Abstract

The growing use of consumer-grade fused deposition modeling (FDM) printers has increased demand for thermoplastic filament, while post-consumer plastic waste—particularly polyethylene terephthalate (PET) bottles—remains underutilized at small scales. Commercial recycling and filament production systems are often centralized or cost-prohibitive, limiting access to local material reuse. This project investigates a compact mechanical and thermal extrusion system designed to convert post-consumer PET bottles into usable 3D printing filament.

The system was developed through multiple prototype iterations addressing challenges in thermal stability, filament diameter consistency, and mechanical alignment. Emphasis was placed on modularity and process transparency rather than full automation, allowing direct adjustment of key parameters such as temperature and pull speed. Experimental validation evaluated filament continuity, dimensional consistency, and printability through test extrusions and comparative print trials. Results indicate that recycled PET filament suitable for functional printing can be produced using an accessible, small-scale system, while highlighting remaining limitations related to material variability and process control.

1. Executive Overview

Problem Statement

Consumer-grade 3D printing is widely accessible, yet the filament supply chain remains centralized, cost-sensitive, and poorly connected to local waste streams. Post-consumer polyethylene terephthalate (PET) bottles are abundant, but small-scale reuse is limited by the difficulty of converting irregular, variable material into dimensionally consistent filament. Existing recycling and filament production systems are typically industrial in scale or opaque in operation, making them impractical for individual users, classrooms, and small makerspaces.

Inspiration

I often had ideas for hardware projects I wanted to prototype, but spending money without a clear, practical outcome wasn't an option. At the same time, we were throwing away large numbers of PET bottles at home and through my mother's restaurant, even as I continued buying filament to support iterative 3D printing. That disconnect became clear after watching an open-source PET bottle recycler demonstrated by CNC Kitchen, built largely from printed parts and repurposed Ender 3 hardware. This project grew out of trying to close that loop—turning material we already had into something directly useful—while exploring how material variability, heat, and mechanical control interact in a hands-on extrusion system.

Proposed Approach

This project explores whether post-consumer PET can be converted into usable 3D printing filament using a compact, accessible system. Rather than prioritizing throughput or full automation, the focus is on transparency and hands-on control to better understand the thermal and mechanical factors that govern filament formation at small scales.

2. Design Motivation & Constraints

Material & Process Constraints

- **PET processing window:** Polyethylene terephthalate exhibits a narrow melt-processing range in which sufficient flow can be achieved without inducing thermal degradation, hydrolysis, or embrittlement. Variability in post-consumer feedstock further constrains allowable temperature margins, requiring stable heating and controlled residence time during extrusion.
- **Tooling and fabrication limits:** The system was designed around fabrication methods accessible in a small workshop environment, excluding precision-machined screws or industrial extrusion hardware. As a result, mechanical simplicity, tolerance to misalignment, and ease of modification were prioritized over tight mechanical control.
- **Operational safety:** Continuous operation at elevated temperatures required physical separation between heated components and user-adjustable elements. Layout and enclosure decisions were constrained by the need to reduce accidental contact while maintaining visual access and manual adjustability during tuning.

Performance Targets

- **Target filament diameter:** 1.75 mm
- **Acceptable tolerance:** ±0.10 mm under steady-state operation
- **Throughput goal:** Sufficient to support continuous printing of small functional parts rather than high-volume production

3. System Architecture Overview

Material Flow Path

1. **Feedstock Preparation:** Post-consumer PET bottles are cleaned, labels and adhesives removed, and the material sectioned into continuous strips suitable for steady feeding. Before sectioning, bottles are thermally reformed under internal air pressure by heating water contained within the bottle, allowing the softened PET walls to expand and smooth out molded grooves and curvature. *(See Figure 3.1)*
2. **Thermal Extrusion:** Prepared PET feedstock is introduced into a heated extrusion assembly, where controlled thermal input softens the material and forces it through a fixed-diameter nozzle. The extrusion zone is designed to provide sufficient residence time for melting while limiting thermal exposure to reduce degradation. *(See Figure 3.2)*
3. **Filament Drawing and Spooling:** Extruded material exits the nozzle and is drawn into filament using a manual or assisted pulling mechanism. *(See Figure 3.3)* Pull speed serves as the primary control variable for filament diameter, linking downstream mechanical action directly to upstream thermal behavior.

The drawn filament is guided onto a spool under controlled tension to prevent diameter fluctuation, buckling, or overlap. Spooling consistency is achieved through mechanical guidance rather than closed-loop feedback, favoring simplicity and transparency during operation. *(See Figure 3.3)*

Figure 3.1

Figure 3.2

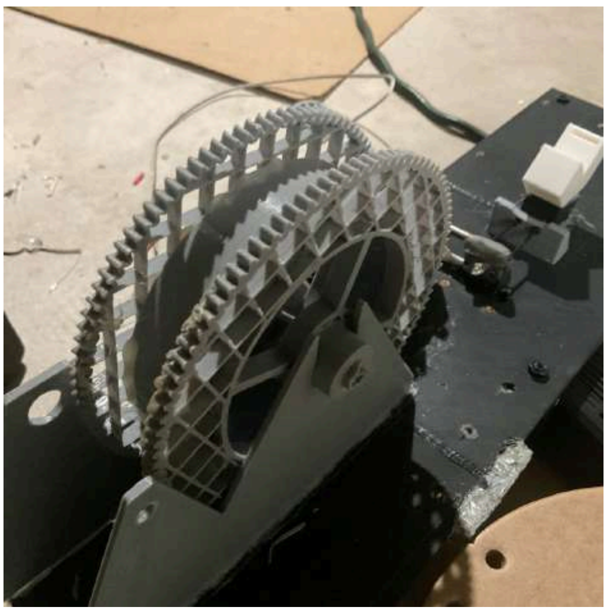

Figure 3.3

Control & Monitoring Philosophy

Active control is applied only where stability is critical to process viability, specifically extrusion temperature and nozzle heating. Other variables, including pull speed and cooling rate, are intentionally left under direct user control or passively tolerated to reduce system complexity while enabling direct observation and iterative refinement of material behavior.

4. Mechanical & Thermal Design

Extrusion Assembly Design

The extrusion assembly is built around a commercially available Ender 3 hot end to leverage a well-characterized thermal system while minimizing custom fabrication. The stock brass nozzle was modified by drilling the orifice to 1.7 mm, reducing flow restriction while maintaining sufficient dimensional control during filament drawing. Heating is provided by the OEM cartridge heater in its standard configuration to ensure stable and uniform thermal input.

Temperature sensing was decoupled from the stock thermistor and replaced with a K-type thermocouple bonded to the upper section of the hot end using thermal epoxy. This placement prioritizes robustness and high-temperature tolerance while providing a consistent reference for melt-zone temperature behavior rather than precise nozzle-tip measurement.

Material Selection

The mounting bracket was fabricated from PETG to improve thermal tolerance relative to PLA while maintaining printability and dimensional stability. To limit heat transfer from the hot end, the heat block was mechanically offset from the PETG structure using an M2.5 × 50 mm fastener, increasing separation between the hot zone and load-bearing components. *(See Figure 4.1)*

Temperature sensing is provided by a K-type thermocouple bonded to the hot end with thermal epoxy, ensuring stable thermal coupling at elevated temperatures. *(See Figure 4.2)*

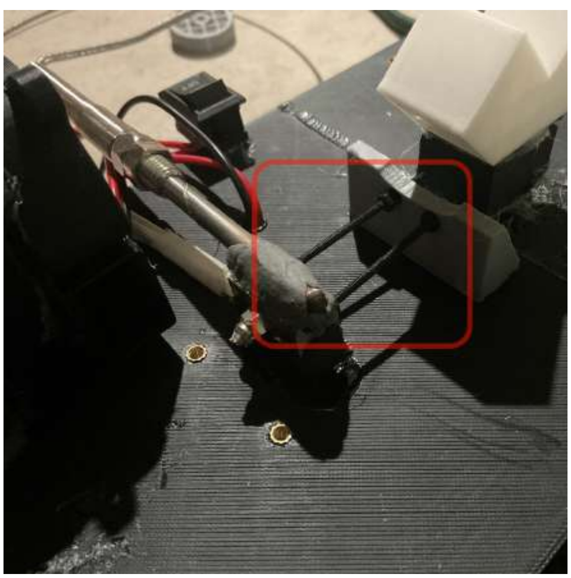

Figure 4.1

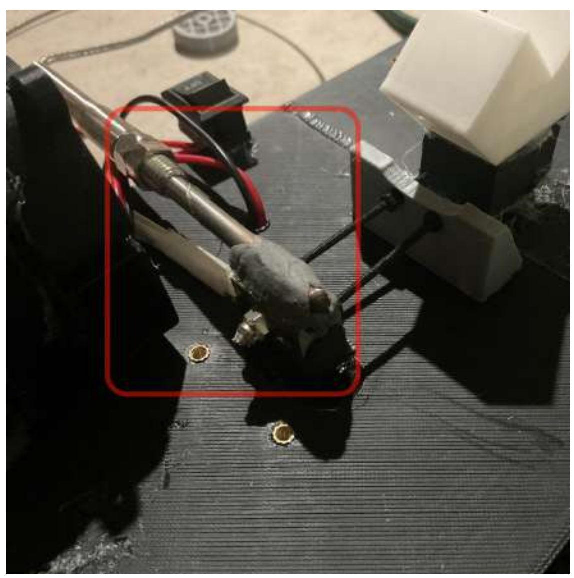

Figure 4.2

5. Iterative Prototype Development

Prototype Iteration Summary

Iteration 1 (Current)

Primary objective: Demonstrate proof of concept for bottle-to-filament extrusion while evaluating thermal isolation between the hot end and 3D-printed mounting components. Additional testing focused on pull-extrusion behavior across varying bottle geometries and basic validation of filament usability through dimensional checks and test prints.

Observed issues: Filament diameter showed strong sensitivity to pull speed and passive cooling, and the absence of active hot-end cooling limited thermal stability during extended operation. Variations in bottle thickness and geometry produced inconsistent melt flow, reducing repeatability across feedstock types. *(See Figure 5.1)*

Iteration 2 (In Development)

Design changes: The modified commercial hot end is replaced with a custom CNC-machined assembly featuring modular nozzles. Active cooling is added for both the hot end and extruded filament, and a filament-joining attachment enables continuous operation using recycled PET filament and standard consumer filament. System control transitions from a thermostat to a custom ESP32-based PCB with a 3.5-inch color display and rotary encoder. *(See Figures 5.2 & 5.3)*

Engineering tradeoffs: System complexity and fabrication effort increase in exchange for improved thermal control, filament consistency, and long-duration stability. Manual tuning flexibility is reduced, but repeatability and process robustness are expected to improve.

Figure 5.1; Note: this represents a 0.25mm deviation from the goal of a 1.75mm diameter filament.

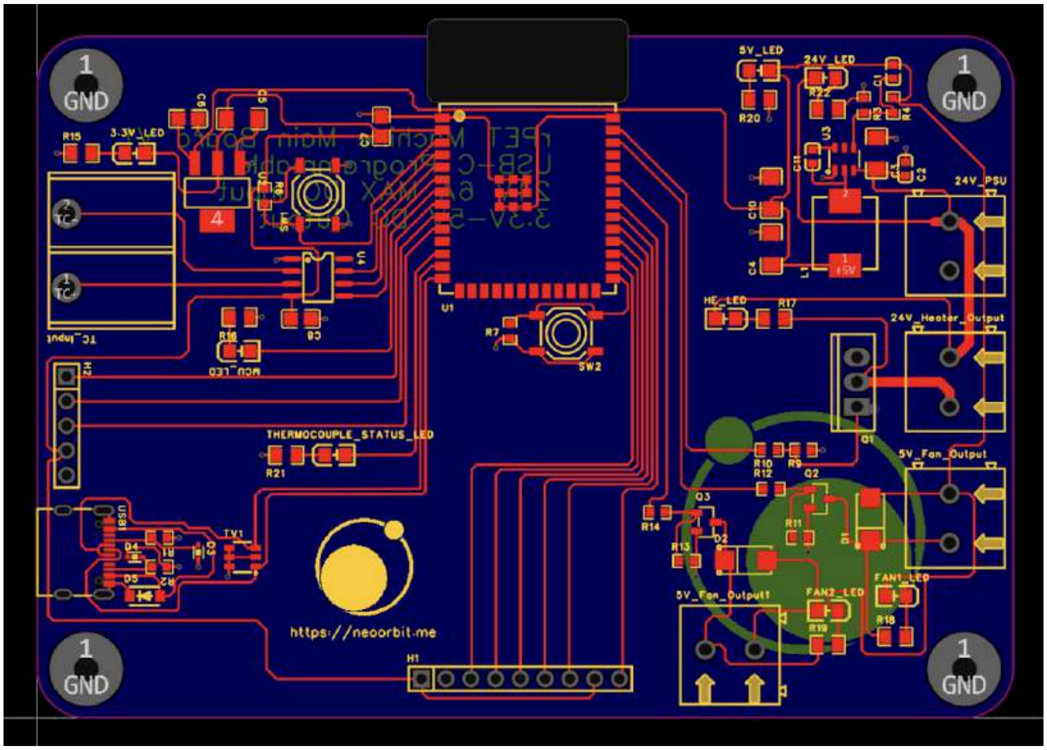

Figure 5.2

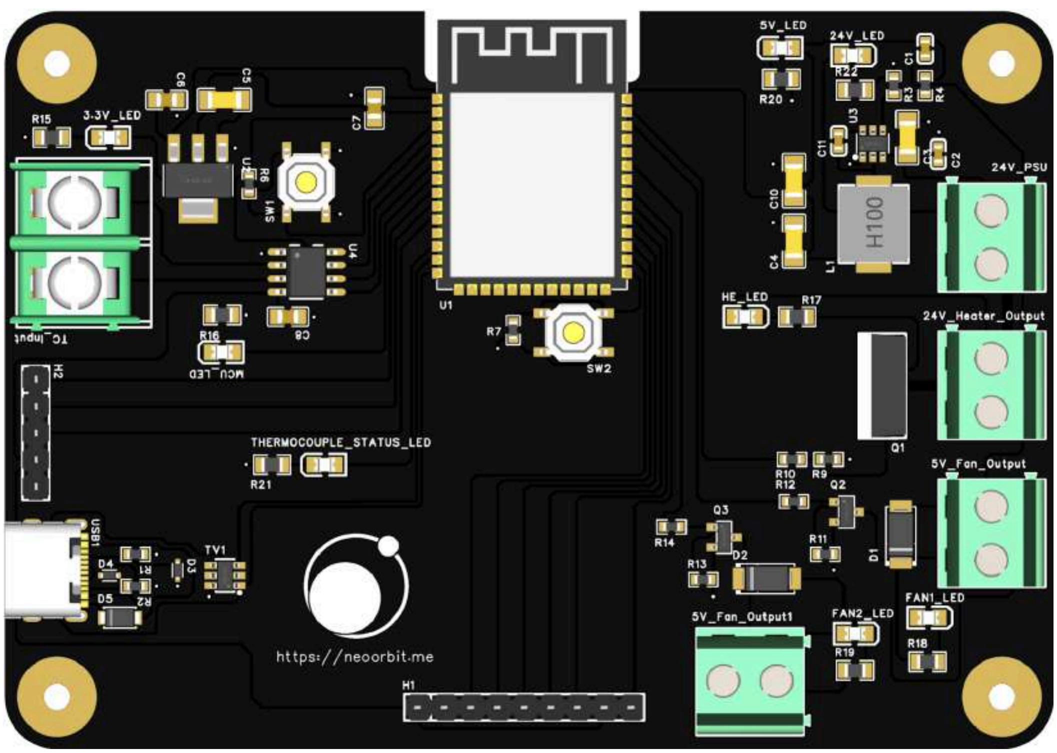

Figure 5.3

6. Process Stability & Quality Control

Diameter Consistency Challenges

Recycled PET filament exhibits inherent dimensional instability due to post-extrusion shrinkage during cooling, a behavior well documented within the 3D printing community. This effect was amplified by inconsistent thermal input from a generic thermostat not matched to the thermal mass and power of the Ender 3 heating element, resulting in frequent temperature overshoot of approximately 10 °C beyond the indicated cutoff. The absence of active hot-end cooling further increased thermal lag, compounding melt-flow variation and necessitating the use of a manual kill switch to safely characterize system behavior.

Mitigation Strategies

Mechanical: A dedicated, gear-reduced pulling system is under development to provide a constant filament draw rate independent of operator input. The mechanism is designed to be hand-driven or drill-driven, enabling consistent pull speed while preserving low system complexity. *(See Figure 6.1)*

Thermal: Replacement of the thermostat with closed-loop control via a custom ESP32-based system, combined with active cooling for both the hot end and extruded filament to reduce thermal inertia and temperature overshoot.

Procedural: Standardization of feedstock preparation and operating sequences, including steady-state warm-up and controlled shutdown, to reduce transient-induced diameter variation.

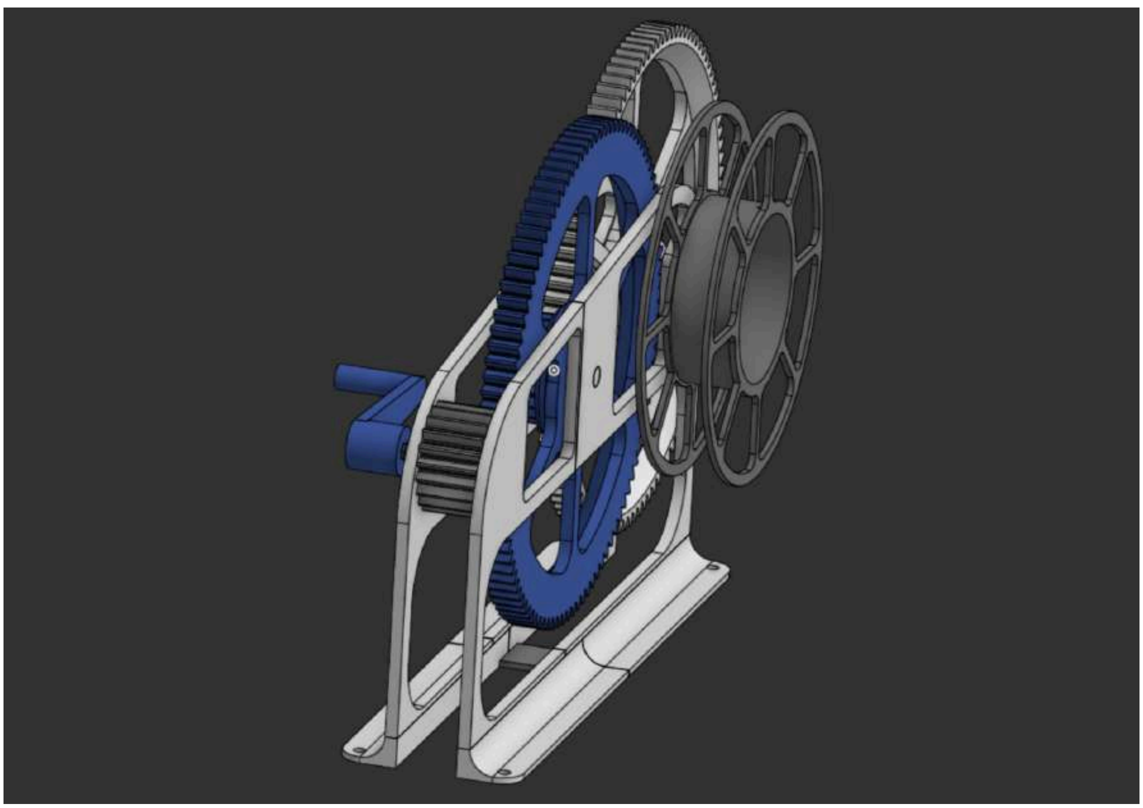

Figure 6.1

7. Experimental Testing & Observations

Testing Setup

Two approximately 5 m batches of recycled PET filament were produced and evaluated through comparative print testing against commercial PETG filament. Identical print settings were used for both materials, with the sole adjustment being a reduced extrusion temperature for rPET to compensate for heat creep associated with the filament's hollow internal structure. Validation prints were selected to probe continuous extrusion stability and stringing behavior, including a vase-style rover wheel geometry designed to require uninterrupted material flow over extended print durations. *(See Figures 7.1 & 7.2)*

Key Observations

Continuous extrusion performance: The vase-style rover wheel print completed successfully using rPET filament, exhibiting stable extrusion and surface quality comparable to PETG. Minor under-extrusion was observed in the middle layers, consistent with passive cooling and extrusion multiplier limitations.

Stringing sensitivity: The pillar-based stringing test failed approximately halfway through when printed with rPET filament; however, the same test also produced significant artifacts when printed with PETG. This suggests the geometry represented an aggressive stress case rather than a material-specific limitation.

Unexpected Behaviors

Despite its recycled origin and dimensional variability, the rPET filament demonstrated reliable performance in continuous extrusion scenarios. This indicates that filament continuity and thermal stability were sufficient for functional printing even without closed-loop diameter control. The fragility of the stringing test geometry further emphasized the role of cooling and pull-rate consistency over material purity alone.

Figure 7.1

Figure 7.2

8. Limitations & Engineering Tradeoffs

The current system prioritizes accessibility and modularity over full automation, resulting in unavoidable variability in filament diameter during manual pull extrusion. While this approach enables rapid iteration and direct observation of material behavior, it limits repeatability and long-duration stability compared to industrial extrusion systems. Thermal efficiency is also constrained by the use of a compact hot end and passive cooling in the initial iteration, increasing sensitivity to transient temperature fluctuations during operation.

Material variability inherent to post-consumer PET introduces additional uncertainty in melt behavior, shrinkage, and long-term filament durability. Differences in bottle wall thickness, prior thermal history, and contamination contribute to inconsistent flow characteristics that cannot be fully mitigated through mechanical design alone. These tradeoffs highlight the distinction between small-scale experimental recycling systems and industrial filament production, while informing targeted design changes focused on improved control rather than increased system complexity.

9. Forward Development & Scalability

Forward development is focused on completing and validating Iteration 2, which introduces improved thermal control, modular extrusion hardware, and an integrated electronics platform to address stability limitations identified in the current system. Testing is planned to evaluate long-duration operation, filament consistency, and usability under non-laboratory conditions. Design features introduced in this iteration—including modular nozzles, active cooling, and a filament-joining attachment—are intended to improve repeatability without significantly increasing system complexity. *(See Figure 9.1)*

Scalability is approached as a validation problem rather than a throughput objective. Instead of speculative expansion, the system is being evaluated through controlled deployment to assess robustness, safety, and instructional usability. A preliminary patent covering key design elements has been submitted, and the system is planned for deployment in several public school environments to gather real-world performance data and user feedback. This approach prioritizes empirical evaluation and refinement over production scaling, aligning development with educational and small-scale recycling contexts.

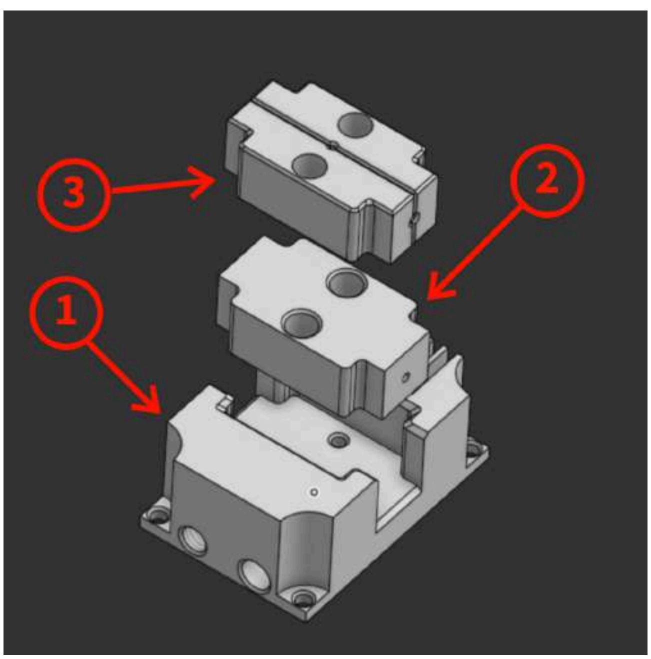

Figure 9.1

Part 1: A custom-designed hot end, with drilled/tapped holes for an M6 K-type thermocouple, and an Ender 3 heater cartridge.

Part 2: Modular nozzle, with a 10mm entry hole and 1.75mm exit hole.

Part 3: Modular filament joiner to join pieces of rPET filament, as well as any other filaments with a 1.75mm diameter.

10. Practical Prints & Application Examples

Beyond test prints, the recycled PET filament was used to fabricate practical parts that addressed real needs within my ongoing projects and daily workflow. These components were selected because they required sufficient strength, dimensional reliability, and surface quality to function as intended. All parts shown were printed using filament produced by the system described in this project. *(See Figures 10.1 - 10.4)*

Figure 10.1

Figure 10.2

Note: Figures 10.1 & 10.2 are validation prints to test the dimensional accuracy of potential upgrades to the rPET Machine iteration 1.

Figure 10.3

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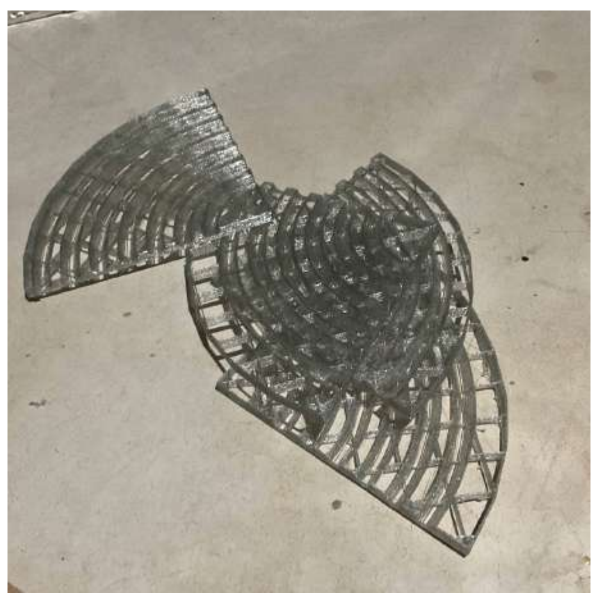

Figure 10.4

Jigs used to test a spiral cooling loop geometry.