Performance Optimization of a Kidney Loop Filtration System for Hydraulic Oil Contamination Control in CAT D6R2 XL Dozers

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ABSTRACT

Particle contamination in hydraulic oil can affect the reliability of hydraulic systems in heavy equipment. This study evaluates a fabricated Kidney Loop system installed and tested on a CAT D6R2 XL Dozer for its ability to reduce particulate contamination in hydraulic oil. An applied experimental approach was used, with oil samples collected before filtration and after 8 and 16 hours of filtration. Samples were analyzed using a Liquid Particle Counter (LPC 500) at the S.O.S Laboratory of PT Trakindo Utama Balikpapan. The reported mean particle count in the ≥14 µm channel decreased from 609.85 particles/mL before filtration to 110.95 particles/mL after 8 hours and 83.55 particles/mL after 16 hours, corresponding to reductions of approximately 81.8% and 86.3%, respectively. The study also reports a single-channel cleanliness parameter for the ≥14 µm channel of 16.30 before filtration, 13.90 after 8 hours, and 13.45 after 16 hours. These values are treated here as reported channel-specific parameters, not as complete three-channel ISO 4406 codes. The measured flow rate was 11.5 LPM at 40–60 psi and 13 LPM at 80–100 psi. Because the comparative test changed both working pressure and filter-element condition, the individual effect of pressure cannot be isolated. The assessment was limited to particulate contamination; water content, kinematic viscosity, and spectrometric wear-metal analysis were not measured. Future testing should independently control pressure and filter-element condition, verify all ISO 4406 channels against the raw laboratory data, and extend fluid diagnostics beyond particle counting.

Keywords: Kidney Loop; hydraulic oil; particle contamination; CAT D6R2 XL Dozer; ISO 4406.

INTRODUCTION

Hydraulic systems are among the main systems in heavy equipment and function by transmitting energy through a fluid to generate motion and force. In dozer units, hydraulic-oil cleanliness is an important factor because contaminant particles can enter component clearances, accelerate wear, interfere with valves and actuators, and reduce system reliability. Research on mining excavators has shown that working-fluid contamination contributes to approximately 70% of hydraulic-system failures; therefore, controlling oil cleanliness directly contributes to unit reliability and service life [1]. The abrasive nature of particles toward hydraulic components has also been demonstrated experimentally: oil contaminated with wear particles can reduce the volumetric efficiency of gear pumps by up to 18% [2]. Therefore, oil cleanliness is commonly evaluated and reported using ISO 4406 cleanliness codes for particle-size channels >4 µm, >6 µm, and >14 µm [3].

Contamination control is not limited to oil replacement and can also be achieved through offline filtration or a Kidney Loop. This system draws oil from the reservoir, passes it through a series of filters, and returns the filtered oil to the reservoir. This concept enables cleaning without draining the entire hydraulic system. Secondary (offline) filtration operates in a separate circuit from the main hydraulic circuit, allowing relatively consistent filtration performance under different system operating conditions and enabling lower oil-cleanliness

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levels than the built-in inline filter [4]. Portable filtration units based on the same principle—drawing oil from the reservoir and returning it after filtration—have also been shown to clean hydraulic oil without adding a bypass component to the main system [5].

This study reports the fabrication and testing of a Kidney Loop system on a CAT D6R2 XL Dozer, using particulate contamination and hydraulic-oil cleanliness as the primary indicators. Laboratory measurements were taken with an LPC 500 before filtration and after 8 and 16 hours. A second configuration was tested at 0, 4, and 8 hours. The discussion focuses on particle-count changes, the reported ≥14 µm channel-specific cleanliness parameter, and flow characteristics under the two operating configurations. Since the comparative test simultaneously changed working pressure and filter-element condition, the results are interpreted as a comparison between configurations rather than as evidence of the independent effect of pressure. Values reported in the original data tables and figures must be checked against the underlying laboratory readings before final publication wherever their means or channel order differ.

RESEARCH METHODOLOGY

Research Design

The study used an applied experimental design with a before–after time-series approach and no independent control group. One CAT D6R2 XL Dozer was observed before filtration (0 hours), after 8 hours, and after 16 hours. A second configuration was tested at 0, 4, and 8 hours. Because the initial conditions and operating configurations were not identical, each configuration was assessed relative to its own initial condition; direct attribution of differences to pressure alone is not justified.

Research Object, Location, and Time

The research object was a Caterpillar D6R2 XL Dozer owned by PT BWB, with hydraulic oil whose contamination level before testing exceeded the CAT hydraulic-oil cleanliness standard of 18/15 based on ISO 4406. Fabrication and testing of the device were conducted within the D-III Heavy Equipment Engineering Study Program, Politeknik Negeri Samarinda, and at the unit's operational site, while sample analysis was performed at the S.O.S Laboratory of PT Trakindo Utama Balikpapan. [Marc, 2026]



Figure 1. Testing of the Kidney Loop System on the Caterpillar D6R2 XL Dozer

Kidney Loop System Design

The Kidney Loop system was designed as an offline filtration unit operating in a separate circuit from the unit's main hydraulic circuit. This configuration allows filtration without dismantling or interfering with the unit's hydraulic components. The main components, specifications, and functions are presented in Table 1.

Table1 Components, Specifications, and Functions of the Kidney Loop System

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Component	Specification	Function
Pneumatic pump	Graco Husky 716, free flow ±60 LPM	Drives oil circulation from and to the reservoir
Water separator	Standard industrial component	Separates free water from oil
Y-strainer	Standard industrial component	Pre-filters coarse particles
Stage 1 filter	26–17 µm element	Coarse filtration
Stage 2 filter	10 µm element	Intermediate filtration
Stage 3 filter	7 µm element	Fine filtration
Flow meter	Standard industrial component	Measures oil flow rate
Pressure gauge	Standard industrial component	Monitors working air pressure
Hose, fittings, quick couplings, supporting frame	Standard industrial components	Flow path and system support

The flow configuration is unidirectional: oil is drawn from the reservoir, passes through the Y-strainer for initial filtration, the pneumatic pump as the circulation driver, the water separator for water separation, three filter stages in sequence (26–17 µm, 10 µm, and 7 µm), and the flow meter, and is then returned to the reservoir. The system is powered by compressed air maintained within the defined working-pressure range for each test configuration.

Test Procedure

a. Main test

The system was operated continuously for 16 hours at a working air pressure of 40–60 psi. Oil samples were collected at three time points: before filtration (0 hours), after 8 hours, and after 16 hours. In this configuration, only the first-stage filter element (26–17 µm) was new, whereas the second-stage (10 µm) and third-stage (7 µm) elements had been used previously.

b. Comparative test

For the comparative test, all filter elements were replaced with new elements and the working air pressure was increased to 80–100 psi. Oil samples were collected at 0, 4, and 8 hours. As both pressure and filter-element condition differed from the main test, this comparison cannot isolate the effect of either variable independently.

c. Operational measurements

Oil flow rate was measured using a flow meter under both working-pressure conditions. The main test produced a flow rate of 11.5 LPM, whereas the comparative test produced 13 LPM. Working air pressure was monitored using a pressure gauge throughout the test to maintain stable circulation.

2. Sample Collection and Analysis

Oil samples were collected from the same sampling point at each time condition following the oil-sampling procedure established by the S.O.S Laboratory of PT Trakindo Utama. Cleanliness analysis was performed using a Liquid Particle Counter (LPC 500) based on ISO 4406, reporting particle counts per milliliter in the ≥4 µm, ≥6 µm, and ≥14 µm size channels together with their cleanliness codes. Each test condition was supported by 20 laboratory readings; therefore, the analysis considered data distributions and averages rather than a single value.

3. RESEARCH VARIABLES

- Independent variables: filtration duration (0, 8, and 16 hours) and system operating conditions (working pressure and filter-element condition in the comparative test).
- Dependent variables: particle count ≥14 µm (particles/mL), three-channel ISO 4406 cleanliness codes (≥4, ≥6, and ≥14 µm), and oil flow rate (LPM).

- Controlled variables: filter-circuit configuration, oil volume in the system, sampling point and procedure, and analytical laboratory.
- Recognized confounder: the condition of the second- and third-stage filter elements in the main test, which were not new; therefore, the effect of working pressure in the comparative test cannot be isolated from the effect of filter-element condition.

4. DATA ANALYSIS

The data were analyzed using three approaches. First, particle concentration reduction was calculated using the following equation:

Reduction (%) = $[(C_0 - C_t) / C_0] \times 100\%$

where C_0 is the mean particle concentration before filtration and C_t is the mean particle concentration after filtration time t. Second, cleanliness codes were determined according to ISO 4406 (a logarithmic scale based on 2 for each particle-size channel) and compared with the ≤15 target used in the study and the CAT 18/15 hydraulic-oil cleanliness standard. Third, descriptive statistics (mean, median, minimum, and maximum) were calculated for each condition from 20 laboratory readings and presented as distribution graphs to assess the consistency of reduction across replicates and the position of the data distribution relative to the target-code range.

5. METHODOLOGICAL LIMITATIONS

The comparative test changed two factors simultaneously: working air pressure increased from 40–60 psi to 80–100 psi, and all filter elements were replaced with new elements. Consequently, the observed differences in flow rate and cleanliness represent differences between two operating configurations and cannot be attributed to pressure alone or to new filter elements alone. The present assessment was limited to particulate contamination and particle-count-based cleanliness indicators. Water content, kinematic viscosity, and spectrometric wear-metal analysis were not measured; the findings therefore do not constitute a complete assessment of hydraulic-oil condition. In addition, reported means and channel-specific cleanliness values must be verified against the underlying raw laboratory readings and the plotted distributions before publication. Future tests should vary pressure and filter-element condition independently, include replicate measurements, and report the complete three-channel ISO 4406 result in a consistent channel order.

RESULTS AND DISCUSSION

Changes in Particle Count

Table 2. Change in Particle Count ≥14 µm with Filtration Time (mean, n = 20)

Condition	Filtration Time	Particle Count ≥14 µm (particles/mL)	Reduction from Initial
Initial	0 h	609.85	—
Filtration 1	8 h	110.95	81.8%
Filtration 2	16 h	83.55	86.3%

The mean particle count showed a strong decrease after the filtration process. It decreased from 609.85 particles/mL initially to 110.95 particles/mL after 8 hours and then to 83.55 particles/mL after 16 hours. In relative terms, the reduction reached approximately 81.8% after 8 hours and 86.3% after 16 hours. The rapid reduction during the initial period followed by a slower decline is consistent with Kołodziejski et al. (2025), who reported that a single 6–8-hour offline microfiltration session can improve hydraulic-oil cleanliness by approximately one class, with the rate of improvement depending on the initial oil condition. The reduction in this study was also greater than the contaminant reduction achieved by a Kidney Loop process on the final-drive lubricant of an HD 785-7 unit, reported as 42% on the RH side and 58% on the LH side [Randis & Na'ali, 2016], indicating the effectiveness of the staged 26–17 µm, 10 µm, and 7 µm filtration sequence.

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The additional reduction between hour 8 and hour 16 was smaller than the reduction during the initial period. This pattern indicates that the Kidney Loop contributed to oil cleaning, but the particle-reduction rate was not constant throughout the filtration period. Quantitatively, the reduction from 609.85 to 110.95 particles/mL represents a decrease of 498.90 particles/mL during the first 8 hours, whereas the 8–16-hour phase added only 27.40 particles/mL of reduction, or approximately 24.7% relative to the 8-hour condition, resulting in a total reduction of 526.30 particles/mL (86.3%).

The reduction occurred progressively through the water separator and the three filter stages (26–17 µm, 10 µm, and 7 µm). As the oil circulated continuously, particles were retained by the filter media according to their pore or rating characteristics, so the number of suspended particles decreased as filtration time increased. The lower reduction rate during the second phase is also consistent with the initial oil condition: when the suspended-particle population is high, filtration proceeds rapidly; after most particles have been removed, the reduction slows because fewer contaminants remain and the residual population is increasingly dominated by fine particles.

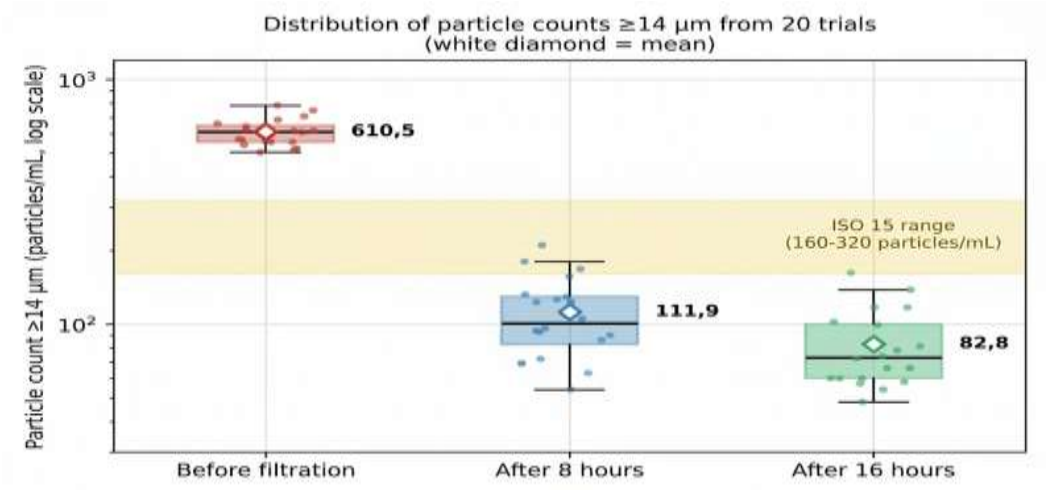


Fig. 2. Distribution of particle count ≥14 µm from 20 tests per condition (logarithmic scale); white diamonds indicate the mean. The summary means used in the text and Table 2 are 609.85, 110.95, and 83.55 particles/mL. These values should be retained only after they have been checked against the underlying 20 readings used to generate the figure.

The distribution visualization in Figure 2 reinforces this reduction pattern: all 20 initial measurements were well above the ISO 15 range (160–320 particles/mL), whereas after 8 hours the entire distribution was below that range, and after 16 hours the distribution shifted further downward. The absence of meaningful overlap among the groups indicates that the reduction was not an artifact of a few extreme measurements but was consistent across all replicates; the between-replicate spread at 8 and 16 hours was relatively broad because the remaining particle population was smaller, increasing relative measurement variability.

Hydraulic-Oil Cleanliness Parameter

Table 3. Cleanliness Parameter of the ≥14 µm Channel Relative to the ≤15 Target

Condition	Reported channel-specific parameter (≥14 µm; not a complete ISO 4406 code)	Interpretation relative to ≤15 target
Before filtration	16.30	Above target
After 8 h	13.90	Meets target
After 16 h	13.45	Meets target

The source project reports channel-specific cleanliness parameters of 16.30 before filtration, 13.90 after 8 hours, and 13.45 after 16 hours for the ≥14 µm channel. Relative to the study's stated ≤15 target for this channel-specific parameter, the 8-hour and 16-hour values meet the target. These values must not be presented as the complete ISO 4406 cleanliness code: ISO 4406 cleanliness is reported as a multi-channel code, conventionally covering the ≥4 µm(c), ≥6 µm(c), and ≥14 µm(c) particle-size channels. The complete code should be reported in a

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consistent channel order using the original laboratory data. Until that verification is complete, 16.30, 13.90, and 13.45 are identified only as the source-reported ≥14 µm channel-specific parameters.

For publication, this terminology needs clarification because ISO 4406 conventionally expresses cleanliness using multiple particle-size channels. Therefore, values of 16.30, 13.90, and 13.45 should not be described as the sole 'ISO 4406 code' without identifying the channel and the other channel data. This article retains the values from the final project but limits their interpretation to the reported ≥14 µm parameter. Complete reporting as described is also standard in construction-machine oil testing according to ISO 4406 and NAS 1638 [6], as well as in hydraulic-oil contamination analysis of excavators in Indonesia, where all three particle-size channels are reported simultaneously [7]. As a reference cleanliness target, the maximum class 20/18/15 is commonly used for heavy-equipment hydraulic systems [3], while research on mining excavators has recommended a 15/13 cleanliness level as an economically and technically suitable condition for unit reliability [1].

The source project also provides three-channel cleanliness results. The manuscript should report the complete ISO 4406 code in the conventional channel order (≥4 µm(c)/≥6 µm(c)/≥14 µm(c)) and ensure that the table, figure labels, and narrative use the same order. The channel-specific values 16.30, 13.90, and 13.45 are not a substitute for a complete three-channel code. The target of ≤15 used in this study applies only to the reported ≥14 µm channel-specific parameter and should not be interpreted as a universal target for every channel.

Table 4. Three-Channel ISO 4406 Cleanliness Codes in the Main Test

Particle-size channel	Before filtration	After 8 h	After 16 h
>=4 µm	23	23	23
>=6 µm	20	20	19
>=14 µm	16.30	13.90	13.45

The pattern across channels provides important information about the system's performance limits. The ≥4 µm channel showed no improvement, remaining at code 23; the ≥6 µm channel decreased by only one code after 16 hours; whereas the ≥14 µm channel decreased by almost three codes. This pattern is consistent with the final filter rating of 7 µm, which is effective in retaining particles larger than its nominal rating but relatively less capable of reducing the population of fine 4–6 µm particles. This condition is reinforced by the fact that, in the main test, only the first filter (26–17 µm) used a new element, whereas the second and third filters used previously operated elements, reducing fine-particle filtration performance.

The implication is that system performance is most appropriately evaluated using the ≥14 µm and ≥6 µm channels, whereas improvement in the ≥4 µm channel requires a finer-rated filter element or an additional filtration stage.

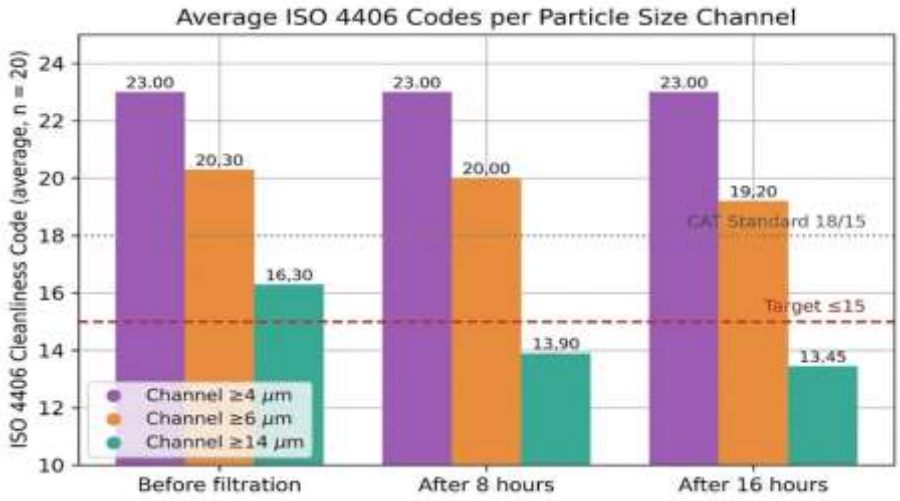


Fig. 3 Mean ISO 4406 cleanliness codes by particle-size channel (n = 20) compared with the ≤15 target and CAT 18/15 hydraulic-oil cleanliness standard.

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Figure 3 shows a visual comparison of the three channels with the target and standard: only the ≥14 µm channel crossed the ≤15 target line and even fell below the CAT standard; the ≥6 µm channel approached the standard only after 16 hours, while the ≥4 µm channel was practically unchanged.

3. Effect of Filtration Time on Oil Cleanliness

Comparison of the 8-hour and 16-hour results indicates that most of the reduction in the reported ≥14 µm channel-specific cleanliness parameter occurred during the first 8 hours: the value changed from 16.30 to 13.90, then to 13.45 after 16 hours. The additional change from 13.90 to 13.45 is approximately 0.45. Under the study's stated ≤15 target for this channel-specific parameter, the 8-hour condition had already met the target. This suggests that extending filtration to 16 hours provided a smaller additional change in this indicator. The conclusion is specific to the reported channel parameter and should not be generalized to the complete ISO 4406 cleanliness code without verifying all channels.

4. Effect of Filter-Element Condition: Main and Comparative Tests

To assess the effects of filter-element condition and working pressure, the final project included a comparative test using the same system configuration, but with all filter elements replaced by new elements and the working pressure increased to 80–100 psi, with test durations of 4 and 8 hours. In the main test, the working pressure was 40–60 psi and only the first filter was new, whereas the second filter (10 µm) and third filter (7 µm) still used previously operated elements.

Table 5. ISO 4406 Codes for the Main and Comparative Tests (mean, n = 8)

Condition	Main test (ISO 4406)	Comparative test (ISO 4406)
0 h	21/17/23	20/16/23
4 h	—	18/13/22
8 h	20/14/23	17/12/22
16 h	19/13/23	—

As reported in the final project (the order of the code follows the final-project reporting; '—' indicates a condition not tested in that configuration), both configurations were able to reduce particle counts, but the rate of cleanliness improvement differed. Using all-new filter elements provided better filtration performance, so particle reduction occurred more rapidly, while higher working pressure increased the oil-circulation rate through the filter media and accelerated filtration. Conversely, the use of previously operated second- and third-stage filters and lower pressure in the main test resulted in slower contamination reduction. Nevertheless, the main test demonstrated that the system could reduce particle counts across the measured sizes even when not all elements were new. Because both variables—element condition and pressure—changed simultaneously in the comparative test, the results indicate a relationship between operating configuration and the rate of achieving oil cleanliness, rather than an isolated pressure effect.

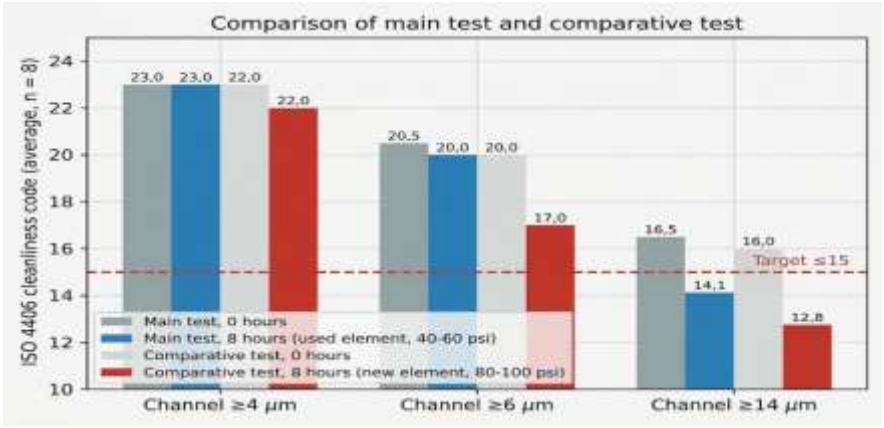


Fig. 4 Comparison of mean ISO 4406 codes for the main test (not all filter elements new, 40–60 psi) and comparative test (all filter elements new, 80–100 psi) at 0 and 8 hours (n = 8).

Figure 4 compares the reported cleanliness results for the main configuration (40–60 psi; only the first-stage filter element was new) and the comparative configuration (80–100 psi; all filter elements were new). The plotted values and the channel order must be cross-checked against the original laboratory data before submission because the text and summary tables do not consistently identify the same channel order. Accordingly, Figure 4 supports only a descriptive comparison between the two configurations; it does not establish the independent effect of higher pressure or new filter elements.

5. Effect of Working Pressure on Flow Rate

Table 6. Oil Flow Rate at Different Working Pressures

Working pressure	Flow rate	Flow-rate change
40–60 psi	11.5 LPM	—
80–100 psi	13 LPM	≈13% higher

The measured flow rate increased from 11.5 LPM in the 40–60 psi configuration to 13 LPM in the 80–100 psi configuration, an increase of approximately 13%. However, all filter elements were also new in the higher-pressure configuration. The result therefore describes the difference between configurations and cannot be interpreted as the isolated effect of pressure on flow rate. A controlled follow-up test should keep filter-element condition constant while varying pressure, then keep pressure constant while varying filter-element condition.

Therefore, filtration performance is not determined solely by operating time, but also by the stability of oil flow rate, pump working-air pressure, initial oil condition, and filter-element condition.

6. IMPLICATIONS FOR HEAVY-EQUIPMENT MAINTENANCE

The results show that offline filtration can be used as part of a hydraulic-oil contamination-control strategy. This approach has the potential to be applied as preventive maintenance to maintain fluid cleanliness without completely replacing the oil. In heavy-equipment maintenance practice, filtration intervals should be determined based on actual oil condition, particle-analysis results, filter condition, and system recommendations.

This is supported by findings that periodic oil replacement alone does not completely clean the system because approximately 5% of contaminants from the old oil remain on pipe walls and hydraulic components and mix with new oil, thereby reducing its cleanliness class [7]. Offline filtration has also been shown to extend oil service life without stopping hydraulic-system operation [8]. A similar approach based on the contamination-balance concept emphasizes that establishing an oil-cleanliness target together with active maintenance actions can improve component service life and hydraulic-system reliability [9].

The final-project summary highlights several system advantages: staged filtration through a Y-strainer, water separator, and three filter stages (26–17 µm, 10 µm, and 7 µm) capable of capturing particles of various sizes; operation without dismantling or interfering with the unit's hydraulic system because the system operates in an external circuit; simple construction using standard industrial components (hoses, fittings, quick couplings, pneumatic pump, flow meter, air filter regulator, pressure gauge, and filter housings), making maintenance straightforward and replacement parts readily available; and potential use as a practical training and research platform for hydraulic-oil filtration.

Field implementation should consider pressure monitoring, flow rate, filter-element condition, leakage, connection cleanliness, and consistent sampling procedures. As a laboratory-scale prototype, the system's performance depends on filter-element condition and a stable compressed-air supply; monitoring is manual through a pressure gauge and flow meter, and oil-condition assessment is currently limited to particle counts. Future validation should include water content or water-separation performance, kinematic viscosity, and spectrometric wear-metal analysis. These additional diagnostics are necessary before making broader claims about overall oil condition or component wear.

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CONCLUSION

The fabricated Kidney Loop system tested on the CAT D6R2 XL Dozer reduced the reported mean particle count in the ≥14 µm channel from 609.85 particles/mL before filtration to 110.95 particles/mL after 8 hours and 83.55 particles/mL after 16 hours, corresponding to reductions of approximately 81.8% and 86.3%, respectively. These mean values should be confirmed against the raw laboratory readings used for the distribution graph before final publication.

The source project reports a ≥14 µm channel-specific cleanliness parameter of 16.30 before filtration, 13.90 after 8 hours, and 13.45 after 16 hours. The 8-hour and 16-hour results are below the study's stated ≤15 target for this parameter; these values are not complete three-channel ISO 4406 codes. The measured flow rate was 11.5 LPM at 40–60 psi and 13 LPM at 80–100 psi (approximately 13% higher), but pressure and filter-element condition changed simultaneously, so the flow-rate difference cannot be attributed to pressure alone.

The study is limited to particulate contamination and flow-rate measurements. Future work should (1) test working pressure and filter-element condition as independent factors, using a controlled test matrix and repeated measurements; (2) expand fluid diagnostics to include water content or water-separation performance, kinematic viscosity, and spectrometric wear-metal analysis; and (3) verify and harmonize all raw readings, calculated means, tables, graph labels, and complete three-channel ISO 4406 codes before publication.

The available channel data suggest that the reported improvement was greatest in the ≥14 µm channel, while the ≥4 µm channel remained at code 23 and the ≥6 µm channel changed only modestly. These channel-level observations should be retained only with consistent channel labels and a verified three-channel code. The comparative configuration showed a larger change in reported cleanliness and flow, but because both filter-element condition and working pressure changed, the experiment does not determine the independent contribution of either factor. Eight hours met the study's stated ≤15 target for the reported ≥14 µm channel-specific parameter; this should not be represented as proof that the complete hydraulic-oil cleanliness code met all required limits.

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