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The Chamber Cooling System of RD-170 Engine Family: Design, Parameters, and Hardware Investigation Data

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Up to now many aspects of a multiuse booster stage for the next generation rockets still remain the subject of research and discussions. One of the issues is selection of propellant, where amongst its selection criteria is possibility of insuring reliable chamber cooling during multiple flights. This article describes the main structural elements and parameters of the chamber cooling passages for RD-170 family of LOX/kerosene engines. Also, herein are evaluation results of chamber hardware after multiple hot fire tests.

I. Introduction

During the period of 1976 to 1987 NPO Energomash developed the RD-171 engine for Zenit launch vehicle (LV) and its modification RD-170 for multiuse booster stage of Energiya LV. RD-171 was certified for single flight use; RD-170 – for 10x reusability. The distinguishing feature of these engines is four chambers.

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Subsequently, in 1995–2002 a 2-chamber derivative engine RD-180 was developed for Atlas LV family; in 2002–2004 – RD-171M, modification of RD-171, for Sea Launch Zenit 3SL LV; the development of single-chamber RD-191 is underway for Russian Angara LV.

All engines of this family feature oxidizer-rich staged combustion (ORSC) and have chambers of same design. This chamber with nominal (design) thrust of 1814.1 kN at sea level (1975.9 kN in vacuum) has uniquely high pressure level of 24.7 MPa and specific impulse of 337.2 seconds in vacuum and 309.5 seconds at sea level.

Actual margins for all loading parameters of the chamber enabled increasing nominal values of designed thrust by 5% for RD-180 and RD-191 engines and mixture ratios from 2.62 to 2.72 for RD-180 and to 2.75 for RD-191.

Combustion stability and cooling reliability of the chamber were validated in the thrust range of 110% - 25% and in the mixture ratio range of 1.8 – 3.2.

More than 1,200 chamber samples have been manufactured and approximately 4,500 fire tests have been conducted through all years.

Three kerosene types can be used as the fuel for this chamber: (1) Russian rocket fuel RG-1; (2) Russian jet kerosene T-6; (3) US rocket fuel RP-1. These kerosene types have similar chemistry, thermophysical properties and energetic qualities. The only parameter which was taken into consideration when using one or another kerosene type was its density. RP-1 has a minimal density of 0.801 g/cm^3 and T-6 has a maximum density of 0.841 g/ cm^3 under room temperature conditions.

II. Design specifics and cooling parameters of the chamber

The chamber (Figure 1) consists of five major sections: injector head, middle part, first, second and third sections. All sections are connected by welding. Each section consists of an internal wall with milled cooling passages and an external wall that is brazed to it.

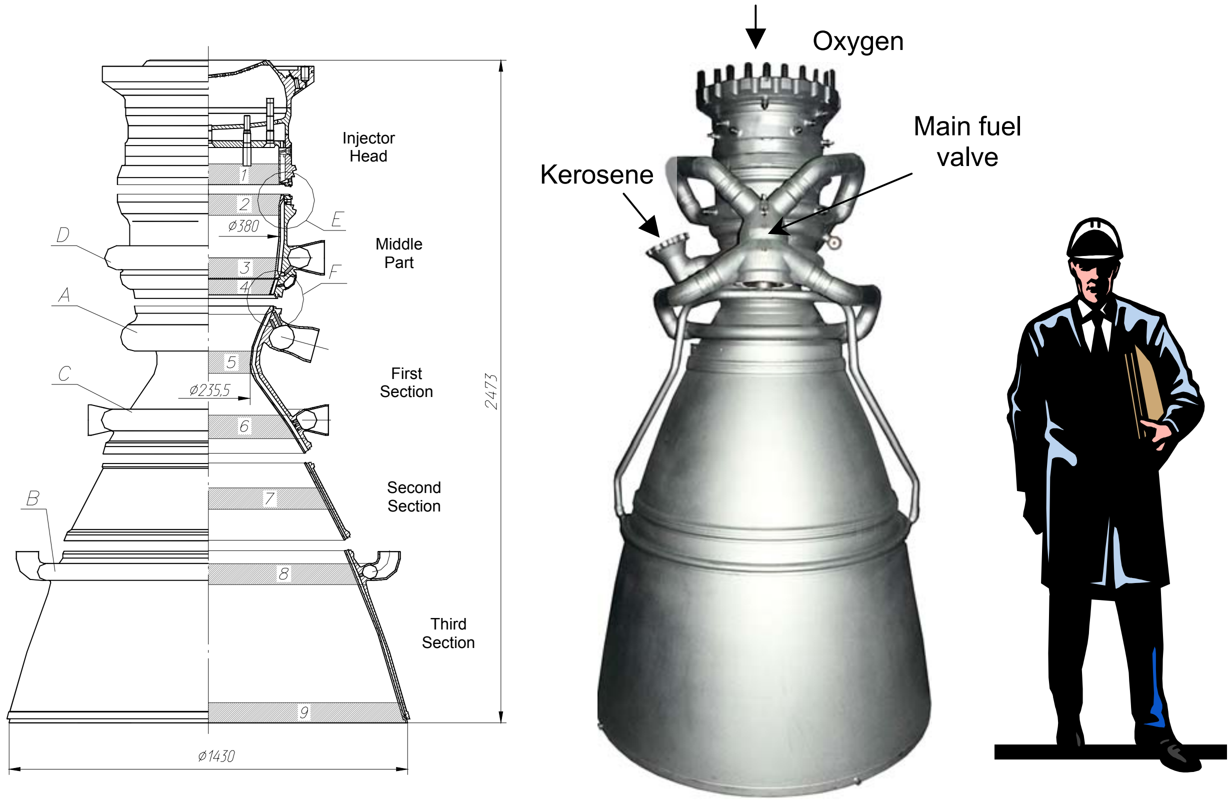


Figure 1. Chamber of RD170 engine family

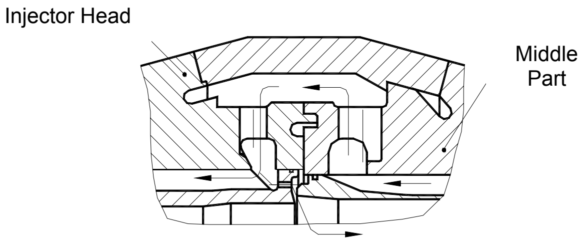
The internal walls of the injector head, middle part, and first section are made from bronze alloy, and the internal walls of the second and third sections from steel. The internal wall of middle part has nickel coating and the internal wall of first section has chromium coating on top of the nickel.

Propellant supply to the chamber is made through lines with flexible assemblies which allows chamber gimballing by 8 degrees in any plane.

Kerosene is used for internal and external chamber cooling.

Internal cooling is provided by three annular slots on the internal wall.

The first slot (Figure 1, region E; Figure 2) is located at the connection between the injector head and the middle part. The second and third annular slots are located in the middle part of the chamber at the connection with the first section (Figure 1, region F; Figure 3).



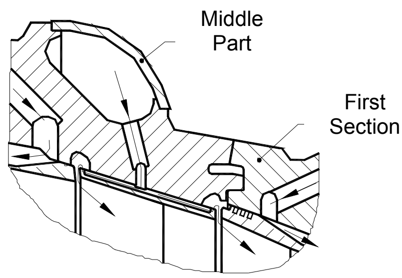


Figure 2. First annular slot of internal cooling.

Figure 3. Second and third annular slots of internal cooling.

External cooling (Figure 1) is accomplished as follows. One part of the fuel from the engine line goes to Manifold A for first section cooling up to Manifold C. The other part is supplied to Manifold B, where it is divided into two flows, one of which goes to Manifold C and the other one to nozzle cut and then to Manifold C. After Manifold C fuel moves through pipelines through Main Fuel Valve to Manifold D and then to the injector head. The nominal values of main heat and temperature parameters for RD-180 are given in Table 1 below for different regions of the internal wall (these regions are shaded and numbered 1 through 9 in Figure 1).

Parameter	Dimension	Location # (Figure 1)								
		1	2	3	4	5	6	7	8	9
Density of total heat flow	x10^2 W/cm^2	16.2	25.6	37.9	37.4	48.4	12.8	4.7	3.0	1.9
Wall temperature from gas side	K	731	853	999	1020	1151	768	868	746	679

Table 1. Heat and temperature parameters of the chamber

III. Research Results

The objective of studies was to determine the condition for the mostly loaded elements of the chamber cooling system and primarily the internal wall.

The study object was a chamber, which went through 21 fire tests as part of an RD-180 engine. The total time of these tests was 4,000 seconds.

Figure 4 shows *pressure data in the combustion chamber* and mixture ratio realized in steady state *regimes* during fire tests of the studied chamber. The region of working parameters is marked with a rectangle in the figure.

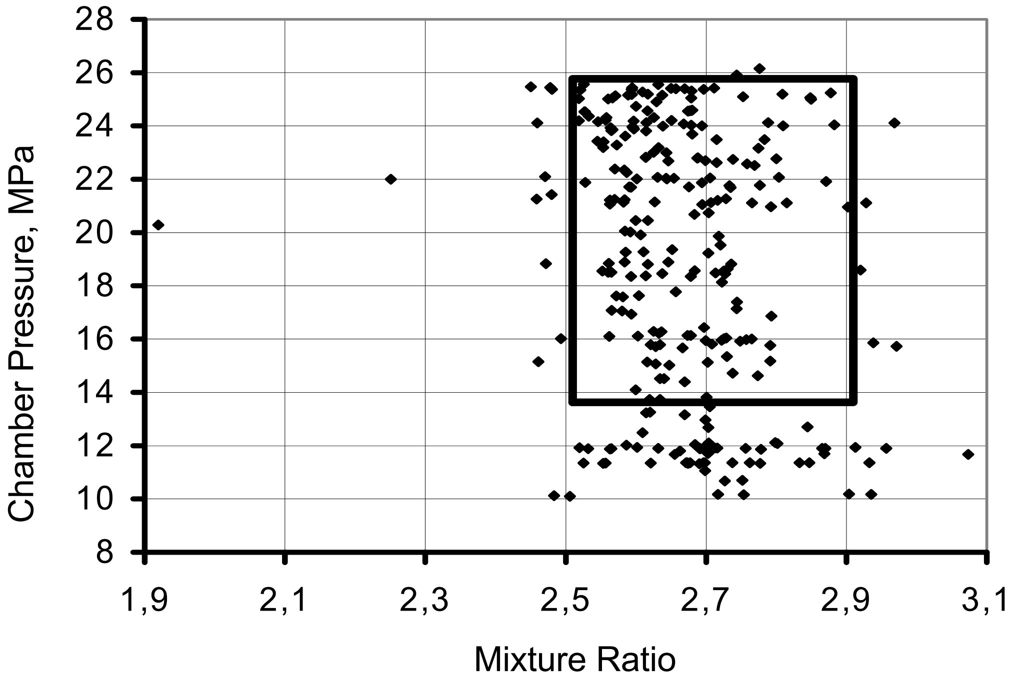


Figure 4. Parameters of stationary testing regimes of the chamber under study

The chamber was part of 5 assemblies of development engines, each of which was tested from two to seven times. One of the main objectives of conducted tests was demonstration of burning stability margins and reliability of the chamber cooling system. The total duration of realized steady state regimes outside of working parameters was 24% of full tests duration.

RP-1 kerosene was used during 3 tests and T-6 kerosene was used for all other tests.

It is worth mentioning that kerosene was removed differently from different parts of cooling system between tests. From the cooling path located behind Main Fuel Valve, kerosene was removed via intensive gas purging. From the cooling path located before the Main Valve, kerosene was removed by drainage after each test. After the last test of every assembly thermo-vacuum drying was employed in addition.

To study the condition of the hardware, the external chamber wall was cut out and 9 regions were cut out from internal wall in form of rings according to Figure 1. Coupons were cut out from each region for studies. The size of each coupon is 40 mm x 50 mm (Figure 5).

Figure 5. External view of the sample

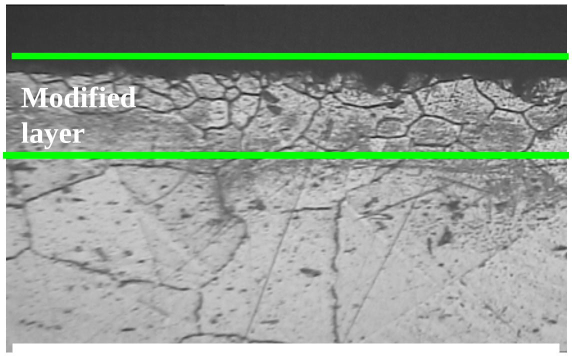


Figure 6. Modified layer in steel wall material

Multiple polished sections have been made for metallographic studies.

Evaluations have been performed using metallography, electron microscopy, x-ray diffraction and chemical analysis. The objective was to determine:

a) Microstructure of the base material of the wall;
b) Presence and characteristics of coating defects (gas erosion, cracks, pores);
c) Boundary between the base material and the coating, and the condition of braze joint for internal and external walls;
d) Presence of solid organic compounds in cooling passages (layer thickness, quantity, chemical composition).

The main results of the study together with some comments are given below.

a) Microstructure of the bronze wall at regions 1, 2, 3, 4, 5 and 6 does not have visible changes. Traces of accumulation of plastic deformations in the form of geometrical changes and cracks were not observed.

The results of previously performed computational estimates showed that in the worst-case scenario (maximum stress level, minimal wall thickness) the internal wall of the chamber in the most stressed location (region 5) accumulates about 6% of plastic deformations after 21 loading cycles each of which corresponds to a flight thrust profile of RD-180 engine. Meanwhile the total number of cycles to wall failure slightly exceeds 50.

Under nominal conditions the predicted number of cycles to wall failure is equal to 200.

In the steel wall material (regions 7, 8, 9) from the gas side, the presence of α-phase (magnetic) was detected with thickness of about 20 μm (Figure 6).

α-phase of the specified thickness was formed during the first test. The same observation was made after the first test of a similar study on another chamber that has been performed earlier.

b) No defects in the form of gas erosion or cracks have been found in regions 2, 3, and 4.

Cracks were found in the chromium coating in regions 5 and 6. In region 6 there are few cracks which are very thin with depth not exceeding the thickness of chromium coating, which is approximately 100 μm.

A grid of cracks is observed at the coating surface in region 5. Fragments of it are shown on Figure 7.

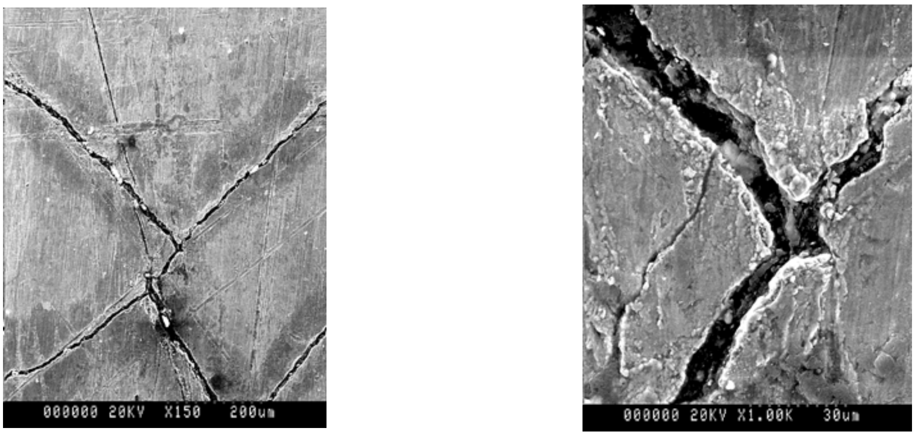


Figure 7. Grid of cracks on the surface of the chromium coating

Representative examples of crack cross-sections are shown on Figure 8.

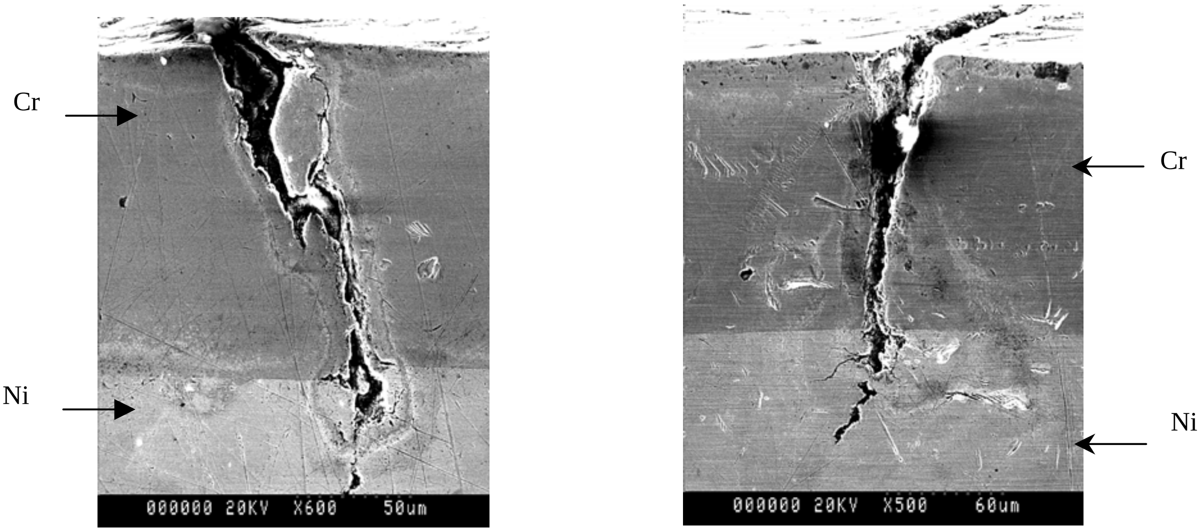


Figure 8. Cross-section of the crack

The cracks are formed on the chromium coating surface and grow inside with each loading cycle. The crack growth rate is significantly reduced when reaching the layer of nickel coating. The depth of crack penetration in the nickel layer is 20-40 μm (nickel layer thickness is ~300 μm). The process of chipping of the chromium coating from the crack surface is observed in parallel with crack length growth. The presence of cracks practically has no effect on the heat exchange and thermal loading of the bronze wall.

c) The boundary between the nickel coating and the bronze wall has no visible changes. Brazing joint of internal and external walls was also found to be in a good condition (Figure 9).

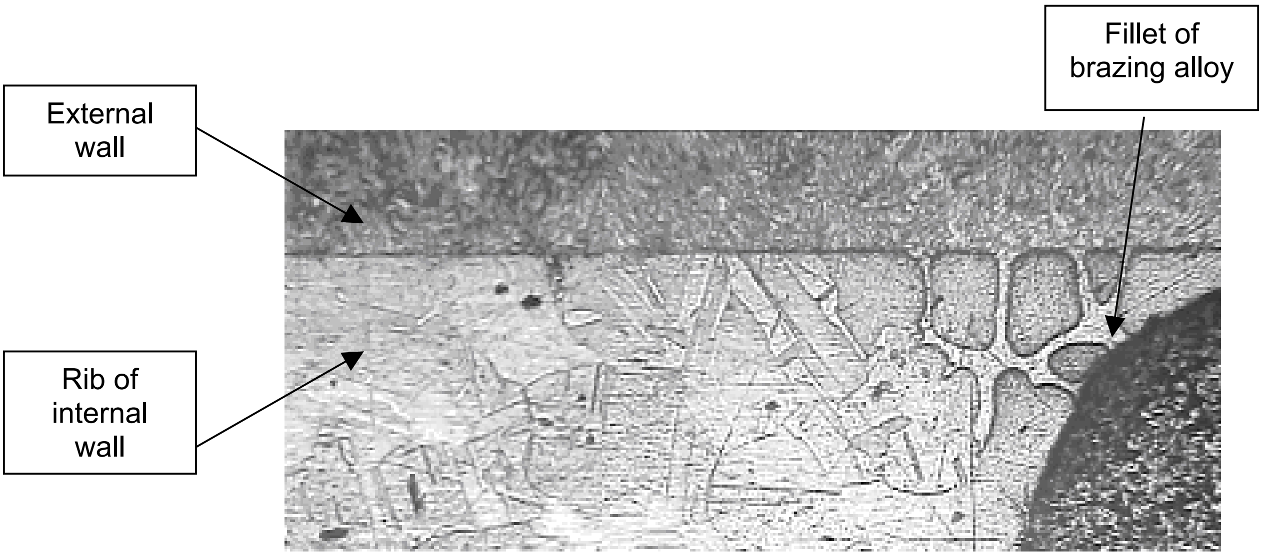


Figure 9. Brazing joint of internal and external walls at the location of critical cross-section

e) Detection of traces of solid organic compounds in internal wall channels from the side of external cooling has been made by various methods. A film of material containing carbon was found in the samples of all 9 regions using an electron microscope with microprobe analyzer. X-ray diffraction microanalysis of the samples was performed using an attachment to electron microscope – microanalyzer (Cameca, France) with the help of wave and solid body Si(Li) detectors. Table 2 (first column) contains the maximum film thickness for each sample representing regions of the cooling path under study. Gas Chromatograph Mass Spectrometry (GC/MS) method was used to study the washes with different solvents from the sample's surface. Halocarbon, acetone, and ethanol were used for washing organic compounds. For GC/MS analysis the washes for each sample were combined, then partially vaporized at room temperature and standards such as benzene tetrachloride were added to the solution in order to perform a quantitative analysis. The results of determination of organic matter quantity on the samples surface are given in Table 2 (second column). It was also determined that the washouts contain saturated hydrocarbons.

Table 2.

Region	Film thickness, μm	Relative mass of organic matter, mg/cm^2
	1	2
1	0.0248	0.19
2	0.0293	0.22
3	0.01	0.11
4	0.0282	0.21
5	0.0659	0.39
6	0.0217	0.16
7	0.0304	0.30
8	0.0143	0.14
9	0.0214	0.18

Scrapings were taken off the samples after solvent application, and later heated. At the beginning of heating water separation has been observed and then at temperatures above 150°C thermal decomposition of the scraping matter takes place with the release of carbon dioxide.

The data shown demonstrate that for multiple chamber tests (or flights) the process of accumulation of solid organic deposits (coking) in cooling path happens extremely slowly. The thickness of deposits does not exceed 0.07 μm after 21 tests even at the location of highest thermal stress. Earlier laboratory studies showed that the solid organic deposits degrade heat exchange processes at thicknesses on the order of 10 μm.

IV. Conclusions

The chamber of the family of oxygen-kerosene engines RD-170 has uniquely high parameters and demonstrates significant margins on combustion stability and cooling.

Evaluation results of the chamber that underwent 21 firing tests as part of RD-180 engine with total working time of 4,000 seconds provide additional proof of existing technology maturity and the possibility of its utilization in reusable engines.