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**INDEPENDENT REVIEW OF THE FAILURE MODES OF F-1 ENGINE AND
PROPELLANTS SYSTEM**

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Introduction

The F-1 is the powerful engine, that hurdled the Saturn V launch vehicle from the Earth to the moon on July 16,1969. The force that lifted the rocket overcoming the gravitational force during the first stage of the flight was provided by a cluster of five F-1 rocket engines, each of them developing over 1.5 million pounds of thrust (MSFC-MAN-507). The F-1 Rocket engine used RP-1 (Rocket Propellant-1, commercially known as Kerosene), as fuel with lox (liquid Oxygen) as oxidizer. NASA terminated Saturn V activity and has focused on Space Shuttle since 1972. The interest in rocket system has been revived to meet the National Launch System (NLS) program and a directive from the President to return to the Moon and exploration of the space including Mars. The new program Space Launch Initiative (SLI) is directed to drastically reduce the cost of flight for payloads, and adopt a reusable launch vehicle (RLV). To achieve this goal it is essential to have the ability of lifting huge payloads into low earth orbit. Probably requiring powerful boosters as strap-ons to a core vehicle, as was done for the Saturn launch vehicle. The logic in favor of adopting Saturn system, a proven technology, to meet the SLI challenge is very strong. The F-1 engine was the largest and most powerful liquid rocket engine ever built, and had exceptional performance. This study reviews the failure modes of the F-1 engine and propellant system.

F-1 Rocket Engine Features

The Engine features include a bell-shaped thrust chamber with a 10:1 expansion ratio, with a detachable, conical nozzle extension, which increases the thrust chamber expansion ratio to 16:1. The thrust chamber is cooled regeneratively by fuel. Gas generator exhaust gases cool the nozzle extension. Liquid oxygen and RP-1 fuel are supplied to the thrust chamber by a single turbo pump powered by a gas generator. RP-1 fuel is also used as the turbo pump lubricant and as the working fluid for the engine fluid power system. There are provisions for supply and return of RP-1 fuel as the working fluid for a thrust vector control system. The engine contains a heat exchanger system to condition engine supplied liquid oxygen and externally supplied helium for stage propellant tank pressurization. An instrumentation system monitors engine performance and operation. External thermal insulation provides an allowable engine environment during operation (MSFC - MAN-507).

Functional Breakdown Of F-1 Engine (Saturn V- Ic Stage)

Function of F-1 Engine: The main function of the F-1 engine has been to provide initial thrust to lift the vehicle from the earth. This is the maximum thrust required for the rocket to overcome the gravitational pull of the earth. The S-IC stage provided the first boost of the Saturn V launch vehicle to an altitude of about 200,000 feet and provided acceleration to increase the vehicle inertial velocity to 9,029 feet per second. Engines similar to the F-1 will most likely be deployed at the first stage of launch vehicle in future. This study was focused to consider the F-1 engine as it was used at the first stage of Saturn-V vehicle.

Functional Breakdown: Eight functional subsystems of the F-1 engine identified were: fuel feed, oxidizer feed, igniter fuel, Gas generator, vehicle pressurization, hydraulic control, electrical, and

flight instrumentation (Rocketdyne, RAR 3181-1503). The Saturn V, S-IC stage propulsion had four outboard systems and one inboard system. Outboard and inboard systems were identical, except Gimbal device provisions, which were required on outboard subsystem only.

Figure1. Shows the subsystems with Saturn code numbers (RAR 3181-1503).

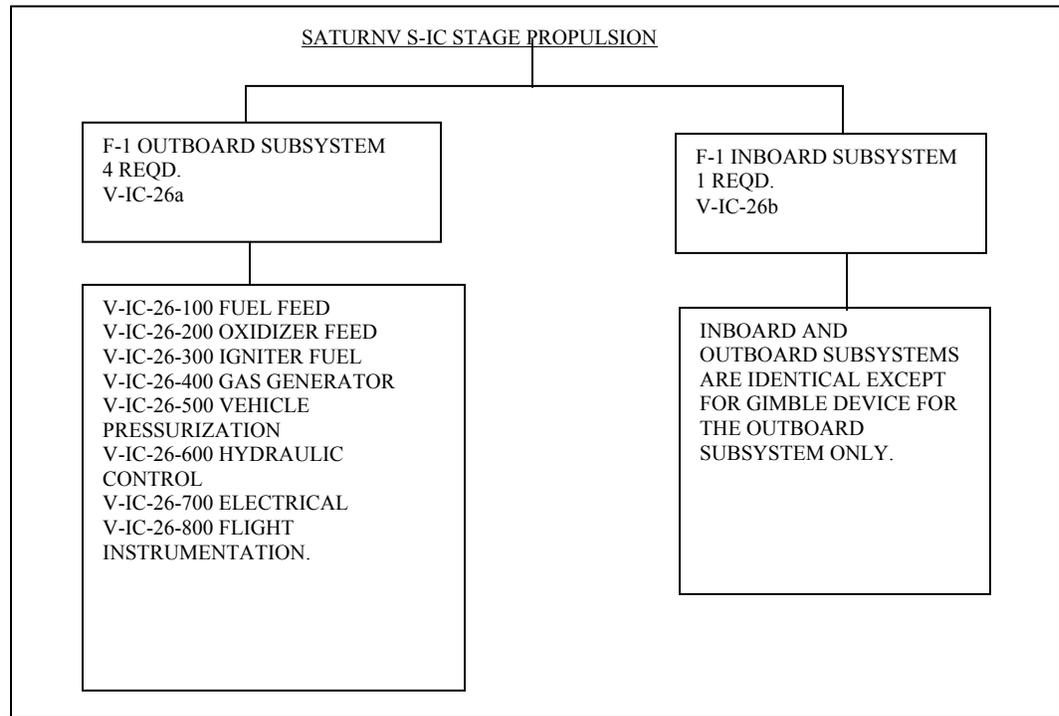


Figure 1. Functional Breakdown of the F-1 Subsystem

Failure Modes Of The F-1 Engine

These data have been adopted from the Rocketdyne report, RAR 3182-1503, for Saturn V, S-IC stage consisting of F-1. The detailed report has been provided to the Transportation Directorate as attachment No.3. Because of the restricted size, only the significant information has been included in this report.

Failure Modes of Fuel feed subsystem (V-IC-26-100): Twenty-five components of the fuel feed subsystem have been identified for failure modes analysis.

Ducting and Connections (26-101) and Tubing and Fittings (26-102): Failure during operation is leakage. The effects of failure are delay in launch. The critical effect is Fire hazard in propulsion section. The severity is dependent on the amount, location, and altitude. Main Fuel Valve (26-107) failure due to poppet seal leakage will displace inert pre-fill fluid by RP-1 and cause thrust chamber rough combustion. This may result in some engine damage and launch delay. Thrust Chamber (26-109a) failure will cause combustion instability and leakage of igniter fuel manifold or tubes between manifolds and injector orifices. This failure will cause severe engine damage

and propulsion loss. Thrust Chamber Drain Plug Leakage will also cause fire hazard and engine damage. Thrust Chamber external tube leakage can result in combustion instability and fire hazard. Thrust Chamber internal tube leakage above or below throat can result in loss of inert pre-fill and combustion instability leading to engine damage. Inert Fill Check Valve (26-110) may fail to open or close and will be detected and corrected. Redundancy will also be provided. This failure will cause launch delay.

Oxidizer Feed (V-IC-26-200): The Oxidizer feed subsystem has eight components.

Ducting, and Connections, (26-201): Minor leakage during operation will cause launch delay for correction. Possible loss due to freezing of hydraulic lines or operating valves may preclude start of the engine. The effects are Launch delay and/or launch abort. Main Oxidizer Valve Purge Check Valve (26-207): The failure may be either failure to open or to close the valve. Failure to open will cause delay for correction and failure to close will allow extra lox to flow to thrust Chamber and may result in engine damage by burning the turbine blades.

Igniter Fuel (V-IC-26-300): The subsystem consists of five components. Tubing and Fittings for Igniter Fuel (26-301): Failure may be leakage, causing launching delay or fire hazard. Hypergolic Cartridge (26-302b): may fail to rupture or lack of hypergolic flow to the Thrust Chamber. This will cause failure to start S-IC stage propulsion and Launch. Abort.

Gas Generator (V-IC-26-400): The subsystem consists of twelve components. Tubing and Fittings (bootstrap assemblies and coolant fittings – 26-401): Lox and Fuel leakage may cause Launch delay or abort. Leakage may also cause fire hazard in S-IC stage propulsion section. The G.G Control Valve leakage below ball seal may hard start and cause damage to G.G. assembly. Hot Gas Duct and Turbine Exhaust Manifold (26- 408): Hot gas leakage during operation will cause fire hazard in lower altitude and engine performance degradation.

Vehicle Pressurization (V-IC-26-500): There are four components of this subsystem. Tubing and Fittings (26-501): Oxidizer leakage may freeze the engine hydraulic control system; result in failure of S-IC stage, and cause launch abort. Heat Exchanger Lox (260502b): Leakage of liquid or gaseous oxygen may cause fire hazard in exhaust ducts, possible damage by burning through. Increased temperature and backpressure may affect turbine operation and stage propulsion.

Hydraulic Control (V-IC-26-600): The subsystem has seven components. Tubing & Fittings and Orifices (26-601): Failure during operation by leakage will cause fire hazard in lower altitude and cutoff may abnormally sequenced or not occur at all. Check Valves (26-603b): Failure may prevent flow of ground supplied hydraulic fuel to high pressure fuel duct and may cause lack of sufficient fuel pressure to 4-way valve start sequence. Engine damage may occur due to hard start and cutoff of S-IC stage propulsion subsystem.

Electrical (V-IC-26-700): This subsystem has three components. Start Solenoid (26-701): Fails to operate at prescribed time. Engine will not start. Expiration of the ignition stage limit timer will initiate safe cutoff. Actual loss may be launch abort.

Flight Instrumentation (V-IC-26-800): The subsystem has two components. Primary Flight Instrumentation (26-801): Fuel and hot gas leakage at pressure connections will cause fire hazard

at lower altitude. Lox leakage at pressure connections may cause freezing of hydraulic control lines and preclude engine start.

F-1 Significant Engine Failure Modes Per Expert Inputs

Interviews were arranged from July 1, to 26,2002 to collect data from the memory of work experience of the engineers who were associated with the Saturn projects. A total of twenty-four engineers were contacted and relevant data were obtained from eight engineers who were actively connected with the operation and testing of F-1 engines. These inputs were of qualitative nature and indicated the risk associated with significant failure modes experienced by them. The following functions and/or components were experienced as of significant risk. The outcome of the survey is given in Table 1 below:

Table 1. Risk Ranking from the Experts

Failure Modes	Gross	Pearson	Galuska	Tepool	Goetz	Hyde	Cornelius	Total
Combustion Instability	5	5	5	5	5	5	5	35
Fuel-Mix at injection Face	3	3	3	4	4	1	1	19
Propellant Leakage	2	3	3	2	1	2	2	15
Structural failures	4	2	2	2	2	3	3	18
Ignition at Start	4	2	2	2	4	3	3	20
Nozzle Tubes	3	2	2	2	3	2	2	16

Legend: The scale of risk ranking is from 1 to 5. 5 indicate the highest risk.

From the survey it is evident that the experts evaluated, combustion instability as the worst risk followed by fuel-mix at injector face, and ignition at start. The risks of Propellant leakage, Combustion chamber nozzle tube failure, and Structural failures represented the risk of the next level.

Conclusion

Though individual data sources vary in identifying failure modes, some common modes appear in some form in all data sources. These Failure Modes are: Combustion instability, Fuel-mix at injection face, Nozzle tubes, Propellant leakage, Hydraulic Valves, and Structural failures. The likelihood of leakage is high as there are so many joints in fuel and Oxidizer lines, but severity in

most cases is not likely to be serious. The mitigation steps are simple and enhanced design may be adequate to remove the risks. Hydraulic Valve and Structural failures can be removed by enhancing the design. Nozzle tube problems may be eliminated by replacing the tubes design by channel design as used in the RD180 engine (Russian design). The Channel-nozzle design takes significantly less time and cost to fabricate (D. Smith, NFFP Seminar July 2002). The operation of a rocket engine with channel nozzles is expected to take significantly less maintenance effort, and be trouble-free compared to that with tube-nozzles (Gautney). However, combustion instability appears to be a major problem, as the current knowledge in this phenomenon is still not adequate (K.Gross), and it will require substantial research and experimentation to comprehend the principles that control the phenomenon. The effect of combustion instability is very severe and may cause loss of engine. The problem with fuel-mix also requires research and trial to formulate the principles guiding the operational efficiency. Rocketdyne report No. R-8099 cited Turbo-machinery is a failure area and likely to be vulnerable to failure as the components are subjected to extreme temperature difference between compressor and turbine sides isolated by bearings.

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