N90-18467

"EFFECT OF CORRELATION ON MULTI–ENGINE ROCKET PROPULSION SYSTEMS"*

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ABSTRACT

A matter of great concern in the design and operation of multi–engine rocket propulsion systems is the effect of the premature shutdown of one engine on the vehicle. This probability that a premature shutdown will cause a vehicle loss is termed "correlation".

Based on airbreathing experience as well as rocket engine data the best estimate of this "correlation" is made and then applied to the overall multi–engine reliability problem to demonstrate its potential effect. At this point, follow–on analyses are pointed out that illustrate how any potential failures that may cause a "correlatable" event can be eliminated; thus bringing this correlation to almost 0.

INTRODUCTION AND BACKGROUND

Rocket propulsion reliability and safety is a matter of great concern since the Shuttle and Titan incidents. The achievement of future space goals hinges on the ability to reliably launch payloads to low earth orbit to support the Space Station, Space Defense Initiative and communications needs. While the Shuttle and Titan solid propulsion were responsible for these incidents we will concern ourselves with liquid rocket propulsion in this paper. Current liquid rocket propulsion systems possess an average .96 mission reliability (or 4/100 failure rate). In addition, when one of the engines in a system fails, it may affect the operation of the entire vehicle. The probability of a premature shutdown causing a vehicle loss is often referred to as correlation.

TURBOJET ENGINE HISTORY

Looking first at the history of engine–caused mishaps across both single, dual, and multi–engine aircraft tells us immediately that multiple engines reduce engine caused vehicle losses (Figure 1). This is due to the ability of an aircraft to operate for some time with one engine out. Indeed, even with single engine fighters after losing power a pilot very often can land safely. In fact, in the commercial arena it is an FAA requirement that an aircraft be able to sustain flight with one engine out – even on takeoff.

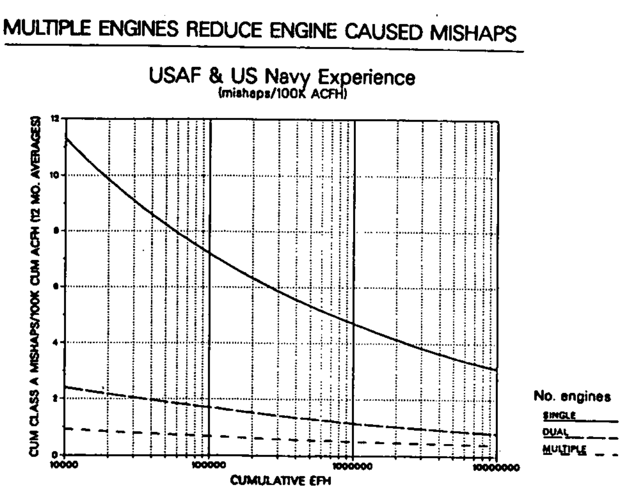

Figure 1
Class A Mishaps Reduced With Multiple Engines

In order to calculate a reasonable facsimile of "correlation" for this data we need to combine the mishap rate data (Figure 1) with the engine–out rate. In military applications the engine out rate used was the engine–caused flight abort rate. This abort rate combined with the mishap rate as follows:

*This work was performed under NAS8–36868 with NASA–MSFC approval.

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ESTIMATED AS $\frac{\text{MISHAP RATE / 100K AFH}}{\text{ABORT RATE / 100K AFH}}$ FROM AVAILABLE USAF/USNAVY DATA SYSTEMS

The estimated correlation so calculated is summarized below on Table I, and we see that across all of these dual and multi–engine applications the "correlation" is <1%.

Table I

CORRELATION IS < 1% FOR
USAF AND US NAVY EXPERIENCE

A/C–ENGINE	CORRELATION
F/15/F100	.9%
F11F/TF30	.4%
F14/TF30	.4%
F111B/TF30	.4%
A–4/A–6/EA6B–J52	.06%
F–4/J79	.08%
T38/J85	.03%
A–10/TF34	.07%
B52/J57	.8%
C–135/TF33	.3%
KC–135/J57	.9%

ROCKET HISTORY

Now let's turn to rocket propulsion systems. Again, we need to know the single engine reliability. This reliability for the SSME, F1, J2, TITAN, and RL10 is illustrated in Figure 2.

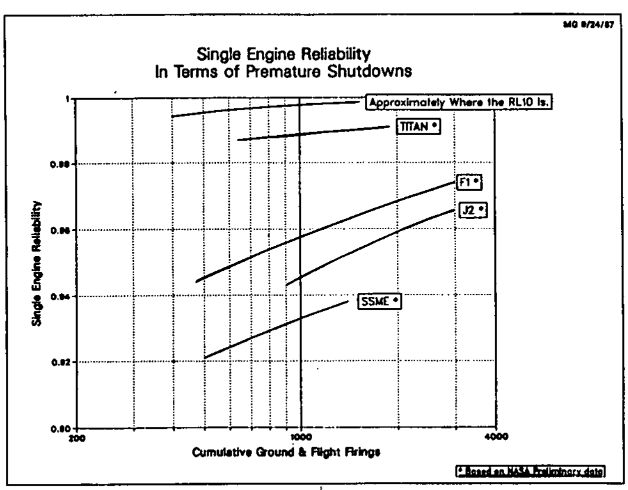


Figure 2
Simple Engine cycle Provides Improved Engine Reliability

Several interesting observations can be made from this plot. The single engine reliability seems to be correlated with type of rocket engine cycle:

Cycle	*Characteristics*	*Reliability*
Expander (RL10)	Low operating pressures & temperatures	.998+
Gas generator (F1, J2, LR87/91)	Moderate operating pressures & temperatures	.94 – .99
Staged Combustion (SSME)	High operating pressures & temperatures	.93

While this is by no means a perfect relationship; since there are other factors involved such as design philosophy, development test philosophy, and quality initiatives, it does indicate an overall trend of higher complexity – lower reliability that intuitively makes sense.

Let's go on to look at rocket propulsion history in terms of engine caused failures and engine caused catastrophic/vehicle losses. Table II represents a summary of all data available to the authors in terms of systems, failures, and catastrophic failures. The background data was provided by NASA MSFC. The correlation column is simply a ratio of the number of engine–caused catastrophic failures to the number of total engine failures. Since rocket engine reliability data (Figure 2) indicates that all rocket engines are not created equal; the one way that might be used to combine the data is to average across all systems to indicate an approximate .07 correlation. Even this average correlation is misleading; however, since it is driven entirely by two systems (Thor/MB3 and Atlas MA3 & MA5) and, in fact, is driven by very early design problems in both of these engines. Because of this lack of overall data on failures/vehicle losses the SSME ground and flight data from 1982 through 1987 was also analyzed. Based on 51 total shutdown events, three of these were of such a nature as to be deemed catastrophic. This then gives a .06 correlation factor (3/15).

Table II

ROCKET ENGINE FLIGHT HISTORY

VEHICLE/ENGINE	NO. ENGINES IN SYSTEM	NO. FAILURES	NO. CATASTROPHIC FAILURES	CORRELATION
THOR/MB3	1	3	1	.333
DELTA/RS-27	1	0	0	0
ATLAS/MA3&MA5	3	14	5	.375
CENTAUR/RL10	2	0	0	0
SATURN/S1-H1	8	1	0	0
SATURN/S1C-F-1	5	0	0	0
SATURN/S2-J2	5	1	0	0
SATURN/S4-J2	1	1	0	0
SATURN/S4-RL10	6	0	0	0
SSME	3	1	0	0

ALL ENGINES ARE NOT CREATED EQUAL, SO AVERAGING ACROSS ENGINES / APPLICATIONS THE CORRELATION ≈ .07

In summary, while the correlation historically is somewhere around 6–7% the number of events that this is based on is so small as to make it reasonable to assume that the correlation is most probably bounded from 0 to 10%, but certainly less than 10%.

This correlation must be taken into consideration in the calculation of propulsion system reliability. Since each engine ignition can be considered as a pass–fail or yes–no event (a Bernoulli trial in statistical terms) the reliability of a propulsion system considering correlation can be calculated as:

$$R_{system} = \sum_{i=k}^{n} \binom{N}{i} p^{i} (1-p)^{N-i} (1-c)^{N-i}$$

R_{system} = System Reliability p = Single engine reliability
N = # of engines in system c = Correlation
K = N–engine out capability

Using this formula, and varying the number of engines in the propulsion system, Figure 3 illustrates the impact of 1 engine out capability on propulsion system reliability. Figure 4 illustrates the effect of correlation on propulsion system reliability for varying single engine reliability using a 4 liquid system with 1 engine out capability.

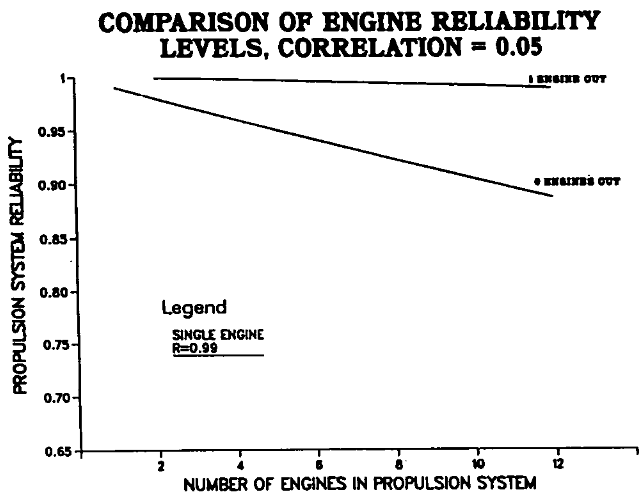


Figure 3
Engine Out Capability provides Improved Reliability

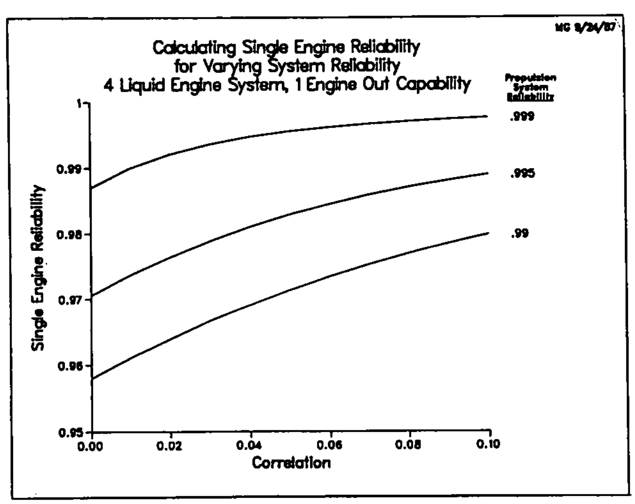


Figure 4
Reduced Correlation Requires Lower Engine Reliability For Same System Reliability

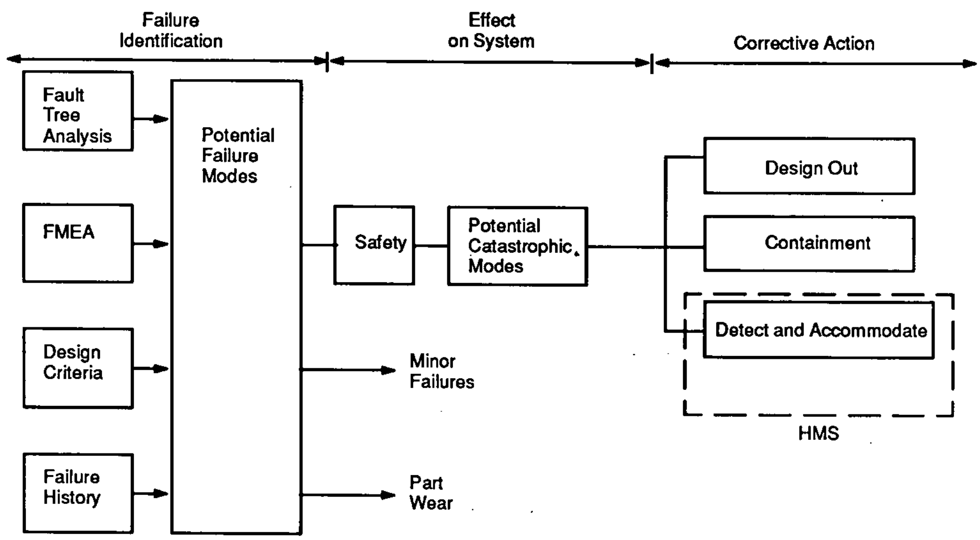
The importance of correlation and of recognizing those failure modes that may be catastrophic is readily seen in Figure 4. for example, by specifying the propulsion system reliability at .995, the single engine reliability that must be demonstrated could vary from .97 to .99. What is the importance of this single engine reliability? Well, if a design/development process is initiated to bring the correlation to near zero, the number of system tests to demonstrate .995 system reliability is markedly reduced:

Correlation	*Reliability Demonstrated at 90% confidence*	*# Tests w/o failure required*
.0	.97	76
.04	.98	114
.10	.99	230

ROCKET ENGINE HEALTH MONITORING SYSTEM (HMS) FOR MINIMIZING CORRELATION

The approach taken for identifying the requirements for a HMS is shown below:

Health Management
Systematic Approach to HMS Requirements



The approach consists of: 1) failure identification, 2) effect on system (without corrective action) and 3) corrective action (and the effect with corrective action).

Failure identification consists of a Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), review of design criteria and failure histories of the components and parts. The FTA is a "tops down" analysis that identifies hazards and reviews failure modes in the engine system that could cause the hazard. The FMEA is a "bottoms up" approach that identifies component and subcomponent failures and the propagation of the failure through the system into a hazardous condition. The design criteria on limits and failure history on life and part failures reviewed to identify additional failure modes. The potential failure modes are then summarized.

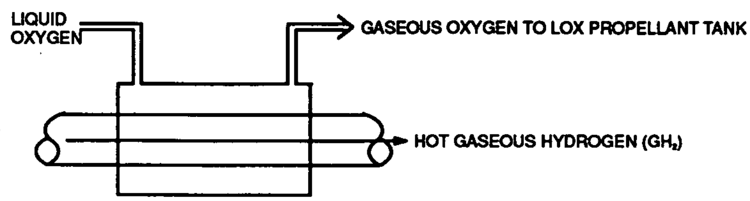
The failures modes are then categorized into three areas: 1) safety (potential catastrophic failures), 2) minor failures (degradation in performance) and 3) part wear (project next maintenance). The minor failures and part wear categories will not be discussed in this paper.

The three approaches for corrective action are: 1) to design out the hazard so as to prevent the failure mode from occurring, 2) contain the failure so that it does not get outside of the engine component or outside the rocket engine and cause catastrophic damage to another part of the vehicle, and 3) detect the impending catastrophic hazard and take corrective action.

1. Example of designing out the failure mode.

Liquid rocket engines incorporate a heat exchanger for providing gaseous oxygen pressurization to the liquid oxygen (LOX) propellant tank. A simplified sketch of the system is shown below:

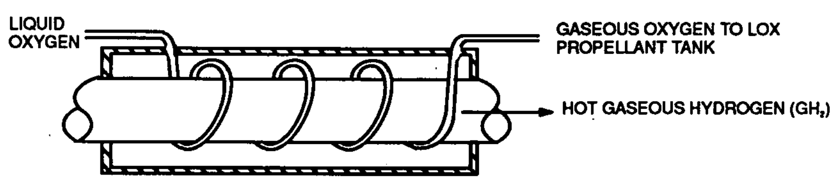
HEAT EXCHANGER
With Potential Hazard



A single failure (crack in the GH2 line) will allow hot GH2 to mix with the oxygen and cause a potential catastrophic failure.

A modification to the heat exchanger design as shown below prevents the catastrophic event:

HEAT EXCHANGER
Redesigned



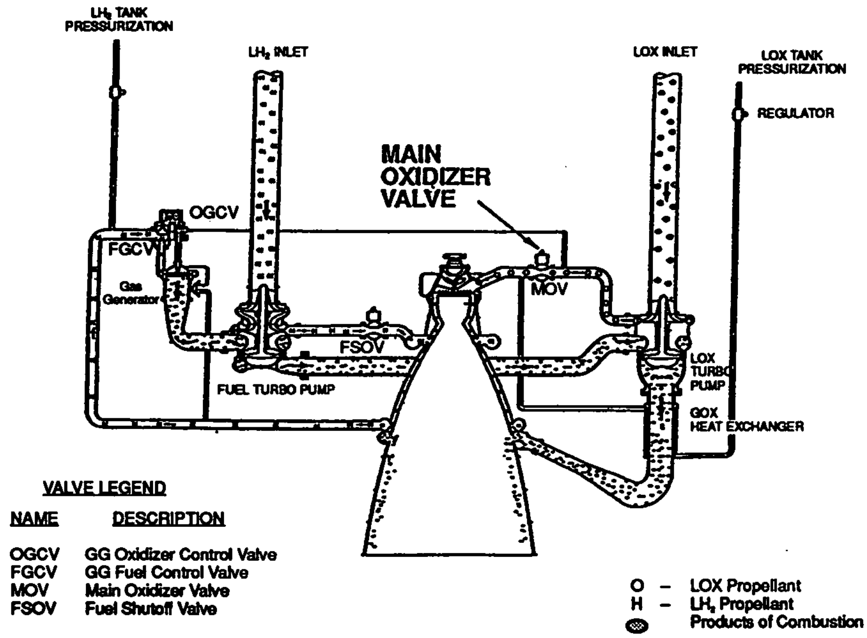
The above design change allows the single failure of the cracked GH2 line without causing a catastrophic failure.

2. Example of containing the failure.

Liquid rocket engines utilize high pressure turbopumps for providing high pressure propellants to the combustion chamber. The high pressure turbopumps contain a turbine, consisting of Disks and Blades. In the event that a blade fails, the blade may penetrate the turbopump housing causing a catastrophic failure. In this failure scenario the energy contained in the blade (stress) is calculated and the turbopump housing thickness (strength) is increased to where the appropriate safety margins ensure that a failed blade is contained by the housing.

3. Example of detecting and taking corrective action.

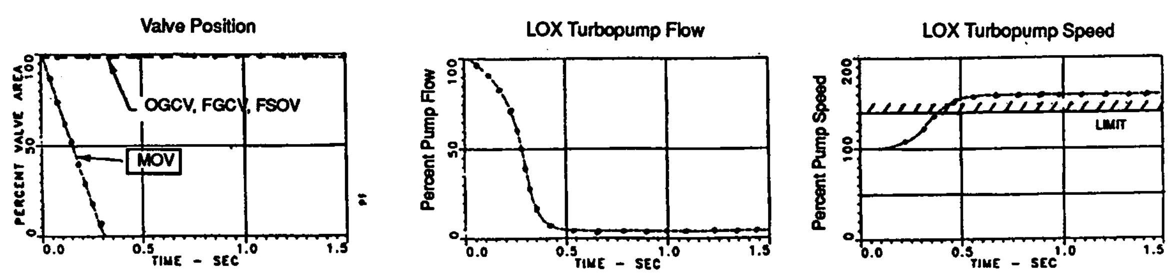
Liquid rocket engines utilize propellant valves to control the engine cycle. A simplified gas generator schematic is shown below, and the main oxidizer valve (MOV) is highlighted. Assume the gas generator to be operating at mainstage (high power) and the MOV fails closed:



The valve failure creates a flow blockage that dead-heads the oxidizer pump and forces additional oxidizer into the gas generator.

The following transients illustrate the effect on the gas generator operation for a failed closed MOV:

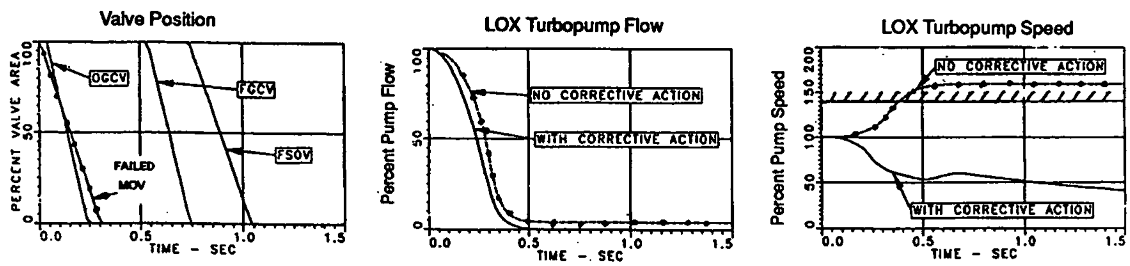
Operation Showing Failed MOV Without Corrective Action



The effect of the MOV failure, without corrective action, is a catastrophic failure of the oxidizer pump. In this case, the MOV closes in 0.3 seconds with the other propellant valves remaining in the opened position. This causes the pump flow to decrease to a very low value, but there is still power available from the turbine. The turbine power causes the pump to overspeed above the burst limit. At the same time, the additional oxidizer flow to the gas generator increases the oxidizer/fuel ratio towards stoichiometric levels which causes a turbine overtemperature.

The catastrophic failure can be prevented by detecting the MOV position and shutting down the engine before damage can occur, as shown in the simulation plots below.

Operation Showing Failed MOV With Corrective Action



As the simulation indicates, when all the valves are closed shortly after the MOV fails closed, the turbine energy is reduced, as indicated by the reduced turbine speed; hence, preventing a catastrophic failure.

SUMMARY

Each potential failure mode identified can be analyzed and the hazard designed out, contained, or detected and accommodated. The described approach illustrates that for those potential failure modes that can be conceived and identified there is a way to prevent the failure becoming catastrophic.

The described approach does not factor in the random failures that occur after the liquid rocket is in operation. The random failure modes considered as part of rocket engine manufacturing process are: manufacturing defects, assembly errors and human errors. In order to quantify this randomness one has to review the liquid rocket engine manufactures engine operation history to quantify the random failures impact on correlation.