

2- Liquid Propellants

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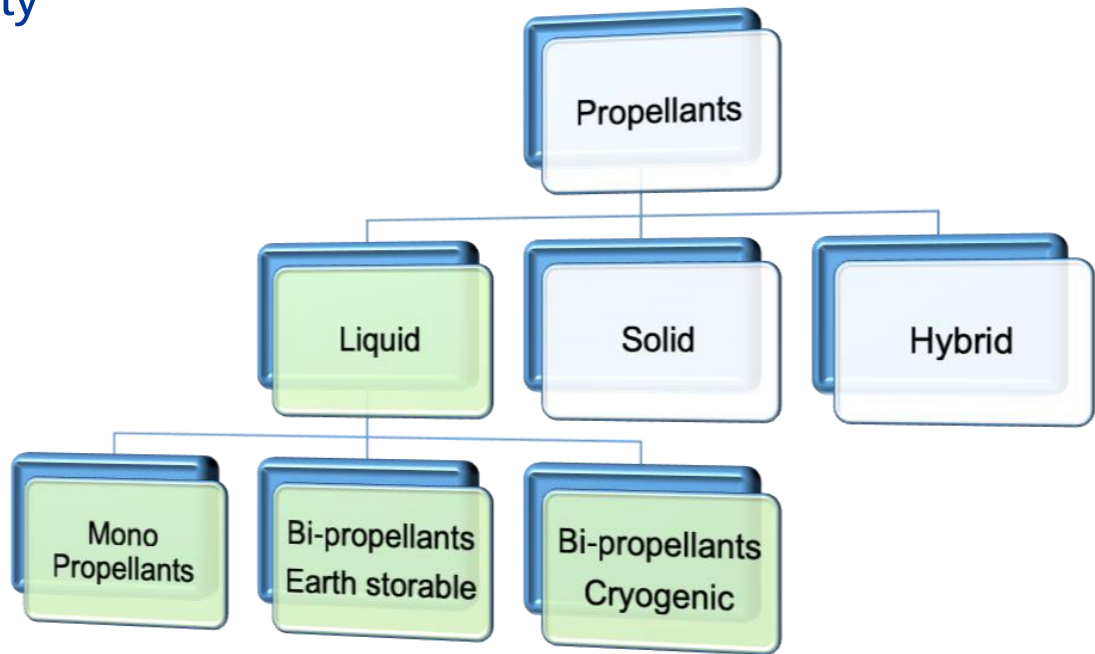
Nov 2024

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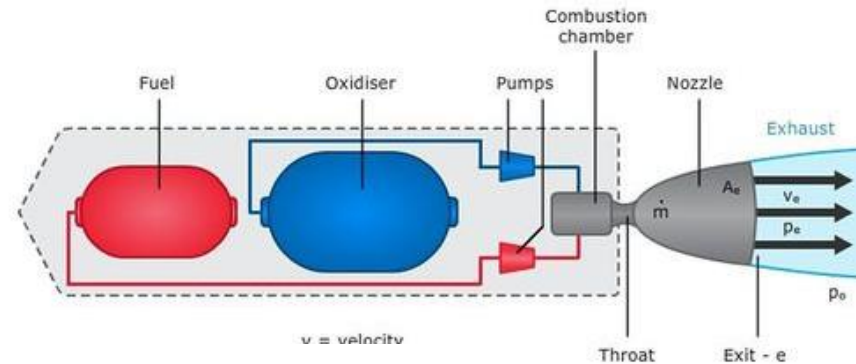
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- **Liquid propellants**
 - Throttling vs Complexity
 - Poor density
- **Mono- propellants**
 - Hydrazine, H_2O_2
 - Poor I_{sp}
 - Simple and flexible
- **Cryogenic**
 - Lq H_2 + Lq O_2
 - High I_{sp} – poor density
- **Earth Storable**
 - Hydrazine + nitric acid
 - Good I_{sp} + good density
 - Toxic + corrosive



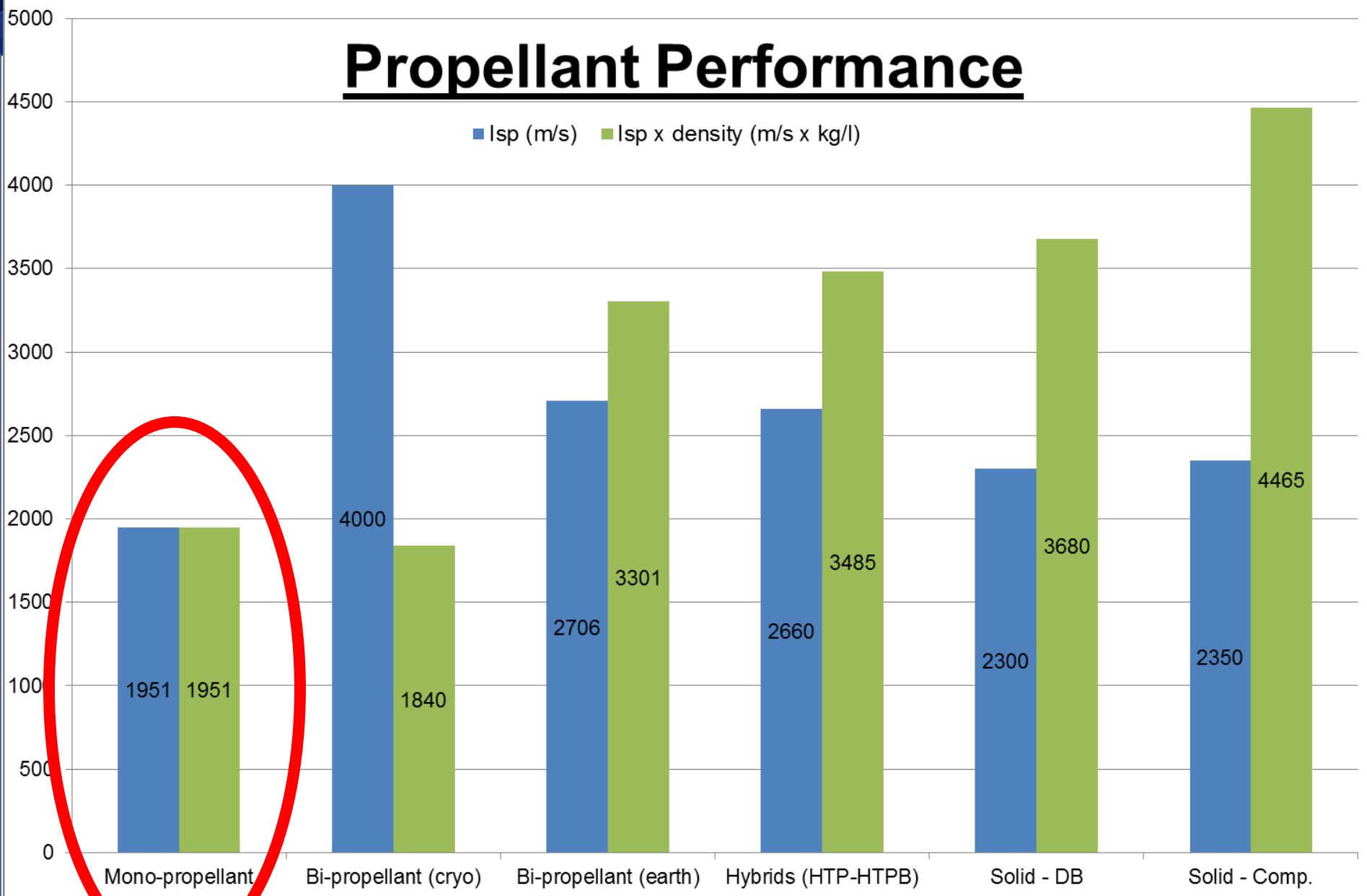
LIQUIDS IN ROCKET PROPULSION



- i. **Throttling (variable thrust) capability is attractive**
 - increases missile manoeuvrability
- ii. **Higher Specific Impulse (Bi propellants)**
- iii. **Propellants less expensive than solids (minimal processing)**
 - used in first modern rockets (Goddard, 1926)
- iv. **Liquid engines are more complex and heavier than solid motors**
 - need for pumps, valves, seals, pipe-work etc
- v. **Propellants more difficult to handle than solids (toxic, corrosive)**
 - gelled liquids are alternatives

Propellant Performance

■ Isp (m/s) ■ Isp x density (m/s x kg/l)



LIQUID MONOPROPELLANTS

HYDRAZINE (H₂N-NH₂)



1 N Hydrazine thruster (Astrum)

- **Single liquids capable of being decomposed into hot gases**
- **Low specific impulse but give simple and reliable rocket motors**
- **Anhydrous hydrazine (N₂H₄) has been most widely used since the development of a spontaneous decomposition catalyst:**

$$2\text{N}_2\text{H}_4 \rightarrow \text{N}_2 + \text{H}_2 + 2\text{NH}_3 \quad (\text{over metal catalyst})$$
- Used in gas generators, thrusters and deep space probes
- Freezing point 2°C, boiling point 113°C, density 1 g cm⁻³
- Incompatible with many materials including copper, PVC, reacts with O₂ and CO₂ in air
- Toxicity is a major concern, inhalation reference exposure level = 0.1 ppb
- Expensive to manufacture

OTHER LIQUID MONOPROPELLANTS

Propellant	ρ (kg m ⁻³)	$\bar{M}$ (g mol ⁻¹)	T_c (K)	I_s^* (N s kg ⁻¹)	$I_s \times \rho$
Hydrazine	1011	10.3	966	1951	1972
Nitromethane	1137	20.3	2646	2500	2843
HTP (Hight Test peroxide)	1442	22.7	1278	1618	2333

* $p_c = 7$ MPa and $p_e = 0.1$ MPa

HTP - High Test (Hydrogen) Peroxide



Green Mono-propellants (HAN, AN and ADN based)

Table 8. Performance and physical parameters of state-of-the-art green monopropellants. (Ideal vacuum specific impulse; Density at 20 °C and 1 atm storage conditions).

Class	Propellant	Theoretical I_{sp} (s) (Vacuum)	Density ρ (g cm ⁻³)	Volumetric ρI_{sp} (g s cm ⁻³)	Chamber Temp. T_c (K)	Conditions
(EIL) HAN-based	AF-M315E	266	1.47	391	2166	2.0 MPa and A_e/A_t 50:1
	SHP163	276	1.4	386	2401	
	HNP221	241	1.22	294	1394	1 MPa and A_e/A_t 100:1
	HNP225	213	1.16	245	990	
	GEM	283	1.51	427	?	
(EIL) ADN-based	LMP-103S	252	1.24	312.48	1903.15	
	FLP-103	254	1.31	332.74	2033.15	2.0 MPa and A_e/A_t 50:1
	FLP-106	255	1.357	344.6	2087.15	
	FLP-107	258	1.351	348.5	2142.15	
Liquid NOx Monopropellants	N ₂ O	206	0.745	153.5	1913.15	0.3 MPa and A_e/A_t 200:1
	Nitromethane	289	1.1371	328.6	2449	1.0 MPa and A_e/A_t 50:1
	NOFBX TM	350	0.700	245	3200	0.7 MPa and stoic O/F = 3
	HyNOx (NOx/ethene)	303	0.879	266.3	3264	2.5 MPa and stoic O/F = 6
Hydrogen Peroxide Aqueous Solutions (HPAS)	NOx/ethanol	331	0.892	295.3	3093	1 MPa and stoic. O/F = 5.73
	HTP 98%	186	1.43	266	1222	1 MPa and A_e/A_t 50:1
	H ₂ O ₂ 90%	172.13	1.39	239.3	1019.3	1 MPa and A_e/A_t 40:1
	H ₂ O ₂ 85%	150.5	1.37	206.2	892.65	1 MPa and A_e/A_t 10:1

<https://doi.org/10.3390/aerospace8010020>

Oxidiser and fuel, stored in separate tanks. Mixed and ignited in the combustion chamber.

Space Storable (Cryogenic)

- Liquified gases that cannot be stored, e.g. O_2/H_2
- Very high performance
- Used only in civil applications, e.g. SSME, Ariane 5

Earth Storable

- Liquids under normal temperatures and pressures
- ‘Packaged’ in storage tanks for use in missiles, e.g. Lance
- Often ‘hypergolic’ (ignite on contact), e.g. IRFNA/UDMH

Monomethylhydrazine (MMH), $\text{CH}_3\text{NH-NH}_2$

Unsymmetricaldimethylhydrazine (UDMH), $(\text{CH}_3)_2\text{N-NH}_2$

Derivatives of hydrazine with lower freezing points

- F. pts: hydrazine 2°C , MMH - 52°C , UDMH - 57°C

Positive heats of formation (ΔH_f)

- More energy released on reaction

Hypergolic (ignite on contact) with many common liquid oxidisers

Very toxic - suspected human carcinogens.

Inhibited Red Fuming Nitric Acid (IRFNA)

- Used in 'packaged' systems such as old Lance missile and Scud.
- Mixture of nitric acid (HNO_3), dinitrogen tetroxide (N_2O_4) and water.
- Inhibitor is 0.7% HF, added to inhibit corrosion in aluminium tanks forms protective AlF_3 coating on the metal surface.

RFNA corresponds to an equilibrium mixture in a closed system:



Specification (by weight):

HNO_3	$83 \pm 1\%$
N_2O_4	$14 \pm 1\%$
H_2O	$1.5 - 2.5\%$
HF	0.7%



RFNA - @Explosions_Fire



LIQUID BI-PROPELLANT PERFORMANCE

Combustion chamber pressure, $P_c = 68 \text{ atm}$ (1000 PSI) ... Nozzle exit pressure, $P_e = 1 \text{ atm}$

Oxidizer	Fuel	Hypergolic	Mixture Ratio	Specific Impulse (s, sea level)	Density Impulse (kg-s/l, S.L.)
Liquid Oxygen	Liquid Hydrogen	No	5.00	381	124
	Liquid Methane	No	2.77	299	235
	Ethanol + 25% water	No	1.29	269	264
	Kerosene	No	2.29	289	294
	Hydrazine	No	0.74	303	321
	MMH	No	1.15	300	298
	UDMH	No	1.38	297	286
	50-50	No	1.06	300	300
Liquid Fluorine	Liquid Hydrogen	Yes	6.00	400	155
	Hydrazine	Yes	1.82	338	432
FLOX-70	Kerosene	Yes	3.80	320	385
Nitrogen Tetroxide	Kerosene	No	3.53	267	330
	Hydrazine	Yes	1.08	286	342
	MMH	Yes	1.73	280	325
	UDMH	Yes	2.10	277	316
	50-50	Yes	1.59	280	326
Red-Fuming Nitric Acid (14% N_2O_4)	Kerosene	No	4.42	256	335
	Hydrazine	Yes	1.28	276	341
	MMH	Yes	2.13	269	328
	UDMH	Yes	2.60	266	321
	50-50	Yes	1.94	270	329
Hydrogen Peroxide (85% concentration)	Kerosene	No	7.84	258	324
	Hydrazine	Yes	2.15	269	328

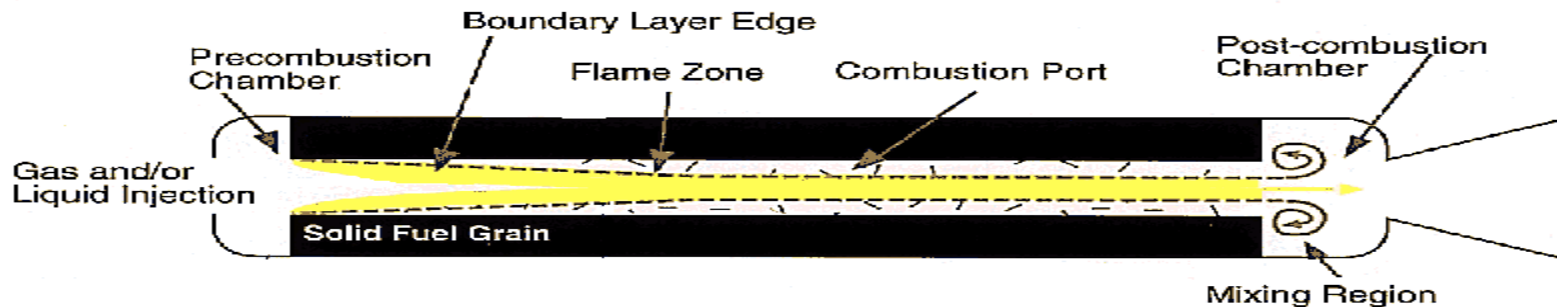
Engines + Bipropellant Types

Engine	Origin	Designer	Vehicle	Stage	Propellant	ISP	Thrust (N)
Merlin 1D FT	USA	SpaceX	Falcon 9 B5	1st	RP-1 / LOX	311	914,000
Merlin Vacuum 1D			Falcon 9 B5	2nd	RP-1 / LOX	348	981,000
Raptor			Falcon Heavy Starship	1st, 2nd	CH4 / LOX	380	2,205,000
RL-10B-2	USA	Aerojet Rocketdyne	Delta III	Upper	LH2 / LOX	465.5	110,093
			Delta IV				
			SLS				
RS-25	USA	Rocketdyne	Space Shuttle	1st	LH2 / LOX	452.3	2,279,000
			SLS			366	1,860,000
YF-21B	China	AALPT	Long March	Booster, 1st	N2O4 / UDMH	260	740,400
YF-22E				2nd	N2O4 / UDMH	298	741,400
YF-40				3rd	N2O4 / UDMH	303	103,000
NK-33A	Russia	JSC Kuznetsov	Soyus-2	1st	RP-1/LOX	297	1,510,00

https://en.wikipedia.org/wiki/Comparison_of_orbital_rocket_engines. (accessed Jan 2022)

HYBRID PROPELLANTS

- **Solid/liquid bipropellant system**
 - oxidiser is usually the liquid (e.g. IRFNA)
 - fuel is usually the solid (e.g. CH-based polymer)



- **Enables thrust to be controlled by adjusting liquid injection**
- **No explosive hazard**
- **More complex than solid-only motor but more manoeuvrable**

<http://www.bbc.co.uk/programmes/p004n0ly>

Hybrid - Peanut Rocket



- Liquid propellants
 - Throttling vs Complexity
 - Poor density
- Mono- propellants
 - Hydrazine, H_2O_2
 - Poor I_{sp}
 - Simple and flexible
- Cryogenic
 - Lq H_2 + Lq O_2
 - High I_{sp} – poor density
- Earth Storable
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Questions?

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Roxel
Propulsion systems