Cheaper, Faster, Lighter EcoZoom Rocket Stove

ME 493 Final Report - Year 2013

Sponsor:	EcoZoom
Team Members:	Peter Ballinger,
	David Morgan,
	Andrew Robinson
Assistant Member:	Laila Rahmatian
Academic Advisor:	Dr. Chien Wern
Industry Advisor:	Ben West, EcoZoom CEO

June 10, 2013

Executive Summary

A rocket stove uses an insulated chimney with fuel and air supply through a port low on the side, and by improved draft conditions and thermal efficiency, can save fuel and reduce emissions, which can lead to improved health, financial situation, security, and quality of life for people in the developing world who would otherwise cook over open fires.

EcoZoom produces a rocket stove consisting of a round metal shell with a fuel port in the side, and a central chimney exiting in the center of a pot supporting top plate. The chimney is insulated with solid ceramic, which weighs 4.5 kg and takes over a month to produce. Stoves are shipped from the manufacturer in China to Kenya fully assembled. EcoZoom's market could be expanded if a lower cost stove could be produced, by some combination of reducing materials, manufacturing, shipping and importation costs.

This project's goal was to design a rocket stove that can be sold for $10 US in Kenya. Options for materials and configuration of functional groups of the design were considered and selected based on previously developed product design specifications. The final concept consists of an external steel rod frame to support the weight of a pot, a non-structural cylindrical sheet metal body with packed vermiculite insulation between the chimney and outer shell, and a sheet metal flame directing cone to maintain heat transfer and low emissions. The basic geometry of the combustion chamber and under pot exhaust gap were left unchanged.

The primary benefit of the selected design is to remove load bearing from heat affected components, flat pack for shipping with easy assembly, and avoid the weight and production expense of solid ceramic, cast iron and iron-chrome-aluminum components. The estimated cost of production and shipping is $11, not including duties, taxes and other fees. 5 L boil test results were within targets, and although slower and less efficient than current models, significantly better than three stone fires. Emissions were similarly compromised but drastically better than open fires.

Many sources in the improved cookstove industry consider a $10 stove to either be impossible, or only possible using monolithic or drastically simplified all ceramic construction. This design does not disprove them, but it does prove that cost can be reduced greatly from some current production stoves.

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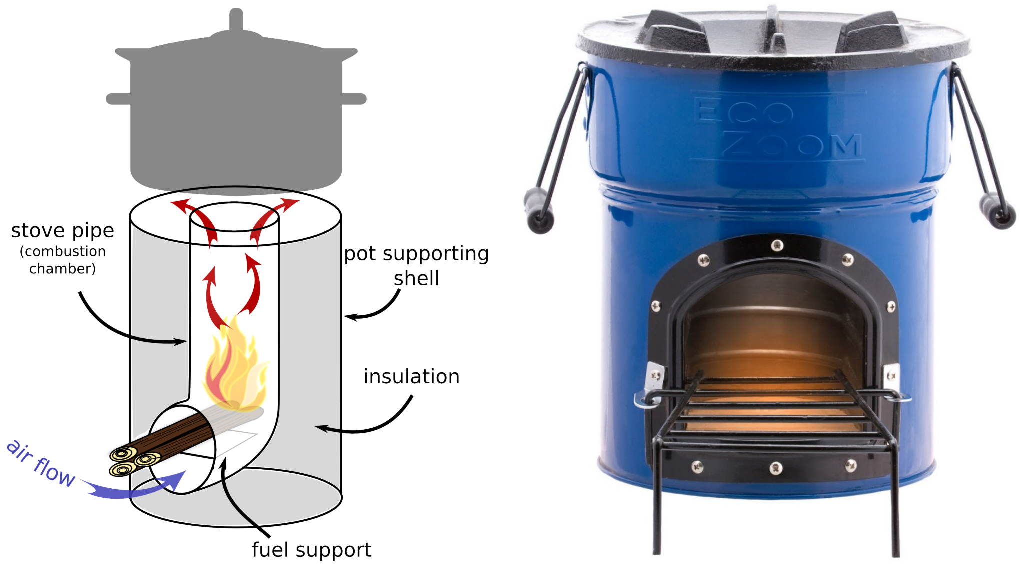
1 Introduction and background



(a) General rocket stove layout
image Creative Commons licensed

(b) EcoZoom Dura model stove
image © EcoZoom

Figure 1.1: General rocket stove principles include an insulated central combustion chamber and flue, with fuel and air intake low on the side, and tightly controlled channeling of exhaust under the pot. EcoZoom's Dura applies these principles well, but is overbuilt and thus too costly for the lowest market segment they wish to reach with improved cookstoves.

EcoZoom produces and distributes portable wood burning rocket stoves. Rocket stoves, invented in 1982 by Dr. Larry Winiarski of Aprovecho Research Center, can cook faster, use fuel more efficiently, and produce less carbon dioxide (CO_2), carbon monoxide (CO), and particulate matter (PM, or soot) than open fires. The typical wood-fuel savings is around 40% compared to a three-stone open fire. Soot and CO emissions of rocket stoves vary widely, with some designs even producing more of either or both than three stone fires.

These fuel and time savings are significant to people in the developing world. They often spend 25% of their household income, or around 5 hours a day, buying or gathering fuel for cooking, water purification, and heating. Lower emissions and fuel consumption can be beneficial to the user's health, security, economic situation, and the environment at large.

Four million deaths annually are attributed to respiratory disease caused by indoor air pollution from cooking fires. Gathering or buying wood often jeopardizes the educational and economic opportunities of cooks, often disproportionately women and girls, and can even present threats to their personal safety. Climate change is accelerated both by deforestation by fuel gatherers, and the CO_2 and PM produced when the fuel is burned.

With a UN goal of 100 million stoves adopted by current open fire users[1] by 2020, EcoZoom sees a market for a low cost, rapid production, easily shipped stove. Their current model, the Dura, shown in Figure 1.1b, is too expensive for their target market, extremely slow to produce, and comparatively heavy and bulky to ship.

We were tasked with designing a stove that solves these pricing and logistic problems, very likely at the expense of some performance, adaptability, and particularly durability when compared with their current line and competitors.

The design presented here significantly reduces cost, to an estimated $11.00 for materials, labor, and freight, reduces shipping mass by 70%, and cuts production time to likely well under an hour.

2 Mission Statement

The team worked to develop, prototype, and test a less expensive rocket stove, as compared to the company's current models. This more affordable stove could have tradeoffs of reduced performance and service life. The design was to allow a simple assembly process, requiring only the use of tools available in Nairobi, Kenya. Component manufacturing was planned to remain in China at the Shengzhou Stove manufacture facility. All information and designs will be shared with EcoZoom.

[1] There are an estimated 3 billion people without access to advanced energy sources, a large majority of whom cook on open fires.

3 Main Design Requirements

A summary of main product design specification requirements is listed below. Two significant changes from earlier versions of the PDS are the removal of 'rigidly mounted handles' as a requirement, on the basis of EcoZoom's contentment with current bail and grip handles currently in use, and the inclusion of welding capacity in Nairobi, as EcoZoom is in the midst of setting up a manufacturing and assembly plant there. Additionally, an error in the shipping volume target has been corrected.

- End cost: 10 USD or less
- Shipping Volume: 21 L or less
- Shipping mass: 7 kg maximum
- Ability to boil 5 L of water:
  - within 33 minutes
  - using 850 g or less of wood
  - producing less than 20.4 g of CO
- Use current manufacturing plant in China
- Simple assembly, possible at EcoZoom's Nairobi Kenya facility with just hand tools and a MIG welder.
- Support 41 kg filled cooking pot
- Service life: 2 years or more
- Replaceable fire chamber

4 Top-Level Conceptual Solutions

After research into the current state of the art in rocket stove design the time came to choose a design for a prototype stove. Initial concepts for a prototype included the following:

- A stove made exclusively from ceramic/clay material. (Ceramic Stove)
- A stove that kept many of the current EcoZoom components only changing the outer shell and insulation material.(Hexagonal Stove)
- A stove that changed the insulation cross-section, the housing and chimney materials, and supported the pot with a "wire" leg.

The concept of the fully ceramic stove is not a new one. Asian cultures have used a similar type of stove (for charcoal burning) for hundreds of years. However, EcoZoom stated in a concept review meeting that their target market was biased against clay and ceramic to the point it would pose a severe marketing problem. Thus, this concept was not pursued further.

The second solution was also not feasible. This prototype design continued to include both the original chimney assembly and the cast iron top of the original EcoZoom stove. In order to meet the PDS requirement of low cost the material and manufacturing costs of these two particular parts needed to be eliminated from a prototype design. Again, this concept was not pursued further.

The final concept called for re-evaluation of all of the major components of the rocket stove. It was found that the best solution was a stove body made from sheet metal, with a simple steel rod support structure. This separated structural elements from containment and insulation elements, and also moved most of the structural elements away from high heat or combustion product exposure. It also allowed for simple hand assembly of the sheet components with tabs and slots, which would not be secure enough fastening for structural sheet components, particularly given thermal expansion issues.

As a further cost saving measure, the inner FeCrAl liner was replaced with 304 stainless, and the liner construction was simplified from three spot welded parts to two tab-fastened parts, which also incorporated the door frame and stick support eyelets. A stainless cone replaced the heavy and expensive cast iron top in the first prototype, and was replaced with a mild steel cone in the second prototypes.

Outside diameter of the stove was reduced while the internal chimney diameter and height were left unchanged. The motivation in reducing diameter was to reduce sheet metal requirements. Two options were available toward this end; either reducing overall height, or diameter. Computational fluid dynamics work presented at ETHOS 2013[4] found that insulation was a relatively minor factor on performance, compared to pot gap and flame temperature, while other work has shown combustion path length is critical to complete combustion and therefore emissions. Thus, the decision was to reduce diameter.

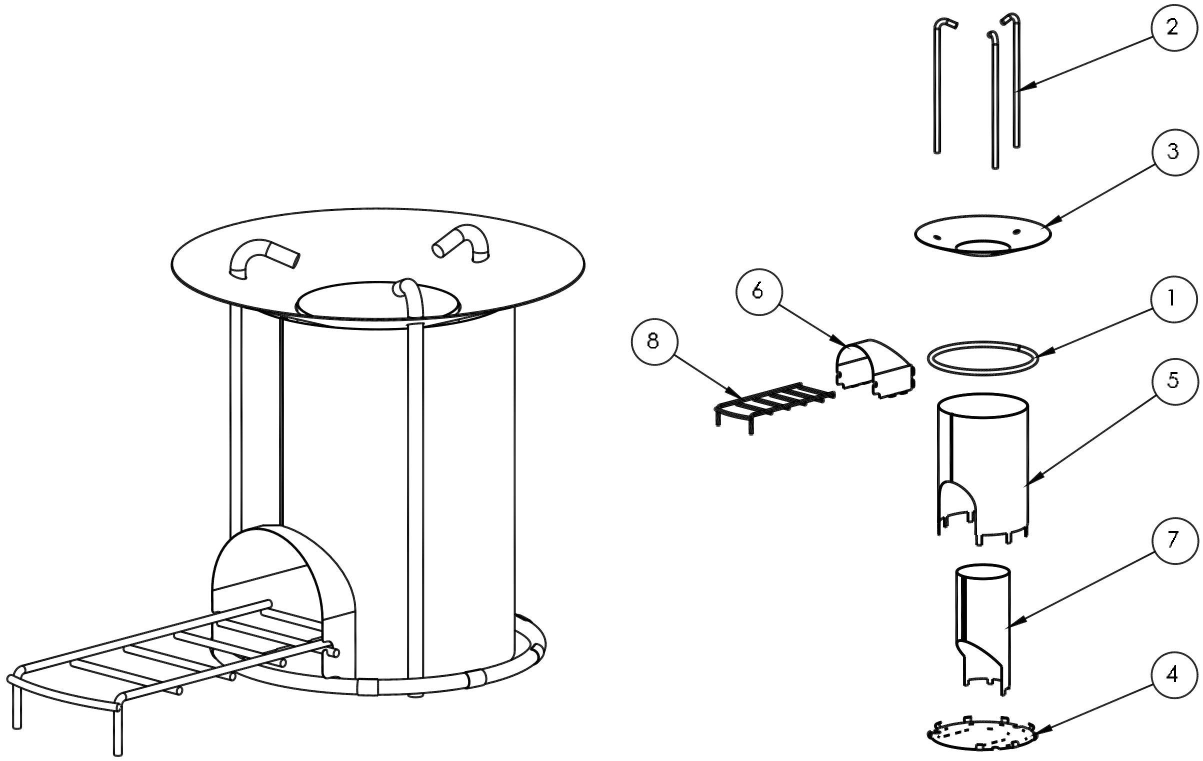
5 Final Design

The final design, shown in Figs. 5.1a and 5.1b, uses five sheet metal parts to contain and direct combustion gases and enclose the insulation, a four-part welded frame to support the pot, a welded wire stick support to properly locate the burning fuel, and loose vermiculite insulation.

5.1 Design Overview

Tab and slot construction is used. During assembly the tabs are folded over once they are inserted through the slots. The thinness of the sheet metal (28 gauge, 0.015 in), less than ideal joint strength of tab and slot construction, and the anticipated loss of material properties all necessitated separating the insulating and structural elements of the stove. As seen in Fig. 5.1, three legs welded to a ring at the bottom of the stove carry the load of the pot. This external structural frame is entirely 0.375 in diameter rod, composed of four pieces joined by three fillet welds.

Other than the welded rod framework and stick support the stove can be assembled with hand tools, specifically three types of pliers: long needle nose, duckbilled, and channel lock types.



(a) (b)

Figure 5.1: The final stove design. 5.1a: Stove design with four part rod structural frame, insulated sheet metal firebox and flame director, and welded wire stick support. 5.1b: Expanded view showing: 1) structural frame base ring, 2) structural frame legs, 3) fire director, 4) base plate, 5) insulation shell, 6) fuel door tunnel, 7) chimney, 8) stick support. Loose insulation between chimney and insulation shell is not shown.

5.2 Design Feature Benefits

The primary benefits of the stove are reduced cost through: reduced shipping weight and volume, and reduced manufacturing time and cost.

The stove can be shipped either entirely flat packed, to be assembled closer to the end users at a facility with the capability to do simple welding, or alternatively it can be shipped with the welded components tightly nested, such that final assembly can be done with simple hand tools only.

5.2.1 For EcoZoom/Partners

The economic benefits of this design include a drastic savings on shipping volume by having the ability to be flat packed. Also, the ability to nest welded assemblies and hand assemble in even more remote locations allows condensed shipping for easier distribution of stoves in remote areas.

5.2.2 For Cooks

Preliminary boiling test results show a fuel savings of 44% over a three stone fire, and a 20% time savings. Beyond the lower initial cost, the tabbed design allows for replacement of the chimney and floor, so the stove's service life could perhaps be extended at lower cost than full replacement.

6 Evaluation

The design meets most requirements, with two main issues. The $11 cost of production rules out any chance of a $10 retail price, and whether the sheet metal can actually give a two year service life is ultimately unknown without more extensive testing. Cooking performance and safety are acceptable.

6.1 Cost

At $11 for materials, labor, and shipping, the design is less costly than current EcoZoom designs, but still does not meet the industry-wide "holy-grail" target of a $10 retail stove. (There is no such stove on the market at present. The lowest retail price we have discovered is $16.75 for the uninsulated and skirtless Ezy Stove.) At both ETHOS 2013[1], a technical conference on improved cookstoves, and in conversation with industry experts there, EcoZoom executives included, all have considered a $10 stove target difficult with any material. Some, including Dean Still, an expert on rocket stove emissions who leads the test lab at Aprovecho and who is recognized throughout the industry as one of the top rocket stove experts, consider it impossible using any metal at all. Since only metal and ceramic can withstand the high temperatures and corrosive environments wood burning cookstoves experience, this may rule out anything but an all ceramic stove as a solution to the $10 industry goal.

It's worth noting that the current design, by nature of its flat pack or nested shipping, and the ability to import as parts rather than finished goods, reduces shipping and duties into the East African Trade Zone by roughly half over existing EcoZoom stoves. This shipping advantage could be useful in other applications as well. If shipped with assembled but nested frame-and-fire director assemblies the stove can be assembled at the end of the shipping pipeline with nothing more than an assortment of pliers.

6.2 Reliability

Whether the design will meet the two year service life requirement is uncertain without longer term testing. The rod frame and stick support are not doubted: the frame is heavy, and the end exposed to the coolest part of the combustion products can function with a great deal of material lost to corrosion, while the stick support is not functionally different from those giving satisfactory service in current EcoZoom stoves.

The sheet components though, particularly the low carbon components exposed directly to combustion products or coals, are much less certain. Since few to no industrial processes burn wood any more, the most applicable data for degradation of sheet metal we found was data for thickness loss in steel trash incinerator walls.[3] At the temperatures measured during testing this data predicts a monthly thickness loss of 0.8 mil, translating to an average of 18.75 months before holes form in 28 ga (0.015 in) metal.

However, a trash incinerator has a number of corrosion mechanisms that a plain wood fire should not: sulfate and salt deposit problems that prevent passivation, higher moisture content, and a wider variety of halides and hydrocarbons that all accelerate corrosion and metal loss. Given the milder environment, the hope is that metal loss would be slower. Ultimately, this question can only be answered with more extensive testing though.

One specific problem area is the combustion chamber floor. During cooking it tends to collect a bed of coals, and invariably has coating of ash left afterwards. The coals expose it to high heat, the highest of anywhere on the stove, and the ash promotes ash-deposit corrosion. The coal bed would degrade even stainless, so changing to the more expensive metal would be a questionable solution, but a ceramic tile floor insert, even a thin one, would shield it from the carburizing atmosphere and much of the ash deposit. Whether this specific use of ceramic would cause a marketing problem is unknown.

6.3 Performance and Emissions

Time and budget constraints only allowed the first prototype to be tested according to international standard, at Aprovecho Research Center, and with a truncated test plan consisting of one cold start 5 L boil test, and one simmer test, rather than three replicates of a cold start boil test, hot start boil test, and simmer test, as called for in the standard. This was agreed to be enough of an indicator of performance for EcoZoom's satisfaction.

The stove performed within specifications on all but one metric: CO emissions were high, 24.4 g rather than 20.4 g. Complete results are shown in Table 6.1. Dean Still, blamed this on the solid 304 stainless sheet stick support used for the first prototype. (Dean Still, Conversation, May 4, 2013) His experience has shown that solid stick supports conduct heat back along the fuel tunnel and radiate back to the sticks, such that a longer length of fuel ignites than is desirable. In this case fuel ignited even before it entered the combustion chamber. The effect of this is improper fuel metering, so that while the fire is hotter and cooking time is reduced, more combustion products are released than can be burned given the air supply and chimney length. Much like a rich fuel mixture in an engine, this causes unburned or incompletely burned products in the exhaust. Experimentally the high CO levels support this argument, as a sign of a rich fuel mix. (Excess fuel to air mix would tend to favor formation of oxygen depleted CO over CO_2.)

Particulate matter levels were also high, but within spec, and observable as copious amounts of black smoke during the test.

The second prototype was tested in less controlled conditions, using the 5 mm wire stick support shown in Fig. 5.1. Emissions were not measured, only time to boil and fuel use. As predicted, the wire stick support prevented early fuel ignition. No black smoke was observed at any time after initial light-

Table 6.1: Results of first prototype tested at Approvecho Research Center

Criteria	Result	Target	Target Met
Fuel	675.5 g	< 850 g	✓
CO	24.4 g	< 20.4 g	✗
PM	704.7 mg	< 980 mg	✓
Time	22.3 min	< 33 min	✓

ing, and boiling required 30.5 min and 697 g of fuel, consistent with a cleaner burn at a lower power, thanks to proper fuel metering. While not quantitative evidence, this tends to support the notion that particulate and CO emissions were lowered. Since the combustion chamber geometry is insignificantly changed from that of the EcoZoom production stoves, a large deviation from their published CO emission of 17 g, such as the 24.4 g of the initial test, would be surprising. Some loss of performance is expected with the lower thermal efficiency reduced insulation entails, but 24.4 g of the first prototype can likely be considered an anomaly of the now rectified fuel metering problem.

Full results of the first prototype's test are included on the accompanying CD.

6.4 Safety

Four PDS items reflect the immediate user safety of the stove, rather than long term emissions exposure safety: the temperature of the handles and shell in use, the stove's resistance to tipping, and the ability to support the load of the cookpot and its contents. Additionally, draft standards for rating cookstove safety came to our attention after the PDS had been developed.

6.4.1 Shell Temperature

Temperatures were measured on the outer shell of the stove operating at high power with an external thermocouple probe. The highest shell temperature recorded was 153 °F. This is above the PDS limit of 140 °F, but close enough it was tested directly by holding the back of a hand against the shell and timing. 800 ms of intential contact was required before pain was felt, well within reaction time to break contact, and no continuing pain or injury occurred. Given the origin of the PDS target, a similar test immersing a hand in a pan of hot water (which has far better heat transfer than a dry metal surface) we consider the requirement of touch safety satisfied for the shell.

6.4.2 Handle Temperature

Since the design specifies the current production handles, and they insulate the grip very well, the prototypes were built without handles. It is assumed that they will function as well for the new design as the old.

6.4.3 Tipping Safety

Tipping resistance was tested by pushing the stove sideways at its highest point and noting the angle from vertical required for the stove to continue tipping on its own. This required the edge to fire director edge to pass over the opposite side of the base, a full 43° from vertical, earning the “Best” rating for tipping safety in the ISO improved cookstove safety standards.

6.4.4 ISO Cookstove IWA Safety Rating

Tests were also carried out in accordance with the February 2012 International Workshop Agreement’s draft ISO cookstove standard[2] safety section. Temperature tests deviated from procedure, but are believed to have given the same results. The standard tests snag risk, tipping risk, fire and heat containment. Details of the standard tests and results are in Appendix C.3.

The stove rates 80.5/100 on the unofficial tests performed, equating to a Tier 2 (of possible 4) rating.

7 Conclusions and Recommendations

This design process confirms, or at least fails to disprove that a $10 retail priced stove with a lifespan of two years or more may not be possible other than by using little or no metal, and primarily ceramic. It may not be possible even then. This is a widely held belief in the improved cookstove industry, particularly that of Dean Still. Our design is expected to meet its 2 year minimum, but at best in a limping-across-the finish-line way, and the service life predictions leave much uncertain. Adding a ceramic tile floor liner would greatly improve the reliability, but at the expense of increased cost and potential marketing difficulties.

Benefits of the design are savings on manufacturing and importing to Kenya, and production is faster and assembly local to Kenya. This design also allows the replacement of the firebox if needed.

Further refinements that could perhaps be incorporated in production would be a rolled or folded edge on the fire director and the exposed fuel tunnel, and better sealing of the chimney-fire director interface, since this is the only point currently prone to insulation leakage.

A more drastic change would be the replacement of the flat fire director with a stamped part formed to the same equal flux-area surface as the cast iron top on current stoves. This would alter packing slightly, requiring nesting of these components, but might improve efficiency. Also worth considering is a meechanically pinched point on the pot support rods, to create a flare on the rods that would set the fire director height correctly relative to the pot supports.

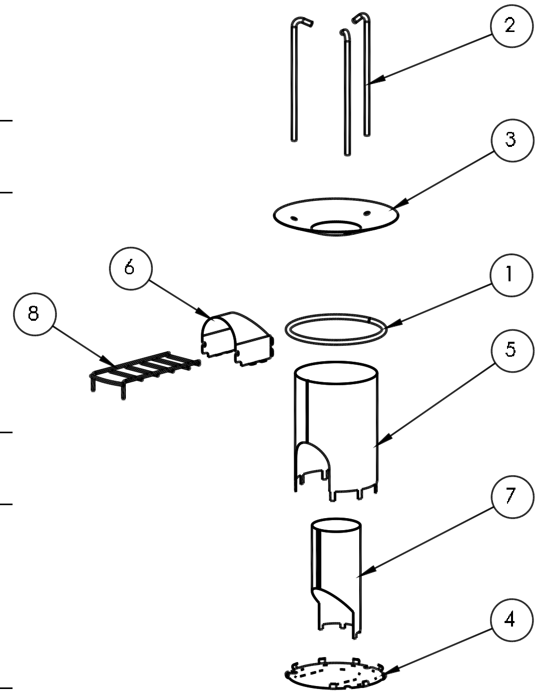
Further cost savings might be possible in exchange for slightly worse emissions: experiments with reduced chimney height and insulation thickness could possibly determine a better price/performance balance than the current stove. Computational fluid dynamics work mentioned previously only predicts efficiency currently, so experiments would still be required to understand emissions in this process.

Ultimately, while the industry cost target has yet to be achieved, and the reliability is not certain, this design does prove that weight, cost, and manufacturing time can be reduced if reasonable tradeoffs are made.

A Manufacturing Details

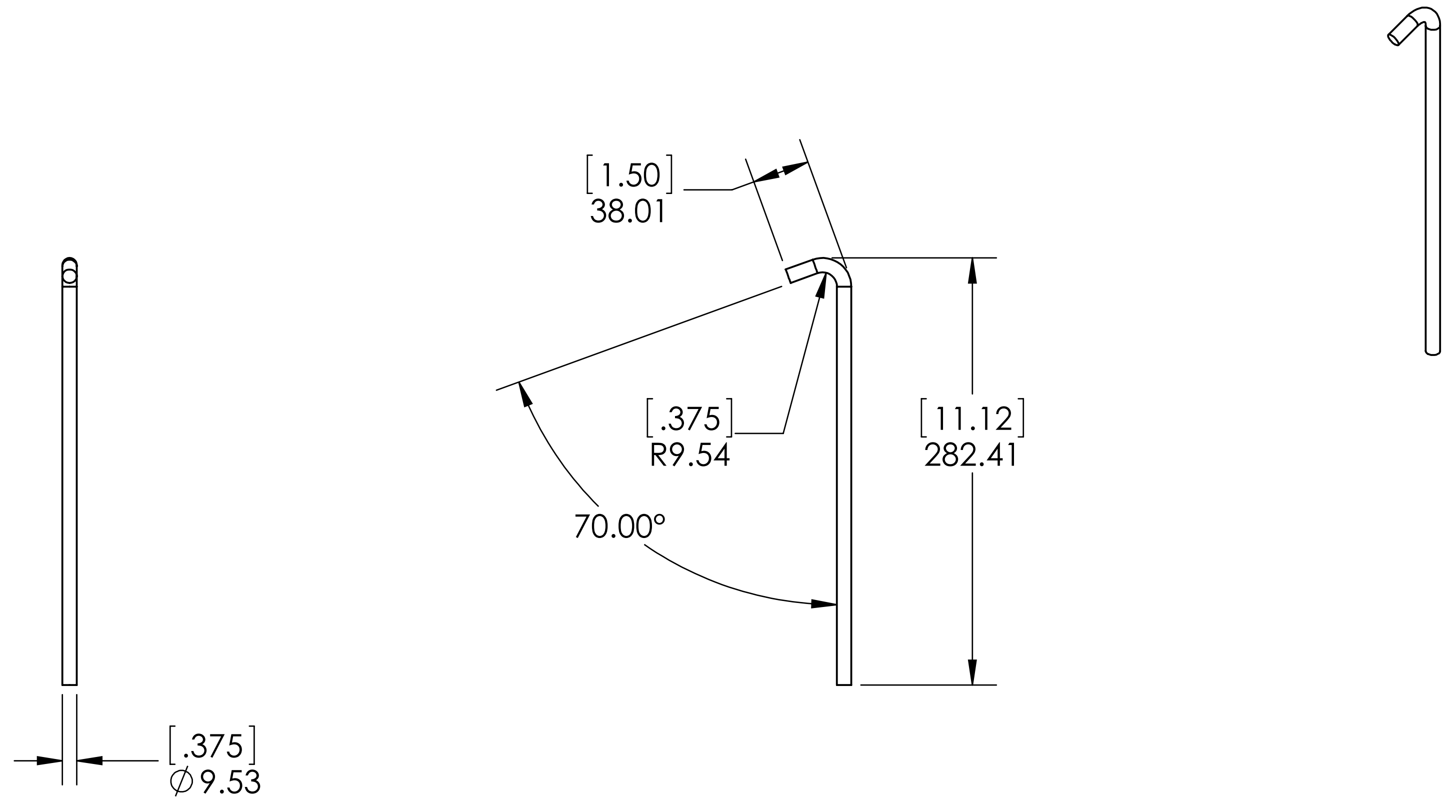
A.1 Bill of Materials

Ref. No.	Name	Req'd.	Price
1	Ring	1	
2	Rod	3	
8	Stick Support	1	
	All rod parts	1	$2.54
3	Fire Director	1	
4	Base Plate	1	
5	Outer Shell	1	
6	Tunnel	1	
-	All 1008 sheet parts	1	$3.51
7	Chimney	1	$1.48
-	Handle Assembly	2	$0.25
-	Vermiculite	1	$0.15
-	Labor	-	$1.62
-	Total	-	$9.80



A.2 Production Drawings

Following are manufacturing drawings for all new components.



NOTES:
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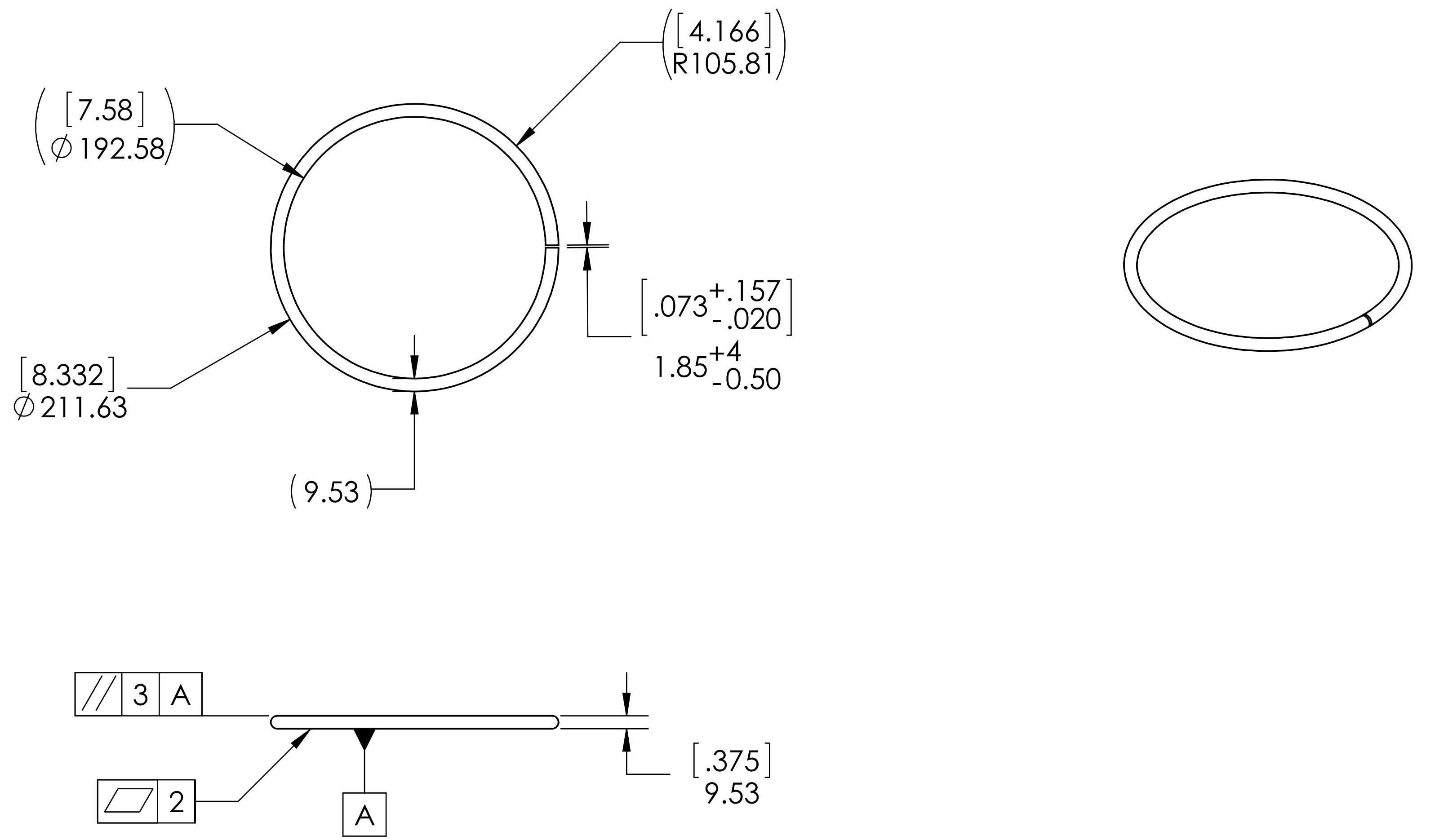

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TITLE:

RING, WELDMENT ASSEMBLY

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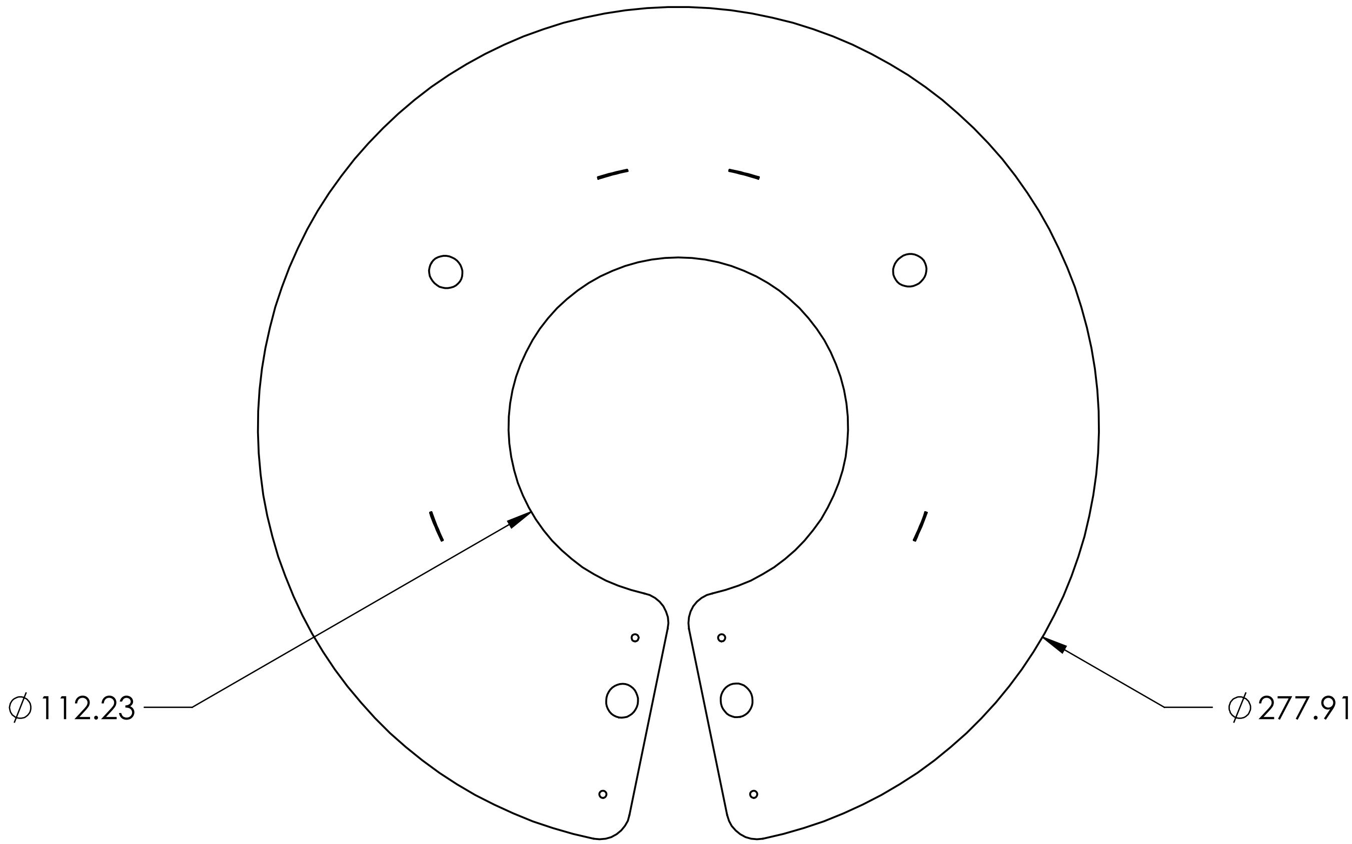

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TITLE:

STOVE FIRE DIRECTOR

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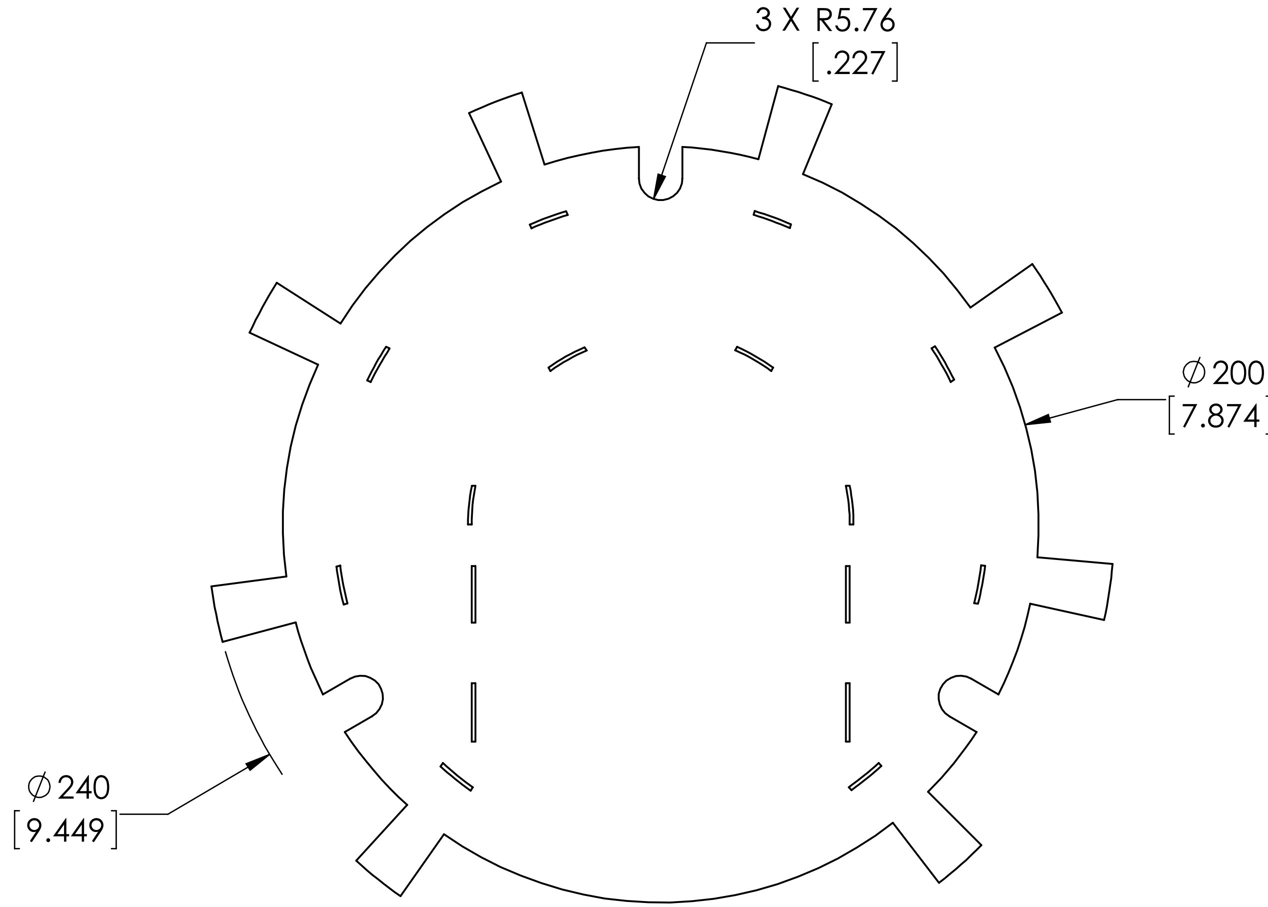

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STOVE BASE PLATE

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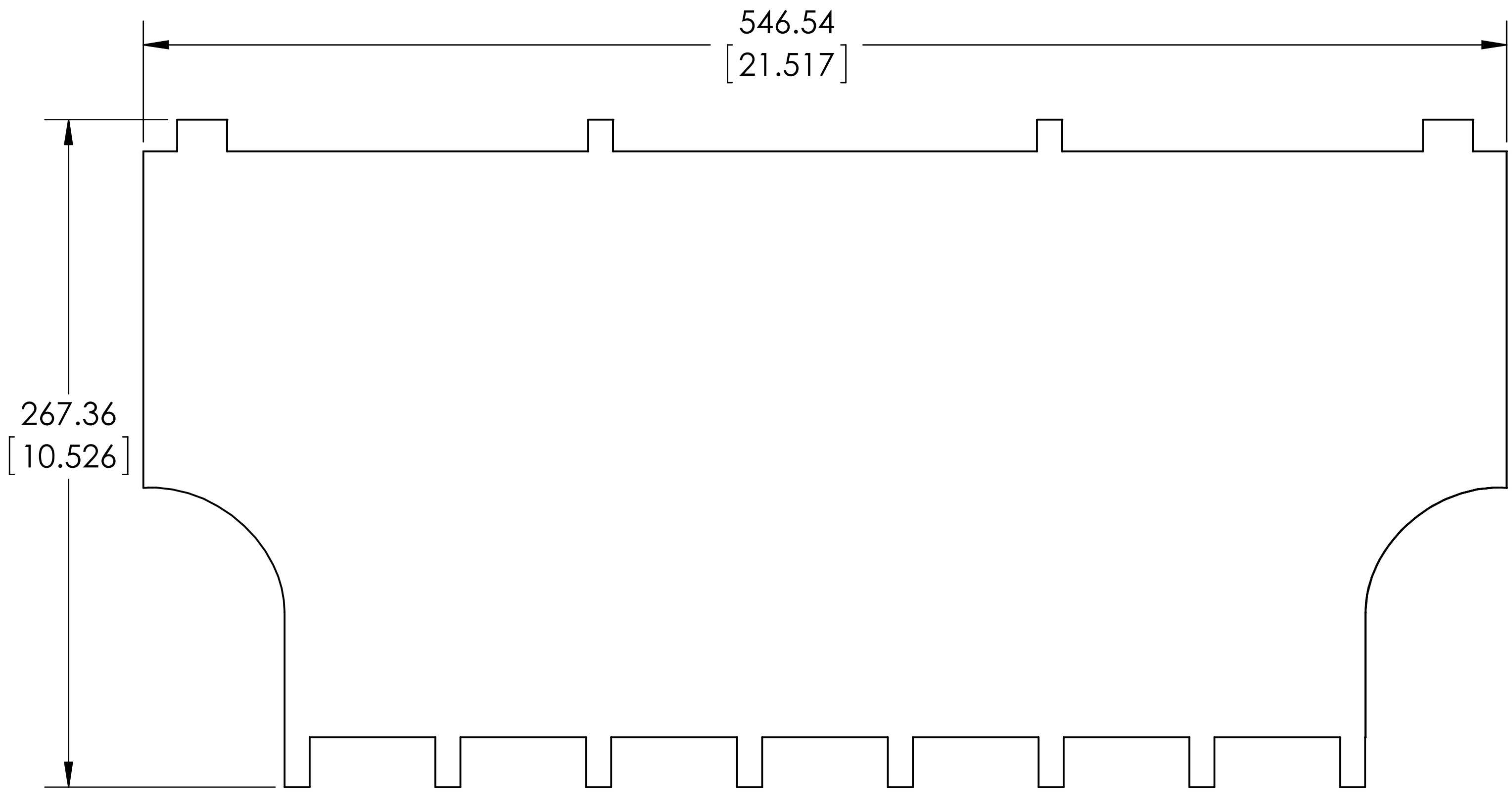

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	MFG APPR.			
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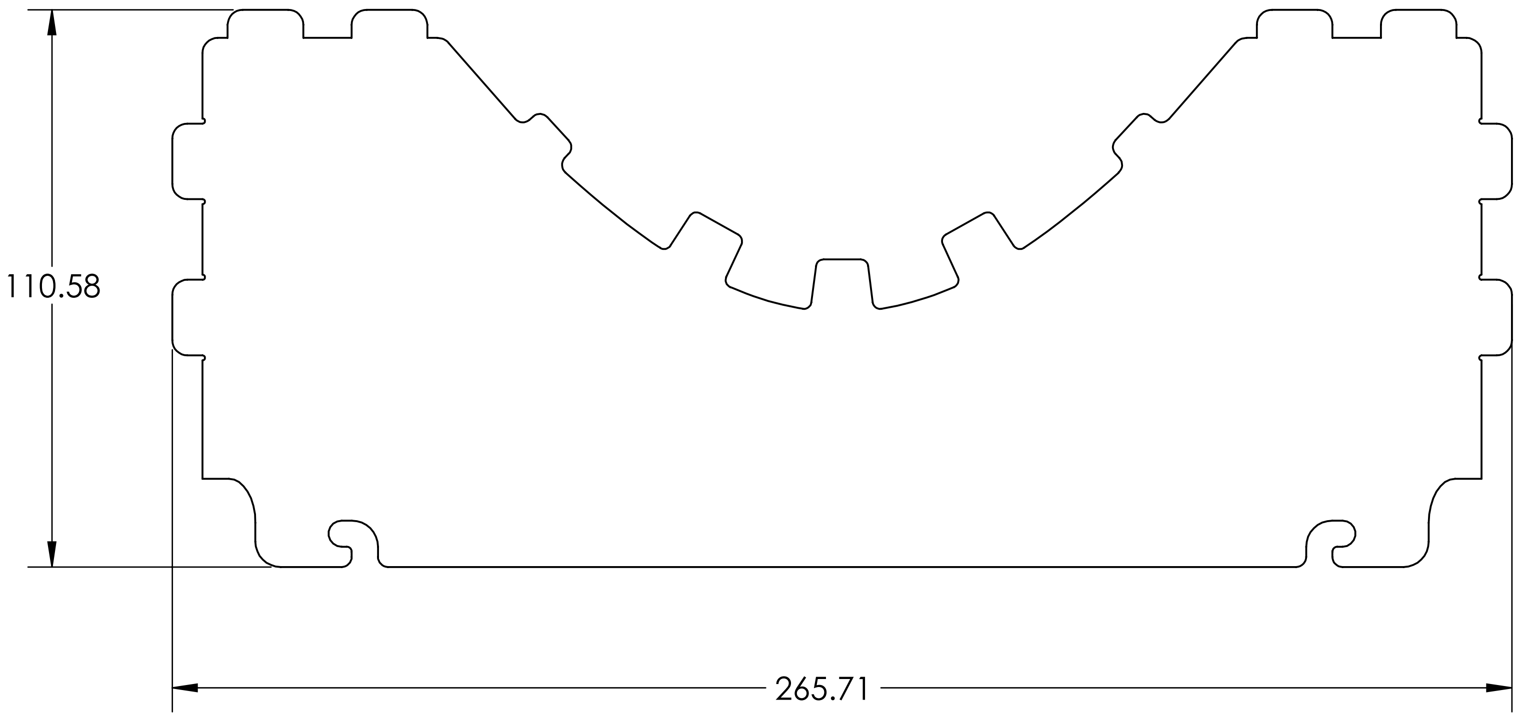

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STOVE TUNNEL

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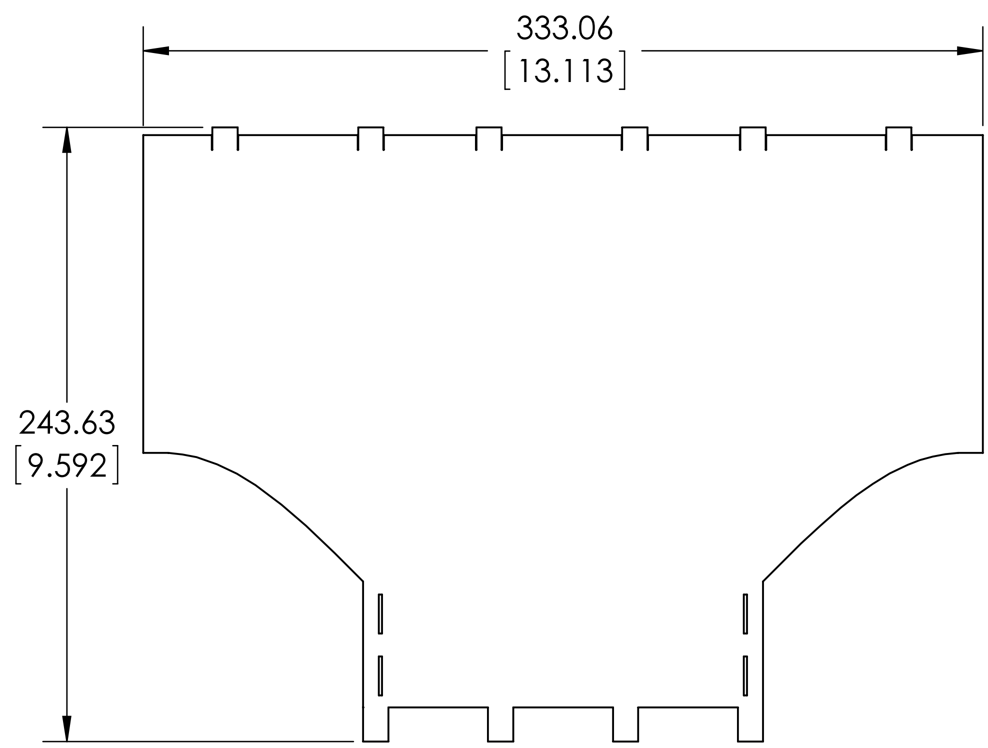

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INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
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TITLE:

STOVE CHIMNEY

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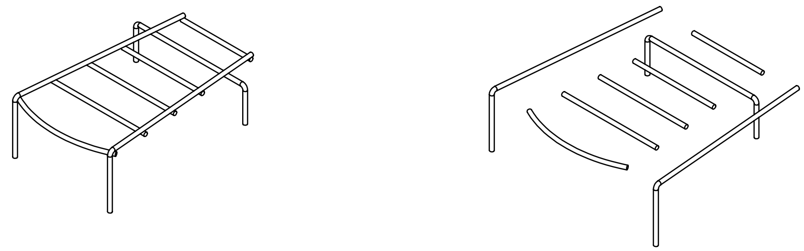
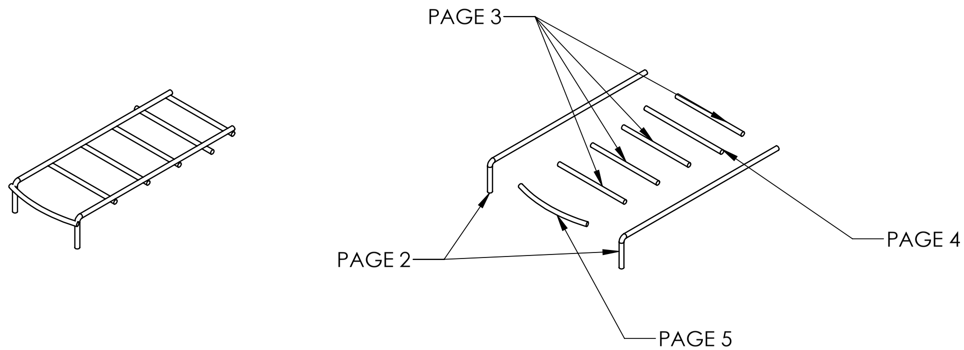
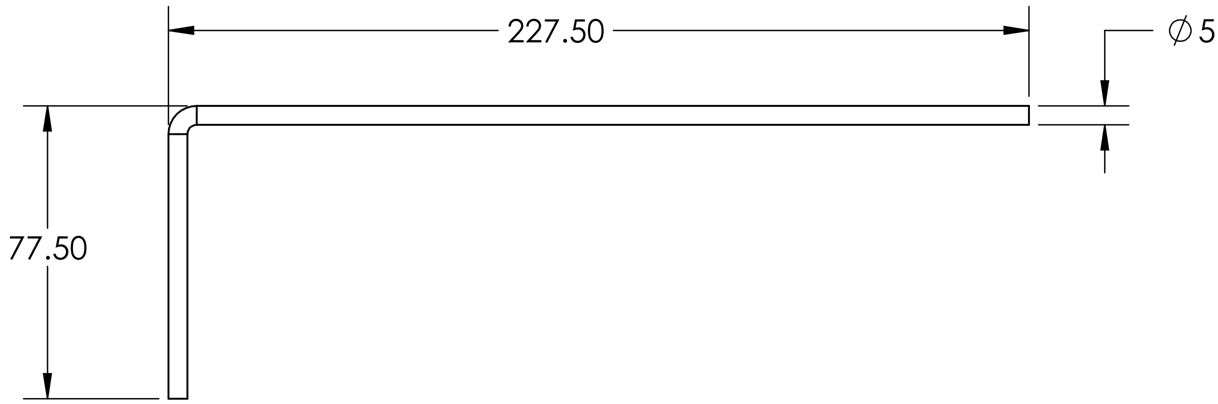


THIS IS THE CURRENT FUEL SUPPORT. IT HAS DIFFERENT LENGTHS
FOR EACH RACK PART.

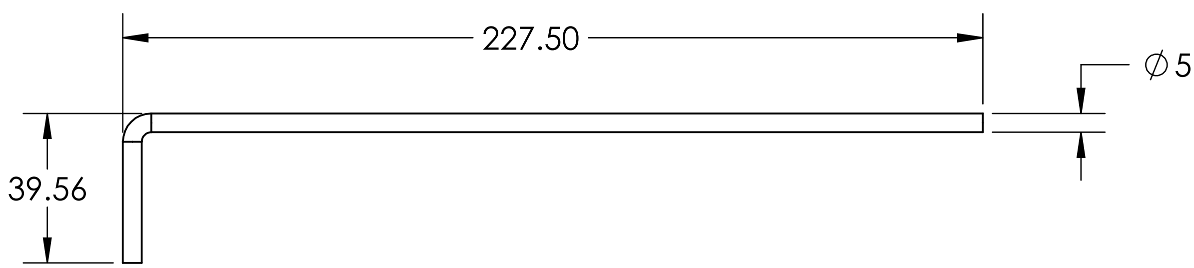


THIS IS THE PROPOSED NEW FUEL SUPPORT. IT HAS PARTS AS OUTLINED IN THE FOLLOWING PAGES

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN MM TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN			TITLE:
	CHECKED			STICK SUPPORT
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE B DWG. NO. Support Assembly REV
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:5 WEIGHT: SHEET 1 OF 5

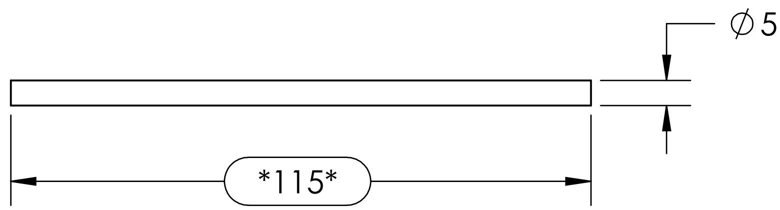


CURRENT SIDE PIECE

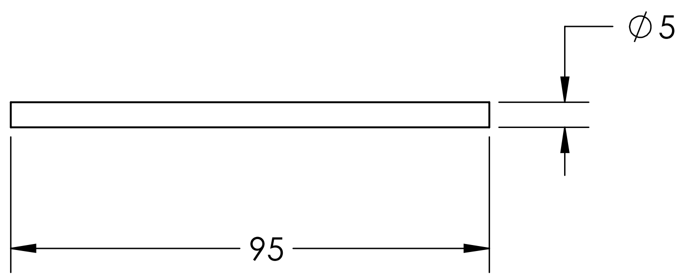


NEW SIDE PIECE

		NAME	DATE	
DIMENSIONS ARE IN MM TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN			
	CHECKED			STICK SUPPORT - ROD 2
	ENG APPR.			
	MFG APPR.			
MATERIAL 5MM MILD STEEL ROD	Q.A.			
FINISH	COMMENTS:			SIZE A DWG. NO. Support Assembly REV.
DO NOT SCALE DRAWING				SCALE:1:2 WEIGHT: SHEET 2 OF 5

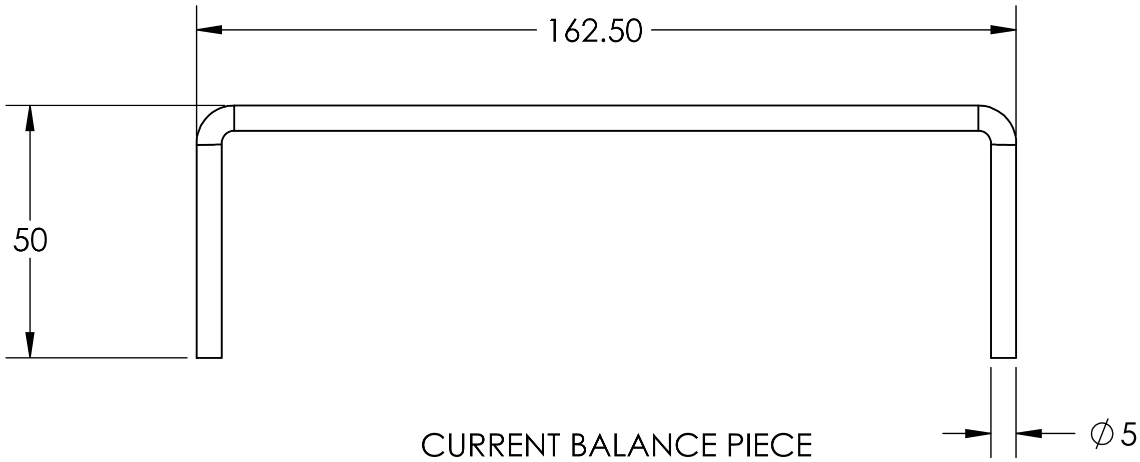


CURRENT RACK PIECE.
RANGES IN LENGTH FROM 100MM TO 135MM

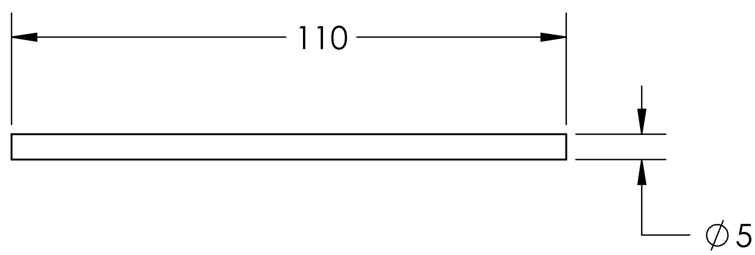


NEW RACK PIECE

DIMENSIONS ARE IN MM TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±		NAME	DATE	
	DRAWN			
	CHECKED			STICK SUPPORT - ROD 5
	ENG APPR.			
	MFG APPR.			
MATERIAL 5MM MILD STEEL ROD	Q.A.			
FINISH	COMMENTS:			SIZE A DWG. NO. Support Assembly REV.
DO NOT SCALE DRAWING				SCALE:2:3 WEIGHT: SHEET 3 OF 5



CURRENT BALANCE PIECE
HAS BENT SECTION TO CATCH EYELETS
ON THE FRONT OF THE STOVE



NEW BALANCE PIECE
REMOVES THE BENT SECTION

DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL
5MM MILD STEEL ROD

FINISH

DO NOT SCALE DRAWING

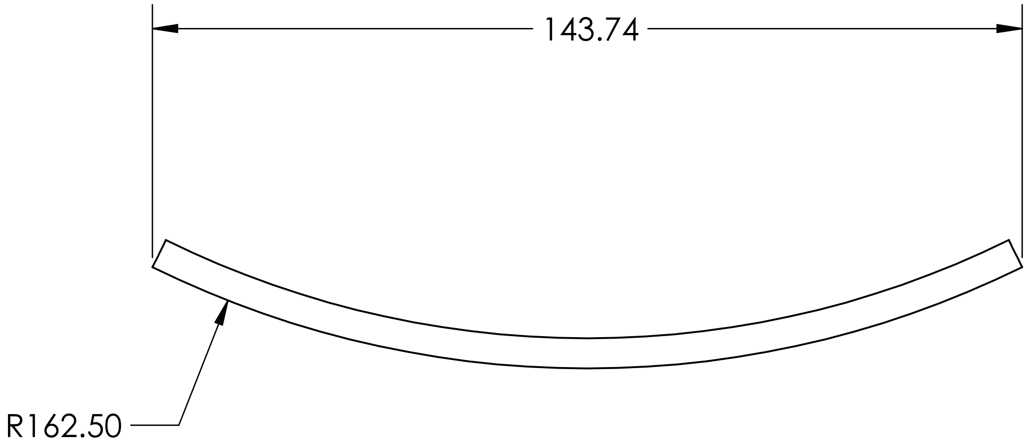
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

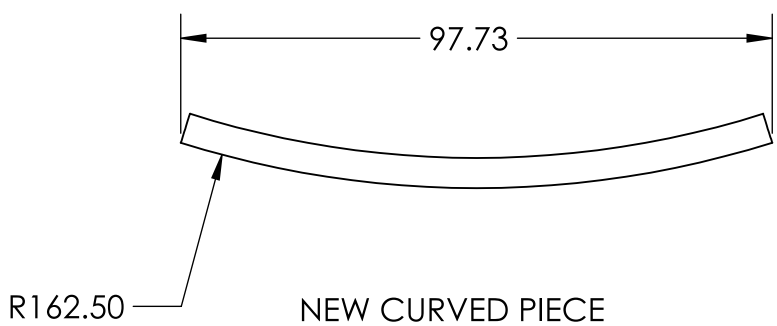
STICK SUPPORT - ROD 1

SIZE A DWG. NO. Support Assembly REV.

SCALE:2:3 WEIGHT: SHEET 4 OF 5



CURRENT CURVED PIECE



NEW CURVED PIECE
MUCH SHORTER

DIMENSIONS ARE IN MM TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±		NAME	DATE	
	DRAWN			
	CHECKED			STICK SUPPORT - ROD 7
	ENG APPR.			
	MFG APPR.			
MATERIAL 5MM MILD STEEL ROD	Q.A.			
FINISH	COMMENTS:			SIZE A DWG. NO. Support Assembly REV.
DO NOT SCALE DRAWING				SCALE:4:5 WEIGHT: SHEET 5 OF 5

A.3 Assembly Methods

Assembly is quite simple, but order is important. Basic order of operations follow.

1. With rod hook ends aligned 120° apart pointed toward the center and spaced so the parallel rods will touch the inside of the ring, place the fire director over the rods, concave side to the rod hook ends and end holes overlapping over a common rod.
2. Using a suitable jig or fixture, position the ring so its top face in the final stove assembly is 30 mm from the bottom of the rods and any opening in the ring is at the back of the stove, aligned with the same leg that has overlapping fire director ends.
3. Weld the ring to the rods taking care that weld material stays on the outside of the legs and will not interfere with either the outer shell or base plate when assembled.
4. Roll the outer shell into a cylinder and fasten its hook edges, then insert its top tabs through the matching slots in the fire director.
5. Roll the chimney into a cylinder and fasten its hook edges.
6. Roll the center section of the tunnel into a half cylinder.
7. Place the stove upside down, insert the chimney from the stove bottom s side until it protrudes from the fire director the proper amount.
8. Insert the tunnel under the base ring and attach it to the chimney with the matching tabs and slots. Bend the tabs further from the base plate to the back of the stove, and the closer tabs toward the front of the stove. This will prevent the tunnel's top edge from "telescoping" into the stove body.
9. Fill the cavity with 0.18 kg of vermiculite, packing as needed.
10. Place the base plate, inserting all matching tabs through their slots, and fasten tabs.
11. Wrap the peripheral base plate tabs up around the base ring and crimp in place with channel lock type pliers as through turning a nut toward the top of the stove.

B Analyses

B.1 Costs

Without a direct estimate, we rely on indirect materials, labor, and shipping and customs/duties/tariff cost estimates. Our current best estimate, based on the following analysis, is $11 cost for materials, labor, and shipping, but not including duties or other fees.

B.1.1 Material Costs

The raw materials requirements are:

- 40 in of 0.375 in diameter round A36, 1018, or low carbon steel rod
- 47 in of 0.25 in diameter round A36, 1018, or low carbon steel rod
- 24 in × 24 in of 28 ga 1008 or low carbon steel
- 13 in × 16 in of 28 or 26 ga 304 stainless steel
- 0.2 kg of vermiculite
- 2 handle assemblies

The sheet steel requirements are conservative, in that these sheets are what all parts for one stove could be layed out on, without great effort to close-pack the patterns (or the possible close-packing advantage afforded by cutting multiple copies of the same part)

Surveys of metal sources including OnlineMetals.com, MetalsDepot.com, AKSteel price lists have found average prices in the US for sheet and rod of:

Material	Unit Price
304 stainless steel, 28 ga	\$2.70/lb
1008 steel, 28 ga	\$1.43/lb
A36 steel, 0.25 in rod	\$0.0225/in
A36 steel, 0.75 in rod	\$0.0371/in

These are presumed to be higher than costs in China, and along with the conservative estimate for material required, the resulting material cost estimates from them can be taken as ceiling values.

Stainless Sheet Cost

$$C_{304} = \$2.70/\text{lb} \times \left(13.2 \times 9.7 \times 0.015\ \text{in}^3\right) \times \left(0.2839\ \text{lb}/\text{in}^3\right. \tag{B.1}$$

$$C_{304} = \$1.48 \tag{B.2}$$

Carbon Sheet Cost

$$C_{\text{FeC}} = \$1.43/\text{lb} \times \left(13.2 \times 9.7 \times 0.015\ \text{in}^3\right) \times \left(0.2839\ \text{lb}/\text{in}^3\right. \tag{B.3}$$

$$C_{\text{FeC}} = \$3.51 \tag{B.4}$$

Rod Cost

$$C_{\text{rod}} = \$0.0225/\text{in} \times 47\ \text{in} + \$0.0371/\text{in} \times 40\ \text{in} \tag{B.5}$$

$$C_{\text{rod}} = \$2.54 \tag{B.6}$$

Vermiculite Cost

Per the digitally included report on vermiculite,[5]14 metric tons of suitable vermiculite can be purchased and sent to Nairobi for \$11800, and 0.18 kg are required per stove. Thus,

$$C_{\text{vermiculite}} = \frac{\$11800}{14000\ \text{kg vermiculite}} \times \frac{0.2\ \text{kg vermiculite}}{\text{stove}} \tag{B.7}$$

and

$$C_{\text{vermiculite}} = \$0.15/\text{stove} \tag{B.8}$$

Handle Cost

EcoZoom have stated that the current handles cost \$0.50.

B.1.2 Labor Cost

China

Parts manufacturing consists of five stamping operations, four heavy rod cuts likely to require a saw, seven light rod cuts that could be done with shears, one coil making operation, and three rod bending operations. All these process are equipment dependent, and having no other estimate for added costs beyond wages, we'll multiply wages by a factor of 3 for plant overhead.

In total these parts are quite simple to make, and as an estimate, 15 minutes for all operations is reasonable.

Minimum wage in Zheijiang province China is \$0.72/hr.Tripling this as well since these are moderately skilled jobs, then manufacturing cost is

$$C_{\text{mfg}} = 0.25 \text{ hr} \times \$0.72/hr \times 3^2 \tag{B.9}$$

$$C_{\text{mfg}} = 1.62 \tag{B.10}$$

Nairobi

Assembly of the prototype took an hour, but this was with no practice and poorly fitted parts. We feel further polishing of tolerances and a handful of stoves' worth of practice could easily halve this time, if not better, so we assume an assembly time of 30 min.

Average wage for skilled labor such as machine attendants, welders, and assembly line workers is \$1.06/hr. Halving this for 30 min work, assembly cost is $C_{\text{assem}} = \$0.53$.

B.1.3 Shipping Cost

Vermiculite shipping to Nairobi is included in its \$0.15/stove material cost, and will not be considered here.

Documents from EcoZoom give the average cost of a 40 ft high cube container from the factory in China to Nairobi as \$5200.

Payload limits for a 40 ft HC container are 26580 kg and 75.3 m^3. Stove mass and volume for shipping (no vermiculite) are 2.55 kg and 1.02 L.

The mass limit is

$$N_{\text{mass}} = \frac{m_{\text{limit}}}{m_{\text{stove}}} = \frac{26580\text{ kg}}{2.55\text{ kg/stove}} = 10423\text{ stoves} \tag{B.11}$$

and the volume limit is

$$N_{\text{volume}} = \frac{v_{\text{limit}}}{v_{\text{stove}}} = \frac{75300\text{ L}}{1.02\text{ L/stove}} = 72823\text{ stoves} \tag{B.12}$$

Rounding down, the mass limit gives 10400 stoves per 40 ft HC container.

At \$5200 per container, this

$$C_{\text{ship}} = \frac{\$5200}{10400\text{ stoves}} \tag{B.13}$$

$$C_{\text{ship}} = \$0.50/\text{stove} \tag{B.14}$$

B.1.4 Total Material, Labor, and Shipping Cost

$$C = C_{304} + C_{\text{FeC}} + C_{\text{Rod}} + C_{\text{vermiculite}} + C_{\text{handles}} + C_{\text{mfg}} + C_{\text{assem}} + C_{\text{ship}} \tag{B.15}$$

$$C = \$1.48 + +\$3.51 + \$2.54 + \$0.15 + \$0.50 + \$1.62 + \$0.53 + \$0.50 \tag{B.16}$$

$$C = \$10.83 \tag{B.17}$$

Given that this is based on a very long string of approximations, round to the nearest dollar, for an estimated materials, labor, and shipping cost of \$11.

B.2 Full Pot Weight Load

To specify structural members the load to be supported must be found.

From field research the largest pot to be accommodated is a 5 gallon pot.

Specifications of pots for sale found a maximum (empty) weight of 48 lb.Since failing to support 5 gallons of boiling water is an extreme safety hazard, this seemingly extreme example (most pots were in the 30-35 lb range) will be used, as a conservative estimate.

Total load is the force of gravity on the pot and water. The intrinsic weight of the structural members is ignored as negligible.

Force f due to gravity acting on a mass m is $f = mg$ where g is the local acceleration due to gravity.

In this case m is the sum of the mass of the pot, m_{pot}, and the mass of the water, m_{water}:

$$m = m_{\text{pot}} + m_{\text{water}} \tag{B.18}$$

Water mass is $m_{\text{water}} = v_{\text{water}} \cdot \rho_{\text{water}}$,

$$m_{\text{water}} = 5 \text{ gal} \cdot 3.785 \text{ L/gal} \cdot 1 \text{ kg/ L} \tag{B.19}$$

$$m_{\text{water}} = 18.9 \text{ kg} \tag{B.20}$$

so, the total mass is

$$m = 48 \text{ lbm} \cdot 0.4536 \text{ kg/lbm} + 18.9 \text{ kg} \tag{B.21}$$

$$m = 40.67 \text{ kg} \tag{B.22}$$

and finally, the force is

$$f = mg \tag{B.23}$$

$$f = 40.67\ \text{kg} \cdot 9.81\ \text{m/s}^2 \tag{B.24}$$

$$f = 398.9\ \text{N} \tag{B.25}$$

<u>The force to be supported is 400 N.</u>

B.3 Leg Strength

Figure B.1 shows the rod of the stove that must support the mass of the full cooking pot (41 kg). The vertical force applied to the rod is offset from the centroidal axis of the rod by a distance of e = 14.3 mm, as shown in the figure. The rod is 1018 steel (E = 200 GPa) with a 9.525 mm diameter. The factor of safety for buckling must be determined.

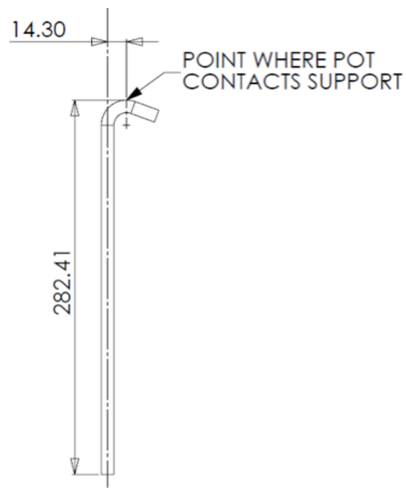


Figure B.1: Support rod

First the area (A), mass moment of inertia (I), and radius of gyration (k) must be found.

$$A = \pi r^2 \tag{B.26}$$

$$= \pi(9.525\text{ mm}/2)^2 \tag{B.27}$$

$$= 71.256\text{ mm}^2 \tag{B.28}$$

$$I = \frac{\pi r^4}{4} \tag{B.29}$$

$$= \frac{\pi(9.525\text{ mm}/2)^4}{4} \tag{B.30}$$

$$= 404.04\text{ mm}^4 \tag{B.31}$$

$$k = \sqrt{I/A} \tag{B.32}$$

$$= \sqrt{\frac{404.04\ \text{mm}^4}{71.256\ \text{mm}^2}} \tag{B.33}$$

$$= 2.381\ \text{mm} \tag{B.34}$$

Slenderness ratio (l/k):

$$\frac{l}{k} = \frac{282.41\ \text{mm}}{2.381\ \text{mm}} = 118.6 \tag{B.35}$$

Since slenderness ratio is less than 120 the column will be treated as an intermediate length column with eccentric loading. Maximum compressive stress at the mid span is found using the secant column formula (Shigley's Eq. 4-49)

$$\sigma_c = \frac{P}{A}\left[1 + \frac{er}{k^2}\sec\left(\frac{l}{2k}\sqrt{\frac{P}{EA}}\right)\right] \tag{B.36}$$

(where P is vertical load)

$$\tag{B.37}$$

$$= \frac{41\ \text{kg} \cdot 9.81 \times 10^3\ \text{mm/ s}^2}{71.256\ \text{mm}^2} \times \cdots \tag{B.38}$$

$$\cdots \times \left[1 + \frac{14.33\ \text{mm} \cdot 4.762\ \text{mm}}{(2.381\ \text{mm})^2}\sec\left(\frac{282.41\ \text{mm}}{2 \cdot 2.381\ \text{mm}}\sqrt{\frac{41\ \text{kg} \cdot 9.81 \times 10^3\ \text{mm/ s}^2}{200\ \text{GPa} \cdot 71.256\ \text{mm}^2}}\right)\right] \tag{B.39}$$

$$= 24.91\ \text{MPa} \tag{B.40}$$

Then factor of safety is

$$\text{F.S.} = \frac{\text{Yield Strength}}{\text{Maximum Compressive Stress}} \tag{B.41}$$

$$= \frac{S_y}{\sigma_c} = \frac{310\ \text{MPa}}{24.91\ \text{MPa}} \tag{B.42}$$

$$\tag{B.43}$$

$$\boxed{\text{F.S.} = 10.0} \tag{B.44}$$

Similar calculations for 5/16 in rod give a factor of safety of 5.8. Given that the rods are subjected to high heat conducted from their top ends, possible corrosion or erosion, and failure to support 5 gal of boiling water is an unacceptable hazard, choose 3/8 in diameter rod for its extra factor of safety.

B.4 Sheet metal durability

The design includes 5 major sheet metal components: the outer shell, the chimney, the fuel tunnel, the floor plate, and the top plate. All are exposed to varying elevated temperatures and all but the outer shell to wood combustion products. Temperature measurements on operating production EcoZoom stoves and the first prototype found the floor directly under the center of the chimney exposed to the highest heat, 650 °C, followed by the chimney, top plate, and tunnel at 350 °C, and shell at 67 °C.

Under these conditions, in addition to simple atmospheric corrosion, several failure modes are possible:

ash/salt deposit corrosion caused by salts and ash interfering with chemical activity and preventing formation (or in cases removing) a passivating layer

carburization caused by a carbon rich atmosphere forming internal carbides and causing pitting and accelerated metal loss

thermal expansion which can cause cyclical fatigue cracking, though this is largely alleviated in this design, by allowing the parts enough tolerance to float, and leaving the stainless chimney, with the highest expansion rate and highest temperature of vertical components, unfixed in the longest axis, such that heating actually relaxes the joint between the chimney and fire director.

stress corrosion cracking from cyclical stress and elevated temperature allowing corrosion sites to exand into cracks slowly. Again, this should be alleviated by the separated containment and load bearing design.

Lai[3] lists a value of 0.8 mil/month material loss at comparable temperatures in a garbage incinerator. Taking this as an extreme case, with several more modes of attack possible in the more complicated combustion products, expected life is

$$L = \frac{0.015 \text{ in}}{0.0008 \text{ in/month}} \tag{B.45}$$

$$L = 18.75 \text{ month} \tag{B.46}$$

Given that the design can continue to function with small holes in the chimney, and that this is an estimate for a more extreme environment, the hope is that this material thickness will perform as needed. Unfortunately, only long term testing can confirm this.

C Experiments

C.1 Insulation material selection

Throughout the design selection process the design categories were simply assigned a subjective consensus value in the appropriate matrix. Choice of insulation material was more complex. Insulation performance is objectively quantifiable, so instead of using the design matrix to select the insulation material an experiment was designed to find the best insulation for a prototype stove.

In the experiment, current Ecozoom stoves were used with varying insulation materials to boil 2 l of water.[1] The time from ignition of the fire until the water boiled was taken as a metric for insulation performance: the insulation producing the shortest boil time was declared the best choice. Table C.1 shows the boil times of each insulation material. While sand gave the lowest average boil time, and the lowest overall time of any single test, it was highly variable, and a fourth test run was discarded as a failure when, in spite of active tending, the fire could not be kept lit long enough to boil 2 l. Excluding sand, vermiculite insulation appears to be the best performing, with a low average boil time and a more repeatable boil time.

C.2 Exterior Temperature Experimentation

Purpose

To quantify safe temperatures for prolonged and momentary skin contact with surfaces, to set limits for handles and exposed surfaces of the stove.

[1] A 5 l boil test is an industry standard for comparing overall performance of stoves, however for the purpose of comparing insulation performance alone, 2 l was chosen to save time and fuel.

Table C.1: 2 l boil test results. While sand's 24.1 min average is the fastest, its variability, and a fourth run where the fire could not even be kept lit excluded it from further consideration. Vermiculite was left as the best performing material.

	burn times (min)			
run	ceramic	air	sand	vermiculite
1	37.1	32.0	32.4	31.5
2	29.2	30.5	26.6	20.8
3	23.6	17.3	13.3	20.3
average	28.2	28.3	24.1	24.2

Assumptions

- Handles must be used by gripping them with the hand for at least 30 seconds, with contact mainly with the palms.
- Accidental contact with the shell would last less than 2 seconds, and possibly involve other skin areas than the palms.
- Burns are caused by heat transferred to tissue.
- Human tissue differs negligibly in thermal properties. Pain tolerance may differ, but for lack of quantifiable information, assume not significantly so.
- Heat transfer from water to a submerged hand will be more rapid than that of contact between tissue and either solid steel, plastics, or wood.

Methods

Water was heated in a frying pan on an electric stove burner while water temperature was measured by a kitchen meat thermometer with its probe end immersed in the water but held well away from the pan bottom.

When the temperature reached 105 °F, 5 °F above the initial test temperature, the pan was removed from the heat source, the thermometer observed as it slowly fell to 100 °F. Then the experimenter's hand was placed in the pan, submerging up to the wrist, and how long it was comfortable to leave the hand there was timed. This procedure was repeated at test temperatures of 110 and 120 °F.

Testing then proceeded by, rather than submerging the hand, dipping the back of a single knuckle of one finger on the left hand quickly, removing it at the onset of pain, and noting rough duration until pain onset from immersion, and the effects.

Results

Table C.2: Low temperature full hand submerged testing data

Temperature (°F)	Comfortable time (s)
100	timing abandoned at 60 s
110	48 s
120	9 s

Table C.3: High temperature rapid testing data

Temperature (°F)	Estimate of time to pain	Effect
130	3 s	No noticeable effect
140	3 s	Redness for several minutes, but no lasting pain
150	> 1 s	Several minutes of painful stinging.

Conclusions

Defining accidental contact to be less than 2 s, 140 °F is a reasonable accidental contact safe temperature, and this also accords with available information of OSHA standards for workplace safety.

Handle temperature appears to be safe and tolerable at 110 °F, and possibly indefinitely comfortable at 100 °F. (Which would make sense, as heat transfer would be low at just under 2 °F above average core body temperature.)

C.3 Safety Testing

C.3.1 Shell temperature

During boiling tests the outer shell was fitted with thermocouples on the rear of the stove as in the separate insulation testing experiment[6], and the temperatures were recorded throughout the test. The highest recorded temperature of the final prototype shell was 153 °F. This was higher than the target value, but close enough the tester risked placing a hand on the shell, and was able to leave it there approximately 1 s. This was deemed acceptable for incidental contact.

C.3.2 Tipping Safety

The stove was pushed sideways at its rim in three directions, and required a 45° angle before it began to tip on its own.

C.3.3 ISO IWA Safety Testing

The International Workshop on Clean and Efficient Cookstoves produced a draft standard for stove performance, including stove safety.[2] Included in the standard are the ten following criteria,

- Sharp Edges and Points
- Cookstove Tipping
- Containment of Fuel
- Obstructions Near Cooking Surface
- Surface Temperature
- Heat Transmission to Surroundings
- Temperature of Operational Construction
- Chimney Shielding
- Flames Surrounding Cookpot
- Flames Exiting Fuel Chamber, Canister, or Pipes

Testing of the temperature criteria deviated from the procedure, in that chalk grids and multiple readings were not used. Instead, highest recorded temperatures were used. However, this could not have changed the outcome, as these ratings were all, on the 1–4 point/Best, Good, Fair, Poor scale, Poor. Thus no higher temperature that went unrecorded could have changed the rating.

Full results of the testing are

Criteria		Rating	*WeightedRating*
1.	Sharp Edges and Points	3	4.5
2.	Cookstove Tipping	4	12
3.	Containment of Fuel	3	7.5
4.	Obstructions Near Cooking Surface	3	6
5.	Surface Temperature	1	2
6.	Heat Transmission to Surroundings	1	2.5
7.	Temperature of Operational Construction	4	8
8.	Chimney Shielding	4	10
9.	Flames Surrounding Cookpot	4	12
10.	Flames Exiting Fuel Chamber, Canister, or Pipes	4	16
Total			80.5

The original standards, adopted essentially unchanged but for rating breakdown, rated stoves on a 100 point scale and break the scale into Best, Good, Fair, and Poor ratings. 80.5/100 equated to a rating of Good. The draft ISO standard uses a 4-tier rating system, with 4 the highest rating, and on this scale 80.5 equates to tier 2.

D Product Design Specifications

Table D.1: Product Design Specifications

requirement	category	customer(s)	metric	target	target basis	verification	met
			High importance				
shipping mass	shipping	EcoZoom, NGO's	mass	7 kg or less	EcoZoom research	testing	✓
manufacturable in existing plant	manuf.	EcoZoom	Y/N	Y	Company Policy	prototyping	✓
rocket stove based design	marketing	EcoZoom	Y/N	Y	Company Policy	inspection	✓
production cost	cost	Cooks	cost	$6 US or less	EcoZoom research	prototyping	✗
maintenance	maintenance	Cooks	maintenance required	cleaning only	EcoZoom research	testing	✓
assembly	manuf.	EcoZoom, NGO's	tools required	hand tools only	EcoZoom research	prototyping	✓
production time	manuf.	NGO's	time to produce one stove	week or less	EcoZoom research	prototyping	✓
handle temperature	safety	Cooks	temperature	38 °C or lower	experiment	testing	✓
pot and food load stability for 45 cm diameter, 25 cm high, 41 kg load	safety	Cooks	height of center of gravity	at or lower than current production	benchmark	modeling, testing	✓
pot and food load support	safety	Cooks	load supported	41 kg	market research	testing	✓
			Medium Importance				
service life	reliability	Cooks	time to failure	2 years	EcoZoom research	modeling, testing	✗
5 l water boil - fuel use	performance	Cooks	mass fuel used to boil 5 l of water	850 g or less	benchmark	testing	✓
5 l water boil - speed	performance	Cooks	time to boil 5 l of water	33 min or less	benchmark	testing	✓
5 l water boil - PM emissions	performance	Cooks, NGO's	mass of particulate matter produced to boil 5 l of water	980 mg or less	benchmark	testing	✓
5 l water boil - CO emissions	performance	Cooks, NGO's	mass of CO produced to boil 5 l of water	20.4 g or less	benchmark	testing	✓
			Low Importance				
shipping volume	shipping	Shipping, NGO's	volume	0.077 m^3 or less	benchmark	testing	✓
replaceable combustion chamber	maintenance	Cooks	Y/N	Y	EcoZoom research	prototyping	✓
non-FeCrAl liner	materials	EcoZoom	Y/N	Y	EcoZoom research	inspection	✓
shell temperature	safety	Cooks	temperature	140 °F or lower	experiment	testing	✓

E Internal and External Search

E.1 Internal search

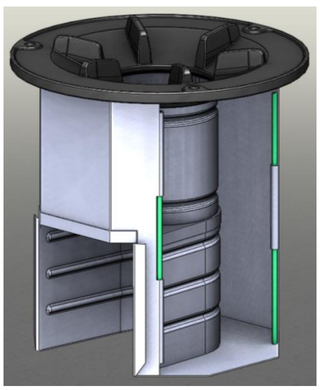
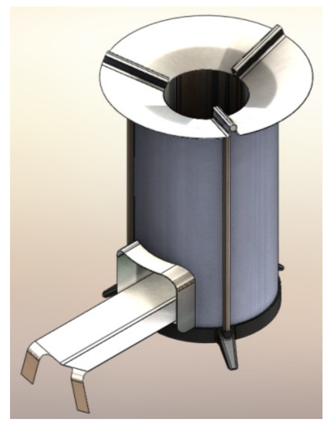
Once the external search was completed three general concepts for design were conceived, and are shown in Table E.1 The main differences between these were the ease and cost of manufacture, ability to ship flat packed, and weight.

With the completion of these concepts it became clear that the stove has a few major functional categories. These categories are: stove shell, fire box, insulation, pot support, fuel support, and handles.

Insulation choice carried special difficulties, as a material choice that affected several other design areas. It determines the temperature other components will be exposed to and possibly the sizing of the overall design. The current ceramic insulation is responsible for stretching the manufacturing lead time to over a month, and accounts for more than half of shipping weight. Insulation materials were researched and air (an empty cavity), sand, and vermiculite were chosen for further investigation.

Air was selected to test of the assumption that insulation is needed at all. Sand was selected as an example of a readily available and cheap, but high thermal mass insulator. Vermiculite was selected on the basis of low heat capacity and conductance, around 0.04 W/m^2K, ease of installation as a loose bulk material, and possible combination of low price (possibly \$0.34, though this needs further research) and availability in Kenya. An experiment was designed to compare the performance of these and the current ceramic insulation, which is discussed in section C.1.

Table E.1: The three top level design concepts from internal search

Name	Octagonal Can	Wire Leg	Cast Leg
Sketch			
Pros	Brings a new look to the rocket stove, with innovative hinge-type assembly of identical sections.	Weight of pot carried by external legs, possibly making insulation optional.	Same as with wire leg.
Cons	Many parts, more complex assembly, reuses much of current design so less weight saving, requires insulation.	Complex bending of steel rods.	Possible tipping risk, depending on geometry.

E.2 External search

External search focused on two areas: Existing stove designs, either rocket stoves or stove designs adaptable to a rocket stove, and materials.

E.2.1 Commercial Stoves

(a) Envirofit M-5000
image © Envirofit Int.

(b) EzyStove
image © Veryday

(c) Grover stove
image © StockStorage LLC

Figure E.1: Existing commercial rocket stoves

EcoZoom

The Dura, shown in Figure 1.1b, is built in China, with sheet metal shell, a refractory metal liner, ceramic insulation, a cast iron pot support, and bucket handles, with 9 kg mass.

Envirofit

The M-5000, shown in Figure E.1a, is built in Nairobi with a sheet metal shell, refractory metal liner, ceramic fiber insulation, a cast pot support, locking handles, costs $15, and has a 5.34 kg mass.

EzyStove

The EzyStove, Figure E.1b, is fabricated in China, and ships either nested, in which case assembly only requires a screwdriver, or flat packed, which requires welding and a screwdriver for assembly. The stove is double walled but uninsulated, built with sheet stainless, possibly mild steel sheet, and mild steel rod. Mass is 3.02 kg and the price is $16.75.

Grover

The Grover stove, in Figure E.1c, is US built for camping, off grid, and disaster preparedness markets. Construction is welded steel with vermiculite insulation, for $135 and an 11 kg mass.

E.2.2 Hobbyist and appropriate technology stoves

Many hobbyists and appropriate technology proponents have built stoves either wholly or partially from clay, mud, brick, ceramic, and even dung. They have the advantage of low cost and technically simple construction, but the disadvantages of high mass, fragility, in some cases permanent installation, and a home built appearance. Another hobbyist avenue is metal stoves built from empty cans, buckets, or general sheet stock, and insulated with firebrick, clay, vermiculite, fiberglass, and a much wider variety of materials, often as experiments.

E.2.3 Materials

Insulation

Possible insulation materials considered:

air free, light, may not perform well

solid ceramic, or fire brick heavy, slow to fabricate, possibly local sourced

ceramic fiber light, simple assembly

vermiculite or perlite light, high performing, possibly inexpensive and local sourced

sand heavy, poor performing, but cheap and widely available

sheet metal or foil baffles possibly costly and slower to fabricate, with unknown performance

vacuum chamber(s) costliest, due to cost of creating a sealed chamber. durability of seal also an unknown.

Structural materials

The high heat that stove components are exposed to dictates material considerations, including thermal cycle cracking, creep, and corrosion. Materials possibly suited to high temperature service are:

- ceramics, though prone to developing cracks, and generally fragile
- stainless steels, such as 316L grades, though more expensive than carbon steel
- refractory metals, such as the FeCrAl alloy already in use as a flue liner, which is yet more expensive
- cast iron, though heavy and possibly complex to fabricate
- mild steel, in larger cross sections

F Decision matrices, and pairwise comparison

The categories of the stove that need decision matrices are: stove shell, fire box, pot support, fuel support, and handles.

In decision matrices, dashes indicate criteria either not applicable or negligibly different between the options, or in some cases a category where only one option stands out.

F.1 Firebox

The firebox geometry is largely constrained, and other than using a combined ceramic insulation and liner, sheet metal is the only viable construction.

The material that the firebox is to be constructed from is Stainless Steel.

Table F.1: Firebox decision matrix, selecting stainless steel for firebox construction

criteria	firebox material			
	stainless steel	plain steel	FeCrAl refractory metal	aluminum
material cost	2	3	1	2
manufacturing cost	-	-	-	-
functional failure risk	3	2	4	1
deadline risk	4	4	3	4
manufacturing speed	2	3	2	3
durability	4	2	3	1
marketing appeal	4	2	2	2
shipping weight	-	-	-	1
shipping volume	-	-	-	-
total	20	17	18	14

F.2 Pot Support

The "pot support" in the current EcoZoom designs is a cast iron conical disk, with either three or six raised ribs to form a trivet, and a hole in the center over the firebox exit. Other materials and configurations were considered:

Cast Iron essentially the current part

none removing the pot support plate (viable with some leg and shell configurations, which could serve as physical supports on their own.)

sheet with channels a sheet metal truncated cone, with formed channels to fit over bent rod legs

sheet with holes a sheet metal truncated cone with holes punched to fit over truncated metal legs

However, a second function of the pot support is to channel hot combustion gas from the firebox along the pot bottom, forming an underside pot skirt. Considering this left the "none" option unacceptable, as a known functional failure, and the sheet-with-holes option preferred.

Table F.2: Pot support decision matrix

criteria	cast iron	none	sheet with channels	sheet with holes
material cost	2	4	3	4
manufacturing cost	1	4	2	3
functional failure risk	3	2	4	4
deadline risk	2	4	3	4
manufacturing speed	2	4	3	4
durability	4	4	2	3
marketing appeal	4	2	3	3
shipping weight	1	4	3	4
shipping volume	2	4	4	4
total	21	32	27	33

F.3 Fuel Support

Table F.3 determines that fuel support would be a bench design, using solid sheet metal, but this caused problems as described in the body of the report, and for the second prototype the design was changed to the tested and satisfactory wire rack design already preferred by EcoZoom.

Table F.3: Fuel support decision matrix

criteria	wire mesh	bench	vented bench	diamond bench
material cost	3	4	4	4
manufacturing cost	3	4	3	3
functional failure risk	4	4	2	3
deadline risk	3	4	3	3
manufacturing speed	2	4	3	3
durability	3	4	2	2
marketing appeal	3	3	4	3
shipping weight	4	3	3	3
shipping volume	3	4	4	4
total	28	33	28	28

F.4 Handle

Handle types considered were fixed contoured handles stamped from sheet metal, the wire “bucket-bail” handles currently used on EcoZoom products, handle loops cast into the edge of a cast pot support, and forming handles from wire hoops otherwise used to stabilize wire rod legs. Ultimately EcoZoom themselves decided they preferred their current handles, for sake of production simplicity and cost. Since those handles are well tested and their attachment method simple rivets, they were omitted from prototypes.

Table F.4: Handle decision matrix

criteria	stamped contour	“bucket-bail”	cast with pot support	leg hoop
material cost	4	4	2	3
manufacturing cost	4	3	3	3
functional failure risk	3	3	1	3
deadline risk	3	3	2	4
manufacturing speed	4	3	2	3
durability	4	3	4	4
marketing appeal	4	2	3	3
shipping weight	4	4	2	3
shipping volume	3	3	3	4
total	33	28	22	26

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