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MODIFICATION AND VERIFICATION TESTING OF A RUSSIAN NK-33 ROCKET ENGINE FOR REUSABLE AND RESTARTABLE APPLICATIONS

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ABSTRACT

Flight-qualified liquid propellant rocket engines from the Russian lunar launch program were received at Aerojet, modified to include reusable and restartable features with modern instrumentation and controls, and test fired to verify the modifications. The NK-33 liquid oxygen/kerosene propellant rocket engine was designed and manufactured by Samara State Scientific and Production Enterprise "TRUD" (now known as N.D. Kuznetsov Samara Scientific and Technical Company) of Samara, Russia, for the Soviet N-1 launch vehicle. This staged combustion engine delivered high pressure (2109 psia chamber pressure) and high performance (331 seconds vacuum delivered specific impulse) that had never been available in the West for an hydrocarbon engine. Aerojet imported 36 NK-33 engines, along with 9 NK-43 engines, an upper stage version of the same engine, from N.D. Kuznetsov SSTC. The first of the NK-33 engines was modified for use on the Kistler K-1 launch vehicle. Modifications included replacement of pyrotechnic initiated valves with solenoid actuated valves; replacement of electromechanical actuators for thrust and mixture ratio control; redesign of purge supply systems; replacement of solid propellant for the turbopump start spinup and the main chamber igniters; redesign and replacement of the thrust frame for addition of a gimbal and thrust vector control mount; addition of valves, pyrotechnics, and plumbing to restart the engine; and replacement of instrumentation and wiring harnesses. This engine was successfully test fired at Aerojet to verify the new components and configurations, and to begin characterization of engine durability for the reusable Kistler vehicle. This paper describes the modifications to the original Russian engine, and reports the results of testing to date.

INTRODUCTION

The NK-33 engine, a 350,000 lb_f thrust class liquid oxygen/kerosene staged combustion engine, was designed and manufactured in the 1960s by the Russian design bureau now known as N.D. Kuznetsov SSTC.[1] The NK-33 engine was a flight qualified, significantly upgraded version of the NK-15, the engine that supplied the main propulsion for the boost propulsion stage of the Soviet N-1 lunar launch vehicle.[2] For the N-1 boost stage flight profile, the NK-15 was ignited at sea level and operated about 120 seconds, producing a nominal sea level thrust of 339,000 lb_f (154 metric tons) with a sea level delivered specific impulse of 297 lb_f-sec/lb_m, and a nominal vacuum thrust of 378,000 lb_f (172 metric tons) with a vacuum delivered specific impulse of 331 lb_f-sec/lb_m.

The NK-15 engine, originally developed for single use, was redesigned to increase component life and include reusable features for conducting acceptance and stage tests along with a cost effective qualification test program for the N-1 and future vehicles.[1] Major improvements on this new engine, the NK-33, were seal upgrades, addition of a TEA preburner start system, and purge systems to allow multiple starts. The NK-33

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engines, which were to have been used on subsequent N-1 flights, completed extensive qualification testing, with nearly 100,000 seconds of testing accumulated on more than 200 engines, following nearly 90,000 seconds of testing on nearly 600 engines for NK-15 development and production prior to the first flight of the N-1.

In 1995, Aerojet brought an NK-33 engine to its liquid rocket test facility and conducted a series of tests as part of its Evolved Expendable Launch Vehicle (EELV) proposals.[3] The objectives of these benchmark tests were:

- Verify engine performance and operability with liquid oxygen/RP-1 propellants from the U.S.
- Verify engine functionality after twenty years of storage.
- Demonstrate engine performance at Atlas inlet conditions.
- Demonstrate Atlas firing duration and profile.
- Demonstrate the ability of Aerojet and N.D. Kuznetsov SSTC to cooperate with technical, logistical, and political issues and successfully test a Russian liquid rocket engine in the United States.

Five tests were successfully conducted on the Benchmark Test Program, ranging in power level from 58% to 113%, for a total duration of 408 seconds. Including the acceptance test in Russia, this engine was tested for a duration of 450 seconds. The success of this test program demonstrated the robustness of the flight qualified engine and convinced Aerojet to pursue its use in the Western launch vehicle market. The excellent specific impulse performance of this staged combustion engine, exceeding the performance of the gas generator cycle engines currently available in the West by 20 to 30 seconds (or 15 to 20 at equivalent mixture ratios and expansion ratios), showed that the engine could become an enabling feature of the new and improved launch vehicles being developed in the Western market.

Modifications to the NK-33 engine for a Western flight vehicle were subsequently initiated for the Kistler K-1 flight vehicle.[4] These modifications included new features for interface to and control by the K-1 vehicle, and variations of the original Russian engine to enhance operability for use on a reusable vehicle.

The modified engine, renamed AJ26-58, was then tested at the Aerojet E-5 liquid propellant rocket test facility in a special verification test program designed to demonstrate that the modified NK-33 engine would meet the Kistler performance requirements, and that the modifications would not alter steady-state performance or transient operation of the engine. The specific objectives of the verification program were:

- Verify chilldown, start, and shutdown sequences with modified engine components.
- Verify new purge systems with modified engine components.
- Verify test-to-test repeatability of steady-state and transient operating conditions.
- Verify capability of new electro-mechanical actuators to control engine power level and mixture ratio as predicted.
- Verify capability to operate with subcooled U.S. RP-1 to be used on Kistler vehicle.
- Verify capability to start with low engine inlet pressures expected for Kistler vehicle upper stages.
- Verify capability and repeatability of restart.
- Verify capability to start, operate, and shutdown with new engine controller.
- Collect data to evaluate engine life characteristics.

At the publication deadline for this paper, five tests of the Verification Test Program have been conducted. This paper will present the results of these tests along with the results of the benchmark tests from 1995, which to date have been unpublished. The NK-33 engine and its modifications will be described in detail, along with its operating and performance characteristics.

NK-33 ENGINE DESCRIPTION

The NK-33 is a staged combustion, pump-fed liquid propellant rocket engine that uses oxidizer-rich combustion gas to drive a single stage turbine.[1] Similar to many Russian liquid rocket engines, the main fuel and oxidizer pumps are driven by a single, spline-coupled shaft and contained within a single housing with multiple bolted pieces.

Engine performance parameters are listed in Table I. For the Kistler vehicle, the main combustion chamber will operate at a nominal mixture ratio of 2.59 and nominal chamber pressure (defined as 100% power level) of 2109 psia.[4] At these conditions, the preburner will operate at a nominal mixture ratio of 58 and chamber pressure of 4670 psia, with a combustion gas temperature of 670 R. Without operation of the mixture ratio valve, the mixture ratio of the engine will increase as the power level is reduced, to about 2.75 at 75% chamber pressure level, and about 2.90 at 50% chamber pressure level. Activation of the mixture ratio control valve will provide 20% control capability in mixture ratio over the whole thrust range. For the Kistler vehicle, however, the lower range is limited by the standard inlet conditions and nominal mixture ratio to about -5%.

Engine repeatability, based on Russian qualification test history and acceptance test instrumentation accuracy, is expected to be +/- 1% on thrust, +/- 1.5% on mixture ratio, and +/- 1% on specific impulse.

For the Kistler vehicle, there will be two different modified versions of NK-33 engines – one basic, renamed AJ26-58; and one restartable, renamed AJ26-59.

Basic Engine

The fluid schematic of the basic modified NK-33 engine is shown in Fig. 1. The turbopump is an inline assembly containing oxidizer boost and main pumps, fuel boost and main pumps, a gas main turbine, and a gas start turbine all within a single bolted housing. All of the oxidizer is provided to the preburner, while most of the fuel is provided to the main combustion chamber coolant jacket. A high pressure, high speed gear driven kick stage pump delivers a small quantity of high pressure fuel to the preburner.

Combustion devices include a liquid/gas coaxial element main injector, regeneratively-cooled main chamber, regeneratively-cooled nozzle, liquid/liquid swirl element preburner, solid propellant pyroignitors for the main chamber, and a solid propellant cartridge to supply gas to a start turbine to prespin the turbopump prior to ignition.

There are three different ignition systems on the engine. The preburner is ignited by a slug of triethylaluminum/triethylborane (TEA/TEB), a hypergolic propellant with oxygen, that precedes the fuel into the preburner during the start transient. The main combustion chamber is ignited by three solid propellant pyroigniters that fire into the chamber through ports on the periphery of the fuel manifold. The main chamber pyroigniters and the solid propellant in the turbopump start cartridge are themselves ignited by squib initiators.

The engine is mechanically controlled by an array of nitrogen-actuated pneumatic valves, electropneumatic pilot valves (EPV), electromechanically actuated regulation valves, and differential pressure hydraulically sequenced main valves. After the preburner fuel shutoff valve is opened and the start purge is initiated by opening a pneumatic valve on the engine, no other valves on the engine need to be externally actuated to provide for engine startup. Pressure-sequenced valves start the flow of oxidizer into the preburner and the main flow of fuel into the main combustion chamber coolant jacket once the start cartridge is prespinning the TPA. "Cutter valves" with blades actuated by gas from the start cartridge cut diaphragms on the TEA/TEB ampoules, and start the secondary flow of fuel into the preburner, although the pressure developed by the kickstage pump during start cartridge operation is also normally sufficient to rupture the diaphragms.

To shutdown, the preburner fuel shutoff valve is pneumatically closed and the shutdown purge valve on the engine is pneumatically opened. When the preburner fuel shutoff valve is closed, the engine shuts off. For redundancy to close the preburner fuel shutoff valve, the shutdown purge is hydraulically tied to the actuation circuit of the preburner valve.

The pneumatic valves are controlled by supplying or removing voltage to the corresponding EPV. Nitrogen is then provided to or removed from the main valve actuation cavity through the EPV, causing the pneumatic valve to operate.

Thrust or power level of the engine is controlled by regulating the fuel flowrate to the preburner. The position of the valve that controls this flowrate is controlled by an electromechanical actuator (EMA). This valve also ensures a benign and controlled engine start with the use of internal hydraulic packages that strictly regulate preburner fuel flowrate during bootstrap.

Mixture ratio through the main combustion chamber is controlled by regulating the fuel flowrate to the main chamber. The position of the valve that controls this flowrate is also controlled by an EMA.

A purging system displaces propellants from the cavities of the engine and its assemblies, preventing accumulation of combustible mixtures and removing propellant from the internal engine cavities at shutdown. There are 3 interfaces to the engine that supply nitrogen purge -- one a low flowrate at two levels (0.0044 to 0.010 lb_m/sec) to the interpropellant seal (IPS), and the other two high flowrate (4.5 and 2.5 lb_m/sec, respectively) for start and shutdown purging. The purging system has been modified from the Russian version of the NK-33 to eliminate on-board bottles of compressed gas and control valves, and now includes only electropneumatic valves and check valves. The start and shutdown purge control valves are identical new valves.

Two internal fluid tapoffs are available on the engine, one of which will be used for the Kistler vehicle and during the verification test program. A high pressure fuel tapoff from the main fuel pump discharge will be used on the Kistler vehicle to supply fluid to power the thrust vector control system. Oxygen-rich turbine exhaust gas, used in the Russian vehicle for oxygen tank pressurization gas supply, is also available but will not be used by the Kistler vehicle, although the port will remain available on the modified engine for other applications.

Restartable Engine

The fluid schematic of the modified restartable NK-33 engine is shown in Fig. 2. The schematic is very similar to the basic engine except for a few variations. There are dual main chamber igniters and dual start cartridges, two parallel TEA ampoules, and two sets of cutter valves. There is an additional valve supplying the two TEA ampoules in the preburner supply line, and there is a parallel fuel supply line between the second TEA ampoule and a new, dual preburner shutoff valve.

These modifications essentially do not alter the original engine transients, so the first start and first shutdown of the restartable engine are exactly the same as for the basic engine. For the second start of the restartable engine, the 3-way valve and dual preburner valve are switched to the opposite leg of the preburner fuel supply system, and the second start then proceeds exactly as the first start. The second shutdown is exactly the same as the first shutdown except that the second valve of the dual preburner valve is deactivated, rather than the first.

Engine Layout

The layout of the basic NK-33 engine is shown in Figs. 3 and 4. The turbopump is connected to the head end of the combustion chamber by the main turbine exhaust duct. The preburner is mounted directly to the main turbine housing which is connected to the oxidizer pump. The turbopump start cartridge is located at the opposite end of the turbopump, connected to the fuel pump. The parallel arrangement of thrust chamber and turbopump was a carefully engineered design to carry load, provide rigidity, and reduce weight.[1] Modifications have not disturbed the maximum length of the original engine, and slightly increased the maximum diameter.

The engine layout of the restartable NK-33 engine is shown in Figs. 5 and 6. The dual start cartridge is an in-line series design that replaces the single start cartridge on the turbopump opposite the preburner. The dual main chamber igniters are also in-line series designs that fit into the existing ports on the main combustion chamber. Both of these pyrotechnic devices incorporate burst diaphragms to separate the multiple ignition components.

Hardware Components

Turbopump

The turbopump assembly (TPA) consists of two independent units: an oxygen boost pump and main pump with the main turbine; and fuel boost pump, main pump, and kickstage pump with the start turbine. Both main pumps are centrifugal. The low pressure, low speed oxidizer boost pump has a hydraulic drive connection to the main oxidizer pump. The low pressure, low speed fuel boost pump is gear driven by the main fuel pump. The mechanical connection between the fuel and oxidizer pump shafts is provided by a spline connection on the shaft. An interpropellant seal prevents the migration of propellants into unlike pump cavities.

The pump housings are made from aluminum sand castings, except the high pressure housings which are forgings made from aluminum. Both low speed inducers and the oxidizer hydraulic turbine are made from investment cast aluminum, while all high speed inducers and impellers are made from investment cast chrome-nickel steel, except the high speed fuel inducer which is made from a titanium alloy. Low speed and main shafts are made from stainless steel, except for the fuel boost pump shaft which is made from a titanium alloy. The turbine housing is made of an Inconel equivalent, and the start cartridge housing is made of titanium.

On the oxidizer pump side of the TPA is a rotor axial thrust balancing device to balance the axial forces of the rotor. Oxygen flow through a regulating passage provides automatic unloading of the axial forces along with individual adjustment capability for each engine.

Radial ball bearings support the TPA rotors. Fuel pump bearings are cooled with fuel, and oxygen pump bearings, which are made from stainless steel, are cooled with oxygen. The fuel bearing cages are made of bronze, while the oxidizer bearings have teflon separator cages.

Preburner

The preburner provides oxygen-rich combustion gas to the TPA turbine, and this gas is then further combusted in the main combustion chamber. The preburner is designed with multiple axial zones for oxidizer injection and mixing, with the majority of oxidizer injected downstream from the injector face. Baffles downstream of the injector face provide high frequency combustion damping.

The preburner injector uses a combination of tangential swirl injection elements and showerhead elements for each propellant. The preburner walls are cooled with liquid oxygen which is then injected at the chamber periphery before the entrance into the turbine nozzles.

The preburner chamber shells and manifolds are made of stainless steel. The injection elements and faceplate are made from a chrome copper alloy.

Thrust Chamber Assembly

The combustion chamber is an inseparable welded-brazed assembly, and consists of subassemblies for the oxidizer gas manifold, main injector, chamber housing, upper nozzle, middle nozzle, lower nozzle, propellant supply ducts, and pyroigniter ports.

The oxidizer gas manifold, made of an Inconel equivalent, directs the oxidizer-rich turbine drive gas from the turbine discharge to the main injector. The manifold contains a flange that attaches the chamber to the engine thrust takeout structure. A spherical plate in the oxidizer stream upstream of the injector provides additional propellant distribution prior to injection.

The main injector consists of upper and lower stainless steel parts that are welded together. The warm oxidizer-rich gas from the turbine exhaust is supplied axially, and the fuel is supplied radially from the main combustion chamber regenerative coolant circuits. Main injector elements are coaxial in nature with fuel swirl. The outer row of injection elements is biased for mass and mixture ratio stratification. There are no baffles, acoustic cavities, or other stability devices in the main combustion chamber. Combustion stability in the main combustion chamber was achieved by proper distribution of propellants across the injector face and in the combustor volume.[1] Since very early in the NK-15 development, there have been no instances of combustion instability in the main combustion chamber.[1]

The chamber housing is a brazed and welded assembly consisting of a stainless steel external jacket, a chrome copper alloy slotted internal liner, and a stainless steel fuel inlet manifold. Fuel from the pump discharge enters the coolant jacket aft of the throat and splits in two directions, up the main chamber and down the nozzle. The coolant in the main chamber flows through milled channels in the liner upstream past the throat section until rejoining with the fuel coolant used to cool the lower nozzle. Some of this fuel is then injected into the combustion chamber through two rows of tangential orifices located in the chamber barrel downstream of the injector face. The remainder is then directed to the lower fuel manifold in the main injector.

The nozzle of the NK-33 combustion chamber consists of upper, middle, and lower sections. Each nozzle section has inner and outer shells made of stainless steel which are fabricated and inspected separately. The inner shell of the upper nozzle is slotted to form coolant passages, and the outer shell is brazed to the inner shell to form the outer wall closure of the coolant passages. The middle and lower nozzle sections are divided by corrugated sections that define the coolant passages. The three nozzle sections are inspected individually and then welded together.

Engine Valves

Automatic control assemblies form the primary elements of the control, regulation, and purging systems. The control system provides propellant flowrate to the engine lines during chilldown, startup, and shutdown, while the regulation system maintains proper flowrate during steady-state operation.

The oxidizer chilldown valve, located on the oxidizer pump discharge upstream of the preburner inlet and main oxidizer shutoff valve, provides a bleed path from the engine during oxidizer pump chill down.

The main oxidizer shutoff valve provides the start and shutoff for the oxidizer system, opening or closing depending upon the differential pressure between the oxidizer pump discharge and inlet. The main fuel shutoff valve provides flow to the main combustion chamber coolant jacket, opening or closing depending upon the differential pressure between the fuel pump discharge and inlet. The preburner fuel shutoff valve supplies fuel to the preburner, and when closed shuts the engine down. Fuel flow to the preburner is started when the diaphragms on the TEA/TEB ampoule are punctured.

The Russian thrust regulation valve was fitted with a new electromechanical actuator to provide throttle capability over the range from 49% chamber pressure to 123% chamber pressure. This valve also strictly controls fuel flowrate to the preburner during the initial portion of the start transient to provide benign pressure and temperature environments in the engine,

The Russian mixture ratio regulation valve was fitted with a new electromechanical actuator to provide a 20% range of mixture ratio control. The actual minimum mixture ratio is dependent upon the mixture ratio valve itself, rather than the range of the actuator, depending upon where the nominal is set. For the Kistler vehicle at 100% power level, the mixture range is about -5%/+15%.

Since the requirements for on/off functions and flowrate regulating functions were divided between separate systems, both systems were optimized for these very different design requirements. The division of these functions contributes to the high reliability and controllability of the NK-33 and NK-43 engines.

Description of the Engine Modifications

The Russian NK-33 and NK-43 engines have been modified for installation and operation on the Kistler K-1 launch vehicle.[4] Modifications on the basic engine are summarized in Table II. Additional modifications required to produce a restartable NK-33 configuration are summarized in Table III.

All new components have undergone qualification testing at the component level. For valves, EMAs, pyrotechnics, and sensors this testing included thermal cycling, performance verification, and vibration testing. All new components, with the exception of the gimbal, were incorporated into the engine and are being verified at the engine level in the Verification Test Program. The thrust frame and gimbal were statically tested to ultimate loads on the component level.

Engine Valves

The original NK-33 and NK-43 engines used three pyrotechnic valves that, when actuated, were either permanently closed or opened. Replacement of the actuator or the complete valve was required to hot fire the engine again. One of the first modifications was to remove the pyrotechnic actuation on these valves, and replace them with gaseous pneumatic actuation controlled by solenoids. Consequently, two of the pyrotechnic-actuated valves were completely replaced, and on the third the actuator was replaced.

The liquid oxygen (LOX) chilldown valve provided the capability to thermally condition the oxygen pump with tank head pressure prior to hot fire. In the original valve, a pyrotechnic charge was fired to wedge a piston in the valve and permanently seal the normally open bleed. To provide multiple chilldown cycles without having to change the valve, this valve was completely replaced with a pneumatic valve remotely piloted by a solenoid valve. Piloting medium was gaseous nitrogen. The valve body was made from Inconel for improved liquid oxygen compatibility and to handle 6000 psia oxidizer discharge pressure in the event of valve operation failure.

On the original engine, another pyrotechnic-actuated valve provided purge to the main combustion chamber during the engine shutdown from an on-board high pressure nitrogen bottle. In this valve, a pyrotechnic charge was fired to wedge a piston in the valve and permanently open the nitrogen bottle discharge. Since the shutdown purge will now be provided from the vehicle, this valve was completely replaced with an internally piloted solenoid actuated valve. The on-board nitrogen purge bottles and regulation system were removed, which considerably lightened the gimbaled engine mass.

The third pyrotechnic actuated valve on the original engine stopped fuel flow to the preburner and precipitated engine shutdown. In this normally open valve, a pyrotechnic charge was fired from a bolt-on actuator to wedge the poppet and close the valve outlet. This single-use bolt-on pyrotechnic actuator was replaced with a gaseous nitrogen driven actuator controlled by a remotely mounted solenoid pilot valve. To retain the flow features of the valve, only the pyrotechnic actuator was replaced. The pilot valve will be powered open prior to engine operation, providing nitrogen to the preburner fuel valve actuator and opening the valve. The solenoid will vent the actuator when engine shutdown is commanded. To ensure correct timing with the onset of the shutdown purge into the preburner fuel injector manifold, which was initiated by opening the shutdown purge valve, the purge was tied into the preburner fuel shutoff valve actuator outlet. Thus the shutdown purge will assist in closing the preburner shutoff valve by pressurizing the actuator to the normally closed valve position.

Another valve was added to the engine that controls the start purge flow. This valve is identical to the shutdown purge valve, and allows the start purge to be provided from the vehicle.

For the restartable NK-33 engine, two new valves were added to provide a parallel TEA/TEB preburner ignition system. A single inlet, dual outlet ("3-way") valve allows selection of the appropriate TEA/TEB leg. This valve will be normally shunted to the initial use circuit. During the shutdown of the first burn and prior to restart, the valve will be shuttled to the second position by a pilot solenoid valve that is remotely mounted, and energized during the entire second burn. The other new valve is a completely new dual preburner shutoff valve at the opposite ends of the TEA/TEB supply lines. This dual valve is a similar design to the single preburner shutoff valve but includes two parallel valves in a single titanium housing, with two inlets and one outlet.

The solenoid pilot valves are common valves currently in production. These solenoid valves were remotely mounted on the engine to reduce vibration levels and provide thermal isolation.

Electromechanical Actuators

Externally commanded changes to mixture ratio and thrust are performed by electromechanical actuators (EMAs) which change the flow area of the mixture ratio and thrust control valves. New EMAs have replaced the existing Russian actuators to provide electrical compatibility with U.S. launch vehicle power requirements, and to increase the control range. The two actuators are similar in design except for the mating interfaces and internal gear ratios. The actuators use harmonic drives with a 60:1 gear ratio for the thrust control actuator and a 160:1 gear ratio for the mixture ratio control actuator. Both actuators incorporate vibration isolation into the mating interfaces similar to the Russian actuators. Individual actuator weight is 11 lb_m.

Both actuators are closed-loop devices with the electronics for both actuators located in a vehicle-mounted actuator controller. Controller weight is 17 lb_m. The actuator controller is electronically redundant, with inputs of primary or secondary channel selection, redundant power inputs, and analog position commands. The controller uses position and velocity output in closed loop control to provide the required position. Controller output includes actuator velocity, position, and torque applied to the actuator.

When configured for the Kistler K-1 vehicle, the thrust actuator will be allowed a thrust range of 68% of chamber pressure. The maximum end-to-end range is 76% of chamber pressure. Thrust change can be commanded up to a rate of 135% chamber pressure per second, given sufficient engine inlet pressures to preclude cavitating the pumps.

The mixture ratio actuator will be allowed a range of about 0.5 units of mixture ratio. When configured for the Kistler K-1 vehicle, the actual range about the nominal mixture ratio is about -0.15/+0.35 due to engine balance considerations. Mixture ratio range can be commanded up to a rate of 5% of full scale range per second.

Main Combustion Chamber Igniters

New main combustion chamber igniters were required because on the original engines these igniters were pyrotechnic based and hence consumable. Even though there were no ignition failures with the original Russian design, the new igniters were designed to provide about 30% more caloric output over the same actuation duration to increase ignition reliability with subcooled RP-1. The igniters for the restart engine have the same basic design as the nonrestartable engine but with a burst disk separating the initial charge from the second charge. Both igniters use a fuel-rich magnesium and teflon propellant to provide afterburning in the main chamber during the oxidizer-rich ignition period.

Thrust Mount

The original NK-33 and NK-43 thrust takeout structures were tubular with four attachment points to the square pattern vehicle structure. To provide capability to gimbal the engine, this frame was removed and replaced with a new frame specially designed and built for the Kistler vehicle. The new thrust mount, shown in Fig. 7, was designed and fabricated by N.D. Kuznetsov SSTC in 1997 to meet the gimbaled and static thrust load of the NK-43 engine. To reduce development costs, the NK-33 engine will use the same thrust mount. The cast steel alloy frame is a 3-piece construction for retrofitting the frame to the existing engine without disassembly of the turbopump assembly from the thrust chamber. The frame has a 2-piece split ring that bolts together around the turbine exhaust duct and to the existing thrust chamber takeout flanges. A conical shell attaches to the two half rings and tapers to interface with the gimbal bearing. The thrust frame also includes two titanium attachment arms for attaching hydraulic actuators to provide gimbaling motion.

Gimbal

A spherical gimbal bearing located at the combustion chamber head, together with flexible elements on pressurant supply lines, allow for the engine to be gimbaled. Requirements for the Kistler K-1 vehicle call for a gimbal range of +/- 6 degrees.[4] The gimbal bearing is modified from the bearing for the space shuttle main engine (SSME). Modifications include shortening the bearing for improved integration into the Kistler vehicle, and replacing the titanium alloy used for the cryogenic environment on the SSME with a readily available and less expensive titanium alloy. Otherwise, bearing material is the same as used on the SSME. The gimbal block will be acceptance tested to obtain a consistent coefficient of friction.

The engine was tested during the verification test program without the gimbal and gimbal actuators. The test facility used a flexible mount to eliminate unrealistic side loads on the thrust frame.

Engine Controller

A new engine control system is being developed for the Kistler K-1 vehicle. Each engine on the vehicle will have a separate dedicated controller. This new controller will house sequencing commands to start and shutdown the engine, circuitry to condition signals from the engine-mounted flight sensors, and software to monitor engine health during the start transient prior to liftoff. Controller weight currently is about 65 lb_m which includes the environmental box and all internal cards and harnesses. Harness weight between the engine and controller is about 20 lb_m for the basic engine and 24 lb_m for the restartable engine.

The engine controller will maintain control over all engine-mounted components that affect engine operation, including the two EMAs, the several solenoid pilot valves controlling pnenumatically actuated valves, and the initiator squibs that ignite the pyroigniters and start cartridge. Electrical power conversion and distribution functions are included. Each engine controller is powered from seven vehicle power busses – triple busses for electronics power and dual busses for both utility power and pyrotechnic power.

The engine controller has redundant channels to prevent single-point failure in case of controller malfunction. A third channel acts as a bus controller and provides decision authority when the two channels disagree. The processor is responsible for coordinating all control operations and monitoring the sensors for proper engine operation. Control system components that are not performing properly are identified and appropriate action is initiated. In this way the engine controller provides self-monitoring capabilities.

The engine controller conditions and records data from flight sensors located on the engine. The engine-mounted sensor suite includes commercially available pressure, temperature, speed, and acceleration sensors. The engine flight sensors chosen for the Kistler K-1 vehicle, which are similar to the sensors used in the Russian flight program, are listed in Table IV.

The engine-mounted control units and sensors are individually connected to the engine controller through a multiple-cable wiring harness, connector bulkhead, and multiple cables. The interconnect cables include multiple conductor power and signal lines and are shielded.

The data collection and conditioning system has been tested during the Verification Test Program, and in upcoming tests the sequencing operations will be verified. During the test program the operation of the engine controller was directed by a PC-compatible Pentium-based system located in the control room. This electrical ground support equipment (EGSE) served as the interface between the engine controller and the test facility and operators. On the Kistler vehicle, the vehicle controller will serve this function.

Engine Characteristics

Engine Weight

Modified NK-33 engine weights are shown in Table V. Dry weights include the weight of all the modifications added to the engine, including the gimbal block, but do not include the engine controller and the electronic control box for the EMAs, nor vehicle dependent items such as propellant feedlines and thermal shielding. The wet pre-fire weights include all the dry weight plus the solid propellant weight and the liquid propellant weight in the engine up to the main shutoff valves. The wet operating weights include all the dry weight plus the liquid propellant weight in the engine, minus the solid propellant mass that had been consumed during the start transient.

Start Sequence

The engine system requires thermal conditioning (chilldown) of the oxidizer pump before firing to stabilize oxidizer flow components at cryogenic temperatures and avoid temperature shocks and gasifying of propellants during start. The chilldown is performed by bleeding oxygen through the system at a controlled rate. During tests at Aerojet, the time required for the thermal conditioning of the engine was typically 15 to 20 minutes for normal boiling point oxidizer (-297 F), and 10 to 15 minutes for subcooled oxidizer (-310 F).

The following description is a typical sequence of events during engine chilldown. The engine controller maintains control of the oxidizer chilldown valve. Commands are transferred from the vehicle or facility controller to the engine controller through a MIL-STD-1553 bus. Sequence times are described before engine start (E/S):

1. **(E/S - 180 minutes)**
   Begin engine purging with the low flowrate (0.0044 lb_m/sec) IPS purge.
2. **(E/S - 120 to 150 minutes)**
   Initiate fuel fill and drain operations
3. **(E/S - 10 to 15 minutes)**
   Initiate low flowrate oxygen circulation. Oxygen is supplied up to the main oxidizer shutoff valve and disposed from the engine through the chilldown valve and recirculation piping. The oxygen flowrate during this period is about 3 lb_m/sec.

Final conditioning before the engine autosequence start is conducted according to the following procedure:

4. **(E/S - 2 to 3 minutes)**
   Initiate higher flowrate oxygen circulation by increasing propellant inlet pressures to values specified at startup. The flowrate at this time is about 6 lb_m/sec.
   Initiate engine purging with high flowrate (0.011 lb_m/sec) IPS purge.
5. **(E/S - 1 minute)**
   Verify that oxygen inlet temperature and oxygen bleed outlet temperature are within specification.

At approximately 45 seconds prior to engine start, the engine controller initiates preignition sequence activities, which include the following events:

6. **(E/S - 45 seconds)**
   Perform internal self-check of engine controller. Engine controller will signal test facility if transfer of test control is or is not accepted.
   Verify valve positions.
   Verify sensor signals.
   Verify pyrotechnics continuity.
   Select EMA command channel B, and move mixture ratio valve and thrust control valve out of position and back into position.
   Select EMA command channel A, and move mixture ratio valve and thrust control valve out of position and back into position.

At this time, the following components and conditions have been verified by the engine controller prior to engine start:

- Controller functions
- EMA operation
- Solenoid valve operation
- Engine IPS purge inlet pressure

The following conditions are then verified by the vehicle controller to test facility prior to engine start:

- Engine tank pressure (to verify engine inlet pressure)
- Engine main chamber wall temperature

The engine chamber wall temperature is monitored prior to firing to preclude excessive chilling of the combustion chamber liner, which may occur due to excessive oxidizer leakage through the turbine seal.

Engine timing during the start transient is shown in Fig 8. The ignition system start is monitored by the engine controller which verifies normal operation before allowing the throttle to full power. Engine start includes the following events which are controlled by the engine controller:

7. **(E/S - 5 seconds)**
   Open preburner fuel shutoff valve.
8. **(E/S - 2 seconds)**
   Open engine start purge valve.
9. **(E/S - 1.3 seconds)**
   Verify start purge inlet pressure downstream of engine start purge valve.
10. **(E/S - 0.50 seconds (latest))**
    Close LOX chilldown valve.
11. **(E/S - 0.40 seconds)**
    Ignite first of three main combustion chamber pyroigniters.
12. **(E/S - 0.39 seconds)**
    Ignite second of three main combustion chamber pyroigniters.
13. **(E/S - 0.38 seconds)**
    Ignite third of three main combustion chamber pyroigniters.

14. **(E/S - 0 seconds)**
    Ignite start cartridge.
15. **(E/S + 1.3 seconds)**
    Verify satisfactory ignition and operation with main injector fuel manifold pressure, turbine outlet temperature, and turbopump rotor speed.
    Close start purge valve on engine.

If the engine has not reached a satisfactory intermediate power level at E/S + 1.3 seconds, the engine controller will command a normal shutdown.

At the time E/S + 1.5 seconds, the engine internal hydraulics have attained steady-state operation, and the engine is ready to be commanded to a different power level or mixture ratio. During the boost phase of the Kistler vehicle, a thrust increase command is given to each engine to synchronize the power levels of the three first stage engines at the time E/S + 1.5 seconds, and then the thrust increase to full power is commanded at E/S + 1.75 seconds. On the flyback stage and the second stage of the Kistler vehicle, the engine is commanded to full power at the time E/S + 1.5 seconds.

Start Performance Characteristics

For normal starts of the NK-33 engine, where engine power is increased up to full power within 2 seconds after command to ignite the start cartridge, the minimum allowable propellant temperature and pressure conditions at the engine interface required during engine start are shown in Figs. 9 and 10 for RP-1 and liquid oxygen, respectively. Slumps or other pressure reductions at engine inlets are not allowed to go lower than the pressures shown in these figures. In a special case being developed for the Kistler vehicle altitude engine starts, as described later, an early portion of the start transient is being allowed to exceed the requirements in Figs. 9 and 10.

The NK-33 engine is capable of starting with these specified inlet conditions, transient temperature conditions, and the specified range of inlet ducting without supplementary pressurization or other augmentation during transient flow conditions.

The NK-33 engine is capable of withstanding maximum pressure limits at the engine/vehicle interface of 327 psia (23 kgf/cm^2) for the oxidizer inlet and 284 psia (20 kgf/cm^2) for the fuel inlet. These pressures include the maximum conditions of transient and steady-state operation during all phases of engine operation.

Steady-state Performance Characteristics

The NK-33 engine inlet temperature and pressure requirements for mainstage (steady-state) operation are also shown in Figs. 9 and 10 for RP-1 and liquid oxygen, respectively. Kistler steady-state standard inlet conditions for the NK-33 verification engine are shown in Table VI.

There are no special inlet flow requirements (e.g., straight run, vane, strut spacing, etc., to minimize flow distortion) at the RP-1 or oxygen pump inlet interfaces.

Shutdown Sequence

The engine is capable of normal shutdown with the same inlet pressure and temperatures as shown in Figs. 9 and 10, and without any supplementary pressurization. The engine is capable of normal shutdown, upon receipt of appropriate signal, from any engine operating condition. The engine is capable of benign shutdown (no damage external to the engine) in the event of loss of vehicle fluids, including propellants.

For the reusable application of the Kistler vehicle, the engine is throttled down to intermediate power (about 55% of full power chamber pressure) prior to shutdown. This throttle period is expected to last from 1 to 5 seconds. The standard shutdown sequence, commanded by the engine controller, shuts the engine down after the engine power level has been reduced.

From the 55% power level, engine shutdown (E/SD) proceeds with the following events:

1. **(E/SD - 0 seconds)**
    Open shutdown purge valve on engine.
    Close preburner fuel shutoff valve on engine.
2. **(E/SD + 2 seconds)**
    Close shutdown purge valve on engine.

The engine will shutdown from 55% power level to 10% of mainstage chamber pressure within 0.8 seconds, +/- 0.3 seconds.

The emergency shutdown sequence is exactly the same as the standard shutdown sequence except that the engine power is not throttled back to 55%.

AEROJET E-5 TEST FACILITY

Tests of the original NK-33 engine in 1995 and of the modified engine in 1998 were conducted at a refurbished test facility at Aerojet originally used for Titan I engine testing. The E-zone facility at Aerojet has also been used for LOX/hydrocarbon and LOX/hydrogen thrust chamber development testing in the last 10 years. The NK-33 tests were conducted vertically at test stand E-5 at sea level conditions. A deflector plate approximately 15 feet below the exit of the nozzle turned the exhaust plume into a flame pit from which the hot gasses were removed from the area. The modified NK-33 engine mounted on the test stand is shown in Figure 11.

The E-5 test facility is capable of moderate duration LOX/RP-1 test firings. The LOX tank holds 20,000 gallons, and the fuel tank, although also sized for 20,000 gallons, is only site-licensed for 10,000 gallons. Maximum duration at full power for NK-33 engine firings is about 200 seconds.

The oxygen tank and the oxygen feedlines are vacuum jacketed. Storage and operation with subcooled liquid oxygen temperatures down to -315 F has been demonstrated in the verification testing. The oxygen feedlines are 12 inch diameter except for a flowmeter section with parallel 8 inch diameter pipes. The fuel feedlines are 10 inch diameter except for a flowmeter section with parallel 8 inch diameter pipes. Flowrate was measured by redundant 8 inch FlowTec turbine flowmeters for both oxidizer and fuel.

A propellant subcooling skid has been developed by Aerojet for use in the Kistler program. The skid uses liquid nitrogen to subcool oxygen from -297 F to -310 F, and cold gaseous nitrogen to subcool the liquid RP-1 from ambient temperature to -30 F.

The vertical position E-5 does not have capability to measure thrust. Thrust was calculated with measurements of engine inlet flowrate and main combustion chamber pressure, together with thrust coefficients provided by N.D. Kuznetsov SSTC. During development and qualification of the NK-33 engines in Russia, thrust was measured at a sea level facility so the thrust coefficient was empirically generated. The 3σ accuracy of the thrust measurement provided by the Russian testing was estimated to be +/- 0.5%, from which the 3σ accuracy of the thrust coefficient curve was estimated to be +/- 0.8%. Total flowrate measurement 3σ accuracy at the E-5 test stand is estimated to be +/- 1.0%, and chamber pressure measurement 3σ accuracy is estimated to be +/- 0.3%. Consequently, the thrust calculations shown later in this paper are estimated to have a 3σ accuracy of +/- 0.8%, and the specific impulse calculations are estimated to have a 3σ accuracy of +/-1.3%.

BENCHMARK TEST RESULTS

In the fall of 1995, Aerojet conducted a test program with an unmodified NK-33 engine to examine the published performance characteristics of the NK-33. The engine test program was the second conducted at Aerojet with a Russian rocket engine, following a test program more than a year earlier of a low thrust rocket engine from the Research and Development Institute of Mechanical Engineering (NIIMash) design bureau.

Although perhaps not having the historic significance of the earlier program, the benchmark test program of the NK-33 engine was certainly more substantial as it represented the first significant hot fire test evaluation of a large Russian rocket engine conducted in the United States. Over the course of one month, 5 tests were conducted which substantiated the Russian performance, and demonstrated the engines could operate after storage of more than 20 years.

The first benchmark test was a 23 second checkout of the engine and the refurbished test facility. The engine was taken to 102% of chamber pressure for 13 seconds after operating at 80% chamber pressure for 9 seconds.

The second benchmark test was a 42 second replication of the original acceptance test of this particular engine, except with normal boiling point liquid oxygen and ambient temperature U.S. RP-1 rather than the subcooled Russian kerosene, for a duration of 42 seconds. In the original Russian engine, the thrust control valve on the engine can increase engine power during the start transient to virtually any level without actuator command. In the first test, the engine automatically throttled up to 80% chamber pressure. In the second test, the engine automatically throttled up to 104% chamber pressure, the normal operating power level for the NK-33 engine for the Russian N-1 vehicle. Throttle changes after these power levels were attained were commanded by the facility to the throttle valve actuator.

The third benchmark test was a 25 second test of the engine operating with conditions equivalent to the end of an Atlas mission. Engine oxidizer inlet temperature ran at a warm -282 F, and the engine inlet pressure was 80 psia, providing 46 psi net positive suction pressure to the oxidizer pump at a power level of 58%.

The fourth benchmark test was a 168 second demonstration of a complete Atlas duty cycle at the required engine inlet pressures. The engine ramp to full power was controlled by the thrust control valve actuator, and the engine ran at 78%, 86%, and 103% power levels at various times in the test profile.

The fifth benchmark test was a 150 second demonstration of engine capability to operate at about 114%, the maximum required power level for EELV with this engine. The engine ran at 113% power level for 130 seconds, and at 103% power level for 10 seconds before and after operation at 113%.

A summary of the data from this test series is provided in Table VII. The 1995 test data and the Russian acceptance test data for this engine had excellent agreement, showing that the engine operated without degradation after storage of 20 years. Specific impulse agreed within 0.6%, providing a very satisfying justification of the published Russian performance. The engine proved to be very durable, even at power levels as high as 113%.

VERIFICATION TEST RESULTS

Following the success of the Benchmark Test Program, the path for testing the modified NK-33 engine was considerably simplified. The operability of the basic engine after a long storage had been proven, and the capability of the test facility had been demonstrated. Aerojet engineers had become familiar with the procedures and operating characteristics of the NK-33 engine, and facility personnel with the handling of the engine.

The Verification Test Program was designed to provide the maximum amount of data on a variety of objectives with a single engine. To date, five tests have been conducted with the modified engine. Measured chamber pressure and mixture ratio profiles for each of these tests, along with the commanded thrust control and mixture ratio control valve angle positions, are shown in Figs. 12 to 16.

The first test was a repeat of the original Russian acceptance test for this engine, except with normal boiling point liquid oxygen and ambient temperature U.S. RP-1, for a duration of 44 seconds. Thrust and mixture ratio commands were provided to the engine through the new EMAs. This test was a significant milestone to check out the new purge valves, plumbing, preburner valve actuator, thrust frame, and ignition hardware that had been put on the engine. All new hardware operated satisfactorily. The main combustion chamber igniters suffered minor erosion through an inner casing, precipitating a minor redesign prior to the next test.

The second test was a long duration test to verify modified engine capability to operate for the full Kistler vehicle boost phase duration. Thrust and mixture ratio were varied extensively, verifying the capability of the EMAs to operate under load as expected. The test was treated as a rehearsal of a flight profile after an acceptance test, with the engine balance carefully programmed to deliver Kistler first stage operating conditions -- a chamber pressure of 2019 psia and a mixture ratio of 2.587. In addition, conditions at start were carefully monitored to compare start transient parameters with the first test. Start cartridge propellant temperature was conditioned for the 24 hour period prior to the test to the same temperature as on the first test. All start transient parameters -- pressure slumps at pump inlets, ignition times of preburner and main combustion chambers, pressure and temperature rises in the engine, and operating parameters at intermediate stage, were within 2% of the parameters for the first test. Various engine internal operating parameters, including pump discharge temperatures, turbine outlet temperatures, and main chamber pressures are shown in Fig. 17.

The third test was a moderate duration test to evaluate the capability of the new propellant subcooling facility to deliver subcooled propellants, and the engine to perform with them. The subcooled oxidizer temperature of -310 F is the nominal temperature for Russian operation, while the subcooled fuel temperature of -30 F is colder than the Russian nominal temperature but still within the range of Russian test history. The test was shut down prematurely due to buildup of ice in a filter in the thrust control valve when throttling down to a lower power level. An investigation of the test facility showed excessive moisture had built up in the RP-1 supply system, which created ice particles when the RP-1 was subcooled to -30 F. Subsequent activities to remove the moisture from the RP-1 have been identified, and the subcooled fuel system will be reactivated when the moisture has been removed. There was no damage to the engine as a result of the ice buildup in the valve, which simply powered the engine down by restricting fuel to the preburner, resulting in an aborted test due to low power level.

The fourth test was a significant development in the Kistler program. One of the Kistler vehicle requirements to the engines was to start with inlet pressures lower than the requirements shown in Figs. 9 and 10 and lower than had been tested during engine development. With these inlet pressures at start, both the oxidizer pump and the fuel pump were expected to cavitate during the start transient. Consequently, tests were required to evaluate the ability of the engine to start under these conditions. Due to the configuration of the E-5 facility, sufficiently low oxidizer inlet pressures at start could not be generated with subcooled temperatures, so a test was constructed with normal boiling point oxygen, taking into account the difference in vapor pressure between -310 F and -297 F.

Results from this test showed that although both the oxidizer and fuel pumps were cavitating, the engine started and operated at intermediate stage power within normal characteristics. Figs. 18 through 20 present composites of various engine parameters during the start transient for all five verification tests. Chamber pressure was essentially unaffected, as shown in Fig. 18, and there were no turbine speed excursions, as shown in Fig. 19. The engine inlet pressures, however, were depressed for a substantially longer time than during other tests, as shown in Fig. 20. Examination of pump characteristics showed that during the initial portion of the start transient, the pump had delivered only 4% of its nominal noncavitating head rise. Comparison with transient analyses of vehicle starts showed that this test, in terms of inlet pressure depression, was an excellent simulation of the Kistler K-1 second stage start, where inlet pressures are expected to be lowest at start.

The fifth verification test was a long duration test designed primarily to add duration for evaluation of engine life. Subcooled oxygen was used. The shutdown was designed to duplicate the Kistler second stage shutdown, which has an extended constant throttle down from full power and a dwell period prior to shutting the engine off. Unfortunately, a facility redline for flame bucket cooling water pressure stopped the test 10 seconds prematurely.

A summary of the data from the Verification Test Series is provided in Table VIII. Sea level specific performance fell well within the NK-33 nominal range of 297 +/- 3 seconds. Comparison of the transients between the benchmark testing and the verification testing showed virtually no differences. The engine start transient envelope had not been changed due to the modifications to the engine.

CONCLUSIONS

A flight qualified liquid propellant rocket engine from the Russian lunar launch program has been brought to the West, modified for attachment to and control by the Kistler K-1, a reusable launch vehicle currently in development in the United States, and successfully test fired at Aerojet. The changes made to the original Russian engine included replacement of three pyrotechnic actuated valves with solenoid actuated valves, replacement of two electromechanical actuators, redesign of the purge supply system including removal of on-engine purge gas supply bottles and replacement of control valves, replacement of the solid propellant for main chamber ignition and start turbine spin up, redesign and replacement of the thrust frame for addition of a gimbal and TVC mount, and replacement of all sensors and wiring harnesses.

The tests reported in this paper comprise about half of the test matrix designed to verify the changes made to the original engine. Tests that have been conducted include evaluation of Kistler K-1 vehicle boost phase duration, operation with subcooled fuel, capability to control thrust and mixture ratio to Kistler specifications, and capability to start the engines with very low inlet pressures expected during the restart stage and second stage start of the Kistler vehicle. The low inlet pressure start of the NK-33 engine is a significant new capability that has now been demonstrated. This type of start demonstrates the robustness of the engine, especially in the critical area of transients.

Modifications to the NK-33 engine have not changed performance parameters, transient operation, or, to date, durability of the original, flight-qualified engine. This is a critical goal of the engine modification program, whose intent is to maintain the flight-qualified status of the engine despite changing some of the engine components and features.

FUTURE PLANS

The verification test program is planned to be completed in July and August of 1998. The engine will be modified while on the test stand into the restartable configuration, which includes new valves, pyrotechnics, and plumbing. Upcoming tests include evaluation of the capability to restart the engine at sea level, integration of the engine controller for sequencing operations, and extended duration to evaluate engine life.

Following the completion of the verification program, the first set of four engines for the first Kistler K-1 launch vehicle will be assembled and acceptance tested. This set of engines includes two basic modified NK-33 (AJ26-58) engines, one restartable NK-33 (AJ26-59) engine, and an NK-43 (AJ26-60) engine. The NK-43 is an NK-33 powerhead and thrust chamber with an altitude nozzle. The engine will be acceptance tested at sea level with the use of a vacuum jacket around the lower nozzle, and without a gas diffuser, based on experience developed in Russia with this engine in the early 1970s. Even at sea level, the gas flow in the large nozzle flows nearly full due to the high chamber pressure provided by the stage combustion cycle. The vacuum jacket is a provision to get the engine through the start transient without damaging the nozzle. The acceptance tests and the remaining verification tests will be reported in a future paper.

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Table I.
Nominal Modified NK-33 Engine (AJ26-58,59) Performance Parameters*

Parameters	**Units**	**Value**
Sea level delivered thrust	lb_f	340,000
Vacuum delivered thrust	lb_f	379,000
Sea level delivered specific impulse	lb_f-sec/lb_m	297
Vacuum delivered specific impulse	lb_f-sec/lb_m	331
Propellant flowrate into main combustion chamber	lb_m/sec	1144
- Oxidizer	lb_m/sec	825
- Fuel	lb_m/sec	319
TVC fuel tapoff flowrate	lb_m/sec	5.0
Main combustion chamber pressure	psia	2109
Main combustion chamber mixture ratio	--	2.59
Preburner combustion chamber pressure	psia	4670
Preburner combustion chamber mixture ratio	--	58
Preburner outlet temperature	F	670
Nozzle exit area ratio	--	27.7:1

* at Kistler vehicle standard inlet conditions for 100% power level

Table II
Modifications for Basic NK-33 (AJ26-58) and NK-43 (AJ26-60) Engines

Component	Modification	Modification Rationale
Thrust and MR valve actuators	Use U.S.-produced 28 volt EMAs	Increase actuation range, make compatible with U.S. power, Russian EMA availability
Pyrotechnic valves (3)	Replace LO2 chilldown, shutdown purge, and preburner shutdown pyrotechnic actuation with solenoid valves	Improve reusability
N2 storage bottles	Remove bottles (2)	Supply gasses from vehicle/facility
Start purge valve	Add new piloted solenoid valve	Generic start/shutdown purge line
Shutdown purge valve	Add new piloted solenoid valve	Generic start/shutdown purge line
Start and shutdown check valves	Add valves in generic start/shutdown purge lines	Eliminate potential backflow
Sensors	Replace with U.S. sensors	U.S. compatibility
Wiring harness	Replace with U.S. compatible harness	U.S. compatibility
Thrust mount	Replaced with new mount	Vehicle interface, gimbal requirements
Gimbal bearing	Add bearing	Vehicle gimbal requirements
Fluid interface panel	Add panel	Improve gimbal capability by grouping lines that cross gimbal plane; isolate pilot valves
Start cartridge and MCC igniter solid propellant	Replace with U.S. ordnance	Russian availability

Table III
Additional Modifications for Restartable NK-33 Engines (AJ26-59)

Component	Modification	Modification Rationale
Start cartridge housing	Replace with dual start cartridge unit	Require second turbopump start spin
Main combustion chamber igniter housing	Replace with dual pyrotechnic charge unit	Require second main combustion chamber ignition
TEA/TEB ampoule	Add parallel ampoule	Require second preburner ignition
Cutter valves	Add cutter valves to parallel TEA/TEB ampoule	Isolate second TEA/TEB ampoule; provide second start identical to first
TEA/TEB ampoule selection valve	Add 3-way valve	Select appropriate TEA/TEB ampoule
Preburner fuel supply line	Add parallel line from TEA outlet cutter valve to preburner shutoff valve	Avoid shutdown purge cleanliness requirements
Preburner fuel shutoff valve	Replace with dual solenoid valve	Isolate second TEA/TEB line
Fuel bleed line from second cutter valve	Add line	Bleed fuel into preburner supply line the same as for first start

Table IV.
Modified NK-33 and NK-43 Engines (AJ26-58,59,60) Flight Sensor Suite

Parameters	No. of sensors	Acronym
Main combustion chamber pressure	1	PC
Main injector fuel manifold pressure	2	PFJ
Oxidizer pump discharge pressure	1	POD
Fuel pump discharge pressure	1	PFD
Fuel kickstage pump discharge pressure	1	PFDKS
Turbine outlet temperature	3	TTO
Turbopump shaft speed	4	NT
Start purge engine inlet pressure	2	PSPI
Shutdown purge engine inlet pressure	1	PSDPI
Interpropellant seal pressure	1	PIPS
Preburner fuel injector dynamic pressure	1	PFJPB
Main chamber jacket temperature	2	RTSCHW
Preburner injector vibration	1	GXPB
Main chamber vibration	1	GXCH
TTO reference junction temperature	3	RTA

Table V.
Modified NK-33 Engine Weights

Parameters	Units	Basic Engine * AJ26-58	Restartable * AJ26-59
Dry weight - pre-fire	lb_m	3104	3216
Wet weight - pre-fire	lb_m	3335	3447
Wet weight - operating	lb_m	3409	3521
Wet weight - second operating	lb_m	N/A	3505

* Note: engine weights include gimbal block, but do not include engine controller, EMA controller, or vehicle dependent items such as propellant feedlines and thermal shielding.

Table VI
Standard Inlet and Engine Tuning Conditions

Parameters	Units	Soviet N-1	K-1 LAP	K-1 OV
Oxidizer inlet pressure	psia	56.9	35.2	35.2
Oxidizer inlet temperature	F	-310	-310	-310
Fuel inlet pressure	psia	56.9	20.6	20.6
Fuel inlet temperature	F	5	-30	-30
Fuel inlet density	lb_m/ft^3	53.4	52.6	52.6
Fuel tapoff flowrate	lb_m/sec	2.4	5.0*	5.0*
Oxidizer hot gas tapoff flowrate	lb_m/sec	8.5	0	0

* Note: Used to power TVC system

Table VII
1995 Benchmark Test Program Data Summary

Test Number	Averaged Time Period τavg seconds	Main Chamber Pressure Pc psia	Percent of Nominal Chamber Pressure %Pc %	Engine Inlet Oxidizer Flowrate Wo lbm/sec	Engine Inlet Fuel Flowrate Wf lbm/sec	Engine Inlet Mixture Ratio MR --	Calc'd Sea Level Thrust Fsl lbf	Percent of Nominal Sea Level Thrust %Fsl %	Calc'd Sea Level Specific Impulse Isp,sl lbf-sec/lbm	Engine Inlet Oxidizer Pressure Pos psia	Engine Inlet Fuel Temp Tos F	Engine Inlet Fuel Pressure Pfs psia	Engine Inlet Fuel Temp Tfs F	Oxidizer Pump Discharge Pressure Pod psia	Fuel Pump Discharge Pressure Pfd psia	Turbine Rotor Speed Nt RPM	Turbine Outlet Temp Tto F
1	4 to 9.9	1665	78.9	661	242	2.73	259460	76.4	287.3	93.3	-293.9	89.9	63	3809	2908	14580	372
	14 to 22	2162	102.5	839	318	2.64	347660	102.4	300.5	79.4	-294.0	81.6	63	5516	4240	17870	610
2	10 to 20	2188	103.8	854	324	2.63	352270	103.8	299.1	77.1	-294.2	76.4	61	5668	4365	18150	635
	28 to 38	1657	78.6	658	239	2.75	258110	76.0	287.6	90.6	-294.1	83.4	62	3787	2893	14550	394
	39 to 41	1762	83.5	696	256	2.72	276630	81.5	290.4	88.1	-294.1	81.9	62	4138	3165	15280	441
3	24 to 25	1215	57.6	N/G	N/G	N/G	N/G	N/G	N/G	80.2	-282.4	87.4	63	2467	1942	11740	244
4	2.6 to 3.2	1825	86.5	723	269	2.69	285900	84.2	288.3	72.5	-290.0	53.3	52	4352	3358	15790	410
	15 to 35	2177	103.2	851	325	2.62	349860	103.1	297.5	63.9	-293.6	52.0	56	5654	4359	18190	632
	45 to 59	1646	78.0	654	239	2.73	255740	75.3	286.3	74.9	-293.6	58.6	56	3766	2879	14580	408
	75 to 130	2164	102.6	845	325	2.60	347310	102.3	296.9	59.3	-293.5	50.5	57	5623	4346	18180	668
	166 to 168	1654	78.4	656	243	2.70	256940	75.7	285.9	70.8	-293.3	56.0	57	3810	2946	14710	489
5	4 to 8	2177	103.2	855	323	2.64	350390	103.2	297.5	85.9	-293.1	83.4	58	5691	4437	18260	611
	15 to 135	2378	112.8	926	358	2.59	385760	113.6	300.4	78.3	-293.4	77.4	61	6527	5138	19740	753
	140.5 to 145.2	2162	102.5	846	323	2.62	347570	102.4	297.3	84.9	-293.3	84.5	62	5657	4409	18250	654

Table VIII
1998 Verification Test Program Data Summary

Test #	Averaged Time Period τavg seconds	Main Chamber Pressure Pc psia	Percent of Nominal Chamber Pressure %Pc %	Engine Inlet Oxidizer Flowrate Wo lbm/sec	Engine Inlet Fuel Flowrate Wf lbm/sec	Engine Inlet Mixture Ratio MR --	Calc'd Sea Level Thrust Fsl lbf	Percent of Nominal Sea Level Thrust %Fsl %	Calc'd Sea Level Specific Impulse Isp,sl lbf-sec/lbm	Engine Inlet Oxidizer Pressure Pos psia	Engine Inlet Fuel Temp Tos F	Engine Inlet Fuel Pressure Pfs psia	Engine Inlet Fuel Temp Tfs F	Oxidizer Pump Discharge Pressure Pod psia	Fuel Pump Discharge Pressure Pfd psia	Turbine Rotor Speed Nt RPM	Turbine Outlet Temp Tto F	Thrust Vector Control Tapoff Flowrate Wtvc lbm/sec
1	10 to 20	2251	106.7	862	349	2.47	361830	106.5	298.8	81.8	-295.2	76.8	41	5754	4512	18260	616	0
	30 to 39	1693	80.3	654	256	2.56	262980	77.4	289.1	94.9	-295.3	81.6	40	3721	2842	14380	369	0
	43 to 44	1823	86.4	700	278	2.52	285870	84.1	292.4	91.7	-295.3	79.4	40	4141	3165	15230	429	0
2	15 to 25	2112	100.1	820	317	2.59	338890	99.7	297.9	85.6	-294.6	62.3	44	5284	4138	17500	542	0
	40 to 50	2107	99.9	830	307	2.70	339380	99.8	298.3	84.8	-294.6	62.1	44	5338	4256	17640	528	0
	60 to 70	2112	100.1	819	317	2.58	338910	99.7	298.3	84.2	-294.6	60.7	44	5289	4121	17500	534	0
	85 to 95	2113	100.2	813	322	2.52	338370	99.5	298.0	83.5	-294.7	57.9	44	5262	4046	17430	528	0
	100 to 110	2196	104.1	843	338	2.50	352870	103.8	298.9	80.5	-294.7	55.2	44	5588	4306	18030	566	0
	115 to 125	2032	96.3	785	308	2.55	324160	95.4	296.7	84.9	-294.7	57.0	44	4970	3801	16860	493	0
	135 to 145	2027	96.1	789	303	2.61	323940	95.3	296.8	83.3	-294.7	54.5	44	4992	3865	16920	483	0
3	8 to 10	1170	55.5	497	N/G	N/G	N/G	N/G	N/G	66.8	-314.5	51.1	-8	2313	1731	11010	164	0
	29 to 34	2096	99.4	820	311	2.64	336500	99.0	297.5	46.0	-314.9	44.0	-36	5130	4022	16940	498	0
	42 to 47	2095	99.3	814	315	2.58	335590	98.7	297.3	45.5	-314.9	40.8	-37	5107	3947	16870	502	0
4	8 to 10	1045	49.6	440	150	2.92	149600	44.0	253.6	42.1	-294.9	26.9	57	2033	1543	10550	157	0
	16 to 21	1048	49.7	438	148	2.97	150300	44.2	256.7	47.0	-295.2	27.6	50	2047	1549	10510	152	0
	35 to 40	1050	49.8	432	151	2.87	150230	44.2	257.8	48.7	-295.3	28.1	49	2040	1525	10510	160	0
	54 to 59	1051	49.8	427	153	2.78	149950	44.1	258.4	51.1	-295.3	27.8	49	2024	1497	10450	165	0
5	19 to 24	2077	98.5	820	305	2.69	334070	98.3	297.3	86.8	-311.8	64.5	46	5094	3684	16730	460	0.5
	29 to 34	2071	98.2	818	308	2.66	332740	97.9	296.7	85.9	-311.8	63.5	47	5089	3666	16720	464	4.7
	44 to 49	2060	97.7	827	298	2.77	331940	97.7	296.3	85.9	-310.8	93.0	47	5135	3778	16870	459	4.8
	54 to 59	2063	97.8	826	295	2.80	332560	97.8	296.8	86.2	-309.4	62.2	48	5137	3796	16880	457	0.5
	74 to 79	2068	98.1	812	307	2.65	332090	97.7	296.9	85.7	-309.3	59.8	50	5082	3667	16740	474	0.5
	84 to 89	2062	97.8	811	309	2.62	330730	97.3	296.4	85.0	-309.3	58.7	52	5074	3646	16730	473	4.7
	94 to 99	2102	99.7	826	316	2.61	337710	99.4	297.0	83.9	-309.3	56.5	53	5223	3752	17010	489	4.8
	104 to 109	2105	99.8	826	313	2.64	338680	99.6	297.5	84.3	-309.2	55.3	54	5227	3776	17020	487	0.5
	119 to 124	2020	95.8	802	294	2.73	324160	95.4	296.0	86.6	-309.2	56.2	55	4948	3608	16520	444	0.5
	134 to 139	2021	95.8	797	297	2.68	323830	95.3	296.1	85.8	-309.2	54.0	55	4927	3772	16470	449	0.5
	144 to 149	2060	97.7	810	304	2.66	330670	97.3	296.8	83.6	-309.1	53.0	55	5069	3677	16730	466	0.5

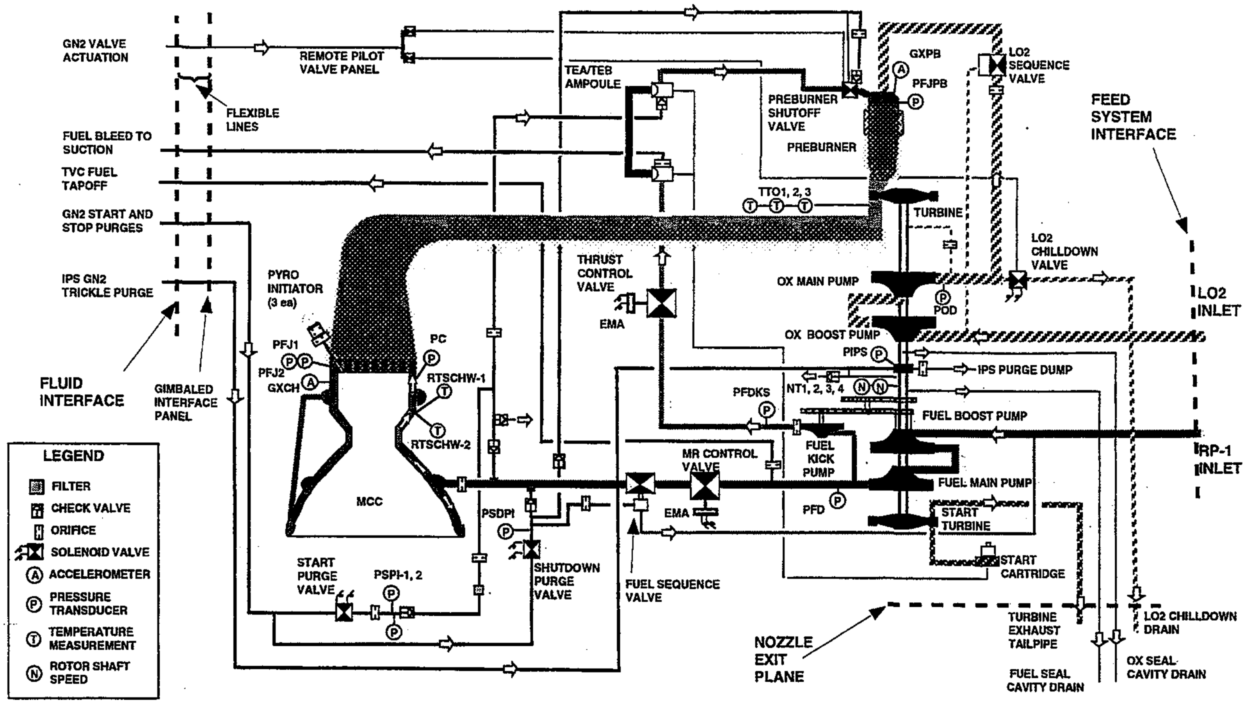

Figure 1. Schematic of the Modified Basic NK-33 Engine (AJ26-58)

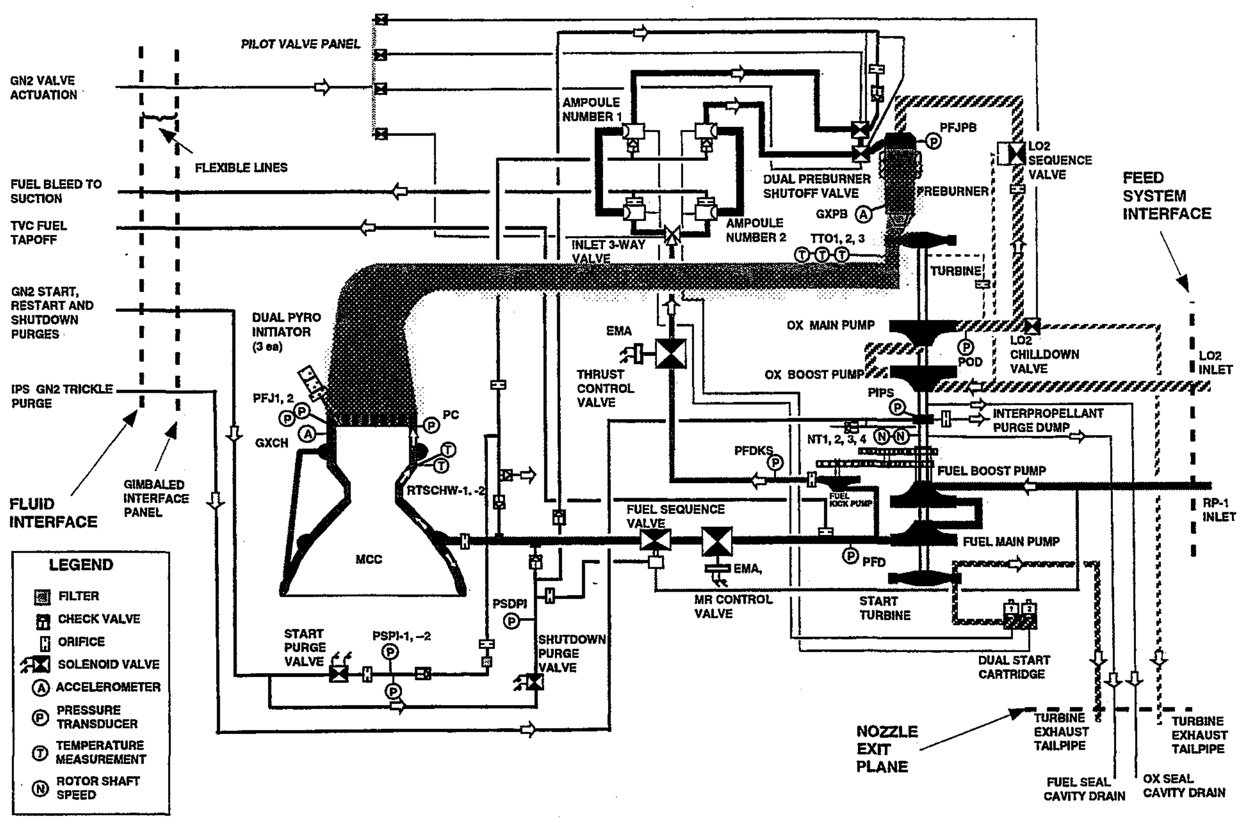

Figure 2. Schematic of the Modified Restartable NK-33 Engine (AJ26-59)

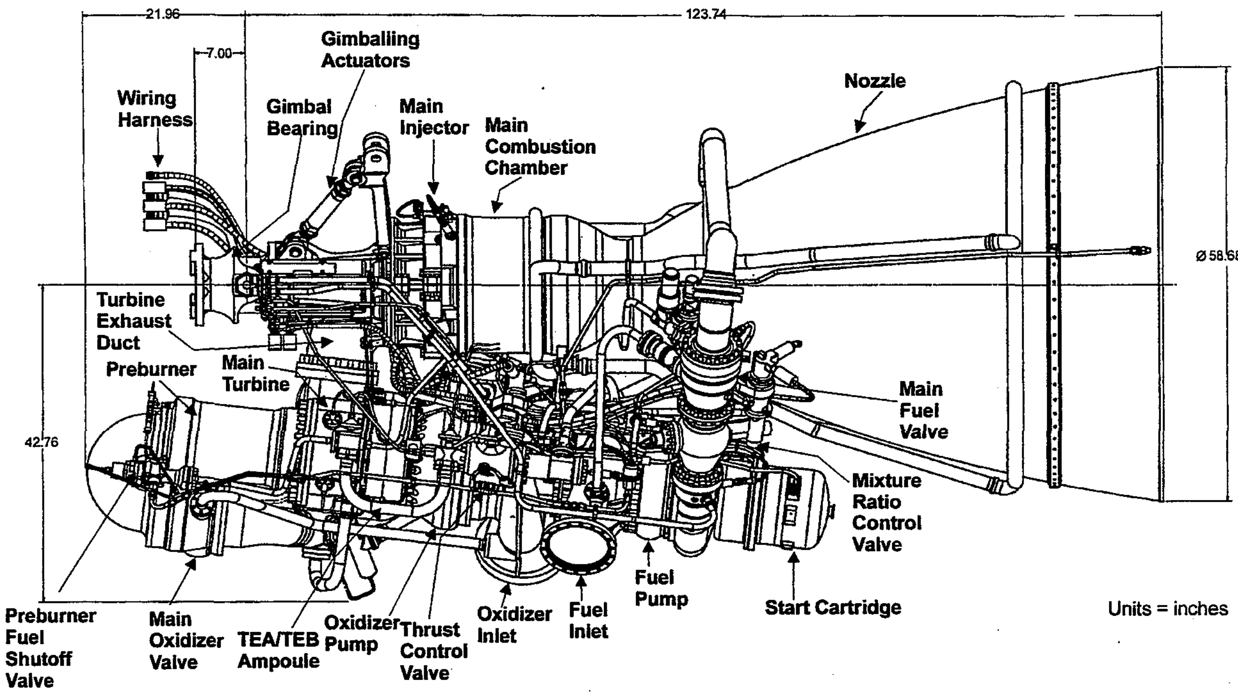

Figure 3. Layout Envelope of the Modified Basic NK-33 Engine (AJ26-58) - Side View

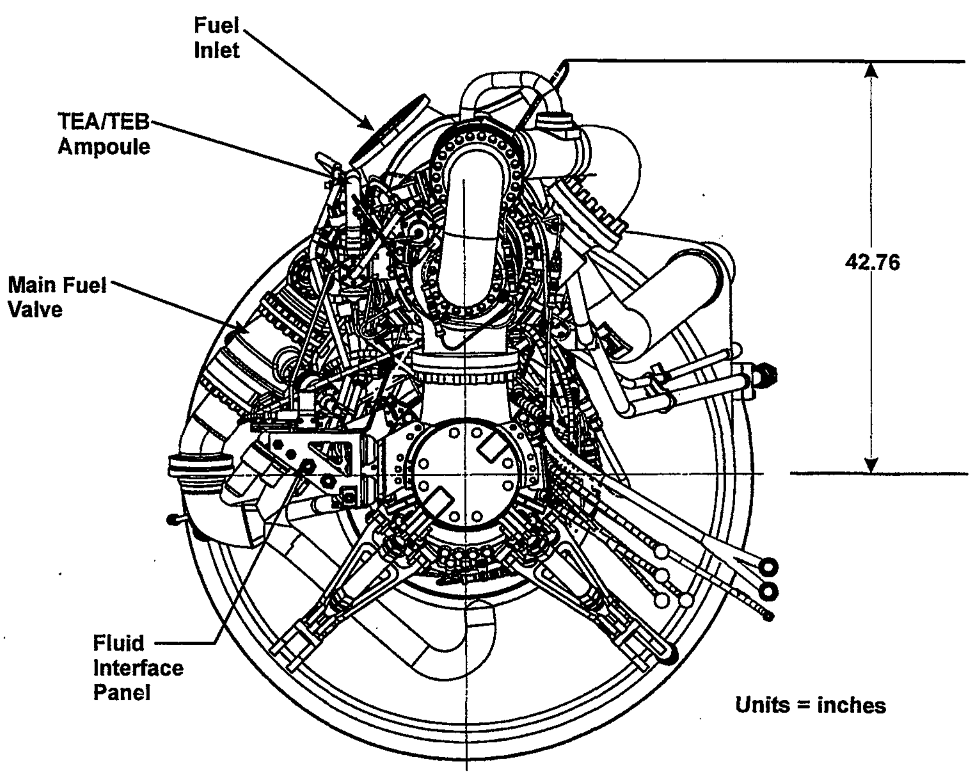

Figure 4. Layout Envelope of the Modified Basic NK-33 Engine (AJ26-58) - Top View

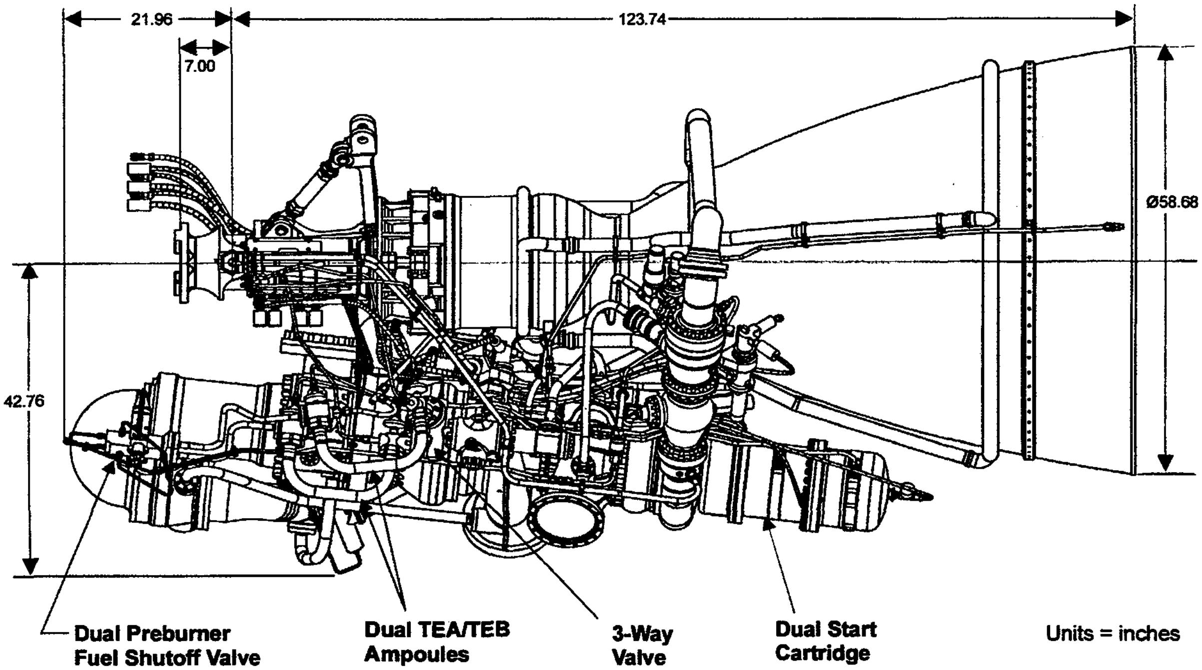

Figure 5. Layout Envelope of the Modified Restartable NK-33 Engine (AJ26-59) - Side View

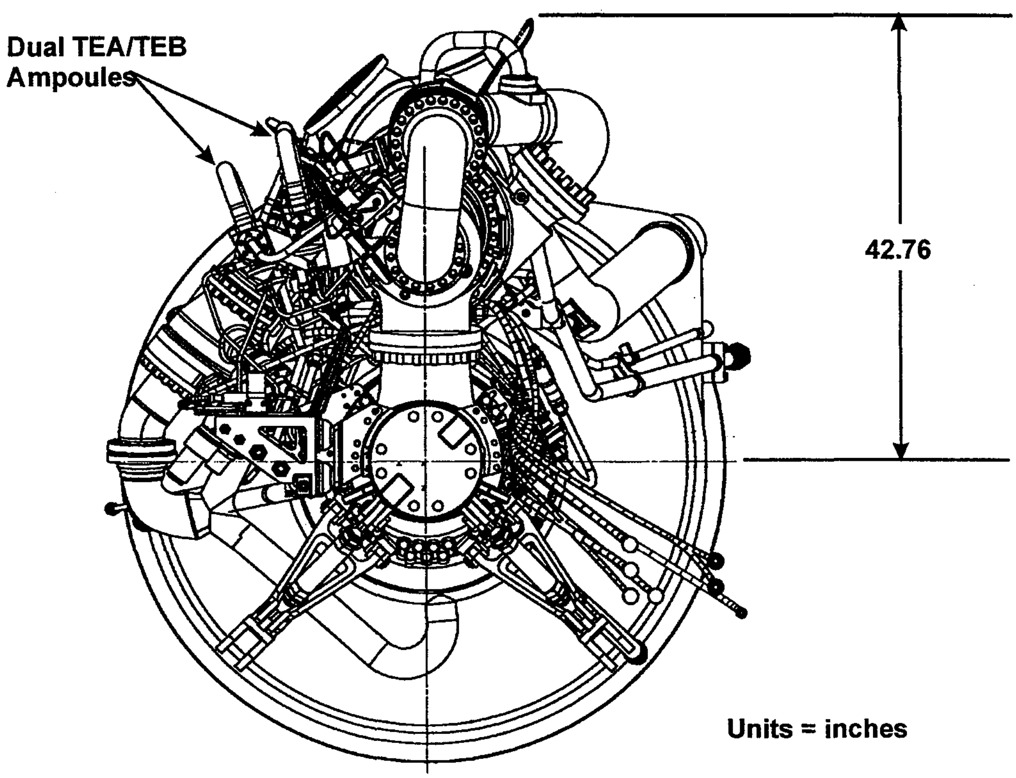

Figure 6. Layout Envelope of the Modified Restartable NK-33 Engine (AJ26-59) - Top View

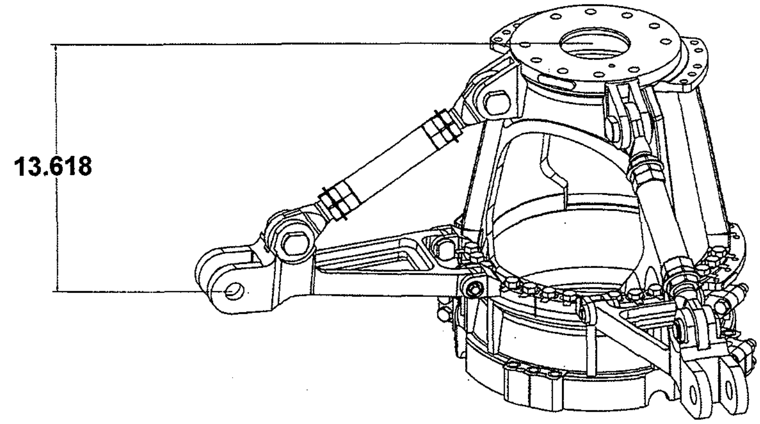

Figure 7a. New Thrust Mount – Side View

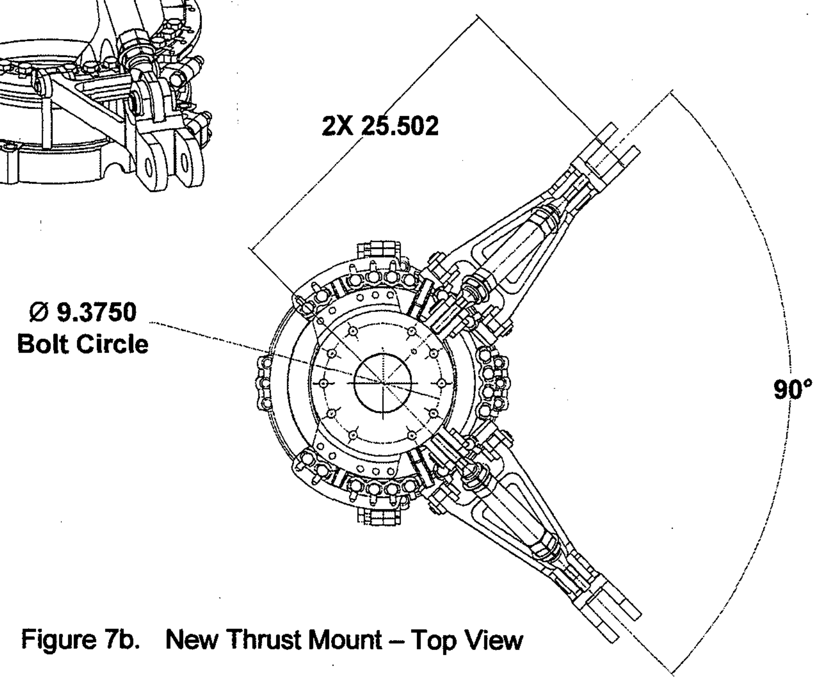

Figure 7b. New Thrust Mount – Top View

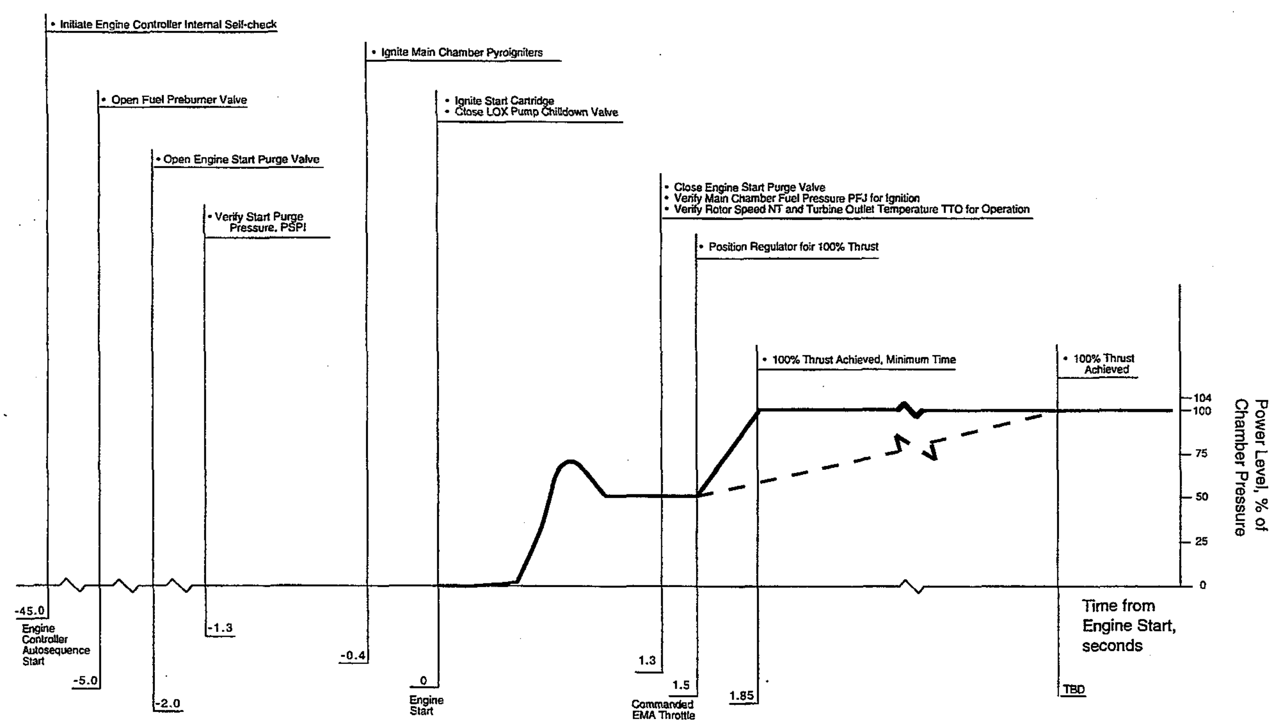

Figure 8. Start Transient of the Modified NK-33 Engine (AJ26-58, 59)

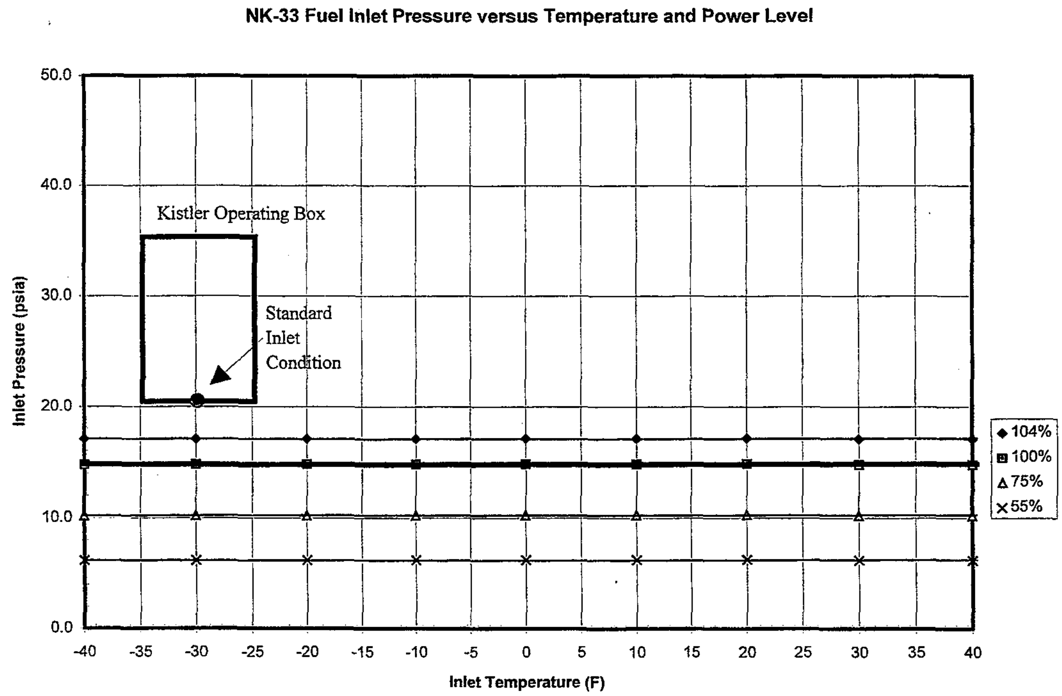

Figure 9. RP-1 Engine Inlet Pressure and Temperature for Modified NK-33 Engines (AJ26-58, 59)

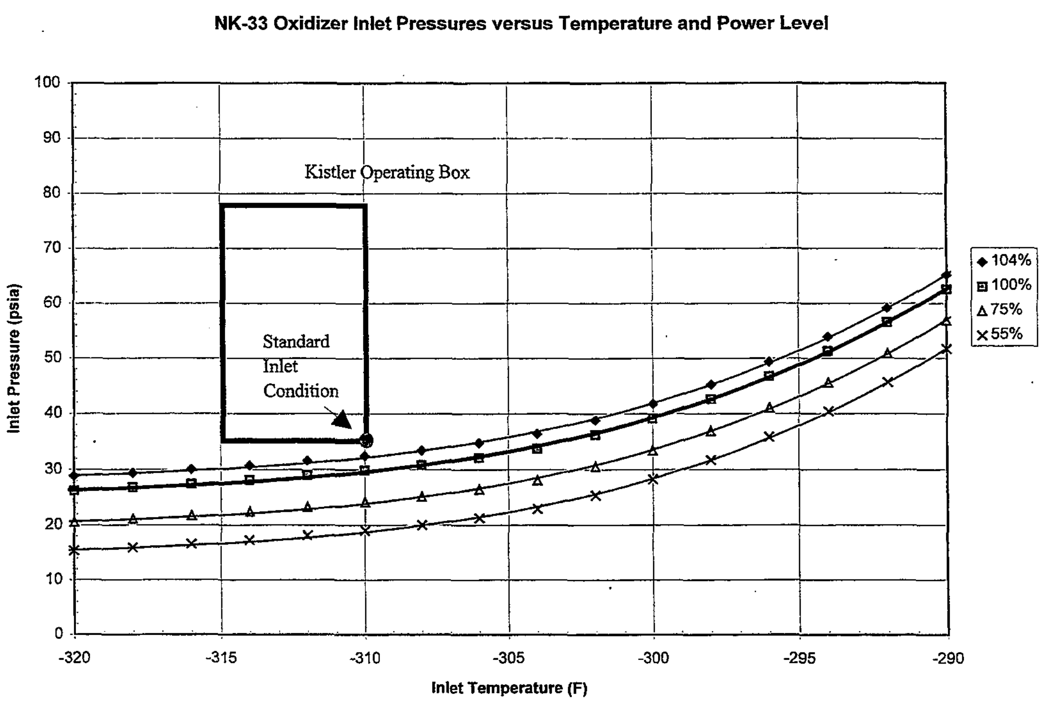

Figure 10. LOX Engine Inlet Pressure and Temperature for Modified NK-33 Engines (AJ26-58 , 59)

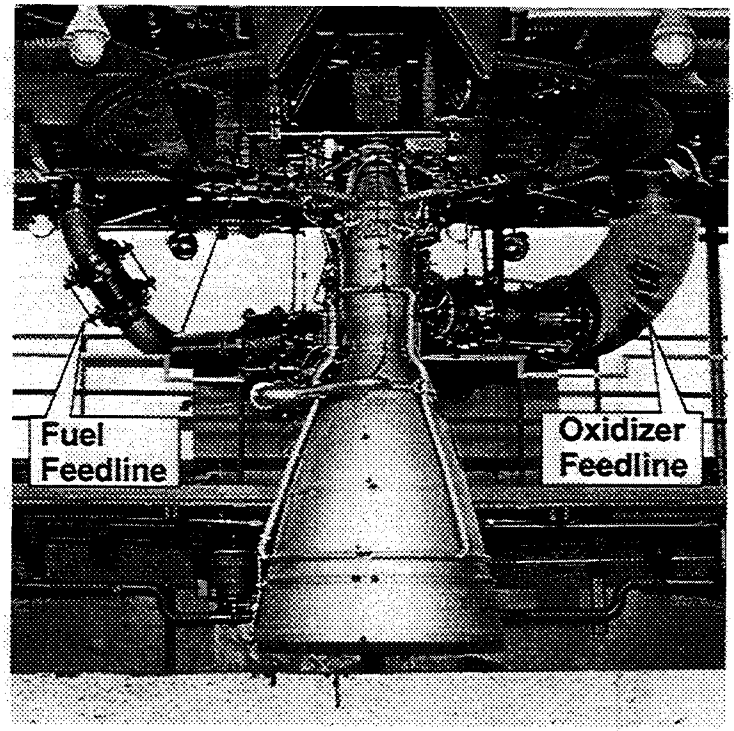

Figure 11a. Modified NK33 Engine (AJ26-58) on Aerojet Test Stand E-5

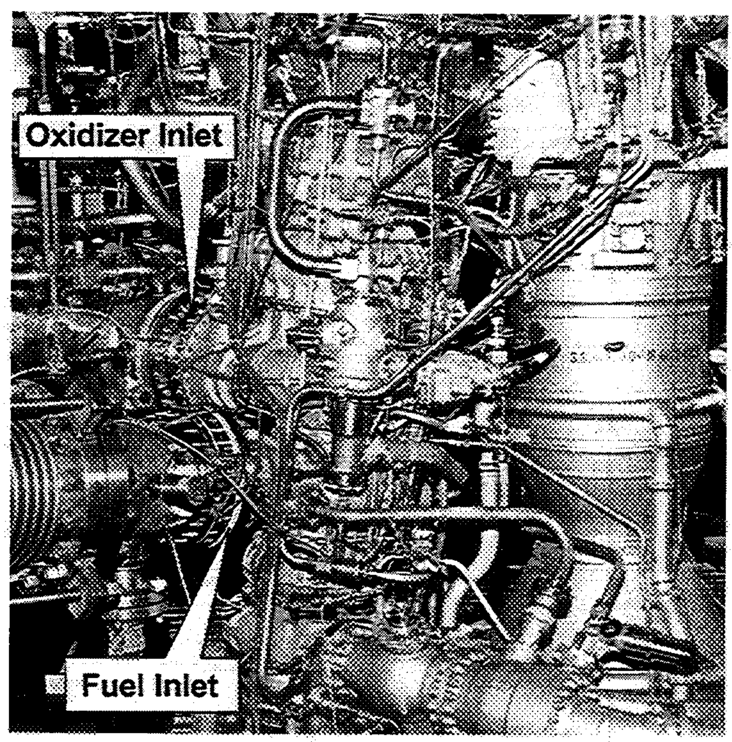

Figure 11b. Modified NK33 Engine (AJ26-58)

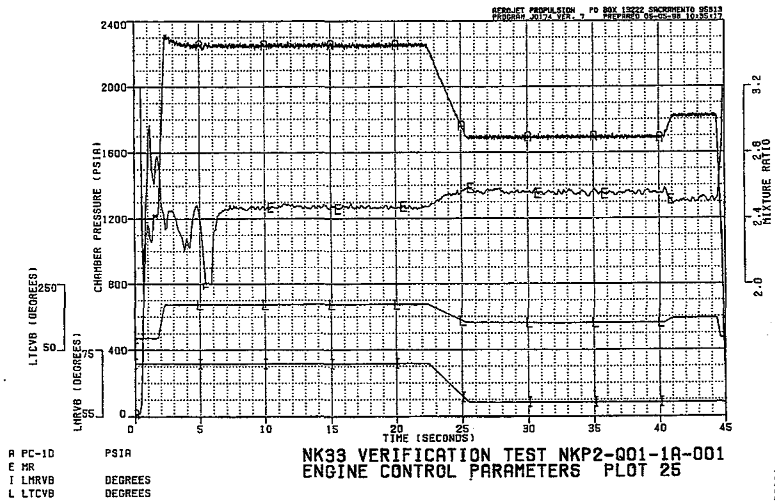

Figure 12. Performance Parameters for Verification Test #001

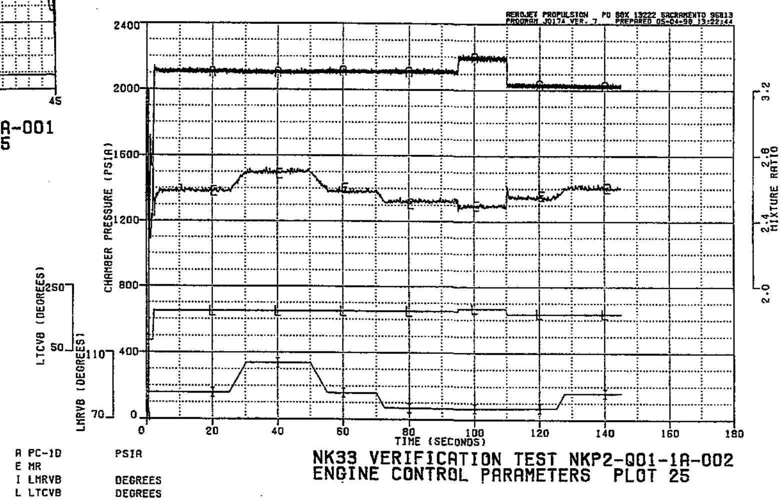

Figure 13. Performance Parameters for Verification Test #002

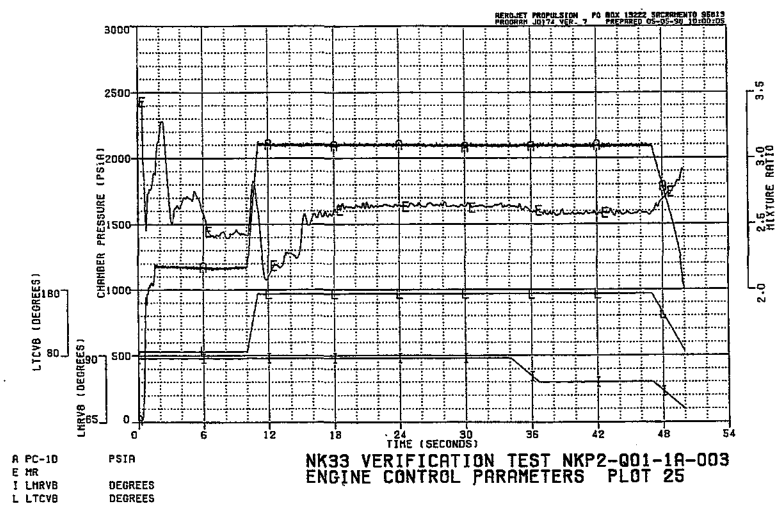

Figure 14. Performance Parameters for Verification Test #003

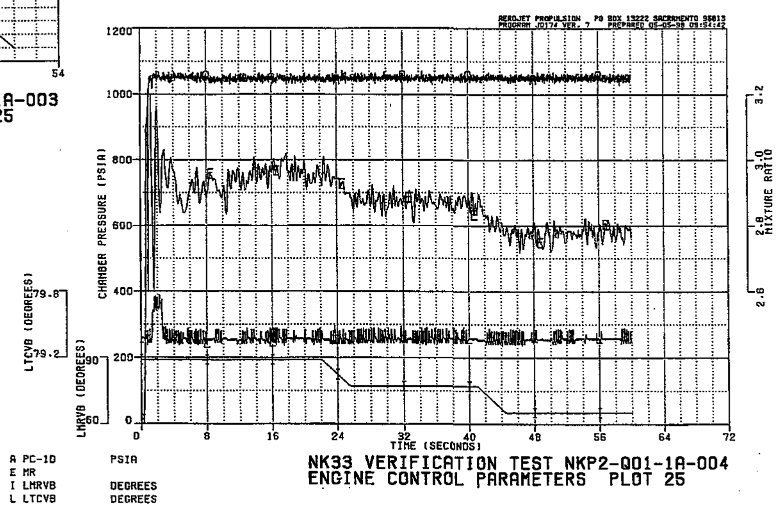

Figure 15. Performance Parameters for Verification Test #004

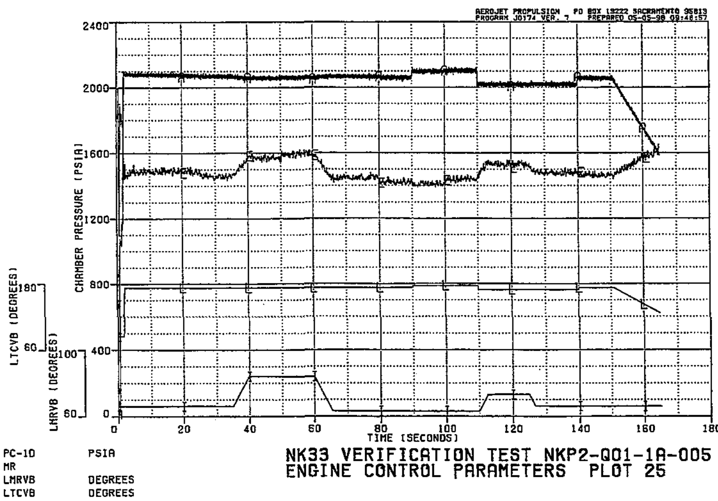

Figure 16. Performance Parameters for Verification Test #005

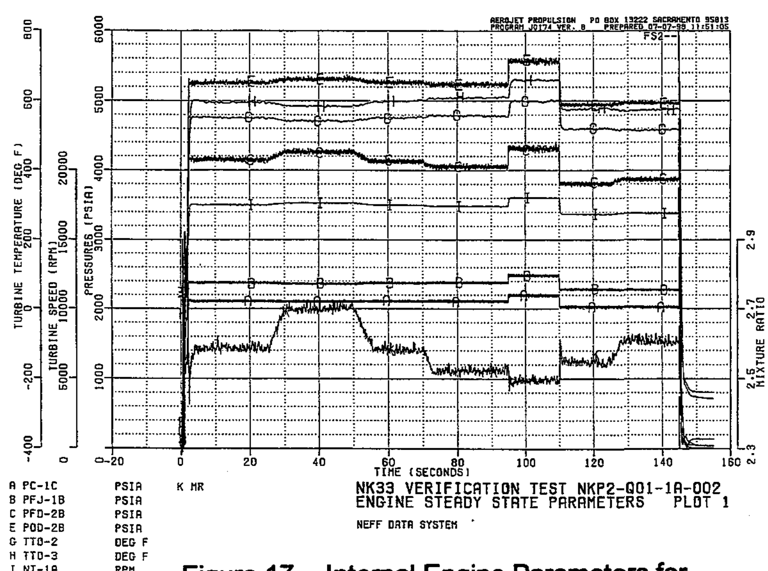

Figure 17. Internal Engine Parameters for Verification Test #002

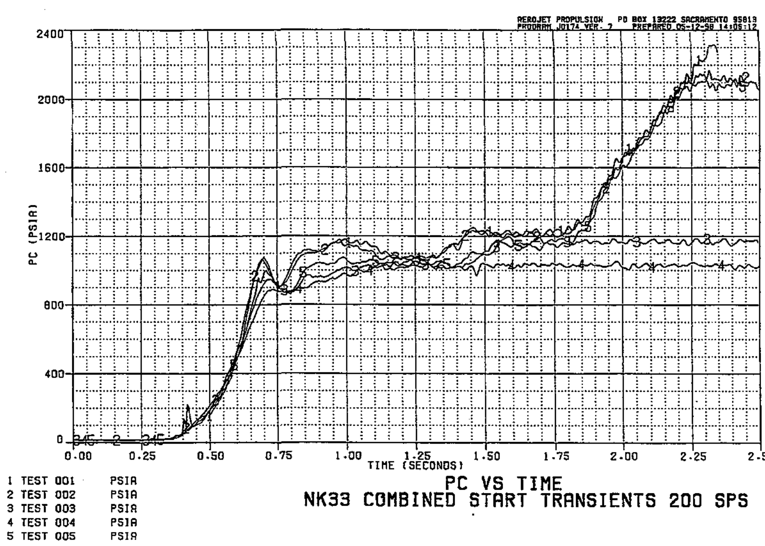

Figure 18. Verification Test Start Transient Comparison of Main Combustion Chamber Pressures

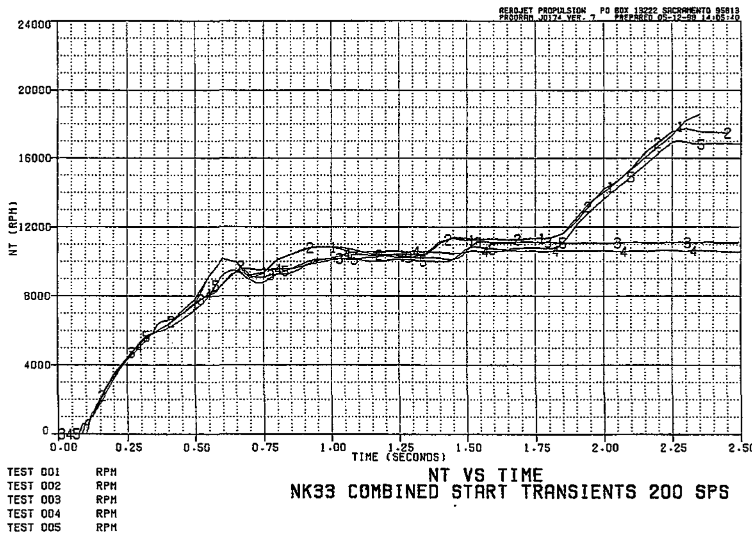

Figure 19. Verification Test Start Transient Comparison of Turbopump Shaft Speeds

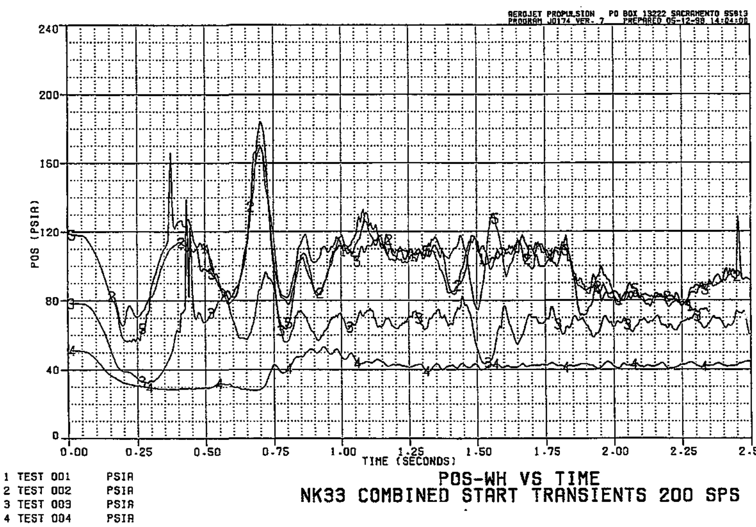

Figure 20. Verification Test Start Transient Comparison of Oxidizer Inlet Pressures