16. XLR99 ENGINE OPERATING EXPERIENCE (U)

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INTRODUCTION

The XLR99-RM-1 rocket engine, which was developed specifically for the X-15 airplane, is the largest rocket engine designed from the outset for use in a manned vehicle to be completely controlled by the crew. In order to provide the desired safety and controllability required by the X-15 mission, many unique features were included in the design. Delays in the development of the engine required that the initial X-15 flights be made with an interim engine.✓ However, the first flight with the XLR99 was made in November 1960, and the engine has been used in government flight operations since February 1961. Since the first flight, fifteen flights have been made with the XLR99. This paper summarizes the XLR99 operating experience during the flight program.

GENERAL DESCRIPTION

The procurement specification of the XLR99 presented a number of special requirements listed as follows: Minimum hazard, variable thrust, multiple restart, prelaunch idle, and long life. These requirements are beyond those heretofore normally expected of a rocket engine. They resulted in additional complexity but also provide the engine its unique capabilities. In defining "minimum hazard," the single malfunction concept was employed. The XLR99 was designed so that, under any single condition of malfunction, the engine would create no hazard to the airplane. This safety concept was demonstrated analytically by malfunction analysis and empirically through 47 malfunction tests during the Preliminary Flight Rating Test (PFRT).

The XLR99 provides variable thrust over a continuous range from 50 percent to 100 percent of rated thrust and is capable of more than five restarts without servicing. The turbopump and both igniter stages are operated as an idle mode before launch, so that an operational check of over 90 percent of the engine's components is provided prior to commitment of the X-15 to free flight.

Of particular interest to the X-15 program is the requirement of long life. The engine life requirement is compared in figure 1 with that for missile engines. In its application as an aircraft engine, the XLR99 was required to accumulate one hour of operation or 100 starts without overhaul, far beyond normal rocket engine life. Note that a logarithmic scale is used. The top shaded area indicates the spread in engine life that is actually being encountered. The design requirement is shown by the point. Data on the present engine are as follows:

Propellants
  Engine - liquid oxygen and ammonia
  Pump - 90 percent hydrogen peroxide

Dry weight - 910 pounds

Specific impulse
  Sea level - 230 seconds
  45,000 ft - 265 seconds

Rated thrust
  Sea level - 50,000 pounds
  45,000 ft - 57,000 pounds

Expansion ratio (area) - 9.8

Rated chamber pressure - 600 psia

Altitude - all altitudes

Attitude - all attitudes

The altitude values of thrust and specific impulse are the more significant since in the research flights the entire period of engine operation takes place at and above this altitude. Engine starts have been demonstrated in the altitude facility of the Arnold Engineering Development Center at altitudes up to 70,000 feet; however, the engine has been designed to operate at any altitude. In regard to attitude, engine operation has been demonstrated at 90° climb, 30° dive, and 45° left and right roll. The engine is shown in figure 2. A 6-percent increase in thrust and efficiency could be achieved through addition of a nozzle extension to expand the gases to an altitude equivalent pressure of 45,000 feet rather than the present 19,000 feet equivalent pressure. However, such a change would result in a significant weight increase with concomitant center-of-gravity effects.

TESTING BACKGROUND

The first complete, flight engine configuration was fired in February 1958, and the Preliminary Flight Rating Test was completed in January 1960. During this program more than 500 minutes of engine operation and over 640 starts were accumulated on 14 engines, utilizing three test stands at the Reaction Motors Division, Thiokol Chemical Corp. The Edwards Propulsion System Test Stand (PSTS), (fig. 3), began operations with the XLR99 in June 1959. This test facility consists of a complete X-15 propulsion system and provides a capability for engine checkout, pilot and maintenance crew familiarization, and limited development firings. To date, over 300 firings have been made in the PSTS. As final confirmation of flight readiness, ground runs in the X-15 at the PSTS facility permit an integrated systems checkout.

PERFORMANCE ACHIEVED

The XLR99 is now operating successfully in the X-15. However, delays in the development program schedule resulted in a decision in September 1958 to freeze the design with a reduced performance requirement rather than to accept further delays in excess of those which could be compensated for by the interim XLR11 propulsion system. Table I shows the resulting specification changes. In addition to the reduction in specific impulse, it will be noted that weight has increased significantly and throttle range has been reduced. Development tests are scheduled for early December 1961 to return the minimum thrust point to the 19,500-pound level.

There is a statistical variation in performance from engine to engine and test to test. Figure 4 is a plot of thrust-chamber data from four engines during PFRT and is in consonance with the performance of flight engines. The present specification specific impulse is superimposed upon these points.

As a part of the PFRT program, two engines were required to accumulate one hour of operation and 100 starts. The requirement was exceeded. The two engines accumulated 64 and 65 minutes, 100 and 137 starts, respectively. Unfortunately, this performance has not continued in field operations. Figure 5 depicts engine service life at Edwards Air Force Base (EAFB). Listed here are all nine flight engines and a ground test engine; Engine serial No. 105 was destroyed in the explosion of X-15 No. 3 on June 8, 1960. The arrows indicate thrust-chamber replacement. Early in the flight program, operations were plagued by several premature chamber failures. These involved failure of cooling tube walls and consequent leakage of fuel into the combustion chamber. This problem is discussed in detail in the paper by Hjelm and Bornhorst (paper no. 17). In addition to the premature failures, three flight engine thrust chamber-injector assemblies have been removed for other reasons. Although in these cases the chambers are not lost to the program, the engines have become inactive pending chamber reinstallation or replacement, seriously impairing the spares capability.

Figure 6 is a plot of throttle actuator position and chamber pressure. Although extremely rapid response is not required by the mission, chamber pressure follows the throttle closely. It might be noted that the thrust chamber pressure lags the throttle position by 0.2 to 0.6 seconds.

Figure 7 is interesting as an indication of the times involved in recovery from a malfunction shutdown after launch. These data are taken from a flight made by Major Robert W. White in April 1961 in which a malfunction shutdown occurred almost immediately after launch. Shown are throttle position, fuel-pump pressure, and chamber pressure plotted against time. The igniter idle switch was actuated approximately 20 seconds before launch and pump discharge is up. The fire switch was actuated 1.3 seconds after drop and the throttle was advanced. Pump discharge and chamber pressures were rising when malfunction shutdown occurred. Restart must be delayed to completion of the purge and engine reprime. The fire switch was actuated at 21.9 seconds. When the pilot saw the pump pressure rise he advanced the throttle. It is interesting to note that the throttle motion was stopped as the pilot checked his chamber pressure as he neared the desired thrust level and the two pressure traces clearly reflect this event. The sequence from launch involved approximately 30 seconds and an altitude loss of 8,000 feet as against a good start drop of about 2,000 feet.

FIELD PROBLEM AREAS

Although PFRT was completed successfully, field operations differ from test-stand conditions, and the PFRT experience did not carry over to operations at Edwards. The problem areas which have become prominent are as follows: Vibration, premature chamber failures, pump seal leaks, corrosion, compatibility, and controls.

The most pernicious problem encountered has been the 1,600 cps vibration. A typical trace of the accelerations at one of the engine mounting points is shown in figure 8. The initial accelerations are low and build up. If the vibration does not exceed 100g at the pickup location, damping occurs. Between 100 and 200g, either damping or divergence can result. Above 200g, divergence always occurs. Therefore, a vibration cutoff was installed to shut down the engine in event of vibration levels above 120g. Inasmuch as there is the possibility of damping in this range, the cutoff includes a 50-millisecond delay to permit this damping and avoid unnecessary shutdowns. The mechanics of this phenomenon have not been determined; however, the incidence rate is known to increase in the higher performing engines and is also aggravated by operation at mixture ratios below design. The incidence rate has been contained within 2 to 4 percent of start attempts through installation of vibration isolators and a quick-change orifice device which permits operations at proper mixture ratios at all times. An interesting facet of this phenomenon is discussed subsequently with regard to compatibility. The vibration situation has not directly delayed flight operations, but is the major contributor to the malfunction shutdown rate during ground operations. A vibration shutdown has not yet occurred in flight.

The premature failure of thrust chambers has produced a direct effect upon engine availability for flight. This problem is discussed in detail in the paper by Hjelm and Bornhorst (paper no. 17).

The pump seal leak involved O-ring deterioration at the pump-fuel casing joint. However, replacement requires removal of the turbine exhaust duct, stator blades, rotor and inlet housing. Thus, O-ring replacement requires 2 to 3 shifts. Just to remove the exhaust ducts necessitates removal and re-safety wiring of 60 bolts. Thus, although the O-ring failure, which results in a steam leak, is not of major significance in itself, repair requires removal of the engine from the aircraft, and time-consuming engine disassembly, directly contributing to flight delays. The deterioration is believed to be due to the longer pump runs utilized in field operations; turbine-case temperatures in the vicinity of the O-ring have been recorded as high as 600° F. An investigation is under way for an improved seal which will withstand higher temperatures. In the interim, pump ground runs are being reduced in duration in an effort to minimize deterioration of the present seals.

Corrosion appears to be largely a result of the unusually long engine life. With a few exceptions, materials used are those reported to be compatible with the propellants. There have been some instances of galvanic action between the magnesium pump case and steel parts with decomposed peroxide as an electrolyte. As is sometimes said, the only thing really compatible with peroxide is more peroxide.

The necessity for component compatibility is not a new idea. In the XLR99 engine, the major component-compatibility requirement has been met; that is, the components work together properly. However, the "vernier" mismatch of individual components still occurs. For example, minor speed control difficulties have been corrected by matching of governor and turbopump. This component match is illustrated again by the vibration problem. During initial checkout of engines serial number 108 and 111 on the PSTS, excessive vibration-incidence rate was observed. The igniter in the engine (serial number 108) was replaced and the vibration incidence rate was reduced within acceptable limits. The igniter removed from the engine serial number 108 was then installed in another (serial number 111) and its incidence rate reduced within acceptable limits. Compatibility is not particularly a problem but does produce the usual puzzling inconsistencies.

The difficulties in the control area are primarily in the hydraulic governor system. The servicing procedure is somewhat complicated and often difficult; production tolerances result in metering-valve binding, and the peroxide and hydraulic oil produce some corrosion. The most surprising occurrence was a siege of problems due to governor housing porosity; however, this problem has been resolved by an epoxy impregnation of the castings.

There are also random failures of pressure switches, relays, etc. These are not unexpected nor is the failure rate high; however, they require removal of the control box with resultant delay.

It might be noted that the premature chamber failures and pump seal leaks have contributed directly to flight delays. The problems of corrosion, compatibility, and control are usually corrected at the PSTS and rarely affect flight engines.

FLIGHT EXPERIENCE

Perhaps this discussion of the problem areas and specification deviations has presented an overly dreary picture of the XLR99 engine. In spite of these troubles and in spite of these delays, the engine has performed well in flight and the aircraft has approached its design speed. The mission experiences of the X-15 with the XLR99-RM-1 engine is indicated in the following tabulation:

Launches	Successful	Engine abort prior to launch	Malfunction with restart
15	15	1	3

[redacted]

The table shows that the X-15 has been launched 15 times with the XLR99 aboard and in each case successful engine operation has been achieved. On three occasions malfunction shutdowns occurred in flight, but each time the first restart attempt was successful and no compromise to the mission resulted. It should be borne in mind that the XLR99 has been designed to shutdown in event of malfunction. Unlike its predecessors, no explosion, fire, or other hazardous condition has occurred in flight. None of the emergency landing areas have been used. On one mission only, the engine failed to operate just prior to launch and the flight was aborted; but this was just one among many such aborts from other causes. (Even this lapse demonstrated the advantage of the prelaunch idle mode.)

FUTURE APPLICATIONS

Other than the previously mentioned increase in range of throttleability, there is no active program at the present time for the advancement of the XLR99 rocket engine. There have been several proposals for increasing the performance of the X-15 airplane through injector redesign, addition of a nozzle extension, and conversion to the more dense storable propellants. Several firings have been made with present pump and chamber assembly with the nitrogen tetroxide-mixed hydrazine propellants. The engine has also been proposed for Dyna-Soar air launch tests. However, for the X-15, the research gains must be weighed carefully against the additional development cost and the time extension required to accomplish the changes.

Regardless of these proposals it is believed that the XLR99 engine has demonstrated valuable new concepts in the application of rocket power to manned vehicles. The most significant of these is the "man-rating" concept evolved. The XLR99 does not depend passively upon reliability for pilot safety. An active approach, designed to react to malfunctions, which do occur, was applied. For the X-15, where safety takes precedence, this reaction is a shutdown for those cases where the malfunction could result in a hazardous condition. (Nonhazardous malfunctions do not produce a shutdown.) It is recognized that all manned rocket-powered vehicles cannot use the shutdown for protection. However, the principle evolved (extremely detailed malfunction analysis, idle modes, continuous igniter operation, selected redundancy) can serve to prevent catastrophic malfunction results and allow time for some alternate action on the part of the crew. The concepts demonstrated in the X-15/XLR99 system deserve close study. Their adaptation to other aerospace vehicles will enhance operational safety and thus, mission success.

[redacted]

TABLE I.- XLR99-RM-1 DEVELOPMENT SPECIFICATION CHANGES

	Initial proposal Feb. '56	Spec. 91F June '58	Spec. 91M March '61
Maximum thrust (45,000 ft), lb	57,000	57,000	57,000
Minimum thrust (45,000 ft), lb	19,500	19,500	31,500
Specific impulse (sea level), sec	241	238	230
Specific impulse (45,000 ft), sec	278	272	265
Engine weight (dry), lb	540	856	910
Engine weight (wet), lb	625	990	1,025

[redacted]

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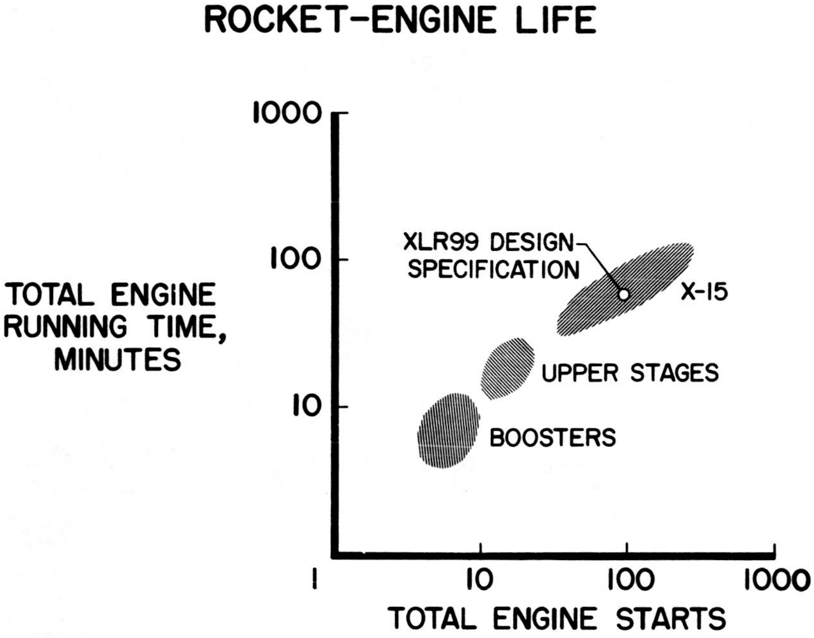

Figure 1

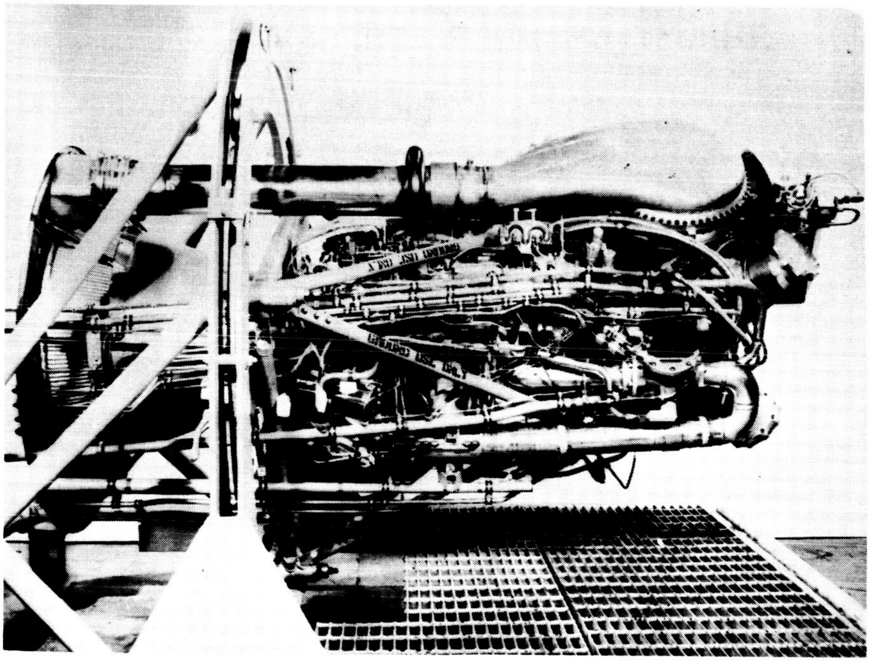

Figure 2

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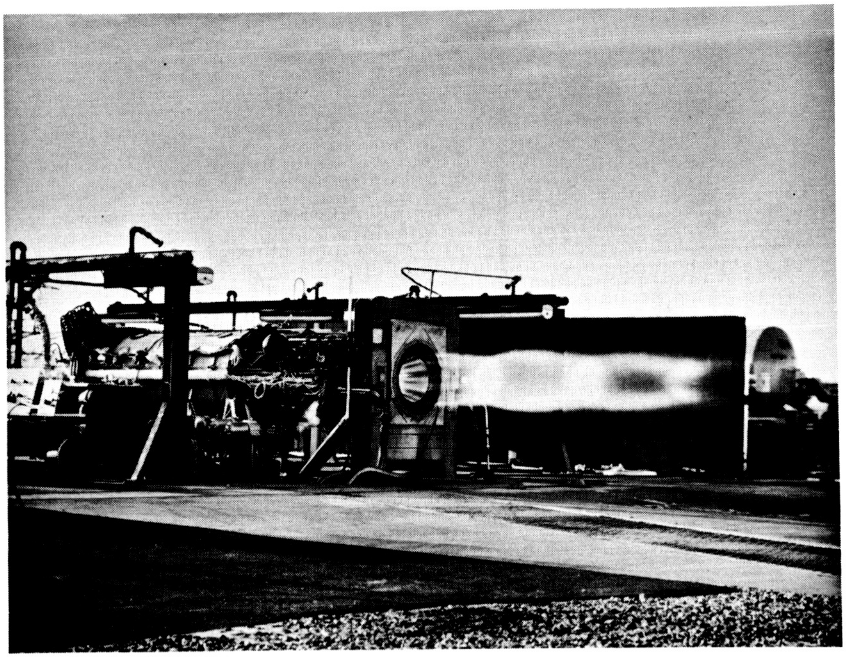

Figure 3

THRUST-CHAMBER PERFORMANCE

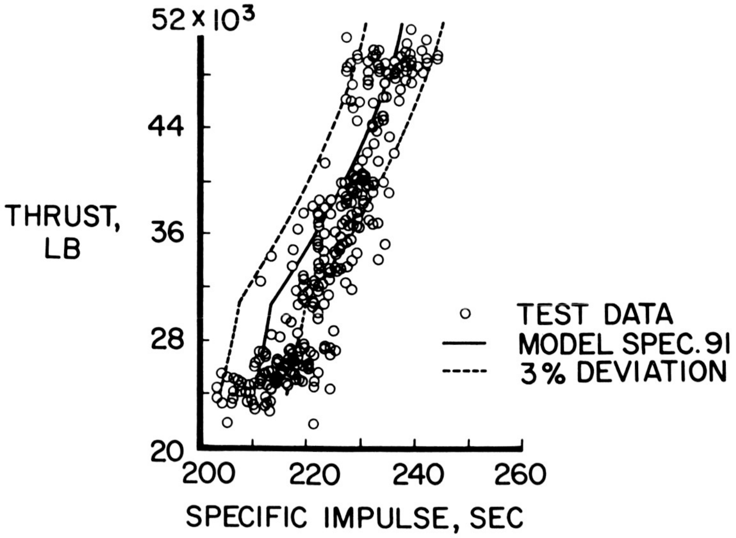

Figure 4

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XLR99 ENGINE SERVICE LIFE

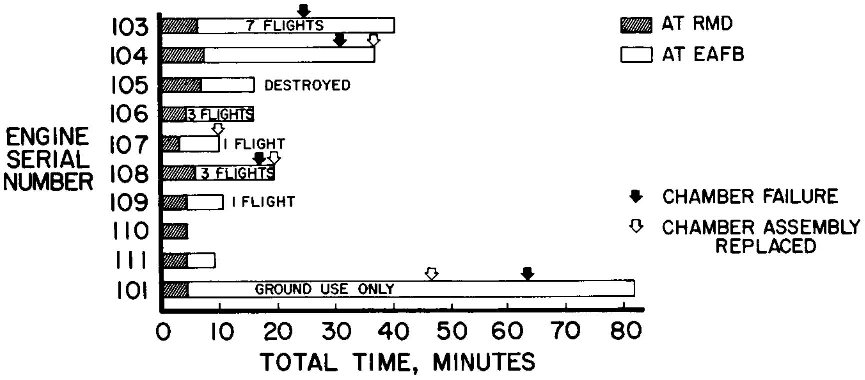

Figure 5

XLR99 ENGINE THROTTLE RESPONSE

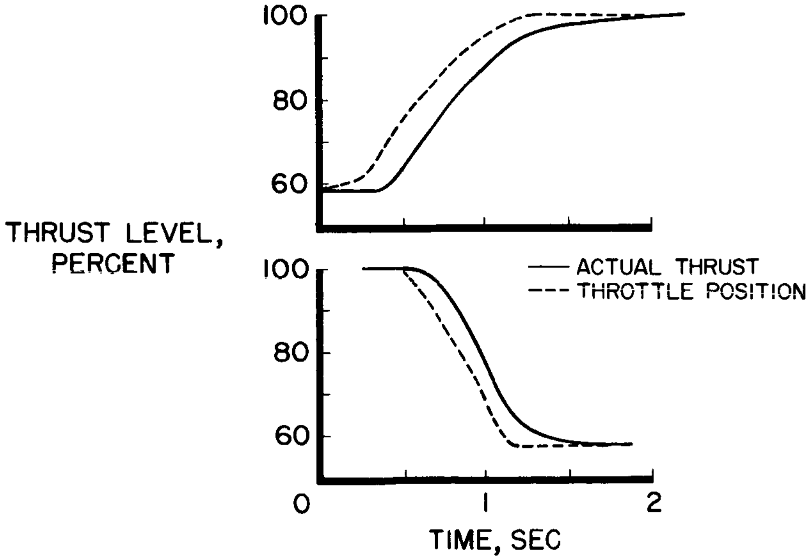

Figure 6

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XLR99 ENGINE
SHUTDOWN AND RESTART RECORDS

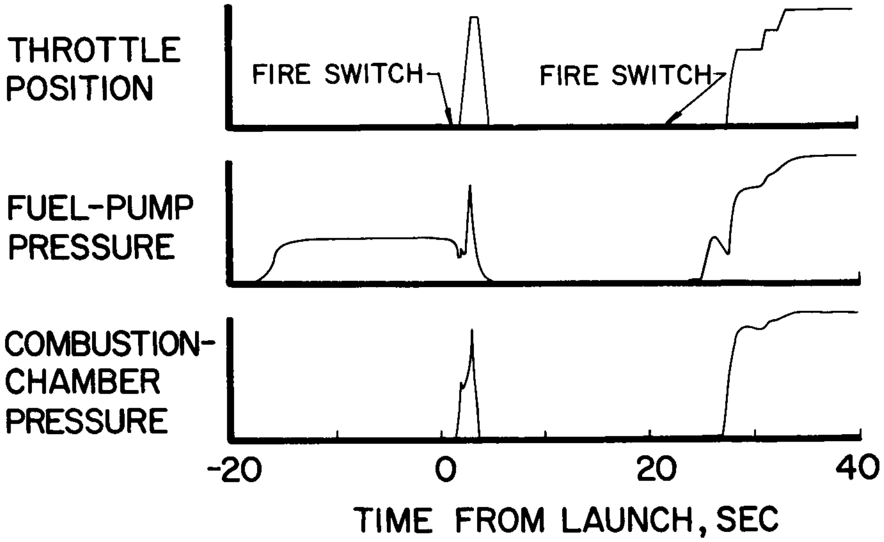

Figure 7

XLR99 ENGINE
VIBRATION RECORD

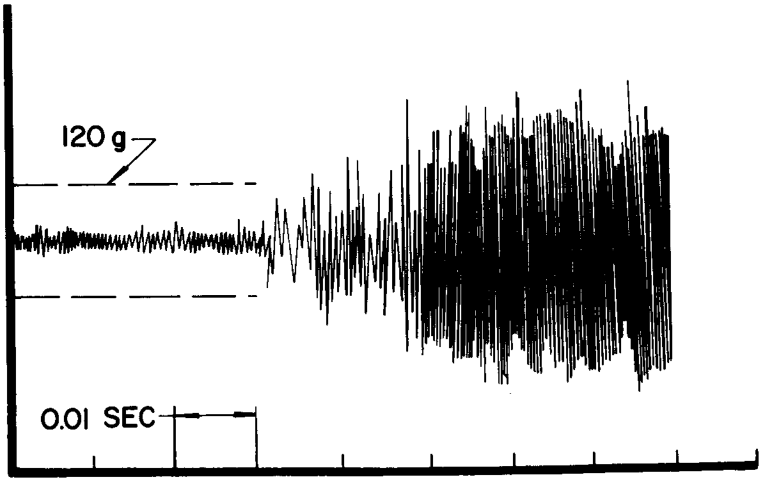

Figure 8

[redacted]