Rotorcraft Lubrication Optimization through Grease Sampling and Analysis

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INTRODUCTION

Rotorcraft, like most machines, require periodic lubrication tasks to ensure continued safe and reliable operation. Optimal lubrication intervals are desired to maintain system performance while minimizing aircraft downtime and maintenance labor. Boeing and AMRRI conducted a Lubrication Optimization Study (LOS) on the H-47 Chinook helicopter to establish the necessary engineering artifacts to define the grease lubrication intervals for selected Drive, Rotor, and Landing Gear components. Grease samples were collected from these components by H-47 operators from multiple nations and submitted for a laboratory analysis to characterize how wear, properties and contaminants change as time and aircraft hours accumulate. The LOS also revealed opportunities to further evaluate and leverage the data produced in this study, including determining superior performance of specific lubricants within the Mil-Spec designation, testing of greases for compatibility[5] when mixed, and enhancing new grease cleanliness to extend component life.

ABSTRACT

Boeing and AMRRI conducted a Lubrication Optimization Study (LOS) on the H-47 Chinook helicopter to establish the engineering basis and artifacts to define the grease lubrication intervals for selected Drive, Rotor, and Landing Gear components. The study's main focus was a laboratory analysis of grease samples collected from these components, to characterize how wear, properties and contaminants change as time and aircraft hours accumulate.

To ensure there was statistical significance in the analysis, almost 1200 samples were collected in two phases from May of 2018 through July of 2019. Five different operators participated in collecting samples. This level of participation provided an opportunity to quantify a diverse range of environmental operating conditions such as "hot", "dry", and/or "salty".

AMRRI evaluated the grease samples for Ferrous Density (FdM), Colorimetry, Die Extrusion (shear flow), Linear Sweep Voltammetry (anti-oxidation properties), Moisture, Particle Contaminants (external sources such as Silicon, Aluminum), Fourier-transform Infrared Spectroscopy (organic contaminants), and Rotating Disc Electrode (RDE) Spectroscopy (wear measurement of non-ferrous components). Oxidation was the primary limiting parameter in most cases, while the secondary limiting parameter were more dispersed.

Boeing conducted a field data analysis on each of the sampled components. This analysis supplemented the grease analysis conducted by AMRRI. Together these analyses produced the engineering basis for the recommended servicing interval for the selected Drive, Rotor, and Landing Gear components. The results of the study showed one interval being decreased, five extended intervals, and eleven intervals unchanged compared to the established grease servicing intervals.

SAMPLING METHODOLOGY

Critical to the success of this program was the development of a sampling procedure and tools that ensured that each sample submitted for analysis was representative of the condition of the component and the grease currently providing protection for that component. The starting point for this was the American Society of Testing and Materials (ASTM) D7718, "Standard Practice for Obtaining In-Service Samples of Lubricating Grease" document which was developed in 2011 and based on research conducted for the power generation industry[i].

This previous research included testing of geared surfaces and both large and small bearings. While some of this prior work was directly applicable to similar component types on the CH-47 drivetrain, there are differences in housing configurations and accessibility that needed to be addressed, particularly for the splines in the Chinook driveshafts. An existing tool, the Pillow Block Grease Thief sampling kit, was used for initial sampling performed at the Boeing service facility. This kit is pictured in FIGURE 1 and consists of a plastic spatula that was used to sample the various Rotor, Drive, and Landing Gear components in the study. The spatula was especially helpful for sampling the surfaces of spline gear teeth, which proved to be the most challenging surface to sample. Initially, this device was modified to create a profile matching the angle of the spline teeth, but because splines in the aircraft have different dimensions and one solution could not be found for all of them, the spatula was maintained in its original shape. Instructions were provided to hold the spatula tip at an optimal angle to scrape the grease from the surface of the teeth. Because of the soft plastic material of the spatula, this could be done without damaging the spline. When sampling components other than splines, the wide end of the spatula served to easily collect the grease. The gathered grease was then packed into a standard 6ml syringe with the plunger removed. When a sufficient quantity of grease was removed from the surface of the spline, the plunger was reinstalled and used to transfer the grease to the Grease Thief, a plastic body sampling device. The syringe used for this transfer was modified to remove the tip, so that a more complete transfer of grease to the Grease Thief could be achieved. The filled Grease Thief was placed in the plastic shipping tube, and an identifying label was affixed for submittal to the laboratory for analysis.

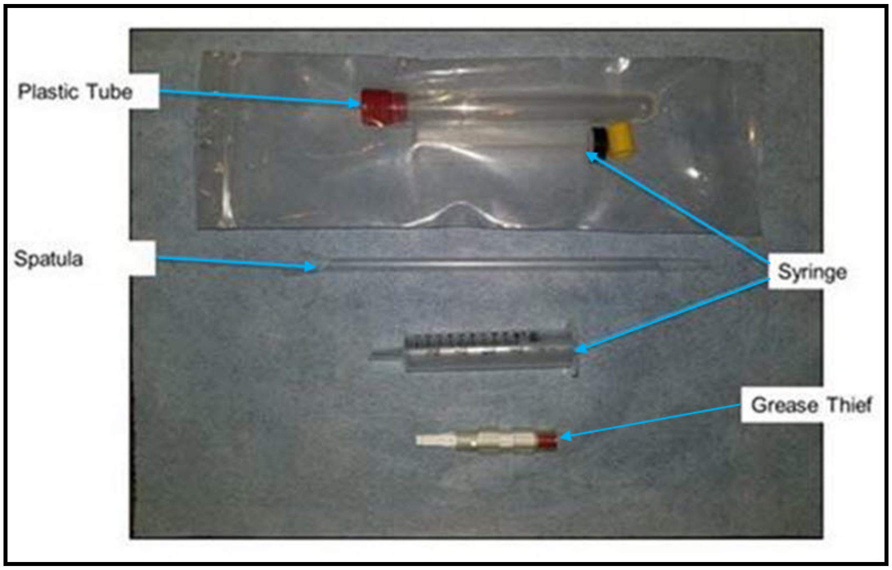
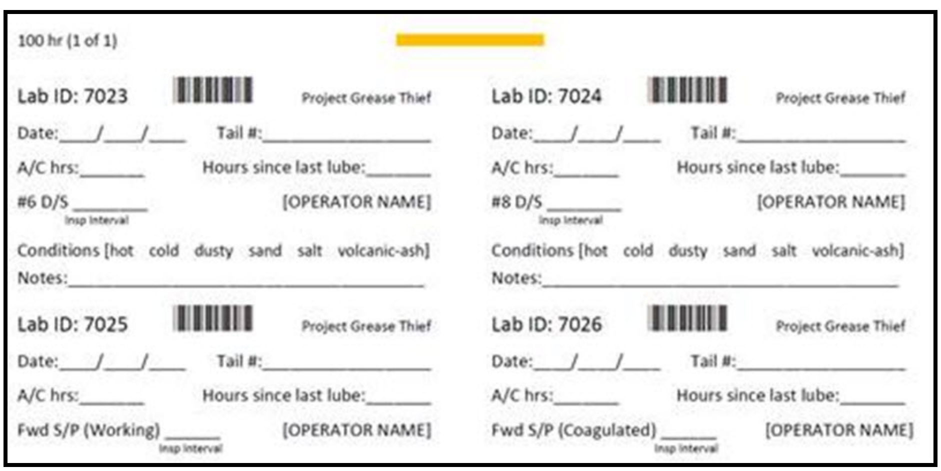


FIGURE 1: Sampling sleeve with Grease Thief and other components


100 hr (1 of 1)

Lab ID: 7023 Project Grease Thief
Date:___/___/___ Tail #:__________
A/C hrs:______ Hours since last lube:______
#6 D/S ______ Insp Interval [OPERATOR NAME]
Conditions [hot cold dusty sand salt volcanic-ash]
Notes:__________

Lab ID: 7024 Project Grease Thief
Date:___/___/___ Tail #:__________
A/C hrs:______ Hours since last lube:______
#8 D/S ______ Insp Interval [OPERATOR NAME]
Conditions [hot cold dusty sand salt volcanic-ash]
Notes:__________

Lab ID: 7025 Project Grease Thief
Date:___/___/___ Tail #:__________
A/C hrs:______ Hours since last lube:______
Fwd S/P (Working) ______ Insp Interval [OPERATOR NAME]

Lab ID: 7026 Project Grease Thief
Date:___/___/___ Tail #:__________
A/C hrs:______ Hours since last lube:______
Fwd S/P (Coagulated) ______ Insp Interval [OPERATOR NAME]

FIGURE 2: Grease Thief sampling kit barcode labels

The labels were designed specifically for this project and came with the kit pre-printed with the locations identified for sampling based on the maintenance interval being performed. In each case, sampling was scheduled with an existing maintenance task to minimize in resource impact of the sampling process. A portion of a sample label page is shown in FIGURE 2. Labels assigned a unique barcode number to each sample for positive identification.

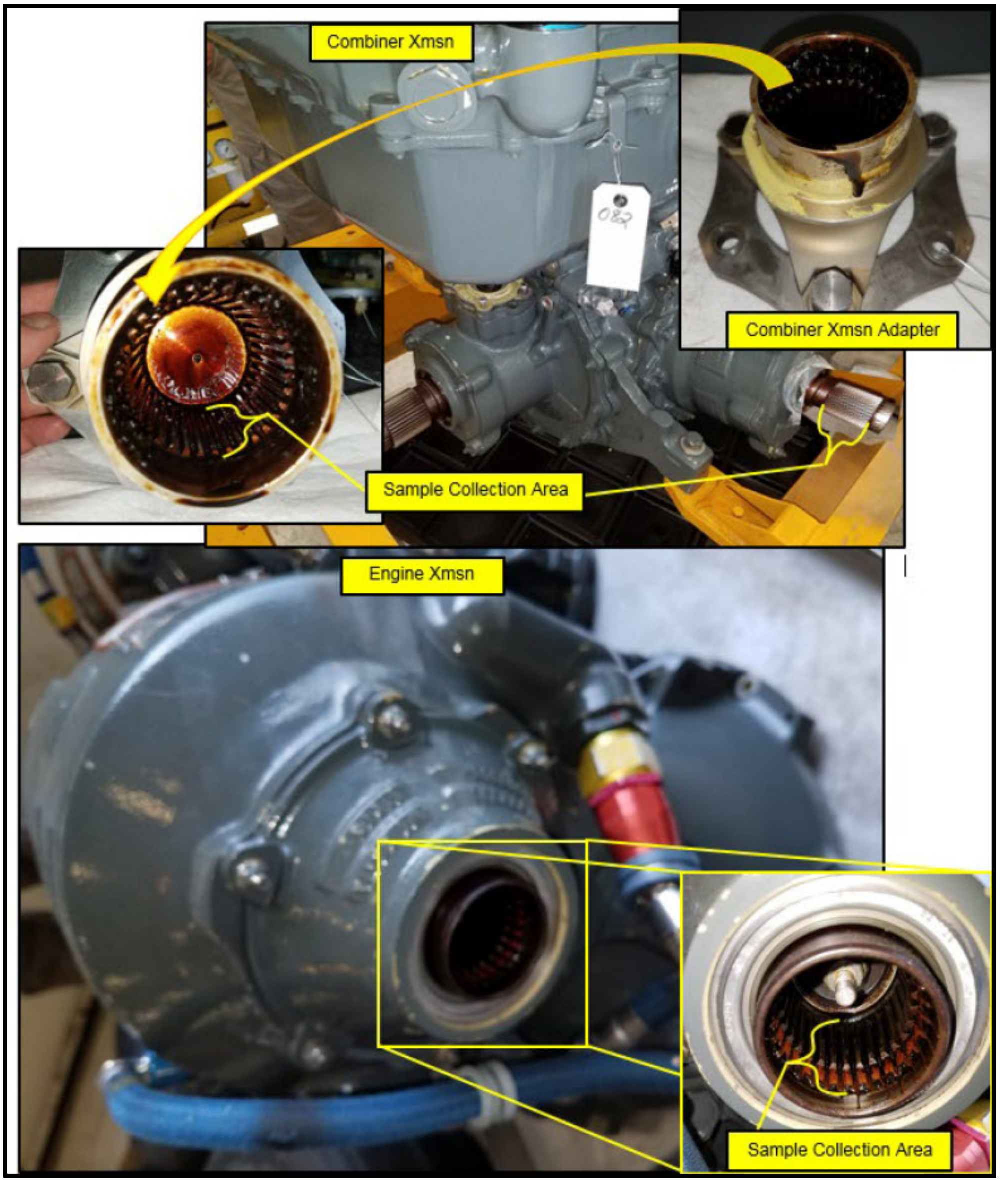


FIGURE 3: Sampling Diagram for Cross Shaft Engine and Combiner Transmission Adapters

Instructions were included in each sampling kit, which included 8 “pouches” with each “pouch” containing the items shown in FIGURE 1. Additionally, training was provided to soldiers and mechanics involved in the sampling process to ensure uniformity of sampling methodology. In each case, the target volume for sampling was a full Grease Thief, which would be approximately 1.5 grams of grease. Each of the locations were carefully evaluated to determine the best area to collect the sample as indicated in FIGURE 3. However, some locations, particularly the smaller splines, did not afford this quantity of available grease, and so a chart was developed to indicate the analyses that could be performed for lesser quantity samples. FIGURE 4 shows the training session for sampling using the modified Grease Thief sampling kit during a scheduled maintenance activity.

FIGURE 4: Soldier obtains spline grease sample during maintenance activity

The tests to be performed were optimized for those samples that had lesser quantity of grease. The "Large Volume" samples, those with more than 0.95 grams of grease, were sufficient for performing all eight of the designated analysis tasks. Samples with greater than 0.69 grams but less than the 0.95 grams were designated as "Small Volume" samples, and could have seven of the tests performed, with Die Extrusion (consistency) not being possible. As a substitution, an alternate consistency test could be performed with less grease using a cone and plate rheometer. Samples with less than 0.69 grams but at least 0.35 grams were designated "Tiny Volume" samples, and could not be used to perform Die Extrusion, ferrous density or RULER (anti-oxidant) testing and so provided limited additional data for the study. Samples with less than 0.35 grams of grease were not used in the study.

GREASE ANALYSIS TESTS

The analysis test slate selected would be based on the known oxidation stressors and contaminant sources found in the machine application and additives present in the grease to extend life. The ASTM Standard Test Method for evaluating in-service greases is D7918. This method uses the tests identified in TABLE 1 which list the key parameters measured and evaluated in the grease. Two additional tests (TABLE 2) are typically included in the analysis although they are not found in the current version of the ASTM D7918 standard. The Rotating Disc Electrode (RDE) Spectroscopy test and Fourier-Transform Infrared (FTIR) Spectroscopy test, provide elemental and molecular spectroscopy results, respectively, and complement the analysis performed in D7918 by monitoring non-ferrous wear particles, additives, contaminants, and the oxidation of the grease. While the ASTM D7918 method does provide for a particle counting test, a thin-film direct imaging technique, it was determined that the variables in the greases used in the aircraft, as well as the anticipated conditions of the greases, may make this method ineffective due to insufficient optical clarity of the grease. Therefore, the particle counting function was substituted by monitoring the elemental Silicon (Si) levels in the grease as measured by the Rotating Disc Electrode Spectrophotometer. As the most common source of external particulate was expected to be sand or dirt based on operating environments and action of air turbulence, Silicon was deemed to be a suitable indicative parameter to measure the ingression of these particles.

TABLE 1: ASTM D7918 Grease Analysis Tests

Grease Test	Parameters Measured	Value of Analysis
Ferrous Density (FdM)	Parts per million (ppm) iron debris/wear	Used to evaluate total accumulated wear between grease replenishments
Colorimetry	A spectral comparison to the new grease in the visible light range	Screen for mixing different greases, aging, and contaminants
Die Extrusion	A variable-rate shear flow of the grease at controlled temperature that compares the load profile to the new grease	Measurement of consistency changes that can predict tendency of grease to harden or soften in service and leak from housings
Linear Sweep Voltammetry	The "RULER" test quantifies the anti-oxidants found in the new grease, and compares the remaining levels and the time in service for the grease sample	Can evaluate the remaining oxidative life of the grease to confirm ability to continue for longer service intervals without degradation
Moisture	Parts per million water is measured by thermal transfer from a grease thin-film and measurement with a humidity sensor	Replenishment of grease can flush contaminants; this can ensure excessive moisture will not intrude at extended service intervals
Particle Contaminants	While ASTM D7918 uses direct imaging particle count method, a measure of the elements typical of contaminants (such as Silicon, Aluminum) from external sources was used instead	Replenishment of grease can flush contaminants; this can ensure excessive particulate will not intrude at extended service intervals

TABLE 2: Additional Grease Tests performed, not in ASTM D7918

Grease Test	Parameters Measured	Value of Analysis
FTIR	ASTM E2412 is widely used in the US Military Joint Oil Analysis Program (JOAP) to detect contaminants and changing oil condition. This Fourier-transform Infrared Spectroscopy evaluates the organic functional groups in the sample.	For greases, this will be used to compare to the new grease formulation to find the presence of different greases mixing, contaminants, and oxidation of the grease. Will help to determine if oxidation is occurring in the existing or projected service intervals. May also be helpful to detect some anti-oxidant additives, depending on the specific grease product formulations.
Rotating Disc Electrode (RDE) Spectroscopy	Parts per million measurement of elemental metals as wear, additives and contaminants, using a solvent-preparation method, and ASTM D6595 standard.	Will complement FdM for wear measurement of non- ferrous components (such as copper), oxidized ferrous particles such as rust, corrosion and fretting wear, and assist in the detection of mixed greases, loss of additives, or contaminants.

SAMPLE ANALYSIS

The participation of multiple international operators was secured for the project, and a scope of up to 1200 samples was set for the study. The original target was to obtain at least 30 samples from each location for the purpose of establishing statistical significance to the findings of the grease analysis and determination of optimal intervals. Sampling kits consisting of 8 pouches in each were distributed to operators. Several kits were designated based on service interval testing, with the variable in each kit being the labels that were included to align with the components being accessible for sampling during the maintenance activity. TABLE 3 provides a list of each component included in the study along with the current established grease servicing intervals. These intervals were determined based on engineering input and operating history.

TABLE 3: Previously Established Grease Service Intervals

Component	Established Grease Service Intervals
Swashplate	50hr
Drive Shaft Bearing	100hr
Combiner Transmission Fan Shaft	100hr
Aft Transmission Fan Shaft	200hr
Aft Transmission Fan	200hr
Combiner Transmission Fan	200hr
Drive Collar	200hr
Forward and Aft Transmission Adapter	200hr
Combiner Output Adapter	200hr
Combiner Input Adapter	200hr
Engine Transmission Output Adapter	200hr
Forward Landing Gear Torque Link	200hr
Aft Landing Gear Drag Link	200hr
Aft Landing Gear Swivel Housing	200hr
Landing Gear Wheel Bearings	400hr
Auxiliary Power Unit Motor Pump	Opportunity
Auxiliary Generator	Opportunity

The individual grease sample results were compiled to find the 7 parameters that influence grease life, which included elemental iron (Fe), elemental silver (Ag), elemental silicon (Si), ferrous debris level, moisture, Die Extrusion Index (consistency), and oxidation index. These parameters were plotted as a function of flight hours since last grease service, to determine the interval at which each parameter began to degrade. A curve fit was developed for each graph based on the flight hour trend behavior of the parameter. These relationships were mostly linear but some were logarithmic. The formula for the curve fit was used to calculate the number of flight hours that corresponded to the target parameter replenishment level. The optimal service interval was described as the number of service hours that would allow replenishment of grease before the onset of degredation. In this way, each component would be adequately protected against wear and damage by ensuring that the grease would be replaced by new grease before it degraded or accumulated significant contaminants. An example of the regression analysis used to project the optimal interval is shown in FIGURE 5. In the case of this parameter, "Oxidation Rating", the target parameter replenishment level was selected at a value of 75, which corresponds to a remaining 25% of the original level of anti-oxidant additive protection. In this case, the curve fit line equation produces a value of 171 flight hours.

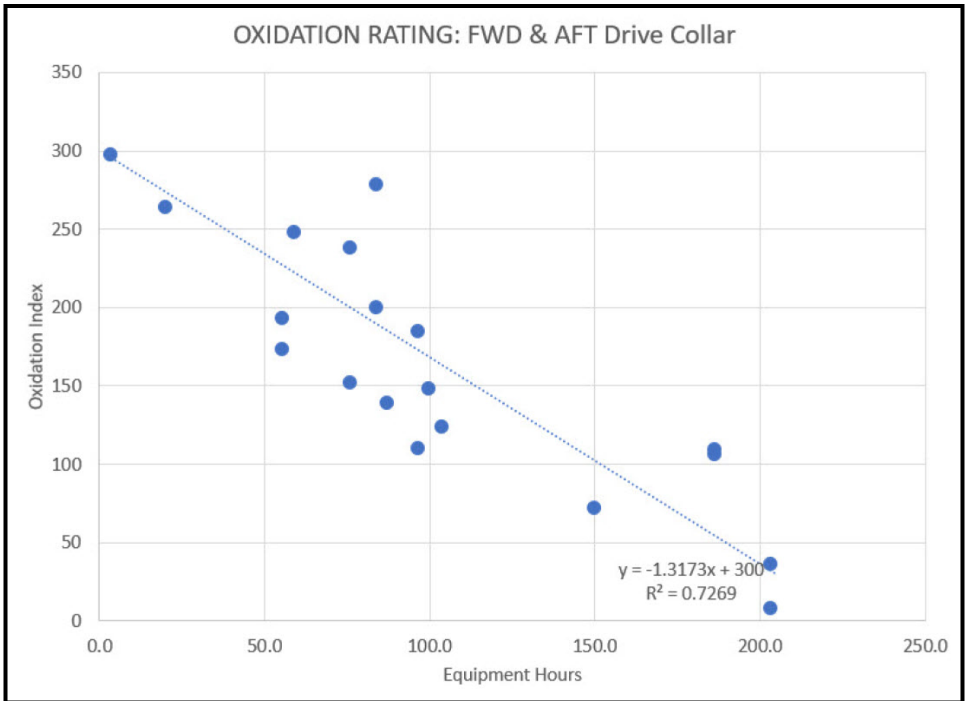


FIGURE 5: Drive Collar samples Oxidation Rating

Among the findings in the study, correlation was found between the amount of silicon detected in the grease (typically a function of the intrusion of sand or dirt during maintenance or while in operation), and the degree of wear measured by both the levels of elemental iron (Fe) and aluminum (Al), as seen in FIGURE 6.

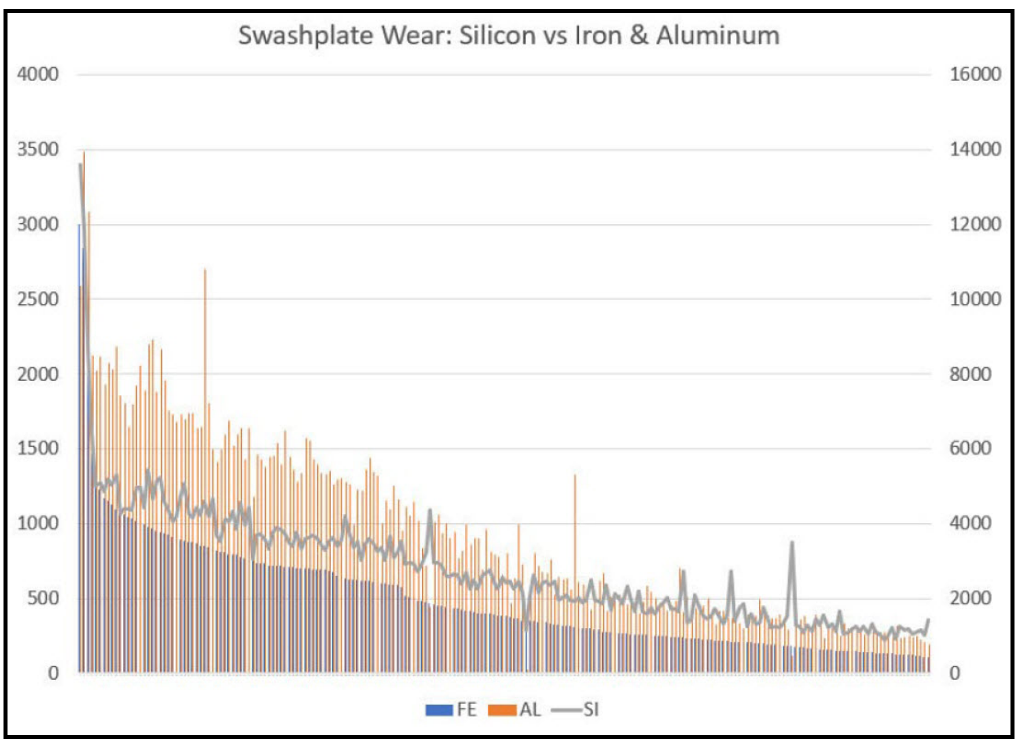


FIGURE 6: All component grease samples, with left Y-axis being elemental iron (Fe) and elemental aluminum (Al) in parts per million, the right Y-axis being elemental Silicon (Si), and the X-axis being a sequential plotting of the highest to lowest values for iron in a scatter chart.

Another unusual finding was the observance of significant levels of the element Silver in the grease samples. Investigation determined that silver was being used as an anti-fretting coating on some bearing cage and spline surfaces. While most grease samples had low silver levels, some locations were significant, with silver levels over several thousand parts per million (ppm). The sacrificial loss of silver is not necessarily problematic, as the design is for this coating to limit wear and structural damage to the drive surfaces. However, a correlation was noted through principal component analysis (PCA) of the relationship between high (>10ppm) levels of elemental silver and higher levels of elemental iron in these locations, as seen in FIGURE 7. This indication may allow for periodic grease analysis as a useful indicator of future wear and directed condition-based maintenance and inspection tasks.

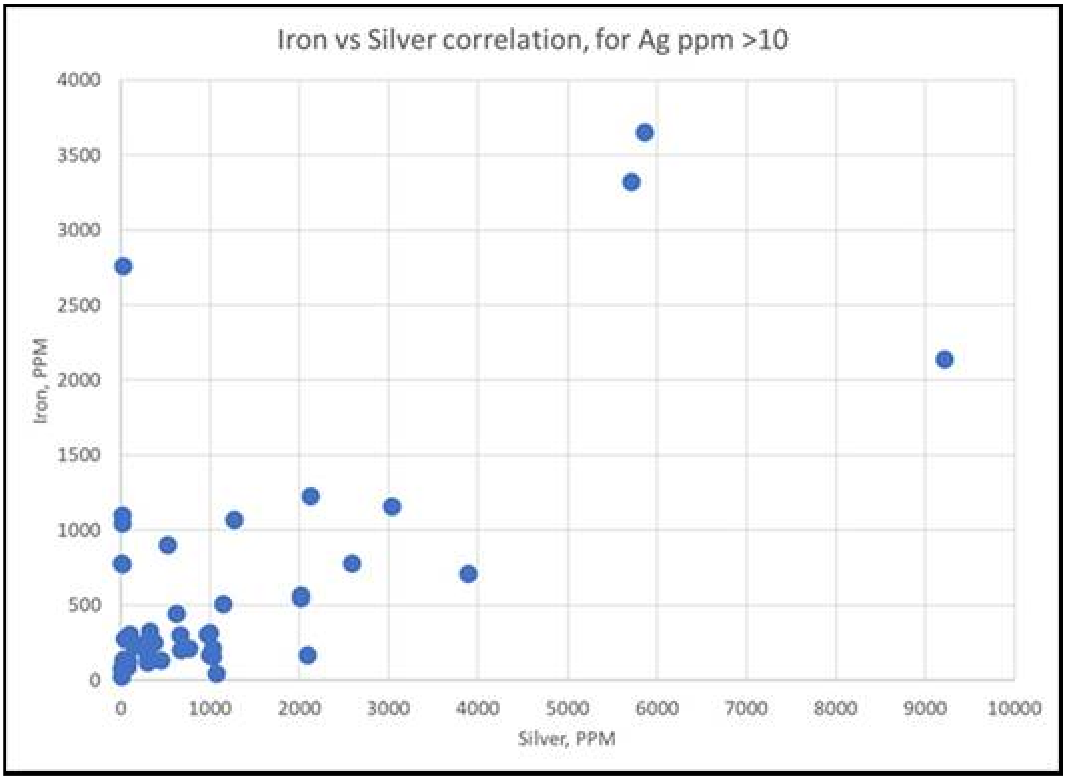


FIGURE 7: PCA Analysis of elemental Silver vs elemental Iron

While the project was not specifically targeting a comparative evaluation of grease products, some findings were presented that did reinforce the effectiveness of certain greases when used in the target application. The chart in FIGURE 8 shows that in a few cases for which an alternate grease was used, wear performance was not as good as those components using the primary designated grease. This does not serve as an evaluation of the relative merits of these products, but rather an assessment of the wear levels observed in a specific application with a limited sample set, and confirms the suitability of the primary product.

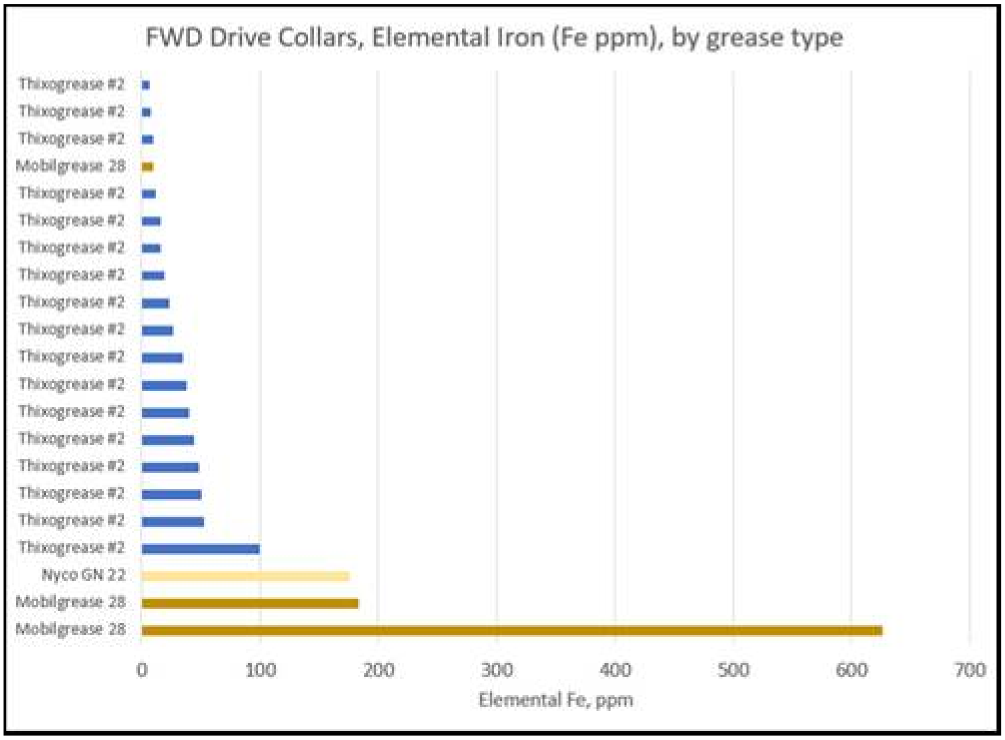


FIGURE 8: Wear levels as a function of grease product

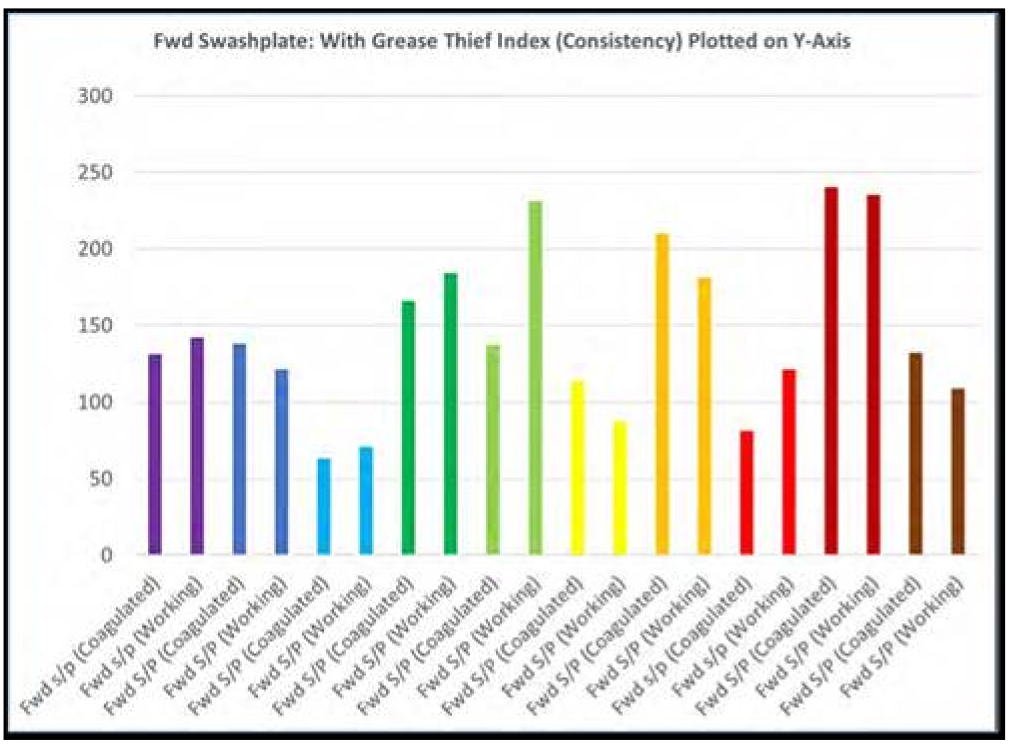


FIGURE 9: Comparison of "Coagulated" to "Working" grease sample consistencies

The swashplate was initially sampled in multiple locations to determine the behavior of the grease that was not found in the “working” area of the bearings. Experienced mechanics described grease in the swashplate after some time in service as being proximal “Working” grease, versus a “Coagulated” grease found some distance away from the lubricated part. In order to evaluate the significance of this observation, both locations were sampled and compared. Somewhat surprisingly, grease taken from both locations in a given swashplate produced very similar results. This included comparisons in consistency, wear levels and even remaining anti-oxidant. The observation of this similarity implies that the grease from these locations are not distinct and separate, but rather flow together and mix while in service. Attributes commonly expected to vary based on distance from the working part, such as wear particles and anti-oxidants, remained similar. Based on this observation, subsequent samples were only obtained from the “Working” area of the swashplate enclosure. The graph of the consistencies, as measured by the Die Extrusion method, are plotted in FIGURE 9.

All 11 of the components shown in TABLE 4 were analyzed using seven identified parameters. These results, produce the grease analysis based recommended servicing intervals.

TABLE 4: Optimal Grease Replenishment Parameters

	Oxidation Index	Moisture	Ferrous Content	Fe ppm	Die Extrusion (GTI)	Ag ppm	Si ppm	Limiting Parameter Interval
Sample Point Criteria:	<75 Index	>10000 ppm, or at Max of non-outliers	Rate of Change >2σ or 2X Max	Rate of Change >2σ or 2X Max	>200 or <40	>500ppm	>10000	
AFT S/P	220	750	425	630	500	None Detected	410	220
FWD S/P	203	**	2000	330	1325	None Detected	860	203
Engine Xmsn Output Adapters	653	Note 2	2700	1600	2600	Negligible Levels	*	653
Drive Collar (w/lube fitting)	171	330	1350	3900	1950	Negligible Levels	Note 4	171
Drive Shaft Bearing	232	485	1060	510	340	Note 3	550	232
Fwd. & Aft Xmsn Adapters	809	1250	2000	2050	1450	Note 4	Note 2	809
Aft Xsmn Fan	646	**	1700	1025	4700	Note 4	Note 2	646
Aft Xsmn Fan Shaft	864	Note 2	1850	1700	860	Note 5	Note 2	860
C-Box Input Adapter	980	Note 3	2400	2000	*	Negligible Levels	Note 2	980
C-Box Output Adapter	1273	278**	2400	2950	1773	Note 4	Note 2	278
C-Box Fan	722	Note 2	1410	1128	1800	Note 4	216*	722
C-Box Fan Shaft	303*	Note 2	838*	1145*	410*	Note 5	Note 2	303

Note 1	Best curve fit is positive, so no degradation trend observed
Note 2	Best curve fit is negative, so no increasing trend observed
Note 3	Limit not exceeded
Note 4	Only a few records had non-negligible levels; insufficient data to compile trend
Note 5	Significant Silver (Ag) levels, but no definitive trend
*	Poor correlation in trend data; other factors should be considered
**	Multiple samples exceed criteria but overall data trend may be misleading; other factors should be considered

FIELD DATA ANALYSIS

In addition to the grease analysis, Boeing utilized field maintenance data obtained from operators' logbooks, part removal records, phase maintenance records, and other published documents to analyze historical and engineering data. Wiebull disturbution analysis was used to generate a survival curve. Conservative ground rules were established for the analysis process to ensure continued safe operation of the H-47 helicopter. Results from this analysis provided validation of the grease sampling analysis and further guidance into the determination of the recommended servicing intervals. The historical data analysis and grease sample analysis were statistically evaluated together in order to determine the data-driven, optimized grease service intervals.

The maintenance data was also used to help determine the component age both from new and from last overhaul providing more insight into the significance of the data set. This gave a means to evaluate the analyzed grease parameters for trends and relationships that correlate to the component age.

CONCLUSION

As a result of the study the majority of the lubrication intervals were extended, many double the established grease service intervals currently fielded by the various operators. This extension provides each operator with an opportunity to adjust their grease servicing intervals thus allowing a reducuction in down time and maintenance costs while ensuring the continued safe operation of the aircraft. The benefit of the study is that final service interval determinations can be aligned with existing maintenance intervals, and to support a maintenance optimization effort completed by Boeing.

These results translate to fewer interruptions to operations for required servicing. In total, an estimated reduction from 98 lubrication tasks per 1000 flight hours to just 56 lubrication tasks per 1000 flight hours, and a reduction from 20 service interruptions per 1000 flight hours to just 10 service interruptions per 1000 flight hours.

ACKNOWLEDGMENTS

This study was conducted with assistance from multiple H-47 Chinook operators, including Canadian CH147F ILS/Projects Management, US Army Cargo Fleet Management, the MH-47 Technology Applications Program Office, the Netherlands Defence Materiel Organisation, and the UK Ministry of Defence. Each operator provided a considerable number of samples at varying intervals and operating conditions which increased the diversity of the data.

The extended Boeing team include members of the affected design teams and Field Service Engineering who was responsible for crafting the Service Bulletin which provided sampling instructions compatible with the customer maintenance personnel and aircraft configurations.

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