Optimization of Oleophilic Skimmer Recovery Surface: Field Testing at Ohmsett Facility.

MMS contract number 1435-01-04-RP-36248

Final Report

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Executive Summary

The primary objective of this research was to determine the relation between the operational variables and oil spill recovery efficiency by performing a full-scale test of novel oleophilic drum recovery surfaces tailored for oil spill recovery. Prototype interchangeable oleophilic skimmer drums covered with various polymeric materials were fabricated, based on previous research (MMS Contract # 1435-04-04-CT-36287; UCSB #20041406), and tested at the field scale at Ohmsett - National Oil Spill Response Test Facility. The major test variables were:

- Oil type (Diesel, Endicott – Alaskan crude oil, and HydroCal 300 lubricant oil);
- Oil slick thickness (10 mm, 25 mm and 50 mm);
- Drum rotation speed (30, 40 and 70 rpm);
- Air temperature (25-30 ºC during the first test series and 10-15 ºC during the second test series);
- Material of the drum surface (Aluminum, Polyethylene, Polypropylene, Neoprene, Hypalon);
- Drum surface pattern (smooth or grooved).

This study increased our understanding of the interactions between oil and the material of the recovery unit and identified operational conditions that will result in higher oil recovery efficiency. The field-scale tests confirmed the results of the laboratory experiments conducted during the previous phase of this project. It was found that:

- The use of a grooved pattern can increase the recovery efficiency by up to 200%. The grooved pattern was proven to be efficient even on Diesel, which is a challenging product to recover due to its low viscosity. The recovery efficiency of the grooved surface can be additionally improved by tailoring the groove dimensions to specific oil properties for a particular region and climate. Using more shallow and narrow groves for light diesel and fuel oil and deeper and more open grooves for heavier oils may lead to higher recovery efficiency.
- The selection of the recovery surface material can increase the recovery efficiency by 20%. The difference between materials is especially pronounced in case of thin oil slicks.
- The recovery efficiency significantly depends on the type of petroleum product and is typically proportional to the oil's viscosity.
- Oil spill thickness has a significant effect on the recovery efficiency. The increase in oil thickness from 10 mm to 25 mm led to 2-3 times higher recovery rates for HydroCal oil. The increase in oil thickness from 25 to 50 mm did not significantly increase the recovery rates. Endicott oil recovery efficiency was found to be less sensitive to the changes in oil slick thickness than the recovery efficiency of HydroCal oil.
- In the case of light and medium viscosity oils, oil recovery efficiency was found to be inversely proportional to the oil temperature. Oil viscosity increases when temperature decreases, leading to the formation of a thicker oil film in every drum rotation. HydroCal recovered by a grooved surface was the only exception. At lower temperatures, the viscosity of HydroCal increased to the point that the oil could not penetrate deep in to the grooves, leading to a lower oil recovery. HydroCal oil recovery was affected more by the slick thickness than by the changes in temperature.
- The amount of entrained free water was typically higher for a 10 mm oil slick than for a 25 or 50 mm oil slick.

- Drum rotation speed had a significant effect on the recovery efficiency. For the skimmer and drums tested, 40 revolutions per minute (RPM) appeared to be a nearly optimal rotation speed in most cases. Beyond 40 RPM, the drum would start to recover a significant amount of free water. If there are adequate storage and handling facilities to store the free water skimmed by the system, and the response team is not concerned with free water in the recovered product, the maximum rotation speed should be used, since this will result in the highest overall oil recovery.

We expect a high level of interest for these research results from manufacturers of oil spill recovery equipment, since they will allow them to fabricate more efficient cleanup equipment without a significant increase in manufacturing costs. The use of more efficient technologies for oil spill recovery can reduce the time required for cleanup, response costs and environmental damage.

1. Background

Mechanical recovery is the most commonly used oil spill response technique. This technique physically removes oil from the water surface. Unlike other cleanup techniques, mechanical recovery can be efficiently applied to treat emulsified oils as well as oils of variable viscosities (1,000 – 20,000 cP). The main weakness of mechanical cleanup is the recovery rate. It may be very time consuming and expensive when employed on a large scale. It may require a large number of personnel and equipment, and every additional hour of cleanup time can significantly increase the cost of recovery. A more efficient recovery device can thus reduce the cost significantly, and reduce the risk of oil reaching the shoreline.

Adhesion (oleophilic) skimmers are one of the most common types of mechanical recovery devices. Recovery is based on the adhesion of oil to a rotating skimmer surface. The rotating surface lifts the oil out of the water to an oil removal device (e.g. scraper, roller, etc.). The adhesion surface is the most critical element of the skimmer since it determines the efficiency of recovery. Various shapes of the recovery unit, such as a mop, belt, brush, disc, and drum, have been developed to increase skimmer efficiency. Despite these changes, the materials used to manufacture the surface of adhesion skimmers have remained the same. Steel, aluminum, and general-use plastics had been in use for more than 25 years. Material selection has not been based on the adhesive properties, but rather on historical practice, price and availability. Very little effort has been made to study the surface properties of the response materials and utilize this knowledge to optimize oil spill recovery.

Several studies were undertaken by the government and private companies in order to test the recovery efficiency of various skimmers (e.g. Foreman and Talley, 2002; Hvidbak, 2001; and Schwartz, 1979). These studies can be used to compare the recovery rates of various skimmer designs, but since the authors did not evaluate or report the influence of operational parameters such as spill thickness, surface pattern, ambient temperature, drum rotation speed, etc. on oil recovery efficiency, it is difficult to make generalizations. The skimmers tested in these studies had different configurations, dimensions, capacities and recovery modes; and in most cases several operational parameters were changed simultaneously during each test making it impossible to distinguish the effect of each variable separately. The current study specifically evaluated both design and operational parameters independently, thus providing key information on the influence of these parameters on the overall oil recovery efficiency.

2. Previous research

Over the past decade, intensive research on wettability and adhesion properties of various materials has been conducted in the fields of sealants, lithography and semiconductors. Although, polymeric materials were tested for their affinity to water and various chemicals, their affinity for oil has not been studied in detail. To our knowledge, there have been only two studies of the dependency of oil recovery on material properties. A laboratory study by Jokuty et al. (1996) aimed to test the adhesive properties of fresh and evaporated oils with a number of materials such as steel, plastic, glass, Teflon, ceramic, and wood. This study indicated that oil adhesive properties differ for various oils, oil weathering degrees and surface material combinations. For certain oils, ceramic and Teflon were found to pick up two times more oil than steel. A laboratory study by S. Liukkonen (1995) on plastics, stainless steel and ice, also found some dependence of oil recovery on surface material type and surface roughness. A full-scale study of the dependency of oil recovery efficiency on the selection of the recovery material has not been previously performed. The effect of a recovery surface pattern on the recovery efficiency has not studied in any detail either.

The study at UCSB of oil adhesion to various materials has been divided into three phases. The first phase was funded by a seed grant through the University of California at Santa Barbara. In this phase we studied the oil adhesion processes at the molecular level. A theoretical model describing the forces and processes influencing adhesion in three-component system (oil-water-solid surface) was completed.

The second phase was funded by the Dept. of Interior's Minerals Management Service (MMS Contract # 1435-04-04-CT-36287). The project started in August 2004 and was completed in December 2005. We evaluated in the laboratory the mechanisms associated with oil adhesion to different recovery surfaces, identified major parameters affecting this process, and determined which novel materials and surface patterns would be most likely to significantly improve oil skimmer performance. The experiments were conducted at 5ºC, 15ºC, and 25ºC using a Dynamic Contact Angle analyzer. Particular attention was paid to the effect of oil chemical composition and weathering degree on adhesive properties. A group of materials and surface patterns with the highest oil recovery rate were identified. A final report was delivered to MMS in January 2006 (Broje and Keller, 2005) and is listed at http://www.mms.gov/tarprojects/511.htm .

The third and current phase of the research, funded through MMS Contract #1435-01-04-RP-36248, involved field scale testing at the Ohmsett National Oil Spill Response Test Facility. These tests are described in detail in the next few sections.

3. Ohmsett tests

Ohmsett (an acronym for Oil and Hazardous Materials Simulated Test Tank) is the world's largest tow/wave tank designed to evaluate the performance of equipment that detects, monitors and cleans up oil spills under environmentally safe conditions. Ohmsett is located on the waterfront at the Naval Weapons Station Earle, in Leonardo, New Jersey. The heart of the facility is the large outdoor, above ground concrete test tank which measures 203 meters long (the approximate length of two football fields) by 20 meters wide, by 3.3 m deep. It is filled with about 10 million liters of sea water, and is maintained at oceanic salinity (35 parts per thousand), through the addition of salt. Water clarity is maintained by the filtration and chlorinating systems, to enhance underwater video of equipment being tested. The facility is maintained and operated by the Minerals Management Service and is open year-round for used by industry, academia and federal agencies (US and foreign) to conduct full-scale oil spill research and development programs. Unlike field-testing which is very expensive, requires permits, and is practically impossible to reproduce conditions, Ohmsett provides a safe, controlled, reproducible testing environment. For more information on Ohmsett see www.ohmsett.com.

Materials and surface patterns selected in the course of the second phase of the project were used to retrofit the recovery drums on an existing skimmer at Ohmsett, manufactured by Elastec American Marine, Inc. (Elastec). A number of skimmer drums were manufactured with various materials and surface patterns. These drums were installed in a standard skimmer body and used to recover an oil slick following the test protocol described in later in this section. The effect of each design or operational variable on oil recovery efficiency was evaluated.

3.1 Materials

Five materials (Aluminum, Polyethylene, Polypropylene, Neoprene, and Hypalon) were used to manufacture drum surfaces by Elastec, based on the recommendations made by UCSB. Neoprene was used in two varieties – applied as a sheet and as a coating. Hypalon was only applied as a coating. Polypropylene was only applied as a sheet. These materials were used to manufacture smooth drums. In addition, three drums had a grooved pattern (30º angle, 1 inch deep) machined in the aluminum drum, and coated with Neoprene and Hypalon. This pattern is protected by U.S. Provisional Patent Application (Serial no. 60/673,043. UCSB). One aluminum drum was left uncoated. A scraper was made to match the grooved pattern. Figure 1 illustrates two grooved drums installed in the skimmer body.

In order to eliminate the variables that could be introduced by using different skimming systems, a frame-type drum skimmer (Elastec Minimax) was used for all tests. This skimmer system uses a simple drum constructed of an oleophilic material (usually polyethylene or polypropylene) that is rotated through the oil layer. The adhered oil is subsequently removed by a plastic blade to an onboard recovery sump. The advantage of this configuration is that drums of different test materials are relatively easy and inexpensive to manufacture. The drums can be manufactured to the same physical specifications so that they may be interchanged in the same skimmer frame. The drums are durable, easy to handle, and easily changed during a set of tests. Additionally, the drum configuration allows for easy monitoring during operation. This ensures control of rotational speed and other real-time experimental observations.

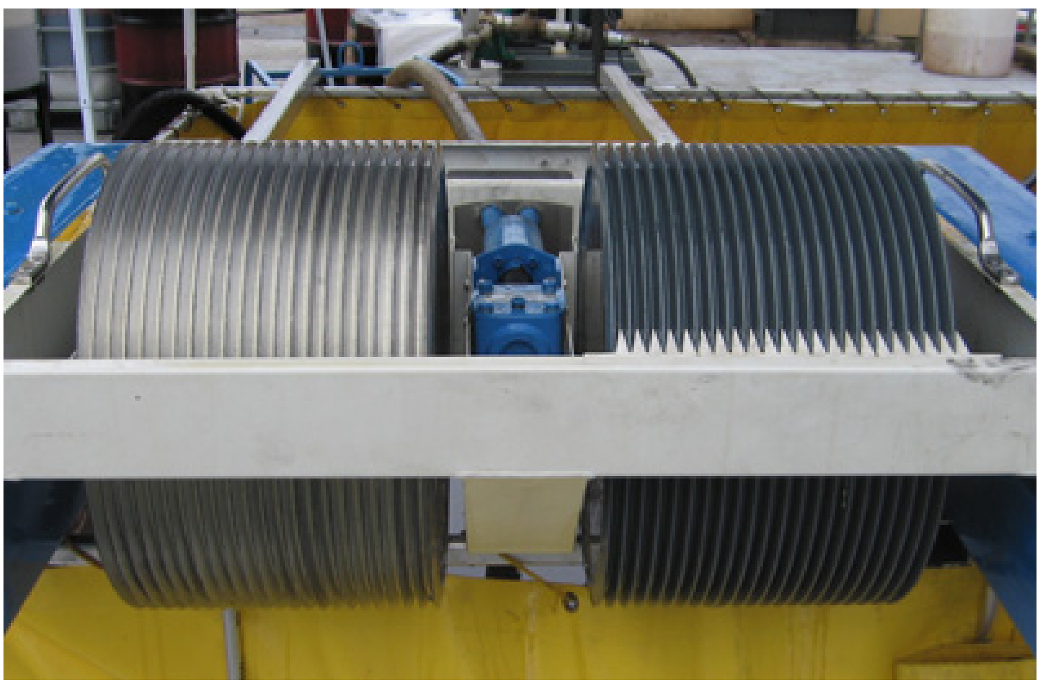

Figure 1. Grooved drums installed into a skimmer frame.
U.S. Provisional Patent Application (Serial no. 60/673,043) by UCSB.
Left - aluminum drum. Right – Neoprene-coated drum with matching scraper.

3.2 Test oils

To select the most efficient oil spill response method, it is important to understand oil chemistry as well as the physical processes associated with oil adhesion to the recovery surface. Oil is a complicated mixture of many components, and its fate and behavior largely depend on its initial properties and environmental conditions at the spill site. Oil spill recovery is complicated by the fact that the physical properties of the oil and its composition vary over a very wide range, from very light fluids with low viscosity to very viscous oils with high asphaltene and wax content that may become semi-solid when spilled in a cold environment. The adhesion between spilled oil and the recovery surface depend on the oil composition and properties at the moment of recovery; these characteristics change over time as the oil weathers. This dependency was studied in the second phase of this research in details. It was confirmed that certain oil properties, especially its viscosity, significantly influence oil adhesion and recovery efficiency.

Diesel, Endicott (an Alaskan crude oil), and HydroCal 300 (a lubricant oil) were used during the Ohmsett tests to study the effect of oil properties on the recovery efficiency. These oils have significantly different properties (Table 1), which allowed us to test the recovery surfaces on a wide range of possible recovery conditions. Diesel was only tested during the second test, at colder temperatures, since it was added later to the protocol.

Table 1. Properties of oils used in Ohmsett field tests

Oil Type	**Density (g/ml)**		**Viscosity (cP)**		**Asphaltenes %**
	15°C	25°C	15°C	25°C	
Diesel	0.833	0.823	6	2	0
Endicott	0.923	0.907	92	50	4
HydroCal 300	0.921	0.905	340	162	0

3.3 Test Protocol

The tests at Ohmsett were conducted in two different test series. The first test series was conducted in August of 2005, at the average ambient temperature of about 25-30ºC. The second test series was completed in October at an average ambient temperature of about 10-15ºC. Diesel was only tested in the second series, since it was not originally part of the protocol. The objective was to simulate an oil spill under warm and cold water conditions, and to determine the effect of temperature and oil viscosity on overall oil spill recovery efficiency. The experimental setup is presented in Figure 2, and an oil flow diagram is presented in Appendix 1.

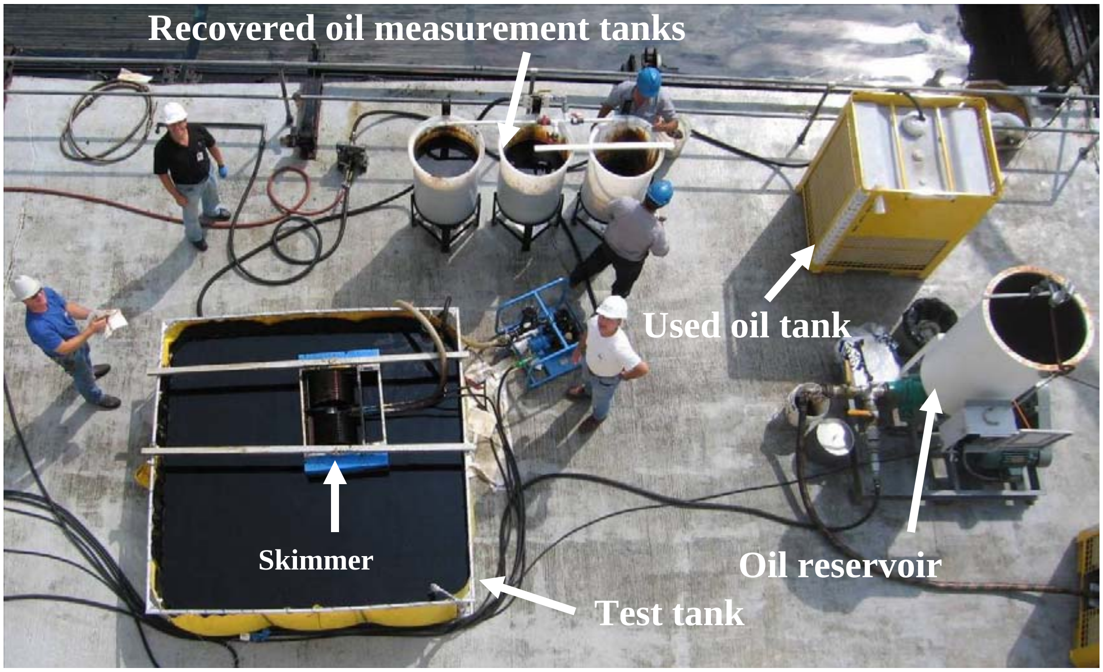

Figure 2. Test setup at Ohmsett.

The test protocol was:

a) A drum with a test surface was installed into the Elastec MiniMax skimmer frame. The skimmer assembly was then secured in the center of the test tank located on the deck of the Ohmsett facility. The test tank had already been filled with seawater from the Ohmsett facility.

b) A known volume of test oil was added to the test tank. This established an oil slick of known thickness. Slick thickness was controlled at a predetermined level throughout a given test. As the oil skimmer recovered oil from the test tank, additional oil was pumped from the oil reservoir at approximately the same rate. In this way, real-time control of the slick thickness was controlled to within ± 20%. After a given test run, an accounting of oil volume recovered and oil volume distributed provided data for a mass balance and a final check of the real-time data. This method was employed for all trial runs and test runs.

c) Varying the speed of the hydraulically driven skimmer drum controlled the encounter rate of the oleophilic surface with the oil front. The speed of rotation of the oil skimmer drum was controlled using the hydraulic system provided with the Elastec MiniMax. A strobe and target marker on the drum helped to ensure a proper control of rotational speeds. Three rotational speeds (30, 40 and 70 rpm) were used for most of the tests. The first two speeds represented the regular operational conditions of a drum skimmer, with minimal free water skimming. The 70 rpm speed represented the maximum rotational speed that was achieved by this particular skimmer. At this speed, more oil was collected, but more free water was entrained by the skimmer, particularly for thinner oil slicks (10 mm). A higher rotational speed also emulsified oil to a greater extent.

d) At the beginning of each test, a preliminary warm-up phase took place. This involved recovering oil while adjusting the operating parameters, achieving a steady state, and establishing reliable data collection. During this preliminary phase recovered oil was returned to the test tank.

e) Once steady state had been established, recovered oil was diverted to a recovery vessel, and the recovery period was timed. At this time rotational rates were adjusted to the next speed, steady state was again established, and a new recovery run was conducted. During the first test series, runs with Endicott and HydroCal at 25 mm oil slick thickness were conducted for 5 minutes. These tests indicated that 3 minutes of test would be sufficient to collect all necessary information. All other runs during the first test series and all runs during the second test series were conducted for 3 minutes.

f) At the end of each test run, the total amount of fluids (oil and water) in the recovery tank was measured. The water was taken out from the bottom of the tank for several minutes until no more free water was evident, and a volume of the remaining oil or oil emulsion was measured again. A sample of the oil or oil emulsion was taken to the Ohmsett laboratory to measure water content. This data, along with recovery time, were used to establish the amount of recovered oil and recovery rates.

g) Other parameters and data that were documented were the initial oil and water temperature, oil and water surface temperatures during the test, and ambient weather conditions. Photo and video documentation, and a number of QA/AC checks were also maintained, such as hydraulic pressure, rotational speed, and flow rates.

3.4 Test Results

All the data collected during the two Ohmsett tests are presented in Appendix 2. A graphical representation of the complete set of collected data is presented in Appendix 3 and Appendix 4. The analysis of these data is presented below.

The recovery efficiency of various skimmer drums tested with Endicott and HydroCal 300 (at an oil slick thickness of 25 mm) during the first test series is presented in Figures 3 and 4. The ambient temperature during the first test ranged from 25 to 30 ºC. The oil recovery rates in gallons per minute (GPM) were estimated through the calculation of oil recovered per unit time. Free water and emulsified water in the recovered oil were subtracted from the volume of the total recovered liquid. Figures 3 and 4 show that at 25 mm oil slick thickness there is about 20% difference in the recovery efficiency of smooth drums covered with various materials. The difference is more pronounced for thinner oil slicks (Appendix 3 and 4).

The difference between smooth and grooved drums was much more significant than the difference between smooth drums covered with various materials. For both oils, grooved drums recovered 2-3 times more oil than smooth ones. A slight decrease in the recovery rates at 70 rpm can be explained by the higher amount of free water picked up by the drums, thereby decreasing the net amount of oil recovered. In a 25 mm oil slick, the drum covered with a smooth sheet of Neoprene recovered slightly more oil than other materials in this same geometry. At high rotational speeds, the smooth aluminum drum collected the largest amount of free water. In a 10 mm oil slick, the smooth polyethylene drum was more efficient than other smooth drums (Appendix 3 and 4).

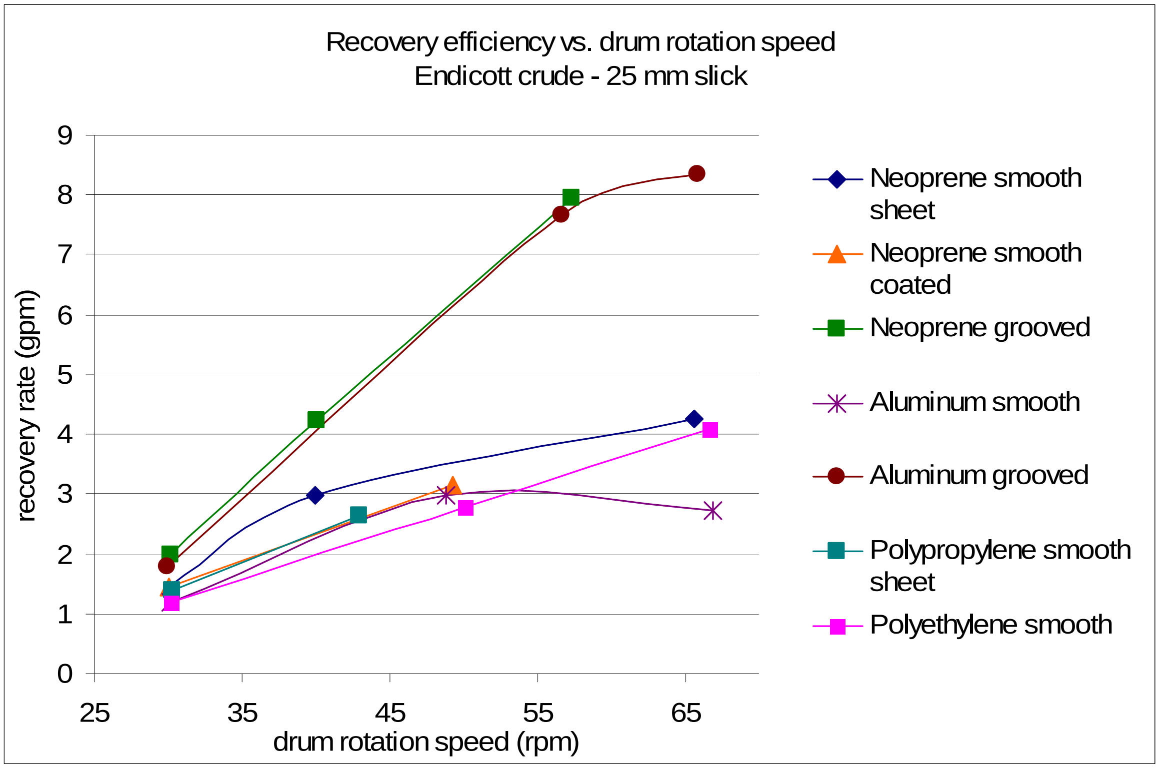

Figure 3. Recovery tests for Endicott crude oil at 25 mm oil thickness. Test at 25-30 ^oC.

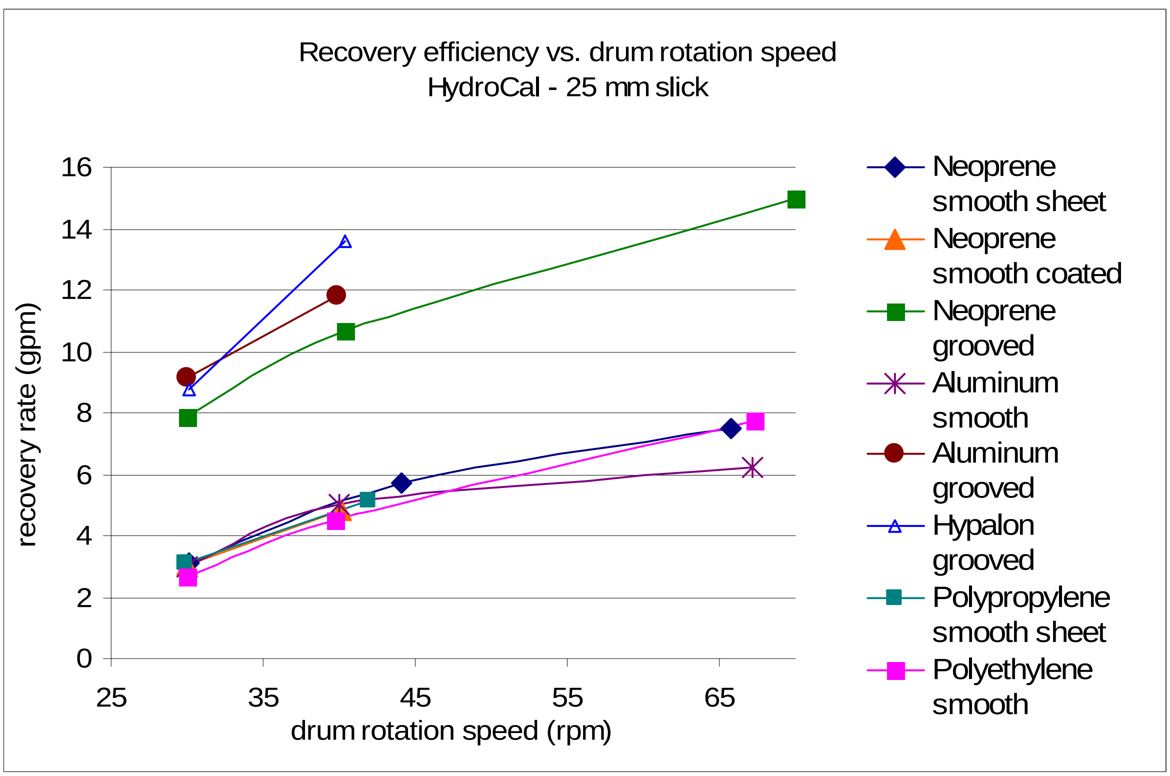

Figure 4. Recovery tests for HydroCal 300 at 25 mm oil thickness. Test at 25-30 ^oC.

At an oil spill thickness of 25 mm, grooved drums entrained an amount of water that was comparable to the amount of water entrained by smooth drums (Appendix 3). Some deviation in results might have been caused by the fact that some runs were performed with oil that was emulsified during the previous run. The water content of some the oils was as high as 6%. This is documented in Appendix 2, in the column "Parent Oil H_2O %". It was observed that HydroCal emulsified easily and had higher water content than Endicott oil, which influenced the overall recovery of free and emulsified water.

The recovery efficiency of various drums tested with Endicott, HydroCal 300 and Diesel oils (at an oil slick thickness of 25 mm) during the second set of experiments is presented in Figures 5 through 7. The temperature during these tests ranged from 10 to 15 ºC.

Figure 5 shows that while there is a only a very slight difference between the oil recovery rates of various smooth drums with different materials, the recovery efficiency of all grooved drums is up to three times higher than the recovery efficiency of smooth drums. The tests with smooth and grooved aluminum drums were repeated twice to study the repeatability of the data. The smooth aluminum drum results were very similar in both runs, but for the grooved aluminum drum the results at high rotational speeds differed noticeably. This was related to the higher volume of entrained free water during the test.

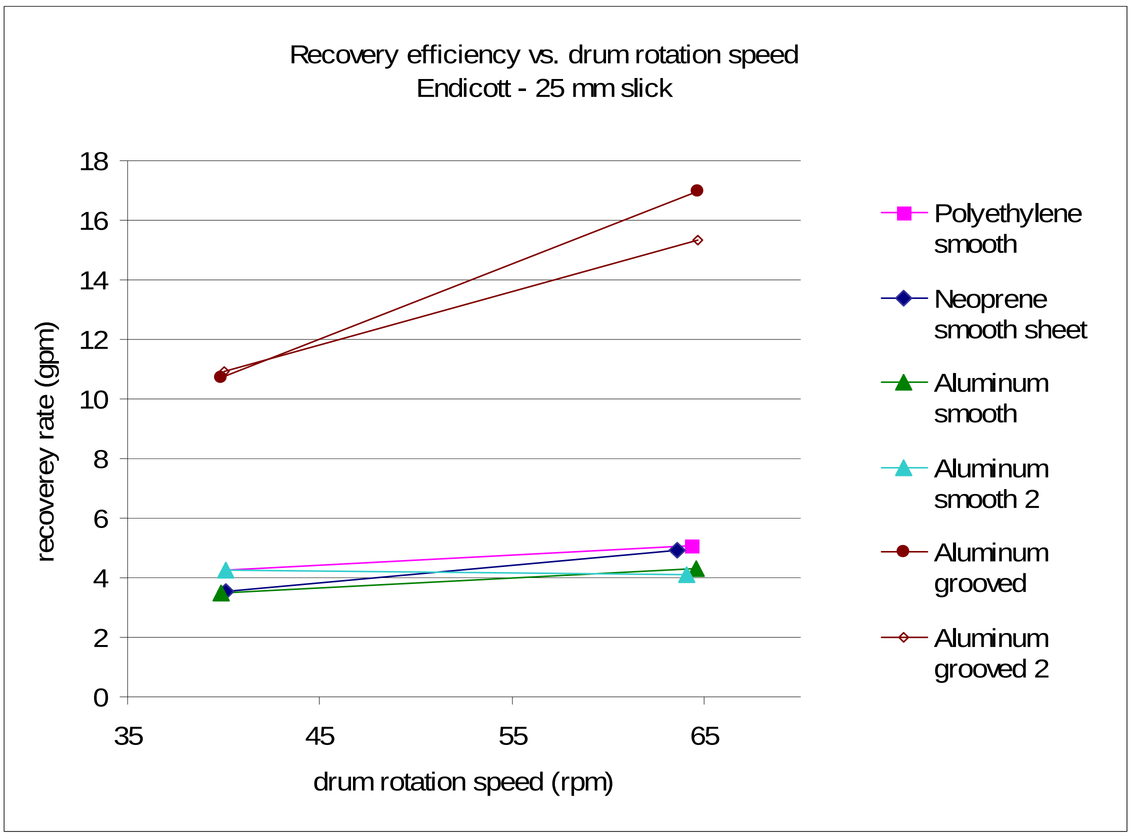

Figure 5. Recovery tests for Endicott crude oil at 25 mm oil thickness. Test at 10-15 ^{o}C.

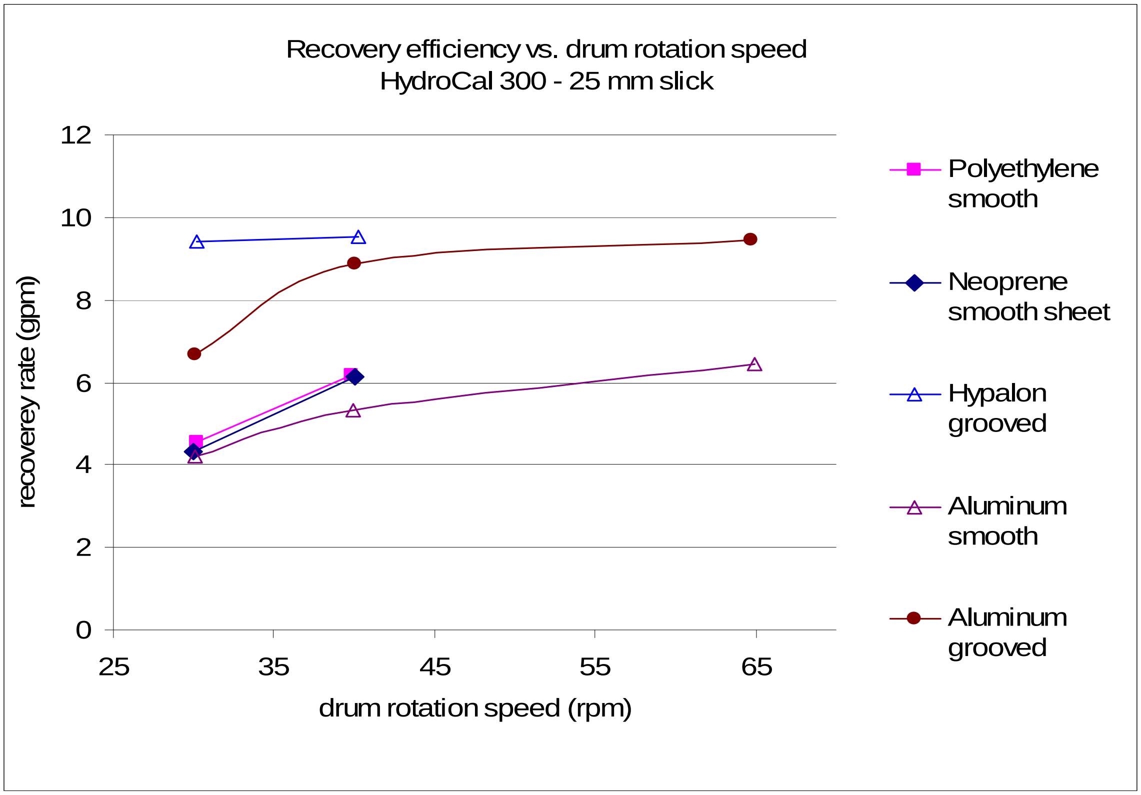

Figure 6. Recovery tests for HydroCal 300 at 25 mm oil thickness. Test at 10-15 ^{o}C.

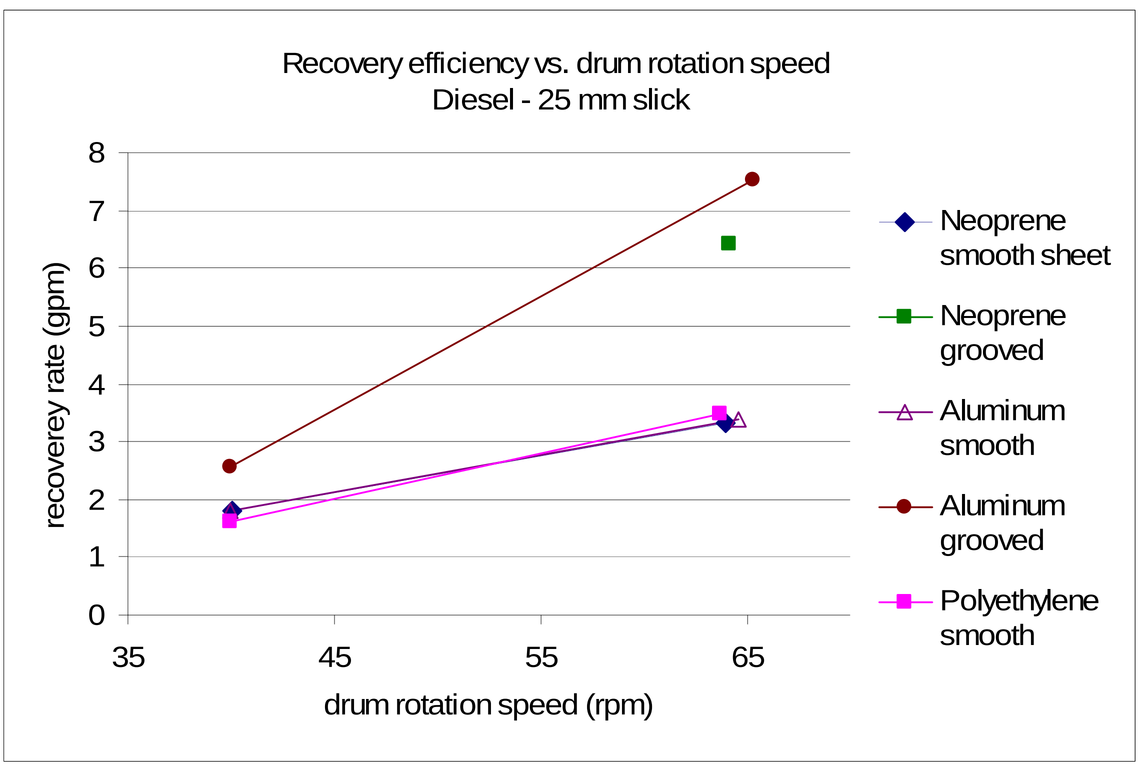

Figure 7. Recovery tests for Diesel at 25 mm oil thickness. Test at 10-15 ^{o}C.

It is interesting to note the difference in the amount of Endicott oil recovered between the first and second tests (Figures 3 and 5). At warmer temperatures (25-30ºC), the recovery rates of smooth drums were in the range of 3-4 gpm. This value increased to 3.5-5 gpm as the temperature decreased from 25ºC to 10ºC. The recovery rates of grooved drums also increased with decreasing temperature, from 4-8 gpm at the warmer temperatures to 11-16 gpm at the colder temperatures. Thus, lower temperatures can significantly increase recovery of oils similar to Endicott, due to the increased oil viscosity.

For HydroCal, the recovery efficiency of grooved drums was twice as high as the recovery efficiency of smooth drums at 10-15 ^{o}C (Figure 6), which corresponded well with the performance of grooved drums at 20-25 ^{o}C (Figure 4). However, the recovery efficiency of grooved drums at colder temperatures was lower than at warmer temperatures (comparing Figures 4 and 6). This was probably due to the much higher viscosity of HydroCal at lower temperatures, which did not allow this oil to penetrate deep enough into grooves, thus reducing the total amount of recovered oil. Thus, recovery efficiency is not always better at lower temperatures, in particular for more viscous oils.

Figure 7 shows that grooved pattern can be efficiently used to recover light petroleum products such as diesel. It can increase the recovery rates by more than 100%.

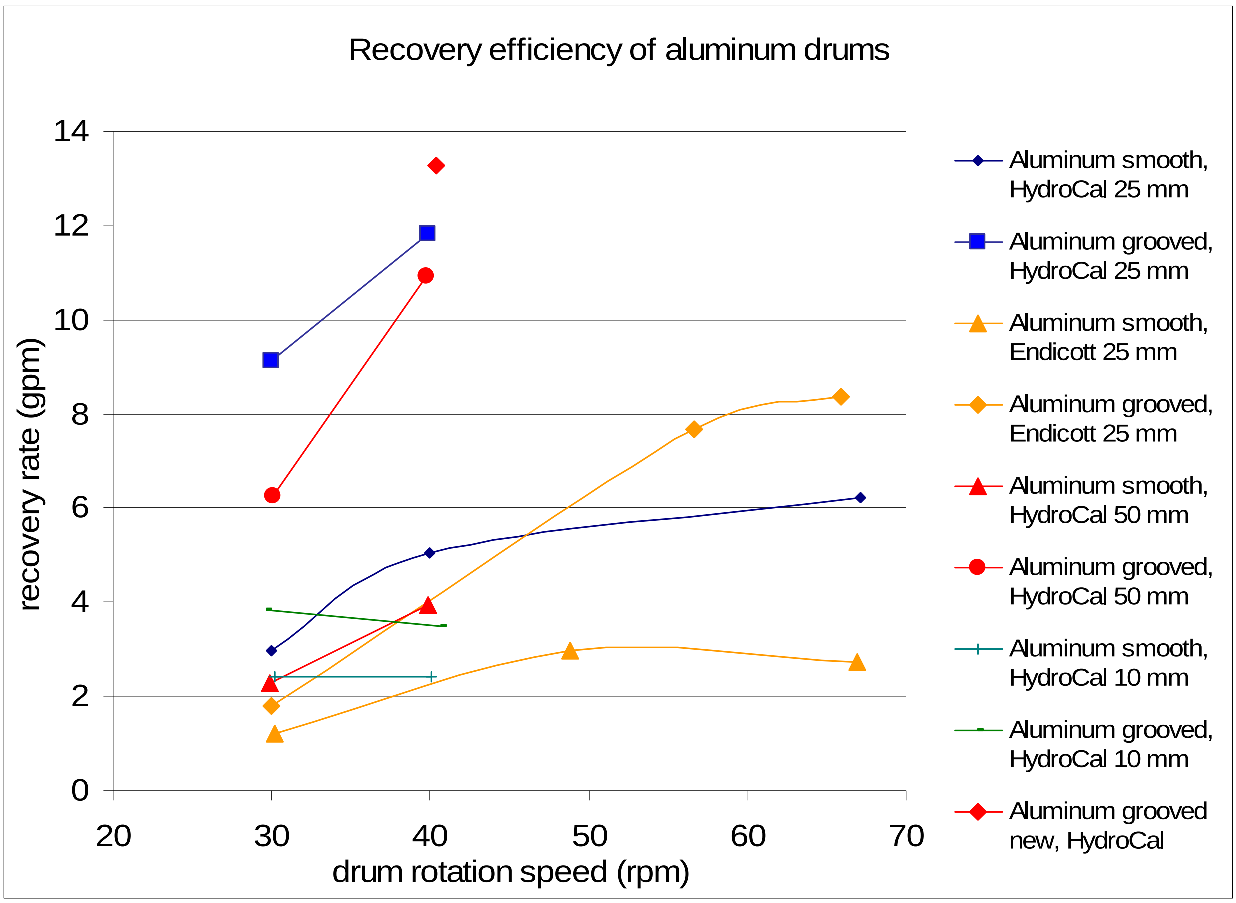

Figure 8. Recovery efficiency of aluminum drums. Test at 25-30 ^{o}C.

A comparison of the effects of oil type, oil spill thickness and drum surface pattern on the recovery efficiency is summarized in Figure 8. There results correspond to grooved and smooth aluminum drums at 25 to 30 °C. The decrease in HydroCal slick thickness from 25 mm to 10 mm led to a significant decrease in oil recovery efficiency. This was especially pronounced in the case of grooved drums. An increase of oil thickness from 25 mm to 50 mm did not increase the recovery rates. Although Figure 8 shows some decrease in the recovery efficiency at 50 mm, it was most likely caused by the fact that oil used for these tests was emulsified and had an initial water content of about 6%. This reduced slightly the total volume of recovered oil. When the grooved aluminum drum was tested with fresh HydroCal oil at 40 rpm and a 50 mm oil slick, the recovery efficiency was higher than the recovery efficiency of the same drum at a 25 mm oil slick thickness. This data point is represented by the single red diamond in Figure 8. Figure 8 shows that the amount of oil recovered by the grooved drums was 2 to 3 times higher than the one recovered by the smooth drums. The oil type was also found to have a significant effect on the recovery efficiency, mostly due to the difference in viscosity.

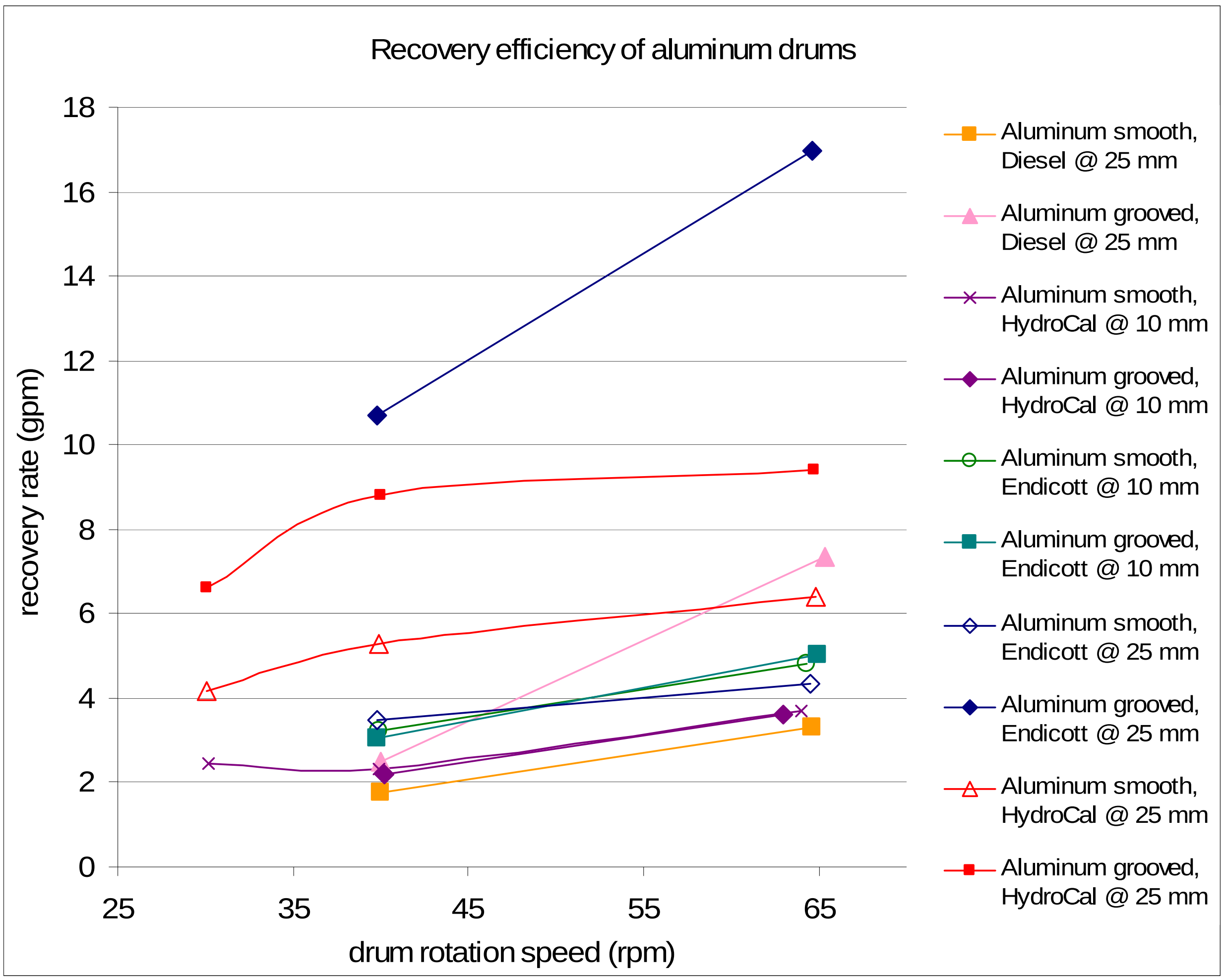

Figure 9. Recovery efficiency of aluminum drums. Test at 10-15 °C.

The effects of oil type, slick thickness and drum surface pattern on oil recovery efficiency observed during the second test series are summarized in Figure 9. For an oil spill thickness of 10 mm there was almost no difference between smooth and grooved drums. The surface pattern was much more effective for thicker oil slicks. At an oil thickness of 25 mm, the grooved pattern proved to be extremely efficient for Endicott oil and diesel, leading to 2-3 times higher recovery efficiency. Although the increase in recovery was less significant for the more viscous HydroCal oil, the recovery efficiency still increased by 50%. At 10 mm slick thickness, the recovery efficiency of HydroCal was lower than the one of Endicott. This may be explained by the increased viscosity of HydroCal at 10-15 ^{o}C. At this lower oil slick thickness water came into contact with the drum and the total contact area between oil and the drum was reduced. The more viscous HydroCal was not able to spread as fast as Endicott did and had lower access to the drum surface, leading to a higher amount of recovered free water and a lower overall recovery

The effect of temperature and oil spill thickness on the recovery efficiency of aluminum drums is illustrated in Figure 10. For the 10 mm oil slick, temperature didn't have a significant effect on the recovery rates of smooth drums. During the colder test series (at 10-15ºC, which for simplicity is denoted as 10C in the graph), grooved drums had recovery rates similar to smooth drums. The recovery rates of grooved drums during the warmer test series (at 25-30ºC, which for simplicity is denoted as 25C in the graph), were significantly higher. Temperature didn't have a significant effect on the recovery rates of smooth drums in a 25 mm oil slick. At a 25 mm slick thickness, grooved drums were considerably more efficient than the smooth drums, although their efficiency was higher at 25ºC.

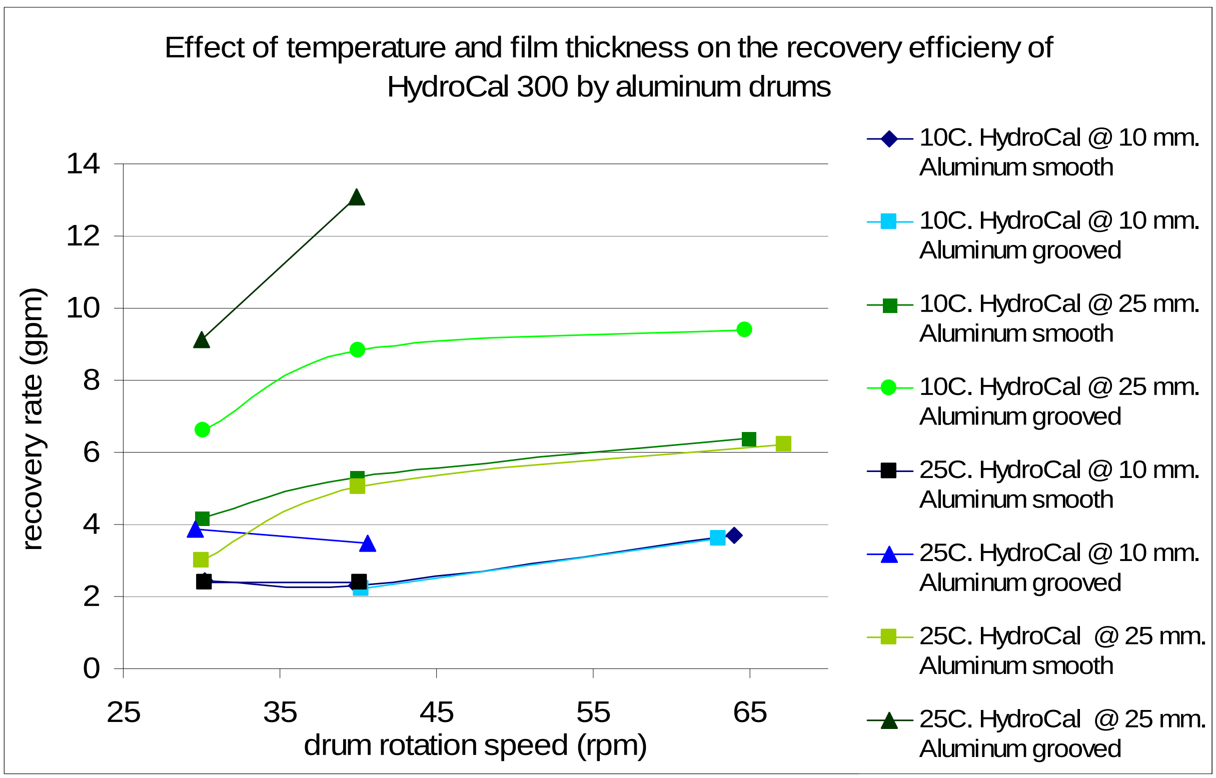

Figure 10. Effect of temperature and slick thickness on the recovery of HydroCal by aluminum drums.

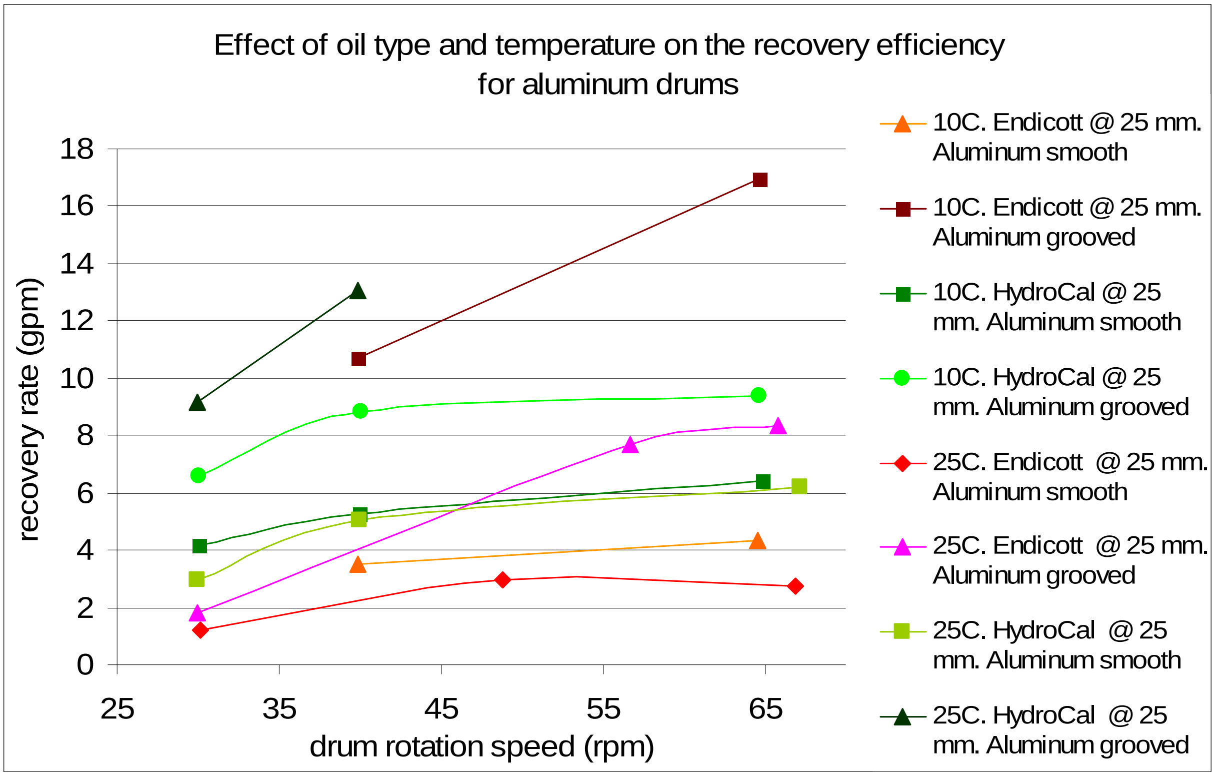

Figure 11. Effect of temperature and oil type on the recovery efficiency of aluminum drums. Oil thickness was 25 mm for all tests.

Figure 11 shows the effect of oil type and temperature on the recovery efficiency of aluminum drums. The decrease in temperature led to a slight increase in Endicott recovery rates using smooth drums. However, for HydroCal there was almost no increase in oil recovery using smooth drums at different temperatures. Higher oil viscosity at lower temperatures led to a significant increase in the amount of recovered Endicott using grooved drums, but the recovery rates of HydroCal were somewhat reduced since it was so viscous that less oil would penetrate into the grooves.

4. Conclusions

The field-scale tests confirmed the results of laboratory experiments conducted during the previous phase of this project. It was found that:

- The use of a grooved pattern can increase the recovery efficiency up to 200%. The grooved pattern proved to be efficient even on Diesel, which is a challenging product to recover due to its low viscosity. The recovery efficiency of a grooved surface may be additionally improved by tailoring the groove dimensions to specific oil properties for a particular region and climate. Using more shallow and narrow groves for light diesel and fuel oil and deeper and more open grooves for heavier oils may lead to higher recovery efficiency.
- The selection of the recovery surface material can increase the recovery efficiency by 20%. The difference between materials is especially pronounced for thin (10 mm) oil slicks.

- The recovery efficiency significantly depends on the type of petroleum product and is typically proportional to the oil's viscosity.
- Oil spill thickness has a significant effect on the recovery efficiency. The increase in oil thickness from 10 mm to 25 mm led to 2-3 times higher recovery rates for HydroCal oil. The increase in oil thickness from 25 to 50 mm did not significantly increase the recovery rates. Endicott oil recovery efficiency was found to be less sensitive to the changes in oil slick thickness than the recovery efficiency of HydroCal oil.
- For light and medium viscosity oils, oil recovery efficiency was found to be inversely proportional to oil temperature. Oil viscosity increases when temperature decreases, leading to the formation of a thicker oil film in every drum rotation. HydroCal recovered by a grooved surface was the only exception. At lower temperatures, the viscosity of HydroCal increased to the point that the oil could not penetrate deep in to the grooves, leading to a lower oil recovery. HydroCal oil recovery was more affected by the slick thickness than by the changes in the temperature.
- The amount of entrained free water was typically higher for a 10 mm oil slick than for a 25 or 50 mm oil slick.
- Drum rotation speed had a significant effect on oil recovery efficiency. For the skimmer and drums tested, 40 revolutions per minute (RPM) appeared to be a nearly optimal rotation speed in most cases. Beyond 40 RPM, the drum would start to recover a significant amount of free water. If there are adequate storage and handling facilities to store the free water skimmed by the system, and the response team is not concerned with free water in the recovered product, the maximum rotation speed should be used, since this will result in the highest overall oil recovery.

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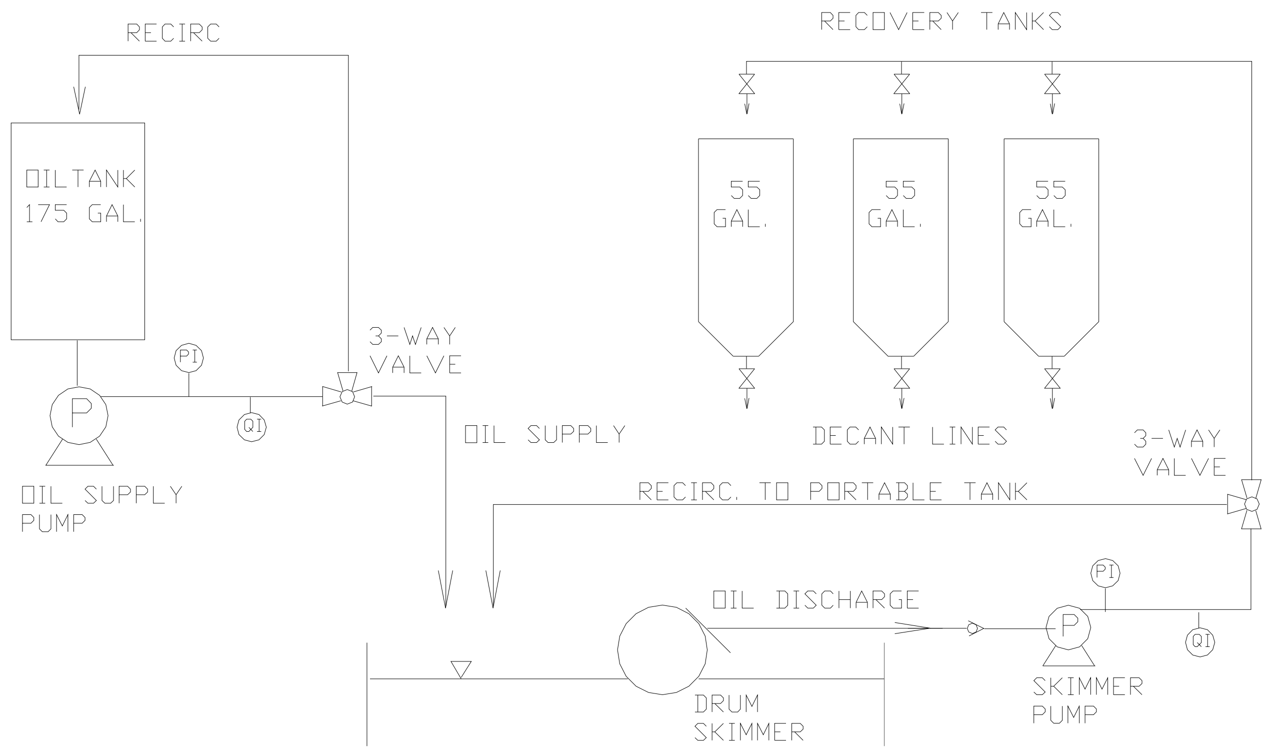
Appendix 1. **Oil recovery test flow diagram.**



Appendix 2. Test Results.

For the tables below, in the column "Description" the following abbreviations were used:

- Al-S – aluminum drum, smooth surface
- PE-S – Polyethylene drum, smooth surface
- Hyp-S – Hypalon drum, smooth surface
- Neo-SH – Neoprene drum, smooth, covered with sheet Neoprene
- Neo-SC - Neoprene drum, smooth, coated with Neoprene
- PP-SH – Polypropylene drum, smooth covered with Polypropylene sheet.
- Neo-G – Neoprene drum, grooved, coated
- Al-G – Aluminum drum, grooved.
- Hyp-G – Hypalon drum, grooved, coated.

- "Std", "Opt" and "Max" after the name of the drum in the Description column denotes the drum speed also specified in the last column entitled as "RPM". For the series1 tests, Std corresponds to 30 rpm, Opt corresponds to 40 rpm, and Max corresponds to a maximum achievable speed between 60 and 70 rpm. For the series 2 tests, speeds were denoted as 30, 40 and Hi.
- "Fluid Rec" column specifies the total amount of recovered fluid (oil and free water) in gallons. This parameter was used to plot graphics in Appendix 3 comparing Recovered Fluid at various drum speeds.
- "Fluid Post Decant" column specifies the amount of recovered oil in gallons after free water was removed.
- "Parent Oil H2O %" column specifies the water content of test oil in the tank prior to test.
- "Recovered Oil % H2O" column specifies the water content of recovered oil (without free water).
- "Oil Rec, gal" column specifies the amount of recovered oil (after all water volumes were subtracted). This parameter was used to plot graphics comparing the Recovery Efficiency of various drums.
- "Rec Time, sec" column specifies the time of oil recovery. Please note that although the recovery efficiencies (recovery rates) in gallons per minute between test series 1 and 2 can be compared, the amounts of recovered water and total recovered fluids can be compared only to the tests that had the same duration. This is due to the difference in the recovery times between test series (5 and 3 minutes).
- "RR, gpm" – column specifies the recovery rates in gallons per minute. This value was calculated by dividing the amount of recovered oil by the recovery time.
- "Temp, C" column specifies the temperature during the test.
- "RPM" column specifies the drum rotation speed.

- **Series 1. HydroCal 300 @ 25 mm**

Test #	Description	Fluid Rec	Fluid Post Decant	Parent Oil H2O %	Rec Oil % H2O	Oil Rec, gal	Rec Time, sec	RR, gpm	Temp, C	RPM
2	Al-S, Std	16.72	16.72	6.00	11.00	14.88	300.00	2.98	30.00	30.00
1	Al-S, Opt	28.95	28.95	8.00	13.00	25.19	300.00	5.04	25.56	40.00
3	Al-S, Max	43.00	42.15	6.00	26.00	31.19	301.00	6.22	27.50	67.17
10	Al-G, Std	63.82	46.38	6.00	1.50	45.68	300.00	9.14	25.83	30.00
11	Al-G, Opt	96.22	63.82	6.00	7.50	59.03	300.00	11.81	25.56	39.87
16	Neo-SC, Std	15.38	15.38	6.00	1.00	15.22	300.00	3.04	28.33	29.97
17	Neo-SC, Opt	24.28	24.28	6.00	1.00	24.03	300.00	4.81	26.67	40.13
18	Neo-SH, Std	15.55	15.55	6.00	0.50	15.48	301.00	3.08	26.67	30.10
19	Neo-SH, Opt	29.34	29.34	6.00	2.00	28.75	301.00	5.73	26.67	44.07
22	Neo-SH, Max	43.26	42.61	6.00	12.00	37.50	301.00	7.47	27.78	65.77
8	Neo-G, Std	45.53	44.68	6.00	12.00	39.31	300.00	7.86	28.61	30.00
9	Neo-G, Opt	58.82	57.08	6.00	12.00	50.23	301.00	10.70	27.78	40.33
	Neo-G, Max	107.04	96.50	6.00	30.00	67.55	301.00	14.99	27.00	70.00
7	Hyp-S, Std	15.78	15.78	6.00	1.00	15.62	300.00	3.12	28.06	30.20
	Hyp-S, Opt	25.42	25.42	6.00	1.70	24.99	301.00	4.98	27.22	40.33
14	Hyp-G, Std	45.75	45.10	6.00	3.00	43.75	300.00	8.75	26.11	30.17
15	Hyp-G, Opt	68.56	67.69	6.00	5.50	63.97	300.00	13.60	26.94	40.33
12	PP-SH, Std	15.80	15.80	6.00	0.60	15.71	300.00	3.14	27.22	29.87
13	PP-SH, Opt	26.40	25.98	6.00	1.30	25.64	300.00	5.13	27.78	41.93
	PE-S, Std	13.65	13.65	6.00	2.50	13.31	300.00	2.66	35.28	30.00
20	PE-S, Opt	24.12	24.12	6.00	6.00	22.67	300.00	4.53	29.17	39.80
21	PE-S, Max	48.10	47.25	6.00	18.00	38.75	301.00	7.72	31.11	67.33

Series 1. Endicott Crude @ 25 mm

Test #	Description	Fluid Rec	Fluid Post Decant	Parent Oil H2O %	Rec Oil % H2O	Oil Rec, gal	Rec Time, sec	RR, gpm	Temp, C	RPM
23	Neo-SH, Std	7.60	7.28	0.00	0.20	7.26	301.00	1.45	26.67	30.07
24	Neo-SH, Opt	15.42	14.98	0.00	0.20	14.95	300.00	2.99	26.94	40.00
25	Neo-SH, Max	22.18	21.75	0.00	2.40	21.23	300.00	4.25	26.39	65.67
26	PP-SH, Std	7.28	6.95	0.00	0.50	6.92	300.00	1.38	31.67	30.27
27	PP-SH, Opt	13.68	13.24	0.00	0.30	13.20	301.00	2.63	28.33	43.00
28	Neo-SC, Std	7.50	7.20	0.00	0.20	7.18	300.00	1.44	29.17	30.07
29	Neo-SC, Opt	15.78	15.78	0.00	0.40	15.71	300.00	3.14	28.61	49.27
30	PE-S, Std	6.10	6.00	0.00	0.10	5.99	300.00	1.20	31.94	30.17
31	PE-S, Opt	14.11	14.01	0.00	0.40	13.95	301.00	2.78	39.72	50.07
32	PE-S, Max	20.90	20.80	0.00	1.80	20.42	300.00	4.08	33.89	66.67
33	Al-S, Std	6.00	6.00	0.00	0.50	5.97	300.00	1.19	39.17	30.17
34	Al-S, Opt	14.98	14.98	0.00	0.40	14.92	300.00	2.98	31.67	48.83
35	Al-S, Max	22.50	14.00	0.00	2.40	13.66	301.00	2.72	29.44	66.87
36	Al-G, Max	49.78	43.40	0.00	3.50	41.88	301.00	8.35	33.89	65.87
37	Al-G, Opt	39.78	39.24	0.00	2.00	38.45	301.00	7.66	28.89	56.67
38	Al-G, Std	9.85	9.00	0.00	0.60	8.95	300.00	1.79	28.89	30.00
39	Neo-G, Std	10.05	10.05	0.00	0.40	10.01	300.00	2.00	36.39	30.17
41	Neo-G, 40	21.33	21.33	0.00	0.40	21.24	301.00	4.23	29.44	40.07
40	Neo-G, Opt	40.65	40.65	0.00	1.80	39.91	301.00	7.96	27.78	57.33

Series 1. Hydrocal 300 @ 50mm

Test #	Description	Fluid Rec	Fluid Post Decant	Parent Oil H2O %	Rec Oil % H2O	Oil Rec, gal	Rec Time, sec	RR, gpm	Temp, C	RPM
52	Neo-SH, Std	8.46	8.02	6.00	1.20	7.92	180.00	2.64	31.11	29.93
53	Neo-SH, 40	13.04	12.83	6.00	1.20	12.67	180.00	4.22	32.22	39.90
54	PE-S, Std	7.28	7.28	6.00	1.00	7.20	180.00	2.40	32.22	30.00
55	PE-S, 40	12.37	12.37	6.00	0.70	12.28	180.00	4.09	31.39	40.20
56	Al-S, Std	7.28	6.85	6.00	0.60	6.81	180.00	2.27	32.78	29.90
57	Al-S, 40	12.37	11.94	6.00	0.80	11.84	180.00	3.95	32.22	39.83
59	Al-G, Std	19.60	18.96	6.00	1.20	18.73	180.00	6.24	29.44	30.13
60	Al-G, 40	41.28	40.43	2..4	1.40	39.86	180.00	13.29	27.22	40.40

Series 1. Hydrocal 300 @ 10mm

Test #	Description	Fluid Rec	Fluid Post Decant	Parent Oil H2O %	Rec Oil % H2O	Oil Rec, gal	Rec Time, sec	RR, gpm	Temp, C	RPM
45	Al-S, Std	8.15	7.94	6.00	9.00	7.22	180.00	2.41	29.44	30.20
46	Al-S, 40	7.51	7.70	6.00	5.75	7.26	181.00	2.41	28.33	40.10
47	Neo-SH, Std	6.34	6.85	6.00	3.50	6.61	181.00	2.19	30.00	29.93
48	Neo-Sh, 40	6.61	6.39	6.00	7.00	5.94	181.00	1.97	31.94	40.13
49	PE-S, Std	7.73	7.30	6.00	2.50	7.12	181.00	2.36	31.11	30.33
50	PE-S, 40	10.70	11.00	6.00	1.80	10.80	180.00	3.60	28.33	39.90
61	Al-G, 40	13.89	13.46	2.40	22.00	10.50	181.00	3.48	28.89	40.63
62	Al-G, Std	14.95	14.10	2.40	18.00	11.56	180.00	3.85	26.67	29.63

Series 2. Diesel @ 25 mm

Test #	Description	Fluid Rec	Fluid Post Decant	Parent Oil H2O %	Rec Oil % H2O	Oil Rec, gal	Rec Time, sec	RR, gpm	Temp, C	RPM
29	PE-S, 40 rpm	5.15	5.15	2.60	8.00	4.74	180.00	1.58	7.78	39.97
30	PE-S, Hi rpm	11.61	11.50	2.60	12.00	10.12	180.00	3.37	8.33	63.73
31	Neo-SH, 40rpm	6.03	5.71	2.60	7.00	5.31	180.00	1.77	6.11	40.03
32	Neo-SH, Hi rpm	11.10	11.10	2.60	13.00	9.66	180.00	3.22	11.67	63.97
33	Al-S, 40 rpm	5.41	5.41	2.60	3.50	5.22	180.00	1.74	15.56	40.00
34	Al-S, Hi rpm	11.34	11.13	2.60	11.00	9.90	180.00	3.30	10.00	64.60
37	Al-Gr, Hi rpm	25.15	24.73	2.60	11.00	22.01	180.00	7.34	12.22	65.33
38	Al-Gr, 40 rpm	7.70	7.59	2.60	1.60	7.47	180.00	2.49	16.67	40.00
39	Neo-Gr, Hi rpm	21.07	21.07	2.60	11.00	18.75	180.00	6.25	11.67	64.17

Series 2. Hydrocal 300@ 10 mm

Test #	Description	Fluid Rec	Fluid Post Decant	Parent Oil H2O %	Rec Oil % H2O	Oil Rec, gal	Rec Time, sec	RR, gpm	Temp, C	RPM
2	Al-S, 30 rpm	13.13	12.15	5.50	33.00	8.14	200.00	2.44	11.67	30.17
1	Al-S, 40 rpm	11.53	10.25	5.50	32.00	6.97	181.00	2.31	11.11	39.90
3	Al-S, Hi rpm	22.18	13.68	5.50	19.00	11.08	180.00	3.69	11.11	64.00
4	Neo-SH, 30 rpm	8.98	8.55	5.50	20.00	6.84	180.00	2.28	12.22	30.03
5	Neo-SH, 40 rpm	13.68	13.24	5.50	29.00	9.40	180.00	3.13	12.78	40.07
6	PE-S, 30 rpm	11.95	11.53	5.50	15.00	9.80	180.00	3.27	12.22	29.90
7	PE-S, 40 rpm	15.69	15.38	5.50	27.00	11.22	182.00	3.70	12.22	39.97
8	Hyp-Gr, 30 rpm	8.66	8.34	1.00	21.00	6.59	181.00	2.18	5.00	29.73
9	Hyp-Gr, 40 rpm	12.81	9.76	1.00	14.00	8.39	180.00	2.80	5.56	40.13
10	Al-Gr, 30 rpm	7.30	7.19	1.00	20.00	5.76	180.00	1.92	8.33	29.97
11	Al-Gr, 40 rpm	11.21	7.70	1.00	14.00	6.62	180.00	2.21	7.22	40.17
12	Al-Gr, Hi rpm	25.42	12.37	1.00	11.50	10.95	181.00	3.63	7.78	63.00
13	Neo-Gr, 30 rpm	12.16	11.53	1.00	22.00	8.99	180.00	3.00	10.00	30.10
14	Neo-Gr, 40 rpm	13.68	11.50	1.00	16.00	9.66	180.00	3.22	8.89	40.10

Series 2. Endicott Crude@ 10 mm

Test #	Description	Fluid Rec	Fluid Post Decant	Parent Oil H2O %	Rec Oil % H2O	Oil Rec, gal	Rec Time, sec	RR, gpm	Temp, C	RPM
40	Al-Gr, 40 rpm	10.68	10.68	0.05	14.00	9.18	180.00	3.06	12.78	39.80
41	Al-Gr, Hi rpm	25.20	17.59	0.05	14.00	15.13	180.00	5.04	11.11	64.93
42	Neo-Gr, 40 rpm	16.01	15.80	0.05	17.00	13.11	180.00	4.37	11.67	40.17
43	Neo-Gr, Hi rpm	27.04	21.09	0.05	12.00	18.56	180.00	6.19	11.11	65.50
44	Al-S, 40 rpm	9.83	9.83	0.05	2.00	9.63	180.00	3.21	12.22	39.93
45	Al-S, Hi rpm	17.59	17.59	0.05	18.00	14.42	180.00	4.81	10.00	64.27
46	PE-S, 40 rpm	13.04	13.04	0.05	2.50	12.71	181.00	4.21	10.56	40.00
47	PE-S, Hi rpm	19.39	19.39	0.05	10.00	17.45	180.00	5.82	11.11	64.53
48	Neo-SH, 40 rpm	6.64	6.64	0.05	10.00	5.97	180.00	1.99	9.44	40.07
49	Neo-SH, Hi rpm	18.68	9.54	0.05	6.00	8.97	180.00	2.99	9.44	63.43

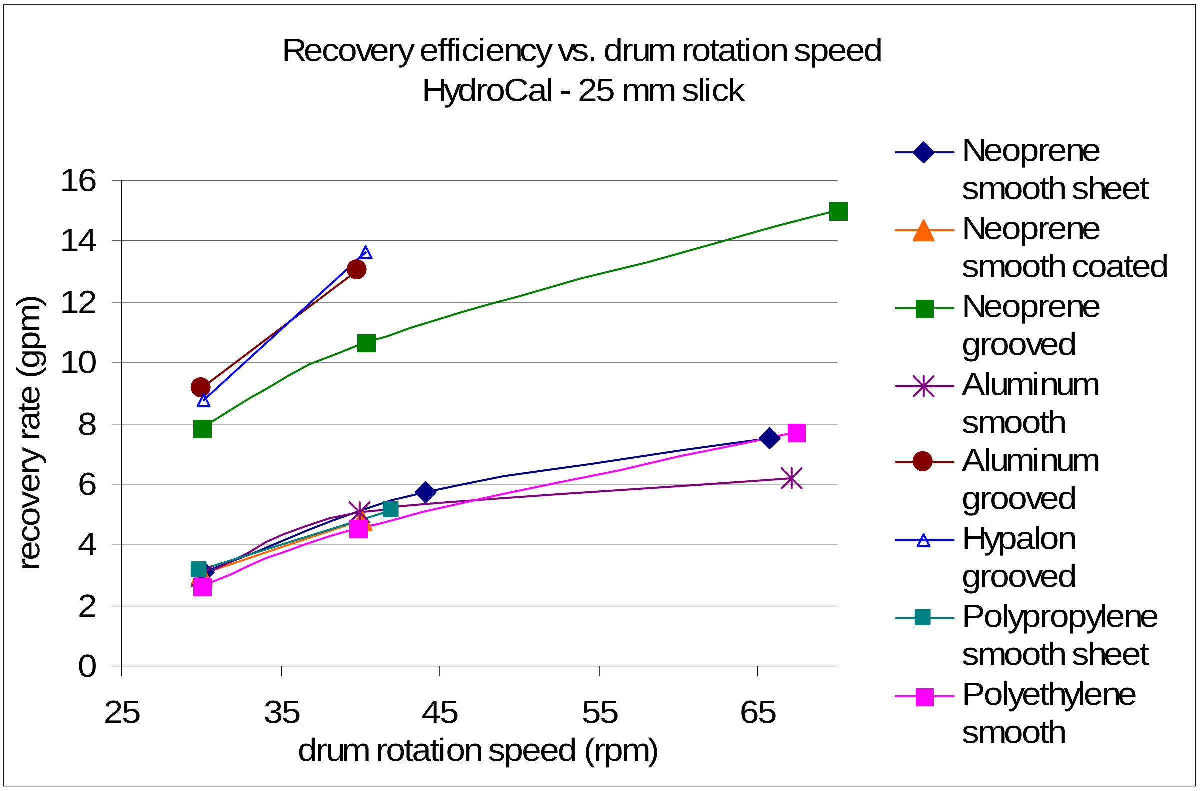
Series 2. Endicott Crude @ 25 mm

Test #	Description	Fluid Rec	Fluid Post Decant	Parent Oil H2O %	Rec Oil % H2O	Oil Rec, gal	Rec Time, sec	RR, gpm	Temp, C	RPM
50	Neo-SH, 40 rpm	10.91	10.91	0.05	3.00	10.59	180.00	3.53	8.89	40.10
51	Neo-SH, Hi rpm	16.84	16.84	0.05	12.00	14.82	180.00	4.94	10.00	63.60
52	PE-S, 40 rpm	13.02	13.02	0.05	1.70	12.80	180.00	4.27	8.89	40.07
53	PE-S, Hi rpm	18.35	18.35	0.05	17.00	15.23	180.00	5.08	9.44	64.30
54	Al-S, 40 rpm	10.68	10.68	0.05	1.70	10.49	180.00	3.50	14.44	39.83
56	Al-S, Hi rpm	15.80	15.80	0.05	18.00	12.96	180.00	4.32	15.56	64.57
57	Al-S, Hi rpm	15.99	15.99	0.05	23.00	12.31	180.00	4.10	12.78	64.10
55	Al-S, 40 rpm	13.02	13.02	0.05	1.70	12.80	180.00	4.27	12.78	40.07
61	Al-Gr, Hi rpm	61.09	61.09	0.05	19.00	49.48	175.00	16.97	9.44	64.67
59	Al-Gr, 40 rpm	32.80	32.80	0.05	2.10	32.11	180.00	10.70	11.11	39.83
60	Al-Gr, Hi rpm	56.15	56.15	0.05	18.00	46.04	180.00	15.35	10.00	64.67
58	Al-Gr, 40 rpm	33.90	33.90	0.05	3.50	32.72	180.00	10.91	11.67	40.00

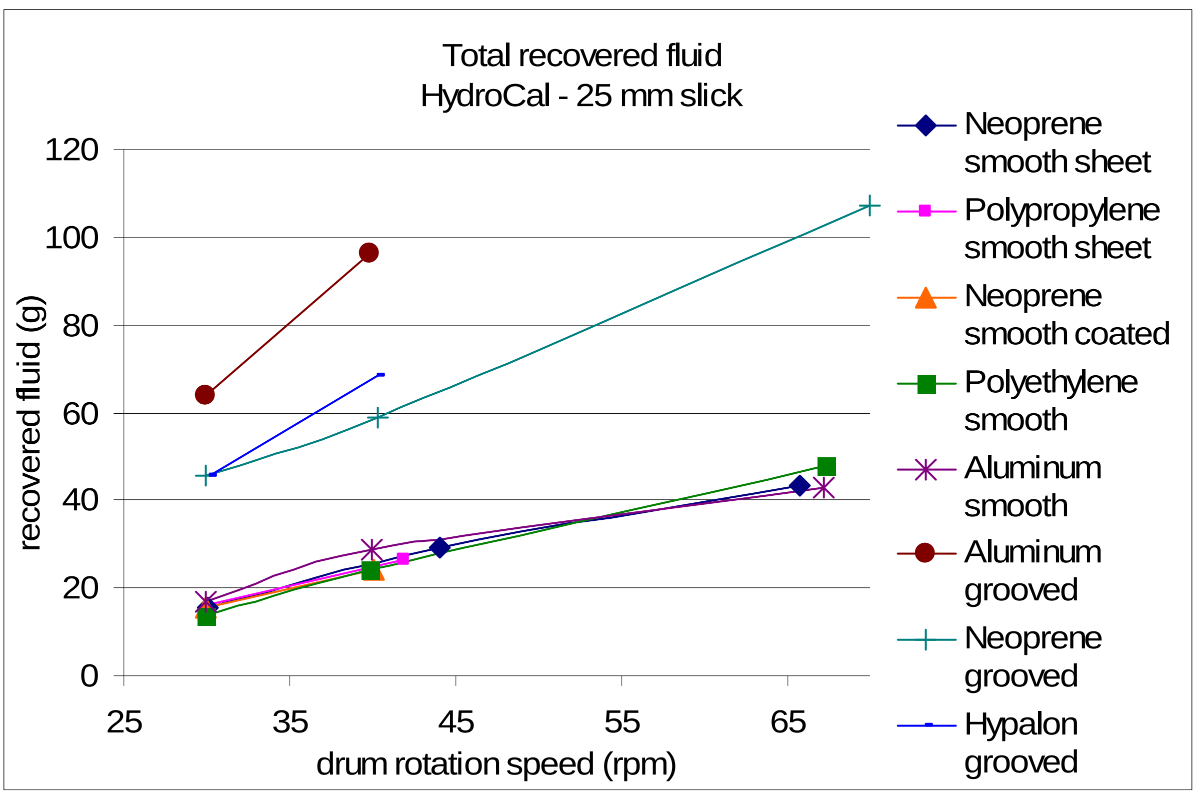
Series 2. Hydrocal 300@ 25 mm

Test #	Description	Fluid Rec	Fluid Post Decant	Parent Oil H2O %	Rec Oil % H2O	Oil Rec, gal	Rec Time, sec	RR, gpm	Temp, C	RPM
17	Al-Gr, 30 rpm	33.03	25.42	0.80	22.00	19.83	180.00	6.61	12.22	30.07
18	Al-Gr, 40 rpm	35.11	29.38	0.80	10.00	26.44	180.00	8.81	13.33	40.03
19	Al-Gr, Hi rpm	52.56	29.83	0.80	5.50	28.18	180.00	9.39	11.67	64.70
20	Al-S, 30 rpm	13.23	13.01	0.80	4.25	12.46	180.00	4.15	13.33	30.03
21	Al-S, 40 rpm	18.35	18.03	0.80	12.00	15.86	180.00	5.29	12.22	39.93
22	Al-S, Hi rpm	28.23	20.90	0.80	8.00	19.23	180.00	6.41	11.67	64.87
23	Hyp-Gr, 30 rpm	30.65	29.80	0.10	5.50	28.16	180.00	9.39	12.22	30.20
24	Hyp-Gr, 40 rpm	38.47	32.82	0.10	13.00	28.55	180.00	9.52	13.89	40.20
25	Neo-SH, 30 rpm	14.08	13.65	0.10	5.50	12.90	180.00	4.30	13.33	29.97
26	Neo-SH, 40 rpm	20.64	20.20	0.10	9.00	18.38	180.00	6.13	13.89	40.07
27	PE-S, 30 rpm	14.31	14.21	0.10	3.75	13.67	180.00	4.56	12.78	30.17
28	PE-S, 40 rpm	20.03	19.60	0.10	5.50	18.52	180.00	6.17	14.44	39.87

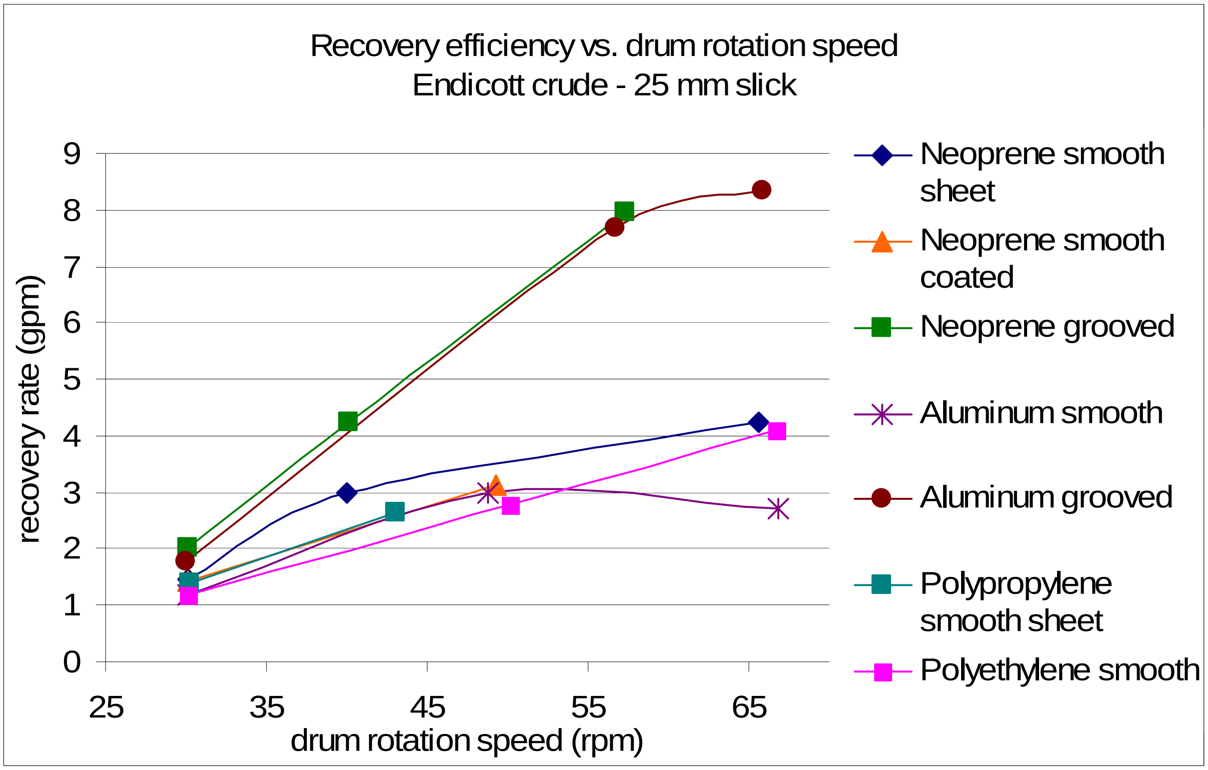
Appendix 3. Data analysis. Test series #1.



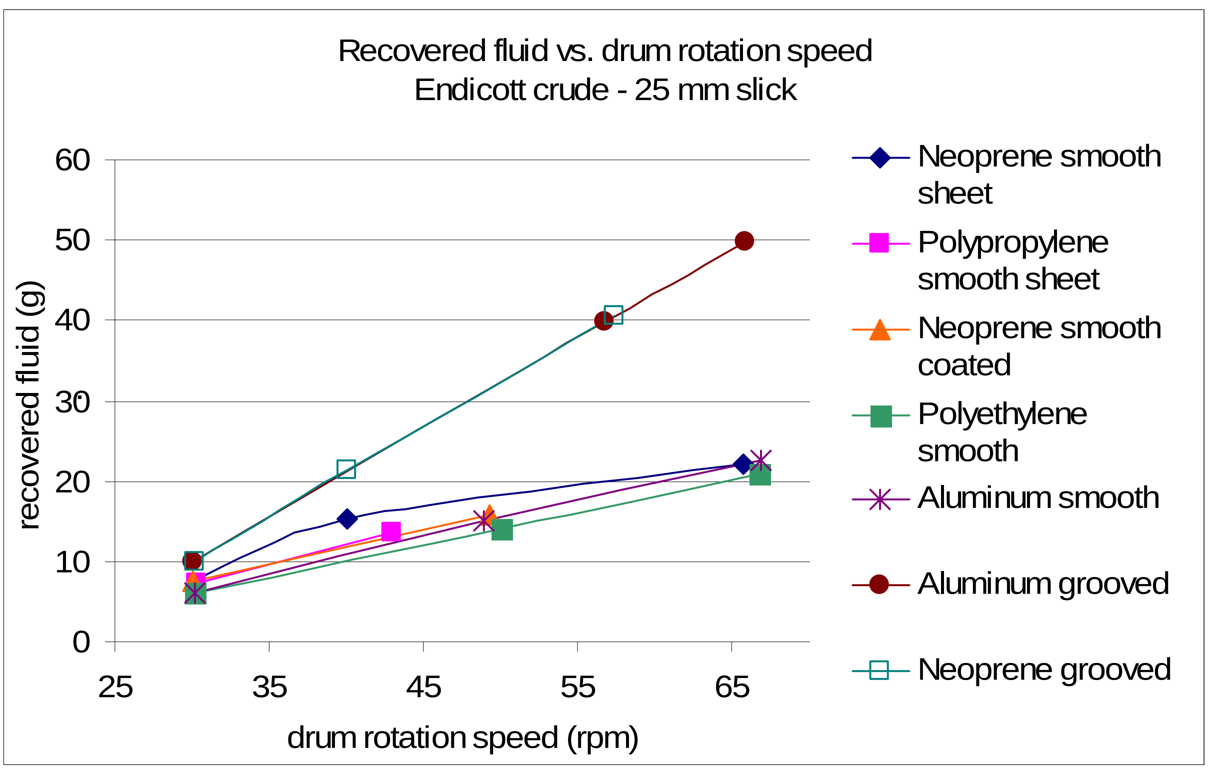
Test duration – 5 minutes



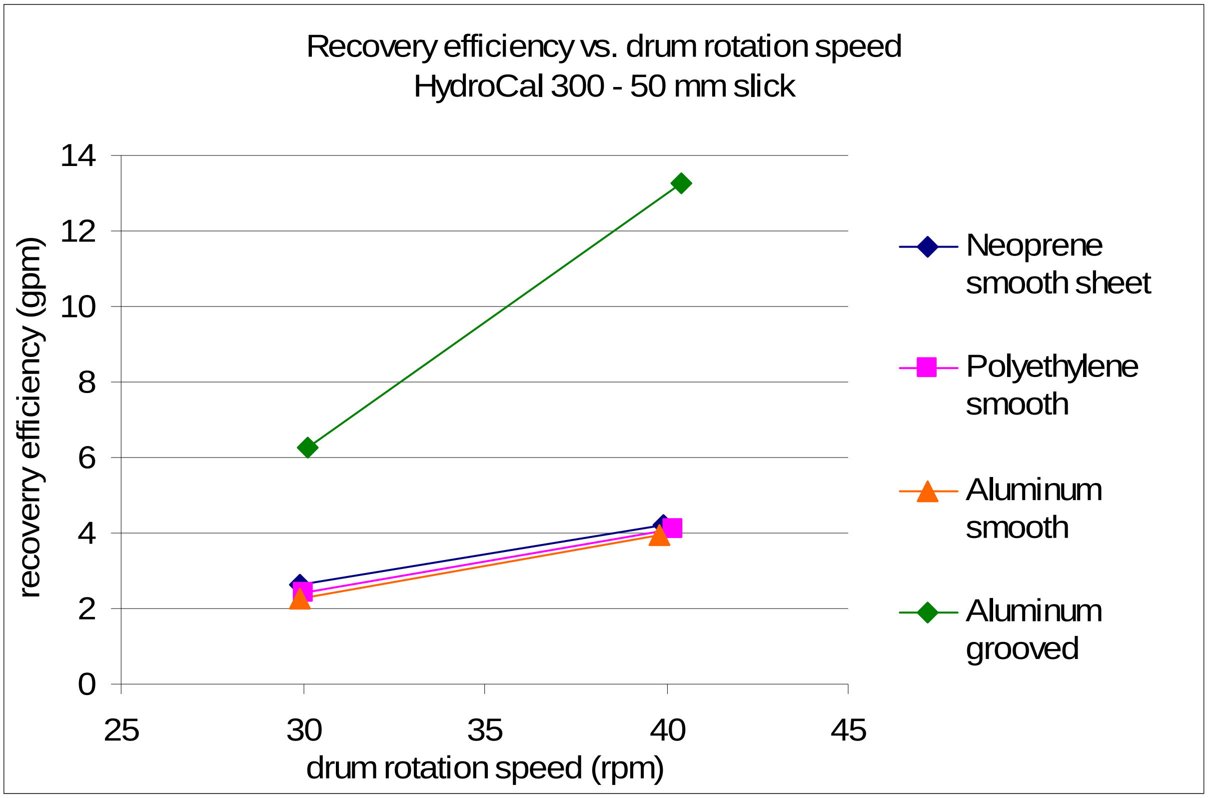
Test duration – 5 minutes



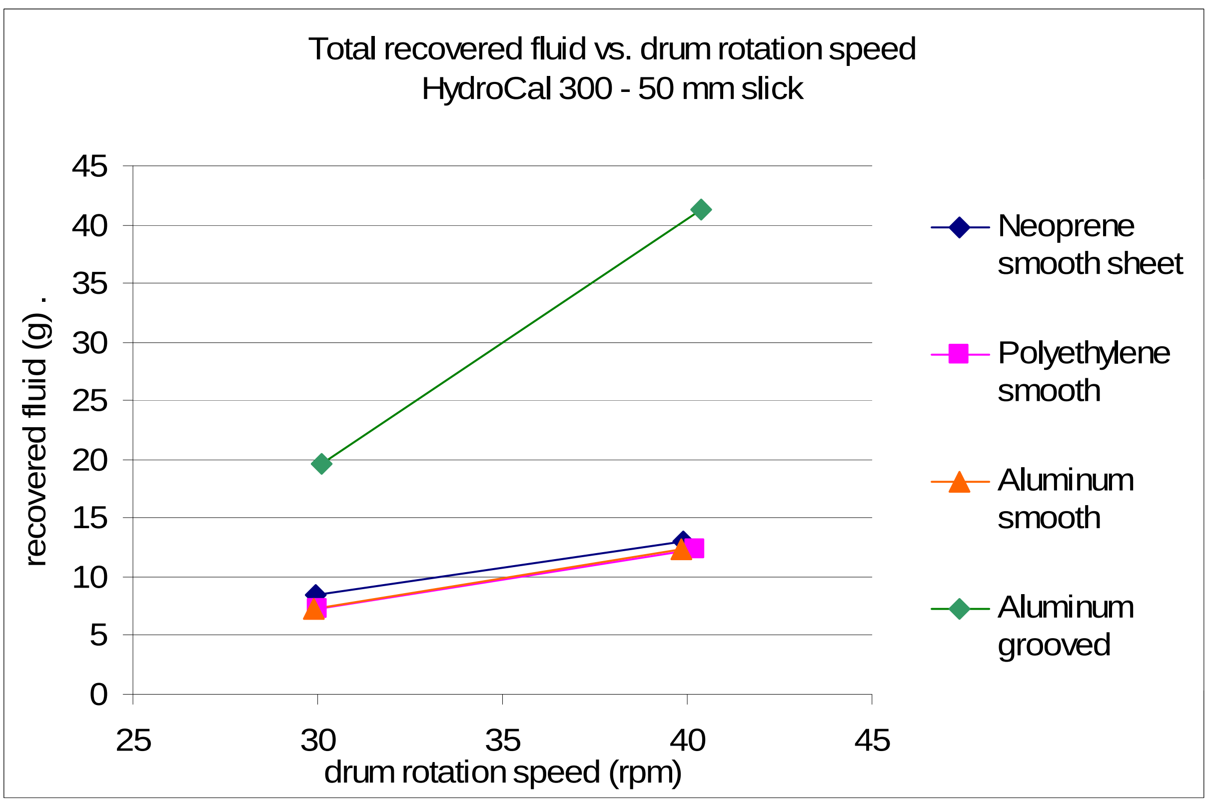
Test duration – 5 minutes



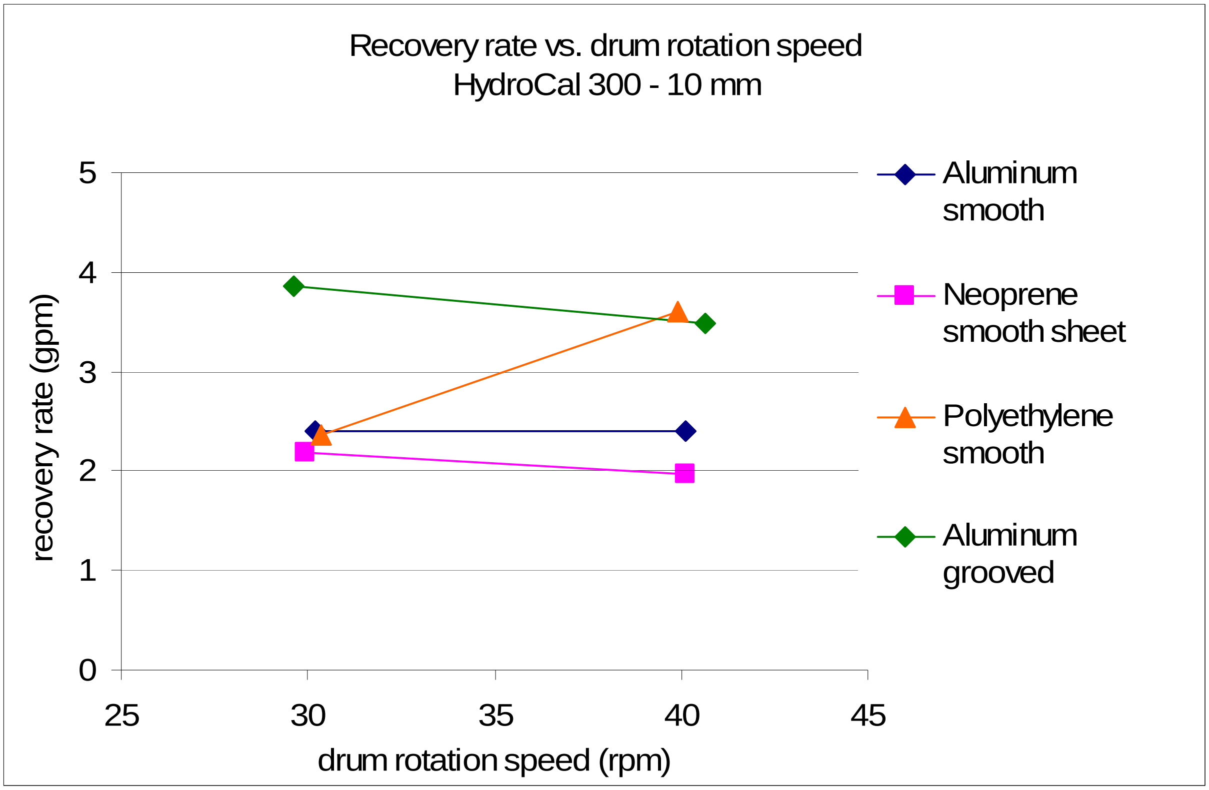
Test duration – 5 minutes



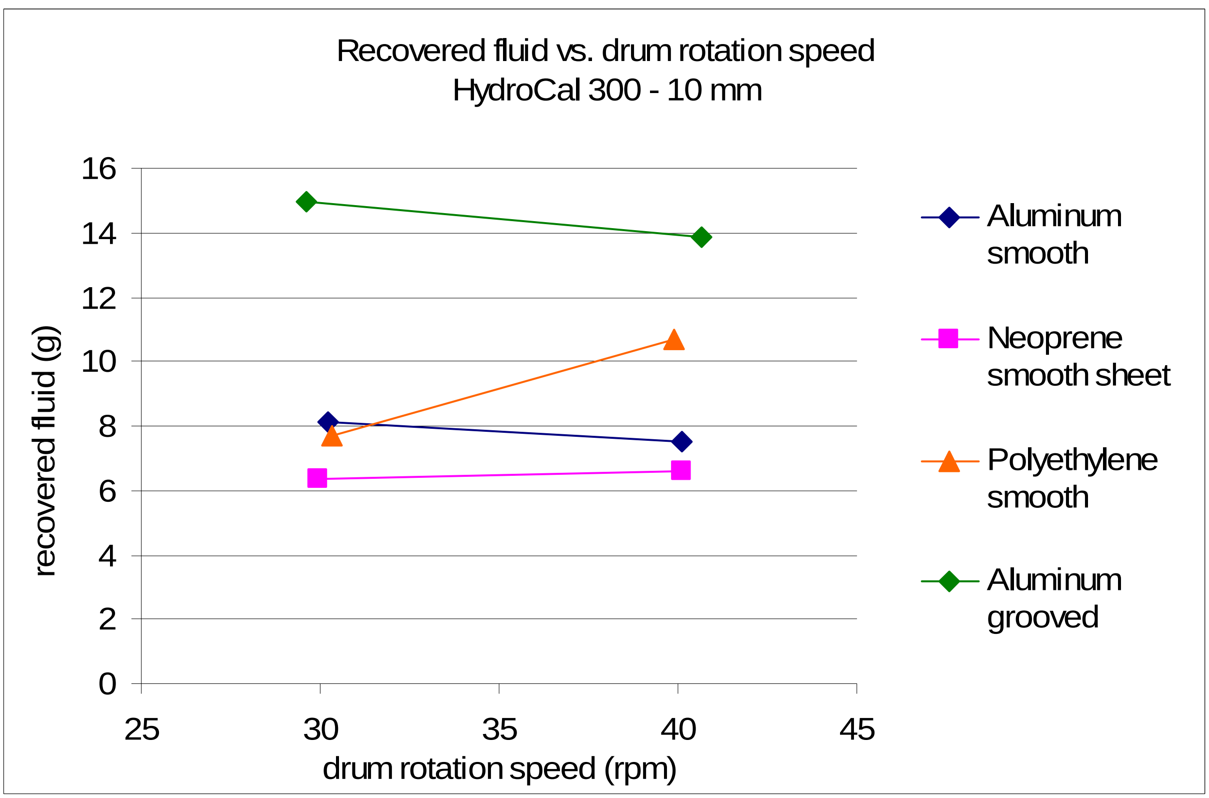
Test duration – 3 minutes.



Test duration – 3 minutes.

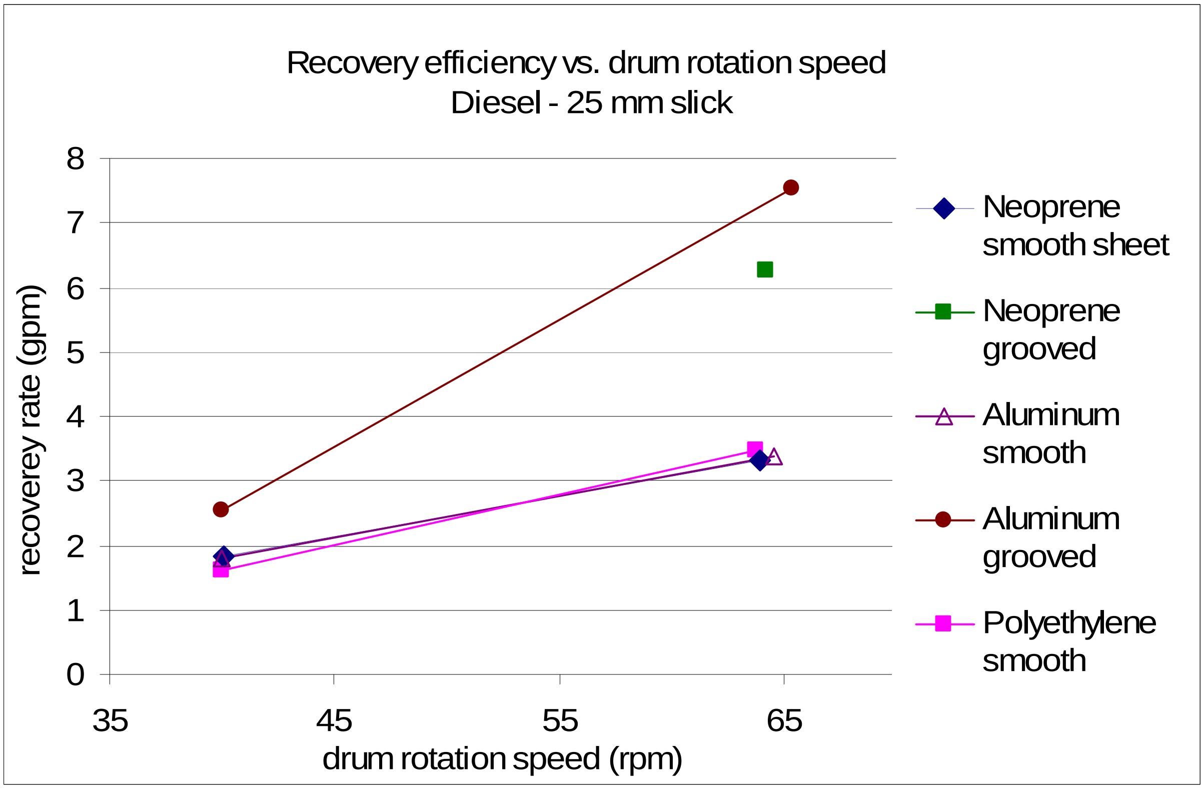


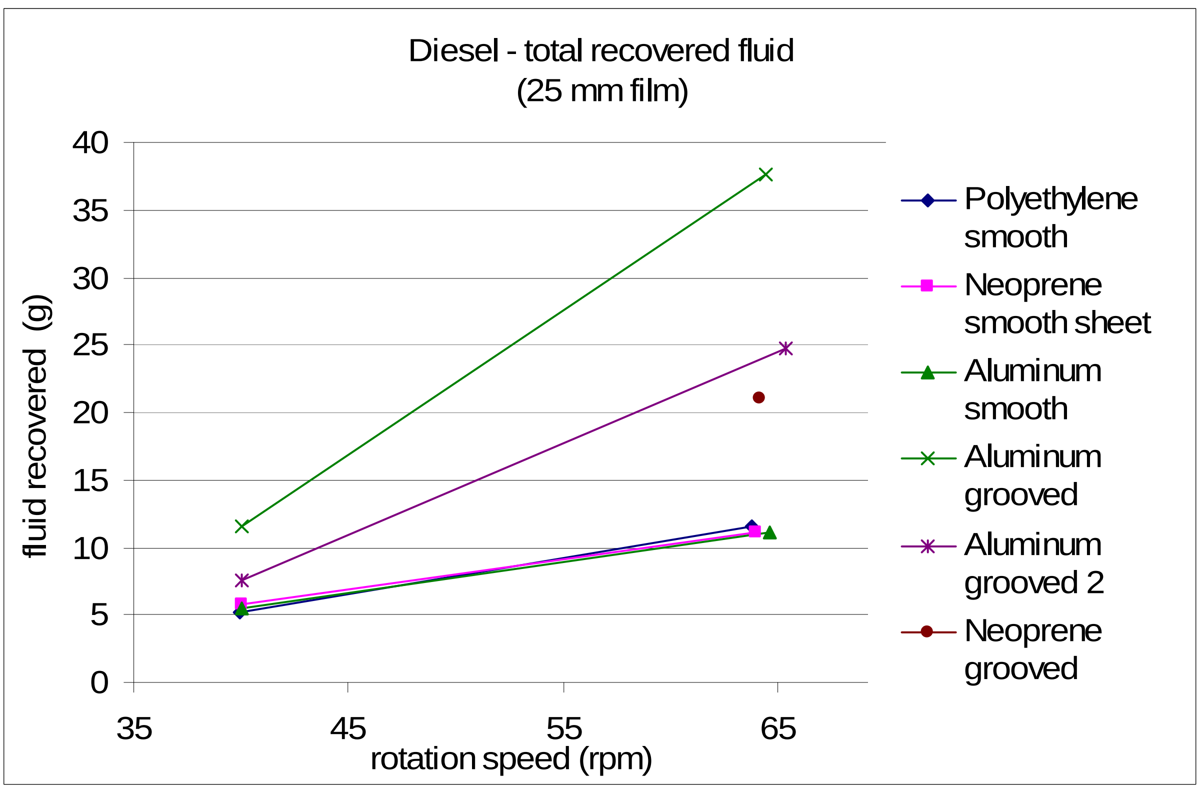
Test duration – 3 minutes.

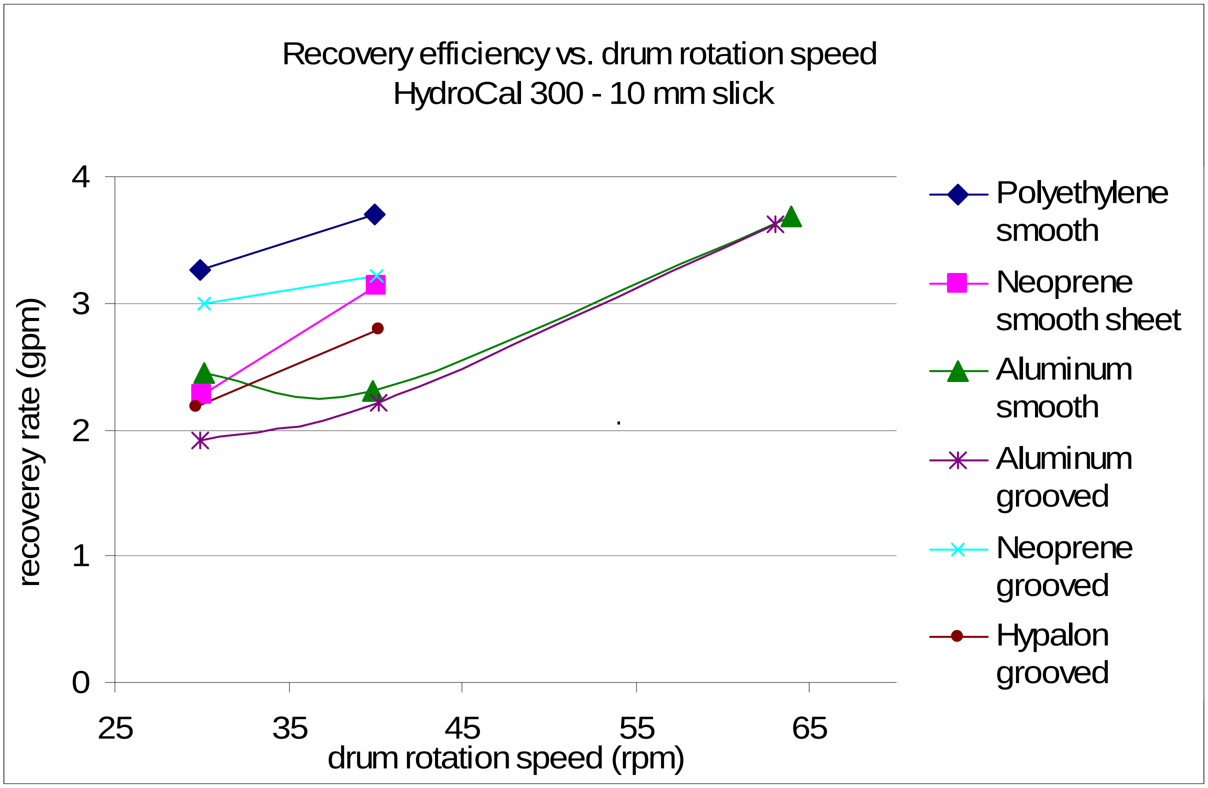


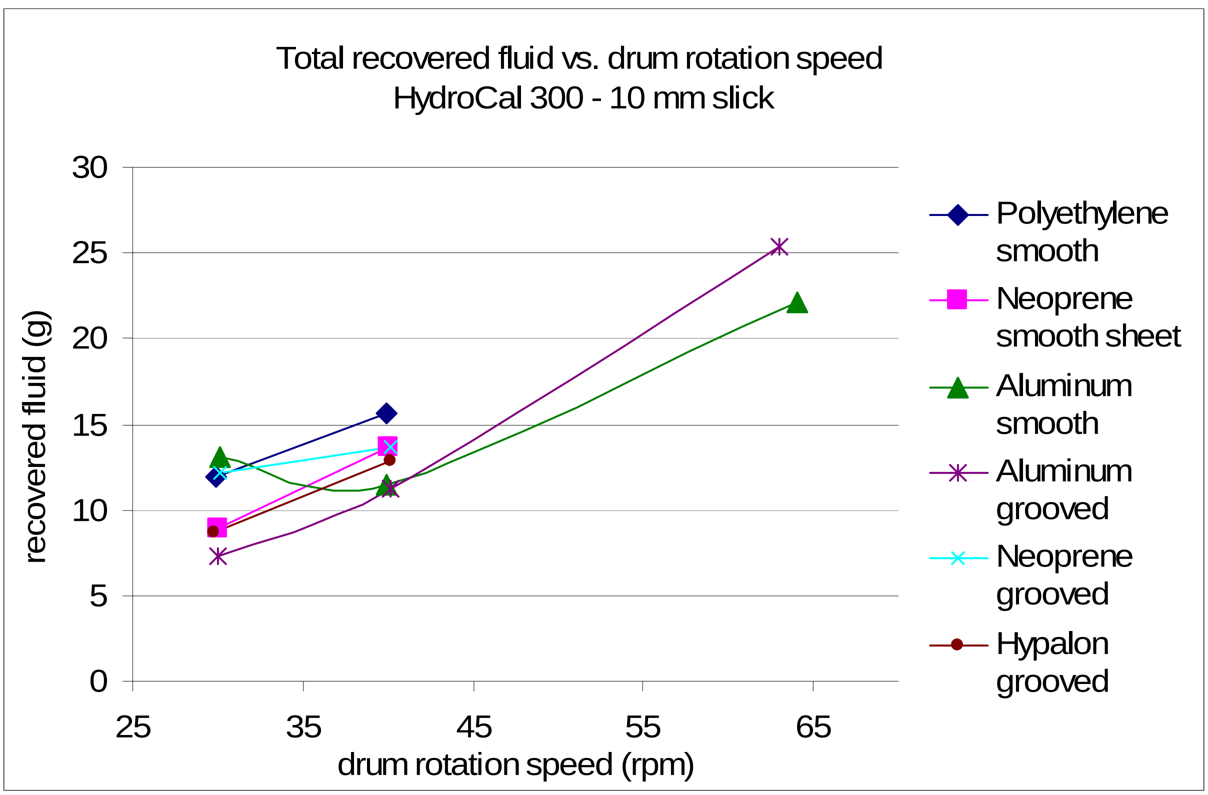
Test duration – 3 minutes.

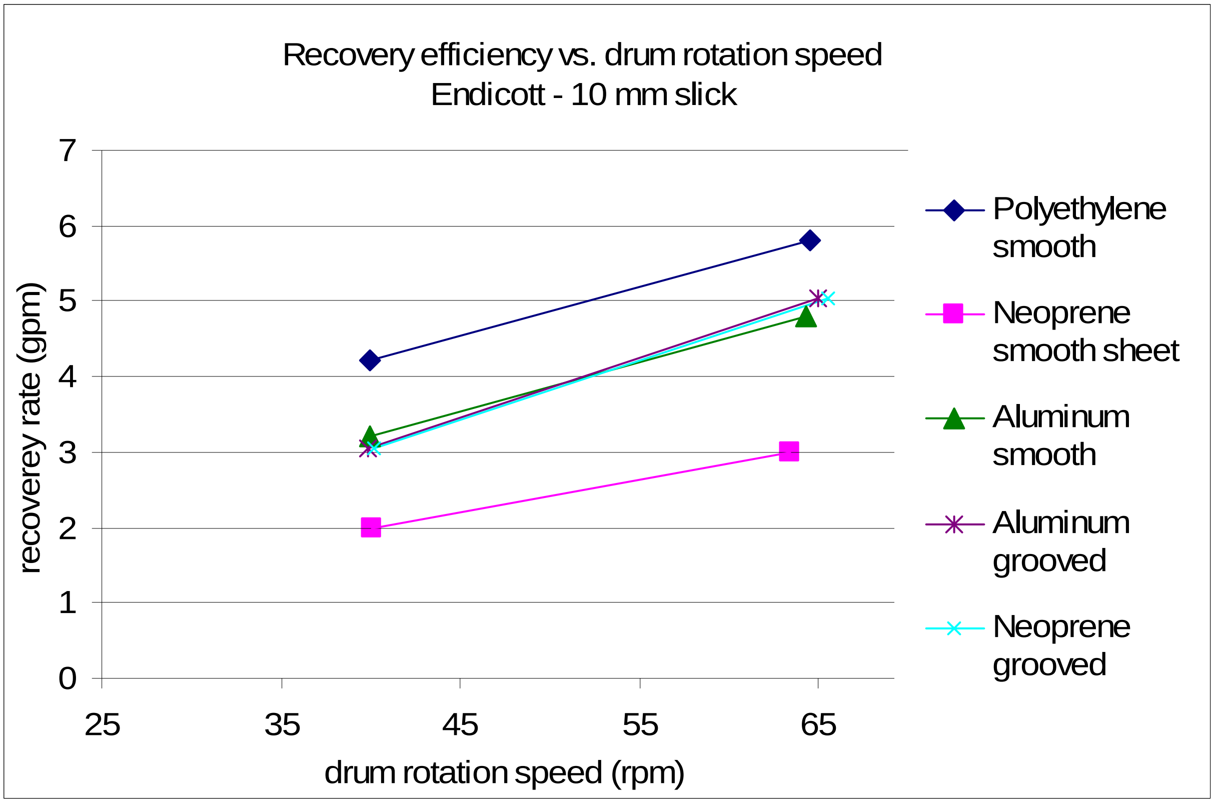
Appendix 4. Data analysis. Test series #2. Duration of all tests – 3 minutes.

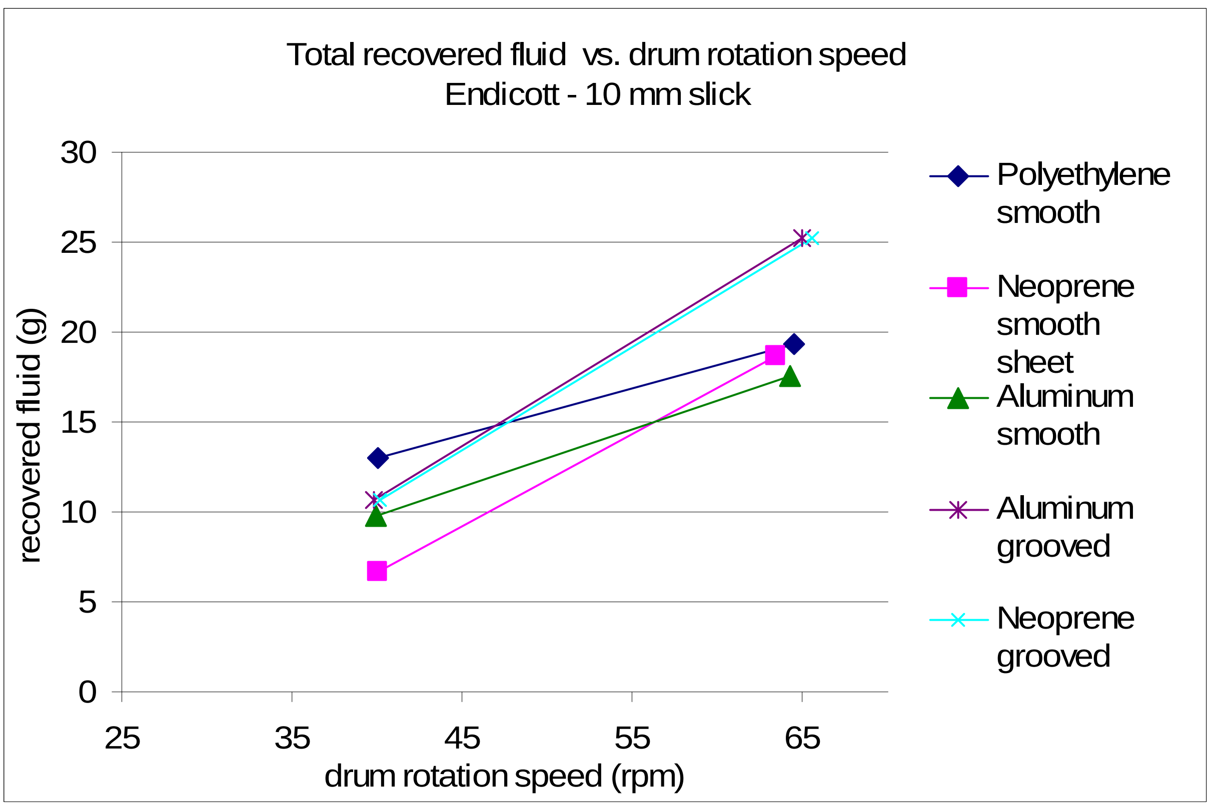


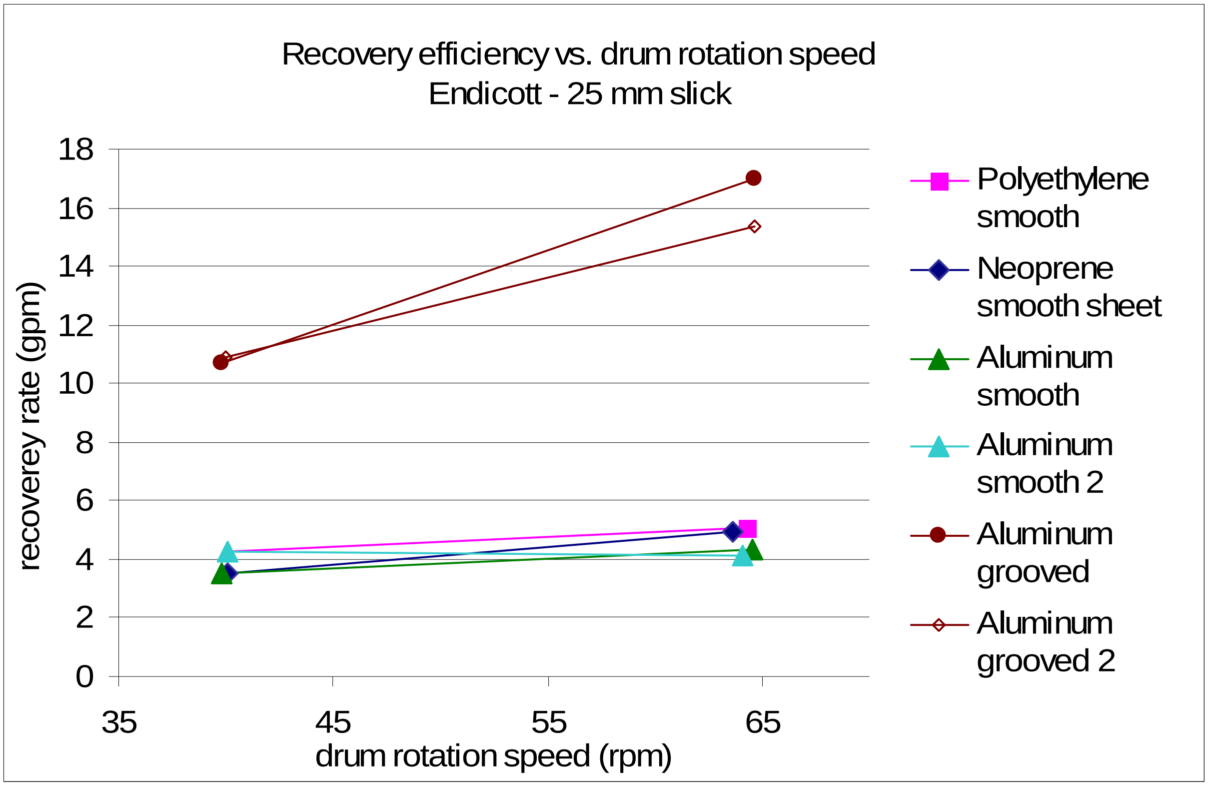


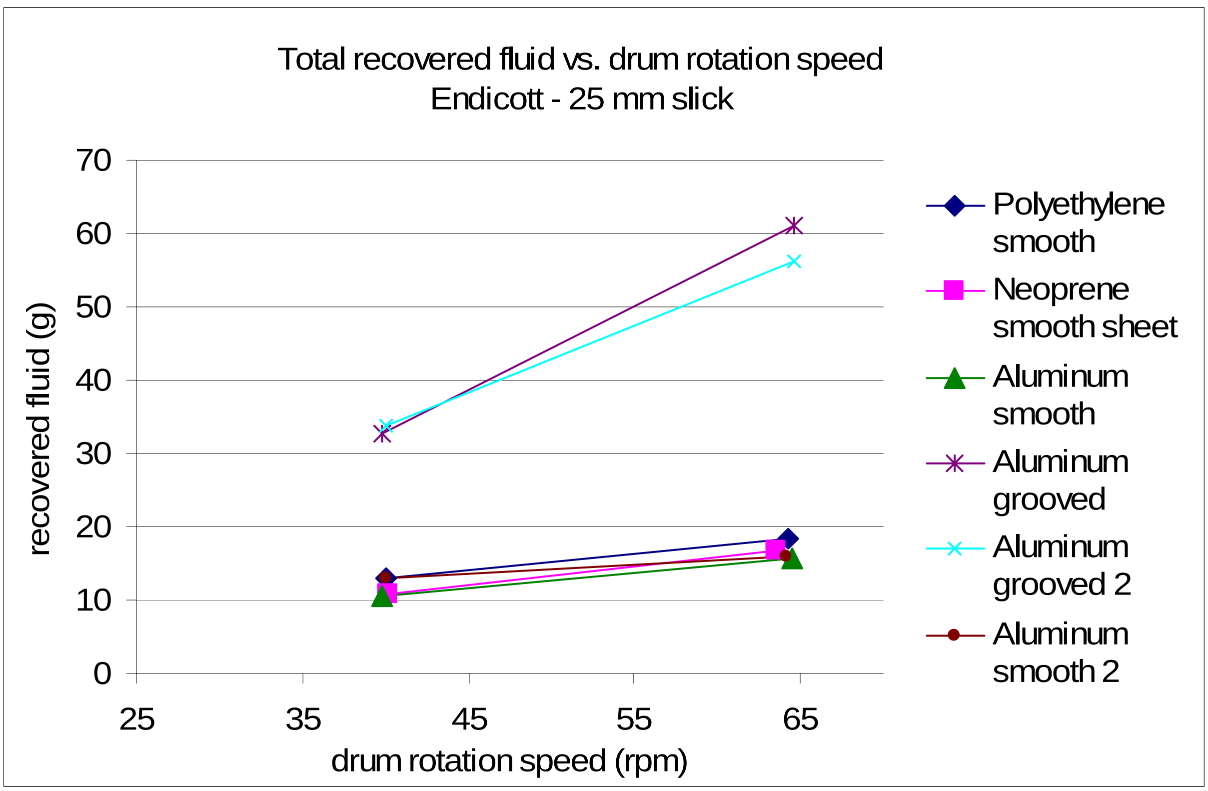

Recovery efficiency vs. drum rotation speed
HydroCal 300 - 10 mm slick
recoverey rate (gpm)
drum rotation speed (rpm)
0
1
2
3
4
25
35
45
55
65
Polyethylene smooth
Neoprene smooth sheet
Aluminum smooth
Aluminum grooved
Neoprene grooved
Hypalon grooved

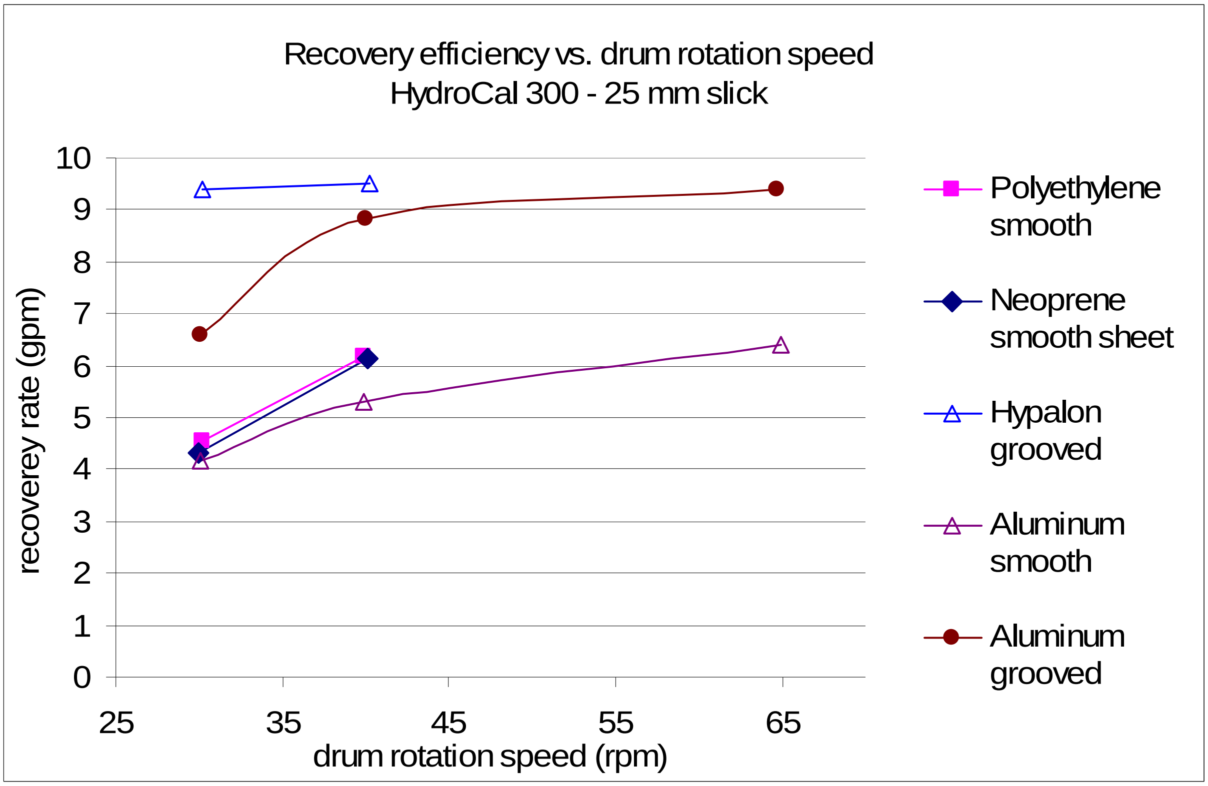

Total recovered fluid vs. drum rotation speed
HydroCal 300 - 10 mm slick
recovered fluid (g)
drum rotation speed (rpm)
0
5
10
15
20
25
30
25
35
45
55
65
Polyethylene smooth
Neoprene smooth sheet
Aluminum smooth
Aluminum grooved
Neoprene grooved
Hypalon grooved

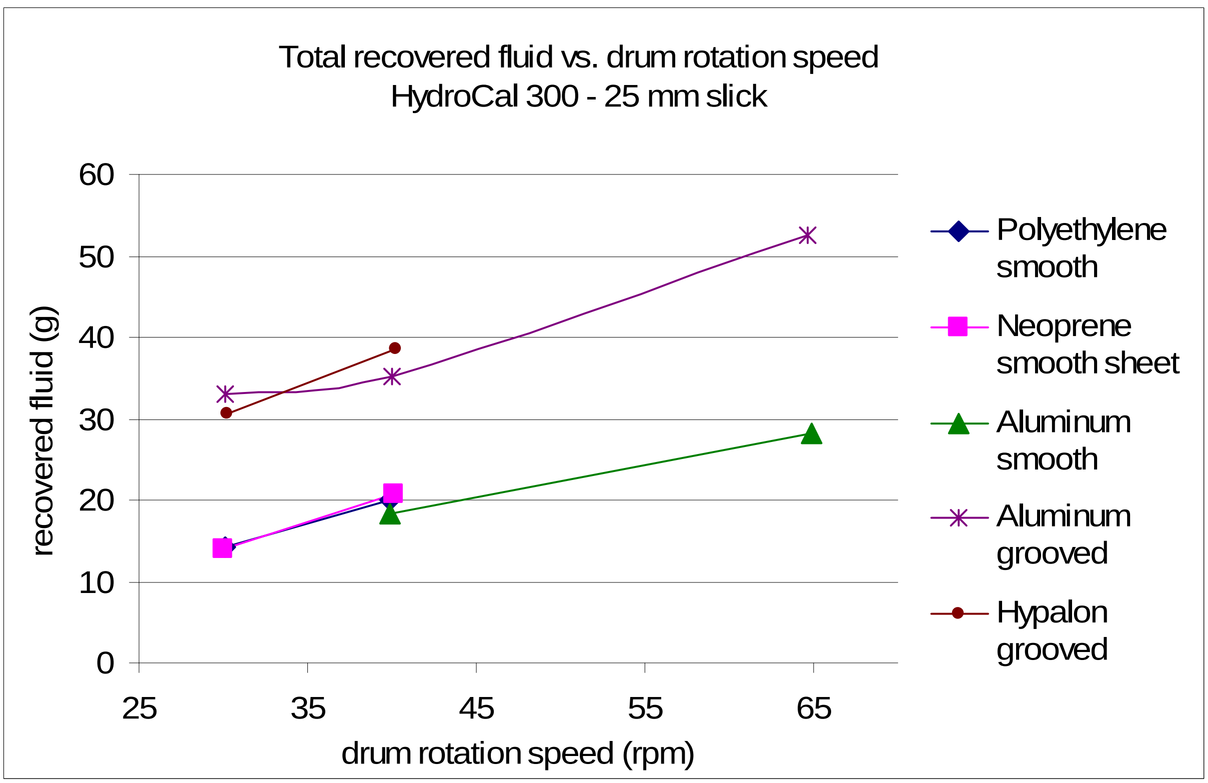

Recovery efficiency vs. drum rotation speed
Endicott - 10 mm slick
recoverey rate (gpm)
0
1
2
3
4
5
6
7
25
35
45
55
65
drum rotation speed (rpm)
Polyethylene smooth
Neoprene smooth sheet
Aluminum smooth
Aluminum grooved
Neoprene grooved


Total recovered fluid vs. drum rotation speed
Endicott - 10 mm slick
recovered fluid (g)
0
5
10
15
20
25
30
25
35
45
55
65
drum rotation speed (rpm)
Polyethylene smooth
Neoprene smooth sheet
Aluminum smooth
Aluminum grooved
Neoprene grooved


Recovery efficiency vs. drum rotation speed
Endicott - 25 mm slick
recoverey rate (gpm)
18
16
14
12
10
8
6
4
2
0
35
45
55
65
drum rotation speed (rpm)
Polyethylene smooth
Neoprene smooth sheet
Aluminum smooth
Aluminum smooth 2
Aluminum grooved
Aluminum grooved 2


Total recovered fluid vs. drum rotation speed
Endicott - 25 mm slick
recovered fluid (g)
70
60
50
40
30
20
10
0
25
35
45
55
65
drum rotation speed (rpm)
Polyethylene smooth
Neoprene smooth sheet
Aluminum smooth
Aluminum grooved
Aluminum grooved 2
Aluminum smooth 2


Recovery efficiency vs. drum rotation speed
HydroCal 300 - 25 mm slick
recoverey rate (gpm)
0
1
2
3
4
5
6
7
8
9
10
25
35
45
55
65
drum rotation speed (rpm)
Polyethylene smooth
Neoprene smooth sheet
Hypalon grooved
Aluminum smooth
Aluminum grooved


Total recovered fluid vs. drum rotation speed
HydroCal 300 - 25 mm slick
recovered fluid (g)
0
10
20
30
40
50
60
25
35
45
55
65
drum rotation speed (rpm)
Polyethylene smooth
Neoprene smooth sheet
Aluminum smooth
Aluminum grooved
Hypalon grooved