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RESEARCH

# Enhanced Low Temperature Flow Behavior of Polyurea EV Greases Using Synthetic Base Oils

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## ABSTRACT

*Electric and hybrid vehicle (EV/HEV) motor bearings demand greases that remain sufficiently mobile at sub-zero temperatures. In this study, a series of polyurea-thickened grease formulations was prepared with three different low-viscosity synthetic base oils: polyalphaolefin (PAO), polyalkylene glycol (PAG), and polyol ester (POE), all with International ISO VG 32. Flow pressure was measured from 0 °C to −40 °C using a tester per DIN 51805-2, where the measured pressure indicates grease yield strength and relates to start-up torque and churning resistance in sealed EV bearings. A modified protocol introduced 4- and 8-hour relaxation periods at −20 °C and −30 °C to evaluate time-dependent stiffening. Under standard conditions, all greases showed acceptable flowability (well below 1400 mbar at −30 °C), with PAO exhibiting the lowest pressures. At −40 °C, PAO and PAG remained extrudable, while POE exceeded the 3225 mbar instrument limit due to crystallization. Extended cold soak caused only modest pressure increases for PAO and PAG but a rapid rise for POE (>3000 mbar after 4 h at −30 °C). These results demonstrate that base oil composition profoundly influences low-temperature grease mobility. In particular, the ester base oil's tendency to crystallize under prolonged cold exposure led to markedly worse flow behavior, highlighting the need for appropriate base oil selection and modified test protocols for EV applications. This test provides a screening measure of cold-flow mobility, not a direct in-bearing torque evaluation.*

## 1. INTRODUCTION

The rapid growth of electric and hybrid vehicles has introduced new challenges for lubricating greases used in electric motor bearings and driveline components. Requirements for electric vehicle (EV) greases differ from those in conventional applications, often needing to accommodate higher motor speeds, elevated operating temperatures, exposure to electrical fields, and stringent durability demands. Among these challenges, low-temperature performance is particularly critical: EVs are expected to operate in cold climates with minimal warm-up, so their bearing greases must remain sufficiently soft and mobile at sub-zero temperatures to avoid starving the bearings or increasing energy losses. It is well established that as temperature decreases, a grease's apparent viscosity and yield stress increase significantly, which can lead to stiffening of the grease structure. If a grease becomes too stiff (high solid-like consistency) at low temperature, it can cause excessive resistance to bearing rotation and elevated start-up torque. This not only impacts energy efficiency and range in an EV but can also lead to bearing damage or failure in extreme cases [1-3].

Commercial electric motor bearing greases used in electric and hybrid vehicles are typically polyurea- or lithium-based formulations designed for sealed-for-life operation, with emphasis on high-speed stability, low noise, and electrical compatibility. While several studies, such as those cited in this paper, have examined grease performance for EV motors under thermal and electrical stresses, publicly available data on low-temperature mobility, particularly under prolonged cold exposure, remain scarce. Moreover, a majority of the recent peer-reviewed literature have focused on short-duration low-temperature torque or flow tests, rather than extended cold-soak conditions that may be encountered in real-world vehicle storage [1, 2]. These gaps motivate the present investigation into time-dependent low-temperature flow behavior of EV motor greases.

Low-temperature behavior of grease is predominantly governed by its formulation. Unlike liquid lubricants, where pour point depressant additives can readily improve low-temperature fluidity, there is no simple additive fix to dramatically enhance a grease's mobility at cold temperatures [3]. Instead, the choice of base oil and thickener system is crucial. The base oil portion, which typically makes up 70–90% of the grease, largely dictates the grease's viscometric properties in the low-temperature regime. For instance, in mineral-oil-based greases, naphthenic oils generally impart better cold-flow properties than paraffinic oils due to their lower wax content and improved low-temperature viscosity profile [4]. Modern EV greases therefore tend to use synthetic base oils with superior low-temperature characteristics (e.g., polyalphaolefins, esters, or certain polyalkylene glycols) [5]. These synthetic fluids typically have very low pour points and remain less viscous at a given low temperature compared to conventional mineral oils, which helps the grease maintain mobility. The thickener type also plays a role in low-temperature performance; different soap or non-soap thickeners can influence how the grease's structure responds to cooling [6]. Polyurea thickeners, in particular, are known for forming a fine, amorphous fiber network that can contribute to good low-temperature flow and are widely used in EV motor greases for their thermal stability and noise-damping characteristics [5,7]. In this work, a polyurea thickener was chosen to isolate the effect of base oil type on low-temperature behavior, since polyurea greases have shown promise in EV applications [8].

While grease flow pressure reflects the composite response of the base oil–thickener system, the temperature dependence of base-oil viscosity plays a central role in governing low-temperature mobility. Synthetic base oils such as polyaphaolefin (PAO) and polyalkylene glycol (PAG) typically exhibit smooth, monotonic viscosity–temperature behavior at sub-zero temperatures, whereas ester-based oils may experience abrupt increases in viscosity associated with crystallization phenomena. Although base-oil viscosity alone does not fully describe grease behavior, its temperature dependence provides important context for interpreting cold-flow trends observed in formulated greases. Recent work has also highlighted low-temperature limitations arising from wax-like phase transitions in bio-derived thickener systems, where crystallization behavior can dominate grease mobility at sub-zero temperatures [9].

Evaluating grease performance at low temperatures involves several standardized test methods. Common industry tests include the ASTM D1478 low-temperature torque test (measuring starting and running torque of a grease-lubricated ball bearing at −20 °C or −30 °C), the U.S. Steel Grease Mobility test (measuring the amount of grease that can flow through a standardized orifice at low temperature, e.g., −20 °C), and the flow pressure test according to DIN 51805 (Kesternich method) [10]. Each test provides insight into different aspects of a grease's low-temperature behavior; torque tests relate to mechanical resistance in bearings, while flow pressure (Kesternich) directly measures the pressure required to force grease through a narrow nozzle at temperature, reflecting its intrinsic flowability at near-zero shear. Recognizing the importance of low-temperature performance, the NLGI's High-Performance Multiuse (HPM) grease certification includes an optional "+ Low Temperature (LT)" tag for enhanced cold-temperature capability. The HPM + LT specification requires greases to meet rigorous criteria in all three aforementioned tests, such as a maximum flow pressure of 1400 mbar at –30 °C (per DIN 51805) among other limits [10]. These requirements set a high bar for formulating greases that can operate reliably in cold climates.

Although sealed-for-life motor bearings are not subject to grease pumping, the flow pressure measured by the Kesternich method reflects the yield-stress behavior that influences start-up torque and early-life churning losses. Greases maintaining low flow pressure at sub-zero temperatures are therefore expected to minimize torque buildup during cold operation. Accordingly, flow pressure serves as a screening metric for evaluating grease stiffness under near-zero shear, aiding pre-selection of candidate formulations for EV and hybrid motor bearings. Other experimental approaches, including low-temperature rheometry with tribological fixtures or full bearing torque measurements, have also been used to study freezing-related grease behavior; however, such methods are more resource-intensive and less suited for rapid formulation screening [1,2]. DIN 51805-2 is, however, an out-of-bearing test; future correlation with torque measurements (ASTM D1478/D4693) and rheological analysis is needed to establish quantitative translation to bearing performance.

One particular challenge identified in recent studies is that traditional low-temperature tests may not capture issues that arise from prolonged exposure to cold. Greases (and oils) can sometimes exhibit time-dependent behavior at low temperature, such as gradual crystallization or gelation, which is not evident if the test is conducted immediately after reaching the test temperature. Researchers have noted that certain synthetic oils, especially ester-based fluids derived from fatty acids, can undergo crystallization if held at low temperature for extended periods, even at temperatures higher than their pour point [4,6,11]. In other words, an oil might appear fluid when quickly cooled and measured at a given temperature, but if kept at that temperature for hours or days, it can slowly form wax or crystal structures that dramatically increase its viscosity or even solidify it. This phenomenon of cold crystallization or time-delayed solidification has been documented for some biobased and synthetic esters [4,11]. In grease form, the presence of a thickener can further promote such crystallization (via heterogeneous nucleation) and raise the effective crystallization temperature of the base oil in the grease matrix. Consequently, the base oil's pour point alone may be an inadequate indicator of a grease's lowest usable temperature, a grease can stiffen at a higher temperature than expected if the base oil slowly crystallizes in the presence of thickener [4]. To address this, extended cold-soak or relaxation periods before measurement can be introduced in test protocols to simulate real-world scenarios (e.g., a vehicle parked overnight in the cold). By doing so, formulators can identify greases that might pass an immediate low-temperature test but fail after longer exposure to the same conditions.

The objective of the present study is to investigate the low-temperature flow behavior of advanced polyurea greases formulated with different synthetic base oils for EV motor bearing applications. We examine how base oil type influences grease flow pressure between 0 °C and –40 °C, and how extended low-temperature relaxation affects flowability. This work builds upon previous findings by the authors on EV grease performance [7,12] by focusing on low-temperature characteristics and introducing a modified test approach incorporating extended cold exposure. Three representative polyurea greases formulated with ISO VG 32 base oils, PAO, PAG, and polyol ester (POE), are evaluated to provide insight into how base-oil chemistry governs cold-flow behavior. The goal is to support the development of EV/HEV greases with improved low-temperature reliability, while informing future formulation strategies that may incorporate lower-environmental-impact components without compromising cold-flow performance.

## 2. MATERIALS AND GREASE PREPARATION

Three lubricating greases were prepared in the laboratory using a polyurea (PU) thickening system combined with different synthetic base oils. Following the supplier's recommended procedure, a commercially available polyurea grease thickener pre-polymer was used, with the urea thickener formed *in situ* during grease preparation. Each grease was formulated to a target consistency of NLGI Grade 2 (worked penetration ~265–295 [13]); to achieve comparable NLGI 2 consistency with different base oils, the thickener content was adjusted for each formulation. After completion of the thickener reaction, all batches were subjected to a finishing step of colloidal milling at ambient temperature to ensure a uniform, smooth texture free of large thickener agglomerates.

The three grease formulations are denoted as PU-PAO, PU-PAG, and PU-POE, where "PU" indicates the polyurea thickener and the suffix refers to the base oil type. Table 1 summarizes the key characteristics of the formulated greases, including thickener content and selected base oil properties. All three base oils had a kinematic viscosity of approximately 32 cSt at 40 °C (ISO VG 32). The PAO base oil is a synthetic polyalphaolefin hydrocarbon, the PAG is an oil-soluble polyalkylene glycol, and the POE is a synthetic polyol ester. These base oils were selected to provide comparable viscosity grades while representing base oil chemistries commonly considered for EV motor grease formulations [5,7,8].

**Table 1.** Characteristics of formulated grease samples (polyurea thickener with different base oils).

| Grease Sample | PU-PAO | PU-PAG | PU-POE |
|---|---|---|---|
| Thickener Type | Polyurea | Polyurea | Polyurea |
| Thickener Content (% w/w) | 12% | 14% | 10% |
| Base Oil Type | PAO (synthetic hydrocarbon) | PAG (oil-soluble polyalkylene glycol) | POE (polyolester) |
| Base Oil ISO VG | 32 | 32 | 32 |
| Base Oil Pour Point (°C) | -68 | -60 | -45 |
| Base Oil Cloud Point (°C) | 32 | -45 | -36 |

The pour points of the base oils ranged from −68 °C for the PAO to −45 °C for the POE, indicating progressively reduced inherent low-temperature fluidity across the series. In prior work by the authors [7], a cloud point (wax crystallization onset) of −36 °C was measured for the POE base oil, whereas the PAO exhibited no measurable cloud point within the test range due to its fully saturated structure; cloud point is not applicable to the PAG, which is a single-phase synthetic fluid with no wax precipitation. These base oil property measurements were obtained and reported in a previous study by the authors [7] and are referenced here as precursor characterization supporting the present low-temperature flow study.

No performance-enhancing additives, such as pour-point depressants or polymeric modifiers, were incorporated into the grease formulations in order to isolate the effects of base oil chemistry and polyurea thickener structure on low-temperature flow behavior. Typical oil separation behavior for polyurea greases formulated with synthetic base oils was also reported in the authors' prior work [7], with values consistent with those generally observed for urea-thickened systems; oil separation was not re-measured in the present study, as the focus was placed specifically on flow-pressure response under controlled thermal histories.

All three greases exhibited a translucent brown appearance and smooth consistency, and quality control testing confirmed that each formulation fell within the NLGI Grade 2 range. In the precursor study [7], these same grease formulations were evaluated for general performance attributes unrelated to low-temperature flow, including dropping point, mechanical stability, oxidation resistance, volatility, wear protection, and copper corrosion. In that work, all greases exhibited high dropping points (>250 °C) and good mechanical stability. The PAO- and POE-based greases demonstrated strong oxidative stability in pressurized DSC testing, while the PAG-based grease showed comparatively lower oxidative life, consistent with known oxidation tendencies of PAG base oils [5]. All greases displayed low oil evaporation loss (<0.5% at 120 °C), typical oil separation for polyurea systems, and good anti-wear performance in four-ball wear tests (wear scar <0.5 mm) [7]. Copper corrosion testing (ASTM D4048) performed in our previous study [7] indicated that none of the greases were corrosive to copper, an important consideration given the presence of copper windings in electric motors.

These prior results establish that the formulated greases meet the baseline requirements for EV motor bearing service, including thermal stability and materials compatibility, thereby enabling the present study to focus specifically on their low-temperature flow behavior and time-dependent cold-soak response.

## 3. LOW-TEMPERATURE FLOW TESTING

This section describes the experimental procedures used to evaluate low-temperature flow behavior, following the grease formulation and baseline characterizations outlined in Chapter 2. The low-temperature flow properties of the greases were evaluated using a Koehler K95300 Low Temperature Flow Tester, following the Kesternich method (DIN 51805-2) for the determination of grease flow pressure. This instrument measures the minimum air pressure required to initiate grease flow through a standardized capillary nozzle at a controlled temperature. A small volume of grease (approximately 0.8 mL) is packed into a stainless-steel cylinder fitted with a narrow nozzle and cooled to the test temperature inside the instrument's temperature-controlled chamber. Once thermal equilibrium is achieved, air pressure is gradually applied to the sample until either the grease extrudes through the nozzle or the sample fractures without flowing. The minimum pressure at which extrusion begins is recorded as the flow pressure (mbar). Lower values indicate a softer, more mobile grease, whereas higher values indicate a stiffer structure resisting flow. The flow pressure reflects the grease's apparent yield stress at very low shear and provides a quantitative measure of its cold-flow mobility under static conditions [10,14]. Flow pressure tests were conducted at five temperatures, 0 °C, –10 °C, –20 °C, –30 °C, and –40 °C, to cover the typical and extreme temperature range for automotive applications, extending beyond the NLGI HPM + LT qualification limit of –30 °C. Before each test, samples were cooled from ambient to the target temperature at a controlled rate and allowed to stabilize in the chamber. According to the standard DIN 51805-2 protocol, the sample was held at temperature for approximately 2 h (7200 s) to ensure equilibrium, and flow pressure was then recorded. The instrument detection limit was 3225 mbar; any sample exceeding this value was considered solidified and reported as "> 3225 mbar." For reference, the HPM + LT specification defines 1400 mbar at –30 °C as the upper limit for acceptable low-temperature performance.

A modified protocol was introduced to examine the influence of extended cold-soak (relaxation) time. Tests were performed at –20 °C and –30 °C, representing moderate and severe cold conditions, respectively. After reaching the target temperature, samples were held for additional periods of 4 h and 8 h before pressure application to simulate prolonged exposure, such as overnight parking in winter. Each temperature–time combination used a fresh specimen to eliminate history effects from prior loading. Comparison between the standard and extended-relaxation results reveals any time-dependent structural changes in the grease matrix caused by base-oil crystallization or network stiffening.

All measurements were performed in triplicate, and reported values represent arithmetic means. The repeatability of the setup was within ± 5 %, consistent with prior DIN 51805 inter-laboratory precision.

## 4. STANDARD TESTING PROTOCOL DIN 51805-2

The flow pressure results obtained under standard stabilization conditions (no extended soak, just enough time to reach thermal equilibrium) as a function of temperature for PU-PAO, PU-PAG, and PU-POE can be observed in Figure 1. All three greases exhibited relatively low flow pressures at 0 °C, on the order of 200 mbar (essentially negligible resistance to flow at freezing point). As the test temperature was decreased to −10 °C and further to −20 °C, the flow pressure of each grease increased gradually, reflecting the expected stiffening of the grease at lower temperatures. At all evaluated temperatures, however, all three formulations remained well below 1400 mbar flow pressure, often cited as a practical maximum for acceptable low-temperature mobility [10]. In fact, at −20 °C, all three greases recorded flow pressures under 500 mbar. These values indicate that, under moderate cold conditions (down to −20 °C), any of the three greases would likely perform adequately in terms of flow, with relatively small differences between them.

A more pronounced divergence in behavior emerged at −30 °C. As shown in Figure 1, the PU-POE grease exhibited the lowest flow pressure among the group at −30 °C, at roughly 500 mbar (indicating it remains quite soft). The PU-PAO grease was slightly higher, around 550 mbar, indicating a somewhat stiffer consistency than the POE-based grease but still well within acceptable limits. Both of these values (PAO and POE at −30 °C) are far below the 1400 mbar threshold, confirming that the PAO- and POE-based greases maintain excellent low-temperature mobility down to −30 °C in the standard test. Even the PU-PAG grease demonstrated a flow pressure of approximately 700 mbar at −30 °C (Figure 1). This is higher than PAO and POE's results but still under 1400 mbar, ostensibly a good result and within specification at −30 °C immediately after cooling. In fact, under the standard methodology, one might conclude that all three greases "pass" a low-temperature qualification at −30 °C with substantial safety margins. The results up to this point could be rationalized by considering the base oil pour points and viscosity traits: PAO (pour point approximately −68 °C) yields the softest grease at −30 °C, PAG (pour point approximately −60 °C) slightly stiffer but still good, and POE (pour point approximately −45 °C) stiffer yet, but perhaps the polyurea thickener's inherently good low-temp characteristics help keep it mobile even with the higher pour point base oil. Notably, the PAO and PAG greases appeared to solidify in a predominantly amorphous manner upon cooling, essentially forming a glass-like structure at low temperature rather than crystallizing. This leads to a steady, monotonic increase in flow pressure with decreasing temperature, but no abrupt jumps.

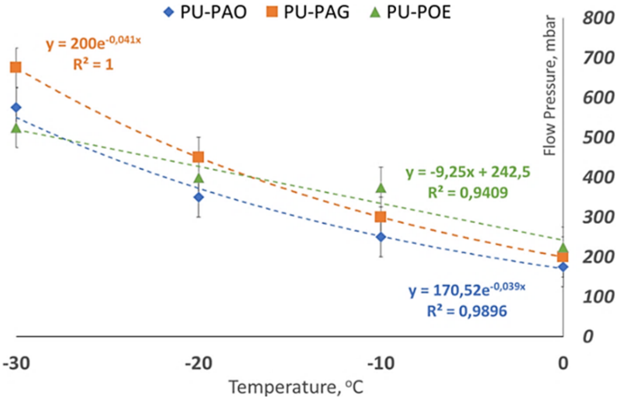

**Fig. 1.** Flow pressure vs. test temperature for the polyurea grease formulated with PAO, POE and PAG base oils (standard test protocol).

When pushed to the temperature of −40 °C, however, the differences became critical. At −40 °C, both the PU-PAO and PU-PAG greases could still be extruded, but their flow pressures climbed to around 900 mbar (PAO) and 1200 mbar (PAG) respectively (observable in Figure 2). Both greases remained sufficiently below the nominal 1400 mbar acceptability limit even at −40 °C, highlighting their superior low-temp performance. In contrast, the PU-POE grease failed to yield a measurable flow at −40 °C under the standard test conditions.

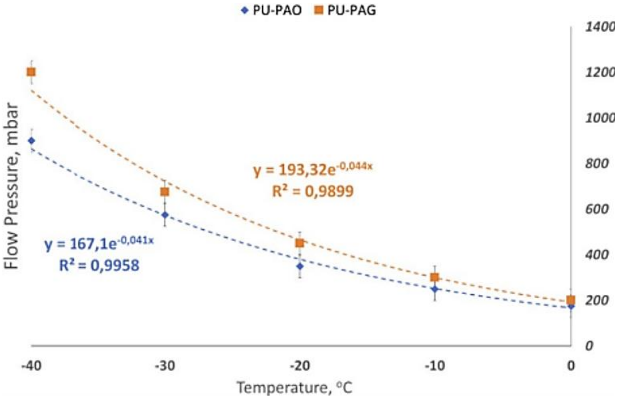

**Fig. 2.** Flow pressure vs. test temperature up to −40°C (PAO & PAG based greases).

In the case of PU-POE at −40 °C, the grease did not extrude from the nozzle even when the maximum pressure of the instrument (3225 mbar) was applied – effectively, the flow pressure exceeded the instrument's range (shown in Figure 3). This indicates that the POE-based grease had solidified to a point where it was no longer mobile at −40 °C. From a practical perspective, this suggests that while a grease formulated with a POE base oil may perform acceptably down to −30 °C, it would not be suitable for applications requiring operation at −40

°C. Many EV applications might not demand –40 °C capability, but the result flags a potential limitation of POE in the coldest climates. The likely cause is crystallization of the POE base oil: as an ester, the POE can form waxy crystalline structures upon deep cooling, drastically increasing consistency. The absence of flow at –40 °C for PU-POE (versus continued flow for PU-PAO and PU-PAG) highlights the fundamentally different low-temperature mechanisms; the POE undergoes a phase change (liquid to solid-like), whereas PAO and PAG remain amorphously solid (supercooled liquid turning into a glass) [4]. This phenomenon aligns with prior observations that certain synthetic esters exhibit a sharp rise in viscosity at the crystallization point, unlike the smoother behavior of PAOs or some PAGs [4]. It also demonstrates that simply having a low base oil pour point is not enough: the POE's pour point (–45 °C) is higher than –40 °C, but the pour point is determined after a short cooling duration. The fact that POE grease fails at –40 °C suggests the base oil's functional low-temp limit (on the time scale of the test) is above its pour point.

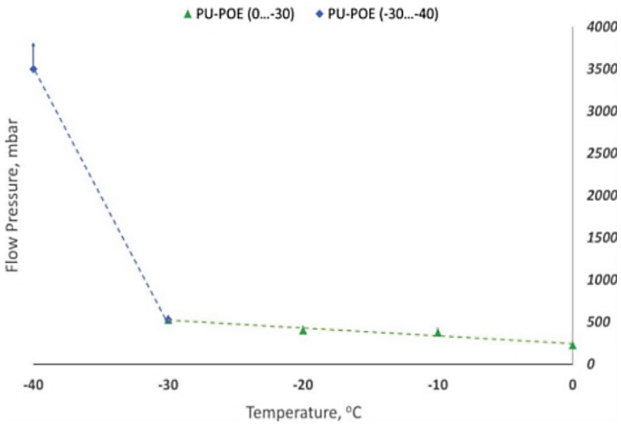

**Fig. 3.** Flow pressure vs. test temperature up to –40°C (POE based grease).

The observed time-dependent stiffening of the POE-based grease is consistent with literature reports showing sharp increases in ester viscosity near crystallization onset, whereas PAO and PAG base oils typically exhibit more gradual viscosity increases with decreasing temperature. As a result, prolonged cold exposure can disproportionately increase the resistance to flow in ester-based systems once crystallization begins, while amorphous base oils continue to stiffen in a more predictable manner. This difference in base-oil viscosity–temperature response likely contributes to the divergent cold-flow behavior observed after extended soak, particularly at temperatures near the ester cloud point.

The results under standard conditions demonstrate that, without extended cold soaking, all three greases would be deemed acceptable down to –30 °C, and two (PAO and PAG) even down to –40 °C. This highlights the beneficial effect of PAO and PAG base oils on low-temperature flow behavior; both enabled the grease to meet stringent low-temp performance targets, with PAO being the best overall performer in terms of lowest flow pressures at each temperature. The PAG-based grease's performance was also strong, though slightly behind PAO at the lowest temperatures. The POE base oil, despite its ISO VG 32 viscosity, clearly imposed a limitation when approaching its crystallization zone, which is around –36 °C, as evidenced by the measured cloud point. Notably, at –30 °C, the POE grease had not yet crystallized under the standard test and thus looked reasonably good in initial flow pressure. This could be misleading if one only considered the immediate test results. To further probe the POE grease's behavior and ensure the other greases have no hidden issues, we conducted the extended relaxation time experiments.

## 5. MODIFIED TESTING PROTOCOL

The modified test results, wherein samples were held at temperature for 4 h and 8 h before measuring flow pressure, are summarized in Figures 4, 5, and 6 for the PU-PAO, PU-PAG, and PU-POE greases, respectively. Each figure shows the flow pressure obtained at –20 °C and –30 °C under three conditions: (i) standard stabilization (minimal soak, labeled 0 h for comparison), (ii) 4 h soak, and (iii) 8 h soak. These experiments revealed marked differences in how each grease responds to prolonged cold exposure.

For the PU-PAO grease (Figure 4), the flow pressure at –20 °C under all conditions (standard conditions, 4 h, 8 h) remained consistent at 350 mbar, well below critical limits. Even after 8 h at –30 °C, the PAO-based grease's flow pressure remained under 600 mbar, which is still an excellent result. This indicates that the PU-PAO grease's microstructure undergoes only minor further solidification or relaxation over that time frame. In practical terms, if an EV equipped with this grease were parked overnight at –30 °C, the grease would not significantly harden beyond its initial condition, a very desirable trait.

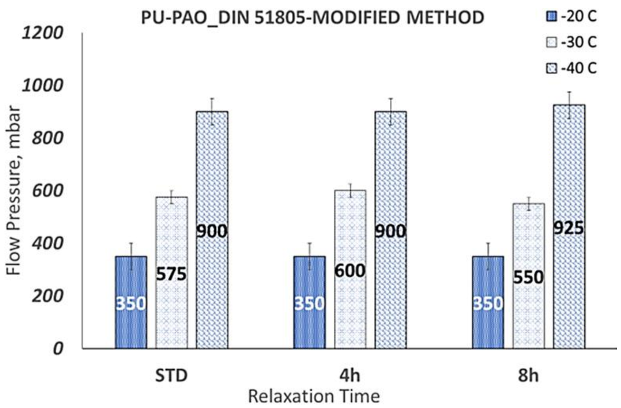

**Fig. 4.** Effect of relaxation time on flow pressure for PU-PAO grease at –20 °C, –30 °C, and –40°C.

The PU-PAG grease (Figure 5) showed a somewhat larger effect of relaxation time, but still moderate. At –20 °C, its flow pressure increased from 450 mbar initially to 475 mbar (4 h and 8 h). At –30 °C, the flow pressure rose from 675 mbar initially to 725 mbar after 4 h, and about 750 mbar after 8 h. Thus, an extended soak at –30 °C led to roughly a doubling of flow pressure for the PAG-based grease. After 8 h, the flow pressure at –30 °C was around 1.3 bar, which is still below the 1.4 bar acceptability criterion, but the margin was reduced. The increase suggests that the PAG-based grease does undergo some slow structural changes at low temperature, possibly slight crystallization of any impurities or a gradual alignment/packing of the urea thickener fibers. PAG oils generally do not crystallize like wax, but some high-molecular components or additives could potentially cause a slow increase in solidity. Regardless, the PU-PAG's extended 8 h value at –30 °C remained acceptable, and at –20 °C, even 8 h of soak kept it just under 500 mbar. So, while the PAG grease is a bit more time-sensitive than the PAO grease, its performance after prolonged cold storage is still quite good and likely serviceable for real-world use (most grease +LT qualifications might not even require performance beyond 4 h soak).

The most striking results were observed with the PU-POE grease (Figure 6). As expected from the prior standard test data, the POE-based grease is prone to significant issues upon extended cold exposure. At –20 °C, interestingly, the PU-POE grease did not show a dramatic change: initial flow pressure 400 mbar, remaining relatively consistent throughout. This suggests that –20 °C is not cold enough to trigger severe crystallization in the POE grease within an 8 h window; the grease stiffens a bit over time, but stays under 1 bar. However, at –30 °C, the picture is very different. The immediate (standard) flow pressure at –30 °C was 525 mbar as noted.

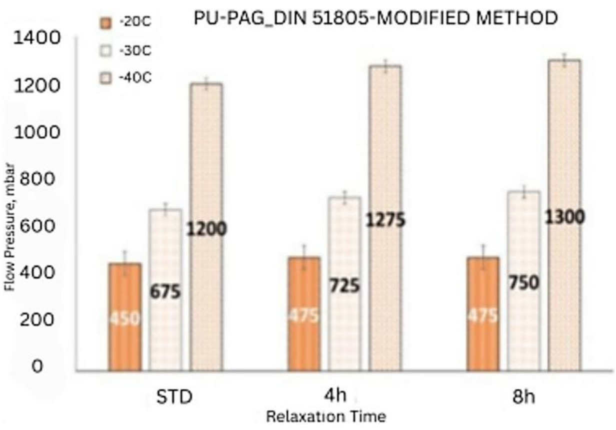

**Fig. 5.** Effect of relaxation time on flow pressure for PU-PAG grease at –20 °C and –30 °C.

After just 4 h of relaxation at –30 °C, the flow pressure greatly increased to 3225 mbar, the maximum reading the instrument could record (the grease barely extruded at the top pressure limit). In other words, the PU-POE grease became extremely hard after 4 h at –30 °C, reaching the same state it would likely have at –40 °C without soaking. After 8 h at –30 °C, the grease did not flow at all; it had fully solidified to the point of no flow under the instrument's capacity (this is inferred as the "flow pressure" remains at the max instrument value, essentially off the charts). These findings dramatically illustrate the time-dependent crystallization of the POE base oil in the grease. The temperature of –30 °C is above the POE's pour point, and initially the grease is semi-fluid there, but given a few hours, enough crystalline structure forms in the oil (with the thickener network promoting nucleation) that the grease transitions into a near-solid. In essence, the critical temperature for the POE grease's usability is around –30 °C, but only if the exposure is brief; sustained exposure pushes the effective limit to higher temperatures. This result aligns with previous experiences with fatty (biobased) lubricants, where performance can degrade over time even at temperatures 10–15 °C above the pour point [11]. It also reinforces that cloud point (–36 °C for the POE oil) is a more meaningful indicator than pour point for such oils' behavior in greases – the cloud point being within a few degrees of the observed "catastrophic" stiffening temperature.

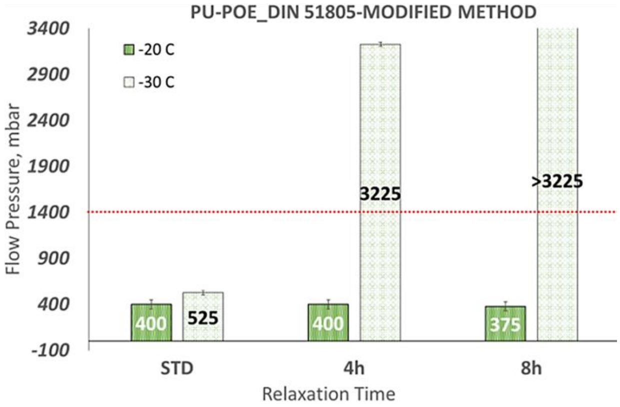

**Fig. 6.** Effect of relaxation time on flow pressure for PU-POE grease at –20 °C and –30 °C.

The extended soak experiments confirm that PU-PAO is the most robust formulation against prolonged cold exposure, with PU-PAG a close second, while PU-POE is severely affected by long cold exposure at temperatures near its crystallization range. After just 4 hours, the POE grease's flow pressures at –30 °C far exceeded the 1400 mbar practical limit, meaning it would not be acceptable for use in an application that sees continuous cold soak around –30 °C. In contrast, the PAO and PAG greases remained under that threshold even after 8 h at –30 °C. From a development standpoint, these findings suggest that PAO is the preferred base oil for formulating EV motor greases when low-temperature performance is paramount. PAO-based greases provided the lowest flow pressures and the greatest resistance to time-dependent thickening (likely because PAOs have no wax content and a very low glass transition temperature, so they stay amorphous and stable). PAG-based greases are also a viable option, offering good initial low-temp mobility; however, one should ensure the specific PAG chosen does not have any crystallization issues (many PAGs are amorphous, especially random copolymer types, but some can have freezing points if they are polyethylene glycol type). The particular PAG used here performed well, though showing a slight time dependency at –30 °C.

It is important to note that among polyurea greases, low-temperature behavior reflects not only base-oil phase transitions but also the ability of the thickener network to retain oil under static conditions. Synthetic-oil polyurea greases are known to exhibit moderate oil separation, which can influence apparent stiffness and resistance to deformation. While oil separation was not explicitly quantified in this study, the consistent low-temperature performance of the PAO- and PAG-based greases suggests stable oil retention during extended cold soak. In contrast, the abrupt stiffening observed for the POE-based grease indicates that base-oil crystallization dominated the low-temperature response, overwhelming any mitigating influence of the thickener network.

The POE-based grease, while showing respectable performance in quick tests, demonstrated a latent risk: a formulator might be tempted to use a POE (for its biodegradability or high-temperature advantages) and see it pass a –30 °C flow test, but in service, after hours in the cold, the grease could stiffen beyond acceptable limits. This underscores the importance of testing greases under conditions that mimic real use. Standard test methods may need enhancements (such as the 4 h/8 h soak procedure used in this study) to screen for such time-dependent behavior, especially as the industry explores more sustainable base oils. Biobased esters, for instance, are attracting interest for eco-friendly EV lubricants [4,15], but many are prone to crystallization due to high saturation of fatty acid chains. Factors like the degree of saturation, branching of the molecular structure, and molecular symmetry can all influence an ester's crystallization tendency [4]. Highly saturated, linear esters tend to have higher freezing points, whereas branching and the presence of unsaturated bonds can depress crystallization (though too many unsaturated bonds can hurt oxidative stability). Thus, future development of low-temperature sustainable greases might focus on structured esters that resist crystallization or blending esters with PAOs to improve cold performance. Additionally, the industry standards may evolve: it has been suggested that committees consider incorporating extended soak protocols into low-temperature grease test standards. The data from this study would support such an initiative, as it differentiates greases in a way that standard tests alone would not have caught.

For grease users (e.g., EV motor designers or maintenance engineers), the results here highlight that not all "-30 °C rated" greases are equal. A grease formulated with an ester base oil might meet the specification in a lab test, but could lead to excessive torque or even lubricant starvation after an overnight cold soak. On the other hand, greases based on PAO (and certain PAGs) provide a more reliable safety margin in cold conditions. Polyurea-thickened greases proved to be a suitable matrix for these base oils, yielding high dropping points and good performance across the board, so the thickener choice can be tuned for other factors (e.g., polyurea for long life, or perhaps lithium complex for cost; though lithium complex greases might have different low-temp traits [6]). The knowledge gained here can aid formulators in creating cold-temperature resilient greases for electrified vehicles: for instance, if one aims to incorporate biodegradable content (esters) for sustainability, one might limit the ester to a certain percentage blended with a PAO or choose an ester with lower crystallinity (such as one with some branching or slight unsaturation), and include extended cold soak tests during development.

## 6. CONCLUSION

This study evaluated the low-temperature flow behavior of polyurea greases formulated with three synthetic base oils for electric and hybrid vehicle motor bearing applications. Flow pressure was measured using the DIN 51805-2 Kesternich method from 0 °C down to −40 °C, including a modified protocol incorporating extended relaxation times of 4 and 8 hours at selected temperatures. Under standard (brief soak) conditions, all three greases exhibited satisfactory flow at −30 °C, remaining well below the 1400 mbar threshold specified in the NLGI HPM+LT framework, which serves as a practical upper limit for acceptable low-temperature grease mobility. At −40 °C, the PAO- and PAG-based greases remained flowable, while the POE-based grease exceeded the instrument limit and failed to flow.

Extended cold-soak testing revealed pronounced time-dependent effects that were not captured by standard short-duration measurements. The PAO-based grease showed minimal sensitivity to prolonged exposure, maintaining low flow pressures even after 8 hours at −30 °C. The PAG-based grease exhibited a moderate, gradual increase in flow pressure with time but remained below the 1400 mbar practical limit. In contrast, the POE-based grease experienced a dramatic increase in flow resistance after extended soak, exceeding 3225 mbar after 4 hours at −30 °C, consistent with progressive crystallization associated with the ester base oil. These results demonstrate that PAO and PAG base oils solidify predominantly in an amorphous manner at low temperatures, leading to smooth and reversible stiffening, whereas the POE base oil undergoes a time-dependent phase transition that severely impairs grease mobility. The observed behavior correlates with the POE cloud point and highlights that pour point alone is an insufficient indicator of low-temperature suitability for greases containing crystallizable oils.

From a formulation perspective, PAO-based polyurea greases represent a robust benchmark for cold-climate EV and HEV applications, offering stable low-temperature mobility even after prolonged cold exposure. PAG-based greases also remain viable, provided that the specific PAG chemistry is verified for low-temperature stability. Ester-based greases, while attractive for high-temperature performance and potential environmental benefits, require careful design, blending with non-crystallizing base oils, or hybrid formulations to mitigate crystallization risks. The findings further suggest that extended cold-soak protocols should be considered alongside conventional tests when qualifying greases for severe low-temperature service. Future work combining flow-pressure measurements with oil-separation data and complementary low-temperature torque or rheological testing would further clarify the interplay between base-oil phase behavior and thickener network stability. In addition, emerging formulation strategies, such as the incorporation of two-dimensional materials (e.g., graphene or molybdenum disulfide), may offer new pathways to tailor grease rheology and maintain mobility under extreme temperature conditions.

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