특별강연

DESIGNING GEAR OILS FOR THE 21st CENTURY

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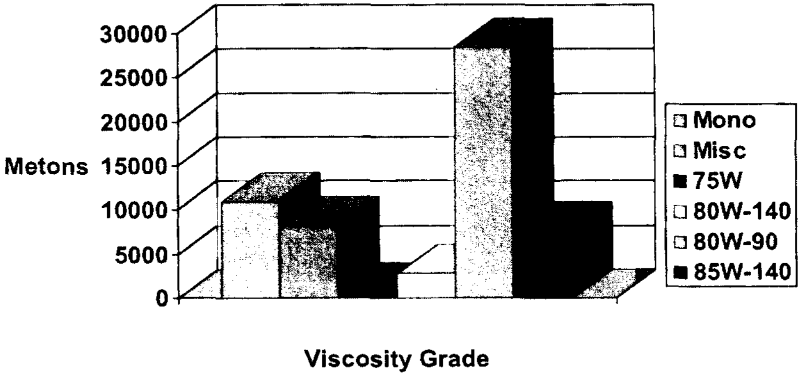
OUTLINE

1. Gear Oil Market Review
   - North American Market
   - Japanese Market
   - European Market
2. Key Technical Issues
3. Recent Technical Activities
   - Surface Fatigue Performance Of Gear Oils
   - Film Forming Tendencies Of Gear Oils
4. Summary

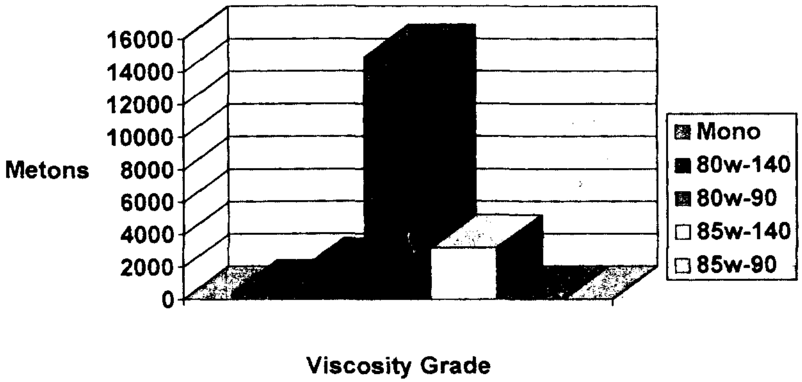
1. *Gear Oil Market Review*

North American Market Review

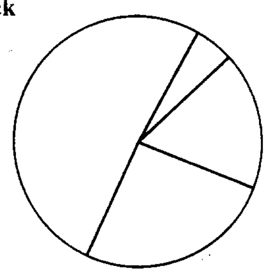
North America
API GL-5/MIL-PRF-2105E



North America
API MT-1



North America
End-Usė Trends: Automotive Gear Oil



- Heavy And Medium Duty Trucks Account For Majority Of Gear Oil Volume
- Passenger Car Is A Relatively Small (But Important) Segment Due To Popularity Of Automatic Transmissions
  — Greater Than 85% Of 1994 Model U.S. Cars Have Automatic Transmissions

U.S. Medium & Heavy-Duty Trucks
1994 and 1995 Production

	1995	%	1994	%	% Change
Navistar	76,430	20.62	64,490	19.34	18.51
General Motors	69,975	18.88	69,890	10.96	0.12
Freightliner	64,810	17.49	53,435	16.03	21.29
Ford	57,640	15.55	58,340	17.50	-1.20
PACCAR	48,070	12.97	37,530	11.26	28.08
Mack	27,750	7.49	25,285	7.58	9.75
Volvo - GM	25,925	7.00	24,405	7.32	6.23
	370,600	100.00	333,375	100.00	11.17

- Component Manufacturers Are Typically More Influential Than Vehicle Manufacturers In Designing North American Gear Lubricant Specifications

  - Primary Heavy-Duty Axle and Transmission Manufacturers:
    -- Eaton
    -- Rockwell
    -- Mack

U.S. Light-Duty Truck Production

	1995	%	1994	%	% Change
Ford	1,996,580	37.85	2,011,337	38.01	-0.73
General Motors	1,781,999	33.79	1,772,018	33.49	0.56
Chrysler	1,141,726	21.65	1,143,420	21.61	-0.15
Nissan	132,552	2.51	131,955	2.49	0.45
Isuzu	99,514	1.89	99,873	1.89	-0.36
Others	121,983	2.31	132,427	2.50	-7.89
	5,274,354	100.00	5,291,030	100.00	-0.32

- Sales of Light Trucks Have Increased More than 60% Since 1990.
- Gear Lubricant Is Typically Fill-For-Life. OEM Defines Performance Requirements.
- Trend Toward SAE 75W-90/140 Formulations for Light-Duty Factory-Fill.
- 90% of Units Are Rear or 4-Wheel Drive.

Japanese Trends

Japanese Passenger Car Production

	1995	%	1994	%	% Change
Toyota	2,557,174	33.60	2,770,503	35.51	-7.70
Nissan	1,508,922	19.83	1,341,264	17.19	12.50
Mitsubishi	908,874	11.94	891,053	11.42	2.00
Honda	811,593	10.66	849,836	10.89	-4.50
Mazda	606,232	7.92	821,453	10.53	-26.20
Suzuki	602,670	7.92	512,911	6.57	17.50
Fuji	296,726	3.90	302,782	3.88	-2.00
Daihatsu	266,431	3.50	264,842	3.39	0.60
Isuzu	51,911	0.68	47,756	0.61	8.70
	7,610,533	100.00	7,802,398	100.00	-2.46

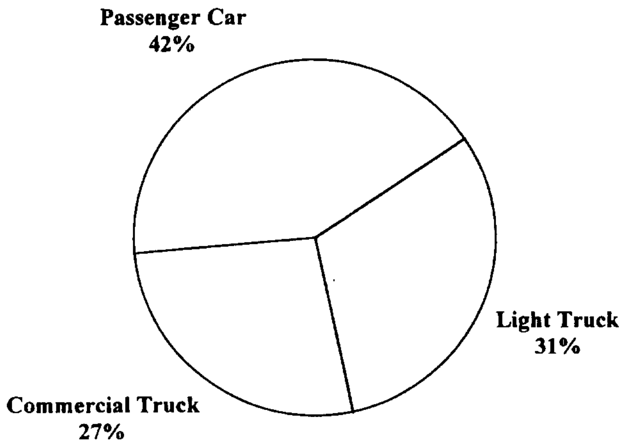
- Approximately 80% of Japanese Passenger Cars Are Front Wheel Drive
- % of Cars Manufactured With Automatic Transmissions:
  - 1990: 72.5%
  - 1993: 76.5%
  - 1995: 80.8%

Japanese Truck and Bus Production

	1995	%	1994	%	% Change
Toyota	614,103	23.76	739,883	26.87	-17.00
Mitsubishi	418,679	16.20	414,944	15.07	0.90
Isuzu	294,812	11.40	329,031	11.95	-10.40
Suzuki	259,620	10.04	264,648	9.61	-1.90
Daihatsu	210,892	8.16	217,414	7.90	-3.00
Nissan	205,060	7.93	216,765	7.87	5.40
Mazda	165,218	6.39	164,396	5.97	0.50
Honda	155,728	6.02	147,890	5.37	5.30
Fuji	122,559	4.74	131,219	4.77	-6.60
Hino	82,768	3.20	75,381	2.74	9.80
Others	55,564	2.15	51,544	1.87	7.80
	2,585,003	100.00	2,753,117	100.00	-6.11

- Hino Is The Largest Producer Of Heavy-Duty Trucks

Japan
End-Use Trends: Automotive Gear Oil

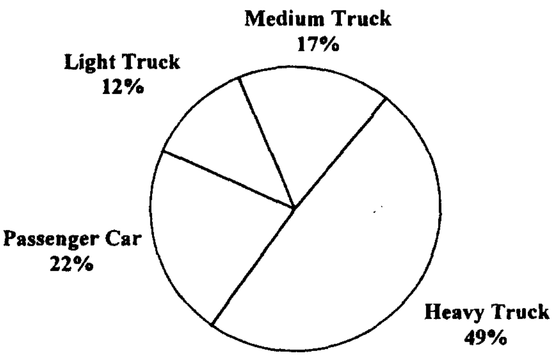


Gear Lubricant Consumption In Passenger Cars Is Declining DueTo Fill-For-Life Application And Increase Use Of Automatic Transmissions

European Trends

Europe

End-Use Trends: Automotive Gear Oil



- **Heavy And Medium-Duty Trucks Account For Majority Of Gear Oil Volume**
- **Passenger Car Gear Oil Consumption Relatively Large Compared To North America Primarily Due To Popularity Of Manual Transmissions**

Western Europe

C/V Registration over 3.50t GVW
(Includes Artics, Excludes Buses)
Provisional AID Sales Estimates

	Year '95	% Share	Year '94	% Share	% Change
Mercedes	70,400	25.4	66,100	28.1	6.5
Iveco	48,400	17.4	42,200	17.9	14.7
MAN Group	32,800	11.8	29,200	12.4	12.3
Volvo	30,900	11.1	23,800	10.1	29.8
Renault RVI	29,100	10.5	22,100	9.5	31.7
Scania	24,200	8.7	16,700	7.1	44.9
Daf	14,000	5.0	9,700	4.1	44.3
Leyland Trucks	7,400	2.7	5,600	2.4	32.1
Motor Iberica	4,000	1.4	3,500	1.5	14.3
ERF	3,200	1.2	2,600	1.1	23.1
Volkswagen	2,700	1.0	2,700	1.1	0.0
Mitsubishi	1,900	0.7	2,500	1.1	-24.0
Foden	1,150	0.4	1,000	0.4	15.0
GM	850	0.3	900	0.4	-5.6
Others	6,400	2.3	6,700	2.8	--
TOTALS	277,400	100.0	235,300	100.0	17.9

Source: AID/Industry Estimates

Western Europe Passenger Car Sales

	6 Months		6 Months		
	1996	%	1995	%	% Change
Volkswagen Group	1,183,700	17.24	1,092,100	16.68	8.39
General Motors Group	886,900	12.92	872,900	13.33	1.60
Fiat Group	817,200	11.90	747,600	11.42	9.31
Ford Group	816,600	11.89	783,800	11.97	4.18
PSA Group	807,800	11.76	788,500	12.04	2.45
Renault	667,900	9.73	694,800	10.61	-3.87
BMW Group	404,000	5.88	384,300	5.87	5.13
Others	1,283,300	18.68	1,185,000	18.09	8.27
	6,867,100	100.00	6,549,000	100.00	4.86

Top Five Passenger Car Producing Countries Account for ~80% of Production

1. Germany (27.8%)
2. France (15.0%)
3. UK (14.6%)
4. Italy (14.5%)
5. Spain (6.7%)

2. *Key Technical Issues*

INCREASED OEM DEMANDS & TRENDS

- Extended Drain Intervals
- Operating Economics
- Higher HP Engines
- Retarder Usage
- Transmission Oils
- Environmental Considerations

KEY TECHNICAL ISSUES

- ***Surface Fatigue***
- Thermal & Oxidational Stabilities
- ***Temperature Reduction***
- Shear Stability
- Seal Compatibility
- Synchronizer Performance
- ***Fuel Economy***

SURFACE FATIGUE

- Surface Fatigue Is Primary Consideration In The Commercial Vehicle Segment (Especially In Europe) Due To The Growing Demand For Extended Drain Intervals By OEMs
- Increased Engine Output And Small Component Size Increase A Possibility Of Gear Surface Fatigue

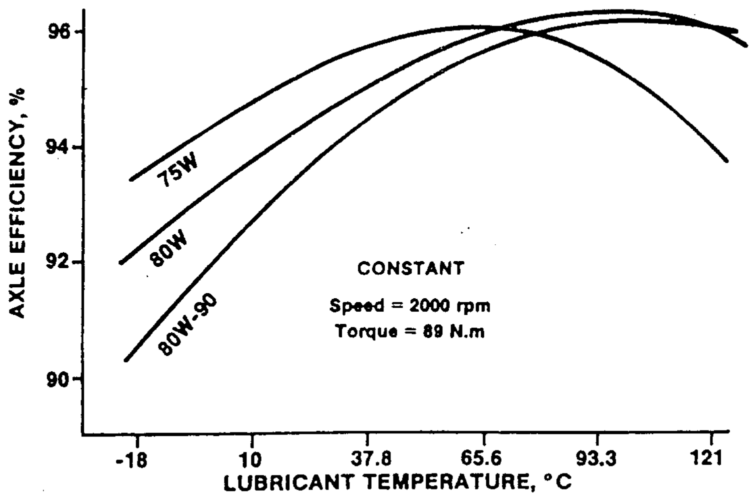
TEMPERATURE REDUCTION

- Higher Operating Temperatures Result From
  - Greater Power Densities
  - Improved Aerodynamics
  - Smaller Gearboxes
  - Noise Shielding
- Need Improved Thermal Stability Oils And Reduced Operating Temperature Oils
- Synthetic Base Fluids Are Preferred Due To Their Good Thermal And Oxidational Stabilities
- Synthetic Base Fluids Provide Lower Operating Temperatures Than Mineral Base Oils

FUEL ECONOMY

- Fuel Economy Benefits End-Users (Lower Cost) As Well As OEMs (CAFE Requirements)
- Moving To Wide Span Multigrade Is Proven To Increase Axle Efficiency Up To 1%
- Fuel Economy Is A Function Of Many Variables, Such As Viscosity, Oil Temperatures, Etc.

AXLE EFFICIENCY
VS.
LUBE TEMPERATURE



3. *Recent Technical Activities*

SURFACE FATIGUE PERFORMANCE OF GEAR OILS

"Effect Of Lubricant Additives On The Surface Fatigue Performance Of Gear Oils"

by
H. Hong, M. Huston, B. M. O'Connor and N. M. Stadnyk
The Lubrizol Corporation

GEAR FAILURE MECHANISMS

- Wear (Loss of Material by Abrasive Contact)
- Plastic Flow (Surface Yielding and Deformation Due to Heavy Loads)
- Surface Fatigue (Failure of Material Due to Repeated Contact)
- Breakage
- Associated Gear Failure (e.g. Lubricant Starvation)

EFFECT OF ADDITIVES ON FATIGUE LIFE OF GEARS

- Townsend et al. ('84, '86)
  - Evaluation of Surface Fatigue Properties of a Reference Fluid (Synthetic Tetraester Containing Oxidation and Corrosion Inhibitors and an Antiwear Additive).
  - The Addition of Phosphate EP Additive to the Reference Fluid Increased the Fatigue Life of Spur Gears.
  - The Addition of Sulfur EP Additive to the Reference Fluid Did Not Show Any Significant Improvement.

OBJECTIVES

- To Study the Effect of Additives Used in the Formulation of API GL-5 Grade Gear Oils with Emphasis on:
  - Development of Stress - Surface Fatigue Life of Gears (S-N Curve)
  - Evaluation of Additive Component Effect on the Surface Fatigue Life of Gears

FZG GEAR TESTER

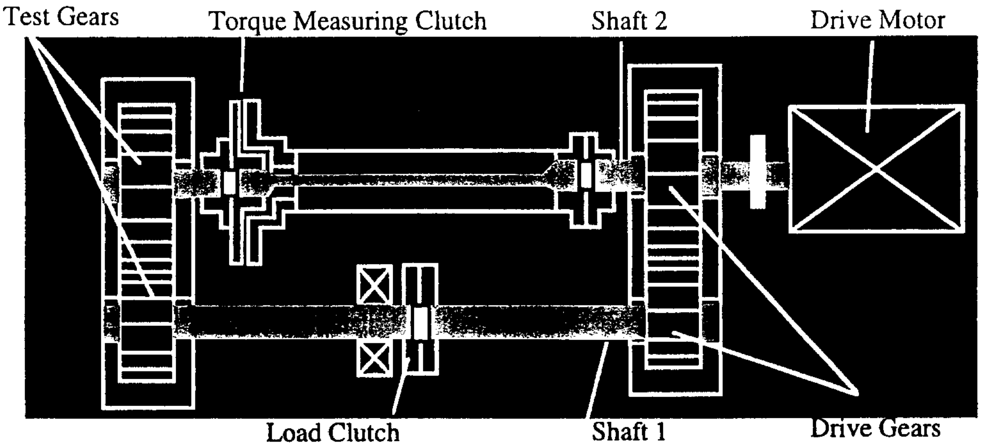


Figure 1. Schematic Drawing of FZG Gear Tester.

REQUIRED LABORATORY TESTS FOR API GL-5 GEAR OILS

Test Designation	Type	Characteristics Measured
L-33	Gear Test Using Axle Components Corrosion	Resistance to Corrosion (Moisture)
L-37	Gear Test Using Complete Axle Assembly	Resistance to Gear Distress (Low Speed and High Torque)
L-42	Gear Test Using Complete Axle Assembly	Resistance to Scoring (high speed and shock loads)
L-60	Bench Test Using Spur Gears	Thermal Oxidation Stability
ASTM D 892	Bench Test	Foaming Tendencies
ASTM D 130	Bench Test	Resistance to Copper Corrosion

TYPICAL GEAR OIL COMPOSITION

Base Oil	60-95%
Viscosity Modifier	0-30%
Pour Pt Depressant	0-2%
Performance Package	5-10%

Which Typically Contains Antiwear, EP, Corrosion, Oxidation and Foam Inhibitors

TEST GEARS

- "C" Profile Gears Made from 16MnCr5 Steel
- Case Carburized to a Surface Hardness of Rc = 60 to 62
- Surface Roughness in the Range of 0.3 to 0.4 µm.

TEST OILS

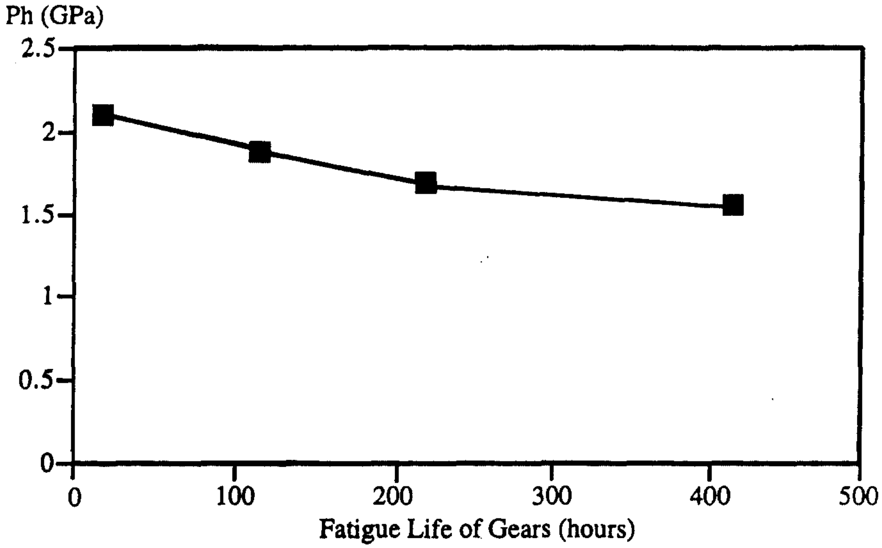
- API GL-5 Grade Gear Oil as a Reference Oil.
- Elimination of AW Additive and/or EP Additive.

Test Fluid	Additive Package	Kin. Vis. at 100°C (cSt)	Kin. Vis. at 40°C(cSt)	%P (theo)	%S (theo)
1	API GL-5 Commercial Formulation	17	189	0.11	2.1
2	GL-5 Less EP Component	18	204	0.11	0.2
3	GL-5 Less AW Component	17	185	0	1.9
4	GL-5 Less AW and EP Component	18	201	0	<0.1

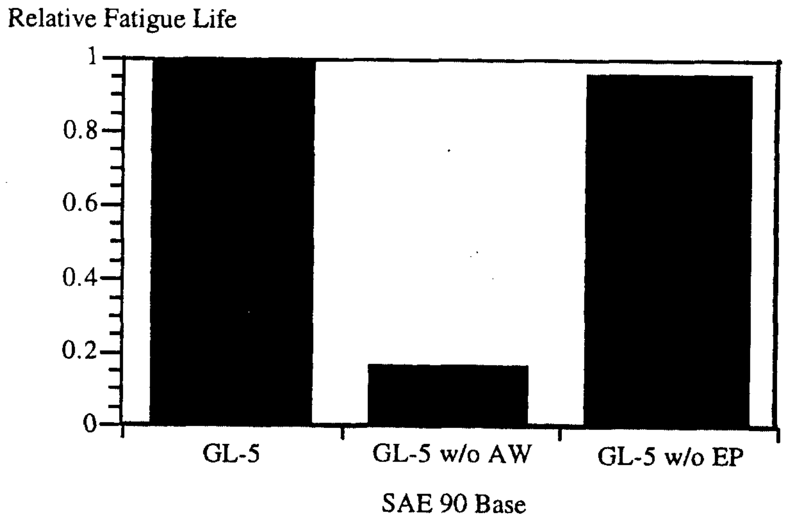
TEST PROCEDURES

- A Break-In Phase at a Relatively Light Load (Approx 1GPa)
- Test Temperature at 90°C
- Testing Conducted at Constant Load (1.5 to 1.9 GPa)
- Inspection of Test Gear Every 14 Hours.
- Failure Criteria:
  - More than 4% of Single Flank Surface Damage or
  - More than 1% Damage of Total Active Surface of Pinion

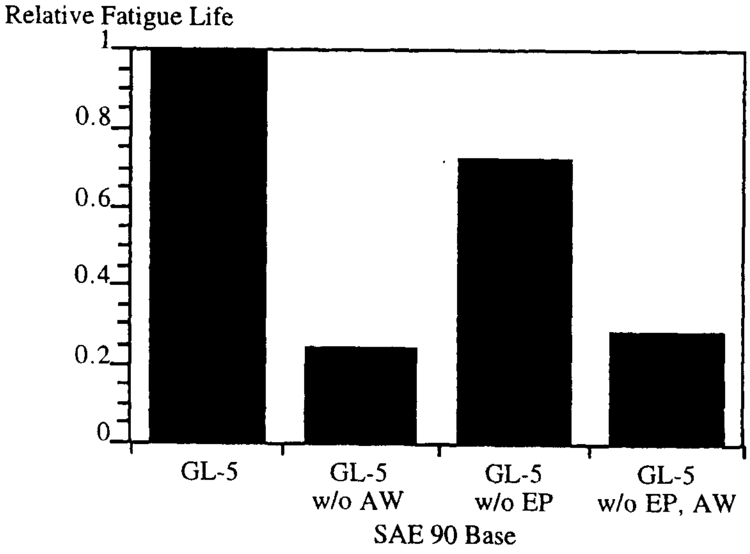
S-N CURVE OBTAINED FROM FZG GEAR TESTS (SAE 90)



FZG PITTING TESTS AT $P_H = 1.52$ GPa



FZG PITTING TESTS AT $P_H = 1.86$ GPa



CHARACTERIZATION

- Initial
  - Photographic Record of Each Gear Tooth
  - Select and Remove Representative Teeth for Analysis
- Surface Morphology
  - Optical Microscopy
  - Scanning Electron Microscopy (SEM)
- Chemical Analysis
  - Scanning Auger Microprobe (SAM)
  - X-ray Photoelectron Spectroscopy (XPS)

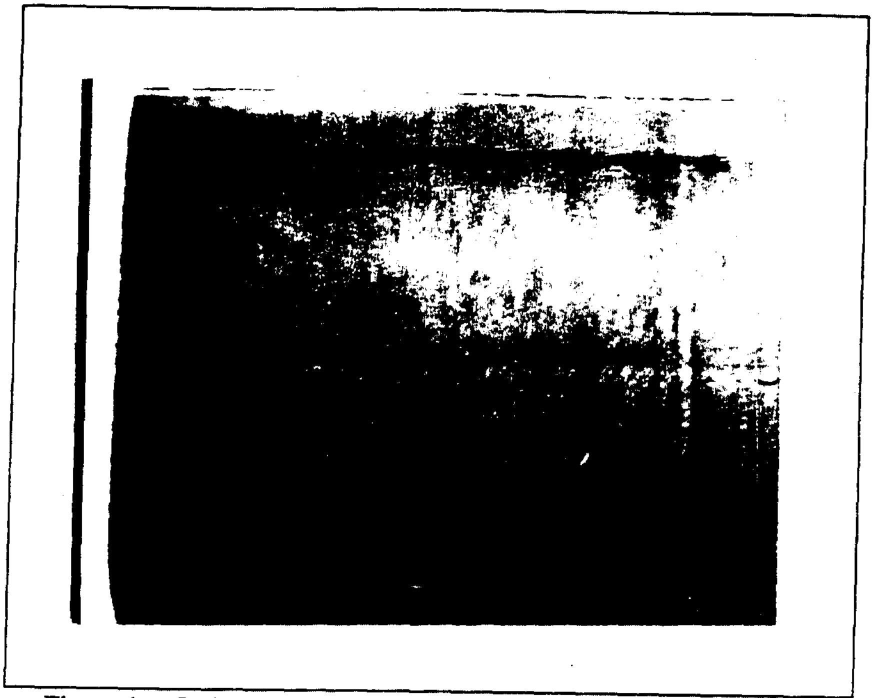


Figure 1a. Optical Micrograph (10x) of Gear Tooth Tested with Fluid 1.

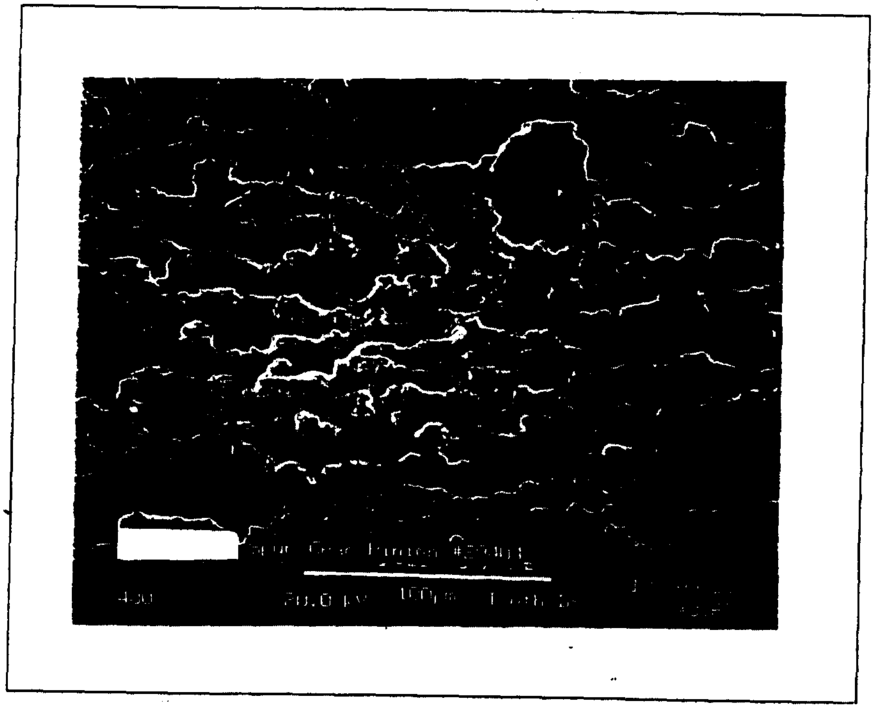


Figure 1b. SEM Micrograph of Gear Tooth Tested with Fluid 1.

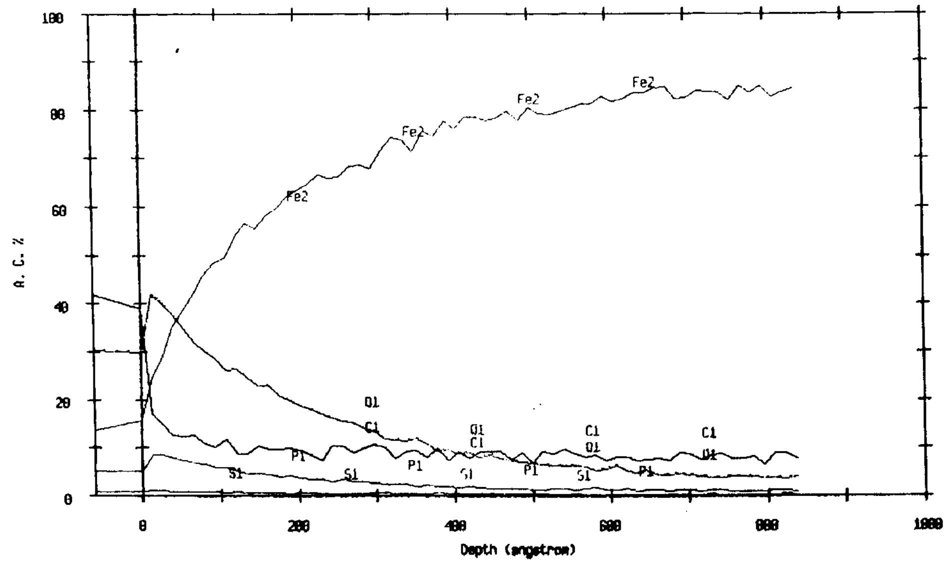


Figure 2a. SAM Depth Profile from Gear Tooth Tested with Fluid 1.

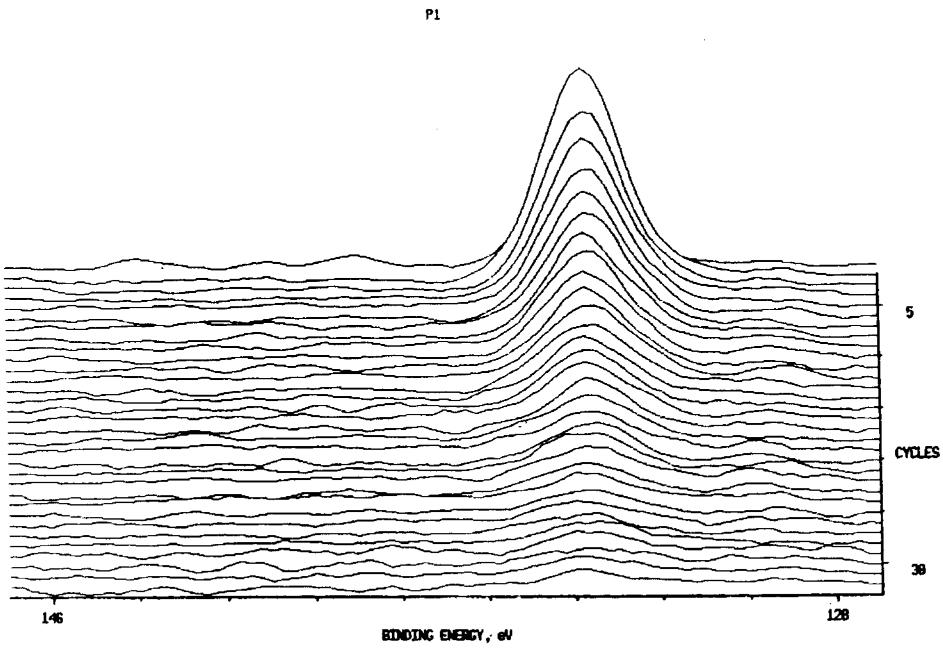


Figure 2b. XPS Spectra of P 2p Peak as a Function of Depth from Gear Tooth Tested with Fluid 1.

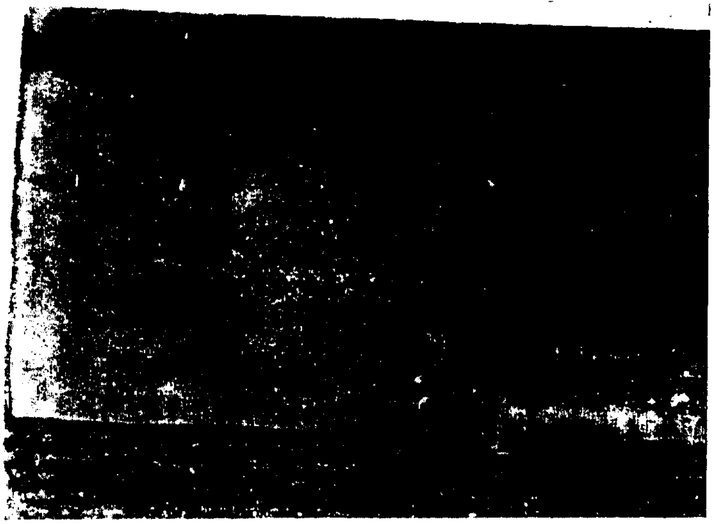


Figure 3a. Optical Micrograph (10x) of Gear Tooth Tested with Fluid 2.

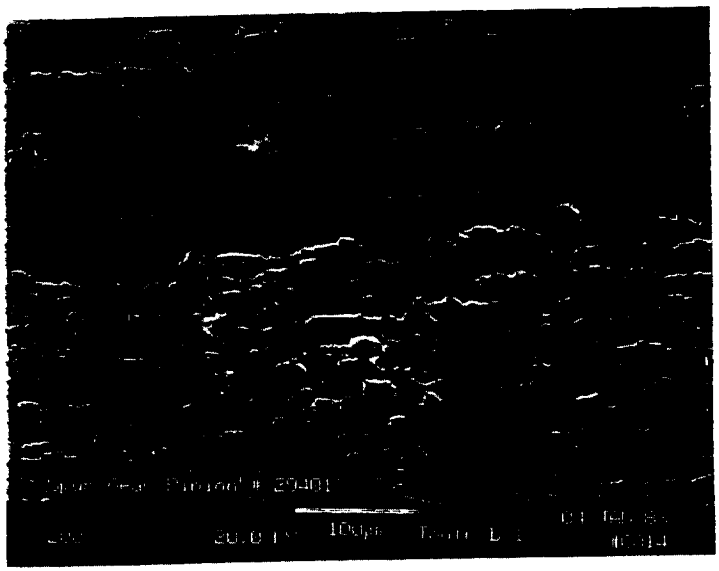


Figure 3b. SEM Micrograph of Gear Tooth Tested with Fluid 2.

Figure 5a. Optical Micrograph (10x) of Gear Tooth Tested with Fluid 3.

Figure 5b. SEM Micrograph of Gear Tooth Tested with Fluid 3.

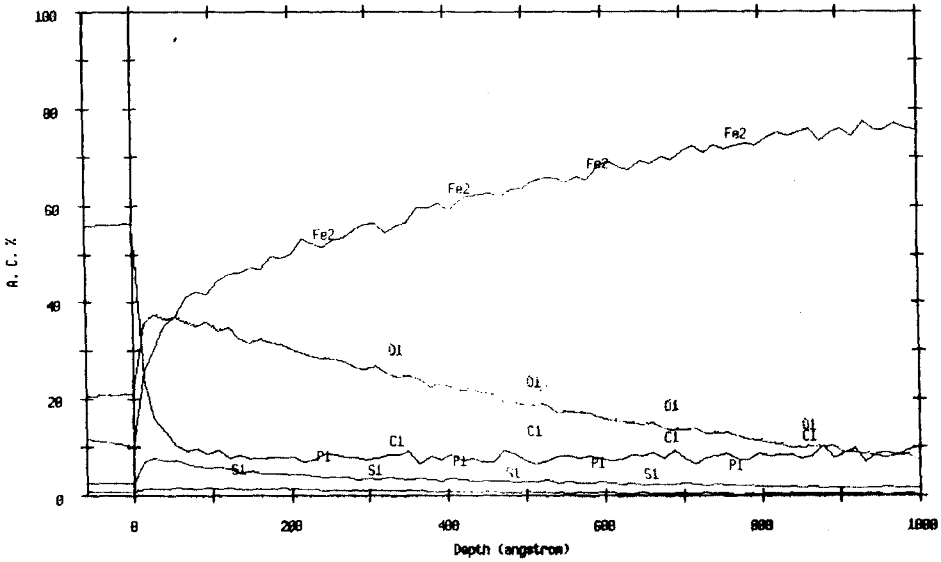


Figure 4. SAM Depth Profile from Gear Tooth Tested with Fluid 2.

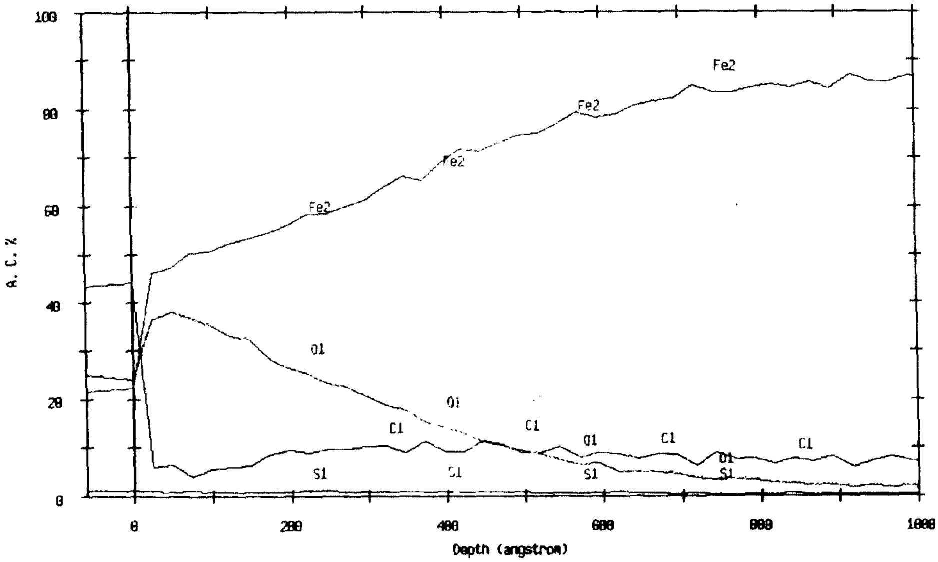


Figure 6. SAM Depth Profile from Gear Tooth Tested with Fluid 3.

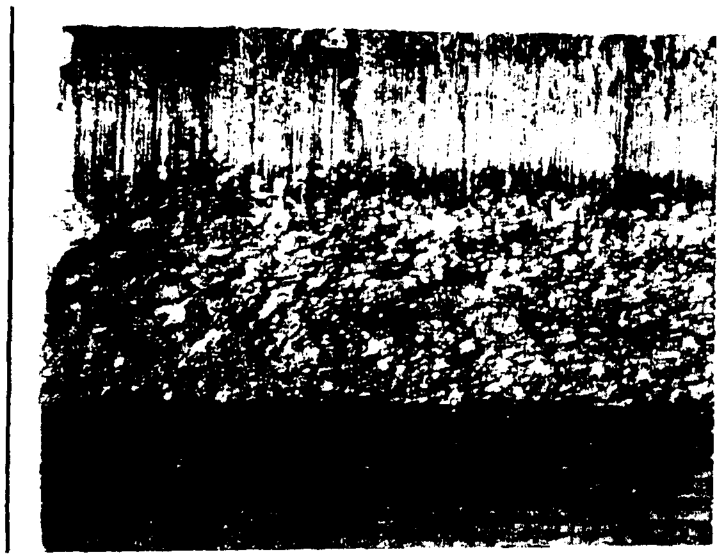


Figure 7a. Optical Micrograph (10x) of Gear Tooth Tested with Fluid 4.

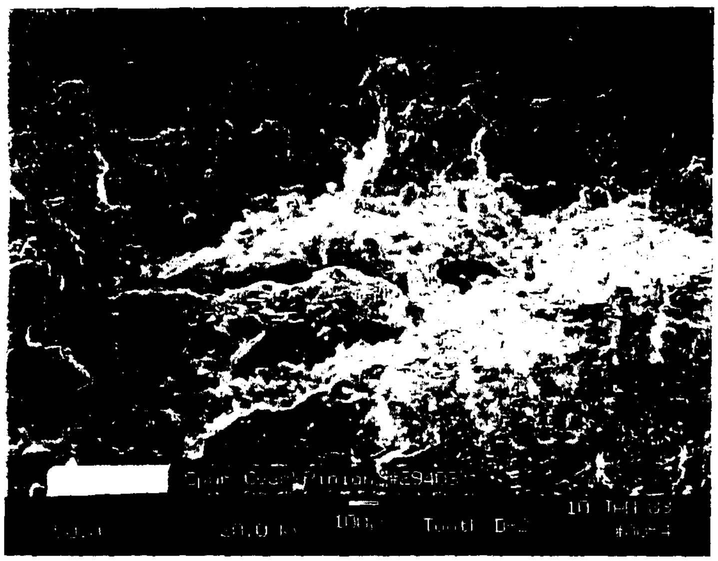


Figure 7b. SEM Micrograph of Gear Tooth Tested with Fluid 4.

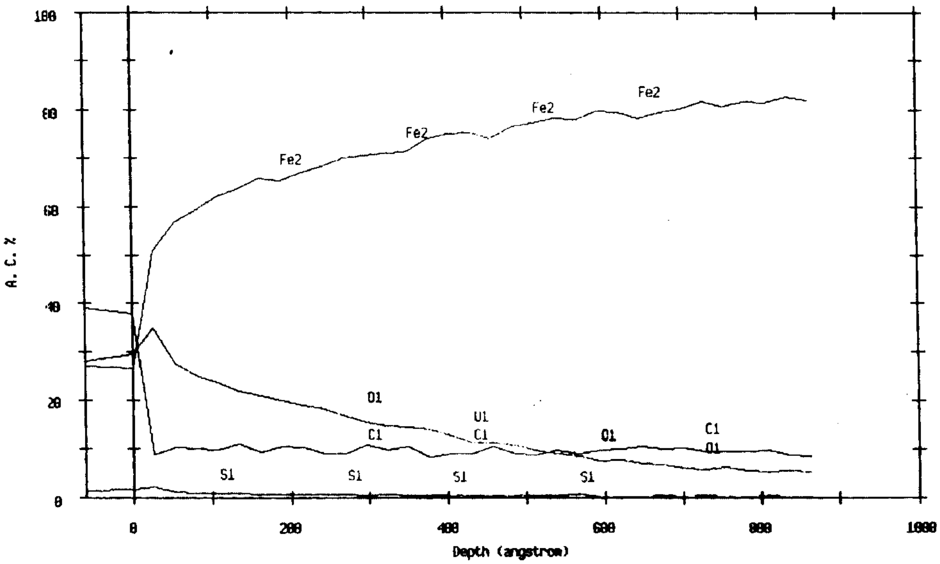


Figure 8. SAM Depth Profile from Gear Tooth Tested with Fluid 4.

SUMMARY

- Phosphate/Phosphite-Oxide Layer Key to Long Fatigue Life
- Micropitting is Dominant Fatigue Mode at High Loads for Fluids Containing an AW Component in Presence or Absence of an EP Component
- Spalling is the Dominant Fatigue Mode in the Absence of an AW Component

CONCLUSIONS

- Results from Tests at P_H = 1.52 GPa
  - Removal of EP Additive --> Slight Decrease in Fatigue Life
  - Removal of AW Additive --> Significant Decrease in Fatigue Life
- Results from Tests at P_H = 1.86 GPa
  - Removal of EP Additive --> 27% Decrease in Fatigue Life
  - Removal of AW Additive --> Significant Decrease in Fatigue Life

Film Forming Tendencies Of Some Base Fluids And Viscosity Modifiers

SYNTHETIC BASE FLUIDS

- The Demand For Extended Drain Interval Of Lubricants

  → Increased Usage Of Synthetic Base Fluids Due To Better Thermal And Oxidational Properties

- The Synthetic Base Fluids Respond Differently Than Mineral Base Oils To A Combination Of High Shear Rates

  → Leads To A Difference In Minimum Film Thickness

- The Change In Minimum Film Thickness Due To The Use Of Synthetic Base Fluids Affects The Performance Of Gear Oils Such As Surface Fatigue (Spalling), Wear, Operating Temperatures, And Fuel Efficiency

THE SPECIFIC FILM THICKNESS (λ RATIO)

- λ Ratio Is The Central Film Thickness Divided By The Composite Surface Roughness Of Two Contacting Surfaces
- The λ Ratio Is Critical To Predict The Performance Of Lubricants
- $\lambda > 2$: No Negligible Solid-Solid Contact
- $\lambda < 0.5$: Considerable Solid-Solid Contact

  → Cause Premature Failure Of The Machine Elements

Film Forming Tendencies of Gear Oils

➢ There are three key parameters which affect the film forming tendencies of gear oils:

- pressure-viscosity coefficients

- shear stability

- traction coefficients

Film Forming Tendencies of Gear Oils

➢ There are three key parameters which affect the film forming tendencies of gear oils:

- pressure-viscosity coefficients

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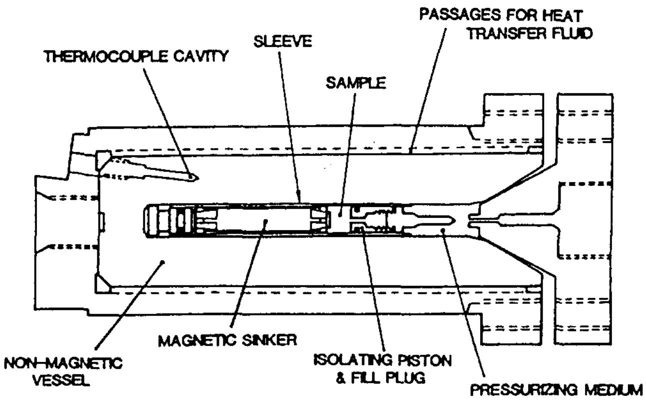
Pressure-Viscosity Coefficient Measurement

- Use a Falling-Body viscometer
- Assume Newtonian behavior
- Use Dowson-Hamrock equation

Falling-Body Viscometer



Dowson-Hamrock Equation

- Central Film Thickness: h

$h = k\ U^{0.67}\eta^{0.67}\alpha^{0.53}$

U: mean rolling speed

η : dynamic viscosity of the lubricant

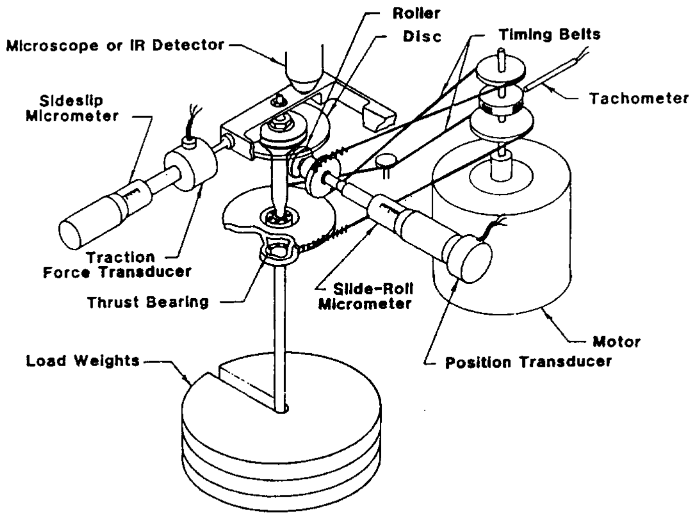
α : pressure-viscosity coefficient

k : constant (as a function of load, geometry, ..)

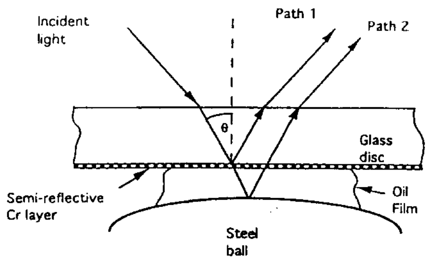
Optical EHD Simulator

- Use interferometry
- High shear rate (> 10^6/sec)
- Measure number of fringe changes to obtain film thickness

Optical EHD Simulator



Principle Of Optical Interferometry



Constructive interference:

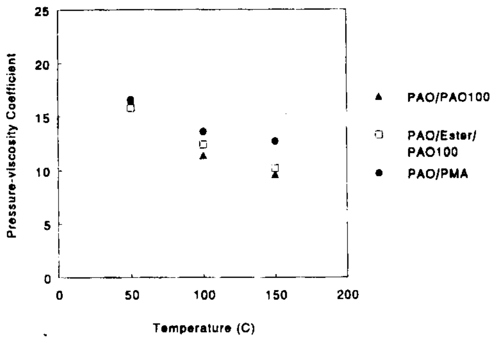
$$h_{oil} = \frac{(N - \phi)\lambda}{2n\cos\theta} \quad N=1,2,3...$$

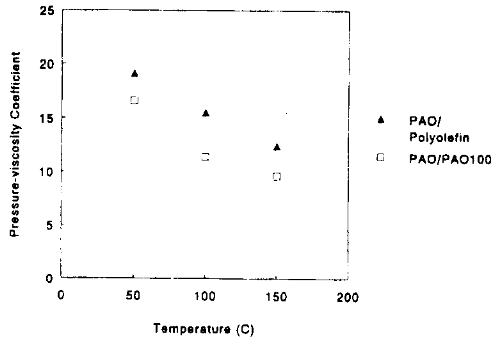
Destructive interference:

$$h_{oil} = \frac{(N + \frac{1}{2} - \phi)\lambda}{2n\cos\theta} \quad N=0,1,2...$$

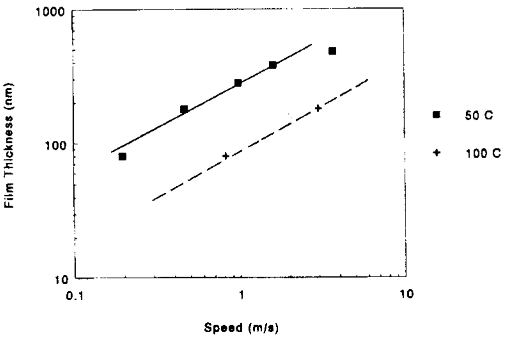
A LIST OF OILS ANALYZED

- PAO4/PAO100 + GL-5 Additive
- PAO4/Ester/PAO100 + GL-5 Additive
- PAO4/PMA + GL-5 Additive
- PAO4/Proprietary Polyolefin + GL-5 Additive

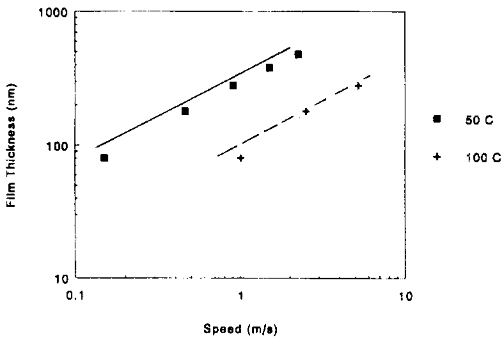




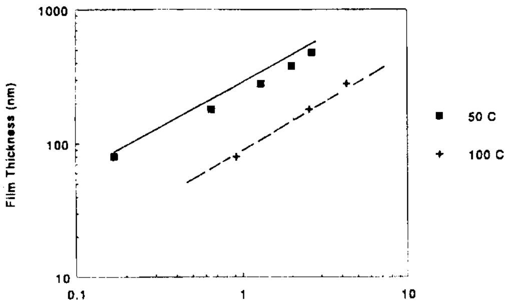
PAO4/PAO100

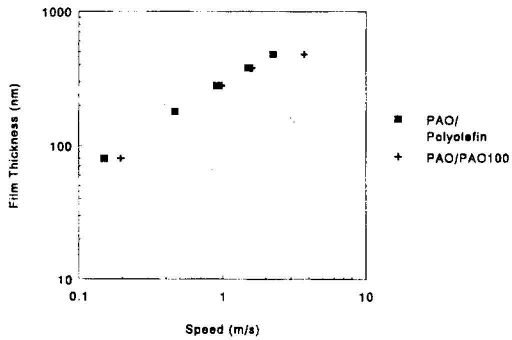


PAO4/Polyolefin

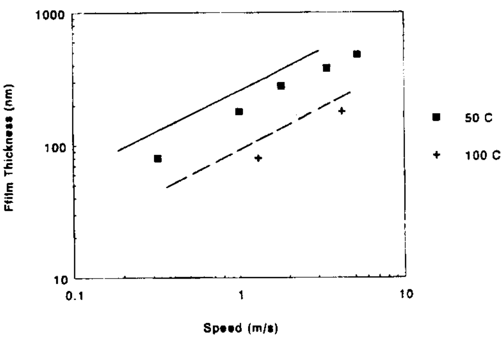


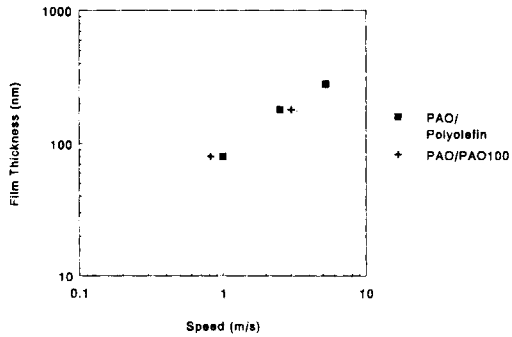
PAO4/Ester/PAO100





PAO4/PMA





CONCLUSIONS

1. The PAO 4 Oil Containing An Inexpensive Proprietary Polyolefin Provided A Similar Film Thickness Compared To The PAO Oil Containing An Expensive PAO 100

2. Better Understanding Of High Pressure Rheological Properties Make It Possible To Develop A Fluid With Optimum Performance And Low Cost

4. *Summary*

SUMMARY

A Development Of Next Generation Gear Oils Is Very Complicated. Balancing Component Durability And Other Requirements (Fuel Economy, Etc.) Are Critical For A Successful Development Of The Next Generation Gear Oils.