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System Trade Parameter Comparison of Monopropellants: Hydrogen Peroxide vs Hydrazine and Others

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Often monopropellant system trade studies are performed which may use outdated data making it difficult to make a logical and unbiased decision. This paper seeks to fill that void and offers direct comparison of standard system level trade parameters for some of the best known and understood monopropellants: hydrogen peroxide and hydrazine. Additionally, information for some of the typical cold gas systems are included along with some hydroxyl ammonium nitrate data.

Nomenclature

CO2	=	Carbon Dioxide
HAN	=	Hydroxyl Ammonium Nitrate
He	=	Helium
H2O2	=	Hydrogen Peroxide
IBD	=	Inhabited Building Distance
ILD	=	Intraline Distance
IMD	=	Intermagazine Distance
LC50	=	Lethal Concentration Causing Death in 50% of the Subjects
LD50	=	Lethal Dose Causing Death in 50% of the Subjects
N2	=	Nitrogen
N2O	=	Nitrous Oxide
N2H4	=	Hydrazine
OSHA	=	Occupational Safety and Health Administration
PEL	=	Personal Exposure Limit
PTR	=	Public Traffic Route

I. Introduction

THE use of monopropellants for smaller scale satellites is often advantageous because of system simplicity. In order to make an accurate assessment of which monopropellant to use data must be acquired for direct comparison. The intent of this paper is not to select a best fit propellant but to provide data that may be used as a guide by the system designer. This paper will compare and contrast several system level parameters: physical properties, performance, cost, storability, toxicity, quantity-distance, accidental release measures and special considerations.

II. Monopropellant Comparison

Monopropellant rockets, by definition, which produce thrust using a single fluid. Usually the monopropellant term is used to describe reacting fluids (i.e. ones that may be decomposed in presence of a catalyst) but for the

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purposes of this paper cold gas (non-reacting) rockets will also be considered. Hence, the “monopropellants” that will be considered are: Hydrogen Peroxide (H2O2), Hydroxyl Ammonium Nitrate (HAN), Hydrazine (N2H4), Carbon Dioxide (CO2), Helium (He) and Nitrogen (N2). The later three being examples of cold gas with CO2 being an example of the liquefied gas family. Carbon dioxide is used for comparison purposes to generally represent the family of liquefied gases (See Ref. 1 for thorough examination of liquefied gases: ammonia, butane, propane, nitrous oxide, carbon dioxide and water).

A. Physical Properties

This section lists the general physical properties of which more detailed information can be found in the references. Note that hydrogen peroxide is presently available at 98-99% wt. but is listed in the table as 100% for comparative purposes. As a comparison the vapor pressure of water is around 0.62 psig at room temperature. As can be noted hydrogen peroxide has a vapor pressure roughly 10% while that of hydrazine is roughly 50% of water. As a result of this hydrazine vapors will exist and open container and present a flammability hazard.

Table 1 Comparison of Monopropellant Physical Properties

Property	**H2O2 (100%) Ref. 2-4**	**HAN-Glycine-Water Ref. 5**	**Hydrazine (100%) Ref. 2, 6**	**CO2 (Liquefied Gases) Ref. 7**	**Helium Ref. 3**	**Nitrogen Ref. 3**
Appearance	Liquid Colorless	-	Liquid Colorless	Gas Colorless	Gas Colorless	Gas Colorless
Odor	None	-	Ammonia	None to Slight Acidic	None	None
Freezing Pt (Deg F)	31	-32	34	-109 Sublimation	-455	-346
Boiling Pt (Deg F)	302	Not Measured	235	-109 Sublimation	-452	-320
Density (g/cc) @ Room Temperature	1.44	1.42	1.01	0.72 Liquefied	0.000178 @ 32 F & 1 atm	.00114
Vapor Pressure (psig) @ Room Temperature	0.054	-	0.373	838	14.7 @ -452 F	19.7 @ -315 F
Flash Pt (Deg F)	None 165 for Rapid Decomposition	-	100	Not Applicable	Not Applicable	Not Applicable
Autoignition Temperature (Deg F)	None 251 for Rapid Vapor Decomposition	-	518	Not Applicable	Not Applicable	Not Applicable
Flammability Limits (% in air)	None	-	Upper: 100 Lower: 4.7	Not Applicable	Not Applicable	Not Applicable

B. Performance

The major comparative performance parameters of a given chemistry are the specific impulse and density impulse (specific impulse times the propellant density). Table 2 shows the values for the reduced set of monopropellants selected. For H2O2, HAN & Hydrazine performance is provided at a chamber pressure of 1000 psia and nozzle expansion ratio of 100 in vacuum conditions. The cold gas family is assumed to have the same specific impulse (at smaller expansion ratio) as Nitrogen for rough approximate purposes. The density used for the CO2 density impulse calculation is that of liquid assuming that it is stored at 1000 psia. As can be seen from the Table 2 Hydrazine has the best specific impulse by about 25% but lower density impulse by about 12% compared to HAN-Glycine-Water or 98% H2O2. The increased density impulse performance would be important for volume constrained systems. The cold gas family is clearly at a much lower performance level both from a specific impulse and density impulse perspective. It is noteworthy that CO_2 storage at elevated pressure (as a liquid) has a clear advantage over He & Nitrogen and would be useful for terrestrial applications where the fluid mass is not as important.

Table 2 Comparison of Monopropellant Chemistry Performance

Monopropellant	Vac Specific Impulse (lbf-sec/lbm)	Vac Density Impulse (lbf-sec/ft^3)
Hydrogen Peroxide (98%)	192 (Ref. 8)	17140
HAN-Glycine-Water	200 (Ref. 5)	17729
Hydrazine (100%)	245 (Ref. 5)	15295
CO2 (Liquefied Gas)	65	4190
Helium	65	48
Nitrogen	65 (Ref. 9)	315

Additionally hydrazine catalyst beds are calculated to be only capable of 50-65% of the flux level that hydrogen peroxide catalyst beds are capable at identical thrust levels and operating conditions according to data in references 10 and 11. The lower capability of hydrazine catalyst beds might be related to physics associated with pebble catalyst beds. Figure 1 shows an example of the thruster difference associated with thrusters of approximately the same size. Note for the figure the hydrazine thruster is operating at roughly 10% of the flux level of the hydrogen peroxide catalyst bed.

C. Cost

Table 3 shows the present day costs associated with each of these propellants in an as delivered value for US customers. As can be noted from the table hydrazine costs are substantially larger than for any other propellant.

Table 3 Comparison of Monopropellant Costs for FY 06[12]

Monopropellant	Unit Pack	Price Delivered
Hydrogen Peroxide (70%)	40,000 lbm Bulk	$0.50/lbm
Hydrogen Peroxide (90-99%)	30 gal Drums	Less Than $5.00/lbm Author Info
HAN-Glycine-Water	None	To Be Determined
Hydrazine (100%)	Bulk	$78.01/lbm
Hydrazine (100%) High Purity	Bulk	$189.00/lbm
CO2 (Liquefied Gas)	Bulk	$0.10/lbm
Helium	Cylinder	$0.45/ft^3
Nitrogen	Bulk - Liquid	$94.75/Ton

D. Storability

Table 4 shows the storability of the fluids of interest. As can be seen H_2O_2 and Hydrazine have about the same storability which for most aerospace applications would suffice. The cold gas systems have no real restriction on storage and in that case it may be more a mater of leak rates. The HAN propellant is still in development and as such its attractiveness would be considerably less than the other propellants listed.

Table 4 Comparison of Monopropellant Chemistry Storability

Monopropellant	Storability
Hydrogen Peroxide (98%)	3+ yrs Sealed - 1965 Demonstrated 15 yrs Sealed – Estimated Modern Chemistry 17+ yrs Vented - Demonstrated (Ref. 13)
HAN-Glycine-Water	Unknown – In Development (Ref. 14)
Hydrazine (100%)	“Excellent if kept blanketed with inert gas” (Ref. 5)

	~10 yrs Sealed (Ref. 15)
CO_2 (Liquefied Gas)	Indefinite
Helium	Indefinite
Nitrogen	Indefinite

E. Toxicity

Table 5 shows the exposure and toxic information for each of the propellants. The cold gases are merely asphyxiants and as such present no real concern. Hydrogen peroxide and Hydrazine both have Personal Exposure Limits (PEL) but the limits are established for different reasons. In the case of Hydrazine the limit is to prevent its absorption in the body. This limit is established because hydrazine is a mutagen and a carcinogen hence absorption in the body is undesired. In the case of hydrogen peroxide the limit is established as about 10% of the limit of irritation. For these reasons hydrazine *is* considered toxic and hydrogen peroxide is *not* considered toxic. The LD50 and LC50 values for Hydrazine and Hydrogen Peroxide inhalation and ingestion suggest that both are high energy chemicals which should come as no great surprise. HAN again is in development and nothing is really known about the toxicity. Hence HAN and Hydrazine are probably on the bottom of the non-toxic list with the other propellants on the top with the cold gases having a slight advantage.

Table 5 Comparison of Monopropellant Chemistry Exposure & Toxicity

Monopropellant	Toxicity
Hydrogen Peroxide (98%)	1 ppm OSHA – PEL (Ref. 4) OSHA Limit Actually ~10% of Irritation Limit (Ref. 16) 805 mg/kg (rat) Oral LD50 70%H_2O_2 (Ref. 4) 170 ppm (rat) Inhalation LC50 50% H_2O_2 (Ref. 4)
HAN-Glycine-Water	Unknown – In Development (Ref. 5)
Hydrazine (100%)	0.1 ppm OSHA – PEL (Ref. 6, pg 1053) 60 mg/kg (rat) Oral LD50 (Ref. 6) 570 ppm (rat) Inhalation LC50 (4 h) (Ref. 6) Mutagen (Ref. 6) Carcinogen (Ref. 6)
CO_2 (Liquefied Gas)	Asphyxiant Other Liquefied Gases May be Oxidizers (e.g. N_2O) or Fuels (e.g. Butane) and Have Exposure Limits
Helium	Asphyxiant
Nitrogen	Asphyxiant

F. Quantity-Distance Requirements

Table 6 shows the quantity distance requirements for storage of energetic liquids per the Department of Defense (DoD) and in general the requirements are for bulk quantities. For reference the DoD hazard classes are segregated as: Class 1 (explosives), 2 (Compressed or Liquefied Gas), 3 (flammable liquid), 4 (flammable solid, self reacting matls), 5 (oxidizers), 6 (toxic/infectious substances), 8 (corrosive), 9 (miscellaneous). As can be seen hydrazine has the most restrictive quantity-distance requirements.

Table 6 Comparison of Monopropellant Quantity-Distance Requirements[17]

Monopropellant	OSHA/NFPA Fuel or Oxidizer Class	DoD Storage Hazard Class	Minimum Quantity-Distance
Hydrogen Peroxide (>60% <91%)	Class 3	5.1 (LA)	800 ft Or 75 ft for < 400000 lbm IBD/PTR/ILD & Aboveground IMD Or None in Approved Fixed Tanks
Hydrogen Peroxide (> 91%)	Class 4	5.1 (LA)	800 ft Or

			75 ft for < 50 lbm IBD/PTR/ILD & Aboveground IMD Or See Table C9.T21 Ref 17 for More Detail. Sprinkler Required > 2000 lbm
HAN	Class 2	8 (LE)	800 ft Or 50 ft for < 600000 lbm IBD/PTR/ILD & Aboveground IMD Or None in Approved Fixed Tanks
Hydrazine (>64%)	II	8 (LC)	800 ft Non-Bulk Or 300 ft Non-Bulk In Unconfined Tanks (< 100 psi) Or 600 ft Or 80 ft protected IBD/PTR 30 ft ILD & Aboveground IMD For < 100 lbm Or See Table C9.T23 Ref. 17 for More Detail.
CO_2 (Liquefied Gas)	-	-	Not Listed
Helium	-	-	Not Listed
Nitrogen	-	-	Not Listed

G. Accidental Release Measures

Table 7 shows the comparison of release responses as stated on up to date material safety data sheets. As can be noted from the table hydrazine because of its toxic nature and high vapor pressure has the most stringent accidental release response.

Table 7 Comparison of Monopropellant Accidental Release Measures

Monopropellant	**Response**
Hydrogen Peroxide (>90%)	Dilute with Large Quantity Water and Dike Until H_2O_2 Decomposes Combustible Material Contacted with H_2O_2 Immediately Submerge or Large Quantity Water Rinse Ref. 4
HAN (>18%)	Contain Spill Prevent Contact with Skin and Clothing Take Up with Non Combustible Material and Place in Containers for Disposal Ref. 18
Hydrazine (100%)	Response Requires Full Encapsulated Suit and Full Face (NIOSH Approved) Self Contained Breathing Apparatus Air: Vapors Suppress with Water Fog and Contain Liquid for Treatment Water: Notify All Downstream Uses of Possible Contamination Land: Contain Spill Dilute to about 10 with Water and Add 5-8% Calcium Hypochlorite (aq) Until Reacted. More Warnings, See Reference Ref. 6
CO_2 (Liquefied Gas)	Evacuate Personnel Ventilate Area, Self Contained Breathing Apparatus Where Needed Ref. 7
Helium	Evacuate Personnel

	Ventilate Area, Self Contained Breathing Apparatus Where Needed Ref. 19
Nitrogen	Evacuate Personnel Ventilate Area, Self Contained Breathing Apparatus Where Needed Ref. 20

H. Special Considerations

It is noteworthy that the prior discussions and selection criteria have made no mention of system location use. In other words the conclusions are applicable to space, air, land and sea utilization. This section makes note of considerations which may be specific to location utilization. Table 8 makes and attempt to summarize some the know considerations. Hydrazine for example has several undesired characteristics which restrict its propulsive use to the space environment. HAN has been in development for the last 20+ yrs as a gun propellant and some effort to turn this fluid into a rocket monopropellant but finding a suitable catalyst has proved elusive. As such this propellant seems to stay restricted to the research lab.

Table 8 Comparison of Monopropellant Chemistry Special Considerations

Monopropellant	**Consideration**
Hydrogen Peroxide (98%)	Environmentally Friendly - Decomposes Into O2 & H2O
HAN-Glycine-Water	In Development from 1980 As Gun Propellant Catalyst Requires 400C Preheat (Ref. 21)
Hydrazine (100%)	Exhaust (H2) Will Afterburn in Atmosphere Exhaust and Propellant are Odorous (Ammonia) Flammability Hazard in Atmosphere
CO2 (Liquefied Gas)	Nitrous Oxide May Be Decomposed See Other Liquefied Gases (Ref. 1)
Helium	None
Nitrogen	None

III. Conclusions

Some of the necessary information to perform a system trade study for monopropellants including some cold gas materials has been presented. The data presented included: physical properties, performance, cost, storability, toxicity, quantity-distance, accidental release measures and special considerations. Some of the relevant conclusions are:

- Hydrazine
  - Highest Performance in Terms of Specific Impulse
  - Most Expensive on a per Pound Basis
  - Most Toxic – Mutagen & Carcinogen
  - Most Stringent Quantity Distance Requirements
  - Most Stringent Accidental Release Measures
- H2O2
  - Highest Performance Density Impulse (Similar to HAN)
- HAN
  - Primarily a Research Fluid
- CO2
  - Looks Favorable for Short Duration Terrestrial Applications
- He & N2
  - Lowest Performance
  - Least Toxic
  - Simplest

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Figure 1. **Left – 150 lbf 90% H_2O_2 Thruster Shown Without Valve After Acceptance Test**
Right – 5 lbf Hydrazine Thruster
Both Shown At Approximately Same Scale vs. US Quarter