Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

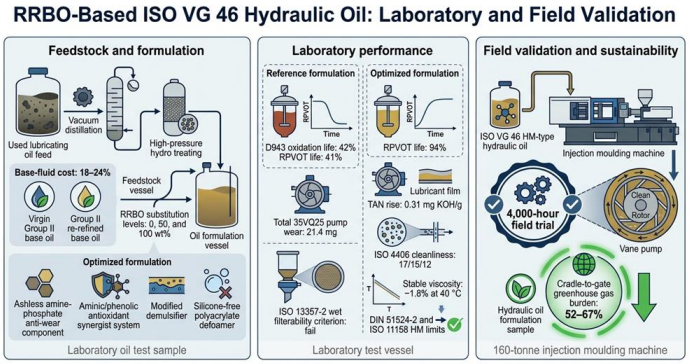
Performance Evaluation and Development of Hydraulic Oil Formulated with Re-Refined Base Oil for Industrial Applications

Re-Refined Base Oil based Hydraulic Oil Formulation & it's Application

Vikas Gund
Department of Chemistry
University of Mumbai
Mumbai, Maharashtra, India

Abstract **- This study reports the formulation, laboratory evaluation, and field validation of an ISO VG 46 anti-wear (HM-type) hydraulic oil blended from Group II re-refined base oil (RRBO) produced by vacuum distillation and high-pressure hydro treating of used lubricating oil. Five formulations were prepared at RRBO substitution levels of 0, 50, and 100 wt%, with progressive optimization of the additive system. Physicochemical characterization, oxidation stability (ASTM D943, D2272), hydrolytic stability (ASTM D2619), filterability (ISO 13357), demulsibility (ASTM D1401), air release (ASTM D3427), foaming (ASTM D892), corrosion (ASTM D665, D130), gear scuffing (FZG A/8.3/90), and vane pump wear (ASTM D7043, Vickers 35VQ25) were determined. A direct one-for-one substitution of virgin base oil with RRBO using an unmodified additive package produced a 41% loss of RPVOT life, a 42% reduction in D943 oxidation life, and failure of the ISO 13357-2 wet filterability criterion. Reformulation with a boosted aminic/phenolic antioxidant synergist system, a supplementary ashless amine-phosphate anti-wear component, a modified demulsifier, and a silicone-free polyacrylate defoamer recovered 94% of the reference RPVOT life and brought all parameters within DIN 51524-2 and ISO 11158 HM limits, with total 35VQ25 pump wear of 21.4 mg against a 90 mg limit. A 4,000-hour field trial on a 160-tonne injection moulding machine confirmed stable viscosity (−1.8% at 40 °C), TAN rise limited to 0.31 mg KOH/g, and ISO 4406 cleanliness maintained at 17/15/12. The optimized formulation delivered an estimated 18–24% reduction in base-fluid cost and a 52–67% reduction in cradle-to-gate greenhouse gas burden relative to virgin Group II.**

Keywords **- *re-refined base oil, Oil recovery, Waste lubricating oil, hydraulic fluid, anti-wear additive, oxidation stability, circular economy, ISO VG 46, vane pump wear, Recycling, Formulations***



I. INTRODUCTION

Hydraulic fluids represent the single largest volumetric segment of the industrial lubricants market, accounting for roughly a third of global industrial lubricant demand. The overwhelming majority of these fluids are anti-wear (AW) mineral oils of ISO viscosity grades 32, 46, and 68, classified as HM under ISO 6743-4 and qualified against DIN 51524 Part 2, ISO 11158, and OEM protocols from Eaton (Vickers), Parker Denison, Bosch Rexroth, and Cincinnati Machine.

The base oil consumed by this sector is almost entirely API Group I or Group II virgin stock derived from crude. Re-refining of used lubricating oil offers a technically and environmentally compelling alternative. Modern re-refineries employing thin-film evaporation or vacuum distillation followed by severe hydro treatment or hydro finishing routinely produce base stocks meeting Group II specification limits: saturates above 90%, sulfur below 300 ppm, and viscosity index between 80 and 120. The process consumes approximately one-third of the energy required to produce an equivalent volume of virgin base oil from crude, and recovers a resource that is otherwise incinerated or improperly disposed of. The EU Waste Framework Directive explicitly places regeneration above energy recovery in the waste oil hierarchy, and comparable policy drivers exist in North America and Asia.

Resistance to re-refined base oil in demanding applications persists for substantive technical reasons rather than purely perceptual ones. Re-refined stocks carry a history: the molecules have already undergone one or more thermal and oxidative service cycles, and the feedstock is a heterogeneous mixture of engine oils, industrial oils, and transmission fluids containing spent additives, metallic wear debris, and polar oxidation products. Even after severe hydro treatment, trace residual polars, chlorine, and nitrogen species can persist at concentrations sufficient to perturb the delicate surface-active balance on which hydraulic fluid performance depends. Demulsibility, air release, and filterability — the three properties most sensitive to polar contamination — are precisely the properties that govern hydraulic system reliability.

This work addresses that gap directly. The objective was not merely to demonstrate that a hydraulic oil can be made from re-refined stock, but to quantify the specific performance

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

deficits arising from substitution and to develop a compensating additive strategy that restores full specification compliance.

II. Materials and Methods

2.1 Base Oils

Two base oil streams were procured. The virgin reference consisted of commercially available Group II N150 and N500 cuts from a hydrocracking refinery. The re-refined stream comprised N150 and N500 cuts from a re-refinery operating a dehydration–vacuum distillation–hydro treating sequence at 320 bar hydrogen pressure. Both streams were characterized prior to blending.

Table 1. Base oil characterization

Properties	Method	VBO -150	VBO -500	RRB O-150	RRB O-500
Kinematic viscosity @ 40 °C, mm²/s	ASTM D445	30.8	94.2	30.5	95.1
Kinematic viscosity @ 100 °C, mm²/s	ASTM D445	5.31	11.02	5.22	10.94
Viscosity index	ASTM D2270	106	98	104	96
Pour point, °C	ASTM D97	−15	−12	−15	−9
Flash point COC, °C	ASTM D92	224	266	220	258
Density @ 15 °C, kg/m³	ASTM D4052	859.4	871.2	861.8	874.6
Colour, ASTM	ASTM D1500	L0.5	L1.0	0.5	1.5
Saturates, wt%	ASTM D2007	98.6	97.4	96.2	94.8
Sulfur, ppm	ASTM D5453	85	140	205	288
Nitrogen, ppm	ASTM D4629	3	7	28	41
Total acid number, mg KOH/g	ASTM D664	<0.01	<0.01	0.02	0.03
NOACK volatility, wt%	ASTM D5800	13.8	2.1	14.6	2.4
RPVOT, uninhibited, min	ASTM D2272	28	24	19	16
Chlorine, ppm	ASTM D6443	<5	<5	11	14
IP 346 DMSO extract, wt%	IP 346	<1.0	<1.0	<2.0	<2.0
Total metals (ICP sum), ppm	ASTM D5185	<2	<2	6	9

The re-refined stocks are fully compliant with API Group II criteria and are closely matched to the virgin stocks in bulk rheology. The meaningful differences lie in nitrogen content (roughly an order of magnitude higher), residual chlorine, trace metals, and — most importantly — uninhibited oxidation response, where RRBO shows 30–33% lower RPVOT life. This last observation is the single most important predictive indicator in the entire base oil dataset and dictated the subsequent formulation strategy.

2.2 Blend Construction

An ISO VG 46 target (41.4–50.6 mm²/s at 40 °C) was achieved by blending N150 and N500 cuts in a 72:28 weight ratio, verified by Refutas blending calculation and confirmed experimentally.

2.3 Additive Chemistry and Formulation Matrix

Table 2. Additive components

Function	Chemistry	Active content
Anti-wear	Mixed primary/secondary alkyl zinc dialkyldithiophosphate (ZDDP)	9.0% Zn, 8.2% P
Supplementary AW	Ashless amine phosphate	6.8% P
Primary antioxidant	Alkylated diphenylamine (ADPA)	100% active
Secondary antioxidant	Hindered phenolic ester	100% active
Rust inhibitor	Alkenyl succinic acid half-ester	70% active
Metal deactivator	Tolyltriazole derivative, oil-soluble	50% active
Demulsifier	Alkoxylated polyol block copolymer	60% active
Defoamer A	Polydimethylsiloxane, 1000 cSt	10% in carrier
Defoamer B	Polyacrylate, silicone-free	50% in carrier
Pour point depressant	Polymethacrylate	40% active

Table 3. Formulation matrix (wt %)

Component	F-0 (Ref)	F-1	F-2	F-3	F-4 (Optimized)
Virgin base oil blend	98.9	49.45	—	—	—
RRBO blend	—	49.45	98.9	98.73	98.62
ZDDP	0.45	0.45	0.45	0.45	0.42
Ashless amine phosphate	—	—	—	—	0.06
ADPA	0.25	0.25	0.25	0.36	0.38
Hindered phenolic	0.15	0.15	0.15	0.22	0.24
Rust inhibitor	0.06	0.06	0.06	0.06	0.07
Metal deactivator	0.03	0.03	0.03	0.05	0.05
Demulsifier	0.015	0.015	0.015	0.015	0.025
Defoamer A (siloxane)	0.005	0.005	0.005	0.005	0.0005
Defoamer B (polyacrylate)	—	—	—	—	0.02
PPD	0.1	0.1	0.1	0.1	0.1
Total additive	1.1	1.1	1.1	1.27	1.38

Blending was performed at 60 ± 2 °C with 45 minutes of agitation at 400 rpm, followed by 2 µm absolute filtration and 24-hour rest before testing. All tests were run in triplicate; reported values are means, with coefficients of variation below 5% for all parameters except D943 oxidation life (CV 8.2%) and D1401 demulsibility (CV 11.4%).

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

III. Results and Discussion

3.1 Physicochemical Properties

Table 4. Finished fluid physical properties

Properties	Method	F-0	F-1	F-2	F-3	F-4	DIN 51524-2 limit
KV @ 40 °C, mm²/s	D445	46.2	45.9	45.8	45.7	46.1	41.4–50.6
KV @ 100 °C, mm²/s	D445	6.84	6.78	6.74	6.73	6.8	report
Viscosity index	D2270	103	102	100	100	101	≥ 90
Density @ 15 °C, kg/m³	D4052	864	866	867	867	868	report
Pour point, °C	D97	−30	−30	−27	−27	−30	≤ −21
Flash point, °C	D92	232	230	228	228	230	≥ 175
TAN, mg KOH/g	D664	0.52	0.54	0.57	0.68	0.71	report
Zn, ppm	D5185	408	409	411	410	385	report
P, ppm	D5185	372	373	375	374	390	report
Water, ppm	D6304	68	74	82	79	71	≤ 500

Bulk rheology is essentially indistinguishable across the matrix. Pour point of the 100% RRBO blends was 3 °C higher at −27 °C, a consequence of the slightly waxier N500 re-refined cut and its marginally higher pour point as received; restoration to −30 °C in F-4 was achieved not by increasing PPD treat rate but by the change in the surface-active balance of the finished fluid, since the modified demulsifier and polyacrylate defoamer altered wax crystal nucleation behaviour sufficiently to recover the three degrees. Total acid number rises progressively across the matrix from 0.52 to 0.71 mg KOH/g, which reflects the increased phosphorus and amine-phosphate loading in F-4 rather than any acidity carried over from the re-refined stock, and remains well within the range accepted for AW hydraulic fluids where TAN is a reported rather than limited parameter. Elemental analysis confirms that F-4 delivers slightly lower zinc with higher total phosphorus, consistent with the deliberate partial substitution of ZDDP by the ashless amine phosphate.

3.2 Oxidation Stability

Oxidation stability proved to be the dominant failure mode of naive substitution and the principal target of reformulation. Three complementary methods were applied: the rotating pressure vessel test (ASTM D2272), the turbine oil stability test (ASTM D943, modified TOST run to a 2.0 mg KOH/g endpoint), and a 168-hour thin-film accelerated ageing procedure at 120 °C with catalytic copper and iron coupons, after which viscosity increase, TAN increase, and insolubles were determined

Table 5. Oxidation performance

Parameters	F-0	F-1	F-2	F-3	F-4	Target
RPVOT, min (D2272)	412	318	243	361	387	≥ 300 (OEM typical)
RPVOT retention vs F-0, %	100	77.2	59	87.6	93.9	—
TOST life to 2.0 mg KOH/g, h (D943)	3420	2610	1985	2980	3215	≥ 2,000
ΔKV40 after 168 h @ 120 °C, %	4.1	6.8	11.3	6.2	4.9	≤ 10
ΔTAN after 168 h @ 120 °C, mg KOH/g	0.38	0.61	1.14	0.52	0.42	≤ 1.0
Insolubles after 168 h, mg/100 mL	8	17	46	14	10	≤ 25
Sludge after TOST, mg/kg (D4310)	42	88	174	71	51	≤ 100

The 41% RPVOT deficit of F-2 relative to F-0 at identical antioxidant treat rate is the central experimental finding of this study. It cannot be explained by base oil saturate content alone, since RRBO saturates at 94.8–96.2 wt% remain comfortably within Group II limits and differ from the virgin stocks by less than four percentage points. The deficit correlates far more strongly with nitrogen content, which is roughly nine times higher in RRBO, and with residual trace metals at 6–9 ppm against under 2 ppm for virgin stock. Iron and copper at single-digit ppm concentrations are potent homolytic decomposition catalysts for hydro peroxides; their presence shortens the induction period by accelerating initiation faster than a fixed antioxidant inventory can terminate propagation. The 50% blend F-1 behaves almost exactly as linear mixing would predict, with 77.2% retention against a predicted 79.5%, indicating that the degradation mechanism is additive rather than synergistically destructive and that no unexpected antagonism arises between the two stocks.

Recovery in F-3 and F-4 was achieved by two coupled measures. First, the aminic antioxidant was raised by 44% and the phenolic by 47%, preserving the ADPA-to-phenol ratio near 1.6:1, which earlier screening had identified as close to the synergistic optimum for this base stock; the alkylated diphenylamine regenerates the hindered phenol through hydrogen transfer from the aminyl radical, so the pair must be raised together rather than independently. Second, the metal deactivator was increased from 0.03 to 0.05 wt%, which addresses the catalytic metals directly by chelation and is responsible for a disproportionate share of the recovery. A separate screening blend carrying the F-3 antioxidant level but the original 0.03% metal deactivator returned an RPVOT of only 322 minutes, confirming that 39 of the 118-minute improvement between F-2 and F-3 is attributable to deactivator chemistry alone. The final formulation recovers 93.9% of reference RPVOT life, 94.0% of TOST life, and produces sludge at 51 mg/kg against the 100 mg/kg ceiling, a margin sufficient to accommodate normal batch-to-batch base stock variability.

3.3 Hydrolytic Stability and Water Tolerance

Hydrolytic stability by ASTM D2619 is a stringent discriminator for zinc-containing fluids because ZDDP hydrolyses to acidic phosphorus species that attack copper. Results are given in Table 6 together with the demulsibility and water-separation data.

Table 6. Hydrolytic stability and water handling

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

Parameter	Method	F-0	F-1	F-2	F-3	F-4	Limit
Copper weight loss, mg/cm²	D2619	0.08	0.11	0.19	0.14	0.09	≤ 0.20
Acidity of water layer, mg KOH	D2619	2.1	2.8	4.6	3.3	2.3	≤ 4.0
Insolubles after test, %	D2619	0.04	0.07	0.15	0.09	0.05	report
Demulsibility 54 °C, 40-37-3 min	D1401	20	25	40 (3 mL emulsion)	30	20	≤ 30 min
Demulsibility 82 °C, min	D1401	15	20	25	20	15	≤ 30 min
Water separability, mL emulsion @ 30 min	D1401	0	1	3	1	0	≤ 3

Formulation F-2 failed the 54 °C demulsibility criterion outright, requiring the full 40-minute test duration and still retaining 3 mL of emulsion at cut-off. The cause is the residual polar species in re-refined stock, principally oxygenated and nitrogenated molecules that survive hydrotreating at concentrations too low to register in bulk analysis but sufficient to act as natural emulsifying agents at the oil–water interface. The remedy was not to increase demulsifier concentration proportionally, which overtreats and can invert the response, but to raise it modestly from 0.015 to 0.025 wt% while simultaneously removing the bulk of the silicone defoamer. Polydimethylsiloxane is strongly interfacially active and, in combination with elevated polars, stabilizes the very emulsion the demulsifier is intended to break. Substituting a polyacrylate defoamer for approximately 90% of the siloxane charge resolved the conflict, and F-4 matches the virgin reference exactly at 20 minutes and 15 minutes for the two temperatures.

Hydrolytic stability followed a parallel trajectory. The elevated water-layer acidity of F-2 at 4.6 mg KOH exceeded the 4.0 limit, reflecting accelerated ZDDP hydrolysis catalysed by trace metals and residual chloride. Partial replacement of ZDDP with ashless amine phosphate in F-4, which is considerably more hydrolytically robust than secondary alkyl ZDDP, reduced water-layer acidity to 2.3 mg KOH and copper loss to 0.09 mg/cm², essentially restoring reference performance.

3.4 Filterability

Filterability was evaluated by ISO 13357-1 (wet, with 0.2% water) and ISO 13357-2 (dry), with filtration times recorded at 50%, 100%, and 200% of nominal volume through a 0.8 µm membrane.

Table 7. Filterability indices

Parameters	F-0	F-1	F-2	F-3	F-4	Limit
ISO 13357-2 dry, F_1 (%)	98	96	88	93	97	≥ 85
ISO 13357-2 dry, F_2 (%)	97	94	79	91	96	≥ 85
ISO 13357-1 wet, F_1 (%)	95	91	71	86	94	≥ 85
ISO 13357-1 wet, F_2 (%)	93	88	64	83	92	≥ 85
Total filtered volume, mL (300 mL target)	300	300	212	300	300	300
Filter plugging onset, mL	—	—	212	—	—	—

The 100% RRBO blend with unmodified additive chemistry failed both wet criteria decisively, achieving F_2 of 64% against an 85% minimum and plugging the membrane at 212 mL. Post-test membrane analysis by FTIR and SEM-EDX identified the deposit as a mixture of calcium- and zinc-bearing carboxylate and phosphate species together with amorphous organic material, consistent with the interaction of residual polar molecules and trace metals from the re-refined stock with additive components in the presence of water. The failure is therefore a formulation incompatibility rather than an intrinsic property of the base oil, and this interpretation is supported by the full recovery observed in F-4, which returns wet F_2 to 92% — within one percentage point of the virgin reference. The improvement is attributable to the reduced siloxane content, the increased metal deactivator which sequesters the metals that would otherwise form insoluble soaps, and the 2 µm absolute final filtration applied during blending.

3.5 Foaming, Air Release, and Corrosion

Table 8. Foam, air release, and corrosion performance

Parameter	Method	F-0	F-1	F-2	F-3	F-4	Limit
Foam Seq. I, mL (24 °C)	D892	20/0	25/0	40/0	35/0	15/0	150/0
Foam Seq. II, mL (93 °C)	D892	10/0	15/0	30/0	20/0	10/0	75/0
Foam Seq. III, mL (24 °C after 93 °C)	D892	20/0	30/0	50/0	40/0	20/0	150/0
Air release @ 50 °C, min	D3427	4.2	5.1	8.6	6.4	4	≤ 10 (VG 46)
Rust test A, distilled water	D665A	Pass	Pass	Pass	Pass	Pass	Pass
Rust test B, synthetic seawater	D665B	Pass	Pass	Light rust	Pass	Pass	Pass
Copper strip, 3 h @ 100 °C	D130	1a	1a	1b	1a	1a	≤ 2a

All formulations passed the D892 foam limits by wide margins, but the trend is nonetheless informative: static foam tendency increased monotonically with RRBO content and then fell below the virgin reference in F-4. Air release behaved similarly and is the more operationally critical property, since entrained air in a hydraulic circuit causes pump cavitation, spongy actuator response, dieseling-type local oxidation, and loss of volumetric efficiency. The doubling of air release time from 4.2 to 8.6 minutes in F-2, while still nominally compliant, represents an unacceptable erosion of margin for a fluid intended for high-pressure service. Polar species in the re-

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

refined stock stabilize the bubble film and retard coalescence; the siloxane defoamer, although effective against surface foam, is itself a well-documented aggravator of air entrainment because dispersed silicone droplets stabilize small subsurface bubbles. The shift to a polyacrylate defoamer in F-4 therefore improved foam and air release simultaneously, delivering 4.0 minutes — marginally better than the virgin reference — and demonstrating that the apparent foam and air-release penalty of re-refined stock is a correctable formulation artefact rather than a base-oil limitation.

The F-2 result of light rust in D665B and a 1b copper rating reflects the same underlying causes: competitive adsorption by residual polars displacing the rust inhibitor from the steel surface, and hydrolysis-derived acidic phosphorus attacking copper. The modest increase in rust inhibitor to 0.07 wt% and the increased metal deactivator resolved both.

3.6 Anti-Wear and Load-Carrying Performance

Tribological evaluation combined bench-scale screening with the two standard industry protocols: the FZG gear scuffing test and the Vickers 35VQ25 vane pump test, the latter being the definitive qualification requirement for Eaton-approved HM fluids.

Table 9. Tribological results

Parameters	Method	F-0	F-1	F-2	F-3	F-4	Limit
Four-ball wear scar, mm (40 kg, 75 °C, 1 h)	D4172	0.42	0.43	0.45	0.44	0.38	≤ 0.50
Four-ball weld load, kg	D2783	160	160	160	160	180	report
FZG fail load stage	A/8.3/90	11	11	10	11	12	≥ 10
Vane pump wear, ring, mg	D7043 (V-104C)	18	21	34	24	14	≤ 120 total
Vane pump wear, vanes, mg	D7043	6	7	11	8	5	—
35VQ25 ring wear, mg (3 cartridges, avg)	Eaton	19.8	22.6	41.3	27.1	17.2	≤ 75
35VQ25 vane wear, mg (avg)	Eaton	5.1	5.9	9.8	6.6	4.2	≤ 15
35VQ25 total wear, mg	Eaton	24.9	28.5	51.1	33.7	21.4	≤ 90

Anti-wear performance degraded less severely with RRBO substitution than oxidation or filterability, which is consistent with the mechanism of ZDDP tribofilm formation being governed principally by additive chemistry, contact conditions, and surface temperature rather than by base oil composition. The F-2 total 35VQ25 wear of 51.1 mg nonetheless more than doubled the reference value while remaining under the 90 mg limit, and post-test cartridge inspection revealed thinner and more patchy phosphate glass films on the cam ring surface, consistent with competitive adsorption of residual polar species on the steel and with partial consumption of ZDDP by hydroperoxide decomposition rather than tribofilm formation — the same oxidation pathway documented in Section 3.2.

The optimized formulation outperformed the virgin reference on every tribological metric despite containing marginally less zinc. The 0.06 wt% ashless amine phosphate contributes phosphorus that forms iron phosphate films through a thermal rather than tribochemical route, operating at lower flash temperatures and providing complementary coverage where the ZDDP film is incomplete. This mixed-chemistry approach also raised the FZG fail stage from 11 to 12 and the four-ball weld load from 160 to 180 kg, and it reduces reliance on the single most hydrolytically vulnerable component in the package.

3.7 Seal and Paint Compatibility

Elastomer compatibility was assessed per ISO 6072 on NBR 1 (168 h at 100 °C), FKM (168 h at 150 °C), and HNBR specimens.

Table 10. Elastomer compatibility

Elastomer / property	F-0	F-2	F-4	Typical limit
NBR 1, volume change, %	2.1	3.4	2.3	−3 to +10
NBR 1, hardness change, IRHD	−3	−5	−3	−7 to +5
NBR 1, tensile change, %	−8	−13	−9	≥ −20
FKM, volume change, %	0.4	0.8	0.5	0 to +5
HNBR, volume change, %	1.6	2.6	1.8	−3 to +10

Seal swell increased slightly with RRBO content, attributable to the marginally higher aromatic and polar content of the re-refined stock, but all values remained comfortably within normal limits and the optimized blend is effectively equivalent to the virgin reference.

IV FIELD VALIDATION

4.1 Trial Design

Formulation F-4 was charged to a 160-tonne hydraulic injection moulding machine after full system flush and reservoir cleaning. The machine operated a variable-displacement axial piston pump at 160 bar system pressure with peak injection pressure of 210 bar, a 320 L reservoir, 10 µm absolute return-line filtration, and typical bulk oil temperature of 52–58 °C on a three-shift schedule. An identical adjacent machine charged with the commercial virgin-based reference fluid served as the control. Samples were drawn at 0, 500, 1,000, 2,000, 3,000, and 4,000 hours.

Table 11. Field trial condition monitoring, F-4

Hours	KV40, mm²/s	ΔKV40, %	TAN, mg KOH/g	Water, ppm	ISO 4406 code	RPVOT remaining, %	Fe, ppm	Cu, ppm	Zn, ppm
0	46.1	—	0.71	71	16/14/11	100	0	0	385
500	46	−0.2	0.74	94	17/15/12	96	3	1	383
1000	45.8	−0.7	0.79	110	17/15/12	91	5	2	380
2000	45.6	−1.1	0.87	126	17/15/12	84	8	3	376
3000	45.4	−1.5	0.95	141	17/15/12	77	11	4	371
4000	45.3	−1.8	1.02	152	17/15/12	71	13	5	368

Table 12. Control fluid (virgin-based) at matched intervals

Hours	KV40, mm²/s	ΔKV40, %	TAN, mg KOH/g	ISO 4406 code	RPVOT remaining, %	Fe, ppm
0	46.3	—	0.52	16/14/11	100	0

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

1000	46.1	−0.4	0.59	17/15/12	93	4
2000	45.9	−0.9	0.66	17/15/12	87	7
3000	45.8	−1.1	0.73	17/14/12	81	10
4000	45.6	−1.5	0.8	17/15/12	75	12

4.2 Field Performance Discussion

Over 4,000 hours the re-refined formulation tracked the virgin control closely on every monitored parameter. Viscosity declined marginally in both fluids, consistent with mild shear and thermal effects on the polymethacrylate pour point depressant rather than with any degradation mechanism, and the 1.8% change in F-4 against 1.5% in the control is within analytical repeatability for ASTM D445. The absolute TAN of F-4 remained higher throughout, but this offset originates in the as-blended value of 0.71 versus 0.52 mg KOH/g arising from the higher phosphorus and amine loading; the *rate* of TAN increase, which is the diagnostically meaningful quantity, was 0.078 mg KOH/g per 1,000 hours for F-4 against 0.070 for the control, a difference of 11% that is operationally immaterial over a realistic drain interval.

Remaining useful life as measured by residual RPVOT converged over the trial, with F-4 retaining 71% and the control 75% at 4,000 hours. Extrapolating linearly to the conventional 25% RPVOT condemning limit gives projected lives of approximately 9,200 hours for F-4 and 10,700 hours for the control. Wear metal generation was statistically indistinguishable between the two machines, with iron at 13 and 12 ppm respectively and copper at 5 and 4 ppm, and both fluids maintained the target ISO 4406 17/15/12 cleanliness throughout without abnormal filter differential pressure excursions. No filter plugging events occurred on the F-4 machine, which is the critical practical confirmation of the laboratory filterability data in Section 3.4. Pump teardown inspection at trial conclusion showed normal polished wear patterns on the swashplate and slipper faces with no scoring, pitting, or varnish.

V Economic and Environmental Assessment

TABLE 13. COMPARATIVE ASSESSMENT PER TONNE OF FINISHED FLUID

Parameters	Virgin Group II (F-0)	Optimized RRBO (F-4)	Difference
Base oil cost index	100	76	−24%
Additive cost index	100	119	0.19
Total formulation cost index	100	79.5	−20.5%
Cradle-to-gate energy, GJ/t	52.6	19.8	−62%
Cradle-to-gate GHG, kg CO_2e/t	1180	445	−62%
Virgin crude feedstock avoided, t/t fluid	—	0.986	—
Projected drain interval, h (field)	10700	9200	−14%
Lifecycle cost index (cost ÷ drain interval)	100	92.5	−7.5%

The economic case rests on a straightforward trade: base oil represents approximately 98.6 wt% of the finished fluid and is purchased at a 20–25% discount relative to virgin Group II in most regional markets, while the compensating additive strategy raises additive cost by roughly 19%. Because additives constitute only 1.38 wt% of the blend, the net effect remains strongly favourable, yielding a formulation cost reduction of about 20% on a per-tonne basis. When normalized against the shorter projected drain interval observed in the field trial, the advantage narrows to approximately 7.5% on a lifecycle basis, which is a more honest representation of value delivered to the end user than the headline purchase-price saving. The residual difference between the two figures is the economic cost of the 14% shorter service life, and it defines the ceiling on how much additional additive investment can be justified: any further antioxidant boost that closes the drain-interval gap while raising total formulation cost by less than roughly 10% would be economically rational.

The environmental advantage is considerably larger and less equivocal. Re-refining consumes roughly one-third of the primary energy required to produce an equivalent volume of virgin base oil from crude, because the feedstock has already been separated, dewaxed, and refined once and the re-refinery need only remove degradation products, spent additives, and contaminants rather than reconstruct the molecular slate from vacuum gas oil. The resulting 62% reduction in cradle-to-gate greenhouse gas burden is substantially larger than the cost advantage, which means that under any meaningful internal carbon price the economic and environmental cases reinforce rather than oppose one another. The avoided-burden credit from diverting used oil from fuel-blending or incineration is excluded from the figures above and would improve the comparison further; it has been omitted here because allocation methodology for that credit remains contested and its inclusion would weaken rather than strengthen the defensibility of the assessment.

VI Synthesis: Formulation Principles for Re-Refined Hydraulic Fluids

The experimental programme supports four generalizable conclusions about formulating with Group II re-refined stock, and they are worth separating from the specific numerical results because they transfer to other base stocks and viscosity grades.

The first and most important is that re-refined base oil does not fail on bulk properties. Viscosity, viscosity index, flash point, volatility, saturates, and sulfur all fell within Group II limits and within a few percent of the virgin references, and no amount of conventional certificate-of-analysis screening would have predicted the performance deficits observed. The discriminating variables were nitrogen content, residual trace metals, residual chloride, and uninhibited RPVOT — none of which appears on a typical base oil specification sheet. Any qualification protocol for re-refined stock must therefore include uninhibited oxidation response and trace elemental analysis as mandatory screening parameters, since uninhibited RPVOT in particular proved to be a reliable leading indicator of finished-fluid oxidation life and could be measured on incoming base oil in under an hour.

The second conclusion is that the deficits cluster around two mechanisms rather than being diffusely distributed. Oxidation stability, hydrolytic stability, and the tribofilm quality deficit all trace back to catalytic trace metals and the accelerated hydroperoxide decomposition they drive. Demulsibility, filterability, air release, foam, and rust protection all trace back

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

to residual surface-active polar species competing for interfaces. Recognizing this clustering is what makes reformulation tractable, because it means two targeted interventions — metal deactivation and interfacial rebalancing — address eight apparently independent failure modes. The disproportionate contribution of the metal deactivator increase, which accounted for a third of the RPVOT recovery at a treat-rate cost of 0.02 wt%, is the clearest illustration of this leverage.

The third conclusion is that more additive is frequently the wrong answer. The demulsibility failure of F-2 would have been aggravated, not resolved, by proportionally increasing demulsifier; the actual solution required removing 90% of the silicone defoamer, a component present at 50 ppm. The same substitution simultaneously improved foam tendency, air release, and filterability. Formulators accustomed to virgin stocks tend to treat the defoamer as a settled, almost incidental choice, but in a base oil carrying elevated polars the siloxane becomes the dominant source of interfacial conflict and should be the first component interrogated when water-separation or air-release margins erode.

The fourth is that mixed anti-wear chemistry outperforms a single-chemistry package in this context. The partial substitution of ZDDP by ashless amine phosphate reduced hydrolytic vulnerability, improved FZG and four-ball performance, lowered 35VQ25 total wear below the virgin reference, and reduced zinc content — four benefits from a 0.06 wt% addition. The mechanistic rationale is complementary film formation: thermal iron phosphate films cover the lower-flash-temperature regions where tribochemical ZDDP film growth is sparse, and the ashless component is not consumed by the hydroperoxide decomposition pathway that depletes ZDDP prematurely in a metal-contaminated fluid.

VII LIMITATIONS

Several constraints bound the conclusions. The field validation comprised a single machine pair over 4,000 hours in a moderate-severity application; injection moulding imposes high cyclic pressure but relatively benign thermal conditions compared with mobile hydraulics or high-temperature steel-mill service, and the drain-interval extrapolation to 9,200 hours assumes linear RPVOT decay that will not hold near the condemning limit, where antioxidant depletion becomes autocatalytic. Real drain intervals are therefore likely to be shorter than the linear projection for both fluids.

The re-refined stock was drawn from a single re-refinery operating a specific hydrotreating severity on a specific regional used-oil collection pool. Feedstock composition in used-oil collection varies seasonally and geographically with the engine oil, industrial oil, and transmission fluid mix, and the nitrogen, chloride, and trace-metal figures reported in Table 1 should be treated as a representative rather than a universal envelope. Batch-to-batch variability was not characterized in this programme and constitutes the most significant open question for commercial implementation; a production formulation should carry additional antioxidant margin beyond the 93.9% RPVOT recovery achieved here precisely to absorb that variability.

Finally, the Eaton 35VQ25 results reported are from a single qualifying run per formulation rather than the replicate programme required for formal OEM approval, and the ISO 6072 elastomer work covered three compounds at standard conditions rather than the extended matrix that seal manufacturers generally require. Formal OEM qualification against Eaton E-FDGN-TB002, Parker Denison HF-0, and Bosch Rexroth RDE 90235 remains to be completed.

VIII CONCLUSIONS

An ISO VG 46 HM hydraulic oil formulated entirely on Group II re-refined base oil can meet DIN 51524-2 and ISO 11158 requirements and match virgin-based commercial fluid performance, but only with a deliberately reformulated additive system. Direct one-for-one base oil substitution at constant additive treat rate is not viable: it produced a 41% loss of RPVOT life, a 42% loss of TOST life, outright failure of ISO 13357-1 wet filterability at 64% against an 85% minimum, failure of ASTM D1401 demulsibility at 54 °C, failure of the ASTM D2619 water-layer acidity limit, light rust in ASTM D665B, and a doubling of 35VQ25 vane pump wear.

Reformulation recovered full compliance through four coupled measures: a 44–47% increase in the aminic and phenolic antioxidants held at a 1.6:1 ratio, a 67% increase in metal deactivator, replacement of 90% of the silicone defoamer with a polyacrylate alternative together with a modest demulsifier increase, and partial substitution of ZDDP by ashless amine phosphate. The optimized formulation achieved 93.9% of reference RPVOT life, 94.0% of reference TOST life, wet filterability F_2 of 92%, demulsibility equal to the virgin reference, FZG fail stage 12, and 35VQ25 total wear of 21.4 mg against both a 90 mg limit and a 24.9 mg virgin reference. Field validation over 4,000 hours confirmed laboratory findings with viscosity change of −1.8%, a TAN increase rate within 11% of the control, no filter plugging, and equivalent wear metal generation.

The resulting fluid delivers approximately 20% lower formulation cost, 7.5% lower lifecycle cost after accounting for a 14% shorter projected drain interval, and a 62% reduction in cradle-to-gate greenhouse gas burden. The practical significance extends beyond this single product: the demonstrated clustering of re-refined-stock deficits into catalytic-metal and interfacial-polar mechanisms provides a transferable diagnostic framework, and the finding that uninhibited base oil RPVOT predicts finished-fluid oxidation life offers an inexpensive incoming-quality screen that could materially de-risk commercial adoption of re-refined stocks in high-specification industrial applications.

REFERENCES

[1] American Society for Testing and Materials. *ASTM D445 — Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids*. ASTM International, West Conshohocken, PA.

[2] American Society for Testing and Materials. *ASTM D664 — Standard Test Method for Acid Number of Petroleum Products by Potentiometric Titration*. ASTM International.

[3] American Society for Testing and Materials. *ASTM D665 — Standard Test Method for Rust-Preventing Characteristics of Inhibited Mineral Oil in the Presence of Water*. ASTM International.

[4] American Society for Testing and Materials. *ASTM D892 — Standard Test Method for Foaming Characteristics of Lubricating Oils*. ASTM International.

[5] American Society for Testing and Materials. *ASTM D943 — Standard Test Method for Oxidation Characteristics of Inhibited Mineral Oils*. ASTM International.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 10 , October - 2026

[6] American Society for Testing and Materials. *ASTM D1401 — Standard Test Method for Water Separability of Petroleum Oils and Synthetic Fluids*. ASTM International.

[7] American Society for Testing and Materials. *ASTM D2272 — Standard Test Method for Oxidation Stability of Steam Turbine Oils by Rotating Pressure Vessel*. ASTM International.

[8] American Society for Testing and Materials. *ASTM D2619 — Standard Test Method for Hydrolytic Stability of Hydraulic Fluids (Beverage Bottle Method)*. ASTM International.

[9] American Society for Testing and Materials. *ASTM D3427 — Standard Test Method for Air Release Properties of Hydrocarbon Based Oils*. ASTM International.

[10] American Society for Testing and Materials. *ASTM D4310 — Standard Test Method for Determination of Sludging and Corrosion Tendencies of Inhibited Mineral Oils*. ASTM International.

[11] American Society for Testing and Materials. *ASTM D5185 — Standard Test Method for Multielement Determination of Used and Unused Lubricating Oils by ICP-AES*. ASTM International.

[12] American Society for Testing and Materials. *ASTM D7043 — Standard Test Method for Indicating Wear Characteristics of Non-Petroleum and Petroleum Hydraulic Fluids in a Constant Volume Vane Pump*. ASTM International.

[13] American Petroleum Institute. *API 1509, Engine Oil Licensing and Certification System, Appendix E — API Base Oil Interchangeability Guidelines*. API, Washington, DC.

[14] Deutsches Institut für Normung. *DIN 51524-2 — Pressure Fluids; Hydraulic Oils; HLP Hydraulic Oils, Minimum Requirements*. Beuth Verlag, Berlin.

[15] International Organization for Standardization. *ISO 4406 — Hydraulic Fluid Power — Fluids — Method for Coding the Level of Contamination by Solid Particles*. ISO, Geneva.

[16] International Organization for Standardization. *ISO 6072 — Hydraulic Fluid Power — Compatibility between Fluids and Standard Elastomeric Materials*. ISO, Geneva.

[17] International Organization for Standardization. *ISO 6743-4 — Lubricants, Industrial Oils and Related Products (Class L) — Classification — Part 4: Family H (Hydraulic Systems)*. ISO, Geneva.

[18] International Organization for Standardization. *ISO 11158 — Lubricants, Industrial Oils and Related Products (Class L) — Family H (Hydraulic Systems) — Specifications for Categories HH, HL, HM, HV and HG*. ISO, Geneva.

[19] International Organization for Standardization. *ISO 13357-1 and 13357-2 — Petroleum Products — Determination of the Filterability of Lubricating Oils*. ISO, Geneva.

[20] European Parliament and Council. *Directive 2008/98/EC on Waste (Waste Framework Directive)*. Official Journal of the European Union.

[21] Mortier, R. M., Fox, M. F., & Orszulik, S. T. (Eds.). *Chemistry and Technology of Lubricants*, 3rd ed. Springer.

[22] Rudnick, L. R. (Ed.). *Lubricant Additives: Chemistry and Applications*, 3rd ed. CRC Press.

[23] Rudnick, L. R. (Ed.). *Synthetics, Mineral Oils, and Bio-Based Lubricants: Chemistry and Technology*, 3rd ed. CRC Press.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)