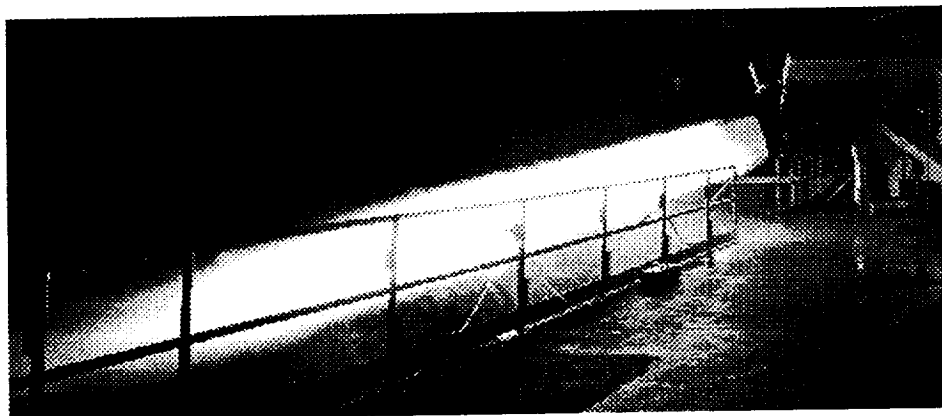


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Development Status of the NASA MC-1 (Fastrac) Engine



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Abstract

The MC-1 (formerly known as the Fastrac 60K) Engine is being developed for the X-34 technology demonstrator vehicle. It is a pump-fed liquid rocket engine with fixed thrust operating at one rated power level of 60,000 lbf vacuum thrust using a 15:1 area ratio nozzle (slightly higher for the 30:1 flight nozzle). Engine system development testing of the MC-1 has been ongoing since 24 Oct 1998. To date, 48 tests have been conducted on three engines using three separate test stands. This paper will provide some details of the engine, the tests conducted, and the lessons learned to date.

Introduction

The MC-1 Engine is a pump-fed liquid rocket engine with fixed thrust and gimbaling capability. The engine was initially designed for the Low Cost Boost Technology (LCBT) Project and for the X-34 vehicle. The engine burns a mixture of RP-1 hydrocarbon fuel and liquid oxygen (LOX) propellants in a gas generator (GG) power cycle. Propellants are tapped from the engine propellant lines, and are burned as a fuel-rich mixture in a GG to power a turbine which rotates an in-line turbopump assembly. Both propellants pumps use a single-stage centrifugal impeller and the turbine is single-stage also. The fuel pump and main fuel injector use a dual-entry configuration to reduce flow velocity entering the component. Turbine exhaust gas is routed overboard via a turbine exhaust duct routed along side the engine nozzle. The chamber/nozzle is built as one piece with ablative liner and composite overwrap. The main injector uses 2-on-2 LOL impinging elements with fuel film cooling orifices drilled at the injector faceplate periphery. With the exception of the ablative thrust chamber, all components on the engine are reusable.

The engine uses a combination of electro-pneumatic and solenoid valves to control engine operation. The valves are designed to be either fully opened or fully closed. Helium is the working fluid in the pneumatic system. The two main propellant valves, the Main

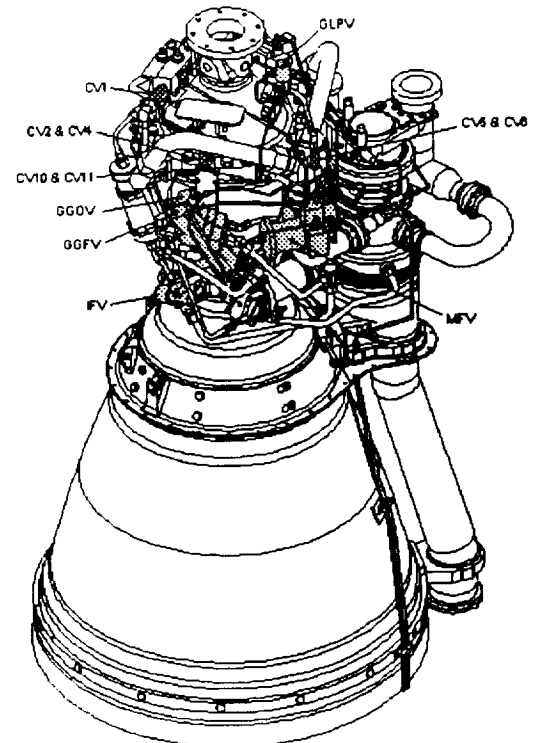
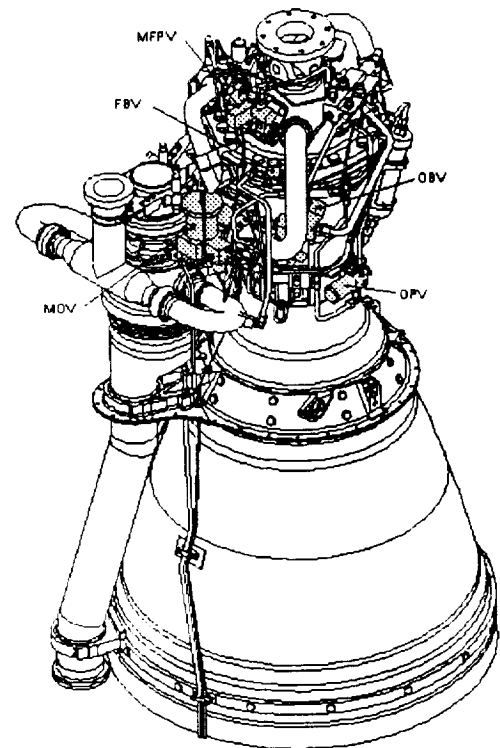


Figure 1: MC-1 Oblique Side Views

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Oxidizer Valve (MOV) and the Main Fuel Valve (MFV), are controlled by separate solenoid pilot valves. Four remaining electro-pneumatic valves, the Gas Generator Oxidizer Valve (GGOV), Gas Generator Fuel Valve (GGFV), Main Fuel Purge Valve (MFPV), and Oxidizer Bleed Valve (OBV) have built-in solenoid pilot valves. The remaining valves, the Ignitor Fuel Valve (IFV), Fuel Bleed Valve (FBV), Oxidizer Purge Valve (OPV), and Gas generator LOX Purge Valve (GLPV) are direct-acting solenoid valves. Seven check valves are also used to isolate the pneumatic system from the propellant systems. Figure 1 provides oblique views of the engine with the locations of most of the major components. Figure 2 shows a simplified schematic of the engine with the pneumatic, purge, and most vent/drain lines omitted.

The engine operates at one rated power level, nominally 60,000 lbf at vacuum conditions for the 15:1 area ratio nozzle configuration, and slightly higher for the 30:1 nozzle. Thrust and mixture ratio are open loop controlled by setting fixed orifices in the engine propellant lines during engine calibration testing. Therefore, variations in engine propellant inlet conditions cause engine performance variations. Electrical commands for engine start and shutdown are issued by an electronic controller external to the engine.

The MC-1 uses two ignition systems for engine start, one for the main chamber and one for the GG. Following spin-up of the turbopump from the vehicle/facility helium spin-start system, main chamber ignition is accomplished by injecting TEA/TEB hypergol from a piston-actuated reloadable cartridge. The IFV controls the timing for actuating the piston under fuel pressure. Ignition in the GG is performed by dual-mounted pyrotechnic squibs.

The engine is configurable for vertical operation, typical of booster application, or for horizontal application as used on the air-launched X-34 vehicle. The engine actuator attach ring includes mounting locations for thrust vector control actuators as required for the X-34 vehicle and Propulsion Test Article 1 (PTA1) test facility. The requirement for altitude start of the engine has made it necessary to simulate temperature conditions at launch altitude (approx. 38,000 ft.) in a "cold box" in order to cold soak the engine before ignition. This testing under a simulated launch environment has been very useful in identifying problem areas in the engine that have been corrected. Further development testing under simulated launch environments is planned.

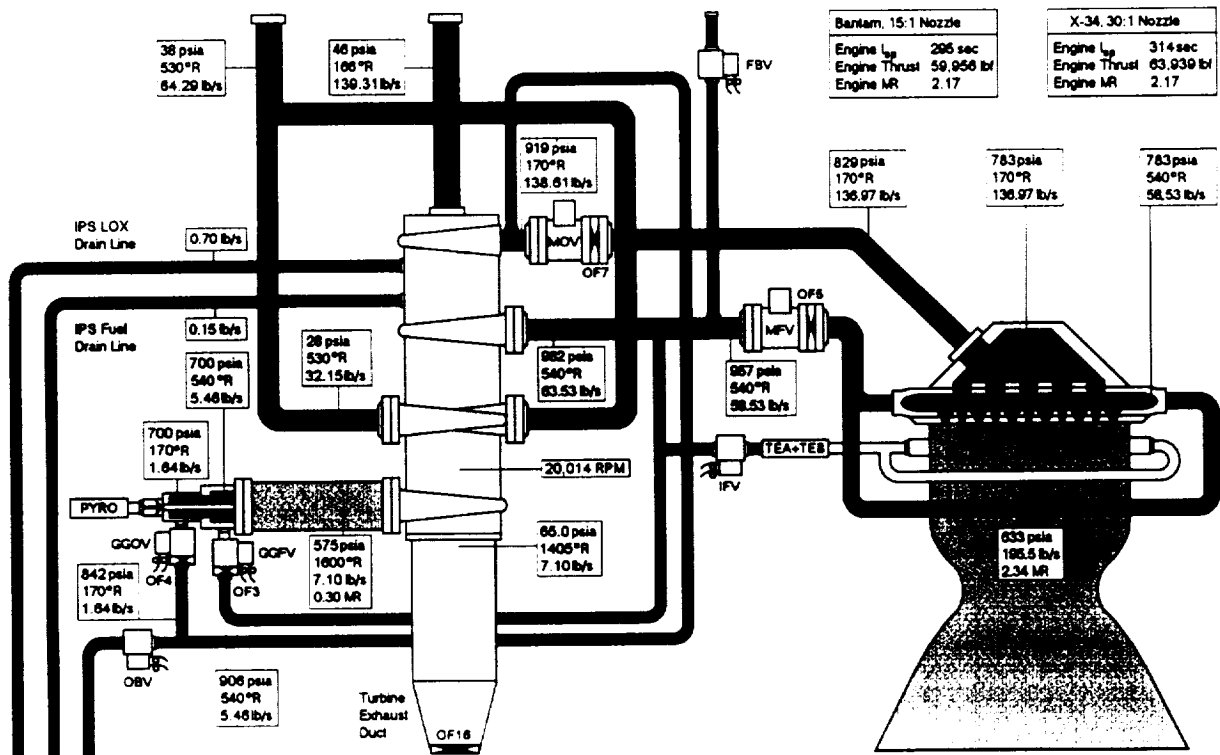


Figure 2: MC-1 Engine Schematic (simplified)

Development Test Summary

Engine system development testing of the MC-1 has been ongoing since 24 Oct 1998. To date, 48 tests have been conducted on three engines using three separate test stands: the Horizontal Test Facility (HTF) and the Propulsion Test Article-1 (PTA1) on the B2 test complex at Stennis Space Center (SSC), and the Alfa-1 test stand at the Rocketdyne Santa Susannah Field Laboratory (SSFL). Of these tests, 33 were hot-fires with programmed durations ranging from 2.5 to 159 seconds, achieving a 58% rate of successfully operating for the full duration. Of the 14 premature cut-offs (PCO's), 10 were initiated by the engine with the remaining 4 caused by the test facility. Table 1 gives specific details of the engine tests conducted to date.

Test H - HTF P - PTA1 R - Alfa1	Date	Time (P/A) (secs)	Notes	Engine	Cold Flow	Hot Fire
H0 Series - Engine/MPS Integrated Cold Flow Activation						
H0-0	24 Oct 98	-- / --	Dry countdown demo	1*		
H0-3	28 Oct 98	-- / --	Wet countdown demo	1*	X	
H0-4	09 Nov 98	2.0 / 2.0	GHe Spin Start Test	1*	X	
H0-4R3	09 Dec 98	2.0 / 2.0	GHe Spin Start Test (repeat)	1*	X	
H1 Series - Start Sequence Definition & Transition to Mainstage						
H1-1	11 Dec 98	2.5 / 2.52	Main Chamber Ignition Test (LOX only); OBV slow response	1*		X
H1-2	07 Jan 99	3.0 / 2.48	Main Chamber Ignition Test (LOX/RP-1); PCO (ambient powerhead temp by TEA/TEB leak); slow OBV	1*		X
H1-3	15 Jan 99	3.0 / 3.00	Main Chamber Ignition & GG Fuel Prime Test; slow OBV	1*		X
H1-3S	22 Jan 99	-- / --	Special OBV/GGOV Cold-Flow Test; slow OBV investigation; data problems require repeat test	1*	X	
H1-3SR	27 Jan 99	-- / --	Special OBV/GGOV Cold-Flow Retest; slow OBV investigation	1*	X	
H1-5	02 Feb 99	5.0 / 3.07	Engine MINJ/GG Ignition & Mainstage Test; PCO (GG Pc ignition detect limit); slow OBV	1*		X
H1-5a	06 Feb 99	5.0 / 3.44	Engine MINJ/GG Ignition & Mainstage Retest; abort (LOX I/F temp); PCO (GG Pc ignition detect); TEA/TEB leak; slow OBV	1*		X
H1-2a	19 Feb 99	3.0 / 2.76	Engine MINJ Ignition Retest; PCO (Fuel I/F pr lower limit); slow OBV; TEA/TEB leak	1*		X
H1-4	24 Feb 99	3.0 / 3.00	MINJ/GG Ignition Test; GOX leak past CV10; slow OBV; TEA/TEB leak	1*		X
H1-5b	02 Mar 99	5.0 / 5.00	Engine MINJ/GG Ignition & Mainstage Retest 2; MFV closure failure; slow OBV; TEA/TEB leak	1*		X
H1-6	11 Mar 99	20.0 / 20.00	Mainstage Dwell Test; MFV ball seal displacement	1*		X
H1-7	15 Mar 99	-- / --	MOV Cold-Flow Test (Rapid Engine Chill)	1*	X	
H2a Series - Propellant Inlet Effects Gains Initial Baseline						
H2a-1	24 Apr 99	12.0 / 12.01	Mainstage Dwell Test	2*		X
H2a-2	30 Apr 99	24.0 / 3.36	Low Pressure Start & Mainstage Test; PCO (GG Pc ignition detect)	2*		X
H2a-2a	06 May 99	24.0 / 1.56	Low Pressure Start & Mainstage Test R1; PCO (SV9 GHe Spin Start Valve deactivated)	2*		X
H2a-2b	08 May 99	24.0 / 24.01	Low Pressure Start & Mainstage Test R2	2*		X
H2b Series - Engine Orifice Gains Validation						
H2b-1	11 May 99	24.0 / 24.01	GGOV Orifice Gains Test #1	2*		X
H2b-2	14 May 99	159.0 / 159.03	GGFV Orifice Gains Test #1	2*		X
H3 Series - Engine Calibration & Helium Consumption						
H3-1	16 Aug 99	24.0 / 24.01	LOX Pump Inlet Variation Test	1*		X
H3-1a	21 Aug 99	24.0 / 9.20	LOX Pump Inlet Variation Retest; PCO (network failure)	1*		X
H3-1b	10 Sep 99	24.0 / 24.02	LOX Pump Inlet Variation Retest #2	1*		X
H3-2	14 Sep 99	24.0 / 3.05	Baseline Inlet Conditions Test; PCO (GG Pc ignition detect limit)	1*		X
H3-3	18 Sep 99	24.0 / 3.13	Start Mod #3; PCO (GG Pc ignition detect limit)	1*		X
H3-4	21 Sep 99	159.0 / 3.12	Orifice Adjustment Test; PCO (GG Pc ignition detect limit)	1*		X
H3-5	07 Oct 99	24.0 / 24.01	Start Mod #5 Test	1*		X
H3-6	07 Oct 99	24.0 / 24.01	Start Mod #5 Verification / RP Ramp Test	1*		X

H4 Series - Cold Engine Start Variations						
H4-1	25 Oct 99	12.0 / 12.01	Baseline Ambient Start Test	2*		X
H4-2	28 Oct 99	12.0 / 11.16	Cold Box / LOX & RP Conditioning Test; PCO (IPS Ghe cavity pr upper limit)	2*		X
H4-3	29 Oct 99	12.0 / 12.01	Cold Box / LOX & RP Conditioning Test; TCA ignition event; MINJ damaged	2*		X
H4-3S	30 Oct 99	-- / --	Investigation of H4-3 Anomaly Test; Cold Box thermal soak w/ MFV cycling	2*	X	
H4-4a	11 Nov 99	-- / --	Cold RP/LOX Drop Test; H4-3 investigation	1*	X	
H4-4b	12 Nov 99	12.0 / 4.05	Evaluation Hotfire Test #1 for H4-3 Anomaly; PCO (slow OBV & MOV)	1*		X
H4-5a	13 Nov 99	-- / --	Cold RP Drop / Cold Box Test; H4-3 investigation; PSC failure; test ops at SSC concluded	1*	X	
P0 Series - Engine/MPS Integrated Cold Flow & Tanking						
P0-1/2	23 Jul 99	2.0 / aborted	Engine/MPS Integrated Cold Flow and GHe Spin Test; aborted during A-S start by GHe supply pr LL	3*	X	
P0-1/2a	27 Jul 99	2.0 / 1.10	Engine/MPS Integrated Cold Flow and GHe Spin Retest; PCO (Facility control net failure)	3*	X	
P1 Series - Start Sequence						
P1-1	02 Aug 99	3.0 / 3.00	Main Injector Ignition Test	3*		X
P2 Series - Initial Calibration & Duration						
P2-1	29 Sep 99	8.0 / 8.01	Full Start Sequence / Mainstage Short Dwell Test	3*		X
P2-2	01 Oct 99	159.0 / 126.11	PTAI Full Duration Test; PCO (False cut in RP-1 I/F Pr lower limit)	3*		X
R0 Series - Engine/MPS Integrated Cold Flow Activation						
R0-0	06 Mar 00	-- / --	Dry countdown demo	3*		
R0-1	18 May 00	-- / --	Wet countdown demo	3*	X	
R0-2	13 Jun 00	2.0 / 2.0	GHe Spin Start Test	3*	X	
R1 Series - Engine Start Sequence						
R1-1	22 Jun 00	3.0 / 3.00	Main Injector Ignition Test	3*		X
R1-2	7 Jul 00	5.0 / 3.12	Full Start Sequence Test; PCO (GG ignitor failure)	3*		X
R1-2a	12 Jul 00	5.0 / ---	Full Start Sequence Test Repeat	3*		X

* - with 15:1 nozzle

* - with 30:1 nozzle

Table 1: MC-1 Development Tests

Engine Performance Summary

The MC-1 engine uses fixed diameter orifices to calibrate the engine to thrust level, turbine inlet temperature, and engine mixture ratio. Table 2 provides a summary of key MC-1 Engine performance requirements.

PARAMETER	NOMINAL	RANGE
Main Combustion Chamber Pressure, Pc (psia)	652.0	639.0-665.0
Turbine Inlet Temperature (°R)	1600.0	1560.0-1640.0
Mixture Ratio (O/F)	2.17	2.14 – 2.20
Vacuum Thrust (lbf)	63,939	60,000 – 69,000
Specific Impulse, I _{sp} (sec)	314.0	310.0 (minimum)

Table 2: MC-1 Engine Key Performance Requirements

Table 3 provides a summary of engine test results that have been normalized to the design point propellant inlet conditions. To date, no engine has been calibrated; the engines tested have run excessively fuel rich in both the main combustion chamber and gas generator. Accordingly, turbine inlet temperatures and engine mixture ratio have been below specification. A primary objective of the next series of engine system development tests will be to calibrate the engine. Orifice sizing to fully calibrate the engine has been confounded by propellant flow-rate measurement problems. The flow meters chosen for engine system testing (and X-34 vehicle operation) were of the differential pressure type and were specifically designed to produce low differential pressures. It has been theorized that a LOX pump rotating cavitation phenomena has induced hydraulic transients in the feed system. These

transients propagate into large uncertainties in the differential pressure flow-rate measurement. Future testing will use turbine flow meters, which are less susceptible to hydraulic transients.

Test	Engine	MCC Pc (psia)	Turbine Temp (°R)	Mixture Ratio*
H1-6	1	616	1491	1.83
H2a-1	2	608	1504	1.86
H2a-2b	2	651	1575	1.92
H2b-1	2	661	1590	1.89
H2b-2	2	652	1561	1.86
H3-1	1R1	639	1500	1.93
H3-1a	1R1	658	1628	1.95
H3-1b	1R1	645	1515	1.89
H3-5	1R1	646	1544	2.00
H3-6	1R1	646	1543	2.06
P2-2	3	640	1546	2.01
H4-1	2	634	1545	2.04
H4-2	2	638	1557	1.99
H4-3	2	619	1532	2.01

* - Flowmeter Data Uncertain

Table 3: MC-1 Engine Test Hotfire Summary

Other performance challenges were addressed during engine system testing. Most of the challenges are typical of an engine development program and are listed below.

- Start sequence modifications were required to make the engine start process more robust.
- Additional film cooling of the GG was required after inspections showed discoloration of the GG chamber wall.
- GG igniter modifications were required to prevent extinguishing of the composite solid propellant plug.

System level issues have been discovered that will have impacts on propulsion system/X-34 vehicle integration. Test data indicates the ablative nozzle throat diameter decreases through time (possibly through carbon deposition). This decreasing throat diameter causes the engine system performance to drift and the engine never truly reaches a steady-state performance level. Test data also indicates large heat input into the GG LOX system (possibly from the mass of the valves and brackets). This heat input causes engine system performance to drift as the system seeks thermal stabilization. Resolution of both of these issues will require integrated vehicle systems analysis.

Development Test Lessons Learned

Results of MC-1 development testing will have impacts on propulsion system/X-34 vehicle integration. A primary objective of development testing of any rocket engine is to identify and correct problem areas. The MC-1 has been rigorously tested under a variety of configurations and environments, including horizontal and vertical orientation, simulated thermal conditions at launch (i.e., Cold Box), and conditioned propellants. This test regimen has been successful in illuminating and correcting several engine issues, some of which are described below:

MFV Cycling Anomaly - During Firing Readiness Test (FRT) operations prior to test H0-4R, it was noted that the MFV cycled open without being commanded by the Propulsion System Controller (PSC). Testing was discontinued until it could be determined 1) if the MFV had actually cycled; 2) how it had cycled without being commanded; 3) how to prevent this event from reoccurring in the future. This caused significant concern due to the possibility that the root cause might allow other valves (esp. MOV) to cycle without being commanded. It was verified that the MFV did cycle without any command being issued by the controller. It was fortunate that the event occurred during the FRT, when no propellants were in the system. A fault tree was developed and investigated, pointing to the possibility that the MFV pneumatic piston may have been actuated by pressure from the MFPV vent port through the RP-1 drain lines and entering the pneumatic piston through the MFVS vent port. Because the drain lines are not

instrumented, verification of this failure mode was not possible. Part of the investigation involved a series of FRTs to cause the event to occur again, but it did not.

On the possibility of the existence of a "sneak circuit" between the vents of the MFPV and MFVS, the drain lines were separated to eliminate it. Lines 96M31270 and 96M31142 were separated from the 96M31274 MFPV drain line, shown below in Figures 3 and 4. To date, this anomaly has not recurred.

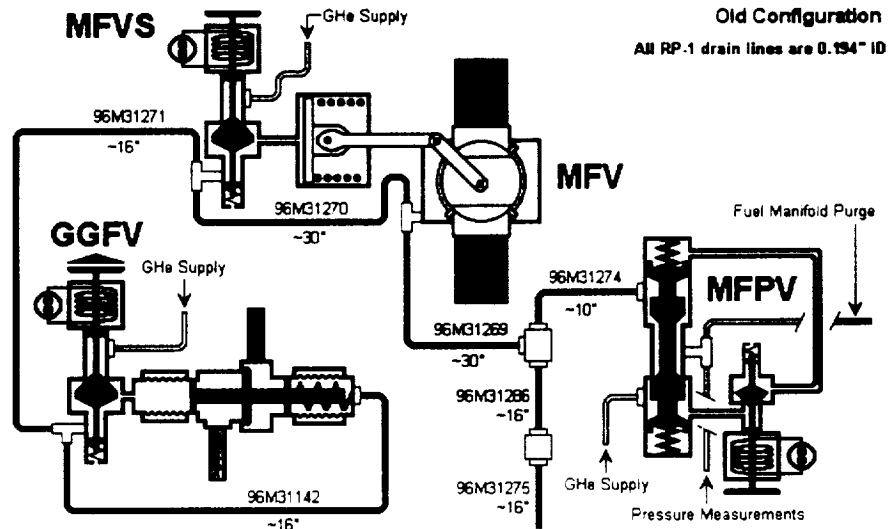


Figure 3: Old Vent Line Configuration

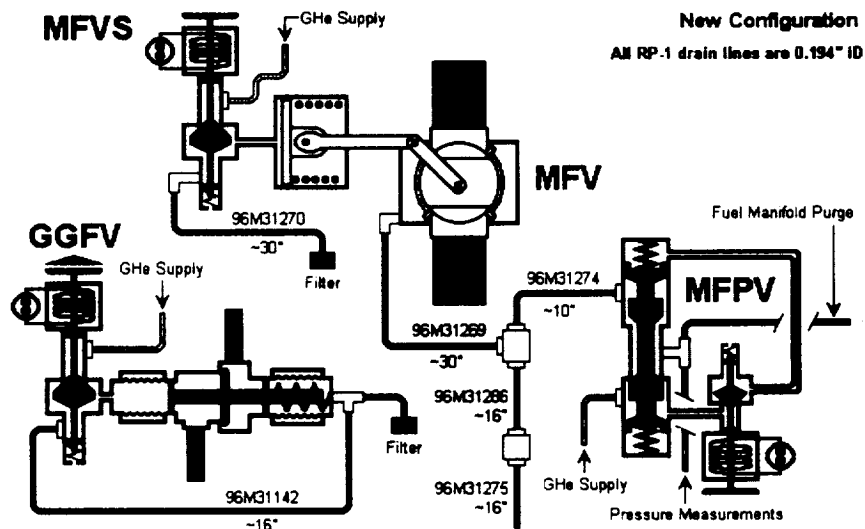


Figure 4: New Vent Line Configuration

Slow OBV Performance - The OBV is open during prestart operations to support engine chill and prevent LOX stagnation in the engine. It is supposed to close during start to prevent oxidizer starvation to the main chamber. Nominally, the OBV completes closure within 0.25 secs after the command is issued. However, it was noted in several tests that although the OBV would usually begin to close almost immediately after the close command was sent, it would take anywhere from several seconds to several minutes to complete closure. A fault tree was developed to investigate this anomaly and eventually a push pin in the pilot valve was removed that was suspected of being affected by cryogenic thermal loading. Removal of this pin resulted in improved valve performance.

MFV Seal Failure - Immediately following shutdown on test H1-5b, some post-burning was noted in the main chamber for several seconds. The RP-1 afterburn stopped when the RP-1 facility preclude closed as part of the normal facility shutdown. Review of the test data showed that during shutdown the MFV left the OPEN switch but did not arrive at the CLOSED switch. This allowed fuel to enter the chamber after shutdown. The MFV was removed and inspected, which revealed the ball seal energizer springs extending into the flowpath (Figure 5), preventing the MFV from closing completely at shutdown. In addition, the ball had been scratched by the springs when it tried to close.

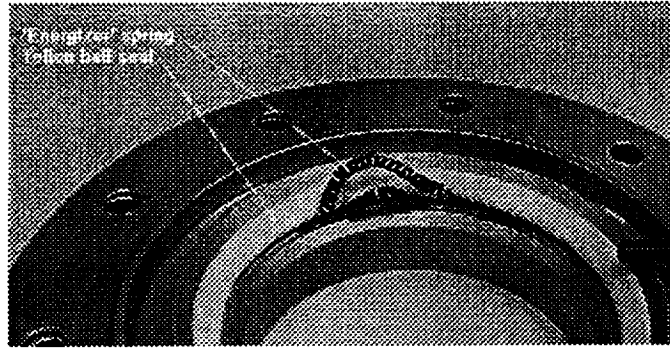


Figure 5: MFV Ball Seal Energizer Spring Extrusion

The MFV was shipped to the vendor for inspection and investigation. A serious concern with respect to this incident was that the MOV used a similar design and ball seal, and if it too failed, would cause a much more catastrophic event. Review of the seal design and water-flow tests revealed that the seal material was too flexible at ambient temperatures to maintain effective capture of the energizer springs. The heritage of the valve was adapted from an MOV design used on the RL10 engine and had been qualified for use under cryogenic temperatures when the material used in the seal is significantly stiffer. Because the GHe spin start pressure had been increased during the course of development testing to ensure adequate startup power to the turbopump, the pressure produced by the fuel pump at start had also increased, causing a high Δp across the valve when it initially opened. The reduced stiffness of the seal material degraded the ability of the seal to retain the energizer springs, which were extruded under the high Δp loading at start. As a corrective action, the ball seal design was modified to use a different material which had better stiffness at ambient temperatures.

GGFV Seal Failure - HTF test H3-1a was terminated prematurely by a facility network failure. However, the GGFV did not close completely at engine shutdown, as evidenced by a post-shutdown fire which video shows to have been caused by flaming RP-1 exiting the turbine exhaust duct. The test data shows that during shutdown: 1) The GGFV leaves the open switch immediately following receipt of the CLOSE command but never arrives at the CLOSED switch; 2) the GGFV discharge pressure does not decay immediately to ambient, which it normally does, but remains at ~23 psia until after E/S+21 and shows some behavior similar to that indicated in the fuel pump discharge pressure as a result of the waterhammer response from the MFV closure; 3) the turbine inlet temperature is significantly cooler than that shown in the previous test, possibly the result of a fuel-richer mixture ratio during shutdown.



Figure 6: GGFV Poppet Seal Spring Extrusion

Post-test inspection of the GGFV showed that poppet seal failure prevented the valve from closing (Figure 6). Because the GGFV is identical to the GGOV and OBV, there was concern over the possibility that the GGOV might fail to close at shutdown under similar circumstances. While a GGFV closure failure is relatively benign, a GGOV

failure would be potentially catastrophic. An investigative team went from MSFC to the valve vendor to determine the cause of the seal failure and develop the remedial action. Water flow tests showed the seal design failed consistently at Δp 's of 100-200 psid under ambient conditions.

The primary cause of the GGFV seal failure was that the seal dimensional tolerances on the inner diameter did not adequately capture seal between the outlet plunger and inlet poppet. This allowed the seal lip on the inner diameter to jump over the retainer of the inlet poppet under high Δp conditions at either start or shutdown. A contributing cause was the inadequate material properties of the seal under ambient conditions did not provide sufficient stiffness to prevent deformation under Δp loading at either start or shutdown. Corrective action to this anomaly was to redesign the seal to tighten dimensions and eliminate energizer spring. The redesign included reduction of the inner diameter and increase in the outer diameter. Elimination of the energizer spring and spring cavity resulted in a solid seal. The solid seal design should provide improved capture between the plunger and poppet, and increased seal stiffness. Water flow testing of the new seal showed significant improvement in Δp range.

Start Sequence Modifications - One of the most critical phases of engine operation is start. During this time, valve sequencing is required to initiate the flow of propellants to the main chamber and GG, terminate oxidizer bleed flow, activate the helium spin start system, and operate the engine purges. The timing of these operations during engine start is crucial to ensure a safe engine start. The use of transient models is initially used to establish a preliminary start sequence, but actual engine hotfire testing is needed to anchor the models and fine-tune the start sequence. Redlines are established in several engine parameters to protect the engine during the start phase. A number of premature cut-offs experienced during engine testing occurred during the start phase and required some adjustments to valve sequence timing, helium spin start pressure, engine redlines, and the GG ignitor to increase the reliability and repeatability of the engine start operation. As a result, start performance has improved as the development test phase has progressed.

H4-3 Pop Anomaly - During hotfire testing to simulate the thermal environment at X-34 vehicle launch (i.e., "Cold Box"), the main chamber and injector of an MC-1 engine was damaged (Figure 7). This was revealed during post-test hardware inspections and engine data review, although the engine itself had operated for the full planned duration. A subsequent investigation suggested that the most probable cause of the event was the presence of residual fuel in the main chamber during engine start (Figure 8), which collected in the acoustic cavity following the previous test and detonated when LOX was introduced into the main chamber during the start sequence. It was also determined that this was not a flight issue, as the nozzle will be replaced after each flight, eliminating the risk associated with residual RP-1 accumulation in the acoustic cavity. Recurrence control included the establishment of requirements to inspect and remove residual fuel from the main chamber prior to hotfire testing.

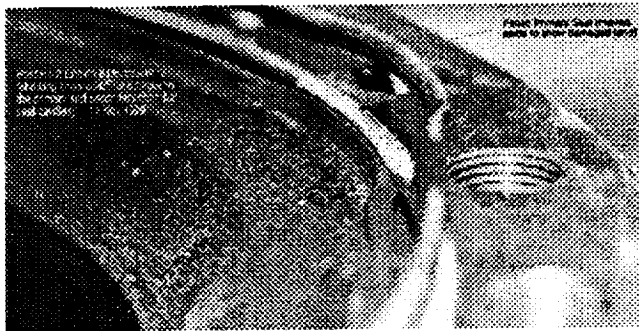


Figure 7: Damage to Chamber/MINJ Interface

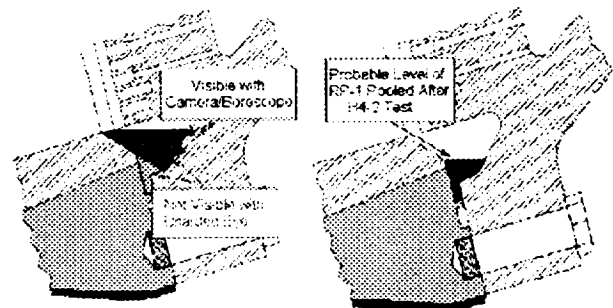


Figure 8: RP-1 Pooling in Acoustic Cavity

Summary

After a brief interruption in testing following the conclusion of testing at the HTF and PTA1 test facilities at SSC, engine test operations have resumed at the Alfa-1 test facility at the SSFL. Development testing is scheduled to be concluded in approximately nine months, followed by the Verification and Certification test phases. The MC-1 engine has shown itself to be a very robust design and no significant problems are anticipated that would prevent its being qualified for flight on the X-34 vehicle.