



AIAA 93-2415

**The RD-170, A Different Approach
to Launch Vehicle Propulsion**

Boris I. Katorgin and Felix J. Chelkis

NPO Energomash, Khimky, Russia

Charles D. Limerick

Pratt & Whitney, West Palm Beach, Florida

AIAA/SAE/ASME/ASEE

29th Joint Propulsion

Conference and Exhibit

June 28-30, 1993 / Monterey, CA

The RD-170, A Different Approach to Launch Vehicle Propulsion

Boris I. Katorgin* and Felix J. Chelkis**
NPO Energomash
Khimky, Russia

Charles D. Limerick***
Pratt & Whitney
West Palm Beach, Florida

Abstract

In the early 1960's, the United States and U.S.S.R. took different paths in developing launch vehicle propulsion. The United States focused on the lower performance gas generator cycle rocket engine because of the less demanding technology involved and the resulting easier development process. The U.S.S.R. adopted the high performance staged combustion cycle with oxygen rich turbine drive gases and have since striven to perfect that system. The RD-170 is the culmination of over 30 years of staged combustion cycle propulsion system development. This paper discusses the evolution of high pressure turbomachinery and combustion chamber designs from the RD-253 (the first operational high pressure staged combustion rocket engine, introduced in 1965) to the RD-170. The operating characteristics of the RD-170 will be explained along with the operability features included as part of the engine system. The quality approach used in the manufacturing, component test, and assembly process will be described and the unique health monitoring and life prediction system will be unveiled. Potential application of the RD-170 to U.S. launch vehicle needs has been studied and these results will also be presented.

-
- * General Director and General Designer
 - ** Chief Designer
 - ***Manager, SE&I, Russian Programs
Member AIAA

Introduction

The RD-170 is a mature engine. Development started in 1976 and the first flight was in 1985. Over 200 engines have been built and over 900 tests accumulating more than 100,000 sec have been completed. The RD-170 is a total propulsion unit with hydraulics for control valve actuation and thrust vector control gimbaling, pneumatics for valve actuation and purging, and a thrust frame to distribute loads all self contained as part of the engine. The engine was developed to provide the booster propulsion for the Energia and Zenit launch vehicles. One of the requirements of the Energia application was reusability, the RD-170 strap-on booster units were intended to be used up to 20 times without overhaul or removal from the booster stage. Hence, along with the traditional requirements of high performance and reliability were reusability and operability requirements not previously demonstrated in rocket engines. It was required that between flight servicing and initial flight preparation be accomplished using a minimum of hand operations.

The engine is the current product of an engine design philosophy initiated with the RD-253 engine which started development in the early 1960's. NPO Energomash embarked on a course to develop high pressure, staged combustion, oxidizer rich turbine drive gas rocket engines, and the RD-253 which became operational in 1965 was the first engine of this type. This

engine which operated at over 2000 psia using the staged combustion cycle was as far in advance of other engines of that generation as the RD-170 is relative to the current generation of engines. Figure 1 shows the chamber pressure versus time characteristics of some representative NPO Energomash developed engines with the U.S. developed F-1 and SSME noted for reference.

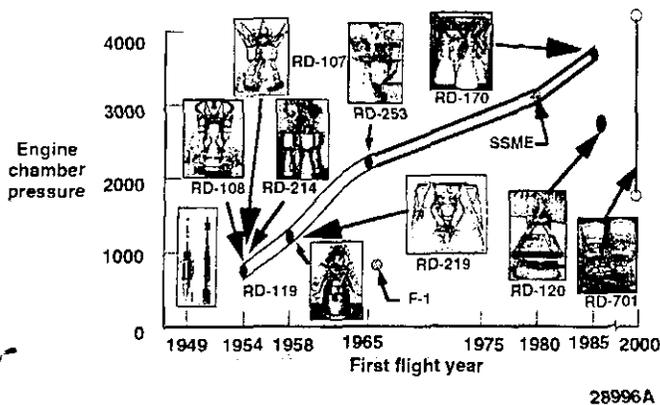


Figure 1
Rocket Engine Development History

RD-170 Engine Characteristics

The RD-170 is a high performance lox/kerosene rocket booster propulsion system with operability and reusability features not previously demonstrated on rocket propulsion systems. The engine was designed to provide a minimum of 20 reuses before overhaul and enable between flight servicing and initial flight preparation with automated operations.

The operability of the RD-170 is a major contributor to the less than 7 day launch timeline of the Zenit launch system. The engine is >10% higher in performance than other lox/kerosene booster engines and has a fully developed, operational,

advanced health monitoring/life prediction system. Development of the engine was initiated in the mid 1970's with the first flight occurring in 1985. The quality control system and specifications were developed from strong requirements close to U.S. standards. The extensive NPO Energomash experience, the 4 chamber modular configuration of the engine, and development of a wide range of similar turbopumps of different thrust sizes provides confidence in low risk, low cost development of Derivative Configurations (1 chamber, 2 chamber, uprating, etc.).

The RD-170 engine assembly shown in Figure 2 consists of a single high-pressure turbopump assembly driven by two preburners, four injector/thrust chamber assemblies, integral fuel and oxidizer boost pumps, helium bottles for valve actuation and start and shutdown purging, thrust structure, gimbal actuators, propellant ducting, hypergolic-fuel cartridges, sequencing and control valves, shielding, and telemetry systems.

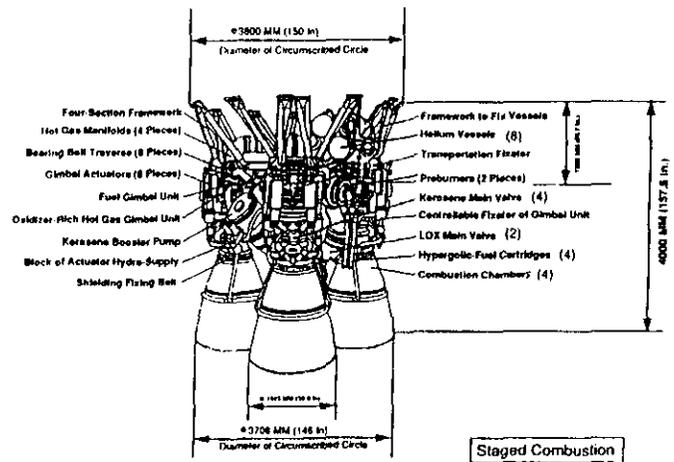


Figure 2
RD-170 Propulsion Assembly

The RD-170 is a staged combustion cycle Lox/Kerosene booster rocket propulsion assembly producing 1.6 million lbs sea level thrust and a sea level impulse of 309 sec at an overall mixture ratio of 2.6 to 1. It has a 2 to 1 throttling range, an assembly dry weight of 26,575 lbs and overall dimensions of 157.9 inches length and 146 inches diameter. The single high-pressure turbopump assembly feeds four identical injector thrust chamber assemblies. Two preburners are used to drive the single stage turbine with oxidizer rich combustion products.

The high pressure turbopump assembly, shown in Figure 3, consists of two rotors connected by a quill shaft. One rotor has the turbine and oxidizer pump and the other the fuel pumps. Both shafts operate with subcritical rotor dynamics.

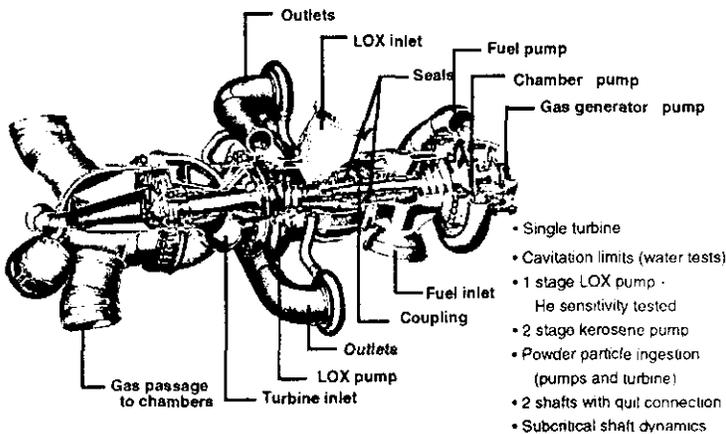


Figure 3
High Pressure Turbopump Assembly

All oxidizer flows through the preburners but the fuel is split between the preburners and chambers (fuel cooled). Thrust control is achieved by regulating fuel flow to the preburners, and mixture ratio by regulating fuel flow to the chambers. An engine flow schematic with only two chambers shown is presented in Figure 4.

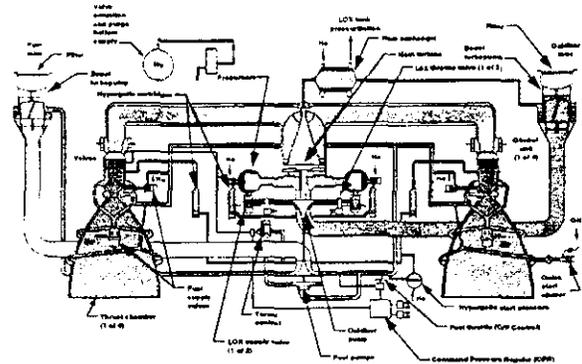


Figure 4
RD-170 Flow Schematic

The fuel and oxidizer boost pumps are integrated into the inlet lines and are driven with turbine discharge gas (oxidizer) and recirculated fuel (fuel) that reenters the propellant flow upstream of the high-pressure pumps. The four injector/thrust chambers are each integrally welded/brazed assemblies with hypergolic ignition and a combination of film and regenerative cooling (shown in Figure 5). All four injector chamber assemblies can gimbal in two directions or can be limited to a single direction by installing a fixed link. The linear actuators are powered by fuel-supplied by the high pressure fuel pump. The two parallel preburners are ignited by a unique single-shot hypergolic ignition system.

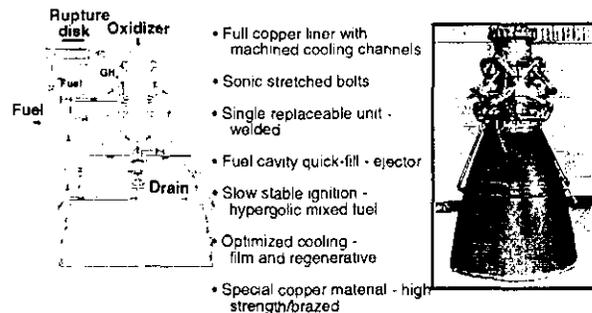


Figure 5
Injector/Thrust Chamber Assembly

Control valve command signals are generated by a vehicle computer running software generated during engine acceptance testing. Heated helium is supplied from the engine for oxidizer tank pressurization. The engine is reusable and over 20 repeat firings have been performed on ground test engines. The health monitoring system automatically assesses engine health and defines/tracks remaining engine life. The RD-170 has completed 28 flight firings (20 ZENIT and 8 ENERGIA) and over 900 test firings with an accumulated total of over 100,000 operational seconds.

Table 1 provides a general description of the RD-170 and characteristics are presented in Table 2.

Table 1

RD-170 General Description

- Staged combustion cycle engine
- Lox/kerosene propellants
- 4 thrust chambers (gimbal+8°)
- 2 oxygen rich preburners
- High pressure turbopump assembly
 - 2 stage fuel pump
 - single stage oxygen pump
 - single turbine
- Hydraulic system (valves, TVC) powered with kerosene from fuel pump
- Hypergolic ignition
- Operational certification 1985
- 200+ engines produced
- > 100,000 sec and > 900 firings
- 28 flight firings (December 1992)
 - 20 Zenit
 - 8 Energia
- Qualified for 10 mission reusability
- Fully developed health monitoring/life prediction system

Table 2

RD-170 Characteristics

- Nominal thrust (S.L.) 1,632,000 lb
- (Vacuum) 1,777,000 lb
- Specific impulse (S.L.) 309 sec
- (Vacuum) 337 sec
- Chamber pressure 3,560 psia
- Nozzle area ratio 36.4:1
- Mixture Ratio 2.6
- Length 157.9 inches
- Diameter (148.8 frame/146 nozzles) inches
- Throttle range 50-105 %
- Total system dry weight 26,575 lbs

Operability Features

The RD-170 was designed for operability, wherever possible flight preparation, and between flight operations (for reusable applications) have been minimized and automated. After installation in the vehicle, all engine operations are automated through the launch phase. The engine requires minimal preparation for launch as shown in Table 3.

Interfaces are minimized and there are no flexible interfaces with the vehicle. The hydraulics systems for the control valves and thrust vector control are self contained as part of the engine with hydraulic power furnished with kerosene from the high pressure fuel pump. There are no hydraulic interfaces with the vehicle or pad.

Table 3

RD-170 Launch Preparation

At the engine factory before shipping

- Line closeouts, chamber throat plugs, and hypergolic start cartridges installed

In the vehicle assembly building

- Continuity and function checks as part of vehicle/engine assembly process

All automated operations on pad

- Helium bottles filled
- Low level GN₂ purge and low level dry air purge at start of LOX tanking
- LOX cooldown by recirculation (15 min after completion of tanking)
- Fuel GN₂ ejector for 10 min
- Control valve hydraulic system prepressurized
- 100 sec to fill fuel system (fuel pre valve opened)
- Hydraulic control valves positioned 60 sec before start
- High level GN₂ fuel side purge 20 sec before start
- Helium bottle pressure, hydraulic control valve position, and GN₂ ejector operation monitored (pressure switches)

Helium for pneumatic valve actuations and purging during the shutdown is also self-contained as part of the engine. This system is automatically filled through a pad interface during the launch preparation process.

The comprehensive health monitoring and life prediction was designed and the necessary data base compiled during development to provide automated reusability of the engines for Energia. The projected launch rates have not materialized for Energia and reuse of the booster modules was never attempted; however, the engine has been qualified for 10 reuses (17 with 5 mission margin and 2 firings in acceptance).

The continuous throttling capability of the RD-170 to less than 50% also provides potential operability advantages. The engine could be started to a low thrust level and checked out prior to committing to launch. The throttling capability could also

be used to provide real time trajectory matching during the boost phase. This would enable a significant reduction in avionics programming, significantly improving the operability of the launch system.

Health Monitoring/Life Prediction System

Evaluation of the engine technical state after firing or flight use is accomplished using a technical diagnostics system (TDS), which deals with measured engine parameters.

The TDS uses both static and dynamic parameters of the engine and consists of the following subsystems:

static parameters diagnostics

- subsystem for evaluating measurement validity
- parameters algorithm evaluation

dynamic parameters diagnostics

- vibroacoustic characteristics evaluation
- subsystem for estimating expired life time

Full cycle of calculations and analysis for all subsystems can be performed within a day after engine testing.

All subsystems use measurements of all engine parameters during a test (or a flight). Total number of measurements is about ~150.

A diagram visually presenting the health monitoring life prediction process is shown in Figure 6.

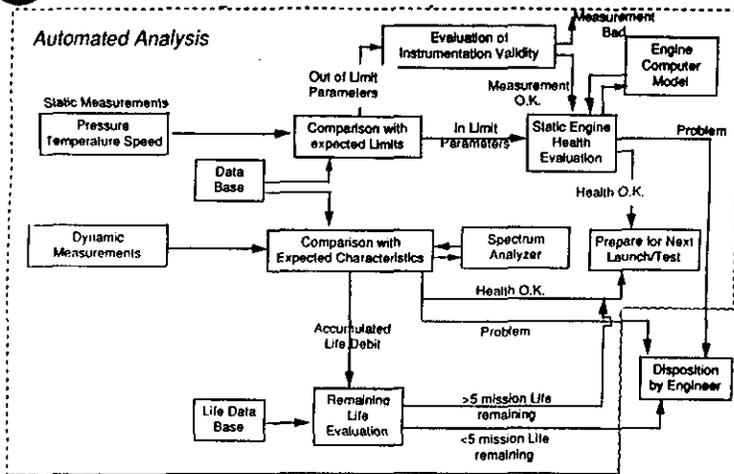


Figure 6
Health Monitoring/Life Prediction Process

Static Parameters Diagnostics

Subsystem for Evaluating Measurement Validity - This subsystem evaluates parameters, which were recorded during engine operation in start-up, steady state, smooth throttling, final stage, and shutdown modes. Totally, this subsystem evaluates over 100 engine parameters.

In the event that some parameters are beyond allowable statistical limits, the causes of why these parameters are out of the limits are analyzed by a special logical model. The procedure of evaluating parameter values and their derivatives and a formal analysis of causes of parameters being out of limits are fully automatic and performed by means of a special software for computers of IBM 360/370 type.

Parameters Algorithm Evaluation - The engine diagnostics for this evaluation is performed on the main mode for 17 engine subsystems for 30 diagnostic indicators. These diagnostic indicators are calculated by a mathematical model using engine parameters measured during operation.

Allowed limits for diagnostic indicators were defined by statistical modeling. In order to make a formal decision concerning a state of engine components, a special logical state model is used. All evaluation and formal analysis procedures are performed with special software on computers of IBM 360/370 type.

Dynamic Parameters Diagnostics

Vibroacoustic Characteristics Evaluation - This subsystem evaluates vibroacoustic characteristics of engine parameters obtained on start-up mode, nominal mode, smooth throttling mode, and final stage mode. The amount of parameter characteristics, which are calculated and evaluated, totals 100. Allowable characteristics limits are obtained from statistics.

Characteristics are calculated and compared with allowable limits by special equipment complex, which consists of spectrum analyzer and a personal computer connected to it. This computer enables the use of spectrum analysis for calculations. The process uses special software for calculating and analyzing vibroacoustic characteristics.

Subsystem for Estimating Expired Life Time - This subsystem evaluates an engine state based on expired life time by the end of the current engine test during all life cycle. Amount of evaluated parameters (which are called "accumulated damage owing to expiring main engine aggregates life time") totals 70. Allowed limits for these parameters are set based on results of durable engine life time testing cycles during development, and on certification and reliability confirmation test results. The "accumulated damage" is calculated by the same equipment complex as for vibroacoustic characteristics control and stability subsystem. There is a software for calculating "accumulated damage" at the end of each testing.

Quality Approach

Quality control system at NPO Energomash meets ISO 9000 series standards requirements. Quality control system procedures are implemented during project development, working documentation development, manufacturing, and testing of engine components and the engine system.

Project Quality

At NPO Energomash, input data for a project ("technical task") are considered by all departments, which participate in the project. Results of such a consideration are certified by department chiefs' signatures. A technical task is agreed upon by scientific organizations. Requirements, which are included in a technical task, should meet the State Standard for Liquid Rocket Engine Reliability.

Development materials ("technical proposal," "sketch project") are subject to standard control procedures, during which a project is checked for whether requirements of Single Design Documentation System State Standard are met. Then a project is directed to scientific organizations that investigate it.

Documentation Quality

During development all documentation passes through a multi-stage quality control process: first, it is controlled by an executor, then by a controller, and managers up to Design Bureau Chief. The documentation is controlled by the Standards Control Department, project management department, and by the experimental plant technological service. An experimental developmental program for engine components and engine system is developed for controlling engine design development process. This program is agreed upon by scientific organizations and

a customer. For controlling the process of developing manufacturing processes for engine components and engine system, the Experimental Plant develops a development program for technological processes. This program is agreed upon by the Design Bureau and a scientific technological institute. Results, reached at design development stages, are reflected in design bureau reviewing reports. Results of manufacturing processes development are certified by engaging specialized industry branch scientific institutes.

Manufacturing and Testing

All materials, purchased parts, semi-finished items, which are supplied to the company, are subject to input control. Control procedures are provided by industry branch and company standards.

All parts and subassemblies during the manufacturing process are subject to control procedures by Technical Control Department employees. Controlling operations are an integral part of the manufacturing process. The fact of passing through a control operation is certified with a mark in documentation for the part by the controller. Periodically units and subassemblies are assembled and disassembled for the purpose of control. Subassemblies that have independent specifications are subject to product acceptance tests (each specimen should be tested) or selective tests (selective specimen of a batch should be tested).

All waivers from a documentation are considered according to company standards. They are recorded and accounted in special forms. A conclusion for every waiver is certified by Technical Control Department Chief. At the moment of engine shipment all single waivers are considered in combination, as a whole. A list of allowed waivers is certified.

Technological, measurement and testing equipment are subject to control. NPO Energomash standards provide an order of controlling procedures.

When the ground development is completed, the engine quality is controlled in "interagencies" tests. A special commission estimates results of the testings and certifies them with a special statement. Each specimen quality is controlled by a fire test (product acceptance test). Periodically (annually) engine manufacturing stability and existing engine design margins are checked out. This procedure is performed in periodical certification tests. After completion of a ground engine development or a break in engine manufacture, qualification tests are carried out.

Quality System Control

The quality system is periodically checked. This is performed by a group of NPO Energomash's specialists under an order of the firm's management.

A part with a waiver can be permitted for further operations, if the waiver does not affect the engine quality and reliability. Such a permission for a waiver is made by a special permission card. In the permission card are shown a waiver cause, a person liable for the waiver, and measures to be undertaken to prevent from waiver causes in the future. A card has marks, which define a job order number, drawing and part numbers, quantity and others. Permission cards are numbered by a fabricating shop number and job order number. Cards are kept in a fabricating shop. The card form allows copying. Specialists and managers sign a card. Then it is certified by Design Bureau Chief and agreed upon by a customer. Then the card is copied and sent to relevant NPO Energomash's departments. When assembling an engine specimen, data for all waivers are gathered in the allowed

waivers list. Before accepting an engine, this list is considered and certified by engine components designers. NPO Energomash's Quality Control Service accounts and analysis waivers in engine system and parts.

Potential Applications

The RD-170 is a mature fully developed engine. It provides the opportunity to develop a high performance new booster stage without the high cost and long lead time of developing a new engine. A common booster stage concept powered with a single RD-170 engine was analyzed to determine its applicability to projected vehicle needs. The booster stage defined is intended to be used as the first stage of a two stage expendable launch vehicle and also as a liquid rocket booster (LRB) that could replace the solid rocket boosters on the Space Shuttle, and also be used on potential early heavy lift launch vehicle. Two ELV missions (20k and 50k payloads to LEO) were used in sizing the common booster stage. The design propellant load for the booster was set by the 50k payload mission at 800,000 lbs, approximately 90,000 lbs greater than the propellant load of the Russian common booster used on the Zenit and Energia vehicles. The two missions require different upper stages, initial thrust settings, and some propellant is off loaded for the 20k mission with a cryogenic upper stage. Figure 7 shows the 2 stage ELV configurations with key characteristics noted.

For use as strap-on LRB's on the Space Shuttle, the propellant load was reduced to 720,000 lbs to optimize payload. The delivered payload to 82 NM was 57,000 lbs, approximately 8,000 lbs less than the baseline Space Shuttle capability with RSRM's. An early Heavy Lift Configuration (External Tank with 3 SSME's at 104%) was defined and evaluated with different numbers of strap-on common boosters.

Table 4

RD-170 Booster Strap-ons Effect on Early Heavy Lift Vehicle Performance

Configuration (Shuttle ET with 3 SSME's @ 104%)	Payload (20 x 185 @ 51.6°)	Wgross millions lbs	T/W Liftoff
2 RD-170 LRB's	156,000	3.6	1.22
3 RD-170 LRB's	234,000	4.5	1.35
4 RD-170 LRB's	287,000	5.4	1.43
6 RD-170 LRB's**	388,000	7.1	1.60

**100 x 100 Circular Parking Orbit

The two strap-on common booster configurations would place 156,000 lbs in a 20 by 185 mile LEO parking orbit. Table 4 lists the additional payload capability available by adding more strap-on boosters.

Summary

The RD-170 rocket engine is:

- High technology
- High performance
- Reusable
- Designed for operability
- Available now

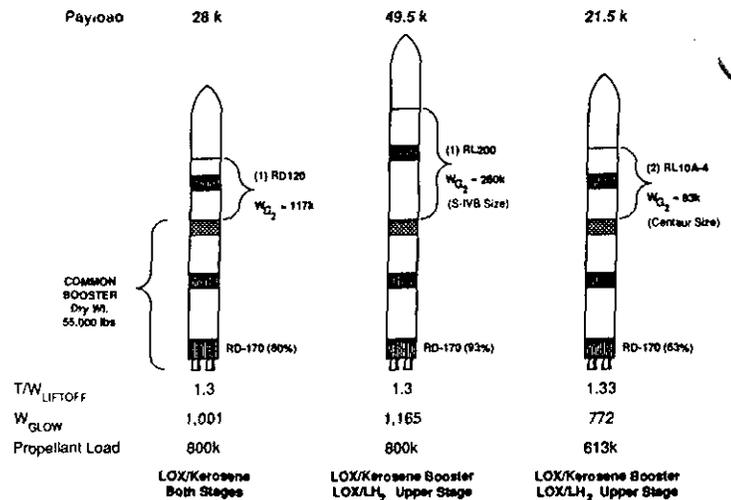


Figure 7
Two-Stage ELV Configurations