Cost-Effective Management of Wind Turbine Lubricants

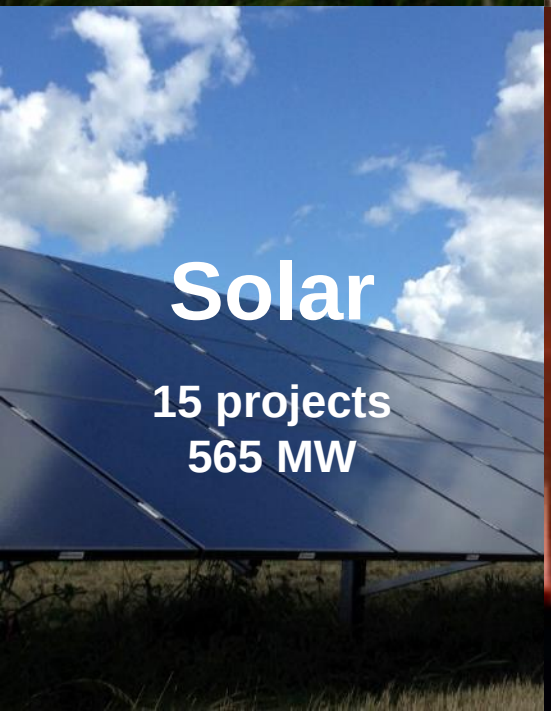
Presented to STLE

Matt Snow

May 24, 2018

Invenergy

About Invenergy



Broad Expertise

We develop, own and operate large-scale renewable and other clean energy generation and storage facilities in North America, Latin America, Japan and Europe.

* As of April 30, 2018; includes projects that are operating, in construction or contracted. Renewables include wind, solar and storage.

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Superior Results

Invenergy performs most work in-house, leading to superior results, lower costs and satisfied customers.

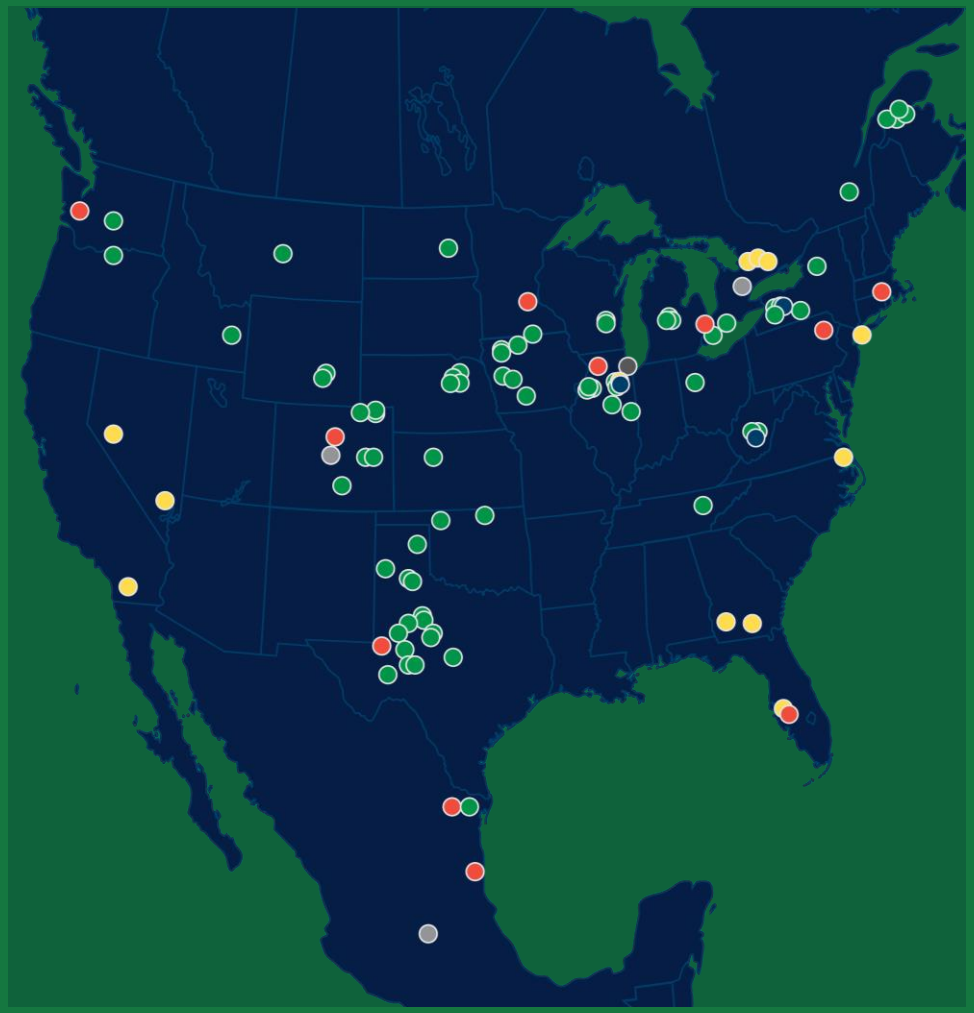
Engineering & Construction
In-House Design
Construction Management

Marketing & Finance
PPAs, Tolls, Hedges
Environmental Commodities
Flexible Structures
$30B+ in Transactions Completed

Project Development
Strategic Siting
Land Acquisition
Permitting
Interconnection

Ownership & Operations
Operations & Maintenance
Asset Management
Community Relations

North American Wind Operations



34 wind projects in the US and Canada

Over 2,500 WTGs

Over 4,000 MW

Geographically diverse

Each project staffed with site manager, maintenance technicians, admin

Majority of our maintenance is self-performed

- Wind
- Solar
- Natural Gas
- Advanced Energy Storage
- Regional Office
- Corporate Headquarters

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Major Lubricant Positions

Position	Lubricant Type	Lubricant Change Difficulty	Lubricant Change Cost	Component Failure Likelihood	Failure Cost
Main Gearbox	Oil	High	$$$$	High	$$-$$$$
Main Bearing	Grease	Low	$$	High	$$$
Generator Bearing	Grease	Impossible		High	$$
Pitch Bearing	Grease	Moderate	$$	Moderate	$$$
Yaw Bearing	Grease	Low	$	Low	$$$
Yaw Drive	Oil	Moderate	$	Low	$$
Pitch Drive	Oil	Moderate	$	Low	$

- OEM generally specifies first fill for all oils and greases as well as maintenance requirements
  - Changing lubricants is frequently restricted for equipment under warranty
- Financial considerations influence maintenance practice
  - Capital expenditures require thorough justification

Goals of Lubricant Management

Our objective is to maximize the value of our wind turbines through optimized operations and maintenance practices. There are several ways to do that.

- Immediate Pay-Off
  - Changing the supply of high-volume consumable parts for lower price or better performance (or both!)
  - Eliminating nuisance maintenances
- Short-Term Pay-Off
  - Upgrading to more expensive, but better performing parts or lubricants
- Long-Term Pay-Off
  - Easy: low cost, low effort changes to the status quo
  - Hard: major capital outlays

Goals of Lubricant Management

Our objective is to maximize the value of our wind turbines through optimized operations and maintenance practices. These are a few that we have considered.

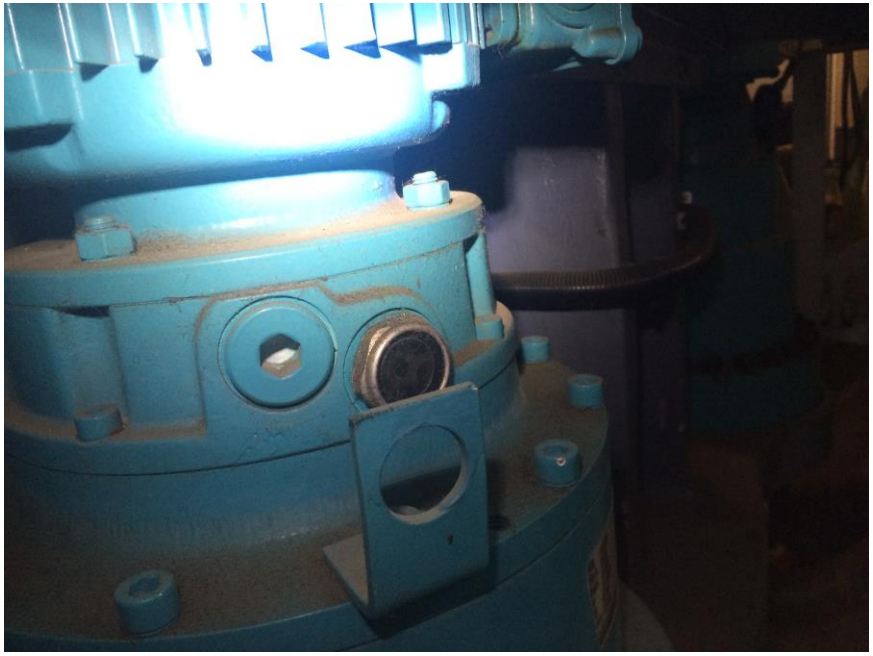
- Yaw and Pitch Drives
  - OEM maintenance mandates oil changes every 3 years
  - Is that the right interval?
- Main Bearing Grease
  - Are OEM maintenance guidelines adequate?
- Main Gearbox Oil
  - What does oil sampling tell us?
  - What can we do about it?

Yaw and Pitch Drives

OEM maintenance mandates changing the oil in the yaw and pitch drives at fixed intervals. We wondered if that was necessary. Mostly because it seems messy and difficult.

Pitch Drive

Yaw Drive

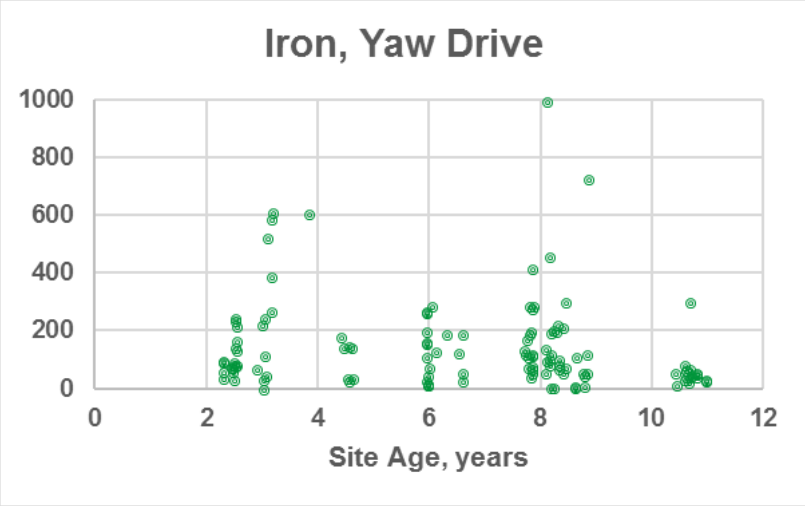


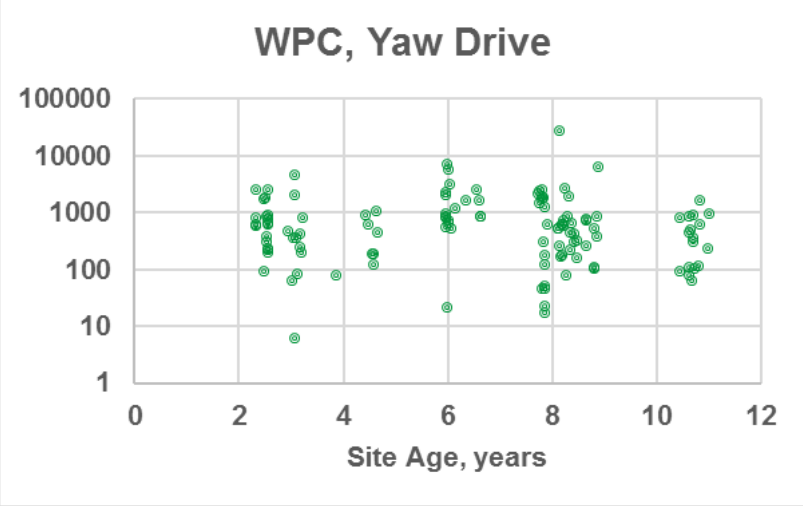
Yaw and Pitch Drives

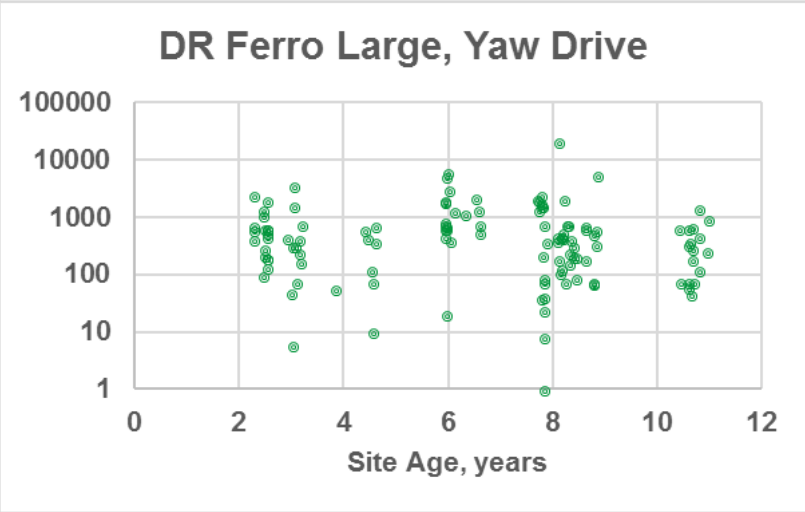
In Q4 of 2016, Invenergy launched a fleet-wide initiative to sample oil from yaw and pitch drive gearboxes.

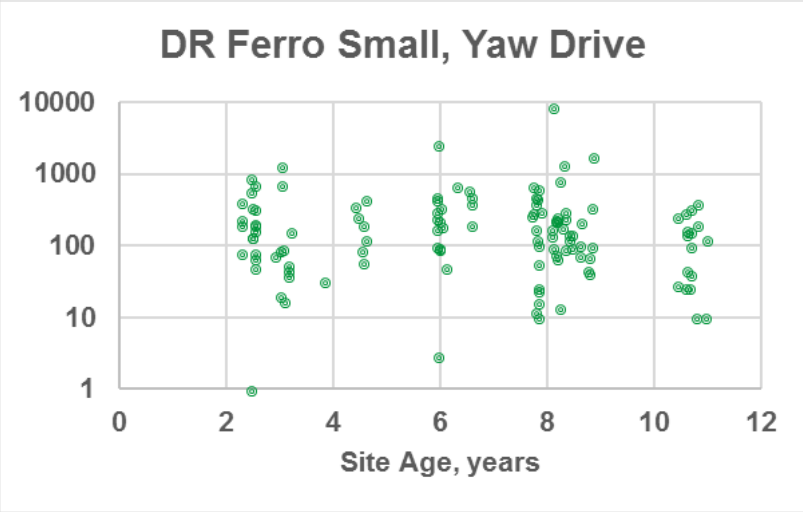
- We sampled the oil from over 100 drives at 16 wind farms.
  - Drives ranged from two to 11 years in service age.
  - The sample assortment included 10 different drive manufacturers and five different oil types.
- We focused our analysis on wear debris and key oil attributes.
  - We used three measurements to evaluate wear debris.
    - Iron ppm, Direct Read Ferrograpy, and ISO particle counts.
  - We evaluated three key oil attributes.
    - Viscosity (at both 40° and 100° C), Total Acid Number, and Phosphorus (the primary additive for all oil types).
- Our data analysis yields two key takeaways.
  - Regardless of drive age, manufacturer, or oil type, the oil is full of wear debris with no clear upward trend over time.
  - Regardless of drive age, manufacturer, or oil type, the oil is in good condition with respect to the key oil attributes.

Yaw Drives - Wear Debris Scatter by Age

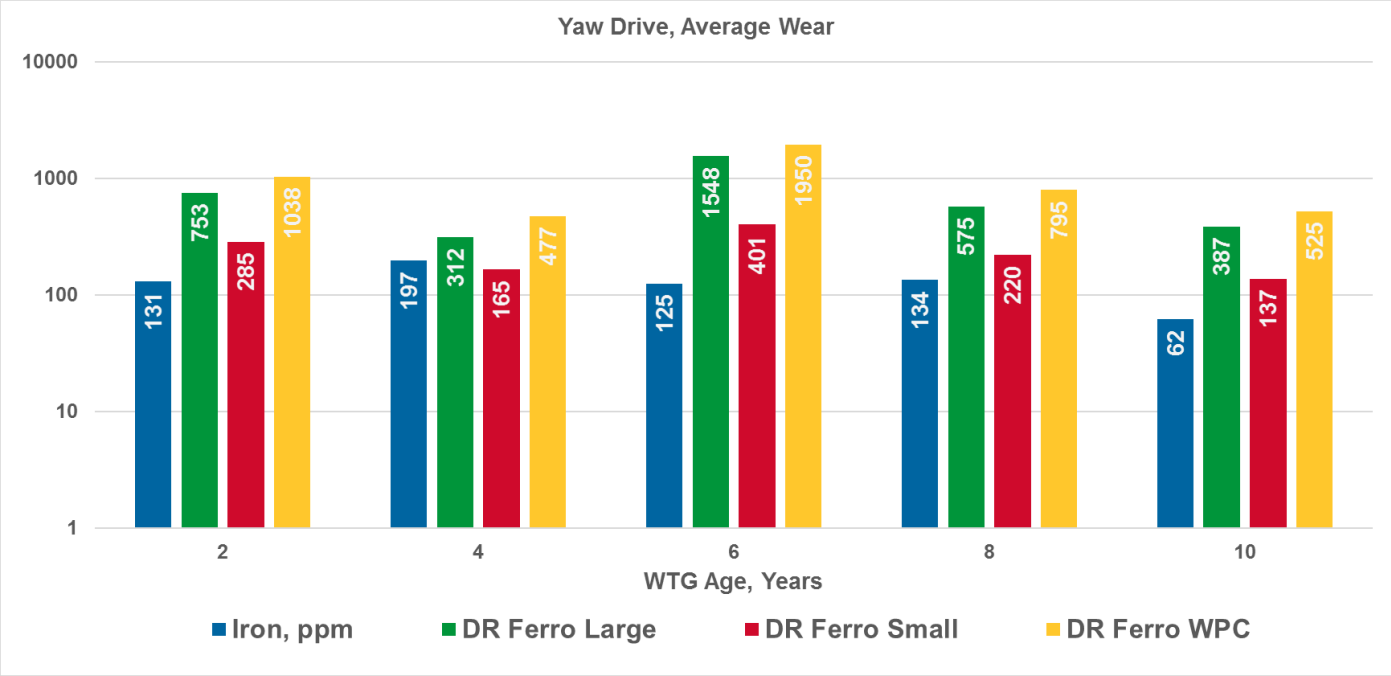








Yaw Drives - Wear Debris Averages by Age



2 years – 25 samples

4 years – 10 samples

6 years –19 samples

8 years – 44 samples

10 years – 17 samples

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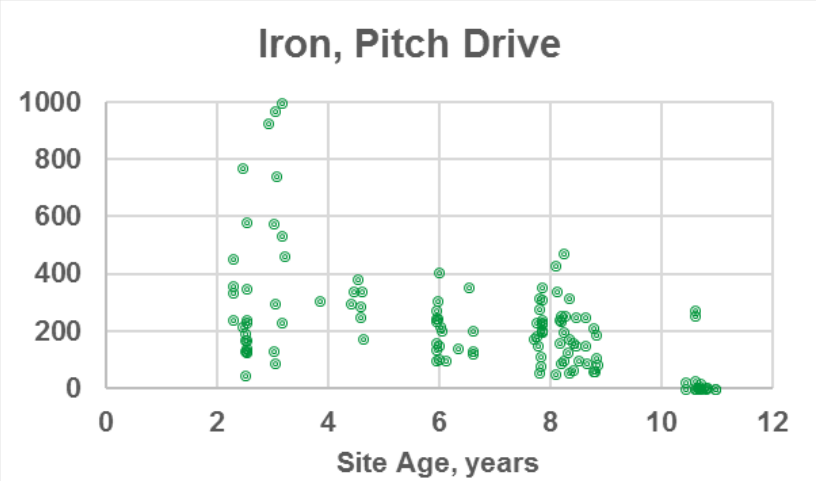
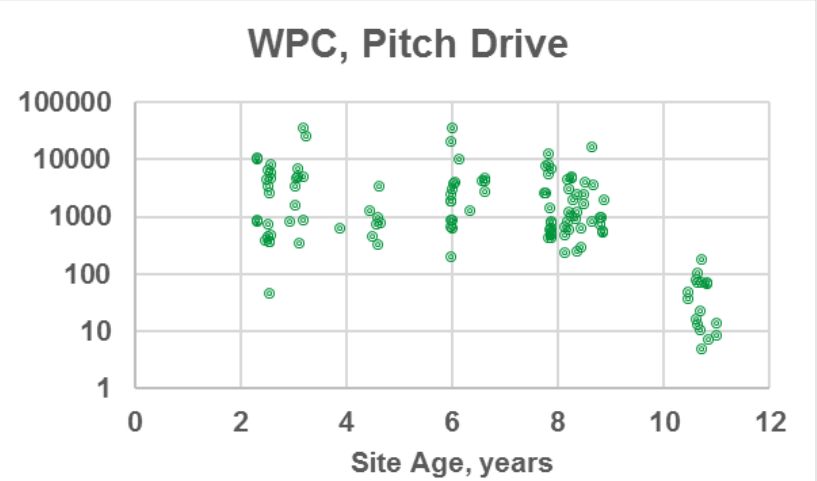
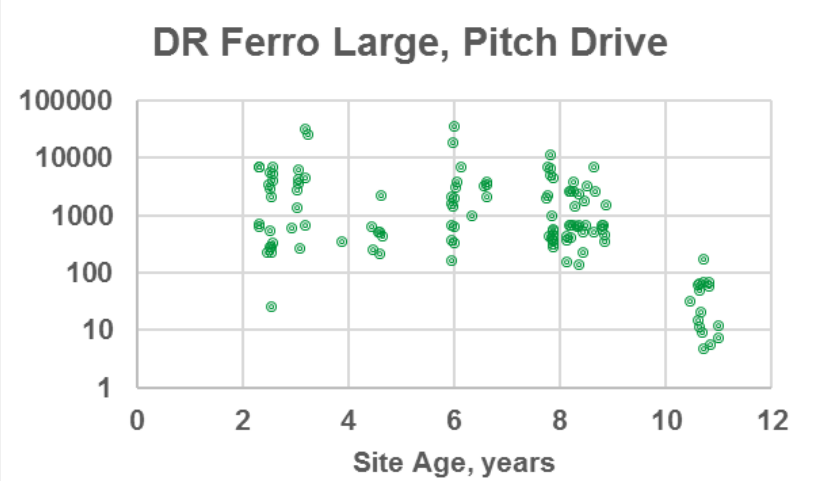
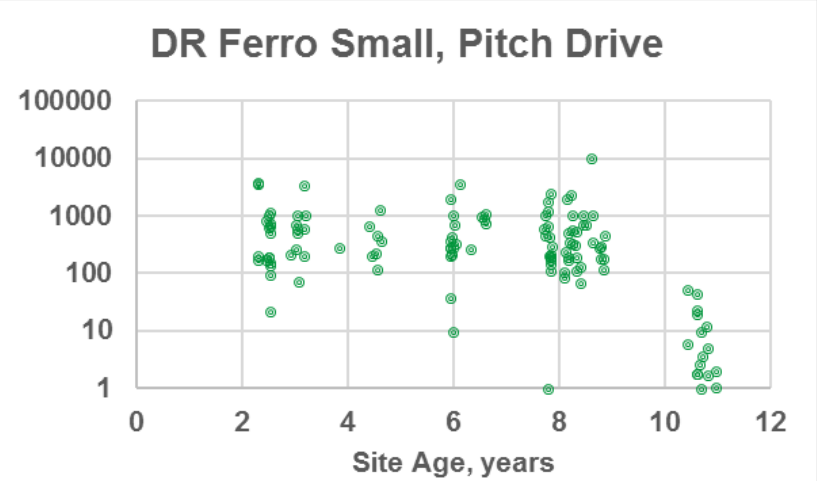
Pitch Drives - Wear Debris Scatter by Age

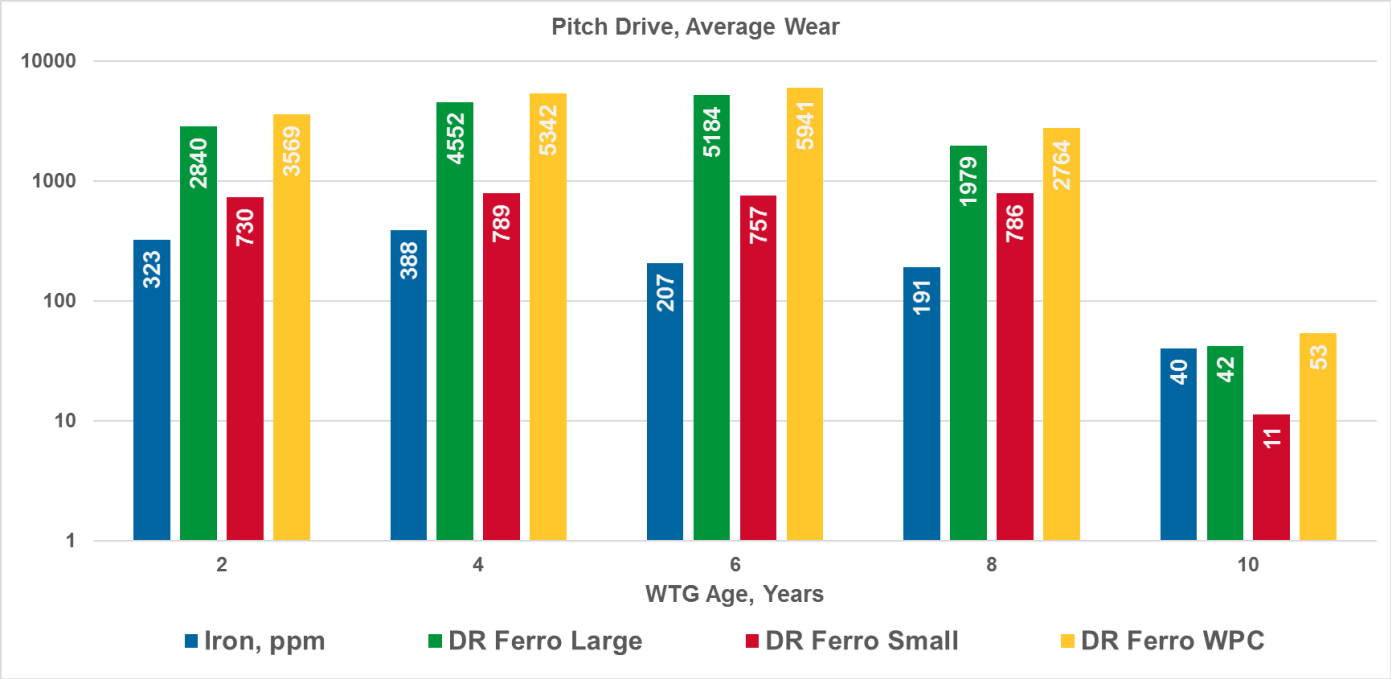








Pitch Drives - Wear Debris Averages by Age



2 years – 24 samples

4 years – 10 samples

6 years –19 samples

8 years – 45 samples

10 years – 17 samples

Drives in the 10 year bin had an oil change around year 5

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Yaw and Pitch Drives

Wear Debris

- Wear debris is almost universally high, even from early in the drive's life.
- It is possible that much of the wear debris is from run in.

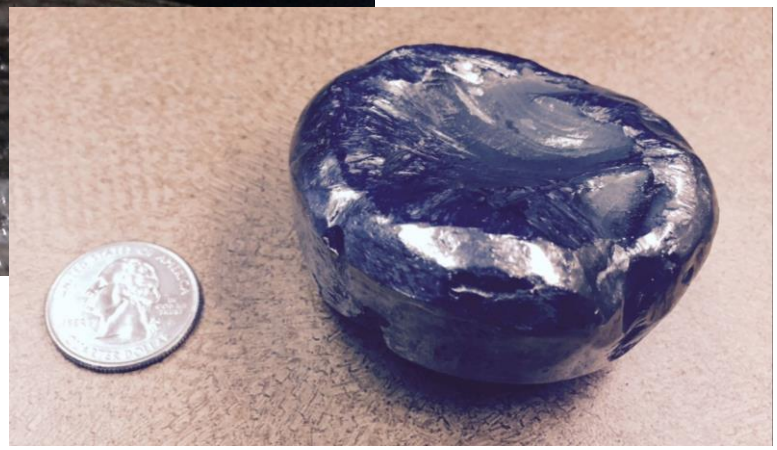
Key Oil Attributes

- The key oil attributes (viscosity, acid number, and additives) are stable for all oil types across all ages of drive.

Next Steps

- Long-term oil sample testing of a small population of turbines
- Possibly change all oils one time during service life.

Main Bearing Failure

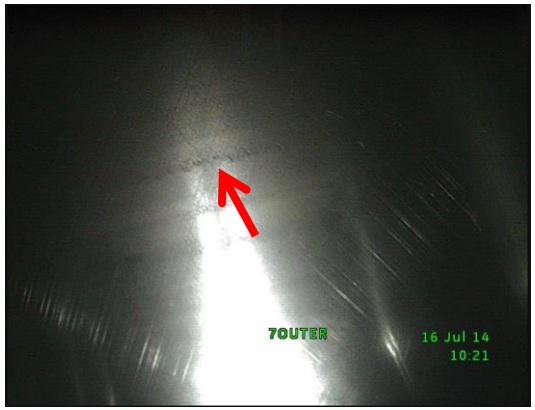


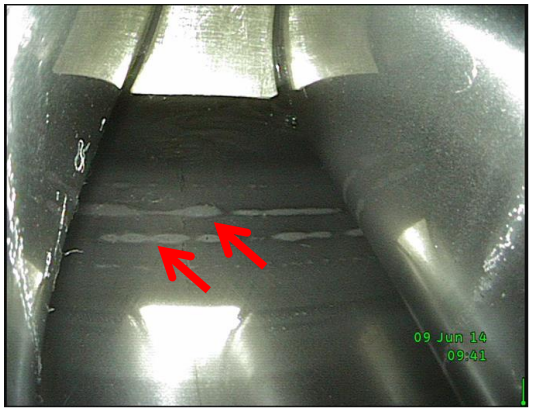
Main Bearing Failure

Main Bearing Failure

Main Bearing Grease

After a few main bearing failures and after many main bearing borescope inspections, we wondered whether we were greasing enough.





How do we prevent this ⬆ **from becoming this** ⬇ **?**

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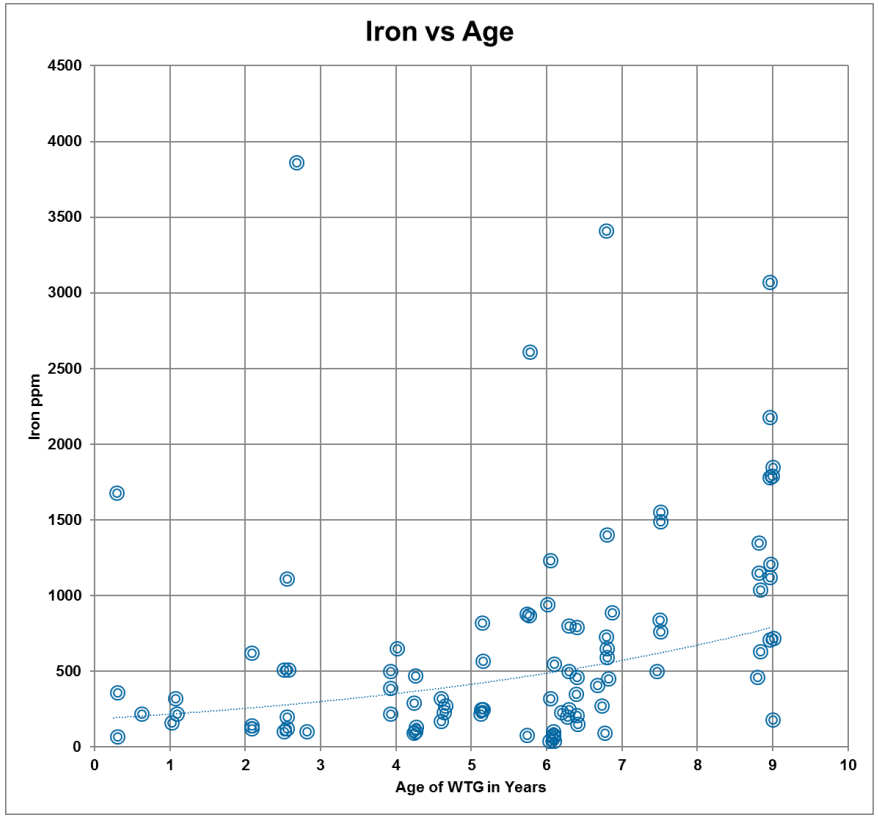
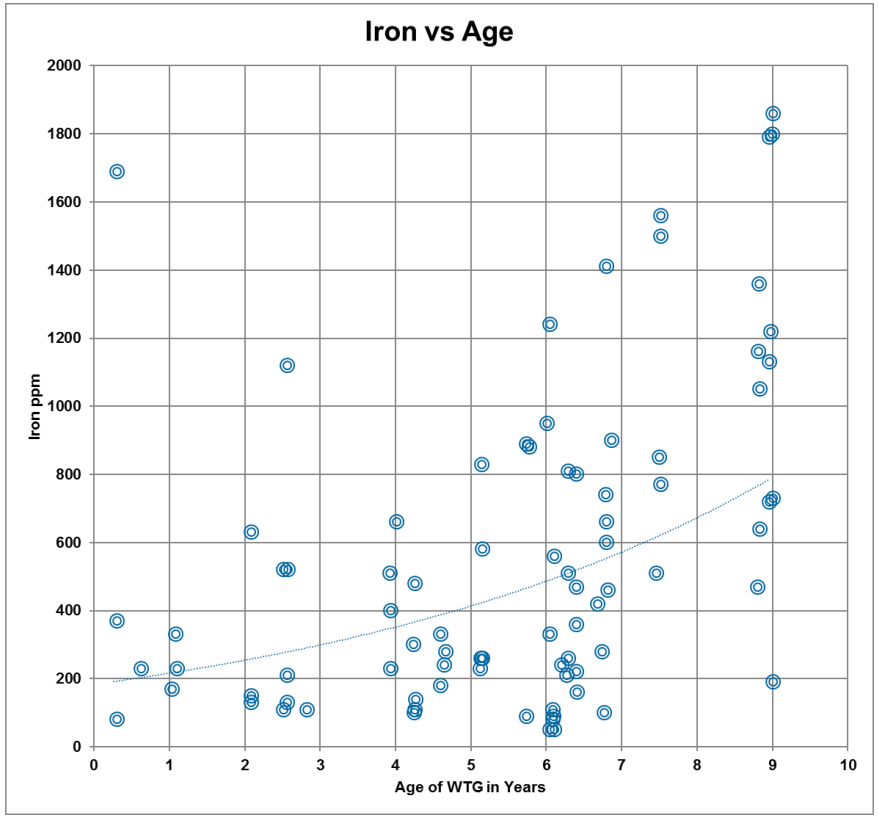
Viscosity @ 40º C over service time





- We sampled the grease from 91 main bearings at 21 wind farms.
  - Bearings ranged from 6 months to 9 years in service age.
  - The sample assortment included 5 main bearing manufacturers but only one grease type.

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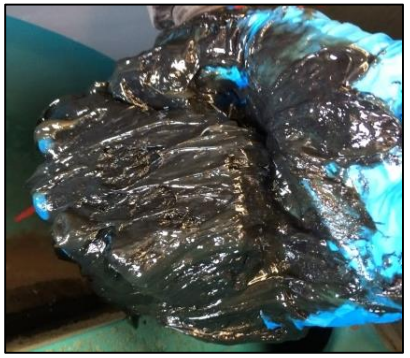
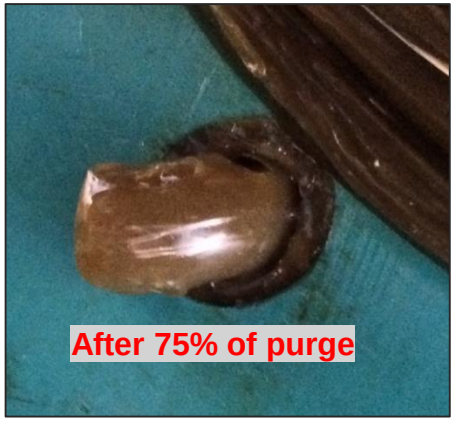
Main Bearing Grease Purge



We performed a very simple grease purge.

We pumped in the nameplate capacity of the bearing of fresh grease into the bearing and let it push out the old grease.



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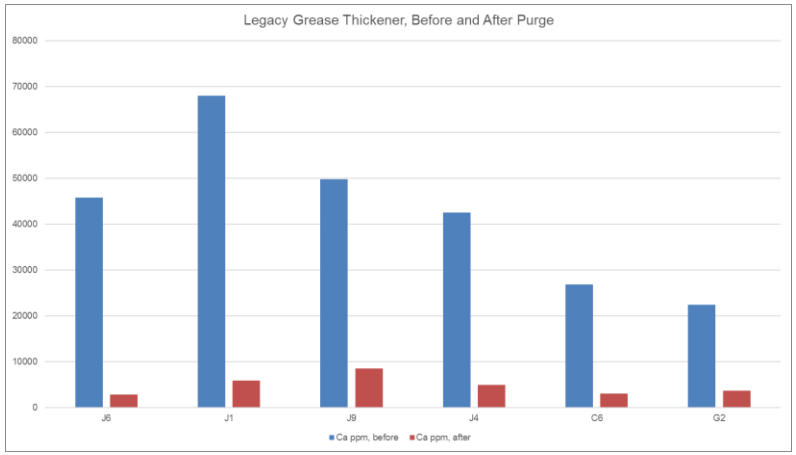
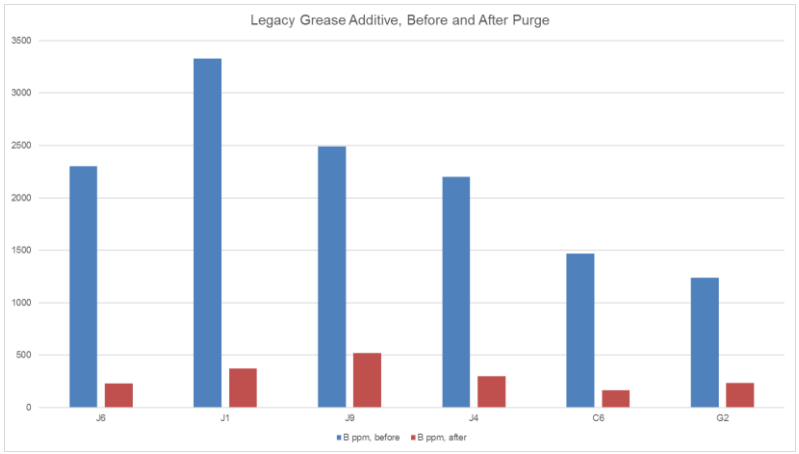
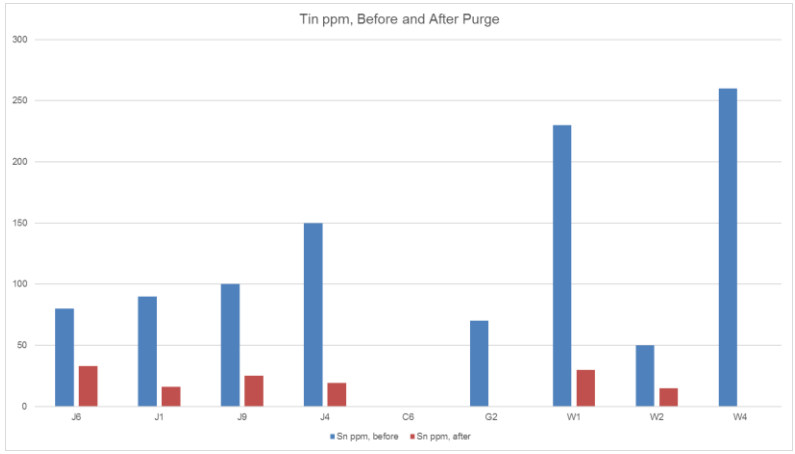
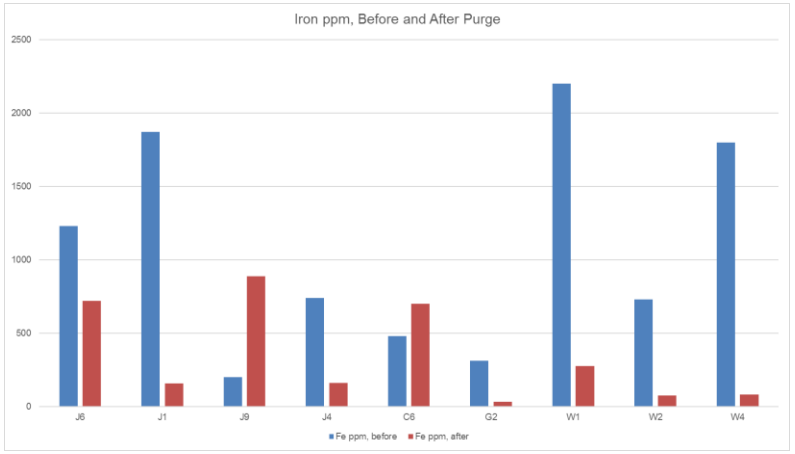
Main Bearing Grease Purge

Early results were largely successful at purging old grease and debris.









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Main Bearing Grease

Grease Purge

- We perform regular main bearing grease purges to clear debris and refresh the grease.
- We also perform grease purges when bearings overheat.
- It’s a relatively low cost and low effort practice for an expensive and critical asset.

Next Generation Greases

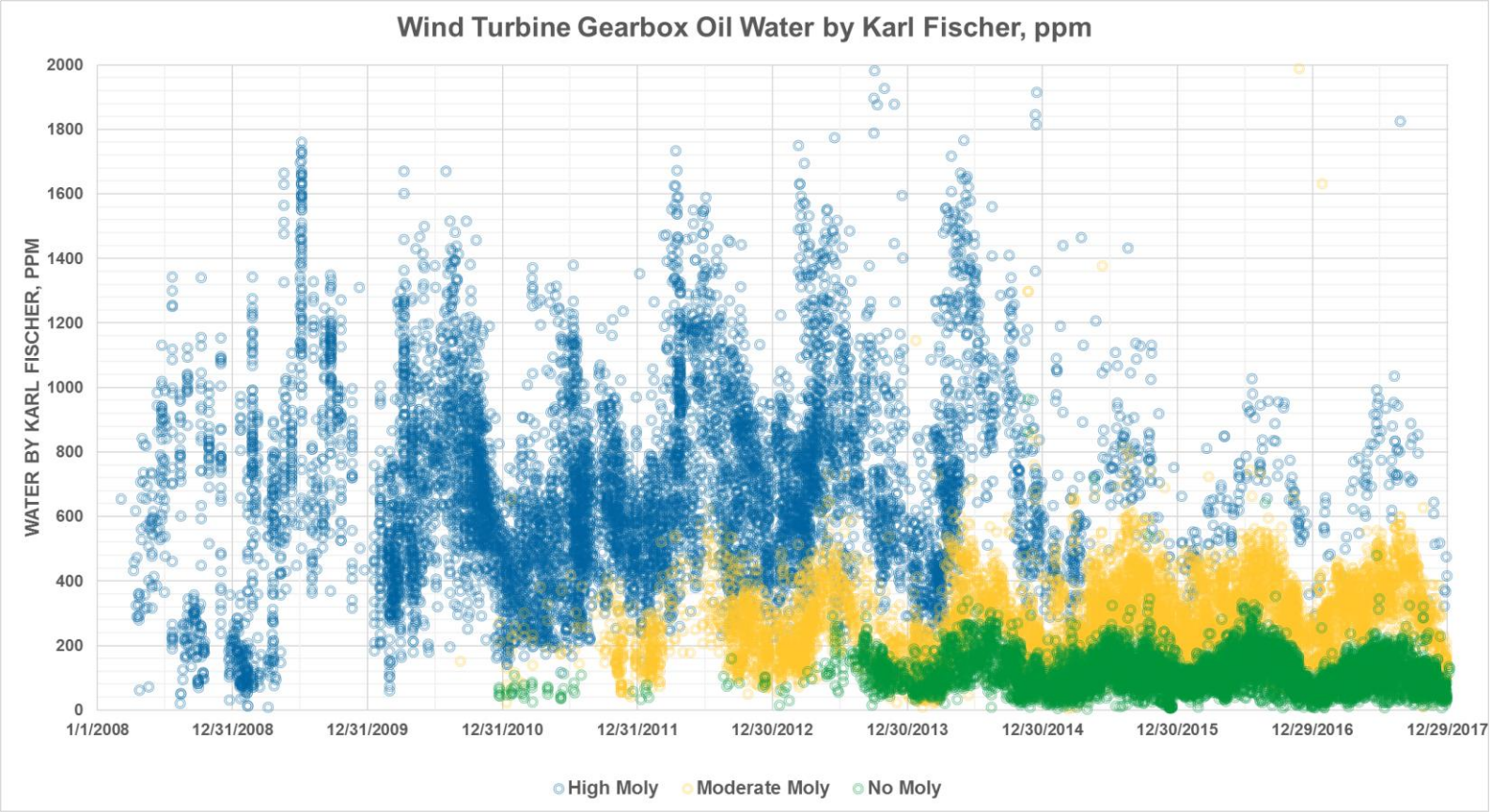
- Higher VG base oils
- Expecting to pilot several products

Gearbox Oil Sampling

We have a lot of data. It seems like that should be useful, right?

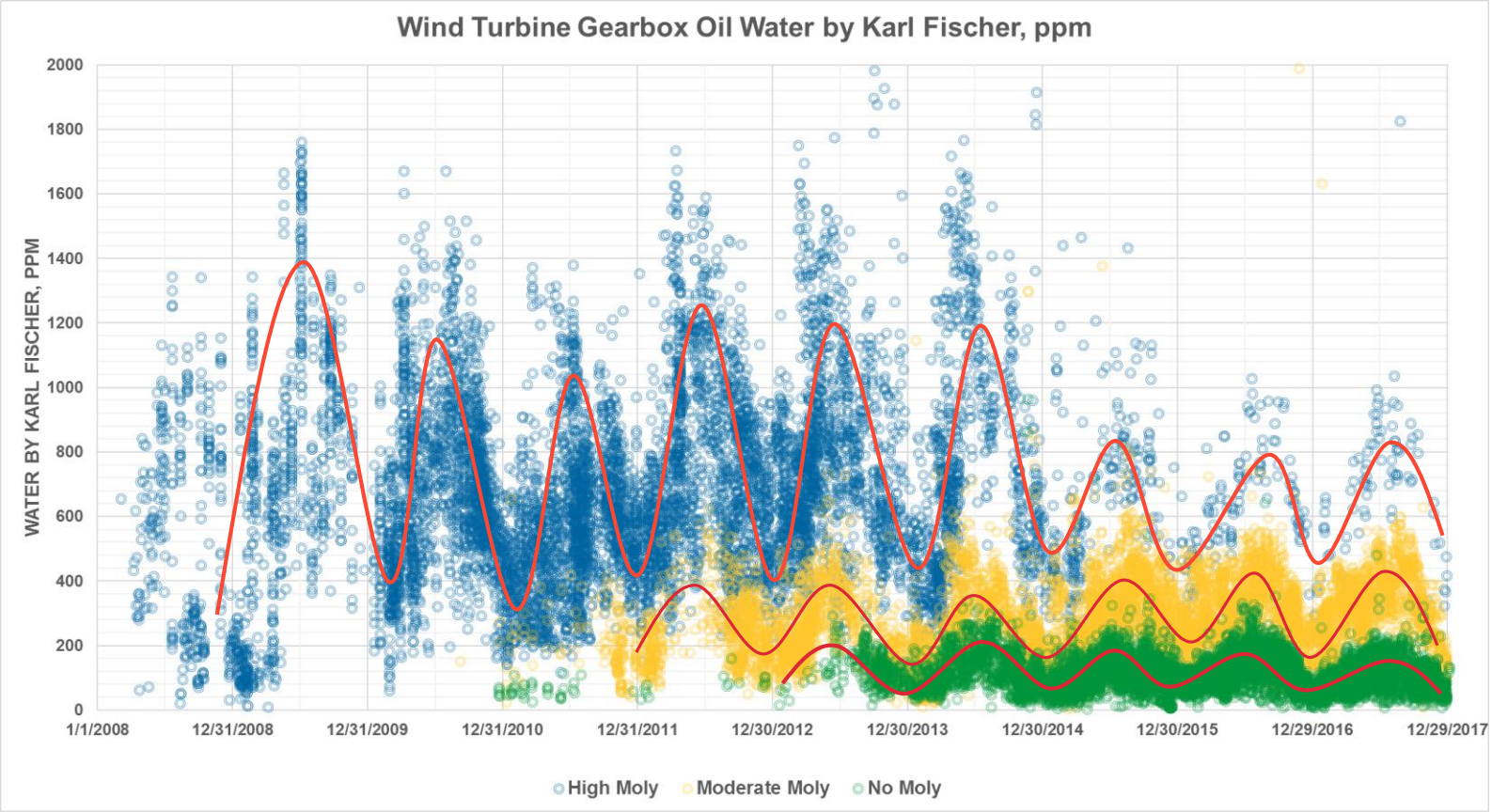
- We sample gearbox oil at least twice per year
  - Standard testing includes: Viscosity at 40º C and 100º C, Viscosity Index, TAN, Water by Karl Fischer, Elementals, Particle Counts, Direct Read Ferrography
  - Occasional testing: Foaming, Analytical Ferrography
  - New testing: Nuclear Magnetic Resonance
- All this data IS useful, with some limitations
  - It's easy to tell if your oil is dirty [***hint:*** *it probably is*]
  - It's hard to tell if your gearbox is failing
  - It can help you identify unexpected problems, in the gearbox and the oil
- What do we do about it?
  - Clean the oil
  - Plan maintenance for the surprises

Water in Gearbox Oil



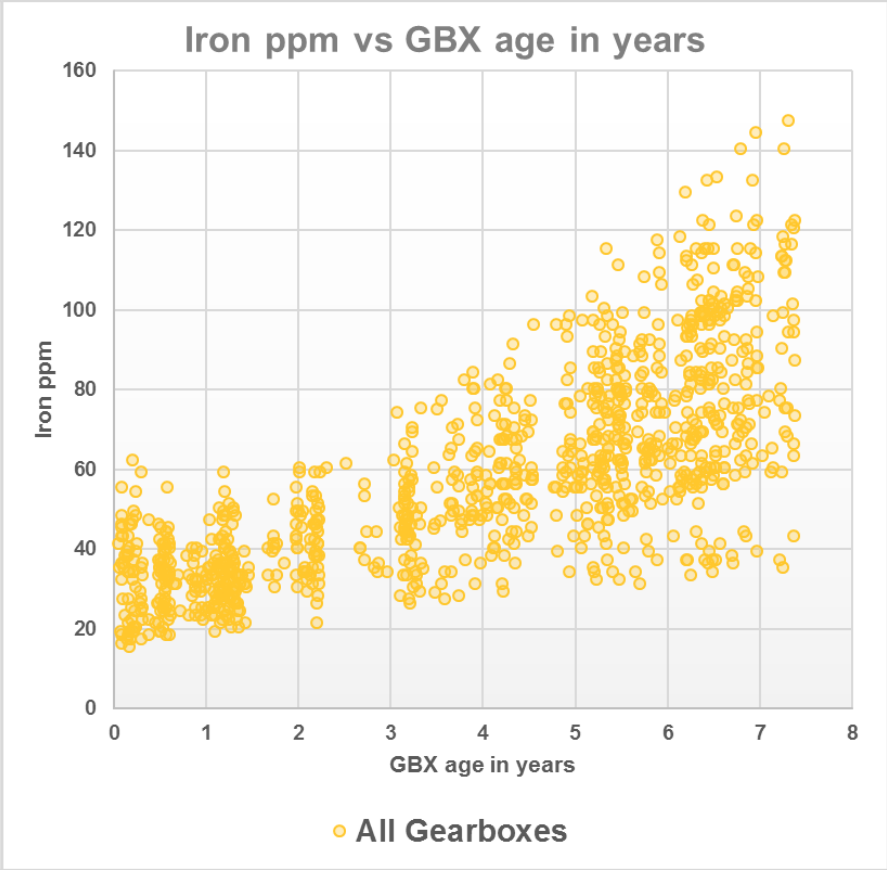
We noticed a few things about water content.

Water in Gearbox Oil



Water level is seasonal, varies by geography, and depends on oil formulation. No desiccant we have tried makes a noticeable difference.

Wear debris in oil



Using a wear index that accounts for particle counts in multiple bins and iron ppm, we concluded that our oil is dirty.

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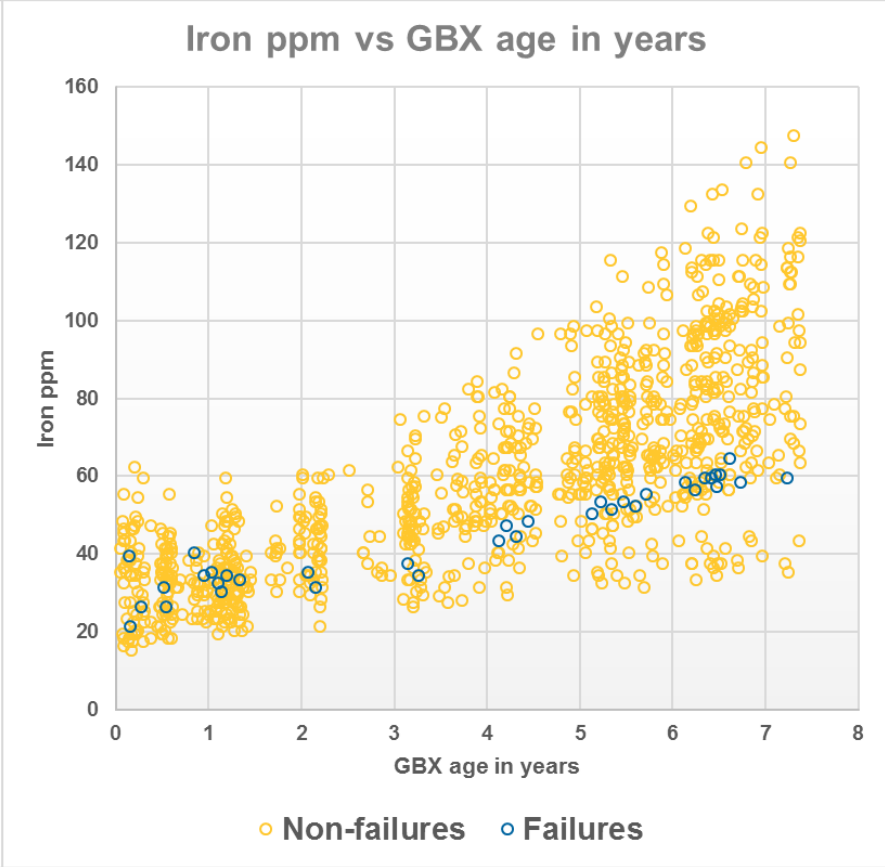
Wear debris in oil



Unfortunately the wear index and iron ppm, didn't help us know which gearboxes were failing.

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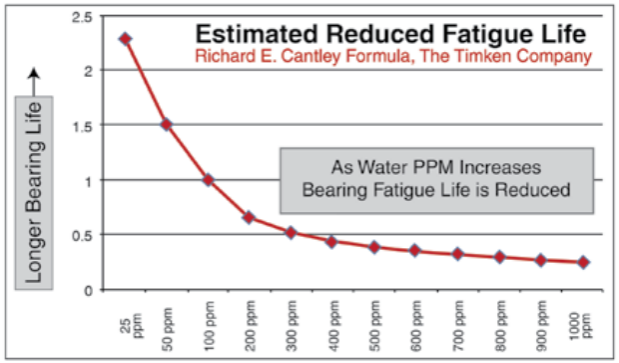
Secondary Filtration



Water is not good for bearings.[1]

New Cleanliness Level (ISO Code)

Current Machine Cleanliness (ISO Code)

	20/17	19/16	18/15	17/14	16/13	15/12	14/11	13/10	12/9	11/8	10/7
26/23	5 3 4 2.5	7 3.5 4.5 3	9 4 6 3.5	>10 5 6.5 4	>10 6 7.5 5	>10 7.5 8.5 6.5	>10 9 10 7	>10 >10 >10 9	>10 >10 >10 10	>10 >10 >10 >10	>10 >10 >10 >10
25/22	4 2.5 3 2	5 3 3.5 2.5	7 3.5 4.5 3	9 4 5 3.5	>10 5 6.5 4	>10 6 8 5	>10 7 9 6	>10 9 10 7.5	>10 >10 >10 9	>10 >10 >10 >10	>10 >10 >10 >10
24/21	3 2 2.5 1.5	4 2.5 3 2	6 3 4 2.5	7 4 5 3	9 5 6.5 4	>10 6 7.5 5	>10 7 8.5 6	>10 8 9.5 7	>10 10 >10 8	>10 >10 >10 10	>10 >10 >10 >10
23/20	2 1.5 1.7 1.3	3 2 2.3 1.5	4 2.5 3 2	5 3 3.7 2.5	7 3.5 5 3	9 4 6 3.5	>10 5 7 4	>10 6 8 5	>10 8 10 6.5	>10 9 >10 8.5	>10 >10 >10 10
22/19	1.6 1.3 1.4 1.1	2 1.6 1.8 1.3	3 2 2.3 1.7	4 2.5 3 2	5 3 3.5 2.5	7 3.5 4.5 3	8 4 5.5 3.5	>10 5 7 4	>10 6 8 5	>10 7 10 5.5	>10 >10 >10 8.5
21/18	1.3 1.2 1.2 1.1	1.5 1.5 1.5 1.3	2 1.7 1.8 1.4	3 2 2.2 1.6	4 2.5 3 2	5 3 3.5 2.5	7 3.5 4.5 3	9 4 5 3.5	>10 5 7 4	>10 7 9 5.5	>10 10 10 8
20/17		1.3 1.2 1.2 1.05	1.6 1.5 1.5 1.3	2 1.7 1.8 1.4	3 2 2.3 1.7	4 2.5 3 2	5 3 3.5 2.5	7 4 5 3	9 5 6 4	>10 7 8 5.5	>10 9 10 7
19/16			1.3 1.2 1.2 1.1	1.6 1.5 1.5 1.3	2 1.7 1.8 1.5	3 2 2.2 1.7	4 2.5 3 2	5 3 3.5 2.5	7 4 5 3.5	9 6 7 4.5	>10 8 9 6
18/15				1.3 1.2 1.2 1.1	1.6 1.5 1.5 1.3	2 1.7 1.8 1.5	3 2 2.3 1.7	4 2.5 3 2	5 3 3.5 2.5	7 4.5 5.5 3.7	>10 6 8 5
17/14					1.3 1.2 1.2 1.1	1.6 1.5 1.5 1.3	2 1.7 1.8 1.5	3 2 2.3 1.7	4 2.5 3.5 2.5	6 3 8 5	8 5 6 3.5
16/13						1.3 1.2 1.2 1.1	1.6 1.5 1.5 1.3	2 1.7 1.8 1.5	3 2 2.3 1.8	4 3.5 3.7 3	6 4 4.5 3.5
15/12							1.3 1.2 1.2 1.1	1.6 1.5 1.5 1.4	2 1.7 1.8 1.5	3 2 2.3 1.8	4 2.5 3 2.2
14/11								1.3 1.3 1.3 1.2	1.6 1.6 1.6 1.4	2 1.8 1.9 1.5	3 2 2.3 1.8
13/10									1.4 1.2 1.2 1.1	1.8 1.5 1.6 1.3	2.5 1.8 2 1.6

Hydraulics and Diesel Engines	Rolling Element Bearings
Journal Bearings and Turbo Machinery	Gear Boxes and Other

Particle contamination is not good for anything in a gearbox.[2]

[1] R.E. Cantley. "The Effect of Water in Lubricating Oil on Bearing Fatigue Life." ASLE Transactions, American Society of Lubrication Engineers, Volume 20, No. 3, p. 244-248, 1977; from a presentation at the 31st Annual ASLE Meeting, Philadelphia, Penn.

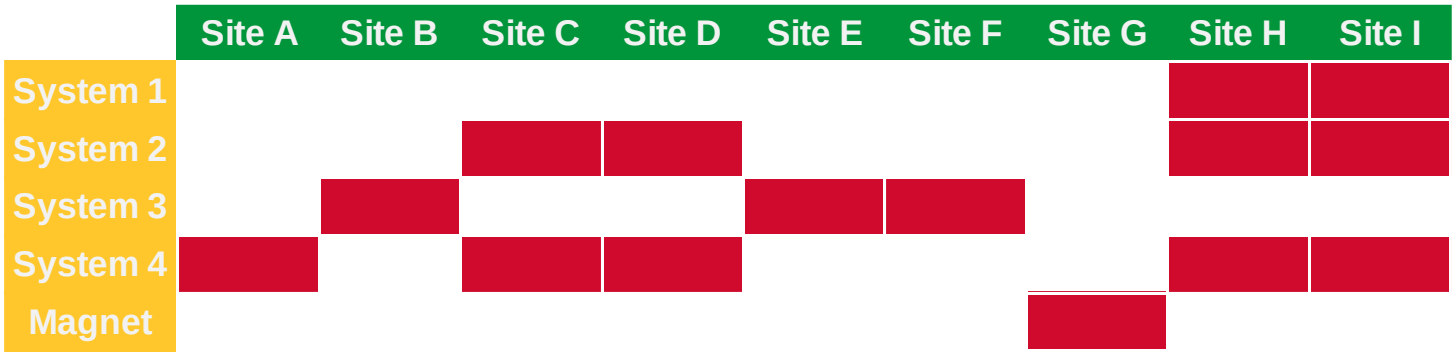
[2] M. Moon. Trends in Food Science and Technology, Vol. 18, Supplement 1. January 2007, p. S74- S88

Secondary Filtration

Some of the systems we tested.

We conducted a test of five systems over a year at nine sites.

	WTGs	Sites	Oil Samples
System 1	10	2	139
System 2	20	4	301
System 3	24	3	115
System 4	51	5	507
Magnet	6	1	121
No Filtration	768	9	6148



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Secondary Filtration

We loved the results.

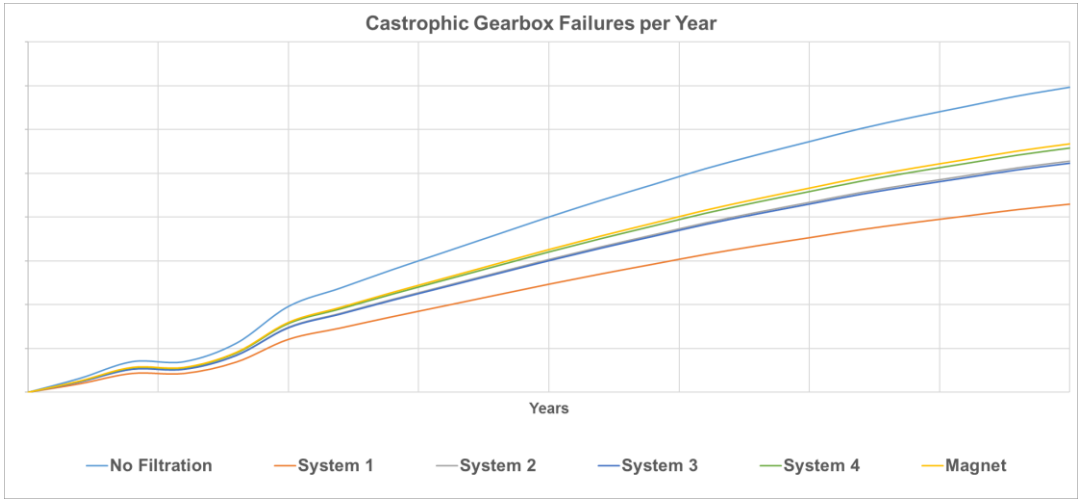
Every system cleaned up the oil.

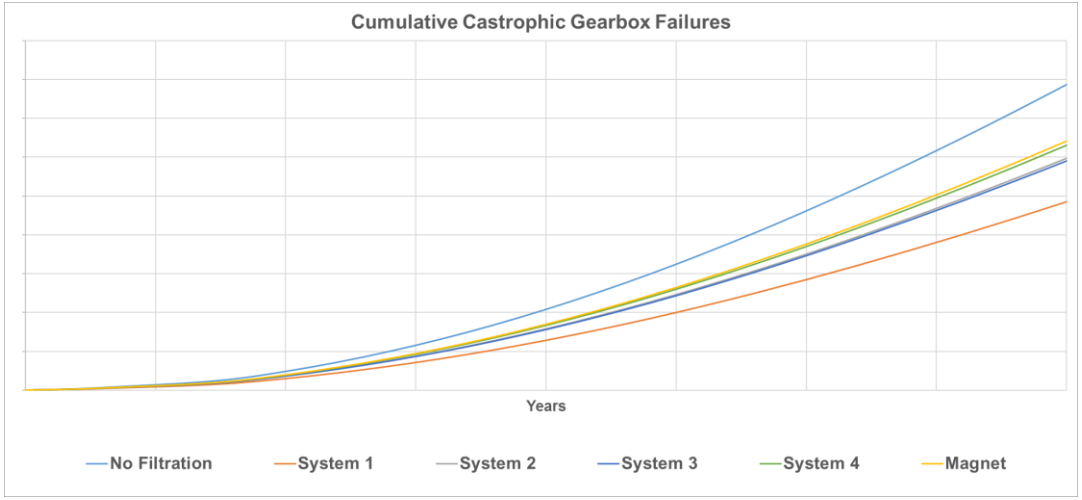
Every system except one reduced the water content. It *is* just a magnet.

Cost is a big factor.

	Life Extension Factors			COST
	Particle-reduction		Water-reduction	
	Gearbox	Bearing	Bearing	
System 1	1.3	1.5	1.5	$$$$
System 2	1.1	1.3	1.3	$$$
System 3	1.2	1.3	1.3	$$$$$
System 4	1.1	1.2	1.2	$$
Magnet	1.3	1.4	0.9	$

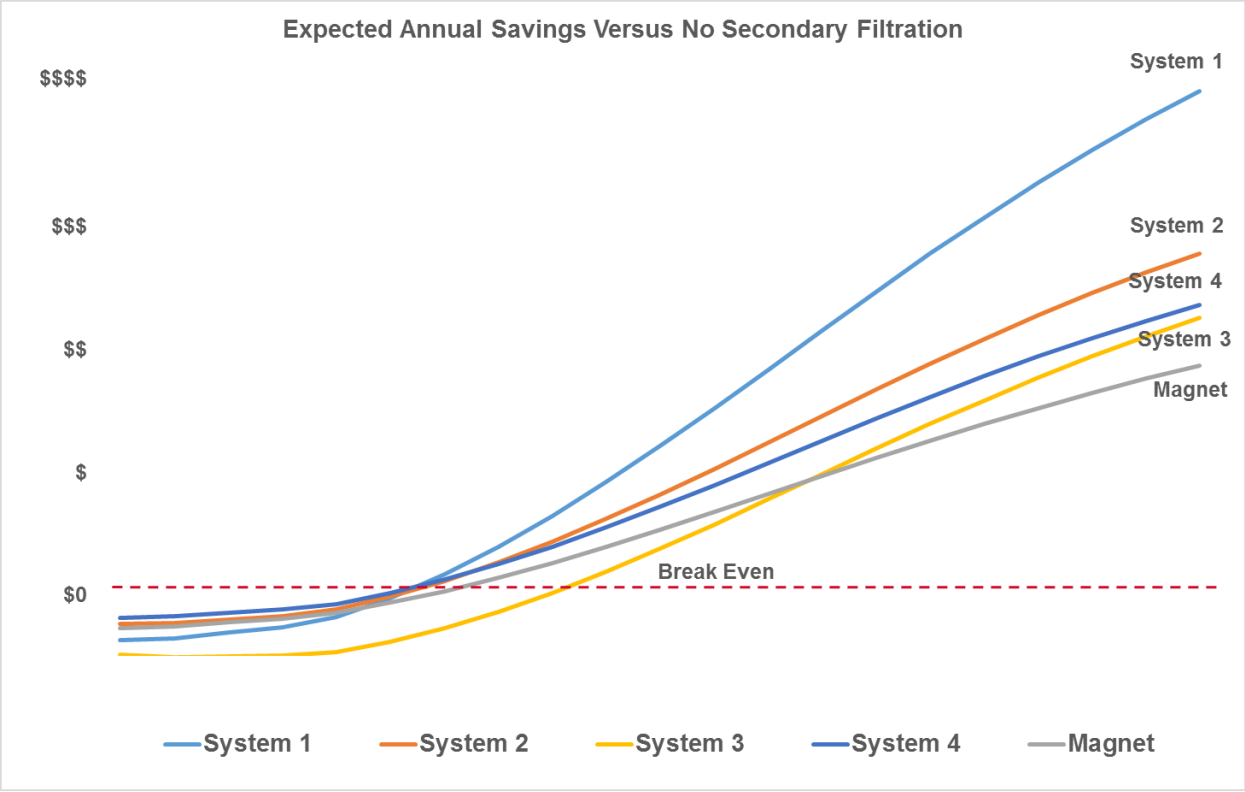
Secondary Filtration





Every system projected to reduce both catastrophic gearbox failures and uptower-repairable gearbox failures.

Secondary Filtration



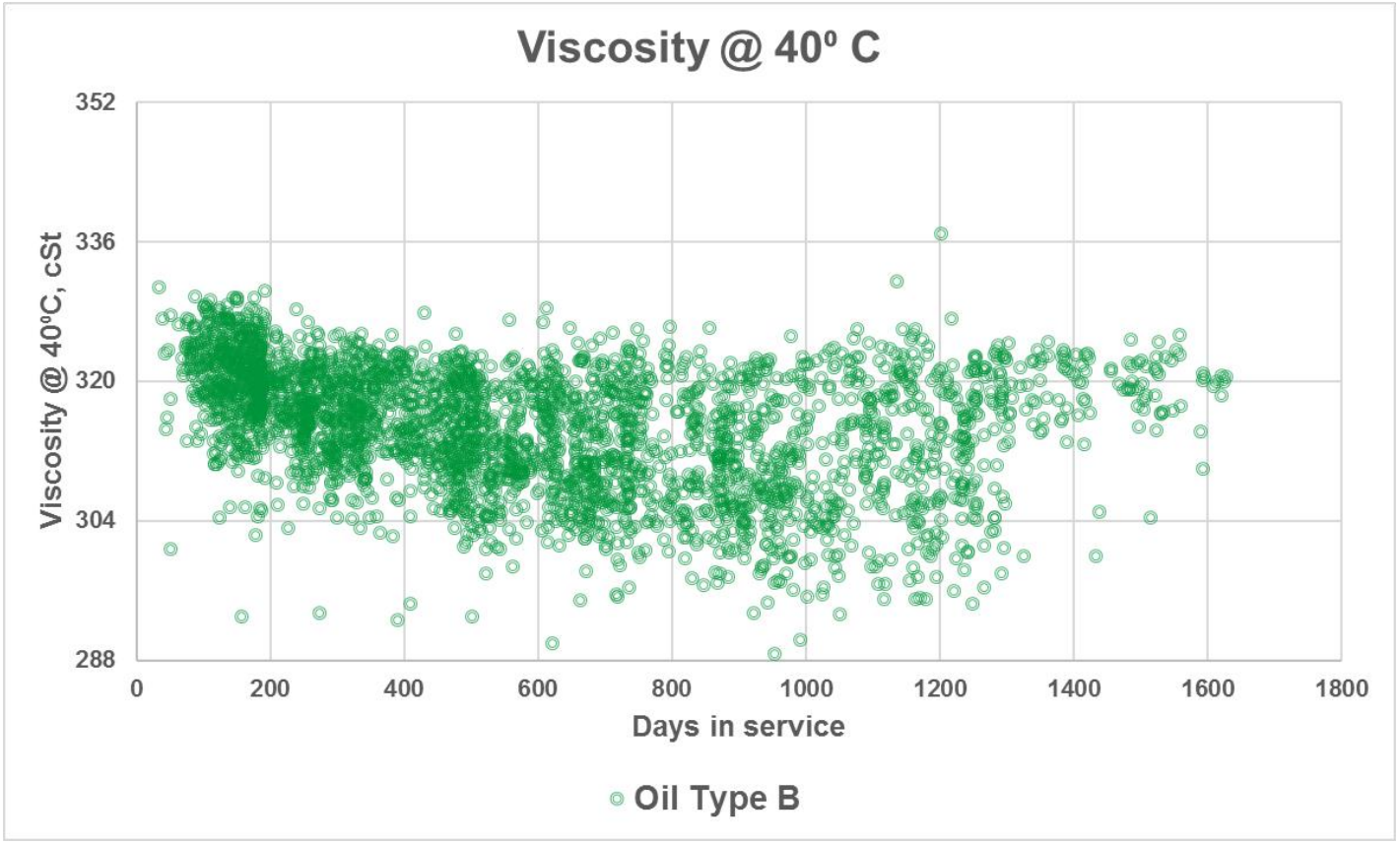
Every system projected to yield a positive ROI.

System 1 projected to yield the highest ROI over a 20 year period.

The magnet is a good option for operators with extremely limited capital resources.

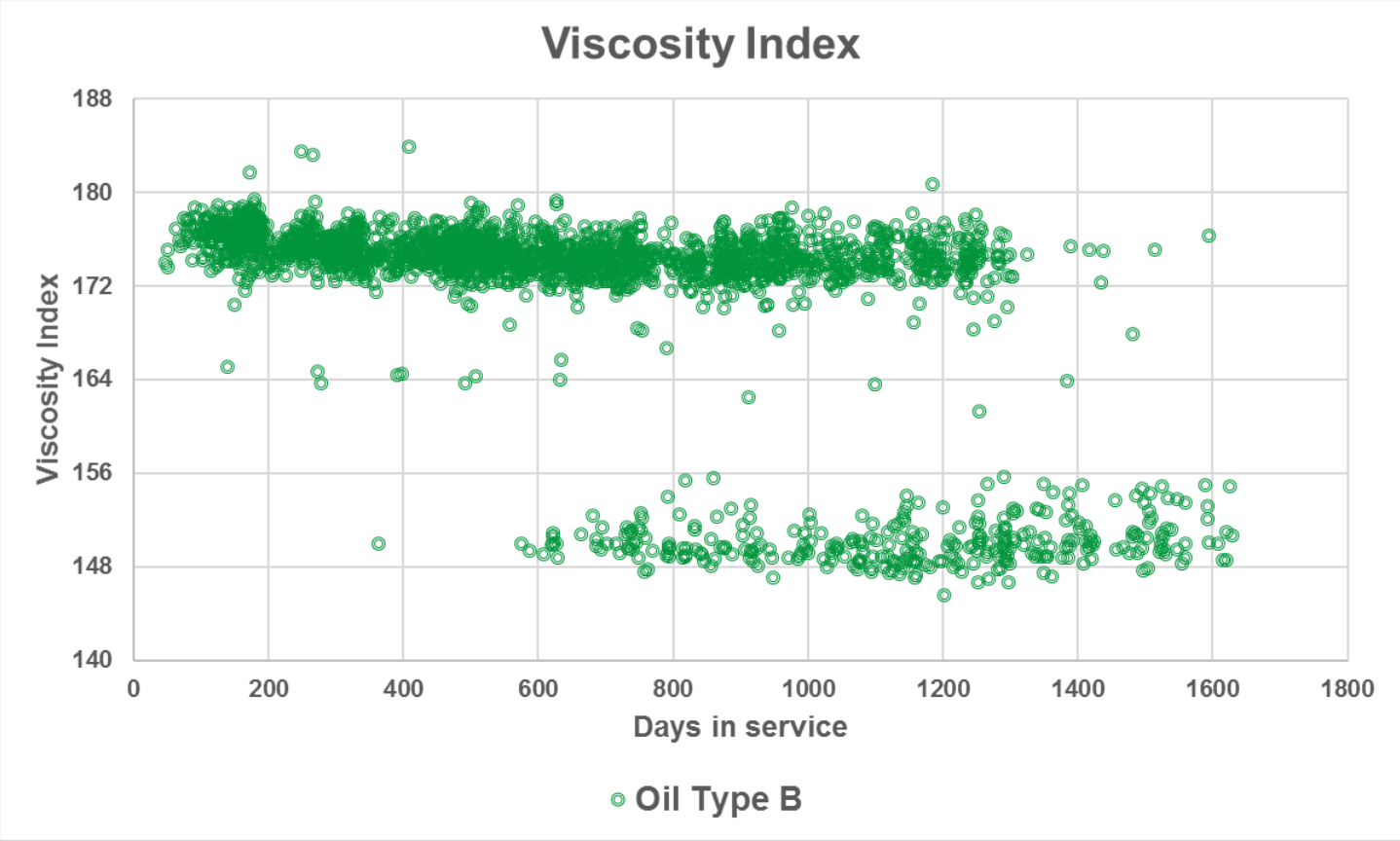
The Unexpected Viscosity Problem

One oil type exhibited a wide spread of viscosity as it aged.



Viscosity Index

Checking the viscosity index suggested that the oil formulation had changed.



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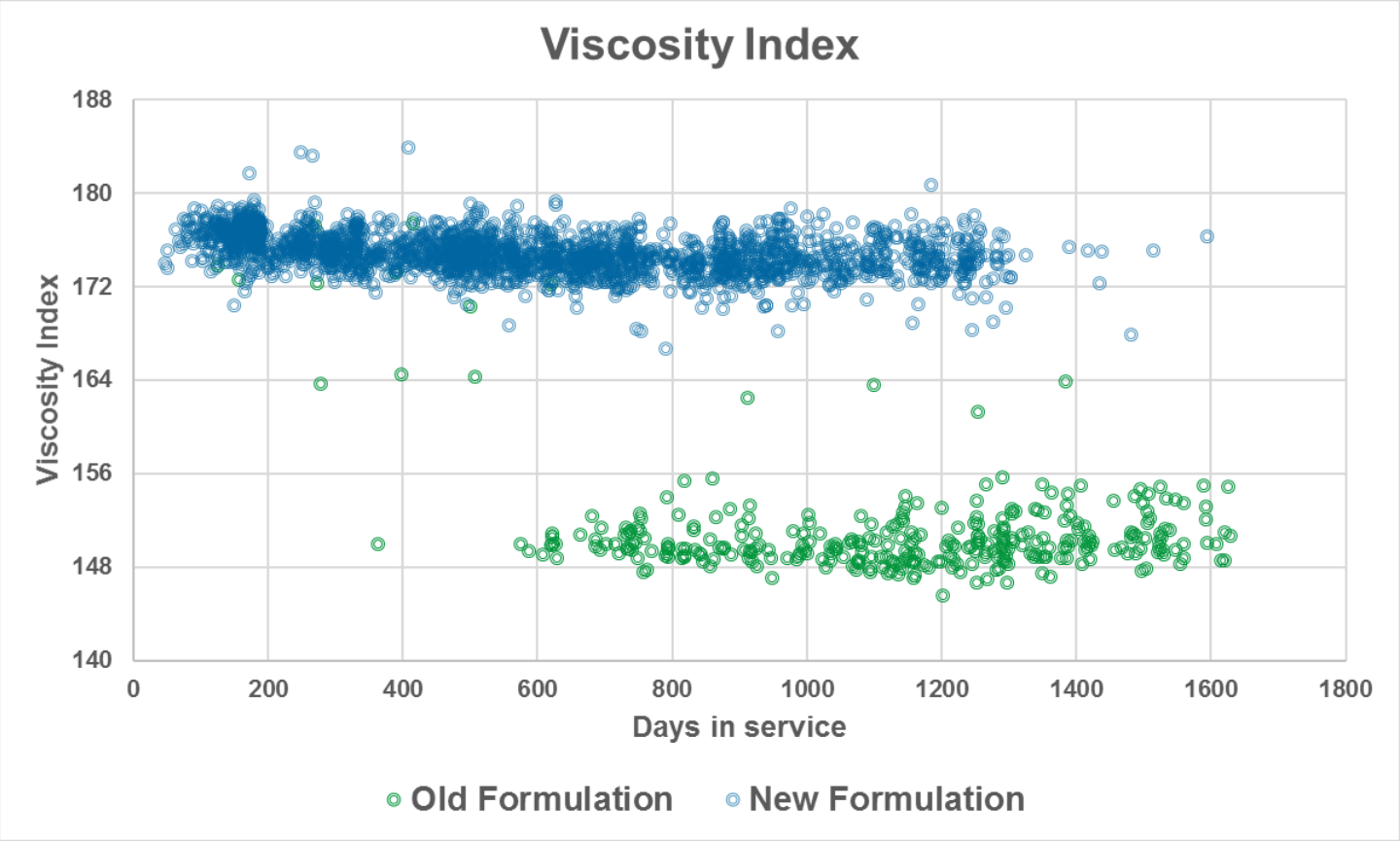
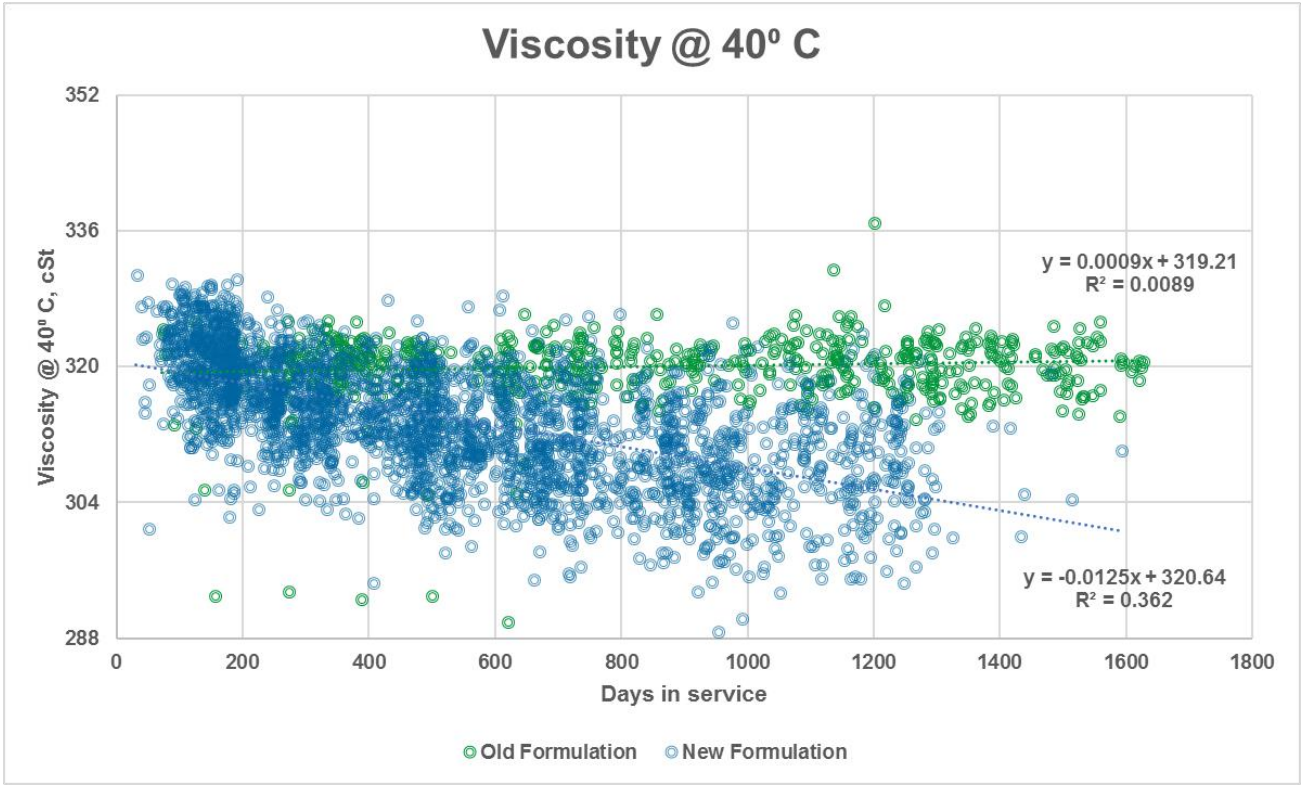


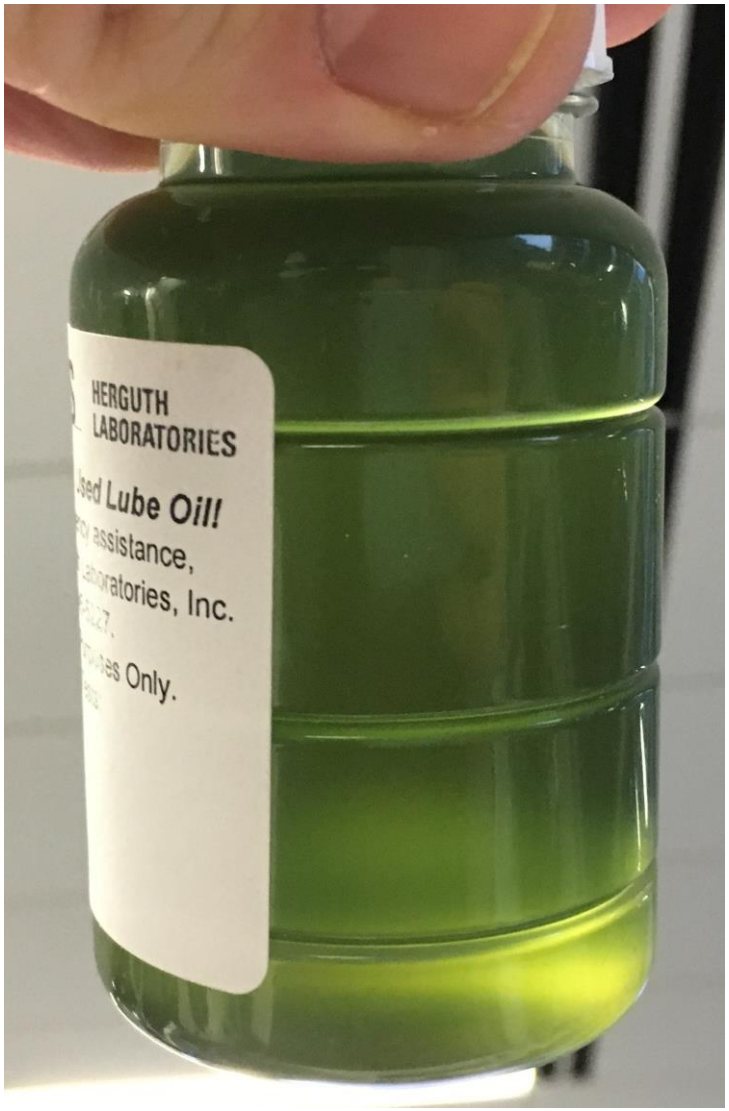
Viscosity @ 40º C over service time

Now we can plan remediation for the viscosity drop

- Inexpensive yet unproven: add several gallons of higher viscosity oil
- Expensive yet proven: oil change



Unexpected Green Oil



We have seen this in a few turbines.

There is nothing odd in the oil sample test results.

We believe the source is a sealant used during gearbox repairs.

Questions?