CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 464

Progressive evolving of a high-performance PCU design: from natural gas to hydrogen applications

Tribology

Frank Berbig, Rolls-Royce Power Systems AG

Philipp Koeser, Rolls-Royce Power Systems AG

ABSTRACT

With Germany's goal to become a climate-neutral industrial country by 2045, enormous efforts are required to reach emission targets and establish the infrastructure for carbon-neutral fuels. Along this path, Rolls-Royce Power Systems with the mtu S4000L64 NG engine will facilitate the transition from pure natural gas to 100% hydrogen applications. In the future, high-efficiency hydrogen applications will play a key role in defossilization, particularly during the transition period when robust support for solar power as a peak-shaving solution is crucial for reliable power supply. Given the limited availability of green hydrogen, interim solutions like the mtu S4000L64 with up to 25% hydrogen blending represent the first step in the transformation process, leading to the first pure hydrogen engine that underscores the necessity of high-efficiency combustion engines as the backbone of the electricity supply.

On this path, the combustion development emerges as the main challenge, with issues like preignition and lube oil ignition - known from natural gas engines - becoming even more severe and limiting factors. The second step focuses on continuously increasing engine efficiency by optimizing the tribological systems of the power cylinder unit, along with extending parts and engine lifetimes.

Over the past decade, intensive in-house research has been conducted to understand the oil transport mechanisms in the power cylinder unit and the phenomenon of lube oil ignition in the latest mtu S4000 NG engine. A comprehensive development tool chain was established, covering the entire design process from initial drafts to design and simulation, component testing, single-cylinder proof of concept, and final multi-cylinder endurance runs. These efforts aim to minimize lube oil consumption and lube oil induced misfiring to enhance the engine performance, reduce the overall PCU friction, and improve the mechanical efficiency. All developments are streamlined towards the utilization of these innovations to the upcoming RRPS hydrogen engine applications.

This paper summarizes the development and validation process, offering insights into the latest innovations in the PCU design for the mtu S4000 NG engines. It concludes with a discussion of final achievements, combining new PCU technologies.

The following innovations were made based on the design process: applying a bottle-shaped honing significantly increased mechanical engine efficiency compared with the cylindrical liner shape. Additionally, reducing the roughness of the honing surface minimized the oil reservoir and supply to the combustion chamber. To counterbalance the wear risk around the top dead center of the liner, a fine honing surface was supplemented by a well-known rough surface, ensuring sufficient lubrication in the highly loaded dry region. As a result, overall oil consumption was reduced, confirmed by both single-cylinder and multi-cylinder endurance testing. Implementing a new oil control ring design stabilized the fluctuation in the instantaneous oil consumption, reducing lube oil ignition and leading to a more robust combustion.

In conclusion, the advancements in the design and efficiency of natural gas engines represent a critical step towards the adoption of hydrogen as a sustainable fuel, supporting Germany's ambitious climate-neutral goals.

1 INTRODUCTION AND MOTIVATION

With Germany's goal to become a climate-neutral industrial country by 2045 [1], enormous efforts are required to reach emission targets and establish the infrastructure for carbon-neutral fuels. Along this path, Rolls-Royce Power Systems with the ***mtu*** S4000L64 natural gas (NG) engine will facilitate the transition from pure NG to 100% hydrogen (H_2) applications. In the future, high-efficiency H_2 applications will play a key role in defossilization, particularly during the transition period when robust support for solar power as a peak-shaving solution is crucial for reliable power supply. Given the limited availability of green H_2, interim solutions like the ***mtu*** S4000L64 with up to 25 vol.-% H_2 blending represent the first step in the transformation process, leading to the first pure H_2 engine that underscores the necessity of high-efficiency combustion engines as the backbone of the carbon neutral electricity supply.

Due to the limited availability of H_2 within the engine development process, especially for Large Bore Engines (LBE), where engine testing is very expensive, a proper development tool chain and testing procedure are required to achieve the given engineering targets. Especially the endurance testing of engine hardware, focussing on topics such as overall performance, lube oil consumption or friction and wear, requires a suitable test engine with acceptable fuel cost. Here the ***mtu*** S4000L64 engine fits perfectly to close this gap. Since the requirements and challenges of the high-performance NG combustion are very similar to the H_2 combustion regarding lube oil consumption (LOC) or lube oil induced combustion anomalies - also known as lube oil ignition (LOI) - the direct transfer of the hardware is possible. The result of this development serves perfectly as a baseline for the further optimization within the design process of the H_2 engine. The overall development targets regarding friction and wear reduction and the overall decrease of LOC are similar for both applications, NG and H_2. Thus, technical optimizations made for ***mtu*** S4000L64 can be directly transferred to the new H_2 platform. The ***mtu*** S4000L64 engine is available at the Rolls-Royce Power Systems premises in Friedrichshafen, offering high accessibility for in-house testing and part inspection. By following that path a consequent step-by-step development and validation were conducted, with new technologies as a stand-alone solution or already packaged in a new piston cell unit (PCU). Thus, over the last years many puzzle pieces were added to the reference system, replacing the series L64 hardware. The utilization of the new hardware can be retrofitted to the NG application backwards and, more importantly, forwarded to the upcoming development of the 100% H_2 application. By incorporating all the puzzle pieces in the final PCU design, the overall performance in the multi-cylinder engine (MCE) was validated in an endurance run with up to 8000 hours of testing experience.

1.1 Rolls-Royce Power Systems strategy towards 100% H_2 application

Rolls-Royce Power Systems follows a stepwise transition (figure 1) to the future 100% H_2 application. The well-known ***mtu*** S4000L64 serves as a baseline for the first pure H_2 engine. Based on this engine design, the successful operation of blends of NG with up to 25 vol.-% H_2 is already developed and validated [2], offering unlimited engine operation on full power with 130 kW/Cyl. This approach requires only minor adjustment of the engine hardware, without changes of the PCU design. In a second step, the transition to pure H_2 combustion focuses on a moderate engine redesign to meet the increasing requirement of the H_2 combustion. The goal is to swap only the engine parts/systems that need to be replaced to reach the target output of 80 kW/Cyl. and a mechanical efficiency of 42%. By doing so, Rolls-Royce Power Systems will bring its first pure H_2 application to the market. Furthermore, Rolls-Royce Power Systems will provide a conversion kit for the existing engines already operated in combined heat and power (CHP) applications. In the third step, Rolls-Royce Power Systems develops a high performance H_2 engine based on a new engine platform to close the gap in power output and efficiency between the S4000L64 NG engine and the first pure H_2 application. To reach the power output of the ***mtu*** S4000L64 NG, a major redesign of the entire engine hardware along with a holistic combustion development will be conducted within the next years. To achieve these challenging targets, Rolls-Royce Power Systems initiated a public funded project with external partners, called “Phoenix” (Performance Hydrogen Engine for Industrial and X), covering the development of: H_2 combustion/gas exchange, hardware design and lubrication [3].

	L64 NG Blending up to 25% vol. H_2	Retrofit 100% H_2	Next Generation 100% H_2
Power per Cylinder	130 kW	80 kW	130 kW*
Mech. Efficiency	~44,4 %*	42 %*	~44,4 %*
Fuel Supply	200 mbar Single Point Injection	~ 10 bar Multi Point Injection	Direct Injection / Multi Point Injection
Emissions / EGA	250 mg/Nm³ NO_x THC, HCHO, CO, …	100 mg/Nm³ NO_x	100 mg/Nm³ NO_x
	2024	2028+	2030+

*min. target value

Figure 1. Rolls-Royce Power Systems H_2 strategy

1.2 S4000L64 as technology demonstrator

The ***mtu*** S4000L64 NG engine (figure 2) is well-known and widely used in the market as CHP application. This state-of-the-art high-performance engine has a power output of 130 kW/Cyl. at 1500 rpm with an efficiency of 44,4%, table 1.

Figure 2. ***mtu*** S4000L64 NG engine [4]

Figure 3 represents the ***mtu*** S4000L64 PCU which involves the piston and the piston ring package, consisting of an asymmetric barrel-shaped top ring, a taper-faced second ring and a twin land oil control ring (TLOCR). Together with the engine oil and, in this case, a wet cylinder liner with a rough honing, the PCU contains several tribological system. The piston rings represent a movable sealing of the combustion chamber towards the crankcase and vice versa. Besides the sealing function, the rings must dissipate the heat towards the cylinder liner and control the oil amount on its surface. The surface parameters of the liner control the amount of oil in the tribological systems, which can easily lead to opposing development targets between friction, wear, oil consumptions and lube oil ignition.

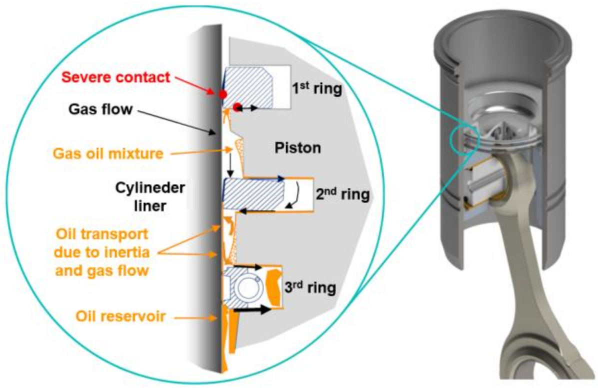

Figure 3. ***mtu*** S4000L64 PCU (baseline) [5]

Running the engine with an average power output of up to 95% for up to 8000 hours per year, Rolls-Royce Power Systems has comprehensive experience with the operation of the engine as well as the system behaviour regarding LOC, friction and wear until the time between overhaul (TBO). Furthermore, using the same combustion, engine operating conditions, and oil conditioning ensures the effects of new engine components to be identified without any ambiguities.

In the early design phase of the high performance H_2 engine, the engine hardware is not yet available for a comprehensive combustion development. In traditional engine development, combustion is developed first, followed by PCU component design, with the underlying assumption the component design is not affecting the combustion. However, in H_2 engines, LOC affects combustion, i.e., the combustion strategy cannot be properly tested with too much LOI. As a result for a proper

H_2 development, the PCU component design needs to be developed and optimized regarding LOC and LOI in advance. A technology demonstrator, as the high-performance ***mtu*** S4000L64 NG engine, can be used to close this gap and can be utilized for testing and validation of the new technologies. In this process the single-cylinder engine (SCE) serves for the first proof of concept and provides comprehensive measurement of the related engine parameters. For the endurance testing, regarding combustion performance, LOC, friction and wear, the hardware is transferred to the MCE and operated in the CHP application. This development methodology is an effective way to address this new challenge and evades the limited availability of H_2 as well as the economical challenges with H_2 to perform extensive testing of new hardware components.

Table 1. ***mtu*** S4000L64 NG specification [4]

Configuration	***mtu*** 16V4000
Bore / stroke in mm	170 / 210
Nominal speed in rpm	1500
Mean piston speed in m/s	10.5
Peak cylinder pressure in bar	170 ± 20
Fuel energy utilization in %	85.9
Electrical output in kW	2028
Mechanical efficiency in %	44.4

2 CHALLENGES WITH NATURAL GAS AND H_2 COMBUSTION

2.1 *mtu* S4000L64 NG engine - Previous findings on LOI behavior

Koeser et al. [5] provided comprehensive insights into lube oil ignition (LOI) in industrial NG engines, with a specific focus on the ***mtu*** S4000 platform. LOI was identified as a significant limitation to engine performance, occurring due to oil transport pathways that lead to anomalous combustion after firing top dead center (FTDC).

Here the increased peak pressure and the rate of pressure rise of an abnormal combustion become the limiting factors because the design of the engine parts do not consider these extraordinary events. The engine as well as the PCU is designed based on a normal combustion. Thus, the accumulation of single pressure events might lead to severe engine damage over the engine lifetime and engine failure before TBO. Figure 4 illustrates the measurement of 500 pressure traces for the normal combustion without the occurrence of LOI in grey (the corresponding averaged trace bold grey) and 20 pressure traces with LOI in red (the averaged pressure trace bold red). In this case the LOI event might increase the peak cylinder pressure by over 60 bar.

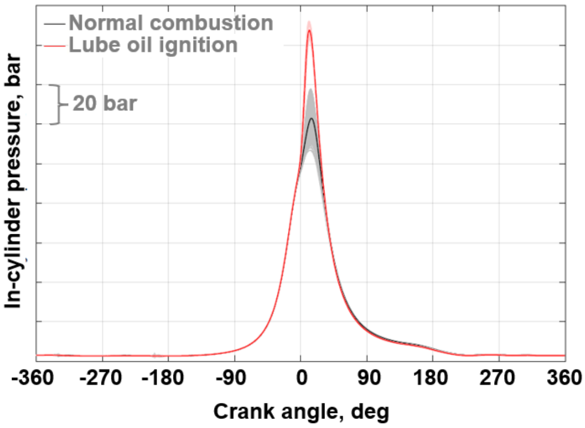

Figure 4. Comparison of pressure traces for a normal combustion (grey, bold: average of 500 cycles) and abnormal combustion with LOI (red, bold: average of 20 cycles) [5]

Figure 5 illustrates critical findings from SCE testing that highlight the relationship between anomalous combustion parameters and lube oil transport. The graph underscores the correlation between peak cylinder pressure, combustion center advancement, exhaust temperature, and soot emissions during combustion anomalies. Notably, earlier combustion center positions improve engine efficiency but also increase cylinder pressure, amplifying the likelihood of oil-induced ignition. The soot signal, derived entirely from burned oil, directly correlates with exhaust temperature drops, reinforcing the conclusion that lube oil transport into the combustion chamber is the primary driver of combustion anomalies such as LOI.

Advanced diagnostic tools, including optical fibers and eddy-current sensors, revealed that LOI originates from oil leakage through the PCU, particularly at the TLOCR gaps. In contrast to low-speed pre-ignition (LSPI), LOI results in a substantial rise in peak cylinder pressure (up to over 60 bars, figure 4) and pressure rise rates, adversely affecting engine durability and leading to potential component failures such as piston scuffing and ring fractures.

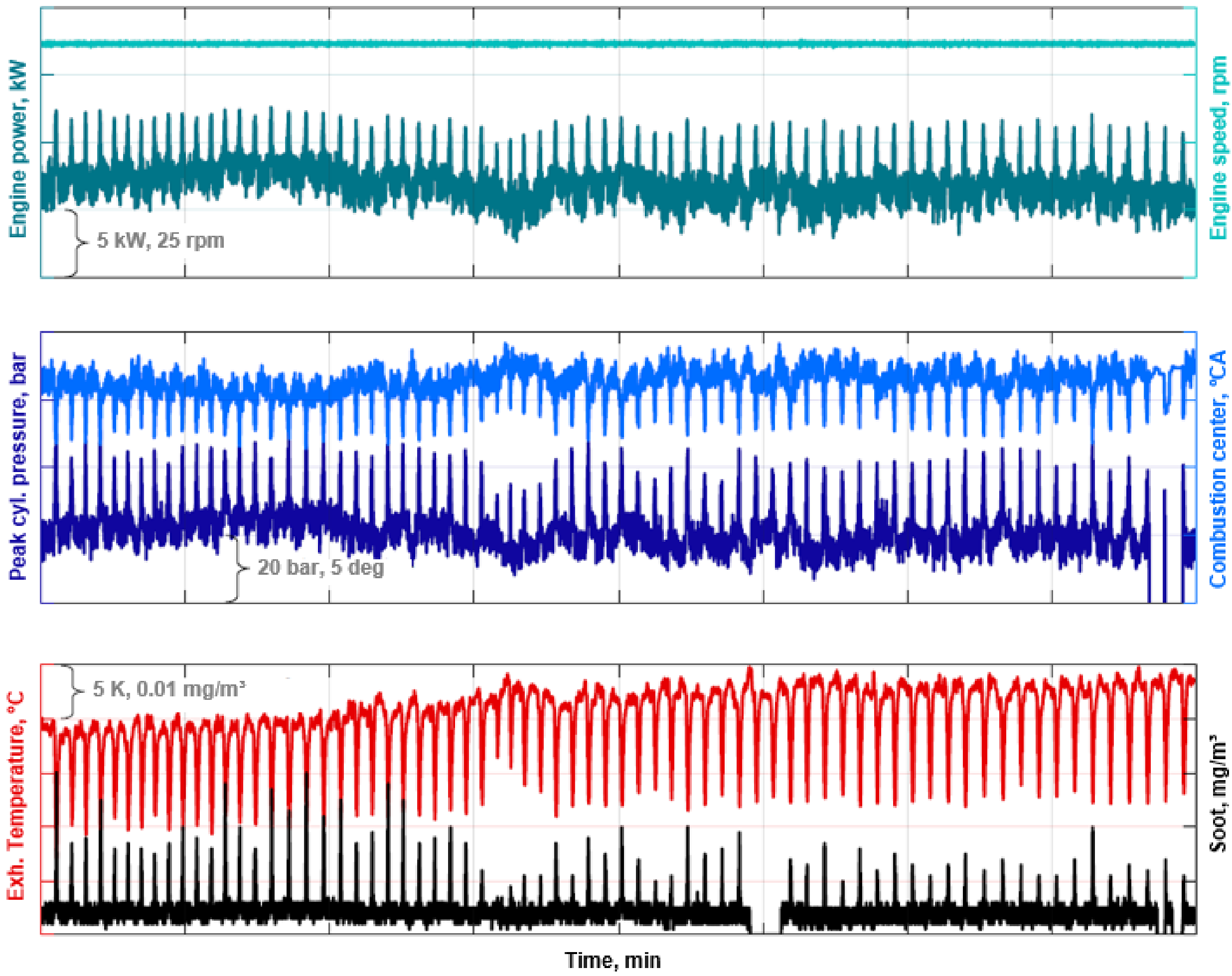

Figure 5. NG SCE results: Correlation of peak pressure, exhaust temperature and soot for an operation sequence with LOI. Spikes in the signals indicating lube oil induced combustion anomalies [5]

The investigation [5] also employed visualization, advanced modeling techniques, and computational fluid dynamics (CFD) to establish a conceptual oil transport model. Key findings highlighted how oil scraped by the top piston ring accumulates in critical regions of the cylinder liner and crown land, ultimately contributing to LOI. Simulations confirmed that during compression and expansion strokes, the scraped oil forms droplets that are entrained into the combustion chamber. The study also validated these mechanisms through experimental methods, including experiments with the 2D Laser-Induced Fluorescence (2DLIF) method and high-speed imaging utilizing the single-cylinder research engine in the Sloan Automotive Laboratory of Massachusetts Institute of Technology (MIT) as presented in figure 6 [6]. It shows six high speed images through a sapphire window capturing the oil pattern for different engine cycles. In cycle 6 and 16 oil droplets detached from the crown land can be seen. As the piston decelerated while approaching FTDC the droplets travel further towards the combustion camber driven by inertia. The image of cycle 11 and 16 evidence oil streaks remaining on the liner surface, not down-scrapped by the OCR in the intake stroke. These oil pattern provide the oil to be up-scraped by the top ring within the compression stroke. To mitigate LOI, the study from 2021 proposed optimized designs for the first piston ring and the oil control ring, achieving significant reductions in oil leakage and friction losses while maintaining the system robustness. These findings not only enhance the performance, reliability, and durability of NG engines but also provide foundational strategies for addressing the more stringent demands of H_2 combustion and further emphasizing the critical role of understanding oil transport mechanisms in mitigating combustion anomalies.

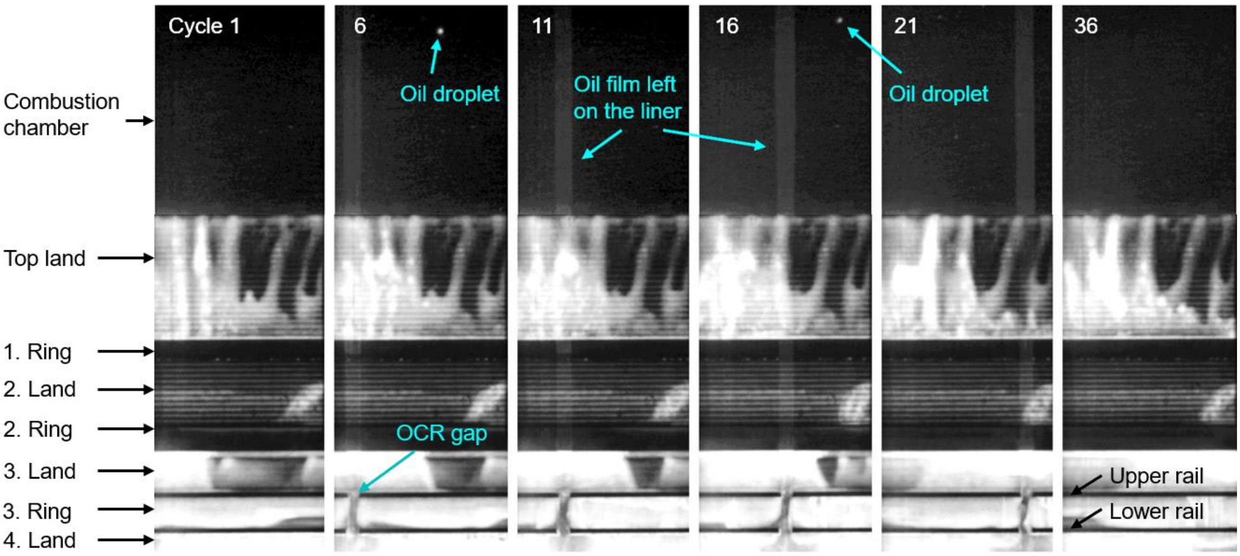

Figure 6. High-speed images from MIT research SCE visualizing oil droplets entrained towards combustion chamber (cycle 6 and 16) and remaining oil streaks (cycle 11 and 16) from the oil control ring (OCR) [6]

2.2 Challenges related to H_2 combustion known from first SCE testing (S4000)

The first H_2 SCE testing by utilizing an available NG PCU reveals very similar engine reaction regarding lube oil induced combustion anomalies. Figure 5 and figure 7 compare a combustion sequence with LOI. Especially for the H_2 combustion (figure 7) LOI is strongly correlated to the increasing power output. While the engine speed is kept constant the load is increased until the engine stops due to peak pressure events. Because of the very low ignition energy (stoch.) of H_2, (less than 10% compared to NG) the combustion is even more sensitive to disturbances such as oil droplets, hot spots, carbon deposit or remaining mixture in the combustion chamber. For the H_2 combustion the instantaneous LOC was measured by utilizing the C-method. By counting the C-atoms in the exhaust gas, subtracting the C-atoms in the intake air, the oil supply from the combustion chamber remains as the single source of LOC. At the beginning of the measurement, for only moderate load, the LOC signal remains flat. As the load increases punctual LOC peaks become more severe for an engine cycle accompanied by increasing exhaust temperature drops. The oil droplet accelerates the combustion, shifting the combustion center, resulting in an increased mechanical output, thus peak pressure. Figure 7 (bottom) illustrates again the correlation between load and the occurrence of LOI. As the load increases, from loading point 1) to loading point 2), LOI occurs and leads to severe peak pressure events, acceleration of the combustion and therefore to earlier combustions centers.

Besides the oil droplets themselves the carbon buildup around the crown land of the piston becomes even more critical compared to NG combustion. Therefore, the optimization of the PCU regarding oil supply and consumption must address the following two issues. First, the oil paths towards the combustion chamber need to be closed to avoid droplet induced combustion anomalies. Second, the oil accumulation in the top ring groove and around crown land must be decreased to a minimum to reduce the carbon build up within TBO as much as possible to avoid carbon particles igniting the gas mixture.

These findings underscore the necessity of reducing the oil supply and oil consumption, both the global oil consumption, mainly determined by the honing (roughness and oil reservoir) and ring pack design, and the local oil consumption, for instance determined by the design of the third ring. As such, the following efforts focus on the reduction of LOC and further the risk of LOI by optimizing the piston rings and the honing layout.

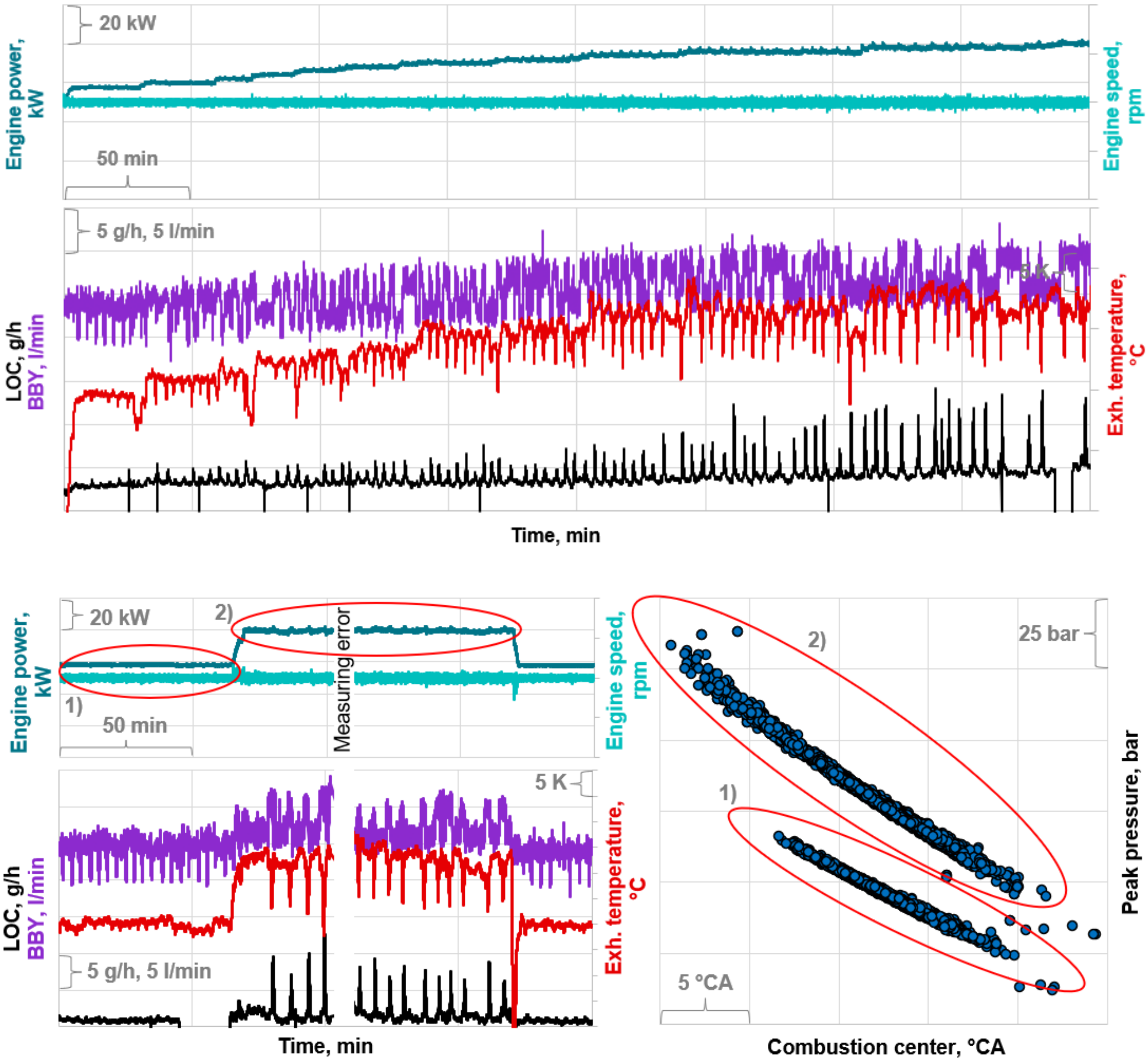

Figure 7. H_2 SCE results: Increasing peaks in LOC signal accompanied by exhaust temperature drops indicating lube oil induced combustion anomalies for increasing engine load (top); Occurrence/extinction of LOI triggered by the engine load (bottom left); Corresponding effect of LOI on peak pressure and combustion center (bottom right) [3]

2.3 Potential improvement of the PCU to increase engine efficiency - theoretical approach

As stated by Tian et al. [7, 8] a "healthy system", including: piston, piston rings, liner and lubricant; provides optimal sealing of combustion gases while maintaining efficient lubrication and minimizing oil leakage, friction losses, and component wear. Providing a minimum amount of oil to the top ring and the harsh region around liner top dead center (TDC) as well as to the lower top ring groove flank are the main challenges the PCU design to address component wear. Key design features are required to maintain this balance:

- Oil paths to the PCU: Efficient oil transport ensures adequate lubrication while preventing excess oil from reaching the combustion chamber. Proper oil drainage pathways are critical to remove oil effectively and prevent accumulation in undesired areas: top ring groove and crown land.
- Circularity of the liner and rings: To ensure effective sealing and uniform contact in circumferential direction, the liner and piston rings must maintain precise roundness. This alignment avoids local oil leakage, minimizes uneven wear, and reduces blow-by.
- Liner surface and oil reservoir: A well-designed liner surface should have optimized texture to support an effective oil reservoir to ensure

minimum oil supply in the highly loaded region around TDC, i.e., promoting sufficient lubrication without excessive oil film buildup. Furthermore, the finish should work harmoniously with the rings to reduce friction.

- Third ring design: The OCR (third ring) must prevent oil leakage by eliminating gaps or non-conforming areas. Its design should ensure consistent contact with the liner in circumferential direction while maintaining efficient oil scraping and drainage functions. For the TLOCR design with almost perfect conformability along the circumference and minimum gap size, the remaining gap seems to be the limiting factor for its overall capability to control the oil film on the liner. Thus, a new design approach is required, that assures non-aligned gaps of the rails.
- Piston/ring pack design: Careful alignment of the piston and ring assembly ensures that axial and radial motions are controlled. Proper ring field design, adjusting inter-ring pressure and blow-by behavior, minimizes ring flutter and suppresses upward oil flow while promoting downward drainage.
- Oil drainage: The oil drainage system should direct oil efficiently back to the crankcase, avoiding accumulation near the ring pack or crown land. This, as well, reduces the likelihood of oil transport into the combustion chamber.

By integrating these elements, the PCU achieves a "healthy system," where gas sealing, oil control, and component alignment work together to enhance combustion efficiency, reduce oil consumption, and prolong the engine's operational life. This comprehensive approach also mitigates carbon deposits and ensures stable operation under a wide range of conditions.

2.4 Development and utilization of the Rolls-Royce development tool chain

The development methodology for the PCU by Rolls-Royce Power Systems is a systematic and holistic approach established to optimize the system performance while minimizing development and testing costs. The process emphasizes a staged progression of tests, starting with simple and cost-effective component-based experiments, before escalating to more complex testing as each stage achieves success.

The development methodology is based on comprehensive fundamental understanding and predictive simulations. These simulation tools, developed in collaboration with the Massachusetts Institute of Technology (MIT), were integrated to the process, enabling precise predictions of gas dynamics, piston ring dynamics, oil distribution and piston secondary motion. These simulations were meticulously validated at each stage with data from component-level tests (e.g., tribometer and floating-liner engine (FLE) experiments), SCE, MCE, and finally, field tests [9, 10].

As illustrated in figure 8, the development workflow begins with elementary tests, such as oscillating and rotating tribometer studies, which are inexpensive and straightforward, before moving on to more advanced experiments like SCE and MCE tests. The complexity and cost of testing increase progressively, culminating in field tests for the final validation. This staged approach ensures that each step builds on reliable data, minimizes risks, and consolidated understanding. This tool chain is incorporated in the design process and the related technology readiness level is evaluated for each testing and validation step.

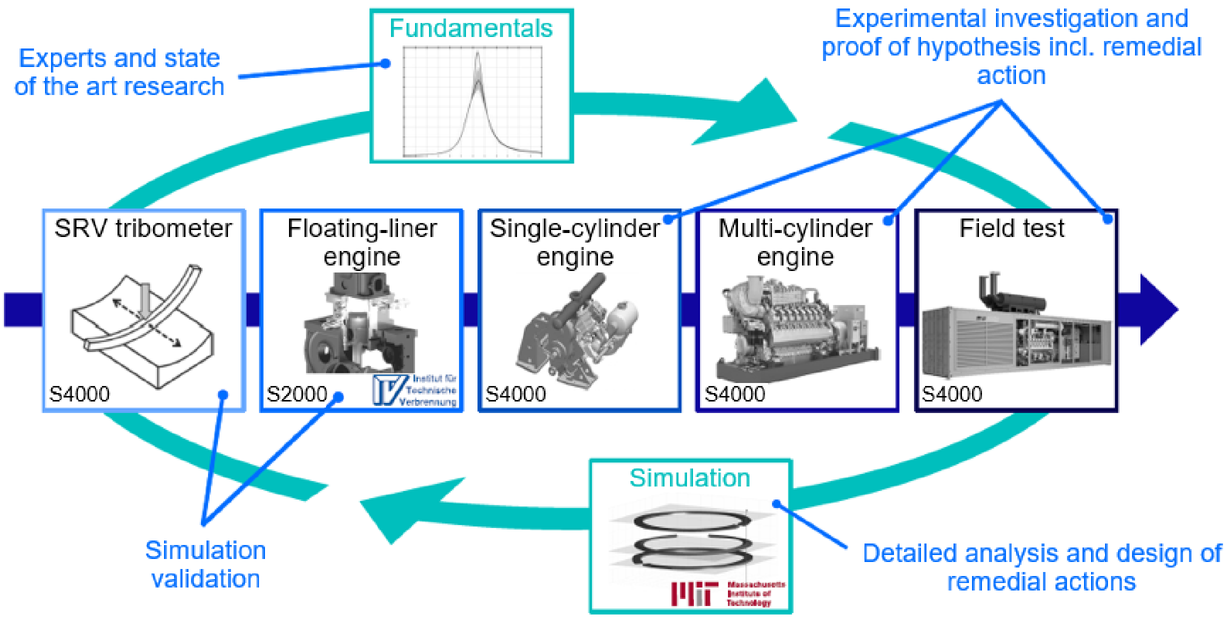

Figure 8. Development tool chain for PCU design and optimization [5]

3 PCU OPTIMIZATION, VALIDATION AND TESTING RESULTS

The following chapter summarizes the most relevant results archived within the project. The PCU redesign was conducted with the focus on minimizing LOC to prevent lube oil-induced combustion anomalies, while optimizing mechanical efficiency and reducing friction and component wear.

3.1 Improvement of mechanical efficiency due to friction loss reduction

From comprehensive inhouse measurement of the engine friction it is known that for the ***mtu*** S4000L64 the friction of the PCU contributes to around 50% of the overall friction power loss [11]. Here around 50% of the PCU friction comes from the piston skirt, depending on speed and loading condition. To reduce friction between piston skirt and the liner surface increasing the cold clearance between both might be a first approach. However, this will result in increased piston secondary motion, thus, piston tilt and lateral motion with higher risk of liner cavitation and noise. To maintain the piston secondary motion, the design of a form honed liner, as already implemented in passenger car applications [13], was developed for the ***mtu*** S4000 size. This new liner design features an increasing bore diameter by tens of microns towards the Bottom Dead Center (BDC).

Figure 9 (right) illustrates the suggested bottle-shape. By superposition of the defined bottle shape to the thermally deformed liner, the liner shape remains almost cylindrical under hot running condition, thus an almost constant operation clearance between liner and piston skirt can be achieved over the entire stroke. By opening the clearance around mid-stroke to the BDC the friction contribution of the piston skirt can be reduced significantly, with only minor effect on the overall piston dynamics. In theory the form honing can be designed as axial symmetrical form at the one end and as 3D-free form with maximum complexity in terms of machinability and cost on the other end.

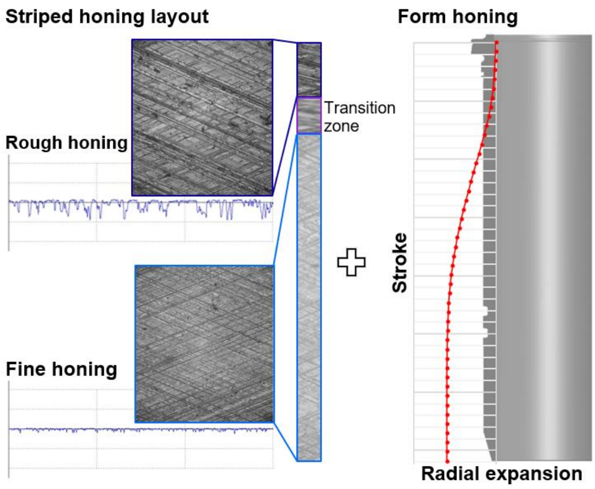

Figure 9. Striped honing layout & bottle-shaped liner

To increase the chance of the technology to be transferred to the series application with a sufficient ratio of benefit to additional cost, the axial symmetrical form was chosen and validated within the MCE testing.

Following the internal tool chain the first idea was modeled in the piston secondary motion simulation and the size and shape of the bottle form were optimized by relative comparison of piston dynamics, piston skirt contact behavior and instantaneous friction power loss. In the second step, the piston design with the desirable piston secondary motion was investigated in the piston-ring and gas dynamics simulation, before being tested in the SCE regarding functionality, LOC/LOI and then forwarded to the MCE for the comprehensive endurance testing. Finally, the solution was validated with over 8000 hours of operational experience in the ***mtu*** S4000L64, without any negative effects on LOC and LOI or wear of the involved tribological systems.

As a major result of the testing, a significant decrease in friction power loss was confirmed and the ***mtu*** S4000L64 engine now reaches 45% mechanical efficiency. Figure 10 compares the relative increase in mechanical efficiency of the cylindrical reference liner with the bottle-shaped liner, including the reproducibility.

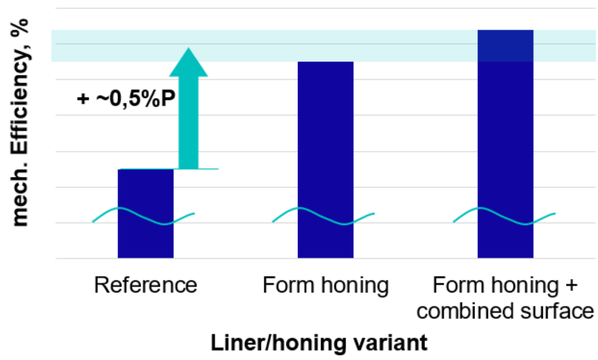

Figure 10. Relative increase in mech. efficiency from ***mtu*** S4000L64 NG MCE measurement

Further advancements in friction reduction were achieved by replacing the standard asymmetric barrel-shaped top ring by a taper-face profile, where the height (h_{MP}) of the minimum contact point between ring and liner is shifted towards the lower edge of the ring running surface, thus increasing the free ring running surface exposed to the combustion pressure, see figure 12. The comparison of the current and optimized design is illustrated in figure 11 (top).

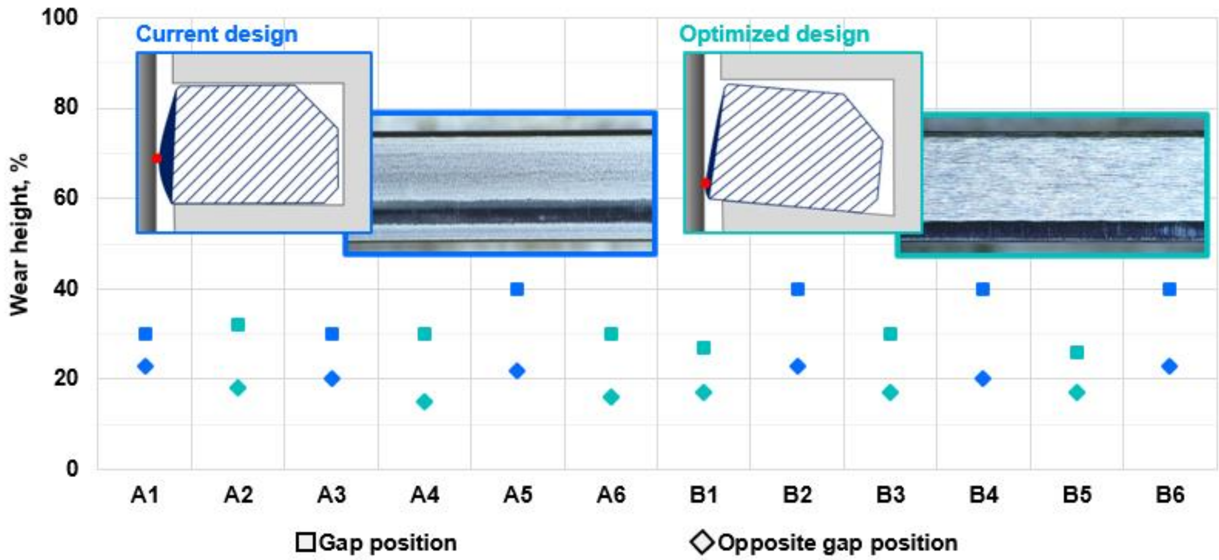

Figure 11. Comparison of the ring cross section: current barrel-shape design vs. optimized taper-face design [5] (top), comparison of axial wear height of barrel-shape vs. taper-face top ring design from ***mtu*** S4000L64 NG MCE testing after 8000 hours

By counterbalancing the rising pressure during late compressing stroke and expansion stroke, this design significantly reduced the radial force on the backside of the ring (F_g, see figure 12) and thus wear on the ring running surface and friction power loss will reduce significantly. Measurements of the worn lower ring groove flank indicated substantial reductions in both radial and circumferential wear.

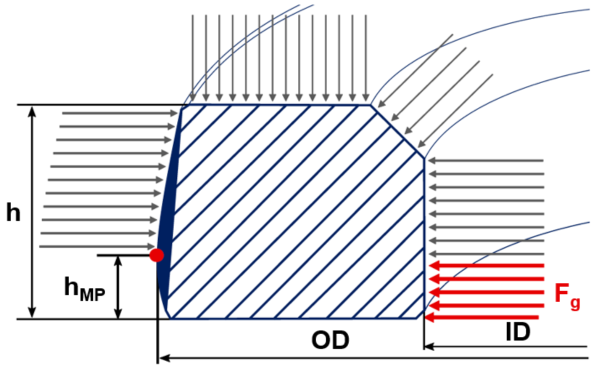

Figure 12. Pressure forces acting on the top ring surfaces [5]

Importantly, this modification decreased LOC, LOI and led to less carbon deposits in the ring groove compared to the reference system. This is because by reducing the resultant radial force, the oil up-scraping effect during late compression stroke is reduced. Consequently, the oil transport towards the combustion chamber from the liner surface along top ring upper flank will decrease, lowering the risk of LOI.

The design was tested and validated with more than 8000 hours of operational experience in the ***mtu*** S4000L64 engine, proving its effectiveness and durability. By comparing the wear pattern on the ring running surface between the reference and the new design, the axial wear height is significantly reduced for the taper face ring profile. Figure 11 summarizes the results of the wear height on the ring running surface of the top ring for 8000 hours operation in the MCE. For each cylinder the wear height at the gap position and opposite the gap were compared for both surface profiles.

3.2 Reduction in lube oil consumption and enhancement of combustion performance

As already indicated in the previous chapter the LOC is highly related to the surface characteristics of the liner surface. Since the reference layout has a rather rough surface, in terms of core roughness (rk), reduced peak height (rpk) and reduced valley height (rvk), the honing provides a huge oil reservoir (figure 13) along the entire stroke, resulting in a very high potential of oil being up-scraped towards the combustion chamber, inducing LOI.

In the first approach the liner roughness was significantly reduced over the entire stroke regarding the structural height to show the potential in LOC reduction by reducing the oil reservoir, see figure 14 and figure 15. However, the homogeneous smooth liner finish may not be robust enough in the top of the liner interacting with the upper and lower compression rings around TDC. To account for these boundary conditions a load/temperature dependent surface layout, concluding and utilizing the results from previous projects [11, 14], was designed. The general design approach aligns with the layout as suggested by MAHLE [12].

The Rolls-Royce Power Systems design, as a striped honing layout, represents a combination of smooth and rough honing surfaces, connected by a narrow transition zone, figure 9 (left). The rough honing ensures sufficient oil is available for lubrication to eliminate excessive wear around TDC, while the smooth honing minimizes oil transport around mid-stroke to the TDC. The exact honing structure, its position, and transitions were simulated using advanced simulation tools developed by MIT and validated through floating-liner experiments conducted at the University of Hannover [14].

The effectiveness of fine honing is further evidenced by the graph correlating the plateau R3p parameter to the structural height R3k, shown in figure 13. This data underscores the superior uniformity achieved with fine honing, reflected in significantly reduced structural variability compared to rough honing. The precise control over honing structure enabled by the striped honing optimally balances lubrication and friction reduction. These results emphasize the effectiveness of fine honing in reducing friction and wear while maintaining durability, which are critical factors in improving mechanical efficiency and operational reliability.

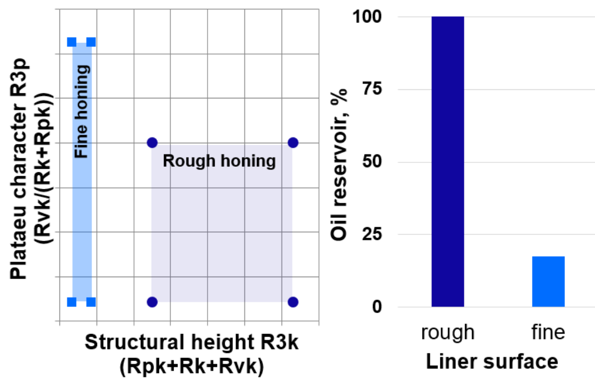

Figure 13. Surface characteristics - Comparison of plateau character vs. structural height (left); oil reservoir for the tested rough and fine honing (right)

Figure 14 highlights the comparison of LOC for rough and fine liner surfaces, tested as stand-alone technology in an H_2 SCE campaign. The results clearly show that the fine honing significantly reduces LOC by 50%, with less fluctuation compared to the rough liner surface. This honing layout was overlaid onto the bottle-shaped liner design displayed on the right side in figure 9, further enhancing its performance and compatibility with the overall engine architecture.

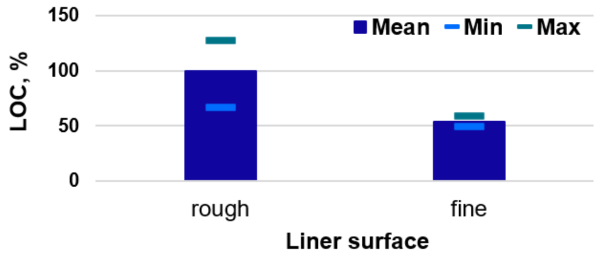

Figure 14. Comparison of LOC reduction for rough vs. fine honing from H_2 SCE measurement

The final validation of these friction reduction strategies within MCE testing for thousands of hours is reflected in the comparative results shown in the figure 15. The graph illustrates the reduction in LOC for the form honing only and the form honing plus the combined surface. Figure 10 shows the increase in mechanical efficiency for the form honing only and the form honing plus the combined surface. The form honing as a stand-alone technology increases the mechanical efficiency significantly, without affecting the global engine LOC or ring and piston dynamics. By adding the striped honing layout cutting the LOC by around 50% compared to the reference can be confirmed. This result aligns with the H_2 SCE results. Contrary to previous measurement the smooth honing does not further reduce friction in a detectable range. This aligns with the research conducted by Liu et. al. [15].

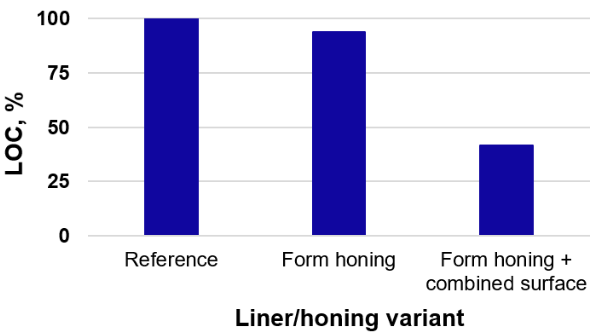

Figure 15. Comparison of LOC reduction: Reference vs. combined surface layout from NG MCE measurement

Nevertheless, these results emphasize the combined benefits of advanced honing techniques and macroscopic liner shape in combination with ring design in enhancing engine performance and durability.

Besides the global LOC already addressed by optimizing the liner layout, the local LOC, especially induced by the gap of TLOCR needs to be reduced as well. Here, the gap area needs to be optimized in a way that the open gap area will be closed within engine operation. Since this requirement regarding gap sealing is well considered for passenger car engines, a solution in the form of a three-piece oil control ring (3POCR) is already available and established for decades [16]. For the H_2 heavy-duty application the utilization of the 3POCR was already suggested by Morgado et. al. [17]. The innovation for the LBE is the scaling of the ring size up to 170mm bore diameter, revealing the main challenges in manufacturing. Thus, the following section of the paper describes the testing results for the utilization of the 3POCR in the ***mtu*** S4000L64 NG SCE, MCE and H_2 SCE.

Figure 16 shows the cross section of both rings comparing the designs of the TLOCR to the 3POCR. For the TLOCR, due to the open gap area, the OCR does not have the capability to down-scrape all the oil from the liner surface along the entire circumferential direction. Thus, a remaining oil streak on the liner surface, as visualized in figure 6 (cycle 11 and 16), at the end of the intake stroke will increase the risk of oil being up-scraped by the top ring in the late compressing stroke. The continuously ongoing oil accumulation on the upper top ring flank and top ring groove, followed by throw-off of oil droplets from crown land towards the combustion chamber, most likely causes LOI.

As the major advantage, for the 3POCR both rails rotate independently to each other, and thus the entire circumference is closed by the upper and/or lower rail, with the capability to down-scrape the oil attached to the liner surface. The condition that both rail gaps align and remain aligned is rare. Thus, oil passing through the lower gap is blocked by the upper rail (or vice versa) and redistributed by the blow-by and inertia force. Potential shape errors along the circumference and the tip area are compensated by the rails. Therefore, the risk of local oil up-scraping, accumulation and throw-off of oil droplets can be significantly reduced.

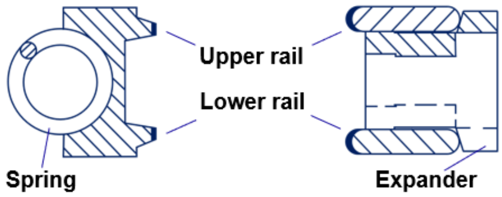

Figure 16. Comparison of TLOCR (left) and 3POCR (right) [16]

For the ***mtu*** S4000L64 NG engine significant progress in reducing LOC/LOI and enhancing combustion performance was achieved through the 3POCR. Top ring, second ring, the piston and liner design remains unchanged for the entire testing campaign. SCE testing using NG revealed that the 3POCR design effectively reduces NO_x emissions and exhaust temperature fluctuations, see figure 17. These improvements indicate a significant reduction in LOC and LOI, empowering the PCU to sustain higher power outputs beyond nominal loads without the risk of LOI.

The 3POCR design has been positively tested in the 12V4000L64 engine over more than 6000 hours, showcasing its long-term viability and effectiveness in real-world applications. These advancements represent a significant step forward in optimizing engine performance and sustainability.

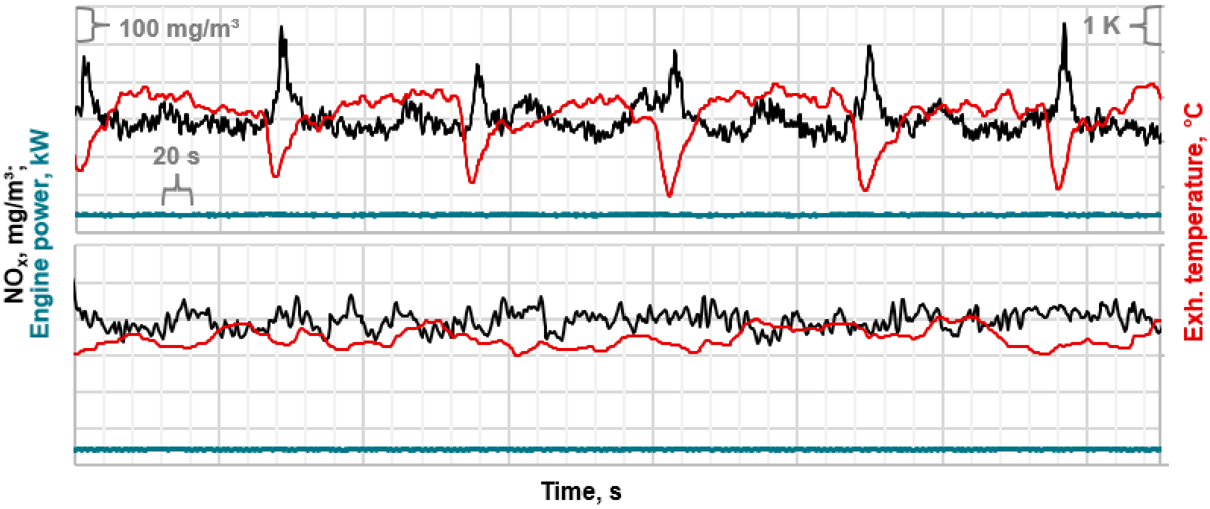

Figure 17. Operational data of combustion (NG SCE) with TLOCR (top) and 3POCR (bottom), NO_x emission and exhaust temperature as indicator for robust combustion

However, the reduction in oil supply introduced an increase in wear on the ring running surface of the top ring. This challenge is being addressed in the second design and testing loop, where the standard top ring will be replaced by a top ring with two different advanced PVD coatings to enhance wear resistance and maintain durability under reduced oil supply conditions. The new coatings currently going through the development procedure and finally will be provided to the MCE for testing and validation. These advancements underline the effectiveness of integrating optimized honing techniques and advanced material coatings to balance LOC reduction and component longevity.

4 CONCLUSION AND OUTLOOK

The continuous development and optimization of todays high-performance ***mtu*** S4000L64 NG engine and the technology transfer to the upcoming H_2 engine are crucial to ensure reliable power supply within the world-wide energy transformation. Since the availability of H_2 is still highly limited and very expensive the already well-known ***mtu*** S4000L64 NG engine can be utilized as a technology demonstrator, the SCE for the proof of concept, and the MCE for the endurance testing regarding LOC, friction and wear behaviour. The challenges within the combustion design process regarding lube oil induced combustion anomalies are similar and transferable between NG and H_2, but more severe for H_2. Thus, all improvements can be utilized and retrofitted to the NG engine and later directly transferred to the H_2 engine. Therefore, all achievements already made are streamlined towards a future high-performance H_2 PCU design. Along with the design process, though consequent in-house research and collaboration with external partners a comprehensive fundamental understanding of the phenomena affecting NG combustion and H_2 combustion was achieved and is still a crucial part of the ongoing activities. Knowing the mechanism behind the occurring combustion anomalies, new technologies can be developed from the idea until the final MCE validation, by consequently applying the development tool chain. By incorporating the LOC measurement, based on the C-method, within the H_2 SCE development a direct comparison of the instantaneous LOC behaviour enables target-oriented optimization of all the components of the PCU affecting the LOC and LOI. As a result, the given baseline PCU was holistically redesigned and tested.

By introducing a form-honed liner design to the ***mtu*** S4000L64 engine the mechanical engine efficiency was increased significantly, now reaching 45%. This technology is already validated for more than 8000 hours in the MCE. By further adding a top ring with taper-face profile the wear of the ring running surface and liner was reduced noticeably. To reduce the global LOC, the rough reference honing was replaced by a very fine honing surface. As a result, the LOC was reduced by almost 50% and the fluctuation in LOC decreases as well. By combining the smooth surface with the well-known rough honing around TDC the robustness of the harsh region was increased significantly.

The implementation of the new 3POCR design reveals high potential to reduce the local oil supply through the ring gap and thus, significantly reduces lube oil induced combustion anomalies leading to a more robust combustion performance with enhanced power output. This effect was already confirmed by NG SCE measurement by running the new design still with the rough honing. The combination with the fine honing layout even reduces LOC and LOI further. The functionality of the new 3POCR design was confirmed within SCE testing and an MCE endurance run for more than 6000 hours.

In the current project phase, the above-mentioned improvements are available as stand-alone technologies, ready to be retrofitted or transferred to other projects. In the final project phase, all these technologies will be incorporated first in the new NG PCU and tested and validated within the MCE as CHP application and second transferred to the high-performance H_2 engine platform. In conclusion, the advancements in the design and efficiency of the ***mtu*** S4000L64 NG engines represent a critical step towards the adoption of H_2 as a sustainable fuel within industrial engines for power generation, supporting Germany's ambitious climate-neutral goals.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

2DLIF = 2D Laser-Induced Fluorescence

BBY = Blow-By

BDC = Bottom Dead Center

CHP = Combined Heat and Power

CO_2 = Carbondioxide

Cyl. = Cylinder

Fg = Gas Pressure Force

FTDC = Firing Top Dead Center

h_{MP} = Height of Minimum Contact Point

ID = Inner Diameter

FLE = Floating-Liner Engine

LBE = Large Bore Engine

LOC = Lube Oil Consumption

LOI = Lube Oil Ignition

MCE = Multi-Cylinder Engine

MIT = Massachusetts Insitute of Technology

NG = Natural Gas

NO_x = Nitrogen Oxide

OCR = Oil Control Ring

PCU = Piston Cell Unit

rk = Core Roughness (Abbott Curve)

rpk = Reduced Peak Height (Abbott Curve)

rvk = Reduced Valley Height (Abbott Curve)

R3p = Plateau Character

R3k = Structural Height

SCE = Single-Cylinder Engine

TBO = Time Between Overhaul

TDC = Top Dead Center

TLOCR = Twin Land Oil Control Ring

Vol.-% = Volume Percent

3POCR = Three Piece Oil Control Ring

6 ACKNOWLEDGEMENTS

The authors would like to express their gratitude for the invaluable support of all colleagues from Rolls-Royce Power Systems project team from Augsburg, Friedrichshafen and Magdeburg to finish this investigation successfully as well as the great collaboration with the Sloan Automotive Laboratory of Massachusetts Institute of Technology. We would like to thank especially Daniel Stecher from Rolls-Royce Power Systems for his extraordinary support, ideas and contribution during this research. Furthermore, we would like to thank MAHLE GmbH for the technical contribution and the provision of the PCU parts.

7 REFERENCES AND BIBLIOGRAPHY

[1] The Press and Information Office of the Federal Government: Promoting climate-friendly and secure energy supply, URL: https://www.bundesregierung.de/breg-en/news/power-station-strategy-2257994, 2024, Accessed on 21.01.2025

[2] Prospero, A.: 100% H2 S4000 engine for PowerGen applications. ATZ Heavy-Duty, On- and Off-Highway Engines 2023

[3] Projektträger Jülich, Forschungszentrum Jülich GmbH: Verbundvorhaben 01253707/1: Phoenix - Entwicklung eines Wasserstoffbrennverfahrens in Industriemotoren zur Dekarbonisierung von BHKW; Teilvorhaben: Motorgesamtkonzept und Brennverfahrensentwicklung, 2023, URL: https://www.enargus.de/pub/bscw.cgi/?op=enargus.eps2&q=%2201253707/1%22&v=10&id=20069067, Accessed on 20.01.2025

[4] Rolls-Royce Power Systems: Power Generation - The Gas-Powered Series 4000. Economical, Sustainable, Reliable, Flexible., 2020. URL: https://www.mtu-solutions.com/content/dam/mtu/download/applications/power-generation/16120795_PG_NaturalGas_S4000_brochure.pdf/_jcr_content/renditions/original./16120795_PG_NaturalGas_S4000_brochure.pdf, Accessed on 6.12.2020.

[5] Koeser, P.: Novel Findings on Lube Oil Ignition and Piston Cylinder Unit for Future Fuel-Efficient Industrial Gas Engines, Phd, Leibniz University of Hannover, 2021

[6] Senzer, E.: Progress report for the consortium on lubrication in internal combustion engines, Massachusetts Institute of Technology, March 2012.

[7] Tian, T., Ahling, S., Liu, Y., Zhang, W.: Developing healthy piston ring pack systems – oil control and its limit, Keynote speech, The Second World Internal Combustion Engine Conference, Shandong, China, April 2021

[8] Tian, T., Shu, Z., Zhong, X., Rabute, R., He, S., Keynote speech, Lubrication of the top ring groove and its effects on friction, wear, oil consumption, and blowby instability in heavy duty engines, in the 31 China SAE Annual Congress and Exhibition, November 11-14, 2024, Chongqing, China

[9] Koeser, P.S., Berbig, F., Pohlmann-Tasche, F., Pasligh, H. et al.: Predictive Piston Cylinder Unit Simulation - Part I: Novel Findings on Cyclic Inter-Ring Pressure Measurements and Piston Ring Dynamic Simulation Validation, SAE Technical Paper 2021-01-0650, 2021

[10] Koeser, P.S., Berbig, F., Pohlmann-Tasche, F., Dinkelacker, F. et al.: Predictive Piston Cylinder Unit Simulation - Part II: Novel Methodology of Friction Simulation Validation Utilizing Floating-Liner Measurements, SAE Technical Paper 2023-01-0415, 2023

[11] Mueller, M., Koeser, P.: Hochflexibles Gas-Genset für eine nachhaltige Energieversorgung, Final-Report, BMWi Program: Das 6. Energieforschungsprogramm der Bundesregierung - Energieeffizienz in der Industrie, MTU Friedrichshafen GmbH, 2021.

[12] Hrdina, D., Maurizi, M., Lemm, B., Kahraman, H., Soares de Faria, G.: Variably honed cylinder liners, iron-based cast pistons and variably coated piston rings as PCU system for friction loss and TCO reduction. In: Siebenpfeiffer, W. (eds) Heavy-Duty-, On- und Off-Highway-Motoren 2019. Proceedings. Springer Vieweg, Wiesbaden. https://doi.org/10.1007/978-3-658-31371-5_7

[13] Merkle, A., Huber, B., Spitznagel, T.: Symmetrische Formhonung in den neuen BMW 3- und 4-Zylinder-Ottomotoren, Reibungsminimierung im Antriebsstrang 2017, Springer Nature, https://doi.org/10.1007/978-3-658-23147-7_5

[14] Pohlmann-Tasche, F., Koeser. P, et al.: Stroke-dependent Coated Cylinder Liners for Large Industrial Gas Engines, MTZ Article, 2022

[15] Liu, Y., Kim, D., Westerfield, Z., Meng, Z., Tian, T.: A comprehensive study of the effects of honing patterns on twin-land oil control rings friction using both a numerical model and a floating liner engine, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology [13506501] 233.2 (2019): 229-255. DOI:10.1177/1350650118774395

[16] Mochizuki, K., Sasaki, R., Yazawa, M., Iijima, N. et al.: Prediction and Experimental Verification for Oil Transport Volume around Three-Piece Type Oil Control Ring Affecting Lubricating Oil Consumption, SAE Technical Paper 2022-01-0522, 2022, doi:10.4271/2022-01-0522.

[17] Morgado, L. et. al.: Dedicated system component development for H2-engines in heavy duty applications. Heavy-Duty, On- and Off-Highway Engines, 2023

8 CONTACT

Frank Berbig
Rolls-Royce Solutions GmbH
Maybachplatz 1, 88045 Friedrichshafen, Germany
Frank.Berbig@ps.rolls-royce.com

9 APPENDIX

The Rolls-Royce business unit Power Systems, headquartered in Friedrichshafen, Germany, employs around 9,000 people. Under the ***mtu*** brand, the company sells high-speed engines and propulsion systems for ships, power generation, heavy land and rail vehicles, military vehicles, and the oil and gas industry, as well as diesel and gas systems and battery containers for safety-critical applications, continuous power generation, combined heat and power, and microgrids. It is the strategic mission of Rolls-Royce Power Systems with its ***mtu*** product and solutions brand to rise to today's challenges in the field of propulsion and energy systems by developing sustainable, climate-neutral solutions.