Synthetic Lubricants

Ken Hope, Ph.D., C.L.S.
Chevron Phillips Chemical Co. LP.

Overview

- A brief historical perspective
- Types of synthetic base oils
- Overview of properties of different synthetics
- Major uses and applications
- New products
- A look toward future trends

Mineral Oil

A Complex Molecular Mixture

Synthetic Base Fluids

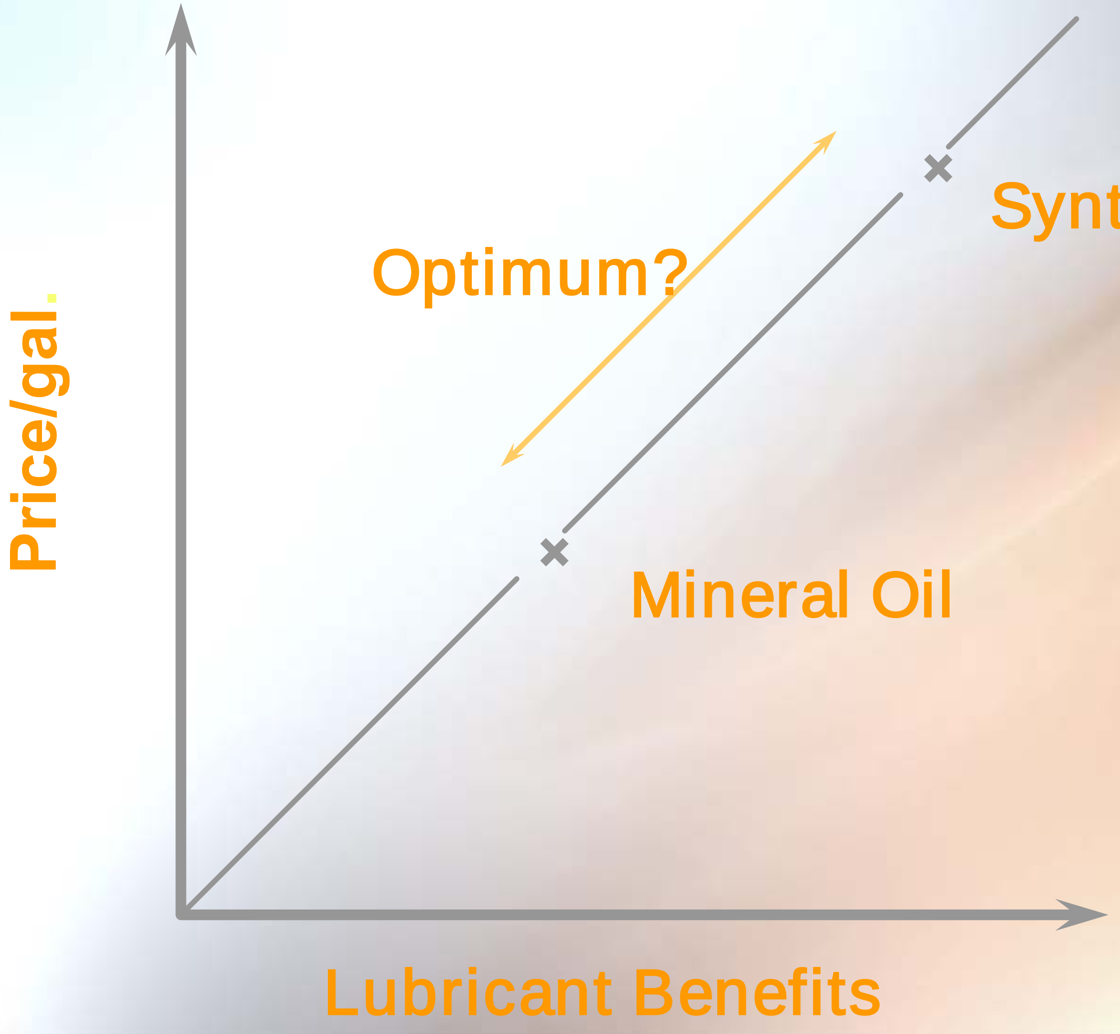
“Man-made” / “Tailored”

Made by combining low molecular weight materials via chemical reaction into higher molecular weight materials.

Chemical Process

- Make molecules from simple building blocks
- Good uniformity/consistency
- High Yields
- Better economics
- High quality lube stocks with “on-target” performance
- Fluid properties unavailable in mineral oil

The Higher Price of Synthetics Must be Justified by Improved Performance



Synthetic Lubricants

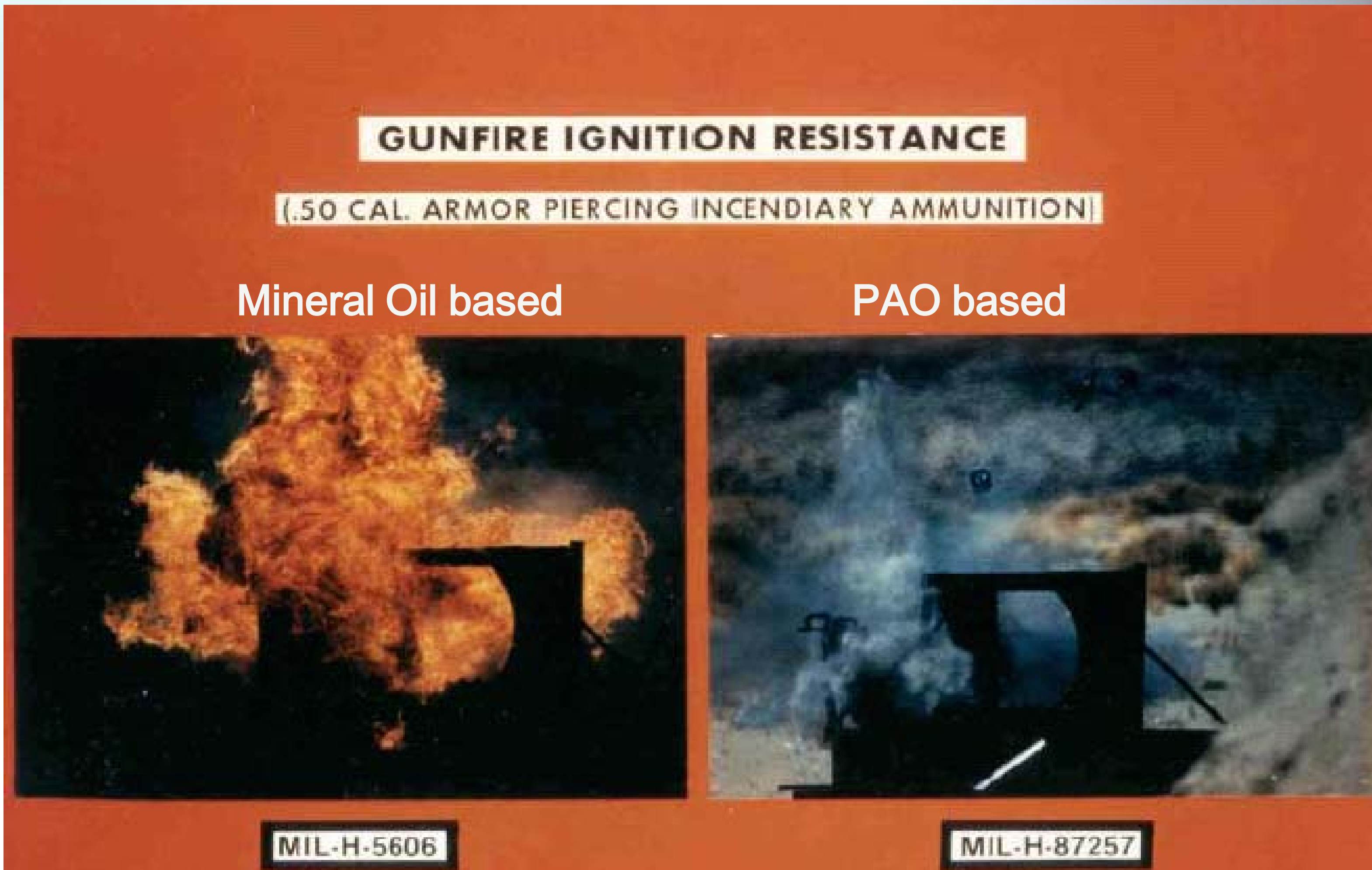
- Predictable Properties and Performance
  - Uniformity of Product Charactericstics
    - Save $$ . . . Lower Product Rejection, Lower Maintenance
- Longer Oil Life
  - Enhanced Thermal and Oxidation Stability
    - Save $$ . . . Use Less Oil, Less Downtime, Longer Filter Life
- Reduced Oil Consumption
  - Lower Volatility
    - Save $$ . . . Less Top Off, Less Inventory

Synthetic Lubricants

- Satisfies Specific Requirements
  - Military Specifications
  - Severe Operating Conditions
    - Make $$ . . . Meet Customer Needs
- Safer Operation
  - High Flash Points, Fire Points, Spontaneous Ignition Temperatures
    - Save $$ . . . Reduced Risk, Less Equipment Loss
- Easier Disposal
  - Lower Toxicity and Better Biodegradability
    - Save $$ . . . Lower Waste Disposal Costs

Photo courtesy U.S. Air Force

Safer Operation



Photos courtesy U.S. Air Force, Materials and Manufacturing Directorate

Synthetic Lubricants

- Definitions

Class - chemical compound

- **Synthetic Hydrocarbons**
  - Polyalphaolefins, alkylated aromatics, polybutenes
- **Organic Esters**
  - Diesters, Polyol Esters
- **Others**
  - Polyglycol Ethers, Phosphate Esters, Silicones, Silicate Esters, Halogenated Hydrocarbons, Polyphenyl Ethers
- **Blends**
  - Mixtures of above

Synthesized Hydrocarbons

Polyalphaolefins - PAOs

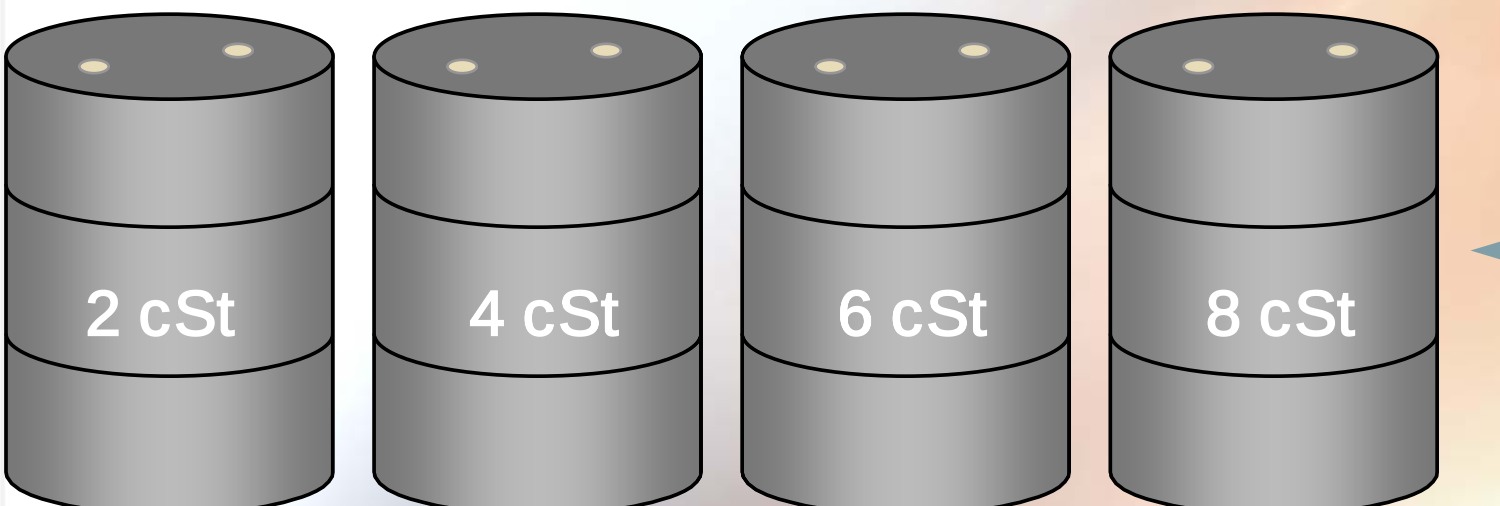
Polyalphaolefin Manufacturing

$$1 - C_{10}^{=} \xrightarrow{\text{Catalyst A}} C_{20}^{=} + C_{30}^{=} \cdots + C_{60}^{=} \xrightarrow{\text{Catalyst B}} C_{20} + C_{30} \cdots + C_{60}$$

n-Alpha Olefin

Unsaturated Polyalphaolefins

Isoparaffinic Synthetic Hydrocarbons (PAO)



+ Other Viscosities (2.5, 5, 7, 9, 10, 40 & 100 cSt)

Principal PAO Grades and Properties Compared to Mineral Oil

Viscosity, cSt	4cSt	6cSt	8cSt	100cSt	Mineral Oil - 100 SUS
at 100°C	4	6	8	100	4
at 40°C	18	31	46	1400	20
at –40°C	2500	7600	18,000	-	-
Viscosity Index	123	136	138	165	97
Pour Point, °C	-73	-68	-57	-21	-15
°F	-100	-90	-70	-5	5
Flash Point, °C	220	246	260	288	200
°F	430	475	500	550	390
Fire Point, °C	249	271	290	327	220
°F	480	520	555	620	428
Evaporation Loss, wt-% 6.5 hrs @ 400°F	11	4	3	2	27

Polyalphaolefins

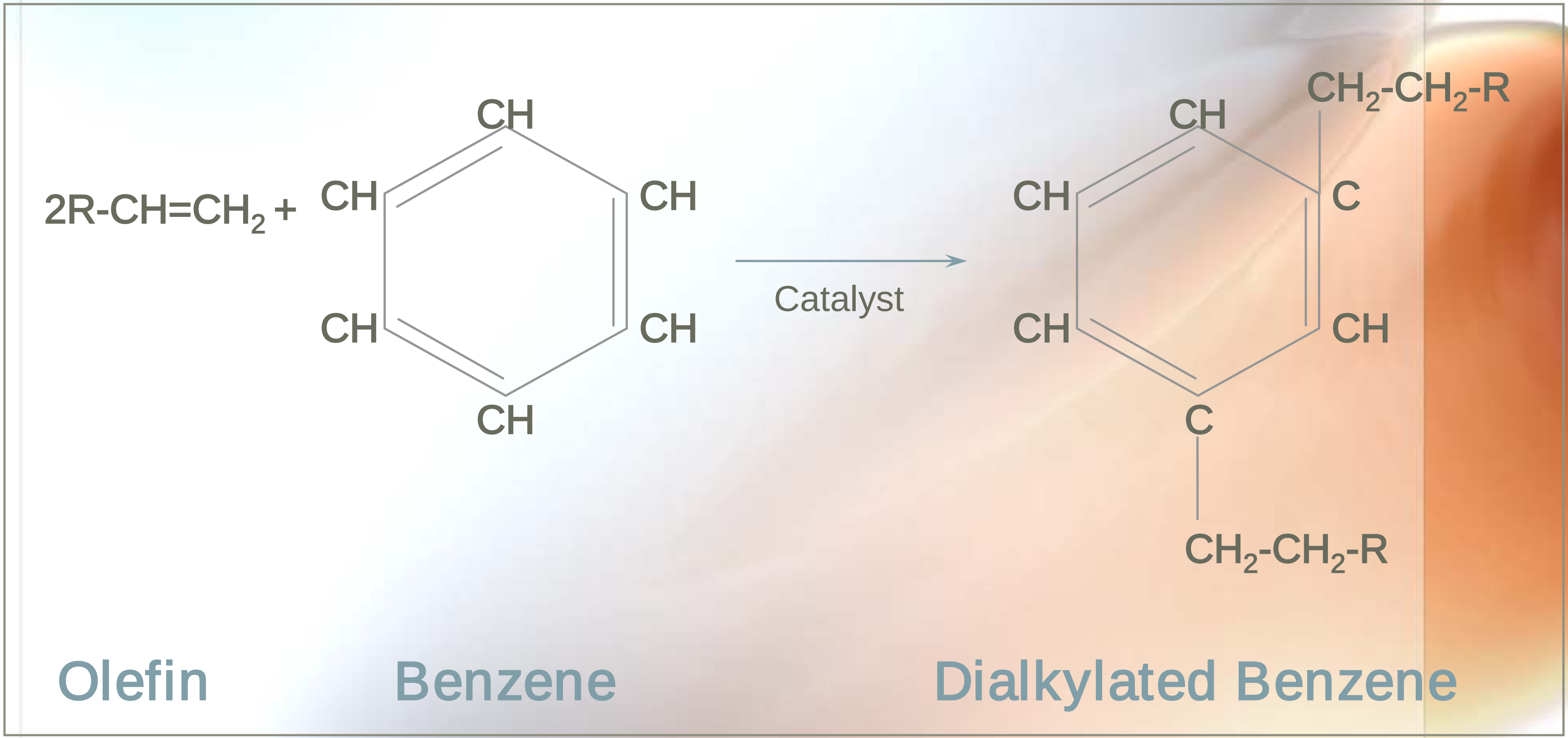
- Key Features

- Low Temperature Fluidity
- High VI
- Low Volatility
- Hydrolytic Stability
- Compatibility
  - Mineral Oils
  - Additives
  - Usual Elastomers

Synthesized Hydrocarbons

Alkylated Aromatics

Dialkyl Benzene Manufacturing



Alkylated Aromatic Properties vs. Naphthenic Mineral Oil

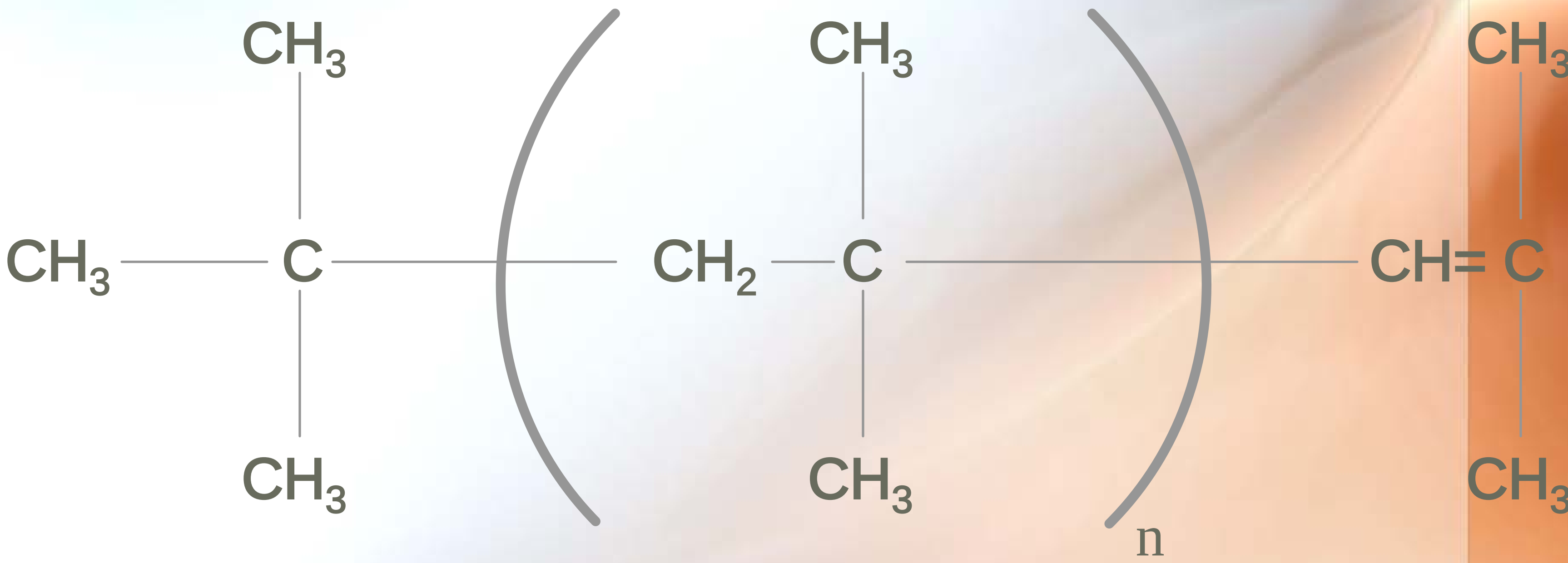
Viscosity, cSt	Alkylated Aromatic	Naphthenic Mineral Oil
at 100 ^{0}C	5.3	4.7
at 40 ^{0}C	29	30
Viscosity Index	115	54
Pour Point, ^{0}C	-54	-40
(^{0}F)	(-65)	(-40)
Flash Point, ^{0}C	229	179
(^{0}F)	(445)	(355)

Alkylated Aromatics

- Key Features

- Low Temperature Behavior
- Compatibility
  - Mineral Oils
  - Additives
  - Usual Elastomers
- Hydrolytically Stable
- Limited by Oxidative and Thermal Stability, and Volatility

Polybutenes (Polyisobutylenes)



- **Made by Polymerizing Isobutene**

Polybutenes

- Key Features

- Low Cost
- “Unzips”; Volatizes Leaving No Residue
- Volatility and Viscosity Index are Limiting Factors
- Widest Range of Grades Available for Synthetics
- Hydrophobic and non-corrosive
- Medium and high viscosity grades provide tackiness and adhesiveness
- Practically non-toxic

Synthesized Hydrocarbons

Organic Esters

Organic Esters

- Manufacturing

$$\mathrm{R-\overset{\overset{\Large O}{\|}}{C}-\boxed{OH + H}O-R'} \underset{}{\overset{\text{Catalyst}}{\rightleftharpoons}} \mathrm{R-\overset{\overset{\Large O}{\|}}{C}-OR' + H_{2}0}$$

Monobasic Acid | Alcohol | Ester | Water

Esters

- Versatility
  - Custom Made for Specialized Applications
- Diesters
  - Approximately Same Price as PAOs
  - Industrial Applications are Highest Growth
- Polyol Esters
  - High Temperature Applications
  - Approximately 50% Higher Priced Than Diesters
  - Used in Virtually All Jet Engines

Dibasic Acid Esters

- Diesters

$$\mathrm{HO-\overset{\overset{O}{\|}}{C}-(CH_2)_n-\overset{\overset{O}{\|}}{C}-OH + 2\,ROH} \xrightarrow{\text{Catalyst}} \mathrm{RO-\overset{\overset{O}{\|}}{C}-\overset{\overset{H}{|}}{\underset{\underset{H}{|}}{(C)_n}}-\overset{\overset{O}{\|}}{C}-OR + 2\,H_2O}$$

Dibasic Acid | Alcohol | Diester | Water

Dibasic Acid Ester Properties

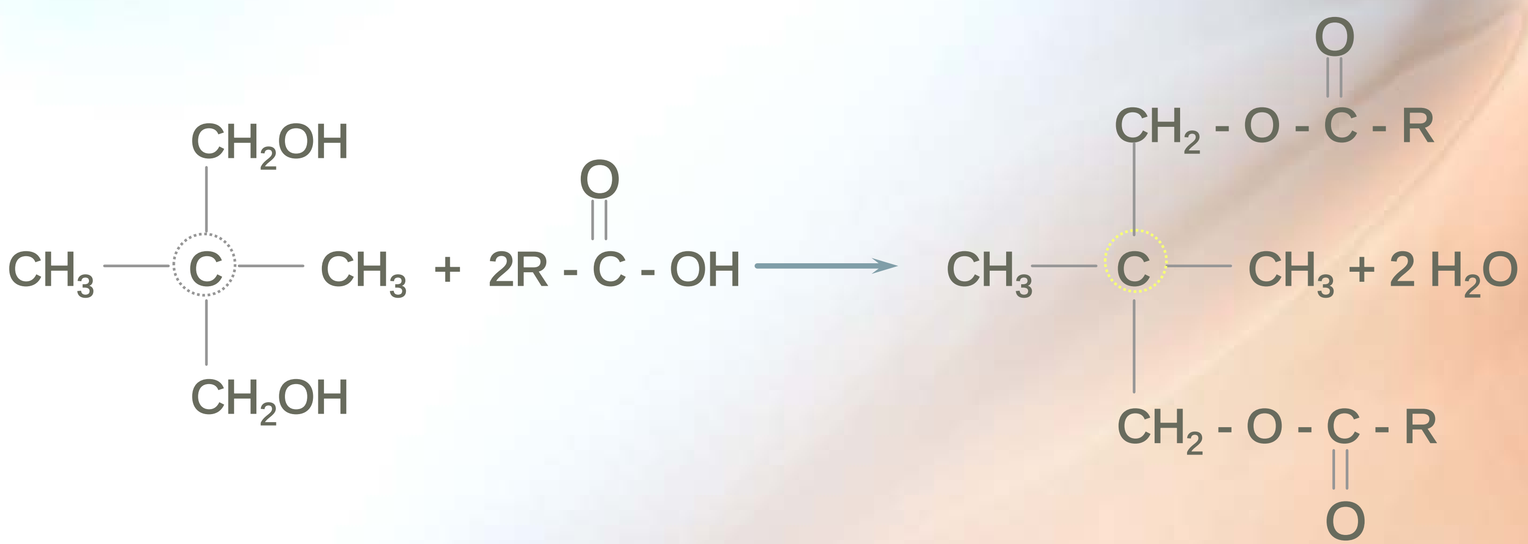
	Diisodecyl Adipate	Ditridecyl Adipate	Diisodecyl Azelate	Diisononyl Sebacate
Viscosity, cSt				
at 100 ^{0}C	3.6	5.5	4.3	4.6
at 40 ^{0}C	15	30	18.6	19
Viscosity Index	148	150	164	176
Pour Point, ^{0}C	-62	-54	-59	-51
^{0}F	-80	-65	-75	-60
Flash Point, ^{0}C	221	235	243	232
^{0}F	430	455	470	450

Dibasic Acid Esters

- Key Features

- Oxidative Stability (Inhibited)
- High Solvency and Detergency
- Metal Wetting
- Seal Swell
- High VI
- Susceptible to Hydrolysis

Polyol Esters



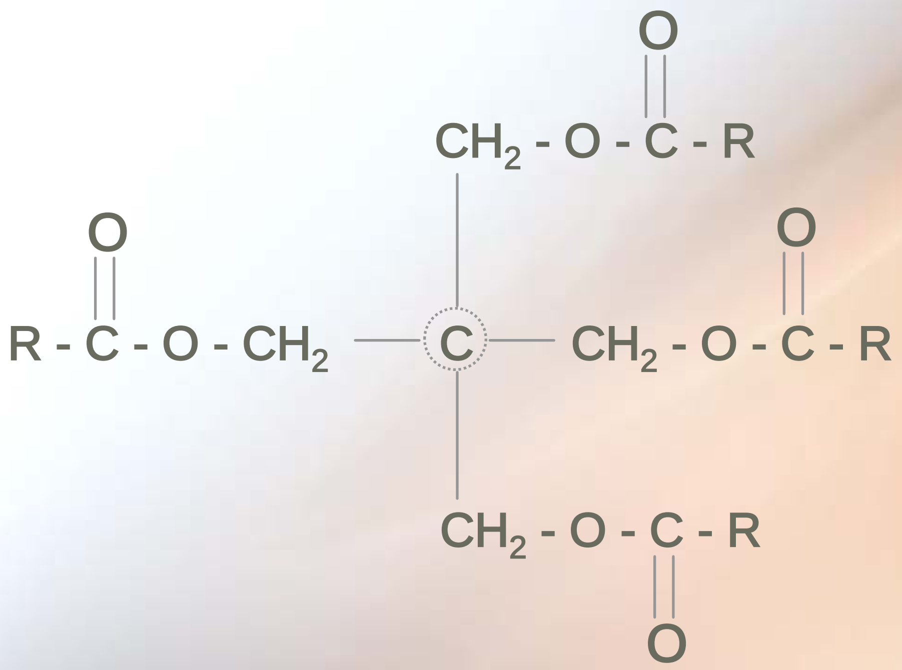
Neo Alcohol

Carboxylic Acid

Ester

Water

Typical Polyol Ester



Polyol Esters (PE)

- Properties

Viscosity, cSt			
at 100 ^{0}C	3.8	5.7	9
at 40 ^{0}C	17	31	57
Viscosity Index	126	144	142
Pour Point, ^{0}C	-68	-62	-56
(^{0}F)	(-90)	(-80)	(-70)
Flash Point, ^{0}C	230	257	287
(^{0}F)	445	495	550

Polyol Esters

- Absence of Beta Hydrogen Creates Greater Thermal Stability
- Outstanding High Temperature Properties
- Low Volatility
- Higher Cost Than Diesters
- Well Accepted in Aerospace Applications But Cost Has Inhibited Ground Transportation Applications

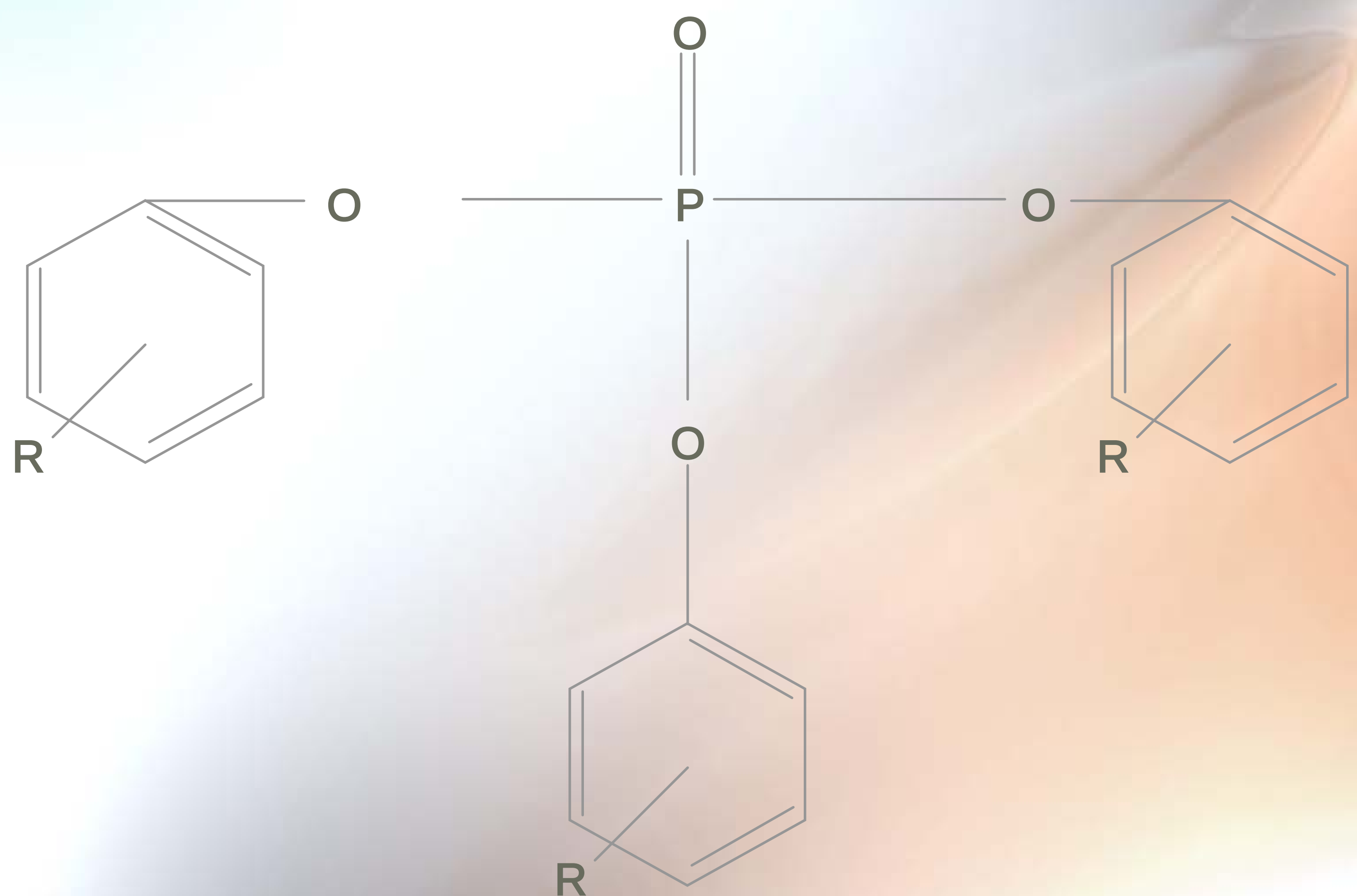
Competing Products

Property	Solvent Refined Mineral Oil	Hydro-cracked Mineral Oil	PAO	Diester	Polyol Ester
Low Temperature Fluidity	Poor	Fair-Good	Very Good	Very Good	Very Good
Compatibility with Mineral Oil	-	-	Excellent	Good	Fair
Stability in Presence of Water	Excellent	Excellent	Excellent	Fair	Fair
Low Volatility	Fair	Good-Fair	Very Good	Excellent	Excellent
Additive Compatibility	Excellent	Excellent	Very Good	Good*	Fair*
Oxidation Resistance	Poor	Fair	Good	Good	Very Good

*Need Special Additives for best results

Typical Phosphate Ester

Tri-aryl Phosphate Ester



Phosphate Esters

- Properties

	Tri - n - Octyl	Tricresyl
Viscosity, cSt		
at 100 ^{0}C	2.5	4.3
at 40 ^{0}C	8.4	35
Viscosity Index	148	-
Pour Point, ^{0}C	-34	-26
(^{0}F)	(-30)	(-15)
Flash Point, ^{0}C	Decomposition products burn	256
Autoignition Temperature, ^{0}C	-	550

Phosphate Esters

- Key Features

- Fire Resistant/Low Flammability
- Low Volatility
- Chemical Stability
- Poor Hydrolytic Stability
- Decomposition Products Corrosive
- Poor Software Compatibility
- Toxicity (for some materials)

Polyalkylene Glycol

$$\begin{array}{ccccccccccccccccc}
 & & & & & & R_1 & & & & & & R_2 & & & & \\
 & & & & & & | & & & & & & | & & & & \\
R & - & O & -(- & C & - & C & - & O & - & C & - & C & - & O-)_n & - & R_3
\end{array}$$

Polyalkylene Glycols

- Properties

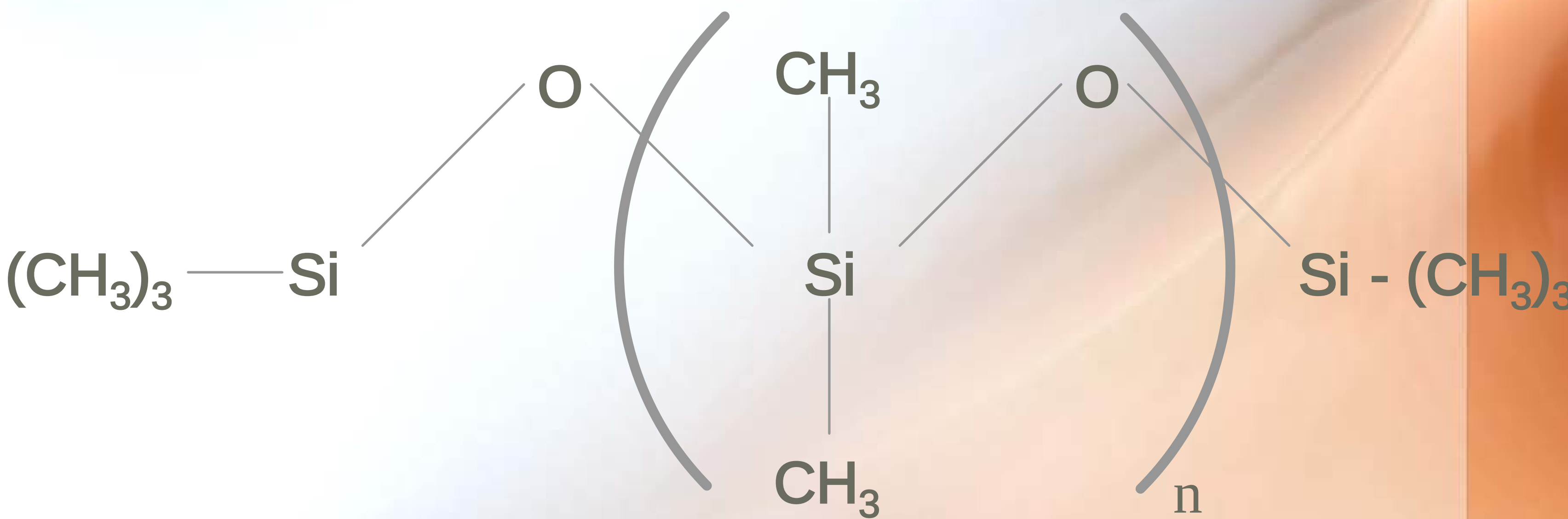
Viscosity, cSt			
$100^{0}C$	5.7	37	120
$40^{0}C$	28	245	760
Viscosity Index	161	214	269
Pour Point, ^{0}C	-48	-29	-29
^{0}F	-55	-20	-20
Flash Point, ^{0}C	119	202	172
^{0}F	246	395	341

Polyglycols

- Key Features

- Water-Soluble and Water-Insoluble Grades
- Fire Resistance (Water-Glycol)
- High VI
- Oxidative Stability (Inhibited)
- Non-Carbonizing
- Good Lubricity
- Limited Hydrocarbon Solubility
- Inverse Solubility/Temperature Relationship

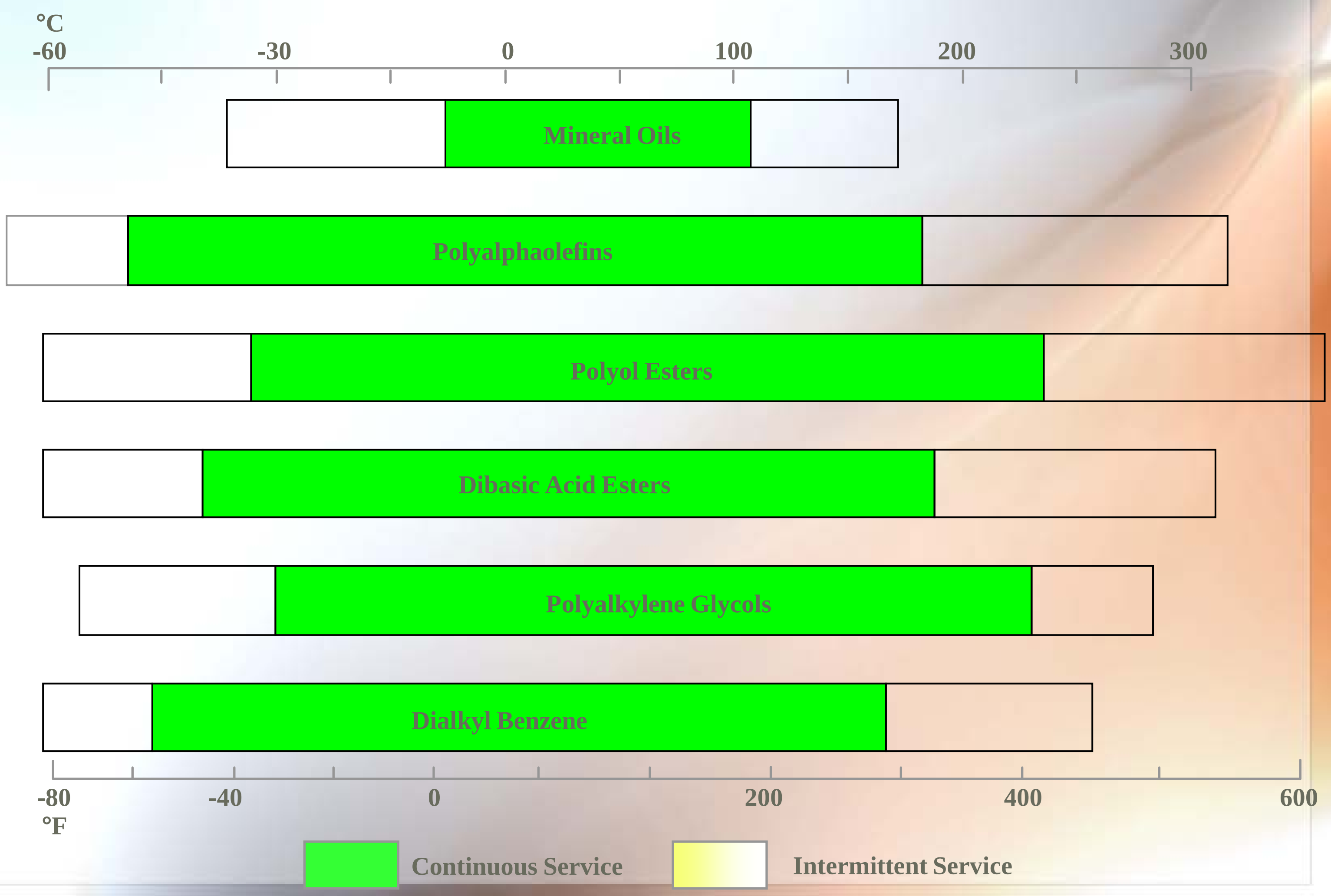
Silicones



Characteristics of Silicone Lubricants

- Very High VI
- Superior Thermal Stability - Oxidation Resistance
- Wide Operating Temperature Range
- Low Volatility
- Nonmetallic Lubrication
- Seal Compatibility
- Resistance to Water, Solvents, Chemicals
- High Price (13-20 x Mineral Oil)
- Poor Load Carrying Ability
- Poor Additive Response (Anti-Wear)

Mineral Oil vs. Synthetic Lubricants Comparative Temperature Limits



Comparisons of Synthetic Lubricants

Synthetics	Strengths	Weaknesses
DAB	Low Temperature	Volatility, Lubricity, Oxidation
PAO	Wide Temperature Range	Additive Solubility
PIB	Low Cost	Volatility Viscosity Index
DAE	Solvency and Detergency	Hydrolytic Stability Additive Technology
Polyol E	Thermal and Oxidative Stability	Additive Technology
PAG	Water Versatility	Compatibility Hygroscopic
Phos. Esters	Fire Resistance	Solvency Viscosity Index

Principle Synlube Uses

Product	MO	PAO	PAG	PIB	DAE	PE	Phos. Esters	DAB
Engine Oils								
Gear Oils								
ATF								
Air Conditioning								
Brake Fluids								
Greases								
Compressors							Oxygen	
Hydraulic Fluids							Fire res.	
Metalworking Fluids								
Textile								
Food grade								
Heat Transfer								
Transformer oils								
Refrigeration								

Sample Calculation

	Petroleum Oil	Synthetic Lube	
		A	B
Oil Consumption, gal/shift	2	0.5	1
Line down for repairs, days/year	12	2	10
Price of lube, $/gal	$2	$10	$22
Annual Cost of Downtime and Lube			
Product value lost, $300/h	86,400	14,400	72,000
Labor, $50/h	14,400	2,400	12,000
Parts/shop, $500/shutdown	6,000	1,000	5,000
Lube	4,236	5,445	23,430
Annual Cost	**$111,036**	**$23,245**	**$112,430**
Cost Difference	-	**$87,791**	**$(1,394)**

Recent Developments Place More Demands on Hydraulic Oils

- Increasing Pump Pressures
- Increasing Operating Temperatures
- Sealed-for-Life-Units
- Energy/Cost Savings
- Biodegradability

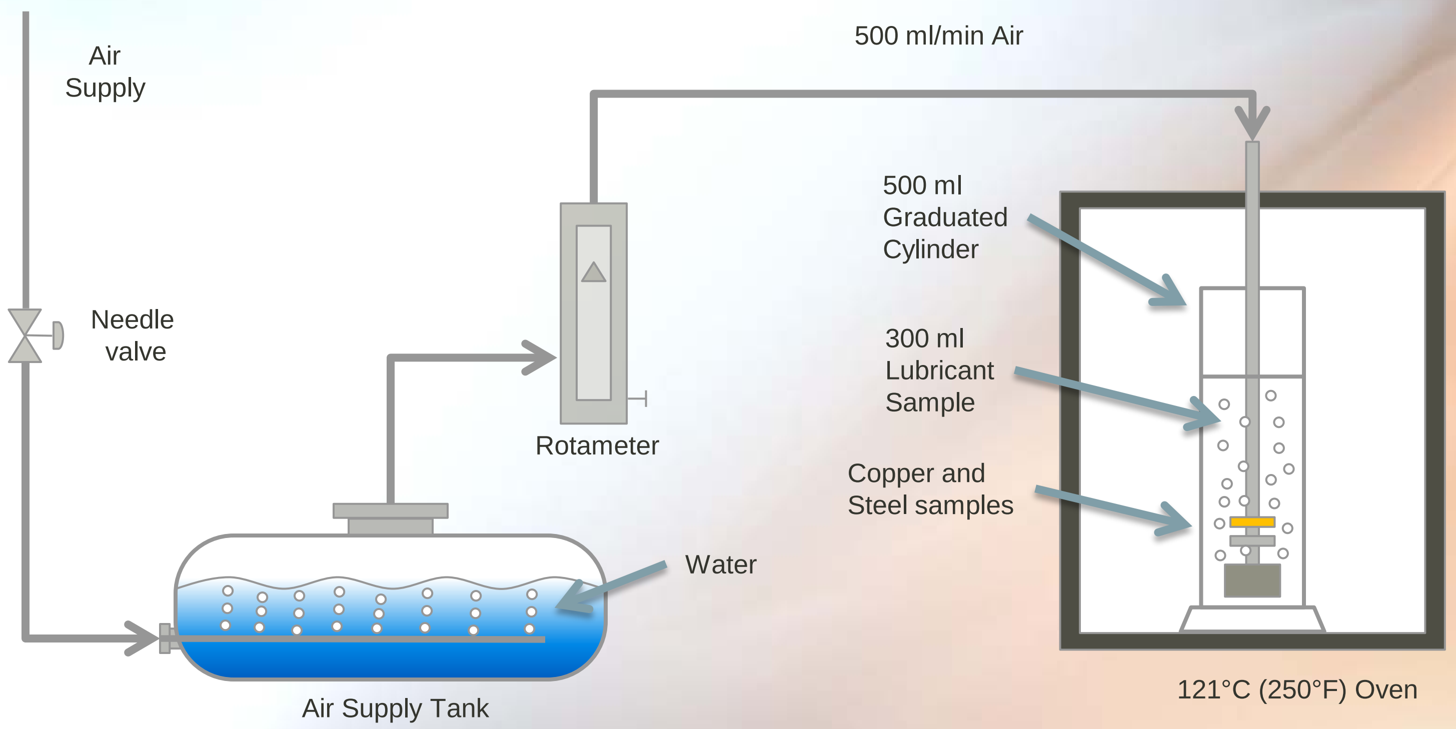
Synthetic Fluids Can Help

Air Compressor Operation is Becoming More Severe

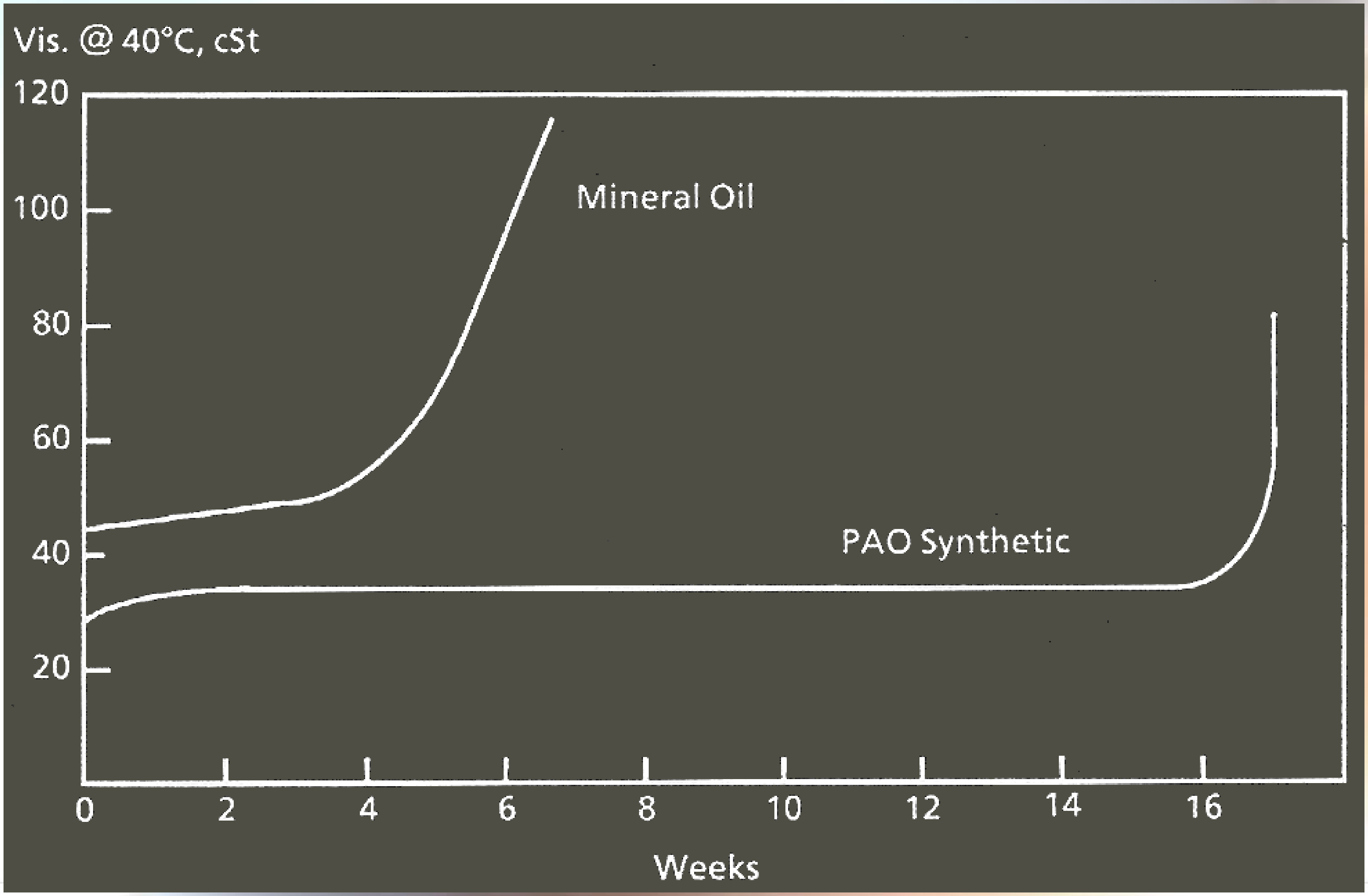
- Increased Operating Temperatures
- Higher Air Throughput
- Finer Air Coalescer Filters
- Extended Drain Intervals
- Energy Efficiency

Opportunities for Synthetic Lubricants

Laboratory Compressor Oil Life Test



Laboratory Compressor Oil Life Test



Rotary-Screw Compressor Oil

Oil Type	Lubricant Life		OEM Recommended Lube Change Interval, h
	Air Oven Test 121°C (250°F)	Field Compressor 82°C (180°F)	
Formulated Mineral	750	2,000	1,000
PAO-Based	6,200	15,000 +	8,000 - 10,000 (One Year)

300-hp Rotary-Screw Compressor

Economics of PAO vs. Mineral Oil

Economics	Premium Mineral Oil	PAO Lube
Initial Fill, gal	60	60
Oil Make-up, gal	25	15
Fluid for Lube Changes, gal		
Mineral Oil: 9 Changes	540	-
PAO Lube: 0 Changes	-	0
Total Lube Use, gal	625	75
Cost per gal, $	3	10
Total Cost of Lube, $	1875	750
Labor Cost for Oil Change at $40/Change	400	40
Number of Replacement Filters	10	2
Total Filter Cost at $30/Filter	300	60
Total Cost, $	2575	850
Savings, %	-	67

Lubricant Survey

Test: comparison between existing lubricants and synthetic

Method: baseline amperage readings were taken with original, conventional oil after 12 hrs after operation of fresh oil. The second stage was to change the oil to synthetic and measure amperage draw after 12 hrs operation. Three to six measurements per piece of equipment were taken.

Equipment	Synthetic Type	AMP Reduction	Annual Est. Power Savings
P507	**A**	**3.2**	**$18,007**
P507A	**A**	**3.25**	**$18,581**
P908A	**A**	**18.27**	**$11,535**
P908B	**B**	**12.9**	**$8,127**
P902A	**A**	**4.88**	**$2,737**
P902B	**B**	**3.68**	**$2,269**
P105	**A**	**1.38**	**$947**
P105A	**B**	**-0.28**	**($264)**

Some scatter in the data was attributed to operating unit variables affecting the load on the test pumps. The most consistent date is from P507 & P507A (350 hp motors) with fairly consistent load throughout the test.. Data courtesy Royal Purple, LTD

Lubricant Survey (Continued)

Equip.	Voltage	Baseline		Synthetic		Cost Diff /Day	Annual Elect. Savings	Inc. Lube Cost	Net Annual Savings	Percent Elec. Savings
		Amps	Elec. Cost/Day	Amps	Elec. Cost/Day					
P105	**460**	**87**	**$174**	**85.09**	**$170**	**$3.82**	**$1,394**	**$60**	**$1,334**	**2.2%**
P105A*	**460**	**93**	**$186**	**91.81**	**$184**	**$2.38**	**$869**	**$60**	**$809**	**1.3%**
P211A	**460**	**20**	**$35**	**19.42**	**$34**	**$1.01**	**$368**	**$60**	**$308**	**2.9%**
P507	**4160**	**41**	**$645**	**36.91**	**$580**	**$64.31**	**$23,475**	**$360**	**$23,115**	**10.0%**
P507A	**4160**	**41**	**$645**	**36.87**	**$580**	**$64.94**	**$23,704**	**$360**	**$23,344**	**10.1%**
P902A	**460**	**88**	**$153**	**85.13**	**$148**	**$4.99**	**$1,821**	**$360**	**$1,461**	**3.3%**
P902B*	**460**	**90.3**	**$157**	**85.41**	**$149**	**$8.50**	**$3,103**	**$60**	**$3,043**	**5.4%**
P908A	**460**	**187**	**$325**	**157.66**	**$274**	**$51.02**	**$18,621**	**$60**	**$18,561**	**15.7%**
P908B*	**460**	**189.1**	**$329**	**168.89**	**$294**	**$35.14**	**$12,827**	**$60**	**$12,767**	**10.7%**
PD506	**460**	**46.8**	**$94**	**46.65**	**$93**	**$0.30**	**$109**	**$60**	**$49**	**0.3%**
PD506A*	**460**	**48.3**	**$97**	**49.76**	**$100**	**$(2.92)**	**($1,066)**	**$60**	**($1,126)**	**-3.0%**
P605	**460**	**48.5**	**$84**	**44**	**$77**	**$7.82**	**$2,856**	**$60**	**$2,796**	**9.3%**
TOTAL			**$2,923**		**$2,681**	**$241.32**	**$88,082**	**$1,620**	**$86,462**	5.7%

** Indicates Synthetic lube B was used. All others used Synthetic lube A.*

IF only 2% was achieved:

➔ $21M / yr from 12 pumps with an increased lubricant cost of ~$1,600.

Recent Trends in EP Gear Oil Applications

- Smaller Gear Drives
- Increased Horsepower
- Increased Operating Temperatures
- Sealed-for-Life-Units
- Energy Savings

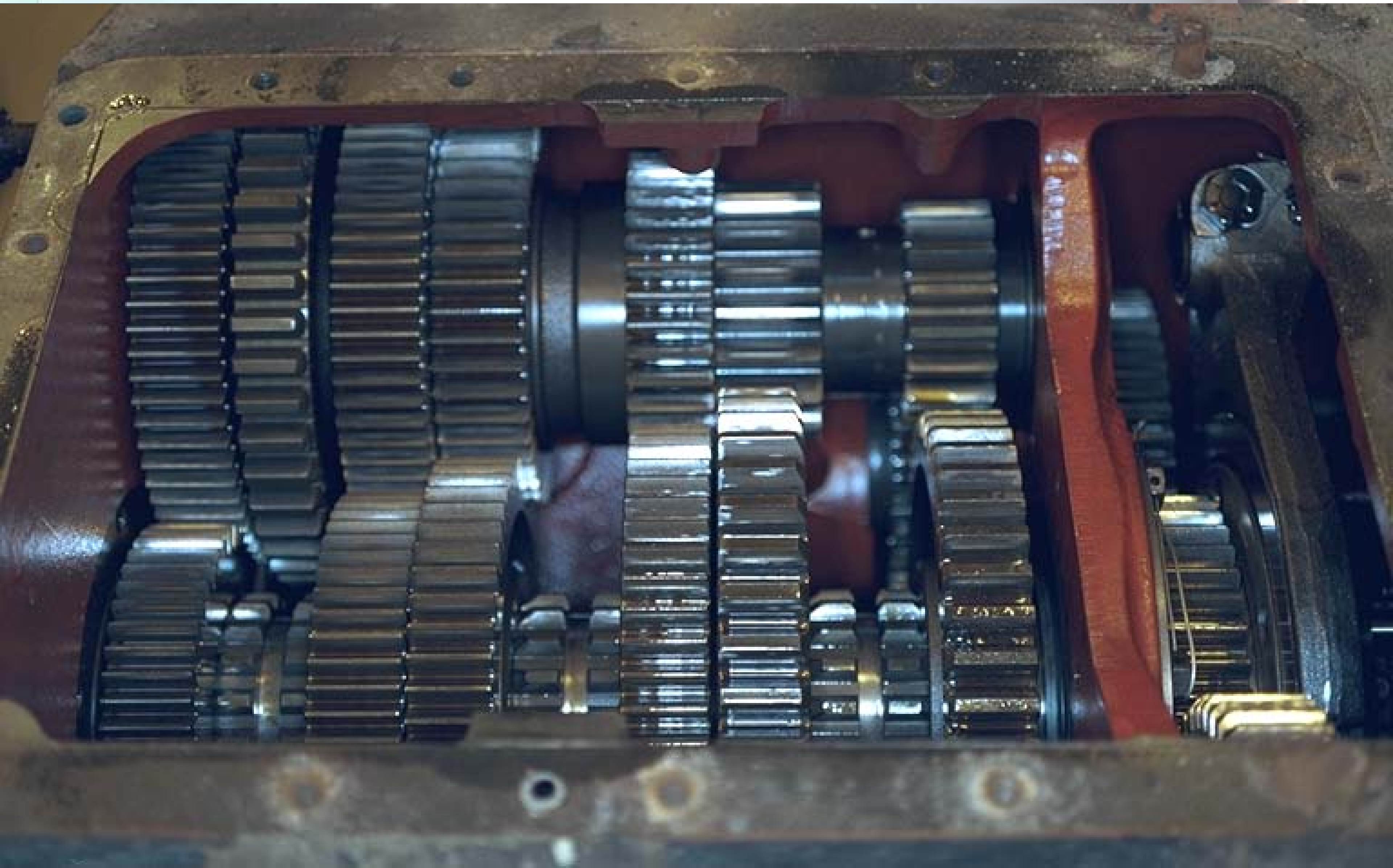
Opportunities for Synthetic Lubricants

Extended Safety Margin

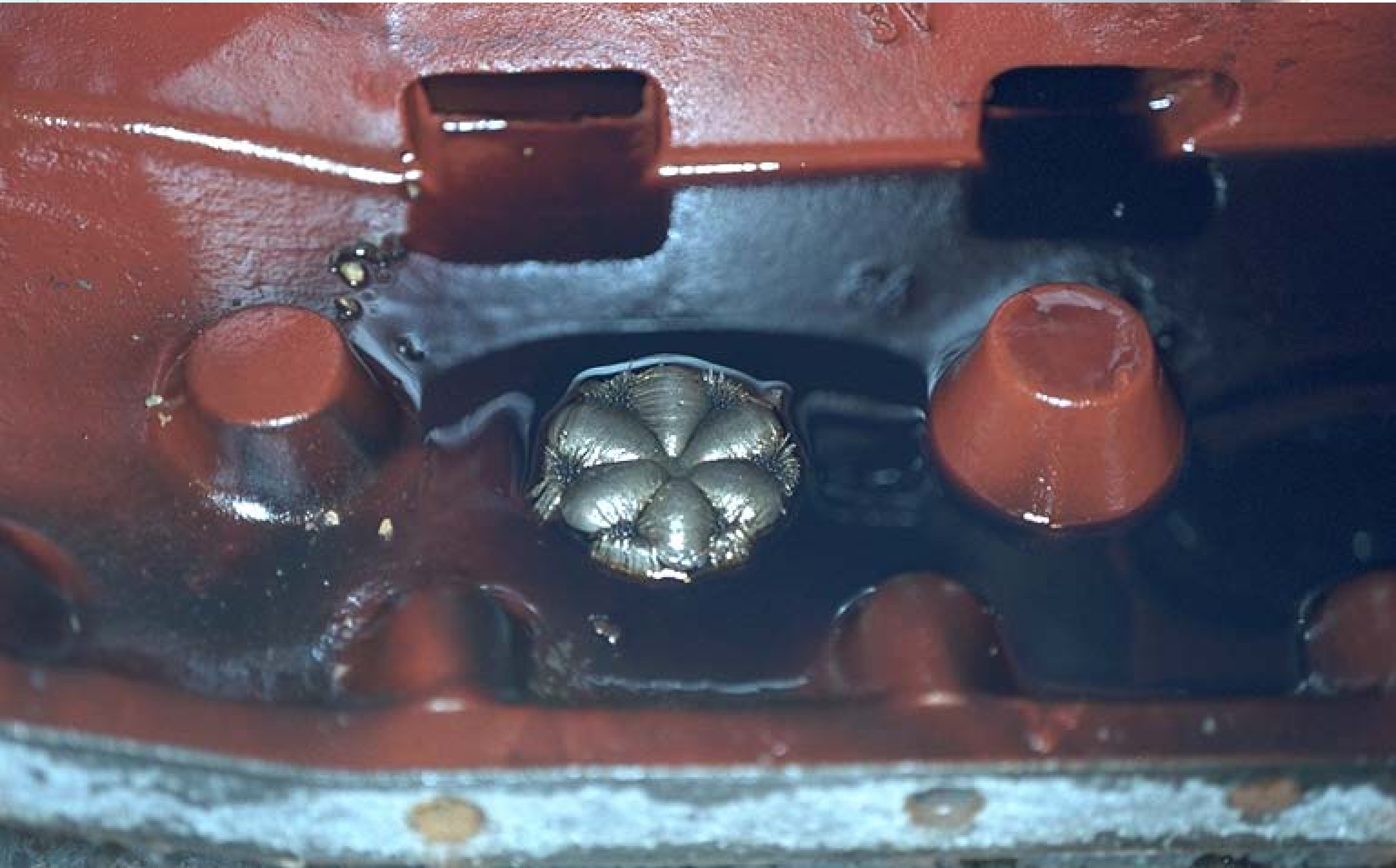
Beyond Warranty

- 1,535,930 miles min.
- 1985 Navistar
  - Cummins NTC 350 engine
  - Fuller RT 14609A transmission
  - Eaton DS 380P drive axles
- Mideastern U.S. operation / >100K miles/yr
- No lubricant change-out
- No major repairs requiring oil change-out

1,500,000 MILE FIELD TEST / OEM INSPECTION



1,500,000 MILE FIELD TEST / OEM INSPECTION



New Materials

mPAO
Phosphate Esters
Oil Soluble PAGs

Benefits of Oil Soluble PAGs (OSP)

Key Advantages:

- Compatible with a wide range of API Group I to IV hydrocarbon base oils
- Conversion of equipment from a hydrocarbon lubricant to a synthetic OSP lubricant is now much simpler than converting to a traditional PAG lubricant (based on EO and PO chemistries)
- Greater functionality than traditional PAGs – can be used in combination with hydrocarbon oils to upgrade their performance (not possible with traditional PAGs due to non-compatibility)
- Inclusion of OSPs into hydrocarbon oils as additives can:-
  - ➢ Significantly improve deposit control and extend lubricant life and change-over intervals. Recommended treat levels are 1-20%
  - ➢ Improve friction control and energy efficiency through their inherent film forming activity. Recommended treat levels are 5-15%
  - ➢ Improve the miscibility of conventional additives in Group II, III and IV base oils due to their high polarity (low aniline point)
  - ➢ Higher viscosity grades provide an alternative to bright stock as viscosity boosters
- OSPs are kinder to paints and elastomers and less hygroscopic than traditional PAGs

Expanding functionality of PAGs using OSPs

Traditional uses of PAGs based on EO and PO derivatives

Primary base oil in formulations
- Compressor and refrigeration oils
- Hydraulic fluids
- Textile lubricants
- Gear & Bearing oils

Additives
- Viscosity builder in water glycol hydraulic fluids
- Lubricity aid in water miscible MWFs

Use of OSPs
Expansion of formulators options

Primary base oil in formulations
- Compressor/refrigeration oils
- Hydraulic fluids
- Gear & Bearing Oils
- Engine/transmission Oils

Co-base oil
- Upgrade Group I-III mineral oils
- Upgrade PAOs

Additives
- Deposit control additive
- Friction modifier
- Viscosity builder in mineral oils

Oil Soluble PAGs – Typical Physical Properties

Polymers derived from downstream derivatives of butylene oxide

	KV40 cSt	KV100 cSt	Viscosity Index	CCS viscosity at -20°C mPa.s	Pour Point °C	Flash Point, °C	Aniline Point, °C
	ASTM D445	ASTM D445	ASTM D2270	ASTM D5293	ASTM D97	ASTM D92	ASTM D611-01
OSP-18	18	4	123	n/d	-41	204	n/d
OSP-32	32	6.5	146	1750	-57	216	<-30
OSP-46	46	8.5	164	2900	-57	210	<-30
OSP-68	68	12	171	5400	-53	218	<-30
OSP-150	150	23	186	17100	-37	228	<-30
OSP-220	220	32	196	29100	-34	226	-22
OSP-320	320	36	163	n/d	-37	230	n/d
OSP-460	460	52	177	n/d	-35	235	n/d
OSP-680	680	77	196	n/d	-30	243	n/d

High Viscosity PAO

- New mPAO materials have been announced
- High Viscosity mPAOs have advantages in:
  - Higher VI
  - Lower Pour Point
  - Better viscosity at low temperatures
  - Improved coefficient of friction

	High Viscosity PAOs										
	PAO 40					PAO 100 & 100+					
Physical Property	Traditional 40 cSt	mPAO A	B	C	D	Traditional 100 cSt	A	B	C	D	E
Kinematic Viscosity @100°C, cSt	40	40.6	40	50.3	50	100	100	98	100	127	150
Kinematic Viscosity @ 40°C, cSt	395	348	400	412	426	1231	992	927	1270	1250	1500
Viscosity Index	147	170	150	186	180	167	194	197	165	207	218
Pour Point, °C	-36	-50	-40	-47	-45	-30	-44	-40	-30	-40	-33
Flash Point (COC), °C	281	256	260	246		283	257	258	280		
Specific Gravity	0.850	0.838	0.838	0.846		0.853	0.845	0.850	0.843		0.850

Synthetic Lubricant Advantages

- Energy Savings
- Increased Efficiency
- Reduced Operating Costs
- Reduced Maintenance and Downtime
- Increased Equipment Life
- Extended Lubricant Life

Synthetic Lubricants

The High-Technology Problem Solvers!