenH, KevinZ, RobertC, RussellJ, WillN	0h - 0h	2021-04-15	
	• Project Management	RussellJ	0h - 0h	2021-04-15	
	Design Work	Group1	0h - 0h	2021-04-15	
	• Brainstorming/Concept Design	BenH, KevinZ, RobertC, WillN, RussellJ	0h - 0h	2021-04-15	
	• Concept Selection	KevinZ, BenH, RobertC, RussellJ, WillN	0h - 0h	2021-04-15	
	• Design Viability Calculations	BenH, RobertC, WillN, KevinZ	0h - 0h	2021-04-15	
	• Design Evaluation Matrix	BenH, KevinZ, RobertC, WillN, RussellJ	0h - 0h	2021-04-15	

	Project Folders	Owners	Remaining Effort	Finish [E]	Dec-24 Jan-01 Feb-01 Mar-01 Apr-01 Apr-16
	CAD modelling/Sketches	BenH, WillN, KevinZ	0h - 0h	2021-04-15	
	Material Evaluation and Selection	WillN, RussellJ, KevinZ	0h - 0h	2021-04-15	
	Flow and Heat Transfer Calculations	RobertC, BenH	0h - 0h	2021-04-15	
	Report Writing	Group1	0h - 0h	2021-04-15	
	Executive Summary	RussellJ	0h - 0h	2021-04-15	
	Cover Letter	RobertC	0h - 0h	2021-04-15	
	Summary/Project Changes	BenH	0h - 0h	2021-04-15	
	Design Analyses	BenH, RobertC, WillN	0h - 0h	2021-04-15	
	Concept Selection	KevinZ	0h - 0h	2021-04-15	
	Preliminary Cost Analysis	RussellJ	0h - 0h	2021-04-15	
	Schedule Summary/Changes	RussellJ	0h - 0h	2021-04-15	
	Report Editing/Finalization	BenH, KevinZ, RobertC, RussellJ, WillN	0h - 0h	2021-04-15	
	Research	BenH, KevinZ, RobertC, WillN, RussellJ	0h - 0h	2021-04-15	
	Phase 3	Group1	0h - 0h	2021-04-15	
	Team meetings	BenH, KevinZ, RobertC, RussellJ, WillN	0h - 0h	2021-04-15	
	Project Management	RussellJ	0h - 0h	2021-04-15	

	Project Folders	Owners	Remaining Effort	Finish [E]	Dec-24 Jan-01 Feb-01 Mar-01 Apr-01 Apr-16
	• Prototype Creation	BenH, KevinZ, RobertC, WillN, RussellJ	?	2021-04-15	
	• Elevator Pitch	BenH, KevinZ, RobertC, RussellJ, WillN	0h - 0h	2021-04-15	
	• Design Conference	RussellJ, BenH, KevinZ, RobertC, WillN	0h - 0h	2021-04-15	
	Detailed Work	Group1	0h - 0h	2021-04-15	
	• Detailed CAD	WillN, KevinZ, BenH	0h - 0h	2021-04-15	
	• Design Calculations	RussellJ, RobertC, BenH	0h - 0h	2021-04-15	
	• Emissions Calculations	BenH, RobertC	0h - 0h	2021-04-15	
	• CFD/Heat Transfer Simulations	WillN, BenH	0h - 0h	2021-04-15	
	• Final Cost Analysis	KevinZ, RussellJ	0h - 0h	2021-04-15	
	• Design Poster	RobertC, BenH, KevinZ, RussellJ, WillN	0h - 0h	2021-04-15	
	• Drawing Package	WillN, KevinZ	0h - 0h	2021-04-15	
	• Design Video	BenH, KevinZ, RobertC, RussellJ, WillN	0h - 0h	2021-04-15	
	• Instruction Manual	KevinZ, RobertC, RussellJ	0h - 0h	2021-04-15	

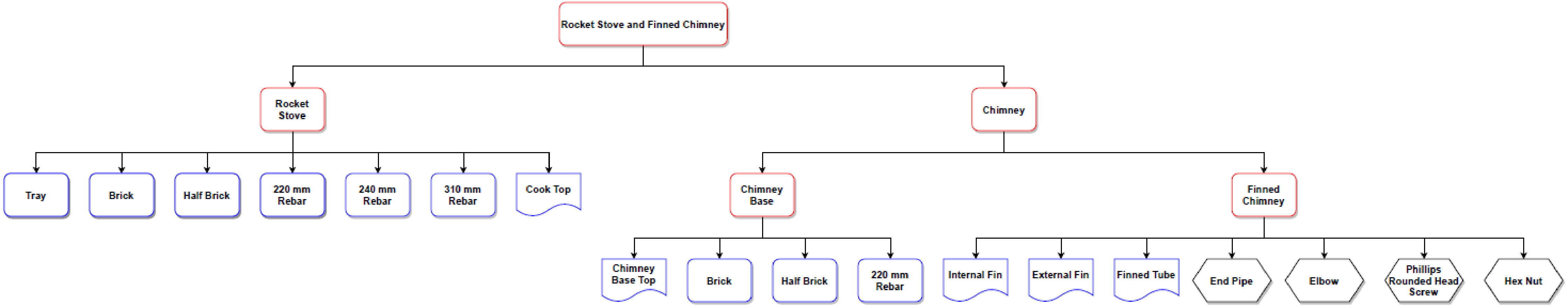
	Project Folders	Owners	Remaining Effort	Finish [E]	Dec-24 Jan-01 Feb-01 Mar-01 Apr-01 Apr-16
	Report Writing	Group1	0h - 0h	2021-04-15	
	Introduction	RussellJ	?	2021-04-15	
	Cover Letter	RobertC	0h - 0h	2021-04-15	
	Executive Summary	WillN, RussellJ	0h - 0h	2021-04-15	
	Detailed Design Report	BenH, KevinZ, RobertC, RussellJ, WillN	0h - 0h	2021-04-15	
	Design Compliance Matrix	RussellJ, BenH	0h - 0h	2021-04-15	
	Project Management	RussellJ	0h - 0h	2021-04-15	
	Detailed Design Calculations	RobertC, BenH	0h - 0h	2021-04-15	
	Design Drawings/BOM	KevinZ	0h - 0h	2021-04-15	
	Report Editing/Finalization	BenH, KevinZ, RobertC, RussellJ, WillN	0h - 0h	2021-04-15	
	Cost and Manufacturing	RussellJ, KevinZ	?	2021-04-15	
	Safety	RussellJ, BenH	?	2021-04-15	
	Phase 1 Report Due	Group1	0h - 0h		
	Phase 2 Report Due	Group1	0h - 0h		
	Design Conference Poster	Group1	0h - 0h		
	Design Conference Video	Group1	0h - 0h		
	Phase 3 Report Due	Group1	0h - 0h	2021-04-16	

21.2 Lessons Learned

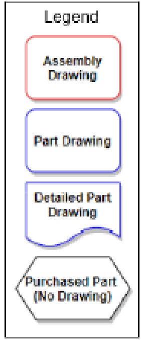
The lessons learned for a project represent the experience and knowledge obtained from the project initiation towards project closure. The following chart lists the lessons learned for the Nepal Stove Project. These lessons are categorized by project knowledge area and descriptions, impacts, and recommendations are provided for consideration on similar future projects. It is important to note that not only failures or shortcomings are included but successes as well.

Problem or Success	Category	Description	Impact	Recommendation
Problem	Scope Management	During the project initiation phase, the scope of the project was not well understood but the project proceeded still in that state.	During the execution phase of the project, time was spent trying to determine constraints while it could have been used to make progress more efficiently on deliverables.	Be sure that all constraints, requirements, objectives, assumptions, and deliverables are understood early to avoid time and effort losses later.
Success	Team Communication	Early on, the team identified effective modes of communication and file sharing.	There was easy collaboration, efficient sharing of ideas and facilitation of consistent support between group members.	Have a system in place for the best mediums for communication and collaboration for all aspects of the project.
Problem	Project Management	Even though the team met and communicated often, the project lead did not regularly refer the team to the project schedule.	The team was constantly going through cycles of effective work and roadblocks, not always knowing how to proceed.	Have an amount of time set in each team meeting to assess where you are in the schedule and what the next steps are.
Success	Team Dynamics	Members of the team were self-motivated and completed work reliably and effectively.	Team morale was generally kept high, and work was not pushed off track by low motivation.	Instill self motivation in team members by maintaining an atmosphere of fun.
Success	Client Communication	There was effective communication between the team and the client on various occasions.	Little time was wasted by not knowing how to proceed without vital information from the client.	Maintain a strong relationship with the client to ensure open effective communication when necessary.

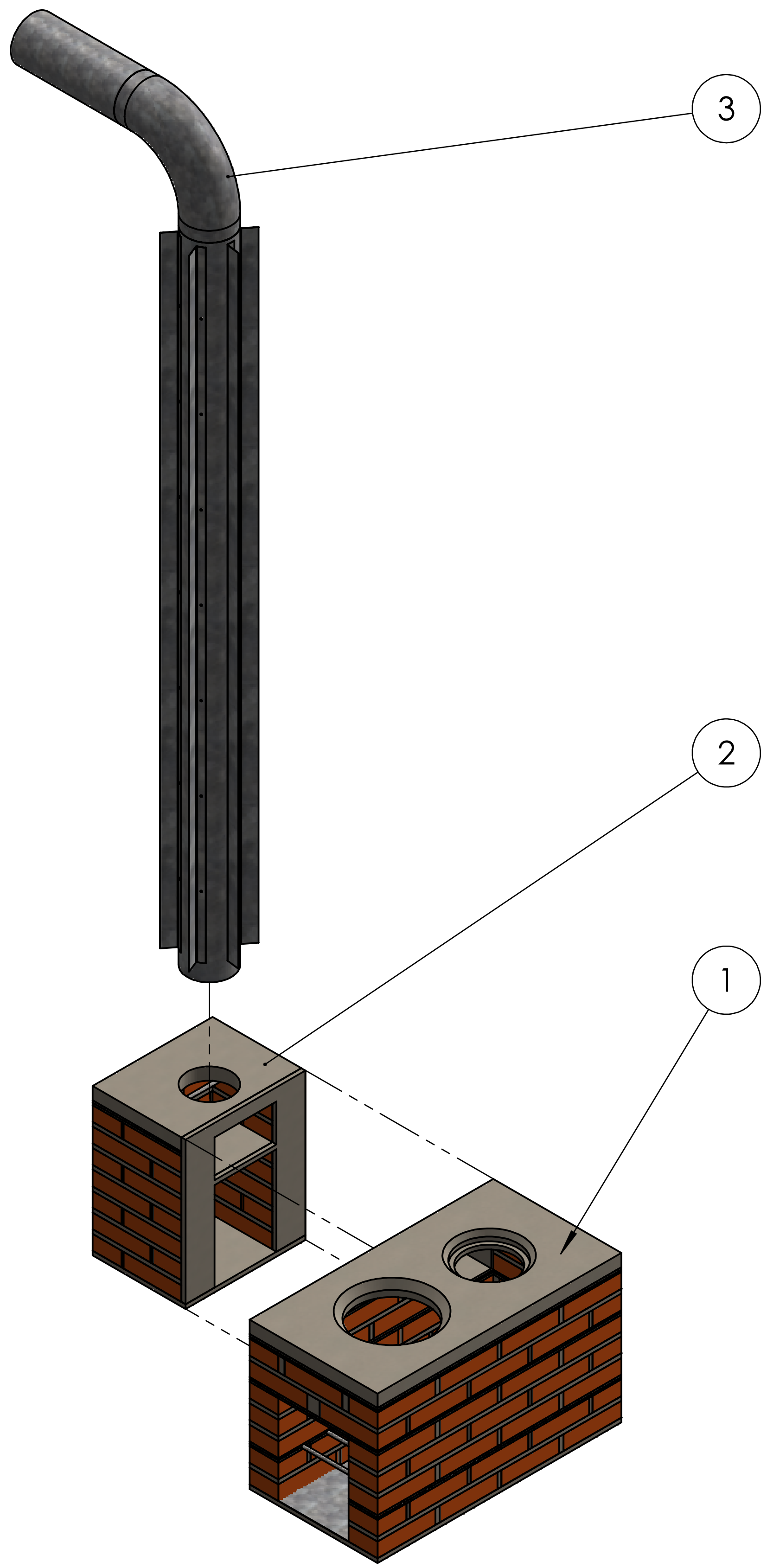
22. Appendix L – Drawing Tree and Engineering Drawings

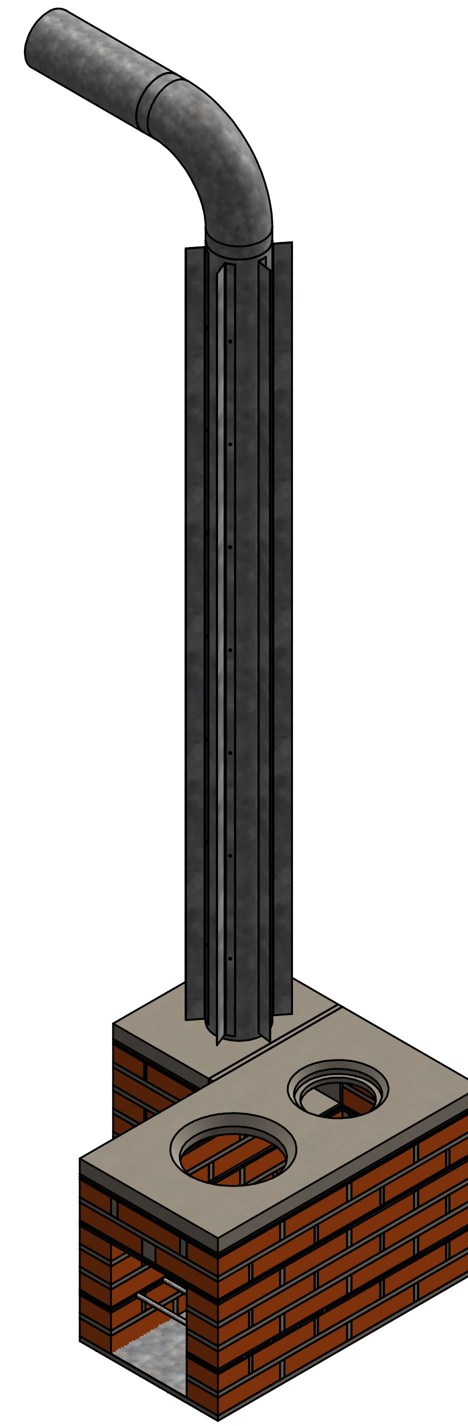


Note to grader: Due to the constraints of the project, most of the design complexity lies in the assemblies rather than individual parts. Therefore, in submitting 5 components for grading, we would prefer the finned tube, cook top, rocket stove, chimney base, and internal fins be marked. If only individual parts may be marked, please mark the 5 detailed drawings as shown on the drawing tree.



ITEM NO.	PART NUMBER	Material	QTY.
1	Rocket_Stove	Various	1
2	Chimney_Base	Various	1
3	Finned_Chimney	Various	1





Mec E 460
Instructor: Dr. Nakashima
Comments:

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025
SURFACE FINISH 0.6 µm
DO NOT SCALE DRAWING

Modeled by **Kevin Zhong**
Drawn by **Kevin Zhong**
Checked by **Robert Chauvet**
Thursday, April 15, 2021 3:04:31 AM
Monday, April 12, 2021 6:26:55 PM

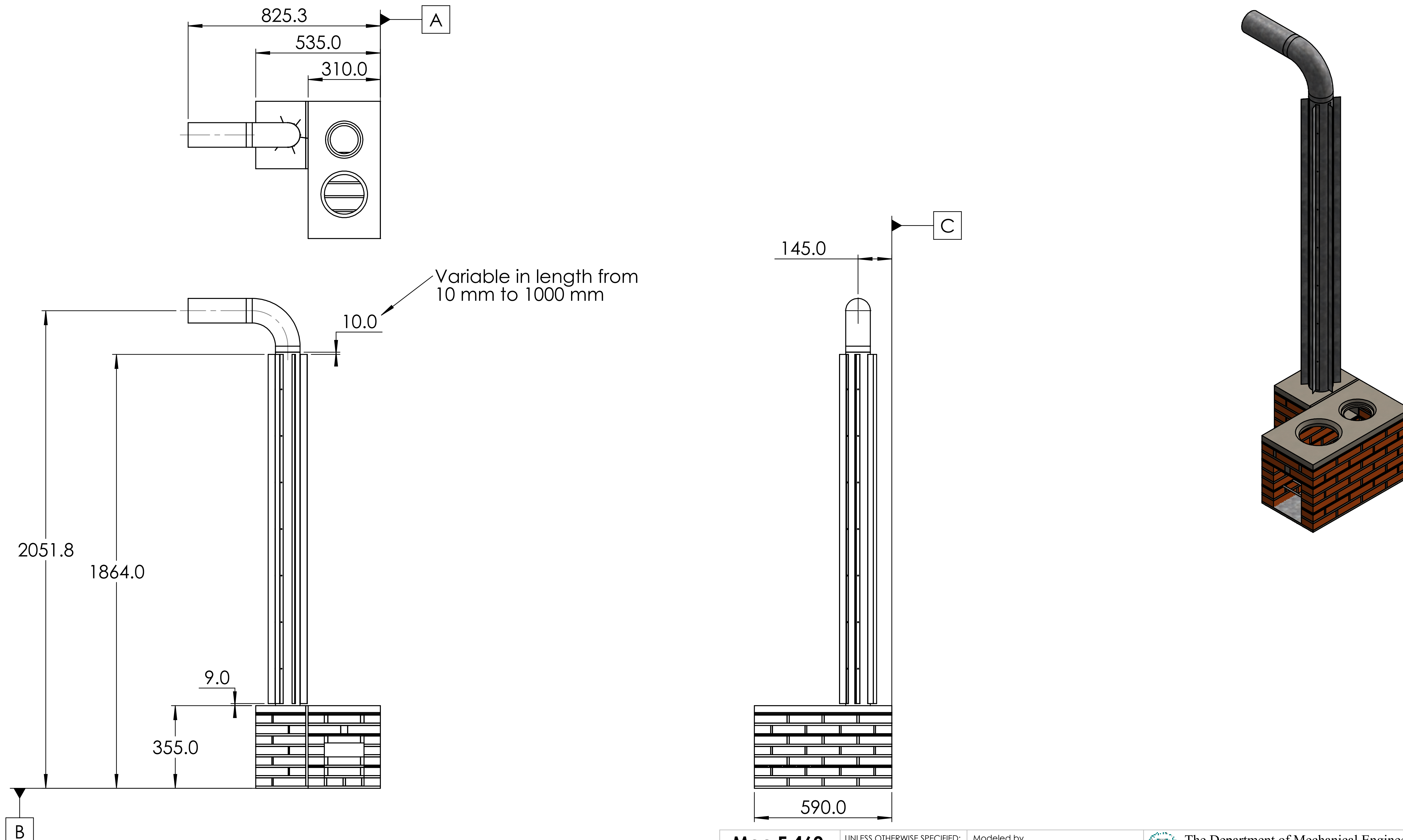
MATERIAL: Various
FILE NAME: Rocket_Stove_and_Finned_Chimney

The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

TITLE: Exploded View of Rocket Stove and Finned Chimney

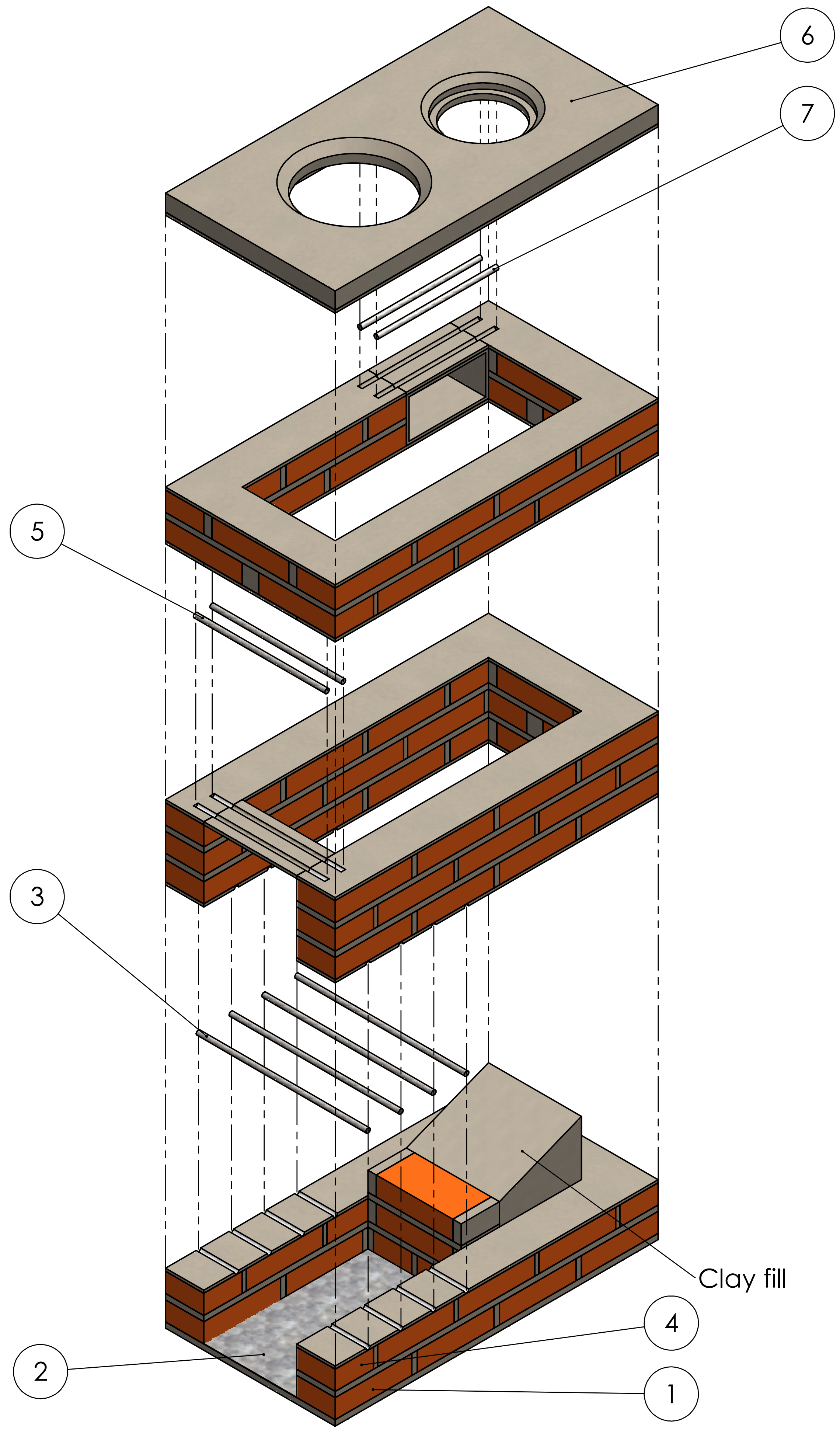
SIZE B | G1 Consulting | REV 1

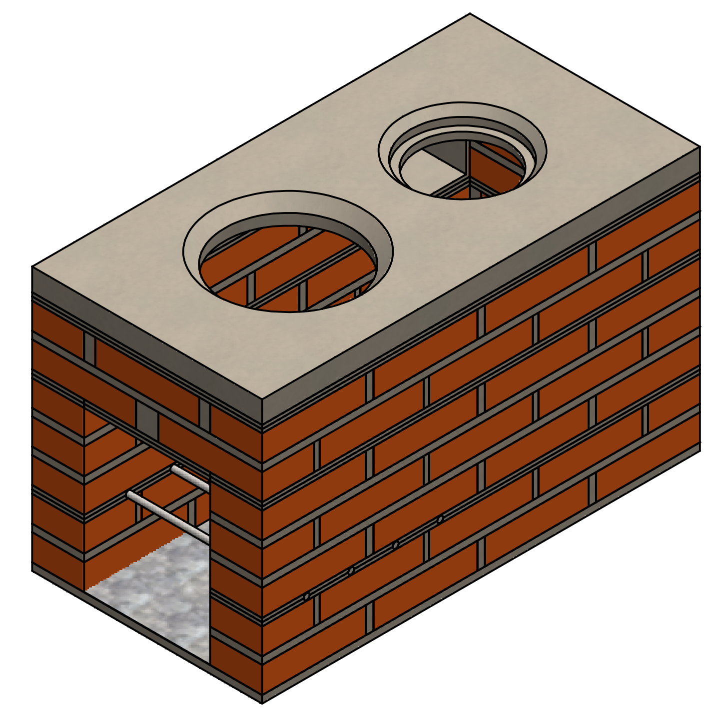
SCALE: 1:12 | Mass: 101231.05 g | SHEET 1 OF 2



Mec E 460 Instructor: Dr. Nakashima Comments:	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH μm 0.6 DO NOT SCALE DRAWING	Modeled by **Kevin Zhong** Drawn by **Kevin Zhong** Checked by **Robert Chauvet**	The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: Rocket Stove and Finned Chimney
MATERIAL: Various		Thursday, April 15, 2021 3:04:31 AM Monday, April 12, 2021 6:26:55 PM	SIZE **B** G1 Consulting REV 1
FILE NAME: Rocket_Stove_and_Finned_Chimney			SCALE: 1:17 Mass: 101231.05 g SHEET 2 OF 2

ITEM NO.	PART NUMBER	Material	QTY.
1	Brick	Adobe	65
2	Tray	Galvanized Steel	1
3	Rebar_8mm_310mm	Plain Carbon Steel	4
4	Half_Brick	Adobe	6
5	Rebar_8mm_240mm	Plain Carbon Steel	2
6	Cook_Top	Clay	1
7	Rebar_8mm_220mm	Plain Carbon Steel	2





Mec E 460

Instructor:
Dr. Nakashima

Comments:
Unlabelled components are clay fill to bind bricks together. Rebar is embedded in the clay.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025
SURFACE FINISH µm 0.6
DO NOT SCALE DRAWING

Modeled by
Kevin Zhong

Drawn by
Kevin Zhong

Checked by
Ben Hallworth

Thursday, April 15, 2021 3:04:31 AM
Sunday, March 14, 2021 4:58:26 PM

MATERIAL:
Various

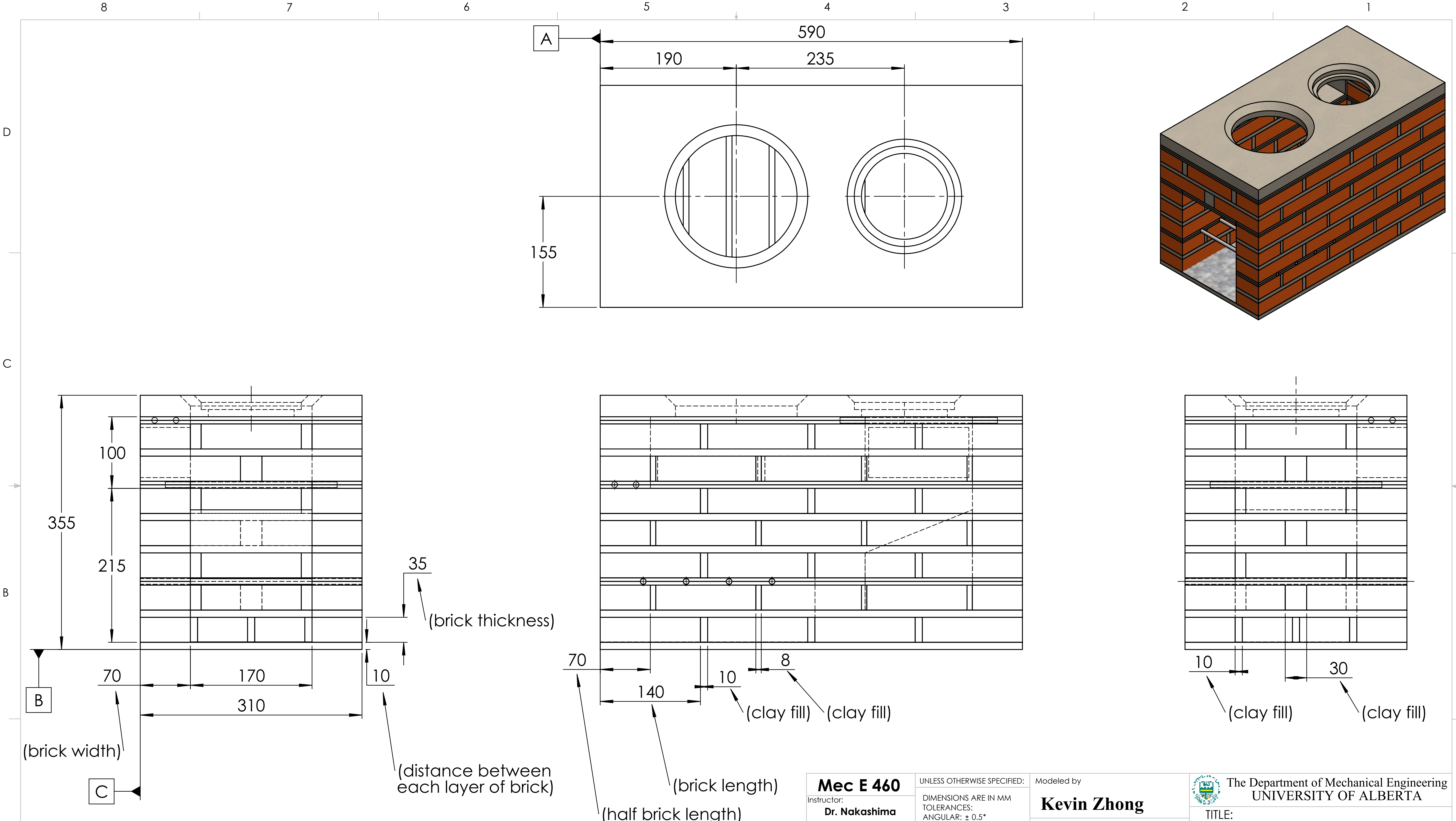
FILE NAME:
Rocket_Stove

The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

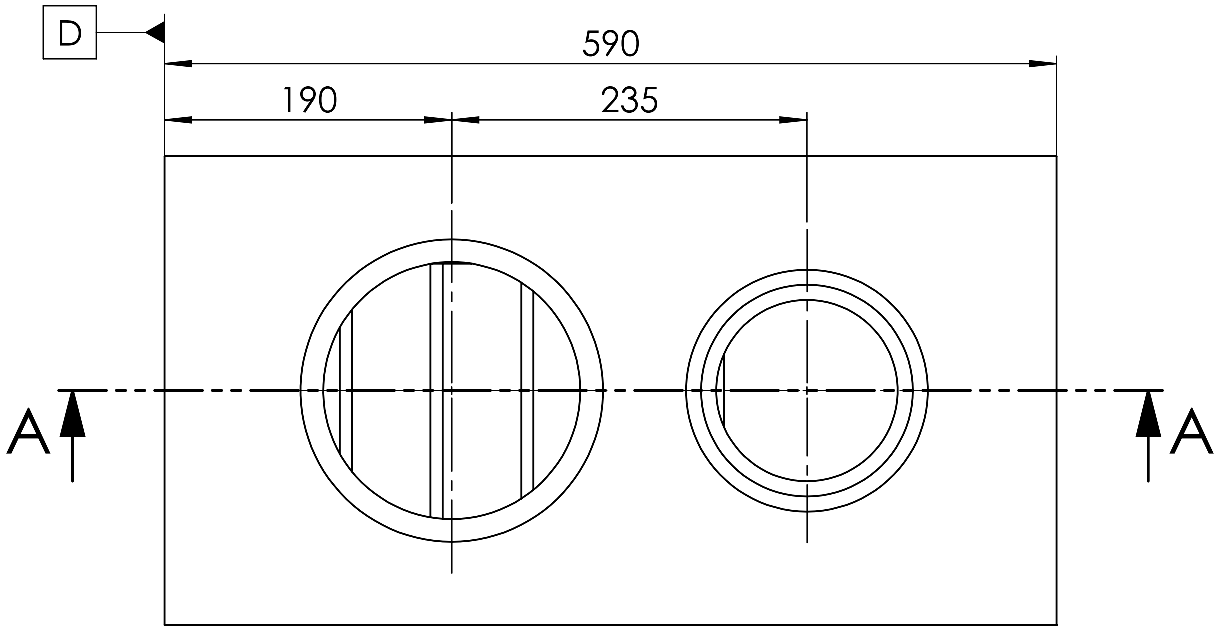
TITLE:
Exploded View of Rocket Stove

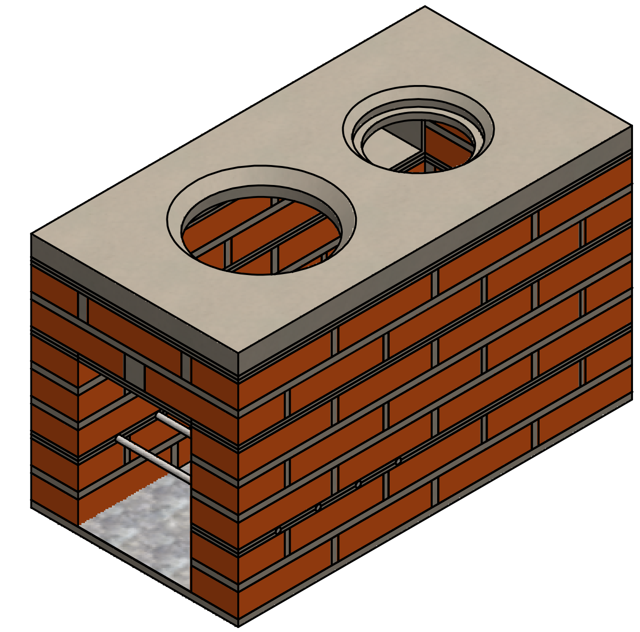
SIZE **B** | G1 Consulting | REV 1

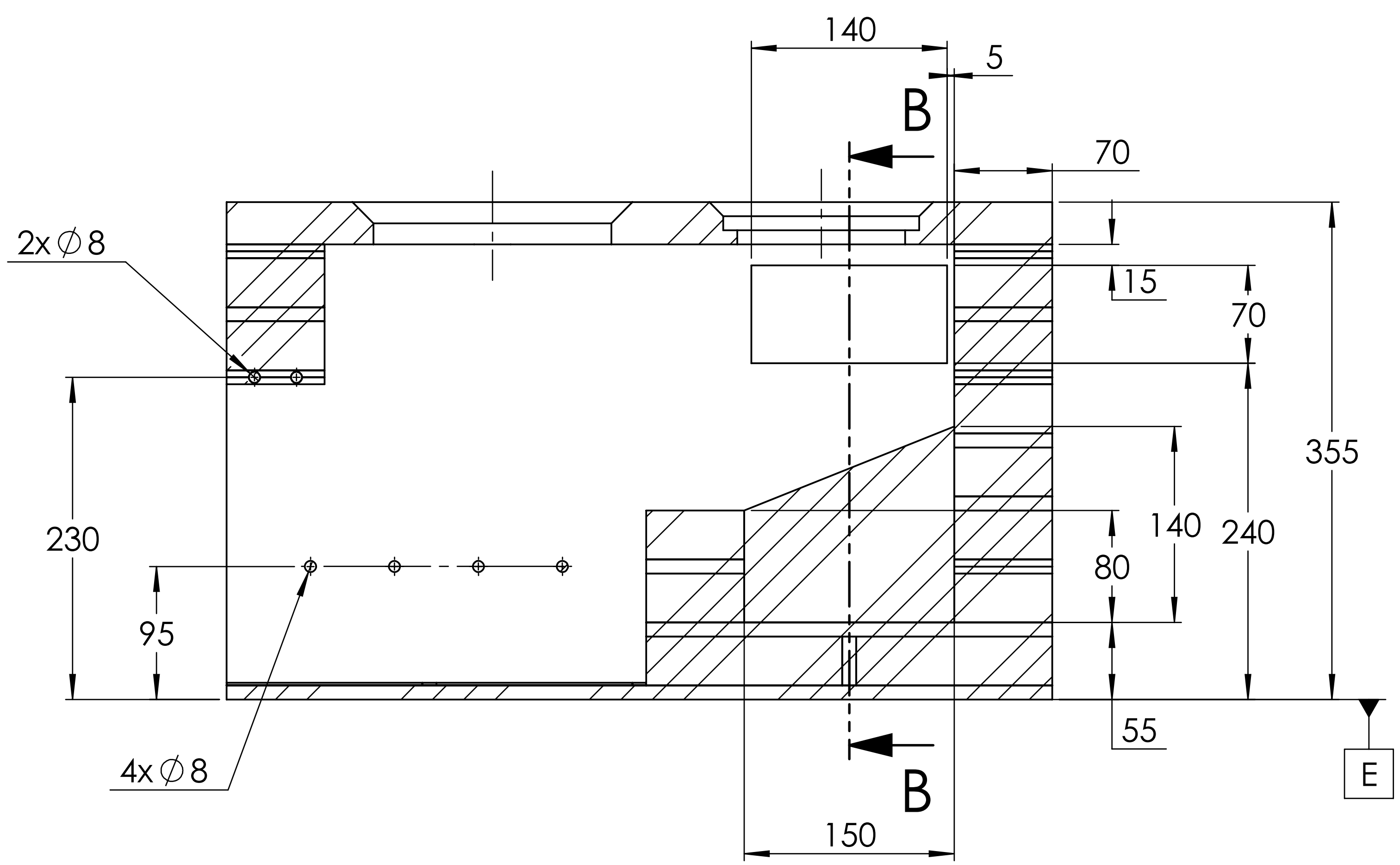
SCALE: 1:7.2 | Mass: 63824.10 g | SHEET 1 OF 4



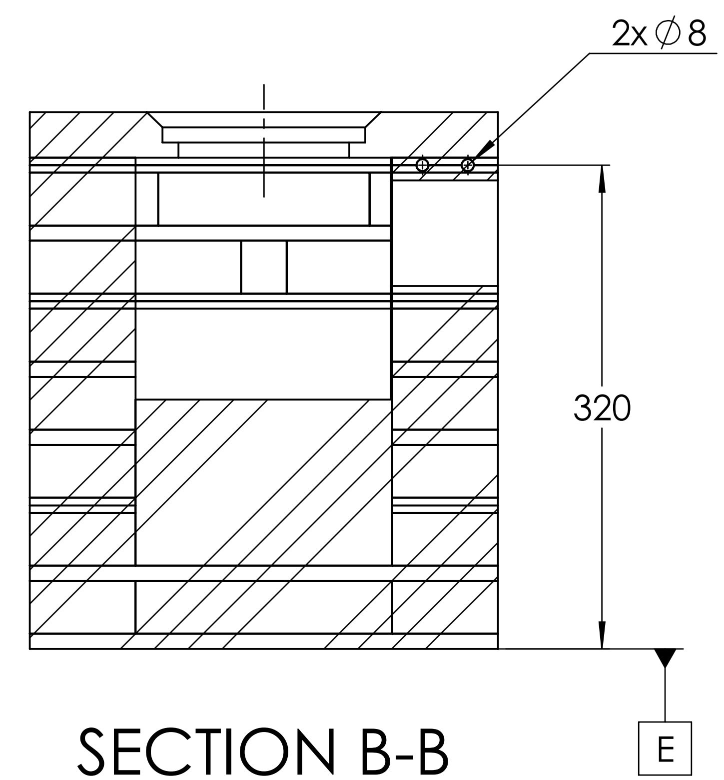
Mec E 460 Instructor: **Dr. Nakashima** Comments: Rebar is embedded in the clay.	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH µm 0.6 DO NOT SCALE DRAWING	Modeled by **Kevin Zhong** Drawn by **Kevin Zhong** Checked by **Ben Hallworth**	The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: Rocket Stove (1)
MATERIAL: Various		Thursday, April 15, 2021 3:04:31 AM Sunday, March 14, 2021 4:58:26 PM	SIZE **B** G1 Consulting REV 1
FILE NAME: Rocket_Stove			SCALE: 1:5 Mass: 63824.10 g SHEET 2 OF 4







SECTION A-A



SECTION B-B

Mec E 460
Instructor: **Dr. Nakashima**
Comments: Rebar is embedded in the clay.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025
SURFACE FINISH µm 0.6
DO NOT SCALE DRAWING

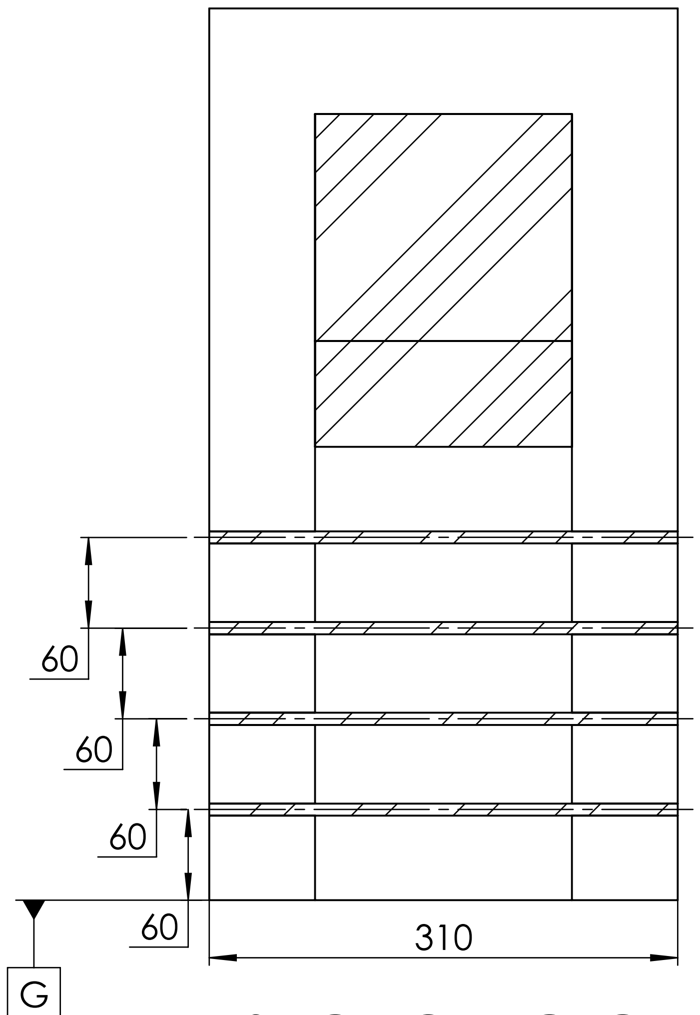
Modeled by **Kevin Zhong**
Drawn by **Kevin Zhong**
Checked by **Robert Chauvet**

The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

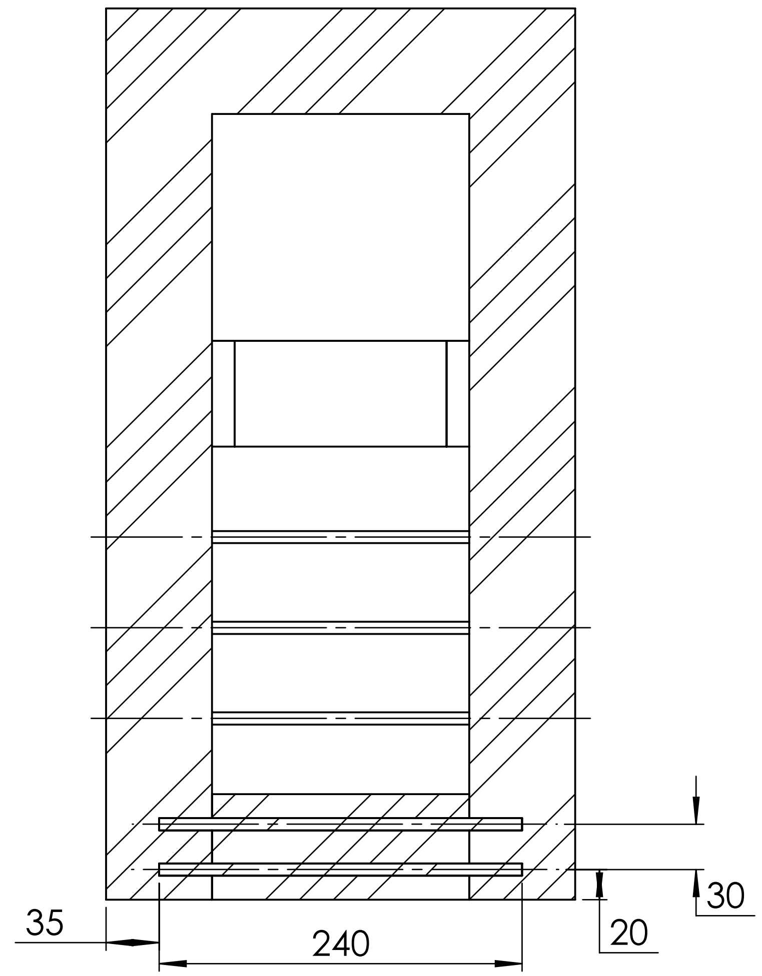
TITLE: Rocket Stove (2)

MATERIAL: Various
FILE NAME: Rocket_Stove
Thursday, April 15, 2021 3:04:31 AM
Sunday, March 14, 2021 4:58:26 PM

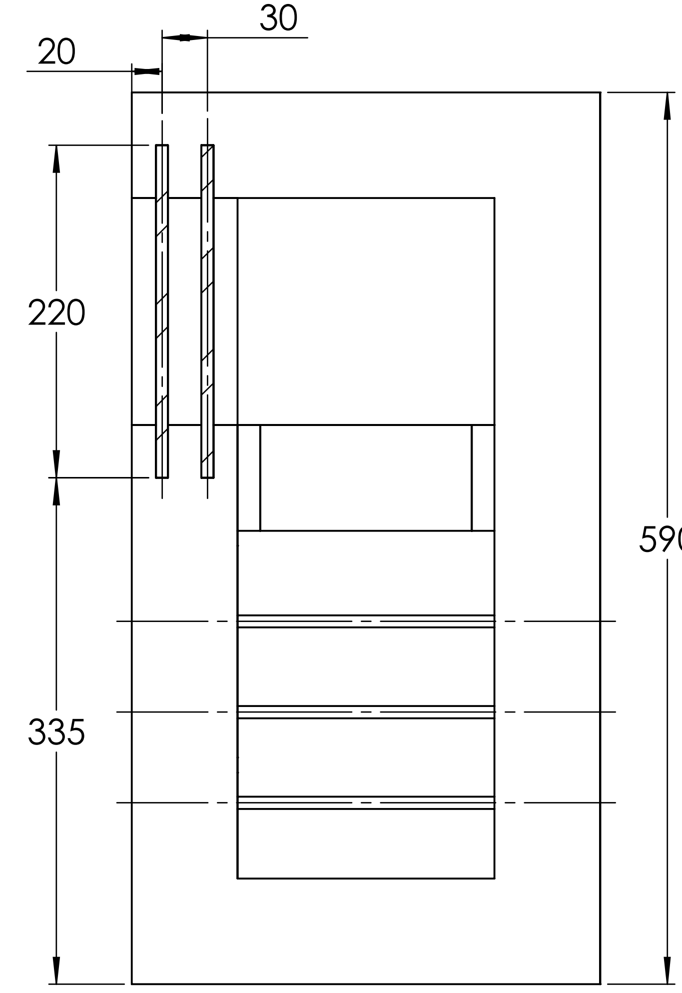
SIZE **B** G1 Consulting REV 1
SCALE: 1:5 Mass: 63824.10 g SHEET 3 OF 4



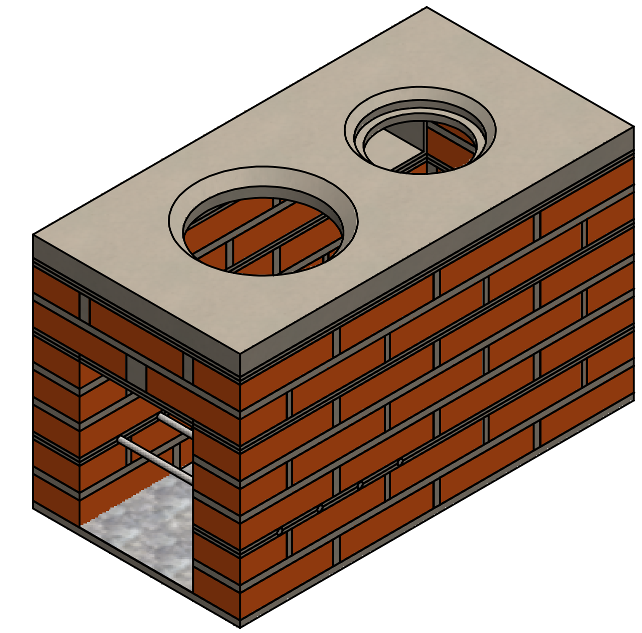
SECTION C-C

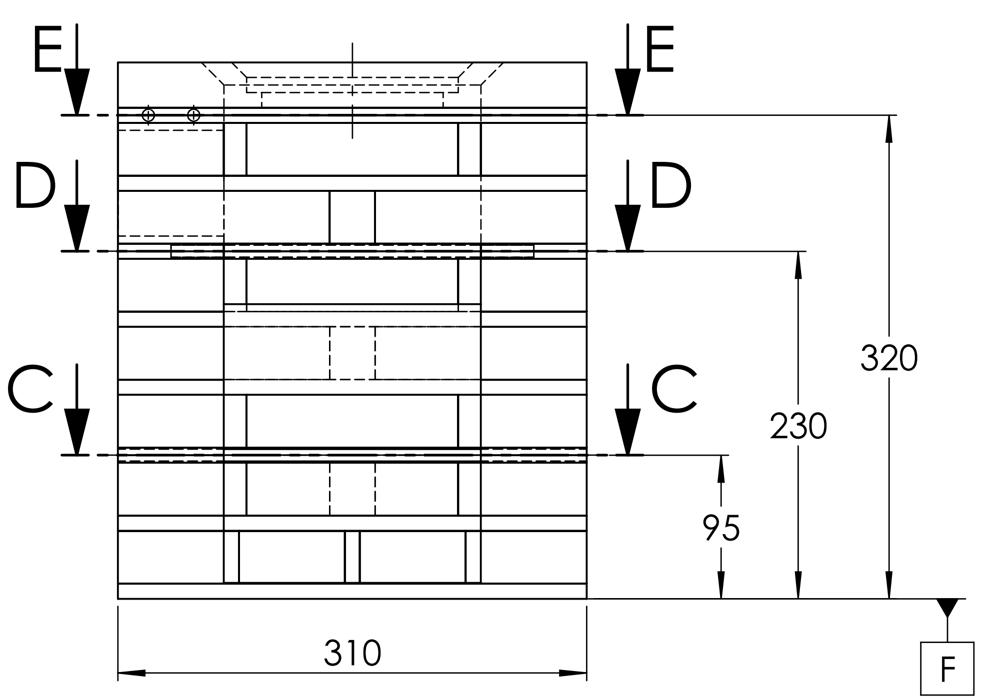


SECTION D-D

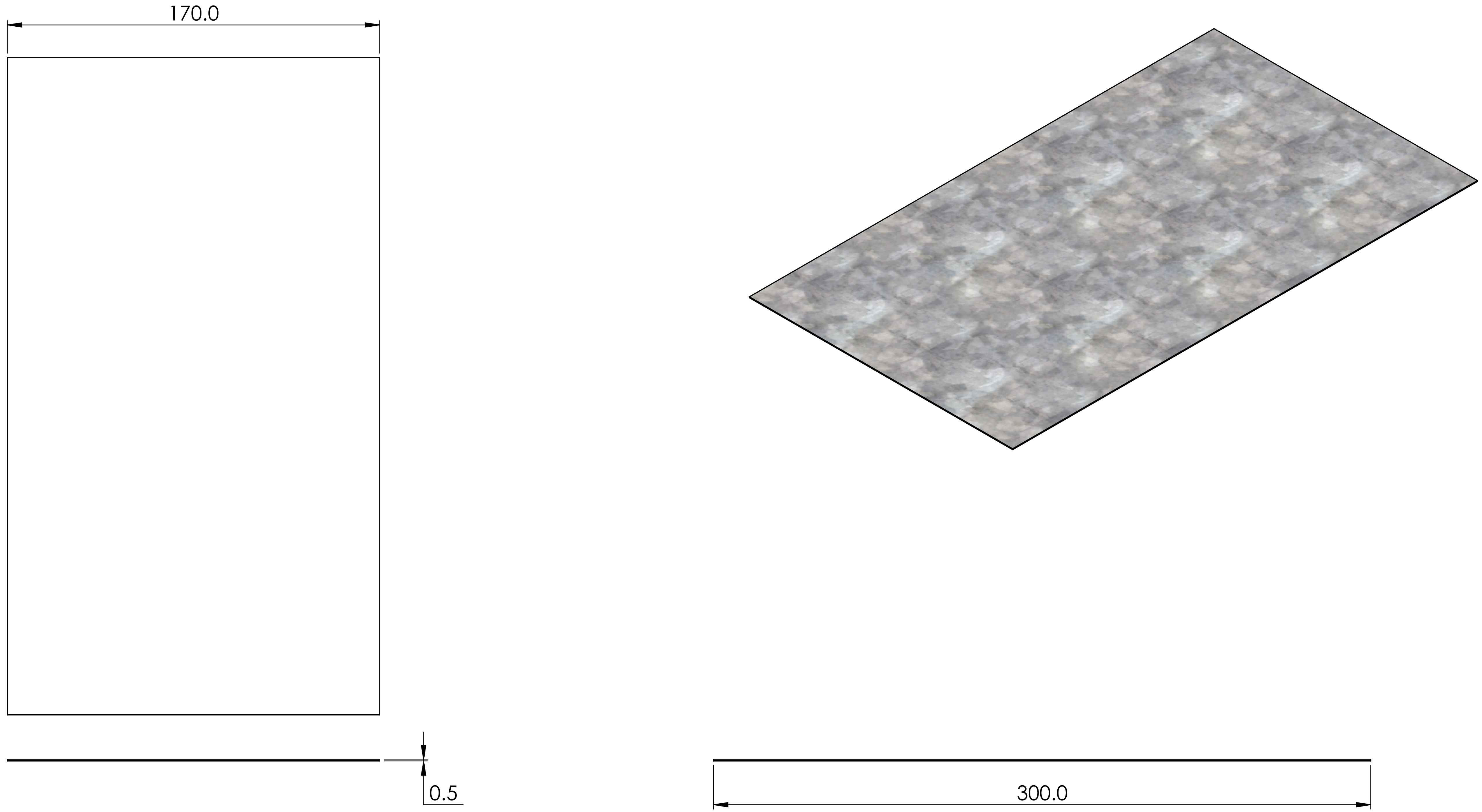


SECTION E-E

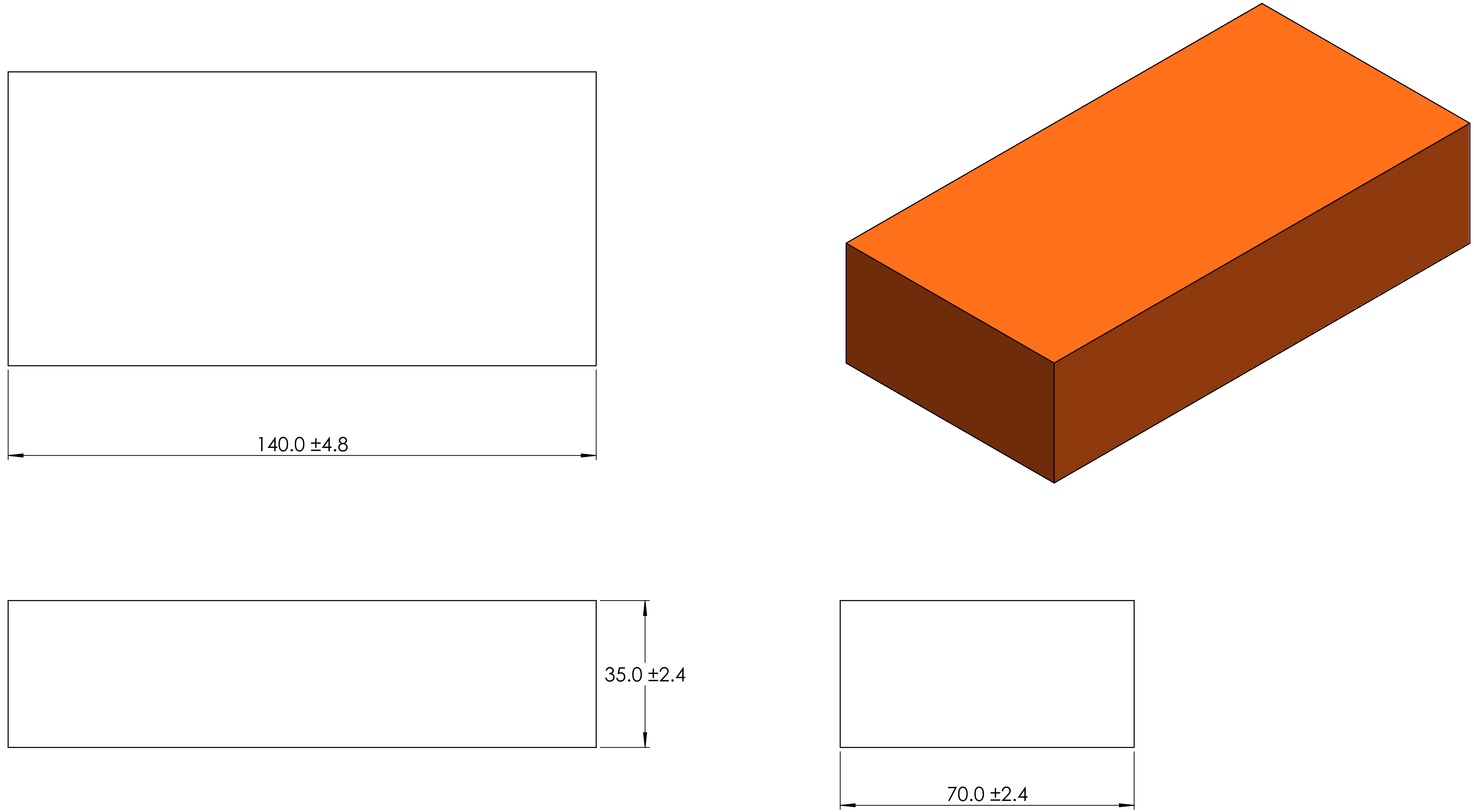




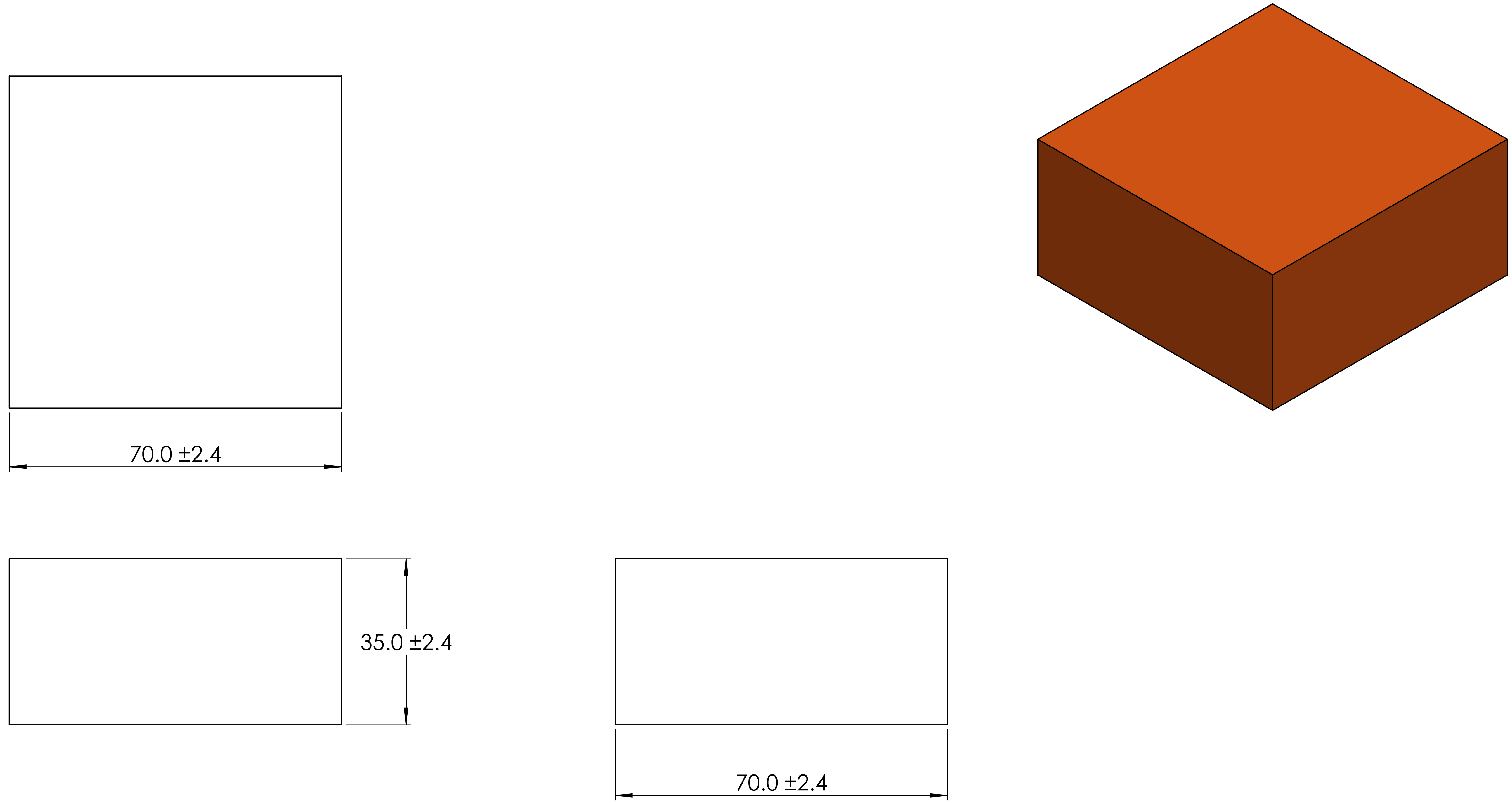
Mec E 460 Instructor: **Dr. Nakashima** Comments: Rebar is embedded in the clay.	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH µm 0.6 DO NOT SCALE DRAWING	Modeled by **Kevin Zhong** Drawn by **Kevin Zhong** Checked by **Ben Hallworth**	The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: Rocket Stove (3)
MATERIAL: Various FILE NAME: Rocket_Stove		Thursday, April 15, 2021 3:04:31 AM Sunday, March 14, 2021 4:58:26 PM	SIZE **B** G1 Consulting REV 1 SCALE: 1:5 Mass: 63824.10 g SHEET 4 OF 4



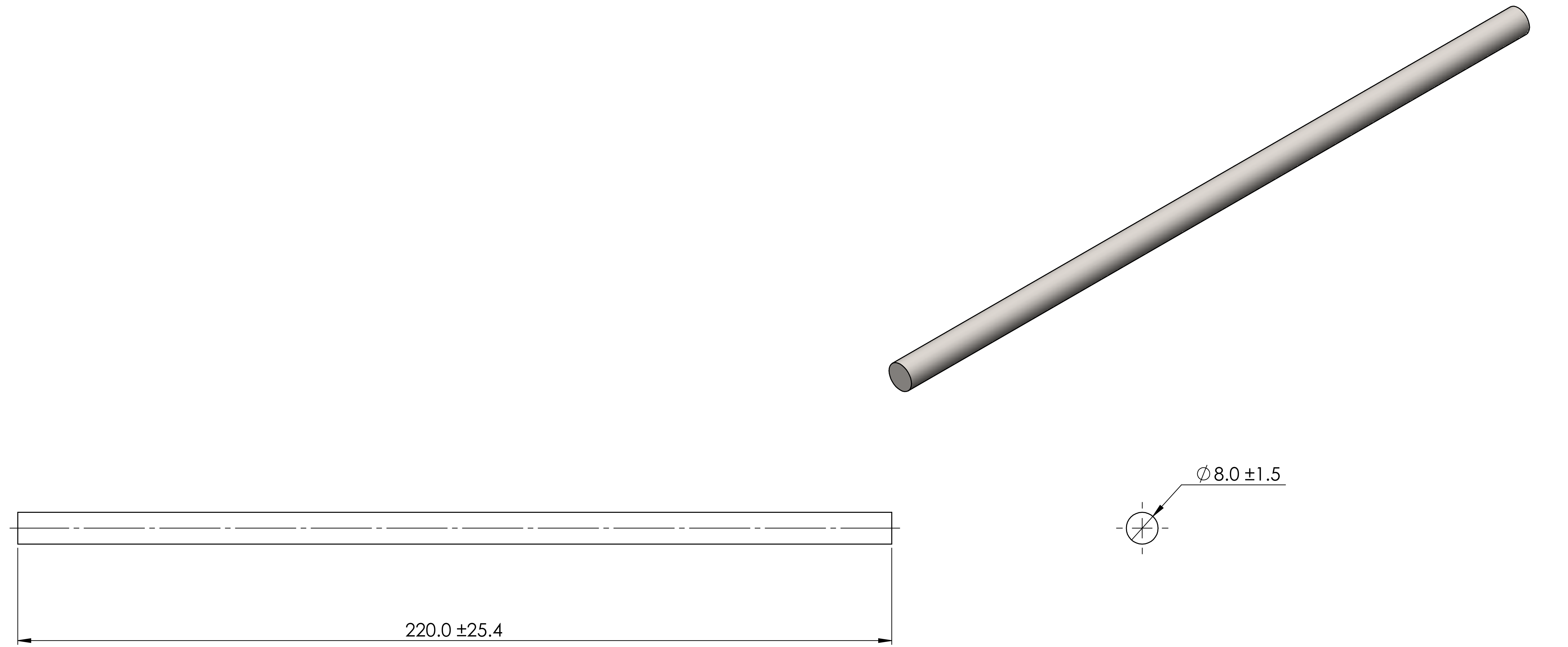
Mec E 460 Instructor: **Dr. Nakashima** Comments:	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH µm 0.6 DO NOT SCALE DRAWING	Modeled by **Kevin Zhong** Drawn by **Kevin Zhong** Checked by **Ben Hallworth**	The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: Tray
MATERIAL: Galvanized Steel		Thursday, April 15, 2021 3:01:43 AM Tuesday, April 6, 2021 11:12:57 AM	SIZE **B** — G1 Consulting — REV 1
FILE NAME: Tray			SCALE: 1:2 — Mass: 200.685 g — SHEET 1 OF 1



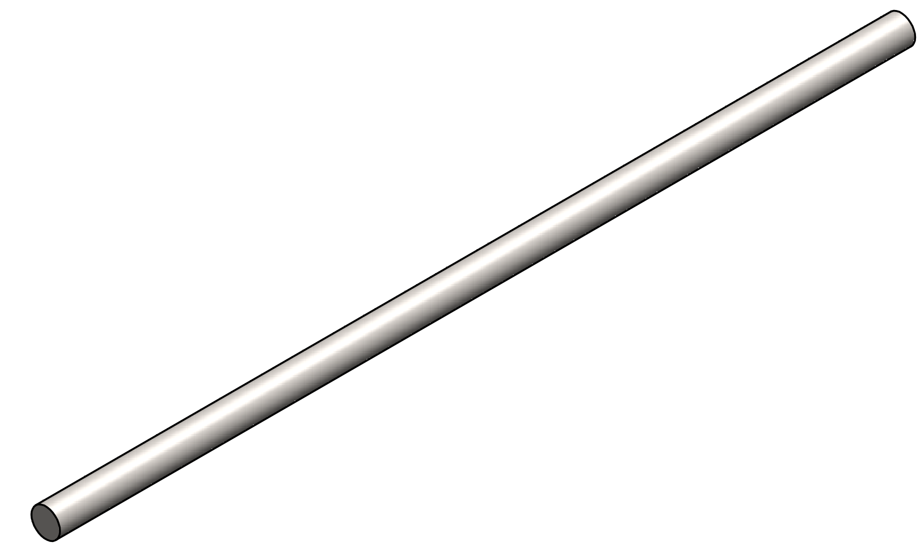
Mec E 460 Instructor: **Dr. Nakashima**	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH µm 0.6 DO NOT SCALE DRAWING	Modeled by **Kevin Zhong** Drawn by **Kevin Zhong** Checked by **Ben Hallworth**	The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: Brick
Comments: Bricks will be formed using wood mold.		Saturday, April 10, 2021 5:15:45 PM Tuesday, March 9, 2021 3:10:55 PM	SIZE **B** | G1 Consulting | REV 1
MATERIAL: Adobe			
FILE NAME: Brick			SCALE: 1:1 | Mass: 445.90 g | SHEET 1 OF 1

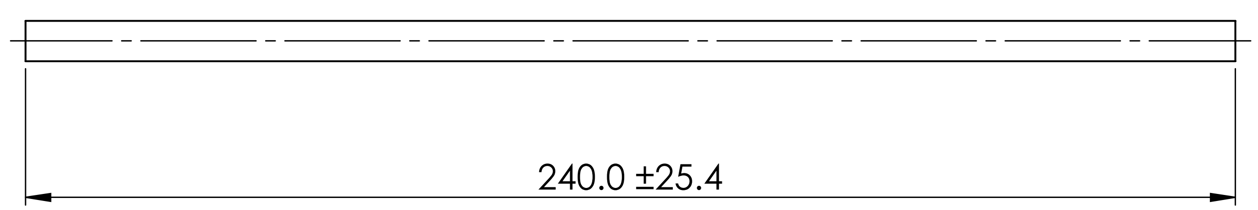


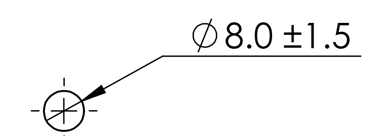
Mec E 460 Instructor: **Dr. Nakashima**	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH µm 0.6 DO NOT SCALE DRAWING	Modeled by **Kevin Zhong** Drawn by **Kevin Zhong** Checked by **Ben Hallworth**	The Department of Mechanical Engineering UNIVERSITY OF ALBERTA
Comments: Half-brick made by cutting a full-sized brick in half after molding (during drying process).			TITLE: Half Brick
MATERIAL: Adobe		Saturday, April 10, 2021 5:17:54 PM Thursday, March 11, 2021 12:40:12 PM	SIZE **B** · G1 Consulting · REV 1
FILE NAME: Half_Brick			SCALE: 1:1 · Mass: 222.95 g · SHEET 1 OF 1



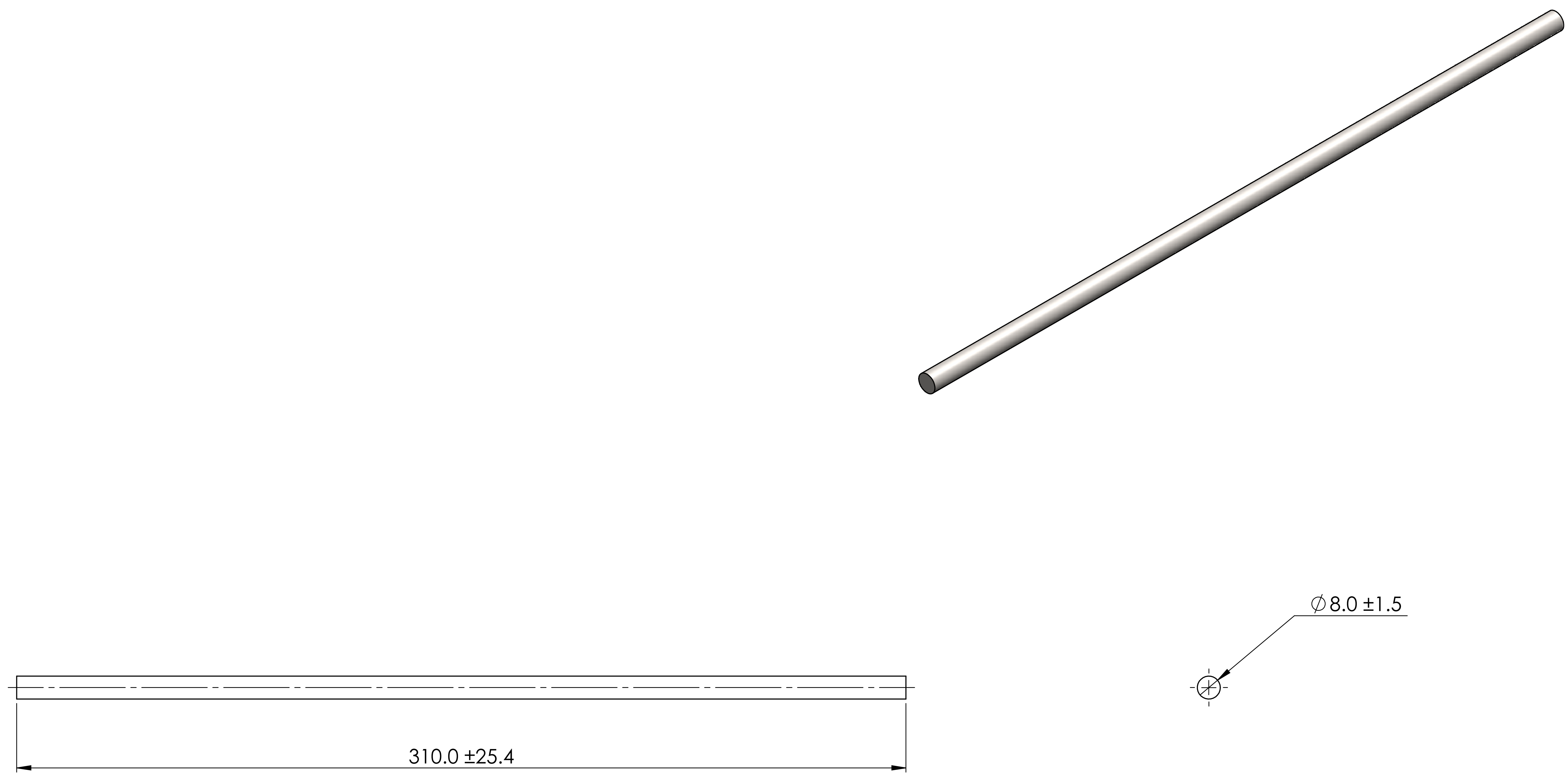
Mec E 460 Instructor: **Dr. Nakashima** Comments:	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH µm 0.6 DO NOT SCALE DRAWING	Modeled by **Kevin Zhong** Drawn by **Kevin Zhong** Checked by **Ben Hallworth**	The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: 220 mm Rebar
MATERIAL: Plain Carbon Steel		Tuesday, April 13, 2021 2:54:14 PM Thursday, March 11, 2021 2:31:41 PM	SIZE **B** — G1 Consulting — REV 1
FILE NAME: Rebar_8mm_220mm			SCALE: 1:1 — Mass: 86.256 g — SHEET 1 OF 1







Mec E 460 Instructor: **Dr. Nakashima** Comments:	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH µm 0.6 DO NOT SCALE DRAWING	Modeled by **Kevin Zhong** Drawn by **Kevin Zhong** Checked by **Robert Chauvet**	The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: 240 mm Rebar
MATERIAL: Plain Carbon Steel		Tuesday, April 13, 2021 2:54:10 PM Thursday, March 11, 2021 2:31:41 PM	SIZE **B** — G1 Consulting — REV 1
FILE NAME: Rebar_8mm_240mm			SCALE: 1:1.5 — Mass: 94.097 g — SHEET 1 OF 1



Mec E 460

Instructor: **Dr. Nakashima**

Comments:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025

SURFACE FINISH µm 0.6

DO NOT SCALE DRAWING

Modeled by **Kevin Zhong**

Drawn by **Kevin Zhong**

Checked by **Robert Chauvet**

Tuesday, April 13, 2021 2:54:02 PM
Thursday, March 11, 2021 2:31:41 PM

The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

TITLE:

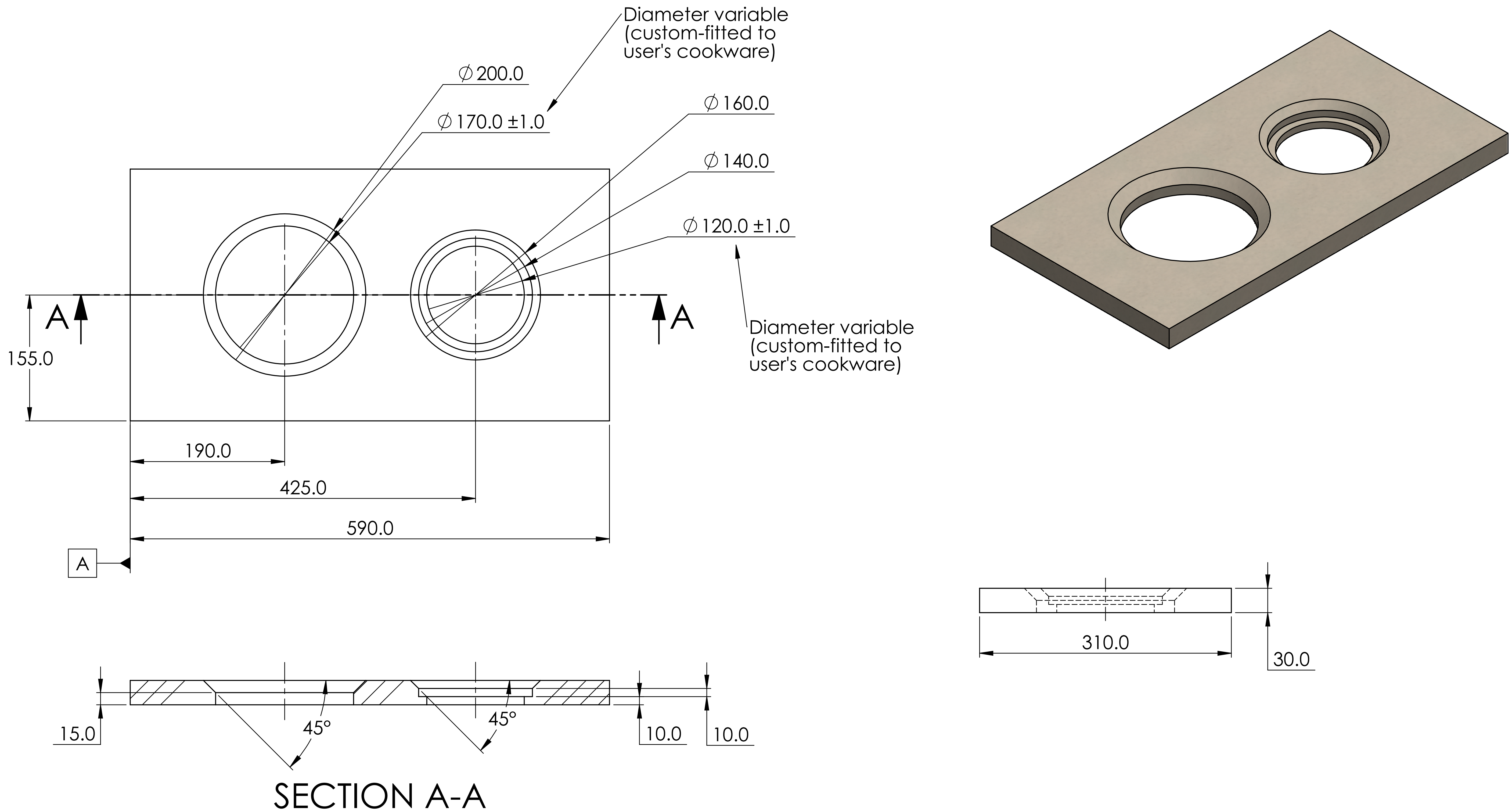
310 mm Rebar

SIZE		REV
B	G1 Consulting	1

MATERIAL: Plain Carbon Steel

FILE NAME: Rebar_8mm_310mm

SCALE: 1:1.5 | Mass: 121.542 g | SHEET 1 OF 1



Mec E 460

Instructor: **Dr. Nakashima**

Comments: The openings on the cook top are custom-fitted to the user's cookware. Exterior dimensions formed using wood mold.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025

SURFACE FINISH µm 0.6

DO NOT SCALE DRAWING

Modeled by **Kevin Zhong**

Drawn by **Kevin Zhong**

Checked by **Ben Hallworth**

Saturday, April 10, 2021 5:23:11 PM
Thursday, March 11, 2021 5:44:54 PM

MATERIAL: Clay

FILE NAME: Cook_Top

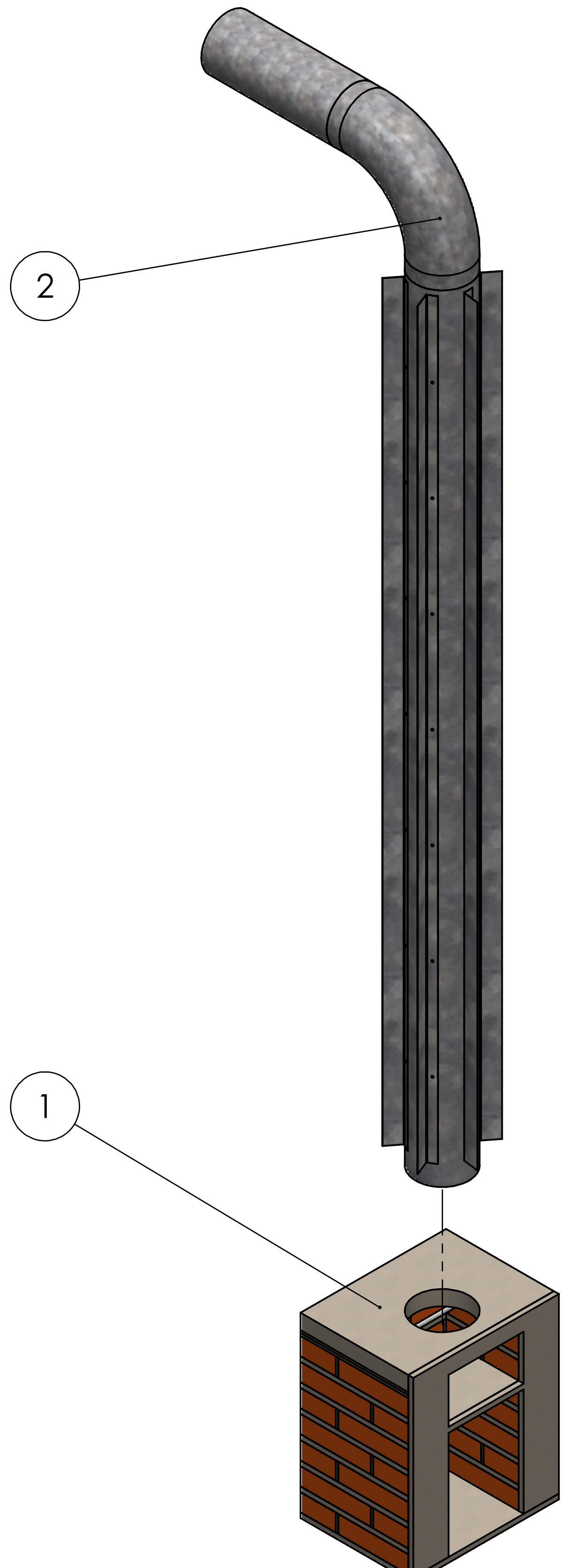
The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

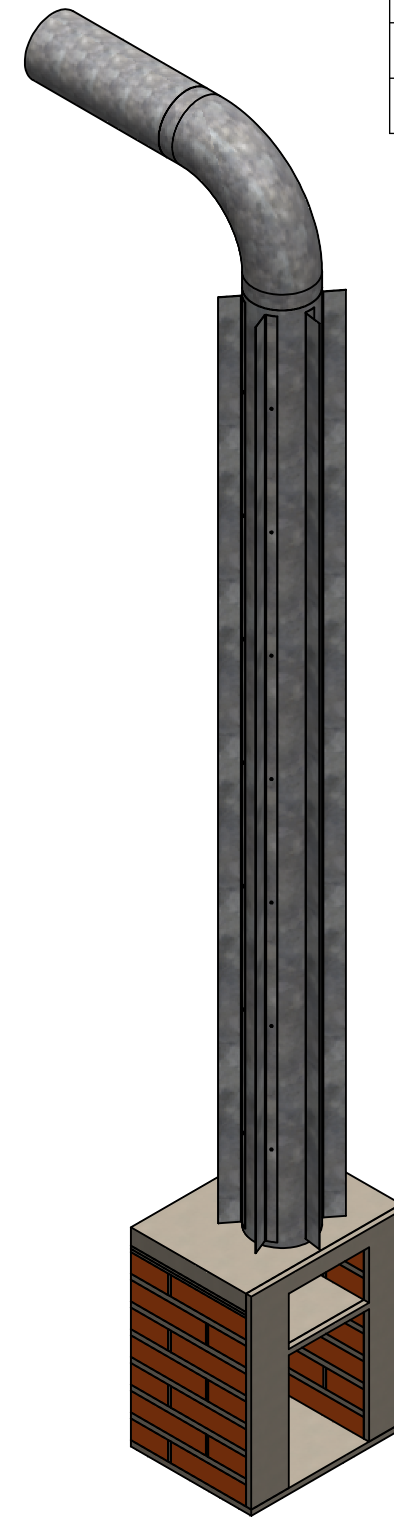
TITLE: Cook Top

SIZE **B** | G1 Consulting | REV 1

SCALE: 1:5 | Mass: 7565.238 g | SHEET 1 OF 1

ITEM NO.	PART NUMBER	Material	QTY.
1	Chimney_Base	Various	1
2	Finned_Chimney	Various	1





Mec E 460
Instructor: **Dr. Nakashima**
Comments:

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025
SURFACE FINISH µm 0.6
DO NOT SCALE DRAWING

Modeled by **Kevin Zhong**
Drawn by **Kevin Zhong**
Checked by **Robert Chauvet**
Thursday, April 15, 2021 3:14:36 AM
Wednesday, April 14, 2021 3:20:44 AM

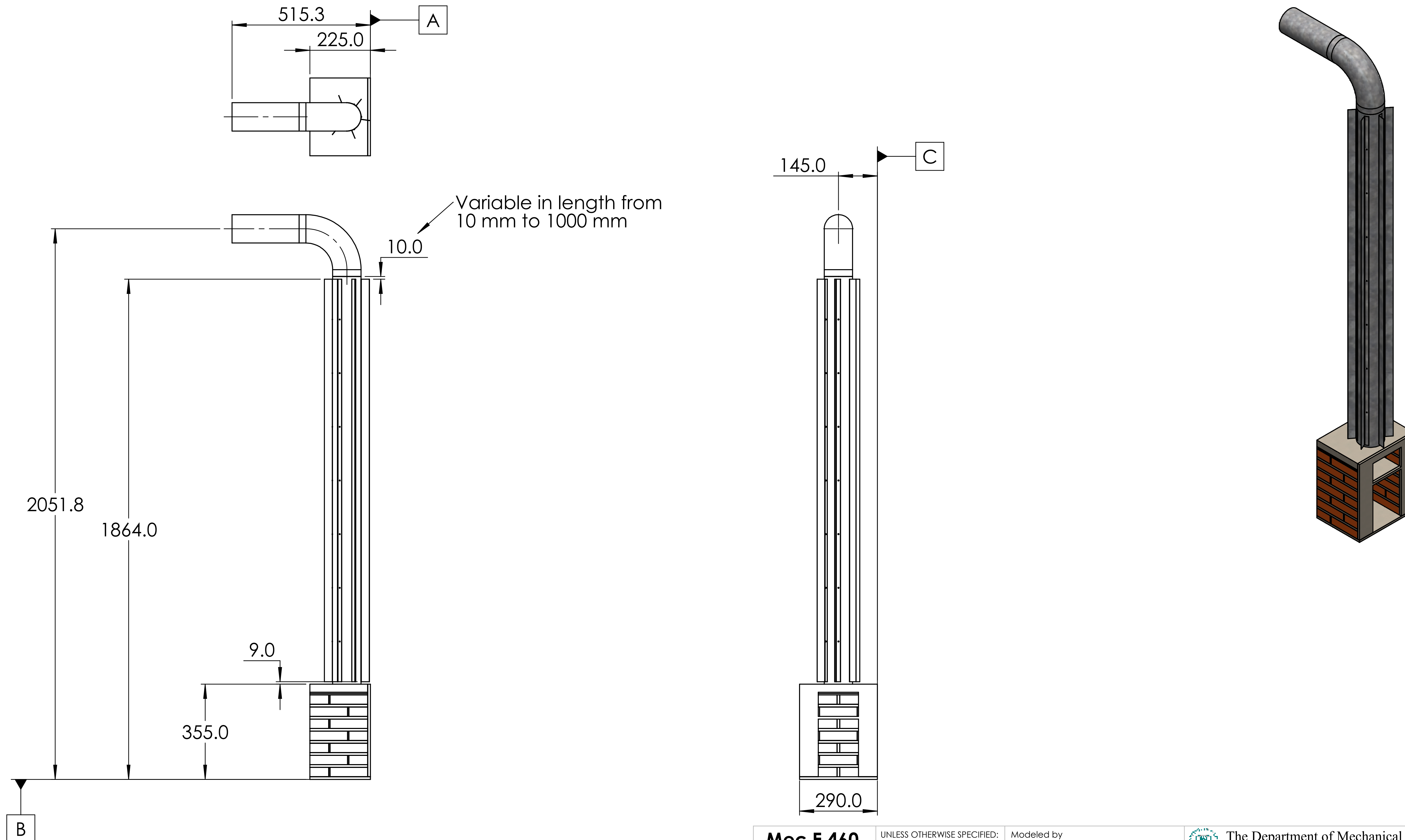
The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

TITLE:
Exploded View of Chimney

MATERIAL: Various
FILE NAME: Chimney

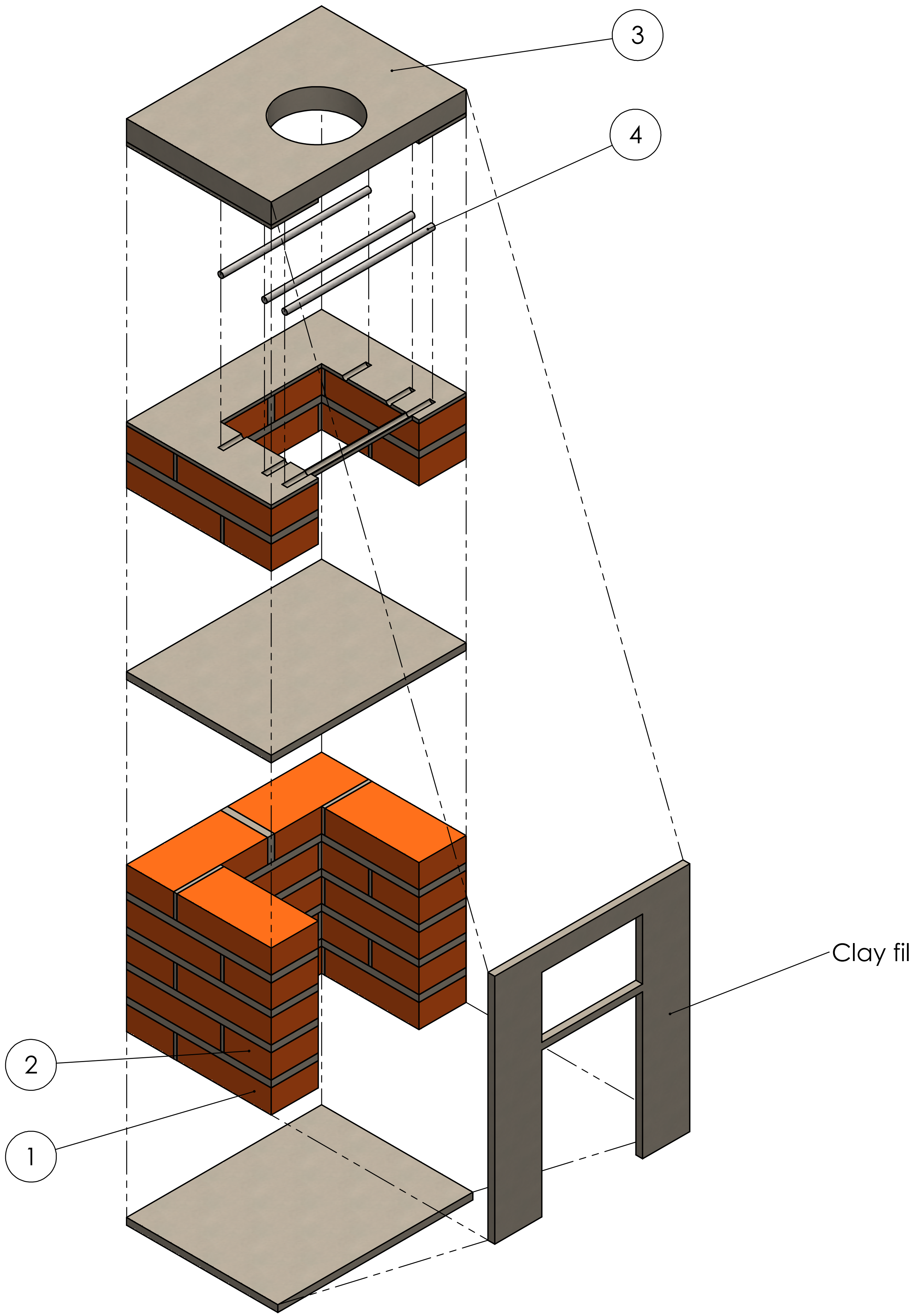
SIZE **B** | G1 Consulting | REV 1

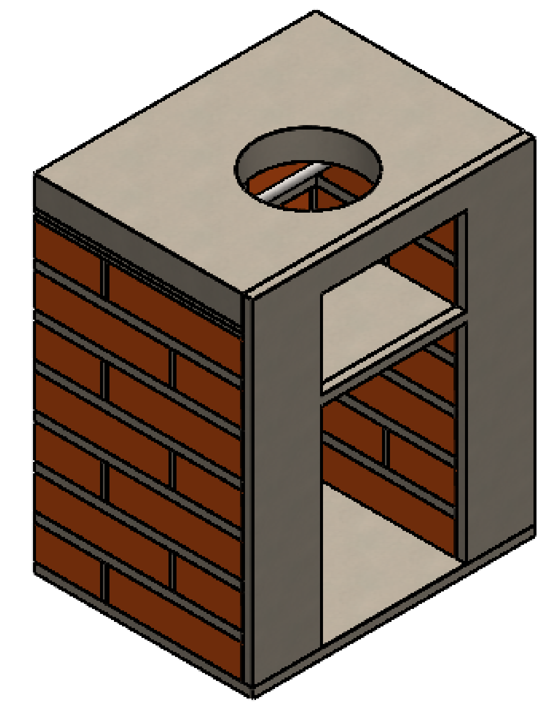
SCALE: 1:10 | Mass: 37406.95 g | SHEET 1 OF 2



Mec E 460 Instructor: **Dr. Nakashima** Comments:	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH µm 0.6 DO NOT SCALE DRAWING	Modeled by **Kevin Zhong** Drawn by **Kevin Zhong** Checked by **Robert Chauvet**	The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: Chimney
MATERIAL: Various		Thursday, April 15, 2021 3:14:36 AM Wednesday, April 14, 2021 3:20:44 AM	SIZE **B** G1 Consulting REV 1
FILE NAME: Chimney			SCALE: 1:15 Mass: 37406.95 g SHEET 2 OF 2

ITEM NO.	PART NUMBER	Material	QTY.
1	Brick	Adobe	25
2	Half_Brick	Adobe	6
3	Chimney_Base_Top	Clay	1
4	Rebar_8mm_220mm	Plain Carbon Steel	3





Mec E 460

Instructor:
Dr. Nakashima

Comments:
Unlabelled components are clay fill to bind bricks together. Rebar is embedded in the clay.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025
SURFACE FINISH µm 0.6
DO NOT SCALE DRAWING

MATERIAL:
Various

FILE NAME:
Chimney_Base

Modeled by
Kevin Zhong

Drawn by
Kevin Zhong

Checked by
Robert Chauvet

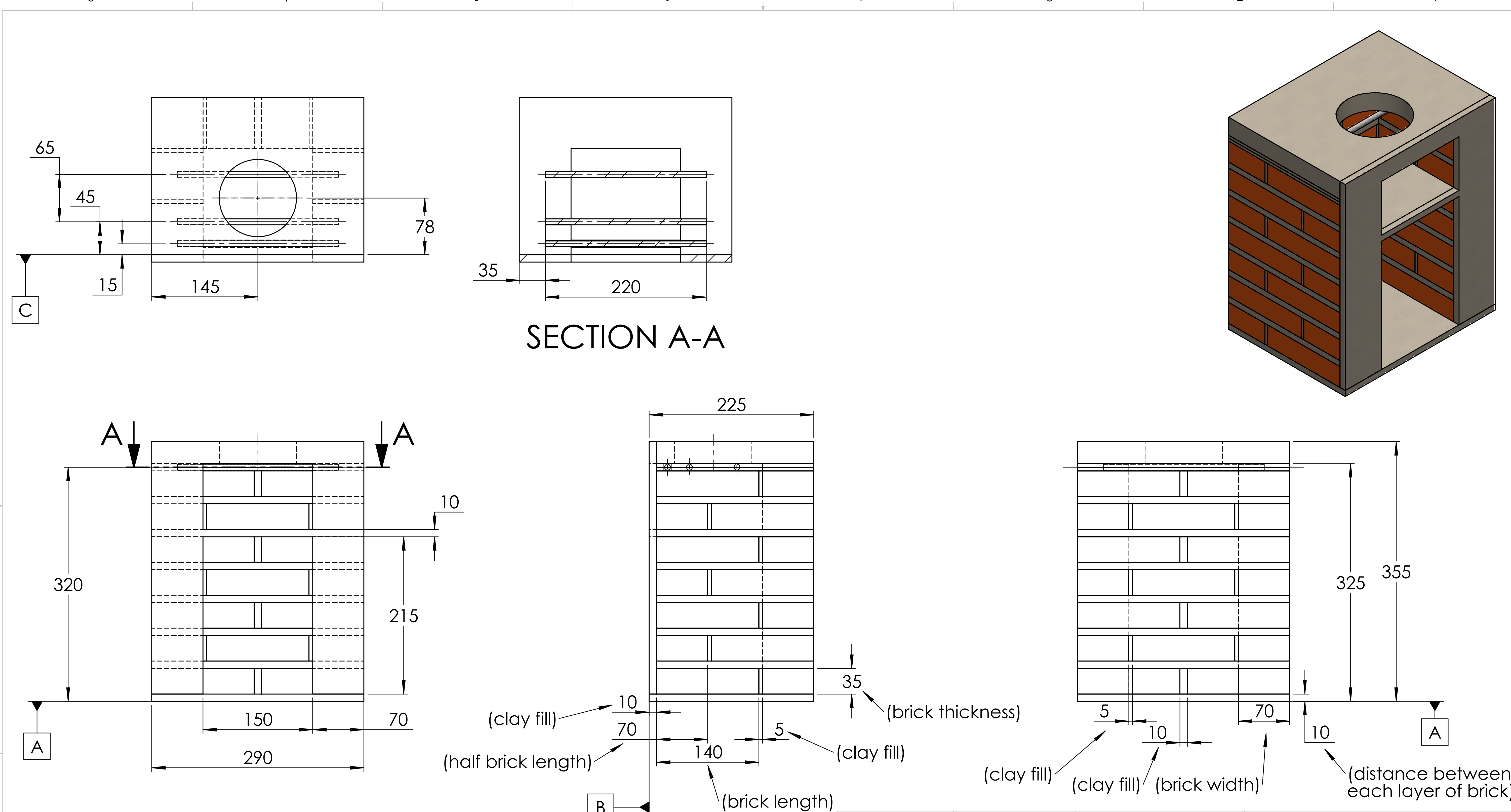
Thursday, April 15, 2021 3:14:37 AM
Thursday, March 18, 2021 2:00:01 AM

The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

TITLE:
Chimney Base Exploded View

SIZE **B** | G1 Consulting | REV 1

SCALE: 1:5.5 | Mass: 23660.08 g | SHEET 1 OF 2



Mec E 460
Instructor: **Dr. Nakashima**
Comments: Rebar is embedded in the clay.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025
SURFACE FINISH μm 0.6
DO NOT SCALE DRAWING

Modeled by **Kevin Zhong**
Drawn by **Kevin Zhong**
Checked by **Robert Chauvet**

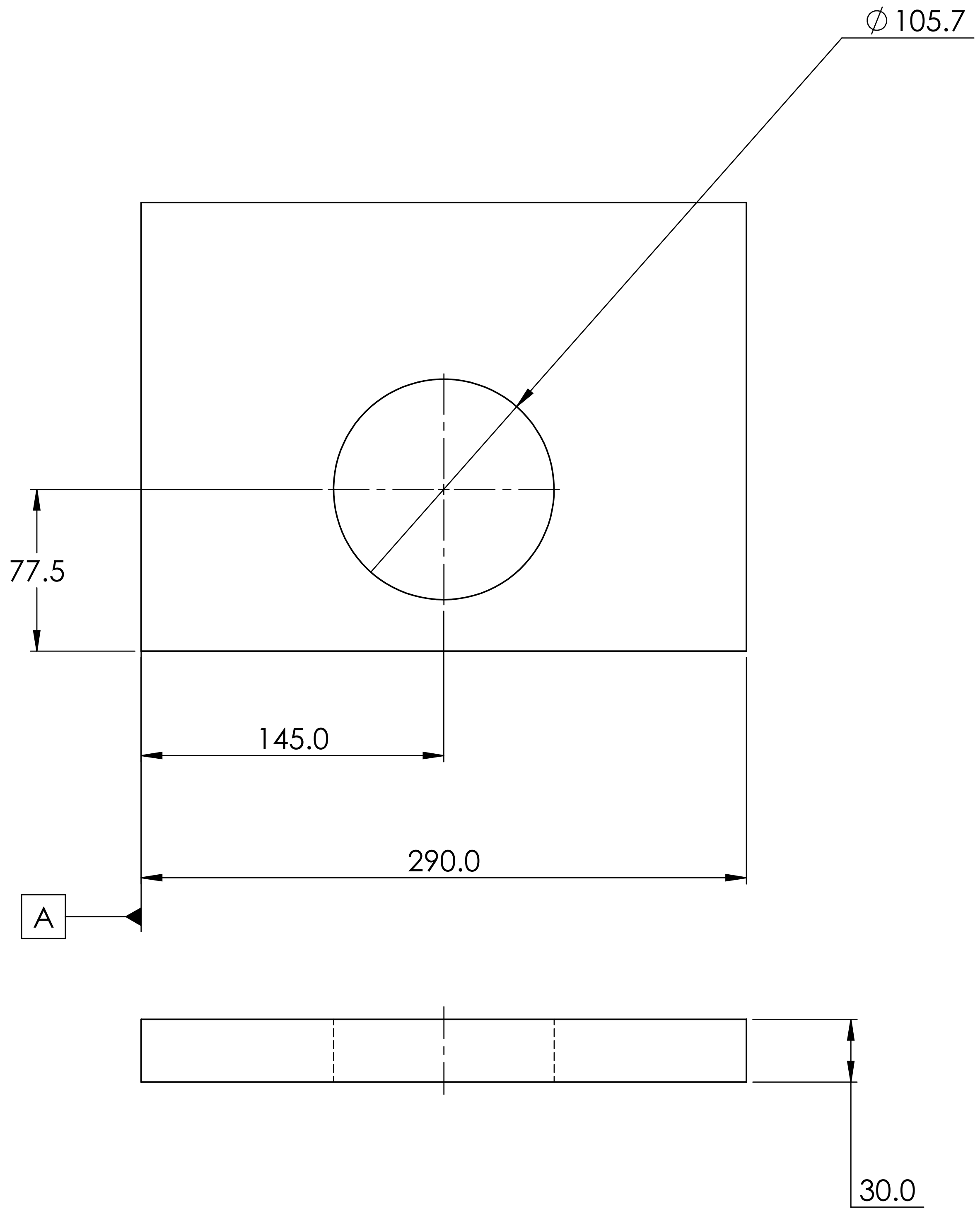
The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

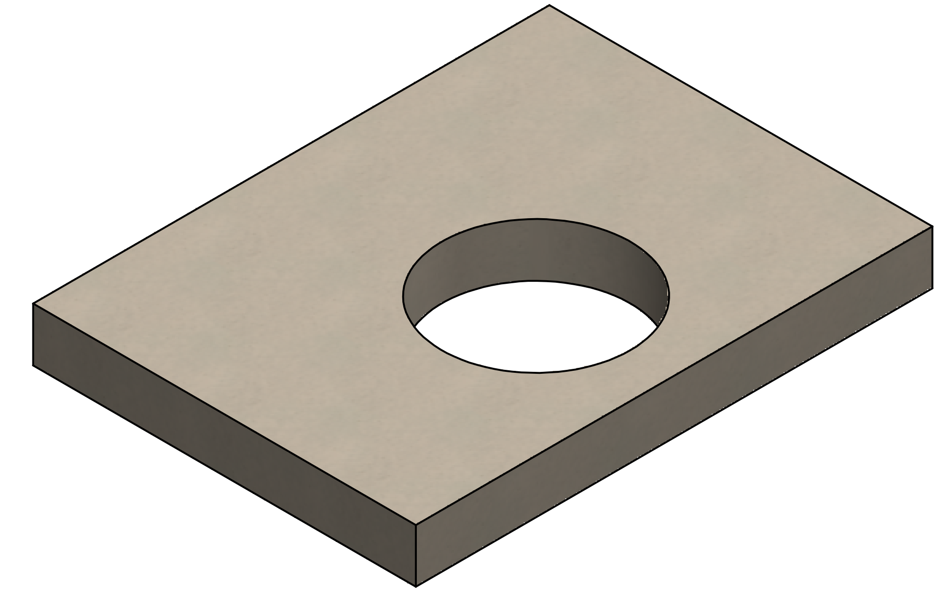
TITLE:
Chimney Base

MATERIAL: Various
FILE NAME: Chimney_Base
Thursday, April 15, 2021 3:14:37 AM
Thursday, March 18, 2021 2:00:01 AM

SIZE **B** | G1 Consulting | REV 1

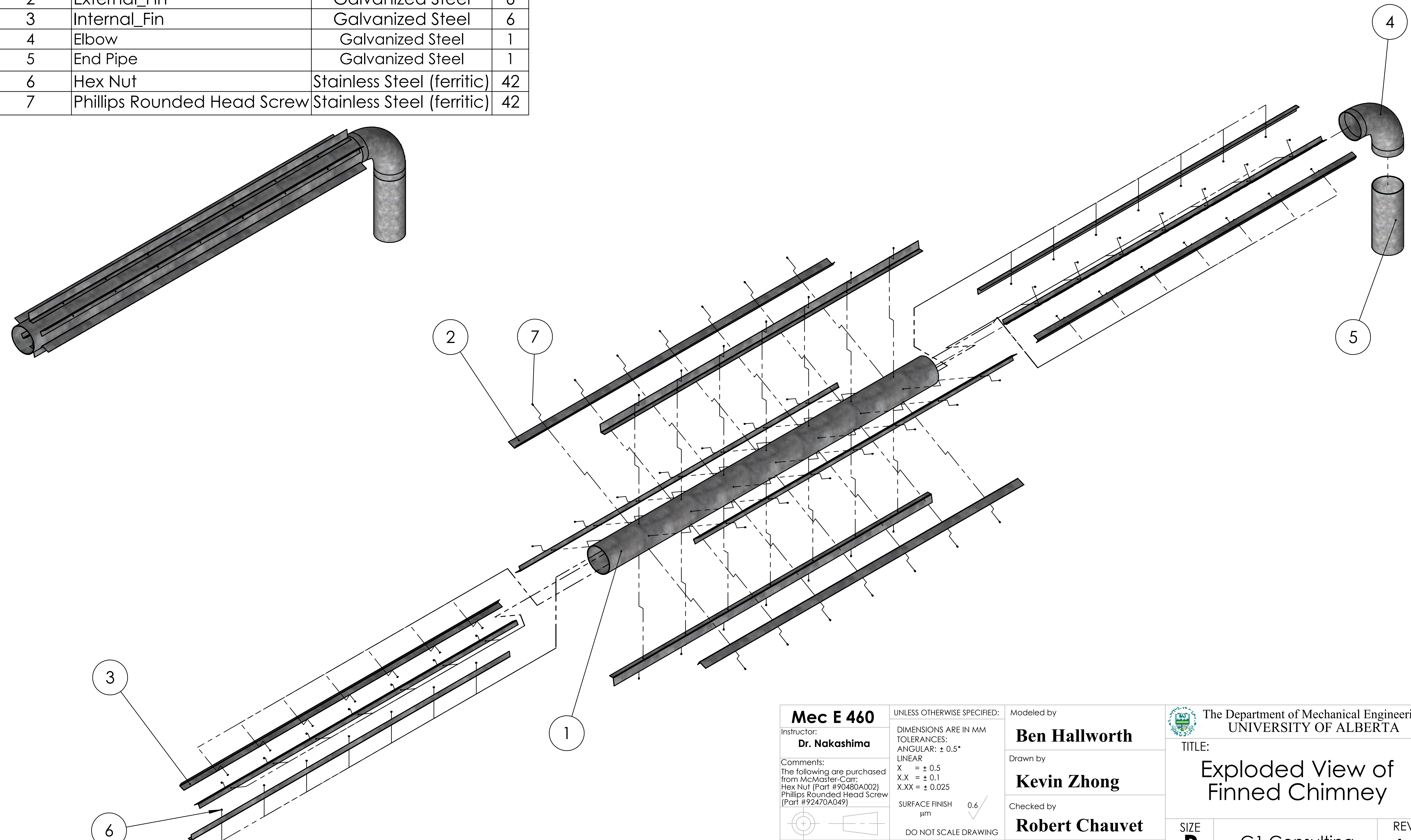
SCALE: 1:5.2 | Mass: 23660.08 g | SHEET 2 OF 2





Mec E 460 Instructor: **Dr. Nakashima** Comments: Exterior dimensions formed using wood mold.	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH µm 0.6 DO NOT SCALE DRAWING	Modeled by **Kevin Zhong** Drawn by **Kevin Zhong** Checked by **Robert Chauvet**	The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: Chimney Base Top
MATERIAL: Clay		Saturday, April 10, 2021 5:31:46 PM Thursday, March 18, 2021 2:21:34 AM	SIZE B · G1 Consulting · REV 1
FILE NAME: Chimney_Base_Top			SCALE: 1:3 · Mass: 2829.083 g · SHEET 1 OF 1

ITEM NO.	PART NUMBER	Material	QTY.
1	Finned_Tube	Galvanized Steel	1
2	External_Fin	Galvanized Steel	6
3	Internal_Fin	Galvanized Steel	6
4	Elbow	Galvanized Steel	1
5	End Pipe	Galvanized Steel	1
6	Hex Nut	Stainless Steel (ferritic)	42
7	Phillips Rounded Head Screw	Stainless Steel (ferritic)	42



Mec E 460

Instructor: **Dr. Nakashima**

Comments:
The following are purchased from McMaster-Carr:
Hex Nut (Part #90480A002)
Phillips Rounded Head Screw (Part #92470A049)

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025

SURFACE FINISH 0.6 µm

DO NOT SCALE DRAWING

MATERIAL: Various

FILE NAME: Finned_Chimney

Modeled by **Ben Hallworth**

Drawn by **Kevin Zhong**

Checked by **Robert Chauvet**

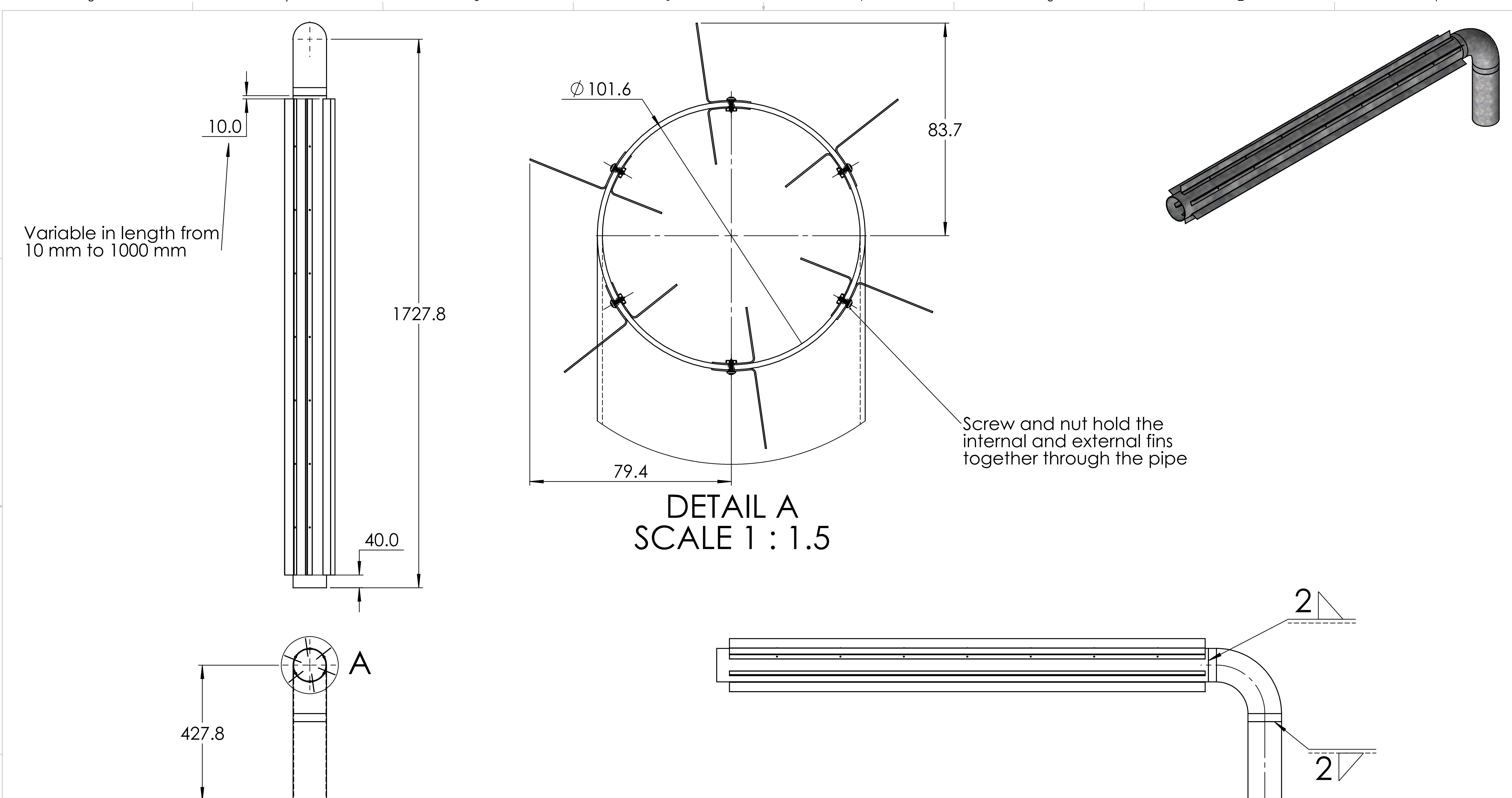
Thursday, April 15, 2021 3:14:36 AM
Monday, April 12, 2021 1:34:37 PM

The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

TITLE:
Exploded View of Finned Chimney

SIZE **B** | G1 Consulting | REV 1

SCALE: 1:12 | Mass: 13746.87 g | SHEET 1 OF 2



Mec E 460
Instructor: Dr. Nakashima
Comments:

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025
SURFACE FINISH µm 0.6
DO NOT SCALE DRAWING

MATERIAL: Various
FILE NAME: Finned_Chimney

Modeled by **Ben Hallworth**
Drawn by **Kevin Zhong**
Checked by **Robert Chauvet**
Thursday, April 15, 2021 3:14:36 AM
Monday, April 12, 2021 1:34:37 PM

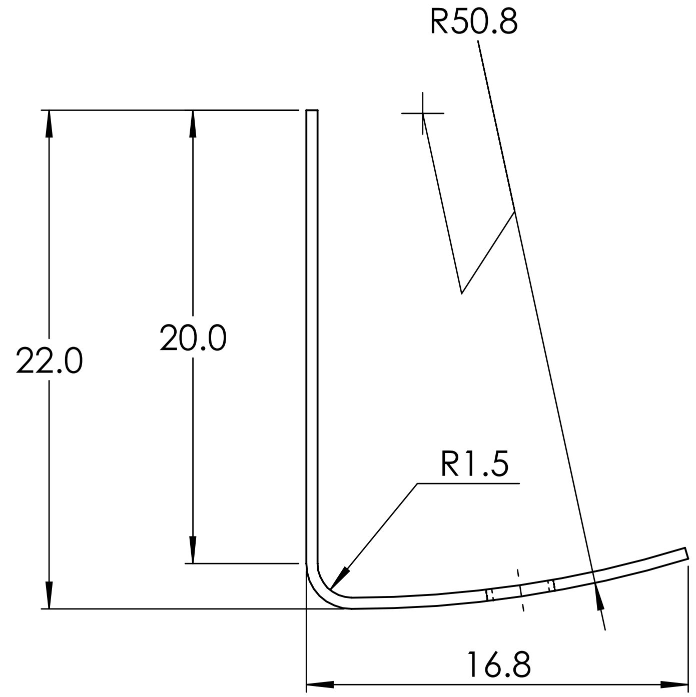
The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

TITLE: Finned Chimney

SIZE **B** | G1 Consulting | REV 1

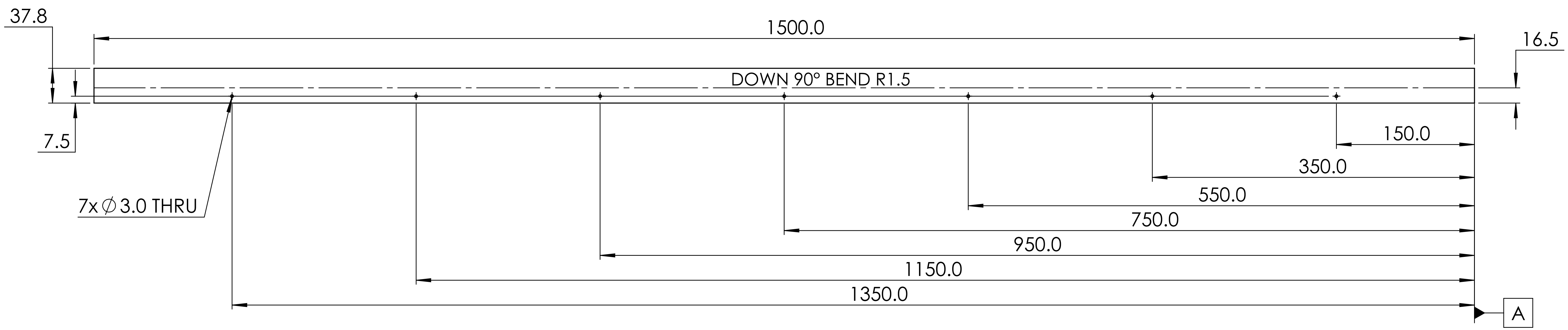
SCALE: 1:12 | Mass: 13746.87 g | SHEET 2 OF 2

As-Bent



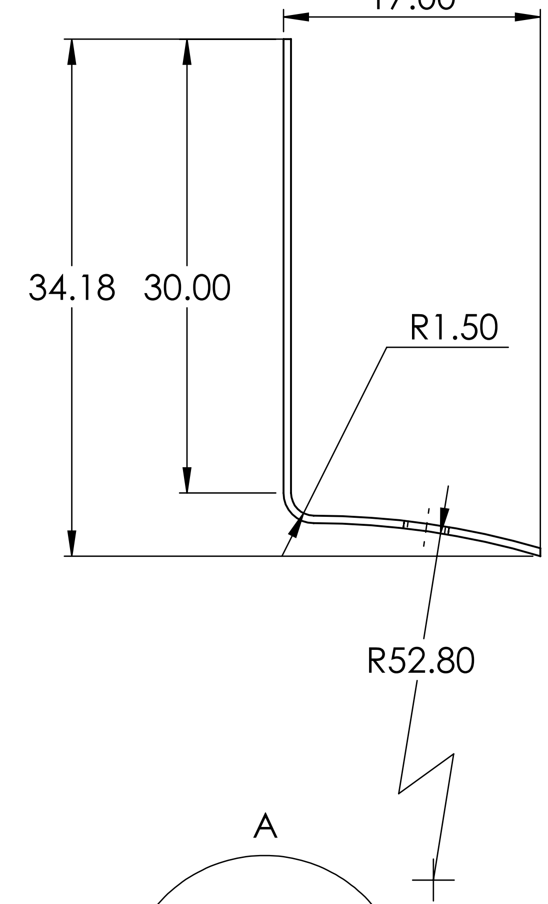
Bottom section may be bent in radius larger than R50.8 (or even flat). Bolting this section to the chimney will naturally curve the section to the chimney's inner radius (50.8 mm). Sheet metal thickness is 0.5 mm.

Flattened

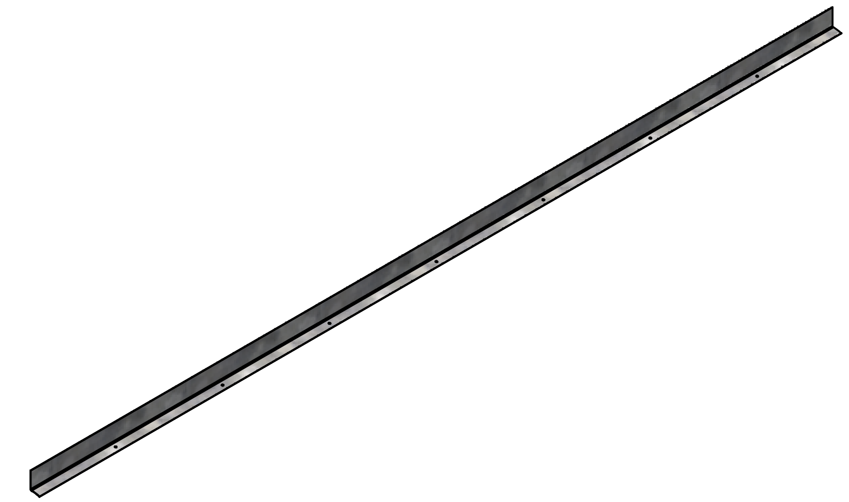


Mec E 460 Instructor: Dr. Nakashima Comments:	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MM TOLERANCES: ANGULAR: ± 0.5° LINEAR X = ± 0.5 X.X = ± 0.1 X.XX = ± 0.025 SURFACE FINISH µm 0.6 DO NOT SCALE DRAWING	Modeled by **Ben Hallworth** Drawn by **Kevin Zhong** Checked by **Robert Chauvet**	The Department of Mechanical Engineering UNIVERSITY OF ALBERTA TITLE: Internal Fin
MATERIAL: Galvanized Steel		Tuesday, April 13, 2021 9:04:08 PM Monday, April 12, 2021 1:48:10 PM	SIZE B — G1 Consulting — REV 1
FILE NAME: Internal Fin			SCALE: 5:1 — Mass: 222.57 g — SHEET 1 OF 1

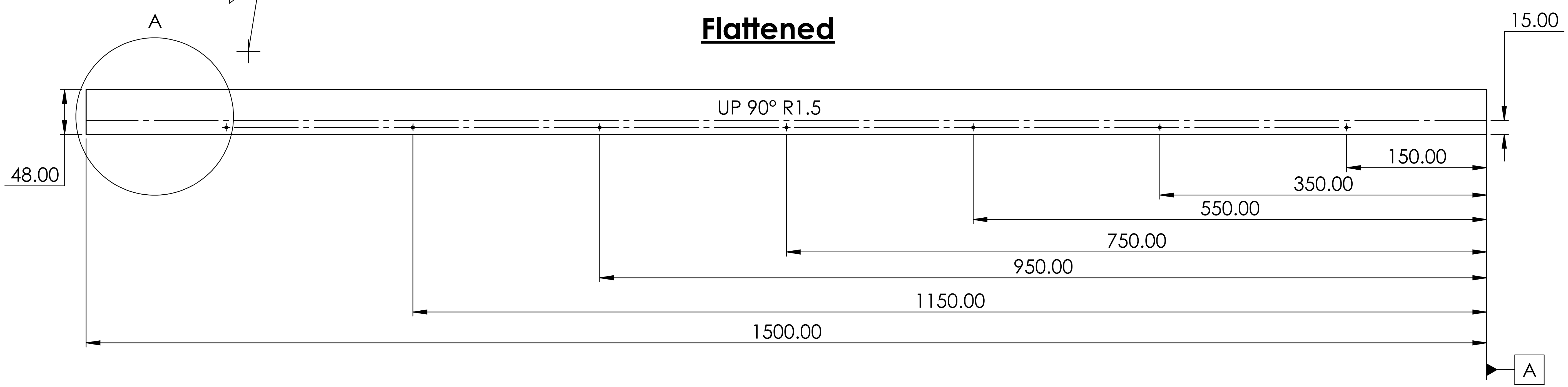
As-Bent

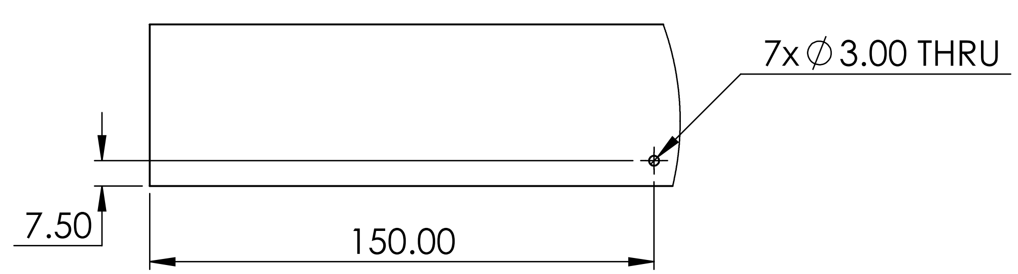


Bottom section may be bent in radius tighter than R52.8 (or even folded). Bolting this section to the chimney will naturally flatten the section to the chimney's out radius (52.8 mm). Sheet metal thickness is 0.5 mm.



Flattened





DETAIL A
SCALE 2 : 4.5

Mec E 460
Instructor: **Dr. Nakashima**
Comments:

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025
SURFACE FINISH µm 0.6
DO NOT SCALE DRAWING

Modeled by **Ben Hallworth**
Drawn by **Ben Hallworth**
Checked by **Robert Chauvet**

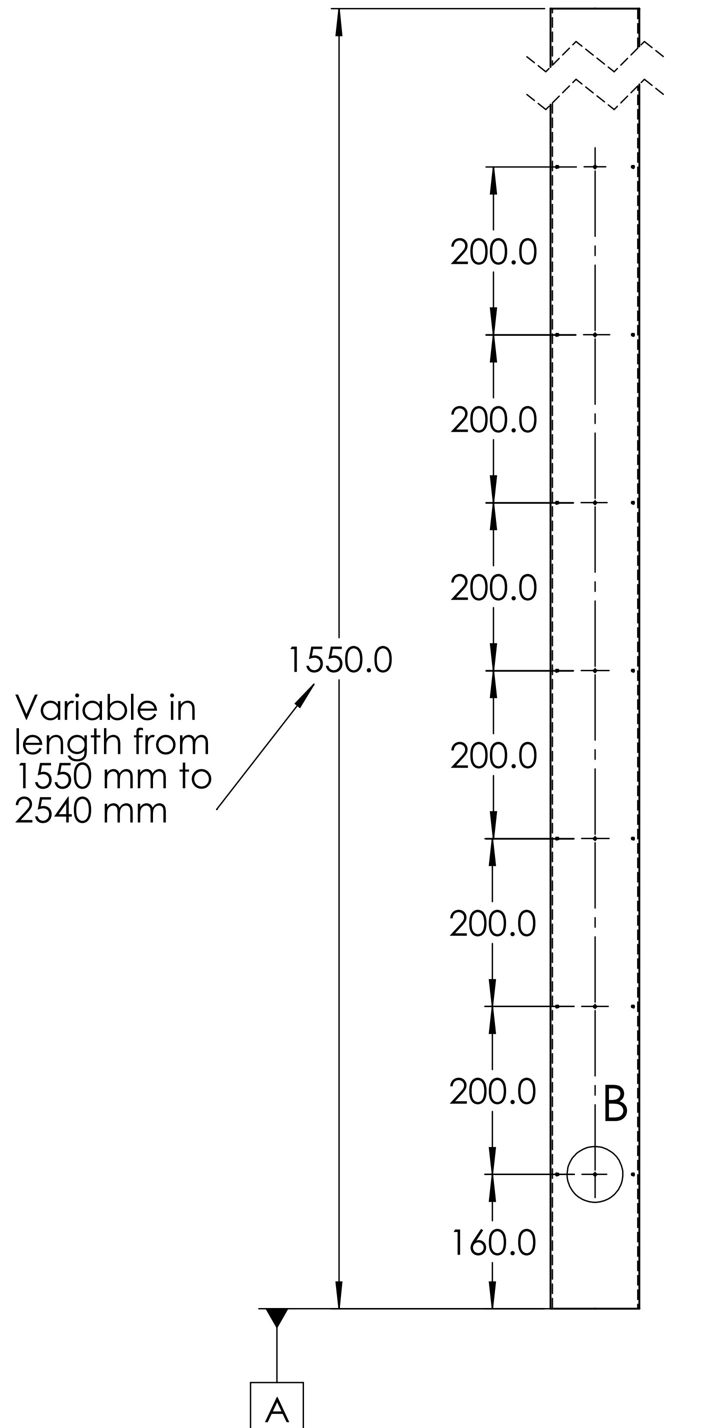
The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

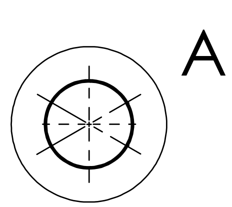
TITLE:
External Fin

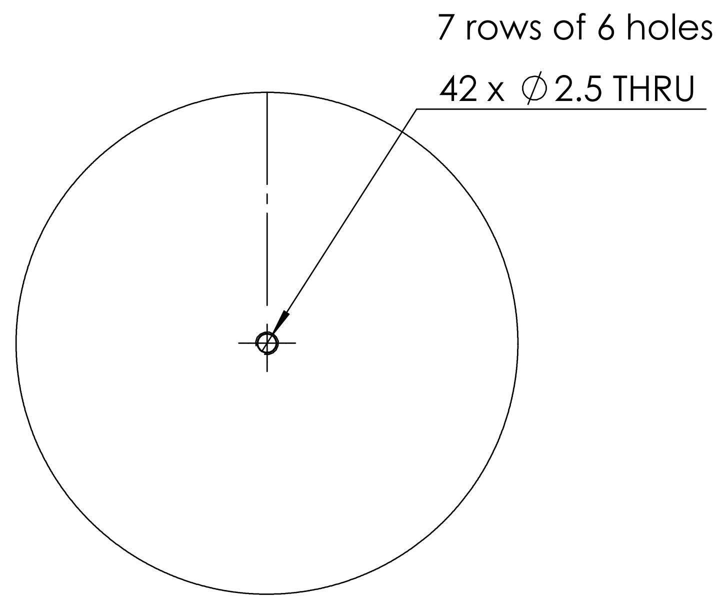
SIZE **B** | G1 Consulting | REV 1

MATERIAL: Galvanized Steel
FILE NAME: External Fin
Tuesday, April 13, 2021 10:25:43 PM
Monday, April 12, 2021 1:23:18 PM

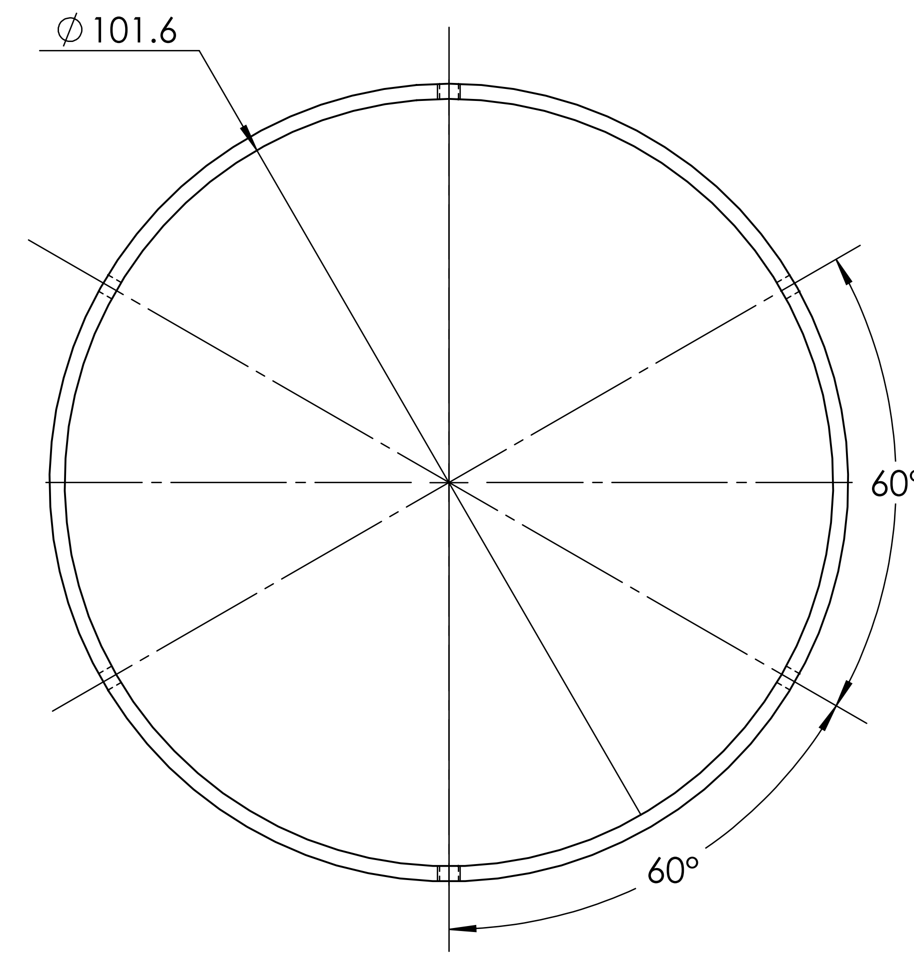
SCALE: 2.5:1 | Mass: 282.93 g | SHEET 1 OF 1



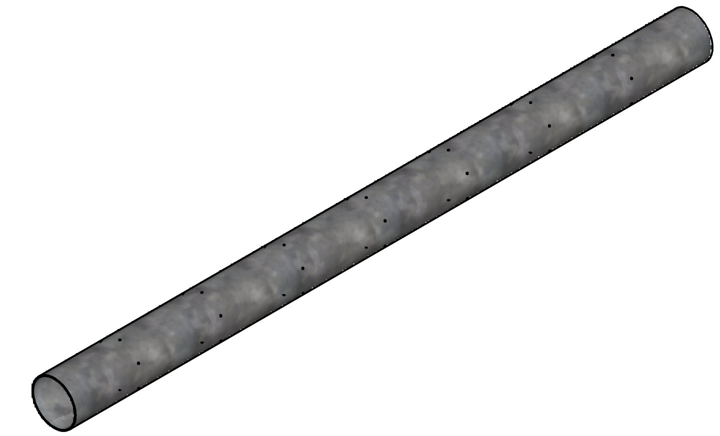




DETAIL B
SCALE 1 : 1



DETAIL A
SCALE 1 : 1



Tube thickness is 2 mm.

Mec E 460
Instructor: **Dr. Nakashima**
Comments: The tube itself is purchased without holes.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
ANGULAR: ± 0.5°
LINEAR
X = ± 0.5
X.X = ± 0.1
X.XX = ± 0.025
SURFACE FINISH µm 0.6
DO NOT SCALE DRAWING

Modeled by **Ben Hallworth**
Drawn by **Kevin Zhong**
Checked by **Robert Chauvet**

Tuesday, April 13, 2021 7:19:08 PM
Monday, April 12, 2021 11:30:31 AM

MATERIAL: Galvanized Steel
FILE NAME: Finned_Tube

The Department of Mechanical Engineering
UNIVERSITY OF ALBERTA

TITLE: Finned Tube

SIZE B | G1 Consulting | REV 1

SCALE: 1:9 | Mass: 7937.22 g | SHEET 1 OF 1