



Piston Bowl Geometry Optimization For Enhanced Internal Combustion Engine Performance And Emission Reduction: A Comprehensive Review

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Abstract

The design of the piston bowl is one of the key factors influencing flow characteristics, combustion, performance, and emissions in modern diesel engines. With the increasing stringency of environmental emission standards and the need to enhance thermal efficiency, the design of combustion chambers has become one of the most important areas of research in internal combustion engine engineering. The objective of this paper is to provide a review of previous studies conducted from 2018 to 2026, which investigated the effect of piston bowl shapes on internal flow, combustion characteristics, emissions, and the thermal and mechanical effects on the piston. The review focused on analyzing engineering variables such as bowl depth, diameter, and cavity design concerning heat release rates, combustion efficiency, and emissions of nitrogen oxides and soot. Additionally, the review included the most significant numerical models used in combustion simulation, as well as the gaps and future trends affecting the design of combustion chambers.

Keywords: piston bowl, combustion efficiency, (CFD,FEA), Alternative Fuels, Thermo Structural

المخلص

يعد تصميم تجويف المكبس أحد العوامل الرئيسية المؤثرة على خصائص التدفق والاحتراق والأداء والانبعاثات في محركات الديزل الحديثة. ومع تزايد صرامة معايير الانبعاثات البيئية والحاجة إلى تحسين الكفاءة الحرارية أصبح تصميم غرف الاحتراق من أهم مجالات البحث في هندسة محركات الاحتراق الداخلي. يهدف هذا البحث إلى تقديم مراجعة للدراسات السابقة التي أجريت بين عامي 2018 و2026 والتي بحثت تأثير أشكال تجويف المكبس على التدفق الداخلي وخصائص الاحتراق والانبعاثات بالإضافة إلى التأثيرات الحرارية والميكانيكية على المكبس. ركزت المراجعة على تحليل المتغيرات الهندسية مثل عمق التجويف وقطره وتصميمه فيما يتعلق بمعدلات إطلاق الحرارة وكفاءة الاحتراق وانبعاثات أكاسيد النيتروجين والسخام. كما تضمنت المراجعة أهم النماذج العددية المستخدمة في محاكاة الاحتراق بالإضافة إلى الثغرات والاتجاهات المستقبلية التي تؤثر على تصميم غرف الاحتراق. الكلمات المفتاحية: تجويف المكبس, كفاءة الاحتراق, (ديناميكا الموائع الحاسوبية - تحليل العناصر المحدودة), الوقود البديل, التحليل الحراري الهيكلي.



1. Introduction

Diesel engines continue to play a vital role in the transportation, agriculture, marine, and power generation sectors, because of their superior thermal efficiency, durability, and ability to operate under demanding conditions[1]. However, increasingly stringent environmental regulations and global efforts to reduce greenhouse gas emissions have heightened the need to improve engine efficiency while simultaneously reducing harmful exhaust pollutants.

The combustion process in diesel engines is highly dependent on air movement within the cylinder and the quality of the air-fuel mixture during the short combustion period. This makes mixture composition a critical factor that directly affects combustion efficiency, fuel consumption, heat release characteristics, and pollutant formation[2]. Consequently, significant research attention has been directed toward improving the mechanisms that control the flow structure within the cylinder and generate turbulence. The piston bowl geometry is one of the most influential parameters in the combustion process. The shape, depth, diameter, and rim profile of the piston bowl, along with the overall volumetric distribution, control the development of vortices and compression during the compression process. This flow structure determines the effectiveness of the fuel spray's interaction with the surrounding air, influencing ignition delay, combustion duration, peak cylinder pressure, heat release rate, thermal efficiency, and emissions composition. Even relatively small geometric modifications can significantly alter the local flow behaviour and combustion characteristics[3].

3. Piston Bowl Geometry Variations in Diesel Engines.

Advances in combustion modeling using computational fluid dynamics (CFD) and experimental diagnostics have significantly improved our understanding of the relationship between piston bowl geometry and engine performance. Many studies have investigated conventional bowl configurations, while others have proposed innovative geometries aimed at improving mixture preparation, enhancing combustion stability, and reducing emissions[4]. In parallel, the growing interest in alternative fuels has added further complexity, as the effectiveness of piston bowl design often depends on fuel and injection characteristics[5].

Despite significant progress, published studies remain sporadic. Reported results frequently vary due to differences in engine configurations, operating conditions, fuel types, injection strategies, and numerical modeling methods.

Therefore, this review provides a comprehensive and critical assessment of the impact of piston bowl design on diesel engine performance and emissions. It focuses particularly on the relationship between bowl design in the cylinder, flow dynamics, combustion characteristics, pollutant formation, and structural thermal behavior. Additionally, the interactions between combustion bowl geometry, fuel properties, and injection strategies are examined to identify the key parameters controlling engine performance. Finally, current research gaps are highlighted, and future directions are proposed to support the development of next-generation combustion



systems that are more efficient and have a lower environmental impact

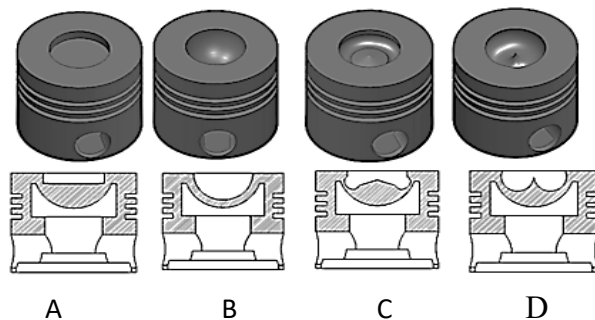


Fig-1 piston bowl shapes,(A)-Flat Bowl Piston,(B)-Hemispherical Bowl Piston,(C)-Re-Entrant Bowl piston,(D)-Toroidal Bowl Piston[6].

3.1. Hemispherical Combustion Chamber (HCC)

The hemispherical combustion chamber represents one of the earliest and most widely adopted piston bowl configurations in conventional diesel engines. Owing to its relatively simple geometry the HCC design promotes moderate air motion and provides stable combustion behavior under a broad range of operating conditions. However the open nature of the bowl limits its ability to intensify turbulence and enhance fuel air interaction often resulting in locally rich regions and incomplete combustion [1] [7] [8][9].

The reviewed literature consistently indicates that HCC geometries generally exhibit lower thermal efficiency and higher Soot, Hydrocarbons (HC) and Carbon Monoxide (Co) emissions than more advanced bowl configurations. Nevertheless the comparatively lower peak combustion temperatures associated with weaker turbulence generation often result in reduced NOx formation[1][4][7][8][9].

3.1. Toroidal Combustion Chamber (TCC)

The annular combustion chamber was developed to overcome some of the mixing limitations associated with hemispherical

designs. Its curved annular shape enhances rotational motion within the cylinder, increasing vortex intensity and turbulence generation. The resulting improvement in mixture homogeneity generally leads to faster combustion, higher thermal efficiency, and less soot formation[7][8][9][10].

Numerous experimental and numerical studies have demonstrated that it exhibits superior combustion characteristics compared to conventional hemispherical combustion chamber designs. However, the enhanced combustion process is often accompanied by higher temperatures within the cylinder, which increases the formation of thermal nitrogen oxides[4][8][11][12].

3.2. Toroidal Re-entrant Combustion Chamber (TRCC)

The toroidal re-entrant combustion chamber (TRCC) has attracted considerable research attention due to its ability to enhance pressure-driven flow and retain the air–fuel mixture within the piston cavity. The re-entrant lip effectively restricts outward flow motion and promotes the generation of intense turbulence during the late compression phase, thereby creating favorable conditions for rapid and efficient combustion. As a result, TRCC designs often achieve higher brake thermal efficiency and lower emissions of soot, hydrocarbons (HC), and carbon monoxide (CO) compared to conventional diesel piston geometries. However, the associated increase in local flame temperature frequently leads to elevated nitrogen oxides (NOx) emissions, necessitating the implementation of NOx mitigation strategies when employing re-entrant combustion chamber designs[4][8] [11][12][13].



3.3. Shallow Depth Combustion Chamber (SCC)

Shallow-depth combustion chambers are characterized by a larger bowl diameter and reduced depth, which enhance radial air motion and improve fuel distribution. Such configurations can promote rapid combustion and high heat release rates, particularly under operating conditions requiring strong squish motion. However, excessive expansion of the bowl may increase fuel transport toward the squish region and cylinder walls, potentially leading to wall wetting and incomplete combustion. Therefore, the effectiveness of shallow-depth combustion chamber designs is highly dependent on injector characteristics, spray targeting accuracy, and operating conditions. Current studies indicate that moderate reductions in bowl depth can significantly improve combustion performance, whereas excessive modifications may adversely affect emission characteristics [3] [13] [14] [15].

3.4. Re-entrant Combustion Chamber (RCC)

Closed-mouth combustion chamber designs utilize a narrow opening that enhances charge confinement and prolongs the residence time of the air–fuel mixture within the combustion zone. This geometric feature intensifies turbulence while simultaneously limiting excessive interaction between the fuel spray and colder wall surfaces [7] [8] [16][17].

Their ability to balance mixture preparation and temperature distribution makes them particularly attractive for applications efficiency and emission control[18].

Consequently, further experimental validation is required before large-scale industrial implementation can be realized.

4. Influence of Piston Bowl Geometry on In Cylinder Flow Dynamics and Combustion Development

Aerodynamic processes occurring within the combustion chamber play a crucial role in determining diesel engine performance, fuel conversion efficiency, and emissions composition. Among the various engine design parameters, the piston bore shape strongly influences the development of vortex compression turbulence intensity and mixture layer formation, which directly affect combustion development and pollutant formation[13][19].

4.1. Influence on Swirl and Squish Motion

Swirl and squish are the primary large-scale air motion mechanisms in diesel engines, governing turbulence generation during the late compression phase and influencing combustion initiation[1][19].

Re-entrant piston bowl geometries with narrow openings (e.g., TRCC) enhance radial flow, air entrainment, and charge confinement, resulting in higher turbulence intensity and improved mixture homogeneity. In contrast, hemispherical and open-bowl designs produce weaker flow structures, often leading to slower combustion and increased soot formation despite more stable thermal distributions. However, excessive turbulence may disrupt spray development and create fuel-rich zones; therefore, an optimal balance between turbulence intensity and spray penetration is essential for maximizing



efficiency while minimizing emissions[4][13][16][17][18].

4.2. Turbulent Kinetic Energy and Mixture Preparation

Turbulent kinetic energy (TKE) is a key indicator of air–fuel mixture quality in diesel engines, as higher levels enhance fuel atomization, evaporation, and mixing, leading to improved combustion characteristics[1][8][13][19]. Advanced piston bowl geometries, particularly toroidal and curved designs, significantly increase TKE by generating strong recirculation zones, thereby improving combustion completeness and reducing Soot, HC, and CO emissions. However, the relationship between turbulence intensity and combustion performance is not strictly linear, as excessive turbulence may destabilize the flame and increase heat losses [4] [8] [11] [20][21]. Furthermore, the role of piston bowl geometry becomes more critical in advanced combustion modes and alternative fuel engines, where combustion stability is highly sensitive to local mixture distribution; under such conditions, controlled turbulence generation is essential for achieving stable and efficient combustion[5][22].

5. Combustion Performance and Emission Characteristics in Diesel Engines

5.1. Brake Thermal Efficiency and Fuel Consumption

Brake thermal efficiency (BTE) is a key indicator of engine performance, with reviewed studies showing that optimized piston bowl geometries generally achieve higher BTE than conventional hemispherical

designs due to improved air–fuel mixing and more complete combustion[4][9][11].

Experimental results also report measurable increases in BTE accompanied by reductions in brake-specific fuel consumption (BSFC), indicating more efficient fuel utilization[4] [7][23]. However, excessive turbulence or improper bowl dimensions may increase heat transfer losses to the combustion chamber walls, partially offsetting these benefits. Consequently, recent research emphasizes geometric optimization rather than merely intensifying in-cylinder flow structures.

5.2. Soot Formation and Particulate Emissions

Soot formation remains one of the most critical challenges in diesel combustion systems. Since soot originates primarily in fuel rich regions characterized by inadequate oxygen availability its formation is highly sensitive to mixture preparation quality and local flow structures.

The reviewed studies consistently indicate that advanced bowl geometries significantly reduce soot formation by enhancing air fuel mixing and improving oxygen distribution throughout the combustion chamber [4] [21] [24]. Reentrant and toroidal configurations are particularly effective because they increase turbulence intensity and promote rapid entrainment of surrounding air into fuel sprays. As a result fuel rich pockets are minimized and soot oxidation processes become more effective.

Several investigations reported substantial reductions in smoke opacity and particulate emissions when TRCC designs replaced



conventional hemispherical bowls[7][11]. Similar trends were observed for biodiesel DME and oxygenated fuels where improved mixture homogeneity further enhanced soot reduction[10][25]. These findings

5.3. NO_x Formation and the Soot–NO_x Trade Off

Advanced piston bowl geometries generally reduce soot emissions but often lead to increased nitrogen oxides (NO_x) formation. Improved mixture preparation and combustion efficiency raise local flame temperatures and oxygen availability, thereby promoting thermal NO_x formation via the Zeldovich mechanism[21][25].

Consequently, configurations that achieve the greatest soot reduction typically exhibit higher NO_x emissions than conventional designs. Studies indicate that TRCC and optimized toroidal geometries provide superior overall combustion performance, albeit with elevated NO_x levels[8][11].

Therefore, the key challenge lies not only in maximizing combustion efficiency but in identifying geometries that balance efficiency gains with acceptable NO_x emissions. Strategies such as split injection, oxygenated fuels, and carefully optimized bowl dimensions have shown potential to mitigate NO_x without compromising the combustion benefits of advanced piston bowl designs[8][10][19][26].

6. Interaction Between Piston Bowl Geometry Alternative Fuels and Injection Strategies

Recent developments in diesel engine research have shifted the focus from isolated geometric optimization toward integrated combustion system design. Increasing evidence suggests that the effectiveness of a given piston bowl configuration cannot be evaluated independently of fuel properties and injection characteristics. Instead

collectively suggest that bowl geometry optimization remains one of the most effective in cylinder strategies for controlling particulate emissions

combustion performance and emission behavior are governed by the complex interaction between bowl geometry fuel chemistry spray dynamics and operating conditions. Consequently modern optimization approaches increasingly consider these parameters simultaneously rather than treating them as separate design variables.

6.1. Interaction Between Bowl Geometry and Biodiesel Fuels

Biodiesel fuels possess physicochemical properties that differ significantly from those of conventional diesel fuel including higher viscosity greater density elevated oxygen content and lower heating value. These characteristics strongly influence spray atomization evaporation behavior ignition delay and combustion development. As a result piston bowl geometry plays a crucial role in determining whether the potential environmental benefits of biodiesel can be fully exploited[27].

The reviewed studies indicate that advanced bowl geometries particularly toroidal and toroidal reentrant configurations effectively compensate for the inherent limitations of biodiesel fuels by enhancing turbulence generation and improving fuel air mixing. Improved air entrainment promotes more complete oxidation of fuel rich regions leading to substantial reductions in smoke HC and CO emissions. Furthermore the oxygen content naturally present in biodiesel complements the enhanced mixing process generated by optimized bowl designs resulting in cleaner combustion and improved thermal efficiency[25].

However the literature also reveals that the improved combustion characteristics



associated with biodiesel and advanced bowl geometries frequently increase combustion temperatures thereby promoting NO_x formation. This behavior demonstrates that the traditional soot–NO_x tradeoff remains relevant even when oxygenated

6.2. Oxygenated Fuels: OME and DME

Among emerging low-carbon fuels, oxymethylene ethers (OME) and dimethyl ethers (DME) have attracted significant research attention due to their exceptionally clean combustion characteristics. These fuels contain oxygen, which enhances combustion completeness and significantly reduces soot formation[26]. studies indicate that piston bore geometry affects OME and DME combustion differently than conventional diesel engine operation[21][26]. Since soot formation is inherently limited with these fuels, engineering optimization focuses primarily on improving thermal efficiency, controlling nitrogen oxide emissions, and managing heat release characteristics, rather than reducing particulate matter.

These findings suggest that future piston bore designs may need to be specifically tailored for oxygenated fuels rather than adapted from conventional diesel engine designs. Therefore, the growing interest in carbon-neutral fuels is expected to stimulate the development of new, optimized engineering concepts to meet the specific combustion requirements of each fuel type.

6.3. Coupling Between Bowl Geometry and Injection Strategies

Fuel injection parameters significantly influence the effectiveness of piston bore design. Therefore, piston bore design and injection strategy should be considered as two complementary design variables [29] [30].

renewable fuels are employed. Consequently optimal biodiesel utilization requires simultaneous consideration of bowl geometry injection timing and operating conditions[28].

Studies show that split and multi-injection strategies significantly improve combustion control when combined with optimized piston bore designs[31]. By distributing fuel delivery across multiple injections, these strategies reduce peak local temperatures and improve mixture gradients[32].

Spray angle also plays a crucial role in determining the interaction between fuel jets and piston bore surfaces. Very wide spray angles can lead to increased fuel wall collisions and deposition within the pressure zone, while very narrow spray angles can result in localized rich mixtures and high heat concentrations[3][33]. Similarly, the injection nozzle diameter and injection pressure significantly affect atomization quality and spray penetration. Several studies indicate that improving these parameters in conjunction with combustion chamber engineering improves fuel efficiency, reduces combustion time, and enhances overall engine efficiency[12][15].

7. Thermomechanical Performance and Material Considerations

Although piston bowl geometry is primarily optimized to improve combustion efficiency and emission characteristics its influence extends beyond combustion related phenomena to include thermal loading structural integrity and component durability [34]. Modifications that enhance turbulence intensity and combustion effectiveness often alter temperature distribution heat flux pressure loading and stress concentrations within the piston [35] [36]. Consequently the thermomechanical performance of piston



systems has become an increasingly important consideration in modern combustion chamber design[35].

7.1. Thermal Behavior of Piston Bowl Geometries

The combustion chamber is constantly subjected to harsh thermal conditions. Published studies indicate that advanced piston cavity shapes generally produce higher local temperatures than conventional designs due to improved combustion completeness and increased heat release rates[13][38]. Annular and concave configurations often generate high temperature gradients near the cavity rim and the combustion zone, where intense combustion activity is concentrated. While these temperature increases typically contribute to increased thermal efficiency, they can simultaneously accelerate thermal stress and material degradation.

Numerical studies have shown that the temperature distribution is highly sensitive to the depth of the cavity shape and the rim configuration. Geometric shapes that effectively confine combustion within the bore zone tend to minimize temperature heterogeneity across the piston head, whereas poorly optimized designs can lead to localized hot spots that increase thermal stresses and shorten component life [13] [33] [39]. These observations highlight the importance of evaluating thermal behavior in conjunction with combustion performance, rather than treating them as independent design objectives.

7.2. Structural Response and Stress Distribution

Finite element analyses reported in the literature demonstrate that stress concentrations are strongly influenced by piston bowl geometry[39][40][41]. Regions surrounding the bowl rim, bowl lip, and piston crown commonly experience the highest stress levels because of geometric

resulting from combustion cycles and high gas temperatures. Since the piston cavity shape directly affects flame development, heat release rates, and local temperature distribution, it also influences thermal loading patterns throughout the piston structure [37][38].

Discontinuities and localized pressure loading. Consequently, modifications intended to improve combustion characteristics may unintentionally increase structural stresses if performed without considering mechanical constraints.

These findings emphasize that combustion chamber optimization should not focus exclusively on performance and emissions but should also incorporate structural considerations to ensure reliable engine operation.

8. Influence of Piston Materials

The growing demand for higher combustion efficiency and elevated peak pressures has increased interest in advanced materials capable of withstanding severe thermal and mechanical environments. Aluminum alloys remain the most widely used piston materials because of their low density, favorable thermal conductivity, and manufacturing flexibility[34][40].

Comparative studies evaluating aluminum alloys such as Al2618, Al4032, and Al7178 have demonstrated significant differences in stress distribution, thermal deformation, and fatigue resistance[40]. Similarly, investigations comparing aluminum and steel pistons revealed that steel designs offer superior strength and reduced thermal deformation but are associated with increased mass and manufacturing complexity[34].

The reviewed literature suggests that optimal piston performance depends not only on geometric design but also on the compatibility between material properties



and combustion chamber operating conditions.

8.1. Coupled Thermo Structural Assessment

Recent advances in computational modeling have enabled the development of coupled thermos structural simulation frameworks that simultaneously evaluate combustion behavior heat transfer temperature distribution and structural response. Several recent studies have employed integrated CFD,FEA methodologies to investigate the combined influence of piston bowl geometry on combustion and structural performance[38]. These studies consistently demonstrate that the most effective piston designs are those capable of balancing thermal efficiency emission reduction and structural reliability simultaneously. CFD-based studies dominate the field but often rely on simplified turbulence, spray,

and combustion models, with validation frequently limited to in-cylinder pressure data, which reduces predictive reliability for detailed flow, temperature, and emission fields.

Furthermore, combustion and durability analyses are typically treated separately, even though improved combustion performance often increases thermal loading and structural stress, highlighting the need for integrated multiphysics approaches.

The growing use of alternative fuels such as biodiesel, hydrogen, DME, and OME further exposes the lack of fuel-specific piston bowl optimization, as most geometries were originally designed for conventional diesel.

Addressing these gaps is essential for developing robust, efficient, and low-emission next-generation combustion systems

Table 1. Classification of Reviewed Studies According to Research Focus, Investigated Parameters, and Performance Indicators

Research Theme	Investigated Parameters	Evaluated Performance Indicators	Representative Studies
Impact of Combustion Chamber Geometry on Engine Performance	Piston bowl geometry, bowl depth, bowl diameter, re-entrant lip, toroidal chamber, hemispherical chamber, combustion chamber volume	Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), Peak Cylinder Pressure, Heat Release Rate (HRR), Ignition Delay, NOx, Soot, CO, HC	[3][11][15][18][20]
Advanced Combustion Mode Impact on Engine Performance	Multiple injection, pilot injection, split injection, post injection, HCCI, PCCI, RCCI, LTC combustion strategies	Combustion duration, ignition delay, HRR, pressure rise rate, thermal efficiency, fuel consumption, NOx, soot, HC, CO	[8][28]
Alternative Fuel Impact on Engine Performance	Biodiesel blends, hydrogen enrichment, methanol blends, ethanol blends, biogas-diesel dual fuel, OME fuel, renewable fuels	Thermal efficiency, combustion stability, fuel consumption, emissions, peak pressure, combustion characteristics	[11][28]

Table 2. Comparative Assessment of Combustion Chamber Geometry, Advanced Combustion Modes, and Alternative Fuels on Engine Characteristics

Research Theme	Impact on In-Cylinder Flow	Impact on Combustion Characteristics	Impact on Emissions
Combustion Chamber Geometry	Very High	Very High	High



Advanced Combustion Modes	Moderate	Very High	Very High
Alternative Fuels	Low to Moderate	High	Very High
Combined Optimization Approach	Very High	Very High	Very High

Table 3. Comparative Characteristics of Common Piston Bowl Geometries

Bowl Geometry	Swirl Intensity	Squish Effect	Mixing Quality	Thermal Efficiency	NOx Emissions	Soot Emissions
Re-entrant Bowl (RCC)	Very High	High	Excellent	Very High	High	Very Low
Toroidal Combustion Chamber (TCC)	High	Moderate	Very Good	High	Moderate	Low
Hemispherical Combustion Chamber (HCC)	Moderate	Moderate	Moderate	Moderate	Low	High
Shallow Bowl Chamber	Low	Low	Poor	Low	Low	Very High
Multi-Spherical Bowl	High	High	Very Good	High	Moderate	Low

9. Conclusions

This review provides a comprehensive critical assessment of the impact of piston cavity geometry on cylinder airflow dynamics, engine performance, thermomechanical behavior, and emissions. The results confirm that cavity geometry is a key factor in air-fuel mixing efficiency, contributing to increased vortex intensity, compressional motion, and turbulent kinetic energy. This translates into greater mixture homogeneity, accelerated heat release and combustion rates, increased cylinder compression and thermal efficiency, and reduced specific fuel consumption.

Environmentally, improved combustion chamber flow contributes to reduced emissions by enhancing oxygen availability and minimizing fuel-rich zones. Structurally, cavity geometry significantly influences the heat distribution and mechanical stresses of the piston, making thermomechanical evaluation a cornerstone for ensuring durability and reliability. Combining artificial intelligence, machine learning, and multi-objective optimization techniques with finite element analysis (FEA) in computational fluid dynamics simulations offers a promising avenue for

developing combustion chambers that achieve a delicate balance between energy efficiency, emissions reduction, and structural sustainability.

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