Herbert Wertheim
College of Engineering
UNIVERSITY of FLORIDA

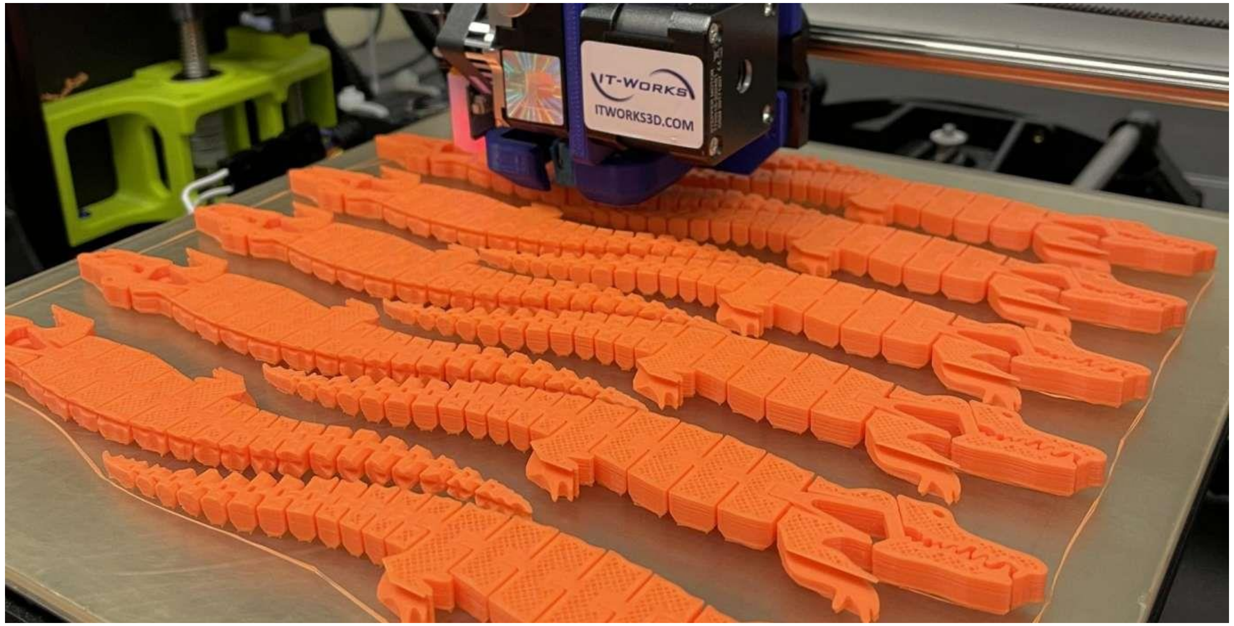
REXTRUDE™ FILAMENT RECYCLER

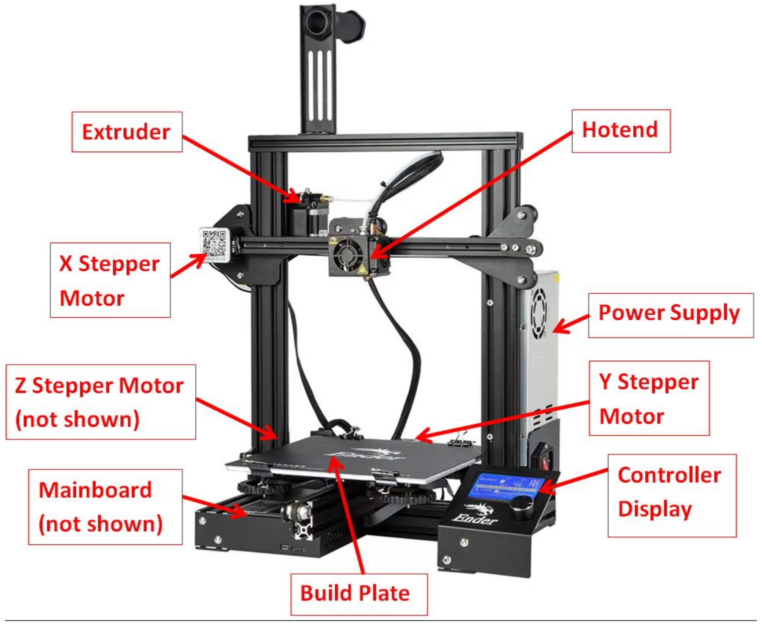
August 5, 2024
MAE-A-221

Chase Eskridge
Chris Lopez
Isabella Camacho
Gabriel Gilvary
Julia Gallo
Nathan Berner
Osaji Skyers
Sophia Sayre

Background

- 3D Printing – Additive Manufacturing Process
- Prototyping – Commonly Used
- Other uses: Functional end-use parts, Manufacturing Aids & Tools, etc.





Project Brief

Problem

1. Produces a lot of waste
2. Current 3D Filament Recyclers – Expensive & Slow!
3. Inaccurate Diameter Readings

Solution

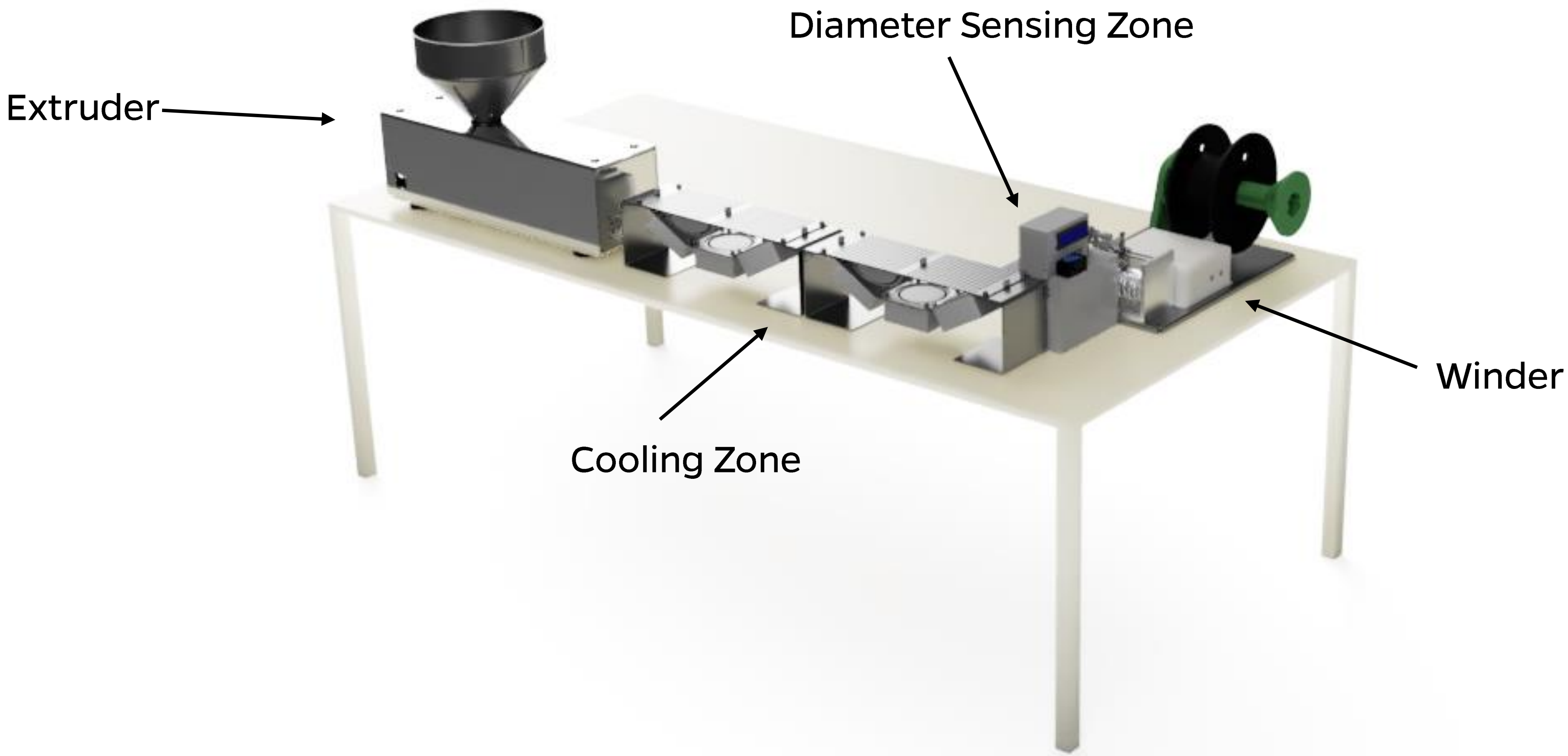
1. Filament Recycler
2. Increased Extrusion Speeds & Affordable Costs
3. Real-time Diameter sensing zone

Herbert Wertheim College of Engineering
UNIVERSITY of FLORIDA

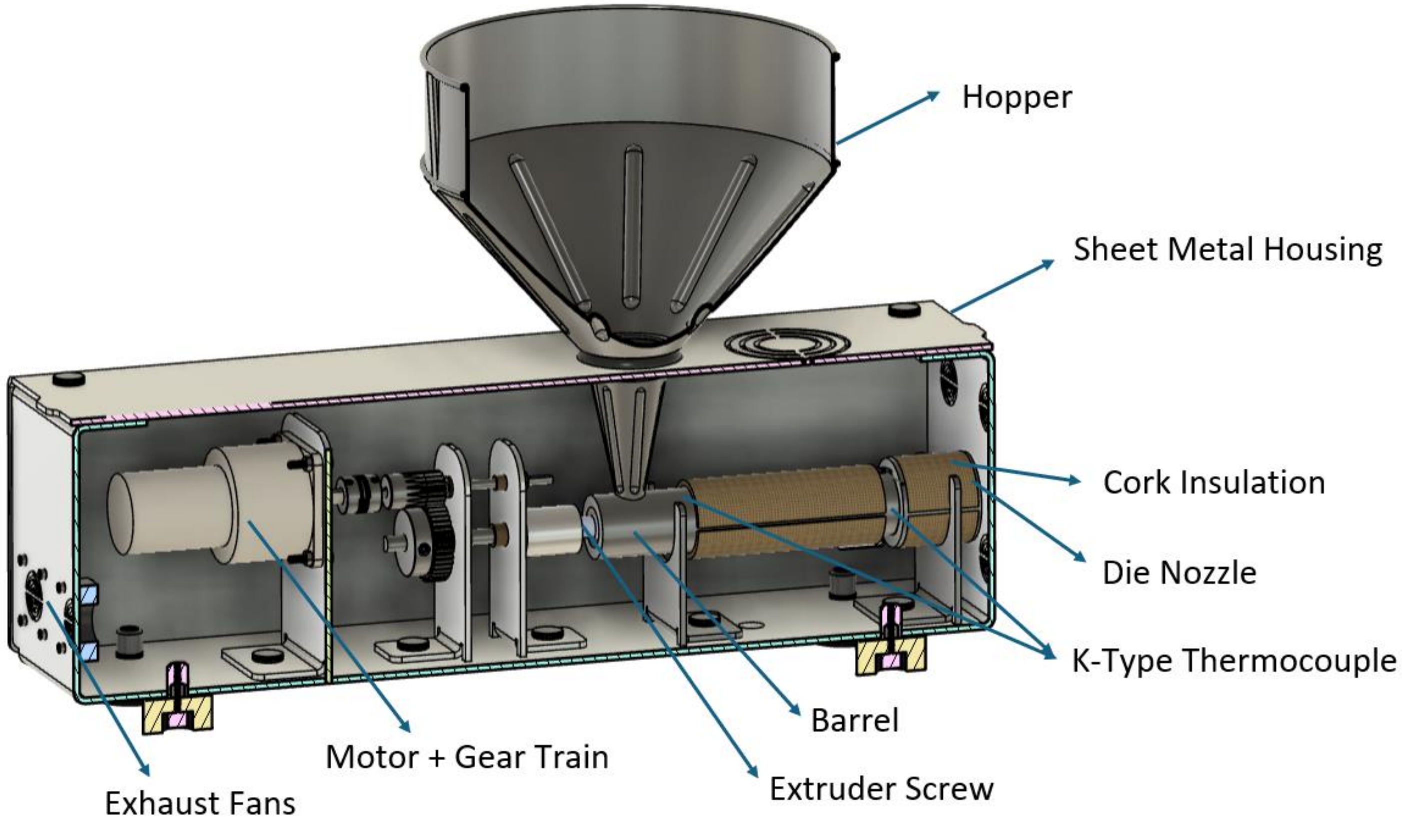
Final Design

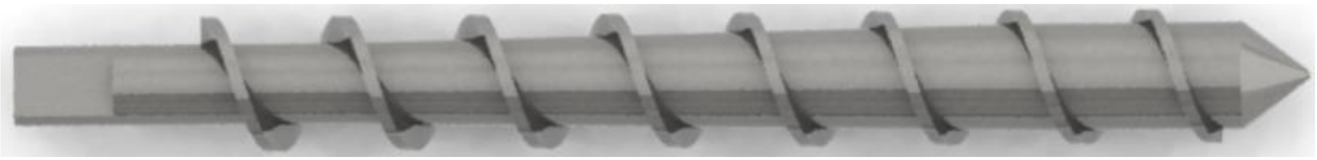
POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Full Design Assembly



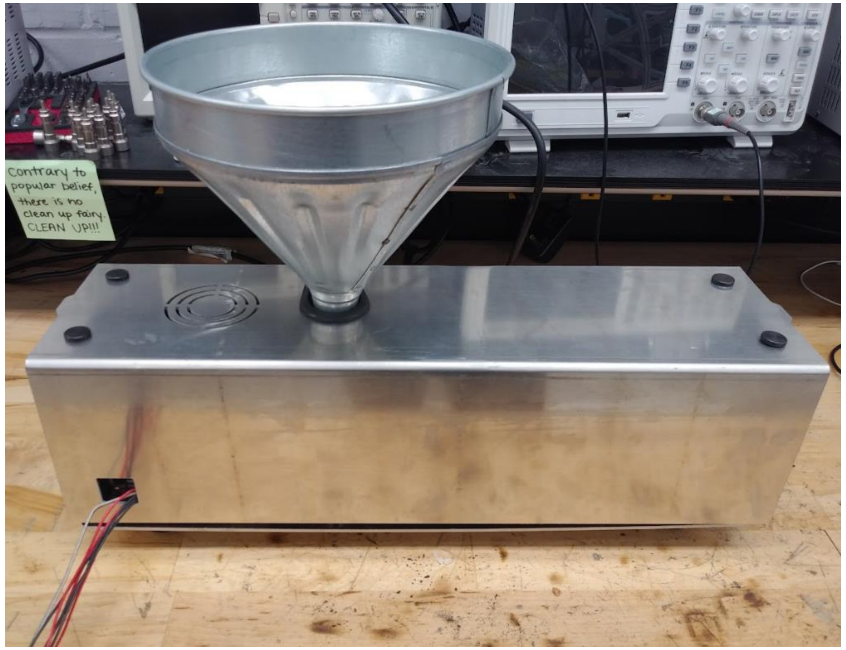
Extruder Subsystem



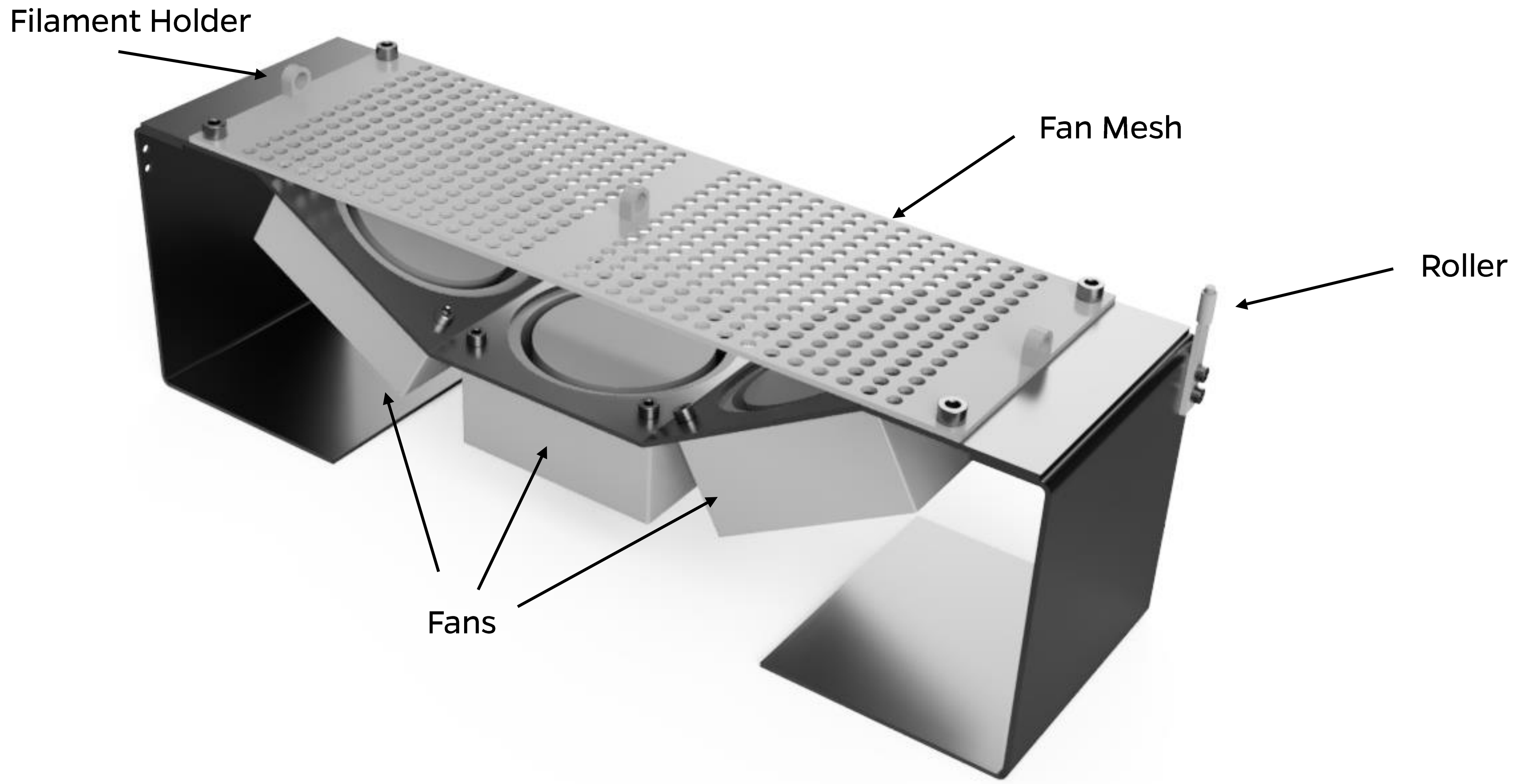


Compressive Extruder Screw
2:1 Compression Ratio
20.2 mm Diameter
4 mm Channel Depth
7.5 L/D Ratio

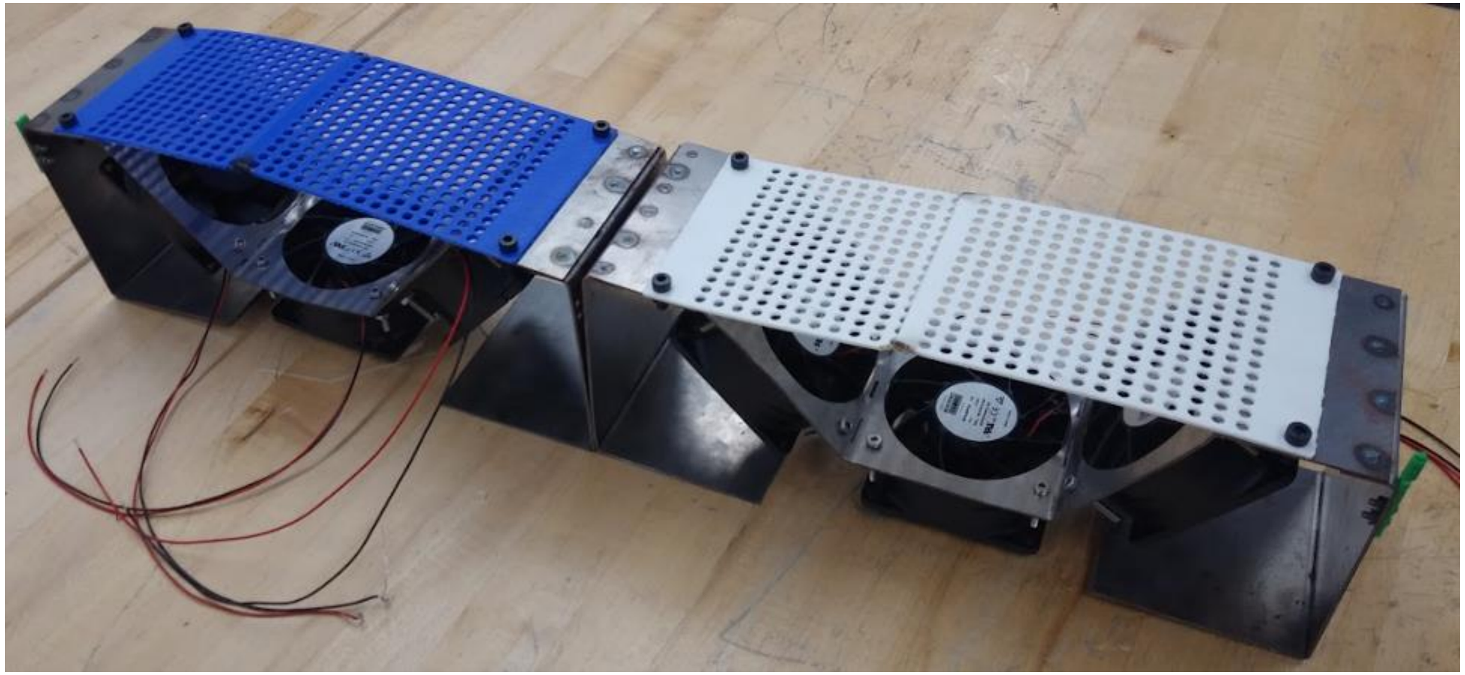
Extruder Subsystem

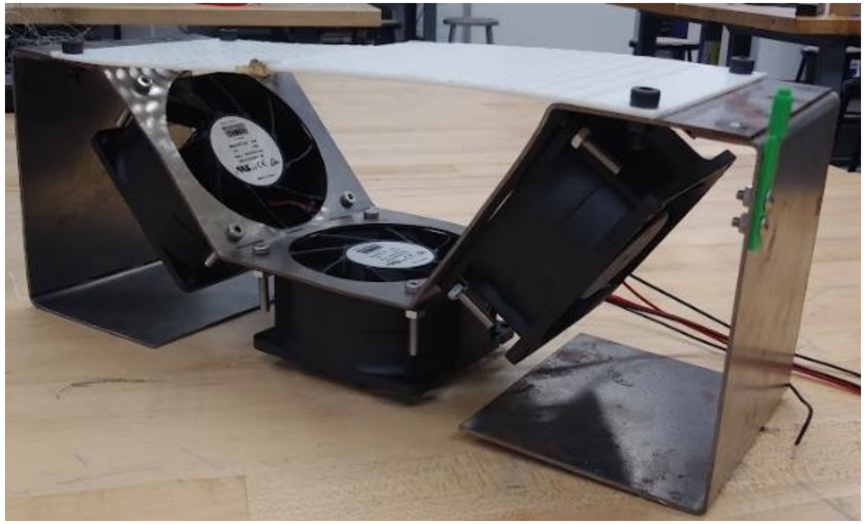


Cooling Zone Subsystem



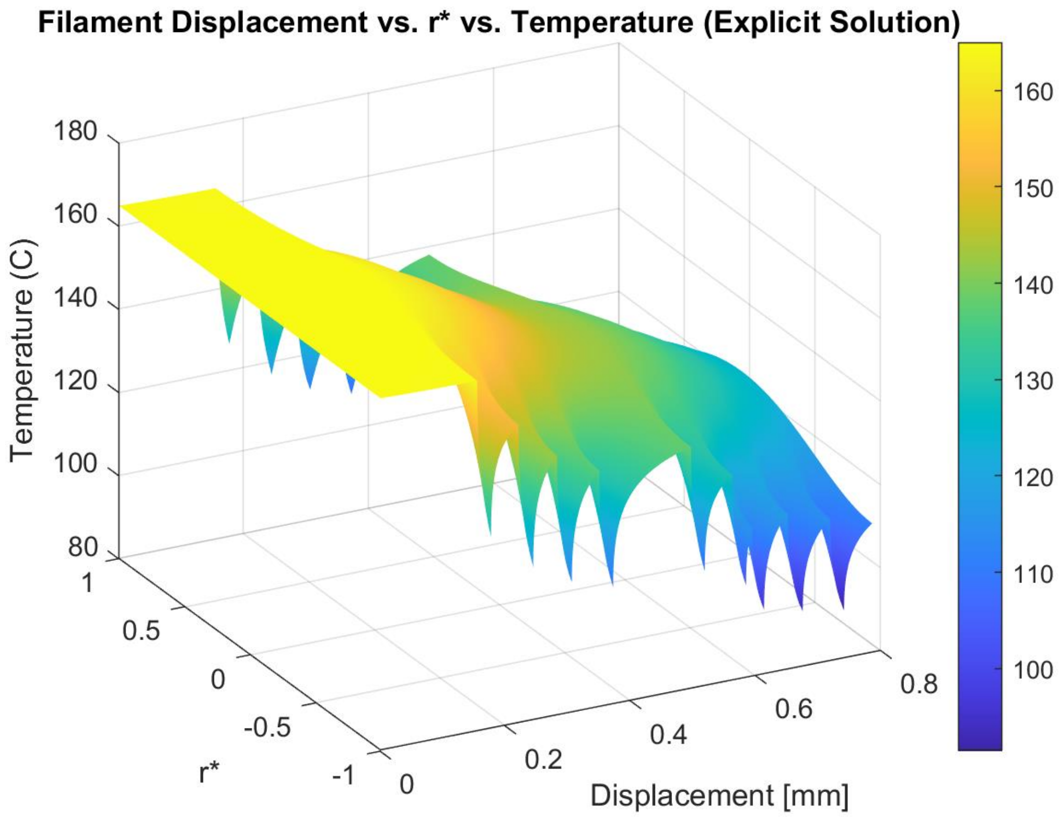
Cooling Zone Subsystem

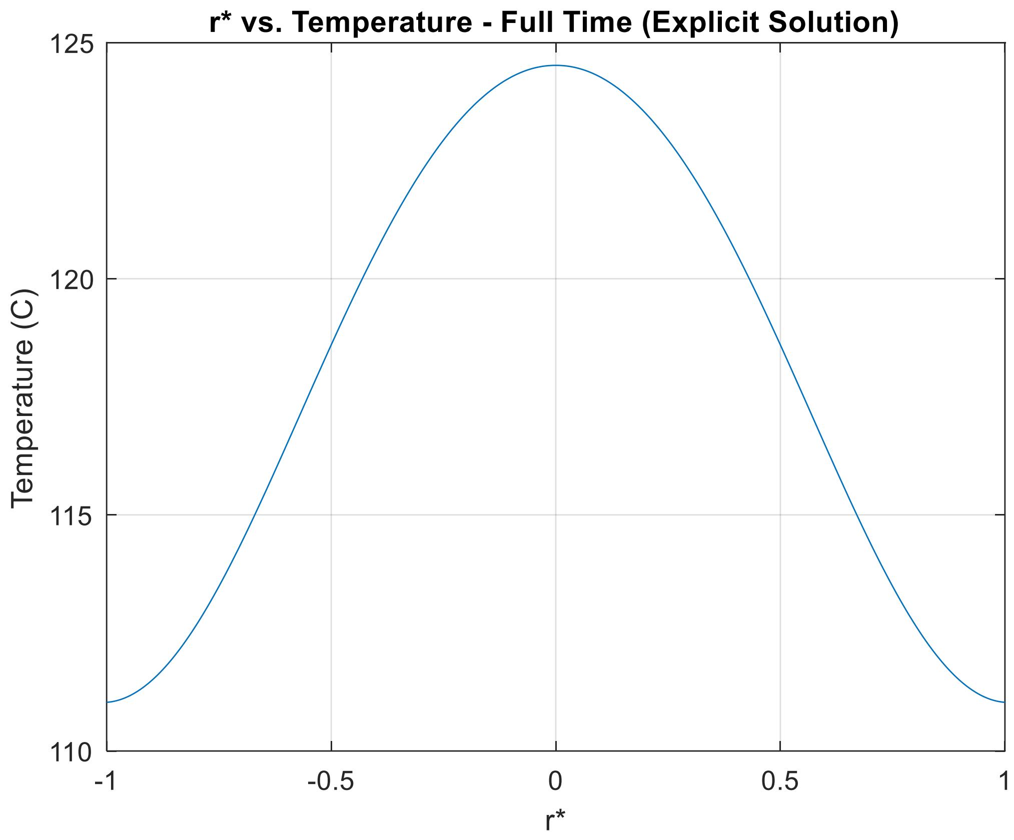




Filament Cooling – Explicit Method

- Temperature distribution along cooling path calculated using explicit transient heat transfer:

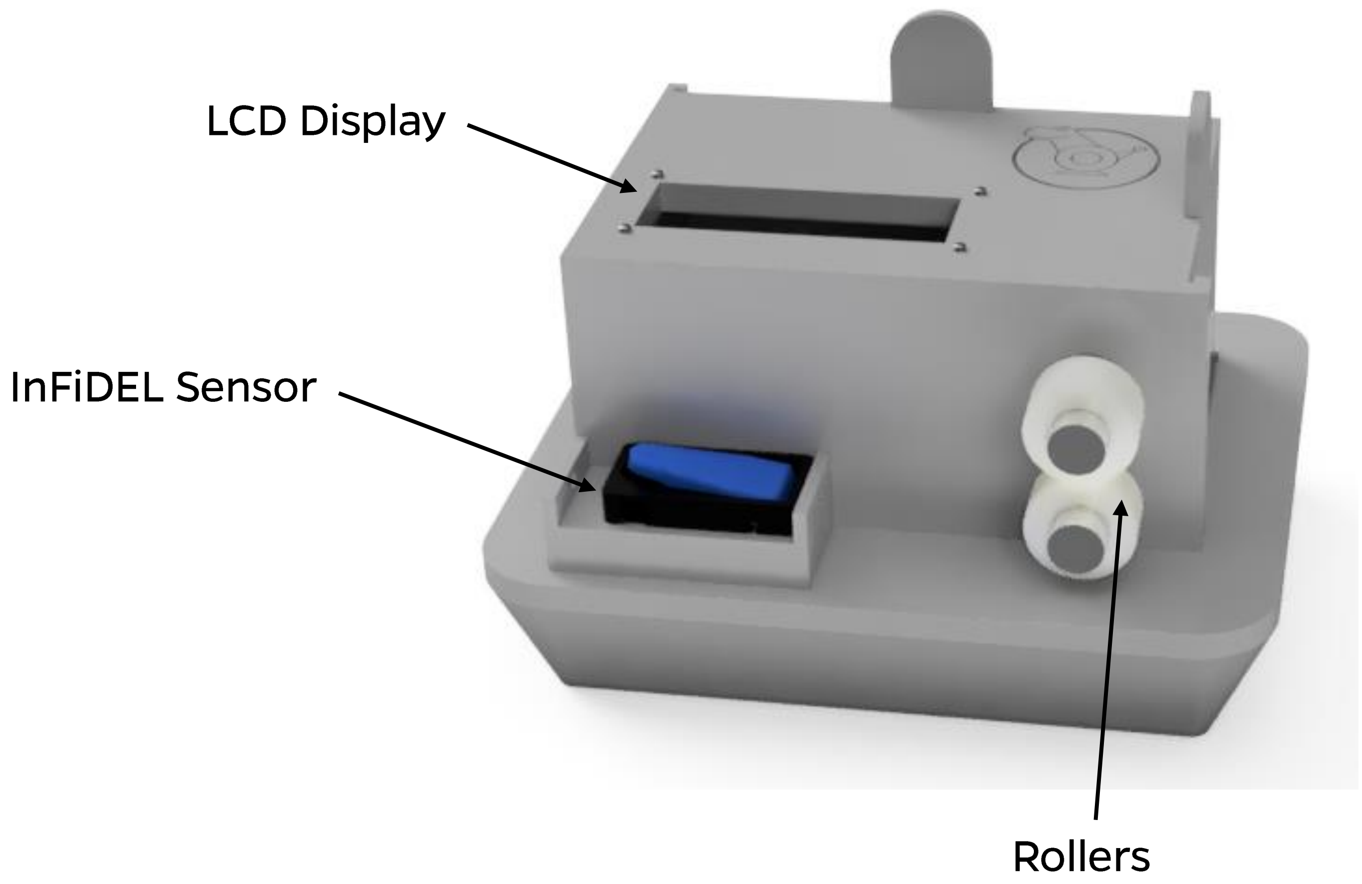




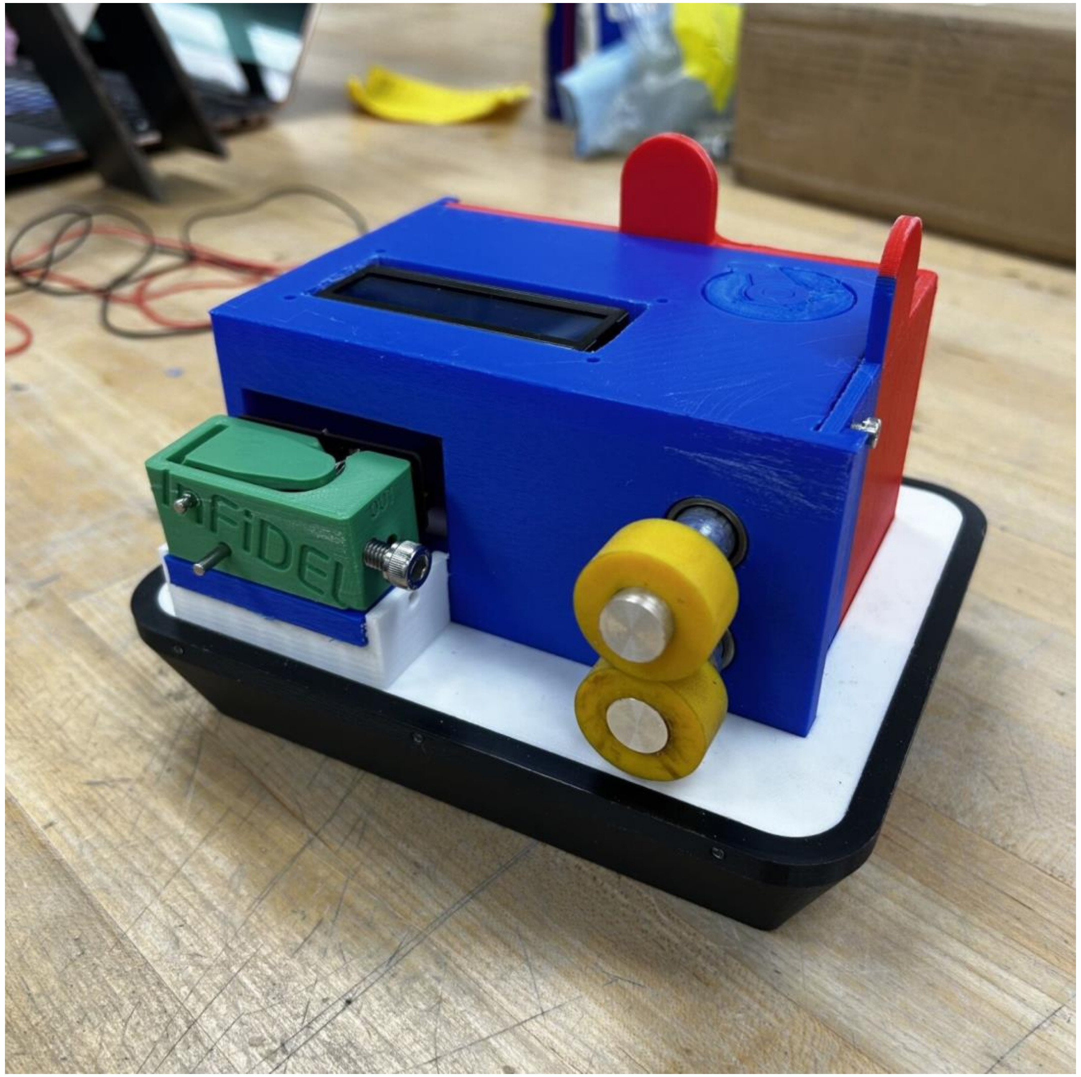
Diameter Sensing Zone Subsystem

Uniform Deformation of extruded Filament

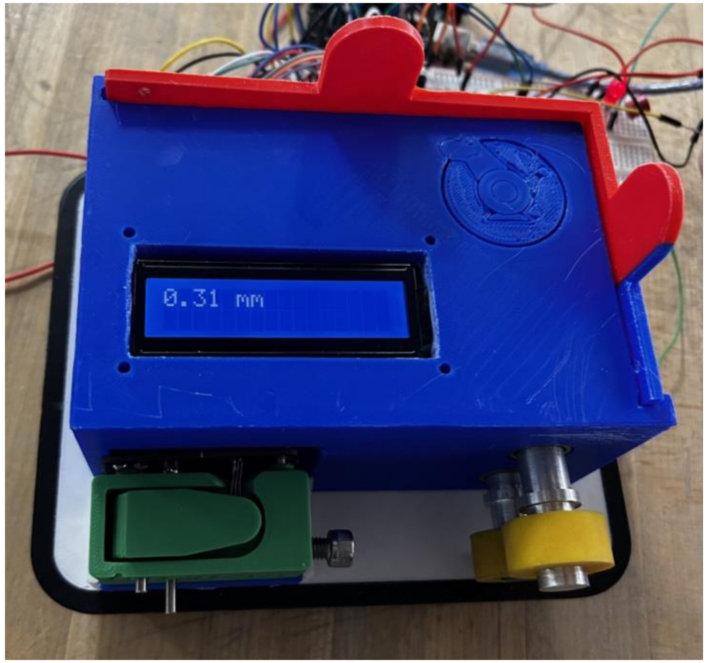
- 30-A Urethane rollers guide filament
- Driven by 12V brushless motor



Diameter Sensing Zone Subsystem



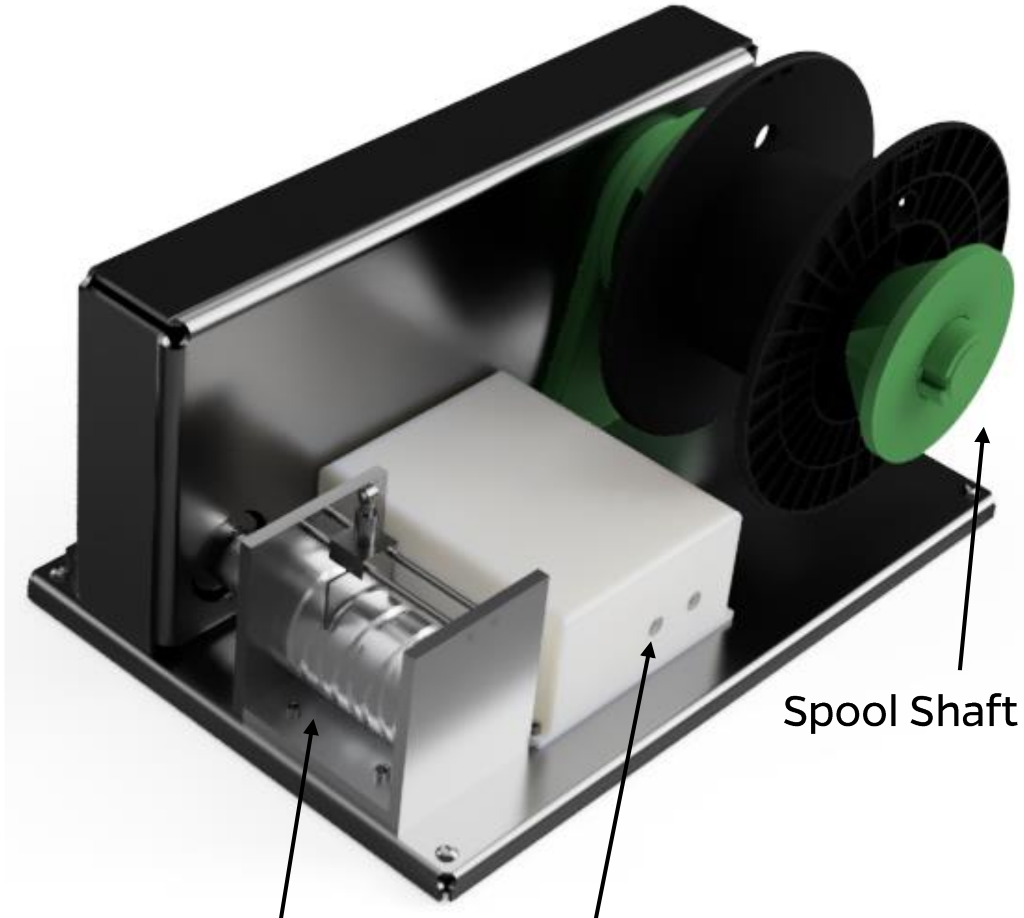
- InFiDEL sensor with hand-soldered PCB
- LCD display for readings
- 1 measurement per second
- Voltage differences measure diameter



Winder Subsystem

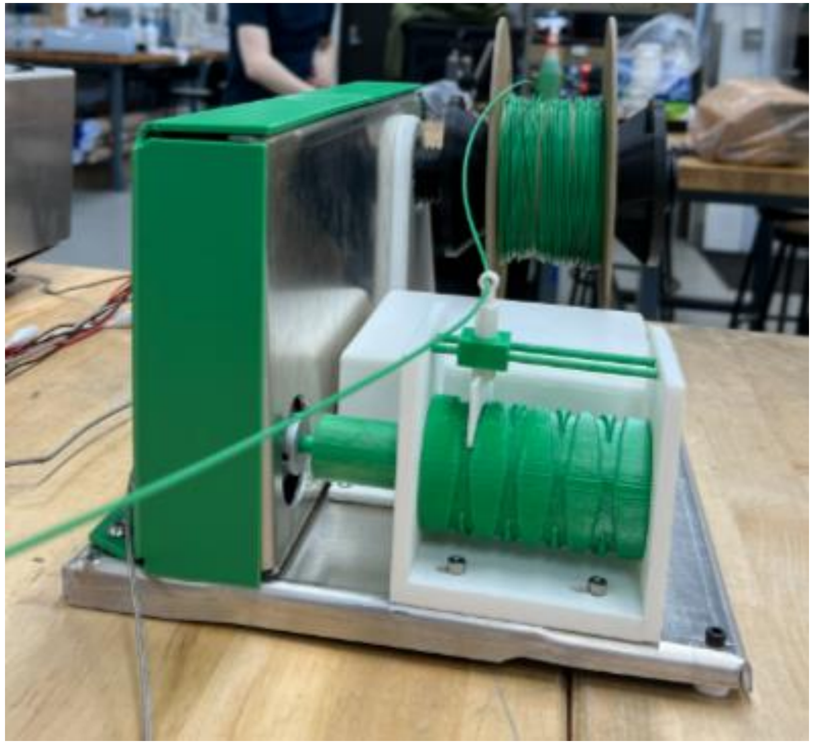
Winds filament onto a spool for 3D printing

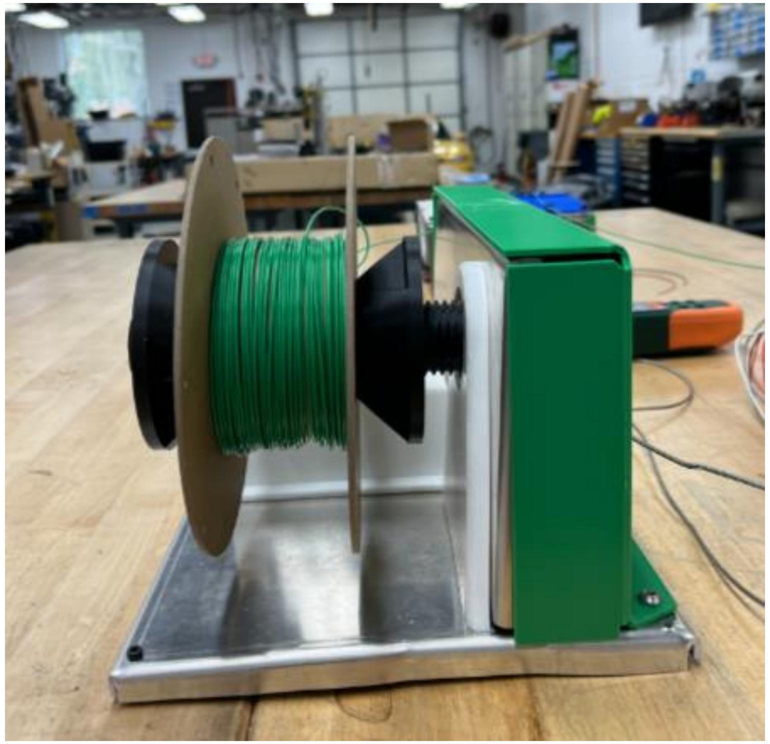
- Aluminum housing
- Adjustable spool holder
- 3D printed gearbox
- Self-reversing screw

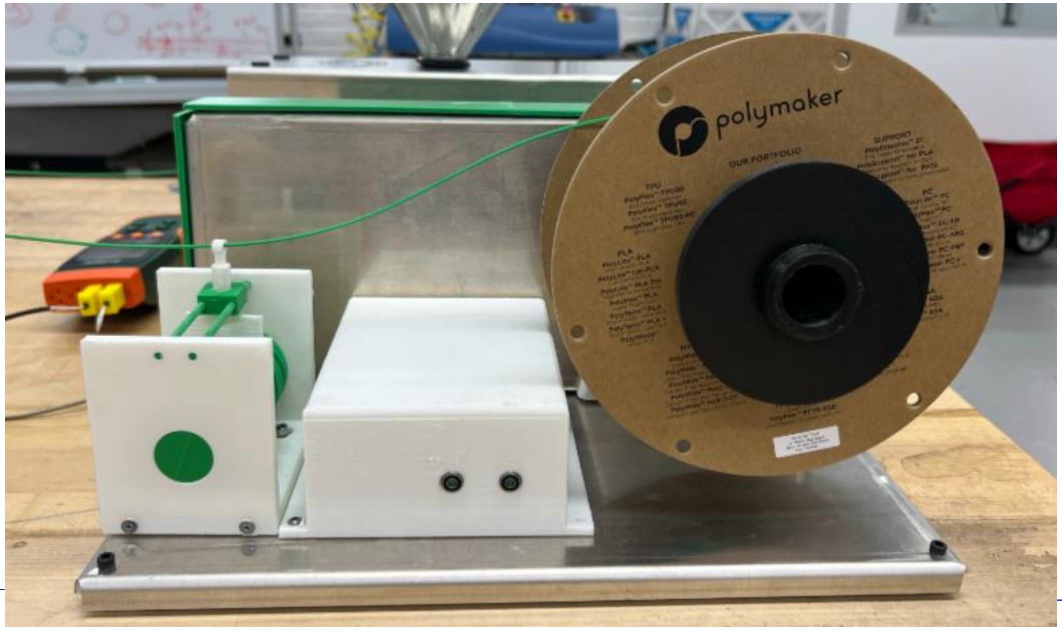


Winder Subsystem

Prototype of the winder

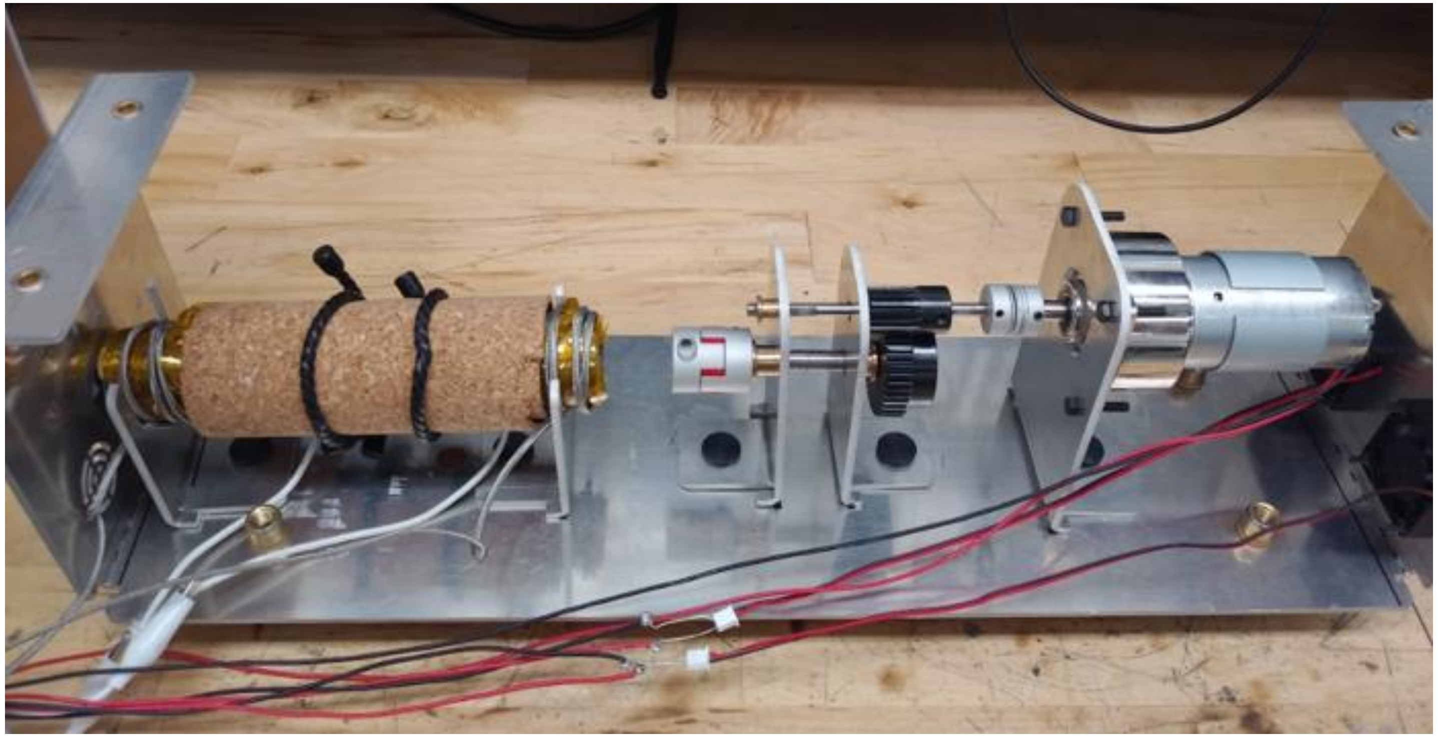


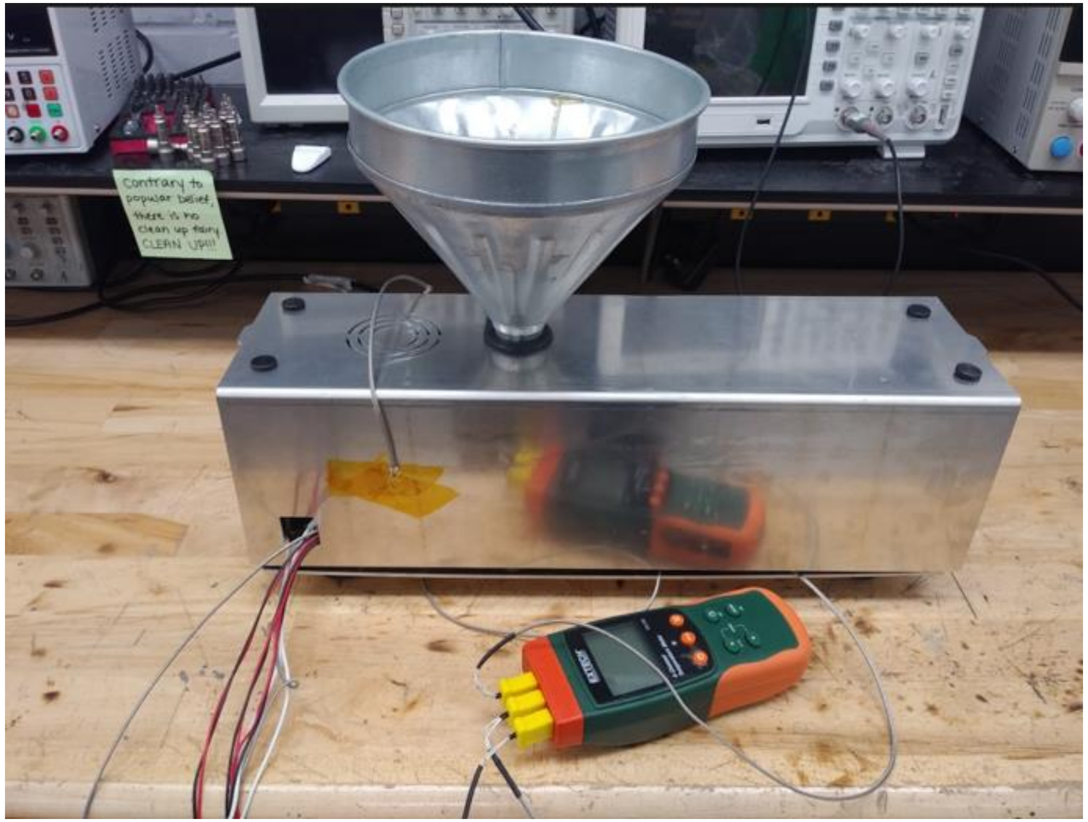




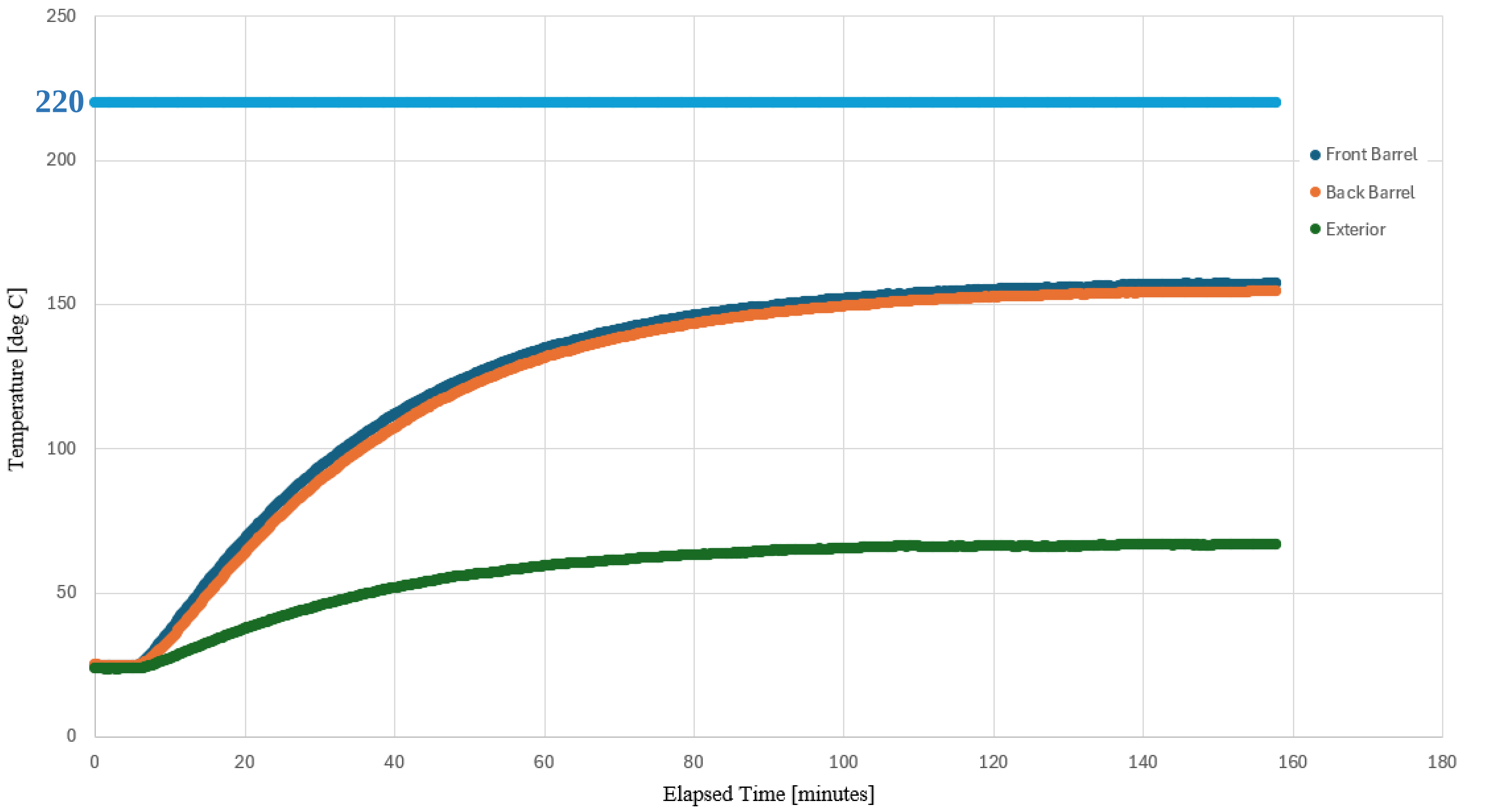
Performance Evaluation/Testing Results

Extruder Barrel Heating

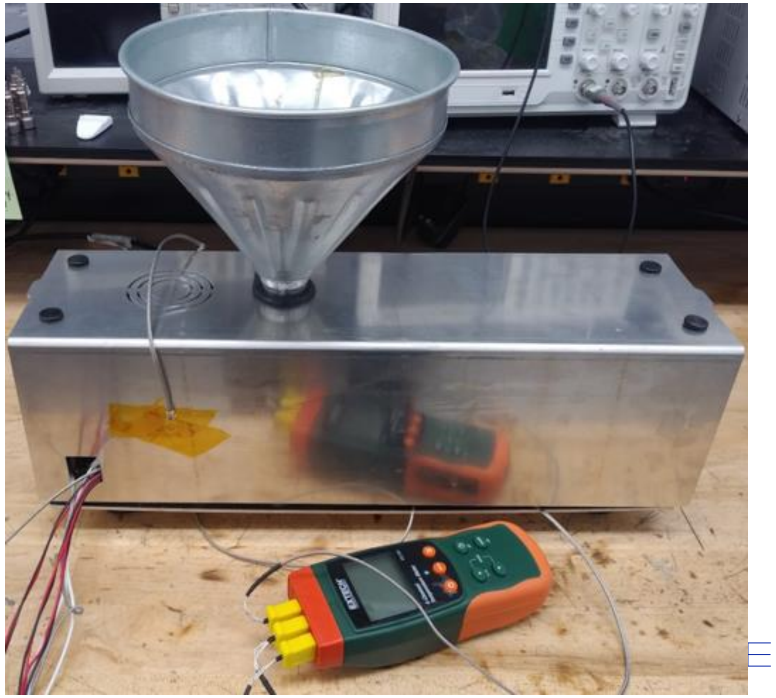


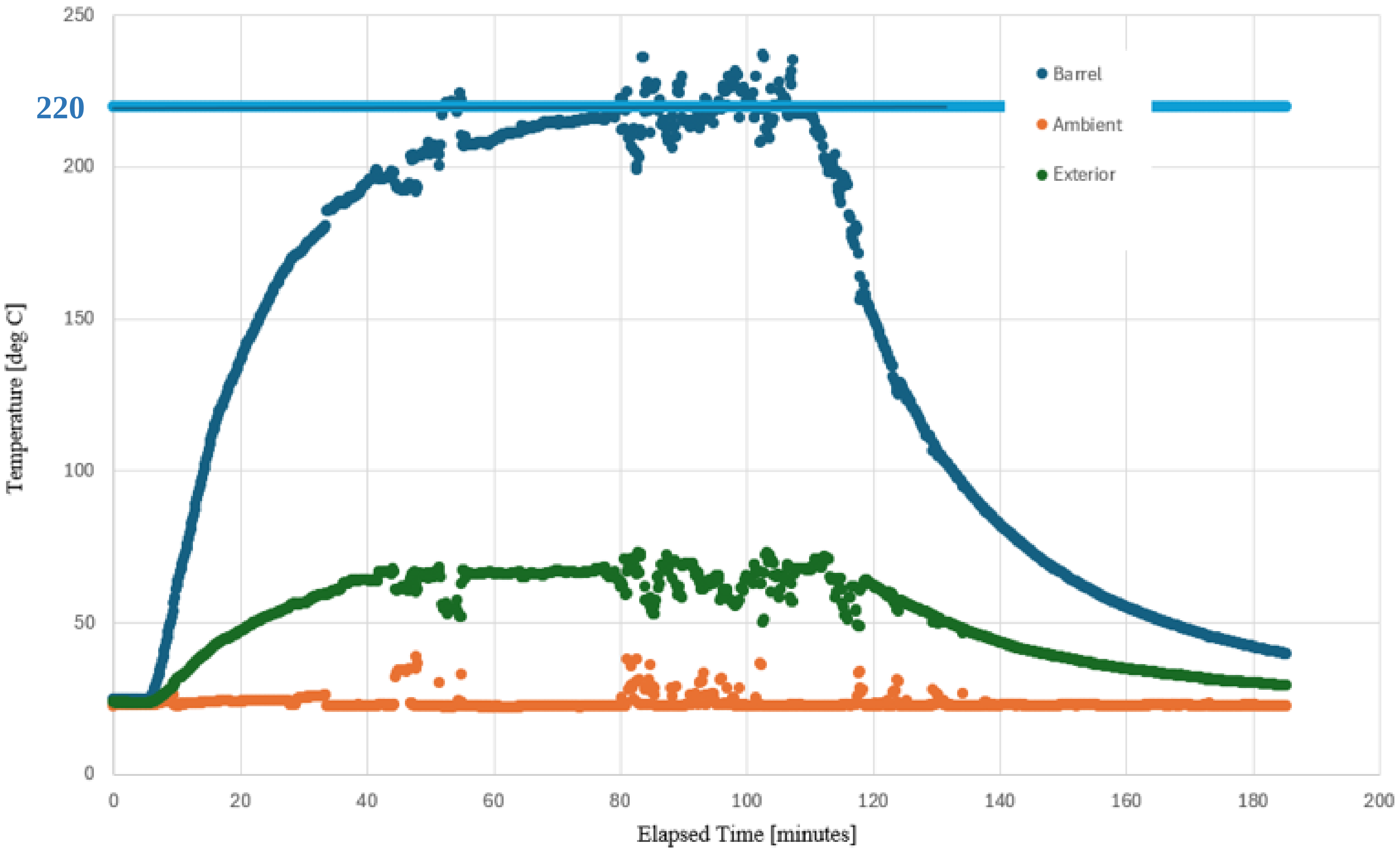


Extruder Barrel Heating

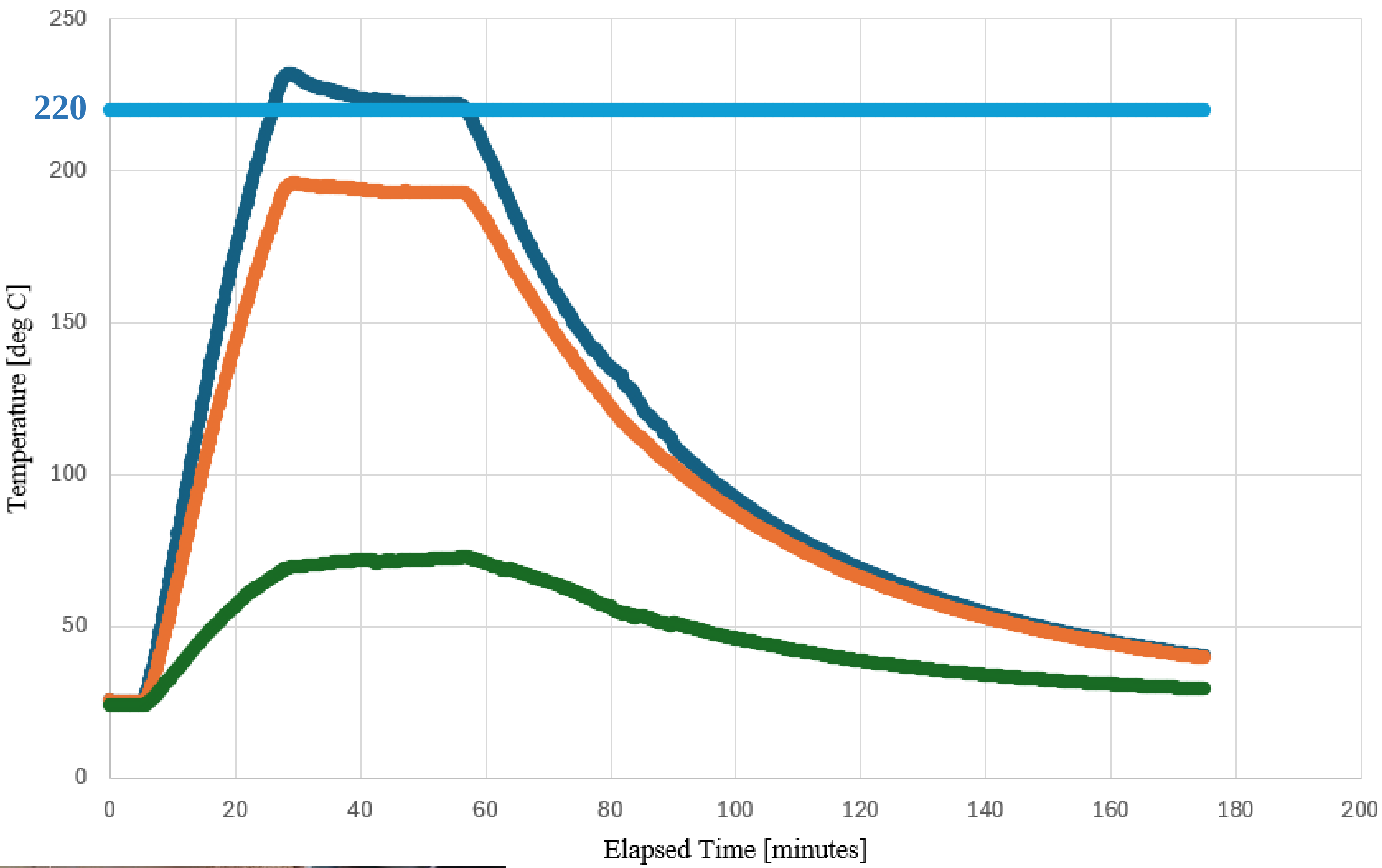


Extruder Barrel Heating

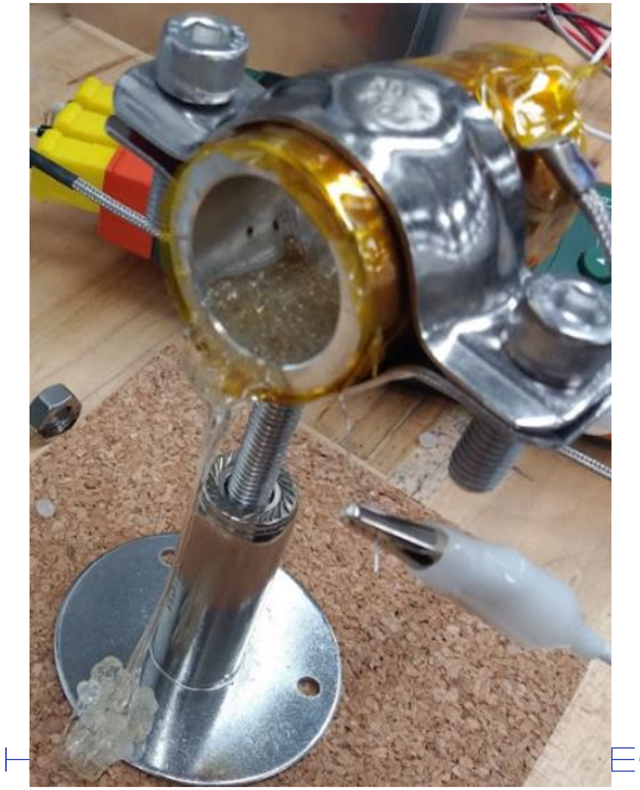




Extruder Barrel Heating



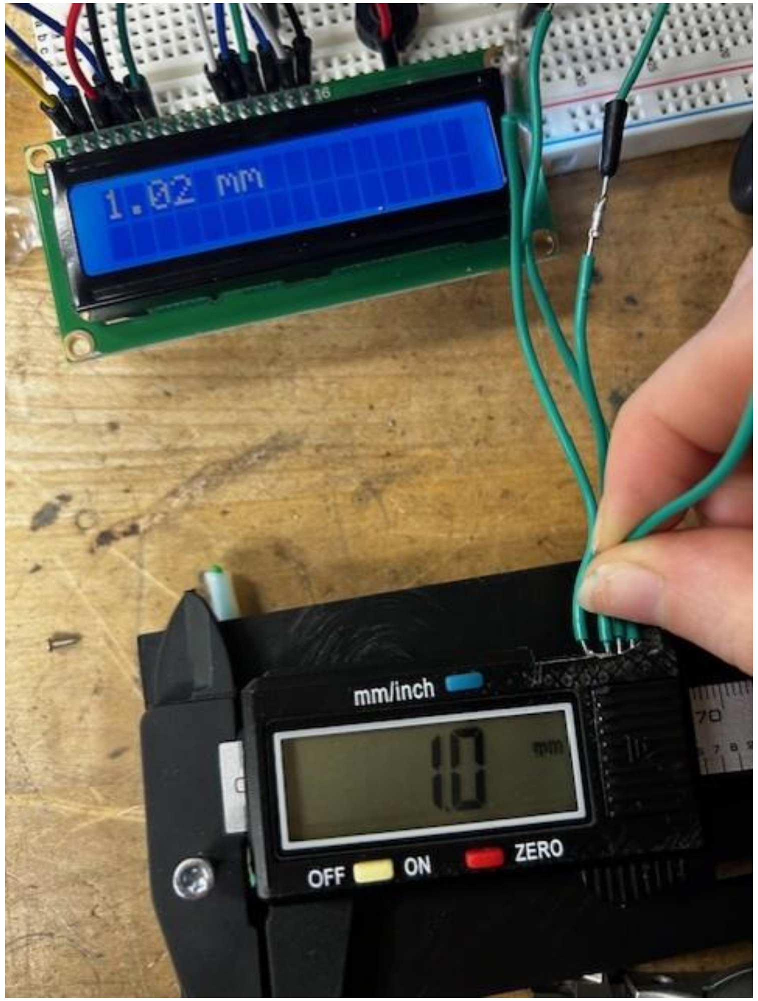
Melting Pellets



Diameter Sensor: Wheels

- High grip, low force
- Rivets for filament

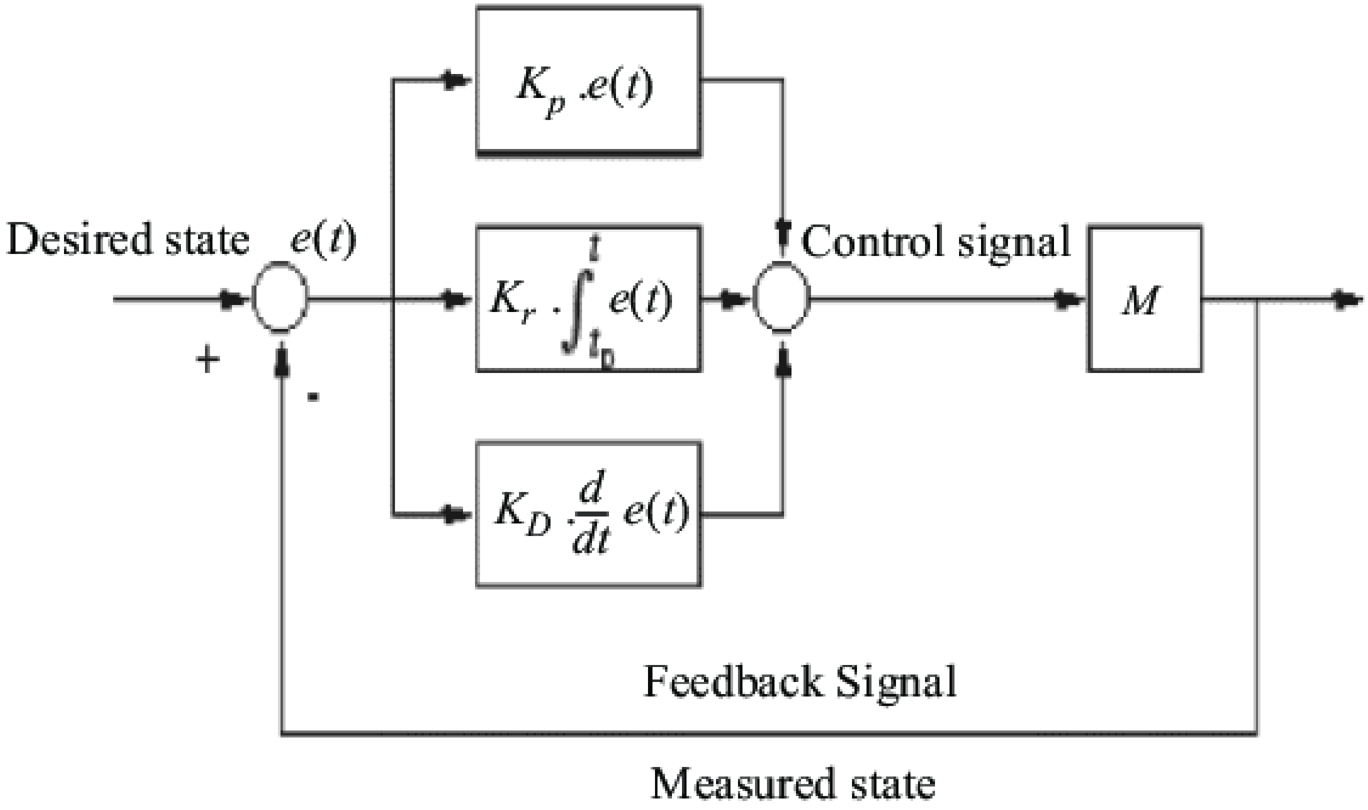
Diameter Sensor: 2nd Prototype



- Automated Caliper
- 2 decimal places
- Bearing displacement
- Precise, but needs calibration
- Accessible and cheap
- Makes use of pre-existing technology

Calculations

PID Controller



Thermodynamics/Heat Transfer – Barrel Heating

1. Customer Needs Statement 18 – Warm Up Rate
2. Needed to calculate energy in vs energy out, steady state
3. Generate 1st law equation:

$$\frac{dE}{dt} = W_{in,mechanical} + W_{in,electrical} - Q_{out} - \frac{dm}{dt}(H_{in} - H_{out})$$

4. Simplifies down to:

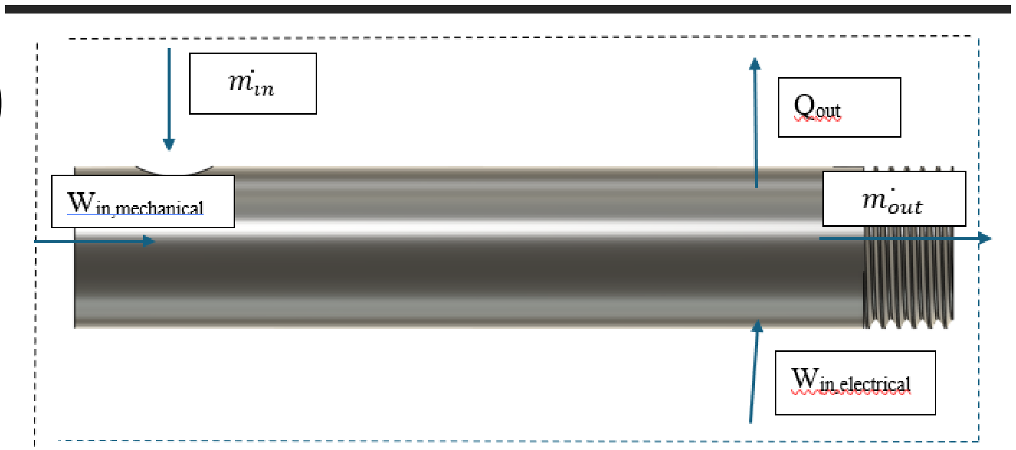
$$0 = (\tau\omega) + (VI) - \left(hA(T - T_{\infty})\right) - (\dot{m}C(T_{in} - T_{out}))$$

5. Solve for h (heat transfer coefficient) using 3 equations:

$$1.\ Nu = \frac{hD}{k}$$

$$2.\ Nu = 0.52\left(R_a{}^{\frac{1}{4}}\right)$$

$$3.\ R_a = \frac{g\beta\Delta T L^3}{\alpha\mu}$$



6. $R_a = 24{,}040, Nu = 6.4751, h = 4.6615$

7. I = 2.386 Amps

Thermodynamics/Heat Transfer – Barrel Heating

8. Barrel requires about 70kJ of energy (Q) to heat:

$$P = \frac{Q}{t}$$

9. P = $W_{in,mechanical} + W_{in,electrical} = 39.1040 \text{ Watts}$

10. Solve the equation for t, time, and you get about 31.4 minutes required to heat up the barrel to $220℃$ steady state temperature

8. Barrel requires about 70kJ of energy (Q) to heat:

$$P = \frac{Q}{t}$$

9. P = $W_{in,mechanical} + W_{in,electrical} = 39.1040 \text{ Watts}$

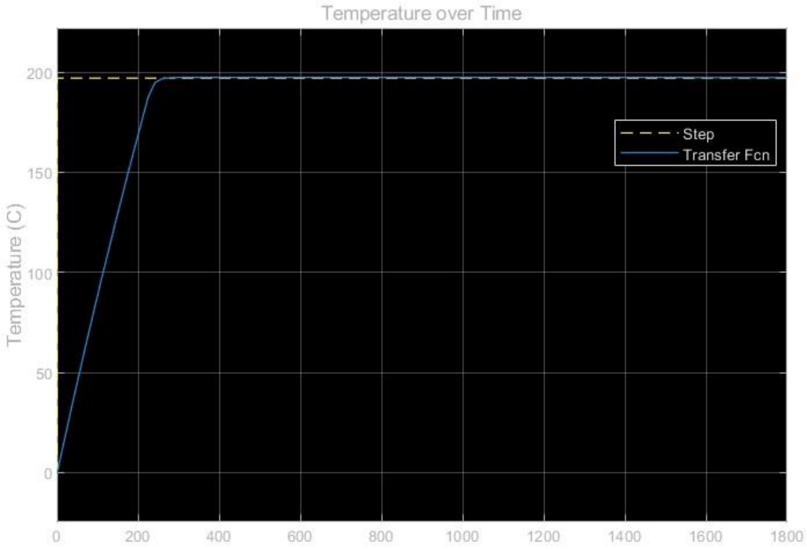
10. Solve the equation for t, time, and you get about 31.4 minutes required to heat up the barrel to $220℃$ steady state temperature

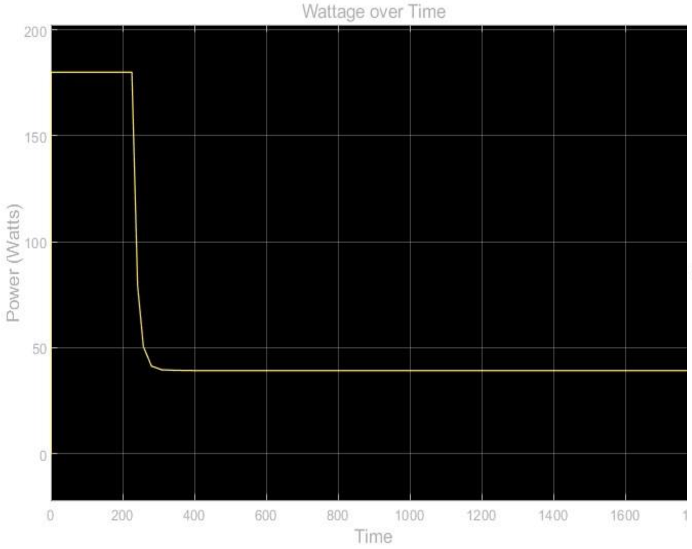
PID Controller – Barrel Heating

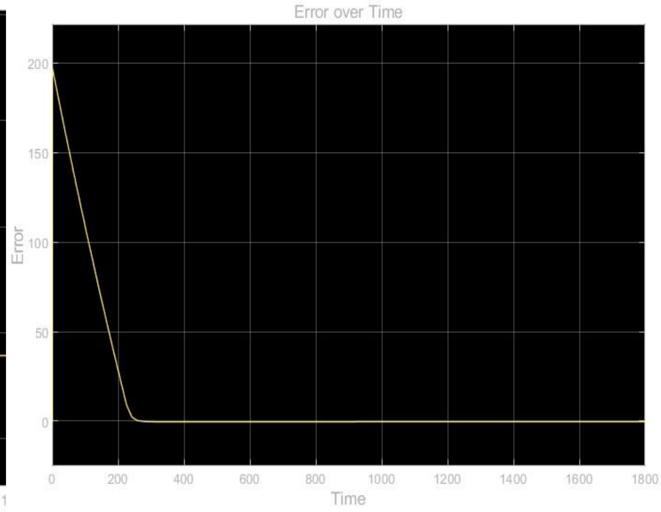
- We can model the dynamics of the system through a transfer function in the form of:

$$G(s) = \frac{K_{DC}}{\tau s + 1}$$

- τ is the time it takes to reach 63% of the final steady state output = 968.3 seconds
- K_{DC} is the relationship between the steady state output and constant input = 5.0378
- Using Simulink, we get the following gains:
- $K_p = 15$
- $K_I = 0.002$
- $K_D = 0$



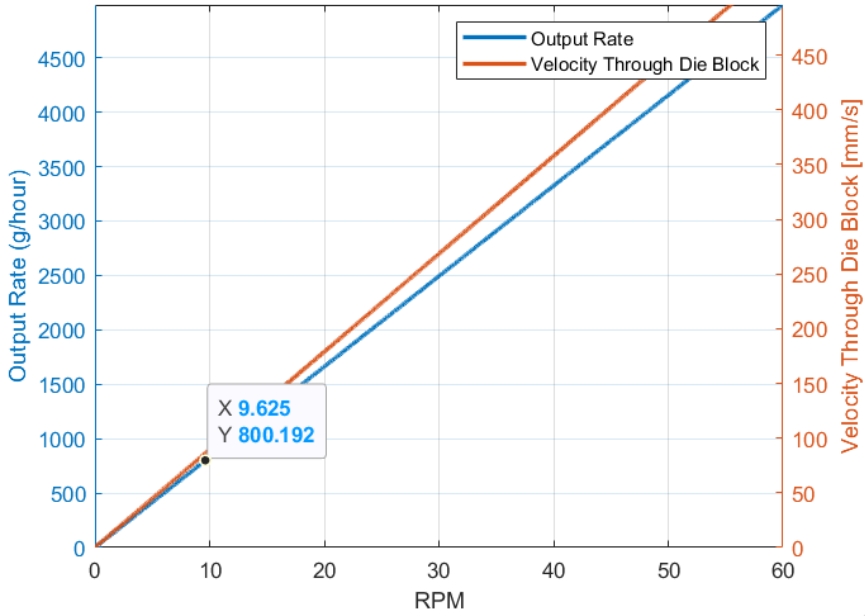




Plastic Extrusion Analysis

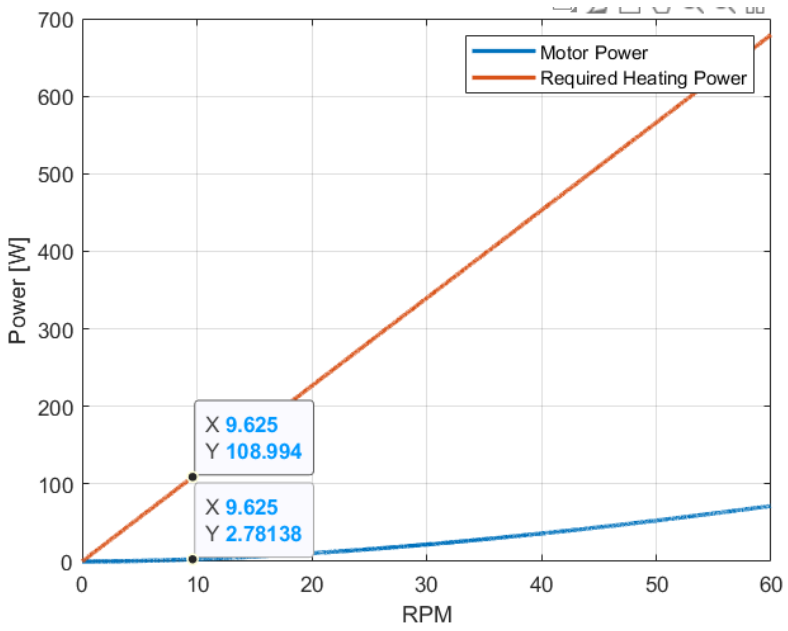
Customer Needs Statement 1 – Able to maintain constant extrusion rate of 0.8 kg/hour

Drag Flow Approximation

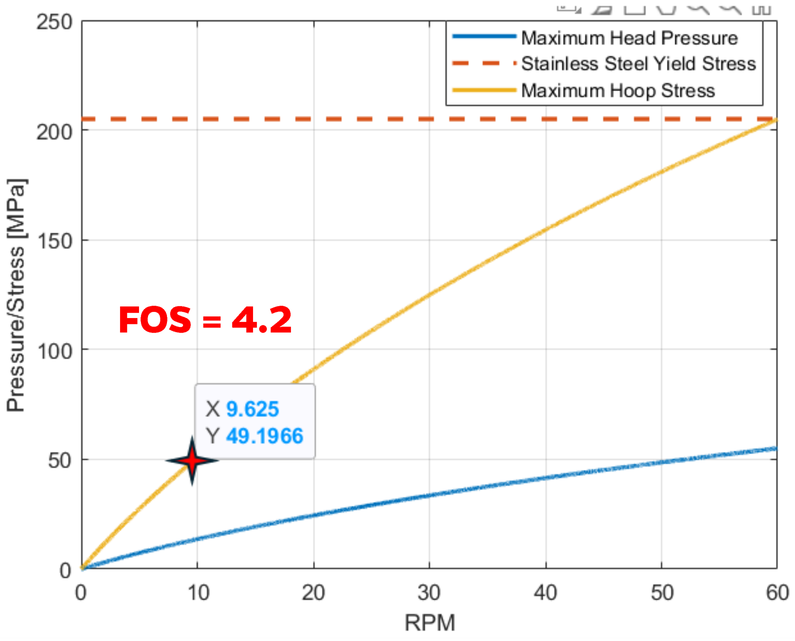


$$Q_d = 0.5\pi^2 * D^2 * N * h * \sin A * \cos A$$

Required vs. Supplied Heating

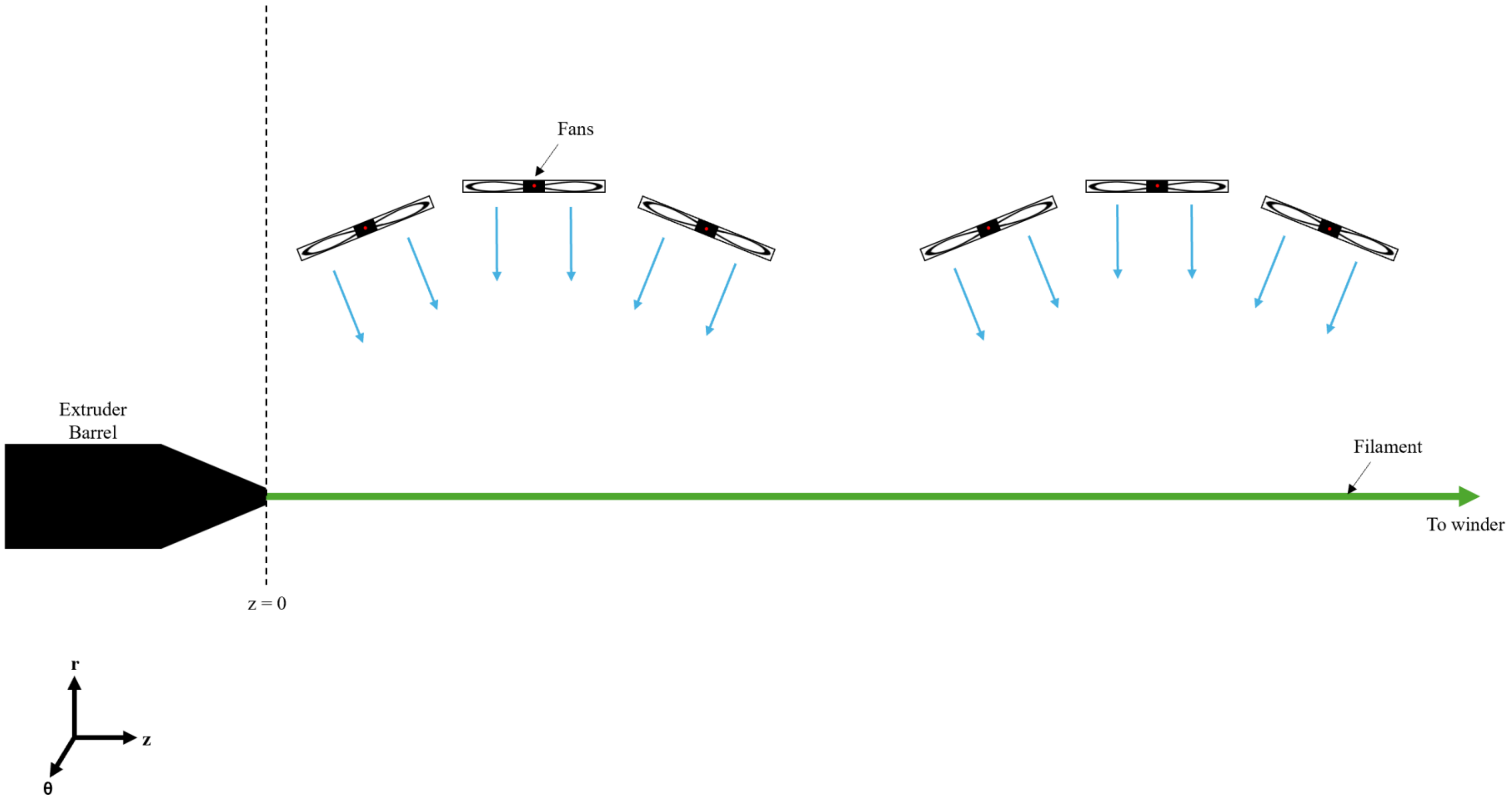


Maximum Thick-Wall Hoop Stress



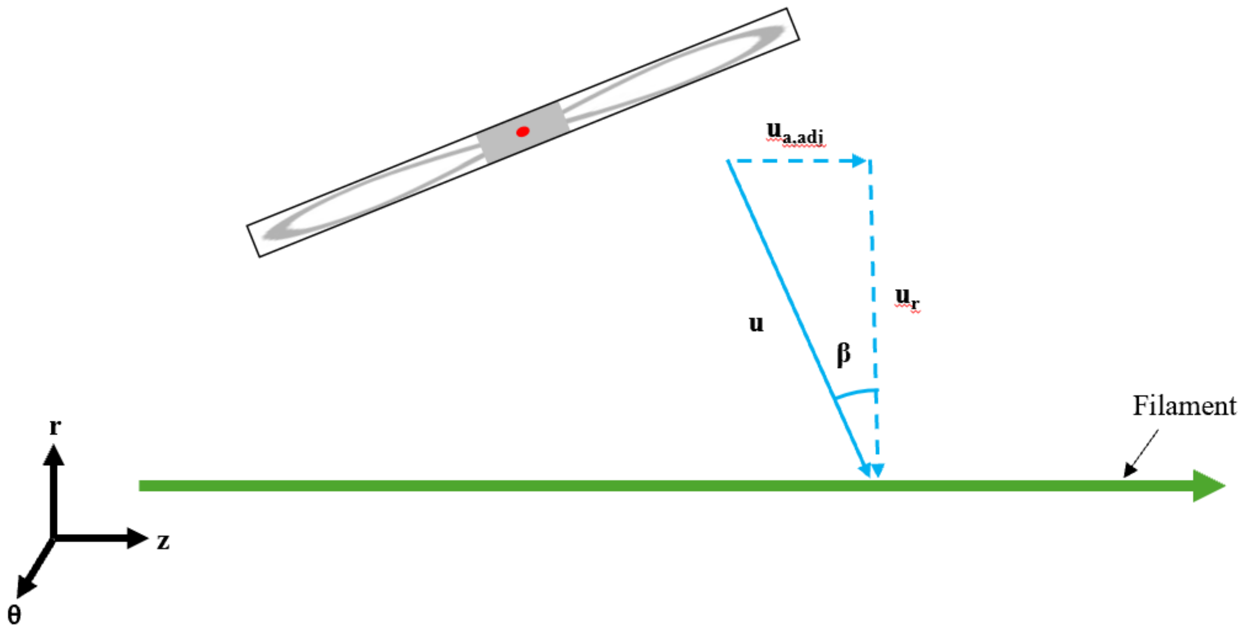
$$\sigma_{circumferential\ ,\ maximum} = P_{max}\left(\frac{r_i^2 + r_o^2}{r_o^2 - r_i^2}\right)$$

Cooling System Configuration



Fan Flow Addition

- Found resultant velocity and direction (angle) interacting with the filament from all fans



$$u_a = \left(\frac{1}{n}\right) \sum_{i=1}^{n} u_{a,fan_i}$$

$$u_r = \left(\frac{1}{n}\right) \sum_{i=1}^{n} u_{r,fan_i}$$

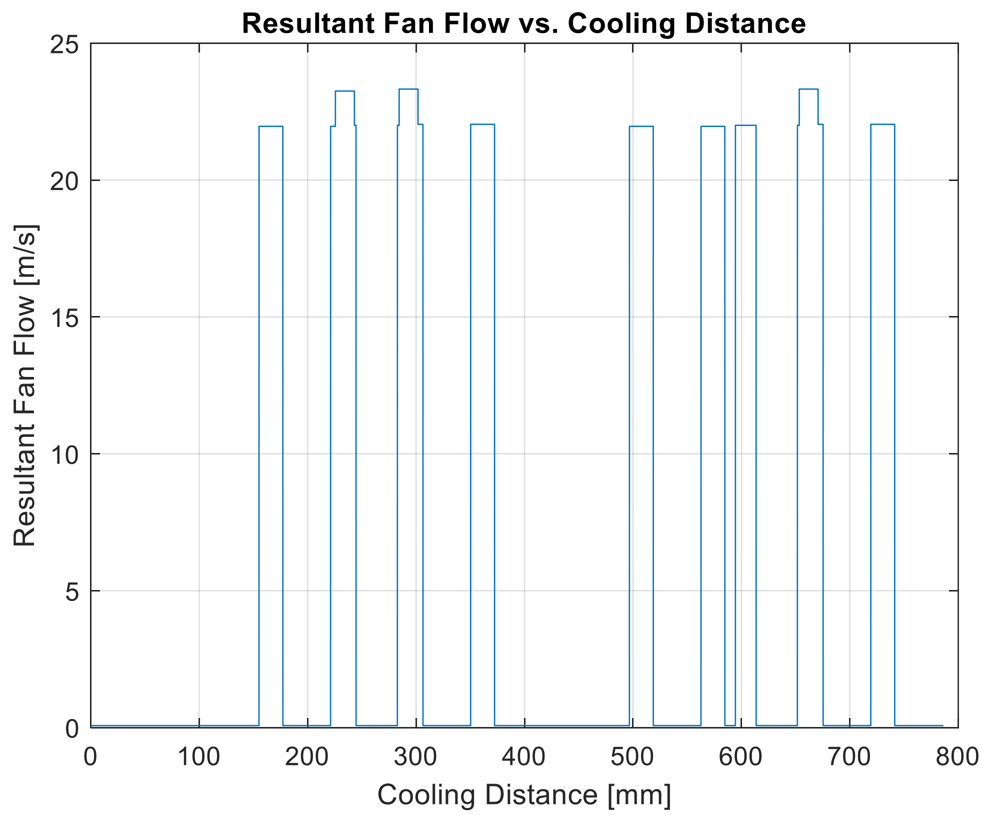
$$u_{a,adj} = u_a - u_{ext}$$

$$u = \sqrt{{u_{a,adj}}^2 + {u_r}^2}$$

$$\beta = \tan^{-1}\left(\frac{u_{a,adj}}{u_r}\right)$$

Fan Flow Addition

- Resultant flow velocity acting on filament over cooling path



Determination of Flow Properties

- Flow parameters used for heat transfer analysis found using empirical Nusselt number equation

$$Re = \frac{uD_{fil}}{\nu}$$

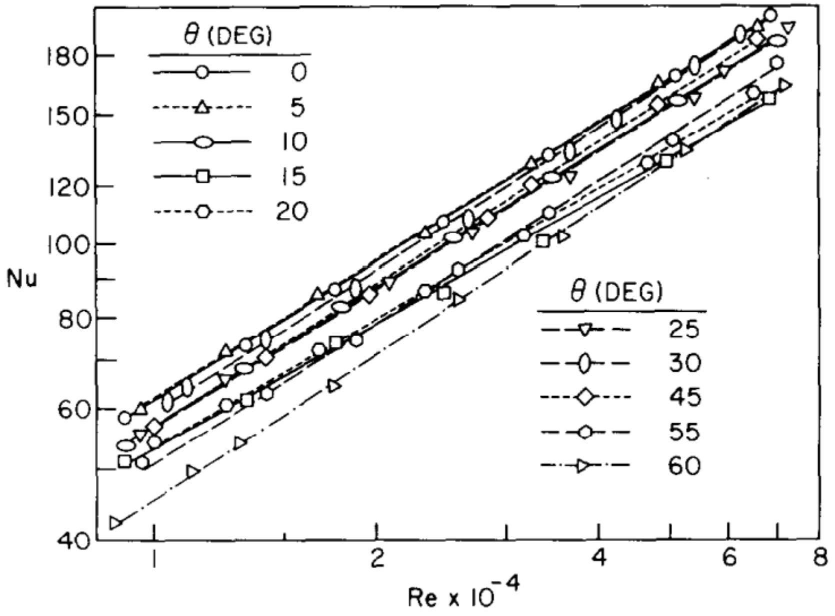
$$Nu = CRe^{n}$$

$$h = \frac{Nu * k}{D_{fil}}$$

Table 2. The constants C and n for equation (5)

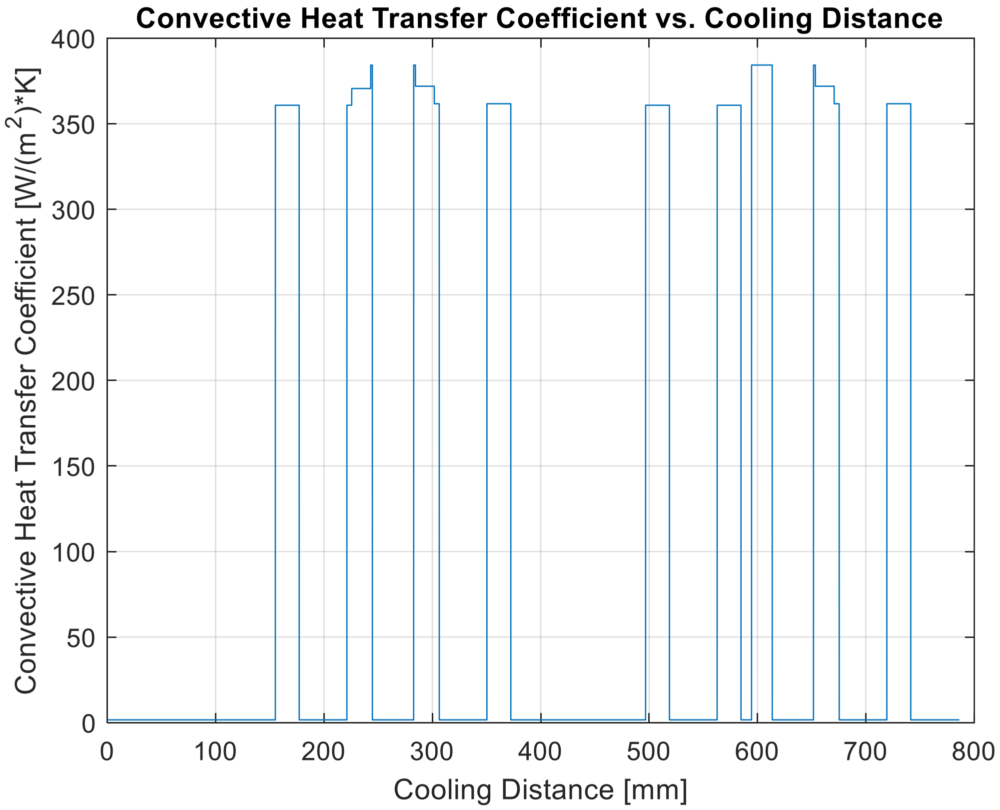
θ (deg.)	C	n
0	0.207	0.618
5	0.217	0.614
10	0.200	0.614
15	0.302	0.561
20	0.270	0.574
25	0.187	0.620
30	0.172	0.634
45	0.161	0.636
55	0.152	0.630
60	0.113	0.651

Effect of yaw on forced convection heat transfer



Determination of Flow Properties

- Convective heat transfer coefficient over length of cooling path



Lumped Capacitance

- Lumped capacitance is invalid because Bi > 0.1 for predicted fan flow of 22 m/s

$$Bi = \frac{h_{max} r_o}{k_{PLA}}$$

$$Bi = \frac{\left(384.31\ {}^{W}\!/_{m^2 * K}\right)\left(8.75 \text{ x } 10^{-4}\ m\right)}{\left(0.183\ {}^{W}\!/_{m * K}\right)} = 1.838$$

Exact Solution

- Exact solution is invalid because external flow conditions change with time
- Iterative solution requires updating non-uniform initial conditions, however, the exact solution assumes uniform initial conditions

$$\frac{T - T_\infty}{T_i - T_\infty} = \sum_{n=1}^{\infty} C_n \exp\left(-\zeta_n{}^2 Fo\right) * \mathrm{J}_0\left(\zeta_n{}^2 r^*\right)$$

$$C_n = \frac{2}{\zeta_n}\left(\frac{\mathrm{J}_1\left(\zeta_n\right)}{\mathrm{J}_0{}^2\left(\zeta_n\right) + \mathrm{J}_1{}^2\left(\zeta_n\right)}\right)$$

$$\zeta_n\left(\frac{\mathrm{J}_1(\zeta_n)}{\mathrm{J}_0(\zeta_n)}\right) = Bi$$

$$Bi = \frac{hr_o}{k}$$

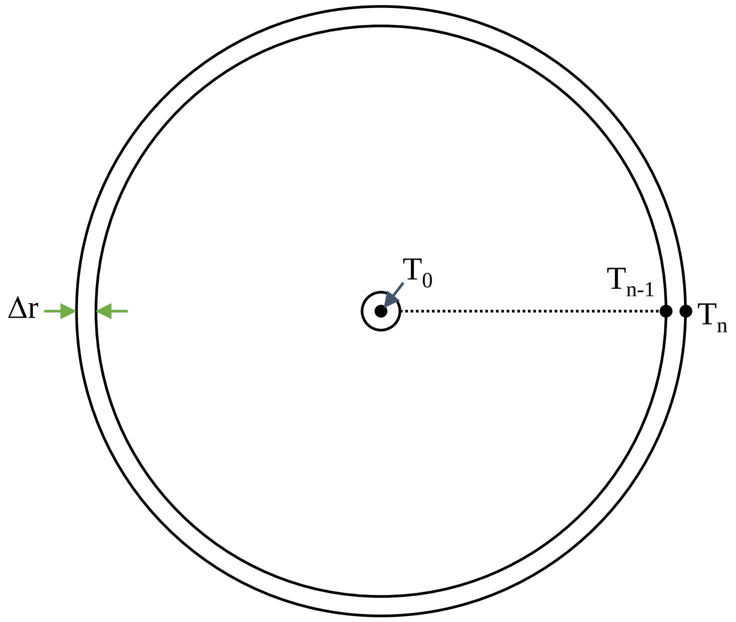
$$Fo = \frac{\alpha t}{r_o{}^2}$$

$$\alpha = \frac{k}{\rho c_p}$$

$$r^* = \frac{r}{r_o}$$

Finite Difference Method - Discretization

- Heat transfer problem was discretized with respect to both time and filament radius
- Temperature is assumed to be constant at each filament radius
- Easy transformation from time elapsed to position along cooling length: $\Delta z = u_{ext}(\Delta t)$



Finite Difference Method - Explicit

- Finite difference methods were used to find temperature distribution across the filament over time
- Explicit method predicts temperature at the next time step directly (explicitly) using the temperature distribution at the previous time step
- Conceptually simpler but requires satisfying convergence conditions
- The maximum time step for convergence is the largest time step that satisfies all convergence conditions

Finite Difference Method - Explicit

- The following are the explicit finite difference method equations and their convergence conditions:

Outer Surface: $$T_n^{p+1} = 2Fo\left[\left(\frac{r_n Bi}{r_{n-1}}\right)T_\infty + T_{n-1}^p\right] + \left(1 - 2Fo - \frac{2r_n BiFo}{r_{n-1}}\right)T_n^p$$

$$\Delta t \leq \frac{(\Delta r)^2}{2\alpha\left(1+\frac{r_n Bi}{r_{n-1}}\right)}$$

Other Elements: $$T_i^{p+1} = \left(\frac{Fo(\Delta r + 2r_i)}{2r_i}\right)T_{i+1}^p + (1 - 2Fo)T_i^p + \left(\frac{Fo(2r_i - \Delta r)}{2r_i}\right)T_{i-1}^p$$

$$\Delta t \leq \frac{(\Delta r)^2}{2\alpha}$$

Central Element: $$T_0^{p+1} = Fo\left(T_2^p - 2T_1^p\right) + \left(Fo + 1\right)T_0^p$$

$$\Delta t \geq \frac{-(\Delta r)^2}{\alpha}$$ (always satisfied!)

Finite Difference Method - Implicit

- There are no convergence conditions for the implicit method, meaning less computation time without sacrificing much or any accuracy

- The following are the implicit finite difference method equations:

Outer Surface: $\left(1 + 2Fo + \frac{2r_n BiFo}{r_{n-1}}\right)T_n^{p+1} - 2FoT_{n-1}^{p+1} = T_n^p + \left(\frac{2r_n BiFo}{r_{n-1}}\right)T_\infty$

Other Elements: $\left(\frac{-Fo(\Delta r + 2r_i)}{2r_i}\right)T_{i+1}^{p+1} + (1 + 2Fo)T_i^{p+1} + \left(\frac{Fo(\Delta r - 2r_i)}{2r_i}\right)T_{i-1}^{p+1} = T_i^p$

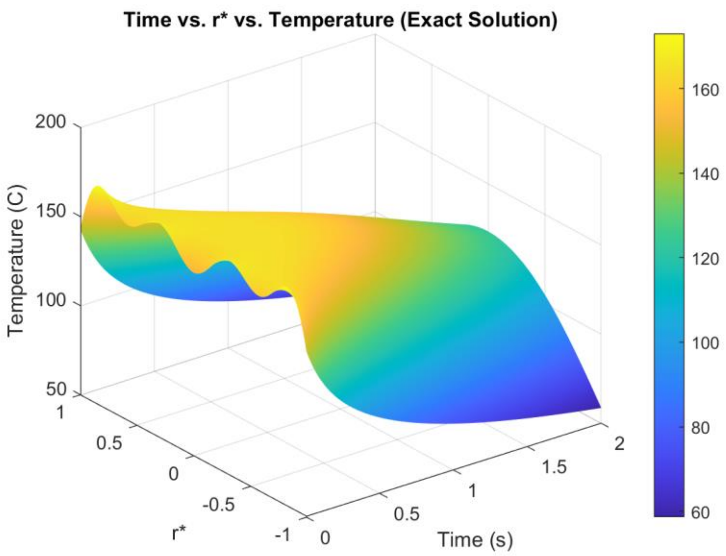
Central Element: $(2Fo + 1)T_0^{p+1} - 2FoT_1^{p+1} = T_0^p$

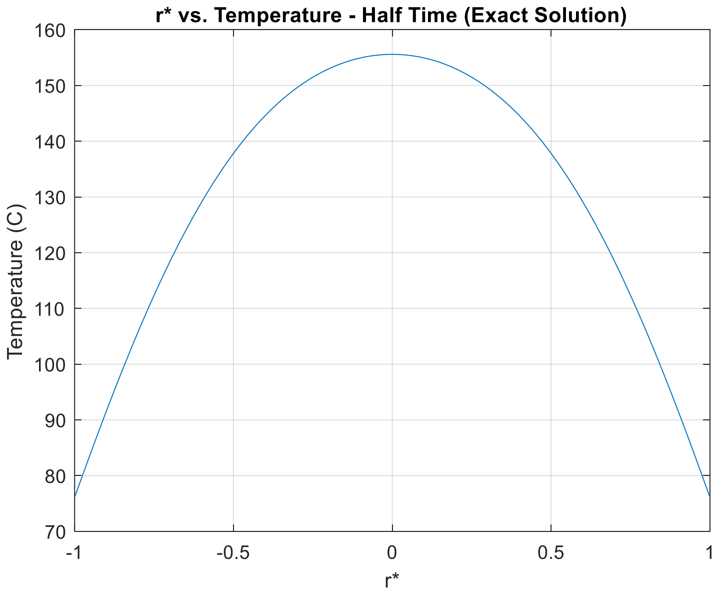
coefficients — constants (including T^p values)

$$\{\boldsymbol{T^{p+1}}\} = [\boldsymbol{A}]^{-1}\{\boldsymbol{C}\}$$

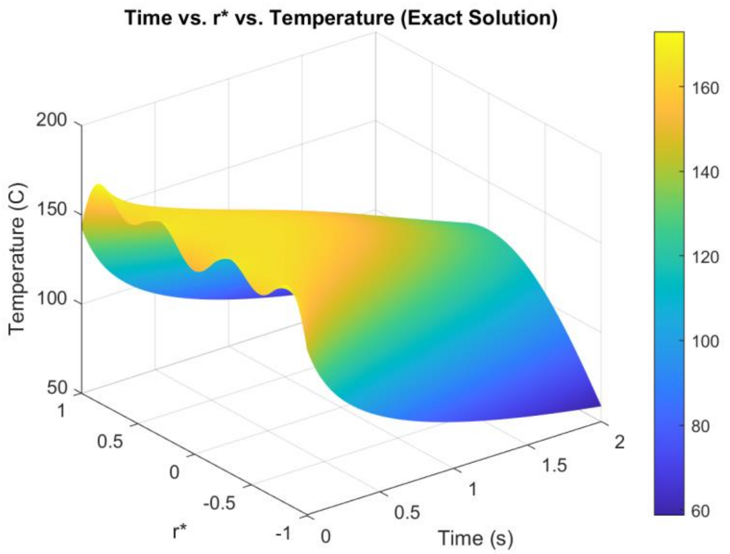
Test Scenario

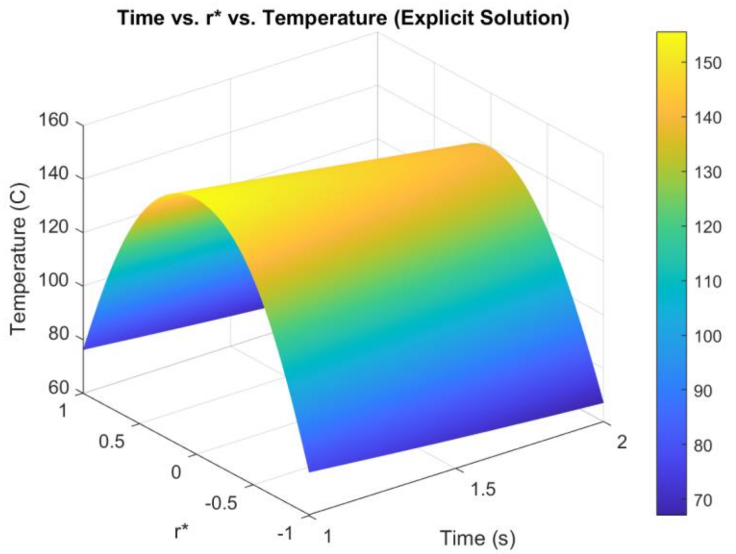
- A test scenario with constant external conditions was performed to assess the validity of the explicit and implicit finite difference methods
- Similar conditions to the actual cooling scenario used for test
- The total test time was 2 seconds, and the exact temperature profile at t = 1 sec was used as the initial condition for the finite difference heat transfer methods

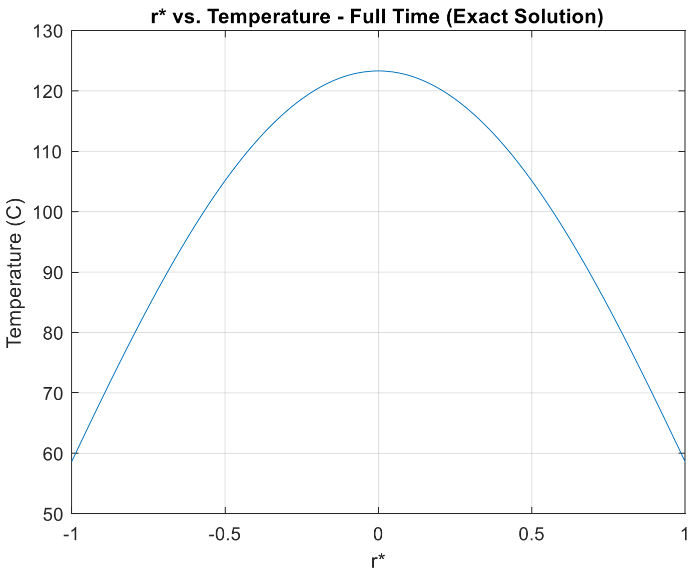


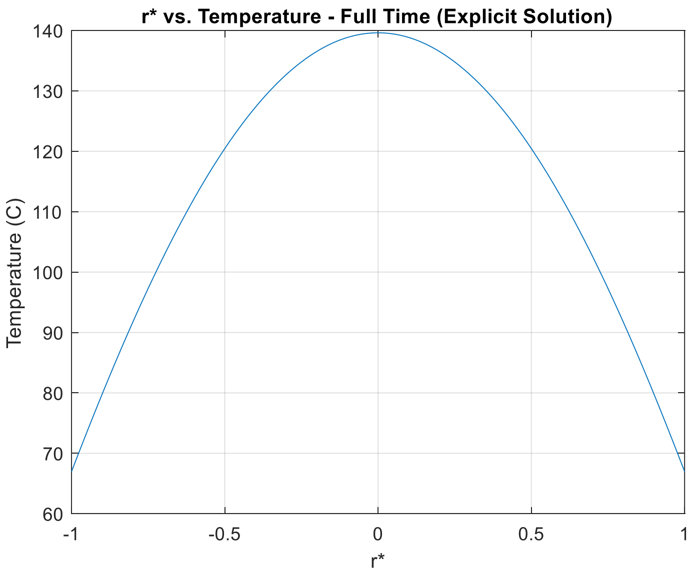


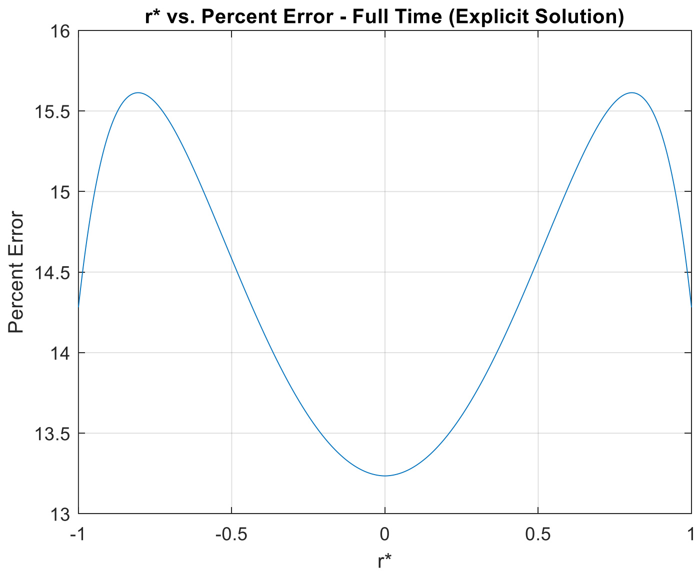
Test Scenario – Explicit Method



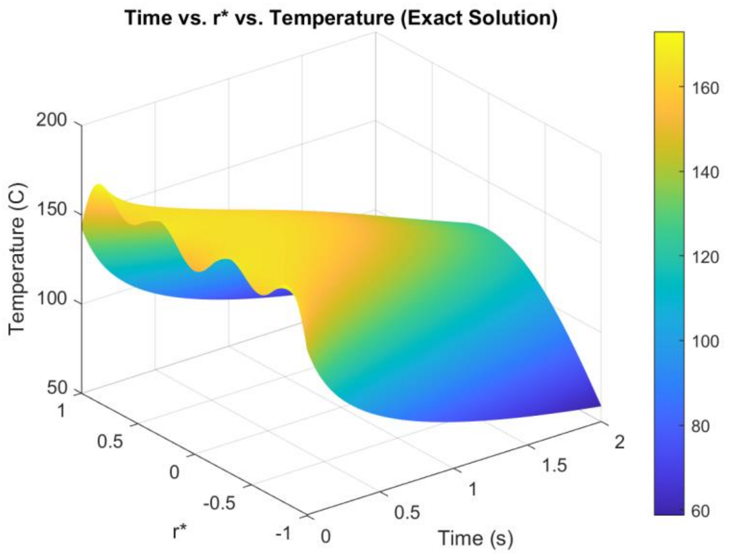


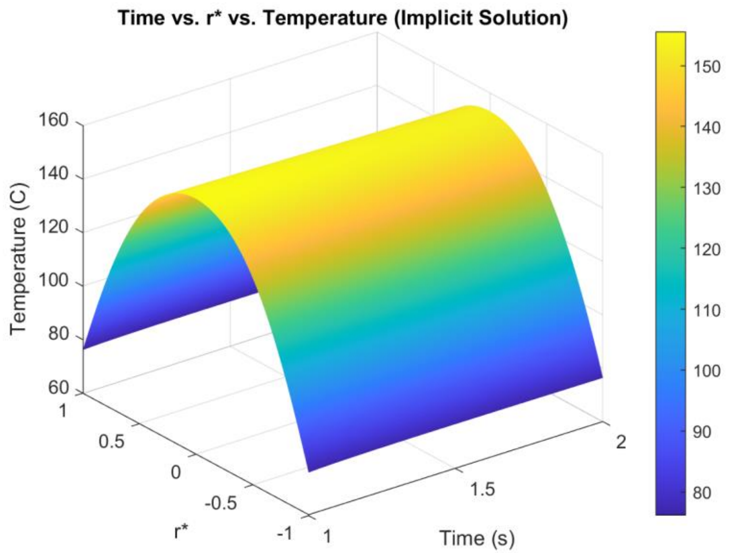


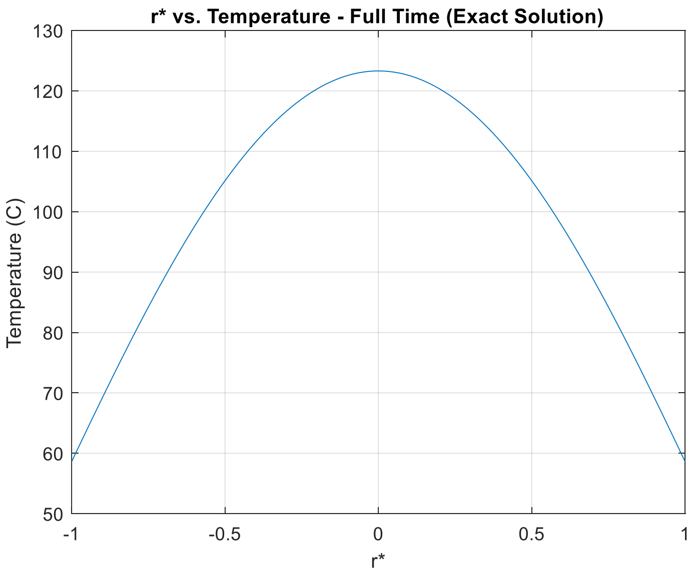


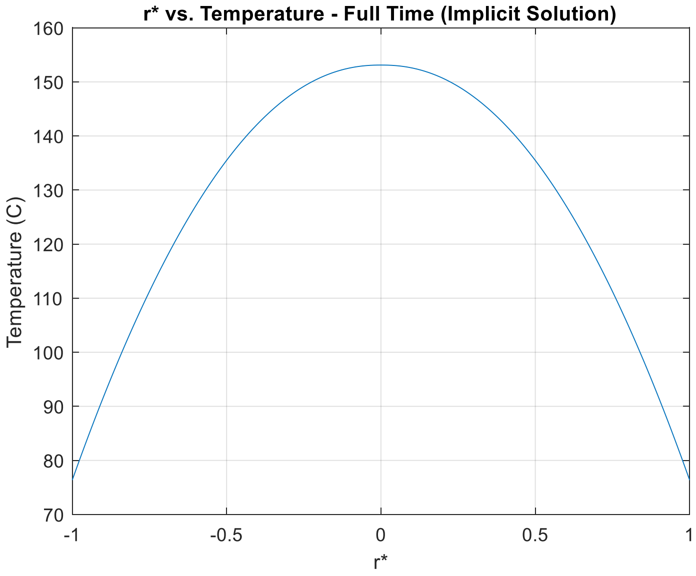


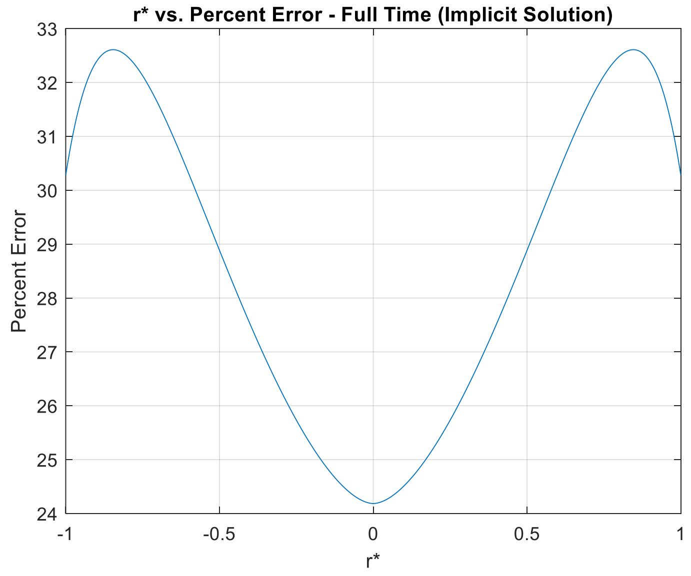
Test Scenario – Implicit Method





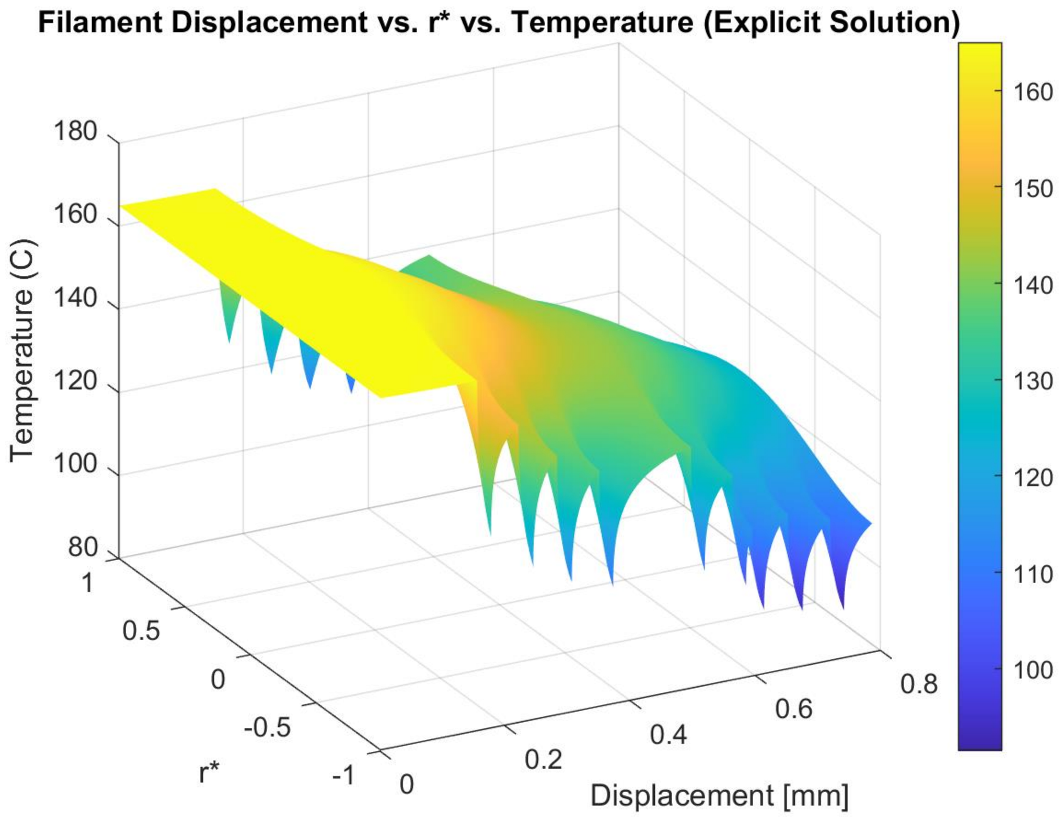


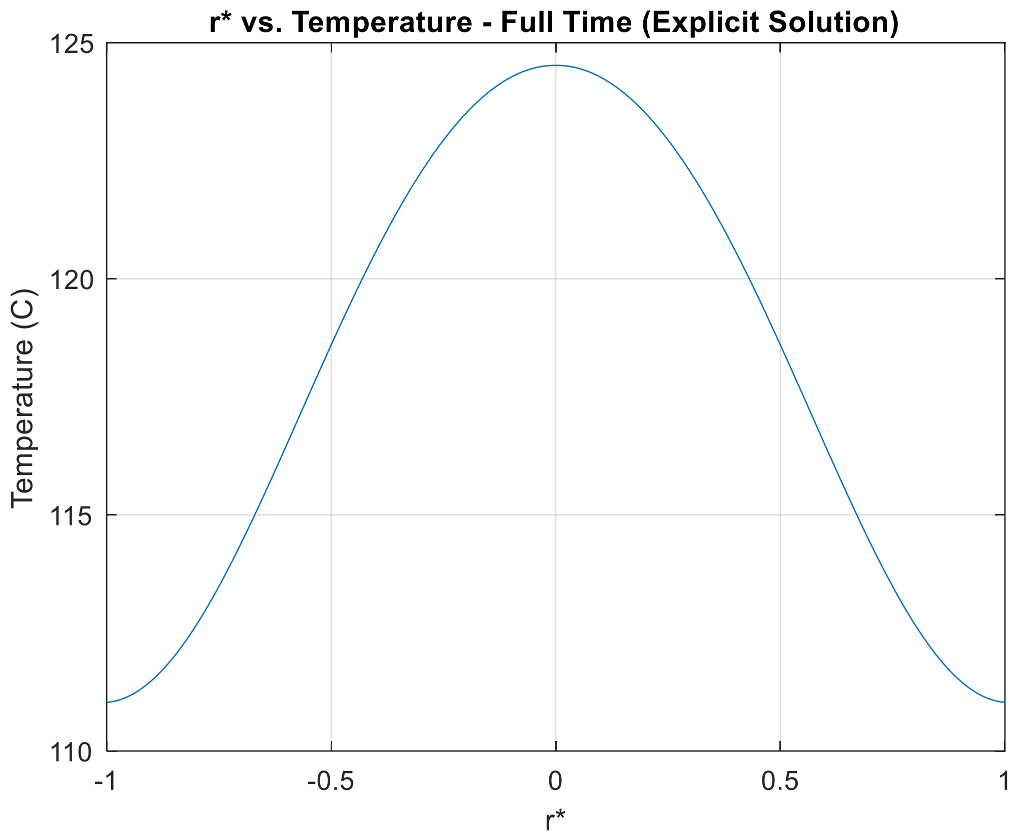




Filament Cooling – Explicit Method

- Temperature distribution along cooling path calculated using explicit transient heat transfer:





Improvements

- Time, Testing, and Tender!
- Trying new sensors
- Create winder based on extruder
- Adding controls for other filament types
- Certain parts manufactured over 3D printed
- Redo extruder design, but reverse engineer Artme3D first

What Makes Our Design Unique

- Diameter sensor is recyclable!
  - Build your own replacement and customizable
- Spool
- 3-D printed parts: Affordability

UF | Herbert Wertheim College of Engineering
UNIVERSITY *of* FLORIDA

Winder Calculations (For Controls)

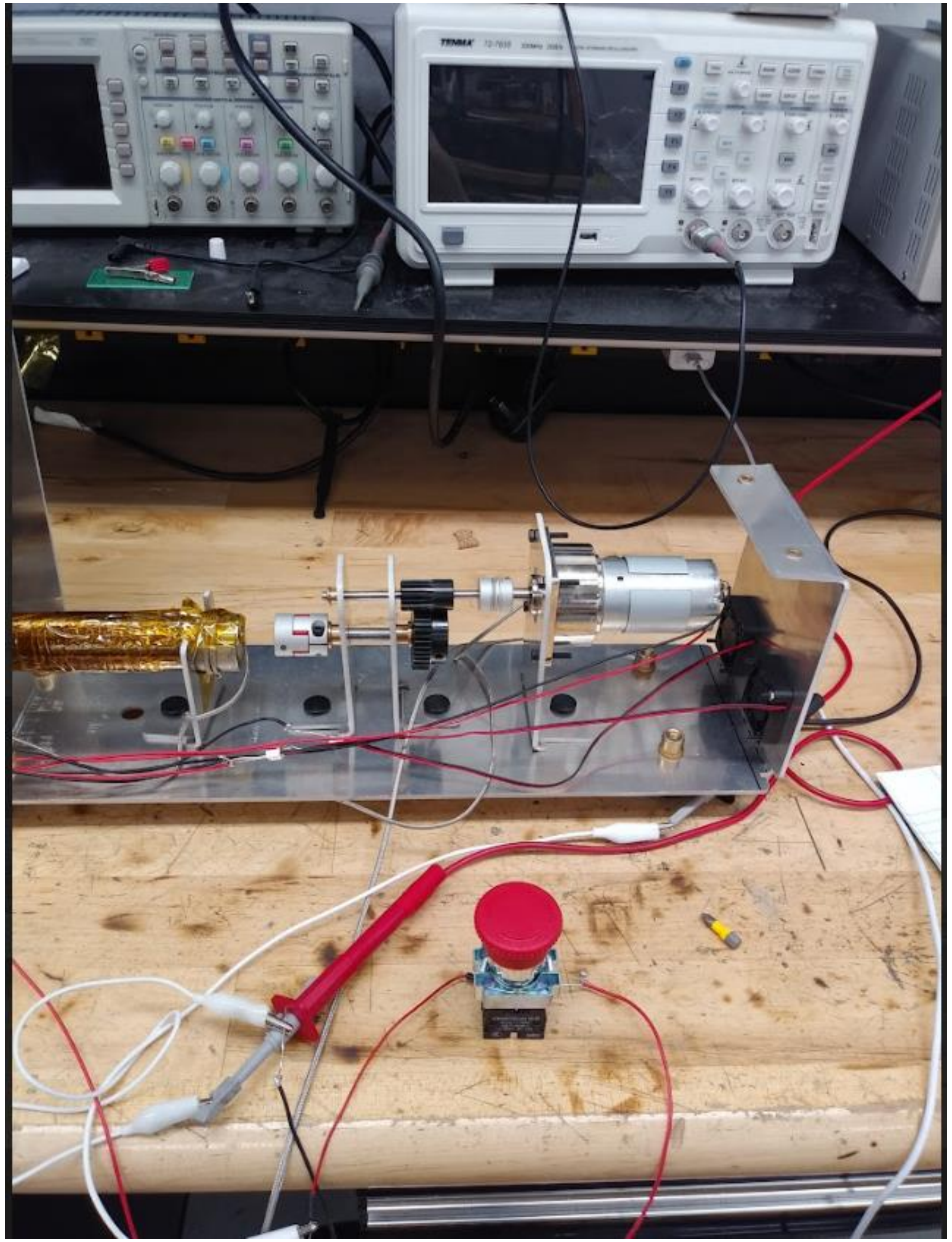
- Follows Customer Need of 800 g/hr at a diameter of 1.75 mm
- Assumes no slipping of gears/belt
- Assumes constant filament density and radius
- Density=1.252 g/cm^3
- Spool Circumference =49.5046 mm

$$\frac{Extrusion\ Rate\ \left(\frac{g}{hr}\right)}{Density * Area} = \frac{\frac{800\ g}{1\ hr} * \frac{1\ hr}{60\ min}}{\frac{0.001252\ g}{1\ mm^3} * \pi\left(\frac{1.75\ mm}{2}\right)^2} = 73.911\ \frac{mm}{min}$$

$$\frac{Extrusion\ Rate\ \left(\frac{mm}{min}\right)}{Circumference\ (mm)} = \frac{73.911\ \frac{mm}{min}}{2\pi * 49.5046\ mm} = 12.471\ rpm$$

$$\frac{\partial}{\partial r}(RPM) = -\frac{73.911\ \frac{mm}{min}}{2\pi * r^2} = -\frac{11.763}{r^2} = Rate\ of\ decreasing\ rpm$$

E-Stop



Calculate: ○ Volts ◉ Temp

Resistance Wire

Nichrome 60

Gauge	Length (inches)
28	36

Transformer Volts Out 25.7

Copper Lead Wire

Gauge	Length (feet)

Resistance Wire

Ω/Ft:	Ohms	Volts:
4.24	12.71	25.7

Dia (in):	Dia (mm)
0.0126	0.321

Copper Wire

Ω/Ft:	Ohms	Volts:
NaN	0	0

Amps	Watts
2	52

Temp °F 830 **°C** 446

Calculate: ○ Volts ◉ Temp

Resistance Wire

Nichrome 60

Gauge	Length (inches)
28	85

Transformer Volts Out 60

Copper Lead Wire

Gauge	Length (feet)

Resistance Wire

Ω/Ft:	Ohms	Volts:
4.24	30	60

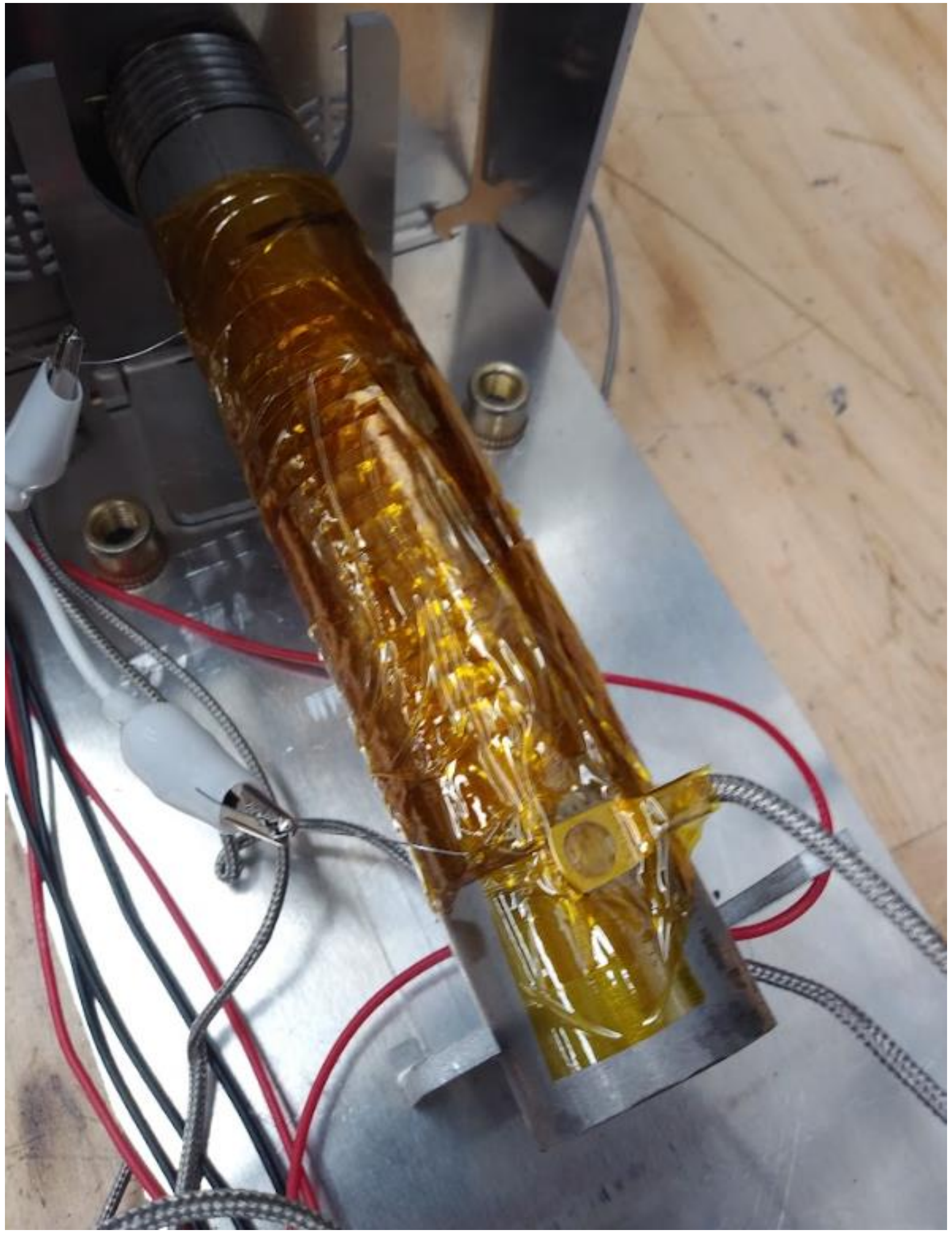
Dia (in):	Dia (mm)
0.0126	0.321

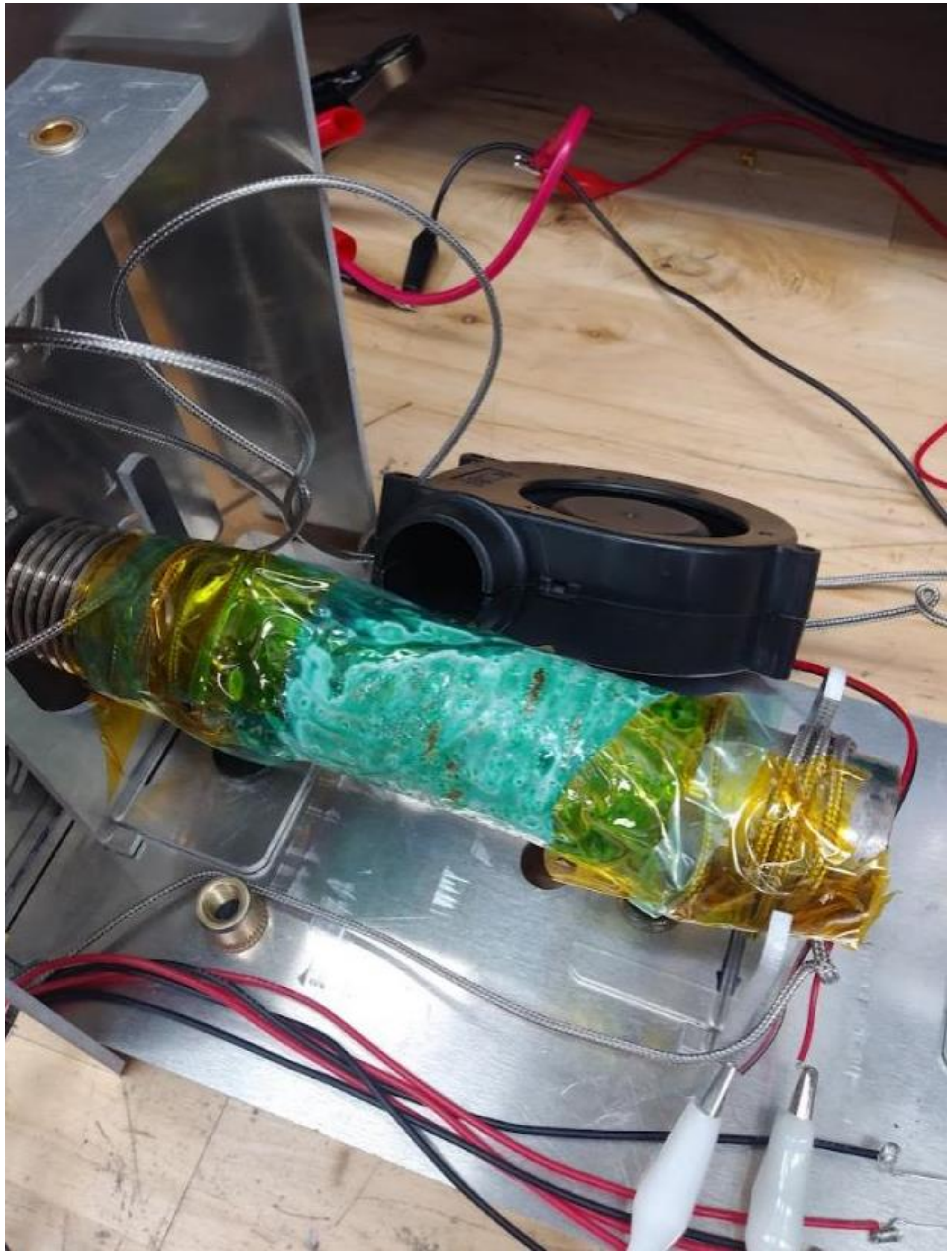
Copper Wire

Ω/Ft:	Ohms	Volts:
NaN	0	0

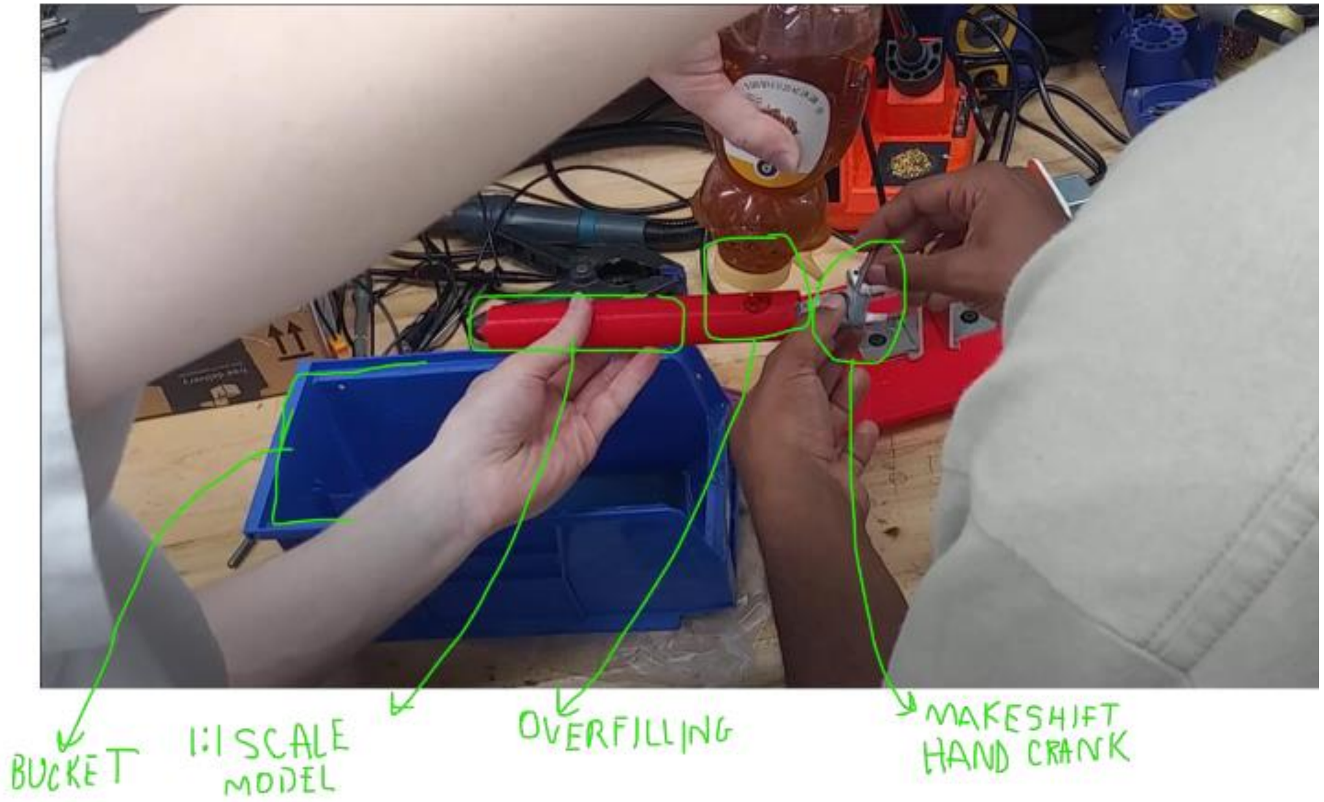
Amps	Watts
2	120

Temp °F 820 **°C** 439





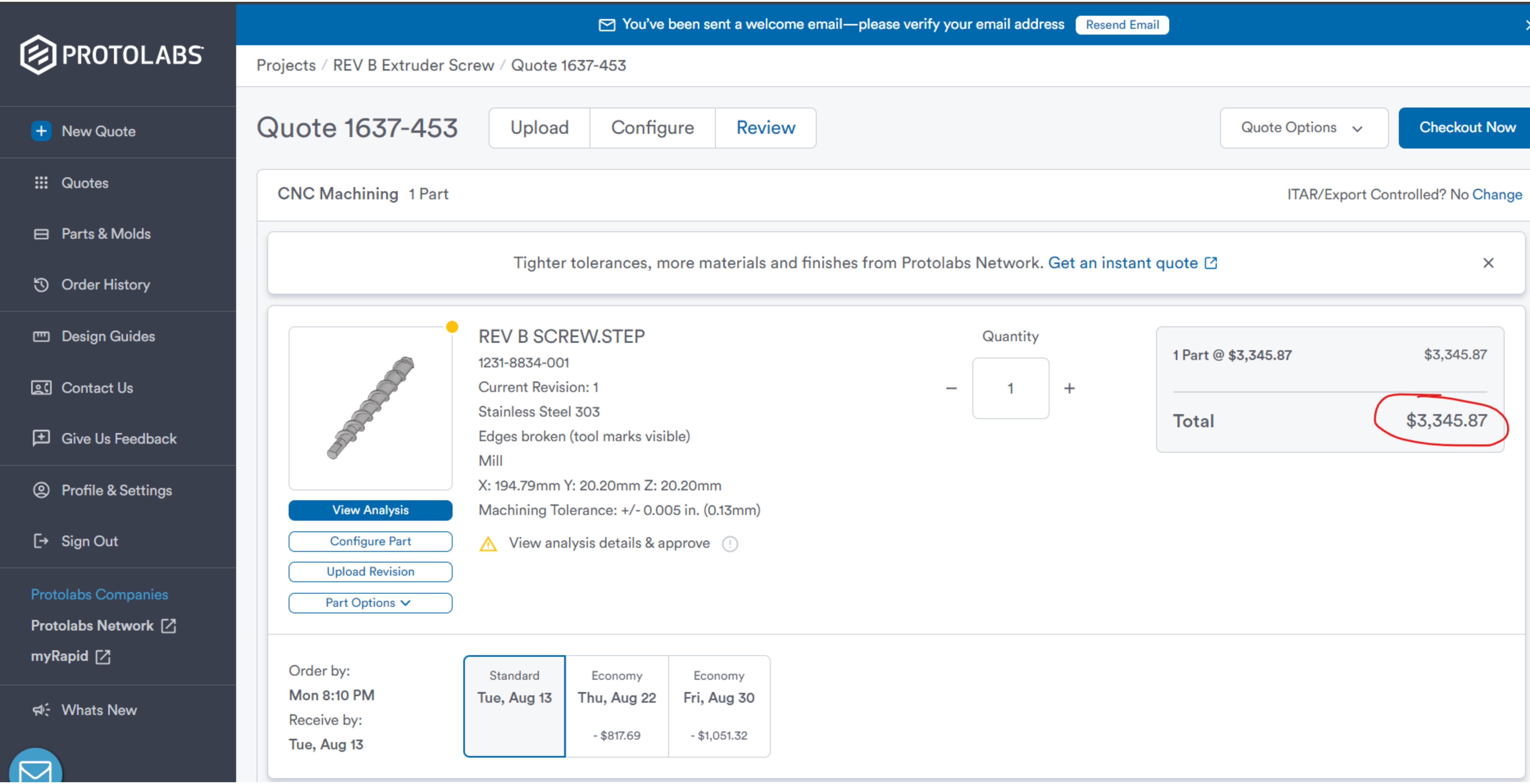
Honey

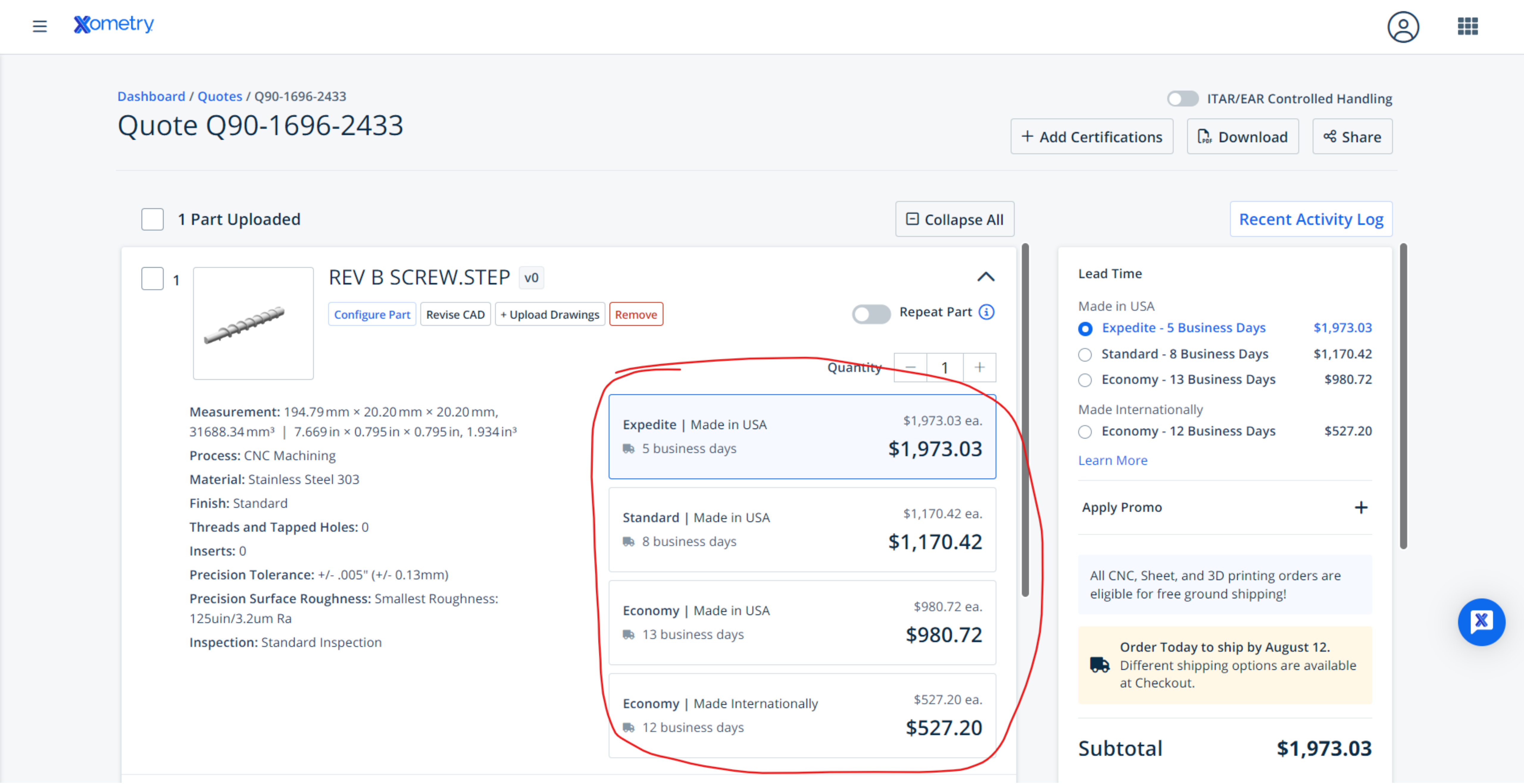


$$Re = \frac{\rho v L}{\mu}$$

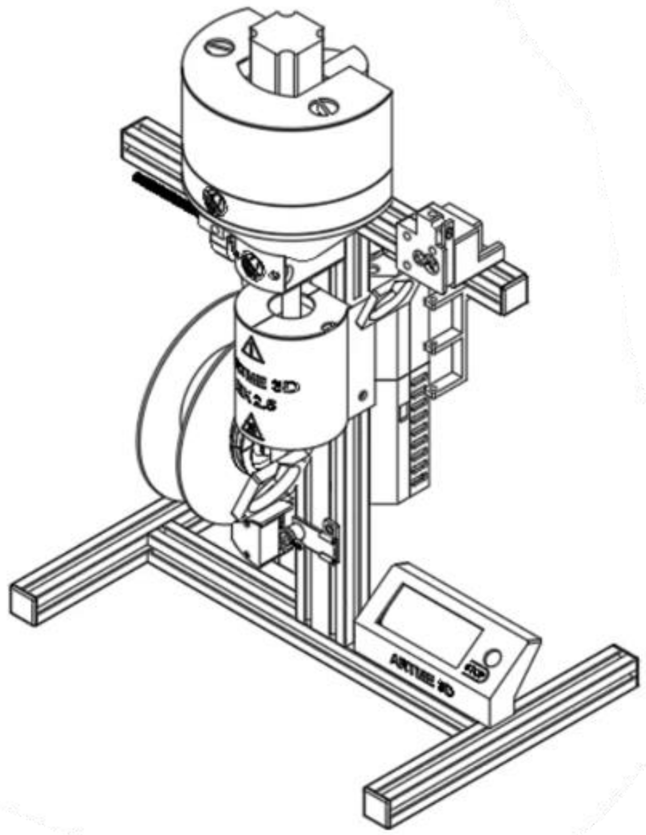
$$\dot{\forall} = 0.5 * \pi * D^2 * \omega * \sin(\alpha) * \cos(\alpha)$$

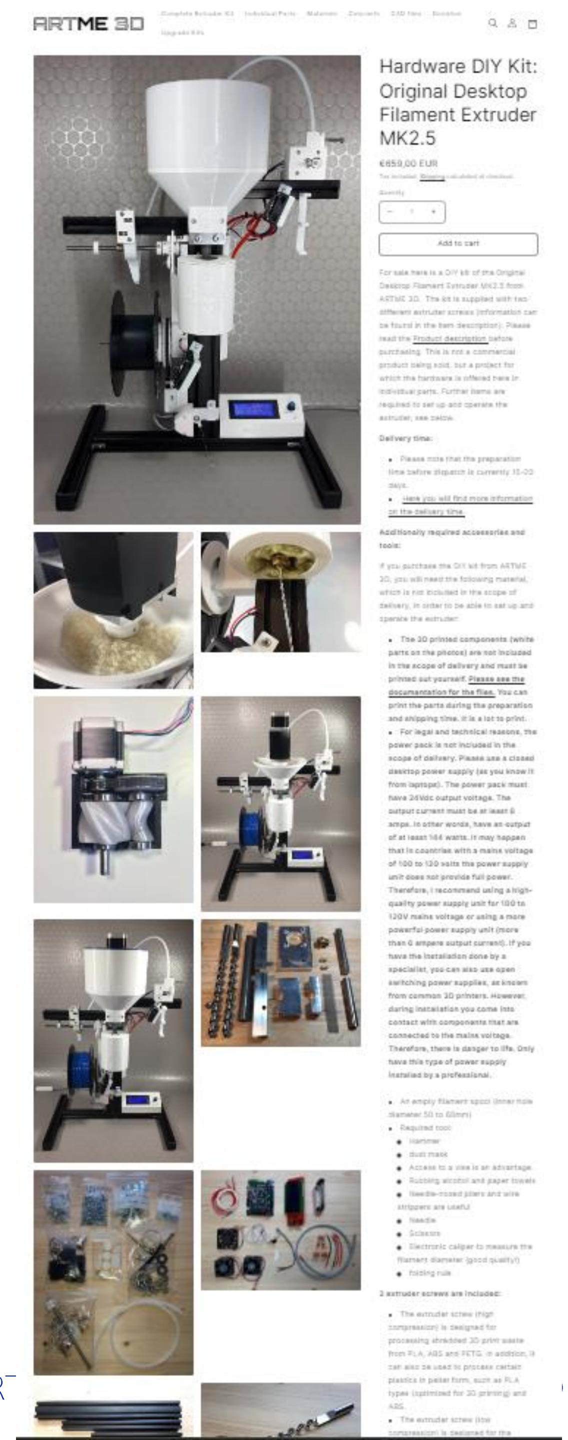
Trial	RPM	Elapsed Time	Actual Output	Expected Output	Percent Difference
1	30	254 s	128 g	0.366 g	199%
2	5	211 s	30 g	0.05 g	199%


You've been sent a welcome email—please verify your email address
Resend Email
PROTOLABS
New Quote
Quotes
Parts & Molds
Order History
Design Guides
Contact Us
Give Us Feedback
Profile & Settings
Sign Out
Protolabs Companies
Protolabs Network
myRapid
Whats New
Projects / REV B Extruder Screw / Quote 1637-453
Quote 1637-453
Upload
Configure
Review
Quote Options
Checkout Now
CNC Machining 1 Part
ITAR/Export Controlled? No Change
Tighter tolerances, more materials and finishes from Protolabs Network. Get an instant quote
REV B SCREW.STEP
1231-8834-001
Current Revision: 1
Stainless Steel 303
Edges broken (tool marks visible)
Mill
X: 194.79mm Y: 20.20mm Z: 20.20mm
Machining Tolerance: +/- 0.005 in. (0.13mm)
View analysis details & approve
Quantity
1
1 Part @ $3,345.87
$3,345.87
Total
$3,345.87
View Analysis
Configure Part
Upload Revision
Part Options
Order by:
Mon 8:10 PM
Receive by:
Tue, Aug 13
Standard
Tue, Aug 13
Economy
Thu, Aug 22
- $817.69
Economy
Fri, Aug 30
- $1,051.32


Xometry
Dashboard / Quotes / Q90-1696-2433
ITAR/EAR Controlled Handling
Quote Q90-1696-2433
+ Add Certifications
Download
Share
1 Part Uploaded
Collapse All
Recent Activity Log
1
REV B SCREW.STEP v0
Configure Part
Revise CAD
+ Upload Drawings
Remove
Repeat Part
Quantity 1
Measurement: 194.79 mm × 20.20 mm × 20.20 mm, 31688.34 mm³ | 7.669 in × 0.795 in × 0.795 in, 1.934 in³
Process: CNC Machining
Material: Stainless Steel 303
Finish: Standard
Threads and Tapped Holes: 0
Inserts: 0
Precision Tolerance: +/- .005" (+/- 0.13mm)
Precision Surface Roughness: Smallest Roughness: 125uin/3.2um Ra
Inspection: Standard Inspection
Expedite | Made in USA
5 business days
$1,973.03 ea.
$1,973.03
Standard | Made in USA
8 business days
$1,170.42 ea.
$1,170.42
Economy | Made in USA
13 business days
$980.72 ea.
$980.72
Economy | Made Internationally
12 business days
$527.20 ea.
$527.20
Lead Time
Made in USA
Expedite - 5 Business Days $1,973.03
Standard - 8 Business Days $1,170.42
Economy - 13 Business Days $980.72
Made Internationally
Economy - 12 Business Days $527.20
Learn More
Apply Promo
All CNC, Sheet, and 3D printing orders are eligible for free ground shipping!
Order Today to ship by August 12.
Different shipping options are available at Checkout.
Subtotal $1,973.03

ARTME 3D





CM-02 Extrusion-Screw

€120,00 EUR

Tax included. Shipping calculated at checkout.

Select compression

high compression

Quantity

1

Add to cart

filabot

Shop News About Learn Contact an Expert United States (USD $)

FILABOT

EX2 Filament Extruder

$3,410.00

FILABOT

EX6 Filament Extruder - Standard Series

$18,224.40

FILABOT

EX6 Filament Extruder - Industrial Series

$22,890.00

FILABOT

EX6 LS Filament Extruder - Laboratory Series

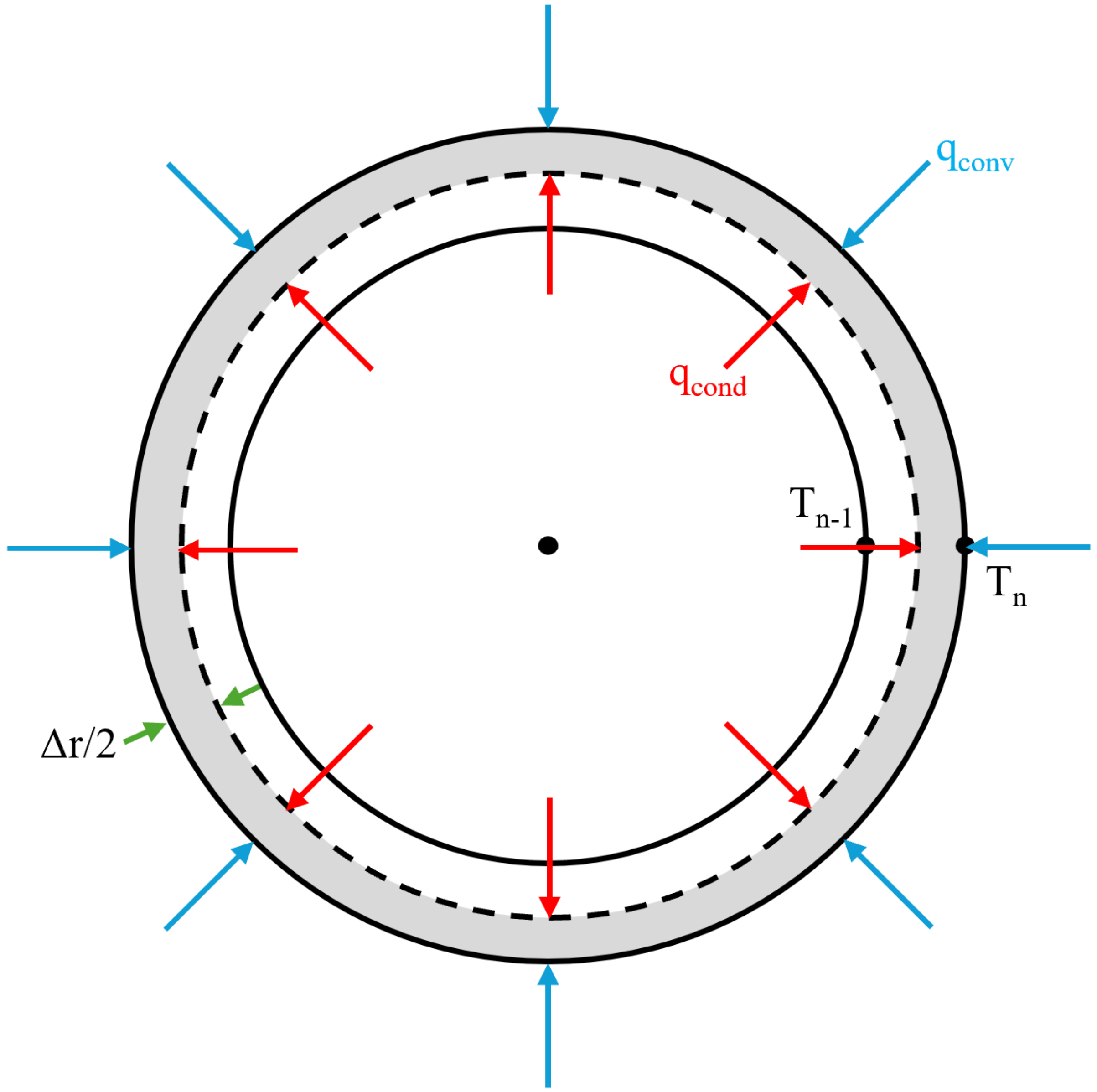
$32,712.00

FILABOT

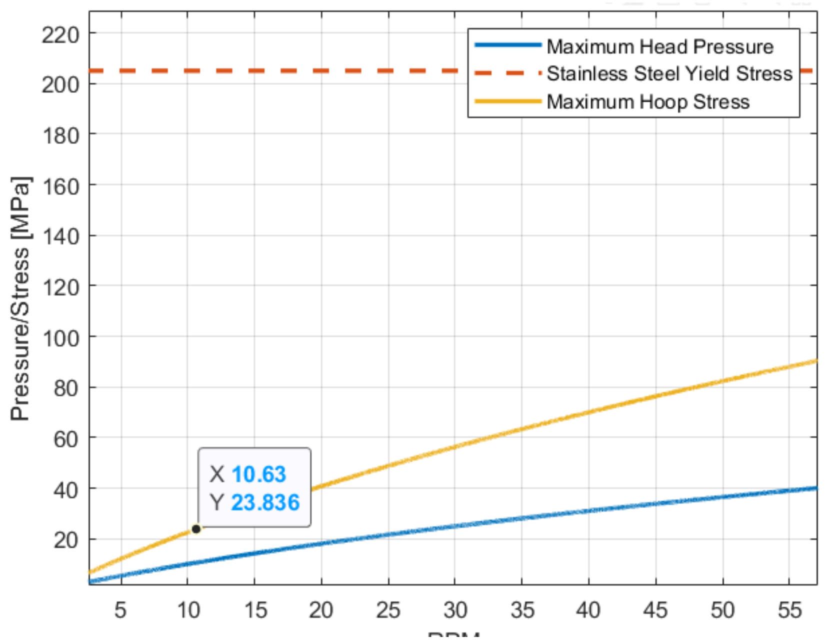
EX6 and MDPE10 Extruder Screws

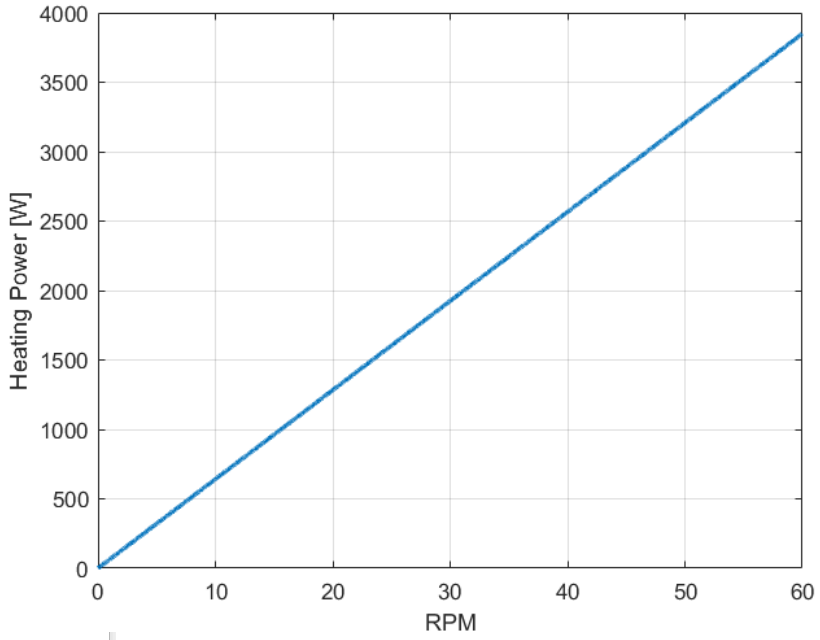
$1,449.00

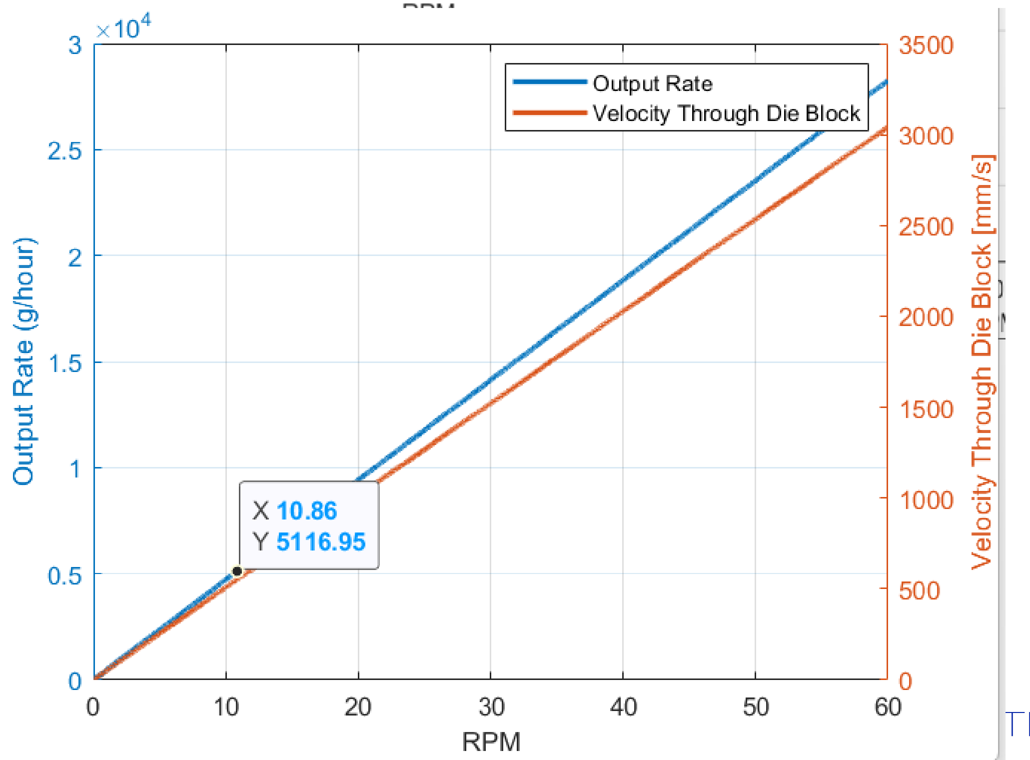
From **$130.78**/mo with shop Pay

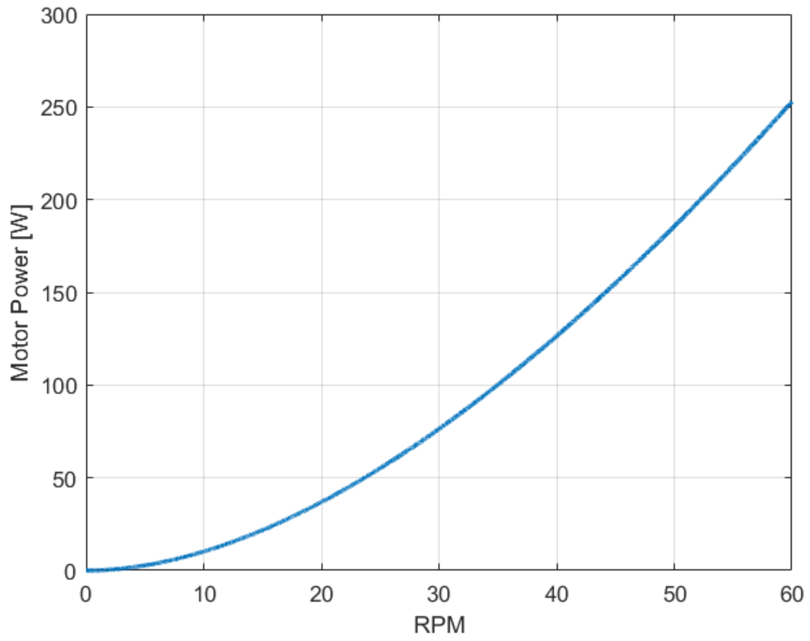


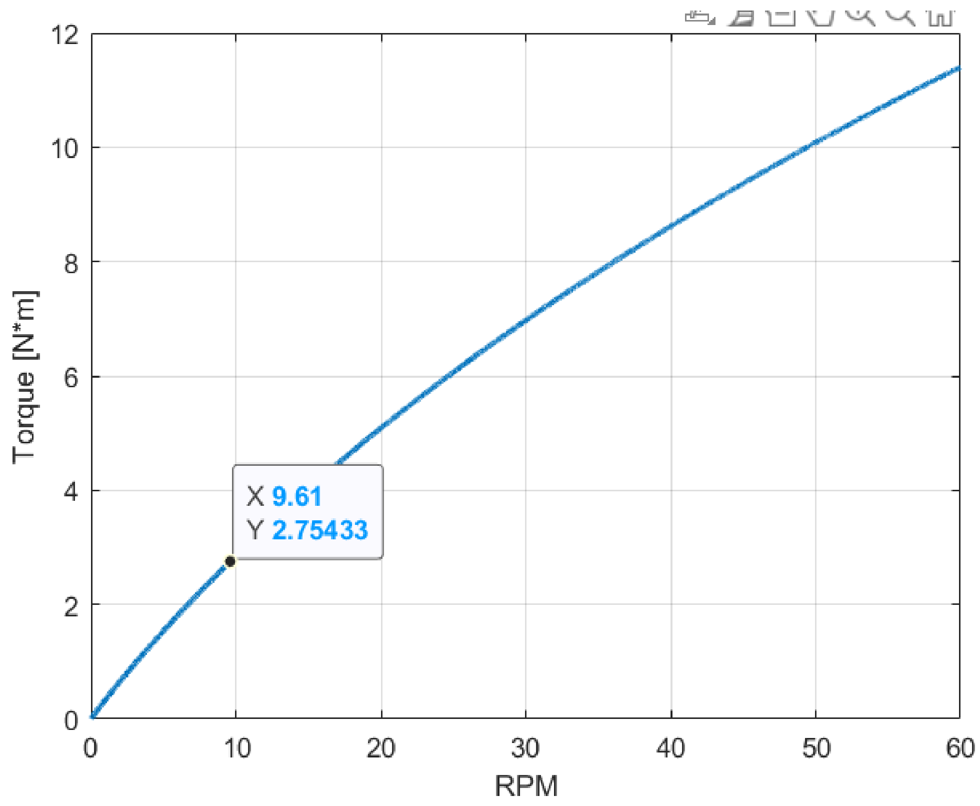
q_{conv}
q_{cond}
T_{n-1}
T_n
Δr/2


Maximum Head Pressure
Stainless Steel Yield Stress
Maximum Hoop Stress
X 10.63
Y 23.836
Pressure/Stress [MPa]

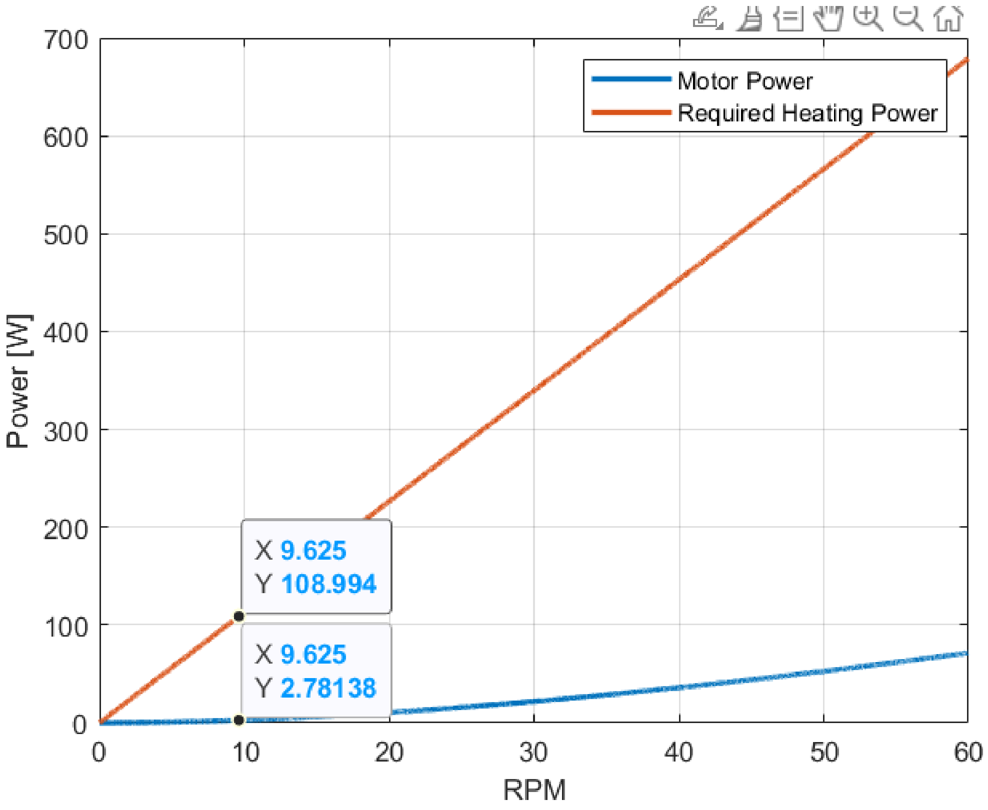

Heating Power [W]
RPM


Output Rate
Velocity Through Die Block
X 10.86
Y 5116.95
Output Rate (g/hour)
Velocity Through Die Block [mm/s]
RPM


Motor Power [W]
RPM

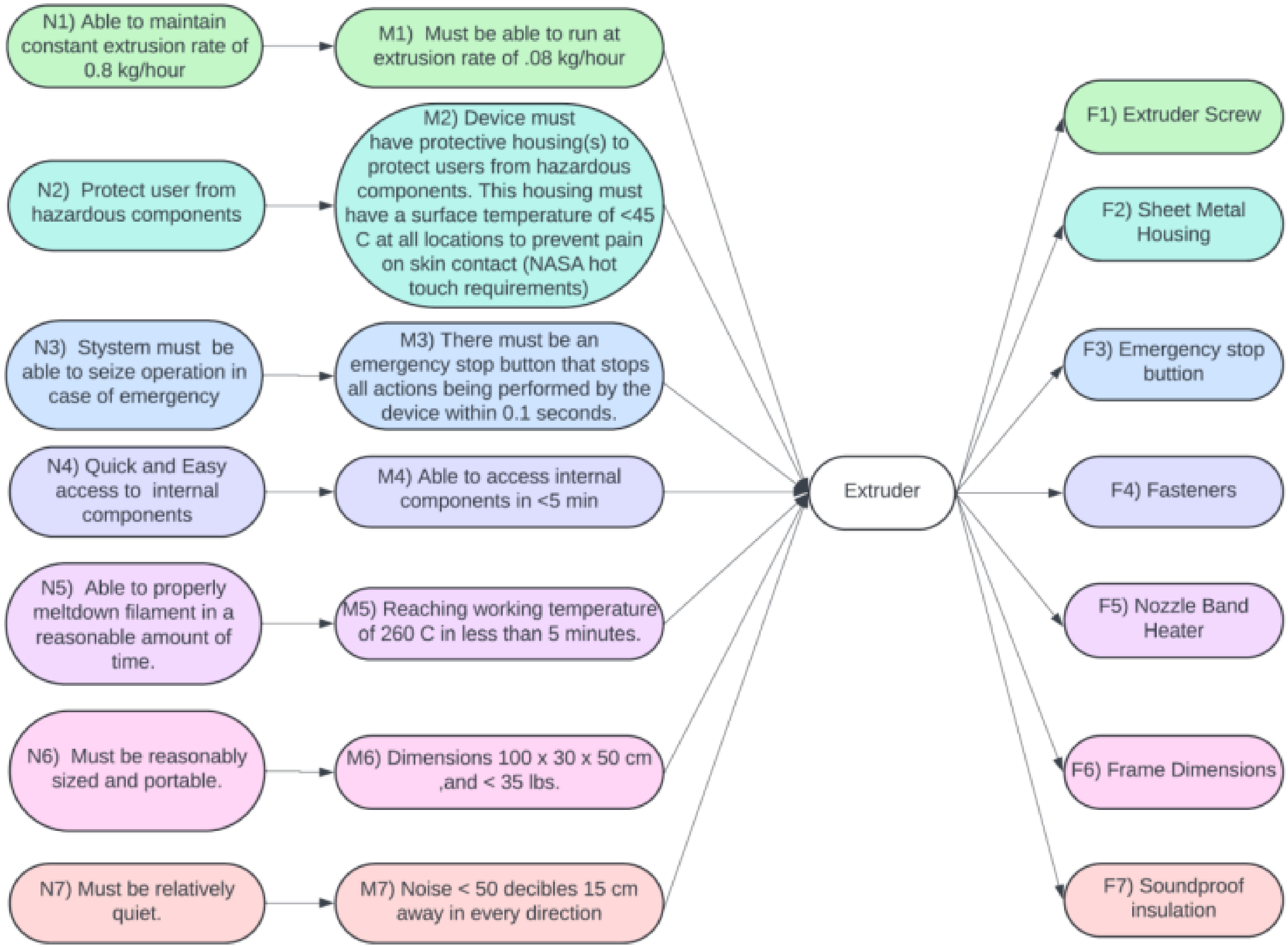


Torque [N*m]
RPM
X 9.61
Y 2.75433
0
2
4
6
8
10
12
0
10
20
30
40
50
60



Power [W]
RPM
Motor Power
Required Heating Power
X 9.625
Y 108.994
X 9.625
Y 2.78138
0
100
200
300
400
500
600
700
0
10
20
30
40
50
60

EXTRUDER

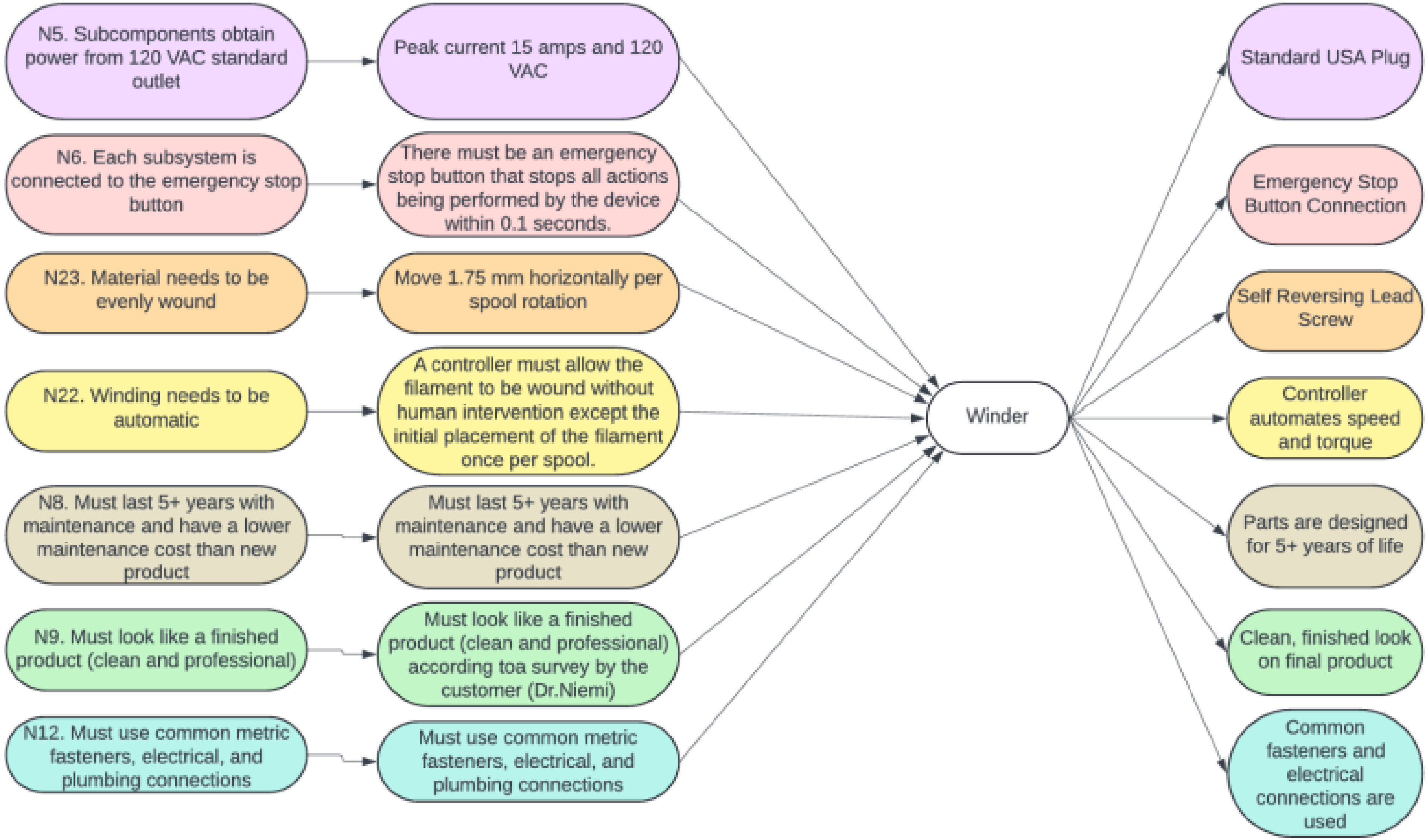


N1) Able to maintain constant extrusion rate of 0.8 kg/hour
M1) Must be able to run at extrusion rate of .08 kg/hour
N2) Protect user from hazardous components
M2) Device must have protective housing(s) to protect users from hazardous components. This housing must have a surface temperature of <45 C at all locations to prevent pain on skin contact (NASA hot touch requirements)
N3) Stystem must be able to seize operation in case of emergency
M3) There must be an emergency stop button that stops all actions being performed by the device within 0.1 seconds.
N4) Quick and Easy access to internal components
M4) Able to access internal components in <5 min
N5) Able to properly meltdown filament in a reasonable amount of time.
M5) Reaching working temperature of 260 C in less than 5 minutes.
N6) Must be reasonably sized and portable.
M6) Dimensions 100 x 30 x 50 cm ,and < 35 lbs.
N7) Must be relatively quiet.
M7) Noise < 50 decibles 15 cm away in every direction
Extruder
F1) Extruder Screw
F2) Sheet Metal Housing
F3) Emergency stop buttion
F4) Fasteners
F5) Nozzle Band Heater
F6) Frame Dimensions
F7) Soundproof insulation

SENSORS


N24) Filament diameter displayed in real time and collected on .CSV file
M24) Filament diameter displayed must have a maximum delay of 0.1 seconds from real time, and must be collected every 0.1 seconds on .CSV file
N25) Filament diameter exiting must be user-adjustable
M25) Adjustable in 0.01 mm increments
N26) Diameter automatically controlled via closed-loop feedback
N27) Filament diameter 1.75 mm
M26,27) Target diameter is 1.75 mm (must be checked by sensor every 0.1 seconds or less)
N28) Tolerance of <3% for filament diameter
M28) 1.70 mm < diameter < 1.80 mm
N8) Must last 5+ years with maintenance and have lower maintenance cost than new product
M8.1) Lifetime > 5 years
M8.2) Maintenance cots < new cost
N12) Uses common metric fasteners, electrical, and plumbing connections
M12) Uses common metric fasteners, electrical, and plumbing connections
Sensor Zone
F24) InFiDEL sensor
F25,26,27) Closed-loop feedback controller
F28) LCD display for diameter
F8) Multiple access points to allow for easy maintenance
F12) Use of standard metric fasteners & electrical components, and standard dimensions for parts

WINDER



N5. Subcomponents obtain power from 120 VAC standard outlet
Peak current 15 amps and 120 VAC
Standard USA Plug
N6. Each subsystem is connected to the emergency stop button
There must be an emergency stop button that stops all actions being performed by the device within 0.1 seconds.
Emergency Stop Button Connection
N23. Material needs to be evenly wound
Move 1.75 mm horizontally per spool rotation
Self Reversing Lead Screw
N22. Winding needs to be automatic
A controller must allow the filament to be wound without human intervention except the initial placement of the filament once per spool.
Winder
Controller automates speed and torque
N8. Must last 5+ years with maintenance and have a lower maintenance cost than new product
Must last 5+ years with maintenance and have a lower maintenance cost than new product
Parts are designed for 5+ years of life
N9. Must look like a finished product (clean and professional)
Must look like a finished product (clean and professional) according toa survey by the customer (Dr.Niemi)
Clean, finished look on final product
N12. Must use common metric fasteners, electrical, and plumbing connections
Must use common metric fasteners, electrical, and plumbing connections
Common fasteners and electrical connections are used

OUTPUT RATE TEST STAND