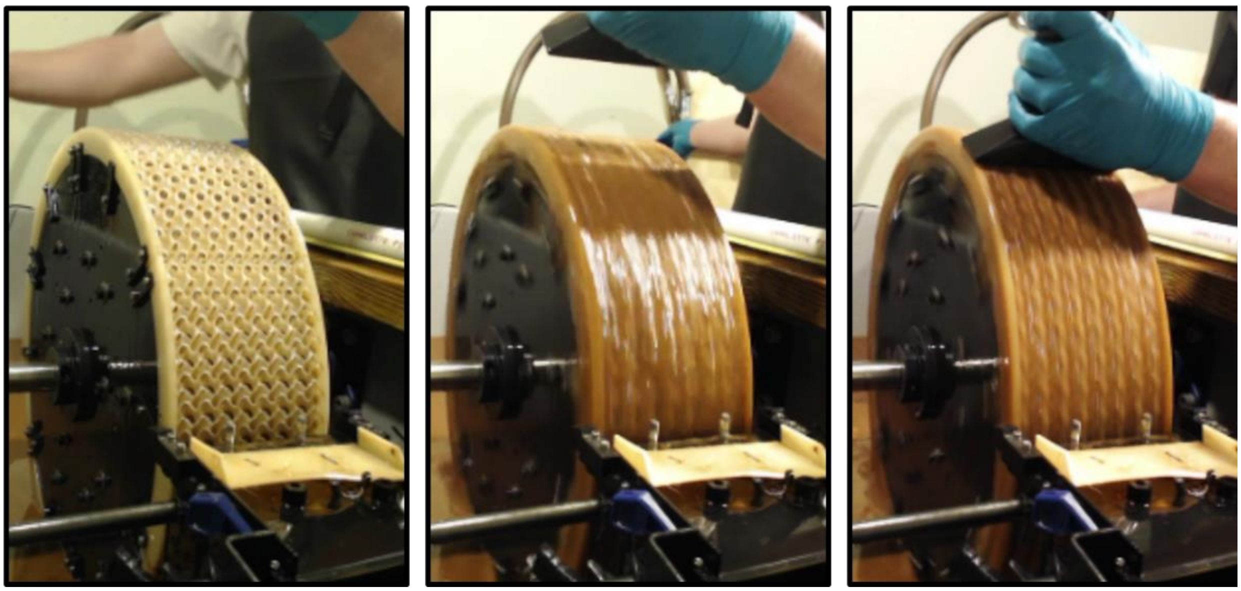
Bureau of Safety and Environmental Enforcement
Oil Spill Preparedness Division

The Use of Additive Manufacturing to Investigate Novel Surface Geometries for Improved Oil Skimmer Recovery in Thin Oil Slicks

Final Report
July 2022



(Photo: Deep Analytics, 2022)

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DEEP ANALYTICS

DISCLAIMER

Contracts:

Study concept, oversight, and funding were provided by the US Department of the Interior (DOI), Bureau of Safety and Environmental Enforcement (BSEE), Oil Spill Preparedness Division (OSPD), Sterling, VA, under Contract Number 140E0121C0008. This report has been technically reviewed by BSEE, and it has been approved for publication. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the US Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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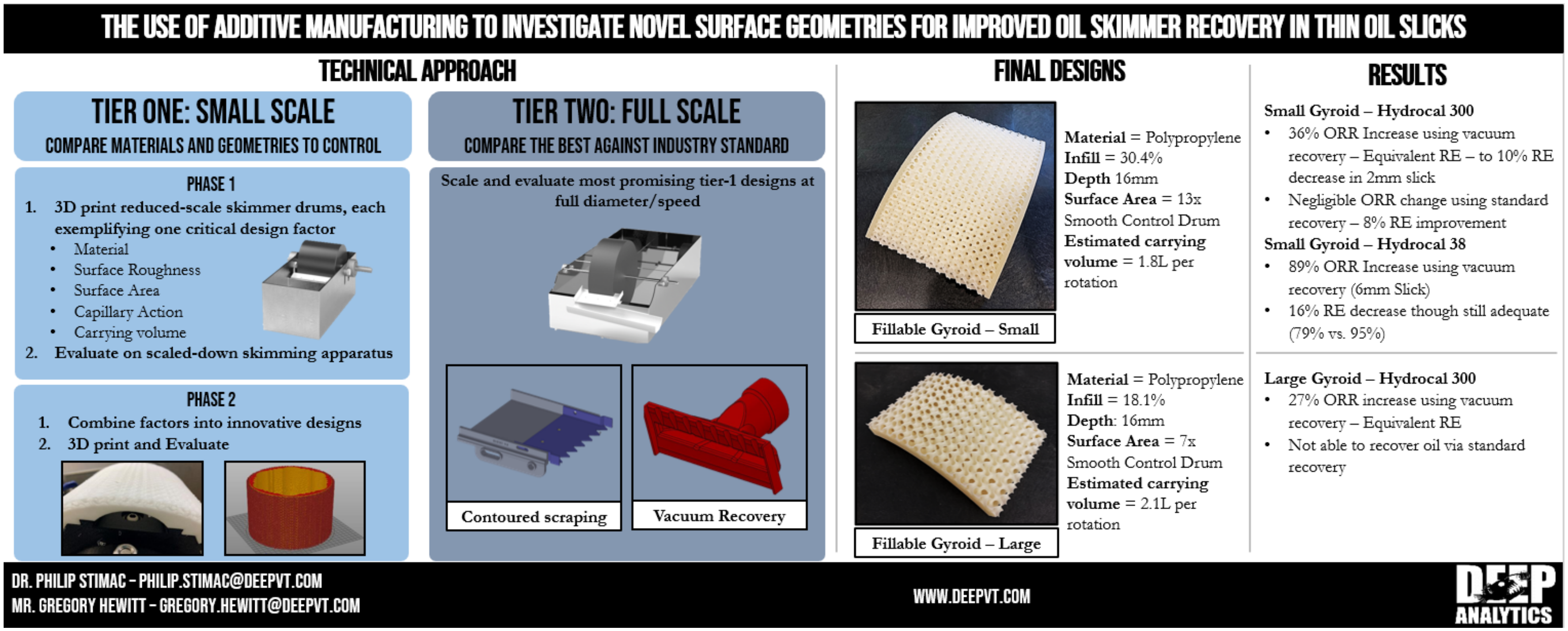
ABOUT THE COVER

Cover image displays one of Deep Analytics' gyroid-based drum surfaces during a vacuum-recovery test on the experimental apparatus used second tier of the project: pre-test (left), ramp to steady-state (center), and during recovery (right).

GRAPHICAL ABSTRACT



Executive Summary

Recently, it has been shown that oil recovery skimmers achieve maximum performance when recovering in oil slicks of 75 millimeters (mm) or greater and that recovery performance degrades significantly in thin slicks, defined here as less than ½ inch or 12.7mm (McKinney et al. 2017). The purpose of this research and development effort was to leverage additive manufacturing to create and evaluate novel skimmer geometries for improved oil recovery and/or efficiency in thin oil slicks. Additive manufacturing enables the rapid production of complex and undercut geometries not possible via standard manufacturing processes in addition to a wide range of manufacturable materials, including but not limited to many currently utilized for existing skimmer drums. Deep Analytics LLC (DA) executed a multitiered research and development (R&D) effort designed to exploit these benefits by rapidly testing many potential geometries and to reduce to practice the factors key to recovery of thin oil slicks. These learnings culminated in an innovative drum surface design and novel recovery method for which testing suggested improved oil recovery performance compared to documented results of industry standard skimmers.

DA executed development and testing over the course of two project tiers. Tier 1 involved testing drum surface geometries using a reduced-scale experimental skimmer apparatus. This tier was broken into two phases: in the first, DA identified numerous critical design factors found in the literature and designed test drums that isolated these factors with the intention of determining which had an outsized effect on recovery performance. During the second phase of Tier 1, DA combined promising factors into innovative geometries and, based on performance, down selected three geometries for testing in Tier 2. Tier 2 consisted of design and evaluation of drums with full-scale diameter and reduced width (when compared to the Elastic TDS 118G drum skimmer) to facilitate realistic comparison to documented results of the current common practice. Over the course of testing DA also developed and tested a proof-of-concept vacuum recovery method used in place of standard scraping. This was in response to observations of oil remaining captured by certain geometries with surfaces/volumes not accessible by standard scraping.

DA created a drum design based on a gyroid surface, mapped to a cylinder, creating a volumetric recovery capacity. When used in conjunction with the described vacuum recovery method, the design achieved a higher Oil Recovery Rate (ORR) than control with comparable Recovery Efficiency (RE) in thin slicks. Quantitatively, the design produced a 36% increase in ORR in a 6mm slick of Hydrocal 300 and an 89% increase in ORR in a 6mm slick of Hydrocal 38. While in Tier 1 this concept also outperformed control using standard scraping, these results were not replicated in Tier 2. DA believes this is due to an increased surface depth added to the Tier-2 iteration of the geometry. Test results suggest that the proposed concept captures more oil in thin slicks; however, recovery from the drum (scraping or otherwise) is an ongoing opportunity. DA recommends further research and optimization of the gyroid-based concept for both standard and vacuum recovery. Furthermore, it is recommended that vacuum recovery be investigated as a potentially improved recovery method for skimmers, especially for geometries not entirely accessible to standard scrapers.

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1 Project Overview

Oil drum skimmers collect oil from bodies of water by submerging and rotating a drum made of a material that has an affinity for oil. The oil adhered to the drum is mechanically scraped and diverted into a collection system. Historically, drum skimmers have employed smooth, cylindrical drums, relying on the oleophilic properties of the drum surface for oil recovery. Research and commercial efforts have since attempted to exploit additional factors that increase effectiveness, one notable success being the introduction of grooved drum surfaces, which under certain conditions have led to increases in recovery efficiency up to 200% in testing when compared to smooth drums (Broje and Keller 2007). While these results are promising, oil recovery skimmers achieve maximum performance when recovering in oil slicks of 75 millimeters (mm) with performance decreasing significantly in thin slicks of 25 millimeters and under (McKinney et al. 2017). Response operations frequently require recovery of thin slicks, thus there is a need for innovation specific to these circumstances.

DA executed a two-tier, 10-month project, shown graphically in Figure 1. This design and evaluation cycle served as a framework for down-selection of promising geometries based on performance. Each tier was designed to further consolidate and optimize an initially large number of designs until one combination of microgeometry, recovery method, material, and surface finish was selected and finalized. The methodology hinged upon additive manufacturing which, with fast lead-times and flexibility in manufacturable geometries, allowed production of over 20 initial test drums. Learnings from testing this initial set of drums informed design of subsequent innovative geometries. Additive manufacturing enabled a test-early, test-often approach, permitting the team to iterate or abandon concepts at a faster pace than is possible with classic manufacturing methods. The following details the approach to each tier.

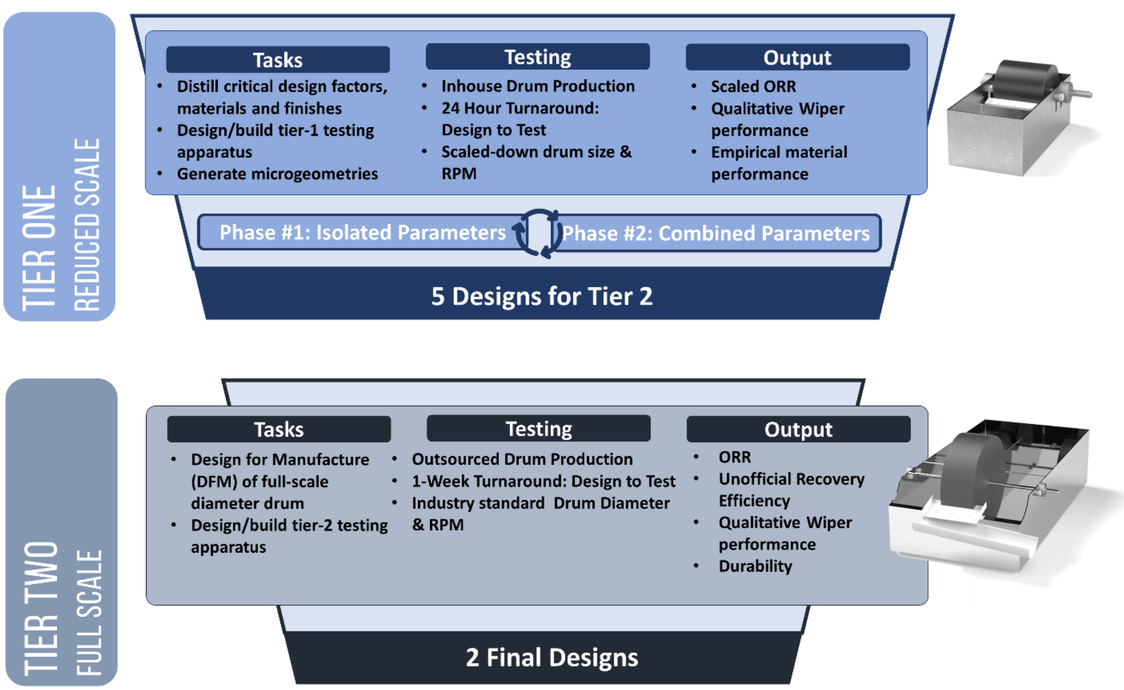


Figure 1: Graphical representation of project structure.

1.1 Tier 1: Reduced Scale

Tier-1 testing occurred at reduced scale for drum diameter, width, and effective speed. Due to an absence of documented recovery performance at this scale, two control drums were developed and utilized as a baseline for comparison to Tier-1 test drums. Both control drums were manufactured from polypropylene via fused deposition modeling (FDM), a process described herein. Polypropylene was selected based on its prevalence in the field and the ability to 3D-print both internally and externally. The first control drum was a smooth cylinder, representing common practice geometry for drum skimmers. The second mimicked the grooved pattern found on the Elastec TDS 118G, as this skimmer has been utilized at OHMSETT for past testing and results of its performance in thin slicks have been documented. Additionally, the Elastec TDS118G was the selected skimmer should evaluation of the final design occur at OHMSETT.

As stated, Tier-1 design and evaluation were performed over two phases to: 1.) isolate critical design factors, and 2.) to develop new microgeometries leveraging the optimized critical design factors. Isolated critical factors were identified in the literature as design elements that contribute to recovery performance. Phase 1 aimed to determine which had significant effect. Critical design factors identified in the literature included the following:

1. Material (Broje and Keller 2007; Keller and Clark 2008)
2. Surface Roughness (Broje and Keller 2005)
3. Surface Area (Broje and Keller 2005; Keller and Clark 2008)
4. Capillary Action (Broje and Keller 2005)
5. Carrying volume[1]

Phase 1 also investigated the effects of specific equipment parameters. This testing largely occurred while establishing baseline performance of the control drums, to ensure the best possible control results and to offer a starting point for future innovations. These parameters and their ranges include the following:

1. Oil Slick thickness: 2mm and 6mm
2. Drum Submergence Depth: Tangent – 24mm
3. Drum Speed: 40, 60, and 80 Rotations per Minute (RPM), standard
4. Oil Type: Hydrocal 300 and Hydrocal 38 (oil characteristics reported in Appendix E)

Phase 2 involved the design and testing of new microgeometries informed by learnings from Phase 1. Based on Phase 1 results described herein, DA developed drums that broadly fit into the categories listed below. At the conclusion of Tier 1 - Phase 2, DA had determined five innovations to be investigated in Tier 2. These innovations were combinations of drum designs as well as a novel vacuum recovery method used to extract fluid from fillable geometries. To summarize, the Tier 1 - Phase 2 engineering effort produced drum designs that fit into one of the following categories:

1. Fillable geometries
2. Compressible geometries
3. Geometries that increase surface area and are highly scrapable

[1] Carrying volume, the volume of liquid captured by the drum per rotation, was not identified in DA's literature review. It was deemed critical through observation of early tests.

1.2 Tier 2: Full Scale

Tier-2 testing evaluated a narrowed set of drums at full-scale diameter, equivalent to the Elastec TDS118G, though still at reduced width, to provide a more reliable comparison to documented field results. While 6mm results in Hydrocal 300 exist for the Elastec TDS 118G (McKinney et al. 2017), DA is unaware of documented performance for a 2mm slick thickness of Hydrocal 300, nor any results for Hydrocal 38. Thus, the smooth control drum was retained for baseline comparison. The grooved control drum was abandoned due to its comparatively lower thin slick oil recovery rate in Tier-1. Testing occurred at 2mm and 6mm slick thicknesses using Hydrocal 300 and 6mm using Hydrocal 38. Both for baseline and innovation testing, drum speed and submergence were optimized for each drum.

2 Technical Methods

2.1 Additive Manufacturing Methods

For this project DA selected two additive manufacturing technologies, namely: 1.) Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) and, 2.) Selective Laser Sintering (SLS). The FDM process works by heating/melting a polymer filament and extruding it onto a surface where the model is built. The model is built up one layer at a time and often support structures must be built as well to support any large overhangs/undercuts in the part while printing. There is a wide range of available materials for this process and models can generally be built very quickly. Selective Laser Sintering works by rolling a thin layer of powdered printing material across a platform, which is then sintered with a laser where necessary. This process is repeated one thin layer at a time until the entire part is built. Because some of each layer is not sintered, the final part will be surrounded by powder. The powder can usually be reused, so there is little waste, though any enclosed areas in the part must have holes built-in to drain captured powder. Due to the nature of this process, manufactured parts can be very complex as no support structures are required and the technology has a fine resolution. Additionally, the process in conjunction with available materials can be used to create truly rugged parts. SLS is generally slower than FDM. It is worth noting that SLS is inherently porous and even for water resistant materials it can be assumed that if untreated, water can penetrate up to 1.5 millimeters. (https://help.prusa3d.com/article/types-of-printers-and-their-differences_112464)

While there are many other 3D printing technologies, FDM and SLS were chosen because 1.) together they offer the capability to print the desired geometries, 2.) together they offer a range of materials that include those common to skimmer drums as well as a host of others worth testing, 3.) Each technology is widespread among additive manufacturing shops across the world (important should additive manufacturing (AM) become a viable drum manufacturing method in future recovery options), and finally 4.) DA has each technology in house, largely due to the same reasons.

2.2 Experimental Apparatus

The goal of the experimental apparatus was to facilitate realistic skimming performance while allowing rapid resetting of trials due to the desired volume of tests. Each tier required a separate apparatus to accommodate the volume of fluid handled, though each were specified with the same critical components shown in Figure 2. The following describes each apparatus in detail.

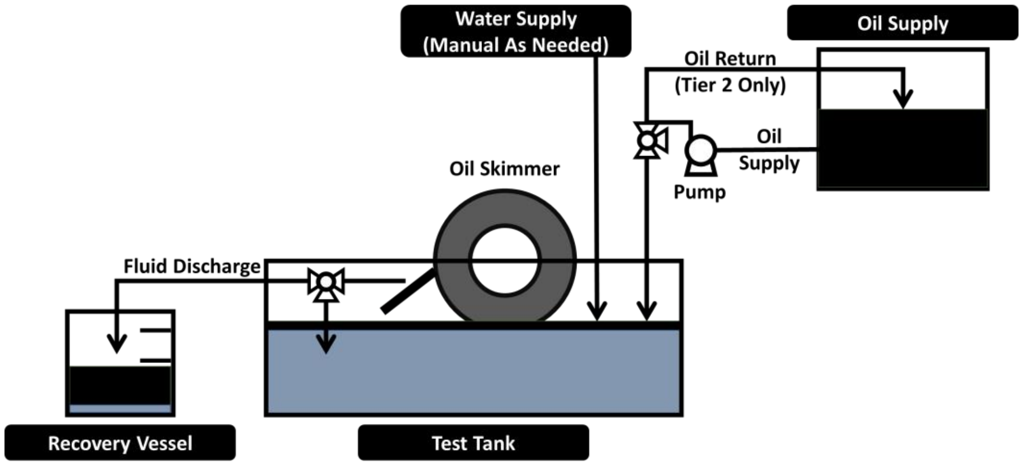


Figure 2: Experimental apparatus process flow diagram

2.2.1 Tier 1

The Tier-1 apparatus was designed to accommodate a drum with a 200mm outer diameter and 135mm width. Additionally, the tank needed to fit within DA's laboratory fume hood for vapor management. The system is composed of the following components, shown in Figure 3:

1. (1) Test Drum and (1) Drum Core (OD=200mm, width=135mm)
2. (1) Scraper assembly, interchangeable
3. (2) Oil replenishment points. PVC construction featuring (8) 4mm holes along horizontal tube for distribution
4. Drain Assembly: Funnel components 3D printed in house from ASA material. Includes ¾" Y valve with dual shutoffs
5. (1) Drive Assembly, including:
    - (1) 12v Brushless DC (BLDC) 115v 230v ac Gearmotor Reversible Variable Speed Drive (150RPM Maximum)
    - 1:2, 1:3, 1:4 available gear reduction for increased drum torque (results in decreased max RPM)
6. (1) Control panel: Controls motor direction & speed. Displays drum RPM.
7. (2) Kamoer Peristaltic Pumps for Oil Replenishment (0-6Lpm ea., found to be ~0-3Lpm ea. In practice with Hydrocal 300).
8. (1) JIH Peristaltic Pump for water replenishment, as needed (0-3Lpm)
9. Measuring Equipment (not shown):
    - 5L measuring pitchers (+/- 100ml)
    - 1L graduated cylinder (+/- 10ml)

- 300mL beakers (+/- 5%)
- 100ml graduated cylinder (+/- 1ml)

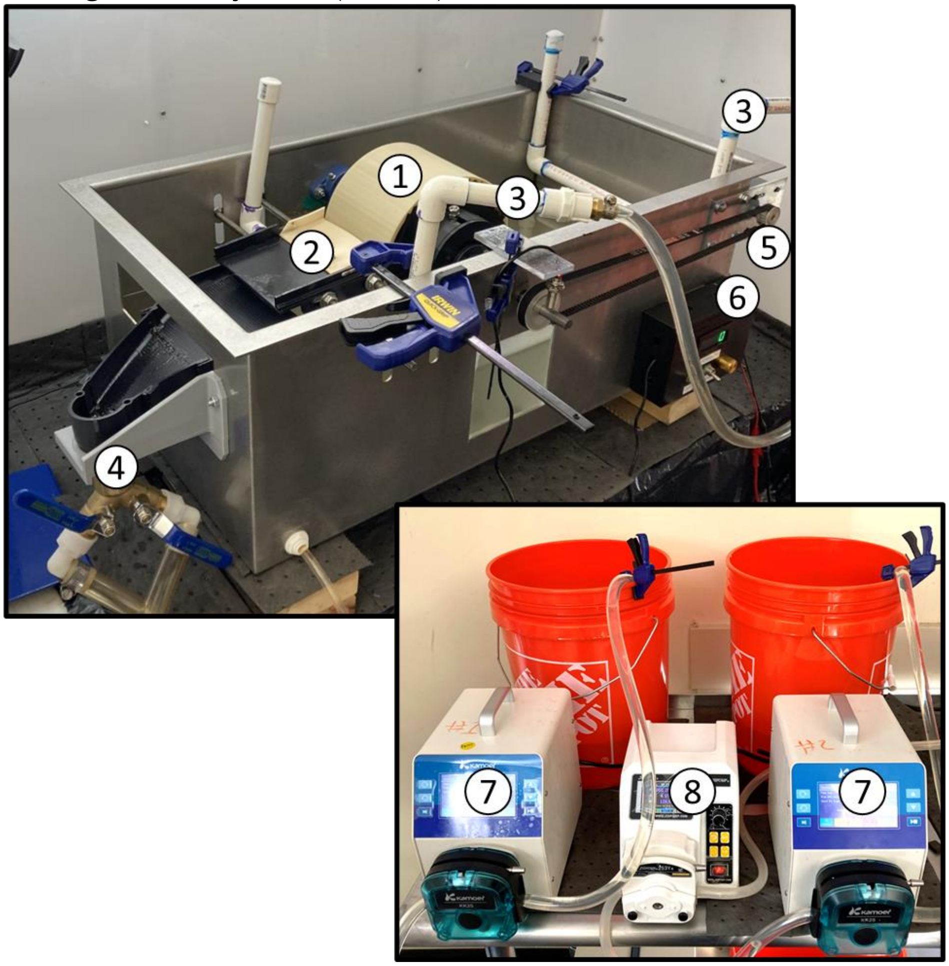


Figure 3: Tier 1 Experimental Apparatus

2.2.2 Tier 2

The Tier-2 apparatus was designed to accommodate a drum with a 430mm outer diameter and 135mm width. The diameter is equivalent to the Elastec TDS118G while the width is still reduced to accommodate rapid lab testing. The system is composed of the following components, shown in Figure 4:

1. (1) Test Drum and (1) Drum Core (OD=400mm, width=135mm)
2. (1) Scraper assembly, interchangeable
3. (1) Oil replenishment point. 1" PVC outlet directly in front of drum (later added deflection plate)
4. Drain Assembly
5. (1) Drive Assembly, including:
    - (1) 24V PMDC Gear Motor, 3/8 HP, 250RPM
    - PWM Speed Controller
    - 2:1 Gearing for increased torque

6. (1) Control panel: Controls motor direction & speed. Displays drum RPM.
7. Oil replenishment manifold
8. Oil Flow Meter
9. Divert to tank
    - Flow control valve
10. Relief valve to supply
11. Oil Flow Control Valve
12. (1) Oil Supply Pump – 120V Gear Pump: ¾ HP, 29.1 LPM
13. Measuring Equipment (not shown):
    1. 5L measuring pitchers (+/- 100ml)

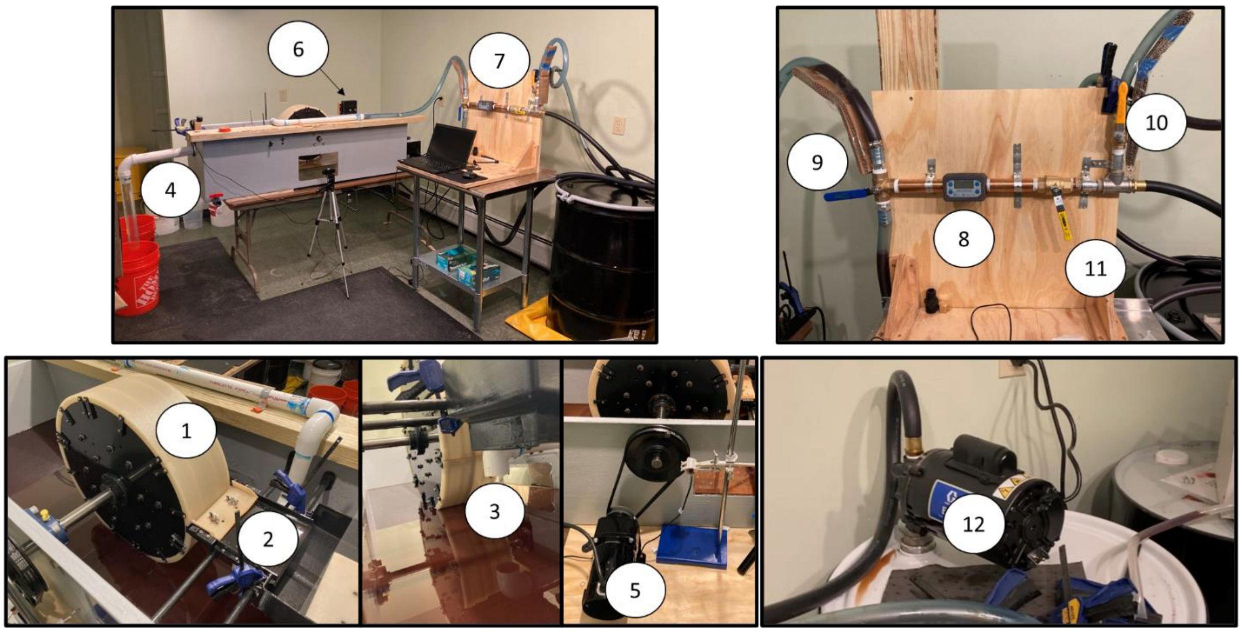


Figure 4: Tier 2 Experimental Apparatus

2.3 Vacuum Recovery System

During initial testing described herein, it was observed that certain drums designs which featured carrying volume, or surface area that could not be contacted by conventional scraping, visually appeared to contain unrecovered oil on each revolution. To confirm this observation, DA developed a vacuum recovery proof-of-concept system designed to recover oil unreachable by a standard scraper. Vacuum recovery was evaluated in both Tier 1 and Tier 2 and the components for each system are described below and shown in Figure 5. The only difference between the vacuum systems for each tier is the size of the oil transfer hose, which had to be larger to accommodate the increased recovery volume seen during Tier 2.

Tier 1:

1. Recovery Nozzle: Contoured to glide on drum. Notched to reduce oil build-up at front of nozzle.
2. ¾" Oil Transfer Hose

3. Intermediate Collection Bucket (5gal)
4. Rigid Shop Vac (120V, 8.3A, 4.25 PHP). Pulls vacuum on collection bucket.

Tier 2:
1. Recovery Nozzle(s): Contoured to glide on drum. Notched to reduce oil build-up at front of nozzle.
2. 1 7/8" Oil Transfer Hose
3. Intermediate Collection Bucket (5gal)
4. Rigid Shop Vac (120V, 8.3A, 4.25 PHP). Responsible for suction to collection bucket.

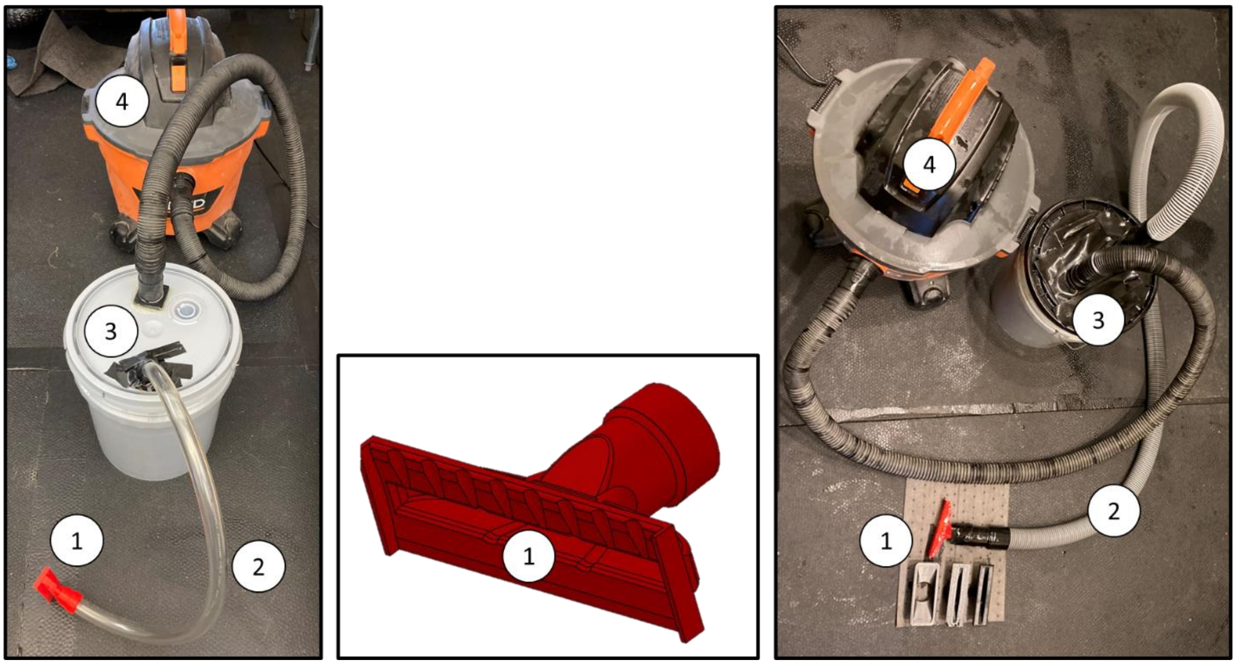


Figure 5: Vacuum apparatus for each tier. Tier 1 (left), Tier 2 (right), and the vacuum nozzle used for each (center).

2.4 System Capabilities

The following describes both the process capabilities as well as the precision achieved by each test apparatus. Furthermore, graphs to follow in this report will feature error bars when possible, representing a single standard deviation in the positive and negative direction from the mean, the value reported. Data without error bars represent a test course comprised of fewer than three trials. Such occurrences signify that steady state either could not be repeated or, due to time constraints, the team decided to move forward with more promising designs.

2.4.1 Tier 1

2.4.1.1 Process Capabilities

The Tier 1 experimental apparatus was designed to achieve the following process capabilities:

- Drum size: width = 135mm; diameter = 200mm
- Submergence Depth: tangent to 18-24mm (depending on drum geometry)
- Drum Speed: 0-100RPM

- Oil Replenishment Rate: 0-6LPM

Apparatus Issues Encountered:

- Submergence Depth: The tank design, in addition to a scaled-down drum diameter, inadvertently limited the effective submergence depth to 24mm, less for ‘fillable’ drums. This restricted the ability to investigate the effect of submergence depth on recovery performance.
- Drum Torque: It was possible to bind the drum and prevent it from spinning should too much pressure be exerted from the scraping assembly. In some instances, high pressure was desired (i.e., for compressible geometries) but was unachievable. This was improved by introducing v-belt pulleys with high gear ratios, though this in turn limited the top drum speed.
- Oil Replenishment: The replenishment flowrate required frequent recalibration and verification after a small number of tests. The transfer hose had to be shifted within the pump as leaving one section engaged with the peristaltic pump head resulted in declining performance.

2.4.1.2 Precision

Tier 1 precision was validated while commissioning the system by repeating tests and evaluating the precision of the tests per course. Approximately 20 test courses consisting of over 200 individual tests were run 5 times each once steady state was found. These tests consisted of a mix of courses utilizing each control drum, as well as several surface area and material drums. Of these, the average standard deviation of ORR values per course was ±35mL. DA decided to reduce the required number of steady-state tests per course to 3 based on this tight tolerance. At the conclusion of Tier 1, the average standard deviation per course with at least three tests were as follows:

- Hydrocal 300 Tests: ±41mL
- Hydrocal 38 Tests: ±15mL

2.4.1.3 A Note on Steady State

Throughout testing during each tier, the procedure was to first determine the steady state oil recovery rate for each drum then repeat the test a specified number of times. Steady state is the point at which the oil recovery rate of the drum matches the oil replenishment rate from the pumps. In theory, this would keep the slick thickness constant, thus imitating a spill of certain thickness. It was found that the Tier-1 system produced repeatable results once steady state was found, as such the team targeted a difference between oil recovery rate and oil replenishment rate of plus-or-minus 100mL per minute. It was thought that this tight tolerance would allow meaningful comparison between drums; however, in review it appears that this constraint added unnecessary time to each test course, limiting the number of drums that could be evaluated. 100mL is less than 4% of the determined ORR for the smooth control drum. Prior studies have utilized tolerances of plus-or-minus 25% i.e., 25mm slick +/- 5mm (Keller and Clark 2008).

2.4.2 Tier 2

2.4.2.1 Process Capabilities

The Tier 2 experimental apparatus was designed to achieve the following process capabilities:

- Drum size: width = 135mm; diameter = 400mm
- Submergence Depth: tangent to 100mm (depending on drum geometry)
- Drum Speed: 0-125RPM
- Oil Replenishment Rate: 0-29.1LPM

Apparatus Issues Encountered:

- Oil Replenishment: The oil replenishment system was not designed to pump and accurately measure low enough flow rates discovered to be required for Hydrocal 38 testing. This was resolved by utilizing the Tier 1 pumps for these trials.

2.4.2.2 Precision

Tier 2 precision was more challenging to evaluate as declining performance was observed in certain drums, described further herein. That said, most test courses were found to be repeatable. Tier 2 featured comparatively fewer test courses than during Tier 1, as such, trial repeatability is described per course in the table below. Please note, statistics are reported only if a minimum of (3) trials in steady state were achieved. DA asserts this data shows tight tolerances between courses and justify use of 3-test courses (when achievable).

	Average ORR (LPM)	StdDev ORR (LPM)	Average of RE (%)	StdDev of RE (%)	# of Runs
Hydrocal 300					
Control-Smooth					
2mm	7.8	0.3	74%	0.9%	11
6mm	10.2	0.1	77%	0.5%	3
Innovation-Gyroid - Large - Vacuum					
6mm	12.8	N/A	76%	N/A	2
Innovation-Gyroid - Small - Scraped					
2mm	7.7	0.2	86%	3.5%	4
6mm - 34 RPM	*8.5*	*0.2*	*93%*	*1.1%*	*3*
6mm - 50 RPM	10.0	N/A	86%	N/A	1
Innovation-Gyroid - Small - Vacuum					
2mm*	10.6	**0.7**	64%	3.8%	4
6mm	13.9	0.1	76%	2.3%	4
Innovation-Rectangular Grooves					
2mm	8.4	N/A	64%	N/A	2
6mm	10.4	0.2	71%	0.8%	3
Hydrocal 38					
Control-Smooth					
2mm	1.8	0.3	90%	0.5%	4
6mm	3.8	0.1	95%	0.5%	4
Control-Gyroid - Small - Vacuum					
6mm	7.2	0.1	79%	1.1%	3

Table 1: Tier 2 Trial Repeatability Statistics. *Denotes results not in steady state though repeated at least 3x.

2.5 Test Procedure

2.5.1 Performance Metrics

To evaluate recovery performance of each test drum DA computed the Oil Recovery Rate (ORR) and the Recovery Efficiency (RE). The Formulas used to calculate ORR and RE are as follows:

$$ORR = \frac{V_{Oil}}{t}$$

Where V_{oil} is the total volume of oil recovered, decanted, and t is the elapsed time of recovery in minutes.

$$RE = \frac{V_{Oil}}{V_{Total\ Fluid}}$$

Where $V_{total\ fluid}$ is the volume of total fluid (oil and water) collected.

2.5.2 Test Protocol

Testing in Tier 1 and Tier 2 involved both standard scraping and vacuum recovery trials, meaning that throughout the project a total of four testing protocols were used. Each protocol, in complete detail, can be found in Appendix B: Test Procedures. While differences exist in equipment, replenishment volumes, etc. each protocol follows the same general form:

1. Install drum and wiper (if used) into test apparatus per test matrix specifications
2. Add known volume of water and test oil into the main tank to establish submergence height and slick thickness
3. Document test parameters
4. Begin video capture
5. Warm-up to steady state:
    a. Divert recovery fluid to slop recovery vessel
    b. Start timer, drum motor and oil replenishment (and water replenishment if required)
    c. Once time to steady state is reached, divert recovered fluid to recovery vessel
6. Run test for predetermined time
7. After test run:
    a. Stop video capture
    b. Allow recovered fluid to settle and separate fully
    c. Measure the total fluid volume in the recovery vessel
    d. Drain free water from recovery vessel and measure volume
    e. Measure remaining oil volume
    f. Document remaining necessary measurements

3 Drum Designs and Test Results

The following describes the designs and subsequent test results for drums developed in both phases of Tier 1 and in Tier 2.

3.1 Tier 1 – Phase 1: Isolated Critical Factors

Tier-1 first focused on isolating individual critical factors followed by an evaluation of innovative geometries that stem from these learnings. Designs and finding are reported from the following categories:

1. Control Drums
2. Material Drums
3. Surface Area Drums
4. Surface Roughness Comparison
5. Innovations

3.1.1 Control

Figure 6 shows the control drums used for baseline comparison during Tier 1. Control drum testing showed that Hydrocal 300 is more conducive to skimming than Hydrocal 38 and that for each slick thickness and oil type, the smooth control drum performed better in thin slicks than the grooved control drum (Figure 7). Of note, RE was high for all control drums at Tier-1 scale, as seen in Figure 8. This was flagged for further investigation in Tier 2. Furthermore, Hydrocal 38 tests yielded extremely low volumes of recovered water, even at high speeds (up to 100RPM).

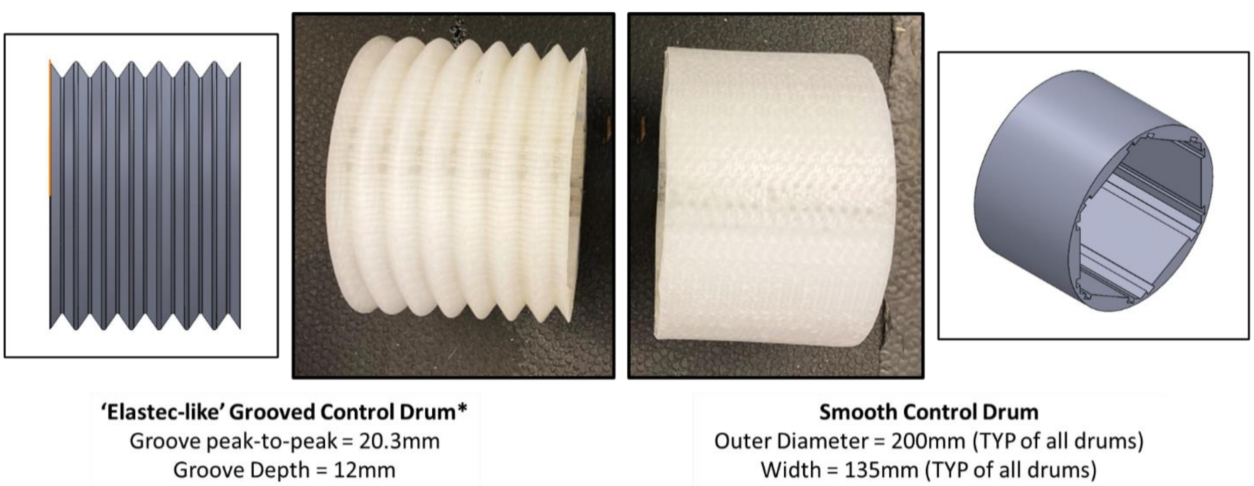


Figure 6: Tier 1 Control Drums

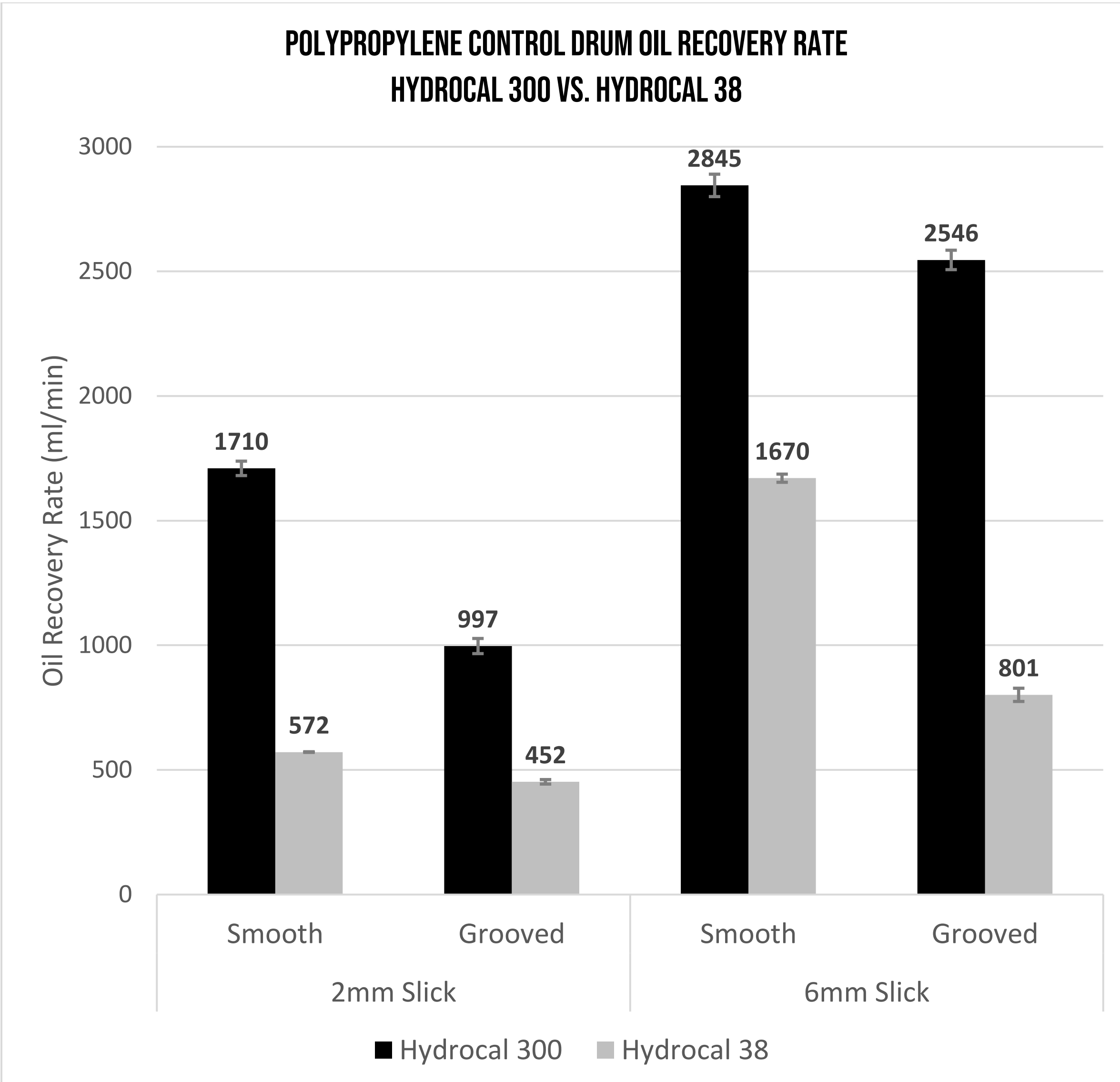


Figure 7: Tier-1 oil recovery rate performance results for each control drum. Some error bars smaller than chart symbol.

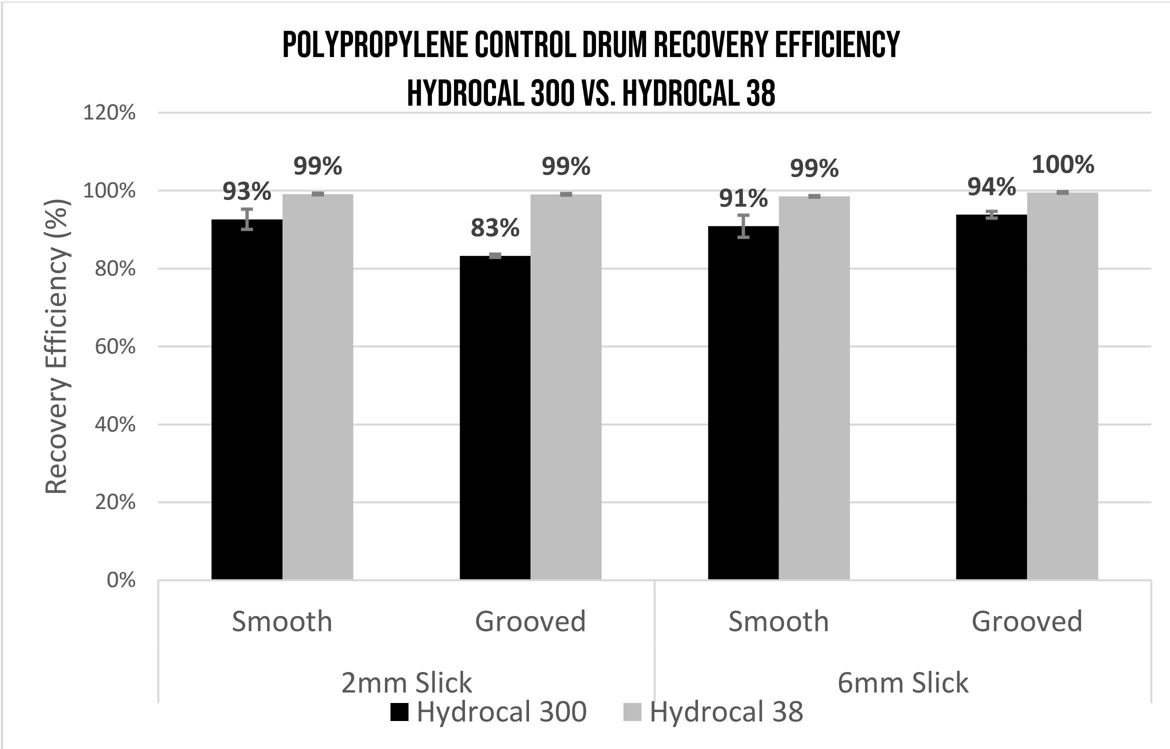


Figure 8: Tier-1 recovery efficiency results for each control drum. Some error bars smaller than chart symbol.

3.1.2 Material

The purpose of the material investigation was to explore the recovery potential of materials and surface finishes readily available for applicable additive manufacturing processes. The selected materials met at least one of the following criteria: 1. Materials previously studied and confirmed to be suitable for oil skimming applications, 2. Additive manufacturing equivalents, and 3. Promising options not known to DA to be utilized for oil recovery. Each material was known to be available for at least one 3D-printing process and many could be manufactured inhouse. The following are the materials and corresponding 3D-printing processes used to produce the test drums. Characteristics of each can be found in the Appendix D:

- FDM: PLA, PP, PVC, Nylon, ABS, ASA, TPU, TPE
- SLS: PP, Nylon, TPU, TPE (Sealed and Unsealed)

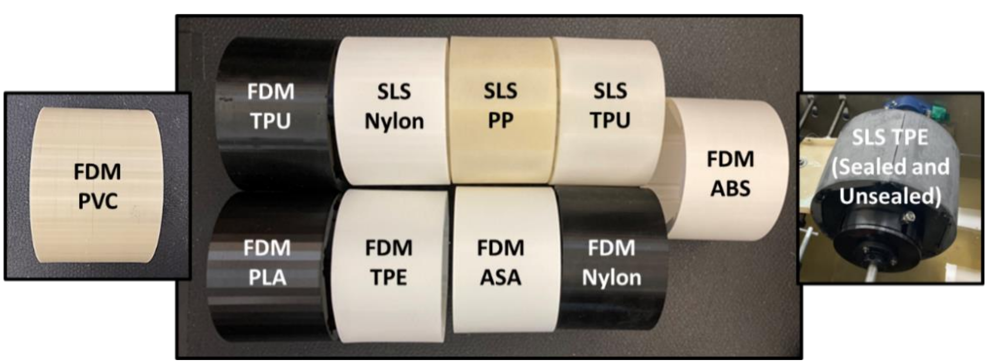


Figure 9: Tier 1 material investigation test drums

To isolate the material as the distinguishing factor between tests, the design, which mimicked the smooth control drum geometry, and the conditions of each test were held consistent. These conditions were based on those that produced the best results for the smooth polypropylene control drum:

- Oil Type: Hydrocal 300
- Slick Thickness: 6mm
- Drum Speed: 60RPM
- Submergence depth: 12mm

The results of the investigation can be seen in Figure 10. No significant difference in ORR was observed for the top 5 performers (standard deviation = 25mL), which includes SLS Nylon and FDM ASA, two widely available materials used in 3D printing shops. FDM PLA and ABS, also common prototyping materials, performed poorly. Recovery efficiency was high across the board, though SLS TPU and PA12 had extremely low water (over 97% RE) while PVC recovered over 20% water. SLS TPE, as manufactured inhouse, was unsuitable for recovery. The material absorbed liquid rapidly and deformed.

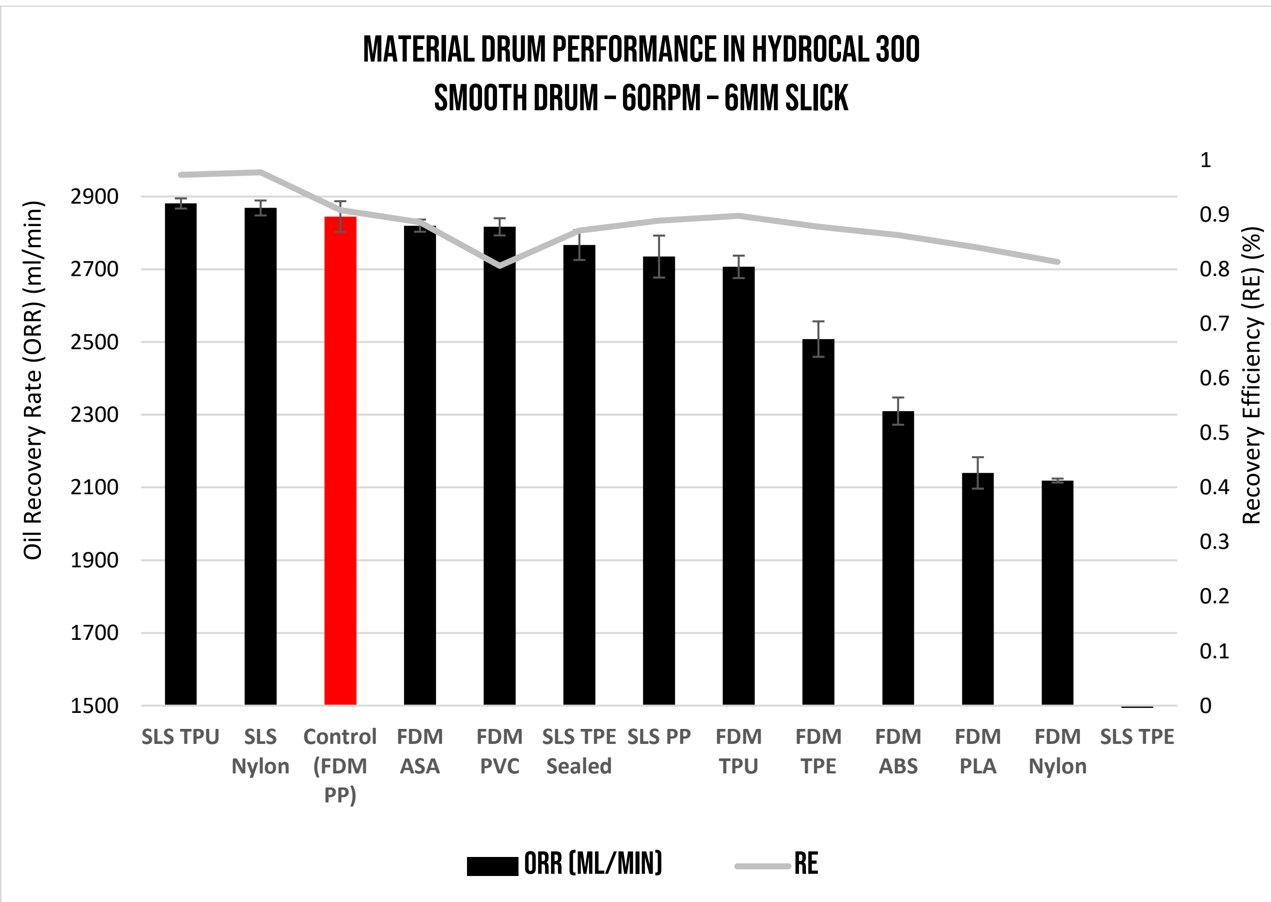


Figure 10: Tier 1 Material Drum Performance

3.1.3 Surface Area

The purpose of the surface area investigation was to determine how recovery performance changes as surface area is scaled. Surface area is identified in the literature as a factor that influences performance though it is a challenging factor to isolate; there are unlimited geometries that can be used to increase the surface area of the drum, each influencing performance in a multitude of ways, from capillary effects to the ability to scrape oil from the drum, and beyond. Additionally, it is not clear from the literature how the effective depth, or depth of the drum surface, measured perpendicular to the drum axis, influences performance. For instance, v-grooves could be manufactured with a 100mm depth, greatly increasing the surface area, but it is not clear that this would be beneficial for recovery, especially in thin slicks. Furthermore, it is unclear from the literature how an increase in surface area, not all of which can be in contact with a scraper, affects performance.

It was decided to conduct tests using different variations of two simple geometries that can easily be scaled to different surface areas: 1.) v-grooves, and 2.) surface dimples. The primary intention was to shed light on the surface area factor, by testing drums across a range of increasing surface areas. Additionally, the goal was to assess the question of effective depth by testing drums with different depths but identical surface area, i.e., the 6mm and 2mm grooves shown below exhibiting equivalent surface areas (81-82% increase over smooth). Note that controlling for equivalent surface area is accomplished by featuring fewer 6mm grooves than found on the 2mm drum. Finally, the difference between fully vs. partially scrapable geometries was investigated by testing a grooved and dimpled drum with identical surface areas.

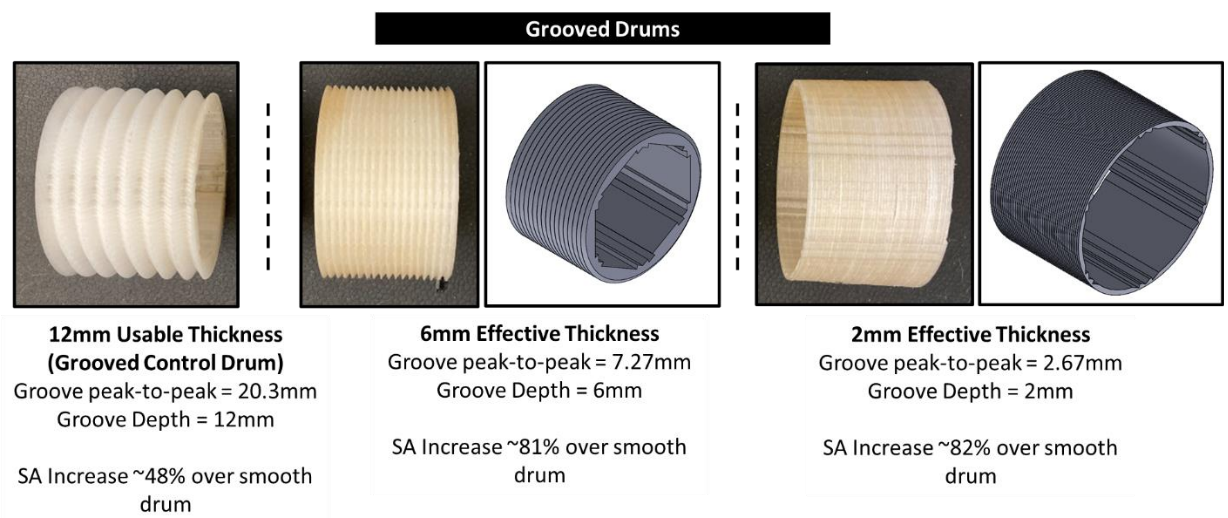


Figure 11: Tier 1 grooved surface area drum designs

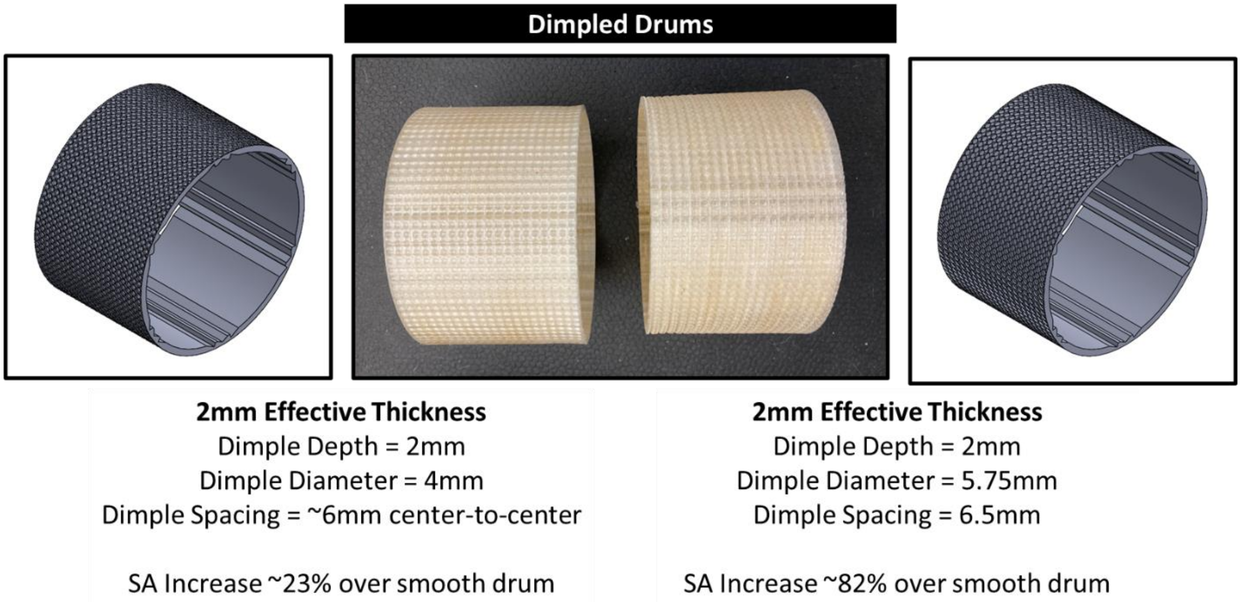


Figure 12: Tier 1 dimpled surface area drum designs

DA was unable to confirm a correlation between increased surface area and increased ORR as a rule. As evidenced in Figure 13 and Figure 14, the smooth control drum outperformed all surface area drums. This was also not the most robust test category, likely because the dimples and smaller grooves were very difficult to scrape effectively, hindering the ability to reach steady state for all drums and to tease out the actual cause of the poor performance. These tests did however lead to observations that fillable drums, such as the dimples, seemed to hold oil despite the inability of a standard scraper to recover it.

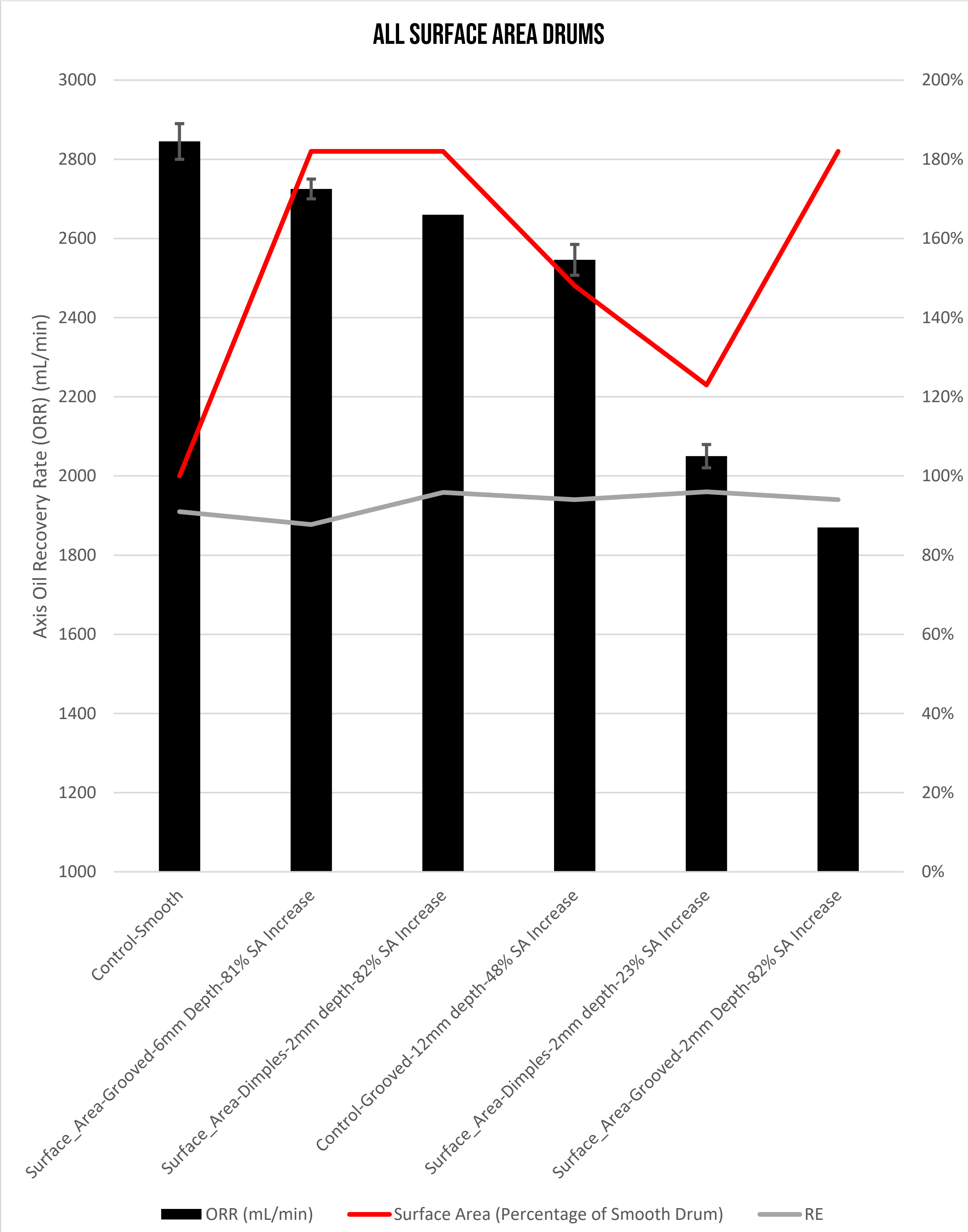


Figure 13: Tier 1 surface area drum performance

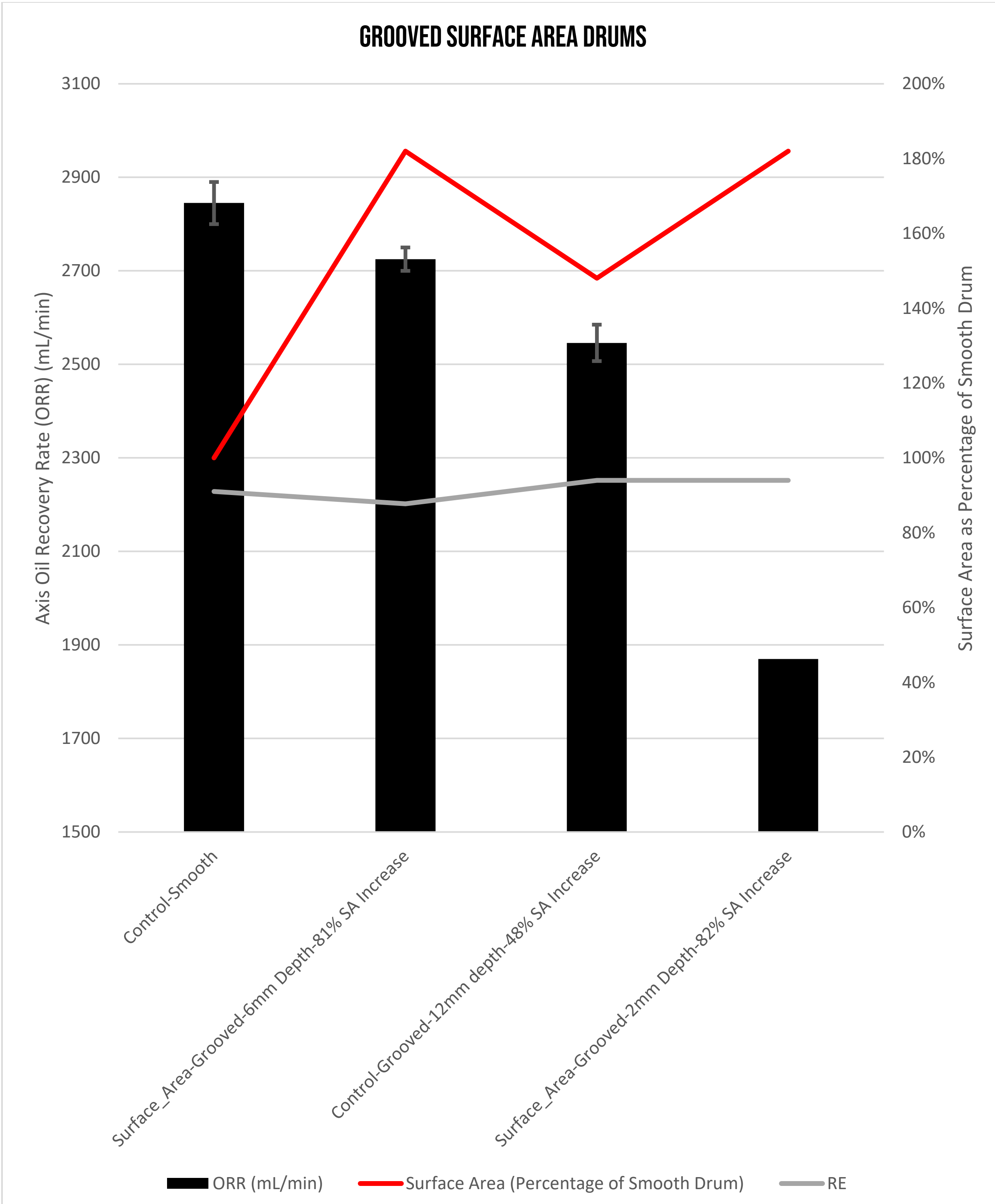


Figure 14: Tier 1 grooved surface area drum performance

3.1.4 Surface Roughness

The purpose of the surface roughness investigation was to determine how surface roughness effects recovery performance. To isolate this factor, four sets of drums were manufactured in the same material by both FDM and SLS. SLS produces an inherently rougher texture compared to FDM, thus these drums were used to assess surface roughness as a critical factor, in addition to the pros and cons of each printing method. In general, SLS outperformed smooth FDM prints. Polypropylene was an exception though the difference was not substantial.

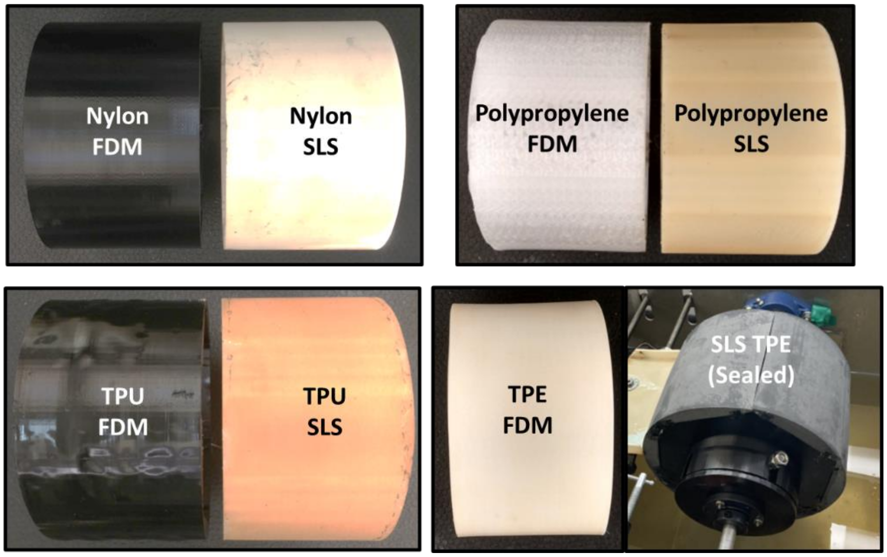


Figure 15: Tier 1 surface area test drums

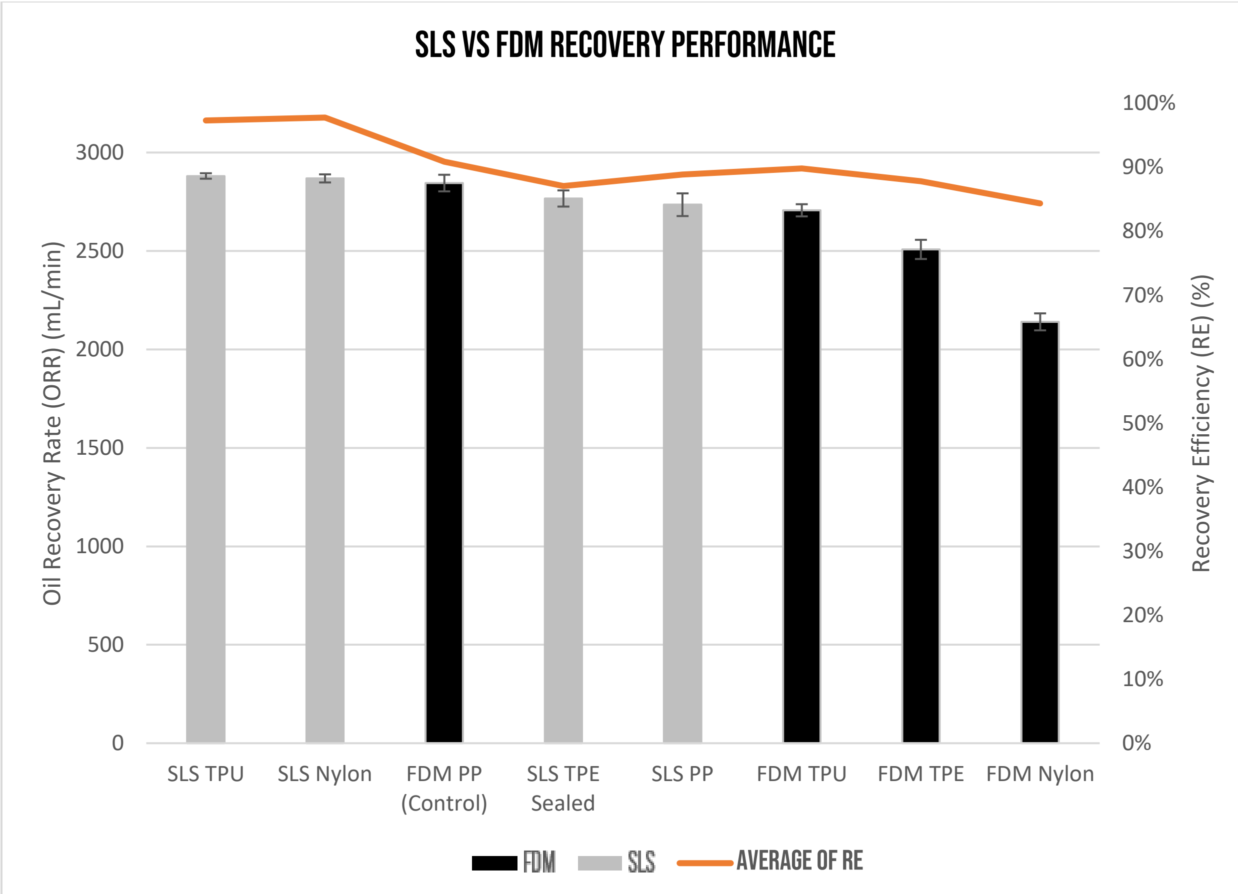


Figure 16: Tier 1 surface roughness test drum performance

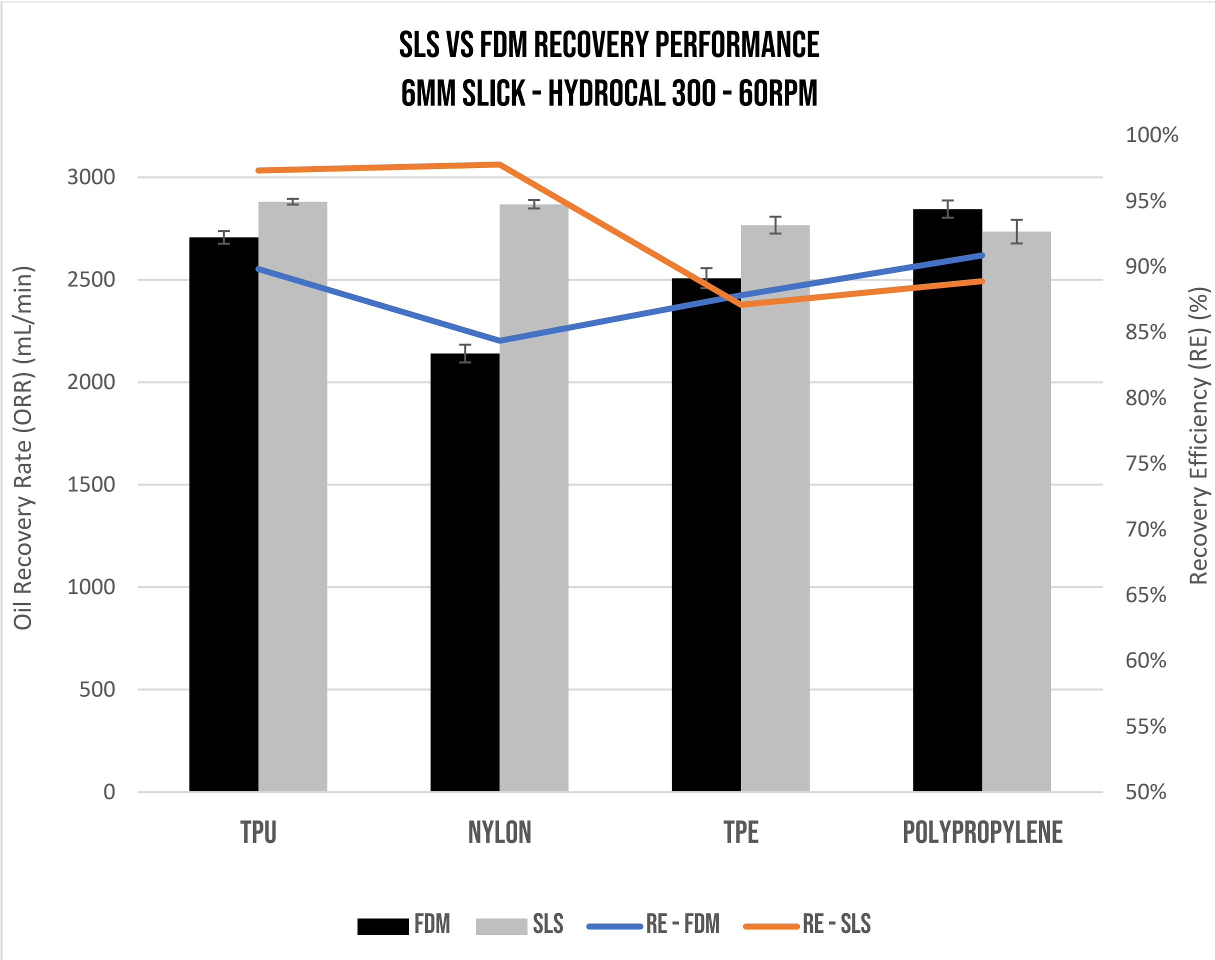


Figure 17: Tier 1 surface roughness test drum performance by material.

3.1.5 Tier 1 – Phase 1 Conclusions

At the conclusion of Tier 1, Phase 1, several key learnings facilitated design of innovations in Phase 2, these included:

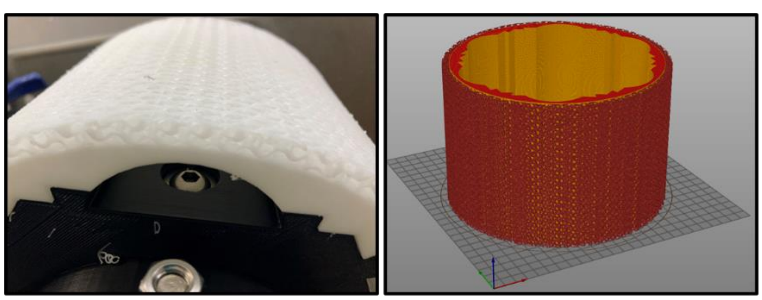
1. Various 3D-printable materials and processes appear suitable for oil recovery, at least over short-term testing.
2. Surface roughness appears to improve recovery performance.
3. Increased surface area alone does not necessarily lead to increased performance in thin slicks, as evidenced by the smooth control drums higher performance over the Elastec-mimicking grooved control drum. It appears that scraping is critical.
4. Fillable drum surfaces, or those with carrying volume, provide an opportunity to recover more oil per revolution than control though recovery via standard scraping may not suffice.

3.2 Tier 1 – Phase 2: Innovations

Based on the results of Tier 1, Phase 1, two broad innovation categories emerged: 1.) fillable geometries and 2.) easily scrapable geometries with increased surface area. Fillable geometries emerged from observations, made during surface area testing, that geometries with fillable volume, such as the dimpled drums, seemed to capture oil that was not recovered by standard scraping. Initially, fillable innovations focused on compressible geometries, and later a novel vacuum recovery method. Easily scrapable geometries with increased surface area were considered despite inconclusive data from the surface area investigation, as it was thought that an increase in oil contact area could still be beneficial if designed to be scraped effectively and to encourage retention of oil throughout the drum rotation. For all innovation drums, learnings from the material investigation were considered and a top performer was utilized unless unworkable. The following describes the design, principle of operation, and results of each Tier-1 innovation drum.

3.2.1 Fillable Geometry - Gyroid Variations

A gyroid is a triply periodic minimal surface with no reflectional symmetries (Weisstein, E.W.). The gyroid creates a network of interconnected channels that are open to each other, allowing the whole volume to be filled with a liquid. Additionally, it is a common 3D-printing infill that exhibits good compressive strength in all directions. To create the various gyroid test drums in Tier 1, inhouse 3D-printer options were utilized to expose gyroid-type infill of a specific thickness and infill percentage, around the perimeter of the drum. Originally, the gyroid was tested as a 'sponge' concept. The intention was that the gyroid volume would fill with fluid as the drum rotated and could be squeezed out by pressing the scraper into the surface. For this reason, it was originally printed with FDM TPE (A poor performer in the material study) for its compressibility (described in the following section). Extracting the fluid via compression was unsuccessful, potentially due to the strength exhibited by the desired infill percentage. However, it was observed that the cavities were filled with fluid that could not be extracted via conventional scraping. In response, a gyroid manufactured via FDM polypropylene was tested with vacuum recovery, in addition to standard scraping.



4mm Gyroid (15% Infill)
Material = Polypropylene
Est. Carrying Capacity = 404ml/rev

Figure 18: Polypropylene gyroid test drum.

3.2.2 Fillable Geometry - Compressible Variations

Two types of compressible geometries were investigated. The first type comprised gyroids manufactured from TPE with a 15% infill and both 2mm and 4mm depth. These were unable to be compressed successfully, likely due in part to the strength of the geometry as well as the limitations of the test apparatus. The second type was referred to as a folding groove. The principle of operation involves low angle flaps designed to capture fluid which is then expelled when a scraper presses the groove flat. Furthermore, the grooves are spiraled, allowing the groove to be open to the fluid after scraping, intended to provide ‘scooping’ action. The low angle aimed to reduce the effective depth of the geometry such that in thin slicks, the drum could be set-up such that surface encounters mainly oil.

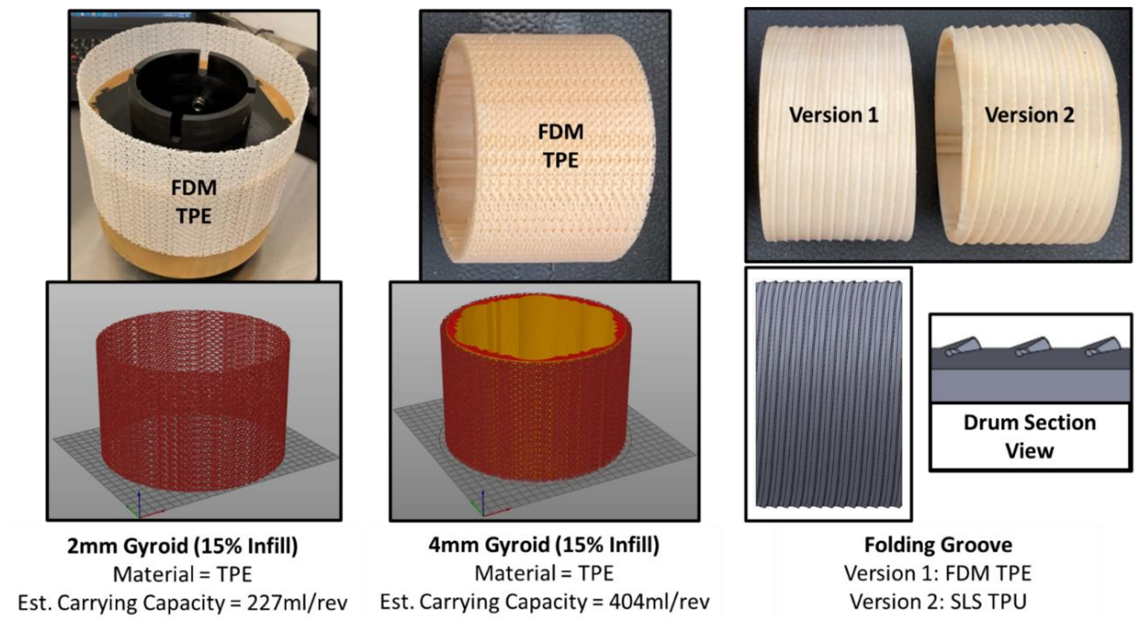


Figure 19: Test drums featuring compressible geometries. From left to right: 1. 2mm TPE gyroid, 2. 4mm TPE gyroid, and 3. two versions of folding grooves

3.2.3 Increased Surface Area - Multi-Surface Drum

The concentric multi-surface drum was created to capitalize on the high performance of the smooth control drum shown in testing. The design aimed to repeat the recovery surface within a useable depth while maintaining the ability to scrape. The test drum is comprised of 3 concentric surfaces and a scraper designed to contact the outer surface and the surfaces of the internal cavity. Testing confirmed that fluid was drawn into the cavities, perhaps due to lower pressure created at the center of the spinning drum.

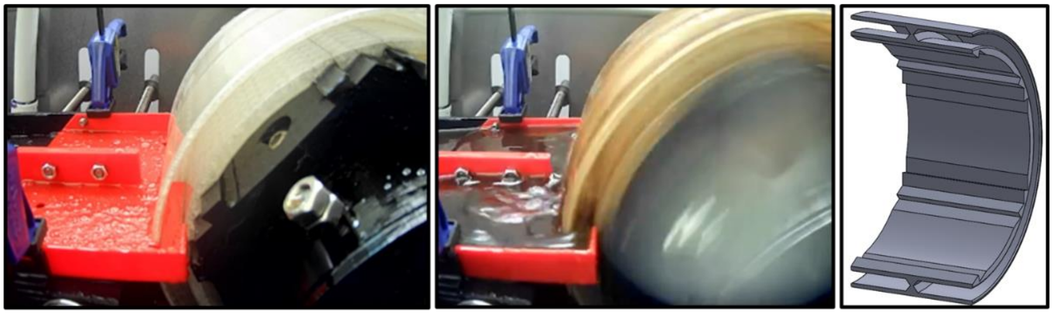


Figure 20: Concentric Multi-Surface Drum. Scraper installed (left). In operation (center). CAD section view (right).

3.2.4 Increased Surface Area – Rectangular Groove Variations

The rectangular groove profile intended to leverage capillary action via narrow groove-wall spacing. Filling of the v-grooved control drum was not observed in testing, perhaps due to the thin slicks, and this drum was designed to determine whether capillary filling could be achieved in thin slicks with tighter wall spacing. A high-level of filling in the grooves was not observed; however, the 3.0mm drum outperformed control. It is not immediately clear why this is the case when the grooved control drum performed poorly. The original 2.2mm grooves were tested in PLA FDM to leverage consistent printing results though SLS polypropylene was selected for the 3.0mm grooves to capitalize on higher material performance.

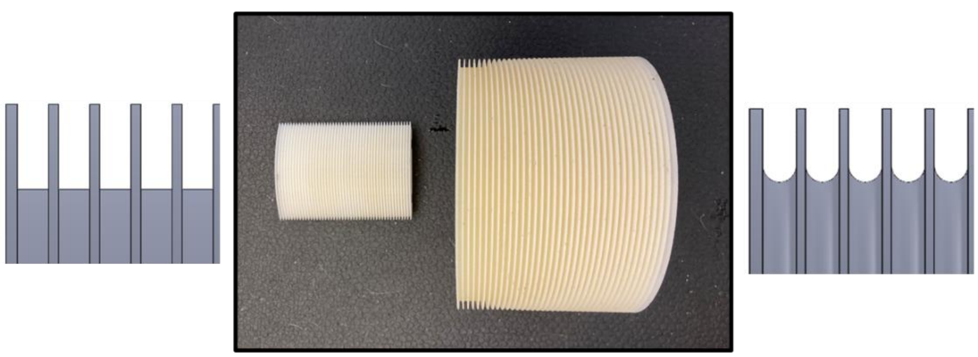


Figure 21: Rectangular grooved drum design iterations

3.2.5 Tier 1 – Phase 2 Results & Conclusions

The following summarize the results of each Tier-1 innovation and can be seen graphically in Figure 22 and Figure 23. Based on these results, the team proposed to scale the design of the gyroid (vacuum recovery), rectangular grooves, and multi-surface microgeometries for full diameter testing in Tier 2.

Gyroid - Scraped

- Scraping the gyroid yielded ORR results from 0mL/min in Hydrocal 38 to a 23% increase over control in a 6mm slick of Hydrocal 300.
- Potential for optimization of gyroid thickness and pore size to control rate of fluid drain.

Gyroid – Vacuum Recovery

- Vacuum recovery of the gyroid can produce large increases in ORR – from 25% (Hydrocal 300 – 2mm-slick) to 126% (Hydrocal 38 – 6mm-slick) over control
- Vacuum recovery decreases recovery efficiency – ranging from 59% (Hydrocal 38 – 6mm-slick) to 82% (Hydrocal 300 – 6mm-slick)
- Vacuum recovery emulsifies/aerates the oil/water mixture and takes much longer to separate than standard scraping

Compressible Geometries

- No compressible geometries were able to outperform control as designed
- Unable to extract fluid via compression in practice despite visual evidence of increased carrying volume

Multi Surface

- The multi-surface drum out-performed control by 7% (Hydrocal 300 – 6mm-slick) at 75% the control-drum width.
- In practice, a full-width drum would likely need openings in the outer surface increments along the width, as opposed to openings at the drum ends used in the test drum, changing the fluid-flow dynamics.

Rectangular Groove

3.00mm

- High-speed (~87 RPM) tests in Hydrocal-38 exhibited 39% increase in ORR over control with negligible RE change.
- Opportunity to optimize groove dimensions in Tier-2

2.2mm

- Testing indicated poor performance in ORR and RE, though this could be attributed to material (PLA subsequently performed poorly in material studies).

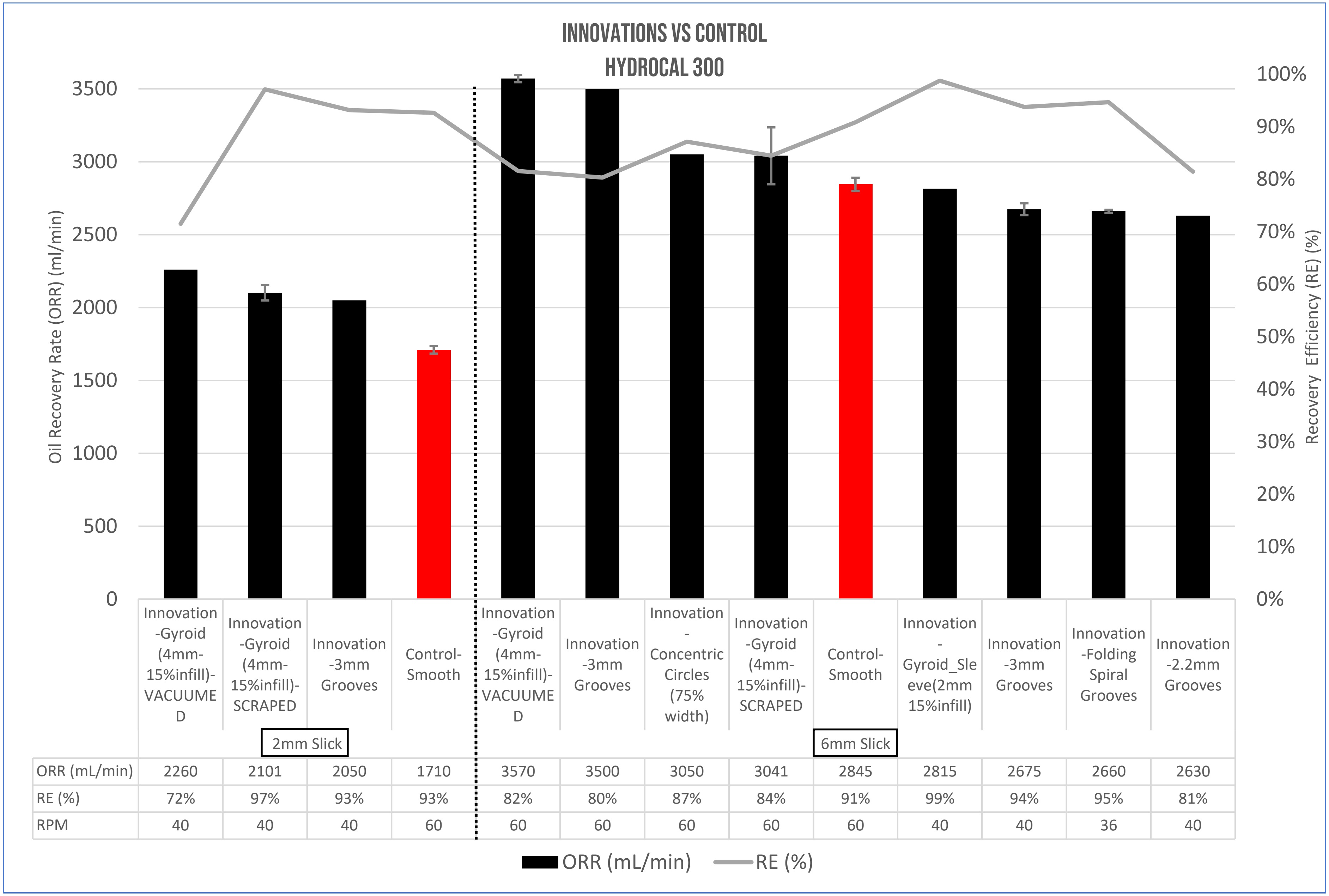
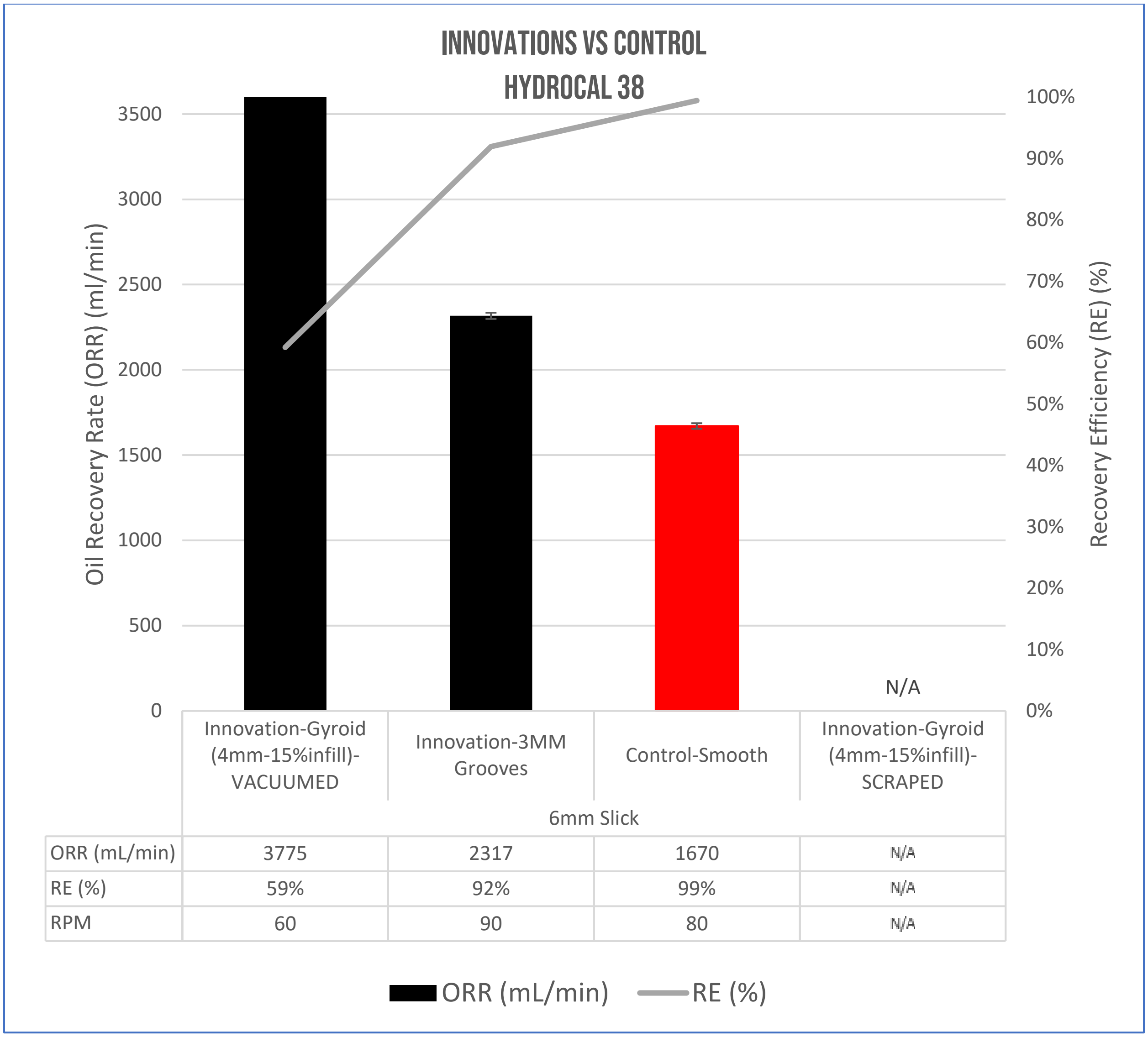


Figure 22: Recovery performance of Tier-1 innovation drums vs. control in Hydrocal 300



	Innovation-Gyroid (4mm-15%infill)-VACUUMED	Innovation-3MM Grooves	Control-Smooth	Innovation-Gyroid (4mm-15%infill)-SCRAPED
ORR (mL/min)	3775	2317	1670	N/A
RE (%)	59%	92%	99%	N/A
RPM	60	90	80	N/A

Figure 23: Recovery performance of Tier-1 innovation drums vs. control in Hydrocal 38

3.3 Tier 2: Full-Scale Diameter

Tier-2 testing evaluated a narrowed selection of full-scale diameter drums to provide more reliable comparison to field results over Tier 1. Four separate drums were tested, including three novel geometries (Figure 24) and the smooth polypropylene control drum. SLS polypropylene was used for all drums. It is worth noting that this is a change from the manufacturing process used for the Tier-1 control drums, and that SLS PP did not perform as well as FDM in the Tier-1 material study. The team decided to move from FDM to SLS PP to keep the control material consistent between tiers, acknowledging the desirable characteristics of PP beyond affinity for oil i.e., water and chemical resistance. Additionally, FDM PP printing services proved very difficult to find while SLS PP is common and the SLS process typically allows for larger print sizes. Future research into the SLS materials that performed well in Tier 1 is recommended, especially as it pertains to absorption and performance over long time periods. Additionally, the innovation subset tested in Tier 2 does not represent the full spectrum of designs originally intended for Tier 2. The team prioritized the gyroid, both scraped and vacuumed, but due to project realities, were forced to abandon further development of compressible and multi-surface geometries. Future work on these concepts is warranted. The following describes further development and evaluation of the four aforementioned drums.

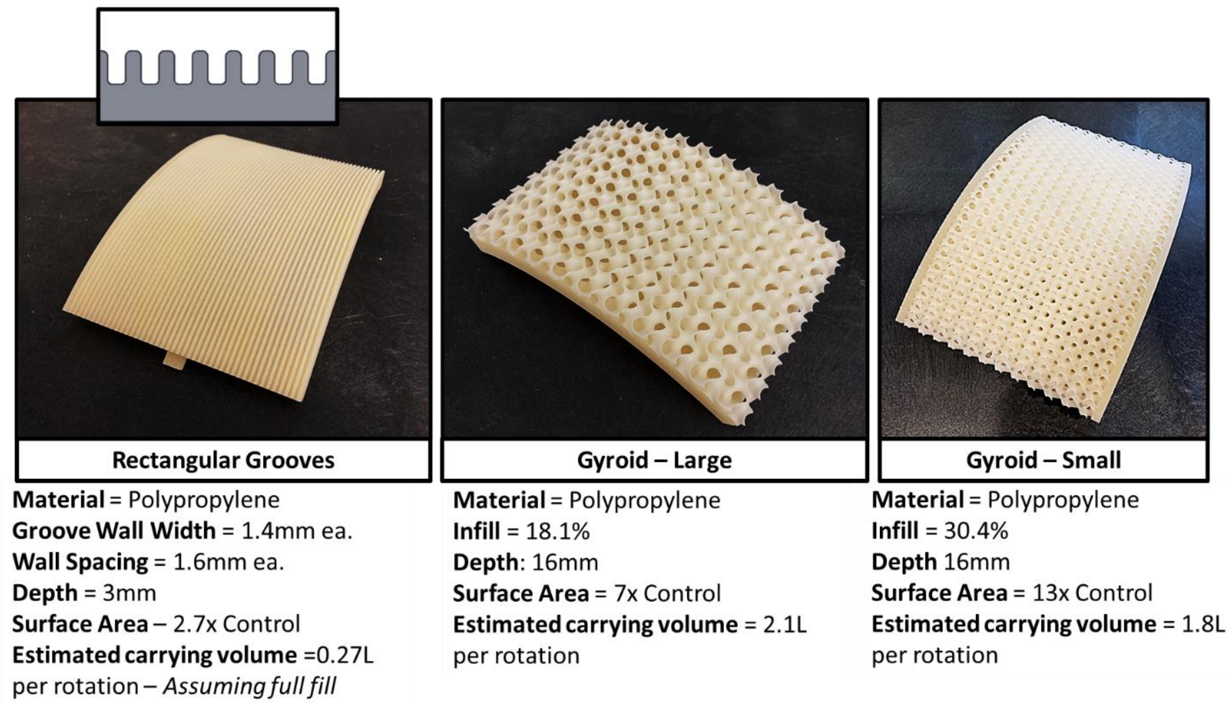
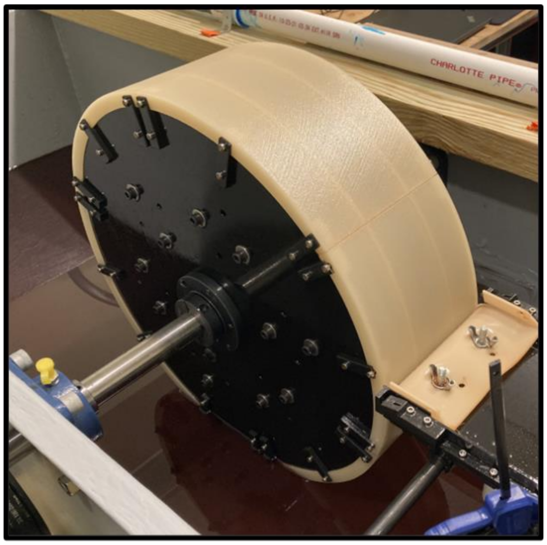


Figure 24: Tier-2 innovation drum designs

3.3.1 Control Drum Design

Figure 25 shows the control drum used for baseline comparison during Tier 2. The design features a diameter equivalent to the Elastec TDS 118G and identical width to Tier-1 test drums. Due to the increased size of the drums, each surface was manufactured in six separate pieces of cladding. This is typical of the innovation drums as well.



Material = Polypropylene – 3D printed via SLS (TYP)
Width = 135mm
Diameter = ~410mm

Figure 25: Tier-2 control drum

3.3.2 Gyroid Surface Design

To create the various gyroid test drums in Tier 1, inhouse 3D-printer options were utilized to expose gyroid-type infill around the perimeter of the drum. Infill percentage could be altered; however, further control over the design was limited. Tier-2 drums required more control and the ability to print via SLS. It was found that 3D-CAD was not optimal for modelling or changing surface parameters, thus an alternate development procedure was adapted. This process is shown graphically in Figure 26 and described here.

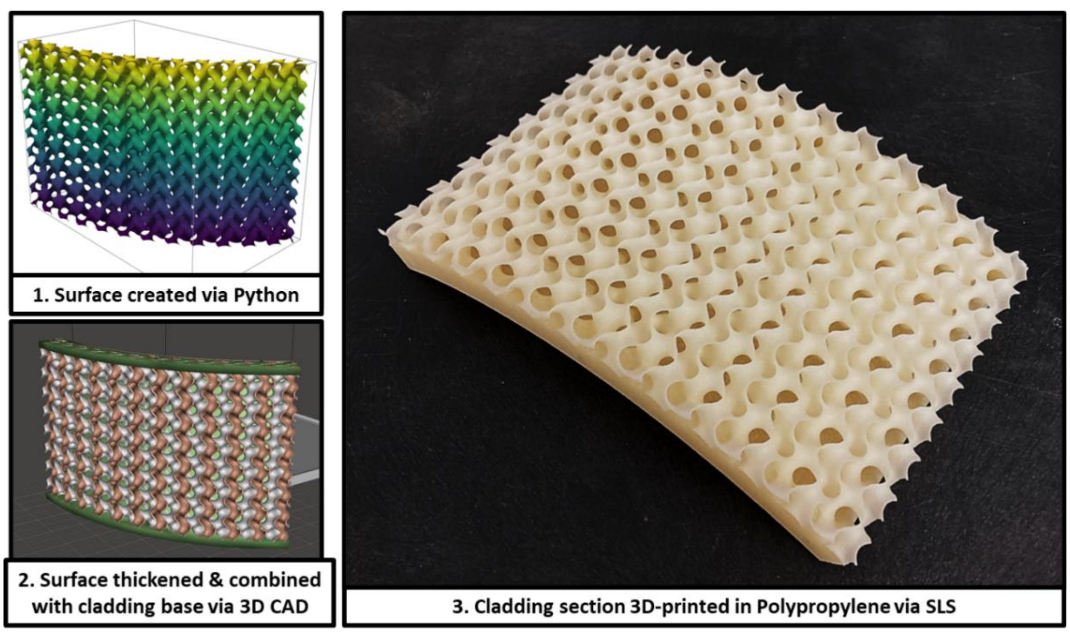


Figure 26: Graphical depiction of gyroid-based drum development procedure

3.3.2.1 Modelling the Surface in Python

Tier-2 drums utilize an approximation of a gyroid, defined by the following trigonometric equation [Dolan et al. 2015, p. 3]:

$$\cos(\tilde{x})\sin(\tilde{y}) + \cos(\tilde{y})\sin(\tilde{z}) + \cos(\tilde{z})\sin(\tilde{x}) = t$$

Where:

- $\tilde{x} = {}^{2\pi x}/_{a}$, $\tilde{y} = {}^{2\pi y}/_{a}$, and $\tilde{z} = {}^{2\pi z}/_{a}$
- a is the cubic unit-cell edge length
- t is the volume fraction of divided space

The variables in this equation, which control unit-cell dimensions and volume fractions of the divided space, were manipulated to achieve the desired channel properties. After which, the resultant surface was curved about a radius to achieve a section of the desired cylindrical-gyroid surface. An STL file was then created for the resultant surface. The process for modeling a cylindrical gyroid mathematically in Python was adapted from (Wang, Y et al. 2020) and (https://stackoverflow.com/questions/68400574/how-to-convert-a-cartesian-problem-in-a-cylindrical-problem). The code used to create the two gyroids tested in Tier 2 can be found in Appendix C: Gyroid-Based Drum-Surface Code.

3.3.2.2 Applying Surface Thickness and Combining with Base

To create a usable drum cladding section from the surface created in Python, the surface required thickness and geometry that allowed attachment to the drum core. To accomplish this, the surface was imported into Meshmixer v3.5 (Autodesk Inc., San Rafael, CA, USA). Within Meshmixer, an extrusion of the desired thickness was applied normal to the surface. Finally, the surface was combined with an STL file of the cladding base, created using Solidworks 2021 (BIOVIA, Dassault Systèmes, San Diego, CA, USA). This procedure is shown graphically in Figure 27 (note that first steps are displayed with a single gyroid unit cell to show extrusion). At this point, the file was ready to be 3D-printed.

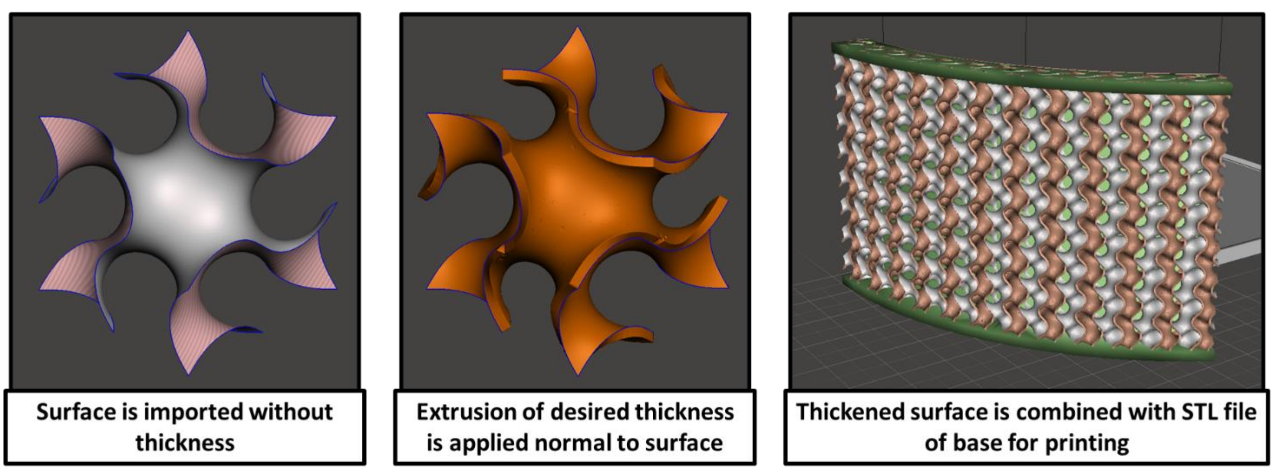


Figure 27: Process of applying thickness to the gyroid-based surface and combining it with the cladding base in Meshmixer.

3.3.3 Tier 2 Results

3.3.3.1 Control

Figure 28 displays the results of baseline testing for the Tier-2 smooth control drum. Based on Tier-1 testing results and published performance for the Elastec TDS 118G with grooved drum (McKinney et al. 2017), the ORR and RE values for the Tier-2 control drum appear in line with what might be expected. According to (McKinney et al. 2017), The Elastec TDS 118G (with grooved drum) achieved 59 Lpm and 75% RE in a 6mm slick at 55 RPM. Scaling this result to the width of Tier-2 drums (135mm), an ORR of 9.3Lpm would be expected. Note that diameters of the TDS 118G drum and the Tier 2 control drum are equivalent.

$$\left(\frac{860mm}{135mm}\right)(59Lpm) = 9.3Lpm$$

The Tier-2 smooth control drum achieved a 10% ORR increase over the grooved drum scaled result with 10.3 Lpm at 78% RE. This is in line with Tier-1 ORR results showing that the smooth control drum's ORR was 11.7% higher than that of the grooved drum for testing in Hydrocal 300. While DA considers the scale factor applied to (McKinney et al. 2017) to be a rough approximation, it is a useful check to confirm that baseline results are satisfactorily representative of field conditions.

Figure 29 shows jump in control drum performance which coincided with the test facility losing heat over a weekend prior to further baseline testing. Note that subsequent testing of all drums was performed at approximately 15ºC, though fluid temperatures below 14ºC were not achievable again.

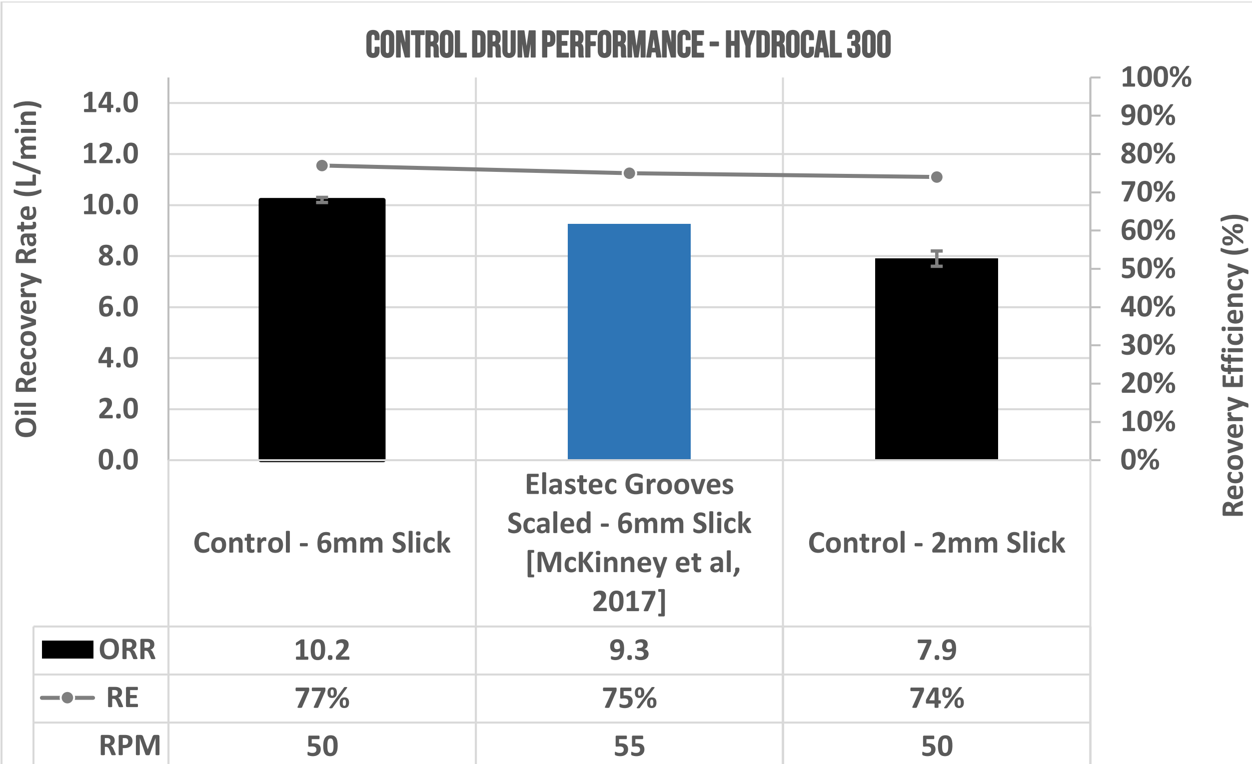


Figure 28: Tier 2 control drum performance and comparison to literature. Some error bars smaller than chart symbol.

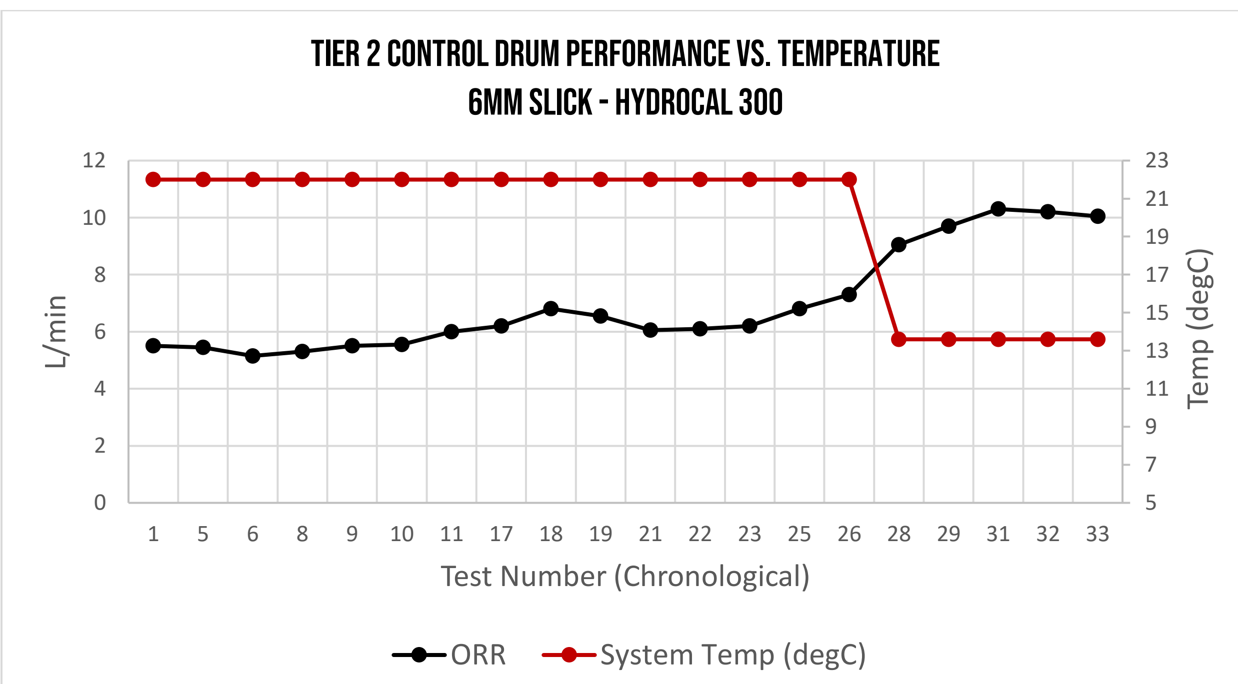


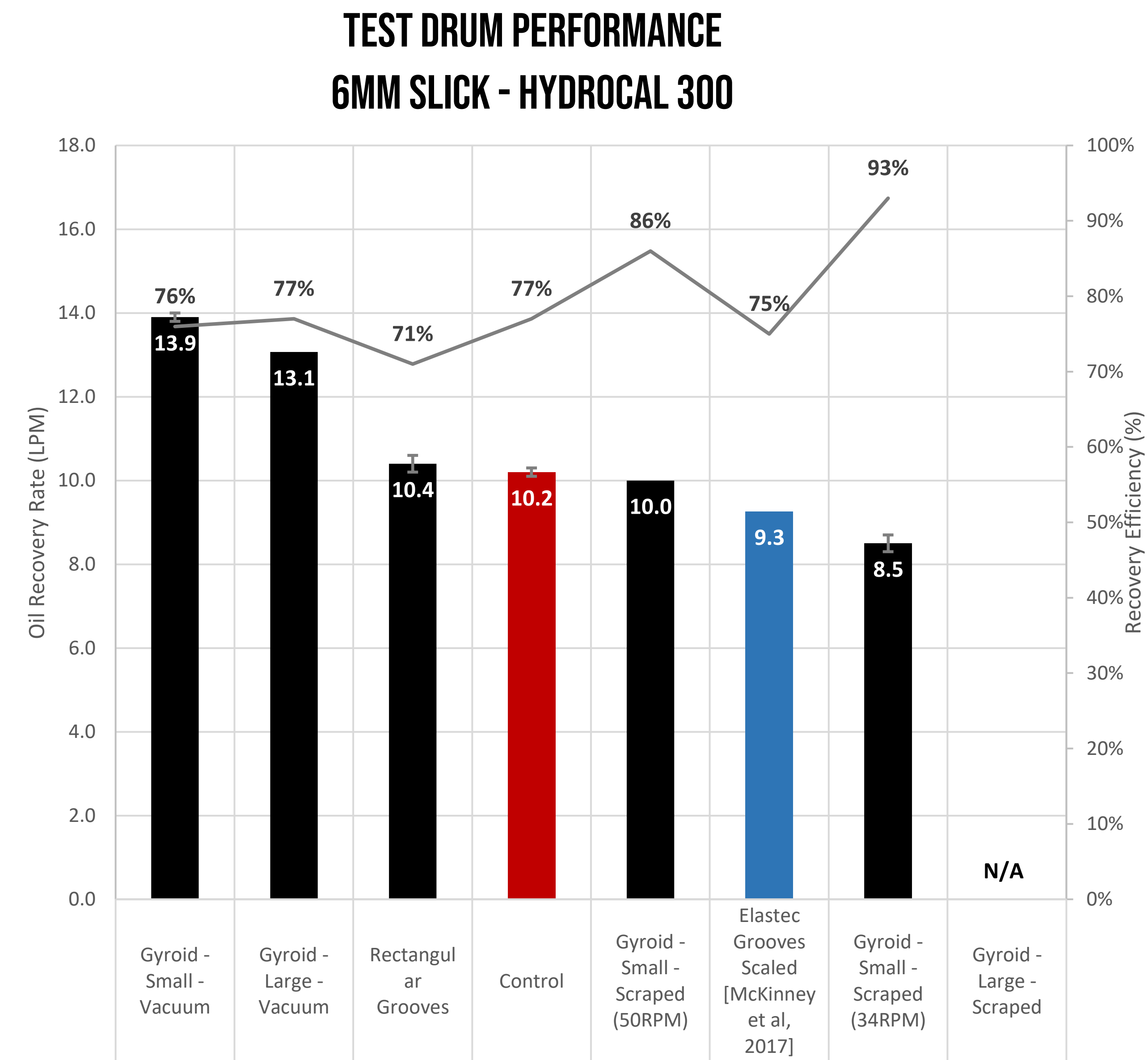
Figure 29: Tier-2 control drum ORR tests in chronological order vs. fluid temperature.

3.3.3.2 Innovations

Figure 30 displays the results of Tier-2 testing using Hydrocal 300 in a 6mm slick. Vacuuming each gyroid drum yielded measurable ORR improvement and maintained RE. Vacuuming (for all slick thicknesses and oil types) still aerates and emulsifies oil, requiring longer separation times, though this could potentially be reduced via further engineering. Scraping the small gyroid yielded negligible change in ORR, though RE was increased. Figure 31 displays the results of Tier-2 testing using Hydrocal 300 in a 2mm slick. Vacuuming the small gyroid yielded measurable improvement though RE decreased. With the thinner slick it is possible that more of the carrying volume is taken up by water. Scraping the small gyroid yielded negligible change in ORR, though RE was again increased.

The results shown for vacuum recovery of the large gyroid in Figure 30 do not represent the best performance achieved during testing. This drum was used for testing across a 16-day period and over the duration performance was observed to decline (chronological performance results are shown in Figure 32). One possible cause is that the relatively thin (~1mm) wall thickness of the drum geometry became soaked overtime, changing the surface properties. Furthermore, there was evidence of brown discoloration of the drum surface after this testing course. The small gyroid also exhibited evidence of beginning to decline in performance, though the test course was 10 days as opposed to 16 and there were two few data points to confirm. Therefore, it is recommended to investigate potential coatings for this material in the future. The results reported are the result of two steady-state tests achieved late in the 16-day period. Furthermore, recognizing the trend, the drum was not used for further testing.

Figure 33 shows the results of Tier-2 testing using Hydrocal 38, for both 6mm and 2mm slicks. Using vacuum recovery on the small gyroid yielded significant improvement in ORR. Furthermore, testing showed that while large amounts of water were recovered when vacuuming at speeds higher than 20RPM, at 20RPM, an RE of 80% was achieved without the anticipated drop in ORR (Figure 34). Anecdotally, all control drum tests were performed above 65RPM as it was clear lower speeds dramatically reduced the amount of oil recovered (Figure 1).



	Gyroid - Small - Vacuum	Gyroid - Large - Vacuum	Rectangular Grooves	Control	Gyroid - Small - Scraped (50RPM)	Elastec Grooves Scaled [McKinney et al, 2017]	Gyroid - Small - Scraped (34RPM)	Gyroid - Large - Scraped
ORR	13.9	13.1	10.4	10.2	10.0	9.3	8.5	0
RE	76%	77%	71%	77%	86%	75%	93%	
RPM	34	40	50	50	50	55	34	
ORR Improvement	36%	28%	2%	0%	-2%	-9%	-17%	

Figure 30: Tier-2 test drum performance in a 6mm slick of Hydrocal 300.

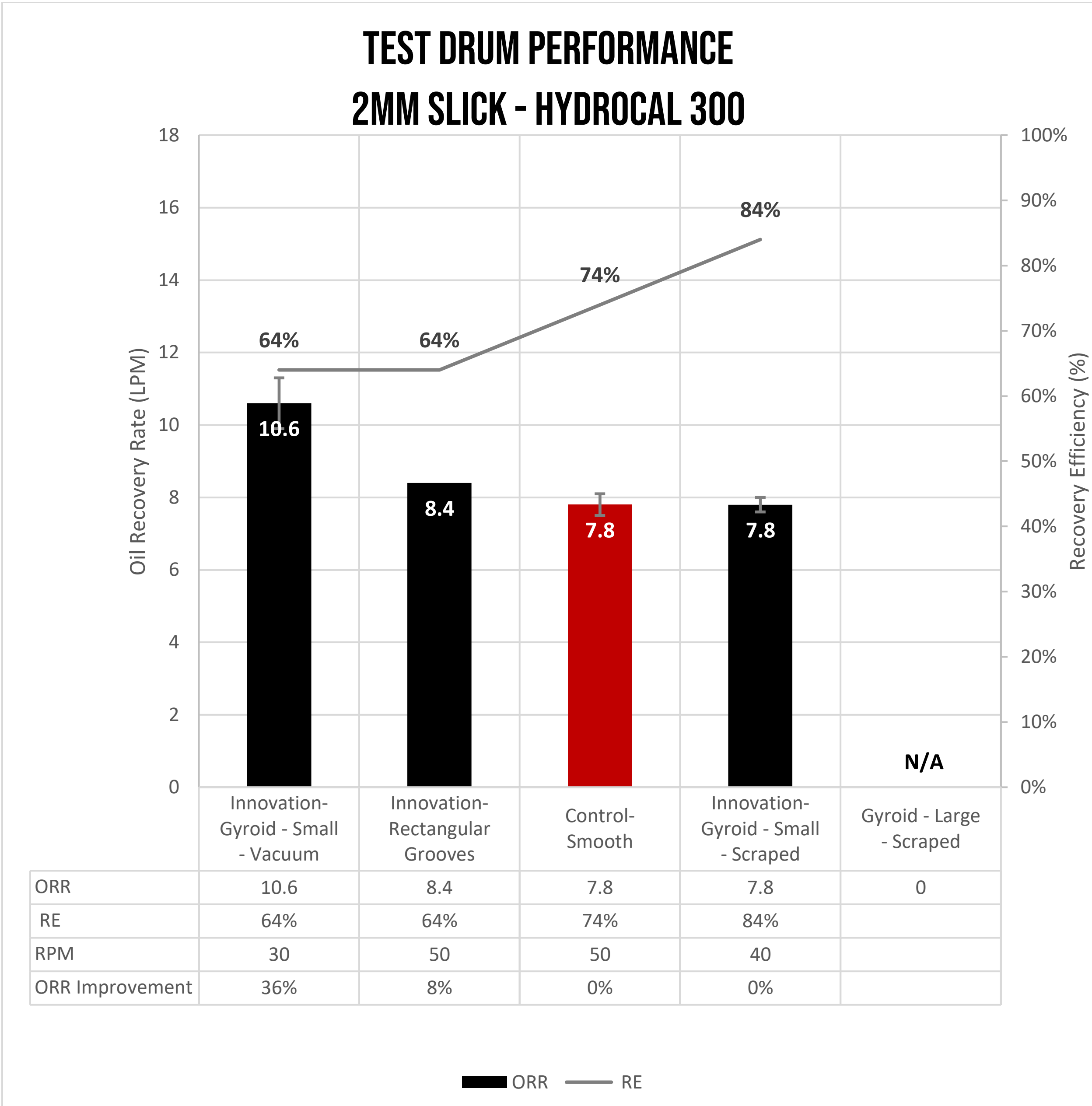


Figure 31: Tier-2 test drum performance in 2mm Slick of Hydrocal 300. Note that the Innovation-Gyroid-Small-Vacuum drum data was not in steady state, rather the drum was starved.

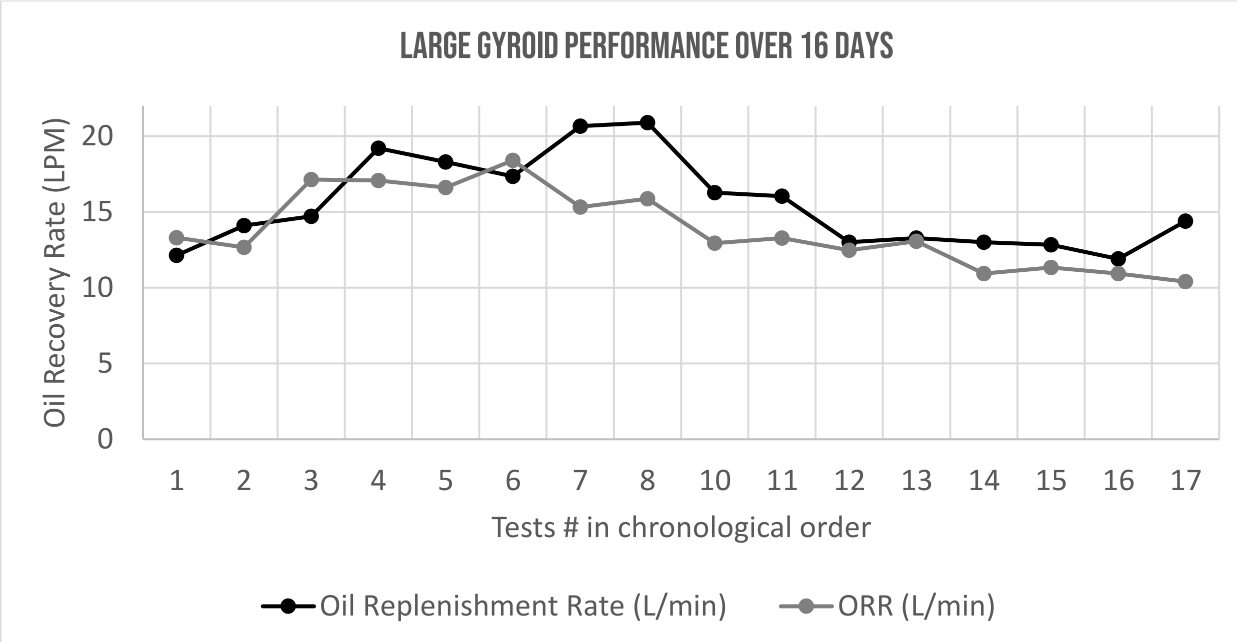
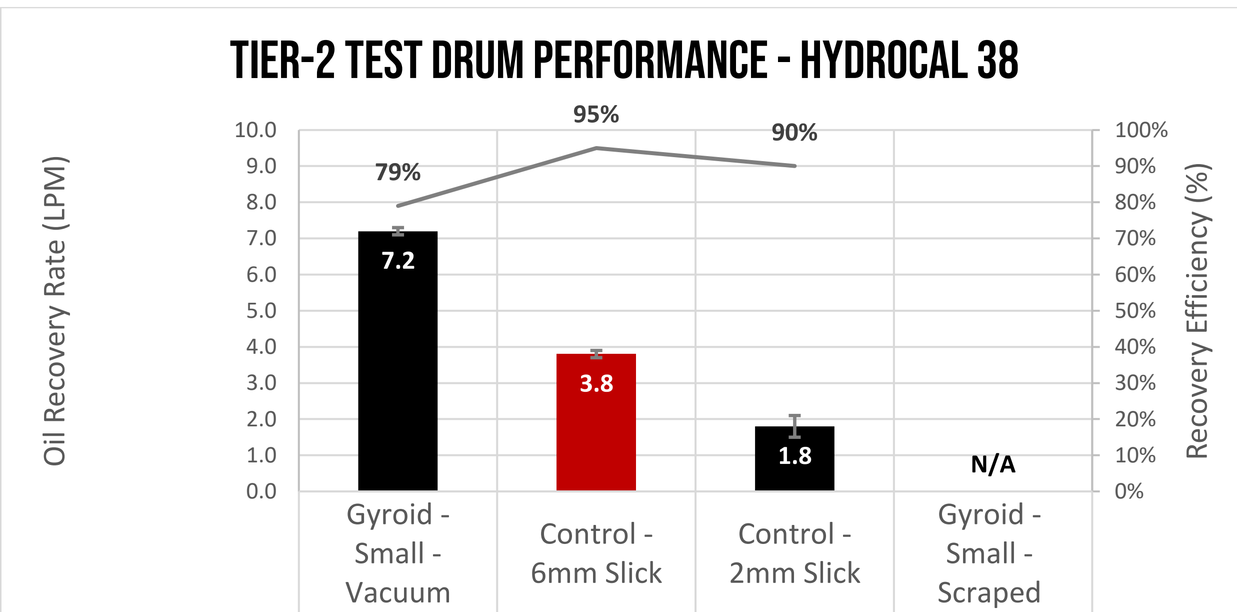


Figure 32: Performance of Tier-2 large gyroid in 6mm slick of Hydrocal 300. Individual tests in chronological order.



	Gyroid - Small - Vacuum	Control - 6mm Slick	Control - 2mm Slick	Gyroid - Small - Scraped
ORR	7.2	3.8	1.8	0.0
RE	79%	95%	90%	
RPM	20	65	65	
ORR Improvement	89%			

Figure 33: Tier-2 test drum performance in Hydrocal 38.

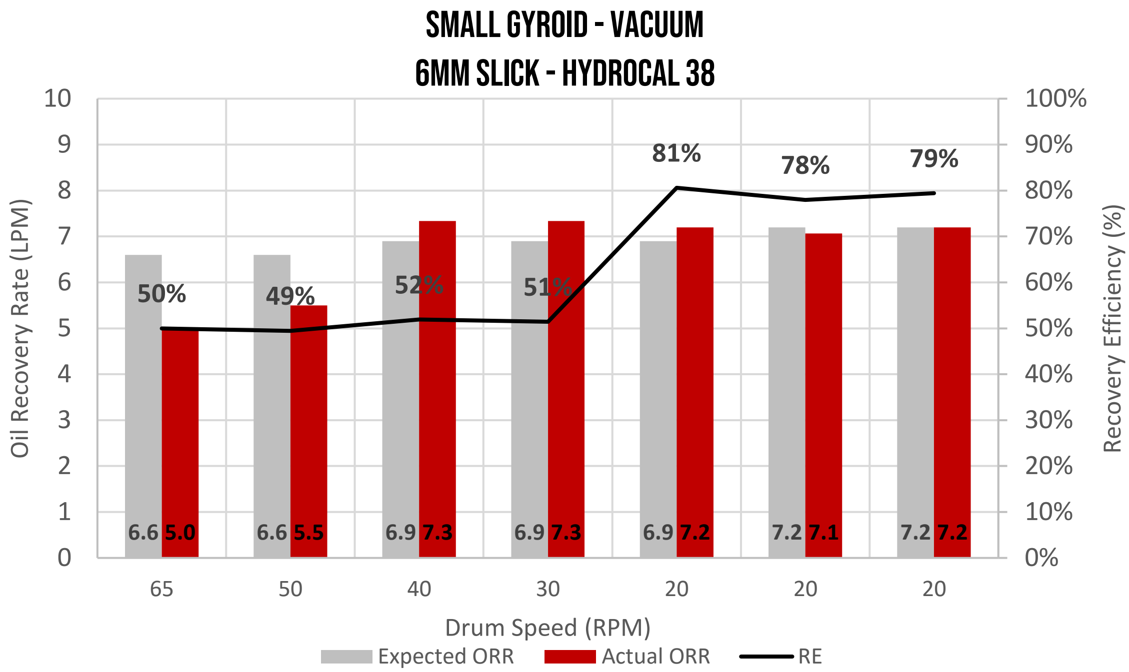


Figure 34: Performance of vacuum recovery of the small gyroid by drum speed

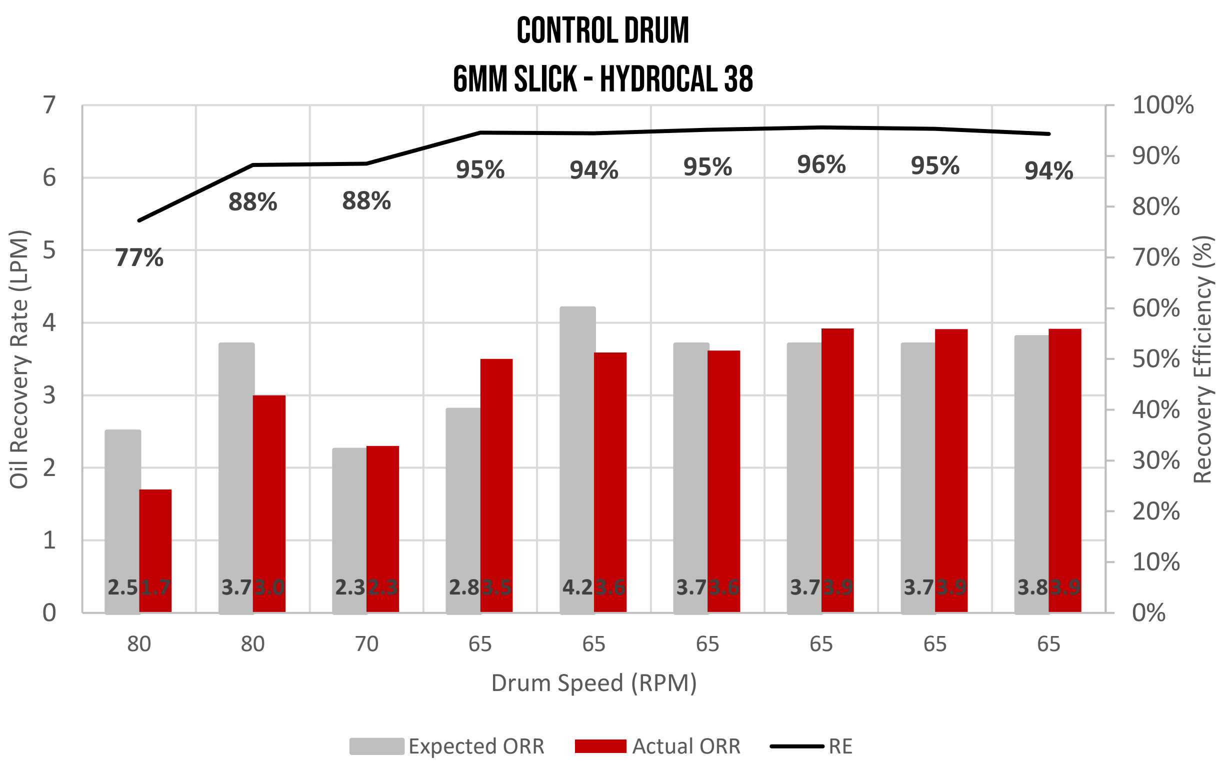


Figure 35: Performance of Tier-2 control drum by drum speed

3.4 Tier 2 Durability Evaluation

As part of the Tier-2 effort, durability of the top-performing additive-manufactured drums was evaluated. Originally, it was thought that an extended single recovery test would be executed, with observations pertaining to durability, wear, and tear made throughout. However, given the length of skimming time each drum accumulated over testing, the team decided to evaluate the condition of the drums post testing.

Approximate time each drum was run:

- Control: ~5 hours
- Small Gyroid: ~4 hours
- Large Gyroid: ~2 hours

In summary, the small gyroid exhibited multiple manufacturing defects that were amplified during testing. The large gyroid, by contrast, exhibited no manufacturing defects and showed limited wear post testing. To achieve field ruggedness, it is recommended that future iterations test the following:

- Minimum wall thicknesses greater than 1.5mm. This should help ensure print quality which appears to be a driving factor in ruggedness.
- Coatings for gyroid surface. There is concern and evidence that SLS prints can become saturated with water, potentially reducing recovery performance and resistance to wear and damage.
- Field drums installed in skimmers will likely require brackets to prevent the drums from bearing the weight of the skimmer on hard surfaces, as is common with certain skimmers such as brush skimmers.

The following offers further detail per drum.

3.4.1 Control Drum

The control drum exhibited no manufacturing defects. The control drum exhibited no visible wear or damage post testing, aside from discoloration from test oil.

3.4.2 Small Gyroid

The small gyroid exhibited manufacturing defects prior to testing. The surface was printed thinner than designed (<than 1mm) and cracks/holes, characteristic of thin features, were visible (Figure 36, right). DA proceeded with testing based on the project timeline and lead-times to replace. After testing, the small gyroid exhibited additional surface wear likely caused by contact with the vacuum nozzle and to a lesser extent, the flexible TPE scraper. Breakage was amplified by existing manufacturing defects, as well as a failure event during a test in which the drum came in contact with scraper hardware (wingnut) while rotating. This resulted in a radial strip of material removed from the surface, about 5mm x 5mm in cross-section.

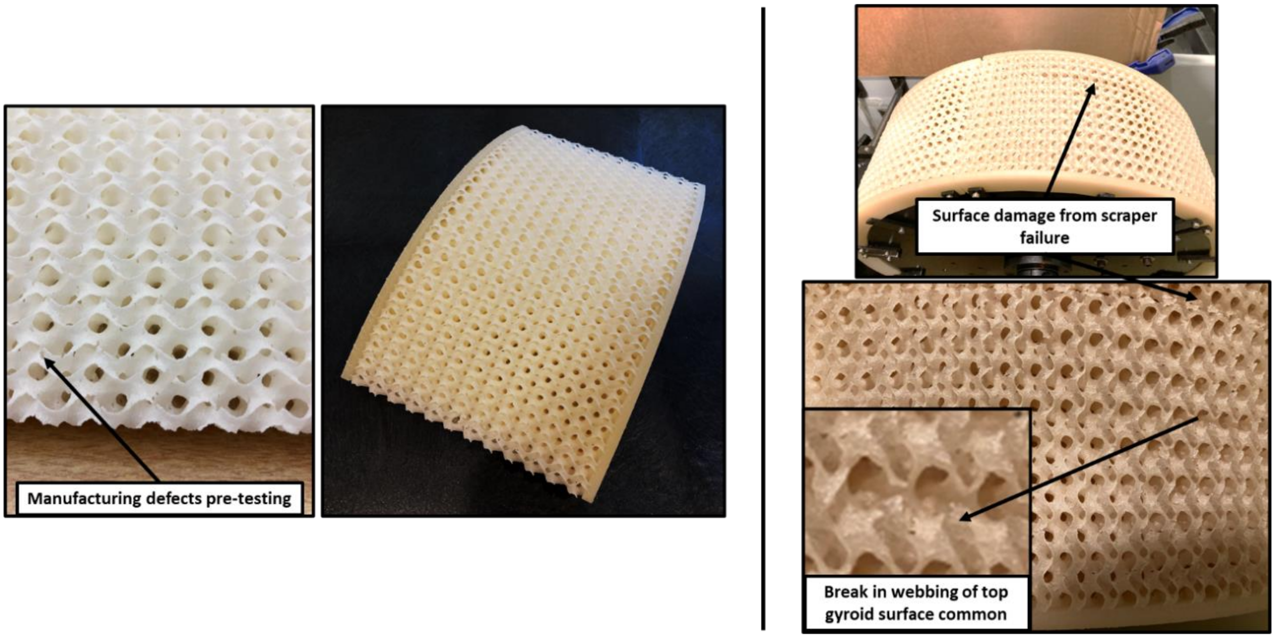


Figure 36: Small Gyroid pre-testing (left) and post-testing (right).

3.4.3 Large Gyroid

The large gyroid exhibited no obvious manufacturing defects. The surface printed as designed with approximately 1mm of wall thickness. After testing, the large gyroid exhibited minimal but consistent surface wear likely caused by contact with the vacuum nozzle and to a lesser extent, the flexible TPE scraper (Figure 37).

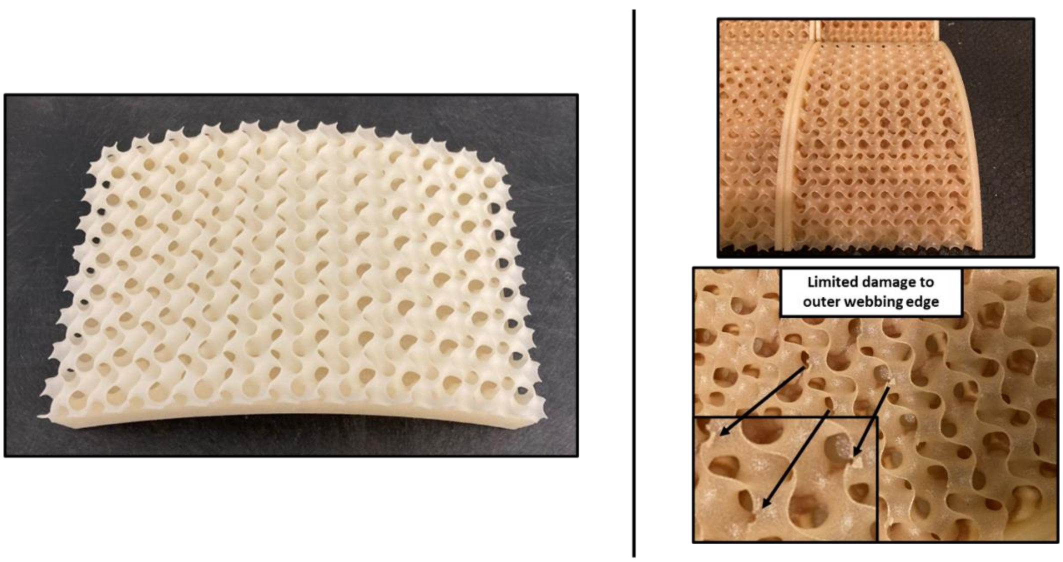


Figure 37: Large Gyroid pre-testing (left) and post-testing (right). Note: The large gyroid shown here was an earlier print without sidewalls. The print quality is representative of those used for testing.

4 Conclusions

The objective of this research was to leverage additive manufacturing to develop and evaluate novel skimmer geometries for improved oil recovery and/or efficiency in thin oil slicks, as well as to evaluate additive manufacturing as a potential manufacturing method for fielded skimmer drums. Significant progress was made toward both goals.

Reduced scale testing in Tier-1 yielded three new microgeometries shown to outperform control. Furthermore, it was observed that the smooth control drum outperformed the 'elastec-mimicking' grooved drum. Results of the innovations were as follows:

1. **Gyroid Surface – Hydrocal 300**
   a. 25%-32% ORR Increase using vacuum recovery, depending on slick thickness
   b. 23% ORR Increase using standard scraping
   Gyroid Surface – Hydrocal 38
   a. Up to 126% ORR increase using vacuum recovery
   b. Not able to scrape
2. **Concentric Surfaces – Hydrocal 300**
   a. 7% ORR increase at 75% width of control
3. **Rectangular Grooves – Hydrocal 300**
   a. 20-23% ORR Increase using standard scraping, depending on slick thickness
   Rectangular Grooves – Hydrocal 38
   a. Up to 39% ORR increase depending on slick thickness

Another significant finding of Tier 1 was the demonstration of the efficacy of a novel vacuum recovery method. Furthermore, Tier-1 provided or confirmed important insights into critical design factors and how they affect recovery performance in thin slicks as well as opportunities provided by 3D printing. These include:

1. Various 3D-printable materials and processes appear suitable for oil recovery, at least over short-term testing.
2. Surface roughness appears to improve recovery performance.
3. Increased surface area alone does not necessarily lead to increased performance in thin slicks, as evidenced by the smooth control drums higher performance over the Elastec-mimicking grooved control drum.
4. Fillable drum surfaces, or those with carrying volume, provide an opportunity to recover more oil per revolution than control (as demonstrated with our gyroid-based surfaces)
5. Additive manufacturing enables new recovery methods, such as complex fillable surfaces and compressible surfaces.
6. The increase in recovered oil per revolution enabled by fillable geometries warrants exploration of novel methods to extract the oil. A vacuum recovery method was proposed and tested as part of this R&D effort.

At-scale diameter testing during Tier-2 provided better comparison to documented performance of equipment used in common practice. Furthermore, this was an opportunity to iterate the gyroid-based surface design and further test the novel vacuum recovery method. Valuable insights regarding the effect of gyroid characteristics, such a pore size and surface depth were gleaned and motivate effective future iterations of this design. Notably, these characteristics can be balanced for specific conditions such that the drum is scrapable by conventional means, or not. Tier 2 yielded two microgeometries shown to outperform control, including:

1. **Small Gyroid – Hydrocal 300**
    a. 36% ORR Increase using vacuum recovery – Equivalent RE – to 10% RE decrease in 2mm slick
    b. Negligible ORR change using standard recovery – 8% RE improvement
    Small Gyroid – Hydrocal 38
    a. 89% ORR Increase using vacuum recovery (6mm Slick)
    b. 16% RE decrease though still adequate (79% vs. 95%)
2. **Large Gyroid – Hydrocal 300**
    a. 27% ORR increase using vacuum recovery – Equivalent RE
    b. Not able to scrape

DA concluded this research effort by providing a design for both a novel skimmer drum geometry and a novel recovery method, which, when used in conjunction, offer a significant improvement in recovery performance in thin slicks. It is this team’s judgment that the gyroid-based design could be further optimized not only for increased performance via vacuum recovery, but that parameters could be defined to allow for standard scraping. In addition to these designs, the testing throughout has provided valuable insight into the potential of additive manufacturing to support oil spill recovery operations. Finally, this work has illuminated numerous avenues for further R&D, expanded upon in the following section.

5 Identification of Future Areas of Research and Development

5.1 Further Gyroid Development

It is believed that the lessons of Tier 2 would enable spiral development(s) worthy of field testing in a scrapable and/or vacuum configuration. It is recommended to both optimize the gyroid based design for scraping and vacuum recovery.

5.2 Vacuum Recovery Engineering

Vacuum recovery was proposed as a method to realize the value of a drum with carrying volume not reachable by standard scraping. As such, the equipment developed during this project was proof of concept and did not benefit from a concerted engineering effort. It is believed that vacuum recovery could be the key to getting thin slicks removed from complex geometries that can successfully capture the surface oil. It is recommended to develop the technology and the additional infrastructure necessary to test on a current skimming vessel.

5.3 Exploration of Compressible and Multi-Surface Geometries

Several valid concepts for recovering oil from thin slicks were designed though not fully tested, with further progress limited by time or resources. As such, further development was not possible in Tier 2, though it is still believed these designs have merit in thin slicks; namely compressible geometries and the multi-surface concentric drum.

5.4 Further Investigation of Recovery Potential of 3D-Printing Processes and Materials

The Tier-1 material investigation identified several materials that are potentially suitable for oil recovery. This testing was both empirical and only exposed each drum to recovery fluid for short periods of time. Furthermore, additive manufacturing methods, materials, and surface treatments are expanding rapidly. Thus, a more detailed exploration of available processes and materials, as well as the long-term efficacy of promising options, would be warranted given future investigation into additive manufacturing as a drum production method.

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Appendices

Appendix A: Technical Data Specifications

REPORT TITLE: The Use of Additive Manufacturing to Investigate Novel Surface Geometries for Improved Oil Skimmer Recovery in Thin Oil Slicks

CONTRACT NUMBER(S): 140E0121C0008

FISCAL YEARS(S) OF PROJECT FUNDING: 2021, 2022

CUMULATIVE PROJECT COST: $256,889.12

COMPLETION DATE OF REPORT:

BSEE COR(S): Kristi McKinney, Program Manager, Mechanical Containment & Recovery

BSEE CO(S): Cielo A. Ibarra, Contracting Officer, Acquisition Operations Branch

PROJECT MANAGER(S): Zachary Clements, Senior Mechanical Engineer

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KEY WORDS: Drum Skimmer, Microgeometry, Oil Recovery, Gyroid

Appendix B: Test Procedures

Tier 1 – Standard Scraping

Tank set-up:

1. Prepare sea water according to supplier (Instant Ocean) instructions.
2. With no oil in the tank, establish the target sea-water level (submergence depth).
    - Tangent: Established visually
    - Add 570ml of sea water for each 2mm of desired slick thickness. Note water height from tank base for reestablishment in subsequent tests.
3. Establish oil slick.
    - Add 570ml of oil for each 2mm of desired slick thickness.
4. Configure each of the two oil supply pumps with the correct flowrate and volume. Test will last 2 minutes (1 minute to reach steady state and 1 minute test). Each pump is responsible for half of the required oil volume; thus, each pump should be configured according to the following:
    - Flowrate = Desired Total Flowrate/2
    - Volume = Desired Flow Rate
5. To ensure pumps are delivering oil at the desired flowrate, calibrate by pumping oil (at the desired rate) into a graduated pitcher for 1 minute and measuring. Adjustments should be made according to results. Options are to adjust the pump flowrate set point and recalibrate or perform a manufacturer pump calibration for the desired rate and retest.
6. Place two graduated pitchers in the collection tub, one for test fluid recovery and one for slop fluid recovery. Place each drain hose into the slop fluid pitcher.

Data Recording Set-up:

1. Open OBS Studio and record a test video to verify each of the (4) webcams and audio are recording (prior to first test of day only).
2. Open Tier-1_Phase-1_Test_Matrix.xls and copy a previous row for a new test to ensure formulas are carried over. Calculation cells are denoted by orange text color. All other cells should be populated manually.
    a. Prior to the test, populate the following sections:
        i. Test Description
        ii. Skimmer Geometry
        iii. Facility
        iv. Test Apparatus
        v. Test Parameters

Running a Test:

1. Each test will run for 120 seconds. For the first 60 seconds, the skim will be collected in the slop pitcher as steady state is achieved, after which the drain hose will be transferred to the test pitcher for the 60 second test. The drain hoses are then transferred back to the slop pitcher to collect final run-off. Use the following procedure:
2. Prior to the test, start recording in OBS studio and verbally state the following:
    a. Test Type (submergence, rpm, etc.)
    b. Test number
    c. Drum Type

    d. Slick thickness
    e. Value of parameter being tested (i.e., 12mm submergence depth)
3. At T=0 seconds: start the pump(s), drum, and the stopwatch.
4. At T=60 seconds: transfer the drain hose from slop pitcher to skim pitcher
5. At T=120 seconds: transfer the drain hose from the skim pitcher back to the slop pitcher.
6. Stop the OBS studio recording.
7. Reestablish the slick by fully skimming any remaining oil and replenishing the slick and recovered water (determined by measuring the water content in the test and slop pitchers)

Recording Results

1. Copy the title of the trial video into the testing spreadsheet.
2. Measure and record the total volume collected in the skim pitcher using the supplied graduations. Estimate to the nearest 10ml
3. Measure and record the volume water in the skim pitcher using the supplied graduations. Estimate to the nearest 10ml. If water is under 100ml, pour off oil and transfer to graduated cylinder. Estimate water to nearest 1ml.
4. Measure and record the volume of water in the slop pitcher. Use this to reestablish the desired submergence depth.

Tier 1 – Vacuum Recovery

Tank set-up:

1. Prepare sea water according to supplier (Instant Ocean) instructions.
2. With no oil in the tank, establish the target sea-water level (submergence depth).
    - Tangent: Established visually
    - Add 570ml of sea water for each 2mm of desired slick thickness. Note water height from tank base for reestablishment in subsequent tests.
3. Establish oil slick.
    - Add 570ml of oil for each 2mm of desired slick thickness.
4. Configure each of the two oil supply pumps with the correct flowrate and volume. Test will last 2 minutes (1 minute to reach steady state and 1 minute test). Each pump is responsible for half of the required oil volume; thus, each pump should be configured according to the following:
    - **Flowrate per pump = Desired Total Flowrate/2**
    - **Volume per pump = Desired Total Flow Rate * 0.75**
5. To ensure pumps are delivering oil at the desired flowrate, calibrate by pumping oil (at the desired rate) into a graduated pitcher for 1 minute and measuring. Adjustments should be made according to results. Options are to adjust the pump flowrate set point and recalibrate or perform a manufacturer pump calibration for the desired rate and retest.
6. Place two graduated pitchers in the collection tub, one for test fluid recovery and one for slop fluid recovery. Place each drain hose into the slop fluid pitcher.

Data Recording Set-up:

1. Open OBS Studio and record a test video to verify each of the (4) webcams and audio are recording (prior to first test of day only).

2. Open Tier-1_Phase-1_Test_Matrix.xls and copy a previous row for a new test to ensure formulas are carried over. Calculation cells are denoted by orange text color. All other cells should be populated manually.
    a. Prior to the test, populate the following sections:
        i. Test Description
        ii. Skimmer Geometry
        iii. Facility
        iv. Test Apparatus
        v. Test Parameters

Running a Test:

1. Each test will run for 90 seconds. For the first 30 seconds, the skim will be collected *by standard scraping* in the slop pitcher as steady state is achieved, after which vacuum recovery will begin and recovered fluid will be vacuumed into a collection bucket:
2. Prior to the test, start recording in OBS studio and verbally state the following:
    a. Test Type (submergence, rpm, etc.)
    b. Test number
    c. Drum Type
    d. Slick thickness
    e. Value of parameter being tested (i.e., 12mm submergence depth)
3. At T=0 seconds: start the pump(s), drum, and the stopwatch.
4. At T=15 seconds: Start vacuum system
5. At T=30 seconds: Engage vacuum nozzle, correct speed to desired rate (vacuum will reduce RPMs)
6. At T=90 seconds: Disengage vacuum nozzle.
7. Stop the OBS studio recording.
8. Reestablish the slick by fully skimming any remaining oil and replenishing the slick and recovered water (determined by measuring the water content in the test and slop pitchers)

Recording Results

1. Copy the title of the trial video into the testing spreadsheet.
2. Allow skimmed fluid to separate for ~24hours
3. Measure and record the total volume collected in the skim pitcher using the supplied graduations. Estimate to the nearest 10ml
4. Measure and record the volume water in the skim pitcher using the supplied graduations. Estimate to the nearest 10ml. If water is under 100ml, pour off oil and transfer to graduated cylinder. Estimate water to nearest 1ml.
5. Measure and record the volume of water in the slop pitcher. Use this to reestablish the desired submergence depth.

Tier 2 – Standard Scraping

Tank set-up:

1. Prepare sea water according to supplier (Instant Ocean) instructions.
2. With no oil in the tank, establish the target sea-water level (submergence depth).
    - Tangent: Established visually

- Add 1.5Lof sea water for each 2mm of desired slick thickness. Note water height from tank base for reestablishment in subsequent tests.

3. Establish oil slick.
    - Add 1500L of oil for each 2mm of desired slick thickness.
4. Configure the oil supply pump with the correct flowrate by diverting oil back to the supply drum and opening/closing the supply ball valve until the flowmeter displays the desired flowrate. Test will last 2 minutes (1 minute to reach steady state and 1 minute test).
5. Place two 5-gallon containers in the collection tub, one for test fluid recovery and one for slop fluid recovery. Place the slop bucket under the drain hose.

Data Recording Set-up:

1. Open OBS Studio and record a test video to verify each of the (4) webcams and audio are recording (prior to first test of day only).
2. Open Tier-2_Phase-1_Test_Matrix.xls and copy a previous row for a new test to ensure formulas are carried over. Calculation cells are denoted by orange text color. All other cells should be populated manually.
    a. Prior to the test, populate the following sections:
        i. Test Description
        ii. Skimmer Geometry
        iii. Facility
        iv. Test Apparatus
        v. Test Parameters

Running a Test:

1. Each test will run for 120 seconds. For the first 60 seconds, the skim will be collected in the slop container as steady state is achieved, after which the drain hose will be transferred to the test pitcher for the 60 second test. The drain hose is then transferred back to the slop pitcher to collect final run-off. Use the following procedure:
2. Prior to the test, start recording in OBS studio
3. At T=0 seconds: start the drum, and the stopwatch and divert oil supply to the test tank.
4. At T=60 seconds: transfer the drain hose from slop pitcher to skim pitcher
5. At T=120 seconds: transfer the drain hose from the skim pitcher back to the slop pitcher.
6. Stop the OBS studio recording.
7. Reestablish the slick by fully skimming any remaining oil and replenishing the slick and recovered water (determined by measuring the water height in the tank, post test)

Recording Results

1. Copy the title of the trial video into the testing spreadsheet.
2. Measure and record the total volume collected in the skim pitcher using the supplied graduations. Estimate to the nearest 10ml
3. Measure and record the volume water in the skim pitcher using the supplied graduations. Estimate to the nearest 10ml. If water is under 100ml, pour off oil and transfer to graduated cylinder. Estimate water to nearest 1ml.

Tier 2 – Vacuum Recovery

Tank set-up:

1. Prepare sea water according to supplier (Instant Ocean) instructions.
2. With no oil in the tank, establish the target sea-water level (submergence depth).
    - Tangent: Established visually
    - Add 570ml of sea water for each 2mm of desired slick thickness. Note water height from tank base for reestablishment in subsequent tests.
3. Establish oil slick.
    - Add 570ml of oil for each 2mm of desired slick thickness.
4. Configure each of the two oil supply pumps with the correct flowrate and volume. Test will last 2 minutes (1 minute to reach steady state and 1 minute test). Each pump is responsible for half of the required oil volume; thus, each pump should be configured according to the following:
    - Flowrate per pump = Desired Total Flowrate/2
    - Volume per pump = Desired Total Flow Rate * 0.75
5. To ensure pumps are delivering oil at the desired flowrate, calibrate by pumping oil (at the desired rate) into a graduated pitcher for 1 minute and measuring. Adjustments should be made according to results. Options are to adjust the pump flowrate set point and recalibrate or perform a manufacturer pump calibration for the desired rate and retest.
6. Place two graduated pitchers in the collection tub, one for test fluid recovery and one for slop fluid recovery. Place each drain hose into the slop fluid pitcher.

Data Recording Set-up:

1. Open OBS Studio and record a test video to verify each of the (4) webcams and audio are recording (prior to first test of day only).
2. Open Tier-1_Phase-1_Test_Matrix.xls and copy a previous row for a new test to ensure formulas are carried over. Calculation cells are denoted by orange text color. All other cells should be populated manually.
    a. Prior to the test, populate the following sections:
        i. Test Description
        ii. Skimmer Geometry
        iii. Facility
        iv. Test Apparatus
        v. Test Parameters

Running a Test:

1. Each test will run for 90 seconds. For the first 30 seconds, the skim will be collected *by standard scraping* in the slop pitcher as steady state is achieved, after which vacuum recovery will begin and recovered fluid will be vacuumed into a collection bucket:
2. Prior to the test, start recording in OBS studio and verbally state the following:
    a. Test Type (submergence, rpm, etc.)
    b. Test number
    c. Drum Type
    d. Slick thickness
    e. Value of parameter being tested (i.e., 12mm submergence depth)

3. Prior to test: start drum and vacuum.
4. At T=0 seconds: Divert oil to test tank, begin stopwatch, and engage vacuum nozzle on drum (if standard scraping is not feasible).
5. At T=40 seconds: Switch vacuum collection vessels
6. At T=45 seconds: Begin official test
7. At T=90 seconds: Disengage vacuum nozzle.
8. Stop the OBS studio recording.
9. Reestablish the slick by fully skimming any remaining oil and replenishing the slick and recovered water (determined by measuring the water content in the test and slop pitchers)

Recording Results

1. Copy the title of the trial video into the testing spreadsheet.
2. Allow skimmed fluid to separate for ~24hours
3. Measure and record the total volume collected in the skim pitcher using the supplied graduations. Estimate to the nearest 10ml
4. Measure and record the volume water in the skim pitcher using the supplied graduations. Estimate to the nearest 10ml. If water is under 100ml, pour off oil and transfer to graduated cylinder. Estimate water to nearest 1ml.
5. Measure and record the volume of water in the slop pitcher. Use this to reestablish the desired submergence depth.

Appendix C: Gyroid-Based Drum-Surface Code

Large Gyroid

```
import numpy as np
from numpy import sin, cos, pi
import matplotlib.pyplot as plt
import pyvista as pv

# Radius of Drum (ID, OD)
r1, r2 = 196.35, 212.35
# Width of Drum
desired_height=135
# Layers of Gyroid Unit Cells
rows=1
lattice=1
height = desired_height/(lattice)

# Surface Resolution
res = 150j
# Volume fractions of divided space. t=0 creates identical channel dimensions
t=0
# lattice parameters control unit cell dimensions
a, b, c = lattice_params = lattice, lattice, lattice
kx, ky, kz = [2*np.pi/lattice_param for lattice_param in lattice_params]
#Create mesh grid
r_aux, phi, z = np.mgrid[0:a*rows:res, 0:b*rows:res, 0:c*height:res]

# convert r_aux range to actual radii
r = r2/a*r_aux + r1/a*(1 - r_aux)

# Divide full cylinder into cladding sections
div=6
```

```
# Equation for gyroid approximation
def Gyroid(x, y, z,t):
    return (  np.cos(kx*x)*np.sin(ky*y)
            + np.cos(ky*y)*np.sin(kz*z)
            + np.cos(kz*z)*np.sin(kx*x))-t

# compute data for cylindrical gyroid
fun_values = Gyroid(r_aux, phi*12, z/(r2-r1),t)

# compute Cartesian coordinates for grid points
x = r * np.cos(phi*ky/div)
y = r * np.sin(phi*ky/div)

# create grid
grid = pv.StructuredGrid(x, y, z)
grid["vol3"] = fun_values.ravel('F')
contours3 = grid.contour([0])
# Create STL surface
contours3.save('File_Name.stl')

# plot surface
pv.set_plot_theme('document')
plotter = pv.Plotter()
plotter.add_mesh(contours3, scalars=contours3.points[:, -1],
                 show_scalar_bar=False)
plotter.add_bounding_box()
plotter.show_axes()
plotter.enable_terrain_style()
plotter.show()
```

Small Gyroid

```
import numpy as np
from numpy import sin, cos, pi
import matplotlib.pyplot as plt
import pyvista as pv

# Radius of Drum (ID, OD)
r1, r2 = 196.35, 212.35
# Width of Drum
desired_height=135
# Layers of Gyroid Unit Cells
rows=1
lattice=1
height = desired_height/(lattice)

# Surface Resolution
res = 110j
# Volume fractions of divided space. t=0 creates identical channel dimensions
t=0
# lattice parameters control unit cell dimensions
a, b, c = lattice_params = lattice, lattice, lattice
kx, ky, kz = [2*np.pi/lattice_param for lattice_param in lattice_params]
#Create mesh grid
r_aux, phi, z = np.mgrid[0:a*rows:res, 0:b*rows:res, 0:c*height:res]

# convert r_aux range to actual radii
r = r2/a*r_aux + r1/a*(1 - r_aux)

# Divide full cylinder into cladding sections
div=6
```

```
# Equation for gyroid approximation
def Gyroid(x, y, z,t):
    return (  np.cos(kx*x)*np.sin(ky*y)
            + np.cos(ky*y)*np.sin(kz*z)
            + np.cos(kz*z)*np.sin(kx*x))-t

# compute data for cylindrical gyroid
fun_values = Gyroid(r_aux*2, phi*24, z/((r2-r1)/1.5),t)

# compute Cartesian coordinates for grid points
x = r * np.cos(phi*ky/div)
y = r * np.sin(phi*ky/div)

# create grid
grid = pv.StructuredGrid(x, y, z)
grid["vol3"] = fun_values.ravel('F')
contours3 = grid.contour([0])
# Create STL surface
 contours3.save('File_Name.stl')

# plot surface
pv.set_plot_theme('document')
plotter = pv.Plotter()
plotter.add_mesh(contours3, scalars=contours3.points[:, -1],
                 show_scalar_bar=False)
plotter.add_bounding_box()
plotter.show_axes()
plotter.enable_terrain_style()
plotter.show()
```

Appendix D: Material Descriptions

The following materials were utilized throughout the project. The descriptions focus on 3D-printing characteristics. Affinity for oil was observed during the material study but was not studied directly. Please note that the following characteristics are general and don't consider the many additives and surface treatments that can be applied to overcome deficiencies. Furthermore, note that the SLS process and materials used in the project create truly rugged parts

1. Acrylonitrile Butadiene Styrene (ABS)
    a. Process Used – FDM
    b. Characteristics
        i. Rigid
        ii. Impact resistant
        iii. High tensile strength
        iv. Chemical/water resistant
        v. Temperature resistant (-20-80degC)
        vi. Degrades under UV
2. Acrylonitrile Styrene Acrylate (ASA)
    a. Process Used – FDM
    b. Characteristics
        i. Rigid
        ii. Impact resistant
        iii. High tensile strength
        iv. Chemical/water resistant
        v. High UV and temperature resistance (up to 93degC)
3. Nylon (Polyamide PA)
    a. Process Used – FDM & SLS
    b. Characteristics
        i. Thin feature flexible, thick features rigid
        ii. Very high impact/abrasion resistance
        iii. High tensile strength
        iv. Temperature resistant
4. Polylactic Acid (PLA)
    a. Process Used – FDM
    b. Characteristics
        i. Rigid/Brittle
        ii. High tensile strength
        iii. Not temperature resistant (deforms above 60degC)
        iv. Not water or chemical resistant
        v. Potentially Biodegradable
5. Polypropylene (PP)
    a. Process Used – FDM & SLS
    b. Characteristics
        i. Moderately flexible

        ii. Difficult to print
        iii. Very high impact resistance
        iv. Very high chemical resistance
        v. Not temperature resistant
6. Polyvinylchloride (PVC)
    a. Process Used – FDM
    b. Characteristics
        i. Rigid
        ii. High impact resistance
        iii. High chemical/water resistance
        iv. Can release chlorine gas while printing
7. Thermoplastic Elastomer (TPE) & Thermoplastic Polyurethane (TPU)
    a. Process Used – FDM & SLS
    b. Characteristics
        i. Flexible
        ii. High chemical resistance
        iii. High mechanical resistance
            1. Abrasion/impact resistance
        iv. Very high tensile strength

Appendix E: Test Oil Specifications

CALUMET
REFINING, LLC

2780 Waterfront Parkway E Dr, Indianapolis, IN 46214.
Phone: 317-328-5660 Sales: 1-800-437-3188 www.calumetspeciality.com

Product Data Sheet

If you have questions regarding this product, please contact your Sales Representative.
Customer Service and Technical Service can be reached at 1-800-437-3188

Product : HYDROCAL 300

Revised Date : 2022-04-18

Product Code : 300732100000

Test	UOM Description	Method Description	Min	Max	Typical
API GRAVITY @ 60°F		D4052			24.7
COLOR, ASTM		D1500		L1.5	L0.5
VISCOSITY @ 40°C	cSt	D445			57.99
VISCOSITY @ 100°F	SUS	D2161	300.0	315.0	304.1
VISCOSITY @ 210°F	SUS	D2161			48.0
VISCOSITY INDEX		D2270			47
FLASH POINT, COC	°C	D92	177		192
FLASH POINT, COC	°F	D92	350		376
POUR POINT	°F	D97			-28
POUR POINT	°C	D97			-33
ANILINE POINT	°F	D611			196.4
ANILINE POINT	°C	D611			91.3

External Notes

CALUMET
REFINING, LLC
2780 Waterfront Parkway E Dr, Indianapolis, IN 46214.

Product Data Sheet

Product : HYDROCAL 38

Revised Date : 3/29/18

Product Code : 300101100000

Test	UOM Description	Method Description	Min	Max	Typical
API GRAVITY @ 60°F		D4052	28.0	30.0	29
COLOR, ASTM		D1500		0.5	L0.5
VISCOSITY @ 40°C	cSt	D445			3.37
VISCOSITY @ 100°C	cSt	D445			1.28
VISCOSITY @ 100°F	SUS	D2161	37.0	39.0	37.8
VISCOSITY @ 210°F	SUS	D2161			30.4
VISCOSITY INDEX		D2270			84
FLASH POINT, COC	°C	D92	96		102
FLASH POINT, COC	°F	D92	205		216
POUR POINT	°F	D97			-81
POUR POINT	°C	D97			-62
ANILINE POINT	°F	D611			138.9
ANILINE POINT	°C	D611			59.4

External Notes

DISTRIBUTED BY: R.E. CARROLL, INC. 1570 NORTH OLDEN AVENUE EXT. TRENTON N.J. 08638 USA
T: 609-695-6211/800-257-9365 F: 609-695-0102 Orders@recarroll.com

Abbreviations and Acronyms

1. Additive Manufacturing (AM)
2. Deep Analytics LLC (DA)
3. Fused Deposition Modeling (FDM)
4. Fused Filament Fabrication (FFF)
5. Recovery Efficiency (RE)
6. Materials
    a. Acrylonitrile Butadiene Styrene (ABS)
    b. Acrylonitrile Styrene Acrylate (ASA)
    c. High Density Polyethylene (HDPE)
    d. Nylon (Polyamide PA)
    e. Polylactic Acid (PLA)
    f. Polypropylene (PP)
    g. Polyvinylchloride (PVC)
    h. Thermoplastic Elastomer (TPE)
    i. Thermoplastic Polyurethane (TPU)
7. Oil Recovery Rate (ORR)
8. Selective Laser Sintering (SLS)