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In lieu of NLGI’s 86th Annual Meeting in Miami, we are excited to announce NLGI’s Technical Week in August 2020! This virtual event will provide a focused selection of the grease technical topics you would normally have been able to access in person at our June Annual Meeting. NLGI’s Technical Week will feature the Basic/Advanced Grease Education courses, technical papers/presentations centered on this year’s Tribology theme, along with our keynote presentation from Industry Speaker Chris DelleCorte, Senior Technologist: Tribology & Rotating Machinery, NASA, Glenn Research Center, and a panel discussion on the new High-Performance Multiuse Grease.

Although this event is virtual, we still invite you to connect with other attendees using The Whoova app. Sponsored by Livent, this app will provide key information for this event including an attendee list, schedule of events, detailed list of abstracts, meeting program as well as a community board where attendees can network with one another.

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- Connect With a Veritable “Who’s Who” of the Grease Industry

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For all other information, visit https://www.nlgi.org/news-events/nlgi-technical-week/
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Abstract
The energy-saving performance of greases has become more and more important for rolling element bearing applications. This study focused on the lithium-type greases widely used all around the world, and investigated the influence of grease components through measurements of the power consumption using real bearings. Regarding thickener types, lithium complex grease was effective in the reduction of power consumption. The mechanisms of the low power consumption were proposed based on the measurements of grease film thickness using an optical interferometry method and friction properties using an MTM (Mini Traction Machine) device. The results suggest the importance of the thickener entrainment in the contact and the grease movement around the contact.

Keywords: grease, energy-saving, EHL, film thickness, lubricants, bearing

1. Introduction
Recently, the development of lubricants has greatly focused on their energy-saving performance in order to reduce CO₂ emissions. Greases are used for lubrication of more than 90% of rolling element bearings [1]. Therefore, in the case of greases, the development trend is to reduce bearing energy consumption such as the bearing torque.

The concept of energy-saving formulations for engine oils can be applicable to the grease development. Regarding base oils, the use of lower viscosity base oil contributes to the reduction of stirring resistance of grease within the bearing. The chemical structure of base oils influences the friction. The base oil with linear shaped molecules such as PAO (polyalphaolefin) provides lower friction coefficient, and therefore, is effective in the reduction of the sliding resistance. The selection of additives is also important for reducing friction. For instance, the friction modifier represented as an organic molybdenum (Mo) compound can reduce the friction coefficient in a reciprocating tribotester.

In addition, greases are semisolid due to thickeners, and therefore, the mechanical energy loss due to friction in a greased bearing is not consistent. The change of mechanical energy loss can be explained by churning and channeling phases. In the initial stage of the bearing operation, the grease is sheared by the moving parts, and this causes high bearing torque (or temperature increase) due to the drag losses [2, 3]. This is called the churning phase. After that, most of the grease is pushed away from the running track. Due to this grease clearing, the drag losses from grease shearing decrease. As a result, the bearing torque reaches at a steady low value, and this is called the channeling phase. The selection of thickener is essential to promote the quick transition from grease churning to grease channeling in the bearing operation. Sakai and co-authors [4, 5] investigated the effect of base oil and thickener types on radial ball bearing torque for lithium-type greases. The fluorescence technique was introduced for
the observation of grease flow behaviors around an elastohydrodynamic lubrication (EHL) contact area. Grease rheological parameters and film thickness were also measured for the discussion of the bearing torque. The grease thickener effect on the film thickness was studied in order to understand the influence of surface conditions [6, 7].

In this study, the energy savings by greased bearings were investigated using an original power consumption measurement device, consisting of a motor, two pairs of bearings with sample greases, and a watt meter. The influence of base oils, thickeners, and additives in greases on the power consumption of the bearing was studied. This study also focused on the thickener type, and the grease properties such as rheology, friction, and film thickness were studied in order to understand the causes of the differences of the power consumption.

2. Experimental methods

2.1. Grease samples

The greases (GA, GB, GC, and GD) used in this study consisted of different mineral base oils, thickeners, and additives as shown in Table 1. The mineral base oils had different kinematic viscosities and viscosity indexes. The thickeners were lithium (Li) type, simple Li soap and Li complex, leaders in worldwide sales by grease type [8]. Phosphorous- and sulfur-type extreme pressure (EP) additives and a molybdenum (Mo) friction modifier (FM) additive were investigated. To focus on the influence of the thickener type, greases without additives were also used, L-A and S1-A in Table 1. The tested greases were prepared through the saponification reaction between fatty acids and lithium hydroxide under the atmospheric conditions.

<table>
<thead>
<tr>
<th>Table 1. Grease formulations.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base oil</strong></td>
</tr>
<tr>
<td><strong>Kinematic viscosity of oil (40°C), mm²/s</strong></td>
</tr>
<tr>
<td><strong>Viscosity index of oil</strong></td>
</tr>
<tr>
<td><strong>Thickener type</strong></td>
</tr>
<tr>
<td><strong>Thickener content, %</strong></td>
</tr>
<tr>
<td><strong>Working penetration</strong></td>
</tr>
<tr>
<td><strong>Additive</strong></td>
</tr>
</tbody>
</table>

2.2. Power consumption

The energy-saving performance of test greases was determined by using an original power consumption measurement device as shown in Fig. 1. Two pairs of bearings with test grease were connected with a motor via a v-belt. While the bearings were rotated for two hours, the amount of the power consumption of the motor was measured. The setups of the two pairs of bearings were adopted for increasing the total load and obtaining the reliable power consumption values. Two types
of bearings (with the same bearing diameter) were used in this study in order to understand the dependence of bearing type. One bearing type was 7008ADF, double row ball bearing, and the other bearing type was 4T-CRI-0868, double row roller bearing.

2.3. Rheology
The apparent viscosity of each of the greases at a shear rate from 0.1 to 2000 s\(^{-1}\) was determined by using a cone-plate type of rotational viscometer (HAAKE Viscometer 550). First, the viscosity was measured while increasing the shear rate, and then the measurement was continued while decreasing the shear rates in order to understand the influence of the shear history. The cone was 20 mm in diameter and had an angle of 1 degree. Measurements of the yield stress of each grease were conducted with a parallel-plate type of rheometer (HAAKE MARS III), using viscoelastic parameters. The diameter of the two plates was 25 mm, and the frequency was 1 Hz. The storage modulus (\(G'\)), the loss modulus (\(G''\)), and shear stress were measured while the deformation was controlled from 0.01 to 100%. The yield stress was defined as the lowest shear stress when \(G''\) was greater than \(G'\).

2.4. Friction property
Friction coefficients were measured using a ball-on-disk tribometer, a PCS Instruments Mini Traction Machine (MTM). An AISI 52100 steel ball with diameter of 3/4 in. and a disk of the same material were selected as the standard specimens. The RMS roughness values of ball and disk were about 6 and 10 nm, respectively. The maximum Hertzian pressure was 0.65 GPa. A scoop was used for maintaining fully flooded conditions during the friction tests. Conditions without the scoop were also evaluated. Tests were conducted at ambient temperature. The velocity range between 0.1 and 3 m/s was selected for these tests. For the slide roll ratio (SRR), 0.03 was selected as representing the typical SRR range found in rolling bearings.

2.5. Thickener structure
Grease thickener fiber structures were observed by TEM (Transmission Electron Microscope). The oil component was removed from each grease with n-hexane solvent, and the residual thickener components were observed by TEM (JEOL JEM-2010). Acceleration voltage was 200 kV.
2.6. Film thickness
Grease and oil film thicknesses were measured by using the colorimetric interferometry technique [9]. The film thickness formed between a glass disk and a steel ball was observed. The contact images were captured by a digital camera. The film thickness was calculated from the interferograms based on colorimetric analysis using a color-matching algorithm and CIELAB color film thickness calibration.

Balls for film thickness measurements in the optical interferometry tests were AISI 52100 steel balls with the diameter of 25.4 mm and the surface roughness RMS of about 15 nm. The elastic modulus and the Poisson’s ratio of the steel ball were 210 GPa and 0.3, respectively. A BK7 glass disk with optically smooth surface was used. The elastic modulus and the Poisson's ratio of the glass disk were 81 GPa and 0.208, respectively. The bottom surface of the glass disk was coated with a thin, reflective chromium layer, and the top of the disk was coated with an antireflective layer. The load used for film thickness measurements was 27 N, and the maximum Hertzian pressure of the contact was 0.43 GPa for the smooth ball-on-disk contact. A v-shaped scoop was used for pushing the grease from the side of the track back to the running track in order to maintain fully flooded conditions. The film thickness observations were conducted as the velocity was increased from 0.01 to 1 m/s under nominally pure rolling conditions and 22 C. The disk was driven and the ball was followed for the smooth ball-on-disk contact. The observed film thickness for greases fluctuated due to the entrainment of thickener particles. Therefore, the average thickness values of the central circular area with a diameter of 100 μm was selected for central film thickness. In addition, the central film thickness values were averaged from the results of 5 captured images.

After the film thickness measurements at each velocity under fully flooded conditions, the grease flow patterns created downstream of the contact on the disk were observed.

In order to observe the grease film thickness decay under starved conditions, film thickness measurements without the scoop were conducted for the smooth surface contact. The contact images were captured as the velocity was increased by 0.024 m/s every 30 seconds.

3. Results and discussion

3.1. Energy-saving performance
Figures 2 and 3 compare the power consumption of the motor connected with ball bearings and roller bearings, respectively. For both bearing types, the power consumption with GB was lower than that with GA, suggesting that lower viscosity base oil was related to less viscosity resistance. The effect of Li thickener type was also confirmed by the comparison of GB and GC. Li complex contributed to less power consumption with GC versus simple Li grease GB. The Li complex grease needed more thickener content for the same worked penetration compared with the simple Li soap grease. That difference could be one of the reasons of the lower power consumption of Li complex grease versus simple Li grease.
The additive effect of the Mo FM is shown by the difference between greases GC and GD. Comparing the bearing types, the effect of Li thickener type was larger in the ball bearings than in the roller bearings. In contrast, the Mo additive effect was larger in the roller bearings than the ball bearings. The energy loss due to the friction between the edge of the roller and the collar of the inner race of the bearing was larger in roller bearings, and therefore, the reduction of friction by the Mo additive provided the lower power consumption.

Focusing on the Li thickener type, the cause of the difference of power consumption will be discussed in the following section.

**Figure 2.** Power consumption in ball bearing tests.

**Figure 3.** Power consumption in roller bearing tests.
3.2. Rheological parameter
The shear rate dependence of the apparent viscosity for grease samples was measured. Figures 4 and 5 show the results for both increasing and decreasing shear rate conditions for the two greases. L-A and S1-A mean Li complex and Li soap thickeners, respectively. Viscosities measured while increasing the shear rate were higher than those measured while decreasing the shear rate for all the greases. The gap between viscosities measured while increasing and decreasing the shear rate differed by the thickener type. For instance, S1-A with Li simple soap showed a larger gap than L-A with Li complex thickener. The viscosity gap was observed when the grease was pushed away from under the when the shear rate was increased. This indicated that Li simple soap grease caused channeling quickly. However, the power consumption of Li simple soap grease was higher than Li complex grease. The viscosity gap cannot be used an indicator of grease channeling.

![Figure 4](image1.png)

**Figure 4.** Apparent viscosity of L-A (Li complex) including high shear history.

![Figure 5](image2.png)

**Figure 5.** Apparent viscosity of S1-A (Li soap) including high shear history.

Figure 6 shows an example of viscoelasticity data of two greases. The yield stress is defined as the lowest shear stress when $G''$ is greater than $G'$, and the results for the yield stresses of greases are summarized in Fig 7. Li soap (S1-A) showed the higher yield stress. This tendency could relate to the viscosity result, because higher yield stress grease did not lead to lower power consumption in bearings.
3.3. Friction property
Friction was investigated using an MTM device. Figure 8 compares the velocity dependence of the friction coefficients of the greases and their base oil (API-Group I mineral oil, kinematic viscosity 33 mm²/s at 40°C, viscosity index 107, abbreviated 'Oil A' in Fig. 8) with 3% SRR. Without a scoop for maintaining fully flooded conditions, greases L-A and S1-A initially showed an increase in friction and then a decrease in friction as the velocity was increased. The friction increased again at higher velocity for L-A (Li complex). However, S1-A (Li soap) kept the constant friction at the high velocity region.

The base oil used for the greases (Oil A in Fig. 8) showed the almost constant friction values through the entire velocity range. The values of the friction for Oil A were close to the friction values of S1-A in the high velocity region.

In addition, the effect of the scoop at a fully flooded condition was also confirmed for L-A. With the scoop, L-A showed a stable friction coefficient close to the friction coefficient for the base oil. This result suggests that the friction properties of the grease depended on the base oil, at least under fully flooded conditions.

The friction increase for greases in the low velocity region could be related to the running-in process of the greases because both samples showed common behavior. At faster speeds, S1-A supplied the lubricant (only oil or grease itself) to the contact, and therefore the friction approached the friction of the base oil. On the contrary, L-A was not able to provide the lubricant to the contact in the high velocity region, and therefore the friction increased. This phenomenon could be related to the channeling in the bearing when it operated at high rotation speeds.
From the above discussion, the grease movement such as channeling seems to be related to the energy consumption of bearings. In order to understand the grease behaviors focused on the thickener type in detail, grease fiber structures and film thicknesses were investigated.

![Figure 8. Velocity dependence of traction property.](image)

3.4. Thickener structure
The thickener structures of greases were examined by TEM observation. Figure 9 compares the thickener structure of Li complex and Li simple soap. The thickeners formed fiber structures. The fiber shape of Li complex (L-A) appears thinner and longer. On the contrary, the fibers of Li soap (S1-A) seems thicker and shorter. The thickener shape of Li complex could be more effective than Li simple soap and better able to hold base oil, promoting grease channeling in bearings.

![Figure 9. TEM images of grease thickener.](image)
3.5. Film thickness

Figure 10 compares the central film thicknesses for greases and base oil under fully flooded conditions. Regarding the low velocity region, Li complex grease (L-A) formed thicker films compared with those formed by the base oil itself (also referred to as Oil A), since the thickener particles were entrained in the contacts as shown in Fig. 11, observed interferometry images at 0.025 m/s. In contrast, film thickness values formed by Li soap grease (S1-A) were close to those of the base oil. At higher velocities, the dependency the film thicknesses on thickener types was less significant, although all the greases formed thicker films than the base oil.

![Flow pattern image](image)

**Figure 10.** Central film thickness of greases and base oil under fully flooded condition.

Flow patterns created on the disk during film thickness measurements under fully flooded conditions were also investigated. Figure 12 compares the patterns at the low velocity of 0.025 m/s. These images show the contact track in the center and the flow patterns on both sides of the track. It was reported that the finger-like patterns are formed by the outlet cavity \(^{10, 11}\). The patterns were dependent on the thickener types in this study. L-A (Li complex) showed flow patterns stretching to the track. In contrast, the pattern formed by S1-A (Li soap) did not reach to the track. This difference can be recognized more clearly in the magnified images of L-A and S1-A. The color of the images is related to the thickness of the grease to some extent. However, it should be noted that the values of the thickness are not precise, because the interference data are not related to the separation between the steel ball and the glass disk but between the air and the disk. Although the interference colors do not show adequate quantitative values, it can be stated that brown and dark blue colors show thinner films, and green and purple show thicker films, and no colors (or grey) show much thicker films. For instance, in the flow pattern of the side track of L-A, there were alternating thick areas (without colors) and thin areas (with some colors). The thick area (without colors) was distributed to the near side of the track. In the case of the S1-A grease, the edge of the track was surrounded by the thin area (such as brown color). The difference should relate to the film thickness behaviors.
Figure 11. Interferometry images at 0.025 m/s.

Figure 12. Grease flow patterns at the downstream side of the contact at 0.025 m/s and magnified images of the zones shown in red rectangles.
Figure 13 shows the grease film thickness transition with the velocity increase without a scoop under starved conditions. The film thickness for all the greases showed the transition to starvation between 0.2 and 0.4 m/s. In the low speed range just before the film thickness dropped, the film thickness values were similar to those under fully flooded conditions as shown in Fig. 10. The film decay of S1-A (Li soap) occurred earlier compared to L-A (Li complex). More frequent particle entrainments of L-A could contribute to the later starvation due to the more lubricant replenishment.

![Figure 13. Central film thickness of greases under starved conditions.](image)

3.6. Correlation of grease properties
The obtained results in this study are summarized in Table 2. The friction increase of Li complex grease that occurred in the high speed range indicated the grease channeling. The typical grease-like behavior was also observed for Li complex grease in the film thickness observations. The main reason for this behavior depended on the thickener particle entrainment in the contact area. On the contrary, for the Li simple soap grease, the thickener entrainment in the contact did not occur.

The thickener entrainment influenced not only the film thickness but also the flow patterns. Li complex grease showed flow patterns at the side track downstream of the contact. In contrast, Li simple soap thickener was not dragged into the contact, and therefore the edge of the track was also surrounded by thin area. For the film thickness measurement under starved conditions without using a scoop, the Li simple soap thickened grease caused quicker starvation. One of the reasons could be that the Li simple soap thickener was not dragged into the contact. Without thickener entrainment, there was less lubricant replenishment to the contact.

Comparing the power consumption results, the channeling effect of Li complex should contribute to the reduction of the grease stirring resistance in bearings as indicated in friction tests. In addition, the superior film formation of Li complex could assist the reduction of the power consumption.
Table 2. Summary of the results.

<table>
<thead>
<tr>
<th>Property</th>
<th>Li complex</th>
<th>Li simple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction without scoop</td>
<td>Friction increase at high speed</td>
<td>Close to base oil</td>
</tr>
<tr>
<td>Film thickness Fully flooded</td>
<td>Thick at slow speed</td>
<td>Close to base oil</td>
</tr>
<tr>
<td>Flow pattern</td>
<td>Finger patterns on side track cried</td>
<td>No fingers</td>
</tr>
<tr>
<td>Film thickness Starvation</td>
<td>Late starvation</td>
<td>Quick starvation</td>
</tr>
</tbody>
</table>

4. Conclusions
The influences of base oil, lithium-type thickener, and Mo additive in grease on the power consumption of bearing operation were investigated in this study. The base oil with lower viscosity and lower friction, the Li complex thickener, and a Mo additive were effective in the reduction of power consumption.
The advantage of Li complex thickener was examined through the measurement of grease properties. The rheological parameters such as viscosity and yield stress did not explain the difference in energy consumption by Li complex grease versus Li simple soap grease. In contrast, friction data from MTM tests suggested that Li complex grease had a greater tendency to undergo channeling in the bearing. The thinner and longer fiber structure of Li complex versus Li simple soap should influence the channeling behavior.

In addition, Li complex grease formed thicker films and delayed the starvation due to the thickener entrainment in the contact versus Li simple soap grease. The flow patterns created on the disk during film thickness measurements supported the interpretation of film thickness behaviors.

References
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Abstract
A novel class of Rheologically Stable Calcium Sulfonate Grease (abbreviated as RSCG) is being developed as a viable and cost competitive option to replace lithium grease. It combines the merits of overbased calcium sulfonate grease and polyurea grease and offers enhanced load carrying performance and structural stability.

1. Introduction
As automakers race to bring new models of electric vehicle (EV) to the marketplace, the grease industry is looking for options to replace lithium-based greases, which could be threatened should the demand outpace the supply in the foreseeable future. According to the NLGI 2017 Global Production Survey, lithium-based greases (shaded in yellow, Table 1) comprised 74% of the total grease market share. Calcium greases, including calcium sulfonate and calcium complex greases, (shaded in green) as well as polyurea greases (shaded in blue) are the two thickener types favored as lithium grease replacements [1-3].

<table>
<thead>
<tr>
<th>By thickener type</th>
<th>2017</th>
<th>2016</th>
<th>2015</th>
<th>2014</th>
<th>3-Yr % Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium Soap</td>
<td>74.35%</td>
<td>75.53%</td>
<td>74.40%</td>
<td>75.67%</td>
<td>-2%</td>
</tr>
<tr>
<td>Calcium Soap</td>
<td>11.26%</td>
<td>10.66%</td>
<td>10.43%</td>
<td>10.15%</td>
<td>11%</td>
</tr>
<tr>
<td>Polyurea</td>
<td>5.93%</td>
<td>6.09%</td>
<td>5.73%</td>
<td>5.31%</td>
<td>12%</td>
</tr>
<tr>
<td>Calcium Anhydrous</td>
<td>3.90%</td>
<td>3.87%</td>
<td>2.62%</td>
<td>3.23%</td>
<td>21%</td>
</tr>
<tr>
<td>Aluminum Soap</td>
<td>3.55%</td>
<td>3.20%</td>
<td>4.04%</td>
<td>3.53%</td>
<td>1%</td>
</tr>
<tr>
<td>Calcium Sulfonate</td>
<td>3.06%</td>
<td>2.62%</td>
<td>2.76%</td>
<td>2.62%</td>
<td>17%</td>
</tr>
<tr>
<td>Organophilic Clay Thickeners</td>
<td>2.16%</td>
<td>1.89%</td>
<td>2.28%</td>
<td>1.89%</td>
<td>14%</td>
</tr>
<tr>
<td>Other Non-soap Thickeners</td>
<td>1.40%</td>
<td>1.43%</td>
<td>1.49%</td>
<td>1.42%</td>
<td>-1%</td>
</tr>
<tr>
<td>Other Metallic Soap</td>
<td>0.92%</td>
<td>0.71%</td>
<td>1.22%</td>
<td>1.05%</td>
<td>-12%</td>
</tr>
<tr>
<td>Calcium Complex</td>
<td>0.83%</td>
<td>0.76%</td>
<td>0.84%</td>
<td>0.75%</td>
<td>11%</td>
</tr>
<tr>
<td>Sodium Soap</td>
<td>0.42%</td>
<td>0.50%</td>
<td>0.42%</td>
<td>0.97%</td>
<td>-57%</td>
</tr>
</tbody>
</table>

Table 1 - 2017 NLGI Production Survey

Yet, each type of grease has its unique characteristics, challenges, and limitations. For instance, overbased calcium sulfonate grease (OBCSG) has gained popularity due to its inherent extreme pressure (EP) performance. Nevertheless, the thickener structure of OBCSG is spherical in shape as opposed to the fiber-like structures in lithium, lithium complex, and polyurea greases. This difference in thickener structure was noted in an AFM study (Figure 1 [4]) of entrapped thickener in rolling contacts undergoing elastohydrodynamic lubrication (EHL) under fully flooded conditions at medium speeds.
Conceivably, the mechanical strength as well as EHL performance are tied to the inherent strength of the spherical cores in OBCSG and to the fiber or platelet thickness in lithium soap, lithium complex, and polyurea greases.

**Figure 1** - AFM study of thickeners entrapped in EHL contacts: lithium (top left), lithium complex (top right), calcium sulfonate complex (bottom left), and polyurea (bottom right) [4]

**Why RSCG?** - This paper covers continued efforts in this laboratory for the development of RSCG. By its name, Rheologically Stable Calcium Sulfonate Grease, RSCG is expected to better maintain the microstructure under loading and thermal stress that can be measured in different ways [5]. For instance, when grease is under a load (high, extreme, and constant mechanical stress), changes in the rheological properties of the grease are readily noticeable. For studying grease under thermal stress at elevated temperatures, a temperature sweep in rheological testing has become a quick, effective, and powerful tool. Rheological stability under stress is one of the new means used to evaluate and optimize grease performance.

The first RSCG example is an OBCSG nicknamed “Jade” Grease, Figure 2 [5]. This nearly transparent grease was found to be rheologically stable at 1500 °C (measured by viscosity) as compared to polyurea grease. The high production cost and availability of the Jade Grease have made it less commercially attractive for general purpose grease applications.

In recent years, new and improved versions of OBCSG were proposed as lithium grease replacements [1], yet challenges remain such as grease softening (sulfonate type under load) and hardening
(calcium complex under mechanical and thermal stress). In 2014, Wei disclosed factors that impact the rheological and tribological performance of OBCSG such as the type of overbase and the microstructures [6]. An OBCSG with optimal rheological stability is called RSCG.

**Figure 2** - Rotational viscosity data at 150 C for polyurea grease (green), two versions of OBCSG (blue and red), and calcium soap grease (purple).

**A Case Study** – In the present study, the approach as shown in Scheme 1 to make RSCG was to select and balance the chemistries between overbased sulfonates and complexing agents. By doing so, this laboratory succeeded in reducing the overbased content from between 35 and 40% to between 10 and 20%.

**Scheme 1 - Synthesis of RSCG Grease**

During the process development, the calcium carbonate gelled from amorphous to a mixture of vaterite and calcite crystalline structures that was confirmed by FTIR, Figure 2. The resulting grease (named Grease V) exhibited a surprisingly high load carrying performance (800 kgf weld load), as also noted previously [5].
However, Grease V did not possess the mechanical stability as good as the traditional calcite-based structure [7]. Vaterite is a metastable crystalline form of inorganic calcium carbonate. Once vaterite is formed, it is possible but difficult to change or alter it to the stable calcite core [7,8]. It is always a challenge and a headache for the grease manufacturers to post treat a grease production batch that does not go as expected in OBCSG grease manufacturing.

The next step was a novel approach to blend Grease V (vaterite and calcite) and Grease C (calcite) with polyurea greases (abbreviated PUG), which were made from preformed polyurea grease powder, as summarized in Table 2. The blending was carried out at ambient temperature. The resulting 50/50 blends exhibited markedly better mechanical stability as compared to lithium soap and lithium complex greases [3]. This improvement appeared to be due to synergy when Grease V (OBVSG) or Grease C (OBCSG) was blended with Grease P2 (PUG) or Grease P3 (PUG), and the thickeners merged into a “hybrid” thickener system that combined the fiber and spherical structures.

<table>
<thead>
<tr>
<th>Blend (50/50) Name</th>
<th>Thickener Structure</th>
<th>P60 D217</th>
<th>P10K D217</th>
<th>P10K-P60</th>
<th>4-ball Weld kgf</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>Vaterite and Calcite</td>
<td>255</td>
<td>311</td>
<td>56</td>
<td>800</td>
</tr>
<tr>
<td>P3</td>
<td>Preform PUG</td>
<td>220</td>
<td>262</td>
<td>42</td>
<td>100</td>
</tr>
<tr>
<td>P2</td>
<td>Preform PUG</td>
<td>308</td>
<td>334</td>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>C</td>
<td>Calcite</td>
<td>271</td>
<td>296</td>
<td>24</td>
<td>500</td>
</tr>
<tr>
<td>P3 + V</td>
<td>Hybrid</td>
<td>262</td>
<td>286</td>
<td>24</td>
<td>620</td>
</tr>
<tr>
<td>P3 + C</td>
<td>Hybrid</td>
<td>283</td>
<td>302</td>
<td>18</td>
<td>400</td>
</tr>
<tr>
<td>P2 + C</td>
<td>Hybrid</td>
<td>312</td>
<td>315</td>
<td>3</td>
<td>400</td>
</tr>
<tr>
<td>P10</td>
<td>Preform PUG</td>
<td>269</td>
<td>270</td>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>

*Table 2 – Grease blends (50/50), thickener structures, and test results for mechanical stability and load carrying performance. Consistency was measured by cone penetration (0.1 mm), ASTM D217, after working 60 strokes and 10K strokes. Mechanical stability was evaluated by the difference between P60 and P10K. Load carrying EP performance was measured by 4-ball weld load (kgf), ASTM D2596.*
Other greases with hybrid-type thickeners, such as lithium-calcium greases, are commercially available. Care must be taken to ensure consistency during the conversion process.

With the aid of preformed thickener, polyurea grease manufacturing is simplified [2]. It is now possible to make blends and adjust the blend ratio (Figure 4) with ease to come up with a lithium-free calcium-polyurea mixed grease (e.g., P2 + C) with the desired and improved performance.

![Figure 4](image1)

**Figure 4** – Worked cone penetration data (P60, 0.1 mm) for PUGs, OBCSGs, and blends

Rheology testing is a powerful tool used to test new and in-service grease [9]. In this study, a HAAKE MARS 40 rheometer (Thermo Fisher Scientific™) was used to measure $G'$ (elastic or storage modulus, solid character of the grease) and $G''$ (viscous modulus, fluid character of the grease) versus rate of shear. Figure 5 reveals that an OBCSG RSCG had higher $G'$, and flow point (crossover of $G'$ and $G''$) was at lower frequency, than two PUGs.

![Figure 5](image2)

**Figure 5** – Rheological data for log $G'$ and $G''$ (Pa) vs. log frequency (rad/sec) for OBCSG RSCG (red) and two PUGs (blue, green)
When grease samples were subjected to thermal stress (a temperature sweep from 25 to 150 °C, Figure 6), there was substantial softening (\(G'\) dropped nearly 70%) for OBCSG Grease C1, whereas polyurea Grease P2 had a minimum reduction in \(G'\), a clear sign of greater temperature stability.

![Rheological data for greases under thermal stress](image)

**Figure 6** - Rheological data for greases under thermal stress

In this laboratory, work is progressing in the development of an RSCG to provide outstanding load carrying performance while maintaining the mechanical and high temperature stabilities. Work is underway to explore fully the synergism seen in the case of RSCG OBCSG-PUG blends reported in this paper.

**Conclusions** - Today, there is a host of modern and powerful tools such as rheological and tribological testing available to evaluate and develop grease for optimal performance. For instance, thermal stress rheology testing revealed the superior thermal stability of polyurea greases that outperformed OBCSGs. Via four-ball tribological testing, the presence of OBCSG in RSCG blends provided the load-carrying performance.

In summary, the results of this study showed that RSCGs combined the merits of overbased calcium sulfonate greases and polyurea greases. The RSCGs in this work offered enhanced load carrying performance and structural stability. Thus, these RSCGs are a viable option to effectively replace lithium and lithium EP greases.

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**References**
5. "The path leading to a Novel OBGS Grease with superior high temperature performance for extended use", Liwen Wei, NLGI Annual Meeting, Palm Beach, FL USA, June 12, 2012; NLGI Spokesman, 77:4, 2013.
Environmental, Health, and Safety (EH&S) regulations for the oil and gas (O&G) industry are plentiful, and the stakes are high if an organization chooses not to comply with them. Even though rules continue to multiply, their implementation creeps slowly, depending on the risk severity. For example, over the past several years, the O&G industry has been slow to phase out lead-based thread compounds and replace them with nonmetallic options.

Thread compounds are grease-based lubricants with a high solids content. The finished product is applied to threads of rotary shoulder connections, casing, and tubing joints in order to lubricate, protect, seal, and control make-up of pipes. Heavy metals such as lead powder, copper flake, and zinc dust are typical solids used in thread compounds. The O&G industry is finally beginning to see a shift where end users want to switch to lead-free products. As a result, many thread compound manufacturers are electing to stop making leaded products. Furthermore, the next wave of regulations, not new but swiftly being accepted globally, to affect the thread compound industry requires environmentally friendly products.

After a brief overview of EH&S regulations, this paper will describe some reasons why anhydrous calcium and calcium complex greases can fulfill the need for a biodegradable, nontoxic, and non-bioaccumulative matrix for environmentally friendly thread compounds. Additionally, this paper will explore the performance characteristics and ecological toxicity of both grease types compared to a conventional lithium grease base for thread compounds. Technical terms specific to thread compounds and their applications are italicized the first time they appear in the text, and they are defined at the end of this paper.
Regulations
OSPAR
There have been stringent environmental regulations on the O&G industry in Europe for over a decade, such as the offshore exploration and production regulations for protection of the marine environment in the Northeast Atlantic Ocean governed by the *OSPAR Convention*. This agreement to reduce pollution in the North Sea was signed and ratified by many European countries. At present, chemicals for offshore use are ranked by their hazard severity, and product use is controlled by each country’s laws. The ranking scheme is based upon bioaccumulation, biodegradation, and marine toxicity test results (see Table 1 – Ecological Toxicity Test Requirements).

For mixtures such as thread compounds, individual substances are evaluated. Many of the solids in environmentally friendly compounds are inorganic or pose little or no risk (PLONOR) when used and discharged offshore; thus, they are exempt from testing. In thread compounds, the grease base consists of a lubricating fluid (oil, PAO, ester, etc.) dispersed in a thickening agent (metallic soap, clay, polymer, etc.) For environmentally acceptable thread compounds, the grease bases must be inherently biodegradable and not bioaccumulate in aquatic organisms. According to ExxonMobil, “The rate of biodegradation is defined as inherent or ready. Inherently biodegradable means biodegradation greater than 20% in 28 days or 12 weeks, depending on the test. Readily biodegradable or ready biodegradability means biodegradation greater than 60% in 28 days, and the 60% level is reached within 10 days of reaching the 10% mark (“10-day window” criterion) using unacclimated bacteria” Actual test results for anhydrous calcium and calcium complex grease are given below in Table 2 - Ecological Toxicity Test Results.

**Table 1 - Ecological Toxicity Test Requirements (OSPAR)**

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Definition</th>
<th>OSPAR Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioaccumulation</td>
<td>A substance accumulates in the fatty tissues of aquatic organisms</td>
<td>Molecular Weight &gt;700 or Log *P&lt;sub&gt;ow&lt;/sub&gt; &lt; 3</td>
</tr>
<tr>
<td>Biodegradation</td>
<td>A substance breaks down relatively quickly by biological means into the raw materials of nature and disappears into the environment. (GreenGood USA, 2013)</td>
<td>≥20% in 28 days; &gt;60% in 28 days</td>
</tr>
<tr>
<td>Marine Toxicity</td>
<td>A substance is fatal to marine life at a certain concentration</td>
<td>**LC&lt;sub&gt;50&lt;/sub&gt; &gt; 10 mg/l or ***EC&lt;sub&gt;50&lt;/sub&gt; &gt;10 mg/l</td>
</tr>
</tbody>
</table>

*P<sub>ow</sub> is the equivalent to K<sub>ow</sub> and means the partition coefficient of a substance between n-octanol and water, measured or calculated according to HOCNF Guidelines.

**LC<sub>50</sub> means the median lethal concentration, i.e., that concentration of the test substance that kills 50% of a test batch of organisms within a defined period of exposure.

***EC<sub>50</sub> means the concentration of a test substance that results in a 50% response to the effect measured by the test (e.g., reduction in either growth or growth rate relative to the control) within a defined period of exposure.
Products complying with the OSPAR requirement also meet the following regimes/programs: United States Environmental Protection Agency (US EPA) definition of an environmentally acceptable lubricant (EAL), US Vessel General Permit (VGP), European Union Ecolabel, Blue Angel, Nordic Swan, Swedish Standard SS 1554701, and EPA's Design for the Environment (DfE) (Environmental Protection Agency, 2018). Products containing heavy metals or persistent chemicals do not meet the above OSPAR requirements. Environmentally unacceptable products are labeled with a substitution warning and require justification for use.

**REACH**

REACH is an acronym for Registration, Evaluation, Authorization, and Restriction of Chemicals. The REACH regulation entered into force June 1, 2007 with progressive deadlines for substances to be preregistered, depending on volumes imported and hazard classification, prior to the ultimate deadline of May 31, 2018 for full registration. Thread compounds may contain substances classified as exempt from REACH regulation. There are several categories of REACH-exempt substances:

- PLONOR according to OSPAR,
- substances of very high concern (SVHC); i.e., carcinogenic, mutagenic, or toxic to reproduction (CMR),
- persistent, bioaccumulative, and toxic (PBT), and
- restricted, i.e., substance shall not be placed on the market or used in certain applications to prevent unnecessary exposure to humans and the environment by limiting treat rates/concentrations.

Environmentally friendly thread compounds are free of CMR and PBT ingredients. Examples of thread compound ingredients in each of these categories will be shared in the Thread Compound Formula section of this paper.

Disposal of packaging containing residual thread compounds is also restricted. End users are advised to contact their local waste disposal facility for proper material disposal recommendations.

**Health and Safety**

Safety Data Sheets (SDS) describe the health, physical, and environmental hazards of a product. Health and Safety regulations differ from region to region. The Globally Harmonized System (GHS), introduced in the US on June 1, 2015, helps to standardize warning language and reduce confusion that was caused by conflicting international requirements.

As previously mentioned, thread compounds contain a combination of lead, copper, zinc, natural nonmetallic minerals, and liquid additives. The solid dusts and flakes are inextricably bound in the grease, which reduces exposure by inhalation. Proper personal protective equipment and hygiene practices are strongly encouraged to decrease the risk of contact. However, lead powder is a carcinogen and considered very toxic to aquatic life. Products that are hazardous to the aquatic environment require the ‘Tree Fish’ pictogram on the SDS. The ‘Tree Fish’ symbol can also be applied to product packaging, depending on the mode of transit to the end user.

O&G service companies and pipe OEMs have taken the initiative to use proprietary connections without pipe dope to eliminate the need for thread compounds, or to use only nonmetallic thread
compounds to eliminate this hazard. Thread compound manufacturers are challenged to formulate metal-free thread compounds without sacrificing performance while staying cost competitive.

**Thread Compound Formula**
The generic formula of a thread compound is: \( \text{grease base} + \text{solids} + \text{additives} = \text{finished product} \).

As mentioned previously, the functions of thread compounds are to seal (prevent leaks), lubricate (reduce the coefficient of friction), protect (prevent metal-to-metal contact resulting in galling and seizing of connections), and control make-up. The solids in the thread compound formulation provide sealing and protection, and assist in controlling make-up when using the appropriate make-up torque. Torque can be measured as foot pound units describing the twisting force. One foot-pound measures the force to move one pound of matter one foot around an axis of rotation with a radius of one foot (“What Is A Foot Pound of Torque?”, 2015).

**Grease Base**
The lubricating grease in thread compounds has many functions. It is the vehicle carrying the solids onto the threads. In addition, the grease ensures adhesion to wet threads, helps reduce the coefficient of friction at make-up and *breakout*, and impacts application at cold temperatures.

Metallic dusts, powders, and flakes are dense. American Petroleum Institute’s Recommended Practice on Thread Compounds for Casing, Tubing, Line Pipe, and Drill Stem Elements (API 5A3), Third Edition (2009, Reaffirmed 2015) requires compound labels to state “STIR WELL BEFORE USING” because the solids can settle to the bottom of the pail or drum in storage. After thoroughly mixing the product, the grease helps keep the solid particles suspended so a uniform coating of solids will be applied on the contact surfaces.

A common feature of grease is its tackiness or stickiness. Thread compounds should be applied to clean, dry threads for best performance. In drilling applications, drilling fluid, also known as *drilling mud*, floods the *connection box* (female end of the pipe) creating a dirty, wet surface. The tackiness of the grease allows thread compounds to stick to metal surfaces covered with water- or oil-based drilling muds and resist washing off when connections are added to the *drill string*.

Thread compound on a threaded connection
The lubricity of the grease is important to control pipe make-up. The oil in the grease allows the connections to rotate when torque is applied until the shoulders join and make-up is complete. Firstly, it is important to know the recommended make-up torque (MUT) for the connections in use. Secondly, the friction factor, or torque adjustment factor, for the thread compound must be multiplied by the recommended optimum MUT. Damage to the pipe can occur if the thread compound’s friction factor is not calculated properly at make-up.

O&G operations take place in every climate around the world. Thread compounds are required to stick to hot metal stored in pipe yards in the Middle East as well as cold steel at temperatures down to -40 F (-40 C) in Alaska or Northern Canada. Providing a product with a wide operating temperature range is achieved by adjusting the finished product penetration or selecting raw materials that are fit for extreme conditions, such as synthetic oils. Solids extend the maximum service temperature of thread compounds because powders or flakes either melt or decompose at temperatures well above ambient or downhole temperatures. The challenge is typically applying a thread compound at arctic temperatures. The selected grease thickener and viscosity of diluent oil can improve brushing application at cold temperatures.

**Solids**

Lead is a SVHC, its use is restricted by REACH, and the O&G industry is demanding a safer alternative. Nevertheless, lead powder works. It is malleable and absorbs much of the energy applied upon make-up by deforming and flattening to reduce the amount of stress on connections under torque. Products containing lead are still used worldwide because they are included on lists of thread compounds approved by pipe OEMs. Some end users are now favoring metal-free thread compounds, and one of the oilfield service companies is restricting the use of metallic thread compounds to eliminate associated health, safety, and environmental risks.

Calcium carbonate, calcium oxide, and graphite are typical thread compound components categorized as PLONOR and exempt from REACH registration. Most nonmetallic solids are brittle and break apart when torque is applied, unlike lead powder. Nevertheless, thread compound formulations have advanced, improving the performance of metal-free products to work as well as their metallic counterparts.

**Surface Protective Additives**

Thread compound formulations contain the same extreme pressure, anti-wear, corrosion inhibiting, and tackifier additives used in industrial lubricants. Many of the environmentally friendly solid minerals and selected greases have inherent performance properties that eliminate the need to top treat thread compounds with surface protective additives that contain harmful components.

**Grease Selection**

Simple lithium 12-hydroxystearate grease is a conventional base for thread compounds because of the following benefits:

- Moderate dropping point
- Good water resistance
- Receptive to additives

Simple lithium soap greases made with naphthenic oil of moderate viscosity are great for use under standard drilling conditions, where a compound is applied by brush at temperatures as low as 10 F
(-12 C) and the maximum service temperature is above 250 F (121 C). Unfortunately, naphthenic oils do not meet OSPAR biodegradation requirements.

Anhydrous calcium 12-hydroxystearate and calcium complex greases are suitable bases for environmentally acceptable thread compounds. According to the European Chemicals Agency (2012) Guidance for Annex V Entry 9, “Vegetable fats, vegetable waxes; animal fats, animal waxes; fatty acids from C6 to C24 and their potassium, sodium, calcium and magnesium salts; and glycerol” are exempt (i.e., pose little or no risk to the environment) if these substances are obtained from natural sources and are not chemically modified, unless they are classified as dangerous according to Directive 67/548/EEC, with a few exceptions. Proving that calcium thickener is not chemically modified can be difficult, and many manufacturers chose to register the substance with REACH, even though ecological toxicity test results for the soap prove to be environmentally friendly when formulated with a light, biodegradable oil (see Table 2).

<table>
<thead>
<tr>
<th>Test</th>
<th>OSPAR Requirement</th>
<th>Anhydrous Calcium 12-Hydroxystearate Grease</th>
<th>Calcium Complex Grease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioaccumulation</td>
<td>Molecular Weight &gt;700 or Log P&lt;sub&gt;ow&lt;/sub&gt; &lt; 3</td>
<td>Molecular Weight &gt; 700</td>
<td>Molecular Weight &gt; 1000</td>
</tr>
<tr>
<td>Biodegradation</td>
<td>&gt;28% in 28 days or &gt;60% in 28 days</td>
<td>&gt; 40%</td>
<td>&gt; 50%</td>
</tr>
<tr>
<td>Marine Toxicity</td>
<td>LC&lt;sub&gt;50&lt;/sub&gt; &gt; 10 mg/l or EC&lt;sub&gt;50&lt;/sub&gt; &gt;10mg/l</td>
<td>&gt; 5,000 mg/l</td>
<td>&gt; 2,000 mg/l</td>
</tr>
</tbody>
</table>

Anhydrous calcium 12-hydroxystearate grease and calcium complex grease have several advantages over lithium 12-hydroxystearate grease in thread compound formulations. Anhydrous calcium greases have good water resistance to aid in keeping the thread compound in place when tripping pipe. Simple lithium greases have moderate water resistance.

Based on experience, the anhydrous calcium 12-hydroxystearate grease has exceptional low temperature brushing application properties below -40 F (-40 C). It is ideal for use in arctic conditions. This grease’s consistency allows for great mobility, and it pumps properly in automatic lubrication systems. Anhydrous calcium 12-hydroxy grease has a lower maximum working temperature compared with other greases. Fortunately, the solid powders and flakes in the thread compound formula increase the service rating temperature of the finished product.

Calcium complex grease has a higher maximum operating temperature and satisfies customer preference for a high temperature grease base compared to simple lithium grease. Other advantages of calcium complex grease are its inherent surface protecting properties, such as extreme pressure performance and corrosion inhibition.
Rust and corrosion protection are important properties for the O&G industry. Drill pipe can be stored in the pipe yard for an extended period of time. Storage compounds are used to protect the threaded area from rust and corrosion, but cannot be used as make-up or casing the well. Storage compounds must be removed before thread compound can be applied. Any residual storage compound, cleaning solution, or moisture displacer can affect the performance of the thread compound. Thread compounds containing calcium complex grease are considered hybrid products because they provide storage protection in the yard and are suitable for make-up.

Table 3 – Typical Grease Characteristics (based on specification sheets and actual test data)

<table>
<thead>
<tr>
<th>Oil Type</th>
<th>Anhydrous Calcium Grease</th>
<th>Calcium Complex Grease</th>
<th>Lithium 12-Hydroxystearate Grease</th>
<th>Anhydrous Calcium Thread Compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dropping Point F (C), ASTM D2265</td>
<td>270 (132), min</td>
<td>450 (232), min</td>
<td>350 (177), min</td>
<td>300 (149), min</td>
</tr>
<tr>
<td>Salt Fog Protection, ASTM B117</td>
<td>0 hours</td>
<td>&gt; 500 hours</td>
<td>Up to 500 hours</td>
<td>0 hours</td>
</tr>
<tr>
<td>4-Ball Weld, ASTM D2596</td>
<td>Fair</td>
<td>Good</td>
<td>Fair</td>
<td>Excellent</td>
</tr>
<tr>
<td>Water Spray Off, ASTM D4049</td>
<td>Excellent</td>
<td>Good to Excellent</td>
<td>Good</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

The incorporated solids boost the grease base functions so thread compounds can withstand the severe drilling and downhole conditions. Figure 1 illustrates the thread compound physical and chemical characteristics tests reported in API 5A3.

Figure 1 - Compound Comparison Chart

Figure Key: Standard compound contains lithium 12-hydroxystearate grease; Environmentally Friendly – A contains calcium complex grease; and Environmentally Friendly - B contains anhydrous calcium 12-hydroxystearate grease. All compounds contain approximately from 50 to 60% grease and from 40 to 50% solids.
All three compounds in this study met or exceeded API 5A3 requirements. The results were further assessed and ranked good, better, or best, depending on test values. The standard grease base compound was best overall, but the environmental compounds fared better than the standard thread compound in dropping point (A), corrosion inhibition (A), and application at cold temperatures (B).

**Future Work**
There are numerous biodegradable greases and oils to consider when developing new and improved, environmentally friendly thread compounds. Cost is a limiting factor. The O&G industry regards thread compounds as commodity products and expects them to be priced accordingly. This challenges thread compound formulators to create innovative products that are affordable with improved performance.

Experimenting with bio-based raw materials that have acceptable thermal stability and oxidative resistance is the next step for development of new thread compound products. Creating cutting-edge solutions to meet the environmental, health, and safety requirements for the O&G industry is an exciting challenge.

**Conclusions**
Thread compound formulations continue to advance in complexity as regulations (and drilling conditions) change. Some end users are selecting thread compounds that are safer for the environment and their employees to handle. As a result, it is necessary for thread compound manufacturers to provide a suitable alternative to conventional products. Fortunately, anhydrous calcium 12-hydroxy and calcium complex greases show promise as means to satisfy these needs for an environmentally friendly grease base for use in thread compound formulations.

**Acknowledgements**
The author wishes to acknowledge Catherine Henderson and Joshua Boone at Bestolife Corporation for their contributions to this work. Also, a special thanks to Bestolife Corporation’s grease suppliers for very helpful discussions. This paper was based on a presentation given at the 86th Annual NLGI Meeting, June 8-11th, 2019, at JW Marriott Resort, Las Vegas, Nevada, USA.

**Technical Terms** *(Schlumberger Oilfield Glossary)*

- **Breakout** – The process of unscrewing threaded drilling components.

- **Casing** - Large-diameter pipe that is lowered into a wellbore, which is an open hole that is drilled as part of the process to discover and recover oil or gas. This process is referred to as “running pipe”. Casing is cemented into place and used to stabilize the wellbore and prevent it from caving in, control fluids and pressure in the wellbore, protect freshwater from contamination, etc. It is designed to withstand collapse, bursts, and tensile failure, and chemically aggressive brines. Most casing joints are fabricated with male threads and joined by couplings with female threads. Casing is often manufactured from heat-treated carbon steel.

- **(Connection) box** - A female thread form (internally threaded) for tubular goods and drill string components.

- **Drill pipe** - Tubular steel conduit fitted with special threaded ends called tool joints. Drill pipe connects the rig surface equipment with the bottom hole assembly and the bit, in order to pump drilling fluid to the bit and to raise, lower, and rotate the bottom hole assembly and bit.
**Drill string** - The combination of the drill pipe, the bottom hole assembly, and any other tools used to turn the drill bit at the bottom of the wellbore.

**Drilling mud** - Any of a number of liquid and gaseous fluids and mixtures of fluids and solids (e.g., solid suspensions) used in operations to drill boreholes into the earth. May be used synonymously with “drilling fluid”, which may refer to more sophisticated and well-defined “muds.” A classification scheme for drilling muds is based solely on the component that clearly defines its function and performance: (1) water-based, (2) non-water-based, and (3) gaseous (pneumatic).

**Friction factor (torque adjustment factor)** – A multiplier (factor) applied to connection make-up torque (MUT) to correct for the frictional property difference between a thread compound and a reference compound:

\[ \text{MUT} = \text{listed MUT} \times \text{friction factor} \]

**Grease base** – A formulation comprised of thickening agent and lubricating fluid.

**Make-up** - To tighten threaded connections.

**Make-up torque** - The rotational force used to make-up a connection in the string.

**Oilfield service company** – A company that provide services to the petroleum exploration and/or production industries, but typically does not produce petroleum.

**OSPAR Convention** - The Convention for the Protection of the Marine Environment of the North-East Atlantic (the ‘OSPAR Convention’) is an agreement that covers all human activities (including prevention and elimination of pollution from offshore sources) that might adversely affect the marine environment of the northeast Atlantic Ocean. It was signed by Belgium, Denmark, the European Union, Finland, France, Germany, Iceland, Ireland, the Netherlands, Norway, Portugal, Spain, Sweden, and the United Kingdom of Great Britain and Northern Ireland along with Luxembourg and Switzerland, and entered into force in March 1998.

**Pipe dope** - A specially formulated blend of lubricating grease and fine metallic particles that prevents thread galling (a form of metal-to-metal damage) and seals the roots of threads. The American Petroleum Institute (API) specifies performance properties of pipe dope, including coefficient of friction. The rig crew applies copious amounts of pipe dope to the drill pipe tool joints every time a connection is made.

**Rotary shoulder connection** – A connection, used on drill stem elements, that has threads and sealing shoulders.

**Storage compound** – A substance applied to threaded pipe connections for protection against corrosion during shipment and/or storage. Storage compounds are not used for connection make-up.

**Thread compound** – A substance applied to threaded pipe connections prior to make-up, for lubrication during assembly and disassembly, and for assistance in providing a seal against internal and external pressures.
**Tripping pipe** - The act of pulling the drill string out of the hole or replacing it in the hole. A pipe trip is usually performed because the drill bit has dulled or has otherwise ceased to drill efficiently, and must be replaced.

**Tubing joint** - A single length of pipe that is assembled to provide a conduit through which oil or gas will be produced from a wellbore. Tubing joints are generally around 30 ft [9 m] long with a threaded connection on each end. The specification of the tubing material, geometry of the tubing, and design of the connection thread are selected to suit the reservoir fluid and wellbore conditions.

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Modern Technology Improves the Grease Making Process

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ABSTRACT
This paper gives a concise review of the history and implementation of programmable logic controls, digital control systems, and digital instruments to replace analog instruments in batch and continuous grease manufacturing systems. These technologies improve grease-making operations and the repeatability of grease formulations in production.

INTRODUCTION
Reproducibility of grease production has been an issue that has plagued the industry nearly as long as grease has been produced. This challenge became more apparent when higher performance products became the standard due to increasingly tight specifications dictated by original equipment manufacturers (OEMs).

Wikipedia defines a true grease as having the following properties:
“A true grease consists of an oil and/or other fluid lubricant that is mixed with a thickener, typically a soap, to form a solid or semisolid. Greases are a type of shear-thinning or pseudo-plastic fluid, which means that the viscosity of the fluid is reduced under shear. After sufficient force to shear the grease has been applied, the viscosity drops and approaches that of the base lubricant, such as the mineral oil. This sudden drop in shear force means that grease is considered a plastic fluid, and the reduction of shear force with time makes it thixotropic”

So, grease is really thickened oil. The thickener is used to provide the shear-sensitive performance. The thickener could be an organic soap, an inorganic powder like fumed silica, a calcite matrix, polymer matrices, or even tar. For this discussion we will concentrate on organic soaps; they are used in the most common and commercially important types of grease.

What is so hard about that?

THE PROBLEM STATEMENT
It is not unusual for grease makers to comment that they can use the same formula and the same raw materials, but obtain different results for batches of grease. Quality control of grease is based on physical measurements of the final product through tests, including ASTM standards, IP standards from the Energy Institute, and British Defence Standards (Def Stan) issued by the Ministry of Defence of the United Kingdom (MODUK):

Grease laboratory tests:
• Dropping Point, ASTM D566, IP 396
• Cone Penetration, ASTM D217, IP 50
• Oxidation Stability, ASTM D952, IP 142
• Copper Corrosion, ASTM D130, IP 112
• Corrosion Preventative Properties, ASTM D1743, IP 220
• Oil Separation, ASTM D6184, IP 121/Def Stan, 05-50 part 9
• Working Stability of Grease Contaminated with Water, ASTM D8022, IP 50/Def Stan, 05-50 part 63
• Low Temperature Torque, ASTM D1478, IP 186
• Fretting Wear Protection, ASTM D4170
• Evaporation Loss, ASTM D972, IP 183
• Anti-Wear Properties by Four-Ball, ASTM D4172, IP 239
• Wheel Bearing Leakage, ASTM D1263
• Compatibility of Mixtures, ASTM D6185 or as required
• Water Washout Test, ASTM D1264, IP, 215

Grease and lubrication engineering tests:
• Grease Rolling Bearing Performance, IP 168
• Pope test (Life of Lubricating Greases in Ball Bearings at Elevated temperatures), ASTM D3336
• Grease Churning test, IP 266

In a production setting, these tests are often abbreviated to Cone Penetration and Drop Point tests as the means of QA/QC of the product prior to packaging and shipping. What are these tests really measuring? They are measuring how well the thickener fibers have been made and how well they “hold” the oil.

Grease manufacturers are the originators of the various grease formulations and production “recipes.” Equipment suppliers provide the process equipment that is required to re-produce the product as developed by the manufacturer’s R&D department. Perhaps the simplest R&D equipment used to produce greases consists of a hot plate, a thermometer, a spatula, and a sauce pan operated manually by a chemist in a laboratory hood. It is possible to make some prototype complex greases in this fashion. This laboratory-scale equipment is a variation of the flame-heated open kettles used for centuries to make grease on a commercial scale. (Frankly, some plants still operate in some capacity with this equipment.) But, when a “recipe” or formulation leaves the laboratory and goes into production, the equipment becomes more complex. Required equipment typically consists of:
• A raw material supply system
• A reaction vessel
• A mixing kettle (which could be the same reaction kettle)
• A milling or homogenization system
• A filtering system
• A packaging system

These processes are supported by utility systems including:
• A heating system
• A cooling system
• Connecting piping
• Ventilation and perhaps vacuum systems
• Manual controls and instruments or an integrated control system with integrated instruments.

The advent of instruments with better repeatability and better process controls has greatly improved the reproducibility of the grease formulations in production, but more opportunities for improvement remain.
**BATCH SYSTEMS**

In the first third of the 20th century, reaction vessels such as the autoclave and the STRATCO® Contactor™ increased the efficiency of soap manufacture by transferring heat into the reactants much more effectively than open kettles. But, controls and control philosophy did not keep pace with the improved reaction capability. Dial gauges, strip charts, or circular recording instruments provided some indication of what was happening in the reactor vessel, but repeatability was uneven from operator to operator and even by the same operator.

Recent installations have seen PLC-based systems and digital instruments replacing the analog instruments of the past with improvements in repeatability. PLC (programmable logic controller) and DCS (digital control system) systems are designed to capture the trends and the history of data, allowing for better analysis of the reaction process.

What does a modern batch system look like?

![Modern batch system diagram](Figure 1)

Well, Figure 1 looks conventional, but the DCS is a critical component:

- The base oil is measured by a mass flow meter controlled by the DCS.
- Water addition is measured by a magnetic flow meter and controlled by the DCS.
- The reactor pressure is sent digitally to the DCS.
- The reactor temperature is sent digitally to the DCS.
- The reactor heating (cooling) valves are controlled by the DCS.
- The circulation current draw is measured by the DCS.
- The reactor pressure and venting are controlled by the DCS.
- Transfers are made automatically through the DCS.
- The addition of base oil to the kettle is measured by a mass flow meter and controlled by the DCS.
- The stirrer current draw is measured by the DCS, and the transition through the fiber forming stage is controlled accordingly.
- The DCS keeps a history of the measurements of each batch, allowing analysis of different reactions and resulting product differences when they occur.

With the proper implementation of instrumentation and control, the DCS allows for improved repeatability from batch to batch – i.e., more consistency of the consistency. This modern setup is one solution to the problem of reproducibility of the grease formulations in production.

CONTINUOUS GREASE PRODUCTION (CGU)

Ever since Texaco commercialized the continuous grease process in the late 1980s (see Witte et al.), little has been done to improve its operation until recently. Control was usually analog, with its inherent imprecision.

By applying a proper modern control philosophy and applying the latest instrumentation to improve the predictability of the reaction, it is possible to improve the repeatability of the product and reduce costs. Related process and instrumentation improvements provide better control of the dehydration, cooling, and finishing of greases. This is all possible in an improved continuous grease production unit.

![Figure 2 Continuous grease unit diagram](image-url)
Implementation of a modern control philosophy using a DCS tied to digital temperature and pressure instruments, digital control valves with zero dead band, variable speed drives on the transfer pumps, and an on-line viscosity instrument that has a positive correlation with penetration, provides more precise control and predictability.

So, similar to the modernized batch process, the measurement and control system improves performance and predictability by implementing the following functions:

• The base oil is measured by a mass flow meter controlled by the DCS.
• Water addition is controlled by the DCS.
• The reactor pressure is sent digitally to the DCS.
• The reactor temperature is sent digitally to the DCS.
• The reactor heating (cooling) valves are controlled by the DCS.
• The circulation current draw is measured by the DCS.
• The reactor pressure and flash vessel venting are controlled by the DCS.
• Transfers are monitored automatically through the DCS.
• The addition of let-down oil and additives to the CGU are measured by mass flow meters and controlled by the DCS.
• The motor current draw is measured by the DCS, and the transition through the fiber forming stage is controlled accordingly.
• The DCS keeps a history of the measurements of each production run, allowing analysis of different reactions and resulting product differences when they occur.

Other advantages include:

• Ability to completely flush the unit between products and save the resulting product for the next production run.
• Ability to make natural and black greases on the same unit.
• NLGI grades from 00 to 2 can be made without additional cooling. But, with additional cooling, NLGI grade 3 is possible.
• Capacities can be from 1 to 2.5 TPH (tonnes per hour) of finished grease.

**Figure 3** Continuous grease unit model (left) and picture (right)
Other steps taken to improve the production process and reduce operating costs in a modern Continuous Grease Unit through process design include:

- Reduction in the water load on the system from the LiOH aqueous solution, resulting in greatly improved energy efficiency,
- Possible elimination of the use of methyl ester or ethyl ester of 12-hydroxy stearic acid and reduction of venting of methanol (MeOH) and ethanol (EtOH),
- Longer continuous production run capability, and
- Non-soap chemistries like polyurea greases.
- The proper implementation of a modernized Continuous Grease Unit can be an advantage in initial and operating costs.

CONCLUSION
The proper selection of equipment, instrumentation, control, and technologies can make a difference in the cost and operational economics of any grease plant. For existing plants, the implementation of new measurement and control technologies is likely to improve the operation and its repeatability. For a new plant, the choice of batch, continuous, or a mixture of both types of processing can be a more involved discussion. Both batch and continuous processing technologies are available in the marketplace based on individual needs.

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ACKNOWLEDGEMENTS
Pictures and diagrams are courtesy of Emerson Automation Solutions. The use of STRATCO® and Contactor™ is by permission. The Author recognizes the contribution of Arnold Witte in the improvement of the Continuous Grease Unit.
South Dakota became the 40th state of the US in 1889; 40 courses were served at a recent nine-hour marathon dinner at Italian restaurant Le Virtu (Philadelphia); and there are 40 stories in the tallest building in the state of Arizona (Phoenix).

Forty U.S. patents? Read (and rock) on!

Career

NLGI: How did you become a scientist?

JAW: Well, to answer that, I need to go back to the fifth grade. Up until then, I had been, at best, a mediocre student with little interest in any subject except recess. But our country entered the so-called “space race” with the Soviet Union and started a new approach to teaching arithmetic in public grade schools called ‘the new math’. Basically, it was arithmetic taught from an algebraic view-point. My fifth-grade arithmetic text book, with equations that had letters instead of numbers, triggered my interest. I spent hours each evening with my (non-electronic) tablet, pencil, and textbook doing problems, manipulating equations, and exploring algebra.

This started a cascade effect where I became interested in science. By the time I was a junior in high school, I knew I wanted to go into chemistry.

I chose to attend Central Methodist College (Fayette, MO) because it was a college that offered smaller classes and more direct interaction with the professors than larger schools. Also, Central had a very good Music Department, and I would be able to be an active part of it even without being a music major. (Besides chemistry, my other great love was and is music, as a trombonist and an avid listener.) I graduated with my Bachelor of Arts in Chemistry.

NLGI: What happened next?

JAW: When I was a junior at Central, I knew that I wanted to continue my education in chemistry and get an advanced degree. One of my chemistry professors had a good friend who was a professor in the Inorganic Chemistry Department at Purdue, and I was impressed by what I learned about that Department. So I applied to Purdue and was accepted. I had originally planned to concentrate in inorganic chemistry. But during my first year in grad school, I was seduced by quantum chemistry and its mathematical foundation. Remember, I loved math, especially calculus, differential equations, and matrix algebra. So, I concentrated in physical chemistry – specifically quantum chemistry.

After three years, I had taken all the required courses and passed all my written exams to qualify for a Ph.D. But when I reviewed my priorities and the job market, I decided to graduate with my Masters degree and launch my career. I have had a very good career, and I am happy with how everything turned out.

Andy working hands-on at the bench
NLGI: What was your first job?

JAW: I joined Land O’Lakes (Minneapolis, MN) as an entry-level research chemist in the Exploratory Research Department. In some ways, this was the most important job I would have because my boss was a very sharp Ph.D. biochemist who had excelled in both academic and industrial research, and who understood the differences between them. He taught me the importance of clearly defining the project objective, keeping that objective in front of my eyes at all times, and properly using the literature to discover things other researchers had missed – diamonds in the rough. It is a method I have used ever since.

After IH filed for Chapter 11 bankruptcy, I joined Amoco Oil Company at their large research center in nearby Naperville, IL where I would stay for 17 years. Once again, I would work for and with people who “just happened” to have the knowledge and experience that I needed to progress in my career. I have so many good memories of my years there! Eventually, British Petroleum bought Amoco and consolidated personnel.

Yet again, I “just happened” to end up at Southwest Research Institute as a Senior Research Chemist. I was able to stay very involved in both the lubricants and the fuels sides of the fence.

NLGI: What were your next career steps?

JAW: I moved to the fuels and lubricants research area at International Harvester in Burr Ridge, IL. Once again, I worked for someone who knew exactly what I needed to learn at that point in my career. He taught me the basics of fluid lubricants, greases, and fuels chemistry, including how to run most of the basic tests.

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I worked there for about seven and a half years, and they were in some ways the happiest years of my career.

Meanwhile, a recruiter had an old copy of my resume. Without my permission, he sent it to NCH Corporation because I appeared to be a perfect match for what NCH was looking for, and that’s how I ended up where I now am. In retrospect, it seems that my career path has been a linked sequence of ‘just happened’ events.

**NLGI: What have been some career learnings?**

**JAW:** For those readers working in any area of science and technology, I recommend that you do not try to find that ‘perfect area or subject’ that you have in mind for work. Go with whatever opportunity you are assigned, and then learn as much as you can from those who know what you do not. Clearly define the objective of everything you do, and maintain a laser focus on that objective. Apply maximum effort at all times in whatever your job requires. If you do these things, then the direction of your career will take care of itself. My career is proof of that, although only now, looking back over the past 43 years, do I really appreciate the truth of this principle.

Another point involves the balance between scientific abilities and ‘soft’ or ‘people’ skills. We all have to work with others. Over the years, I have seen the pendulum swing back and forth between these two skill sets. At one point, it was very fashionable to emphasize being personable to the point where technical mediocrity was acceptable. And we have all heard of individuals who do not hesitate to trample others in order to make things technically correct (or move themselves upward). Both of these approaches are eventually self-defeating. It has taken me years to really grasp this concept!
Finally, when it comes to scientific honesty within an industrial environment, DO NOT COMPROMISE TECHNICAL/SCIENTIFIC TRUTH. Not ever! If someone tries to redefine dishonesty as ‘making a business decision’, understand that it is dishonesty, plain and simple. I am not talking about vague business jargon and indefinite, qualitative claims that all companies make to create a positive environment for sales. There is nothing wrong with that. But if someone tries to make a very specific and quantitative technical claim that is false, that is not acceptable. As scientists, we must never go along with such things, no matter what the cost may be to us.

Do not compromise technical/scientific truth. Not ever!

NLGI: What is your current role at NCH?

JAW: At NCH, my work is involved primarily in developing new product and process technology for fluid lubricants, lubricating greases, and fuel additives. NCH has allowed me to use whatever abilities I have to push the chemistry/technology envelope, and I am grateful for that opportunity.

I also am involved with solving technical problems, especially those that – for whatever reason – have been most problematic. Over the last few years, I have become increasingly involved in providing guidance and mentoring to colleagues. This is important to me because I received so much similar help during the early years of my career.

Andy at the controls of an oscillatory rheometer at NCH

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LUBES’N’GREASES We are the most diversified and respected resource for independent news, data and information for global lubricants industry. www.LubesnGreases.com
NLGI: What is a typical work week like for you?

JAW: Tempest in a teapot. Well, that may be a bit of an exaggeration, but there is scarcely a week when my plans are not sidetracked, at least to some extent. I am involved in lots of things – my own core projects, work being done by others, and unexpected things that come up. Mercifully, I am not involved in many meetings. At this point in my career, time is not something to be treated casually.

NLGI: Are you starting to think about retirement?

JAW: Well, yes, of course. And if I don’t, then my wife, Patty, does! However, I will not retire from something; I will retire to something. I have not yet decided exactly when it will be, but it is not too far in the future.

There are a few things I would still like to accomplish. I see so many specific potential new chemistries and technologies that I am virtually certain will be useful (and be of significant commercial value) if I can get to work on them. But in science, there have been and always will be bright young people coming up to build on what has previously been built. If I have done anything that even in a small way is part of what they build on, then I will be happy. Very happy.

Patents and Papers

NLGI: What work habits helped you obtain 40 U.S. patents?

JAW: On my first day at Land O’Lakes, my first boss and mentor took me to my office and my desk. On the wall beyond my desk and in my direct line of sight was a framed quote. My boss pointed it out to me and told me to memorize it. I did.

The more you know about what has been done, the more you will know about what needs to be done.

Over the next months, he showed me how to look at...
the scientific literature as it applies to any exploratory research effort. The area of science related to your project objective is a picture. But the picture is in pieces, like a jigsaw puzzle. Each piece of the puzzle is a published paper, presentation, patent, etc. When the technical points of two such pieces are in agreement or complementary to each other, their borders fit together in the jigsaw. In this way, the various aspects of the ‘literature pieces’ fit together to display a complete picture.

But not quite. Technical aspects of some of the literature pieces will not fit other parts of the literature. Instead, they appear to contradict each other. When you see this, it is almost always a mistake to assume that one of the seemingly contradictory literature pieces is wrong. Instead, there is almost always a good reason for the apparent contradiction, and the reason may be buried in the details.

Those reasons, if you can find them, define the border of an adjacent puzzle piece – a puzzle piece that is missing, a puzzle piece without a corresponding entry in the literature.

The job of an exploratory research scientist is to examine the known literature (the known puzzle pieces) until you have defined the entire boundary of the missing piece (or pieces). Once you do this, you zero in on that area in your own research work.

I mentioned ‘diamonds in the rough’ earlier. Those diamonds are found in the missing pieces of the jigsaw puzzle. I realize that this approach might sound a bit contrived, even overly romanticized. All I can say is that this was the approach I was taught, the approach I have taken, and the one I still use. It has worked for me.

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NLGI: Please tell us about your patents.

JAW: My first U.S. patent was about a new method to efficiently sulfurize heavy duty metal cutting oils. One of the senior research scientists at Amoco suggested an approach to me. I did some “quick and dirty” work (a favorite expression of my mentor at Land O’Lakes). The idea appeared to work.

My colleague and I moved the idea forward, and at his request, I wrote an invention disclosure. I remember that he laughed, because I had left enough holes for someone to drive a fleet of 18-wheelers through my first draft. But he worked with me, and eventually the disclosure was submitted and approved. Then, we submitted a patent application to the U.S. Patent and Trademark Office for prosecution. About one year later, the patent was issued. I will always be grateful to this senior scientist for allowing me to be part of this project. It opened my eyes to something I had not even considered before – patents!

When I moved to the lubricating grease area, there was plenty of opportunity for me to develop new technologies – lots of missing pieces in jigsaw puzzles. Some of the resulting U.S. patents involved greases used in CV joints, automotive wheel bearings, U-joints, steel mill continuous casters, railroad locomotive wheels/flanges, and a couple of military specification greases.

My most recent patented work in greases is based on highly overbased calcium sulfonates. That work has been very satisfying for me. I think the potential for that technology is still largely untapped.
**NLGI: Do you have a favorite project?**

**JAW:** After I joined SwRI, we were funded to do a very large project by the agency of the Federal Government that procures fuels for our military. For over 40 years, there was a problem related to aviation turbine (jet) fuel – a sometimes thick material dropped out of the fuel and caused various problems. This material was called ‘apple jelly’, but it was not the stuff you would want to put on your breakfast toast. Many attempts were made to determine just what this material was and why it formed, but none of those attempts were successful.

Then apple jelly was observed in the wing fuel tanks of our fighter aircraft, and a solution was needed. This material had very high electrical conductivity, and it was causing the fuel gauges to indicate full tanks even when they were nearly empty – obviously a problem!

I was given the task of heading up the project to solve the apple jelly mystery. After looking at what was already known (remember that framed quote from my first job), I knew what approach I would need to take. With some very good help from numerous co-workers, we determined the root cause of apple jelly and came up with specific recommendations to prevent its formation.

I actually gave a talk about this work at the 2003 NLGI Annual Meeting (Hilton Head Island, SC). As it turns out, the thick variety of apple jelly that we observed was a grease! The ‘base oil’ was a solution of water, diethylene glycol monomethyl ether (jet fuel de-icer), and certain soluble extracted components from jet fuel. The thickener was a partially-neutralized polyacrylate polymer extracted from the super-absorbent media in the water.
filter monitors in jet fuel installations at our U.S. Air Force bases. The success of this project resulted in a national news release and an interview with myself and my boss on the local CBS network TV station.

“Ladies and gentlemen, our country is at war. This meeting is concluded.”

However, the main reason this project will always stick out in my memory has to do with my presentation of the final project report to the U.S. Air Force personnel and the agency that funded the work. My boss picked me up at Reagan International Airport, and we drove to Fort Belvoir, VA. I remember how nice the early autumn weather was on that Monday afternoon.

The next morning, we gathered in a conference room on the base. An Air Force colonel was presiding, and all military personnel were in their full dress uniforms. During the preliminaries, a secretary kept calling the colonel out of the room. Just before I was about to take the podium, the colonel came back into the room and announced that two commercial aircraft had smashed into the Twin Towers of the World Trade Center in New York City. One Tower had collapsed, the other was on fire and about to collapse. And a third aircraft had smashed into the side of the Pentagon.

The colonel ended the meeting with these exact words: “Ladies and gentlemen, our country is at war. This meeting is concluded.” The next day, my boss and I began the two-day drive back to San Antonio. Months later, I gave my report in a multimedia video conference from SwRI.

It is often said that people instantly remember what they were doing when they learned about 9/11. This is my 9/11 story.

I had already written, presented, and published three other review papers, so I knew how to do it. But I also knew something else. Listening to, or reading, a review paper can be a bit like watching paint dry unless it is on a subject that you are interested in.

So I asked myself, how do I write and present this body of work in a way to grab everyone’s interest and hold it? That is where The Moody Blues album, Days of Future Passed, came in. This was a concept album featuring a series of songs about an average day, starting just before sunrise. Each track or song was about a part of the day as it progressed from dawn to dusk.

I realized that the development of new technology resembles the progression through the hours of an average day. When I looked at the lyrics of each track or song, I found a couplet, a pair of lines, that perfectly applied to a phase of development of overbased calcium alkylbenzene sulfonates. I discovered three things:

- the story was fascinating and featured extremely interesting chemistry;
- and no one had written a review paper on this interesting and critically important subject.

I realized that the development of new technology resembles the progression through the hours of an average day. When I looked at the lyrics of each track or song, I found a couplet, a pair of lines, that perfectly applied to a phase of development of overbased calcium alkylbenzene sulfonates. The whole thing fit perfectly. So, I wrote the paper and the presentation using the album track titles as my section headings for each range of years and the corresponding...
technology. I also incorporated appropriate bits of lyrics at the beginning of each section with the name of the Moody Blues musician who wrote them.

Did my approach work? Well, from my vantage at the speaker’s podium, it seemed like no one was dozing off. Since that presentation, at least one person has come up to me during each NLGI Annual Meeting and asked me if I was going to do another ‘Moody Blues paper’. (That is what everyone seems to call it now.) My paper, ‘Days of Future Passed: A Critical Review of the Development of Highly Overbased Calcium Alkylbenzene Sulfonates’, was presented at the NLGI 83rd Annual Meeting, Hot Springs, VA, June 2016 and published in *The NLGI Spokesman*, 81(4), Sept./Oct. 2017.

I have also been told that at least one major additive company has used my published paper as a technical guide for their development work. I consider that to be as good a compliment as I could possibly hope for. But to answer the question I keep getting: no, I have no plans for another Moody Blues paper. That is something I will do only once in my career!

**NLGI: Do you have any advice to inspire colleagues and help them develop new technologies?**

**JAW:** Read everything and forget nothing. But developing an encyclopedic knowledge base is not enough. Seek out and work with those who obviously have that creative spark. Notice what they are doing that you are not. Most importantly, understand that there is so much that is not well understood. Don’t fool yourself into thinking you have everything figured out. You don’t; I don’t. No matter how much any of us accomplish, there will always be plenty left for the next generation. So, get to it!

**Grease Industry**

**NLGI: What are your thoughts about the future of the grease industry?**

**JAW:** I think that the challenges that we face within our industry are actually opportunities.

**NLGI: What are some opportunities for the grease industry?**

**JAW:** There are so many. I will mention just one. Although overbased calcium sulfonate greases have been around since the mid-1960s, there never has been any published work that explains the step-by-step chemical mechanism of conversion, the process whereby the amorphous calcium carbonate changes to a (hopefully) nano-dispersion of calcite particles.

My 2017 Moody Blues paper, *The NLGI Spokesman*, 81(4), gives some evidence that challenges current beliefs about the structure of the amorphous calcium carbonate. If the correct structure of the initial overbased calcium sulfonate and if the exact step-by-step mechanism whereby it is changed to a grease thickener are not known completely, then new improvements in lubricant technology are possible. The researchers who unravel these mysteries will hold in their hands the key to revolutionary improvements of grease technology.

The paper that I presented at the NLGI 2019 Annual Meeting provided some insight into the conversion mechanism. As far as I know, it was the first glimmer of insight published in the open literature. More than anything else, that paper shines a spotlight on just how much we yet need to understand about something we have been using for more than 50 years.

This paper, 'New Process Methods to Improve the
The Thickener Yield of Calcium Sulfonate-Based Lubricating Greases, was presented at the NLGI 86th Annual Meeting, Las Vegas, NE, June 2019 and published in *The NLGI Spokesman*, 84(1), Mar./Apr. 2020.

**NLGI: What are some threats to the grease industry?**

**JAW:** I feel that one threat is a shortage of scientists in the lubrication area. Why do some talented people enter our industry, but then do not stay there?

When anyone begins their career, they want to feel that their efforts are noticed and appreciated, especially when they do truly exceptional work. Historically, science- and technology-based companies have recognized this.

For example, when I worked at Amoco (1982-99), that Company recognized and rewarded R&D personnel for their truly outstanding work. Three times a year, corporate executives hosted formal meetings for the Laboratory where selected scientists and engineers gave presentations about their recent technical work and received patent plaques, awards, and cash. (And it was more than one dollar!) During my years at SwRI (1999-2007), the Organization openly recognized excellent performance by scientists and engineers.

My concern is that a growing number of science- and technology-based companies in our industry may not be openly recognizing their R&D personnel in such ways. Furthermore, when a company justifiably lavishes recognition and rewards on individuals in sales, management, and marketing while effectively ignoring R&D, this sends a message that the company has a very low view of science and technology and those who work in those areas. Under these circumstances, what will young, talented scientists think about their chances for any real recognition and reward if they do exceptional work?

True motivation must always come from within an individual. But many motivational models show that a lack of recognition and reward is a definite demotivator. Simply put, outstanding scientists and engineers who are not appreciated by their employers will eventually go somewhere else, even a completely different scientific area.

If companies within the lubricating grease business want to have the best scientists and engineers working for them, then they need to openly recognize them when they make exceptional contributions. And the recognition must be just as open and significant as the recognition given to those in other areas of the company.

**NLGI: Do you have a favorite grease chemistry? A favorite grease test?**

**JAW:** Over the years, my favorite grease chemistry has been whatever I was working on. During my Amoco years, it was mostly polyurea. During my SwRI days, it was carbon nanotube-thickened greases. More recently, I have been heavily working on greases where the thickener system comprises one of several new chemistries that have involved overbased calcium sulfonate.

I would say that my favorite grease test involves the almost limitless procedures that can be done with an oscillatory rheometer.

**NLGI: What are some of your favorite memories about working in the grease industry?**

**JAW:** The great people I have been privileged to work and associate with are my favorite memories. I won’t try to list names because I might leave some out. Some are no longer with us. Fortunately, many still are. I am grateful to all of them.

[Andy presented a technical paper at the 86th Annual NLGI Meeting, 2019]
How did you become involved with NLGI?

JAW: When I joined IH, my boss told me that I needed to go to the next NLGI Annual Meeting and take the NLGI Grease Course. (There was only one course back then.) So, I attended my first NLGI Annual Meeting in November 1980, in the French Quarter of New Orleans, and I took the Course.

And have you attended other NLGI Meetings?

JAW: I have attended them as much as my employer support would allow through the years. I have attended NLGI Meetings regularly for at least the last 12 years. Benefits include presentations of the technical papers, almost all of which I try to hear.

Attending an NLGI Meeting is a great way to stay in touch with friends and colleagues that you have known for years. Networking is easy and natural. All of this allows me to stay up to date on developments that I need to know in the industry. And sitting in on meetings of NLGI-ELGI Working Groups allows me to stay informed about what is on the horizon. The current effort to create new and more meaningful grease performance specifications is a perfect example.

I also enjoy talking with young people who are just getting started and may be attending their first NLGI Meeting. I see the young version of myself in them.

What is your favorite memory of an NLGI event?

JAW: If I had to pick just one, it would be the NLGI 83rd Annual Meeting in Hot Springs, VA in June 2016. That was where I received the Clarence E. Earle Memorial Award for my contribution to the technical literature relating to lubricating greases in 2015. It was such a pleasure to find out that others whom I respect liked what I have done. But of course, that is not what motivates me to write a paper (or do anything else for that matter). My primary goal in whatever I try to do is always to satisfy myself with the result. Then, when I find out that others also like it, it is just a wonderful bonus.

How does NLGI add value to the grease industry?

JAW: The NLGI is the largest and most dominant organization that covers all the scientific areas of the lubricating grease industry and is shaping its future. NLGI Annual Meetings are a forum for technical papers, sponsor booths, and networking, where everyone resets their dials on whatever aspect of our industry they are involved in. I do not know of any other event in the U. S. that offers all of these opportunities in one venue.

I am a member of the NLGI Membership Retention Committee. If you are reading this interview and your job is within the lubricating grease industry, but your company, research organization, or educational group is not yet an NLGI member, I would like to make two suggestions. First, join. It is easy. Contact NLGI using the information on their webpage or within this
issue of The Spokesman. Or go to the NLGI central table at the next NLGI Meeting. Or contact me at the next NLGI Meeting. Second, get involved. There are so many ways to do this. Committee work and presenting papers are just two. Actual NLGI members are organizations, but the building blocks of NLGI are people. Be one of them.

Plus

**NLGI: Do you have time to be involved in volunteer activities? Hobbies? Travel with your family?**

**JAW:** I am often guilty of taking work home. Nonetheless, I always make time for non-work related things. My primary hobby is playing the trombone in my church orchestra and, for more than 40 years, in a jazz band, Reunion Jazz. We have performed at various venues, and we may play at a jazz club in the French Quarter in New Orleans, LA this summer. I practice nearly every day just to keep my chops up and to decompress. Playing a musical instrument is a great way to remove stress.

Another way to remove stress that I employ is exercise. I work out almost every day using my elliptical trainer. During the warm months, I am an avid cyclist. I have a nice bike, and a typical ride for me is 30 miles with an average speed of around 22 MPH.

I also love listening to various types of music: classical, jazz, bluegrass (if it is good), progressive rock, and prog pop. In addition to the great symphony orchestras, some of my favorites include (of course) The Moody Blues, The Traveling Wilburys, Electric Light Orchestra (ELO), and nearly everything recorded by Rick Wakeman, an English keyboardist, songwriter, and former member of Yes, a famous prog rock band. After singer and songwriter Jeff Lynne reformed his ELO in 2014, I attended U.S. tour concerts with my son in 2018 and 2019.

When it comes to organized professional sports, I follow only one team. I am from St. Louis, MO, I grew up playing baseball, and my blood is Cardinal-red. ‘Nuff said.

I also enjoy reading, but over the most recent years, I have not had enough time to really do what I would like in that area. When I do finally retire, I plan to do more of that. I also like poetry. Poetry is word music. Robert Frost is one of my favorite poets.

I have three children – two daughters and a son. My oldest daughter is married and has two daughters, ages 7 and 5. My granddaughters are my true joy on this earth. When I finally retire, I will have more time to be with my kids, who all live in Ohio.
NLGI: Where is your favorite place to travel?

JAW: My wife, Patty, and I have been to Kauai three times. Kauai is one of the Hawaiian islands, nick-named ‘the Garden Isle’ because of its tropical rainforests, and probably my favorite place. The U.S. Virgin Islands are also nice. I have been to St. Thomas and St. John, and would like to visit St. Croix. I like the northeastern U.S. I have been to Maine in the winter, and I would like to go there during the summer. I would also like to see the nearby White Mountains in New Hampshire (in the summer), which inspired some of Robert Frost’s poems.

NLGI: Do you have any suggestions for NLGI members who might visit Texas?

JAW: Good Texas BBQ is a must. Lots of good places to get that. Also, there are some really good Tex-Mex places, but also some that are not as good. Probably a bit of research is needed before picking one.

Texas Hill Country, an area of 14,000 square miles in the central and southern parts of the State, is beautiful during the spring and summer. Every spring, Texas Bluebonnets and other wildflowers bloom into a carpet that covers Texas Hill Country. There are some really good state parks in the Hill Country near Austin. Try Enchanted Rock State Natural Area (Fredericksburg, TX) and Lost Maples State Natural Area (Vanderpool, TX) to start with. But keep your eyes on the trails. There are rattlesnakes that you might occasionally encounter.

NLGI: If you could have dinner with any three people, living or deceased, who would they be and why? And what might be on the menu?

JAW: The first one is easy. Galileo Galilei. He is the father of experimental science. I would ask him, what initially made him decide to do experiments instead of just accepting the philosophy explanations of astronomy and physics that had been believed for more than 1,500 years? What did it feel like when the Roman Catholic Church forced him to recant his heliocentric theory under threat of death? Was it true that after he made his forced recant, he really did say (under his breath), “E pur si muove”. (And yet it moves.)

My second choice would be Jack Teagarden, a great jazz trombonist from Vernon, TX.
How did he teach himself to play the trombone at age 8? How did he develop his incredible and effortless technique and 'laid back feel' that great symphony trombonists today still admire? What was it like to be a working jazz musician from the days of the Great Depression through the early 1960s? What were his experiences when he arrived in New York City in 1927, and how did he become the top freelance trombonist in that City just a few months later? How did it feel to be a close friend and bandmate with the great Louis Armstrong during a period of time when there was so much racial prejudice?

Finally, I would choose Sir Winston Churchill, the greatest political leader in Europe during the 20th century. I would ask him about his famous resolve against obvious evil, especially after the extreme naiveté of his predecessor, Neville Chamberlain. What would be his opinion of today’s world?

As far as what would be on the menu, I would let my guests decide. And I would enjoy watching them reach a consensus!

This interview series, started in 2019 by Dr. Moon and Dr. Shah, gives NLGI members a bit of insight into the professional and personal lives of their colleagues, developments in the grease industry, and the role of NLGI worldwide. If you would like to suggest the name of a colleague for an interview (or volunteer to be considered as a candidate), please kindly email Mary at mmmoon@ix.netcom.com or Raj at rshah@koehlerinstrument.com.

Dr. Mary Moon is Technical Editor of The NLGI Spokesman. She writes scientific and marketing features published in Lubes'n'Greases and Tribology & Lubrication Technology magazines, book chapters, specifications, and other literature. Her experience in the lubricant and specialty chemicals industries includes R&D, project management, and applications of tribology and electrochemistry. She served as Section Chair of the Philadelphia Section of STLE.

Dr. Raj Shah is currently a Director at Koehler Instrument Company and was an NLGI board member from 2000 to 2017. He is an elected fellow of NLGI, STLE, INSTMC, AIC, Energy Institute and the Royal Society of Chemistry. A Chartered Petroleum Engineer from EI and a Chartered Chemical Engineer from IChemE, he is currently active on the board of STLE and on the advisory boards of the Engineering Departments at SUNY Stony Brook, Auburn University and Pennsylvania State University. More information on Raj can be found at https://www.astm.org/DIGITAL_LIBRARY/MNL/SOURCE_PAGES/MNL37-2ND_foreword.pdf
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