Rocket Engines from the Glushko Design Bureau: 1946-2000

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Valentin P. Glushko (1908-89) oversaw the most influential rocket engine design organization in the Soviet Union. Originally known as OKB-456, the design bureau designed first stage engines for almost all operational Soviet ICBMs, the exceptions being the UR-100 (U.S. Department of Defense code name SS-11) and the UR-100N (SS-19). According to official information, the design bureau has developed more than 120 engines since the end of World War II [1]. This article will attempt to summarize the development of engines at the Glushko Design Bureau and identify its the main thematic trends over the course of 55 years.

Keywords: Soviet rocket engines, Russian rocket engines, Valentin Glushko, OKB-456, NPO Energomash

1. History of the Design Bureau

Depending on the source, historians have traced the lineage of the Glushko Design Bureau back to different points in time. Glushko himself had somewhat disingenuously claimed the formation of the organization to 15 May 1929. It was then that the Gas Dynamics Laboratory (GDL) established a subdivision headed by a young Glushko to work exclusively on electric and (later in 1930) liquid propellant rocket engines [2]. This unit was later absorbed by the Reactive Scientific-Research Institute (RNII) in September 1933 but suffered a major discontinuity in March 1938 when Glushko was arrested by the Soviet secret police NKVD on trumped up charges of sabotage. In September 1939, still a prisoner, Glushko was allowed to form a new independent team of rocket engine experts, the Special Group of the 4th Special Department of the NKVD, at Plant No. 82 in Tushino. A year later, Glushko's team of prisoners moved to Plant No. 16 at Kazan to continue their work. Here, they were part of the NKVD's 28th Special Department. Glushko led one of the subdivisions of OKB-16 at Plant No. 16, working on engines with thrusts ranging from 300 to 1,200 kilograms. The following year, he was officially named Chief Designer of OKB-16 although he was still a prisoner of the so-called *sharaga* system of "prison scientists." Glushko was among 35 men at OKB-16 released from confinement on 27 July 1944. A reorganization at the time led to the formation of the Experimental Design Bureau of Special Engines (OKB-SD) in the People's Commissariat of Aviation Industry with Glushko as Chief Designer. The OKB-SD personnel comprised, for the most part, the same engineers who had been grouped with Glushko in 1939.

OKB-SD ultimately served as the basis for the future Glushko design bureau. On 3 July 1946, the Ministry of Aviation Industry issued an order to convert the facilities at Plant No. 456 in the city of Khimki for the design and production of liquid propellant rocket engines; the order called for the transfer of Glushko's OKB-SD team (107 employees) from Kazan to Khimki and reformed it into the new OKB-456 [3]. After a second supplementary order was issued on 29 September 1946, almost all of Glushko's group arrived in Khimki in November and December 1946, many of them from Germany where they had been scouring through the remains of A-4 (V-2) missile wreckage.

The OKB-456 and its Plant No. 456 were unified into a single entity on 27 October 1954 under Glushko's leadership [4].

OKB-456 was renamed the Design Bureau of Power Machine Building (KB Energomash) on 1 January 1967 [5]. Eight years later, on 22 May 1974, in one of the most dramatic reorganizations in the Soviet space industry, Glushko's KB Energomash was merged with Sergey P. Korolev's old design bureau, thus creating the giant conglomerate of the Energiya Scientific-Production Association (NPO Energiya) [6]. With the formation of NPO Energiya, Glushko took over administrative duties over the whole organization, appointing Viktor P. Radovskiy (1920-) as Chief Designer of the Energomash subdivision. This arrangement stayed in place for 15 years until Glushko's death on 10 January 1989. A year later on, 19 January 1990, Energomash once again separated from Energiya. Radovskiy remained at the helm of the new organization until 14 March 1991 when Boris I. Katorgin (1934-) took over as the new General Designer. Two months later, on 15 May 1991, the organization was officially renamed "NPO Energomash Named After V. P. Glushko" [7]. In Early 1998, the organization was privatized. At this time, it had 6,500 employees and a work space of 282,000 m² [8].

For a list of leading OKB-456 personnel, see Table 1. For a list of all the OKB-456 branches, see Table 2.

TABLE 1: *OKB-456 Personnel.*

General Designers		
V. P. Glushko	22 May 1974	10 Jan 1989
B. I. Katorgin	30 Jan 1992	present
Chief Designers		
V. P. Glushko	3 Jul 1946	22 May 1974
V. P. Radovskiy	11 Jul 1974	14 Mar 1991
B. I. Katorgin	14 Mar 1991	30 Jan 1992
First Deputy Chief Designers		
D. D. Sevruk	Nov 1946	Mar 1952
V. A. Vitka	27 Oct 1954	19 Aug 1961
V. I. Kurbatov	19 Aug 1961	6 Jun 1974
V. P. Radovskiy	6 Jun 1974	11 Jul 1974
V. F. Trofimov	22 Aug 1974	1993
Plant No. 456 Directors		
B. I. Svet	14 Mar 1946	1 Oct 1946
A. G. Ploskinny	1 Oct 1946	1 Nov 1946
L. A. Grishin	1 Nov 1946	23 Aug 1952
V. A. Kolychev	23 Aug 1952	16 Dec 1955
A. A. Yevteyev	16 Dec 1955	16 Dec 1960
Yu. D. Solov'ev	16 Dec 1960	1 Dec 1969
S. P. Bogdanovskiy	1 Dec 1969	1 Feb 1992
G. G. Derkach	1 Feb 1992	present

TABLE 2: *OKB-456 Branches.*

BRANCH	ESTABLISHED	LOCATION	CHIEFS	MANDATE
No. 1	20 Mar 1958 dissolved 1989	Primorsk	Ye. N. Kuz'min	fluorine
No. 2	1958	Privolozhsk (Plant No. 24)	Yu. D. Solov'ev/58-60 R. I. Zelenev/60-75 A. F. Udalov/75-78 A. A. Ganin/78-present	production
No. 3	Dec 1958 dissolved 1968 reestablished 7 Jun 1983	Omsk	V. F. Khomrachem/58-? A. V. Umrikhin/83-93 A. M. Vergun/93-present	production
No. 4	18 Jul 1959	Kamskiy	Yu. D. Plaksin/59-80 N. V. Piksotov/80-82 D. L. Zhuravlev/82-present	production
No. 5	14 Sep 1959 dissolved 18 Dec 1961	Krasnoyarsk (Plant No. 1001)	A. Ya. Kitayev/59-61	production

2. Engine Classifications

All engines designed at Glushko's design bureau are divided into six categories, each one associated with a particular designation series:

(1) RD-100 series (liquid oxygen engines);

(2) RD-200 series (nitric acid and nitrogen tetroxide engines);

(3) RD-300 series (fluorine engines);

(4) RD-400 series (nuclear engines);

(5) RD-500 series (hydrogen peroxide engines);

(6) RD-700 series (tri-propellant engines) [9].

A seventh category is for non-engines:

(7) RD-600 series (chemical lasers).

By their own definition, Glushko's engineers divided the six engine categories into two main generations of engines. The first generation of engines were all of the "open cycle" or "liquid-liquid" type – called gas generator cycle in the West. The second generation engines, introduced in the early 1960s, were of the "closed cycle" or "gas-liquid" type – called staged combustion cycle in the West. Glushko himself described the difference. In the latter:

> The gas generator gas expands in the turbine and ignites in the main combustion chamber when being mixed with the remaining propellant component [that not being used in the gas generator] . . . losses due to driving the turbopump assembly are practically absent in this case. In such engines the mixture of propellant components entering the combustion chamber occurs according to the gas-liquid scheme [turbine exhaust gas + liquid propellant], unlike the conventional liquid-liquid system [10].

The two main advantages of the closed cycle engine is the elimination of losses of driving the turbine and the increase in chamber pressure, both of which lead to much higher specific impulses than usual; the disadvantage is the much higher pump pressure required. Glushko based much of his early work on closed cycle engines on pioneering work performed at NII-1 in 1958-59 when that institute developed the first experimental closed cycle engine in the Soviet Union [11].

Like most other engines developed in the USSR, Glushko's engines followed a clear evolutionary path, often stretching over a decade or more. With a few exceptions, the main design philosophy was one of gradual technological improvement rather significant technological leaps. Marginal modifications to a particular engine resulted in better performance and a new designation.

For a complete list of Glushko's engines, see Table 3. For a summary of the main evolutionary trees, see Table 4. For a list of where Glushko's engines were applied, see Table 5 (ICBMs) and Table 6 (space launch vehicles).

TABLE 3: *Engines Developed by the Glushko Design Bureau 1946-2000.*

NAME	NAME	NAME	NO. OF CHAMBERS	PERIOD OF DEV.	PROPELLANT	VACUUM THRUST (tons)	S.I. (sec)	APPLICATIONS
RD-100	8D51		1	1946-48	LOX-eth 75%	31.0	232.5	R-1
RD-101	8D52		1	1946-49	LOX-eth 92%	41.2	237	R-2
RD-103M	8D54		1	1950-53	LOX-eth 92%	51.0	243	R-5M
RD-103RD	8D54		1	1954-56	LOX-eth			M5RD
RD-3A			1	1951-53	LOX-eth	44.0	214*	R-3A
RD-105	8D71		1	1952-54	LOX-ker	61.0		R-6
RD-106	8D72?		1	1952-54	LOX-ker	65.8		R-6
RD-107	8D74		4	1954-57	LOX-T-1	99.0	306	R-7 stage I
RD-107	8D74PS		4	1956-57	LOX-T-1	99.0	306	8K71PS stage I
RD-107	8D76		4	1956-58	LOX-T-1	99.0	310	8A91 stage I
RD-107	8D74		4	-58	LOX-T-1	101.0	312	8K72 stage I
RD-107	8D74		4	-59	LOX-T-1	101.5	313	8K72K stage I
RD-107	8D74K		4	-60	LOX-T-1	101.5	313	8K78 stage I
RD-107	8D728		4	-63	LOX-RG-1/T-1	101.5	314	8K78 stage I
RD-107	11D512		4	-66	LOX-T-1	102.0	313	11A511U stage I
RD-108	8D75		4	1954-57	LOX-T-1	93.0	308	R-7 stage II
RD-108	8D75PS		4	1956-57	LOX-T-1	93.0	308	8K71PS stage II
RD-108	8D77		4	1956-58	LOX-T-1	82.0	315	8A91 stage II
RD-108	8D75		4	-58	LOX-T-1	95.5	315	8K72 stage II
RD-108	8D75		4	-59	LOX-T-1	95.9	315	8K72K stage II
RD-108	8D75K		4	-60	LOX-T-1	95.9	316	8K78 stage II
RD-108	8D727K		4	-62	LOX-RG-1/T-1	99.6	316	8K78 stage II
RD-108	8D727		4	-63	LOX-RG-1/T-1	99.6	316	8K78 stage II
RD-108	11D511 [1]		4	-66	LOX-T-1	96.0	316	11A511U stage II
RD-109	8D711	GDU-10	1	1957-60	LOX-UDMH	10.36	334	8K73 stage III
RD-110			1	1947-51	LOX-ker	140.2	285	R-3
RD-111	8D716		4	1959-62	LOX-T-1	166.0	317	R-9A stage I
RD-112			1	1960-	LOX-UDMH	111.1	344	ICBM stage I concept
RD-113			1	1960-	LOX-UDMH	116.1	360	ICBM stage II concept
RD-114			1	1961-65	LOX-UDMH	168.7	341	ICBM stage I concept
RD-115			1	1961-65	LOX-UDMH	176.1	357	ICBM stage II concept
RD-117 [1]			4	1990s	LOX-sintin			
RD-117PF [1]			4	1990s	LOX-sintin			
RD-118 [2]			4	1990s	LOX-sintin			
RD-119	8D710		1	1958-62	LOX-UDMH	10.7	352	Kosmos-2 stage II
RD-120	11D123		1	1976-85	LOX-ker	85.0	350	Zenit-2 stage II
RD-120.01			1		LOX-ker	80.0	329	
RD-120M			1	mid-90s	LOX-ker	87.0	330	Pac-2 stage I, Soyuz-2
RD-120.03			1		LOX-ker	90.0	353	
RD-120K			1		LOX-ker	86.7	330	Kvant
RD-123				1973-74	LOX-ker	800		early Energiya concept
RD-123 (new)				mid-90s	LOX-ker			Soyuz-2 concept
RD-124			3	mid-1970s	LOX-ker	379.5	340	early Zenit stage I
RD-125			1	mis-1970s	LOX-ker	130.2	350	early Zenit stage II
RD-134			4	mid-90s	LOX-ker	35.0	357	Angara concept
RD-146				mid-90s	LOX-ker	90.0		Angara concept
RD-150				early 1970s	LOX-ker	1500		heavy booster concept

TABLE 3: *Engines Developed by the Glushko Design Bureau 1946-2000 (Contd).*

NAME	NAME	NAME	NO. OF CHAMBERS	PERIOD OF DEV.	PROPELLANT	VACUUM THRUST (tons)	S.I. (sec)	APPLICATIONS
RD-160 [3]			1		LOX-LCH4	2.0	381	
RD-161			1	1988-	LOX-ker	2.0	360	Soyuz-2 stage concept
RD-161P			1	1993-	H202-ker	2.5-1.5	319	Soyuz-2
RD-167 [4]			4		LOX-LCH4	36.0	379	upper stage
RD-169 [5]			1	mid-90s	LOX-LCH4	17.0	349	Riksha stage I
RD-170 [6]	11D521		4	1976-87	LOX-ker	806.0	337	Energiya stage II
RD-171 [6]	11D520		4	1976-87	LOX-ker	806.0	337	Zenit-2 stage I
RD-172 [7]			4	-94	LOX-ker	847.6	337	Zenit-2 stage I
RD-173 [7]			4	mid-90s	LOX-ker	918.0	337	Zenit-3 stage I
RD-174			4	mid-90s	LOX-ker	806.1		Angara stage I
RD-180 [8]			2	1992-	LOX-ker	423.4	337.8	Atlas-3A
RD-181					LOX-ker	426.2	337	
RD-182 [9]				mid-90s	LOX-LCH4	91.0	353	
RD-183				mid-90s	LOX-LCH4	1.0	358	Riksha apogee motor
RD-184				mid-90s	LOX-LCH4	0.0015	322	Riksha apogee motor
RD-185 [10]				mid-90s	LOX-LCH4	18.0	374	Riksha stage II
RD-190 [11]			1	mid-90s	LOX-LCH4	102.0	347	Riksha stage I
RD-191M [12]			1	mid-90s	LOX-RG-1	201.6	337.5	Angara stage I
RD-192 [13]				mid-90s	LOX-LCH4	207.8	356	
RD-192.2				mid-90s	LOX-LCH4	198.0	354	
RD-192.3				mid-90s	LOX-LCH4	213	341	
RD-192S				mid-90s	LOX-LCH4	217	371.5	upper stage
RD-200				-51	HNO3-TM-114	10.0	234	
RD-210				-54	HNO3-TM-114	3.0	241	
RD-211			4	1952-55	AK-20-TM185	65.5	261.8	R-12 1st version
RD-212			4	1954-56	AK-27I-TM185	44.6/63.6	253	M-40 1st version
RD-213			4	1956-57	AK-27I-TM185	56.0/77.0	255/254	M-40 2nd version
RD-214 [14]			4	1955-57	AK-27I-TM185	74.5	264	R-12 final version
RD-215			2	1958-60	AK-27I-UDMH	88.1	291.4	R-14
RD-216 [15]	11D614		4	1958-60	AK-27I-UDMH	176.3	291.4	R-14
RD-216M			4	1960s	AK-27I-UDMH			Kosmos-3M stage I
RD-217	8D515		2	1958-61	AK-27I-UDMH	88.2	289	R-16 stage I
RD-218 [16]	8D712		6	1958-61	AK-27I-UDMH	264.5	289	R-16 stage I
RD-219 [17]	8D713		2	1958-61	AK-27I-UDMH	90.1	293	R-16 stage II
RD-220			1	1960-	AK-27P-UDMH	109.6	306	stage I application
RD-221			1	1960-	AK-27P-UDMH	114.1	318	stage II application
RD-222			1	1960-61	AK-27P-UDMH	166.7	302	stage I application
RD-223			1	1960-61	AK-27P-UDMH	173.2	314	stage II application
RD-224 [18]	8D721		4	1960-62	AK-27P-UDMH	181.4	294	R-26 stage I
RD-225			2	1960-62	AK-27P-UDMH	90.7	294	R-26 stage I
RD-250			2	1960-62	N204-UDMH	90.0	301	R-36 stage I
RD-251 [19]	8D723		6	1961-65	N204-UDMH	270.0	301	R-36 stage I
RD-252 [20]			2	1961-66	N204-UDMH	92.0	317.6	R-36 stage II
	11D43		1	1960-61	N204-UDMH	172.3	308	Proton stage I concept
RD-253	11D48		1	1961-65	N204-UDMH	167.0	316	Proton stage I
RD-253	14D14		1	-86	N204-UDMH	178.1	317	Proton stage I
RD-254 [21]			1	1962-	N204-UDMH	175		N1 concept
RD-261 [22]			6	1967-69	N204-UDMH	309.4	301.4	Tsiklon stage I
RD-262 [23]			2	1967-69	N204-UDMH	96.0	317.6	Tsiklon stage II
RD-263			1	1969-73	N204-UDMH	117.8	318	R-36M stage I
RD-264 [24]	11D119		4	1969-73	N204-UDMH	461.0	318	R-36M stage I
RD-268 [25]			1	1969-73	N204-UDMH	126.0	319	MR UR-100 stage I
RD-270	8D420		1	1962-71	N204-UDMH	685	322	UR-700 stage I
RD-270M			1	1962-70	N204-B5H9	730.5	365	
RD-273 [26]			1	1975-80	N204-UDMH	126.3	296*	R-36MU stage I
RD-274 [27]			4	1975-80	N204-UDMH	505.3	296*	R-36MU stage I
RD-275 [28]			1	1990s	N204-UDMH	178.0	317	
RD-280			1	1965-68?	N204-AZ50	12.0	350	

TABLE 3: *Engines Developed by the Glushko Design Bureau 1946-2000 (Contd).*

NAME	NAME	NAME	NO. OF CHAMBERS	PERIOD OF DEV.	PROPELLANT	VACUUM THRUST (tons)	S.I. (sec)	APPLICATIONS
RD-301 [29]	8D21		1	1969-77	LF2-NH3	9.8	400	Proton upper stage
RD-302	11D130F		1	1965-69	LF2-NH3			
RD-303	11D14		1	1960-65	LF2-NH3	10.0	400	
RD-350				1963-	LF2-LH2			
RD-410			1	1960s	nuclear	7.0		UR-700M concept
RD-501			1	1960-	H2O2-B5H9			
RD-502			1	1960-66	H2O2-B5H9	10.0	380	
RD-510				1965-75	H2O2-CxHy			
RD-510T				1965-75	H2O2-CxHy			
RD-511				1965-75	H2O2-CxHy			
RD-550			1	1963-70	H2O2 / 70% N2H4 + 30% beryllium	10.0	400	
RD-560				1965-71	H2O2 / 70% N2H4 + 30% beryllium			
RD-600				1974-	laser	30 kW		
RD-701			2	1988-	LOX-ker + LH2	408.5/162.0	415/460	MAKS
RD-704 [30]			1	1990s	LOX-ker + LH2	200.6/79.8	407/452	
MD-185 [31]			1	1980-	LOX-ker			proposed for Zenit

Notes:

1. The RD-117 and RD-117PF are probably replacements versions of the RD-107 which use sintin instead of kerosene.
2. The RD-118 is probably a replacement version of the RD-108 which uses sintin instead of kerosene.
3. The RD-160 is a methane-based version of the RD-161.
4. The RD-167 is a methane-based version of the RD-134.
5. The RD-169 design is based upon the RD-120.
6. The RD-170 and RD-171 are almost identical save for gimballing capabilities.
7. The RD-172 and RD-173 are uprated versions of the RD-171.
8. The RD-180 is a two-chamber version of the RD-170.
9. The RD-182 is a methane variant of the RD-120.
10. The RD-185 is an altitude version of the RD-169.
11. The RD-190 is comprised of six RD-169 engines.
12. The RD-191M is a single chamber version of the RD-170 / RD-171.
13. The RD-192 is a methane version of the RD-191M.
14. The RD-214 was derived from the RD-211.
15. The RD-216 is comprised of two RD-215 engines.
16. The RD-218 is comprised of three RD-217 engines.
17. The RD-219 is an altitude version of the RD-217.
18. The RD-224 is comprised of two RD-225 engines.
19. The RD-251 is comprised of three RD-250 engines.
20. The RD-252 is an altitude version of the RD-250.
21. The RD-254 was an altitude version of the RD-253.
22. The RD-261 was derived from the RD-251.
23. The RD-262 was derived from the RD-252.
24. The RD-264 is comprised of four RD-263 engines.
25. The RD-268 was derived from the RD-263.
26. The RD-273 was derived from the RD-263.
27. The RD-274 was an altitude version of the RD-273.
28. The RD-275 is an uprated version of the RD-253.
29. The RD-301 was derived from the design of the RD-302 and RD-303.
30. The RD-704 is a single chamber derivative of the RD-701.
31. The MD-185 was a single-chamber engine projected for use on the first stages of the Zenit and Energiya.

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Explanatory Notes: (1): All thrust and specific impulse values are in vacuum conditions unless listed with an asterisk in which case they are then at sea level conditions. (2): Propellant abbreviations:

eth ethanol   ker kerosene   sintin synthetic fuel

AZ50	aerozene-50	LH2	liquid hydrogen
B5H9	pentaborane	LOX	liquid oxygen
H2O2	hydrogen peroxide	N2H4	hydrazine
HNO3	nitric acid	N2O4	nitrogen tetroxide
LCH4	liquid methane	NH3	ammonia
LF2	liquid fluorine	UDMH	unsymmetrical dimethyl hydrazine

AK-20	nitrogen tetroxide in concentrated nitric acid = 80% HNO3 + 20% N2O4
AK-27I	nitrogen tetroxide in concentrated nitric acid = 73% HNO3 + 27% N2O4
RG-1	kerosene derivative
T-1	kerosene
TG-02	amine-based fuel (TG is the abbreviation of 2nd fuel of GIPKh)
TM-114	hydrocarbon fuel/kerosene
TM-185	hydrocarbon fuel/kerosene

3. The Role of Germans in Soviet Rocket Engine Development

The degree of the Germans' contributions to early Soviet *engine* design (as opposed to *rocket* design) has been clouded over the years. Most Soviet-era historians completely discounted any major influence. In the post-Soviet era, some Russian historians and former participants admitted that German help was crucial, especially in the 1945-47 period when the Soviet rocketry effort was based in Germany. But while conceding that the Germans were critical to early development, Russians have rejected the notion that German engineers (who were forced to move to the Soviet Union in 1946) had any significant impact on later Soviet rocket engine design. For example, Viktor L. Shabranskiy, one of Glushko's closest friends, and a Deputy Chief Designer at OKB-456 for many years, wrote in 1998 that "we received the greatest help from the Germans only at the testing base at Lehesten [in Germany]," i.e. that their contribution was minimal *after* moving to Soviet territory [12]. On the other hand, Germans, both historians and those who worked for the Soviets in the 1940s, have recently suggested that these German scientists and engineers may have engaged in important design work during their stay in the USSR that was the basis for much of Soviet rocket engine design up to the late 1950s [13].

The Soviets transferred 24 German men (65 people total with their families) to Khimki in late 1946 to work for Glushko. Among them were designers, engineers, mechanics, shop technicians, welders, etc. Of the group, seven had higher educations. None played any important design role in the Peenemunde effort, but many had significant expertise in production and assembly. Most notable was Werner Baum, who had been a controlling engineer for the A-4 at the Armed Forces' Weapons Office during the war. Willi Schwarz had taken part in the construction of engine plants in Saalfield since November 1943. From the Soviet perspective, the most important man was Oswald Putze, who had worked as the technical director of the Linke-Hoffman plant where A-4 combustion chambers had been manufactured during the war. Putze was in the fact the second highest paid employee at the design bureau in August 1948 (after Glushko himself). A list of their assigned titles back in the Soviet Union in 1947 and the first half of 1948 underline their role in production and testing rather than design: deputy chief of experimental production, chief engineer for experimental production, chief of oxygen production,

TABLE 4: *Base Engine Modules for Glushko's Engines.*

RD-215			
Steps			
1	RD-215		
2	2 x RD-215	= RD-216 (R-14 stage I)	modified to RD-216M
3	RD-215 modification	= RD-217	
4	3 x RD-217	= RD-218 (R-16 stage I)	
5	high altitude RD-217	= RD-219 (R-16 stage II)	
RD-250			
Steps			
1	RD-250		
2	3 x RD-250	= RD-251 (R-36 stage I)	modified to RD-261 (Tsiklon stage I)
3	high altitude RD-250	= RD-252 (R-36 stage II)	modified to RD-262 (Tsiklon stage II)
RD-263			
Steps			
1	RD-263		
2	4 x RD-263	= RD-264 (R-36M stage I)	
3	modified RD-263	= RD-268 (MR UR-100 stage I)	
4	modified RD-263	= RD-273	
5	3 x RD-273	= RD-274 (R-36M2 stage I)	

BASE MODULE COMBINATIONS

"Base" Engine X Number	Combination Module	Missile Used On
RD-215 x 2	RD-216	R-14 stage I
RD-217 x 3	RD-218	R-16 stage I
RD-250 x 3	RD-251	
	uprated RD-251 = RD-261	R-36 stage I
		Tsiklon-2 stage I
RD-263 x 4	RD-264	R-36M stage I
RD-273 x 4	RD-274	R-36MU stage I

TABLE 5: *Engines used on Soviet/Russian Land-Based ICBMs.*

MISSILE	MISSILE	STAGE I	STAGE II	STAGE III
SS-1	R-1	1 x RD-100		
SS-1a	R-11	1 x S2.253		
SS-2	R-2	1 x RD-101		
SS-3	R-5	1 x RD-103		
SS-4	R-12	1 x RD-214		
SS-5	R-14	1 x RD-216		
SS-6	R-7	1 x RD-108	4 x RD-107	
SS-7	R-16	1 x RD-218	1 x RD-219	
SS-8	R-9A	1 x RD-111	1 x RD-0106	
SS-9	R-36	1 x RD-251	1 x RD-252	
SS-10	UR-200	1 x RD-0202	1 x RD-0205	
SS-11	UR-100	3 x RD-0216 1 x RD-0217	1 x 15D13	
SS-X-15	RT-20P		1 x 15D12	
SS-17	MR UR-100	1 x RD-268	1 x 15D169	
SS-18	R-36M	1 x RD-264	1 x RD-0228	
SS-18	R-36M2	1 x RD-274	1 x RD-0255	
SS-19	UR-100N	3 x RD-0233 1 x RD-0234	1 x RD-0235 1 x RD-0236	
SS-24	RT-23	? x 15D305	? x 15D339	? x RD-866

deputy chief of various machine shops, deputy chief of the testing station, technical consultants, etc. According to official Russian sources, sometime in the middle of 1948, at about the time that OKB-456 began to expand its research to the future modernization of the original A-4 engine (the Model 39), "German specialists...were removed from the primary thematic work at the OKB and fulfilled work on separate assignments of an auxiliary character" [14]. The USSR Council of Ministers issued an official decree on 13 August 1950 ordering the repatriation of German engineers back to their homeland. By the end of the year, all the Germans at Glushko's design bureau were gone [15]. They had been there for a total of four years. They worked together with the Soviets in the first two years and independently of them during the last two.

There is no doubt that the original German engine for the A-4 missile was the foundation for Glushko's engines for the Soviet R-1, R-2, and R-5 missiles. Engines for each of these rockets were incremental (and very effective) improvements of the original Peenemunde engine. Recent German historians, however, have made more radical claims that center on three main points related to German *expertise* and not hardware. They argue: that the Germans at OKB-456 were involved in more than just production and testing; that the Germans were involved in the design of a critical test engine chamber in the period 1948-50; and that this engine chamber served as the basis for almost all Soviet rocket engines culminating in the engines used on the famous R-7 ICBM [16]. Soviet sources have indeed long referred to work on two experimental combustion chambers in the late 1940s that were crucial for further development of Soviet rocket engines. The first unit was the water-cooled KS-50 (informally called the "Lilliput") with a thrust of 50 to 100 kilograms intended as a testbed to identify prospective propellant combinations. The second of these was the ED-140, a combustion chamber working on LOX and kerosene (as opposed to LOX and alcohol solution of the German A-4 engine) with a thrust of 7 tons and an initial gas pressure of 60 kilograms/cm^2 [17]. Both of these combustion chambers were developed to overcome some central bottlenecks in rocket engine development that had plagued engineers for decades.

For many years, rocket engineers had been well-aware that one of the possible ways of increasing engine performance was to raise combustion chamber pressure. Increased pressure, however, resulted in increased heatflow through a chamber's cooled firewall. To protect the chamber from overheating, the solution was to make the chamber walls thinner. But thinner walls in turn would not be able to withstand the higher chamber pressures required – leading to a conundrum. Conventional regenerative cooling solutions would not be effective in breaking this vicious cycle. Glushko's engineers found a solution to the problem by using what was later known as an "integrated solder-welded design" where the chamber had relatively thin walls with numerous thin ribs for coolant to pass through. Soviet historians point to two sources for the idea for the integrated solder-welded ribbed design. Back in the days of the GDL, in 1933, Glushko himself

TABLE 6: *Rocket Engines used on Soviet/Russian Space Launch Vehicles.*

BOOSTER	STAGE I	STAGE II	STAGE III	STAGE IV
8K71PS/Sputnik	1 x RD-108	4 x RD-107		
8A91/Sputnik	1 x RD-108	4 x RD-107		
8K72/Luna	1 x RD-108	4 x RD-107	1 x RD-0105	
8K72K/Vostok	1 x RD-108	4 x RD-107	1 x RD-0109	
8A92/Vostok-2	1 x RD-108	4 x RD-107	1 x RD-0109	
8A92M/Vostok-2M	1 x RD-108	4 x RD-107	1 x RD-0109	
11A57/Voskhod	1 x RD-108	4 x RD-107	1 x RD-0108	
11A511/Soyuz	1 x RD-108	4 x RD-107	1 x RD-0110	
11A511L/Soyuz-L	1 x RD-108	4 x RD-107	1 x RD-0110	
11A511M/Soyuz-M	1 x RD-108	4 x RD-107	1 x RD-0110	
11A511U/Soyuz-U	1 x RD-108	4 x RD-107	1 x RD-0110	
11A511U2/Soyuz-U2	1 x RD-108	4 x RD-107	1 x RD-0110	
8K78/Molniya	1 x RD-108	4 x RD-107	1 x RD-0107	1 x S1.5400
8K78M/Molniya-M	1 x RD-108	4 x RD-107	1 x RD-0107	1 x S1.5400A1
11A59	1 x RD-108	4 x RD-107		
11A510	1 x RD-108	4 x RD-107		
63S1/Kosmos-2	1 x RD-214	1 x RD-119		
11K63/Kosmos-2	1 x RD-214	1 x RD-119		
65S3/Kosmos-1	1 x RD-216M	1 x S5.23		
11K65/Kosmos-3	1 x RD-216M	1 x S5.23		
11K65M/Kosmos-3M	1 x RD-216	1 x S5.23		
8K82/Proton	6 x RD-253	3 x RD-0208		
		1 x RD-0209		
8K82K/Proton-K + Blok D	6 x RD-253	3 x RD-0210	1 x RD-0212	1 x RD-58
		1 x RD-0211		
8K82K/Proton-K	6 x RD-253	3 x RD-0210	1 x RD-0212	
		1 x RD-0211		
8K69/	1 x RD-251	1 x RD-252		
11K67/Tsiklon-2A	1 x RD-261	1 x RD-262		
11K69/Tsiklon-2	1 x RD-261	1 x RD-262		
11K68/Tsiklon-3	1 x RD-251	1 x RD-252	1 x RD-861	
11A52/N1	30 x NK-15	8 x NK-15V	4 x NK-21	1 x NK-19
11A52F/N1F	30 x NK-33	8 x NK-43	4 x NK-39	1 x NK-31
11K77/Zenit-2	1 x RD-171	1 x RD-120		
11K25/Energiya	1 x RD-0120	4 x RD-170		
-/Rokot	3 x RD-0233	1 x RD-0235		
	1 x RD-0234	1 x RD-0236		
-/Shtil-1N	1 x RD-0243			

had developed an engine called the ORM-48 which used ribbed steel wall for its nozzle for water cooling. Almost simultaneously and independently, the German Eugen Sanger, in 1934, also tested (and later patented) a combustion chamber with a similar design. The Soviets faced significant problems in manufacturing such chambers because they were unable to produce *firmly* interconnected shells (an inner and outer one) with ribs within them. These shells needed to be firmly interconnected since differing thermal stresses in the constituent shells of the chamber would cause major failures in the chamber. Only in 1944, at the NII-1 institute, designer Aleksey M. Isayev pioneered a new integrated solder-welded method. In the late 1940s, Glushko's engineers resurrected the old ribbed wall design, but this time used Isayev's welding method to produce the KS-50 and ED-140 chambers. As one Soviet historian recalled:

> In such [an integrated solder-welded design] with frequent connections, the walls could have a small width, since, thanks to the numerous thin ribs, the individual conduits obtained for the passage of the coolant were narrow. Thus, the combustion wall could be produced from a relatively flimsy, but still highly heat-conductive copper alloy... [18].

Using this design, OKB-456 engineers static-tested the KS-50 for the first time on 26 April 1949 [19]. Tens of models were built and tested subsequently with exotic propellants such as fluorine-based oxidizers. The larger ED-140 was then built, among other things, to improve methods of mixing propellants in the combustion chamber; it used special flat injector "mixing heads" for injecting propellants into a cylindrical combustion chamber. The flat injector head design as well as the introduction of so-called "film cooling" were new innovations in Soviet rocket design. The architecture of the 7 ton thrust ED-140 was such that it simulated processes on a much more powerful 120 ton thrust engine known as the RD-110 which was intended for a powerful new missile called the R-3. The RD-110 would use 19 of the ED-140's "mixing heads." Tests with the ED-140 were apparently quite successful [20]. Using the experience with the KS-50 and ED-140, Glushko's engineers introduced a variety of innovations into the next generation of Soviet rocket engines including improved cooling methods and better mixing of propellants. Glushko's engineers, in cooperation with other scientific-research institutes, also developed improved welding methods (including vacuum soldering of chamber joints in a neutral protective medium such as nitrogen) and introduced corrugated walls (as opposed to ribbed walls) for cooling on engine nozzles. There was another important element of Glushko's work on these experimental chambers: he switched from alcohol to kerosene as fuel, thus making a conscious departure from the German antecedents of alcohol [21]. The change was motivated by the promise of better performance with kerosene. Cumulatively, all these innovations, especially the solder-welded designs, were critical to the development of the landmark RD-107 and RD-108 (Fig. 1) engines used on the famous R-7 ICBM. Solder-welded designs allowed increasing operating pressures and reducing relative dimensions and the specific masses of the new engines.

Recent German accounts suggest that the KS-50 chamber was developed under the leadership of the German Werner Baum in 1948. The Germans claim to have participated in early static tests of the chamber. According to these accounts, Glushko then used a German blueprint – without the knowledge of the Germans – to build the ED-140. The evidence for German development of the KS-50 is convincing, suggesting that modern Russian accounts are still omitting a key side of the story. German engineers were instrumental in optimizing the design of the chamber's new innovative nozzle and were also responsible for introducing a shorter cylindrical chamber on the KS-50 instead of the older spherical one. The most obvious case of the Soviets using German expertise was in the *initial* attempt to build the RD-110 engine. Here, Glushko almost certainly used a German plan to radically scale up the original A-4 engine (including its spherical combustion

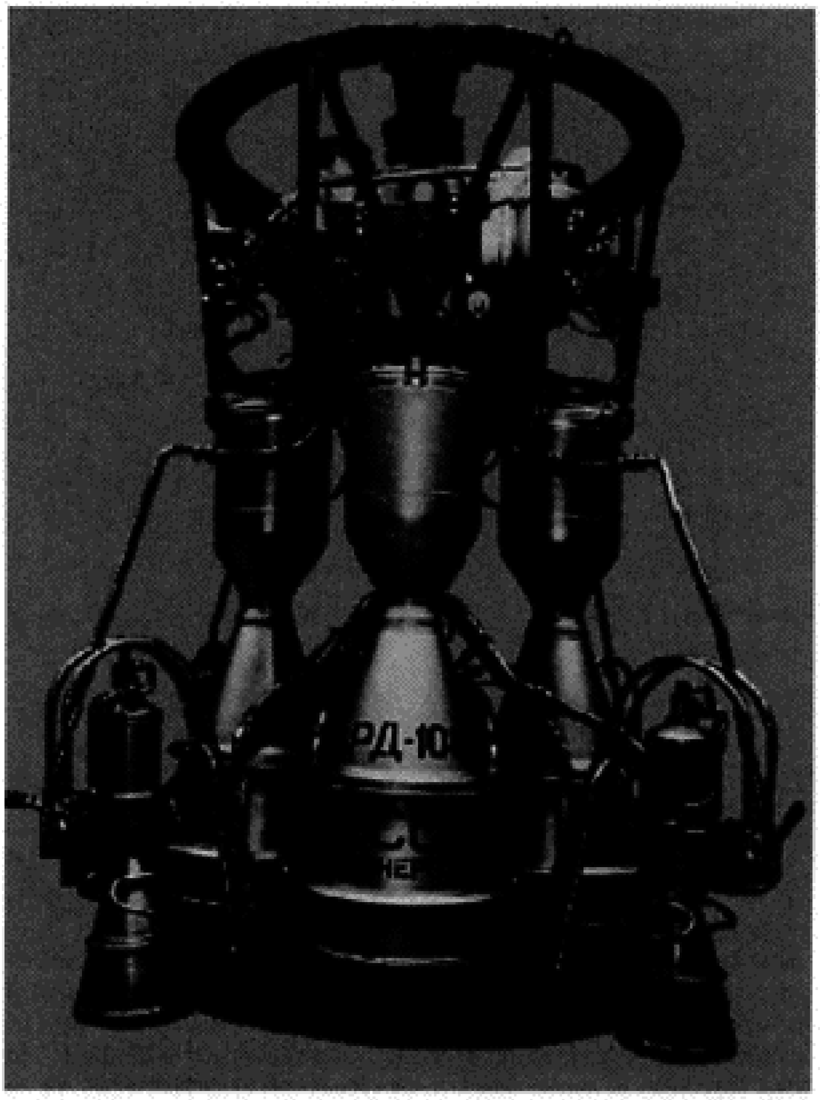

Fig.1 This is the RD-108 engine used on the core of the R-7 ICBM and subsequent launch vehicles using the R-7 as the base. Shown clearly are the vernier engines as well as the characteristic cylindrical combustion chambers which the Soviets adopted because of German influence. © Dietrich Haeseler

chamber) to meet the demands of a 120 ton engine [22]. On the other hand, the contention that Glushko essentially appropriated the design of the ED-140 from the Germans is less convincing. Many of the innovations on the ED-140 were derived from earlier Soviet antecedents (such as integrated solder-welded shells and ribbed cooling). Furthermore, the main direction of German work in the Soviet Union in the late 1940s concentrated on LOX and alcohol, while the ED-140 was a LOX-kerosene based engine. In 1954, Glushko's engineers scaled up the basic ED-140 architecture (with alterations to the nozzle) to develop a 23-ton thrust "module" chamber that served as the basis for the RD-107/RD-108 – four of these 23-ton modules were grouped in each of the RD-107 and RD-108 engines. The German Werner Baum has recently claimed that Glushko essentially appropriated the design for these chambers from a paper design for a 25-ton chamber that the Germans had carried out in a hurry in mid-1950 right before their departure later that year. Like Glushko's 23-ton chamber, Baum's 25-ton chamber was evidently a scaled up version of the ED-140 [23]. Because both the Glushko and Baum designs were descendents of the ED-140, it is not surprising that they are similar. However, one should note that the ED-140 itself incorporated both indigenous Soviet *and* appropriated German innovations. Additionally, Glushko introduced a number of important innovations between the ED-140 and the final RD-107/RD-108 engines that were independent of German design. These innovations focused on nozzle design, turbopump design, cooling systems, propellant mixture methods, and metallurgy. In sum, there is evidence to suggest that the Soviets benefited from the German contribution much more than they have admitted so far, but much less than some recent German accounts have claimed.

4. The "Liquid-Liquid" Engines

The first postwar Glushko engine was the RD-100, essentially a copy of the German A-4 (V-2) engine (with some improvements in chamber construction, the turbopump, and liquid oxygen injectors). The RD-100 was created using a set of 14 fully assembled A-4 engines, and equipment from a further 15 A-4 engines which were transferred from the Montania plant in Germany to Khimki in the Soviet Union in early 1947. The RD-100 engine was first used on the R-1 (SS-1), a Soviet copy of the German A-4, in September-November 1948 from the desert at Kapustin Yar.

By gradually uprating the RD-100 (c. 27 tons at sea level), Glushko also developed the RD-101 (c. 37 tons) and the RD-103 (c. 44 tons) in the late 1940s and early 1950s. In developing the latter two engines, Glushko's engineers focused on four major areas of improving the basic German engine: increasing the effectiveness of the propellants used; increasing combustion chamber pressures; optimizing the layout of engine design; and modernizing actual construction processes and materials used [24]. For example, for the RD-101, Glushko appropriated German recommendations and used a more modern pneumo-hydraulic and electrical layout and a steam gas generator with a solid catalyst instead of a liquid one. Chamber pressure was increased from 16 to 22 atmospheres. The RD-101 and RD-103 were used in Korolev's R-2 (SS-2) and R-5 (SS-3) missiles respectively. The latter was the first Soviet missile capable of striking "strategic" distances (with a range of about 1,200 kilometers) and was declared operational in its nuclear tipped version on 21 June 1956 [25]. These would be the last engines using the liquid oxygen (LOX)-alcohol combination as propellant and the last which owed their design in a direct way to the Model 39 German engine.

One technological leap that came to a dead end was the RD-110, Glushko's first major LOX-kerosene engine, developed between 1947 and 1951, and meant for Korolev's ambitious R-3 missile project. The engine would have a sea level thrust of 120 tons and a specific impulse of 243 seconds, values far in excess of any engine built before. Initially, Glushko attempted to develop the engine by simply scaling up the original German A-4 spherical engine chamber. When that idea failed to bear fruit, he opted to use a more ambitious scheme, based on the ED-140, with the integrated solder-welded "coupled shells," but then ran into numerous stability problems during testing [26]. It was primarily because of engine trouble that the Soviet government suspended the R-3 program in 1951 and then eventually cancelled it formally two years later. Glushko at the time noted to his ministerial boss that "the creation of an engine of 120-140 ton thrust is connected with the solution of a number problems which happen to be at the limits of modern science and technology" [27]. Although the RD-110 project was ultimately a failure, the experience with the 7-ton ED-140 was useful in pointing the way to a host of new innovations, including closed cycle engines. Most important, the RD-110 debacle may have underlined for Glushko that the best way to building new powerful engines was not by scaling up smaller chambers, but by combining smaller chambers into one big engine.

In 1951-52, almost simultaneously with the abandonment of the RD-110 engine, Glushko began work on three new engines that were significantly different from the earlier German A-4 motor [28]. The first two were the RD-105 and RD-106, intended for the first Soviet ICBM, with sea level thrusts of 55 and 53 tons respectively [29]. The third was the RD-211 (see later below). The first two were evidently radically scaled up and improved versions of the basic ED-140 design – with the cylindrical combustion chamber and the flat injector head. Unfortunately, ground tests of the RD-105 and RD-106 were less than successful because of instabilities in the combustion chambers. At the same time, the Soviet government also altered the requirements for the first Soviet ICBM, stipulating that it be capable of lifting a 5 ton warhead instead of a 3 ton one, i.e. the missile would need more powerful engines than the RD-105 and RD-106. Trapped in a technical deadlock, Glushko opted for a conservative but very effective design solution. He decided to group together four 23 ton combustion chambers (each, scaled up and modified versions of the ED-140) into a single unit and fed by a single turbopump. With this design, the length of the engine was significantly reduced, thus lowering the mass of the rocket. Additionally, the philosophy of modular construction would enable mass production without significant changes to factory machinery. Based on this design, Glushko produced two nearly identical engines, each with four main chambers, the RD-107 and the RD-108. The latter differed from the former in having four (instead of two for the RD-107) additional steering chambers and a different design of the throttle [30]. Both of these engines used solder-welded construction with both ribs and corrugation, i.e. indigenous design elements. They also used cylindrical combustion chambers, stemming from the German influence. Korolev's R-7 (SS-6) ICBM used a single RD-108 on the core stage, and four RD-107 engines as strapons.

These four-chambered RD-107 and RD-108 engines have been extensively modified over the past 40 years and still remain in use in the *Soyuz-U*, *Molniya-M*, and *Vostok-M* space launch vehicles. Although multiple chamber engines are generally considered inefficient due to increased mass, Glushko's engineers have over the years incorporated some notable innovations that have led to high specific impulses for engines of its class. In January 1958, production of the RD-107 and RD-108 engines was initially assigned to Plant No. 24 Named After M. V. Frunze (currently named the AO Motorostroitel') in Kuybyshev (now Samara) with design escorting provided by the OKB-456's Privolzhk Branch established the same year. The same plant still manufactures them. Note that the actual combustion chambers and nozzle extensions are produced at the OAO Metallist-Samara also based at Samara [31].

A major problematic engine was the RD-111 which proved to be the last LOX-kerosene engine developed by Glushko's design bureau before the advent of the *Energiya* project in the mid-1970s. It was also the very last engine Glushko developed for a missile or launch vehicle produced by Korolev. The RD-111 was a four chamber engine designed for the first stage of the Korolev's R-9A (SS-8) ICBM in 1959-61. It had a sea level thrust of 144 tons and was the first operational Soviet rocket engine to incorporate gimballing as a means of steering. Because of serious doubts about Glushko's ability to develop such a high thrust LOX engine, Korolev for a brief time unsuccessfully attempted to eliminate Glushko from the program [32]. The R-9 suffered serious delays, primarily because of "explosions of the liquid propellant engines in the first stage due to high frequency oscillations in the combustion chambers," before it was declared operational on 21 June 1965 [33]. These problems finally convinced Glushko to decline work on LOX-based engines for Korolev's famous N1 superbooster.

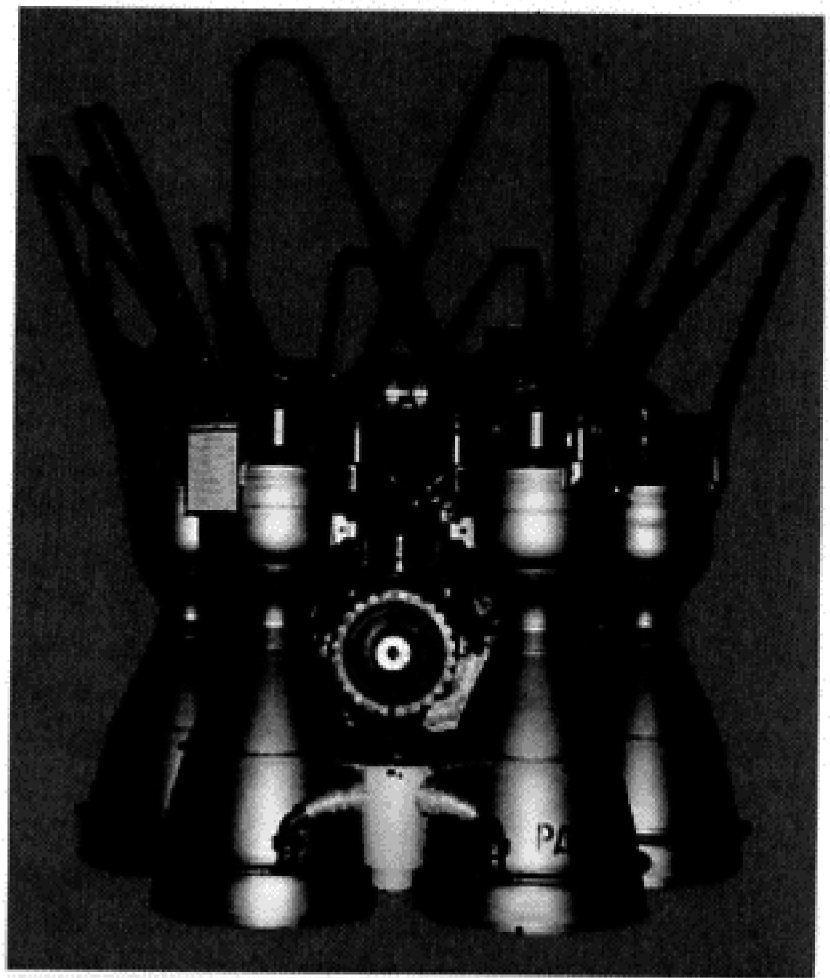

Fig. 2 This is the RD-251 engine, developed for the first stage of the R-36 (SS-9) ICBM. The engine was basically a cluster of three RD-250 engines, each with two combustion chambers. Thus, at launch, a total of six combustion chambers fired (four of which are visible in the photo). © Dietrich Haeseler

In the same RD-100 series, Glushko in the late 1950s began pursuing the use of other fuels apart from kerosene. One of the most promising such propellant components was unsymmetrical dimethyl hydrazine (UDMH), first synthesized in the Soviet Union in 1949 by the State Institute of Applied Chemistry (GIPKh). UDMH was first paired with LOX in the single chamber RD-109 engine meant for the third stage of Korolev's 8K73 booster for robotic lunar probes in the late 1950s. Serious problems during engine development led Glushko to abandon work on the engine in early 1960 in favor of an improved version named RD-119 which Glushko also offered to Korolev. By this time the relationship between Korolev and Glushko had seriously deteriorated, and the RD-119 was also never used for any of Korolev's launch vehicles. Luckily, OKB-586 Chief Designer Mikhail K. Yangel' adopted the RD-119 as the engine for the second stage of his *Kosmos-2* launcher, first used in October 1961 [34]. The RD-119 was series produced initially at a plant in Omsk, and then at Plant No. 1001 in Krasnoyarsk (from October 1961) and at Plant No. 172 in Perm (from July 1962). From 1968, the engines have been produced in-house at the Glushko design bureau's own plant.

The RD-109 and RD-119 engines were anomalies. For the most part, UDMH was not used in pairing with LOX but with other oxidizers, principally

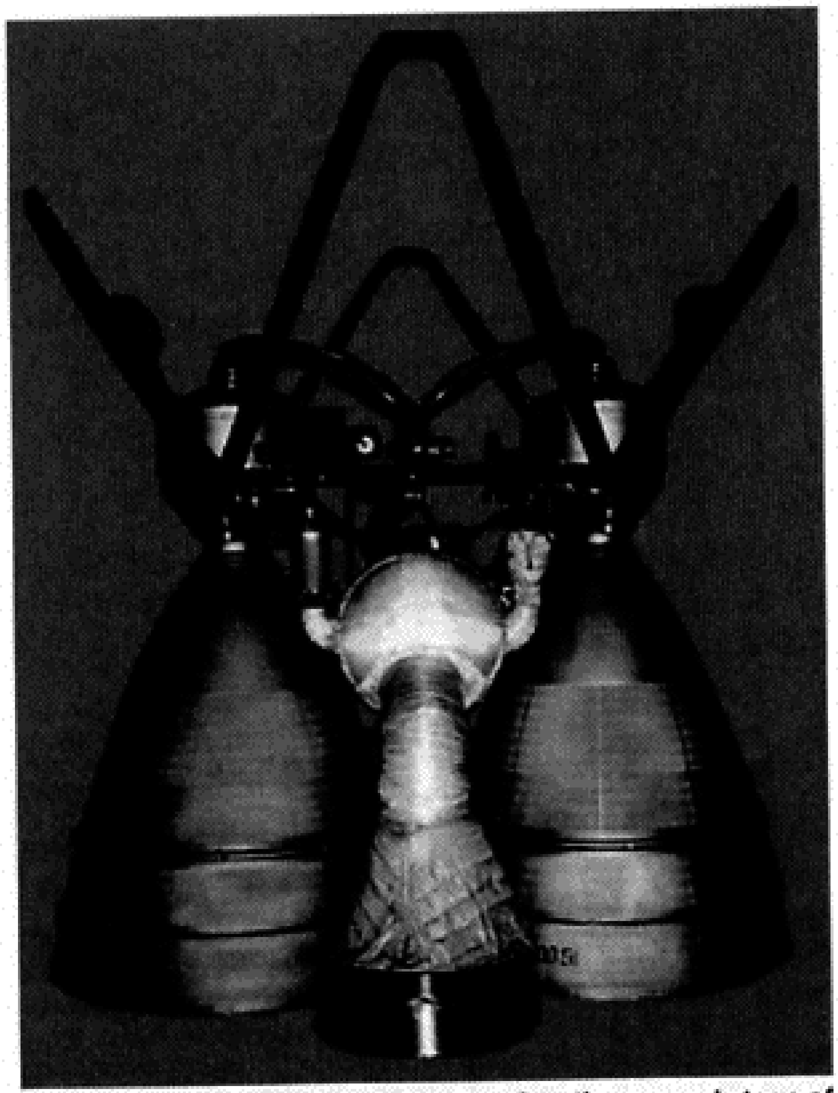

Fig. 3 Here is the RD-252 engine, used on the second stage of the R-36 (SS-9) ICBM. The RD-252 was essentially a high altitude version of the RD-250 engine, a two-chamber engine used as the 'base module' for all the engines on the R-36 ICBM developed in the 1960s. © Dietrich Haeseler

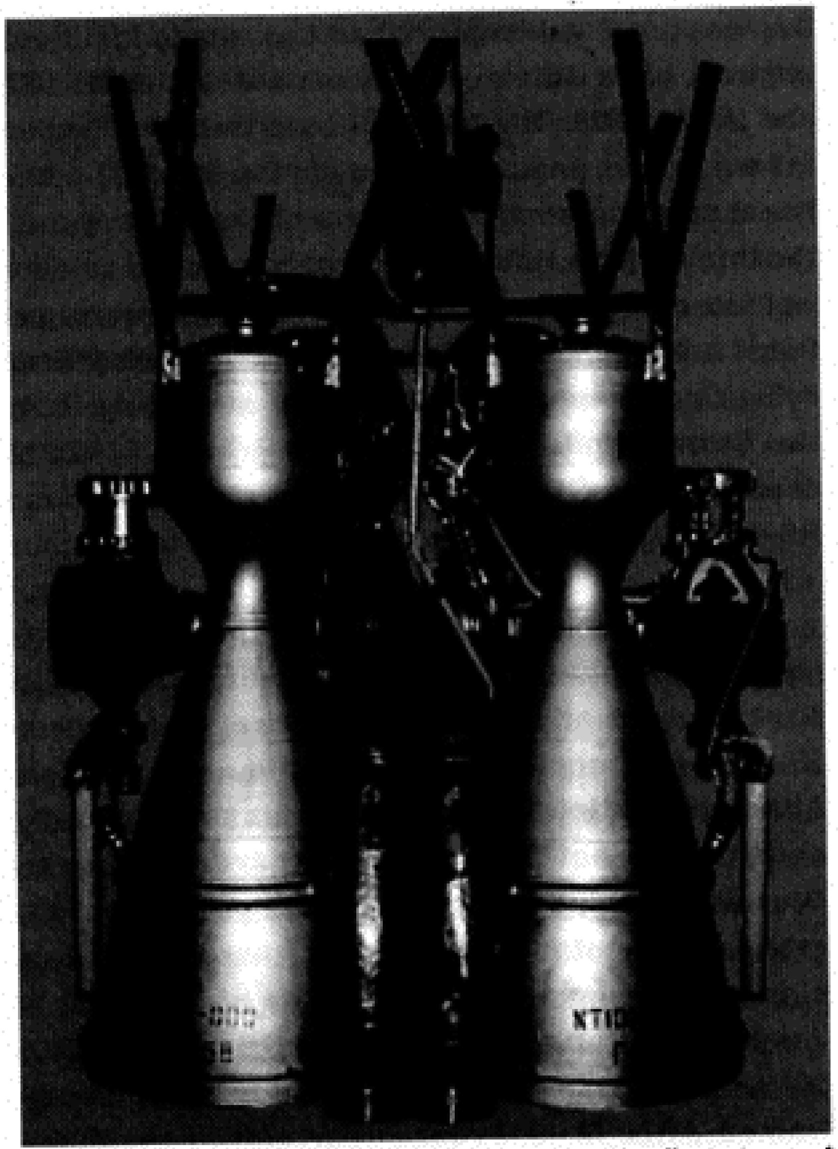

Fig. 4 This is the RD-216M engine used on the first stage of the Kosmos-1 and Kosmos-3 boosters. The engine was derived from the RD-216 engine, originally developed for the R-14 (SS-5) IRBM produced by Mikhail Yangel's design bureau in the late 1950s and early 1960s. © Dietrich Haeseler

nitrogen tetroxide (N_2O_4). Oxidizers apart from LOX were first introduced operationally by Glushko in the early 1950s as part of his RD-200 series, beginning with the RD-211, whose development began in 1952. This engine used a nitric acid derivative named AK-27I (a solution of 27% nitrous oxide in concentrated nitric acid – "AK" is the Russian abbreviation for nitric acid) as oxidizer and a kerosene derivative named TM-185. The RD-211 was slated for use as the main engine for Korolev's first foray into designing a long-range storable propellant missile, the R-12 (SS-4). Unfortunately, the engine displayed very poor results, and its thrust levels proved insufficient after a redesign of the R-12. In 1954, Glushko abandoned work on the RD-211 and began work on the RD-214 which was later used as the R-12's first stage engine. By this time, Yangel' had inherited work on the R-12 missile. It was the first storable propellant rocket engine used on a Soviet strategic ballistic missile, introducing a trend that would be common for almost all Soviet era missiles.

Another parallel engine development program was that of the RD-212 for OKB-23 Chief Designer Vladimir M. Myasishchev's M-40 *Buran* intercontinental cruise missile. This engine was also abandoned in the mid-1950s when Myasishchev required an engine with a 22% increase in thrust. Glushko offered the modified RD-213. Ultimately neither engine was ever used: the *Buran* project was canceled in November 1957 [35].

By adhering to the philosophy of combining combustion chambers to produce a variety of different propulsion units, Glushko developed several engines for military ballistic missiles in the 1950s and 1960s. For example, a single engine, the RD-215, was used as the basis for all the engines on Yangel's R-14 (SS-5) and R-16 (SS-7) missiles. This particular engine had two identical chambers supplied by a single turbopump assembly – situated between the chambers in the area of the critical cross-sections of the nozzles in order to reduce the size of the engine. For the R-14, he combined two such identical RD-215s via a frame with a common starting system to create the four-chambered RD-216 with a sea level thrust of about 151 tons. A slightly modified version of the RD-215, called the RD-217, was used on the first stage of the R-16. Three such modules were put together to create the six-chambered RD-218 with a sea level thrust of about 246 tons. Each of the three units had two starter chambers, a turbopump, a fuel-rich gas generator, and a solid propellant starter. A single high altitude variant of the RD-217 called the RD-219 was installed on the R-16's second stage [36]. Thus, one single engine (the RD-215) provided the basis for all the engines on these two missiles (See Table 4). Series production of these engines was carried out at the Krasmash Plant (RD-216) in Krasnoyarsk and the P. I. Baranov Motorostroitel'nyy Plant (RD-218 and RD-219) in Omsk.

The same principle of modular engine development was applied on Yangel's famous R-36 (SS-9) missile. These engines used – for the first time – the N_2O_4-UDMH combination which would become a standard for most of Glushko's engines. Decrees in support of R-36 development were issued on 16 March and 12 June 1962 at the ministry and government level respectively. The missile's first stage used three two-chamber RD-250 engines on its first stage, collectively called the RD-251 (Fig. 2). The second stage used an altitude version of the RD-250. The design layout of the RD-250 was identical to the earlier "base" engine, the RD-215. The difference between the new "base" variant (RD-250) and its altitude variant (RD-252, Fig. 3) was increased combustion chamber pressure (91 atmospheres in place of 84 atmospheres) and different exhaust nozzles [37]. As with the RD-217, the RD-250 was the victim of high frequency oscillations during ground testing which destroyed the engine assemblies. The R-36 missile was eventually declared operational on 21 July 1967 after much redesign and testing of the engines.

Apart from boosters such as the *Sputnik*, *Vostok*, *Soyuz*, and *Kosmos-2*, several other first generation engines were used on Soviet space launch vehicles. On 31 October 1961, the Soviet government permitted the Yangel' design bureau to begin work on a two-stage launcher based on the R-14 missile that would later receive the designations *Kosmos-1* and *Kosmos-3* [38]. For the "space" version, the Glushko design bureau's Omsk Branch undertook a modernization process of the RD-216 engine focused primarily on reducing high frequency instability during the primary firing regime. The modified engine, the RD-216M (Fig. 4), was used for the first time during the first orbital launch of the *Kosmos-1* rocket in August 1964. These engines were manufactured initially at the Krasmash Plant and then from 1968 at the Yuzhmash Plant in Dnepropetrovsk. By this time, overall launch vehicle development of the *Kosmos-1* was tasked to OKB-10 Chief Designer Mikhail F. Reshetnev who also designed the second stage of the booster [39]. By the late 1970s, due to heavy production orders at the plant, a severe shortage of the RD-216M engine prompted Glushko's engineers to look for an alternative. They went back to decommissioned R-14 missiles and took the old "unmodified" engines, incorporated some cosmetic modifications, and began using them for orbital launches. At least 50 of these engines had been used by 1998. They are currently manufactured at the AKO Polet plant in Omsk [40].

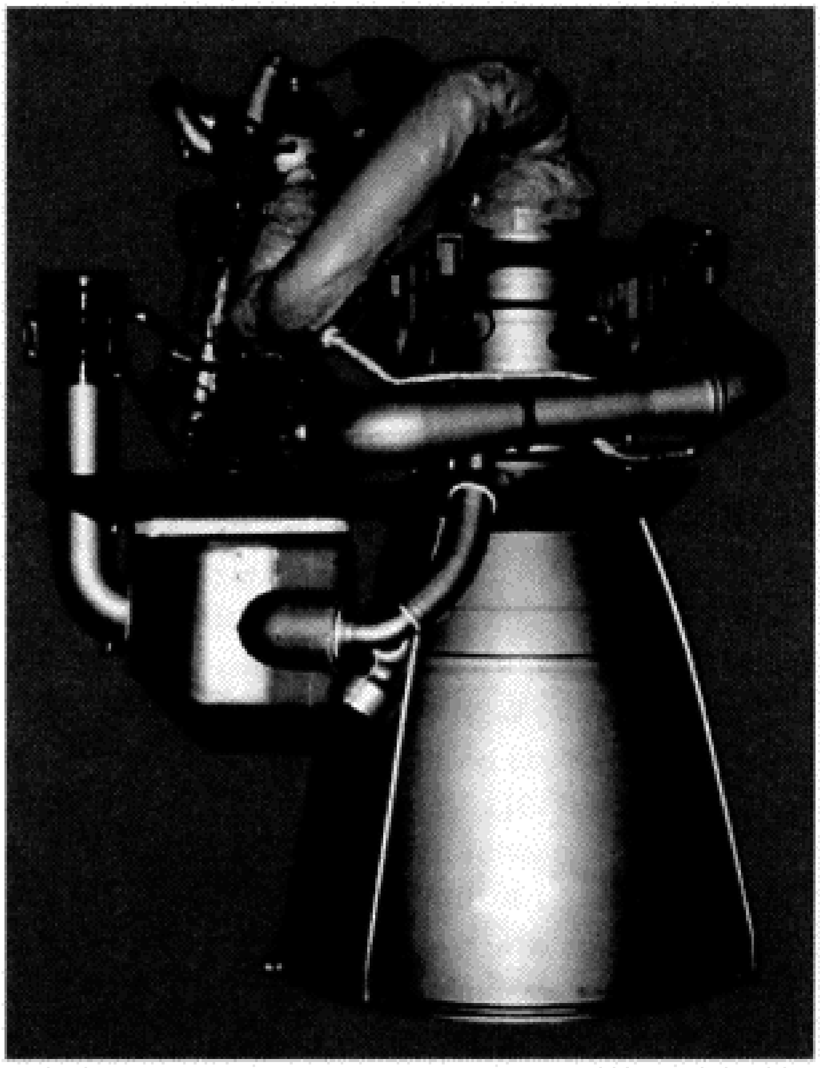

Fig. 5 Here is the RD-253, the first Soviet closed cycle engine using hypergolic propellants. The engine, originally developed in the early 1960s, is still in use (with upgrades) to this day as the first stage engine of the famous Proton booster.
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A similar production evolution followed another important Soviet launch vehicle, the *Tsiklon-2*. In August 1965, the Soviet government allowed the Yangel' design bureau to begin work on new orbital boosters based on the powerful R-36 ICBM [41]. These would be used for launching IS (anti-satellite) and US (ocean reconnaissance) satellites. As with the *Kosmos-1* booster, Glushko's engineers developed modernized variants of the original R-36 for the *Tsiklon-2*, the RD-261 (first stage) and RD-262 (second stage), testing of which ended in August 1973. By the mid-1970s, Glushko decided to use the reserve of original "unmodified" engines from the R-36, i.e. the RD-251 and RD-252, which were then introduced to both the *Tsiklon-2* and *Tsiklon-3* launch vehicles [42].

5. The "Gas-Liquid" Engines

Glushko began development of his "second generation" engines, i.e. closed cycle engines, in 1961. Before the advent of the *Energiya* program, all of these used the N_2O_4-UDMH combination.

His first such engines were the single chamber RD-253 (Fig. 5) and RD-254 engines which he originally proposed for the ill-fated N1 program. The RD-254 was an altitude variant of the ground-firing RD-253 which had a vacuum thrust of about 167 tons. These engines were characterized by relatively high specific impulse ratings and extremely high chamber pressures. On 26 May 1962, Glushko signed a formal agreement with Chelomey to use these engines (six RD-253s) on the first stage of the *Proton* launch vehicle [43]. The first ground test was in November of the same year. Series production was eventually tasked to the Glushko design bureau's Kamskiy Branch which was also engaged in design escorting of the manufacture of the RD-214 engine for the R-12 missile. The *Proton* was first launched in July 1965 in its two-stage version. By 1998, about 1,780 such engines had been used. Glushko's engineers had incorporated a first series of major modifications to the engine by 1986, and is continuing with new changes at the present time. For the Proton-M (which uses the Briz M upper stage instead of the Blok DM stage), Energomash is gradually uprating these engines by increasing thrust by about 7%. The RD-253 remains the highest thrust (150 tons at sea level) single-chamber engine operating on storable propellants in the world. Since the beginning of the *Proton* program, the RD-253 engines have been manufactured at the Perm Production Association Named After Ya. M. Sverdlov (currently known as Perm Motors Holding Company) in Perm. They are currently produced at an offshoot of that plant, the ZAO Proton-PM, which gained semi-independence in 1995 [44].

Other second generation engines were used on Yangel's MR UR-100 (SS-17) and R-36M (SS-18) ICBMs. For the R-36M, Glushko had originally proposed using six single-chamber engines on the first stage and a single one on the second stage. All engines, as in previous models, would be based on a "unitary" base model. Yangel', however, refused to allow Glushko to design engines for both stages, apparently because Yangel' had been unhappy over Glushko's collaboration with Chelomey on the development of the *Proton* and UR-700 boosters. This was at a time when Yangel' and Chelomey were at loggerheads with each other in the midst of the infamous "civil war" over missile development that would destroy the fabric of the missile community like no other conflict before [45]. Eventually, for the R-36M, Glushko designed four single-chamber closed cycle engines, each of them designated the RD-263. Their collective designation was the RD-264. Total sea level thrust was on the order of 425 tons. Thrust vector was controlled by pivoting the chambers of each unit in one plane. For the first stage of the MR UR-100, Glushko offered the RD-268, which was simply a modified version of the RD-263 (combustion pressure was increased). In this case, for both missiles, the base model was the RD-263 engine. All engines were manufactured in-house at the Energomash Plant. After a long troublesome test series related to problems with the RD-264 engine's propensity to display high frequency oscillations in the combustion chamber, the R-36M was declared operational on 30 December 1975. Yangel's other missile, the MR UR-100, also received its operations certification on the same day [46]. The R-36M (with the "open" designation RS-20) launched the small UoSAT-12 into orbit in April 1999 as part of a program to convert the ICBM into a light space launcher.

Glushko also reluctantly agreed to develop engines for the modernized variants of these two of Yangel's missiles. This hesitancy was apparently based on a severe overload of work connected with the *Energiya* program in the late 1970s and early 1980s. Glushko's engineers eventually issued a draft plan for the RD-274 engine, comprising three RD-273 modules. The RD-273 was essentially a modification of the RD-263 – it was originally in fact called the RD-263F. This "new" engine would now power the first stage of the R-36MU (SS-18 mod 4) which was declared operational on 17 December 1980 [47]. For the last major iteration of the R-36M missile, designated the R-36M2 (SS-18 mod 5), Glushko chose to use the same RD-274 engines, but in significantly uprated form. This missile, which was declared operational on 11 August 1988, was the last new military missile to use an engine designed by Glushko's design bureau [48].

6. The "Gas-Gas" Engines

One engine that was slightly different from first and second generation categories was the single-chamber RD-270 developed for a heavy lift booster in the 1960s. Instead of the "liquid-liquid" or "gas-liquid" layout, this engine used a "gas-gas" layout (which strictly speaking is a subgroup of the "gas-liquid" scheme). In such a design, almost all the propellant is burned in two separate gas generators, which drive the two turbopumps. One of the gas generators uses almost all the oxidizer with a small portion of the fuel while the other uses almost all the fuel with a small part of the oxidizer. The two precombusted gases are then burned in the main combustion chamber after passing the turbines [49]. Such a layout in the RD-270 allowed for extremely high chamber pressure (266 kg/cm^2) and thus high specific impulse for an engine of its thrust range, 685 tons in vacuum. Development of this engine, a sort of parallel to the American F-1 engine, began as a result of an official government decree issued on 26 June 1962 [50]. Propellants were the standard storable N_2O_4-UDMH combination. Between October 1967 and July 1969, Glushko's engineers carried out 27 static tests of 22 such engines, of which only nine passed without problems. According to a semi-official history of the Glushko design bureau:

> the main results of the work we could say was to show the full reality of a [liquid propellant rocket engine] created on the 'gas-gas' scheme with mechanically separated turbopumps and also [to show] the reliability of ensuring static and dynamic stability [51].

By the late 1960s, the RD-270 was slated for use as the first stage engine of Chelomey's giant UR-700 lunar rocket. Development of the RD-270 ended in the third quarter of 1969 in connection with termination of the UR-700 lunar program. Glushko's engineers apparently never pursued work on another engine of the "gas-gas" layout after 1969. Although such engines offered very high chamber pressures, the extremely complex designs discouraged hope for reliably using them in operating conditions. OKB-456 pursued a second engine with a similar design in the 1960s; a two-chambered experimental engine known as the RD-280 using different propellants. The government issued a decree on its development on 28 April 1965, although Glushko appears to have abandoned work on it after three years or so [52].

7. Very High-Thrust Engines

Glushko pursued work on extremely high thrust engines for several years. On 16 July 1961, the Soviet government (i.e. the USSR Council of Ministers) issued a decree approving work at Glushko's design bureau on "search work on selection of optimal layout and parameters" for a single-chamber liquid propellant rocket engine with a thrust of up to 1,000 tons [53]. At a time when he refused to participate in work on the N1, Glushko even considered using the LOX-kerosene combination in this R&D effort. Eventually, the research was downsized by the late

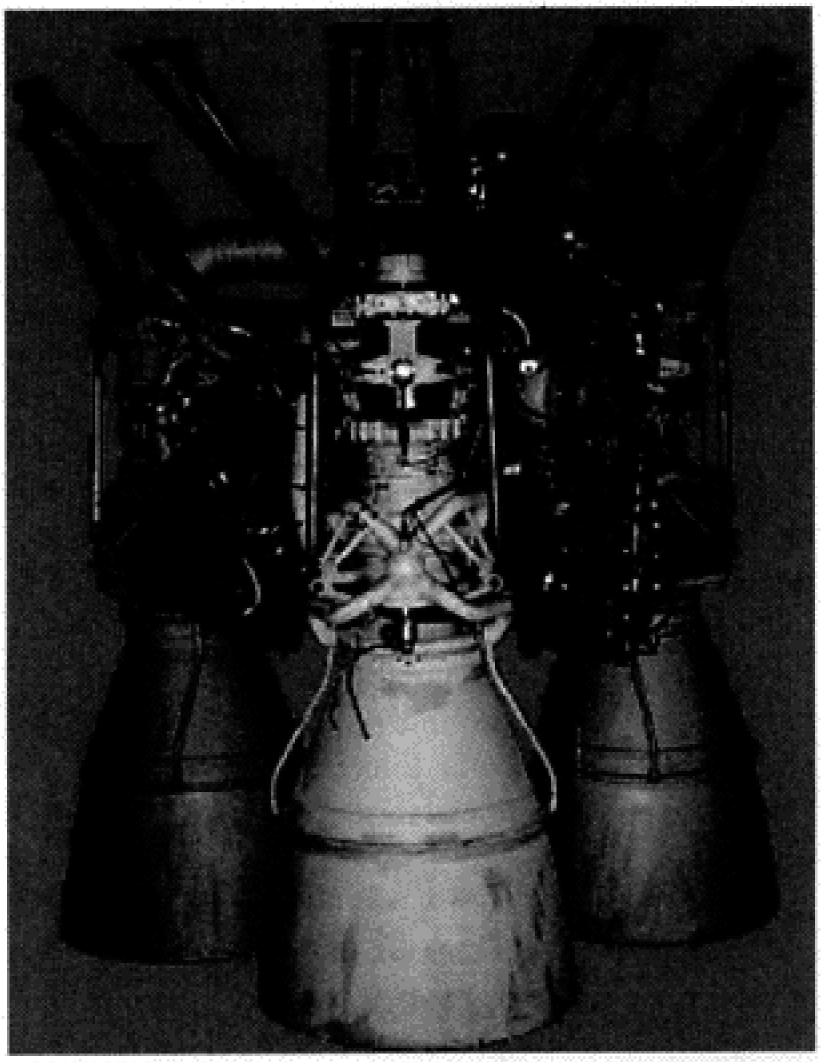

Fig 6. This is the RD-171 engine, a four-chamber engine that is similar to the RD-170 engine used on the giant Energiya booster. The RD-171 is still currently used on the first stage of Ukraine's Zenit-2 and Zenit-3SL boosters.
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1960s to a closed cycle 600 ton thrust engine. Glushko's engineers found that it would have been realistically possible to develop such an engine at the time, but that for use on the N1, it would have required substantial redesign of the booster which was not possible at such a late stage in development [54]. Although work on this engine was terminated, Glushko, in the early 1970s, studied several other very high thrust engines such as a 600 ton thrust engine using LOX and liquid hydrogen (LH_2). At the same time, he directed a team under Sergey P. Agafonov to study a 5,000 ton thrust engine with an annular combustion chamber and a nozzle of external expansion with a central body that could be used on the first stage of the N1 rocket [55]. None of these proposals were pursued with any serious intent, but they did point the way to the engines that would lay the basis for the future superheavy *Energiya* rocket.

8. *Energiya* and *Zenit*

After the major reorganization in the space industry in 1974, the lion's share of rocket engine work at the Glushko design bureau was focused on the *Energiya* program. In 1974, while Glushko oversaw the entire NPO Energiya, Radovskiy served as the Chief and Chief Designer of the Energomash Design Bureau.

Engine design for the *Energiya*-class booster began in the first half of 1973 when preliminary research was focused on a basic layout. In mid-1973, at a meeting of the scientific-technical council of the design bureau, engineers discussed possible approaches to creating an engine with a thrust no less than 500 tons using LOX-kerosene. They considered single chamber, two-chamber, and four-chamber designs. Eventually, Glushko chose the four-chamber design, partly because his organization had considerable experience in designing multi-chamber engines. At the same meeting, Glushko decided to use the "block principle" in designing the engine – so as to make it possible to develop in the future a variety of engines using the basic 500 ton version [56]. It was this engine –uprated slightly – which was the core of future Soviet plans to create a new generation of launch vehicles. The Soviet government issued the formal decision to build *Energiya* on 17 February 1976. The decision was part of an integrated plan to develop several launch vehicles, spacecraft, and weapons systems. For *Energiya*'s first stage (i.e. the strapons), Glushko proposed four four-chambered RD-170 engines, each with a ground thrust of 740 tons. These would be the most powerful rocket engines created in the history of the Soviet Union. They would also be the first LOX-kerosene engines designed under Glushko since the troubled RD-111 created for the R-9 missile.

The program to develop the RD-170 was long and plagued by malfunctions and delays. Initial requirements stipulated an engine that would be reusable and easily refurbishable without significant repairs, characteristics that far exceeded any previous engines built by the organization. Although the creation of the RD-170 was a fundamentally new innovative leap in engine design in the Soviet Union, Radovskiy's engineers used a significant amount of existing equipment and documentation from a prior 100 ton thrust engine powered by storable propellants. The three main directions in developing the RD-170 comprised creating combustion chambers, gas generators, and the turbopump assembly. For the combustion chambers, engineers created a model chamber known as the 2UKS which demonstrated 80% thrust levels of the actual working chambers. In the initial development phase, engineers conducted at least 68 "fire-stand" tests of this chamber. Using experience from the 100 ton thrust engine, Glushko's team created a gas generator for the RD-170 that simulated up 80% of the firing regime of the nominal engine during 132 ground tests. Finally, the last segment to be developed was the turbopump assembly, almost identical to the "real" engine, on which engineers conducted 32 full-scale ground tests which were finished by 1979.

The first full-scale ground test of the RD-170 on 25 August 1980 was a complete failure. The turbopump assembly was destroyed due to excessive vibrations in the assembly. To the increasing alarm of engineers and managers, the subsequent 15 tests of the engine were also failures. In desperation, Energomash Chief Designer Radovskiy opted to reduce thrust to 600 tons to test out the reliability of the various components. Finally, the 17^{th} test on 9 June 1981 was a success. Two days after the firing, engineers carefully dismantled the engine and associated equipment and carried out a detailed diagnosis. The results provided engineers with the first light of hope that the job they had been assigned could be completed [57].

As finalized in 1976, the *Energiya* booster was created on a modular design, i.e. each of its "strapons" were modified versions of individual launch vehicles called the *Zenit-2*. For this booster, a single RD-170 was used in a slightly modified variant known as the RD-171 (Fig. 6). The differences between the two engines were minor and involved differences in axis gimballing (1-axis for the RD-171, 2-axis for the RD-170). After the successful ground test of the RD-170 in 1981, managers decided to move ahead with a full-scale ground test of the first stage of the *Zenit-2* with its RD-171 engine with only one difference from a real model – instead of the nominal 740 tons, the engine thrust would be throttled down to 600 tons to ensure success. In the meantime, however, during a ground test of a single engine in September 1981, engineers had detected some troubling signs. Engineers found stress tracks on the rotor blades of the turbine, possibly from small particles which had fallen into the turbine or perhaps shearings from the walls of the propellant tank or the engine itself. Unfortunately, at the time, engineers did not place to much significance on these findings and a few months later the problem disrupted the schedule in a most dramatic fashion during the *Zenit-2* first stage ground test. On 26 June 1982, at the premises of the Scientific-Research Institute of Chemical Machine Building (NII Khimmash) at Novostroika north of Zagorsk (now Sergeyev Posad), Radovskiy's engineers fired the huge stage. A massive explosion ensued that destroyed both the stage and its unique one-and-only kind test stand. In their search for a fix, engineers introduced a set of changes to the design of the engine, including filters to prevent shavings and particles from entering the turbine assembly, and strengthening the construction of all engine parts to prevent excessive vibrations of the turbopump assembly. By this time, as delays piled upon delays, it had already been six years since development had started of the *Energiya* booster, and Glushko's engineers had yet to show much in terms of success.

As dissatisfaction with the program rose, different voices called for a reevaluation of the entire project. Opponents proposed terminating work on the RD-170 and instead switching to four less powerful engines instead of one very powerful one. In this design, *Energiya* would fire 20 engines at lift-off (4 engines X 4 strapons + 4 core engines). These smaller engines, named MD-185, would essentially be one of the four chambers on the RD-170 and would each have 185 tons thrust (hence the designation). Glushko ordered a team in his design bureau to immediately begin work on the MD-185 as Minister of General Machine Building Sergey A. Afanas'yev, the head of the Soviet missile and space industry, established an "Interdepartmental Commission" to recommend a specific course of action, i.e. to stay with the RD-170 or to move ahead with the MD-185. Staffed by such luminaries of the Soviet rocket engine industry as General Designers Arkhip M. Lyul'ka and Nikolay D. Kuznetsov and scientists such as Vsevolod S. Avduyevskiy (from TsNIIMash) and Valentin Ya. Likhushin (from NIITP), the Commission met to decide *Energiya*'s fate in early September 1982. One of the more unusual topics raised during this period was the possibility of using Kuznetsov's old NK-33 engines from the N1 lunar rocket as a possible alternative for *Energiya*. Despite severe criticism of Glushko's approach to building a four-chamber 740 ton thrust engine (especially from Lyul'ka and Kuznetsov), Glushko held his ground and patiently proved to the Commission that sticking to the original course would be the best option under the circumstances. He explained how the RD-170's problems could be fixed and how switching gears in the middle of the program would be costly in terms of money and time. By this time, his engineers had already introduced several new modifications to the RD-170 design, and were ready to manufacture the newer models by May of the following year.

As this debate was finally subsiding, in late May 1983, Glushko's engineers finally successfully ground-fired an RD-170 engine for the first time to its full 740 ton thrust regime. In 1983-84, engineers also solved one of the most critical problems, that of estimating the dimensions and mass of aluminum particles that could potentially destroy engines. Finally, Energomash fired the entire first stage of the *Zenit-2* (with the RD-171) on 1 December 1984, a full two-and-a-half years after the first unsuccessful one. A second test, later the same month, was also successful, clearing the way for actual flight tests of the *Zenit-2* booster, the first of which was on 13 April 1985. *Energiya* was launched for the first time, two years later, on 15 May 1987. Its four RD-170 engines performed flawlessly [58].

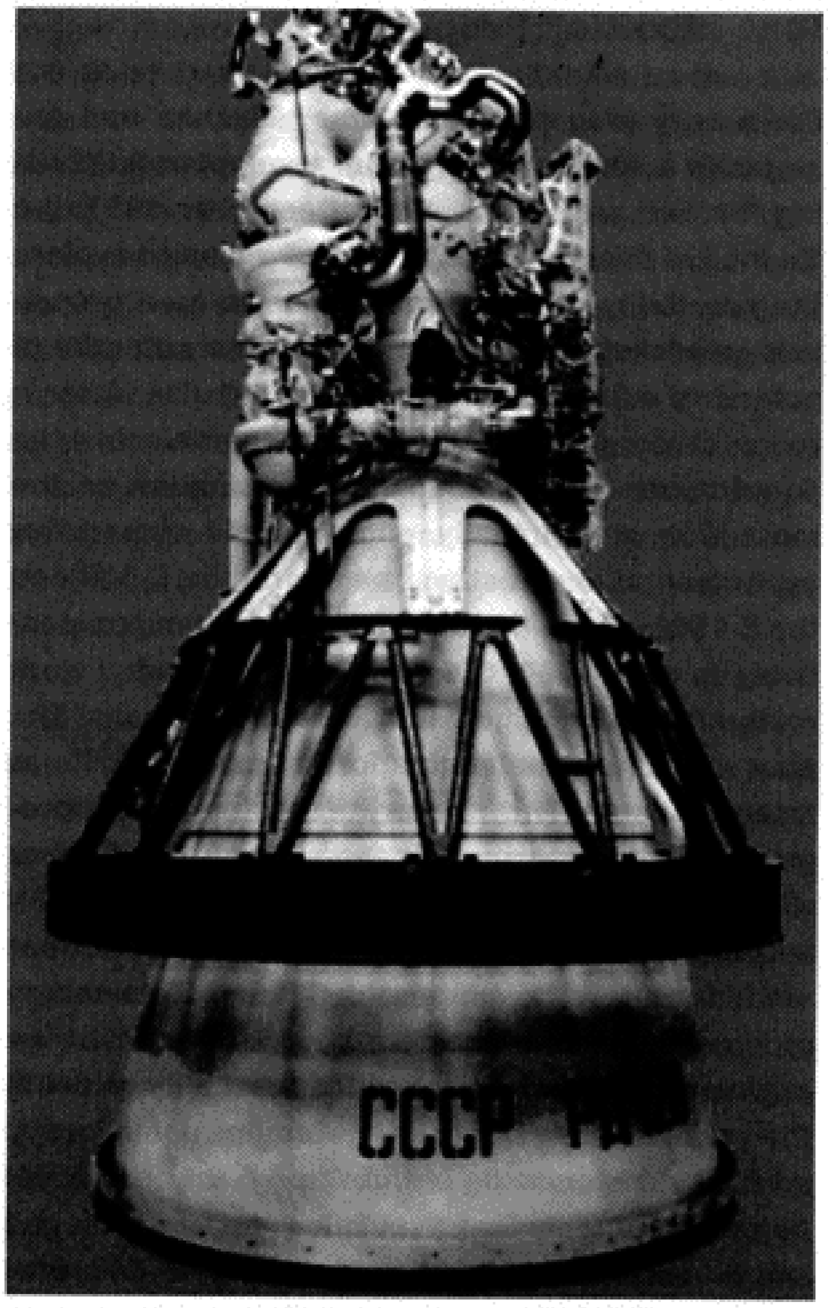

Fig 7. This is the RD-120 engine used on the second stage of the Zenit-2 booster. © Dietrich Haeseler

The *Zenit-2*'s RD-171 is also used on the new SeaLaunch version of *Zenit-2* known as *Zenit-3SL*. The *Zenit-2* second stage uses the single chamber RD-120 (Fig. 7), which is currently manufactured at the Yuzhmash Plant in Dnepropetrovsk, Ukraine. Originally, this engine was to have been developed by Design Bureau of Chemical Automation (KB Khimavtomatiki), the design bureau of the late Semyon A. Kosberg, but because that organization was overloaded with work on the cryogenic engines for the *Energiya* core, Energomash took over the work and produced the RD-120. The cryogenic RD-120 was largely derived from the storable RD-268 engine originally developed for the MR UR-100 ICBM [58a].

9. "Exotic" Propellants

For a very long period of time, Glushko had engaged in a serious program to develop engines using "exotic" propellants. On 3 December 1953, the Council of Ministers had approved a plan to explore the possibility of using liquid fluorine as a propellant on rocket engines because of the potential of achieving extremely high specific impulse. After a research program, the design bureau selected the liquid fluorine-liquid ammonia combination as the most promising. Initially, engineers developed two experimental combustion chambers, the E-500 and the E-1500, with a thrust of 0.5 and 1.5 tons respectively. In early 1960, Glushko began dedicated work on the RD-303 engine with a thrust of 10 tons. The plan was to use the engine for an upper stage of a heavy booster. The primary executor of the program was the design bureau's Primorsk Branch where the engine was fired at least 98 times between August 1963 and late 1965. On 23 November 1962, the State Committee of Defense Technology ordered Glushko to accelerate work on the fluorine engine project with the specific possibility of using the engine as an upper stage engine for a heavy booster developed by Yangel', probably the R-56. As a result of technical discussions between Yangel' and Glushko, a modified version of the RD-303, now called the RD-302, was created. This engine in turn underwent 309 ground firings totaling 40,000 seconds of firing time. After the R-56 was abandoned, Glushko turned to use the engine on the *Proton* booster – specifically for launching a massive geostationary communications satellite developed by Reshetnev's design bureau. In July 1969, a new government decree approved this program for the development of the RD-301 (Fig. 8) engine with a thrust of 10 tons and a specific impulse of 420 seconds. Testing of the engine began in January 1973 at the design bureau's Primorsk branch. The actual upper stage, known as the 11S813, would be designed by Reshetnev. This program appears to have progressed to a very advanced stage – to the point where ground tests of the complete upper stage were imminent. On 22 April 1976, an interdepartmental commission signed a decision to release the RD-301 for ground-testing on the upper stage. Unfortunately, a decree on 3 February 1977 terminated the RD-301 program. The official reason was a dramatic redirection of the Soviet communications satellite program. By this time, Glushko's design bureau had tested 274 such engines for a firing time exceeding 200,000 seconds [59].

Another "exotic" propellant engine was the closed cycle single chamber RD-502 developed in 1960-66 which used highly concentrated hydrogen peroxide and pentaborane as propellants. Work on a prototype named RD-501 began as a result of the famous "big space" decree of 23 June 1960. There is no public information to suggest any particular application for this engine, but it was quite likely intended for an upper stage application on the Proton booster [60].

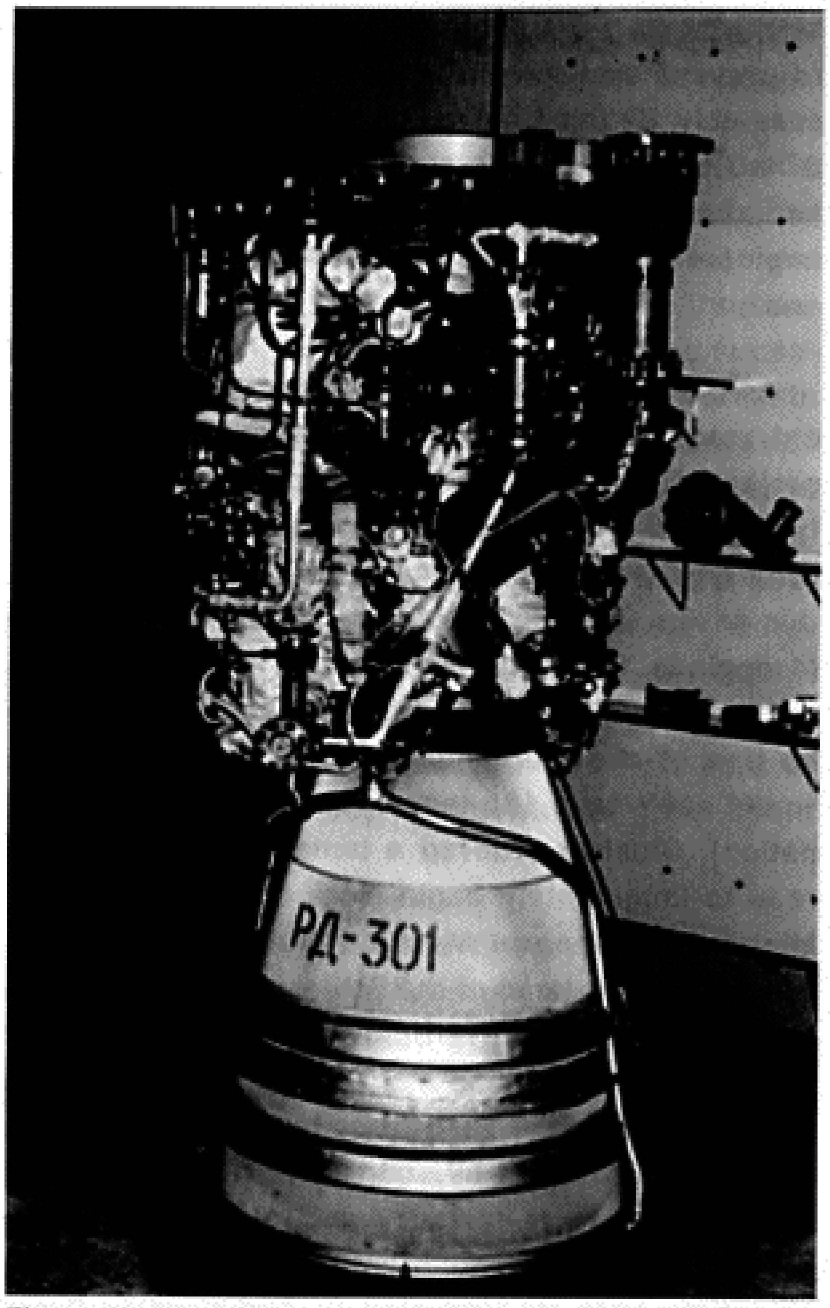

Fig. 8 Here is the RD-301 engine, an experimental upper stage engine using liquid fluorine, developed in the 1960s. The engine was designed for use on the 11S813 upper stage designed by KB Prikladnoy mekhaniki (former OKB-10) for the Proton booster. THe program was cancelled in February 1977. © Dietrich Haeseler

10. Nuclear Rocket Engines

Like several other space organizations (such as NII-1, OKB-1, OKB-670, and OKB-154), Glushko's design bureau also pursued active work on nuclear rocket engines during the early space era. While the NII-1 institute oversaw the general work on such engines, subcontracts for actual design work were handed out to several design bureaus including Glushko's organization. The principle behind the operation of nuclear rocket engines is relatively simple: instead of utilizing chemical combustion, nuclear engines force a propellant of low molecular weight (such as LH_2) through a high-temperature reactor. The reactor then flashes the propellant into a powerful propelling jet which exhausts from a convergent-divergent nozzle. The main advantage is the extremely high exhaust velocity (which implies a high specific impulse rating) which can be twice that of chemical propellant rockets [61].

Prior to an initial governmental decree in 1956 initiating such work, the Physical-Power Institute (FEI) of the Ministry of Medium Machine Building had issued a document proposing that the best results could be gained by using LH_2 as the working fluid for the engines. Glushko appears to have vehemently opposed using hydrogen since it would require very high pressures and would also reduce the mass characteristics of any engine. A switch to other propellants such as ammonia would, however, significantly reduce specific impulse ratings. Through 1955, Glushko's engineers had worked on a preliminary report on nuclear rocket engines which was issued in February 1956 entitled "Thermonuclear Rocket Engines" in which they conducted comparative analyses of various types of chemical propellants and nuclear reactors (solid phase, liquid phase, and gas phase) for nuclear engines. Glushko, notably, did not consider LH_2 as a possible propellant at the time. Later in early 1958, Glushko established a special "design-computation brigade" at the design bureau led by R. A. Glinik to oversee the work. This brigade was "promoted" to the status of a design department in 1966 [62].

On 30 June 1958, the USSR Council of Ministers issued a decree on future work on nuclear rocket engines and assigned OKB-456 as the chief R&D organization for the creation of an engine of the "type A," i.e. a solid-phase reactor [63]. In 1959, Glinik's team produced a draft plan for a powerful nuclear rocket engine (a predraft plan was produced in June 1958) using a solid-phase reactor which was examined by a special expert commission headed by Academician Aleksandr A. Aleksandrov and which included rocket engine General Designers Arkhip M. Lyul'ka and Nikolay D. Kuznetsov. By 1962, after several government decrees, Glinik's group had produced an amended draft plan which, despite Glushko's initial doubts, used liquid hydrogen as the working fluid. By the early 1960s, about the time that actual construction work was about to begin, Glushko's work ran into political trouble. First of all, Chelomey, who was not involved in any of the work on nuclear rocket engines, strongly opposed such work. Given his power and influence at the time, he was apparently able to obstruct advances in the program. Secondly, Korolev opposed Glushko's involvement in the nuclear rocket engine program, and instead suggested that OKB-670 Chief Designer Mark M. Bondaryuk be the sole executor of the effort. Additionally, after a request from the NII-1 research institute, in July 1963, Glushko decided to abandon the solid phase reactor in favor of a "gas phase" reactor design despite counsel from leading engineers in his design bureau (including Glinik). This had the effect of seriously delaying the program. As Glushko's work on the RD-410 engine came to a virtual standstill, the nuclear engine project was moved to another design bureau by 1965, that of the late Chief Designer Semyon A. Kosberg. The latter's effort was substantially more modest than Glushko's original conception of the program.

At the same time, Glushko's design bureau independently continued to pursue the gas phase reactor engine approach through the late 1960s and early 1970s. Such work was evidently geared not towards space applications, but for use on OKB-156 General Design Andrey A. Tupolev's nuclear airplane project. Korolev's OKB-1 worked on the specifics of the nuclear reactor for the engine. Glushko defended a draft plan for the new redesigned engine in 1971 at the Ministry of Medium Machine Building, which was greeted with very high praise. By the early 1970s, however, Glushko began to rapidly lose interest in the nuclear rocket engine program. His lack of interest was fatal to the project. In 1974, when he became General Designer of NPO Energiya, he sharply reduced all work on such engines to this dismay of many who had worked on the effort for over a decade [64].

11. Tri-propellant Engines

Since 1981, NPO Energomash has explored development of a tri-propellant engine using oxygen, hydrocarbon-based fuels, and hydrogen. The culmination of this program was the start of official work on the RD-701 on 16 February 1988 when Glushko named his deputy M. R. Gnesin to head the project. At the time, the engine was intended for use on the MAKS single stage-to-orbit vehicle developed by NPO Molniya. The twin nozzle RD-701 engine has common intakes for fuel to feed two main combustion chambers. The propellants are LOX, LH_2, and kerosene. The engine has two main regimes of operation: LOX-kerosene is used for the first phase for about 2.5 minutes when the engine develops 204 tons thrust. Cooling is by LH_2. It then switches to less dense LH_2 for the remaining 6-8 minutes to orbit at 81 tons of thrust per nozzle. A single chamber version, the RD-704, has also been developed [65]. Energomash performed the first ground test of an experimental engine at Sergeyev Posad on 9

August 1994. The same month, NASA awarded Pratt & Whitney a $5.4 million contract to explore the possibility of converting the RD-704 into an engine appropriate for an American launch vehicle [66]. The current status of the joint Energomash-Pratt & Whitney program is unclear.

12. Chemical Lasers

Apart from rocket engines, Glushko's design bureau has expended considerable effort to develop "energy units on new physical principles – continuous chemical lasers using fluorine-based oxidizers." In 1972, a Soviet government decree authorized work on such lasers (presumably for battle applications). Glushko established a team under Sergey P. Agafonov to work on this theme. On 19 December 1974, the first work site for testing such lasers (with a power rating of 30 kW) was put into operation at the design bureau branch on the territory of the State Institute for Applied Chemistry's plant in Leningrad. At least 1,100 tests were conducted here over an unspecified time period. A second site was commissioned on 29 April 1979 for power ratings of up to 400 kW of which there were 520 tests. Judging by the fact that from December 1985, the project was headed by Deputy Chief Designer Boris I. Katorgin, the effort appears to have had a high priority and was probably part of the Soviet "star wars" program known as *Fon*. The work continued well into the 1990s. In 1996, the Russian government handed out awards to a group of leading engineers from Energomash who had participated in the development of continuous chemical lasers for "laser complexes" – 8 basic types, including the RD-600, had been created (with 40 modifications) with power ranges from 3 to 400 kW [67].

13. Post-Soviet Developments

13.1 Angara

In the 1990s, Energomash has been engaged in developing engines for a new generation of Russian launch vehicles. Most notable of these is the *Angara*-class boosters which the Russian government officially approved for development in August 1994. By August 1997, there were two "light" conceptions of the *Angara*, complex 1 and complex 2, both of which used a single RD-191 engine on the first stage. The RD-191 is a one-chamber version of the *Energiya* rocket's RD-170 [68]. By early 1998, the M. V. Khrunichev State Space Scientific-Production Center (GKNPTs Khrunichev), the prime contractor for *Angara*, had unveiled a complete family of *Angara* vehicles built on modular construction. Each of these Universal Rocket Modules (URMs) will be equipped with a single RD-191M engine. The original complexes 1 and 2 became the *Angara 1.1* and *Angara 1.2* respectively. The "medium" and "heavy" versions, the *Angara A-5I* and *Angara A-4E*, will both have five and four RD-191s respectively. The first launch of *Angara 1.1* was tentatively set for the year 2000 [69]. Within a year, Khrunichev had expanded its core group of 4 variants to as many as 17 versions of the Angara. All of them would use various combinations of the URMs with the RD-191M – thus promising a lucrative future for Energomash.

13.2 Rus

Energomash is modifying its old RD-107 engine for use on the new *Soyuz-2* launch vehicle under the framework of the *Rus* launch booster program which is designed to replace the old *Soyuz*-class workhorses in operation for the past few decades [70]. Similar modifications on the *Zenit-2*'s RD-171 is leading to the RD-172 with a 5% increased thrust level.

13.3 Natural Gas

Since as early as 1981, Energomash has carried out research on the use of liquefied natural gas (which is up to 98% liquid methane) as fuel for a new generation of rocket engines. The claim is that methane engines will provide much better efficiency, lower cost, and better ecological side effects than usual LOX-kerosene or storable propellant combinations. In recent years, Energomash has actually built several such engines including the RD-169, RD-182, RD-183, RD-185, RD-190, and RD-192, all powered by LOX-natural gas. All except the RD-183 are of the closed cycle type. Many of these engines have design architectures derived from already proven engines. For example, the RD-182 is based on the RD-120K engine (itself a modified RD-120 developed for a projected light launcher such as *Kvant* or *Unity*). The RD-185 is an altitude variant of the RD-169.

Energomash has proposed use of the RD-169, RD-190 (both stage I), RD-185 (stage II), RD-183 and RD-184 (both for the apogee boost stage) for AO Kompomash's *Riksha-1* launch vehicle concept, but a lack of funds makes it likely that it will be many years before they are operationally used [71].

13.4 International Ventures

Among the Energomash's first forays into international ventures in the post-USSR era was an agreement signed in 1992 between NPO Energomash and Pratt & Whitney to market and license rocket engine technology internationally based upon *Zenit-2*'s RD-120 engine. There was a further clarification of the plan in July 1995 which stipulated the marketing of a modified version of the RD-120 named the RD-120M (also called the RD-120.01) which had slightly different expansion and mixture ratios as well as different values for throttling and gimballing. For a short while, American Space Lines, comprising Rockwell International and Orbital Sciences Corporation, expressed interest in using the RD-120M for one of its proposed X-34 variants. Among other companies, the PacAstro company also explored the possibility of using the engine on the first stage of its proposed *PacAstro-2* launcher while Kistler Aerospace originally considered the same engine for its own K-1. The first model of a working RD-120 was flown to West Palm Beach, Florida on 29 June 1995. Russians claimed that it was the very first time that a Russian (or Soviet) rocket engine had ever crossed the border into the United States [72]. Three static tests in the United States of the RD-120 took place on 11, 18, and 25 October 1995 on Pratt & Whitney's E-8 stand in Florida finishing phase one of testing. All three tests were considered full successes [73].

The work with the RD-120 was key to further cooperation between Energomash and Pratt & Whitney. Since at least late 1994, Lockheed Martin (at that time just Martin Marietta) had been seriously considering using the RD-180, a two-chamber version (with a redesigned turbopump) of the giant RD-170 used on the *Energiya* booster, on its new (then named) *Atlas IIAR* booster. At the same time, the Nikolay D. Kuznetsov design bureau offered up its NK-33 engines, left over from the N1 program, as a competitor to the Energomash engines [74]. On 12 January 1996, Lockheed Martin officially announced that the RD-180 would be used on the *Atlas IIAR* (the actual agreement was signed on 20 December 1995). The agreement was vital to the very survival of Energomash which, like most other defense companies, had been hit hard by post-Communist economic ruin [75]. Less than six months later on 5 June 1996, Pratt & Whitney and Energomash signed a formal agreement to jointly develop and manufacture experimental models for testing and certification of the RD-180 [76]. Energomash began the first phase of ground testing (comprising four firings) of the new engines in November of the same year at its testing ground in Khimki. A second series of five firings took place in January 1997 [77]. The first production model of the engine (No. 1T) was fired on 5 May 1998 in preparation for shipment to the United States for installation on the first *Atlas 3A* (as the *Atlas IIAR* was renamed) launcher. The first test-firing of the RD-180 on U.S. soil took place on 29 July 1998 at NASA's Marshall Space Flight Center in Huntsville, Alabama. The contractual cost with Lockheed Martin for each of the 18 initial RD-180 engines was said to be $8-10 million [78]. The first flight version of the engine was delivered in late December 1998.

On 24 May 2000, the first *Atlas 3A* lifted off from the Cape Canaveral Air Force Station with its *Eutelsat W4* satellite payload, becoming the first American rocket to be powered by Russian rocket engines. The mission was completely successful. The Atlas 3A has the capability to insert about 4,060 kilograms into geostationary transfer orbit. Sea level thrust of the single RD-180 engine was 390.2 tons. In its final version, the RD-180 uses about 70% of the construction elements from the original (and much larger) RD-170. By March 2000, Lockheed Martin had put in orders at least 101 of the RD-180s. The engines are produced and delivered by the RD-AMROSS company which is the joint financial venture between Energomash and Pratt & Whitney headed by CEO Robert Monaco. For commercial launches, the engines will be manufactured in Russia, while for national launches (e.g. for the DoD), the engines will be produced in the United States.

Lockheed Martin has further plans for the RD-180 beyond the Atlas 3A. In February 1999, the company announced that they would use the RD-180 on the new generation *Atlas 5* launch vehicles which will use a central block known as the Common Core Booster (CCB). The basic *Atlas 5* variant will have a capability to launch more than 5 tons into geostationary orbit.

Energomash had also by mid-1998 begun preparations for a variant of the RD-180 for a new generation of Evolved Expendable Launch Vehicles (EELV) developed by Lockheed Martin in cooperation with the U.S. Air Force. Unlike the version slated for *Atlas 3A* which would operate at 84-85% of nominal thrust levels, the RD-180 for the EELV is to fire at 100% thrust level [79].

Apart from Energomash's involvement with RD-AMROSS and with SeaLaunch (see section on *Energiya* and *Zenit*), the organization is exploring other international options. For example, although the *Energiya* booster has been consigned to history, there may yet be hope to use the RD-170 on a future launch vehicle. In mid-1999, officials from Israel Aircraft Industries announced a proposal to use the RD-170 on a heavy-lift booster known as *Star-460* [80]. While the prospects for such a booster (designed for launch from

Brasil) remain uncertain, the proposal is one manifestation of the worldwide interest in Russian rocket engines after the end of the Cold War.

Energomash also planned to use a modification of the RD-120 as the first stage engine for the *Yedinstvo* (or ULV-22) launch vehicle proposed by United Launch Systems International (ULSI), a multinational company, one of whose shareholders is the Academician V. P. Makeyev KB State Rocket Center (the designer of Russian submarine-launched ICBMs). The two-stage *Yedinstvo* was to be launched from an island off the east coast of Australia [81]. In late March 2000, however, ULSI informed the Makeyev Center that they would not be able to finance the project because the Australian government had rejected a credit line for the project. There is speculation that the project was thwarted partly under pressure from SeaLaunch, a direct competitor to the *Yedinstvo* project. Energomash has temporarily stopped all work on the DP-220U engine for the first stage of *Yedinstvo*. Ironically, Energomash also has a stake in SeaLaunch.

14. Conclusions

The history of the Glushko design bureau suggests that one of the underpinning philosophies behind rocket engine design is modular development, i.e. creating a single unitary engine and building as many variations and combinations as possible for a variety of applications. At the same time, the evolution of engine design at the organization suggests an eagerness to tackle innovative areas such as nuclear rocket engine design, exotic propellants, and chemical lasers. Glushko's design philosophy also suggests an affinity towards simple and robust designs that provide high specific impulse ratings. It would not be an overstatement to say that Energomash has produced some of the best rocket engines in the world.

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