Polyalkylene Glycol (PAG) Based Lubricant for Light- & Medium-Duty Axles

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June 7, 2017

Project ID # FT023

Presentation Outline

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II. Relevance and Scope
III. Milestones
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V. Project Progression
VI. Technical Accomplishments and Progress
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OVERVIEW- HIGH LEVEL LOGISTICAL DETAILS OF PROJECT

TIMELINE

PROJECT START DATE:	**10/1/2013**
PROJECT END DATE:	**9/30/2017**
PERCENT COMPLETE:	**75%**

BARRIERS ADDRESSED

- ❑ IMPROVED FUEL ECONOMY
- ❑ USE OF NON-PETROLEUM BASED LUBRICANTS (ENERGY INDEPENDENCE)
- ❑ NO-HARM ON EMISSIONS

PARTNERS

PROJECT LEAD: **FORD MOTOR COMPANY**

COLLABORATORS: **DOW CHEMICAL** (NOT ACCEPTING DOE FUND)

ARGONNE NATIONAL LABORATORY (ANL)

BUDGET

TOTAL PROJECT FUNDING **$700,000**

- DOE SHARE **$350,000**
- CONTRACTOR SHARE **$350,000**

EXPENDITURE OF GOVT. FUNDS

- FY13: **$473**
- FY14: **$13,321**
- FY15: **$22,324**
- FY16: **$7,229**

(ANL FUNDING NOT INCLUDED)

Relevance and Scope

- **Project Objective**
  - Develop novel lubricant formulations that are expected to improve the fuel efficiency of light, medium, heavy-duty, and military vehicles by at least 2% over SAE 75W-140 axle lubricants without adverse impacts on vehicle performance or durability.
- **Objectives for this presentation**
  - Polyalkylene glycol formulation iterative development
  - Friction and wear data on laboratory bench tests
  - Polyalkylene glycol performance in axle testing
- **Relevance to Vehicle Technology Office Objectives**
  - Reduce petroleum consumption by improving fuel economy
  - Reduce energy dependence by using non-petroleum based lubricants
- **Impact**
  - Reduce fuel consumption (Save 0.13 billion gallons of petroleum fuel per year[1,2])
  - New lubricant technology has no negative impact on durability and emissions

1 http://www.nada.org/NR/rdonlyres/C1C58F5A-BE0E-4E1A-9B56 1C3025B5B452/0/NADADATA2012Final.pdf
2 http://www.epa.gov/fueleconomy/fetrends/1975-2012/420s13001.pdf

Milestones – Project budget timing and expectations

Milestone Description	Type	Status
Budget Period 1		
Define initial PAG lubricant formulations	Technical	Completed
Define additive components	Technical	Iterative
Select lubricants showing friction and wear characteristics (on preliminary bench friction & wear tests) equal to or better than 75W-140 lubricant	Go / No-Go	Iterative
Budget Period 2		
Demonstrate formation of durable antiwear film	Technical	Iterative
Demonstrate thermal performance of formulations	Technical	Completed
Select lubricants showing friction and wear characteristics equal to or better than 75W-140 lubricant	Go / No-Go	Completed
Budget Period 3		
Demonstrate 2% improvement in vehicle level fuel economy	Technical	Pending
Demonstrate durability in system (axle) level test	Technical	In Progress
Axle efficiency showing improvement over 75W140 lubricant	Technical	In Progress

Project Approach and Strategy

1. **Bench Test Screening:** PAG Initial and iterative formulation development

   - ❑ **TOST**
   - ❑ **4 Ball-wear**
   - ❑ **Falex-EP**
   - ❑ **Ball on Disc**
   - ❑ **Rust Prevention**
   - ❑ **Copper Corrosion**

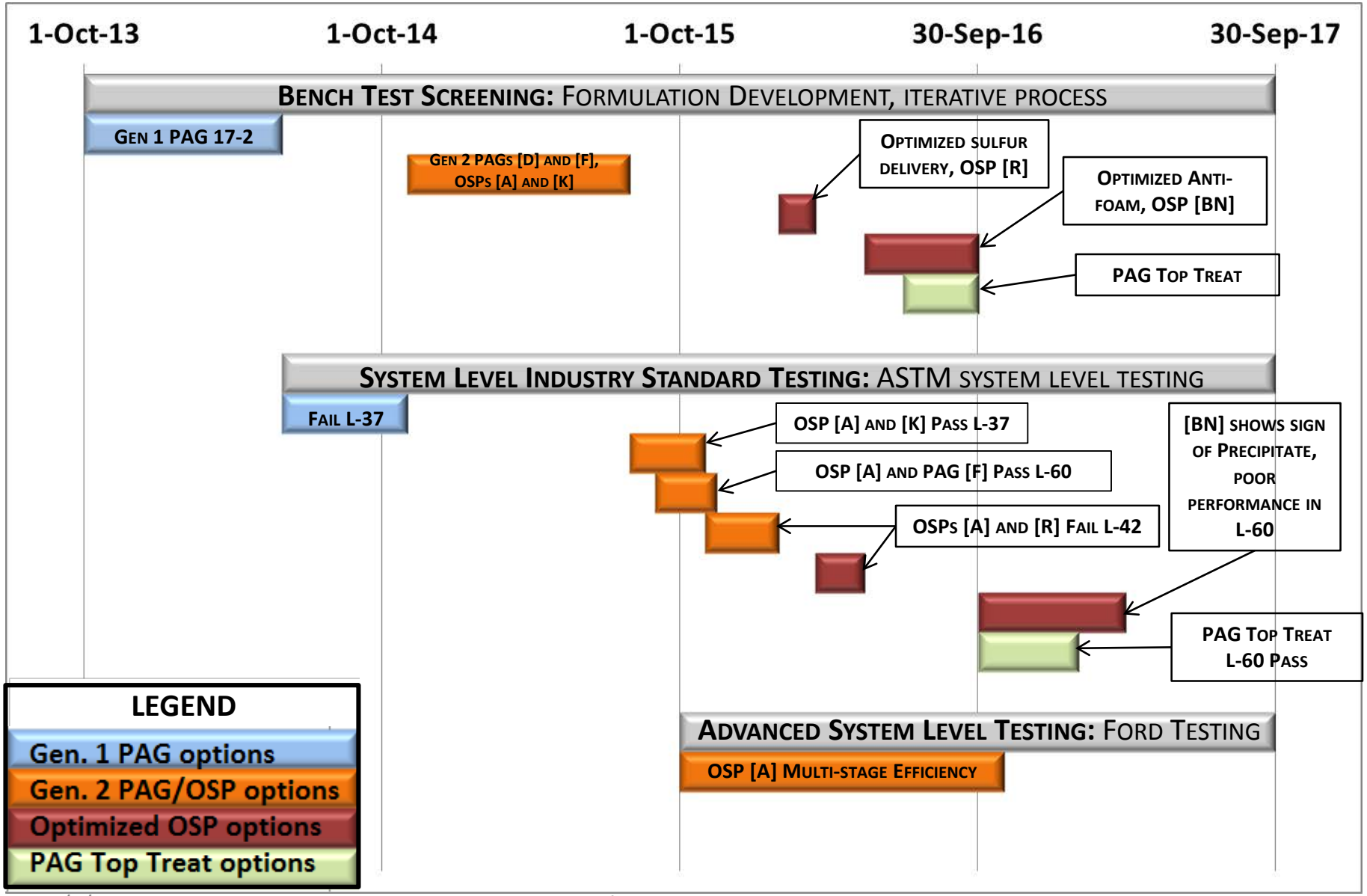
2. **System Level Industry Standard Testing**: PAG testing in ASTM standardized axle tests

   - ❑ Load Carrying Capacity under Low Speed and High Torque (**L-37/ASTM D6121**)
   - ❑ Thermal and Oxidative Stability (**L-60/ASTM D5704**)
   - ❑ Load Carrying Capacity under High Speed and Shock Loading **(L-42/ASTM D7452**)
   - ❑ Moisture Corrosion resistance (**L-33-1/ ASTM D7038**)

3. **Advanced System Level Test:** Ford Specific Axle testing, efficiency and fuel economy test

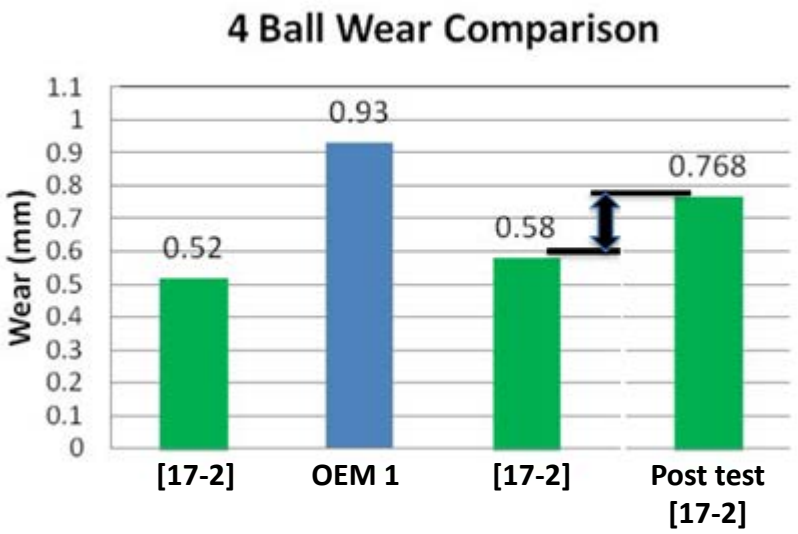
   - ❑ **Ford 44 Hour Hypoid Gear Wear**
   - ❑ **Ford Multi-Stage Axle Efficiency**
   - ❑ **Ford Chassis Roll for Fuel Economy and Vehicle Efficiency**

PROJECT PROGRESSION – ACCOMPLISHMENT ALIGNMENT WITHIN STRATEGY

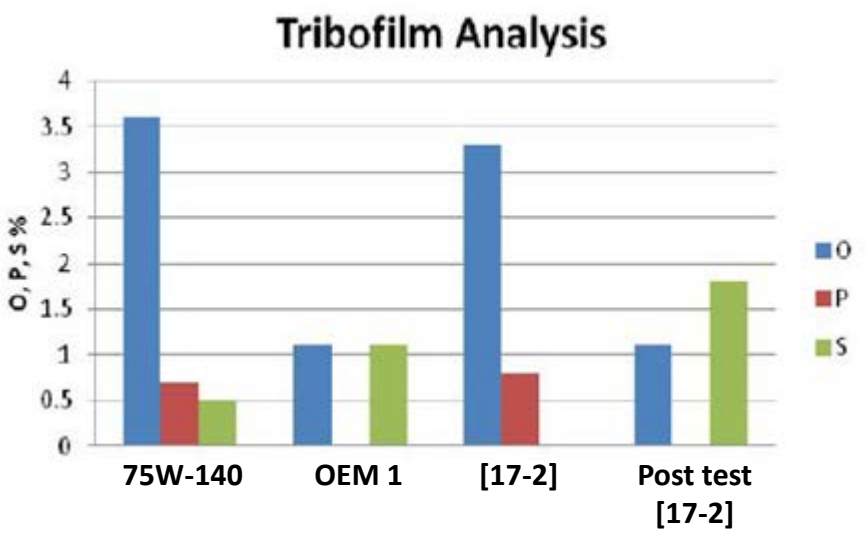


Technical Accomplishments and Progress

Lesson Learned from Gen I [17-2] formulation deficiencies



The **[17-2]** formulation was tested with 4 ball wear after completing MTM testing and **showed higher wear compared to virgin fluid.**

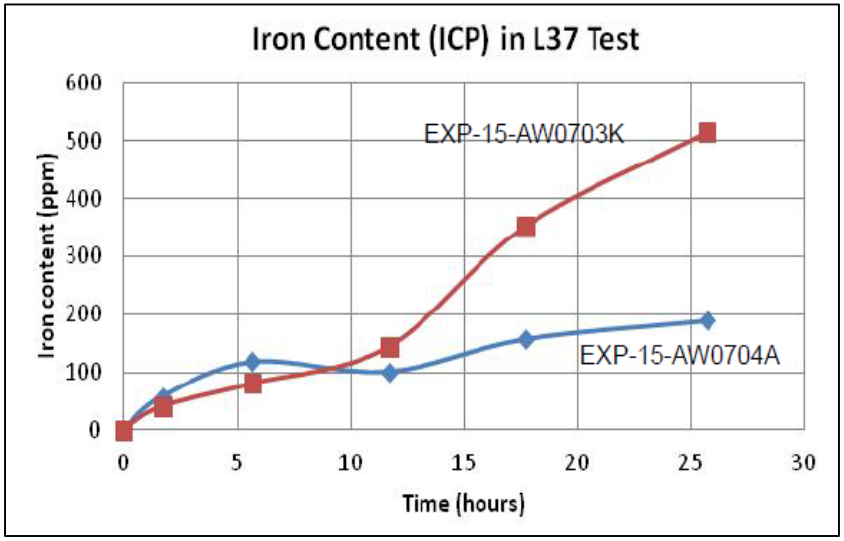


Tribofilm analysis shows that **higher sulfur content** and **the absence of phosphorous** in the tribofilm directly correlates to increased observed wear in the 4 ball wear test. The failing L-37 performance of **[17-2]** can be attributed to this observed Phosphorous depletion.

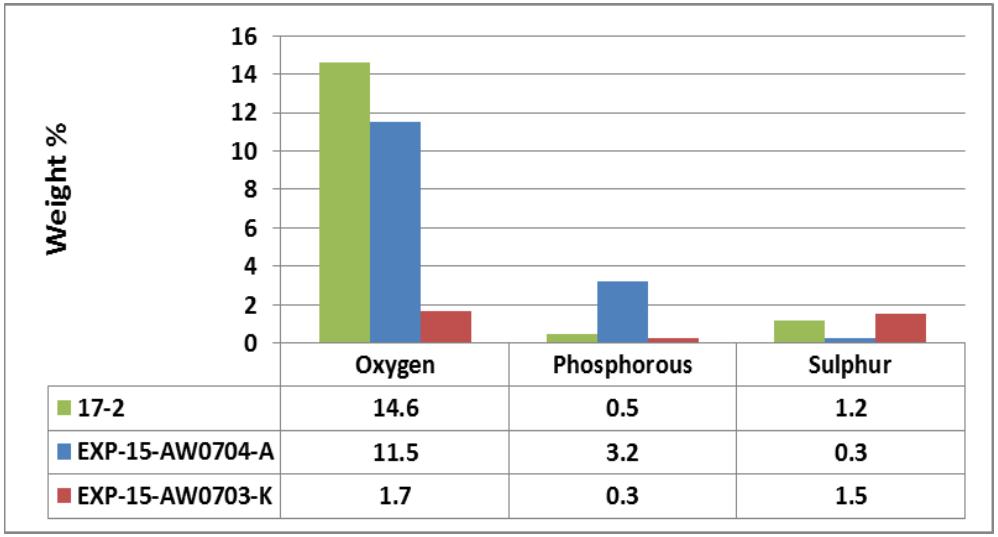
Technical Accomplishments and Progress

OSP Formulation [A] and [K] Pass System Level Testing, L-37

OSP PAG AW0704-A			
Gear Condition	**Ring Rating**	**Pinion Rating**	**Minimum Required**
Wear	**8**	**7**	**5**
Rippling	**10**	**9**	**8**
Ridging	**9**	**9**	**8**
Pitting/Spalling	**9.9**	**9.9**	**9.3**
Scoring	**10**	**10**	**10**



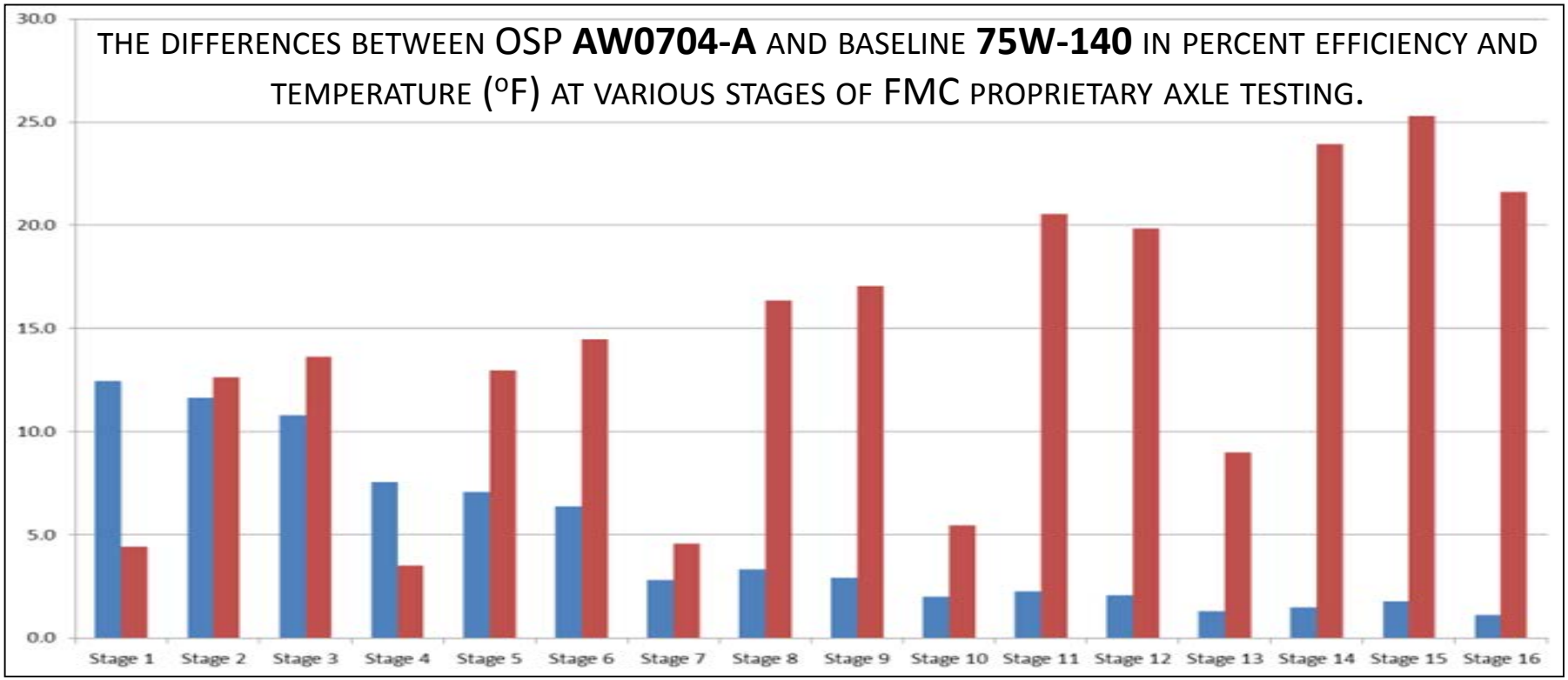
Post L-37 test ICP shows AW0704-A objectively has lower wear indicating metals in suspension



Post L-37 test SEM/EDS shows AW0704-A objectively delivered more Phosphorous to the gear surface for better wear protection

Technical Accomplishments and Progress

OSP [A] Formulation Axle Efficiency



- The bars in blue are representative of the percent efficiency of AW0704-A minus the percent efficiency of 75W-140 at each respective stage.
- The bars in red are representative of the axle temperature of 75W-140 minus the axle temperature of AW0704-A at each respective stage.

Technical Accomplishments and Progress

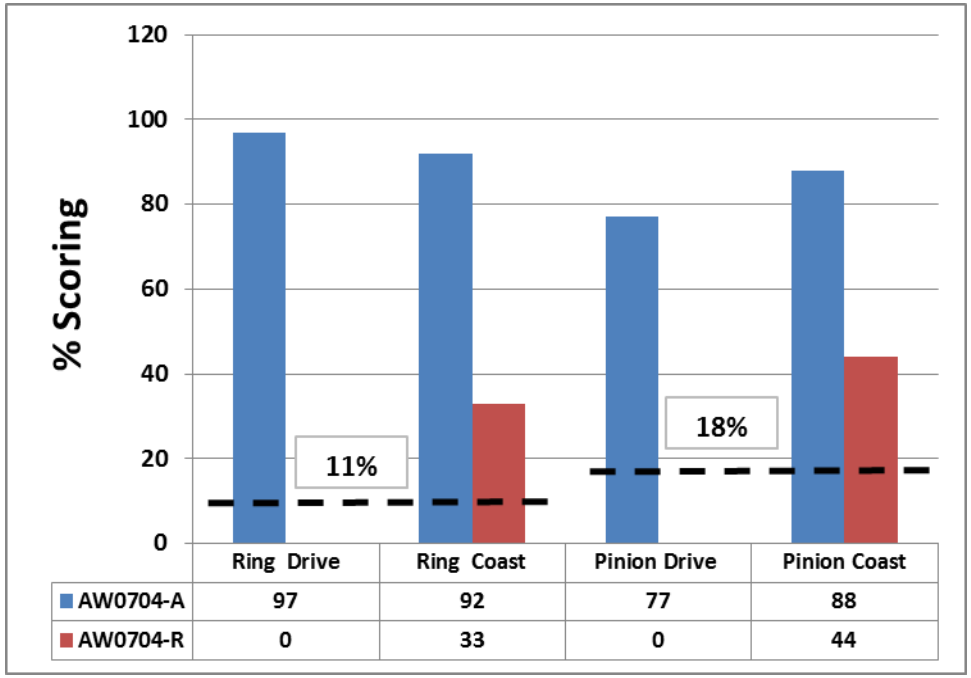
OSP Formulation [A] Fails System Level Testing, L-42

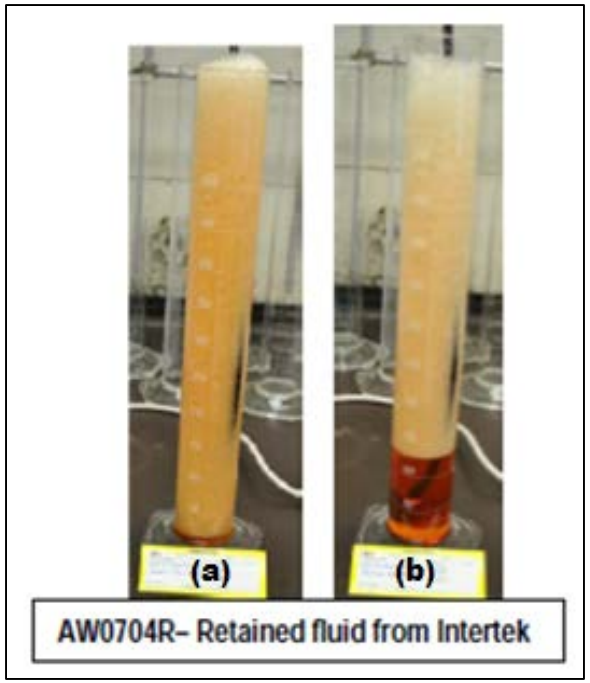
- AW0704-A exhibited significant scoring on both drive and coast side of the ring and pinion gears – **Test failed**

Key Note: Technicians at Intertek reported that there was noticeable foaming of AW0704-A when the axle was opened for gear rating inspection

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

OSP FORMULATION SULFUR DELIVERY AND ANTIFOAM OPTIMIZATION



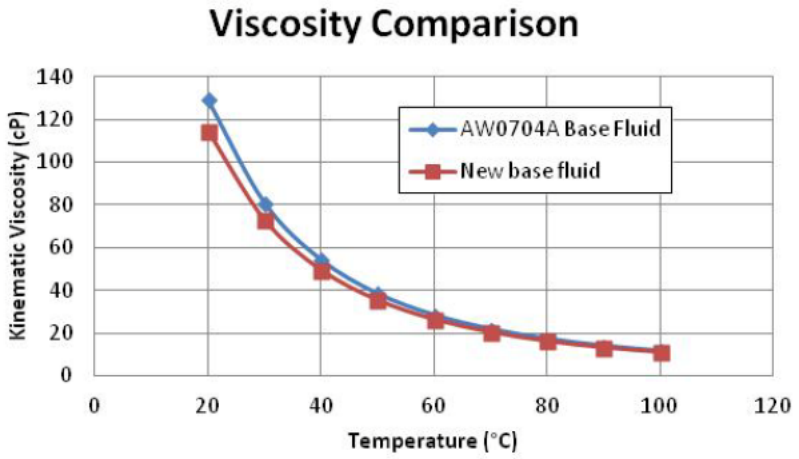


KEY NOTE: FOAMING WAS OBSERVED AGAIN DURING THE **AW0704-R** L-42 RETEST.

		Foam Tendency, Static Foam, mL		
ASTM D892 / D6082	**Temp, °C**	**AW0704-A**	**AW0704-R**	**AW0704-BN**
Sequence I	24.0	**545**	**530**	50
Sequence II	93.5	**310**	**630**	65
Sequence III	24.0	**545**	**530**	40
Sequence IV	150.0	**640**	**>950**	60

Technical Accomplishments and Progress

Base Fluid Change Required for Safety and Toxicology Requirements



AW0704 VI = 217
New base fluid = VI 225

50hour 162°C TOST Test

Fluids	Delta TAN	% change in viscosity
AW0704A base fluid	2.1	17
New base fluid	1.1	11

The base fluid for **AW0704-A** and **AW0704-R** does not meet Ford Toxicology standards for health and safety. New Base Oil used for **AW0704-BN.**

Alternative base fluid showing comparative properties selected as replacement. The key difference is molecular weight of the polymer chains.

Technical Accomplishments and Progress

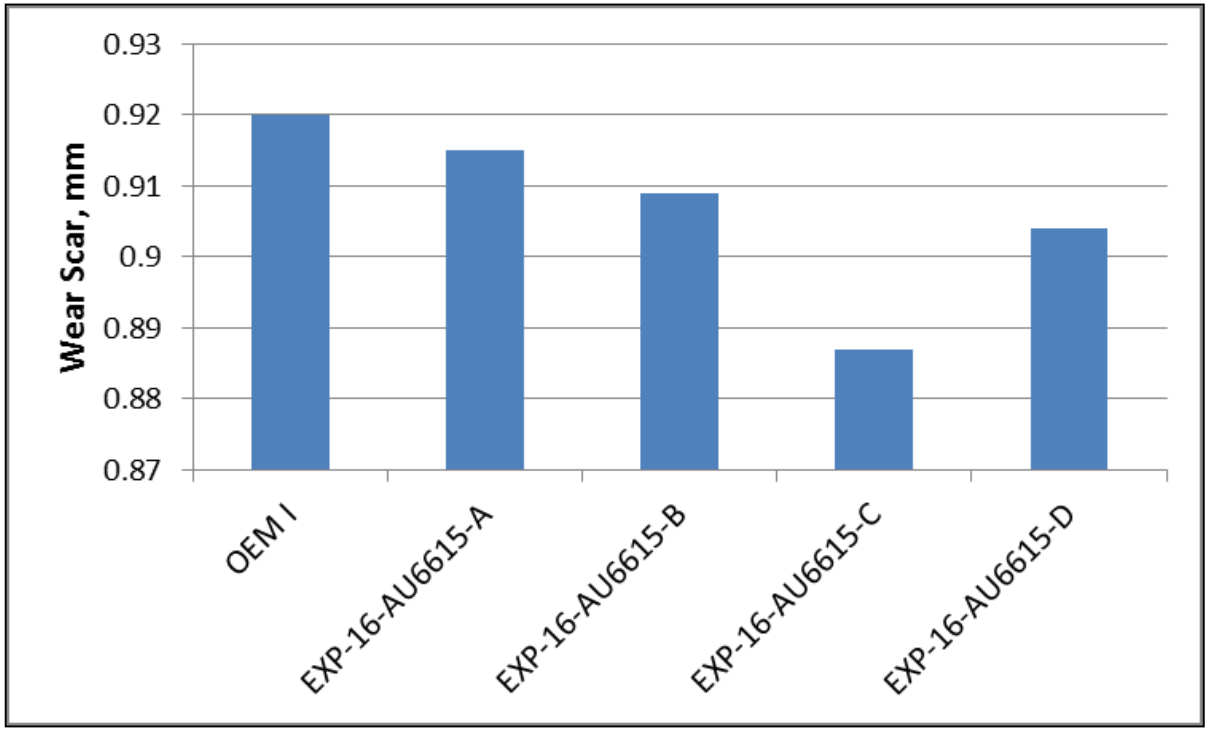
Evidence of Precipitate in OSP Formulation [BN]

- Cloudiness shows **evidence of precipitate**
- **No noticeable correlation** with the presence or absence of other specific additives.
- **Suspected salt formation** involving active sulfur and/or phosphate ester additives.

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

APPROX. 30% OSP ADDITION TO GEAR OIL

COMPARATIVE WEAR SCAR DATE FOR OSP TREATED GEAR OIL OPTIONS IN 4-BALL WEAR TEST, CONDITIONS AT 40 KG LOAD, 2 HRS, 600 RPM AND 100 ^{O}C



OPTION **AU6615-C** HAS BEEN SELECTED TO CONTINUE WITH BENCH TESTING AND AXLE LEVEL EVALUATIONS

Collaboration and Coordination with Other Institutions

Collaborators	Responsibilities and Contribution
Ford Motor Co. Project Lead	▪ Project approach and direction ▪ Proprietary axle and vehicle testing
Dow Chemical Collaborator *(not accepting DOE funding)*	▪ PAG oil formulations development ▪ Viscometric characterizations, bench screening ▪ Hardware surface analytics
Argonne National Lab Subcontractor	▪ Laboratory bench tests for friction and wear evaluation ▪ Tribology expertise and analytics for understanding tribofilm and friction reduction mechanism
Intertek Hired Service	▪ Conducted L-37 and L-42 testing
Southwest Research Institute Hired Service	▪ Conducted L-60 testing

Remaining Challenges and Barriers

- Solve precipitate issue with **[BN]** formulation; improve formulation to pass L-42
- Demonstrate moisture corrosion resistance on L-33-1 testing
- Demonstrate wear, efficiency, and fuel economy improvement on Ford specific axle and vehicle testing
- Lack of participation of any additive company
- Environmental and Toxicology requirements for safety
- Availability of test resources: L-42 throttle controller issues

Proposed Future Work

Remaining FY17

- Explore optimization of PAG formulation
- Assess [and re-assess] performances of PAG option and Top Treat option in:
  - L-33-1 test (Moisture Corrosion Resistance)
  - L-42 test (Shock Loading)
  - Ford axle wear and efficiency and vehicle fuel economy testing
- Continue to build understanding of friction reduction mechanism

Any proposed future work is subject to change based on funding levels

Summary Slide

- **Achievement to scope of project**
  - ☑ PAG formulations have consistently exhibited performance improvements compared to baseline gear oils in bench friction and wear testing
  - ☑ PAG Formulation **[A]** passed **L-37 load carrying capacity testing**: major improvement to Gen I PAG performance
  - ☑ PAG Formulation **[A]** passed **L-60 thermal oxidative stability testing**
  - ☑ PAG Formulation **[A]** exhibited improved temperature profile and efficiency in **Ford multi-stage axle efficiency**
  - ❑ Positive friction and wear results for top treat option present another option for incorporating PAG technologies

- **Shortcomings of PAG formulations**
  - ☒ Multiple PAG formulations failed **L-42 shock loading testing**
  - ☒ Balancing of additive packages for specific performance attributes proving to be bottleneck for project, as shown in **[BN]** precipitate
  - ❑ Necessary to validate derivative formulations in previously completed system level standard testing
  - ❑ Have yet to complete **L-33-1 moisture corrosion resistance testing** with a PAG
  - ❑ Have yet to evaluate performance of PAG in **Ford axle wear and vehicle efficiency and fuel economy testing**

Technical Back-up Slides

1] Gen 2 PAG and OSP Formulation Development

2] OSP L-37 Performance Data

3] L-60 Performance Data

4] Sulfur Delivery Optimization – Extreme Pressure Improvement

5] Top Treat Bench Friction and Wear Data

Technical Accomplishments and Progress

Gen 2 and OSP Formulation Development

Formulation	TOST Viscosity Increase (%)	TOST TAN Change (Δ)	4 Ball Wear (mm)	Falex EP (lb)	4 Ball EP (kg)	Ball on Disc Ball Wear (mm)	Ball on Disc Disc Wear (mm)	ANL Ball on Disc Wear Volume (mm^3)	Rust Prevention	Copper Corrosion
OEM 1	20	1.75	0.92	2505	340	0.63	0.54	5.9E-13	PASS	1B
75W-140	20	1.5	0.42	2807	420	0.44	0.41	2.3E-14	PASS	2A
17-2 [58-1]	4.7	0.4	0.58	3609	400	0.48	0.47	1.14E-12	PASS	1B
AW0703-K	8.6	0.87	0.44	3623	320	0.32	0.3	2.81E-14	PASS	1B
AW0704-A	3.9	1.26	0.36	2885	**280**	0.32	0.31	5.34E-14	PASS	1B
AW0705-D	11.5	0.7	0.42	4000	**260**	0.39	0.28	7.28E-14	PASS	1B
AW0705-F	14.7	1	0.41	2926	**280**	0.38	0.34	1.57E-14	PASS	1B

GEN II PAG formulations: generated from chemistry changes and additive pack adjustments to 17-2 formulation, difference between options are AD-PACK differences

OSP (oil soluble PAGs) option explored, differences between formulations are the same AD-PACK differences in GEN II PAGs.

Technical Accomplishments and Progress

OSP Formulation L-37 Performance

OSP PAG AW0703-K			
Gear Condition	**Ring Rating**	**Pinion Rating**	**Minimum Required**
Wear	**7**	**6**	**5**
Rippling	**10**	**8**	**8**
Ridging	**8**	**8**	**8**
Pitting/Spalling	**9.9**	**9.9**	**9.3**
Scoring	**10**	**10**	**10**

OSP PAG AW0704-A			
Gear Condition	**Ring Rating**	**Pinion Rating**	**Minimum Required**
Wear	**8**	**7**	**5**
Rippling	**10**	**9**	**8**
Ridging	**9**	**9**	**8**
Pitting/Spalling	**9.9**	**9.9**	**9.3**
Scoring	**10**	**10**	**10**

Technical Accomplishments and Progress

L-60 Performance Data

*The **L-60 test (ASTM D5704)** shows the oil-thickening, insolubles formation, and deposit formation of manual trans/final drive axle lubricants to high temp oxidizing conditions*

- After passing the L-37 durability testing formulations **AW0704-A**, **AW0704-F**, **AW0704-BN**, and AU6615-E were submitted for L-60 testing

	Viscosity				Pentane Insolubles, % wt.	Toluene Insolubles, % wt.	Avg. Carbon/ Varnish (merits)	Avg. Sludge (merits)
	Initial	After 50 hr	Change	% Change				
AW0704-A	11.36	11.58	0.22	2	4.69	0	9.5	9.5
AW0705-F	10.16	10.86	0.7	7	2.2	0.2	9.8	9.5
AW0704-BN	10.92	11.04	0.12	1	15.7	0.7	7.0	9.5
AU6615-E	11.09	14.67	3.58	21	0.1	0.2	9.9	9.5

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

OSP FORMULATION [A] SULFUR DELIVERY OPTIMIZATION, L-42

	Formulation Number	Wear Tests			EP Tests		TOST Results		Rust Prevention	Copper Corrosion
		4 Ball wear (mm)	B.O.D. Disc wear (mm)	B.O.D. Ball Wear (mm)	Falex EP (lb)	4 Ball EP (kg)	Δ TAN	Viscosity Increase, %		
Baseline	75W-140	0.42	0.44	0.41	**2807 3041**	**420**	1.50	20.0	PASS	2A
OSP	AW0704-A	0.36 0.42	0.32	0.31	**2885**	**315**	1.26	3.9	PASS	1B
	AW0704-R	0.49	0.36	0.22	**>4500**	**400**	1.8	4.5	PASS	1B
	AW0704-W	0.38	0.35	0.22	**4172**	**315**	1.3	5.4	PASS	1B

- BENCH SCREENING SHOWED THAT **AW0704-R** WAS THE STRONGEST CANDIDATE, AND IN L-42 RE-TEST, IT SHOWED IMPROVED RESULTS TO **AW0704-A** BUT STILL DID NOT PASS

TECHNICAL ACCOMPLISHMENTS AND PROGRESS

TOP TREAT BENCH FRICTION AND WEAR DATA