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In-service Grease Testing Techniques That Can Save Money and Time for Grease Manufacturers

Richard N. Wurzbach
MRG Labs, York, Pennsylvania, USA

Is it Time to Retire the Grease Penetration Test?

Wade Flemming and John Sander
Lubrication Engineers, Inc., Wichita, KS

Award for Achievement

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Lithium ion battery demands and a discussion of lithium supply crisis: How worried should we be?

Dr. Raj Shah and Ms. Shana Bruff
Koehler Instrument Company
Holtsville, NY, USA

Year End Recap

Advertisers Index

Industry Calendar of Events

ON THE COVER
Happy Holidays!
The past year has been one of changes and transitions. Starting with the addition of our new Executive Director, to revamping NLGI’s committee structure, fostering relationships with our industry and media partners, conducting an excellent Annual Meeting in Coeur d’Alene, ID, launching a new website including access to technical articles dating back to the 1960’s, we’ve accomplished a lot this year. I want to thank you all for joining us in the journey.

Please check out our year-end recap including highlights in areas such as Membership, Finance, Governance, Education, Volunteer Management and Business Development.

Budgets for 2019 have been approved and planning is underway for the New Year. In 2019, we will continue to focus on our strategic priorities including:
• Enhancing membership growth and outreach
• Providing expanded educational opportunities
• Funding basic research
• Effectively communicating the value of NLGI technical resources and certifications
• Expanding global outreach of NLGI
• Enriching governance and leadership for NLGI

As we look ahead into 2019, the NLGI leadership would encourage you to get involved. We invite you to join one of NLGI’s revamped committees. For more information, please contact Crystal O’Halloran at crystal@nlgi.org or 816-524-2500. Please review a list of NLGI committees in the year-end recap section of this issue.

Also, if you haven’t had a chance, please visit the new and improved NLGI website at www.nlgi.org. The new website features:
• Colorful and easy to use quick links
• Robust members’ only area with various resources
• Technical articles dating back to the 1960’s
• and more!

Join us in June 2019 for another great NLGI Annual Meeting in Las Vegas, NV. The theme Is “Bearing the Load: Back to the Basics of Grease”. Technical presentations will focus on the use of lubricating grease in bearings and include discussion of topics such as:
• Additives
• Testing
• Environmental impacts
• Safety concerns
• Cost savings
• Improved performance/efficiency
• Condition monitoring/in-service

On behalf of the NLGI leadership team, we would like to wish you Happy Holidays and a successful New Year!

Joe Kaperick
Afton Chemical
NLGI President 2018-2020
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Abstract

Manufacturers of lubricating greases can benefit by adopting simple tests already in use to evaluate the condition of in-service greases. Methods to collect and analyze samples of lubricating oils are used widely and effectively to monitor the condition of critical machinery and optimize its reliability. While grease serves a similar role in lubricating components, it is often overlooked for sampling and analysis. Multiple industries have begun to analyze in-service grease to enhance assessments of machine condition and to provide input on decisions about whether to replenish grease and when to perform condition-based maintenance. Now, some of these simple tests can be applied in the manufacturing and quality control processes of new grease. These tests can streamline grease production and ensure that products are clean and free of contaminants and can compete in the marketplace. New test results for grease samples from packages and grease guns show a wide range of cleanliness, as measured by particulate and moisture levels, raising the question of how these contaminants may impact machine life.

Sampling and Testing In-Service Grease

The current best practice for collecting a sample of in-service grease from machinery is defined in ASTM D7718 Standard Practice for Obtaining In-Service Samples of Lubricating Grease. D7718 explains how to collect a 1 g sample of grease in a clean standard container or “thief”. The development of D7718 followed several years of research in the power generation field. A number of leading companies in the Danish wind industry invested in several projects to evaluate and perfect the tools and techniques to sample grease from blade and main bearings in wind turbines. The Electric Power Research Institute also contributed to the body of knowledge in this area with the Effective Grease Practices project, which identified methods for sampling grease from gearboxes and bearings.

With grease sampling defined in D7718, an additional standard was developed for analyzing the typically small samples obtained from in-service equipment. D7918 Standard Test Method for Measurement of Flow Properties and Evaluation of Wear, Contaminants, and Oxidative Properties of Lubricating Grease by Die Extrusion Method and Preparation defined methods to measure wear particles, consistency, contamination, and oxidation parameters of in-service grease samples collected according to D7718. While D7918 differed from the existing standards used primarily for quality control and performance testing of new, unused grease, these tests of in-service grease found a ready audience in robotics, power generation, pharmaceutical manufacturing, and mining industries.

Further research led to the development of methods to measure moisture at the ppm level in greases (humidity sensor), grease color (colorimetry), and particles in grease (particle counts). In particular, these new tests have begun to cross the barrier to be adopted by end users to evaluate the quality of newly manufactured and stored greases. With end users of grease now having tools to make them aware of the cleanliness of the products they are purchasing, it becomes important for grease manufacturers to measure and control these variables.

Importance of Grease Cleanliness

The impact of particulates and moisture on the life of lubricated components has been understood for many years, and significant investment has been made to develop the technology to measure, remove, and prevent the ingress of these contaminants into lubricants. Many manufacturers and end users employ filtration and moisture removal technologies to ensure that lubricating oil is clean and dry to reduce component damage and extend machine life.
Grease-lubricated components are often similar or even identical to their oil-lubricated counterparts, and can be subject to damage and life reduction when contaminants are not controlled. Grease presents special challenges to filtration, and in some cases cannot be readily filtered to particulate levels pursued for lubricating oils without risking the disruption or separation of grease thickeners. Therefore, the practices employed in making, packaging, and storing greases must be the focal point for the limitation of contaminants that can harm the machines. If grease manufacturers are not aware of the cleanliness of their products, then they may miss the opportunity to prevent the introduction of contaminants.

A clean, dry grease has a significant impact on the Return on Net Assets (RONA) experienced by the asset owners using that lubricant. Because the asset owner cannot simply run the purchased lubricant through a filter prior to use (as is possible with oils), it is vital that they start with clean grease. But even a clean, packaged grease can suffer from contamination during storage and handling. Therefore, it is also critical that the asset owner monitor their grease supplies at the point of application to ensure that their own processes, such as loading grease guns, refilling automatic grease lubrication devices (auto-lubers), etc., do not introduce contaminants into an otherwise clean product.

**New Grease Cleanliness Test Results**

Developed originally in 2015, the ASTM D7918 grease analysis standard introduced methods to analyze a grease sample that had been collected in a standard container per D7718. The grease-filled container fits into an integrated tester that can measure multiple grease parameters from a single small sample. In order to deal with only 1 gram of grease in the sample container, the analysis process was designed to be efficient. The integrated process ensures that a maximum number of effective and representative tests can be performed on a sample. The original version of the analysis standard included testing for ferrous debris (ppm), die extrusion (flow properties/consistency), linear sweep voltammetry (anti-oxidant levels), and color.

In 2017, the D7918 standard was revised and two new tests were added, grease particle counts and moisture by humidity sensor. This paper reports results from these two tests from a comparison study of unused and in-service grease samples.

**Comparison of Unused and In-Service Greases**

To evaluate the current state of greases in use by asset owners, two studies were performed to analyze contaminant levels in various points of use and in multiple industries. In the US, samples were submitted from power generation, mining, food processing, testing labs, and wastewater processing companies. Each participating company took samples from new, previously unopened grease packages, grease guns, and in-service bearings. A similar study was performed using the same criteria at pharmaceutical, transportation, and wind energy companies in Ireland.

The results from both studies showed a wide range of moisture and particulate levels in all three areas tested – packages, grease guns, and bearings. The highest moisture and particulate levels were seen in grease samples from new, previously unopened packages.

The results from the US study are shown in the charts below. Particle count data are given in units of mg of particles with diameter greater than 25 μ (microns) per g of grease, and moisture content is expressed as ppm (parts per million) or ug (micrograms) of water per g of grease. Colors correspond to grease samples from new packages (blue), grease guns (green) and in-service bearings (yellow).
**Figure 1** Particle data for mg particles with diameter > 25 u per g of grease) for 9 grease samples from new packages (blue), 3 grease samples from grease guns (green), and 6 grease samples from in-service bearings (yellow).

**Table 1** Grease samples taken from new packages (blue), grease guns (green), and in-service bearings (yellow) and particle data shown in Figure 1

<table>
<thead>
<tr>
<th>Particles (mg/g grease)</th>
<th>Grease Thickener</th>
<th>Base Oil</th>
<th>Application Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.07 Polyurea</td>
<td>Mineral</td>
<td>Electric Motor Grease</td>
</tr>
<tr>
<td>b</td>
<td>0.40 Lithium Complex</td>
<td>Mineral</td>
<td>High Water Washout</td>
</tr>
<tr>
<td>c</td>
<td>1.18 Calcium Sulfonate</td>
<td>Mineral</td>
<td>High Temperature</td>
</tr>
<tr>
<td>d</td>
<td>1.52 Lithium Complex</td>
<td>Mineral</td>
<td>High Temperature High Viscosity</td>
</tr>
<tr>
<td>e</td>
<td>3.18 Unknown</td>
<td>Unknown</td>
<td>-</td>
</tr>
<tr>
<td>f</td>
<td>3.48 Lithium Complex</td>
<td>Mineral</td>
<td>High Temperature High Viscosity</td>
</tr>
<tr>
<td>g</td>
<td>3.70 Calcium Sulfonate/Carbonate Complex</td>
<td>Synthetic</td>
<td>Food Grade</td>
</tr>
<tr>
<td>h</td>
<td>7.25 Aluminum Complex</td>
<td>Synthetic</td>
<td>-</td>
</tr>
<tr>
<td>i</td>
<td>8.14 Lithium Complex</td>
<td>Mineral</td>
<td>High Temperature High Viscosity</td>
</tr>
<tr>
<td>j</td>
<td>0.0 Lithium Complex</td>
<td>Synthetic</td>
<td>-</td>
</tr>
<tr>
<td>k</td>
<td>1.83 Calcium Sulfonate</td>
<td>Mineral</td>
<td>High Temperature</td>
</tr>
<tr>
<td>l</td>
<td>3.44 Calcium Sulfonate/Carbonate Complex</td>
<td>Synthetic</td>
<td>Food Grade</td>
</tr>
<tr>
<td>m</td>
<td>0.09 Lithium Complex</td>
<td>Synthetic</td>
<td>-</td>
</tr>
<tr>
<td>n</td>
<td>0.88 Calcium Sulfonate/Carbonate Complex</td>
<td>Synthetic</td>
<td>Food Grade</td>
</tr>
<tr>
<td>o</td>
<td>1.83 Lithium Complex</td>
<td>Mineral</td>
<td>High Temperature High Viscosity</td>
</tr>
<tr>
<td>p</td>
<td>3.62 Lithium Complex</td>
<td>Synthetic</td>
<td>-</td>
</tr>
<tr>
<td>q</td>
<td>8.50 Lithium Complex</td>
<td>Mineral</td>
<td>High Temperature High Viscosity</td>
</tr>
<tr>
<td>r</td>
<td>13.72 Lithium Complex</td>
<td>Synthetic</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 2 Moisture data (ppm water) for 10 grease samples from new packages (blue), 3 grease samples from grease guns (green), and 8 grease samples from in-service bearings (yellow).

Table 2 Grease samples taken from new packages (blue), grease guns (green), and in-service bearings (yellow) and moisture data shown in Figure 2

<table>
<thead>
<tr>
<th>Moisture (ppm)</th>
<th>Grease Thickener</th>
<th>Base Oil</th>
<th>Application Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>319 Polyurea</td>
<td>Mineral</td>
<td>Electric Motor Grease</td>
</tr>
<tr>
<td>B</td>
<td>679 Aluminum Complex</td>
<td>Synthetic</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>925 Lithium Complex</td>
<td>Mineral</td>
<td>High Water Washout</td>
</tr>
<tr>
<td>D</td>
<td>1,285 Lithium Complex</td>
<td>Synthetic</td>
<td>-</td>
</tr>
<tr>
<td>E</td>
<td>1,356 Unknown</td>
<td>Unknown</td>
<td>-</td>
</tr>
<tr>
<td>F</td>
<td>3,654 Lithium Complex</td>
<td>Mineral</td>
<td>High Temperature High Viscosity</td>
</tr>
<tr>
<td>G</td>
<td>4,026 Lithium Complex</td>
<td>Mineral</td>
<td>-</td>
</tr>
<tr>
<td>H</td>
<td>4,331 Lithium Complex</td>
<td>Mineral</td>
<td>-</td>
</tr>
<tr>
<td>I</td>
<td>4,817 Lithium Complex</td>
<td>Mineral</td>
<td>-</td>
</tr>
<tr>
<td>J</td>
<td>15,781 Calcium Sulfonate/Carbonate Complex</td>
<td>Synthetic</td>
<td>Food Grade</td>
</tr>
<tr>
<td>K</td>
<td>5,081 Calcium Sulfonate</td>
<td>Mineral</td>
<td>High Temperature</td>
</tr>
<tr>
<td>L</td>
<td>5,488 Calcium Sulfonate/Carbonate Complex</td>
<td>Synthetic</td>
<td>Food Grade</td>
</tr>
<tr>
<td>M</td>
<td>15,944 Lithium Complex</td>
<td>Mineral</td>
<td>High Water Washout</td>
</tr>
<tr>
<td>N</td>
<td>1,341 Calcium Sulfonate</td>
<td>Mineral</td>
<td>High Temperature</td>
</tr>
<tr>
<td>O</td>
<td>1,628 Lithium Complex</td>
<td>Mineral</td>
<td>High Temperature High Viscosity</td>
</tr>
<tr>
<td>P</td>
<td>2,075 Lithium Complex</td>
<td>Synthetic</td>
<td>-</td>
</tr>
<tr>
<td>Q</td>
<td>2,098 Lithium Complex</td>
<td>Synthetic</td>
<td>-</td>
</tr>
<tr>
<td>R</td>
<td>2,165 Lithium Complex</td>
<td>Synthetic</td>
<td>-</td>
</tr>
<tr>
<td>S</td>
<td>4,808 Lithium Complex</td>
<td>Mineral</td>
<td>High Water Washout</td>
</tr>
<tr>
<td>T</td>
<td>7,564 Calcium Sulfonate/Carbonate Complex</td>
<td>Synthetic</td>
<td>Food Grade</td>
</tr>
<tr>
<td>U</td>
<td>8,890 Calcium Sulfonate</td>
<td>Mineral</td>
<td>High Temperature</td>
</tr>
</tbody>
</table>
Table 2 Grease samples taken from new packages (blue), grease guns (green), and in-service bearings (yellow) and moisture data shown in Figure 2

Findings
- Of the 25 total samples, 18 were analyzed by both methods, 4 were too dark to report particulate results, and 3 had insufficient quantity to perform any of the tests.
- Sample point breakdown:
  - 8 from bearings (yellow bars on graph)
  - 3 from grease guns (green)
  - 11 from new tubes (blue)
- The cleanest grease sample (lowest amount of particles) was taken from a bearing.
- One of the dirtiest samples (highest amount of particles) was taken from a new tube of unused grease.
- 7 samples had a total debris concentration of particles with diameter > 10 μ that was >20 mg/g, which would be ‘off the charts’ (excessive) in the case of oil samples, and 4 of those 7 were samples from new tubes of grease.
- 4 samples had particle counts at or near the lower limit of detection (LLD) of the method, and 2 of them were bearing samples.
- Only 3 samples had moisture levels below 1,000 ppm, generally thought to be an action level for oils to prevent machine damage.
- The highest findings were in Calcium Sulfonate greases. Some other studies (Cyriac, Lugt, Bosman) suggest that Calcium Sulfonate formulations may absorb more water while retaining their structure, as compared to other thickener systems, and so the significance of these levels and the development of criteria for potential impact on machinery may require more research.

Status
Having completed these two initial studies, we continue to work with interested asset owners and grease manufacturers to analyze contaminant levels in greases in new packages, transfer devices (auto-lubers and grease guns), and machines in an effort to identify opportunities to
improve grease cleanliness and to extend equipment life. Some manufacturers have utilized the information obtained from testing greases in their production environment to direct process improvements to reduce the likelihood of particulate and moisture contamination during the manufacturing process.

An additional development is the Grease Thief Colorimeter. This small and portable device allows for the quick evaluation of the color of a small grease sample using a visible light spectrometer and a variable path press to allow the testing of greases from translucent to near black. This non-subjective method for establishing the color of a grease sample and comparing it to a library of previously tested products will allow for the creation of criteria for new grease manufacturers to minimize the instance of product appearance changes. The ability to generate a “Delta” value for color can also be used to establish criteria for in-service greases. This has been shown to be very promising in the area of robotic grease analysis.

Conclusions
Grease quality and cleanliness testing can serve as an important predictor of grease performance with respect to extending bearing life by reducing particle- and moisture-induced wear and fatigue. While end-users do not now routinely test new greases for contaminant levels, this study shows significant variability in contaminant levels of new packages and transfer devices. Testing new greases for levels of particulates and moisture can allow asset owners to select products that support their goals for return on asset

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investments. Testing new greases at various stages of production and packaging can allow for the identification of process improvement opportunities to enhance grease cleanliness. A greater awareness of grease cleanliness levels by suppliers and end-users may reveal opportunities to improve product cleanliness and extend equipment life.

The standard container for grease sample collection and instruments for sample analysis are currently used in laboratories across the US, in Europe, and in Asia for evaluating samples of in-service grease. This paper shows the value of applying these techniques to samples of greases as supplied and from distribution devices as well as machinery. Work is underway to develop a new screening test method to measure grease color. The ultimate goal is to provide tools to help grease manufacturers and end users implement strategies to extend equipment life and improve reliability of assets.

Acknowledgements
Richard Janosky and Evan Bupp of MRG Labs contributed to the testing in this study.

Reference
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Abstract

It has been said that the most important property of a lubricant is the viscosity, the resistance to flow. This is a true statement for fluid lubricants but not most grease products that are semi-solid. Grease marketers often sell grease first by thickener type, and second by consistency number, often called the NLGI grade. Described in basic terms, grease consistency is a measure of the “hardness or softness” of a grease. The most common test for evaluating grease consistency is the penetration test. This test has stood for many years as the standard for evaluating grease consistency.

In this test, a standardized cone is dropped onto a flat surface of grease packed in a standard cup, allowed to sink for five seconds, and then the depth the cone has sunk is measured. Perhaps it is the simplicity of the test that has helped it to maintain its position as one of the most important grease evaluation tests. Still, it may be argued that this simplicity has caused complacency within the industry about the true value of this test. Formulators and engineers may have noticed that while several grease products may all have the same NLGI grade per the penetration test, their physical properties can be noticeably different.

The main question, then, is what is the importance of grease consistency? The answer is really two more questions. How easy is it to pump a grease into an application? Once it is in that application, how well does the grease flow into the areas that must be lubricated? It has been observed that various greases with the same NLGI consistency grade may not have the same pumpability or flow properties. Therefore, it really begs a new question, what is the real value of the grease consistency number obtained from the cone penetration test?

Another disadvantage of the cone penetration test is the amount of grease needed to run the test. There are scaled down versions of the penetration test, but they have worse test precision than the full-scale test.

The goal of this paper is to point out several alternative tests that are available and to encourage dialogue about potential replacement of the cone penetration test in the future.

1. Introduction

Most equipment users are familiar with fluid lubricants and can easily understand the concept of viscosity, the resistance of the fluid to flow. While there are varieties of fluid lubricants, and many ingredients used to formulate them are similar, it is visually obvious that grease products are a completely different type of lubricant. Grease is commonly used in applications where oil would run right out, such as a bearing with no seals. Grease could be described as a dispersion of a thickener in a lubricating fluid that keeps it from leaking out of applications. It would seem that the goal is for grease not to flow. However, for it to lubricate moving parts, it must flow. Grease must flow, but under the proper circumstances. So when users need to select grease for a particular application, how do they decide? In training classes, instructors from Noria explain that it is important to consider the base oil, thickener and consistency to make a proper grease selection. [1]

Consistency is a measure of the hardness or softness of grease. The test used to evaluate grease consistency is the cone penetration test. In fact, grease products are often sold according to their National Lubricating Grease Institute (NLGI) consistency grade numbers, as listed in Table 1. The thickness, or stiffness, of the grease increases as the NLGI grade number increases. Typically, the NLGI range could be used as an indicator of how well grease might pump into a lubricant contact zone. Once there, it should sufficiently flow to provide proper lubrication. As such, grease consistency is a physical parameter used by
lubricant manufacturers, equipment manufacturers and end users to specify, recommend and purchase greases for their applications. The importance of this parameter to the end user is very high.

It is obvious to anybody who has actually looked at, touched or pumped grease that two greases of the same NLGI consistency range are not necessarily the same in other respects. This point was demonstrated by Flemming et al. in experimentation with a controlled stress rheometer that showed that various NLGI grade 2 greases possessed very different properties. While the penetration result is a quantitative physical measurement, it can be noted that some greases—although the penetration test result says they are the same—are more difficult to pump than others, are stickier than others or look harder or runnier than others.

While the grease penetration result has been the standard for measuring consistency, newer tools and techniques have been developed that could provide a more complete picture of grease consistency. It is not new to suggest that the penetration test is insufficient to properly evaluate grease consistency, yet the test has endured as the standard for many years. In 1991, Hamnelid presented a paper outlining various limitations in using the penetration test to evaluate grease consistency. However, the test has become engrained in the grease industry. It is not the goal of this paper to provide an immediate replacement to the penetration test, but rather to provoke thought and spur discussions needed to encourage development of a new standard for evaluating grease consistency.

### 2. Consistency

The Merriam-Webster dictionary defines consistency as: “1. The property of holding together and retaining its shape, 2. A harmonious uniformity or agreement among things or parts.” Grease consistency is defined by NLGI as “the degree to which lubricating grease resists deformation under the application of force. Consistency characterizes the plasticity of a solid in much the same way that viscosity characterizes a fluid. Grease consistency is usually measured by cone penetration according to ASTM D217 (IP 50) or D1403.”

Table 1: NLGI Consistency Grades [2]

<table>
<thead>
<tr>
<th>NLGI Grade</th>
<th>Range, 1/10 mm</th>
<th>Appearance</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>445-475</td>
<td>Fluid</td>
<td>Cooking Oil</td>
</tr>
<tr>
<td>0</td>
<td>400-430</td>
<td>Semi-Fluid</td>
<td>Apple Sauce</td>
</tr>
<tr>
<td>0.5</td>
<td>355-385</td>
<td>Very Soft</td>
<td>Brown Mustard</td>
</tr>
<tr>
<td>1</td>
<td>310-340</td>
<td>Soft</td>
<td>Tomato Sauce</td>
</tr>
<tr>
<td>2</td>
<td>265-295</td>
<td>Normal Grease</td>
<td>Peanut Butter</td>
</tr>
<tr>
<td>2.5</td>
<td>220-250</td>
<td>Firm</td>
<td>Vegetable Shortening</td>
</tr>
<tr>
<td>3</td>
<td>175-205</td>
<td>Very Firm</td>
<td>Frozen Yogurt</td>
</tr>
<tr>
<td>3.5</td>
<td>130-160</td>
<td>Hard</td>
<td>Smooth Pate</td>
</tr>
<tr>
<td>4</td>
<td>85-115</td>
<td>Very Hard</td>
<td>Cheddar Cheese</td>
</tr>
</tbody>
</table>

It was noted in the previous section that grease products are sold based upon their NLGI grade, which is measured after the grease sample is subjected to 60 strokes of shear. This procedure is intended to reduce or eliminate possible effects of varying amounts of shear when the test operator fills the penetrometer cup with grease for the test. However, many in the industry also test the grease prior to shearing it in the grease worker. In other words, both 0-stroke and 60-stroke penetration tests are performed. As previously mentioned, grease is a dispersion of additives and thickener in base fluid. It is the goal of the manufacturer to properly disperse the thickener into the fluid to ensure that the grease has the required NLGI consistency. Yet, many manufacturers also evaluate the stability of the dispersion by evaluating the spread between the 0- and 60-stroke penetrations. A large spread could indicate poor thickener dispersion and unstable grease. Of course, a large spread might be desirable for a particular type of end-use application. Poor dispersion of the thickener could result in excessive grease bleeding, hardening or softening once shear is applied in the moving grease application. From the standpoint of the authors, the only real value of the 60-stroke penetration consistency value is to let the user know whether or not the grease will pour out of its packaged container.
The ingredients used to formulate grease are what affect its consistency. The selection of these should be the responsibility of the formulator and not a concern of the user. Consistency should be the major focus of the user. Table 2 provides a brief look at how consistency can affect the grease user.

Table 2: Selecting the Correct Consistency for an Application [1]

<table>
<thead>
<tr>
<th>High Consistency (Higher NLGI Numbers)</th>
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<tbody>
<tr>
<td>• Journal bearings, low-speed, such as locomotive block grease</td>
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<tr>
<td>• High-speed ball/roller bearings (with low-viscosity base oil)</td>
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<tr>
<td>• To avoid water washout</td>
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<tr>
<td>• To avoid bleed</td>
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<tr>
<td>• To avoid excessive leakage</td>
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<tr>
<td>• High ambient operating temperatures</td>
</tr>
<tr>
<td>• To seal out environmental dust (very dusty conditions)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Low Consistency (Lower NLGI Numbers)</th>
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<tbody>
<tr>
<td>• Low-speed rolling element bearings (with high viscosity)</td>
</tr>
<tr>
<td>• Cold temperature operation</td>
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<tr>
<td>• Pumpability requirements</td>
</tr>
<tr>
<td>• Gearbox—lubed for life</td>
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</tbody>
</table>

It is apparent from looking at Table 2 that there are many aspects to consider, including pumpability, bearing speed (flow), operating temperature, grease bleed and environmental conditions. The grease penetration test is insufficient to provide detailed information about any of these. Another big limitation of the penetration test is the evaluation of grease when it has been in service. Perhaps it would be a good idea to break down these points, look at other tests currently available and then describe options that could potentially be better than cone penetration for evaluating grease consistency.

3. Considerations in Selecting the Correct Grease Consistency

3.1. Flow
Grease undergoes two types of flow, flow from the grease gun and into the bearing, and flow within the lubrication contact zone where surfaces are moving. At this point, two other terms should be introduced, cohesion and adhesion. Cohesion is defined as attractive forces between molecules in a substance. Adhesion refers to the force or forces between two materials in contact, such as lubricating grease and a metal substrate, that causes them to stick together. [6] Both of these types of forces can affect how difficult or how easy it is to make a grease begin to flow.

The first challenge is to get the grease moving when it is at rest. In more technical terms, this is called overcoming the “yield stress” or “yield point”, which is the minimum amount of shear stress needed to make a plastic-like material flow. [6] In general, flow is affected by the dynamic viscosity of the lubricant, which is the viscosity under conditions of shear, such as in moving equipment. In fact, much emphasis has been placed on the development of low dynamic viscosity engine lubricants to reduce fluid friction and increase fuel economy or energy savings. It is much more difficult to measure viscosity for most greases than liquids because most greases do not flow easily. Grease is designed not to flow too much, but still it must flow. For example, a grease may undergo laminar flow in a pipe but turbulent flow in a moving bearing. Both of these types of flow are affected by the cohesive and adhesive properties of grease, as well as the temperature of the grease in use.

3.2. Pumpability
One of the most important grease properties for end users is whether the grease can be pumped from a grease gun or lubricator. The grease will not lubricate if it cannot be transported to the grease point. Today, centralized lubricant systems are used frequently to improve efficiency, convenience and safety. These are great tools, but one drawback can be the distance the grease must be pumped to reach the lubrication contact area. Various factors can affect pumpability, such as temperature, distance to be pumped, input pressure of the pump and the inner diameter of the line in which grease must travel. Most of all, pumpability comes down to the cohesive and adhesive forces described in the last section. Typically, it is the job of a grease pump or a maintenance professional to provide the proper amount of shear force to overcome the grease yield stress and make it flow.

3.3. Operating Temperature
Typically with fluid lubricants, the viscosity decreases as the temperature increases.
Normally, the same is true of grease consistency when using the penetration test. The standard grease penetration test is performed at one temperature, 25°C (77°F), which is comfortable room temperature. Grease might sometimes be pumped from a gun near this temperature, but this is not a typical operating temperature in many applications in the field. Some fluid lubricants are called Newtonian fluids, meaning that the viscosity of the fluid remains constant with changing shear rate. The viscosity of these fluids is only affected by temperature. Grease, however, is a fluid lubricant that contains a thickener and is non-Newtonian. Back in 1988, Gow presented a paper explaining how the grease deformation/response time is outside the sensitivity range of the cone penetrometer instrument because the instrument is not sensitive enough to be able to be able to study short response times. [7] Gow continued that other testing had shown the dynamic viscosity of various lithium greases to be non-linear, although the NLGI consistency system is linear.

3.4. Grease Bleed
There are at least three uses of the term “grease bleed.” First, grease is said to bleed when it becomes thin enough (or the dynamic viscosity is low enough) to leak out of the bearings. For the purpose of this paper, that type of bleed would actually be considered flow.

Second, the technical definition of grease bleed is when some of the base fluid and additives are released from the grease. Sometimes this is observed when a puddle of oil forms on the top surface of grease in its container. This type of bleed is unfavorable as it can create housekeeping problems and can result in the grease becoming thicker than if the oil had not separated from the grease.

Third, grease bleed can refer to a beneficial phenomenon in moving bearings where the thickener releases some of the oil and additives into the bearing contact zones to do the lubricating. In this case, the viscosity of the base fluid is very important for lubricity.

Is the grease thickener nothing more than a vehicle to transport oil and additives into the bearing and keep it in place when the bearing is not moving?

There are a number of publications that have shown that thickeners can contribute to the lubrication process. Sometimes, the viscosity of the bleed oil can be several times higher than the viscosity of the base oil if polymers (oligomers) have been used in the formulation. In other words, the bleed oil from grease may contain more elements than the base fluid and subsequently may have significant impact on lubrication and film thickness. [8]

It is difficult for these authors to believe that the turbulent shear in a moving bearing would not result in some of the grease thickener and other polymer(s) ending up in the contact zones, not just the base fluid and additives. Therefore, measurement of the viscosity of grease bleed could be considered an important consistency property.

3.5. Environmental Conditions
Regardless of whether grease is in storage or in service, it can be affected by the environment. Temperature has already been discussed and is understood to have a dramatic effect on grease consistency. Another important environmental factor is contamination. Contaminants can come in various forms. One example is contamination from another grease. This is such an important consideration that it has been given a name, compatibility. How can two greases get mixed? Most often, it is through operator error; the wrong grease is pumped into the application. Another possible source of grease mixing is poor practices at a manufacturer, or changing a product formula without ensuring compatibility.

Environmental contaminants include dirt, water, chemicals and wear metals. Depending upon concentration, any and all of these can affect grease consistency. In a presentation made at the 2014 Reliable Plant conference, Flemming et al. presented data obtained using a controlled stress rheometer to test consistency changes in new and contaminated greases. Some contaminants were proven to dramatically affect greases of the same starting consistency but different formulations.
Therefore, consideration should be given to selecting grease ingredients such that consistency can be optimized to manage contamination, for example increasing the adhesive properties in order to withstand water washing. Typically, wear metals would not be prevalent in grease while in storage, but improper storage techniques could allow contaminants to find their way into grease and affect the consistency even before it is placed into service. A serious disadvantage of the penetration test is the evaluation of in-service greases, because of the amount of grease (400 grams) needed to properly perform the test.

4. Consistency Test Methods

It has already been noted that the current test of choice for evaluating grease consistency is the penetration test. However, other tests are available that might provide a better picture of how a grease could really perform in applications. In fact, more than one test may be needed to properly measure consistency. Perhaps it should be described using a variety of tests. Viscosity for fluid lubricants is often described using several tests, as illustrated in the Society of Automotive Engineers (SAE) viscosity classifications SAE J300 and J306. The former is used to describe engine oils, while the latter is used for gear oils. With each test, operating temperature and low temperature viscosity are specified. SAE J300 even includes an element of high temperature along with high shear. What if this type of approach is taken with greases? If so, then what test or tests should be used? Perhaps it would be helpful to look at a few of the available tests.

4.1. Penetration Test

The penetration test has been around for a very long time. ASTM first approved D217 Standard Test Methods for Cone Penetration of Lubricating Grease in 1925 [10] and its sibling, D1403 Standard Test Methods for Cone Penetration of Lubricating Grease Using One-Quarter and One-Half Scale Cone Equipment, in 1956 [11]. The penetration test is performed by first bringing the grease to the test temperature of 25 ± 0.5°C (77 ± 1°F). Next, the grease is packed into a grease cup of standardized dimensions. Careful packing of the grease cup is required to minimize inclusion of air into the grease, which can affect the test results.

The grease sample is subjected to 60 double strokes in a grease worker. Immediately after working the grease, the penetration is determined by releasing the cone assembly, of standard mass and dimensions, from the penetrometer and allowing the cone to drop freely into the grease for 5 ± 0.1 seconds. The depth that the cone penetrated into the grease is measured in tenths of a millimeter. The NLGI classifies grease according to its consistency as measured by ASTM D217 worked penetration test. (See Table 1.) While the penetrometer has been modernized since the introduction of the grease penetration test 91 years ago (Picture 1), the theory behind the data gained has not.

Picture 1: Modern Day Penetrometer (l) vs. 1940s Era Penetrometer (r)

4.2. Measuring Apparent Viscosity of Lubricating Greases

One of the more important considerations when selecting grease for a particular application is how well the grease flows under low-temperature operating conditions. This is especially important when centralized lubricant systems are used to supply the grease to the application. The ASTM D1092 Standard Test Method for Measuring the Apparent Viscosity of Lubricating Greases was developed to determine the apparent viscosity of grease at varying shear rates to better predict pressure drops in grease distribution systems under steady-state flow at constant temperatures. [12]

In the ASTM D1092 test, the grease is forced through a series of capillaries using a hydraulic floating piston apparatus. From the flow rate and the force developed in the system, the apparent...
viscosity is calculated by means of Poiseuille’s equation. [12] By using eight different capillaries and two pump speeds, the apparent viscosity of the grease can be determined at 16 different shear rates. These data can then be used to predict the flow characteristics of the grease through various pipes, lines and dispensing equipment at the test temperature. While the ASTM D1092 test method provides useful apparent viscosity data vs. shear rate, the test method requires several pounds of grease to complete and can be very time consuming, especially if apparent viscosity determinations are required at several different temperatures.

4.3. U.S. Steel Mobility Test
Like the ASTM D1092 test method, the U.S. Steel Grease Mobility test was developed to measure the resistance of grease flow at various temperatures and pressures, predicting the pumpability characteristics of grease under low-temperature operating conditions. [13] The U.S. Steel Mobility test is performed by placing the grease into a Standard Oil Development pressure cylinder and then cooling the cylinder to the desired test temperature, usually -17°C (0°F). Next, 150-psi nitrogen gas is supplied to the pressure cylinder, forcing the grease through a 6-inch-long capillary attached to the pressure cylinder, with a 0.15-inch diameter opening. After the initial flow of the grease through the capillary, the grease is collected for a given amount of time to establish grams of flow per second. This measurement can then be used to determine if the grease has the desired flow characteristics at the selected pressure and temperature. By varying the temperature and pressure at which the test is conducted, grease can be evaluated for known supply systems. The U.S. Steel Mobility Test can provide useful flow data for grease at different pressures and temperatures, but the test method is not standardized so its repeatability/reproducibility is unknown.

4.4. Lincoln Ventmeter Test
The Lincoln Ventmeter test is another means to evaluate the pumpability characteristics of grease and was developed as a rapid alternative to the ASTM D1092 Apparent Viscosity test method. [13] The Lincoln Ventmeter test results can be used to approximate the maximum (or minimum) size of the supply line needed for a particular grease at a given temperature. This information can be useful in predicting the pumping performance of the grease in a given lubrication system or to help design a system for a particular grease.

The test is performed using a ventmeter that consists of a 25-foot coil of ¼-inch copper tubing with a pressure gauge at one end of the copper line and a grease fitting at the other. The grease is pumped into the ventmeter by a lever gun until the pressure in the line reaches 1800 psi. The pressurized ventmeter is then brought to test temperature, usually the lowest temperature expected where the grease is to be used, and allowed to remain at this temperature for a given amount of time. After the ventmeter has been allowed to soak at the appropriate test temperature, the valve at the end of the ventmeter is opened to release pressure. After 30 seconds have passed, the pressure reading on the ventmeter pressure gauge is recorded. This pressure reading at the end of 30 seconds of venting is termed the ventmeter viscosity. Comparing this ventmeter viscosity reading with “Supply Line Charts” that are supplied with the ventmeter instrument, the pumpability characteristics of the tested grease in a particular system can be predicted. [13] At the time of this writing, ongoing efforts continue to make the Lincoln Ventmeter test an ASTM standardized test.

4.5. Low-Temperature Torque Test
In certain applications, it is necessary for grease to be pumpable at sub-ambient temperatures as well as flow and provide adequate lubrication at the point of contact. The ASTM D1478 test method evaluates the extent to which a grease retards the rotation of a slow-speed ball bearing by measuring the starting and running torques of the bearing packed with the test grease at low temperatures (below -20°C (0°F)). [14] The test is performed by using a standardized No. 6204 ball bearing packed full with the test grease. The grease-packed bearing is placed in the torque test apparatus, cooled to the test temperature and held at the test temperature for two hours. At the end of the two-hour hold time, the inner ring of the ball bearing is rotated at 1 rpm while the restraining force on the outer ring of the bearing is measured. This test method is helpful
in selecting appropriate greases for applications requiring greases to exhibit low yield stress and maintain suitable consistency at low temperatures and speeds, but it requires time and large samples to determine data at several temperatures.

4.6. Grease Bleed Testing
The grease bleed phenomenon and its importance have already been discussed briefly in this paper. There are a few different standardized methods for testing oil separation from grease. The ASTM D1742 Standard Test Method for Oil Separation from Lubricating Grease During Storage and the ASTM D6184 Standard Test Method for Oil Separation from Lubricating Grease (Conical Sieve Method) are two standardized methods for determining the amount of oil bleed from a grease under static conditions. These two oil separation methods are intended to evaluate the amount of oil bleed from grease that could be detrimental to consistency at elevated temperature and during storage. The ASTM D6184 method purports that “Test results obtained with this procedure are not intended to predict oil separation tendencies of grease under dynamic service conditions.” [15] On the other hand, the dynamic test procedure ASTM D4425 Standard Test Method for Oil Separation from Lubricating Grease by Centrifuging (Koppers Method) may better correlate with a grease’s bleeding tendencies in applications where the grease is subjected to high centrifugal forces, such as flexible shaft couplings, universal joints and rolling element thrust bearings. [16]

4.7. Rheological Testing of Greases
Rheological testing to determine the deformation and flow of matter is not a new concept and has been used in many other industries for years. A quick online search reveals the extent to which controlled stress/strain rheometers are being used to determine how different substances deform and flow. A very small grease sample (1-2 grams) is required for testing on modern day rheometers. The grease sample is placed between two parallel plates on the rheometer and is subjected to controlled stress/strain rates (or ramps) by rotation or oscillation of the upper plate. This small grease sample can be evaluated for consistency, flow properties, pumpability, yield stress, thixotropic performance, temperature limits and even tackiness at various different shear rates and temperatures. The small amount of grease sample required for rheological evaluation is also ideal for evaluating samples of used greases.

While determining the deformation or flow properties of grease using a controlled stress/strain rheometer can be more complicated than other established grease industry test methods, the flexible test parameters and the data generated make rheology testing an ideal way to evaluate consistency, flow and pumpability of grease. Research in the area of using controlled stress/strain rheometers to evaluate grease consistency, yield and flow continues to grow. Recently, several DIN methods have been developed to evaluate the rheological properties of lubricating grease, such as the DIN 51810-2 test method used to determine the flow point using an oscillatory rheometer with a parallel-plate measuring system.

4.8. Grease Tackiness and Adhesion Testing
Another important grease attribute to consider when selecting the appropriate grease for an application is the tackiness of the grease. Tackiness is defined as the ability of the grease to form threads when pulled, which favors an easy transfer of grease to the contacting areas. [17] The tackiness and cohesiveness of a grease depend on both time and temperature. Tackiness of grease can be a desired attribute for some applications, while it may be detrimental to performance in other applications. The amount of tack a grease possesses can be controlled to a large extent by its formulation. Currently, there are no known established methodologies to efficiently and accurately evaluate the tackiness and adhesion of grease. However, current research is making strides in developing methods and test equipment to evaluate these two properties of grease. One method has been proposed to determine adhesion based on the ASTM D2979 probe tack test. [18] Falex Tribololgy Company has evaluated quantifying grease tackiness by measuring the force during the approach-retraction cycle of a ball or pin contacting a layer of grease on a steel substrate. [17] Finally, new rheometers have been developed with the capability of measuring normal
force along with rotational displacement, possibly allowing for simple plate pull-off methods to quantify tackiness properties of grease.

4.9 Proposed Consistency Specification
It is the opinion of these authors that a new consistency specification be developed, such as the Proposed Consistency Specification in Table 3 below, using several different test methods to describe grease consistency.

Table 3: Proposed Consistency Specification
The Proposed Consistency Specification in Table 3 is intended to be a launch pad for future discussion. It does not include the cone penetration test because it did not fit into any of the categories suggested in Table 3. Like the SAE viscosity classifications, a grease consistency specification could provide users with a much more detailed description of the grease’s physical attributes than a single 60-stroke worked penetration measurement. It is probably not possible for one single test to fully characterize grease consistency. The rheometer does show particular promise as it can be used to evaluate several different properties of grease.

5. New Activities
It was noted by Graham Gow in 1988 that the rheometer might be a better instrument to use than the grease penetrometer to evaluate grease consistency. [7] Why haven’t rheometers gained more acceptance by the grease industry since that time? Rheometers are already heavily used in other industries, such as the food, ink, paint and coatings industries. The answer is likely, “This is the way we have always done it.” It is hard to change old habits, especially away from a test that was originally standardized almost a century ago. On top of that, in most cases, greases recommended on the basis of the traditional NLGI grade scale have worked well, and there is much comfort with long-term experience.

Learning to use a rheometer may present a challenge to formulators and engineers accustomed to the penetration test. Instead of simply filling a cup with grease, adjusting the temperature, dropping a cone and measuring the cone depth after five seconds, rheometers have many options for temperature settings, shear rates and shear stresses. Rheometer data are reported as storage and loss modulus or $G'$ and $G''$, respectively. These terms are not common in the lubricant industry, much less understood by the OEMs who specify greases and the users who apply them. Therefore, the challenge for lubricant researchers is to translate $G'$ and $G''$ into language that is more common to this industry and then incorporate rheology testing into the daily business.

Perhaps something like a new consistency specification might act as a catalyst for change. The theme of last year’s NLGI meeting was “Revolutions in Grease: Changing Technology for Changing Times.” Graham Gow was the keynote speaker and he commented with disappointment that he started the revolution to replace the penetration test back in the 1980s, and now his career may end before this comes to fruition. [19] That is the way it is with pioneers! The theme of the upcoming meeting of European Lubricating Grease Institute (ELGI) is “Innovation: The Future of Grease Lubricants.” [20]

In December 2016, the ASTM D02.0G.07 Grease Working Group on Research Techniques met in Orlando, Florida. During this meeting, comparative data were shared from various labs that had analyzed several grease samples using rheometers. [21] A debate ensued as to whether the research report should also include correlations between the rheometer and the penetration test data. The room was split between those who felt they should both be reported and those who wanted the penetration data left out of the report. Unfortunately, no consensus was reached by the group. Yet, this could be a good indication that
the “revolution” continues and innovations will be made, finally leading to the retirement of the grease penetration test.

6. Conclusions
The grease penetration test has been an accepted standard for evaluating grease consistency for many years. This paper, as well as various others, have shown that the grease penetration test has many limitations. Today, newer tools offer the possibility to better define the grease property of consistency. While this paper did not conclusively demonstrate that one or more of these tools can provide a direct replacement for cone penetration testing, a Proposed Consistency Specification has potential to provoke thought and experimental studies to move the Industry forward.

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1952 T.G. Roehner, Socony Mobil Oil
1952 G.W. Miller, Battenfield Grease & Oil Corp.
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Lithium ion battery demands and a discussion of lithium supply crisis: How worried should we be?

Dr. Raj Shah and Ms. Shana Braff
Koehler Instrument Company
Holtsville, NY, USA

Lithium is an essential ingredient in three-quarters of grease production worldwide. During the last decade, the grease industry warily took note of surging demands for lithium for batteries used in plug-in electric vehicles (EVs) and other popular applications. This paper reviews global trends affecting demands and supplies of this unique metal.

Lithium Greases
According to the 2018 survey of worldwide grease production prepared by NLGI (National Lubricating Grease Institute), 74.18% by volume contains lithium soap thickener. Conventional lithium greases make up 54.51%, and lithium complex greases make up 19.67% of the market share. This was a small decrease from the lithium grease market share of 76.70% reported in the 2017 NLGI survey.

Greases thickened with lithium soap were patented in the early 1940s and used initially for aircraft lubrication, according to NLGI’s Lubricating Grease Guide. Most lithium soap greases currently are prepared by reacting lithium hydroxide with 12-hydroxystearic acid in oil to make lithium 12-hydroxystearic acid thickener. Complex lithium greases are prepared by including a short chain dicarboxylic acid, boric acid or other complexing agent in the reaction to form thickener.

David Turner noted that conventional or simple lithium greases are popular multi-purpose products because they are economical and have desirable resistance to heat and water, good shear stability and easy pumpability. Complex lithium greases have higher dropping points (~500 F or 260 C) than simple lithium greases (~385 F or 195 C) as well as even better mechanical stability and water resistance.

Mike Johnson discussed the various grease thickener chemistries that are available. Barium and calcium soap greases typically have better water-resistance properties compared to lithium greases but have other disadvantages related to oxidation stability and pumpability. Sodium greases are usually more cost-efficient than lithium greases, but their water-resistance is significantly weaker. Aluminum complex multi-purpose greases are water-resistant but saddled with modest oxidation resistance, and they are relatively expensive. Polyurea-thickened greases are ashless and have outstanding oxidation resistance and low noise emissions, but their corrosion resistance and work stability are limited.
Wayne Mackwood described calcium sulfonate greases as having inherent extreme pressure and anti-wear protection properties as well as good mechanical stability and adequate corrosion resistance. They are limited by their pumpability and cost. However, recent technological advances have brought these greases up to par with lithium complex greases for some applications in rolling equipment and pulp and paper, mining, construction, automotive, and other industries. However, calcium sulfonate greases are relatively expensive, and their supply depends on the availability of calcium carbonate, according to Bill Ward.

Thus, complex and conventional lithium multi-purpose greases have endured as mainstays of the grease industry (excepting food grade applications). Their broad range of performance strengths and good pumpability more than overcome their need for certain additives.

However, supply-demand imbalance cast a shadow on lithium grease production. According to a 2017 paper by Gareth Fish, Chris Hsu and Robert Dura, the amount of lithium used in the manufacture of batteries was six times the amount used in grease production in 2015, and the demand for lithium was expected to increase four-fold (300%) by 2025. Moreover, in 2015, the average price of lithium hydroxide monohydrate doubled in North America and tripled in most of the rest of the world. Fish estimated that the rising cost of lithium boosted the cost to prepare simple lithium base grease by about 13% and complex lithium base grease by about 19%. He proposed modifications to lithium thickeners and other options for greases.

Lithium Demand

Increased awareness of the environment has brought about a surge of interest in electric vehicles and solar power. As a result, there is an exponential increase in the need for crucial components of those technologies: batteries. Lithium is used in electrolytes and electrodes in rechargeable lithium-ion batteries as well as disposable lithium batteries.

SQM estimates that global demand for lithium metal is projected to rise ~20% next year, reaching 60,000 MT as lithium metal at the end of 2019. In lithium carbonate equipment (LCE) terms, the value of the global lithium market is projected to reach close to US$4.5 billion.

The term LCE is used commonly to refer to the amount of lithium carbonate that is needed to make other lithium compounds. The atomic weight of Li is 6.941 g/mol, the molecular weight of Li$_2$CO$_3$ is 73.891, and the ratio is 73.891/(2 x 6.941) = 5.232. In other words, it takes 5.232 kg of lithium carbonate to obtain 1.000 kg of lithium metal.

This growth is driven primarily by rapid expansion in the lithium-ion battery industry as world demand for EVs, energy storage systems and portable electronics continues to expand. Production of non-rechargeable or primary lithium batteries is expected to increase as well to meet demands as emerging economies improve. Lithium demand should hold steady in the niche markets for aluminum alloys where lithium is used to lower weight and reinforce alloy strength.
The tremendous upswing in the use of solar power over the course of the last few decades has expanded the battery industry. A market research study conducted by London-based Technavio concluded that the global battery market for solar power applications is slated to expand at a CAGR of more than 16% through the year 2020.

Global lithium-ion battery deployments predict that annual lithium-ion installations will grow more than eightfold, from 2 gigawatt-hours in 2017 to 18 in 2022. For comparison, EV sales produced a demand for 112 gigawatt-hours of batteries in 2017 alone. Boasting 55 percent annual growth, though, grid storage will soon be sufficient to shift the performance of electrical systems around the world.

Lithium-ion batteries have much higher energy densities than lead-acid batteries. A lithium ion battery can store and deliver more energy than a lead-acid battery of equivalent weight. In addition, lithium-ion batteries can be discharged more completely than lead-acid batteries. A lead-acid battery must be recharged after only one-half to three-quarters of its total energy is discharged, whereas suggested discharge levels for lithium ion batteries are typically about 80 percent.

Increased efficiency and reduced costs combine to make lithium-ion batteries the leading choice for energy storage today. In the past, the most prominent advantage of lead-acid batteries, as opposed to lithium ion batteries, was their price. But ongoing advancements in lithium ion technology, increased battery materials production and the lightning-fast pace of the development of the lithium ion battery industry have led to rapidly decreasing costs. This advantage depends on the availability and cost of lithium.

Lithium-ion batteries are also used in EVs. By 2030, EV production is expected to be 30 times greater than today. By 2037, up to 40% of all vehicles, including personal vehicles, service and public transportation, could be electric. At that time, the EV industry will be worth more than $200 billion thanks to lithium-ion batteries.

AlixPartners concludes, “Tesla Inc. is by far the top-ranking manufacturer in the auto-company measures, with sales in the second quarter of 2017 (the most recent quarter measured in the Index) totaling 6.6 million miles’ (10.6 million kilometers’) worth of e-range and with a fleet e-share of 100%.” Tesla projects to produce 500,000 Model S, Model X, and Model 3 EVs per year.

Ford, Fiat, Chrysler and GM share a mutual interest in producing more powerful, economical and efficient lithium batteries for their EVs, whose sales are projected to expand significantly. These companies fund the U.S. Advanced Battery Consortium, part of the U.S. Council for Automotive Research.

China is slated to thrust itself onto the world stage as a leader in the EV industry. According to Clean Energy Trust, its global share of battery cell production is predicted to increase to more than 70% by 2020.

Insideevs.com reports that 116,099 full EVs were sold in the U.S. and 441,179 worldwide in 2015. They project that U.S. sales will at least triple to 335,870 EVs by 2040.

According to SQM, a Tesla Model S sedan contains close to 12 lbs of lithium metal or 65 kg LCE. This means that 335,870 sedans would require approximately 22,000 t LCE.

A full electric vehicle (not a hybrid) uses approximately 40 kg LCE. At this level, worldwide annual sales of 1.3 million vehicles would require approximately 90,000 t LCE.

Deutsche Bank believes global demand will be 2.4 million EVs sold in 2025. They estimate total demand will be 534 kt LCE, of which batteries would make up 45%. 
The solar and auto industries are not the only fields that are dependent on lithium: smart watches, cell phones, portable music devices, laptops and many other electronic staples of modern day life also require lithium ion batteries.

While battery production is slated to increase exponentially in the next decade, this is a continuation of a fairly longstanding trend: From 2007 to 2014, the percentage of lithium devoted to battery production rose by a staggering 50%, and this is only the beginning. By 2015, according to Clean Energy Trust, analysts at Deutsche Bank anticipate that battery production will take up almost three quarters of worldwide lithium supplies.

According to Statistica.com projections, the worldwide demand for lithium for non-rechargeable batteries is expected to reach 4,450 metric tons (MT) LCE in 2025. Battery demand will be a strong driver of lithium consumption in the near future.

Are lithium suppliers prepared to meet levels required for greases as well as batteries?

**Lithium Supply**

Three years ago, fears of a lithium shortage almost tripled prices for the metal in less than a year to more than $20,000 per ton. This was the result of an uptick in the demand for EVs, which rivaled smartphones and laptops for lithium ion batteries.

For many, the current situation of the lithium market evokes what transpired in the iron ore market at the dawn of the 21st century. According to Financial Times, “It took many years for [iron ore] supply to catch up with demand -- this will be the case in battery materials if capital is not available to develop new projects,” says Reg Spencer, an analyst at CanaccordGenuity, who foresees that a $3 billion investment is required to procure more lithium from South American deserts as well as from Australian hard rock. “We saw several examples of steel mills acquiring iron ore resources or investing in mine capacity to ensure security of supply, something we might expect in battery materials as well,” continued Mr. Spencer.
Lithium Properties

- Lithium is the lightest metal, half dense than water with good electrical and heat conductivity.
- Due to its high reactivity is never found pure in nature, but contained in salts and minerals.

Figure 3 Lithium properties (Courtesy of SQM, Sociedad Quimica y Minera de Chile)

The element lithium (Li) is a highly reactive, unstable, flammable alkali metal that is usually stored in oil. Elemental Li is not a naturally-occurring material due to its instability. Instead, lithium is present in the form of compounds such as lithium carbonate and lithium hydroxide in rocks and as an ion (Li+) in bodies of water. Lithium is produced by processing rocks and treating brines.
As reported in Wikipedia, Australia, Chile and Argentina are the top lithium-producing countries. The region at the intersection of Chile, Bolivia, and Argentina, called the Lithium Triangle, is believed to contain over 75% of existing known lithium reserves in brine pools and hard-rock mines.

The majority of accessible lithium is contained in salty brine lakes. It is important to note that the process to obtain lithium compounds from brine is more economical than mining but very slow. The evaporation process requires 12 to 18 months.

Lithium carbonate is obtained from brines and hard-rock deposits. It is a precursor to lithium hydroxide and is used in other applications besides batteries.

Lithium hydroxide is used to manufacture lithium-ion batteries for EVs. While lithium hydroxide is more expensive than lithium carbonate, it can also be used to produce cathode material more efficiently, and is actually necessary for nickel–cobalt–aluminum oxide (NCA) and the newer chemistries of nickel-manganese-cobalt oxide (NMC) batteries. Lithium hydroxide is expected to outpace lithium carbonate in terms of demand growth for EVs.

In April of 2016, at an Annual Meeting of the European Lubricating Grease Institute (ELGI) in Venice, Felipe Smith, Sociedad Quimica y Minera, announced that SQM had plans to increase lithium production and sales by 20% that year. A preeminent company with a 26% share of the lithium market, SQM predicts a 20% increase in lithium demand through this year.
SQM plans to invest US$525 million to expand its LCE production in Chile to 70,000 tonnes by 2018 from 48,000 t currently. Additionally, the Company is targeting to finish 2019 with an effective capacity of 180,000 t. It also has a joint venture in Australia to develop a hard rock deposit that is expected to enter into production of lithium hydroxide by 2021 with more than 40,000 t of capacity.

SQM in Chile: Investing US$ 525 Millions to expand Capacity

- **Lithium Carbonate:**
  - Current capacity: 48 kMT/year
  - Expansion to 70 kMT/year (end 2018)
  - Expansion to 120 kMT/year (end 2019)
  - Expansion to 180 kMT/year (end 2021)

- **Lithium Hydroxide:**
  - Current capacity 6,000 MT/year
  - Expansion to 13,500 MT/year (end 2018)

**Figure 5** SQM in Chile is investing US$ 525 million to expand capacity (Courtesy of SQM)

Albemarle is planning to expand its LCE to 165,000 tonnes by 2021 from 89,000 tonnes this year, a spokesperson said. “We anticipate spending $700 million and $1 billion over the next 5 years.”

Demand for lithium hydroxide, preferred over carbonate as it allows greater battery capacity and longer life, is expected to grow at a faster pace. Benchmark predicts the price to average $18,000 a ton. Roskill managing director Robert Baylis estimates FMC, Albemarle, SQM and China’s Tianqi Lithium Corporation together accounted for 66 percent of the world’s lithium carbonate equivalent last year. Wood Mackenzie consultant James Whiteside puts the figure at 78 percent.

FMC’s lithium hydroxide capacity rose 80 percent in 2017 to 18,000 tons a year, and it has plans to boost that to 30,000 tons by the end of 2019. After that, capacity will be expanded as required by demand, FMC’s Schneberger said.

As EV production is predicted to increase more than thirty times over current production by 2030, the clamor for this metal won’t be satisfied any time soon, according to a report by Bloomberg New Energy Finance.
Even in light of this steep increase, demand during the next decade will use less than 1% of the total reserves of lithium in the earth, according to BNEF.

**Figure 6** Facilities for the treatment of brines to obtain lithium-bearing compounds
(Courtesy of SQM, Sociedad Química y Minera de Chile)

Price projections out to 2025 are not available, but benchmark estimates prices of lithium carbonate will average $13,000 a ton over the 2017-2020 period from around $9,000 a ton in 2015-2016.

The good news is that recent research has unveiled that lithium supplies will eventually meet the growing demand: This will happen by tapping new reserves and exploring and perfecting more efficient lithium recovery processes which will bring an influx of lithium to the market.

Furthermore, according to the USGS, other metals such as calcium, magnesium, mercury and zinc could be used in the not-so-distant future for battery applications in lieu of lithium. However, lithium substitutes may not be so easily obtained. The metal’s value is intricately linked to its ability to provide a high amount of energy in a lightweight package. Alternatives such as using calcium or magnesium are being developed but are still in the exploratory stages.

“It has taken more than 50 years to develop lithium ion batteries to the point that they are now at, so don’t expect any of these early-stage technologies to hit the market anytime soon,” admonishes James Frith, an energy storage analyst at Bloomberg New Energy Finance
Steep inflation in prices of lithium has followed worries over a potential shortage. Prices are currently double those of 2015. Over the next two years, however, prices are expected to swing heavily in the other direction, albeit, not nearly back down to 2014 levels.

Prices of stocks related to lithium production soared in 2017, fueled by the expectation that the increase in demand would cause a dearth of supply. However; thus far in 2018, lithium stocks have plummeted following Morgan Stanley voicing concerns that output by producers will be increased too quickly, according to the Wall Street Journal.

Conversely, WSJ added that investors who shorted lithium stocks have been successful during this lag. Shorts against eight of the most actively-traded lithium companies have already made more than $550 million in profits this year, as stated in an analysis by financial technology and analytics firm S3 Partners based on stock prices through mid August 2018.

Some investors and companies remain bullish regarding the volatile lithium market. In fact, Tesla Inc. and SoftBank Group Corp. recently signed deals to secure lithium supplies. Nevertheless, this has not been enough to counteract the bearish outlook of many traders and investors regarding this precarious market area,

**Conclusion**

There is more than enough lithium in brines and mineral deposits to supply growing demands for batteries for EV, solar and electronics applications as well multi-purpose lithium greases. It will be up to lithium suppliers to expand production to take advantage of these demands.

**Authors**

Dr. Raj Shah is currently a Director at Koehler Instrument Company, NY, a Chartered Petroleum Engineer from the Energy Institute, and a retired member of NLGI Board of Directors. More information on Raj can be found at https://www.che.psu.edu/news/2018/Alumni-Spotlight-Raj-Shah.aspx

Ms. Shana Braff is a customer service specialist at Koehler Instrument Company’s headquarters in Holtsville, NY.

**Acknowledgments**

The authors gratefully thank Andres Fontannaz and Sociedad Quimica y Minera de Chile for permission to use graphics from their presentation at the 2018 NLGI Annual Meeting, SQM’s Lithium Market and Energy Storage Outlook, and Dr. Mary Moon for her help in editing this document.

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NLGI Year End Recap 2018

MEMBERSHIP

24 new members recruited in 2018

91% member retention rate

RESEARCH GRANTS

NLGI funded two research grants in 2018:

1. **Louisiana State University** for their research proposal titled "Determination of Grease Life in Bearings via Entropy." This grant will take place over a three-year period (2018-2020).

2. **University of Akron** for their research proposal titled "A Fundamental Examination of Grease Thickener Self-Assembly." This grant will take place over a one-year period (2018-2019).

*NLGI liaisons have been assigned to each of these research projects and will provide updates to NLGI members on the status of the research, discoveries, etc.*
GLOBAL OUTREACH

NLGI India Chapter – Represents 8% of NLGI’s total global membership and growing.

Relationships with
Chinese Lubricating Grease Institute & European Lubricating Grease Institute

NLGI provides
GC-LB reference grease worldwide

NEW COMMITTEE STRUCTURE

NATIONAL LUBRICATING GREASE INSTITUTE COMMITTEE ORGANIZATIONAL CHART

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- Vice President
- Secretary
- Treasurer
- Annual Meeting
- Nominating
- Finance Committee
- Membership
- Production Survey
- Site Selection
- Awards
- Awards
- Membership Retention
- CLGS
- Working Groups
- Basic Education Course
- Advanced Education Course
- Research Grants
- Ask-the-Expert
- Editorial Director
- (Home Office)
- Spokesman
- Editorial Review

2018-2019 BOARD MEMBERS

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Afton Chemical Corporation

Vice President:
**Jim Hunt**
Tiarco Chemical

Secretary:
**Anoop Kumar**
Chevron

Treasurer:
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Immediate Past President:
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R.T. Vanderbilt Company, Inc.

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CITGO

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Molykote Lubricants

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**Willie Carter**
Calumet Branded Products, LLC

**Anik Kurkjian**
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**Pat Walsh**
Texas Refinery Corp.

**Chuck Coe**
Grease Technology Solutions LLC

**Matthew McGinnis**
Daubert Chemical Company

**Tom Schroeder**
Axel Americas, LLC

**Mike Washington**
The Lubrizol Corpo ration

**Ruiming “Ray” Zhang**
R.T. Vanderbilt Company, Inc.

*NLGI would like to thank two retired board members for their dedication and service over the years.
Lisa Tocci, Lubes’n’Greases and Gian Fagan, Chevron*
NLGI is financially healthy. Estimated 140% over budgeted revenue in 2018

85TH ANNUAL MEETING

June 9-12, 2018
Coeur d'Alene, ID USA

<table>
<thead>
<tr>
<th>Total Number of Attendees:</th>
<th>Total Number of Attendees from Abroad:</th>
<th>Number of Technical Presentations:</th>
<th>Basic and Advanced Course Participants:</th>
<th>Total Number of Individuals who Passed the CLGS Exam</th>
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<td>435</td>
<td>75</td>
<td>24</td>
<td>60</td>
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</table>

Thank you to those who attended the 85th Annual Meeting in Coeur d'Alene, ID. It was a wonderful meeting, filled with various networking and education opportunities including:

- Informal Networking Reception on Saturday
- Welcome reception on Sunday
- Networking breakfast & lunch on Monday
- PM break on Monday
- Networking breakfast & lunch on Tuesday
- Closing party on Tuesday
- Technical Presentations
- Basic & Advanced Grease Courses
- Working Group Meetings

2018 DEVELOPMENTS

New NLGI website

Features include:
- Simplified navigation
- Streamlined menus
- Technical Articles dating back to the 1960’s
- More information on products and services
- Creative, colorful and easy to use
- Quick links
- Robust Members’ Only area including a complimentary copy of the Grease Production Survey and more
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Vanderbilt, Inside Front Cover
**Application:** Industrial Gear Lubricant Formulation

**Recommendation:** IRGALUBE® 353

Monson, an Azelis company, is the best partner to solve your formulation needs. We recommend IRGALUBE® 353, an easy to handle liquid EP/antiwear additive providing excellent gear protection. Acts as a FZG “enhancer” with commercial gear oils. Good compatibility with water, Ca detergents and ZnDTPs. No antagonism towards iron and yellow metal protection. Leverage our full range of technical resources and quality products by contacting customer sales and service at 1-800-235-0957, or via email to csr@monsonco.com for your local sales representative.
Thank You
Thank you for your generosity. Your investment in me is greatly appreciated as it allows me to make the most out of my time at Auburn University. I will continue to exemplify the Auburn Creed as I become a true Auburn Man. I am very involved in campus through things such as the Phi Kappa Psi Fraternity, the Honors Congress, undergraduate research through the Mechanical Engineering Department, and tutoring through the Engineering Student Services. Your donation allows me to stay involved in all of this and allows me to continue to strive towards greatness.

Why I Chose My Area Of Study:
I chose Mechanical Engineering mainly because of my love for designing, building, and tinkering. From the start I grew up with parents that supported the development of interests. This lead me to take apart old electronics like alarm clocks whenever they broke down. At first it was just taking it apart and seeing how it worked, but it has developed into tinkering with and fixing any electronics.

Nowadays, I come up with my own ideas on what I want to build and try to go through the process from design to production. The challenge of creating something from a vision I had and making something new that has never existed makes me exuberant. Through the Mechanical Engineering program, I hope to continue to build upon my knowledge of how things work and how to correctly follow through on the design process, so I can put my love for designing and building into innovating bigger and better things, and into a job that I am passionate about.

I want to work in Research and Development in a company that is highly innovative. I want to use my passion for designing and apply it within a company that I think is making the world a better place. Eventually I want to become the Research and Developer Manager so that I am a part of the entire process of innovation and can use my position to design something that will make a lasting impact on the world.

My Favorite Auburn Experience:
My favorite experience at Auburn has to be all the opportunities the University has to offer. Within my first year here, I started to do undergraduate research and was allowed to jump right into doing work that I am passionate about. I get to do meaningful work that has already gotten my name on an abstract that was expanded into a paper.

Alongside my work as an undergraduate researcher, I seized the opportunity to become a tutor for the Engineering Student Services. I get to spend my time helping struggling students through one of the most important times of their lives. I get to help those around me and get to see the joy in their face when they do well on a test.

Finally on the weekends, I get to spend time with the fraternity I joined, Phi Kappa Psi, of which I was the Service and Philanthropy Chairman. I lead the fraternity to participate in the Relay for Life and was awarded the Best Campsite Fundraiser since we raised the most money of any group that participated in the event.

What This Scholarship Means To Me:
Receiving this scholarship takes a huge weight off of my shoulders. It means I get to spend my time at Auburn participating in all the things that I love and am passionate about. It allows me to continue to be a part of my fraternity and to continue to participate in the service and philanthropy events that are a part of the fraternity. The money for this scholarship means that I do not have to worry as much about making money while I am in college and to do unpaid undergraduate research because it is something I love.

My favorite thing I get to do because of this scholarship is working on my own projects. Without the fear of not having enough money due to this scholarship, I get to put some of my own funds toward funding my passion for building. I get to buy supplies and tools that I get use to try to build the next great innovation of our time.
November 28 - 30, 2018
The 14th ICIS Pan American Base Oils & Lubricants Conference
Hyatt Regency Jersey City, NJ USA

November 28 - 29, 2018
The 2018 European Base Oils & Lubricants Interactive Summit

February 7 - 10, 2019
21st NLGI India Chapter Annual Meeting
Hotel Taj Vivanta Guwahati, Assam, India

March 4 - 7, 2019
F+L Week 2019
Grand Hyatt Singapore

April 13 - 16, 2019
31st ELGI Annual General Meeting
Hotel Divani Caravel
Athens, Greece

May 19 - May 23, 2019
STLE 74th Annual Meeting & Exhibition
Omni Nashville Hotel
Nashville, TN USA

June 8 - 11, 2019
86th NLGI Annual Meeting
JW Marriott Las Vegas

Please contact Denise if there are meetings/conventions you’d like to add to our Industry Calendar, denise@nlgi.org.
(Your company does not have to be an NLGI member to post calendar items.)
Gain deeper insight through research

Lubes’n’Greases Custom Research is the only market research service that gives you access to the targeted and highly influential Lubes’n’Greases audience. We have partnered with proven industry researchers combining their expertise with our in-depth sector knowledge to give you deeper insight through research.

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| Understand consumer behavior relative to your brand and objectives | Benchmark your company’s performance against your competitors | Develop your strategy for new product development or market expansion | Identify threats and look at new business opportunities for growth |

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