SwRI®

SOUTHWEST RESEARCH INSTITUTE

RHEOLOGY

Research and Evaluation

Testing Consulting Training Failure Analysis

Advanced Science. Applied technology.

Contents

Examples of SwRI Quality Accomplishments

- The Institute has been inducted into the U.S. Space Foundation's Space Technology Hall of Fame.
- SwRI has received two Department of Defense James S. Cogswell Outstanding Industrial Security Achievement Awards.
- The American Society of Mechanical Engineers has recognized the Split-Hopkinson Pressure Bar apparatus as an ASME National Historic Engineering Landmark.
- Numerous departments and divisions have achieved certifications and accreditations from ISO and other organizations.
- Examples include:
  - ISO 9001:2015, Quality Management System Requirements
  - ISO 14001:2004, Environmental Management Systems
  - ISO/IEC 17025:2005, General Requirements for the Competence of Testing and Calibration Laboratories
- The Ford Motor Company has designated the Institute a Tier 1 product development engineering services supplier and has presented the Institute a Q1 award.
- Since 1971, SwRI has earned 52 R&D 100 awards (including three in 2021) for developments recognized by R&D Magazine as among the 100 most significant technical accomplishments of the year.

On the cover: Sub-ambient valve seat adhesion test

SwRI Tribology Research and Evaluation – Rheology Lab

Recognized worldwide as a leader in many fields, Southwest Research Institute (SwRI) established extensive tribology test facilities in 2011. Tribology is the study of friction, lubrication, and wear. To better understand and offer more insight toward the lubrication aspect of tribology, the rheology capabilities at the lab were increased. The Rheology Lab within the Tribology group offers many test types for evaluating fluids and materials and continues to expand to meet the needs of our clients. The Tribology Research and Evaluation group combines world-class expertise from across the Institute's eleven technical divisions to offer testing, test rig design, consultancy, training, and failure analysis in a variety of tribology fields from deep sea to deep space.

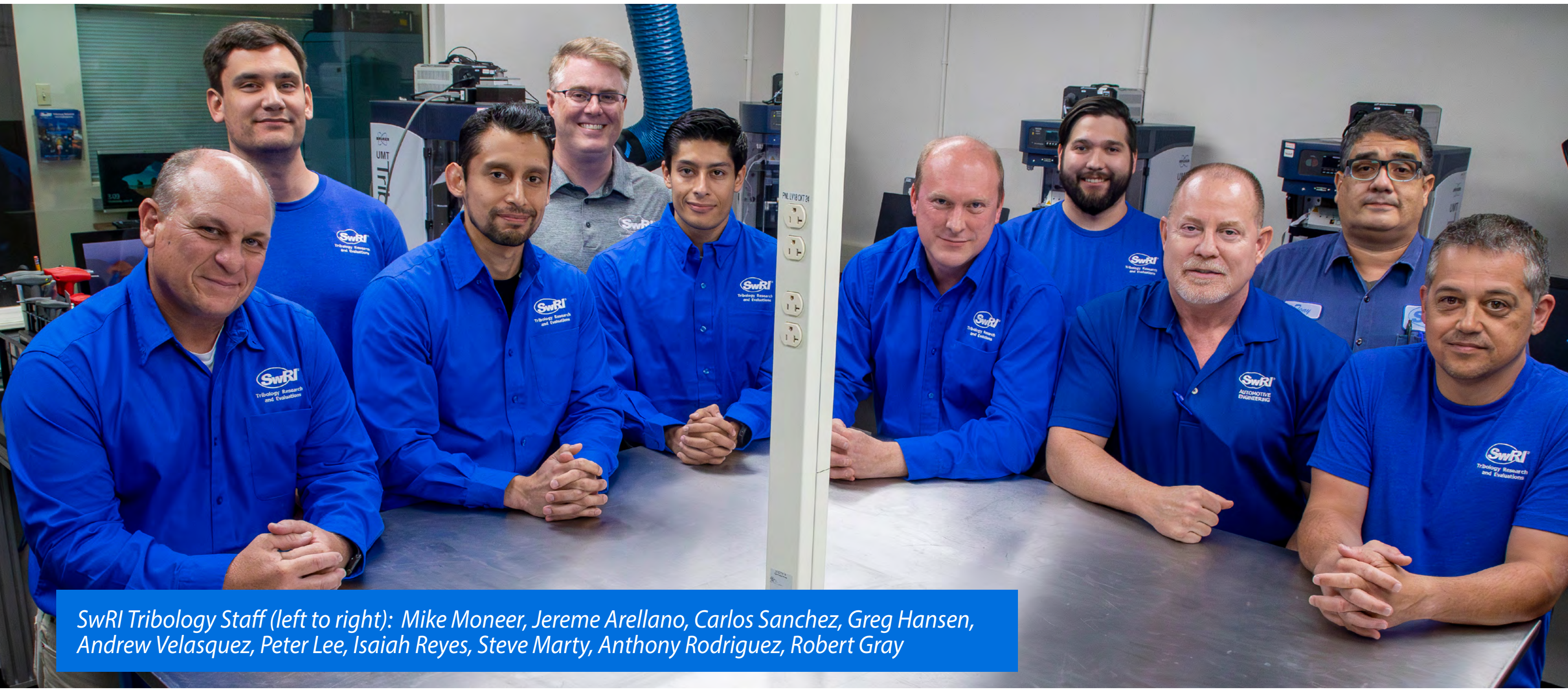
Definition of Rheology

Rheology is the study of flow and deformation of materials, which can include liquids, solids, semi-solids, gels, and many more. Rheology aims to understand the flow of viscous liquids, the deformation of elastic solids, and the complex behavior of viscoelastic materials.

Advantages of Rheology

Rheology extends beyond typical viscosity measurements and allows for more tailored solutions to flow-related problems. While most fluids like water and oil flow easily and somewhat predictably at most conditions, many materials like greases, paints, cosmetics, and adhesives do not. How well does a particular oil hold up to high temperatures and pressures? How long will it take for an epoxy to cure and to what strength? Will grease stick to the surface that it is applied to, and will it work at high speeds or temperatures? What is the glass transition or melting point of a polymer? These types of questions can be answered with rheology. Rheology tests can be performed at wide ranges of temperatures, pressures, shear rates, and other stresses to better simulate the actual working conditions of nearly any material.

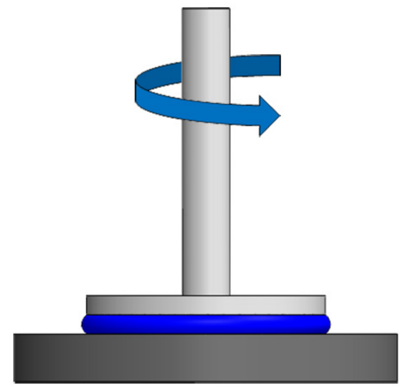
This brochure gives a high-level overview of the capabilities at SwRI. Contact us today to develop test programs to meet your requirements, develop your products, and solve your rheological challenges.



SwRI Tribology Staff (left to right): Mike Moneer, Jereme Arellano, Carlos Sanchez, Greg Hansen, Andrew Velasquez, Peter Lee, Isaiah Reyes, Steve Marty, Anthony Rodriguez, Robert Gray

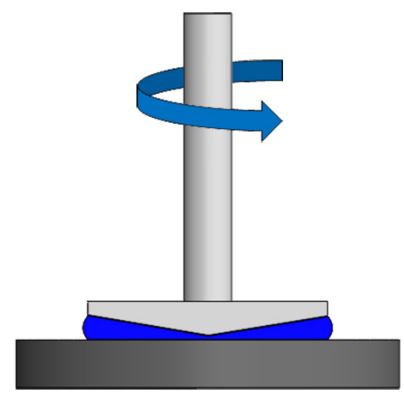
Rheology Testing 101

One of the most common rheology test types is parallel plates. A sample is placed between two plates at a set separation, or gap. The lower plate is stationary, while the upper plate rotates or oscillates under controlled conditions. Typically, the lower plate is a larger diameter than the upper plate. The upper plate may also have a truncated cone shape, typically used for low-viscosity samples. This test type requires a very small sample volume and is a preferred method for studying viscoelastic materials.



Parallel Plate

For an oscillation test, the amplitude and frequency of oscillation are controlled and the response of the material is measured. The results from this type of test are the viscoelastic response represented by the storage modulus (G′), and loss modulus (G″). The storage modulus represents the elastic, or solid-like, behavior of the material. While the loss modulus represents the viscous, fluid-like behavior. The magnitude of each value, the shape of each curve, the separation of the curves, and the intersection of these curves give insight into material performance. Another way of representing these results is with the loss factor, or dampening factor, which is the ratio of both moduli (G″/G′). The loss factor is a single curve that can be used to represent flow characteristics across a wide range of temperatures, and other stresses. In summary:



Cone and Plate

G′ = storage modulus [Pa], elastic behavior (curve with square markers)

G″ = loss modulus [Pa], viscous behavior (curve with triangle markers)

tan δ = G″/G′ loss factor, dampening factor

 δ = 0^0 for ideally elastic behavior

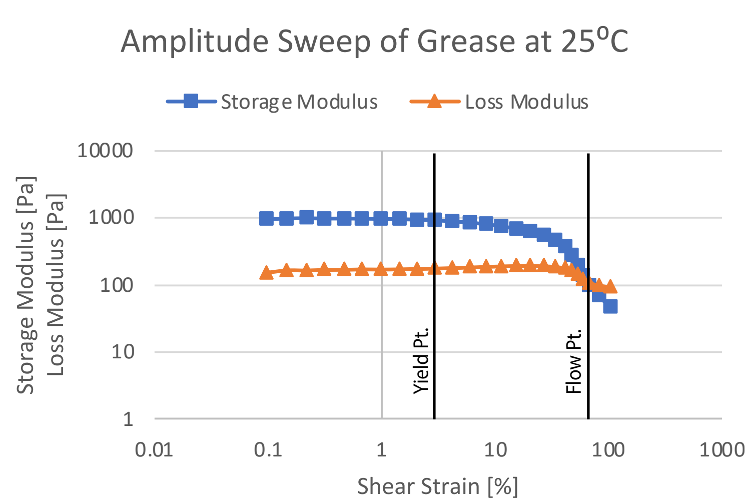
 δ = 90^0 for ideally viscous behavior

Amplitude Sweep – LVER

Typically, an amplitude sweep at constant frequency is performed on a sample to determine the linear viscoelastic region (LVER): the region in which the storage and loss modulus curves are constant and linear, before changing suddenly. This test indicates the stress range where the internal structure of the material is unaffected and determines the appropriate amplitude to perform a frequency sweep. These curves also indicate the yield point (linear maximum) and the flow point (where the two curves cross over G′=G″) of the material.

Frequency Sweep

A frequency sweep is performed at variable frequency and constant strain amplitude, as determined by the LVER analysis. These tests aim to study the time-dependent response of a sample. Low frequencies are used to simulate slow or moderate motions, while high frequencies are used to simulate quicker motions. The magnitude, shape, separation, and intersection of the two viscoelastic curves will indicate various behaviors of the material. These tests can also be performed at a wide range of temperatures and can be modified to meet the operating requirements of a given material. Further analysis can be performed to extend results beyond the operating conditions of the instrument; for example, time-temperature superposition (TTS) analysis for response at frequencies in the kHz range.



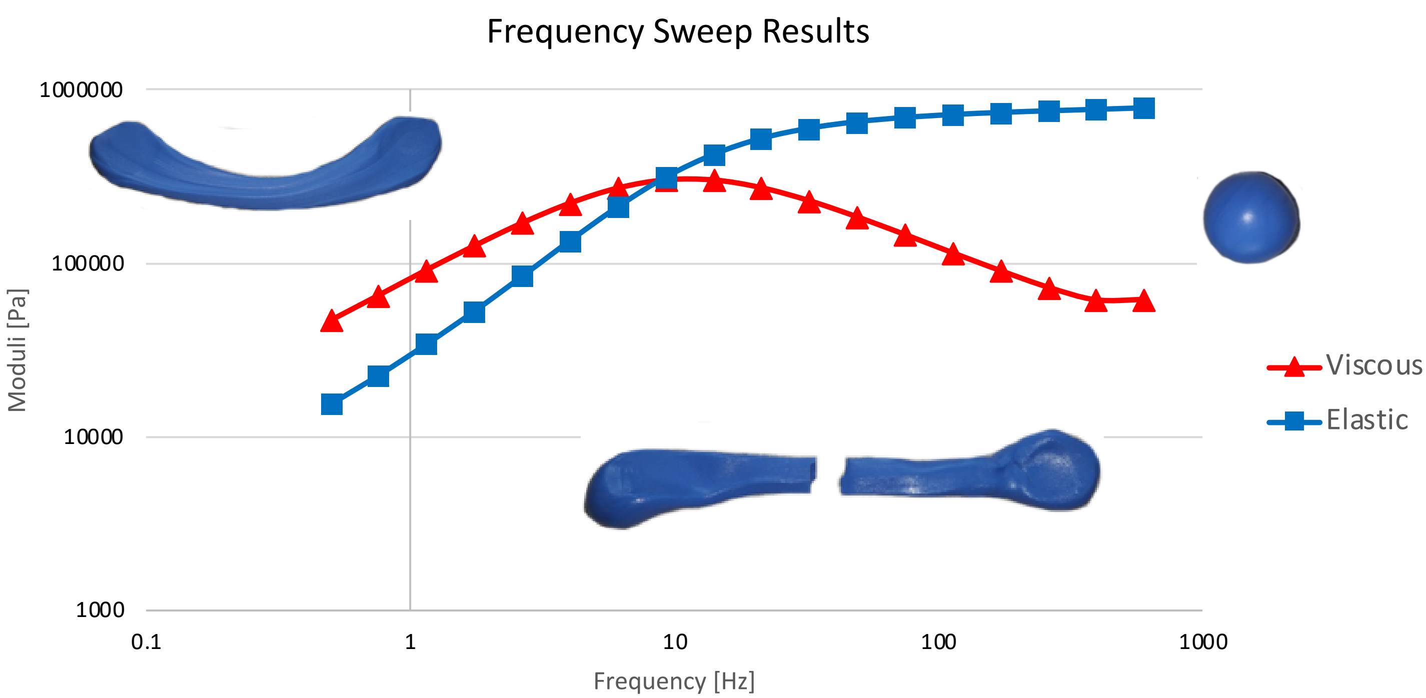
Rheology of Crazy Putty

Crazy putty is a fun toy that has a very interesting behavior. It stretches Easily when pulled slowly but can snap apart if pulled too quickly. It can even be rolled into a ball and bounced against a solid surface. If left alone it will relax and form into the shape of its container.

What is going on rheologically? Crazy putty is a perfect example of a viscoelastic material. It behaves like a viscous liquid able to flow easily under one condition, and like an elastic solid breaking apart and bouncing under other conditions.

This behavior can be analyzed using a parallel plate rheology test. The putty is subjected to variable frequency oscillation at room temperature. The result is the plot of loss modulus (viscous) and storage modulus (elastic) shown below. The two curves indicate how the putty will respond under a certain frequency of stress. At low-frequency pulling of the material, the viscous curve dominates; hence the putty can flow easily. At high-frequency stress the elastic curve dominates; hence the putty acts like a solid and either snaps or bounces like a ball. At a certain point in the middle, the two curves cross over. This is a critical point that indicates a limit in the material where it will transition from one behavior to another.

Many materials such as greases, gels, epoxies, condiments, and polymers will exhibit this type of response to various degrees. This information can be used for quality control, performance evaluation, and operating limits, among others.



Rheometers

Anton Paar MCR 702e MultiDrive with CTD600 oven

The MCR series rheometers have a wide range of capabilities, including electrorheology (AC and DC), pressure viscosity, vapor pressure, extensional viscosity, dynamic mechanical analysis (DMA), and dynamic thermal mechanical analysis (DTMA).

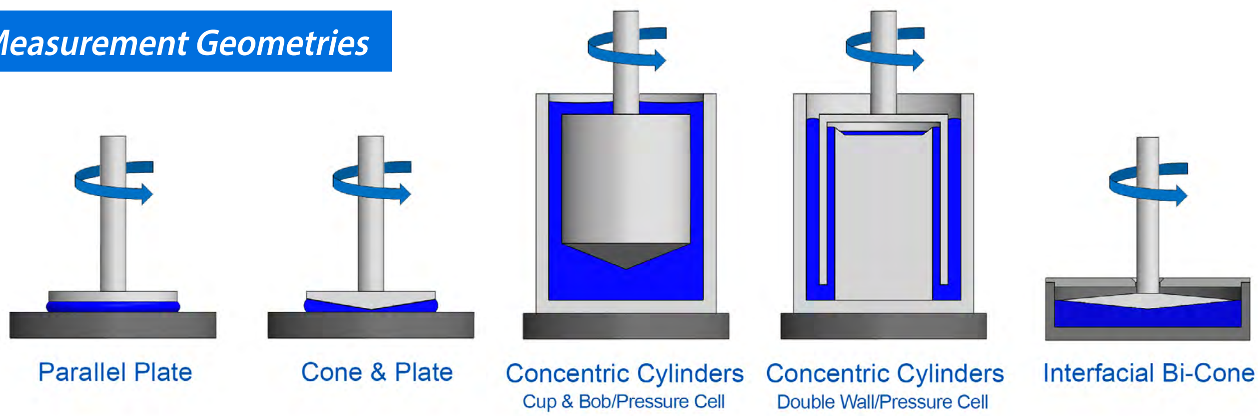
Standard test methods are available as well as custom-designed tests for various applications, such as electric vehicle (EV) fluid and grease analysis.

Standard Test Methods

- ASTM D4440 – Plastics: Dynamic Mechanical Properties Melt Rheology
- ASTM D7175 – Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer
- ISO 3219 – Determination of Viscosity Using a Rotational Viscometer with Defined Shear Rate

MCR Series Rheometers	
Speed	314 – 10^3 rad/s
Temperature	-160 – 600°C
Angular frequency	10^{-7} – 628 rad/s
Normal force	-50 – 50 N
Torque	1 nN-m – 2230 mN-m
Voltage	0 – 12.5 kV AC & DC
Pressure	Ambient – 1000 bar
Sample Size	0.5 – 100 ml

Measurement Geometries



Measuring System Specifications			
Measuring Tool	Shear Rate (x10^3) [1/s]	Temperature (°C)	System
8 mm parallel plate	0 – 2.5	-160 – 600	Peltier hood / Convention oven
15 mm parallel plate	0 – 5	-160 – 600	Peltier hood / Convention oven
25 mm parallel plate	0 – 5	-160 – 600	Peltier hood / Convention oven
50 mm 1° cone	0 – 20	-160 – 600	Peltier hood / Convention oven
50 mm serrated plate	0 – 10	-160 – 600	Peltier hood / Convention oven
Standard cup and bob	0 – 5	-30 – 200	Concentric cylinder
High shear cup and bob	0 – 45	-30 – 200	Concentric cylinder
Bob for electrorheology	0 – 5	-30 – 200	Concentric cylinder
Double wall concentric cylinders	0 – 5	0 – 200	400 bar pressure cell
Concentric cylinder	0 – 3	25 – 30	1000 bar pressure cell
Interfacial bi-cone	0 – 2.5	5 – 70	Interfacial rheology

Rheology Test Types

Rheology testing offers a wide range of options for fluid analysis that cannot be achieved with standardized viscosity testing. Examples include dynamic mechanical analysis (DMA), and viscosity sweeps as a function of different parameters.

Amplitude sweeps

- Linear viscoelastic region determination
- Flow and cure point

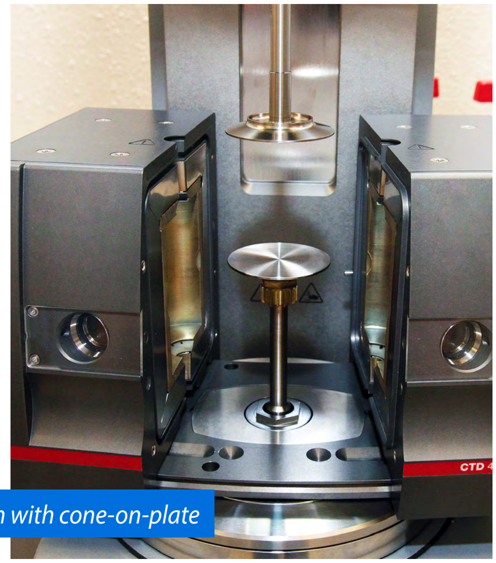
Frequency sweeps

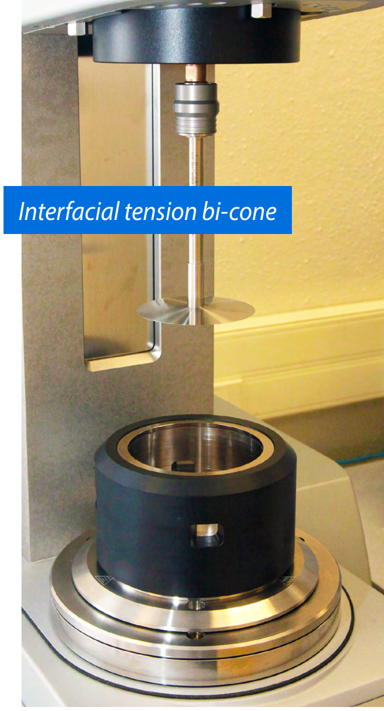
- Viscoelastic stability
- Crossover points
- Frequency response
- Melt flow
- Thixotropy
- Master curve generation
- Tack testing
- Adhesive and cohesive behavior
- “Stickiness”

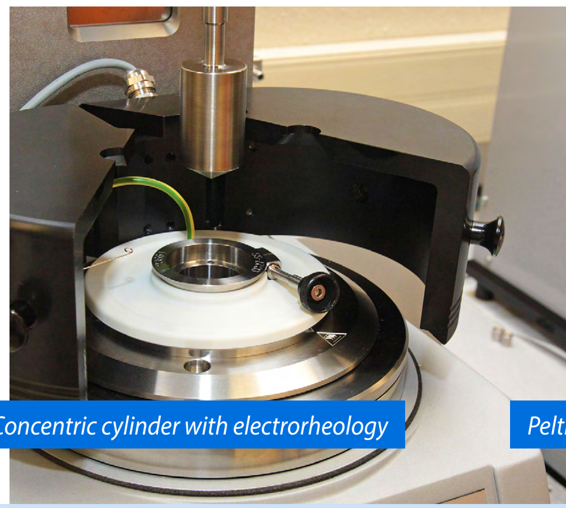
Viscosity sweeps

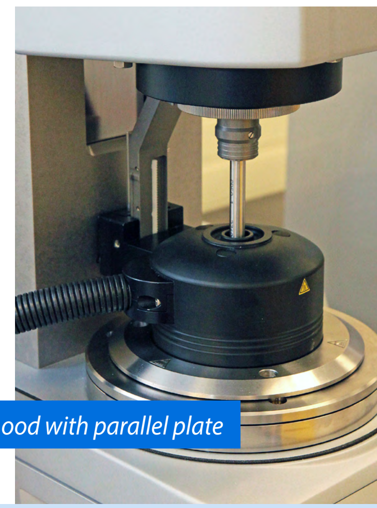
- Pressurized viscosity
- Temperature dependence
- Effects of shear rate and shear stress
- Viscosity under electric field (AC & DC)

Rheology Measuring Systems

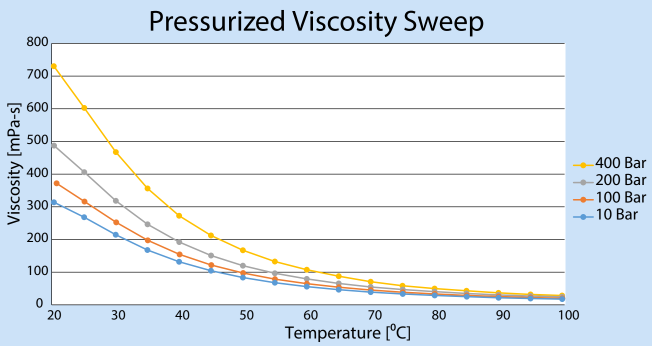

Oven with cone-on-plate

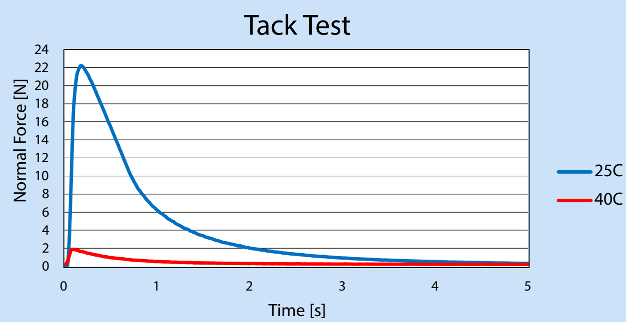

Interfacial tension bi-cone

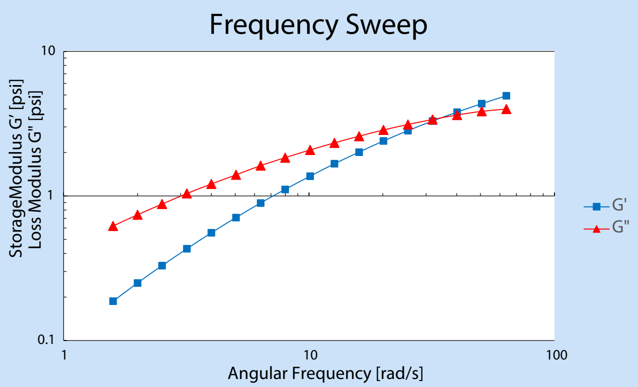

Concentric cylinder with electrorheology

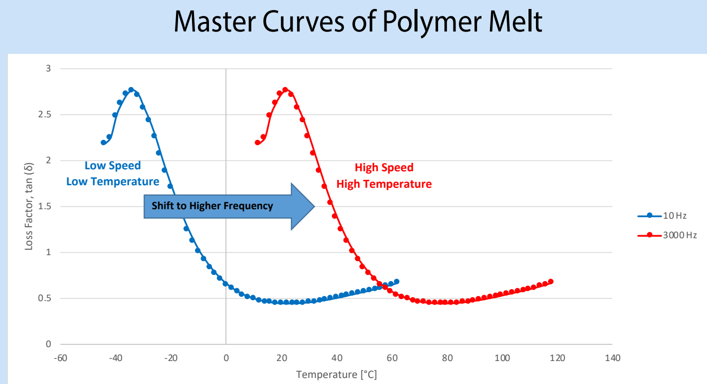

Peltier hood with parallel plate

Example results from rheology testing









Pressurized Viscometry

Pressurized viscosity is relevant to applications such as oil and gas drilling, fluid film modeling, and electric vehicle (EV) fluid analysis. The MCR502 rheometer offers two options for pressurized fluid analysis: a 400 bar (6000 psig) cell and a 1000 bar (14,500 psig) cell.

The 400 bar cell is pressurized with inert gas such as nitrogen or argon, but nearly any gas can be used. This cell is also useful for measuring vapor pressure of fluids, with sensitivity of 0.1 bar. The 1000 bar cell uses a hydraulic system to apply pressure to the test fluid.

Two different sized cylinders are available to measure a wide range of fluid viscosities. Both pressure systems can be programmed to measure viscosity at variable shear rates and temperatures.

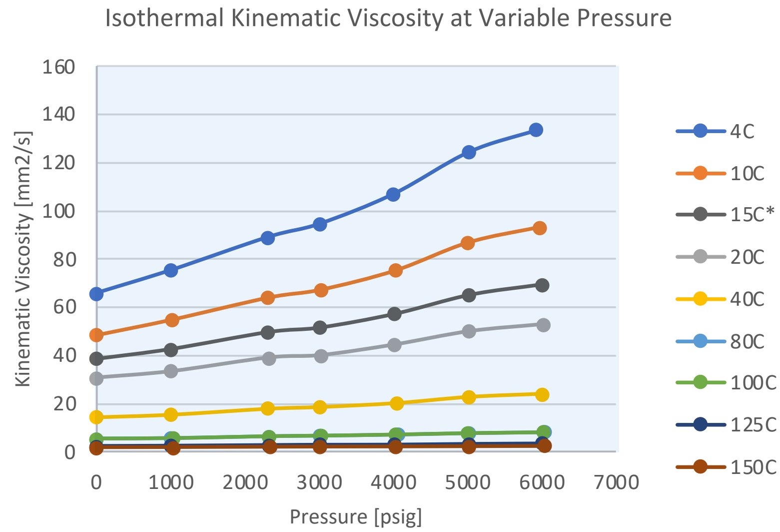
These systems output dynamic viscosity, but combined with our high-pressure density meter (DMA 4200M, page 22) kinematic viscosity up to 480 bar (7000 psig) may also be calculated.

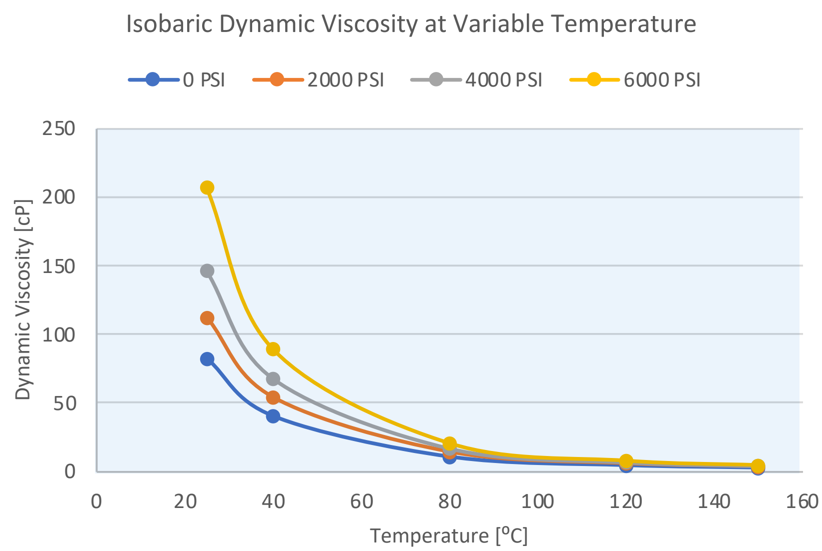
400 bar pressure cell

1000 bar pressure cell

Pressure Viscosity

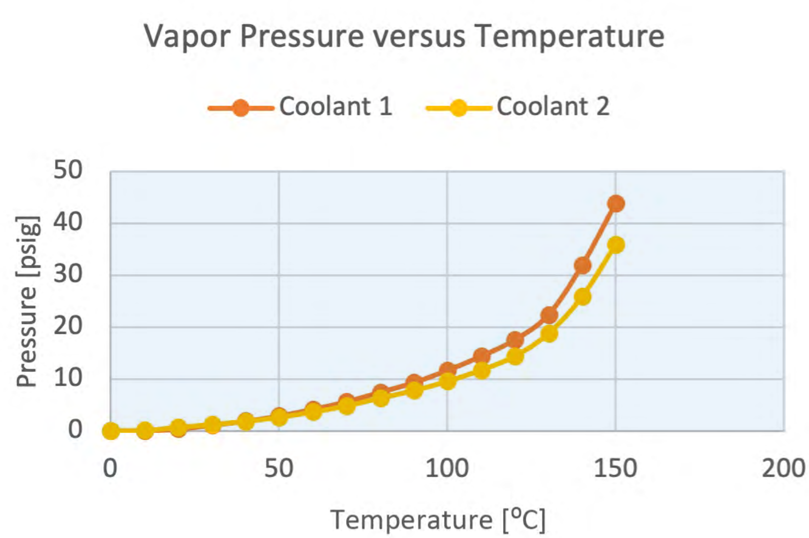
Pressurized viscosity testing up to 400 bar (6000 psig) requires about 10 ml of fluid. Here the pressure is applied with compressed gas such as nitrogen or argon. Studies can also be performed to investigate the effects of gas saturation such as helium or carbon dioxide. Pressurized viscosity testing up to 1000 bar (14,500 psig) requires about 80 ml of fluid. The pressure is applied hydraulically. Both systems output dynamic viscosity, but kinematic viscosity can be calculated up to 7000 psig with high-pressure density measurements.





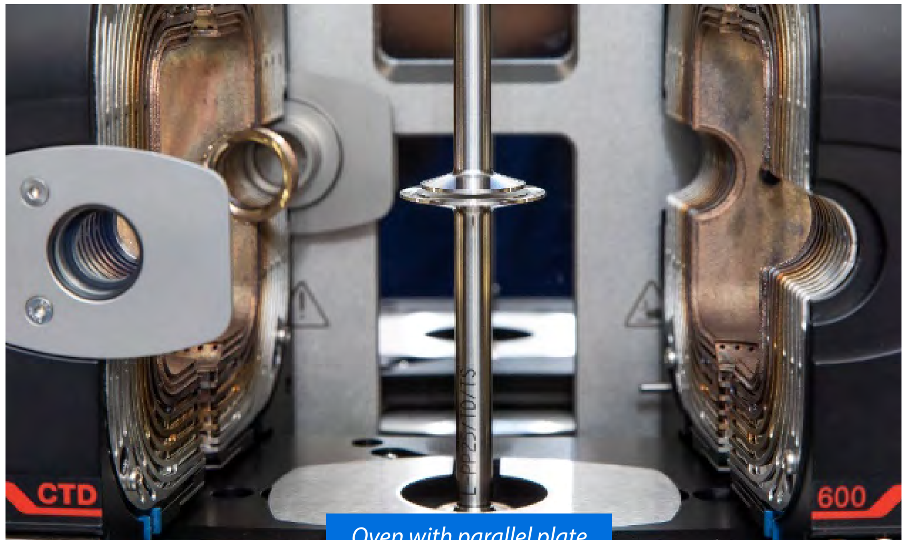
Vapor Pressure Testing

The pressure cells can also be set up to measure vapor pressure of fluids. The small volume headspace and precise temperature control of the rheometer allow for reliable measurements of pressure changes within the cell. Example vapor pressure plots for engine coolants are presented here.



Dynamic Mechanical Analysis (DMA)

The MCR 702e MultiDrive rheometer offers a lower rotational and linear motion drive for a wider range of testing and measurement options over traditional rotational rheometers. The upper and lower drives can be independently controlled in different modes for more advanced mechanical analysis of materials. The combination of CTD convection oven and LN2 evaporation control unit provides precise temperature control from -160°C to 600°C for all measurement systems. A camera is available to image samples at different stages during testing inside the chamber. Standard and custom test profiles are available.

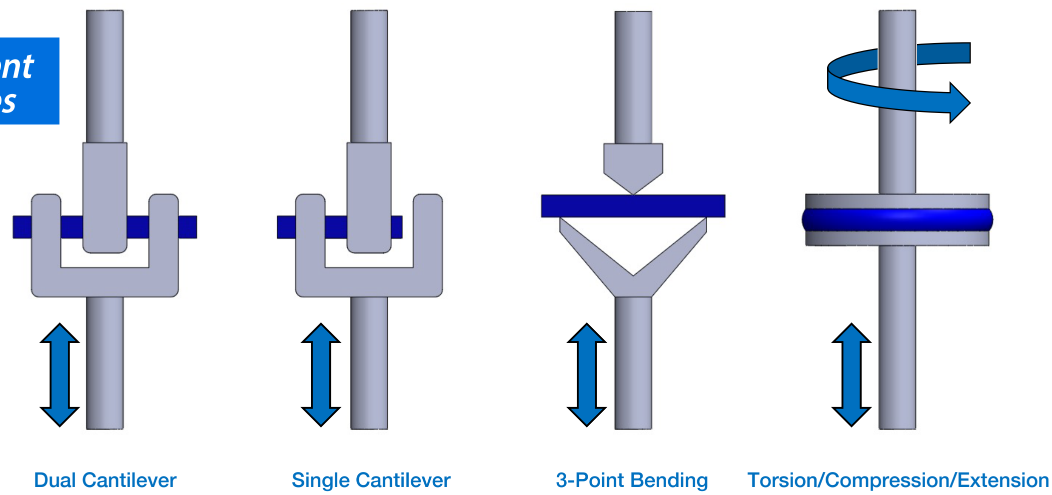


Oven with parallel plate

MCR 702e DMA Sample Specifications				
Measurement System	Thickness (mm)	Length (mm)	Modulus (Mpa)	Material Type*
Cantilever	≤ 2 / ≤ 4	15 or 20 / 35	10^1 – 10^4	Rubbers, plastics, thin metals
3-Point Bending	< 4 / ≥ 4	10 or 20 / 40	10^2 – 10^6	Plastics, glass, ceramic
Compression/Torsion	< 2	5-10 (diameter)	10^{-4} – 10^2	Elastomers, foams, foods

*Not limited to these materials

Measurement Geometries

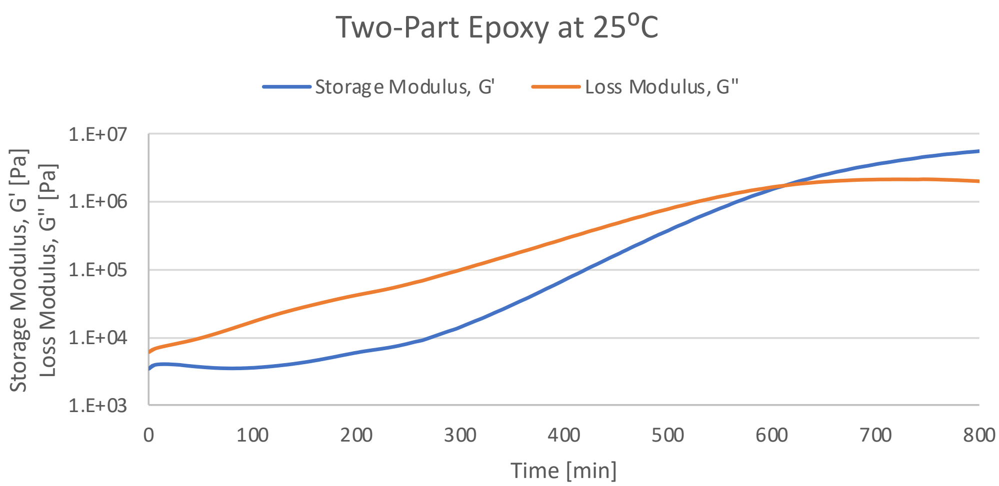


Oven with 3-point bending

Oven with cantilever

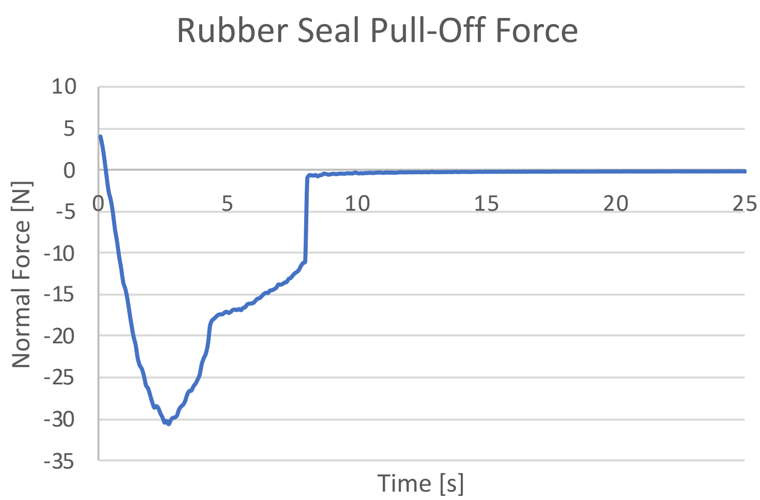
Curing Behavior

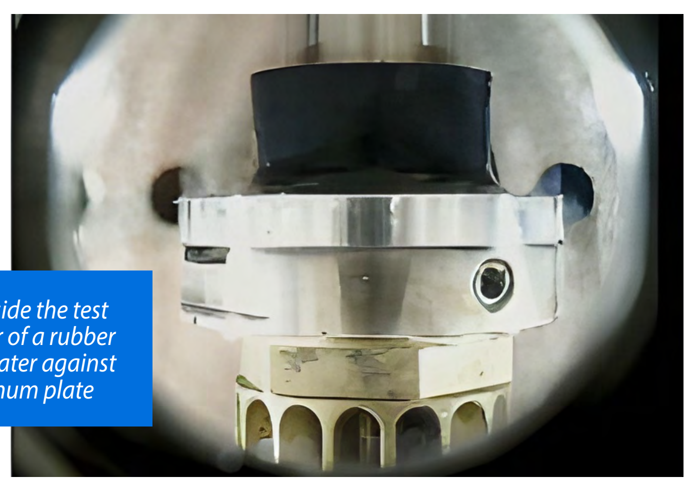
How quickly does glue dry, or epoxy set? A parallel plate rheology test can be used to answer these questions. Similar to a viscoelastic study, this test type places a glue, resin, or epoxy between two plates. The sample is then subjected constant strain, frequency, and temperature. As the adhesive begins to cure, the rheometer will measure the gradual change in viscous and elastic behavior. The loss modulus will have a higher magnitude than the storage modulus at the start of the test, indicating the adhesive still has some flowability. But as it hardens, the moduli will begin to cross over with the storage modulus increasing in magnitude and the loss modulus decreasing. The rate of increase, the crossover point, and the final values will give valuable information about the adhesive's rheological behavior. This test type uses disposable plates, since the end result is the adhesive gluing them together. The used plates are discarded and new ones are used for each test.



Sticking Force of Rubber Seals

A rheometer is highly sensitive to measuring forces in the mN range. The parallel plate geometry can be modified to measure sticking or pull-off forces acting on materials such as valve seats and rubber seals. The example plot shows the force required to separate a rubber seal that was set against a wet aluminum plate at -40°C for four hours. The seal was pulled at a constant 1mm/min velocity, and the required force to separate it from the ice was about 30 N. The seal was fully separated after about 8 s.

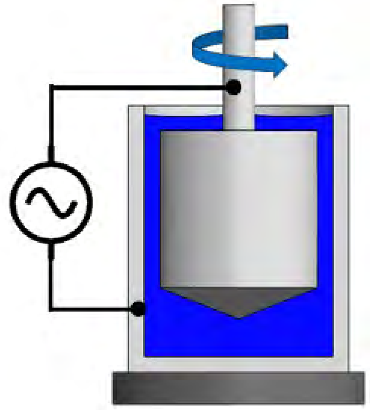




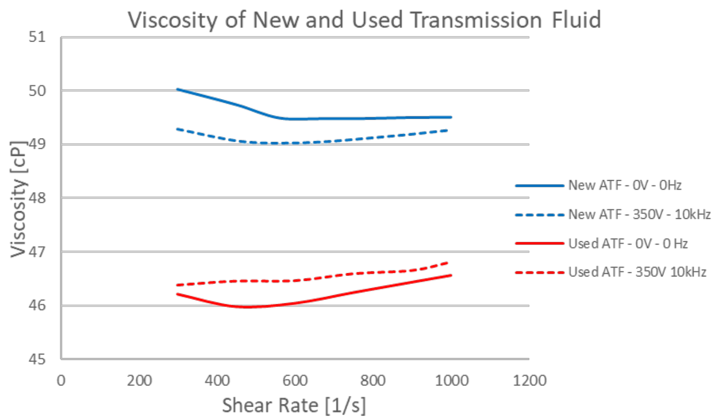
View inside the test chamber of a rubber seal in water against aluminum plate

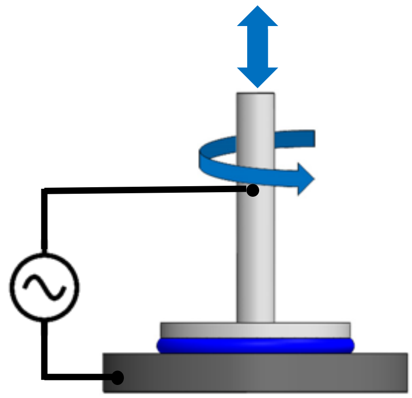
Electrorheology

Several rheology test types can be modified to support electrified studies, both AC and DC. The systems include parallel plate, and cup and bob with various gap sizes. This allows for analysis of materials and fluids used in applications such as electric vehicles (EVs). Many test types available at SwRI were developed to meet the demands of the EV industry but are applicable to any fluid that operates in an electrified environment. A few examples of test results are presented here.

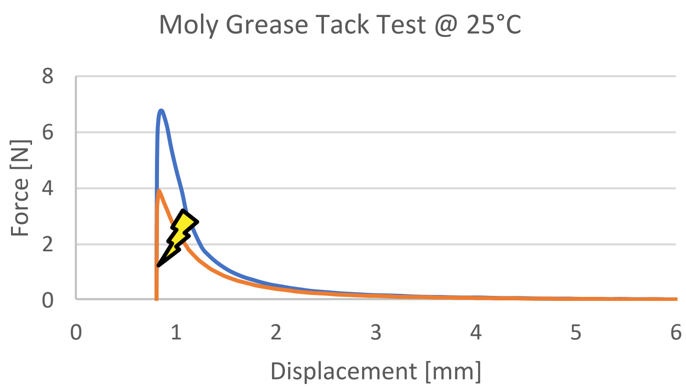


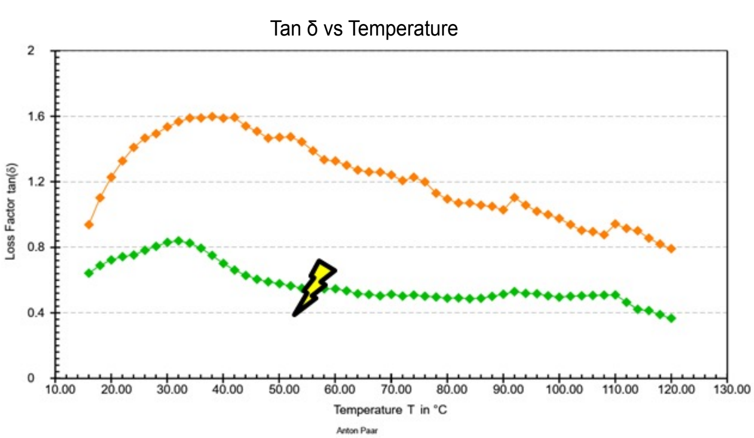
Concentric Cylinders Cup & Bob



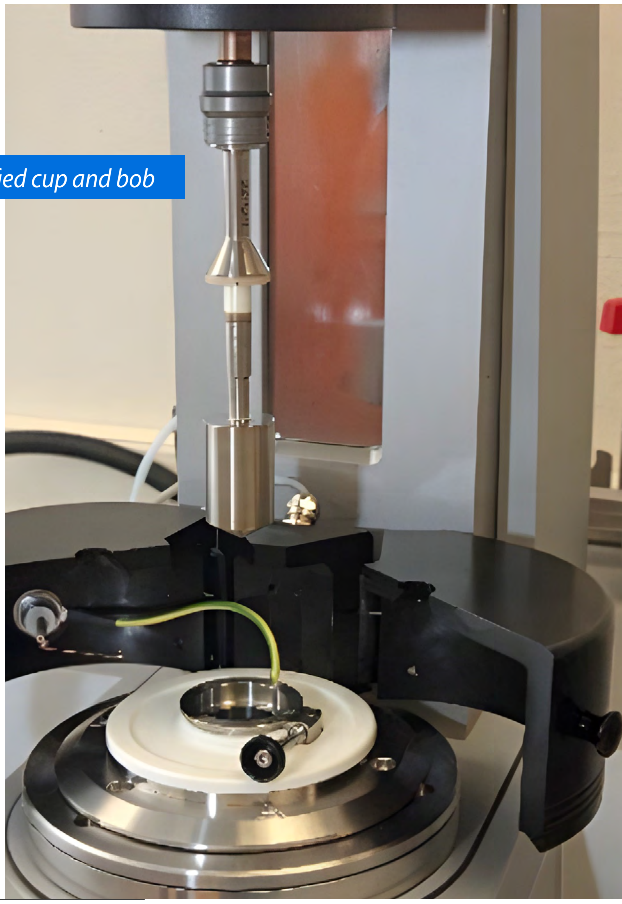


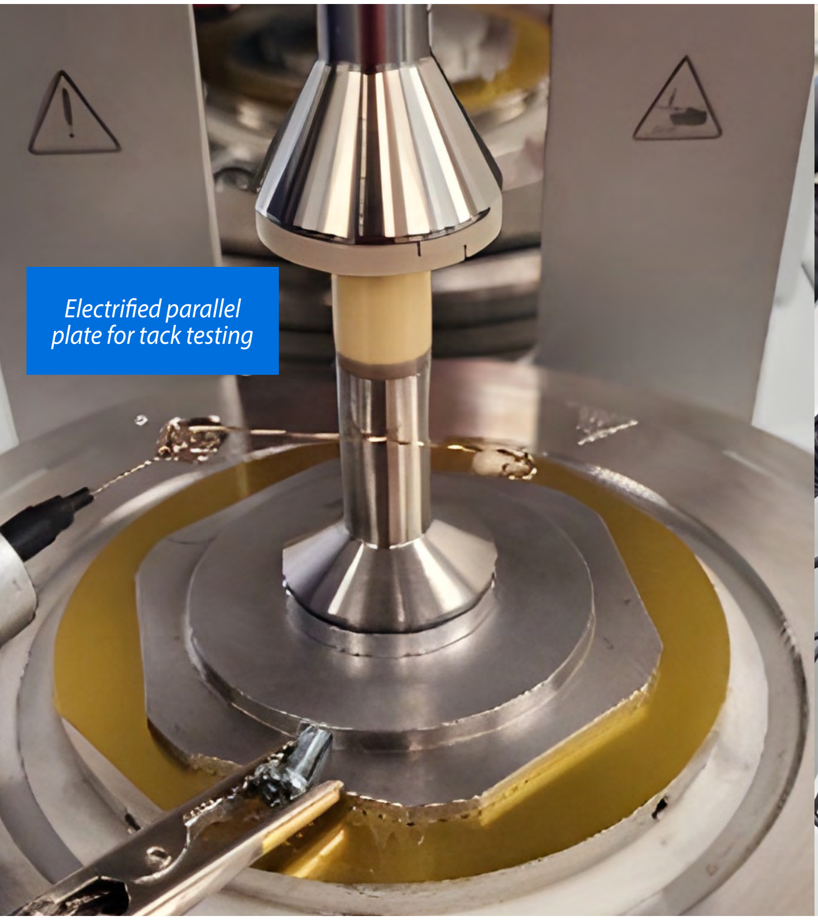
Parallel Plate



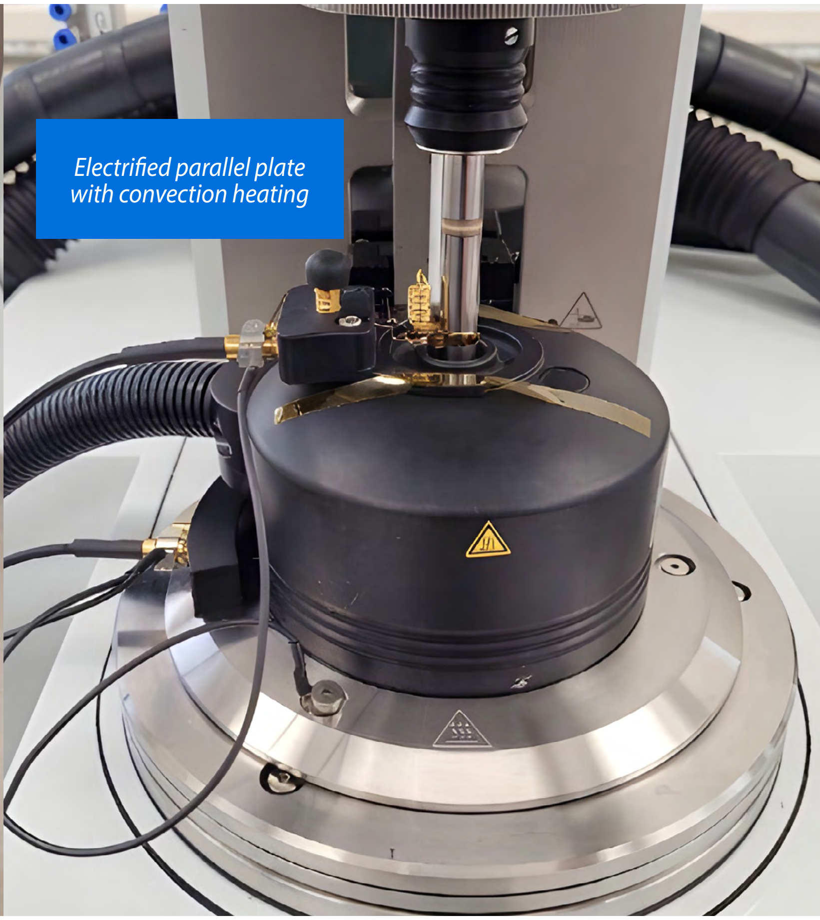


Electrified cup and bob





Electrified parallel plate for tack testing



Electrified parallel plate with convection heating

Dielectric Breakdown Voltage Testing

The TOR-80 tester measures the dielectric breakdown voltage of insulating fluids according to ASTM D877, ASTM D1816, and IEC 60156, in applications with high electric potentials such as transformers or oil circuit breakers.

The test chamber is filled with the lubricant and two electrodes are spaced an equal distance to each other. The electrodes subject the fluid to an AC voltage, where the breakdown occurs between the two electrodes. The maximum voltage value is recorded and repeated 5 times before reporting the average breakdown voltage value.

TOR-80 Specifications	
AC voltage	85 – 264 V
Temperature	Ambient
Power frequency	48 – 63 Hz
Voltage increase rate	0.1 – 5 kV/s
Lubricant charge	1 L
Test duration	1 hr

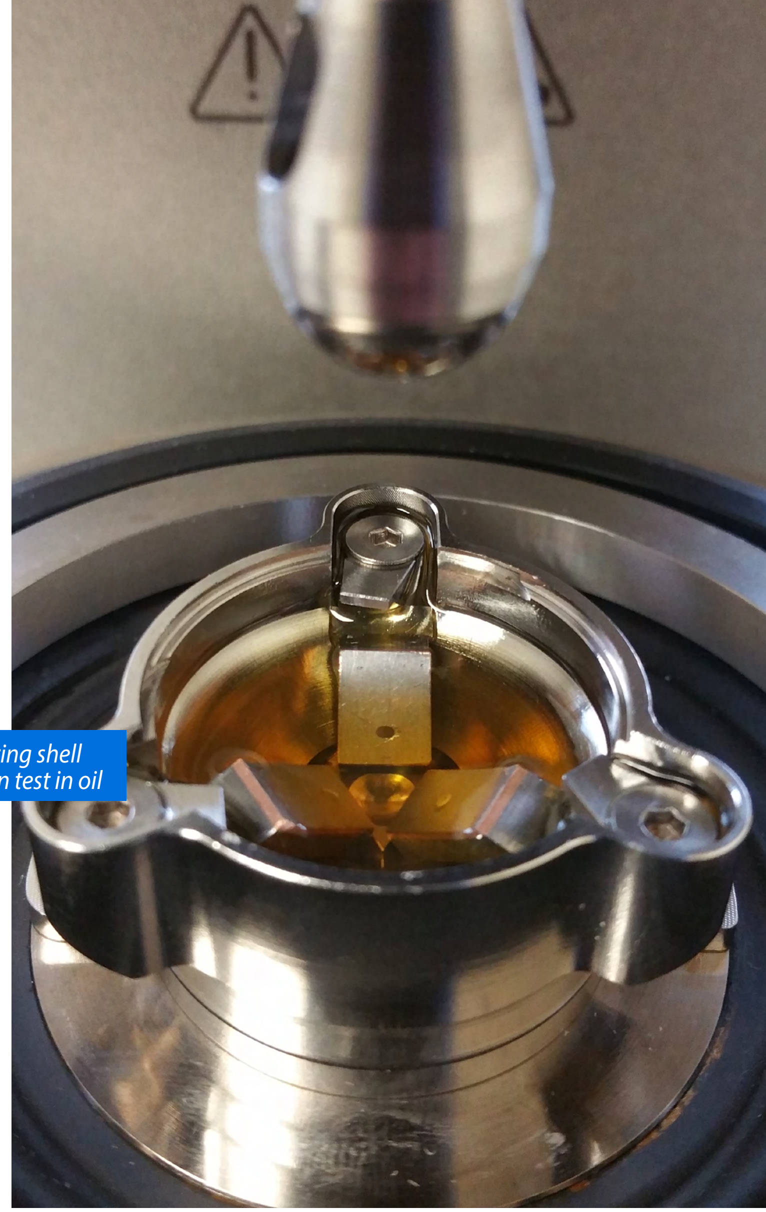
Soft Contact Tribology

Soft tribology aims to understand the frictional behavior of compliant surfaces and/or materials that experience light contact stresses. For this purpose, SwRI utilizes the tribology cell for the Anton Paar MCR 502/702e rheometers, which allows for homogenous application of light loads and sensitive measurement of the resultant friction force. Soft tribology has applications in a wide range of industries from characterizing thin coatings and lubricants for automotive use, to quantifying "mouth feel" for food science studies, to modeling biological skin friction for cosmetics.

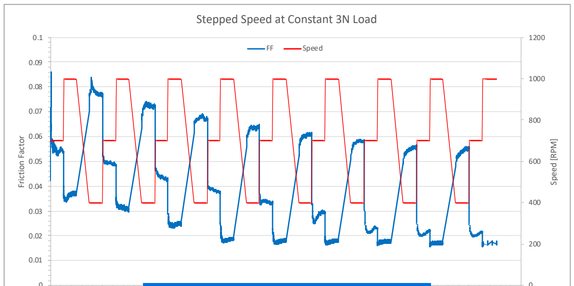
Roller bearing performance can also be investigated. This configuration allows for measurement of different bearing types, greases, and other lubricants while under controlled axial loads and rotational speeds. Configurations Include:

- Ball on 3 plates
- Ball on 3 pins
- 4 ball
- Roller bearing test

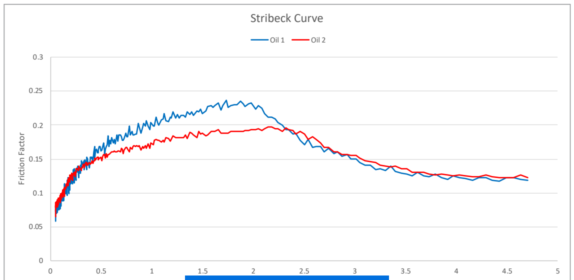
Balls, plates, and pins can be manufactured from nearly any material and/or coated to meet client needs. Roller bearings can be varied in size, style, and material.



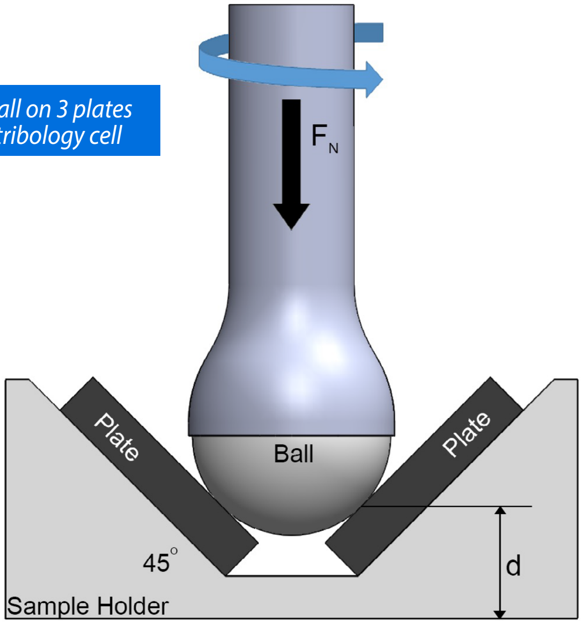
Bearing shell coupon test in oil



Custom test profile to simulate real system



Stribeck curve generation



Ball on 3 plates tribology cell

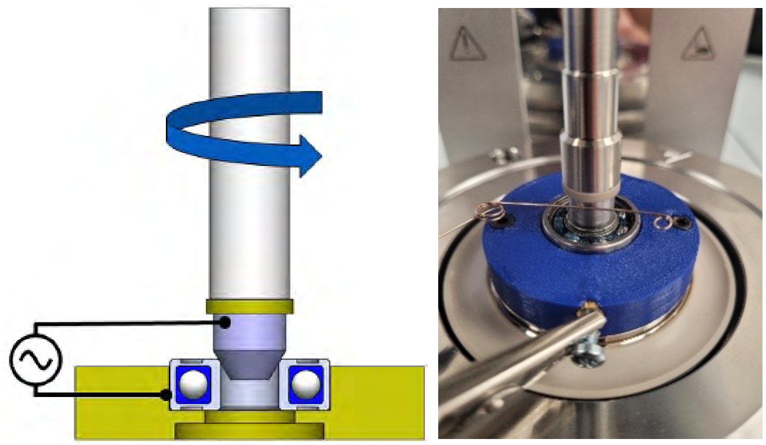
Tribology Cell	
Normal force	1 – 24 N
Sliding speed	10^{-8} – 3.3 m/s
Temperature	-40 – 200°C
Torque	2 nNm – 300 mNm
Motion	rotary, oscillation
Revolution	10^{-6} – 3000 rpm
Deflection	1 µrad – INF µrad

Electrified Roller Bearing

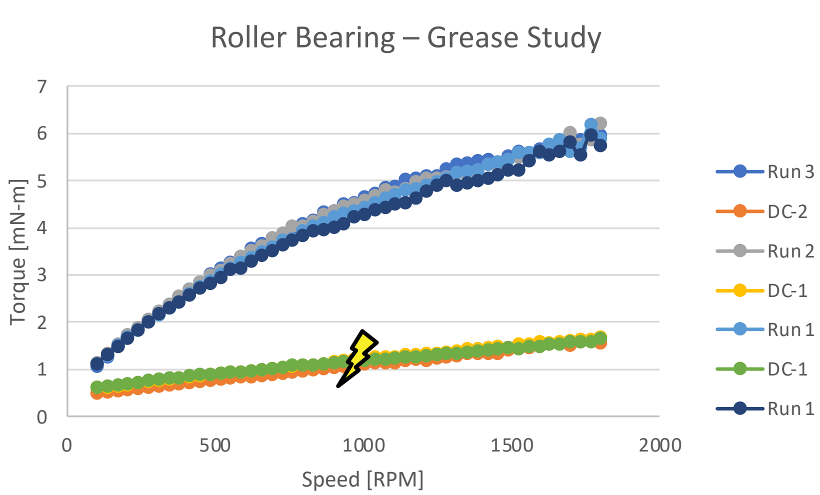
The roller bearing setup is used to measure the torque response of greases or oils set in a small roller element bearing, typically a 608 size bearing (22mm OD, 8mm ID, 7mm thick). The outer race is held stationary, while the inner race is rotated with the rheometer spindle. The output is torque in the mN-m range, versus rotational speed. This test can also be run electrified with either AC or DC current. It has been observed that electrification can have an effect on torque response, as well as cause some oxidation to the fluid and light damage to the bearing.

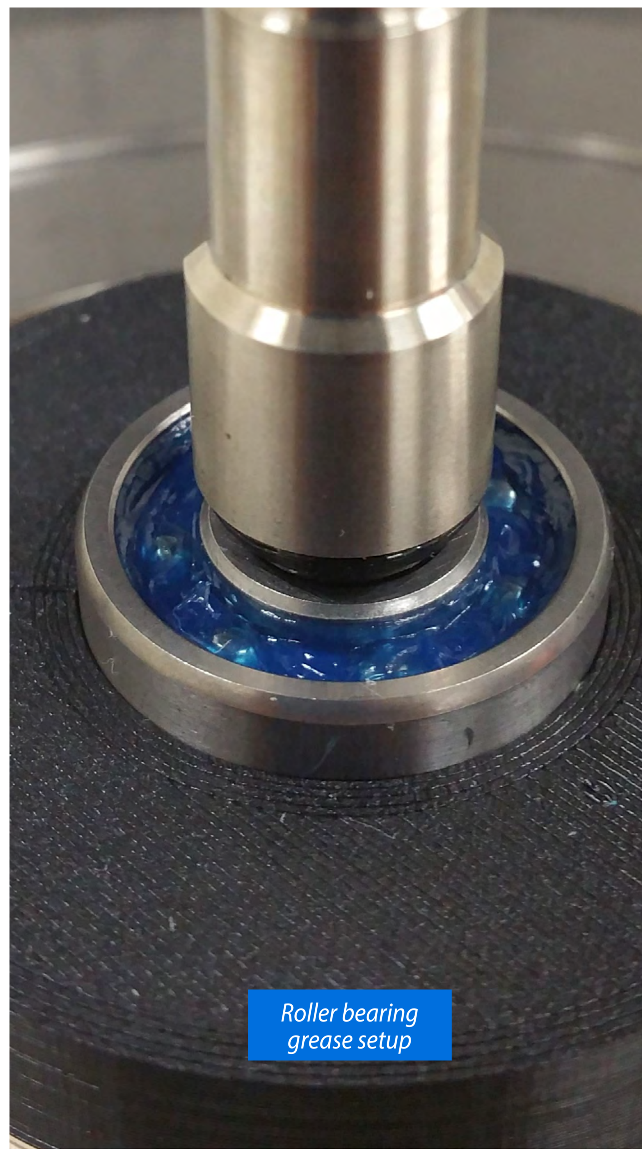
Non-electrified end of test

Electrified end of test



Electrified Roller Bearing





Roller bearing grease setup

Viscosity and Density

SwRI utilizes two viscometers and a density meter to investigate the properties of a wide range of fluid types.

The Anton Paar SVM 3001 Stabinger Viscometer, a rotational viscometer with concentric geometry, can determine dynamic and kinematic viscosity as well as density from a 2.5 ml sample. The enclosed test chamber allows mass continuity to be preserved throughout the measuring procedures, even at high temperatures.

The PCS Instruments Ultra Shear Viscometer (USV) provides accurate measurement of dynamic viscosity at very high shear rates. Because lubricants developed for many applications, including use in motor vehicles, are typically non-Newtonian, the shear rate experienced by the lubricant during use must be reproduced in order to accurately measure the lubricant viscosity. The USV can measure between 106 and 107 1/s at temperatures between 40˚C and 150˚C. One use for the USV is to study temporary and permanent shear effects.

The Anton Paar DMA 4200 M offers reliable and repeatable density measurement at a wide temperature range and elevated pressures for 2 – 3ml samples. The robust measurement system offers high chemical resistance and is suitable for upstream and downstream petroleum products. This versatile instrument replaces traditional pycnometers and hydrometers, and conforms to several ASTM methods.

Anton Paar SVM 3001 viscometer

SVM 3001 Specifications

Sample volume		2.5 ml	
Dynamic viscosity		0.2 – 20,000 mPa•s	
Density		0.65 – 3.0 g/cm³	
Temperature		-60 – 150°C	
Repeatability	Viscosity	0.1%	
	Density	0.0002 g/cm³	
	Temperature	0.02˚C	
Reproducibility	Viscosity	0.35%	
	Density	0.65 – 1.5: 0.0005 g/cm³	0.151 – 3.0: 0.0020 g/cm³
	Temperature	0.05˚C	

PCS Instruments Ultra Shear Viscometer

USV Specifications

Shear rate range	10^6 – 10^7 1/s
Testing temperature	40 – 150˚C
Test sample volume	< 5 ml
Temperature control	± 0.1˚C

Anton Paar DMA 4200M density meter

DMA 4200 M Specifications

Density		0 – 3 g/cm³
Temperature		-10 – 200°C
Pressure		0 – 480 bar
Accuracy	Density	0.0002 g/cm³
	Temperature	0.03°C
Repeatability	Density	0.00005 g/cm³
	Temperature	0.01°C
Reproducibility	Density	0.0001 g/cm³

Standardized Fluid Analysis

SwRI conducts numerous standardized tests for clients on gasoline and diesel engine oils, gear oils, transmission fluids, hydraulic oils, coolants, and greases. SwRI scientists help clients fulfill requirements to meet specifications, monitor trends, and solve unique problems. SwRI offers oil qualification analytical and bench testing for API, ILSAC, SAE and ACEA, as well as OEM specifications such as Mercon®, Dexron®, Caterpillar, Allison, John Deere, and others.

Laboratory test methods include test procedures from ASTM, DIN, CEC, JIS, FTM, JDQ, VW, and other standards developers. SwRI testing is an essential tool for maintaining quality processes for a variety of clients including OEMs, suppliers, and fleet owners.

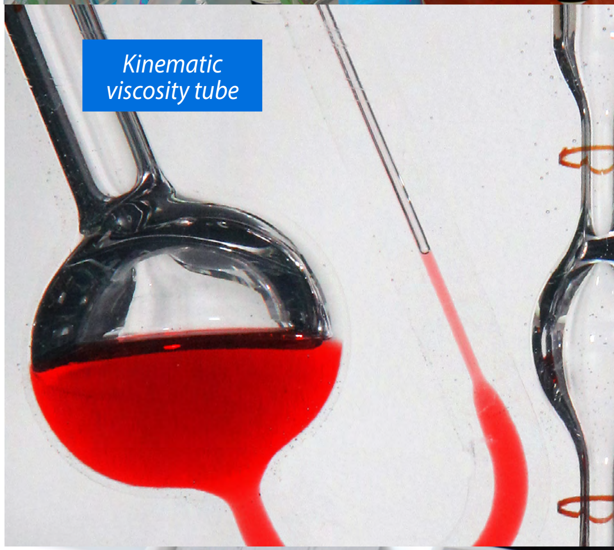
Standard Test Methods

- ASTM D445 – Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)
- ASTM D1475 – Standard Test Method for Density of Liquid Coatings, Inks, and Related Products
- ASTM D4052 – Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter
- ASTM D5002 – Standard Test Method for Density, Relative Density, and API Gravity of Crude Oils by Digital Density Analyzer
- ASTM D6448 – Industrial Burner Fuels with Used Lubricating Oils
- ASTM D2270 – Calculating Viscosity Index from Kinematic Viscosity at 40˚C and 100˚C
- ASTM D2501 – Calculation of Viscosity-Gravity Constant (VGC) of Petroleum Oils
- ASTM D5931 – Standard Test Method for Density and Relative Density of Engine Coolant Concentrates and Aqueous Engine Coolants by Digital Density Meter
- ASTM D6074 – Standard Guide for Characterizing Hydrocarbon Lubricant Base Oils
- ASTM D6823 – Standard Specification of Commercial Boiler Fuels with Used Lubricating Oils
- ASTM D7042 – Dynamic Viscosity and Density of Liquids by Stabinger Viscometer (and the Calculation of Kinematic Viscosity)
- ASTM D7152 – Standard Practice for Calculating Viscosity of a Blend of Petroleum Products

Test Types	Examples
Condition Monitoring	Viscosity (Brookfield, kinematic, dynamic, high/low temperature), total acid number (TAN), total base number (TBN), oxidation and nitration value by FTIR, elemental analysis, TGA soot, moisture analysis, fuel dilution by GC
Oxidation and Deposit	ROBO, DKA, CMOT, RBOT, TEOST MHT, PDSC, ABOT, TOST
Corrosion	Panel rust/humidity cabinet, pin rust, copper strip, corrosion bench test (CBT), high-temperature CBT (HTCBT), TO4 rust, salt fog
Friction and Wear	Falex Pin & Vee, four-ball, Timken, coefficient of friction, extreme pressure
Shear	KRL shear, Bosch shear, Sonic shear
Other	Elastomer and seal compatibility (LDEOC, EOEC, CEC L-39, others), clay gel, sulfated ash, filterability, foam, simulated distillation, gas bubble separation/air entrainment, miscibility, flashpoint, NOACK volatility, insolubles, panel coker, particle count, ion chromatography

More comprehensive details available at pprd.swri.org


Oil oxidation test

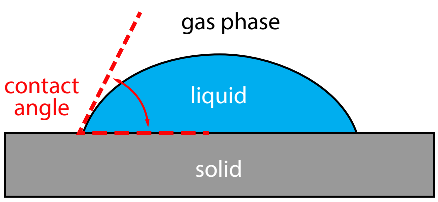

Kinematic viscosity tube


Ash from petroleum products

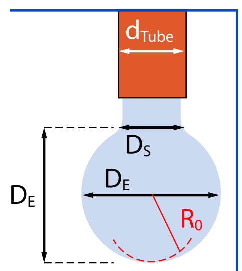
Surface Tension and Contact Angle

The interaction of a fluid with a surface, gas, or other fluid is an important characteristic for many applications such as lubricant compatibility with coatings, and nozzle spray patterns. A goniometer can be used to measure the contact/wetting angle of a fluid against any surface. Using a high-precision pump and capillary tube, the pendant drop method can be used to measure the interfacial tension of a fluid.

Interfacial viscosity can be measured with a bi-cone system on the rheometer. For this method a razor-sharp cone is placed at the surface of a fluid, without breaking surface tension. The cone is carefully rotated, measuring the viscosity at the interface of the fluid and the air above it.

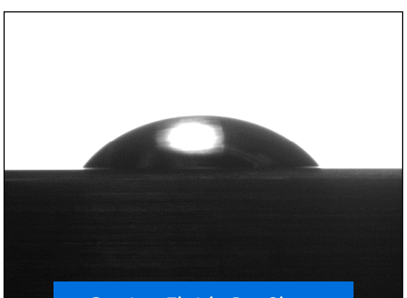


Contact/Wetting Angle Measurement

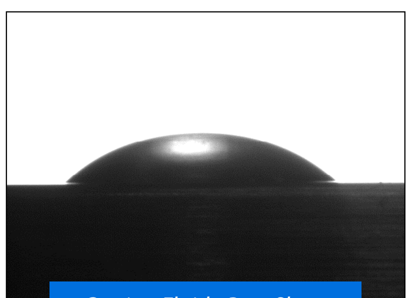


Pendant Drop for Interfacial Tension

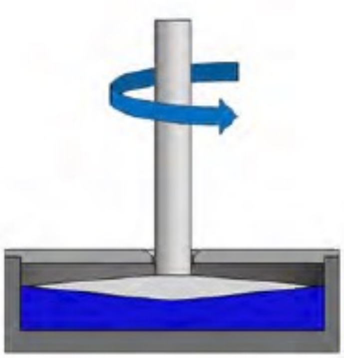
Engine oil



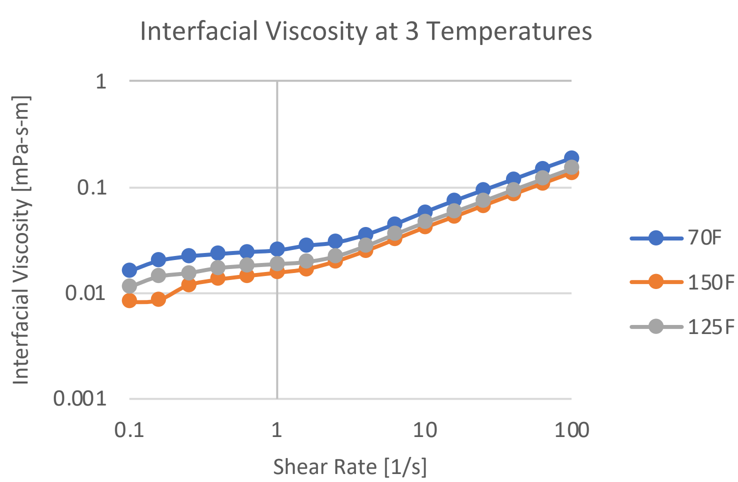
Cutting Fluid– Pre Shear



Cutting Fluid– Post Shear



Interfacial Bi-Cone



Southwest Research Institute

Southwest Research Institute, headquartered in San Antonio, Texas, is one of the oldest and largest independent, nonprofit, applied research and development organizations in the United States. Founded in 1947, SwRI provides contract research and development services to industrial and government clients. The Institute is governed by a board of directors, which is advised by approximately 100 trustees.

With more than 2.5 million square feet of laboratories and offices, SwRI's eleven technical divisions provide multidisciplinary, problem-solving services to research and physical sciences projects for government and industry. In 2023, we funded 103 internal research projects with a contract value of more than $9.3 million. Total revenue was $844 million.

Our staff numbers more than 3,000, including 315 staff members with doctorates and 612 with master's degrees. In 2023, staff members published 517 technical papers, made 577 technical presentations, and hosted 41 webinars and 15 podcasts. We submitted 36 invention disclosures, filed 34 patent applications, and received 42 patent awards.

A partial listing of research areas includes:

- Automation, robotics, and intelligent systems
- Bioengineering
- Chemistry and chemical engineering
- Corrosion and electrochemistry
- Emissions research
- Engineering mechanics
- Fluid systems and machinery dynamics
- Fuels and lubricants
- Geochemistry and mining engineering
- Hydrology and geohydrology
- Materials sciences and fracture mechanics
- Modeling and simulation
- Nondestructive evaluation
- Oil and gas exploration
- Pipeline technology
- Space science and engineering
- Surface modification and coatings
- Vehicle, engine, and powertrain design/R&D

Automotive engineering at SwRI encompasses engine, vehicle, emissions, lubricants, and fuels research and development. We perform design, development, and test programs on a wide range of components, engines, transmissions, vehicles, and batteries. These programs are supported by research and modeling of fuel mixing, combustion, tribology, filtration, structural analysis, noise and vibration harshness, and fluid flow analysis.

A broad range of services are available for product research, development, and qualification of automotive components and automotive fluids for on-road, off-road, rail, and water transportation systems as well as recreational vehicles and stationary power equipment.

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