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Review of US Historical Rocket Propellants: Accidents, Mishaps & Fatalities

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In many circumstances system designers or users often refer to a specific propellant as being "unsafe" or being the cause of accidents, mishaps or fatalities. This paper seeks to explore the historical data of propellant operations and offer some metrics and broad conclusions for specific propellants/combinations. Historical data will be limited to US launch vehicles from 1945 to 1999, Apollo from 1963 to 1971 and the Soviet Soyuz launch vehicle history up to 1999. It is shown that all rocket propellants/combinations having widespread adoption and use to be roughly comparable in terms of failures per mass of propellant consumed.

Nomenclature

A50	=	Aerozine 50 (50/50 Blend of Hydrazine and UDMH)
H2O2	=	Hydrogen Peroxide
HNO3	=	Nitric Acid
LH2	=	Liquid Hydrogen
LOX	=	Liquid Oxygen
N2H4	=	Hydrazine
NTO	=	Nitrogen Tetraoxide
RP	=	Rocket Propellant = Kerosene Type Fuel
UDMH	=	Unsymmetrical Dimethylhydrazine

I. Introduction

ROCKET propellants have been used in the United States since shortly after World War II when the German technology was recovered and reverse engineered. Since that time many different propellants have been in use and many have achieved common usage. This paper examines those propellants that have seen common usage and perform a literature search for historical records related to accidents, mishaps and fatalities. These historical records are then mined to determine failures on a per unit mass consumed basis. As such the paper is not intended to be a reliability paper but to provide some sort of metric that may be used for discussion concerning one's preferred propellant. The paper focuses on liquid propellants/propellant combinations in particular using data from the launch vehicles of SCOUT, Atlas, Delta, Space Shuttle and Titan. Additionally, accident/failure data from the Apollo time period 1963-1971 and from the Soviet Soyuz vehicle will be reviewed. Hence the paper contains the three data sets mentioned: US launch vehicles, Apollo, Soyuz

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II. US Launch Vehicles (1958-1999)

Because of the limited availability of historical accident data in the aerospace community the following ground rules and assumptions were used as the basis for the launch vehicle data:

1. Failures which occurred on US Launch vehicles (commercial, military & civilian payloads).
2. Emphasis on liquid propulsion – solids portions also included as a subsystem (see Ref 1 for more complete coverage of solids failures).
3. Solids systems with liquids insertion stages are not included.
4. Some Department of Transportation data is available but not presently considered.
5. Military accidents related to aircraft, etc. is not considered.
6. Vehicles developed after 1945 and operational as of 1990.
7. Failure is defined as any event (catastrophic or otherwise) which causes the system to fail to meet the intended mission.
8. Blindly accept that a failure of a propulsion unit is the fault of the specific propellant or propellant combination being used. This is primarily necessary because the specific details of failure are not available to the author and is often the case the "cause" is the subject of debate. In cases where the failure is non-propulsive the failure will not be counted.
9. Seeking information on propellants, as such in the majority of cases will group fluids together as used. Example being stage 1 of Soyuz is LOX/Kerosene so propulsive failure of stage 1 will assign failure to propellant combination of LOX/Kerosene.
10. Open source literature only, most recent dates limited to 1999 due to limitations on available references.

Given the above restrictions this limits the launch vehicle study to the following vehicles: SCOUT, Atlas, Delta, Space Shuttle & Titan. Strictly speaking the SCOUT vehicle does not fit our definitions but does utilize hydrogen peroxide for stabilization during stages 2 & 3 and will provide comparison data for the hydrogen peroxide utilized on the Soyuz vehicle. Table 1 shows the respective propellants/combinations associated with each vehicle and as can be seen the propellant list is limited to the following eight (8) propellants/combinations: Solids (making no distinction for binder, etc), hydrogen peroxide (H2O2), LOX/RP (assumed synonymous with LOX/kerosene variations), Nitric Acid/Unsymmetrical Dimethylhydrazine (HNO3/UDMH), Nitrogen Tetraoxide/Aerozine 50 (NTO/A50), Nitrogen (Helium also exists on some of the vehicles in small mass quantity with no specific failures assigned so is not listed), Liquid Oxygen/Liquid Hydrogen (LOX/LH2), Nitrogen Tetraoxide/MonoMethyl Hydrazine (NTO/MMH). The combination of NTO/A50 is similar to NTO/MMH in that both fuels are in the hydrazine family however the data was kept separate to look to see if a difference exists. For comparison the data for Apollo and Soyuz are also shown and will be discussed in subsequent sections. Additionally for rough comparison is shown the number of flights in the population that is to be examined.

Table 1 US Launch Vehicle Platforms vs. Propellant/Combinations[2-4]

Propellant/Combination	SCOUT	Atlas	Delta	Shuttle	Titan	Apollo	Soyuz
Solids	X	X	X	X	X		
H2O2	X						X
LOX/RP		X	X			X	X
HNO3/UDMH		X	X		X		
NTO/A50			X		X	NTO/UDMH	
Nitrogen			X				X
LOX/LH2		X		X	X	X	
NTO/MMH		X		X			
No. Flights in Population	113	299	271	94	203		1573

References 5 & 6 show the reliability of these launch vehicles increases with increased launch attempts as one would expect with learning. No attempts were made to compensate for this fact and the entire vehicle's history was included in the analysis. The most recent data available to the author was 1999, hence the periods studied were as follows: SCOUT 1960-1990, Atlas 1958-1999, Delta 1960-1999, Shuttle 1981-1998, Titan 1964-1999. The data failure records for each vehicle were then examined and propulsive related failures were then assigned to a specific propellant or propellant combination. The entire family history was then segregated into its respective configurations and then each configuration was examined for nominal propellant consumed specific to each propellant or combination. The results provided total propellant consumed over the study period for each propellant/combination. Hence from this information the number of failures per million pounds of propellant consumed per specific propellant is then calculated. References 1-4 were extensively used for this examination and in some cases discrepancies existed between each and some data was lacking (i.e. H2O2 loading for SCOUT). In such cases the best guess judgment was used to resolve the discrepancy. Additionally, most vehicle use some pressurant gases, the contribution from this fluid were ignored in the cases where they were not specifically assigned a failure. In particular Delta uses gaseous Nitrogen for attitude and roll control of stage 2 which was the cause of a few failures. It is also worth noting and astounding that the only fatalities within this population of vehicles related to propulsion (or a propellant) is the Challenger incident of 51L.

Results of the aforementioned analysis are shown in Table 2 & 3. Table 2 shows that there is a very large variation in failures associated with particular propellant/combinations with some propellants appearing to have no failures (H2O2 & NTO/MMH). Examination of the total propellant mass consumed shows that if the examination is narrowed to those propellants where more than 10 million pounds consumed there exists roughly similar result. The propellants, by launch vehicle, which have consumed more than 10 million pounds are highlighted in Table 2. As can be seen all of these propellants have been the cause of failures on at least one launch vehicle (see Figure 1 for some pictures of spectacular failures) and very successful the absence of failures in some special cases (Shuttle – LOX/LH2, Delta – LOX/RP). Within the greater than 10 million pounds of propellant population it appears that the failures per mass are somewhat similar. This would lead to the suggestion that the failures are all approximately the same if sufficient propellant is consumed. Hence in Table 3 is presented the failures per million pounds of propellant over the entire US launch vehicle population in the study (980 launches). Those propellants in the greater than 10 million pounds of propellant are highlighted in Table 3. This reduces the population to just four propellants: Solids, LOX/RP, NTO/A50, LOX/LH2. Each of these propellants has a very similar failure per mass number ranging from 0.045 to 0.082 (failures per million pounds of propellant). With Solids being roughly half of NTO/A50 with 4 to 5 times the propellant consumed.

Table 2 US Launch Vehicles - Failures per Million Pounds of Propellant Consumed – By Vehicle[1-4]

Propellant/Combination	SCOUT	Atlas	Delta	Shuttle	Titan
Solids	1.33	0.67	0.18	**0.0048**	**0.021**
H2O2	0.0				
LOX/RP		**0.086**	**0.0**		
HNO3/UDMH		4.0	0.0		3.26
NTO/A50			0.0		**0.087**
Nitrogen			158		
LOX/LH2		1.13		**0.0**	2.96
NTO/MMH		0.0		0.0	

Table 3 US Launch Vehicles - Failures per Million Pounds of Propellant Consumed – Entire Population[1-4]

Propellant/Combination	Failures/Million Lbm	Million Lbm Consumed - Total
Solids	**0.045**	333
H2O2	0.0	0.23
LOX/RP	**0.062**	112
HNO3/UDMH	2.19	2.3
NTO/A50	**0.082**	73
Nitrogen	159.9	0.019
LOX/LH2	**0.052**	155
NTO/MMH	0	3.0

III. Soyuz Comparison (1957-1999)

Given the results of the prior section the author performed the same type of analysis on the Soviet Vostok/Soyuz/Molniya Vehicle (subsequently referred to as Soyuz for shorthand). As such the data will provide a mild comparison between US and Soviet experiences. For simplicity the entire population was approximated as a Soyuz U vehicle, a few of the more recent flights have used an upper stage with NTO/UDMH but this was ignored since there would be insufficient propellant consumed to get over the 10 million pound mark. Complicating the issue is the fatal failure which occurred during prelaunch on March 18, 1980. The official report placed blame on a LOX leak caused by ground crew error. However, later it was recognized that the H2O2 tankage system may have erroneously use incompatible materials which may have been at fault. Review of several sources (references 3, 4, 7-9) reveals a variety of stories and biases toward one story or the other. As such the results shown in Table 4 are calculated with the failure grouped with LOX/Kerosene and the other grouped with H2O2.

As can be seen in Table 4 H2O2 now has more than 10 million pounds consumed and irrespective of including the March 18, 1980 incident the number of failures per mass is within the US population noted for other propellants. Additionally, the value of failures per mass obtained for LOX/Kerosene is also within the US population and only about 25% less with approximately 9 times the total mass of propellant consumed.

Table 4 Soviet Vostok/Soyuz/Molniya Vehicle - Failures per Million Pounds of Propellant Consumed[2-4]

Propellant/Combination	Failures/Million Lbm	Million Lbm Consumed - Total
H2O2	**0.039**	25.5
H2O2 w/ Mar 1980	**0.078**	
LOX/Kerosene	**0.044**	986
LOX/Kerosene w/ Mar 1980	**0.045**	
Nitrogen	0.175	5.7

IV. Apollo Program Accident Reports (1963-1971)

Flight and ground operation accident information for most of the Apollo program was found to be available from two review studies that NASA had contracted. The first covers the years 1963-1969[10] and the second 1970-1971[11]. Different from the prior sections insufficient data was available to compare all of the failures or accidents on a per mass basis. However, these reports do provide some insight to ground operations. From Table 1 in a prior section we see that the major propellants of the Apollo program were: LOX/RP, NTO/UDMH & LOX/LH2. A quick review of the document from the 1963-1969 period shows the phase "… exploded …" associated with each of the mentioned propellants (less RP). Table 5 shows just a few samples of these accidents with at least one being fatal. Hence it may be concluded that each of these propellants are capable of causing a launch failure as noted in the prior sections.

V. Conclusion

The public domain US liquid propellant launch vehicle information up to 1999 has been reviewed and contrasted to the Soviet historical experience with the Soyuz launch vehicle. The historically adopted propellants in the launch vehicle systems are comprised of eight propellants: Solids, H2O2, LOX/RP, HNO3/UDMH, NTO/A50, Nitrogen, LOX/LH2 & NTO/MMH. In addition the Apollo accident reports were reviewed for information. Consequently the following conclusions are draw:

- All historically adopted propellants/combinations have caused US launch vehicle failures.
- The phrase: "… exploded …" applies to all historically adopted propellants/combinations.
- Not all propellants/combinations have directly caused a fatality which only seems to be fortuitous because not all failures or "… exploded …" events had humans in close proximity.
- Failures per million pounds of propellant seems to range between 0.04 - 0.08 (failures/Mlbm) when more than 10 Mlbm have been used. This applies to: H2O2, LOX/Kerosene, Solids, LOX/LH2 & NTO/A50.
- *All propellants can and will get you – they must be respected for their high power density.*

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Table 5 Sample Accidents from Apollo 1963-1969 – Accident, Cause & Corrective Action[10]

2. When the valve was opened, a liquid oxygen container exploded due to use of improper lubricant on the LOX fittings.	Inadequate procedures and training to prevent use of unauthorized lubricants on LOX fittings.	Ensure that procedures are established to require use of only non-petroleum based lubricants on LOX fittings. Special fluorolubes or perfluorolubes should be specified.
4. During qualification test of a LOX turbo pump for a booster engine, the pump exploded on the 33rd start.	A design deficiency in that there was inadequate clearances between the LOX seal and the slinger and between the impeller and the backplate.	Insure that adequate clearance is provided in LOX pumps for pump cavitation conditions. Provide for positive flow of LOX to seal area at all times.
16. Flashback explosion occurred in a barge LH_2 vent stack during transfer of propellant to storage. Explosion occurred when LH_2 line was disconnected without GH_2 purge and without closing of the line valve.	The test procedure was not complete. Valves were not identified as to function, there was no QC monitoring and tasks were being performed without central TC direction. Communications were poor and technician failed to close vent valve and test conductor failed to purge system prior to disconnection of lines.	During fuel and propellant transfer operations, all valves should be identified as to function on the valve and in the test procedure. All tasks performed during transfer should be only as directed by the test conductor. No lines should be disconnected during fuel transfer until verified by QC and directed by the test conductor.
23. Main stage exploded during final countdown phase of static firing, destroying the stage and causing major damage to the facility.	Failure of the LOX vent valve to function due to solid LOX particles. Contributing causes were failure to follow approved procedures and an unsatisfactory Helium shut off valve during cold conditions. Test preparation was inadequate as evidenced by 9 valves being overlooked during pretest checks and not in the proper position.	Ensure that all valves and components have been pre-qualified for cryo operations prior to tests. Prohibit deviations from test procedures without prior approval. Ensure that all critical steps in the procedure such as switches, valves and control movements are verified by QC.
26. An LH_2 tank exploded resulting in fatal injuries and major damage when hot wire sensors were used in the tank after purging.	The crew had been instructed to remove the cover without positive sampling to ensure a non-explosive atmosphere. The hot wire sensors provided an ignition source for residual hydrogen vapors in the tank.	Require that positive sampling of all propellant tanks is carried out prior to removal of tank covers. Sampling should assure that hydrogen residue (vapor) does not exceed 5%. Prohibit the use of hot wire sensors in propellant tanks unless specifically authorized by Engineering.
27. A LOX system exploded during a static firing due to cleaning fluid corrosion in the system.	Non-compatible cleaning fluids were used and periodic inspection for corrosion was not accomplished.	Ensure that cleaning procedures are adequate to prevent residual cleaning fluid in propellant systems. Require frequent inspection of LOX systems for corrosion.
4. Following draining of N_2O_4 from a Spacecraft Reaction Control System, the drain drum exploded causing minor facility damage. Explosion resulted from mixture of fuel with contaminants in the drum.	No formal procedure was being followed and the drain drums had not been properly maintained, controlled or cleaned to prevent contamination. Contributory causes were inadequate marking and identification of lines, drain drums, and contents of drums.	All drain drums for oxidizers and fuels be positively marked and identified as to their contents. All fuel and oxidizer drain lines be color coded and connections be sized or keyed to prevent interconnection with the wrong drain drum. All drain drums be emptied after each drain operation, cleaned, sealed, and positively controlled.
30. An explosion occurred approximately 5 minutes after personnel emptied 3 UDMH hoke bottles into a drain barrel and left the bottles attached to the barrel to drain. Hoke bottles and barrel were destroyed.	The exact cause was undetermined, however the probable cause was due to residual calcium hypochlorite oxides or static electricity in the barrel.	Require all drain barrels to be cleaned after each operation. Ground and bond drain barrels and hoke bottles. Require rust be removed from all fuel propellant containers and dump hoke bottles into waste pond.

Figure 1. US Launch Vehicle Failures – Atlas, Delta & Titan (Top to Bottom)[12-14]