# WORKING LIFE OF DIESEL ENGINES: A RETROSPECTIVE ANALYSIS (PART 2)

***Sirotenko, Igor V.,*** *JSC «VNIIZhT» (All-Russian Scientific Research Institute of Railway Transport), Moscow, Russia.*

***Gogrichiani, Georgy V.,*** *JSC «VNIIZhT» (All- Russian Scientific Research Institute of Railway Transport), Moscow, Russia.*

## ABSTRACT

This is the final part of the review article (for the first part see World of Transport and Transportation, 2014, Vol.12, Iss. 6, pp.212–221) showing that diesel engines of the first post-war II generation were characterized by inherent structural deficiencies of new developments, unfinished ideas. The results of studies carried out in that period are considered, technical solutions taken at that time are critically analyzed, including those that aimed at addressing identified problems. The analysis allowed the authors, in particular, to draw conclusions that for this generation of diesel engines brands of used metals, wear resistance and fatigue strength of cast iron, features of bearing fillets, cylinder block group, the quality of welded joints had the fundamental importance. As follows from the obtained data, engine components are not equal in their impact on engine reliability and working life, form their levels of importance, have their own «place» in the design of the engine structure as a system.

Keywords: *railway, history, diesel locomotive manufacturing, diesel locomotive, working life, failures, retrospective analysis, regularities of the postwar generation.*

**Background.** *This article further investigates diesel engines of the first post-war generation. The first part can be found in the previous issue of the Journal.*

**Objective.** *The objectives of the authors are to investigate diesel engines of the first post-war generation, find out their advantages and disadvantages and to draw a conclusion on their working capacity.*

**Methods.** *The authors use historical retrospective method and engineering analysis.*

**Results.**

***2.***

*At the beginning of operation, it became clear that the locomotives with diesel engine 2D100 (series TE3, TE7) with regard to their power and traction qualities were not sufficiently capable to work with trains of normalized weight. Estimated traction and speed did not meet current requests of railways, and even more so – the requirements for the future. Calculations showed that a locomotive was required to have power of sections of 3000–4000 hp each, while keeping previous mass-dimensional parameters of diesel, so as not to raise weight of a coupled locomotive [1].*

*To solve this problem, there were two ways: forcing of the diesel 2D100 from 2000 to 3000 hp, which in those years, apparently, seemed the promptest and the most rational variant or development of a new engine, fundamentally different structurally, with a prospect for a power range.*

*The forced diesel 10D100, created by the first embodiment, largely repeats its predecessor 2D100. On the new diesel a two-stage boost air charging system is applied, one stage consists of two turbochargers type TK34, working in parallel, water coolers of the charged air, another stage is a gear-driven centrifugal-type supercharger. To control complex power system a first common regulator, controlling both rotation frequency and power, was mounted. The design of the main load-bearing components and engine mounts remained unchanged, the developers thought that strength margin would be sufficient [2].*

*At the same time the works on the enforcement of the second alternate solution were carried out. Kolomna Plant built a new diesel 11D45 with capacity of 3000 hp, the most advanced at that time by its performance indicators: with the classic V-shaped arrangement, suspended hardened (nitrided) crankshaft, welded-cast steel cylinder block, crank mechanism with the auxiliary connecting rod. The prototype was a marine diesel of type 30D created five years earlier, and commissioned by the Navy.*

*Engines 30D and 11D45 organically entered then modern range of engines, which appeared in the US, Europe and had features of a forced engine (level of mean effective pressure), used powerful charging sets, providing a high level of charged air pressure. It should be noted that for a medium-speed diesel power of 3000 hp was extremely high for all engine-building companies.*

*As for the design, new engines, manufactured at that time in the country, significantly predominated their predecessors, more advanced design and technological solutions were used for their construction, they are conventionally called* **second-generation** *diesel engines.*

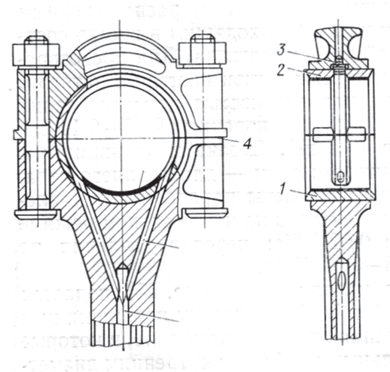
*Diesel 10D100 does not belong to this generation, only indices of air supply, efficiency, control devices comply with the level. Logically, after a short time the engine had to give way to more modern samples, but it did not happen.*

*The most problematic diesel parts were pistons, cylinder liners, the system «crankshaft-bearing».*

*For a more powerful 10D100 a new design of piston of option 27 was proposed, a thin-walled, made of gray cast iron alloy. The piston had an annular shape of the bottom, which formed a combustion chamber of symmetrical shape close to the Hesselman's shape. This ensured a reduction of the maximum combustion pressure of 5–6 kgf / cm $^2$, the ability to increase internal volumes and freely arrange the cavity to cool the piston. The designers returned to the inertial cooling method as in the original version of the diesel engine 2D100 [3].*

*Three-year operating experience showed that this type of pistons again was short-lived one, and had the same faults as the piston 14B: cracks in stack bolts under tie rods, in streams of piston rings, sickle-shaped cracks of the bottom. Average service life turned out to be 1, 5 times shorter than that of 14B, during repairs with lifting of the locomotive, 33–38% pistons were replaced [4]. It was required to urgently develop pistons of options 3 and 3A with a more intense cooling of the head through the use of oil circulation (3) in the central part and the internal radial finning (3A).*

*Failures of the option 3 should be emphasized particularly. Nature of the damage remained the same, a number of pistons, failed before first regular repair with locomotive lifting reached 23%, and num-*




**Pic. 1. Lower head of the crank rod of the diesel 10D100: A – sloping channel for supplying lubricant to the piston; B – the axial channel; C – groove-less part of the bearing; 1 -insert with a partial groove; 2 – insert with an annular groove; 3 – pin; 4 – connector.**

*ber of scratches of cylinder liners increased dramatically, while they had been once rare. Since 1967, this type of defects of pistons and cylinder sleeves became widespread [5]. In essence, the situation worsened since, as together with the scratch of the lateral surface of the piston scuffing cylinder liner failed. This was caused by use of new alloyed cast iron, which had a greater ability to irreversible changes in the volume under cyclic temperature changes. The gradual increase in the diameter of the piston head to 0,8–1,2 mm resulted in predictable consequences.*

*After failures of the piston of the option 3 VNIIZhT proposed option 1C, initially for a diesel engine 2D100. The design was more workable because it managed to solve the problem of heat dissipation and to avoid stress concentrators. Its main features were: the rejection of the bottom profile, entered from the option 27; return to the «cup» as at the piston 14B; exclusion of the pins, tightening the spacer and the piston head and causing additional mounting tension; introduction of cooling of circulation type with two oil streams moving symmetrically to the axis of the combustion chamber [6].*

*Thus, design solutions, which strongly increased efficiency and durability of the piston 10D100, were efficient cooling system, ensuring uniform cooling of its head across the surface, and the exclusion of tightening pins from the design.*

*On diesels type D100 up to 24 thousand cylinder liners were replaced each year, and cracks (56%) and scratches of the working surface (27%) prevailed among failures. Cracks were of a fatigue character and were developed in the area of openings for the so-called adapters – tube sections, in which injector components were installed. Cracking has been reduced due to structural reinforcement of the sleeve in the area of holes and by technological measures [7]. A more complex problem was the removal of scratches of the working surface of pistons and sleeves.*

*Previously marked increase in scratches was caused not only by the properties of alloyed cast iron. The main causes of scratches, as experimentally proved, were deformation of the liner, and because of that piston contacted liner's wall. These deformations are specific to diesel 10D100, they were caused by the forced character of the engine, resulting at a number of operation modes in unexpected heat of conjugate parts – mounting seats, place in a block of diesel, exhaust manifold [8].*

*Changes were made in the design of conjugate parts (mounting seats in the diesel block, cases, exhaust manifold) in order to minimize relevant causes of failure of cylinder liners (thermal deformations of walls during heating).*

*Another drawback was the increased number of failures within node «crankshaft-bearing». During 1963–1967 a number of diesels 10D100, on which scratches of rod and main bearings were observed, amounted to 10% of in-service bearings [9]. Loads on the bearings of the engine were increased by 1,5 times as compared to less forced 2D100, and the deterioration of working conditions contributed to the unfavorable, badly bedding in metal structure of the necks of the shaft of ductile iron.*

*What is the design of the bearing? It included suspension of the crankshaft, lower head of the crank rod had flat connectors (Pic. 1, position 4), characteristic of the early designs of engines (first generation), in more recent designs the connector due to insufficient stiffness was transformed into ridged: the spline joint with an angle at the vertex from $60^0$ to $90^0$. The bearing had a sufficient high-ratio of main design parameters of width and diameter – a necessary condition for enabling work, in its middle part there was an annular groove. Inserts had soft, easily bedded in and relatively quickly worn coating of babbitt BK-2.*

*Designers decided: axial channel B in the crank rod pin, through which oil was supplied to the piston, was drowned, instead of it two inclined channels A were drilled, which went to the annular groove, and thus in the center of the insert zone without groove was formed B in [9,10]. Due to increased area of the working surface of the bearing, the minimum film thickness increased by 1, 5–2, 5 times. In addition, treatment of surface of crankshaft journals Rz was increased from 8–9 to 4–6 microns. These steps fully reduced tendency of a bearing to be scratched. In addition transition was performed to the engine oil M14V with a higher kinematic viscosity of 14 cSt as compared to the previously used (12 cSt) [11].*

*We can say that the most important acquisitions were the development of the working surface of the bearing (the exclusion of the groove in the center), improvement of treatment of surface of crankshaft journals, the transition to higher quality engine oil.*

*The main problem of the new second-generation diesel engine 11D45 were failures of pistons. In calculation per one engine from 6,5 to 11 pistons (of sixteen) were replaced annually, the maximum outturn fell to the mileage of 150–200 thousand km [11]. The main reason for failures (about 80%) was associated with the development of cracks along the ridge of the bottom of the piston head, the so-called «pockets» and sickle through cracks like in the pistons of the option 27 [4, 12].*

*The initial design of the piston is composite (Pic. 2a), the head was made of ductile alloyed cast iron Mg (1), a trunk was made of an aluminum alloy (5). It was cooled by circulating oil supplied through the apertures of the crank rod into the central upper cavity, then into cavities at the edges of the head.*

*At the first stage of modernization oil supply was improved, the head of the piston was made of heat-resistant steel 2X13 instead of cast iron, however, it was not possible to significantly reduce failures. As a temporary solution the order was introduced in which heads were replaced forcefully at the run of 125–150 thousand km. Work on the pistons were resumed in the early 1970s. An improved piston was structurally quite different from the original (Pic. 2b): wall thickness of the piston head (A) was re-*

duced, the central cavity (B) was significantly increased by reducing the size of the chamber, finning was made, volume of cavities- pockets (B) was increased. Motor oil with antivarnish additives (M14VTS) came into use, which contributed to the improvement of the thermal state of the pistons.

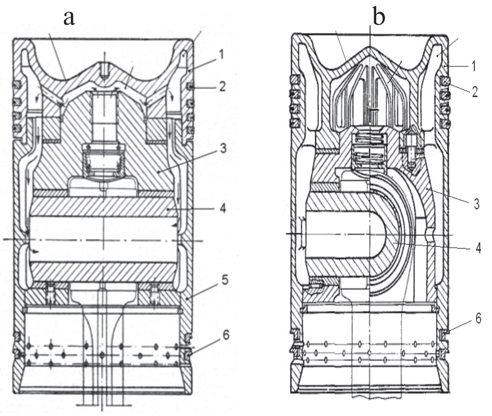
Designers, apparently, did not follow the ways of increasing the heat resistance of the material of the head, but applied thermally conductive material – alloyed cast iron and provided more heat dissipation due to more effective inertial head cooling [13, 14]. In the new piston (Pic. 2b), the head and trunk are molded together, because there is no need in heat-resistant alloy. There are similar pistons of Kolomna Plant for diesel engines and of VNIIZhT – for repair enterprises.

So, at that time the solution of the problem of reliability of the pistons of diesel engines 11D45 was reduced to the use of efficient cooling system of the head (inertial), to increase in cavities pockets, to development of cooling surface due to finning, to use of thermally conductive material (alloyed cast iron) and anti-varnish additives for motor oil.

Over time, structural defects of the crankshaft became apparent in diesel engines 11D45, ultimately led to a reduction of the resource. Failures began to emerge at an operating time of over a million kilometers. The share of crankshafts, discarded during overhaul, was 16–25% of the totally received crankshafts, that is on average two to three times higher than that of the most common type diesel engines D100. The main reason (66%) is fatigue cracks and fractures on the crank pins.

As the analysis of the factors affecting the working conditions of the shaft [15] showed, the failures were caused primarily by the growing deterioration of its support units – suspensions with a gear connector. The majority of previously operated suspensions received a fatal draw of screw bolts (reduction in tightening force by 37–50%), and closer to overhaul time wear of cloves of the connector and misalignment beyond the permitted limits were observed, thus indicating a strength unsafety of the structure.

Check of a strength version, apparently, was first performed by calculation using then the most advanced method, in which the crankshaft was regarded as a continuous spatial statically indeterminate elastic system. The maximum bending stresses were calculated in the zone of the interface fillet of the web and journal of the crankshaft (the most intense section at bending), evaluation criterion was the safety factor for endurance of journals of crank portions of shaft.

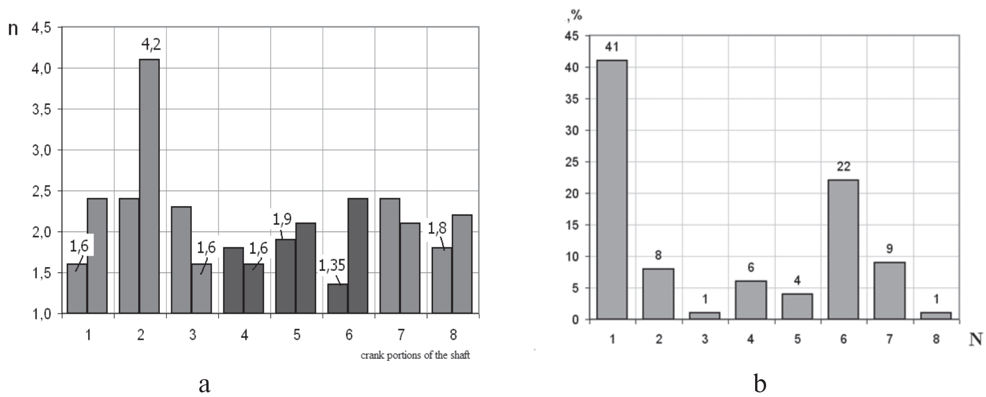



**Pic. 2. The piston of the diesel 11D45: a) the original design (1959); b) solid-cast design of VNIIZhT. 1 – head; 2 – compression ring; 3 – insert; 4 – piston pin; 5 – trunk; 6 – scraper ring; A – bottom, B – inner cavity, C- side pocket.**

The test results confirmed that the misalignment dramatically weakened the structure of the shaft. Pic. 3a shows the values for the right and left journals of each crank portion of the shaft, out-of-alignment support groups marked in a dark color. Reserves at the endurance margin in the middle of the shaft on crank portions 1,3,4 fall to n = 1,6, on the shaft 6 – to n = 1,35 (Pic. 3a).

Emphasis is placed on some contradictions. The greatest number of failures (41%) falls on the first crank pin with minimal endurance margin n = 1,6 (Pic. 3b), twice as likely fails the sixth crank pin (22%) with n = 1,35, the lowest number of cases falls on the third crank pin (n = 1,6), the eighth (n = 1,8), the fifth (1,9), the fourth (1,6). In other words, with the same margin coefficient the first crank pin has maximum damage rate, the third and the fourth have minimum damage rates. More likely, the working conditions of the crankshaft were strongly influenced by other factors, by, for example, residual stresses, as mentioned above.

Surface hardening of the shaft fillet by rolling was introduced, like for shafts of the diesel D100; the position of the shaft during manufacture and repair of the unit began to be controlled by optical devices, rather than using a false shaft, which gave a great error. These and other taken measures softened the situation with damage rate of shafts, but could not solve the problem finally.




**Pic. 3. a –coefficients of endurance n on the left and right crankshaft journals of the diesel 11D45 at disalignment in bearing supports 4, 5, 6; b – distribution of damage of crankshafts (cracks, breaks) on the crank pins, in% of those faulty, according to data of [15]. N – serial number of the crank pin.**

*In summary, it can be noted that the analysis of the calculated and experimental data shows that a construction of the suspension mounting group with a gear connector was unpromising, for durable work of the unit «crankshaft-bearing» it was required to strengthen the suspension of the shaft, to rework it significantly to avoid deformation and wear of kinks, and to start hardening of the crankshaft, or to change the material of the shaft from iron to steel.*

*Design solutions, fundamentally important to ensure trouble-free and durable operation of the second generation of diesel engines, must be recognized:*

*1. Selection of an effective cooling system for the piston head (discharging for 10D100 and inertial for 11D45) for its uniform cooling over the entire surface (circulation type with two streams of oil moving symmetrically to the axis of the combustion chamber), the use of thermally conductive material (alloyed cast iron) and anti-varnish additives to the engine oil.*

*2. Development of the working surface of the bearing by eliminating the groove in the center, the improvement of treatment of the surfaces of crankshaft journals from 8–9 to 4–6 microns, the transition to high viscosity engine oil.*

*3. Strengthening the suspension of the crankshaft to avoid deformation and wear of a gear connector, the use of a steel crankshaft.*

*4. Reduction of thermal deformation of parts adjacent to the cylinder sleeve: of mounting seat of the case, cylinder block, exhaust manifold.*

**Conclusions.** *The article presents a study on the reliability and service life of diesel engines in the post-world war II period of their development. The retrospective analysis helps assess the direction and character of design ideas, perspectives of development of engine industry.*

*The material, presented in two parts of the article,, gives a reason to conclude that the nodes or groups of engine nodes form conventional levels on the importance and impact on the performance, or the hierarchy, the account of which is advisable when creating new and modernizing existing diesel engines. The elements of this hierarchy are:*

*(1) a crankshaft, bearing assembly of the crankshaft in the cylinder block, working bearing inserts;*

*(2) a piston, a cooling system;*

*(3) engine oil, anti-varnish additives;*

*(4) cylinder sleeve.*

*Logical and common conclusion is the following: in the development of new diesel engines it is necessary to pay attention to the priority of some nodes in relation to others, to compare technical requirements for them according to the established hierarchy of importance and risks.*

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Information about the authors:

**Sirotenko, Igor V.** – Ph. D. (Eng.), senior researcher at the department of Traction rolling stock of JSC «VNIIZhT» (All-Russian Scientific Research Institute of Railway Transport), Moscow, Russia, sirotenko.igor@vniizht.ru.

**Gogrichiani, Georgy V.** – D. Sc. (Eng.), professor, head of the graduate school of JSC «VNIIZhT» (All-Russian Scientific Research Institute of Railway Transport), Moscow, Russia, +7 (499) 260–41–32.


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