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EPFL Space Center eSpace

Space Propulsion ENG-510

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Lecture # 4 Introduction & General Course Information

Brief update on space propulsion course

Oral Exam

Exercise Date:

- Oral exam will take place on Wednesday, July 2 and Thursday, July 3 between 9 am and 5 pm
- Excel spreadsheet with time slots will be uploaded next week on Moodle
- Please book your timeslots starting from Tuesday, April 8
- First in, first choice

Special Lecture

Special Lecture:

- Presentation on ***Electric Thrusters in VLEO + Test Facilities for Electric Thruster at EPFL*** will be given on Tuesday, May 27

Test Facility Visit

ERT Test Facility Visit (including firing demonstration):

- Test facility visit is proposed for Wednesday, May 28 starting between 9 to 10 am
- Who is interested to join?
- Agenda:
  - Test facility tour
  - Hot firing test (TBC)

LOx/LH2 versus LOx/LCH4

Sustainability:

- Which propellant combination is more sustainable?
  - It is difficult to compare the two fuel propellants
  - The pollution from Hydrogen mainly comes from the electricity used on ground to produce it
  - During the combustion mainly Water vapor is released which is the first greenhouse gas
  - For Methane the extraction and production is not that high compared to Hydrogen
  - On flight it releases several particles and it is not known today how soot is developed in the plume
  - And effects of emissions in the upper atmosphere are poorly known

LOx/LH2 versus LOx/LCH4

Sustainability:

- Which propellant combination is more sustainable?
  - So potentially Methane as we lack knowledge on impact of sooth in upper atmosphere…

Lecture # 4 Part # 3 Introduction in Propulsion Systems

Brief overview on all space propulsion systems

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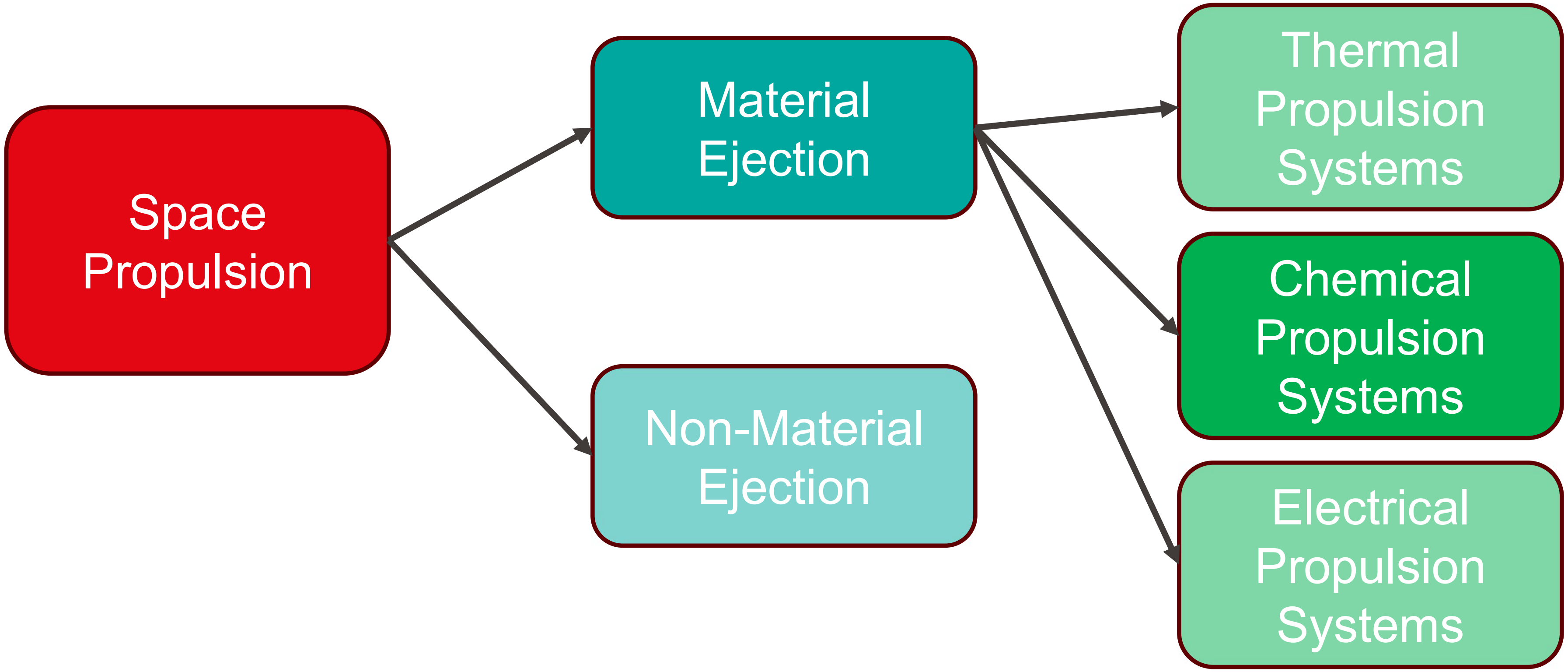
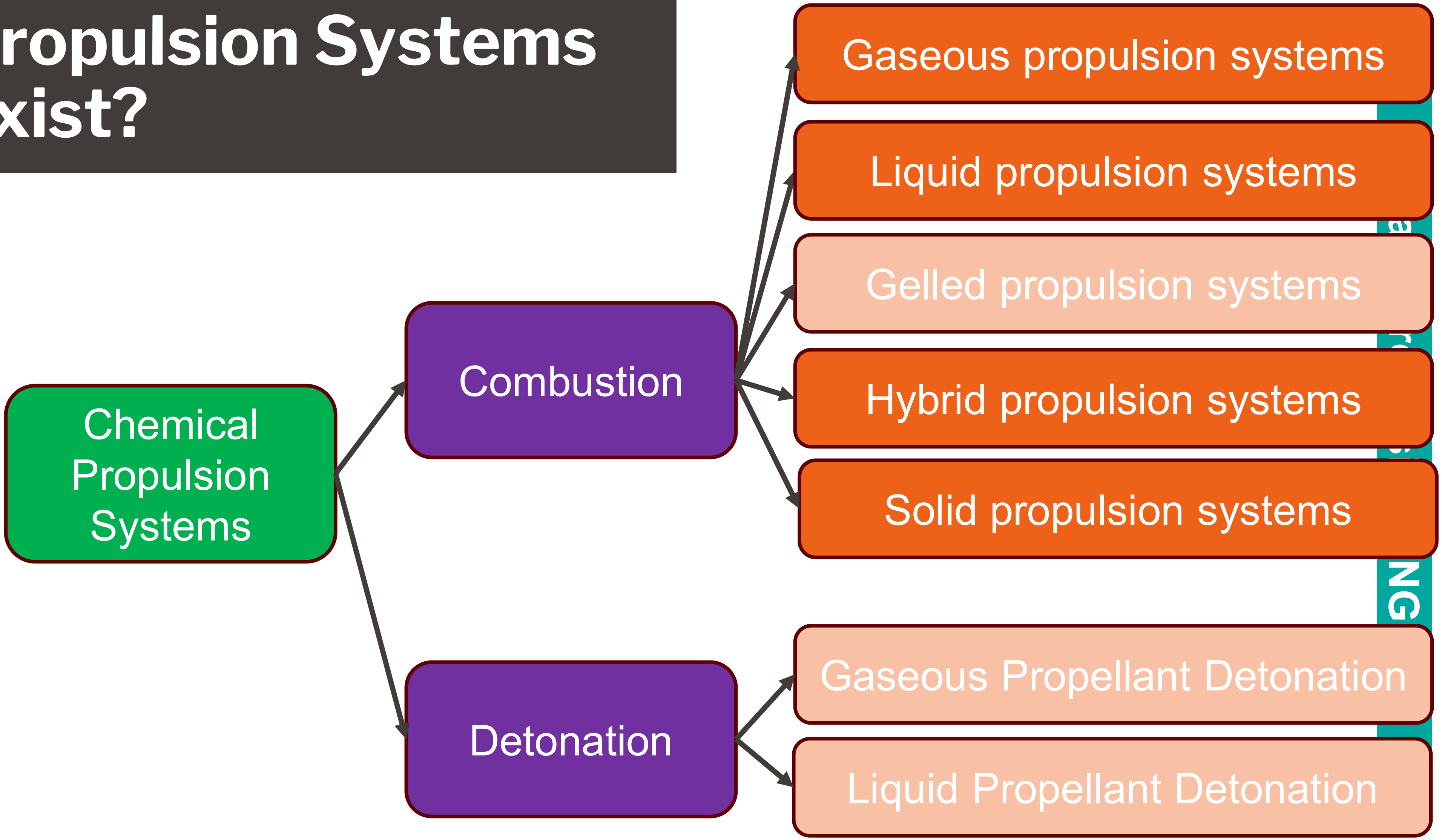
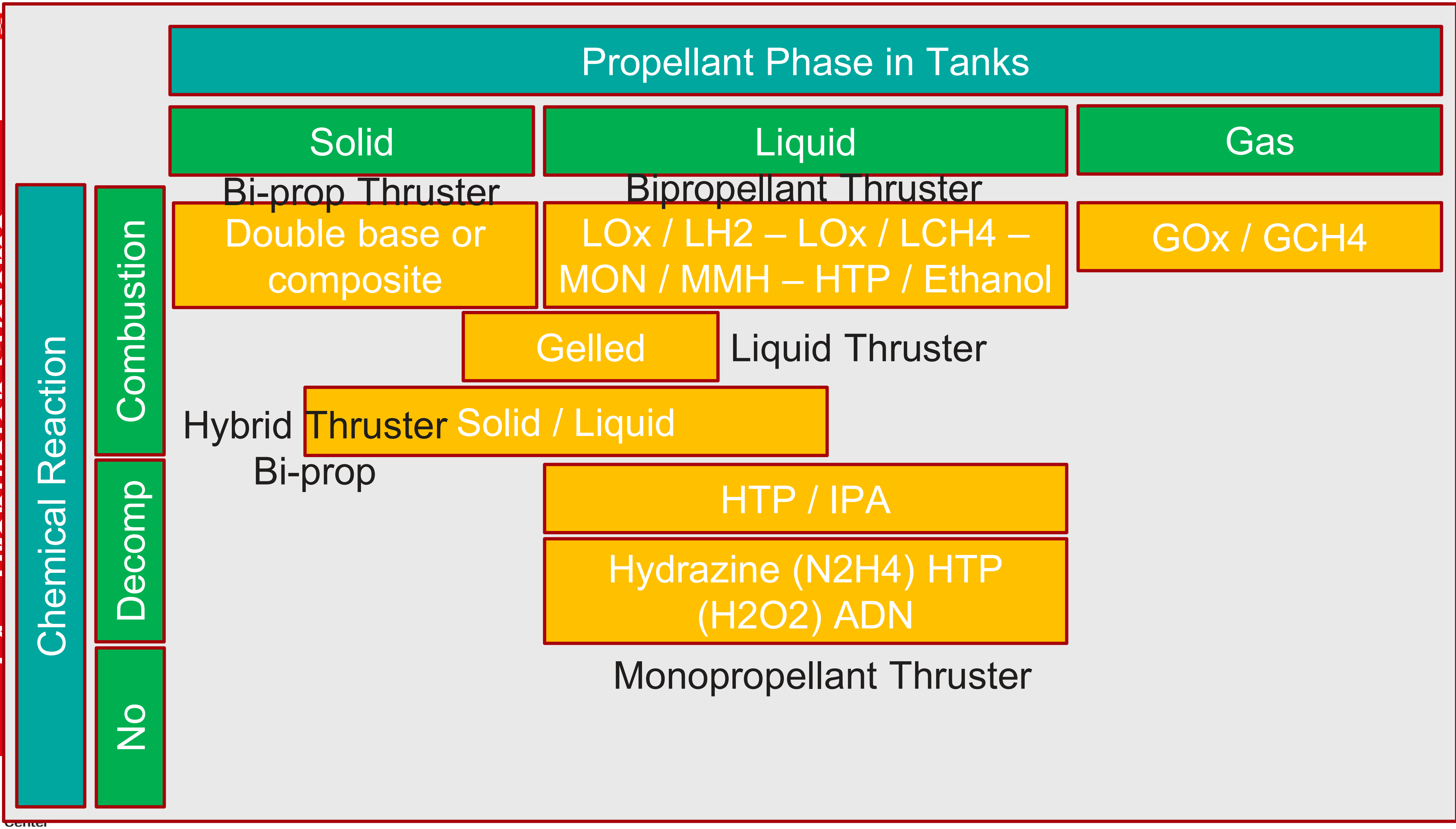
Which Chemical Propulsion Systems exist?

Objective: To develop the basics of chemical propulsion

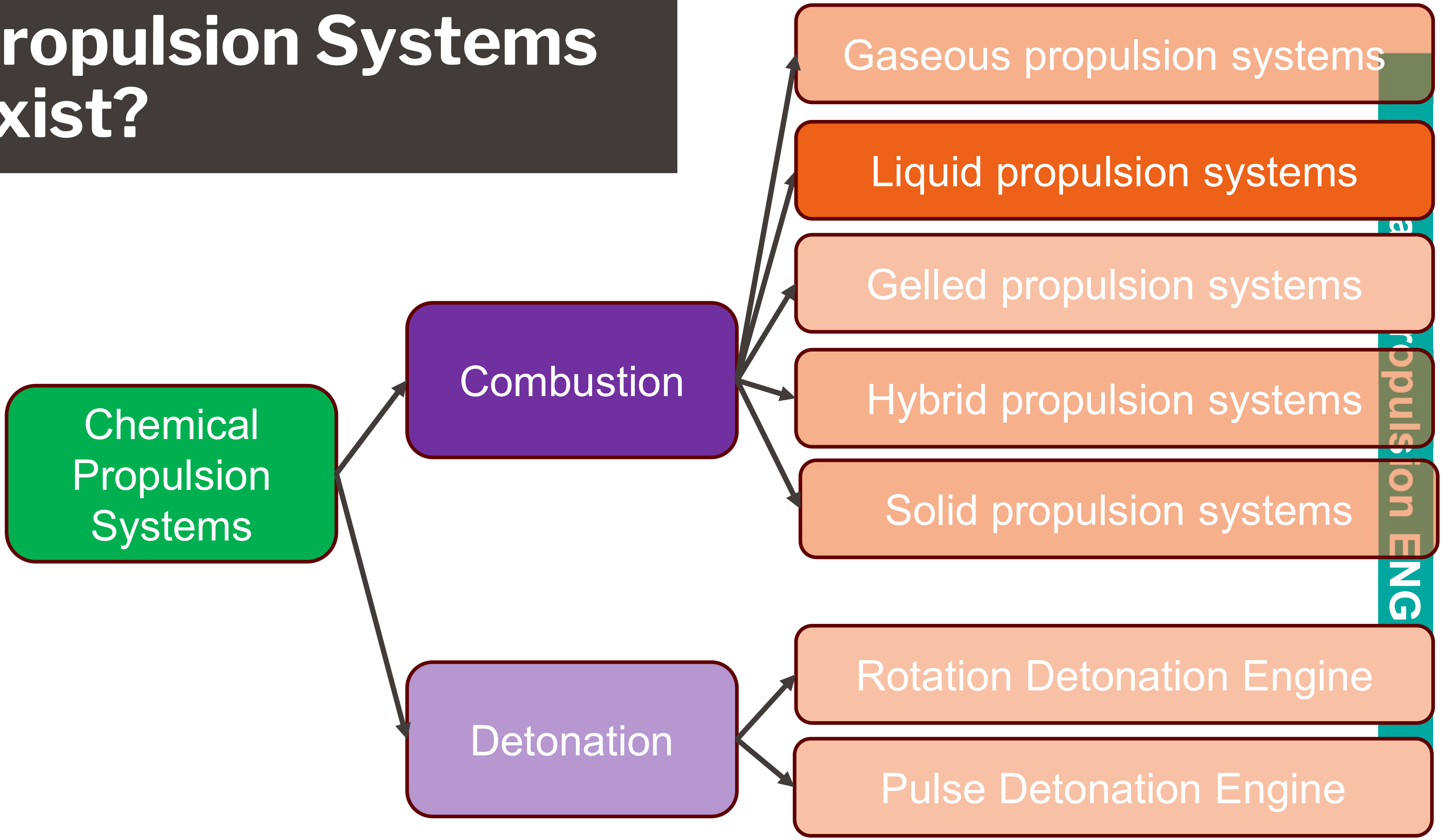


Which Chemical Propulsion Systems exist?

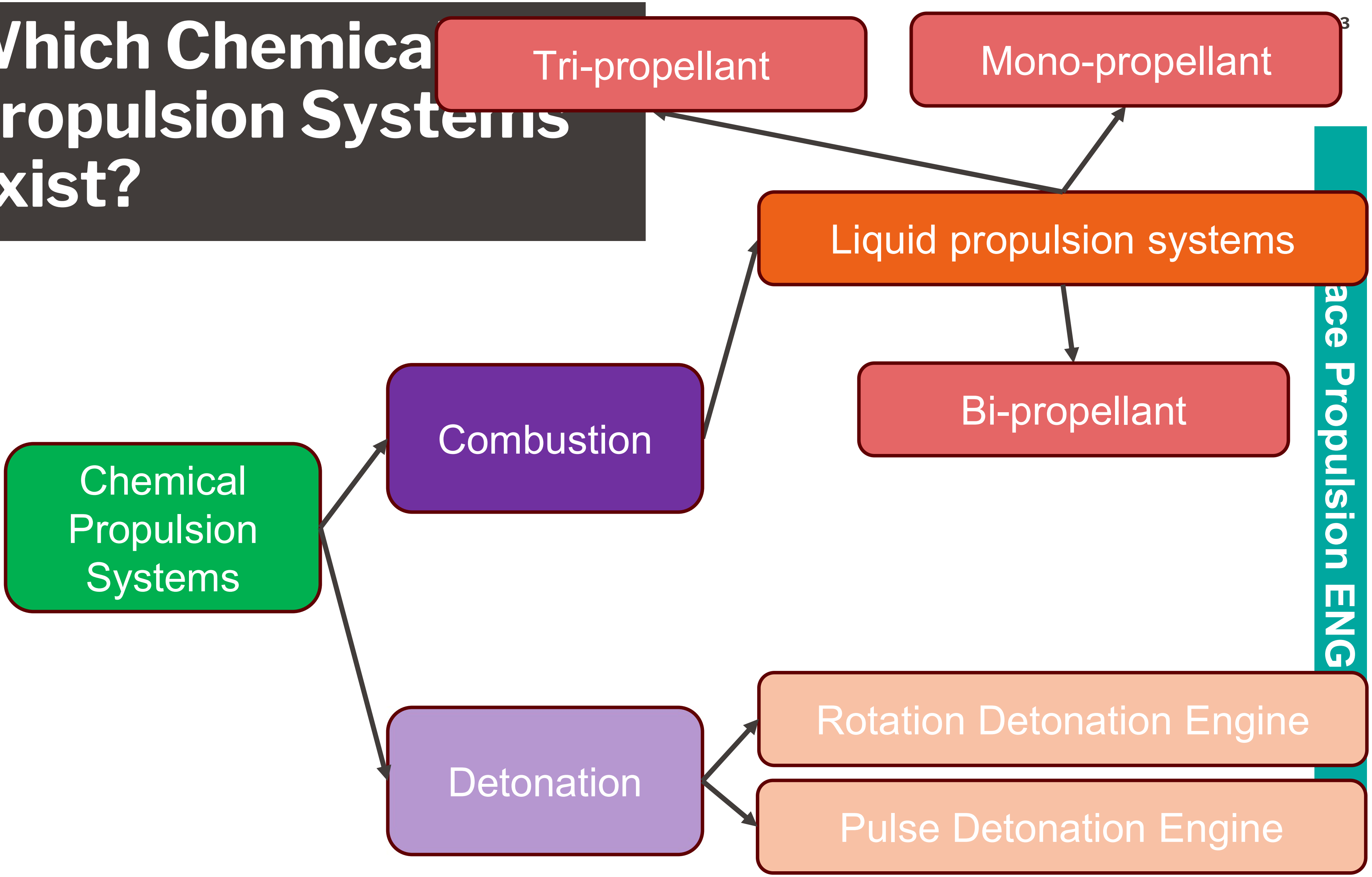



Propellant Phase in Tanks
Solid
Liquid
Gas
Chemical Reaction
Combustion
Decomp
No
Bi-prop Thruster
Double base or composite
Bipropellant Thruster
LOx / LH2 – LOx / LCH4 – MON / MMH – HTP / Ethanol
GOx / GCH4
Gelled
Liquid Thruster
Hybrid Thruster
Solid / Liquid
Bi-prop
HTP / IPA
Hydrazine (N2H4) HTP (H2O2) ADN
Monopropellant Thruster

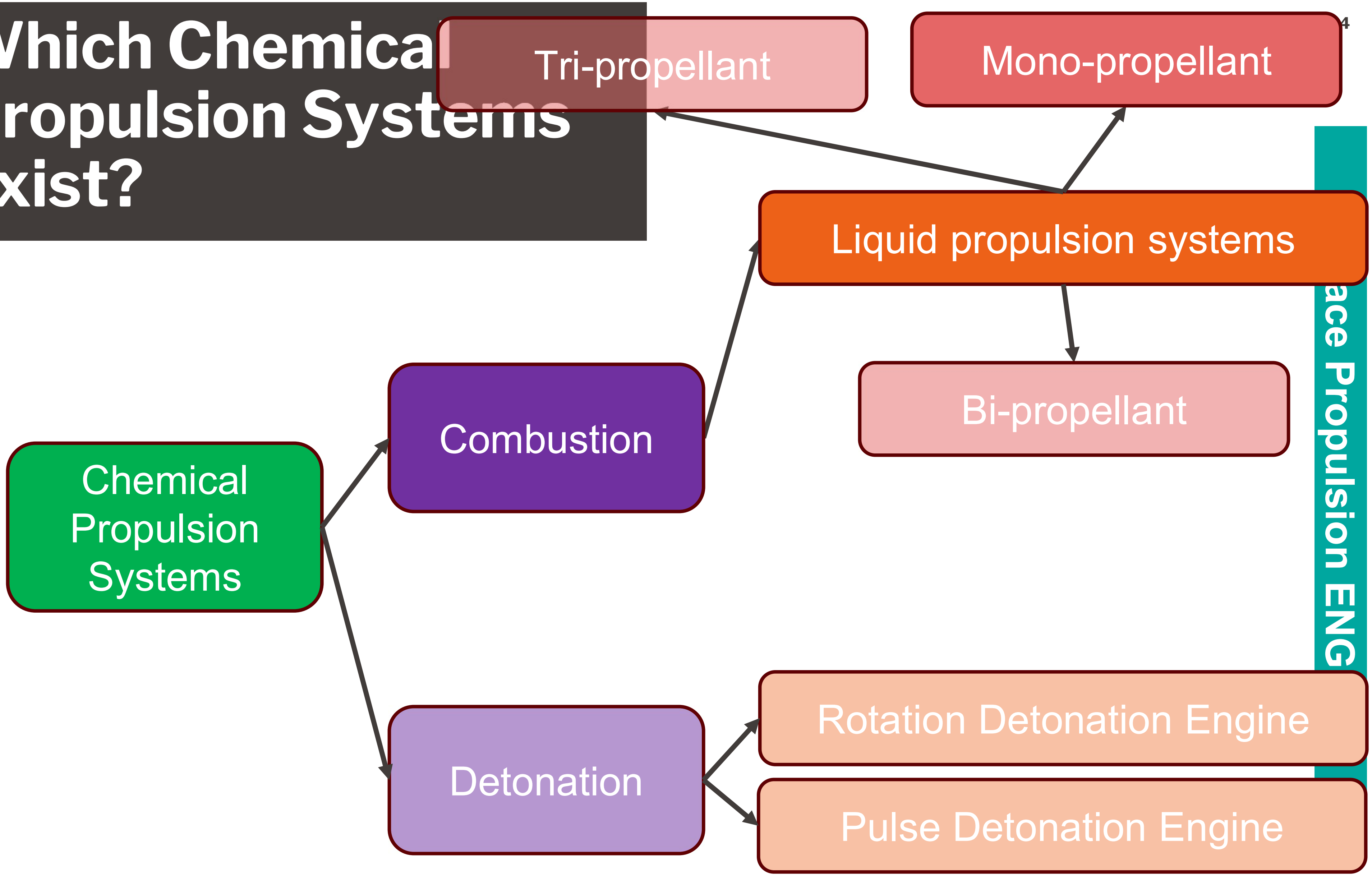
Which Chemical Propulsion Systems exist?



Which Chemical Propulsion Systems exist?



Which Chemical Propulsion Systems exist?



Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of liquid combustion mono-propellant propulsion

- Liquid propulsion systems
  - **Monopropellant**, bi-propellant or tri-propellant
  - Storable or cryogenic propellants
  - Toxic or non-toxic (hazardous or green) propellants
  - Hypergolic or non-hypergolic propellants
  - Pressure-fed (self-pressurization, blow-down or regulated) or pump-fed propulsion

		Propellant Phase in Tanks		
		Solid	Liquid	Gas
Chemical Reaction	Combustion			
	Decomp		Hydrazine (N2H4) / HTP (H2O2) / ADN / HAN / LMP	
	No			

Monopropellant Thruster

HAN..Hydroxyl Ammonium Nitrate

ADN…Ammonium Di-Nitramide

LMP-103S…ADN + Methanol + Water + Ammonia

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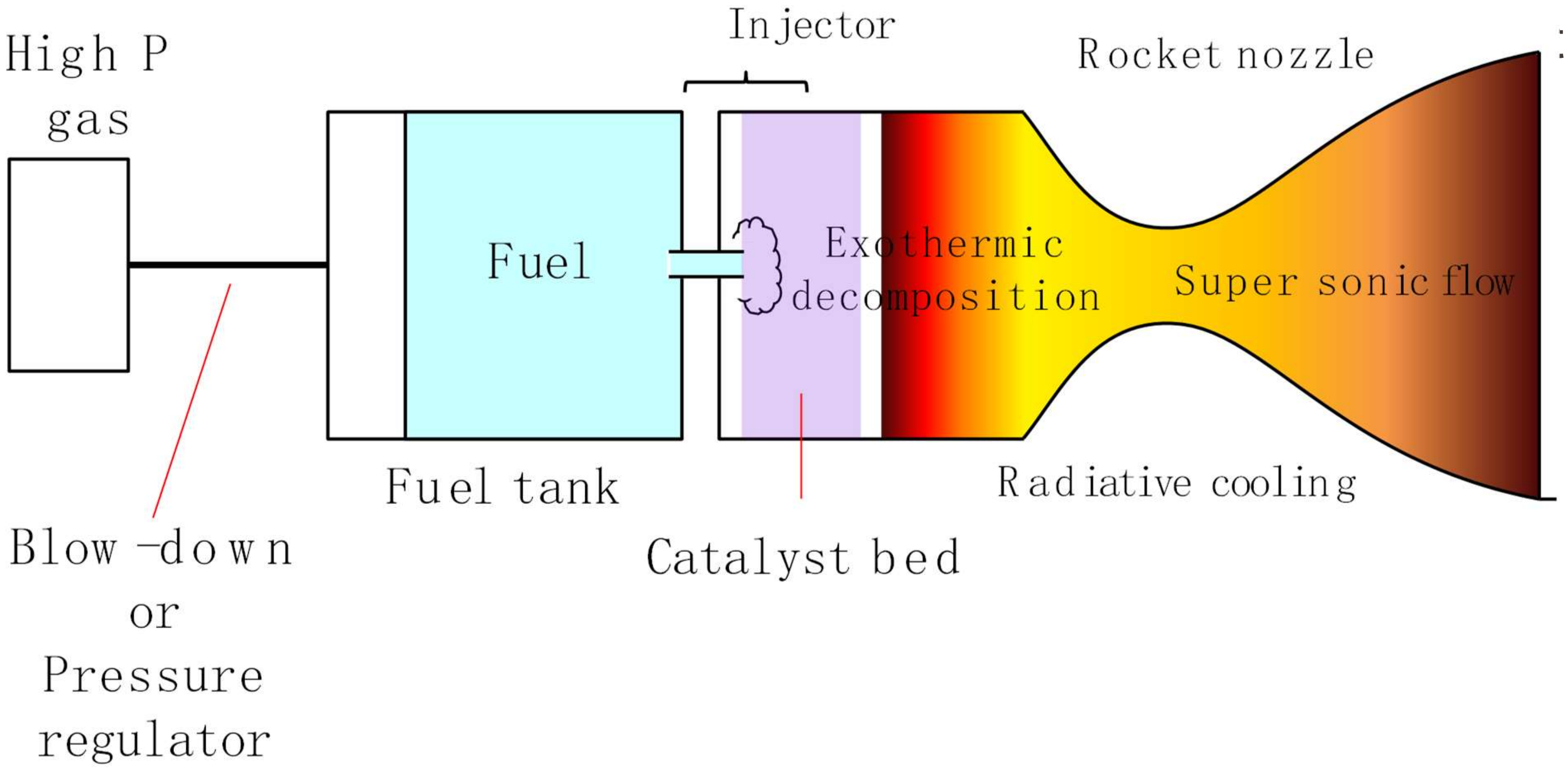
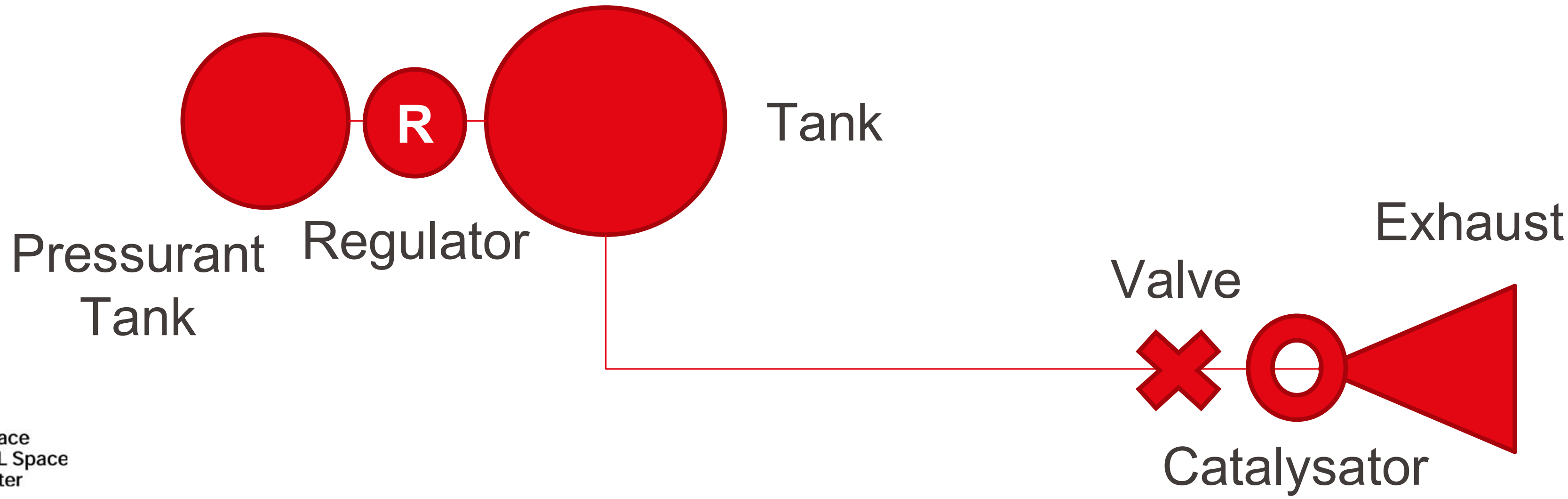
Which Liquid Mono-propellant Propulsion Systems exist?



Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

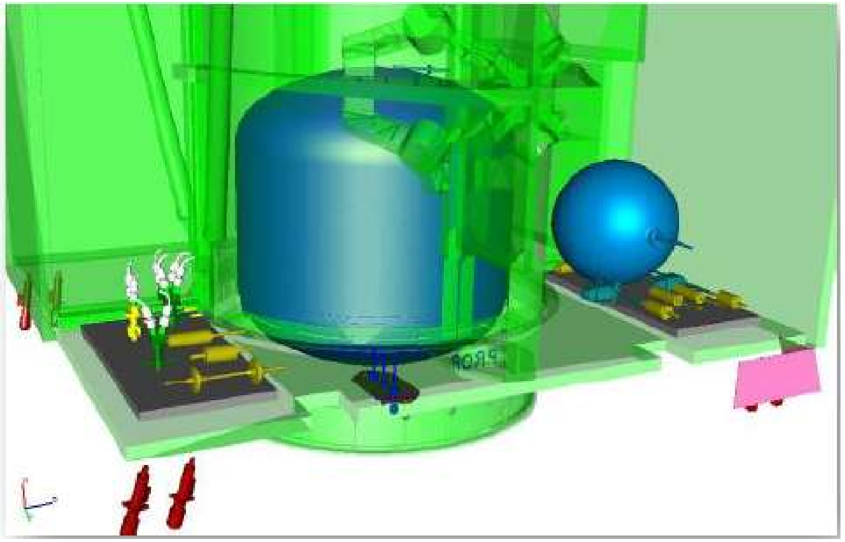
- Architecture for liquid mono-propellant decomposition propulsion systems:

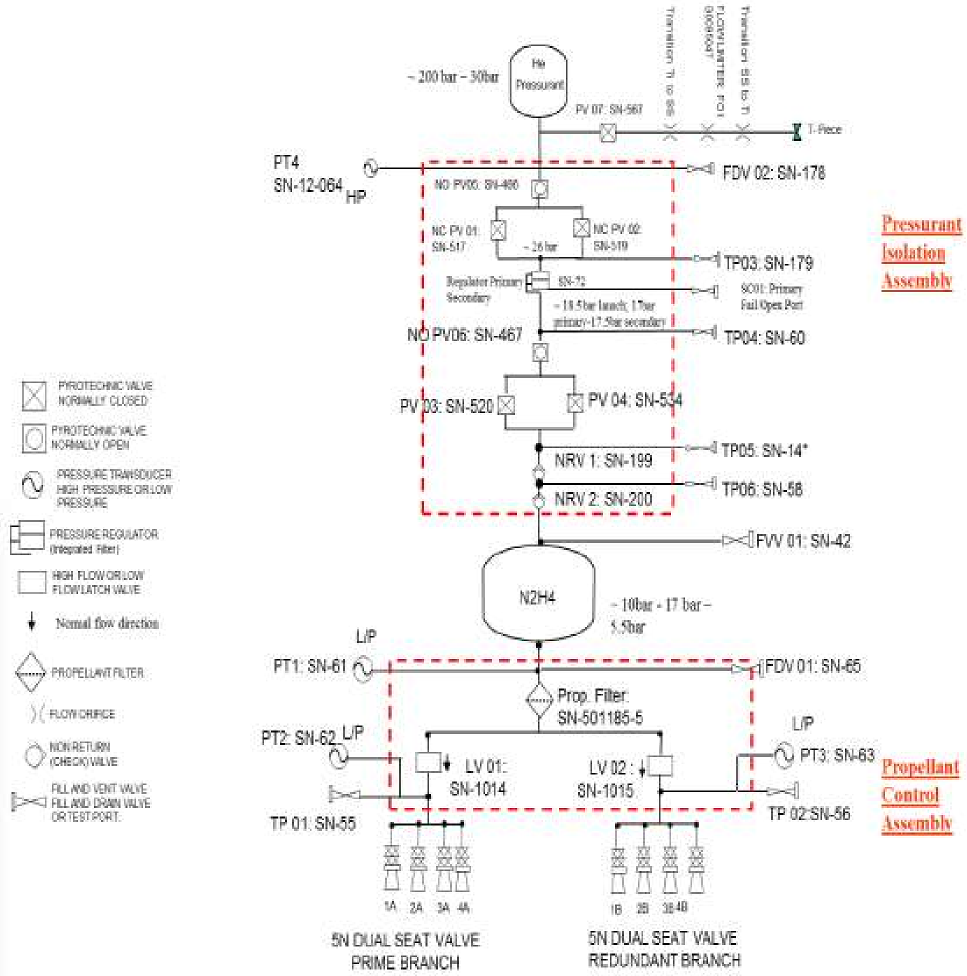


Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of ch
propellant propulsion

- Example: Pressure-regulated

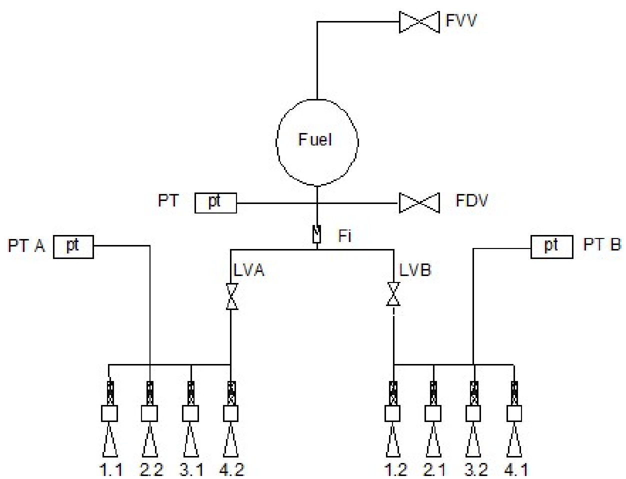




Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- Example: Blow-down



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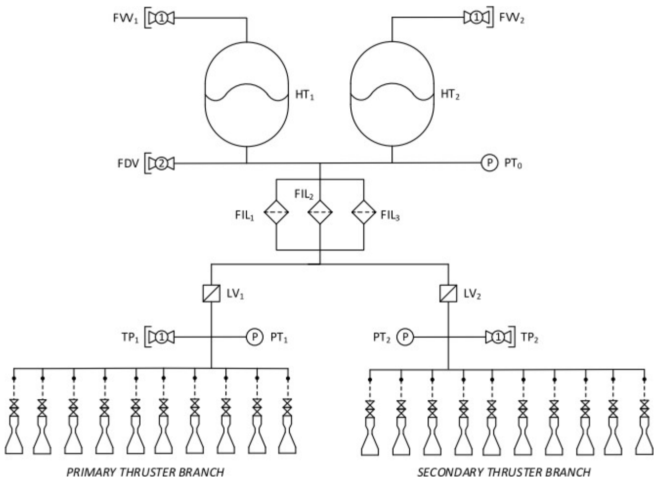
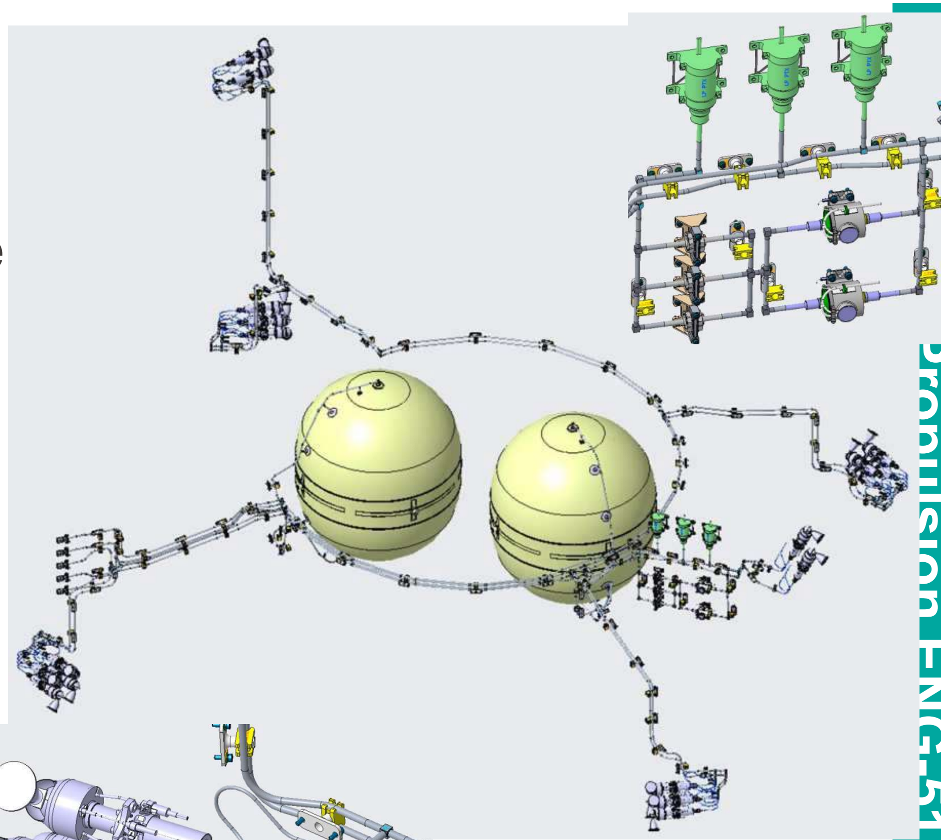
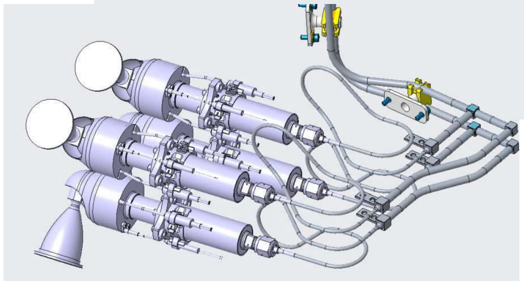
Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of che
propellant propulsion

- Mono-propellant propulsion systems (including redundancy)







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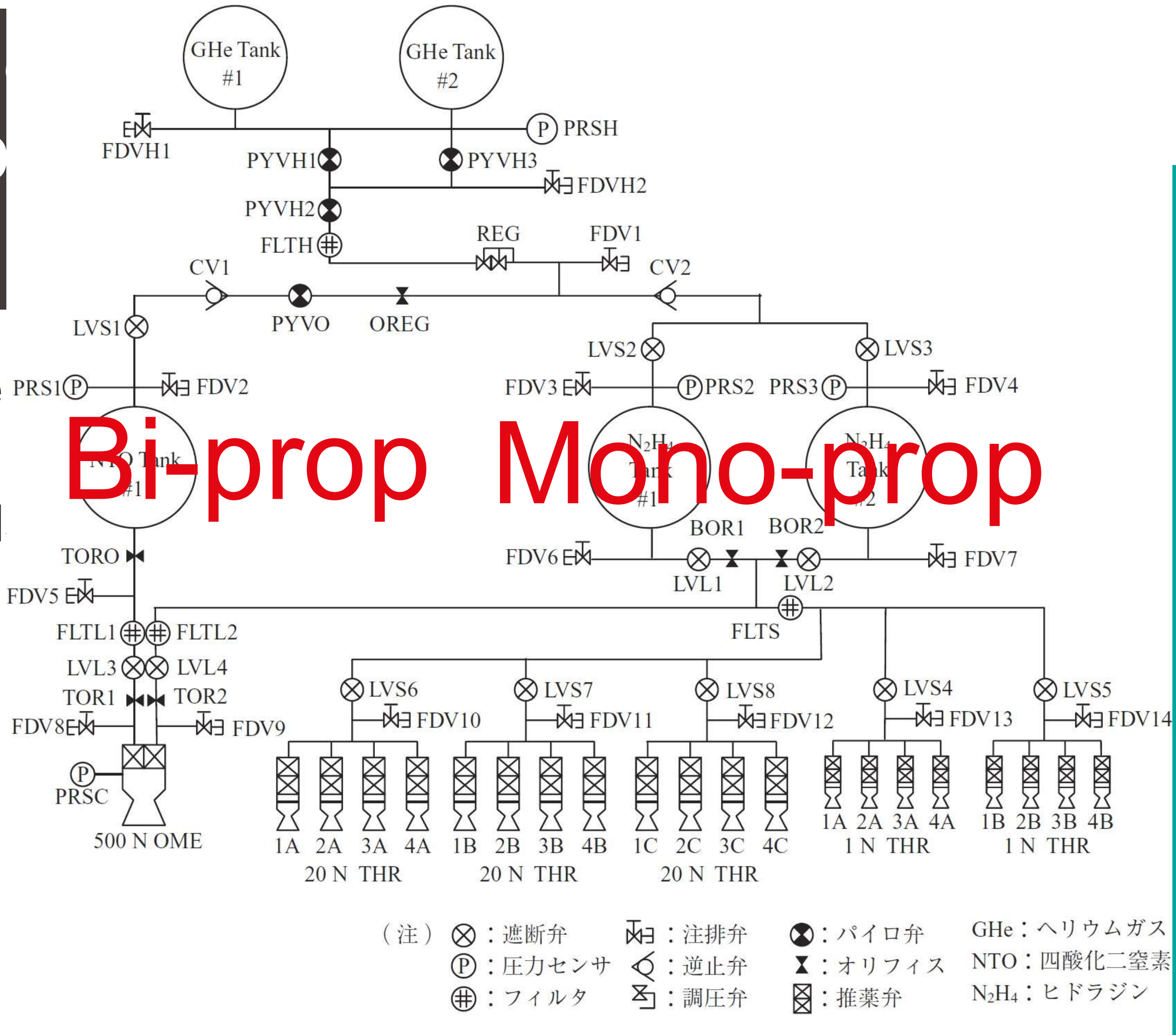
Which Liquid M[...] propellant Prop[...] Systems exist?

Objective: To develop the [...] propellant propulsion

- Mono-propellant propul[...]



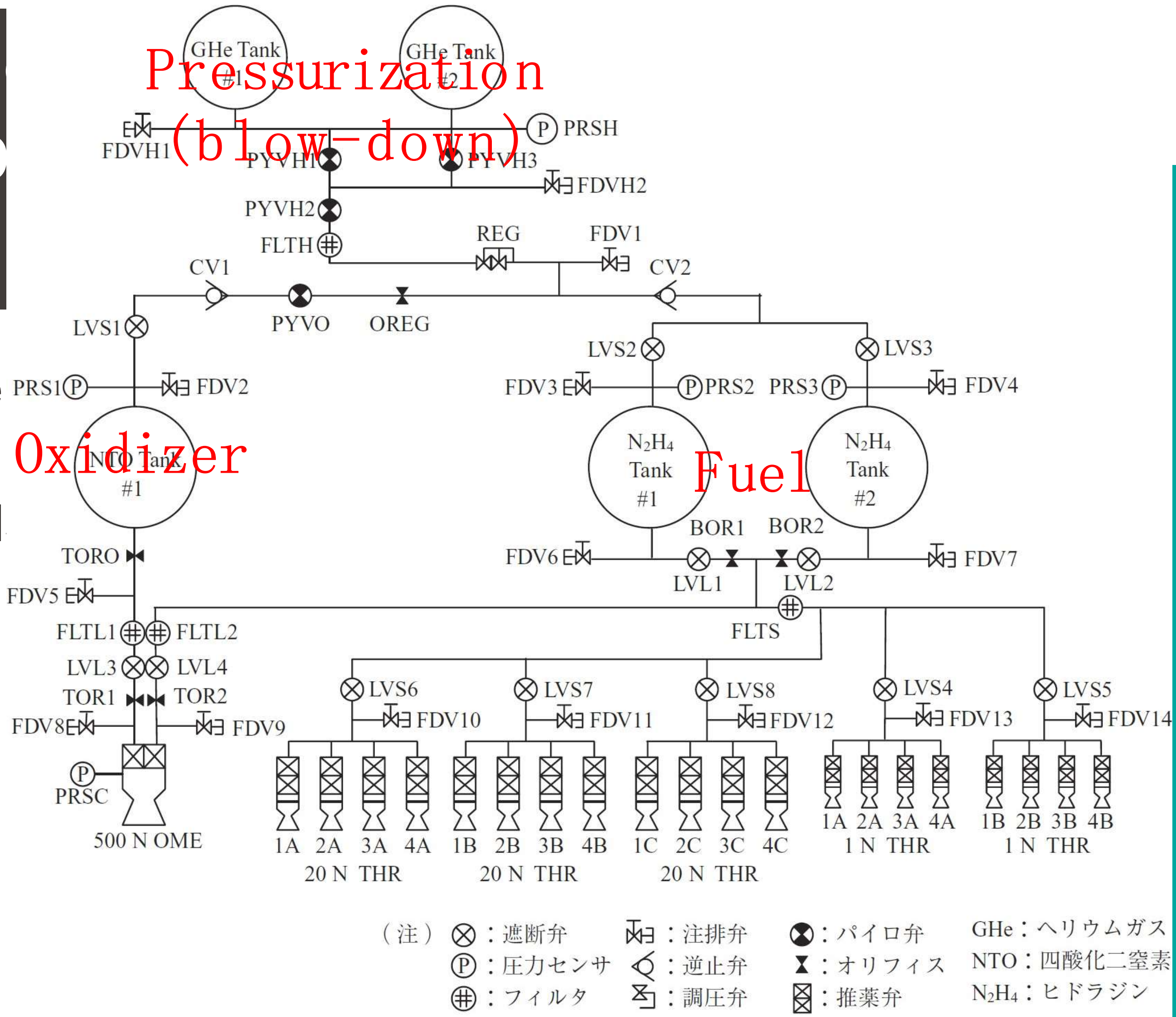
第 1 図　かぐや推進系系統図

Fig. 1　Propulsion system schematic

Which Liquid M
propellant Prop
Systems exist?

Objective: To develop the
propellant propulsion

- Mono-propellant propul



第 1 図 かぐや推進系系統図

Fig. 1 Propulsion system schematic

Which Liquid Mono-propellant Propulsion Systems exist?

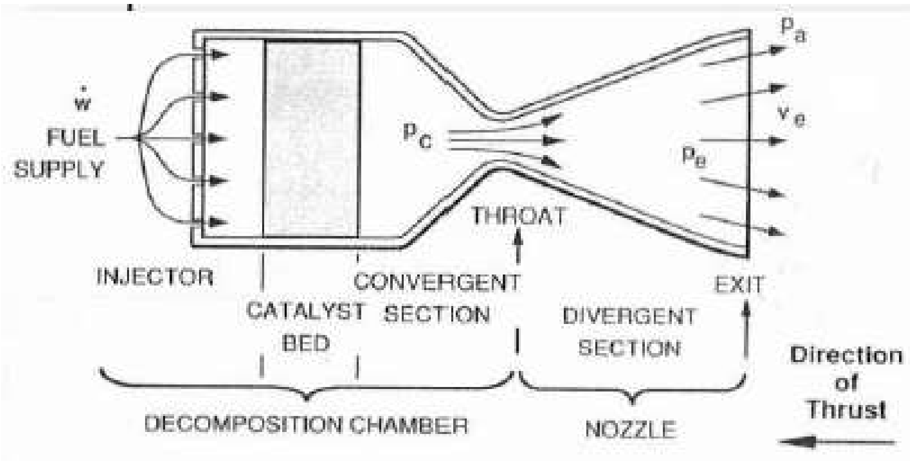
Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

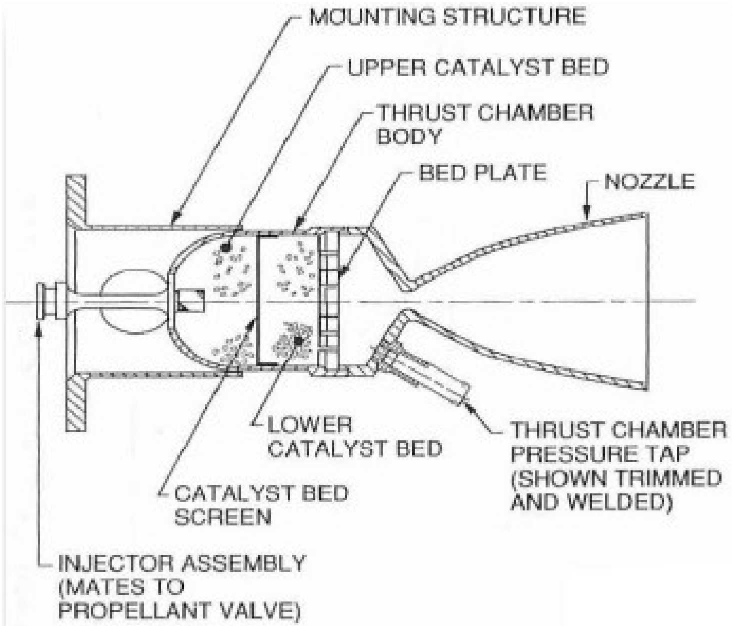
- Characteristics of a mono-propellant propulsion system
  - Relatively simple, robust, cheap
  - Toxic propellant (Hydrazine is very often used) but also more and more 'green'
  - Catalysator is needed for decomposition
  - Blow-down mode is very often used (ratio of 4 to 1)
  - Pressure range between 5.5 bar to 24.6 bar
  - Isp is between 210 to 230 s (Exhaust velocity of 2.0 km / s to 2.3 km / s)
  - Thrust between 1 N to 1 kN
  - Modular set-up is possible using COTS (cost optimization)
  - Temperature and heat exchange must be controlled

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- Mono-propellant propulsion system thruster design

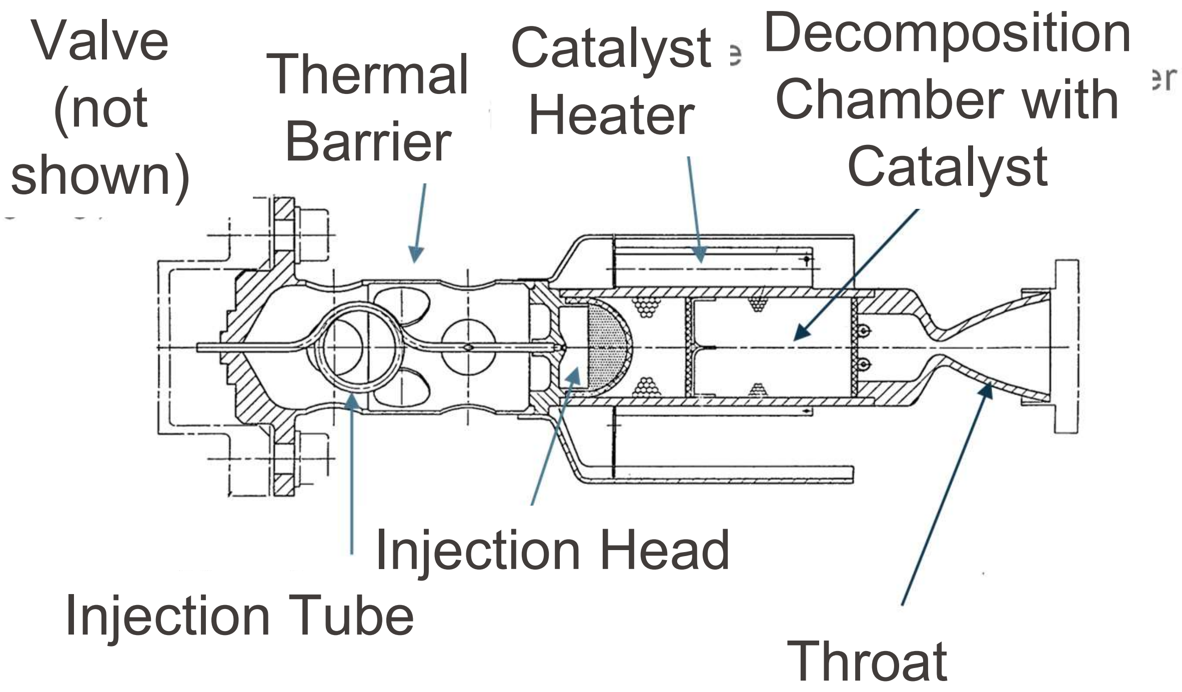


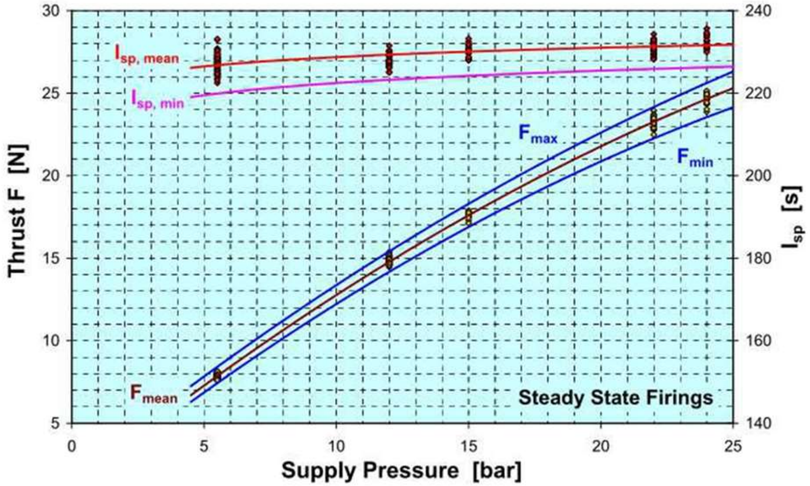


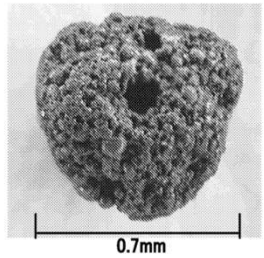
Which Liquid Mo propellant Propu Systems exist?

Objective: To develop the l propellant propulsion

- Mono-propellant propuls







alumina-based Ir metal granules

Which Liquid Mono-propellant Propulsio Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-

Scarved Thruster

1N

20N

400N

Canted Thruster

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- Thruster design:
  - Catalyst bed must be heated prior to firing
    - Typically takes 45 minutes to reach temperature of ~ 250 °C
  - Thruster can be fired cold (< 10 °C) however the degradation increases
    - Typically a thruster will have been qualified to 10 to 15 cold starts as part of the life test (safe mode recovery)
    - The thruster can also be started between 10 and 250 °C (pre-heat start) but number of starts will also be limited (~ 1000 starts)
    - Once the thruster has performed one cold start, the temperature will be in the pre-heat range from the thrust reaction
  - Catalyst is made from Alumina granules, with Iridium coating

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

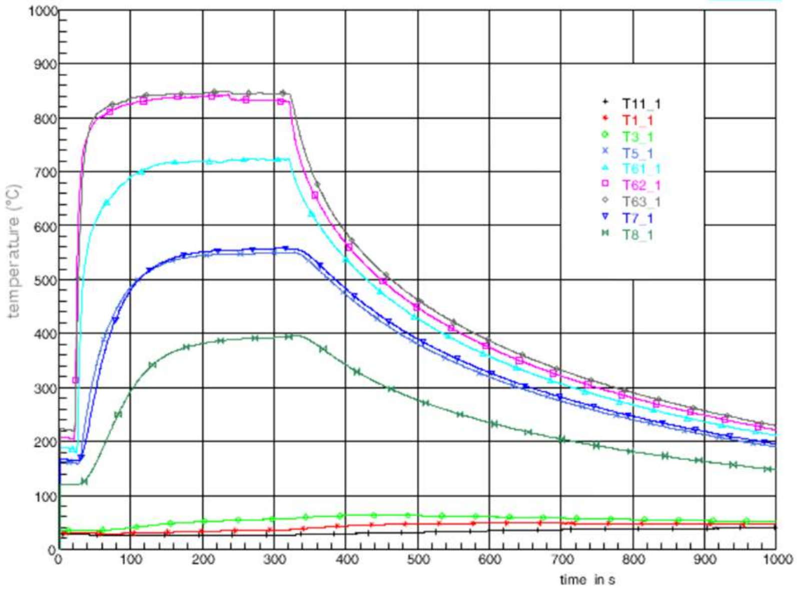
- Thruster design:
  - Catalyst is made from Alumina granules, with Iridium coating
  - Catalyst bed is susceptible to:
    - Catalyst poisoning –amines and silicates particularly
    - High gas flow will damage the catalyst bed

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- Functional principal for liquid mono-propellant decomposition propulsion systems:
  - Exothermal decomposition of Hydrazine
  - Hot gas is accelerated in the Nozzle and ejected
  - Typical catalysator are S405 or KC12GA
  - Reaction equation:

$$3N_2H_4 \rightarrow 4NH_3 + N_2$$
$$4NH_3 \rightarrow 2N_2 + 6H_2$$



Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- Hydrazine (N2H4) Characteristics
  - Hydrazine: colourless hygroscopic liquid, oily, flammable,
  - Stable chemical, can be stored for long periods of time without loss of purity
  - Boiling point = 113.5 °C, Freezing point = 2 °C
  - Density ~ 1008 kg/m³ at 20 °C
  - Fumes in air with vapours which are 4 % heavier than air
  - Fishy Ammonia-like odour detectable at a mean of 3.7 ppm

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- Hydrazine is a hazardous chemical!
  - Air vapour mixture can be highly flammable
  - Can cause fire on contact with rust
  - Protective clothing and breathing apparatus must be worn
  - Can detonate if subjected to physical shock (rapid adiabatic compression e.g. during priming)

W
p
S

C -
p

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- ‘Greener’ propellant…
  - HTP – High Test Peroxide (H2O2 – Hydrogen Peroxide concentration > 85 %)
  - ADN
  - HAN
  - LMP-103S
  - In principle very similar to Hydrazine [N2H4] but potentially some specific features like decomposition, catalyst composition, heating, …
  - Catalyst lifetime…
  - Density Isp…

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

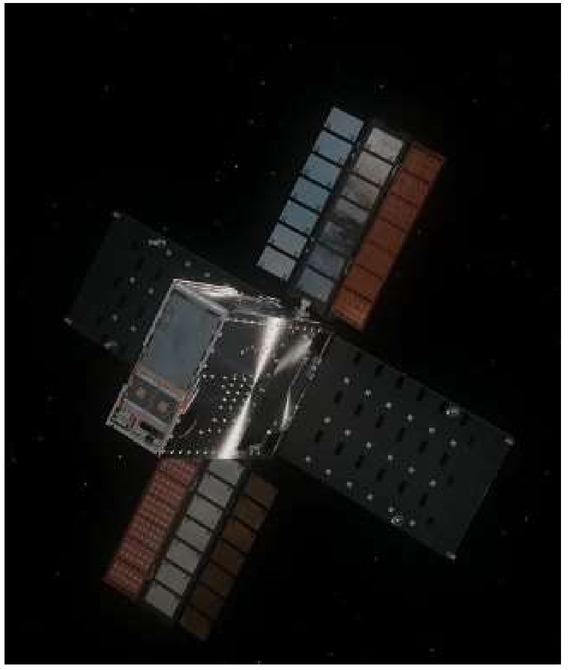
- ‘Greener’ propellant…
  - Energetic ionic liquids
    - By definition, an ionic liquid is a salt with a melting point below 100 °C used in the liquid state
    - Ionic liquid mono propellants are usually mixtures of an oxidizer salt, a fuel and water
    - The most studied oxidizer salts for propellant applications are HNF (Hydraziniumnitroformate), HAN (Hydroxylammoniumnitrates) and ADN (Ammoniumdinitramide)
    - Two ADN formulations LMP-103S and FLP-106, have received particular attention in Europe

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- 'Greener' propellant…
  - Energetic ionic liquids
    - LMP-103S has been selected by the Swedish company ECAPS
    - A successful in-space demonstration was achieved on the PRISMA mission, using 1 N thrusters and the monopropellant LMP-103S
    - Since then the HPGP technology based on LMP-103S now provides a low-hazardous and flight-proven, performance enhancer for small and secondary satellites

Which Liquid Mono-propellant Propulsion Systems exist?



Objective: To develop the basics of chemical liquid propellant propulsion

- ‘Greener’ propellant…
  - Energetic ionic liquids
    - An important HAN formulation is the monopropellant AF- M315E respectively ASCENT (Advanced Spacecraft Energetic Non-Toxic Propellant)
    - The ASCENT propellant is used on the NASA cube sat mission which failed to go into orbit around the moon earlier 2023 when debris blocked propellant lines for the spacecraft’s thrusters
    - Otherwise it could be stated that the propellant has performed a successful in-orbit demonstration as it is suspected that foreign object debris somewhere in the propulsion system caused the thruster problems

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- ‘Greener’ propellant…
  - Nitrous oxide
    - Another promising class of Green Propellants are the so called nitrous oxide fuel blends
    - Those fuel blends consist of nitrous oxide mixed with different hydrocarbons (e.g. C_2H_2, C_2H_4, or C_2H_6)
    - To obtain the propellant, the single components are pressurized, cooled (down to about 220K) and mixed
    - Characteristic for the blends are the high vapor pressures, which could enable self-pressurization of the whole propulsion system
    - One the one hand the high reactivity of the mixture offers the opportunity of a simple ignition system (e.g. a spark plug)

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- ‘Greener’ propellant…
  - Nitrous oxide
    - On the other hand, the whole propulsion system needs a proper flashback arrestor to avoid flame propagation into the tank during all possible operation modes
    - Another challenging aspect is the high combustion temperature of those premixed propellants
    - A reliable cooling system must be established to handle combustion temperatures up to 3500 K

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- ‘Greener’ propellant…
  - Nitrous oxide
    - A significant advantage of the nitrous oxide fuel blends is their high Isp
    - Depending on the mixture composition, an increase of 100 s compared to hydrazine is possible
    - Furthermore only minor health hazards arise, dealing with those propellant mixtures
    - So cheaper and easier handling seems to be possible

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- 'Greener' propellant…
  - Nitrous oxide
    - But…
    - Three people have been killed and numerous persons injured by a prior explosion involving (nitrous oxide) in the motor design of Virgin Galactic space ship
    - A report by the California Division of Occupational Safety and Health said the 2007 blast occurred three seconds after the start of a cold-flow test of nitrous oxide
    - The engine was not firing during the test at the Mojave Air and Space Port

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- ‘Greener’ propellant…
  - Hydrogen Peroxide
    - Hydrogen peroxide is a third group of green propellants currently under investigation
    - Typically the concentration for H_2O_2 used as a rocket propellant is in between 80 to 90 %
    - Those concentrations are needed to achieve an Isp of about 150 s as a mono-propellant, which is quite low compared to hydrazine
    - Characteristic for hydrogen peroxide is its decomposition to O_2 and H_2O with time

Which Liquid Mono-propellant Propulsion Systems exist?

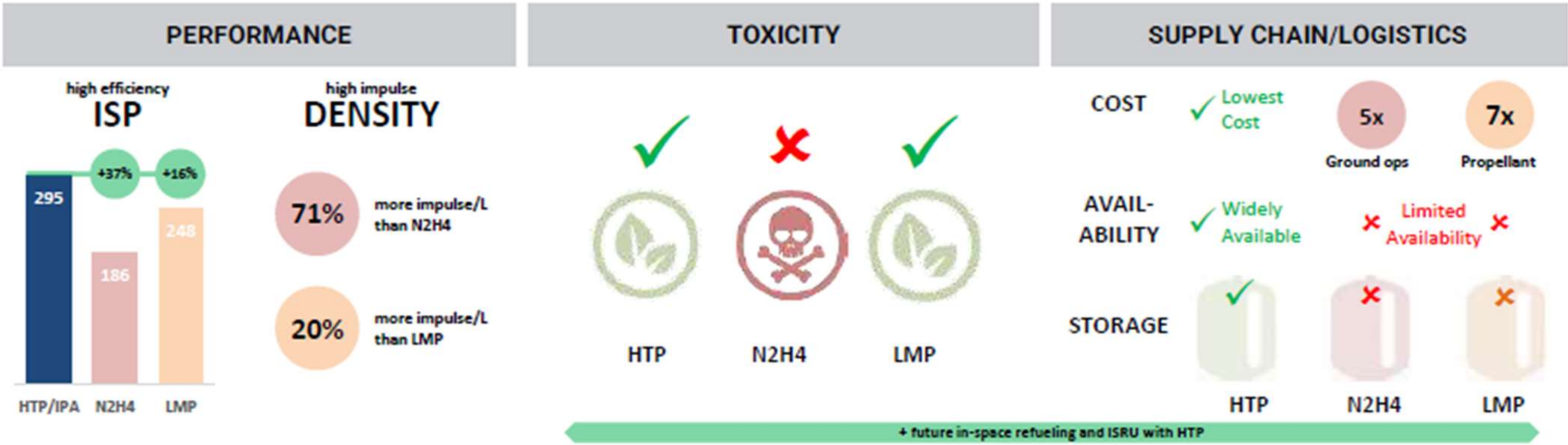
Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- ‘Greener’ propellant…
  - Hydrogen Peroxide
    - Due to its reactivity, compatible materials have to be selected carefully
    - Advantages of H_2O_2 are its benign effect on environment and the low health hazards
    - Furthermore a catalytic decomposition is possible and the combustion temperature is significant lower than that of other green propellant candidates
    - The explosive hazards coming along with the use of hydrogen peroxide need to be more thoroughly investigated

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

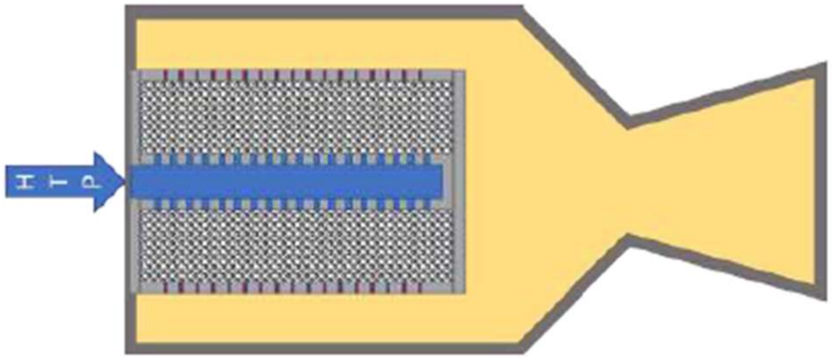
- 'Greener' propellant…



Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

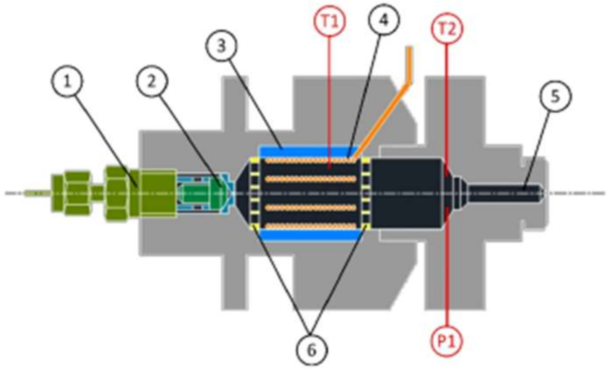
- Example: Benchmark Space Systems Ocelot thruster using HTP
  - HTP (High Test Peroxide with concentration of more than 85 % H_2O_2) provides interesting performance



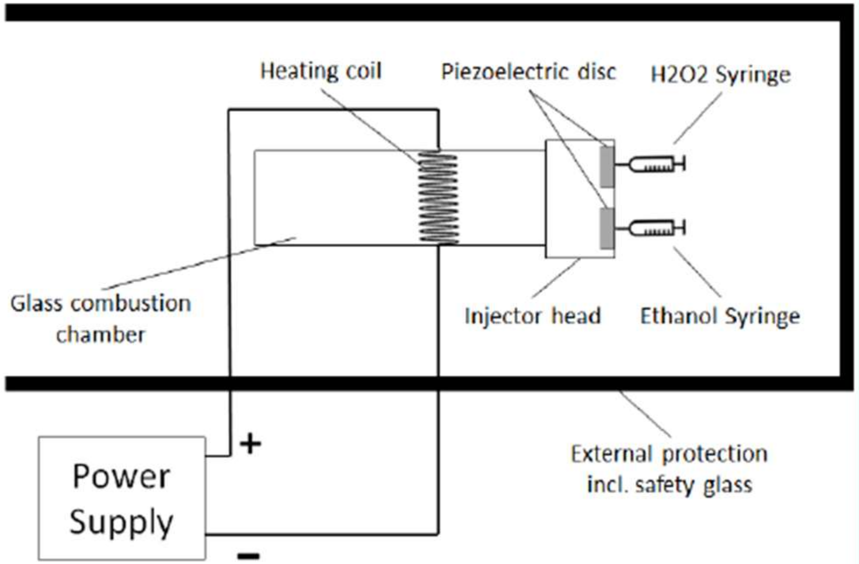
Which Liquid Mono-propellant Propulsio Systems exist?

Objective: To develop the basics (propellant propulsion

- Example: TU Delft thruster using HTP
  - HTP (High Test Peroxide) could also be ignited by thermal decomposition and not only exothermic decomposition (e.g. thermal wire)



Schematic view of thermal igniter [4]. 1: Connector, 2: Injector, 3: (ceramic) Insulator, 4: Heating wire, 5: Nozzle, 6: Holding plates.



Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- Example: TU Delft thruster using HTP
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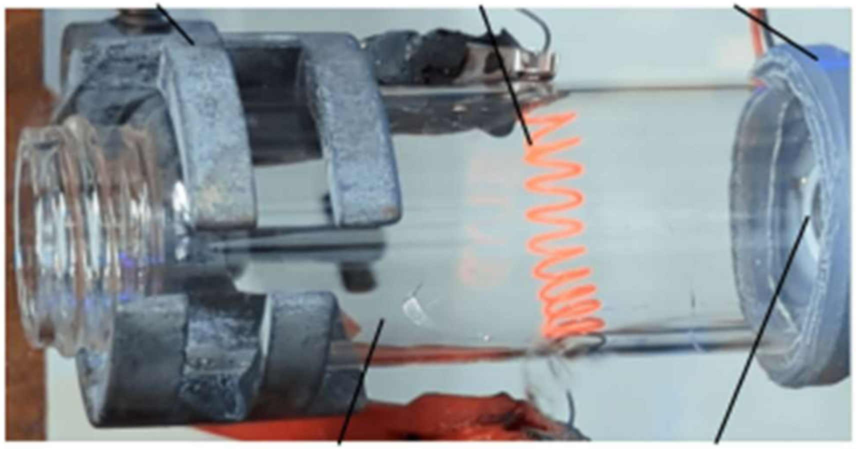


Which Liquid Mono-propellant Propulsion Systems exist?

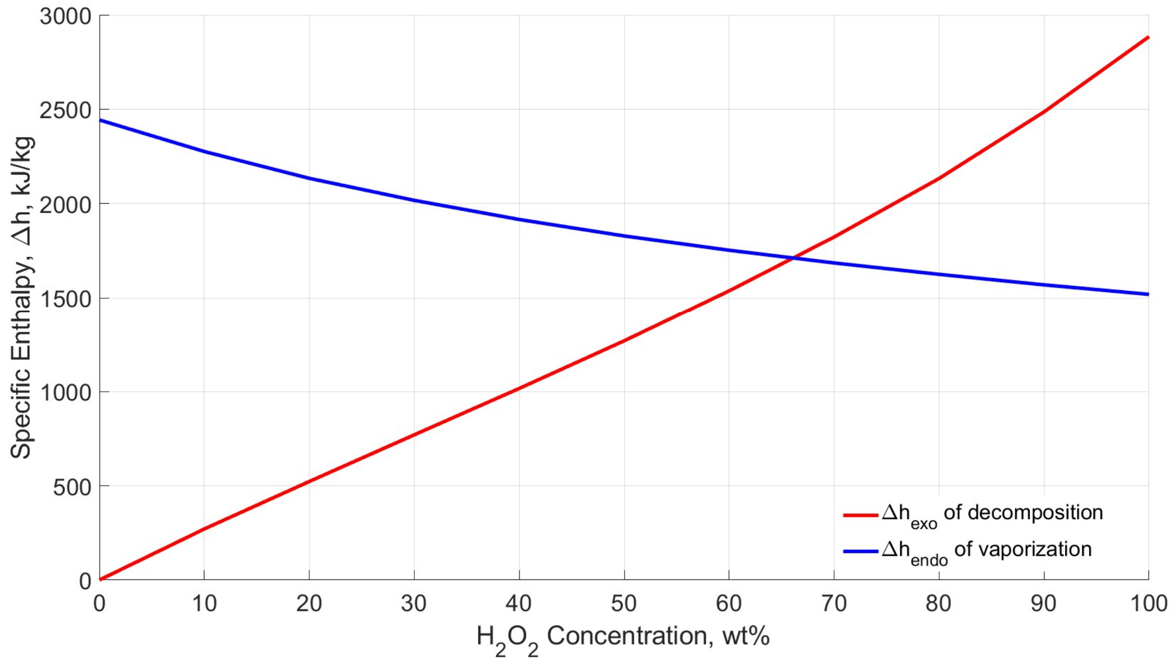
Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- Example: Benchmark Space Systems Ocelot thruster using HTP
  - But HTP decomposes over time…

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- Examp … HTP
  - But



Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of ch
propellant propulsion

- Example: Benchmark Space Syste
  - HTP was used a lot at the beginning of the space race

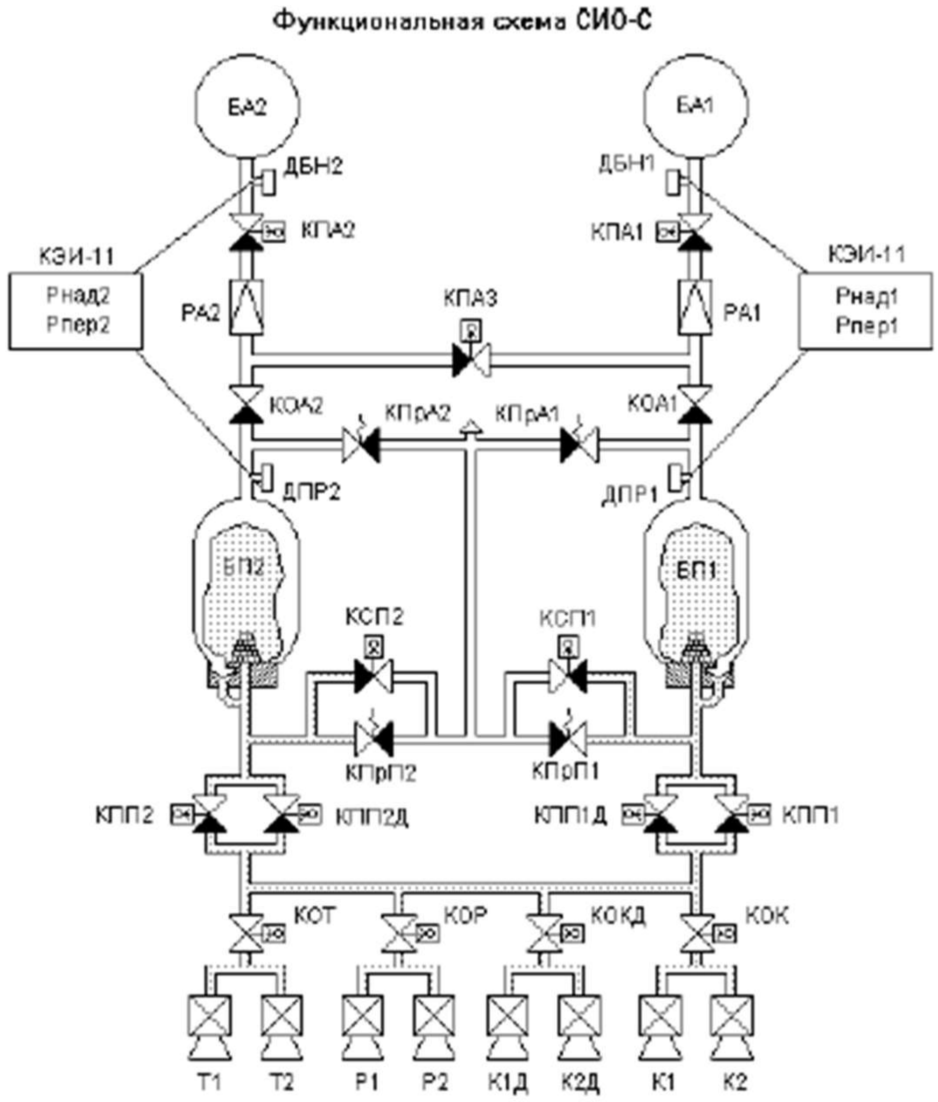


Fig. 1. СИО-С System Functional Block Diagram

Which Liquid Mono-propellant Propulsion Systems exist?

	Flamable	Corrosive	Toxic	Health hazard	Environm hazard	Explosive	Harmful	Oxidizing	Compres sed gas
Hydrazine	X	X	X	X	X	(X)			
Ammonium Dinitramide (ADN)	X			X		X	X	(X)	
Hydroxylammonium nitrate (HAN)			X	X	X	X	X	(X)	
Hydrogen Peroxide	X	X				(X)	X	(X)	
Nitrous Oxide						(X)	X	X	X
Water									

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- ‘Greener’ propellant…
  - Green Hydrazine
    - Blend of Hydrazine with other liquids to 100- to 1000-fold reduced vapor pressure compared to neat hydrazine
    - Such propellants present a previously-unexplored path to realize the same benefits offered by current high-TRL green ionic liquid propellants while preserving the favorably low operating temperatures and preheat power requirements of heritage monopropellant technologies

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- 'Greener' propellant…
  - Green Hydrazine
    - Specifically, green hydrazine-based propellants:
      - Can be fired in conventional, low-cost nickel-based super-alloy thrusters
      - Deliver specific impulse equal to hydrazine and 25-35% greater density-specific impulse
      - Do not require higher catalyst bed preheat temperatures than hydrazine
      - Remain liquid below -50ºC, potentially obviating the need for feed system heating

Which Liquid Mono-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical liquid combustion mono-propellant propulsion

- Summary
  - Monopropellant liquid propulsion systems provide interesting performance for small spacecraft and limited Δv need
  - Monopropellant systems are getting once again popular by the use of greener propellant

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Liquid propulsion systems
  - Monopropellant, **bi-propellant** or tri-propellant
  - Storable or cryogenic propellants
  - Toxic or non-toxic (hazardous or green) propellants
  - Hypergolic or non-hypergolic propellants
  - Pressure-fed (self-pressurization, blow-down or regulated) or pump-fed propulsion

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- A little bit of history…
  - The idea of liquid rocket as understood in the modern context first appears in the book *The Exploration of Cosmic Space by Means of Reaction Devices*, by the Russian school teacher Konstantin Tsiolkovsky
  - This seminal treatise on astronautics was published in May 1903, but was not distributed outside Russia until years later, and Russian scientists paid little attention to it

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- A little bit of history…continued
  - Pedro Paulet wrote a letter to El Comercio in Lima in 1927, claiming he had experimented with a liquid rocket engine while he was a student in Paris three decades earlier
  - Historians of early rocketry experiments, among them Max Valier, Willy Ley and John D. Clark, have given differing amounts of credence to Paulet's report
  - Valier applauded Paulet's liquid-propelled rocket design in the Verein für Raumschiffahrt *Die Rakete*, saying the engine had "amazing power" and that his plans were necessary for future rocket development

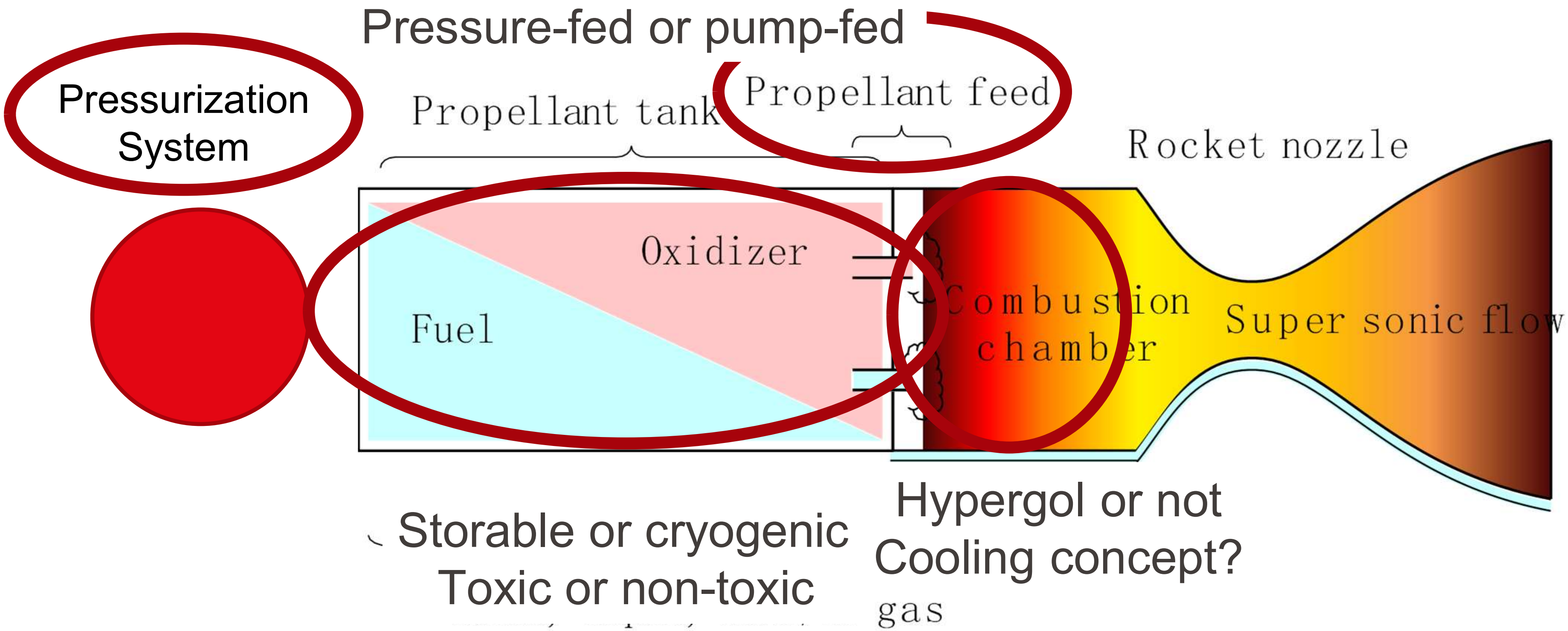
Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- A little bit of history…continued
  - Wernher von Braun would later describe Paulet as "the pioneer of the liquid fuel propulsion motor" and stated that "Paulet helped man reach the Moon "
  - The first *flight* of a liquid-propellant rocket took place on March 16, 1926 at Auburn, Massachusetts, when American professor Dr. Robert H. Goddard launched a vehicle using liquid oxygen and gasoline as propellants
  - The rocket rose just 41 feet during a 2.5-second flight that ended in a cabbage field, but it was an important demonstration that rockets utilizing liquid propulsion were possible

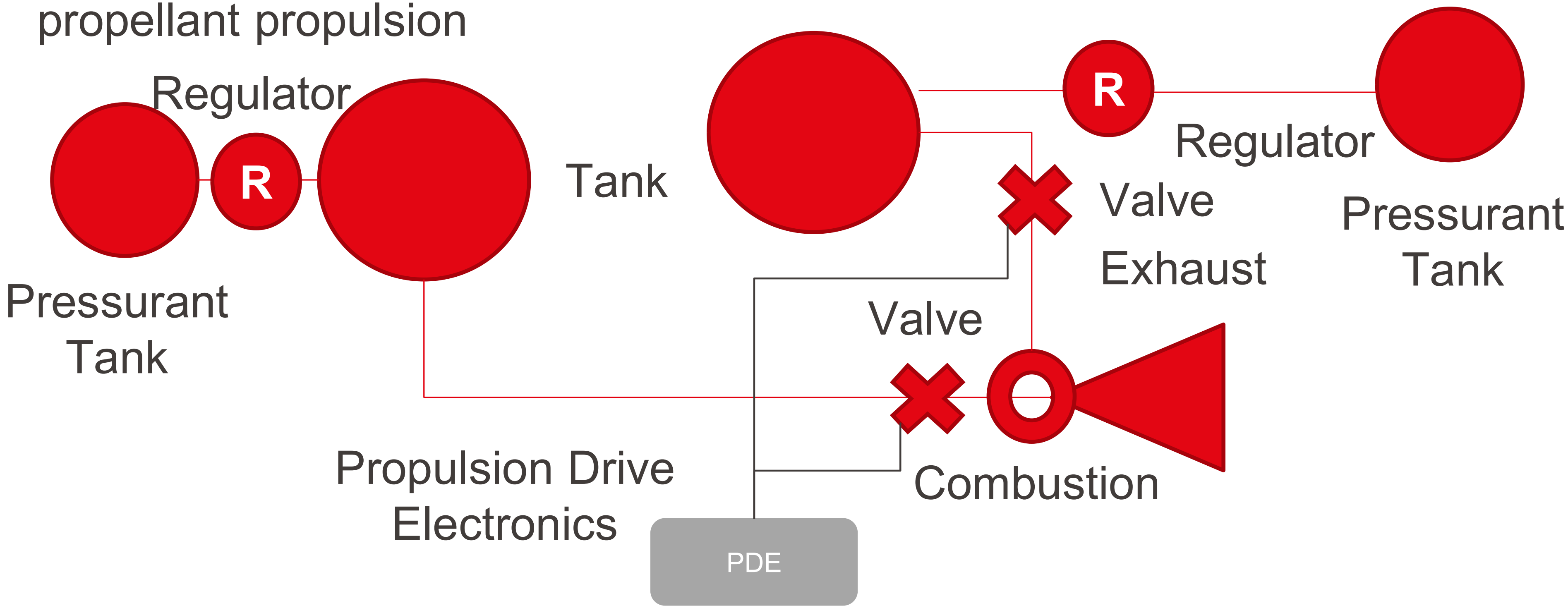
		Propellant Phase in Tanks		
		Solid	Liquid	Gas
Chemical Reaction	Combustion		Bipropellant Thruster LOx / LH2 – LOx / LCH4 – MON / MMH – HTP / Ethanol	
	Decomp		HTP / IPA	
	No			

Which Liquid Bi-propellant Propulsion Systems exist?



Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion



Which Liquid Bi-propellant Propulsion Systems exist?

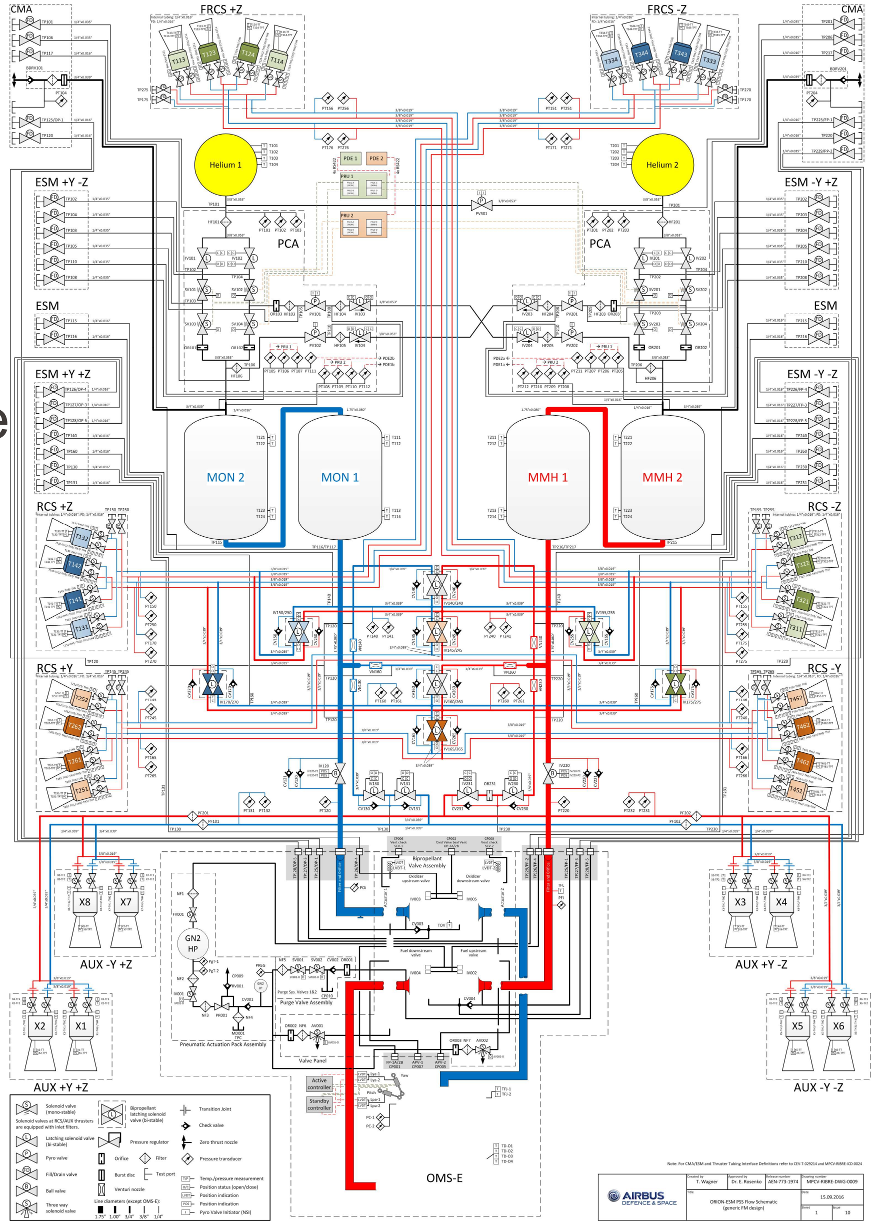
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Characteristics (advantages) of a Bi-propellant Propulsion System
  - Highest achievable specific impulse for chemical rocket propulsion
  - Controllability (on / off control, restart ability, throttable, pulse mode firing which results in important engine parameter for reaction control thruster – minimum impulse bit)
  - Easy adaptation to launcher or S/C architecture
  - Possibility of realistic ground testing and pre-launch check-out
  - Enable component redundancy to virtually any level

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of che
propellant propulsion

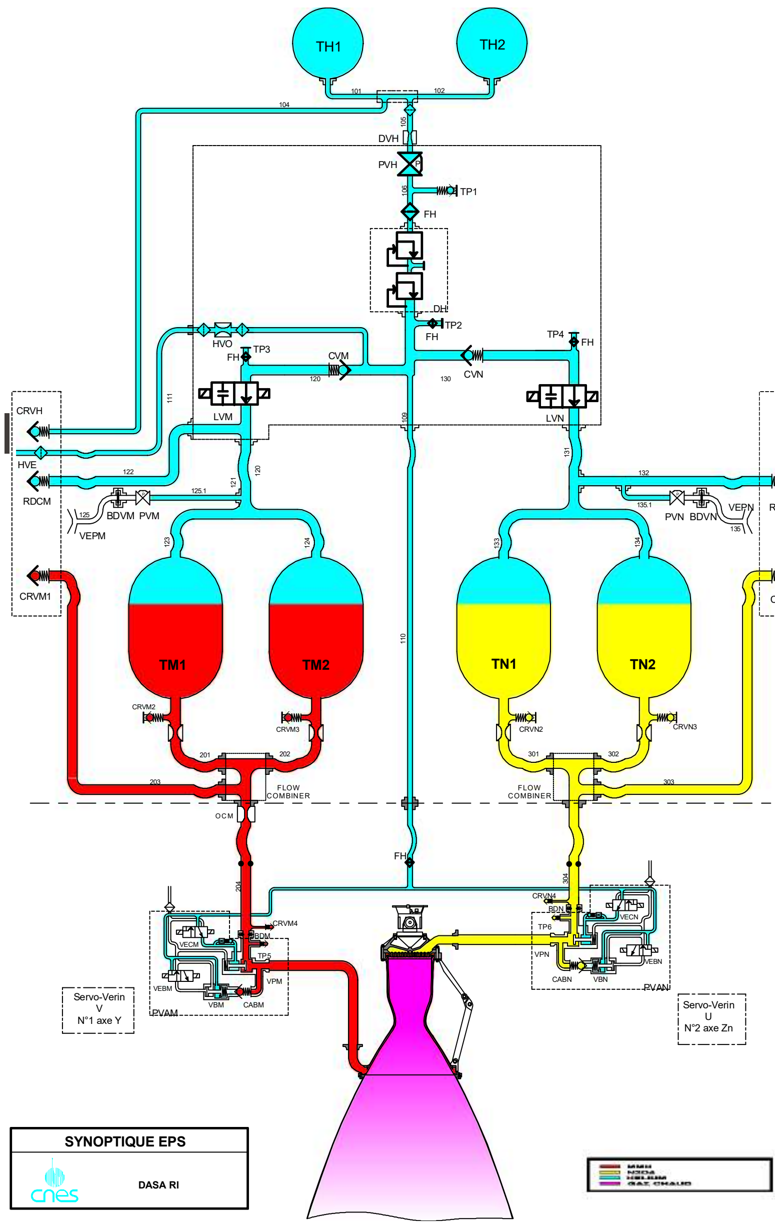
- Example: Orion-ESM Propulsion System
  - Human-rated



Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical propellant propulsion

- Example: A5 Upper Stage EPS Propulsion System
  - Commercial launch vehicle



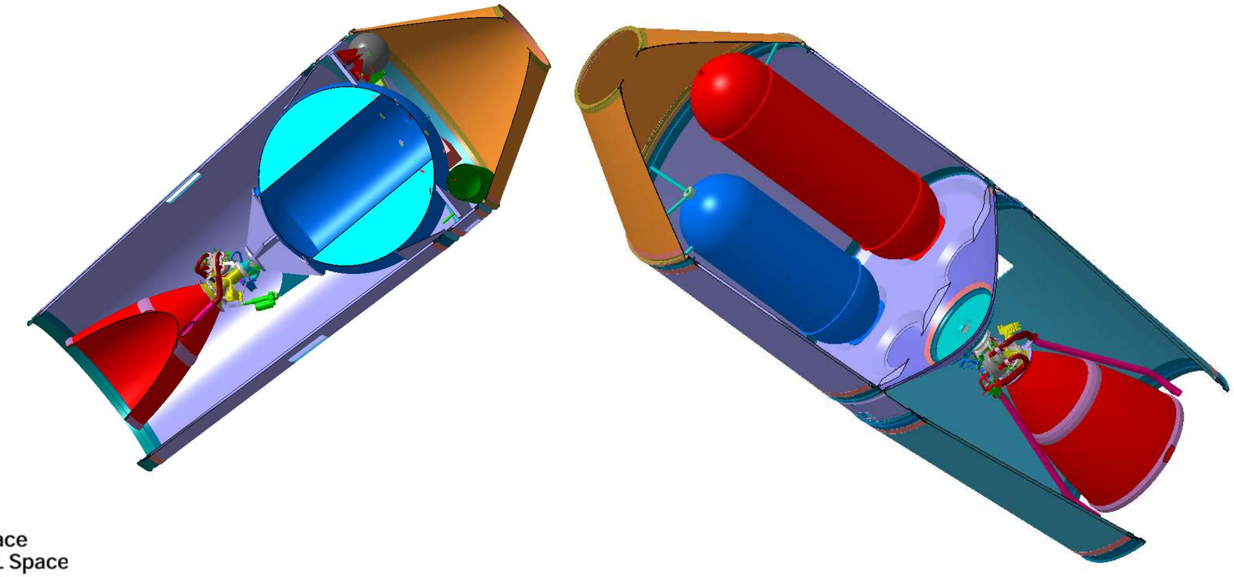
Which Liquid Bi-propellant Propulsion Systems exist?

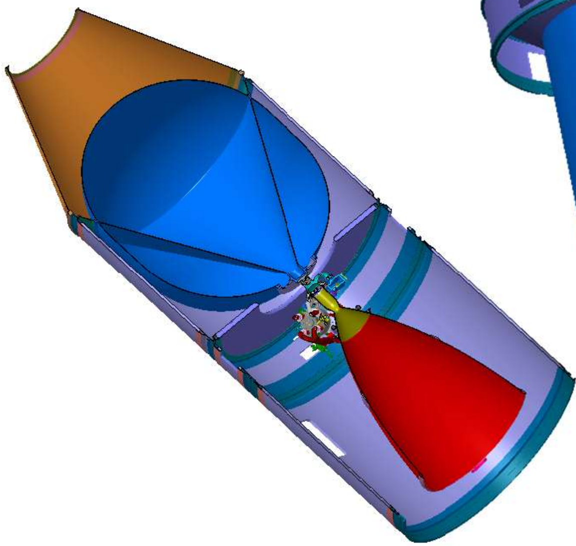
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

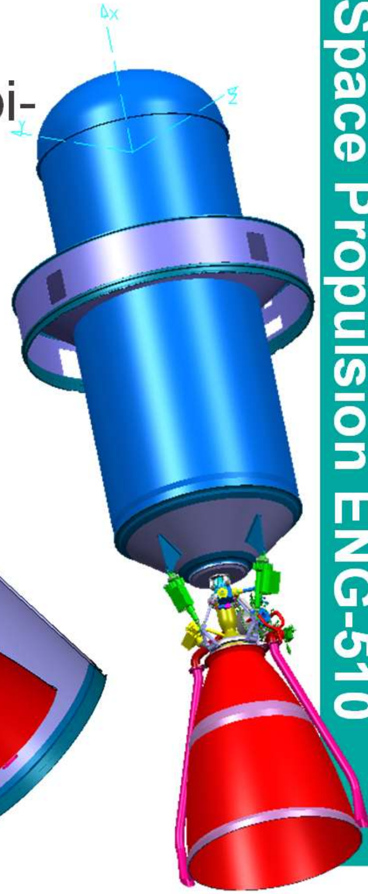
- Architecture for Liquid Bi-propellant Combustion Propulsion Systems :
  - Liquid propellant must be stored in separate tanks (e.g. cylindrical tanks, spherical tanks, torus tanks, spherical + conical tanks, …)
  - It allows to operate all Equipment below the regulator at lower pressure and therefore has lower strength requirements
  - It allows to operate the thruster at constant inlet pressure until the storage tank pressure drops below the regulator pressure and therefore ensures consistent level of thrust

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion



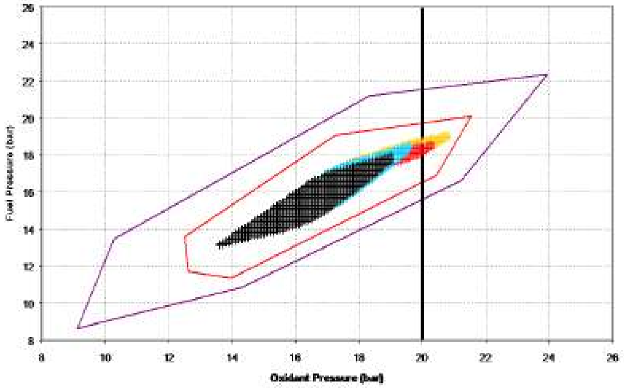




Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Characteristics (disadvantages) of a Bi-propellant Propulsion System
  - Lower density than solid propellants
  - Higher parts count than other chemical systems
  - High complexity
  - Concerns on leakage
  - Concerns on combustion stability
  - Difficult to control flow
  - Need mixture ratio control
  - Need special design for zero-g ignition



Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Characteristics (advantages) of a Bi-propellant Propulsion System
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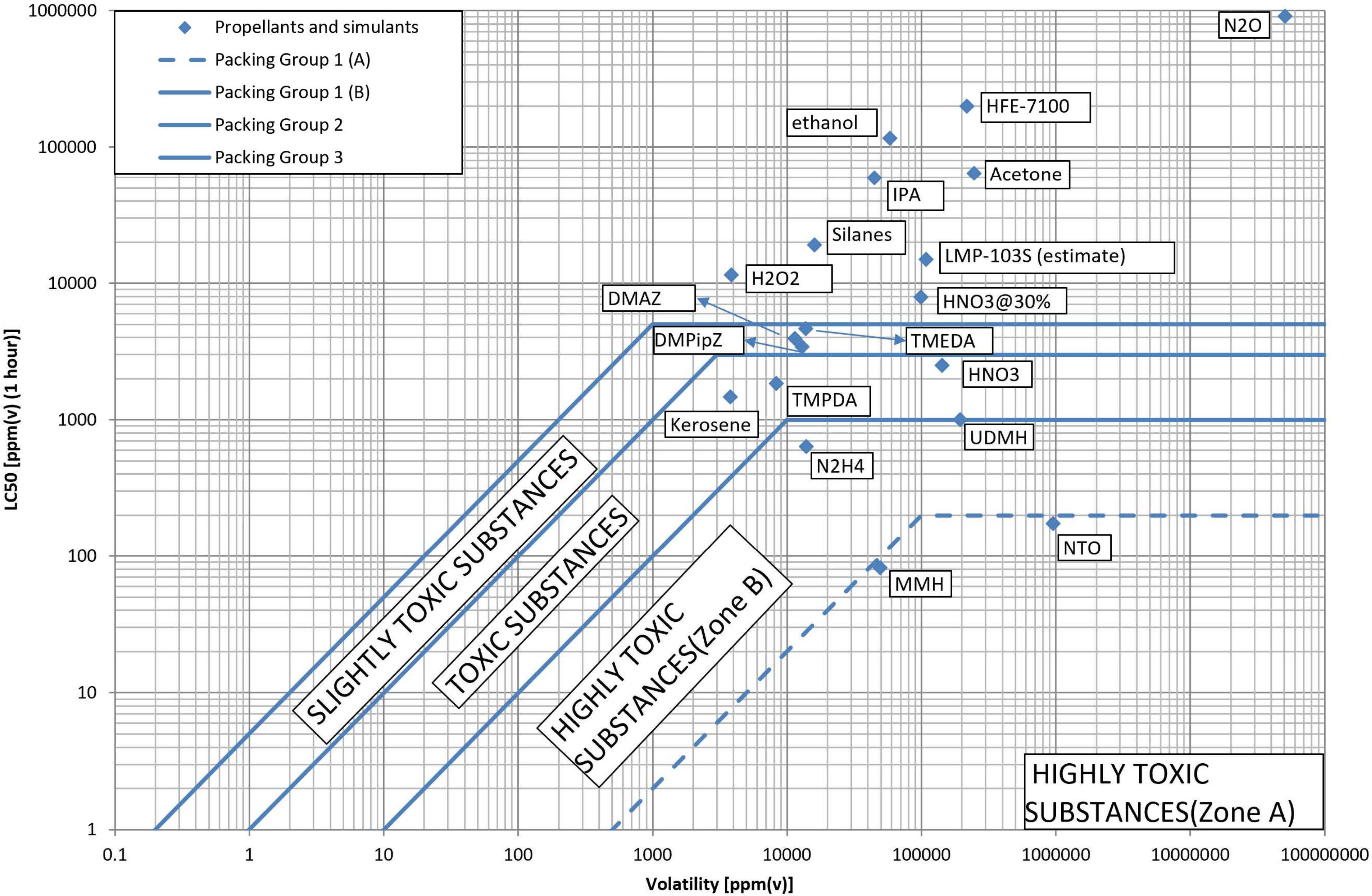
  - Possibility of realistic ground testing and pre-launch check-out
  - Enable component redundancy to virtually any level

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Additional classification of liquid bi-prop systems:
  - Cryogenic or storable propellants (higher performance but also need for thermal insulation)
  - Hypergolic or non-hypergolic (dedicated ignitor needed versus risk of hard start)
  - Toxic or non-toxic (similar to mono-propellant…)
  - Pressure-fed or pump-fed (pressure-fed similar to mono-prop versus higher performance by pump-fed)


Propellants and simulants
Packing Group 1 (A)
Packing Group 1 (B)
Packing Group 2
Packing Group 3
N2O
HFE-7100
ethanol
Acetone
IPA
Silanes
LMP-103S (estimate)
H2O2
DMAZ
HNO3@30%
DMPipZ
TMEDA
HNO3
TMPDA
Kerosene
UDMH
N2H4
NTO
MMH
SLIGHTLY TOXIC SUBSTANCES
TOXIC SUBSTANCES
HIGHLY TOXIC SUBSTANCES(Zone B)
HIGHLY TOXIC SUBSTANCES(Zone A)
LC50 [ppm(v) (1 hour)]
Volatility [ppm(v)]
1000000
100000
10000
1000
100
10
1
0.1
1
10
100
1000
10000
100000
1000000
10000000
100000000

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Toxic or non-toxic (similar to mono-propellant…)
  - Conventional Bipropellant are:
    - Fuel: Monomethyl Hydrazine MMH
    - Oxidiser: (Di)Nitrogen Tetroxide NTO

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Toxic or non-toxic (similar to mono-propellant…)
  - Mono-methyl Hydrazine, MMH (CH3NHNH2) Characteristics:
    - Mono methyl hydrazine is a clear, water-white, hydroscopic, toxic
    - Stable chemical, can be stored for long periods of time
    - MMH is not sensitive to shock or friction and is more stable than hydrazine under conditions of mild heating
    - MMH is very reactive and will undergo a wide variety of reactions with both organic and inorganic compounds.

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Toxic or non-toxic (similar to mono-propellant…)
  - Nitrogen Tetroxide (N_2O_4) Characteristics:
    - Nitrogen tetroxide, also known as dinitrogen tetroxide, is a red/brown liquid
    - Highly reactive, very toxic oxidiser which is thermally stable and insensitive to mechanical shock and impact
    - Non-flammable but will support combustion and react hypergolically with high energy fuels
    - Boiling point = 21°C at atmospheric pressure
    - Freezing point = -13 °C (MON-3)

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Toxic or non-toxic (similar to mono-propellant…)
  - Nitrogen Tetroxide (N2O4) Characteristics:
    - Density ~ 1.44 kg / litre at 20 °C (MON-3)
    - Irritating, unpleasant odour, similar to bad eggs
    - Nitrogen Tetroxide is a hazardous chemical!
    - Air / vapour mixtures can be flammable
    - Will not burn by itself, but will support combustion of other chemicals
    - Protective clothing and breathing apparatus must be worn whilst handling

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Toxic or non-toxic (similar to mono-propellant…)
  - Mixed Oxides of Nitrogen, MON (today in propulsion applications, Nitrogen Tetroxide is mixed with Nitric Oxide gas, NO) (not to be confused with Nitrous Oxide or Nitric Acid)
  - When NO is in solution the resultant chemical mixture is called Mixed Oxides of Nitrogen or MON
    - Written as MON-i, where i indicates the percentage NO (volume)
    - 1 % NO content = MON-1 –most used with UDMH fuel
    - 3 % NO content = MON-3 –most used with N2H4 and MMH

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Toxic or non-toxic (similar to mono-propellant…)
  - NO addition slightly decreases oxidation potential, and makes it more expensive
  - Corrosiveness is decreased however, particularly in contact with titanium alloys
  - Addition of NO turns the NTO from red / brown to clear green!

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Architecture for Liquid Bi-propellant Combustion Propulsion Systems:
  - Propellant feeding cold be performed as pressure-fed or pump-fed system
  - Pressure-fed is either self-pressurized or with inert gas support
  - Pressure-fed with inert gas could be either in blow-down modus or pressure-regulated
  - Pump-fed could be performed with turbopump or e-pump

Which Liquid Bi-propellant Propulsion Systems exist?

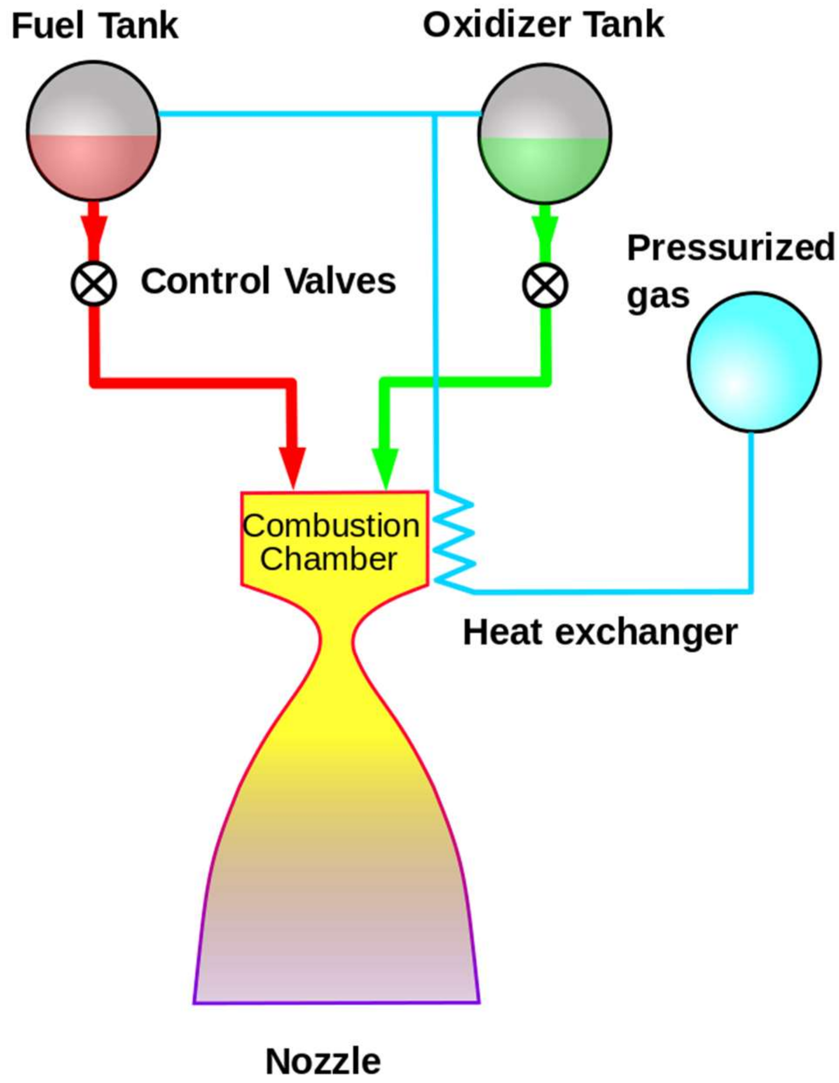
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pressure-fed system is feeding liquid propellant to the Combustion Chamber by large pressure difference (>> 20 bar in propellant tank versus vacuum in combustion chamber)
  - Blow-down system
  - High pressure (gaseous) storage system in pressurant vessels
  - Low pressure (solid powder) storage on ground ignited in orbit
  - Self-pressurization

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of ch
propellant propulsion

- Pressure-fed cycle



Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pressure-fed system
  - The pressure-fed engine / propulsion system is a class of rocket engine designs
  - A separate gas supply, usually Helium or Nitrogen pressurizes the propellant tanks to force fuel and oxidizer to the combustion chamber
  - To maintain adequate flow, the tank pressures must exceed the combustion chamber pressure
  - Pressure fed engines have simple plumbing and have no need for complex and occasionally unreliable turbopumps

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pressure-fed system
  - A typical startup procedure begins with opening a valve, often a one-shot pyrotechnic device, to allow the pressurizing gas to flow through check valves into the propellant tanks
  - Then the propellant valves in the engine itself are opened
  - If the fuel and oxidizer are hypergolic, they burn on contact; non-hypergolic fuels require an igniter
  - Multiple burns can be conducted by merely opening and closing the propellant valves as needed, if the pressurization system also has activating valves

Which Liquid Bi-propellant Propulsion Systems exist?

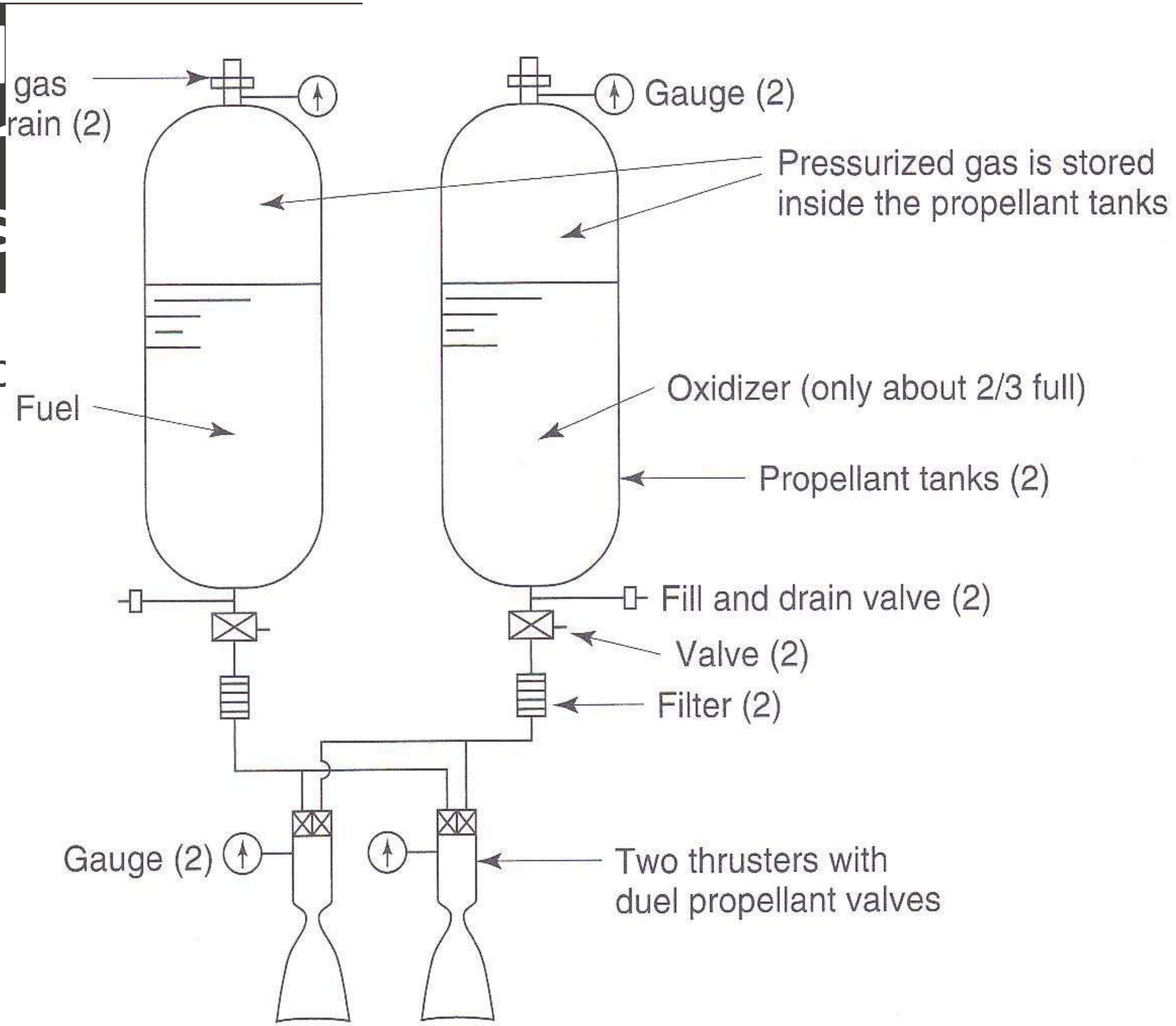
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pressure-fed system
  - They can be operated electrically, or by gas pressure controlled by smaller electrically operated valves.
  - Care must be taken, especially during long burns, to avoid excessive cooling of the pressurizing gas due to adiabatic expansion
  - Cold gas could freeze a propellant, decrease tank pressures or damage components not designed for low temperatures
  - Pressure-fed engines have practical limits on propellant pressure, which in turn limits combustion chamber pressure
  - High pressure propellant tanks require thicker walls leading to higher mass

Which Liquid propellant Pr Systems exis

Objective: To develop propellant propulsion

- Blow-down pressure-fed system



L4 – Propulsion Systems

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Self-pressurized pressure-fed system
  - Self-pressurized pressure-fed system leads t mass
  - But not dedicated pressurization system is needed
  - Vaporization need limits use for long duration burns
  - Example: Gate Space with NOx / Ethane

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Self-pressurized pressure-fed system
  - Hydrogen Peroxide / Fuel (Octane, Ethanol, …)
    - Effect of self decomposition
    - Compatibility aspects
  - Nitrous Oxide / Ethane
    - Self-pressurization
    - High tank pressure, tank mass

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pressure regulated pressure-fed system
  - Pressure-fed regulated system requiring pressure regulator (Reducing the input pressure of a fluid by passive mechanism)
  - Pressure-fed regulated system results in constant propellant tank pressure = constant flow rate = constant reaction = constant thrust
  - Only gas tank needs high-pressure
  - But chamber pressure < O/F tank pressure ≪ gas tank pressure

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

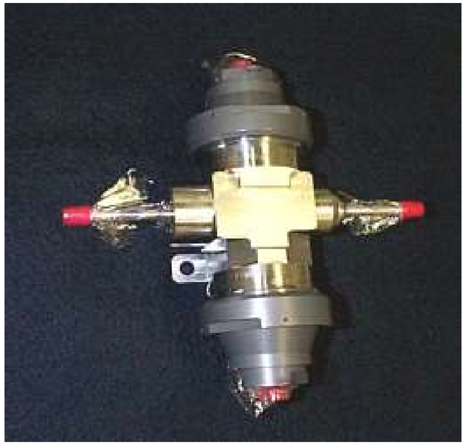
- Pressure regulated pressure-fed system
  - Mechanical pressure regulator
    - The mechanical pressure regulator controls the flow of gas into the propellant tanks
    - The PR will convert a range of high pressures into a constant low pressure (within limits)
    - The pressure regulator will work automatically based on the inlet pressure
    - Most types are series redundant (if the primary valve fails, the outlet pressure will rise until the secondary seat takes over)

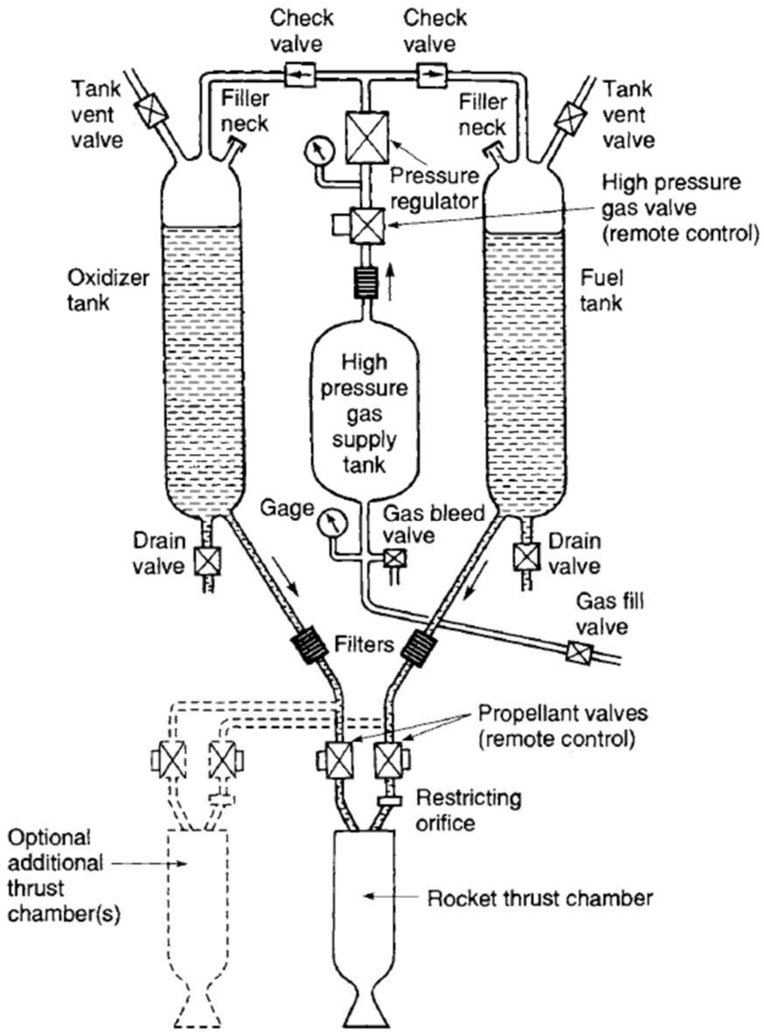
Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical propellant propulsion

- Pressure regulated pressure-fed system
  - Mechanical pressure regulator

Space Components Pressure Regulator
(PN 9414001-501)





Which Liquid Bi-propellant Propulsion Systems exist?

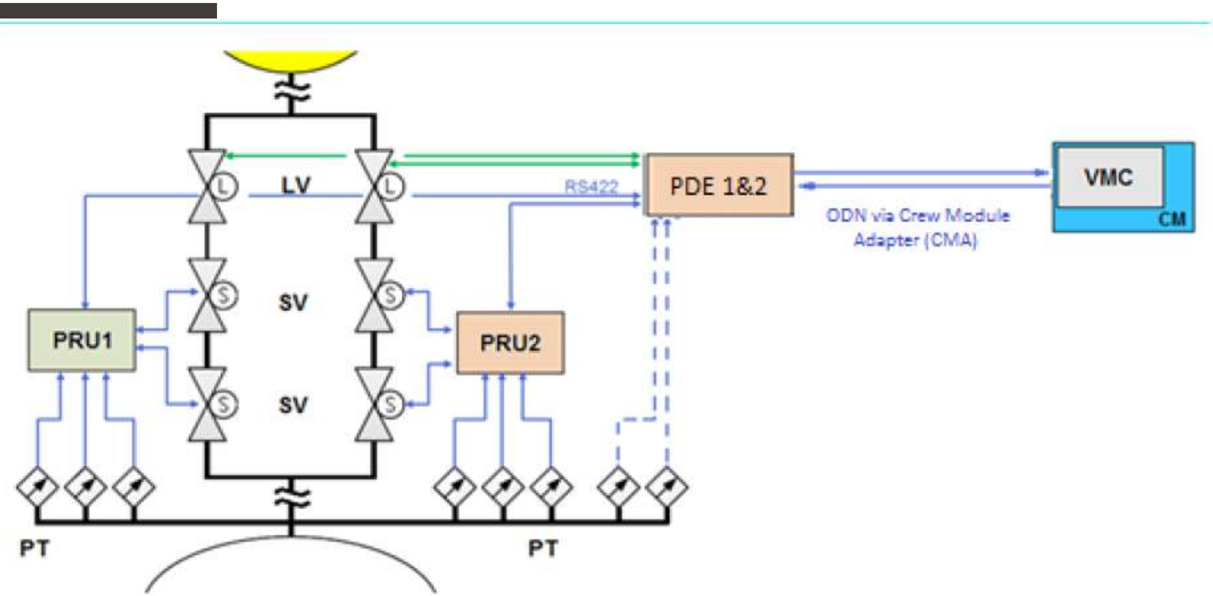
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

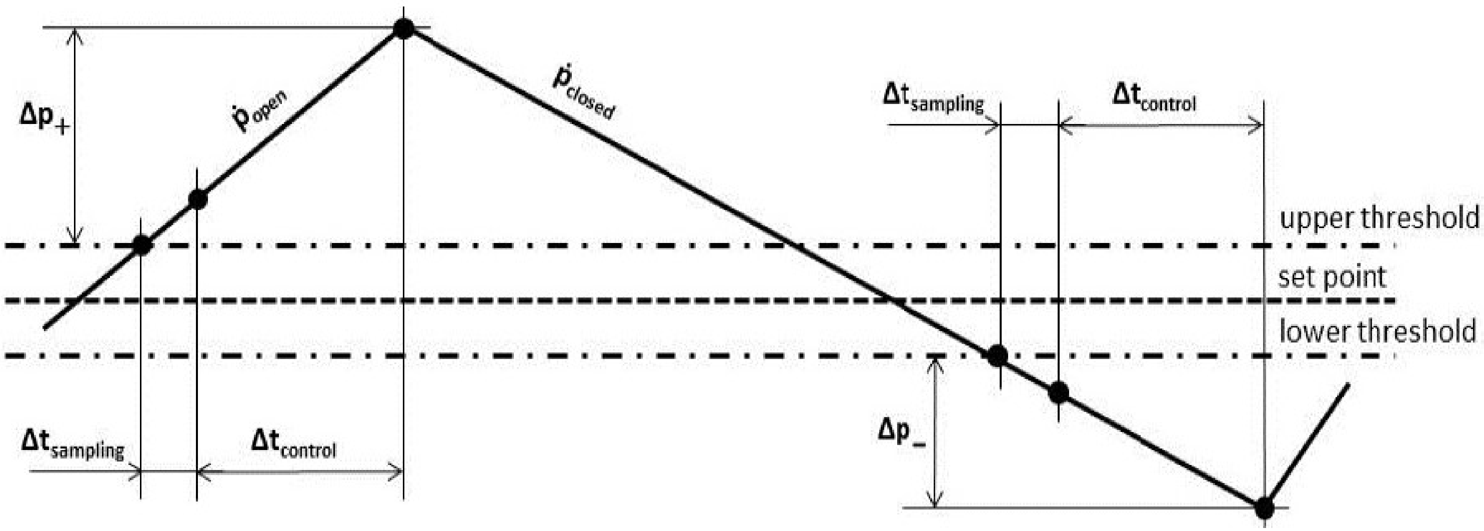
- Pressure regulated pressure-fed system
  - Electro-mechanical pressure regulator
  - Bang-bang regulation with solenoid valves

Which Liquid Bi-propellant Propu… Systems exist?

Objective: To develop the b… propellant propulsion

- Pressure regulated press…





Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pressure regulated pressure-fed system
  - Ball valve…

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed system:
  - Pump-fed system is feeding high pressure to the Combustion Chamber resulting in low tank pressure = light weight tank
  - Today turbo-pumps are mainly used but also more and more electro-pumps are considered
  - Turbo-pumps are technically very difficult equipment
  - Electro-pumps require lot of power (i.e. batteries, mass, …)
  - Note: Cryogenic propellant require a very low tank pressure

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Turbo-pumps architecture
  - Gas generator cycle
  - Combustion tap-off cycle
  - Expander-bleed cycle (single or dual expander cycle)
  - Full expander cycle
  - Staged combustion cycle (fuel-rich, Ox-rich, full flow)
- Electro-pumps architecture

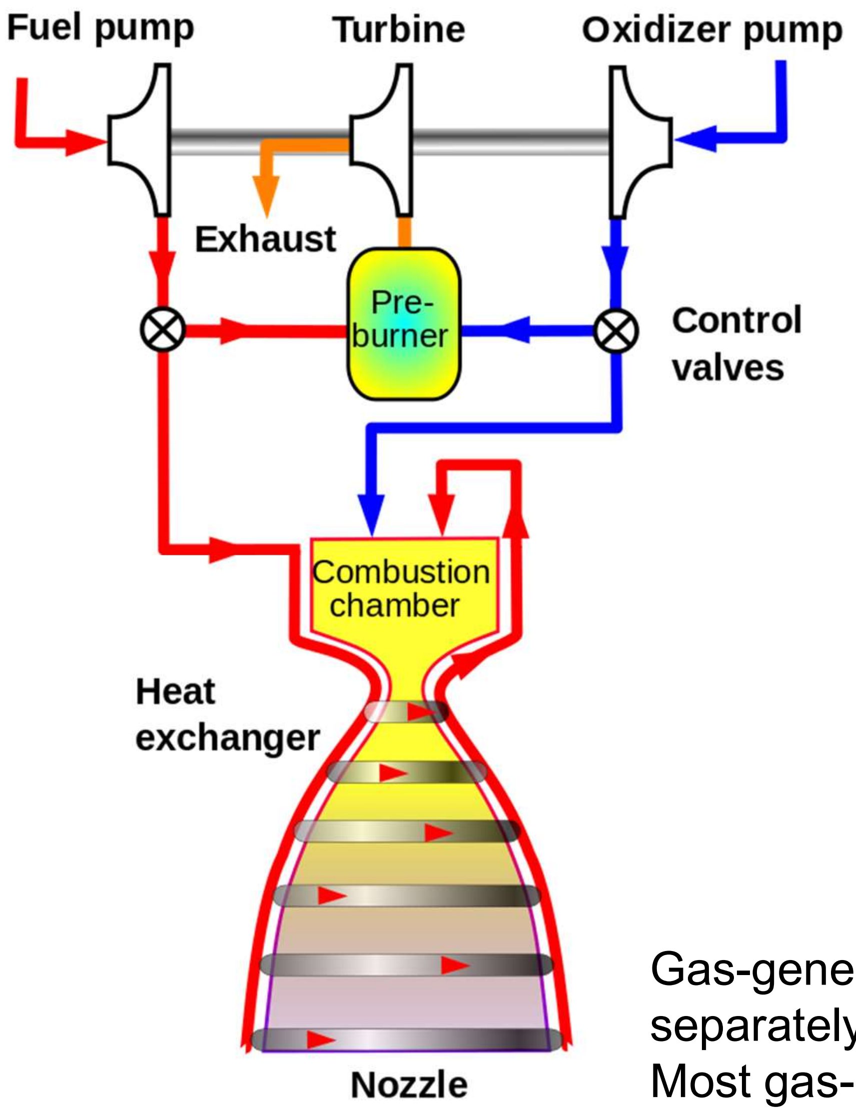
Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Turbo-pumps architecture

Engine Cycle	Open Cycle (Dump Gas)	Closed Loop (Re-use Gas)
Burner	Gas Generator Combustion Tap-off	Staged Combustion
Regenerative cooling	Expander-bleed	Full expander

Gas Generator Cycle



Turbine gas :

Tapping a part of the propellants form the main line and dump after the usage

Lowering the effective velocity

Gas-generator rocket cycle - Some of the fuel and oxidizer is burned separately to power the pumps and then discarded

Most gas-generator engines use the fuel for nozzle cooling

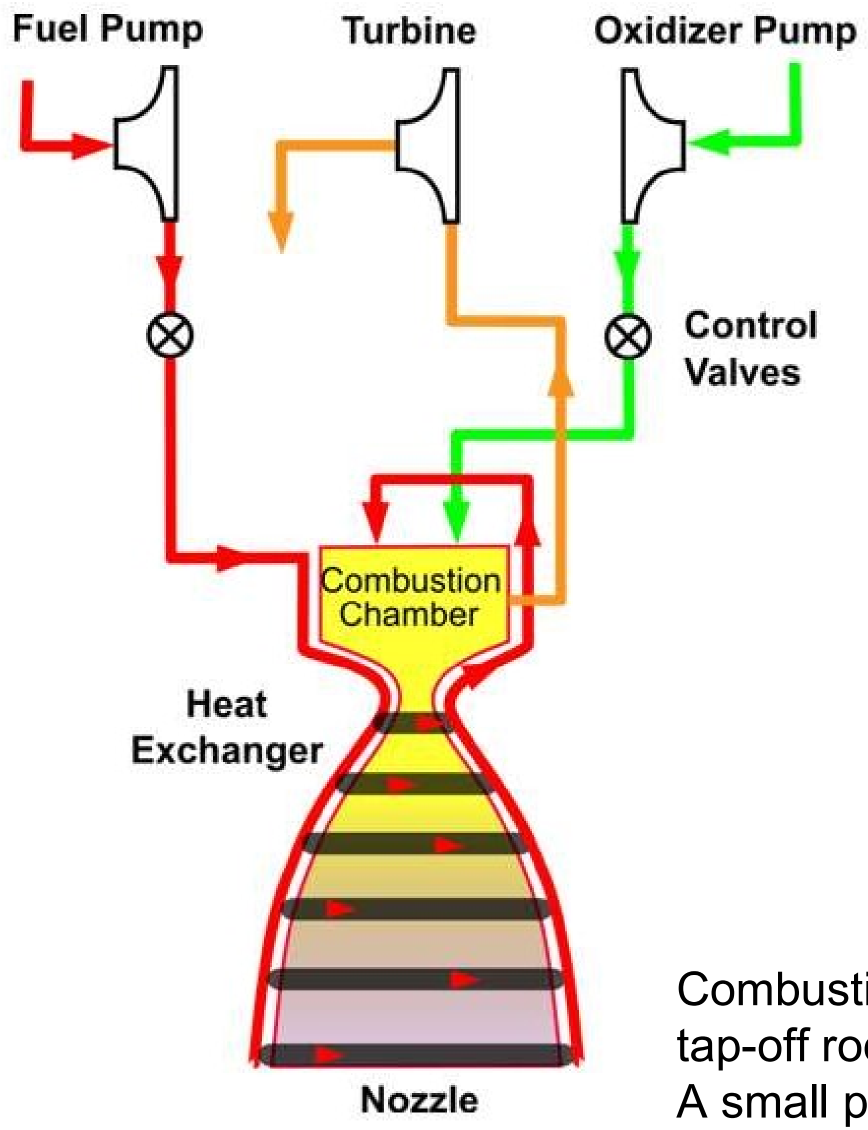
Burner dedicated for the turbine

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed gas-generator cycle:
  - The **gas-generator cycle** is a power cycle of a pumped liquid bi-propellant engine
  - Part of the unburned propellant is burned in a gas generator (or pre-burner) and the resulting hot gas is used to power the propellant pumps before being exhausted overboard and lost
  - Because of this loss, this type of engine is termed **open cycle**

Combustion Tap-off Cycle



Combustion tap-off cycle - Diagram of the open-cycle combustion tap-off rocket cycle

A small portion of exhaust from the combustion chamber is tapped off to power the turbine(s)

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

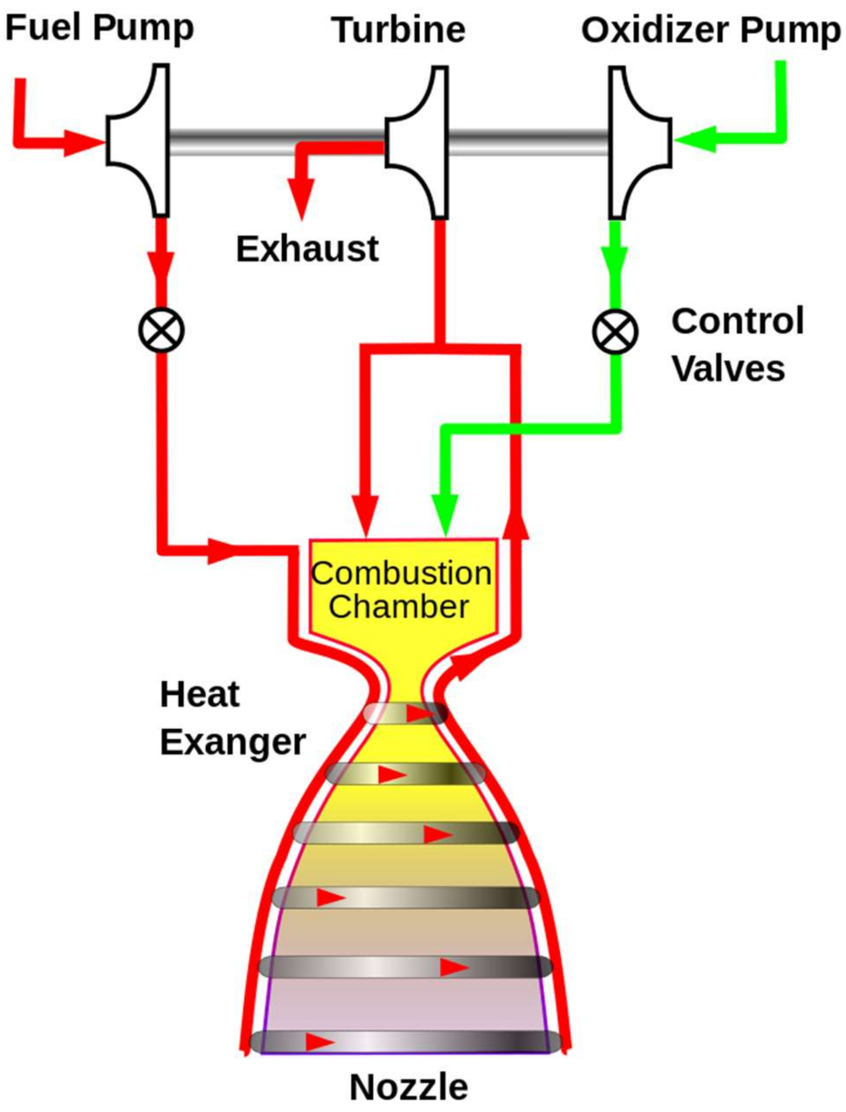
- Pump-fed combustion tap-off cycle:
  - The combustion tap-off cycle is a power cycle of a bi-propellant engine
  - The cycle takes a small portion of hot exhaust gas from the combustion chamber and routes it through the turbo-pump turbines to pump fuel before being exhausted (similar to the gas generator cycle)
  - Since fuel is exhausted, the tap-off cycle is considered an open-cycle engine. The cycle is comparable to a gas-generator cycle engine with turbines driven by main combustion chamber exhaust rather than a separate gas generator or pre-burner

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed combustion tap-off cycle:
  - Example: Blue Origin BE-3 engine
  - The cycle is simple with only one combustion chamber and a less stressful engine shutdown process
  - However, engine startup is more complicated and due to the hot gas fed from the main combustion chamber into the turbopumps, the turbine must be built to withstand higher-than-normal temperatures

Expander-bleed Cycle



Opened expander cycle

Increase the pressure drop at the turbines.

Still, there is a limit of the heating

Lowering the ex. velocity

Expander-bleed Cycle - Expander open cycle
(Also named coolant tap-off)
Bleed a part of expanded (coolant) gas

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed expander-bleed cycle:
  - The **expander-bleed cycle** is a modification of the traditional expander cycle
  - In the bleed (or open) cycle, instead of routing all of the heated propellant through the turbine and sending it back to be combusted, only a small portion of the heated propellant is used to drive the turbine and is then vented overboard without going through the combustion chamber
  - The other portion is injected into the combustion chamber
  - Bleeding off the turbine exhaust allows for a higher turbopump efficiency by decreasing back-pressure and maximizing the pressure drop through the turbine

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed expander-bleed cycle:
  - Compared with a standard expander cycle, this allows higher engine thrust at the cost of efficiency by dumping the turbine exhaust
  - Example: Mitsubishi LE-5A engine was the world's first expander bleed cycle engine to be put into operational service

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

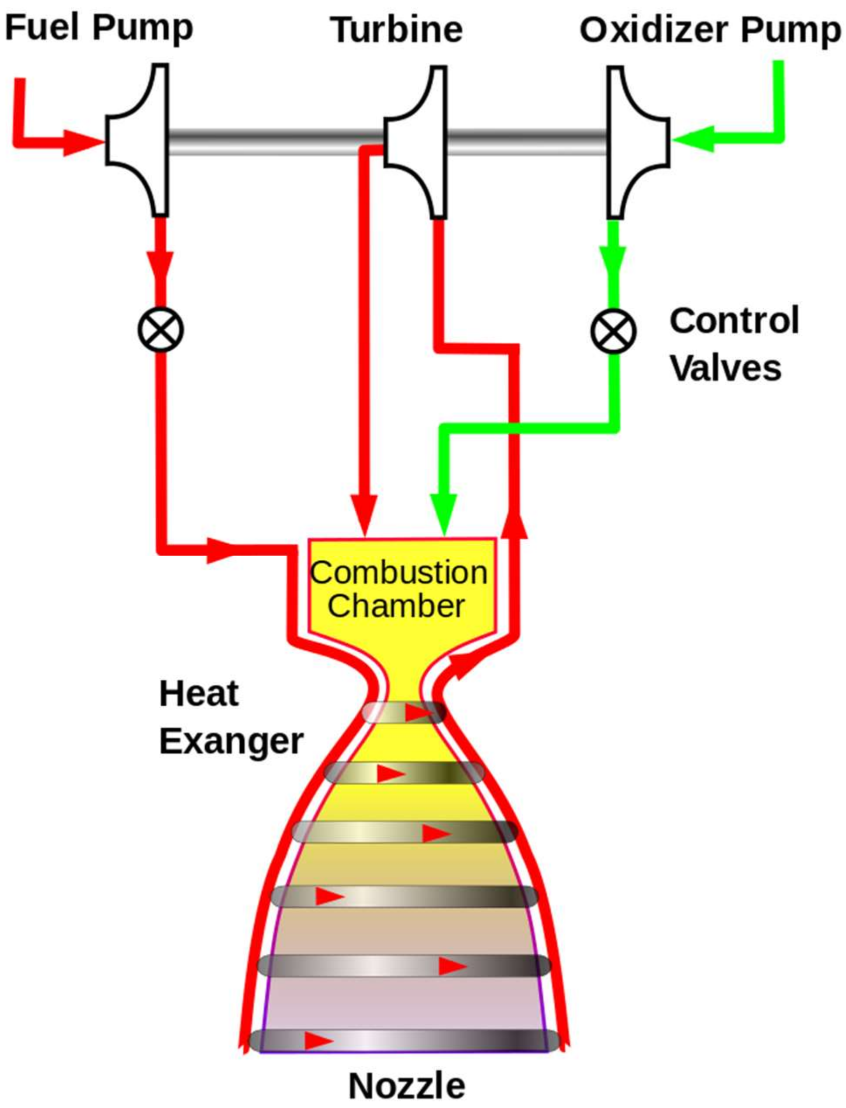
- Pump-fed dual expander cycle:
  - In a similar way that the staged combustion cycle can be implemented separately on the oxidizer and fuel on the full flow cycle, the expander cycle can be implemented on two separate paths as the **dual expander cycle**
  - The use of hot gases of the same chemistry as the liquid for the turbine and pump side of the turbopumps eliminates the need for purges and some failure modes
  - Additionally, when the density of the fuel and oxidizer is significantly different, as it is in the LH2 / LOx case, the optimal turbopump speeds differ so much that they need a gearbox between the fuel and oxidizer pumps

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed dual expander cycle:
  - The use of dual expander cycle, with separate turbines, eliminates this failure-prone piece of equipment (i.e. gear box)
  - Dual expander cycle can be implemented by either using separated sections on the regenerative cooling system for the fuel and the oxidizer, or by using a single fluid for cooling and a heat exchanger to boil the second fluid
  - In the first case, for example, you could use the fuel to cool the combustion chamber, and the oxidizer to cool the nozzle extension
  - In the second case, you could use the fuel to cool the whole engine and a heat exchanger to boil the oxidizer

Full Expander Cycle



Turbine gas :

Expanded coolant

Allpropellant usage

High effective velocity

Regenerative cooling

Limit of heating

Limit of thrust

Good for the tubine

Expander rocket engine (closed cycle) - Heat from the nozzle and combustion chamber powers the fuel and oxidizer pump

Use of expanded (coolant) gas

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed full expander cycle:
  - The full expander cycle is a power cycle of a bi-propellant engine
  - In this cycle, the fuel is used to cool the engine's combustion chamber, picking up heat and changing phase
  - The now heated and gaseous fuel then powers the turbine that drives the engine's fuel and oxidizer pumps before being injected into the combustion chamber and burned
  - Because of the necessary phase change, the expander cycle is thrust limited by the square-cube law
  - When a bell-shaped nozzle is scaled, the nozzle surface area with which to heat the fuel increases as the square of the radius, but the volume of fuel to be heated increases as the cube of the radius

Which Liquid Bi-propellant Propulsion Systems exist?

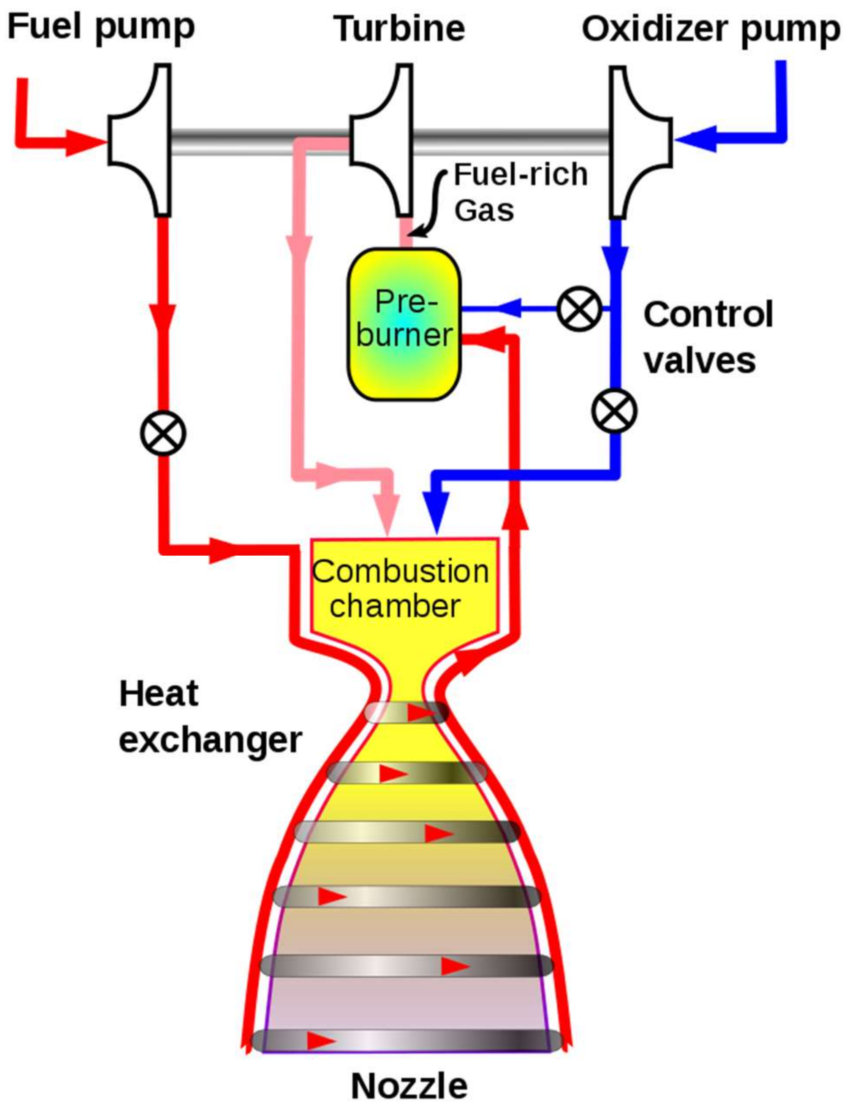
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed full expander cycle:
  - So, beyond approximately 300 kN of thrust, there is no longer enough nozzle area to heat enough fuel to drive the turbines and hence the fuel pumps
  - Higher thrust levels can be achieved using a bypass expander cycle where a portion of the fuel bypasses the turbine and or thrust chamber cooling passages and goes directly to the main chamber injector

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed full expander cycle:
  - All expander cycle engines need to use cryogenic propellant such as liquid Hydrogen, liquid Methane or liquid Propane that easily reaches its boiling point
  - Some expander cycle engines may use a gas generator of some kind to start the turbine and run the engine until the heat input from the thrust chamber and nozzle skirt increases as the chamber pressure builds up
  - An example of an expander cycle engine is the Vinci engine for the Ariane 6 launch vehicle



Staged Combustion Cycle – Fuel Rich

Turbine gas :

By preburner

All propellant usage

High effective V

High thrust

Highest-performance cycle

Pre-burner system with 2 chambers

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed staged combustion cycle:
  - The **staged combustion cycle** (sometimes known as topping cycle, pre-burner cycle, or closed cycle) is a power cycle of a bi-propellant engine
  - In the staged combustion cycle, propellant flows through multiple combustion chambers and is thus combusted in stages
  - The main advantage relative to other rocket engine power cycles is the high fuel efficiency measured through the specific impulse, while its main disadvantage is its complexity

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed staged combustion cycle:
  - Typically, propellant flows through two kinds of combustion chambers: the first called pre-burner and the second called main combustion chamber
  - In the pre-burner, a small portion of propellant, usually fuel-rich, is partly combusted, and the increasing volume flow is used to drive the turbo-pumps that feed the engine with propellant
  - The gas impulse, is then injected into the main combustion chamber and combusted completely with the other propellant to produce thrust

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed staged combustion cycle:
  - The main advantage is fuel efficiency due to all of the propellant flowing to the main combustion chamber, which also allows for higher thrust
  - The staged combustion cycle is sometimes referred to as closed cycle, as opposed to the gas generator cycle or open cycle where a portion of propellant never reaches the main combustion chamber, here the full flow passes the main combustion chamber
  - The disadvantage is its complexity, partly a result of the pre-burner exhaust of hot and highly pressurized gas which, particularly when oxidizer-rich, produces extremely harsh conditions for turbines and plumbing

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

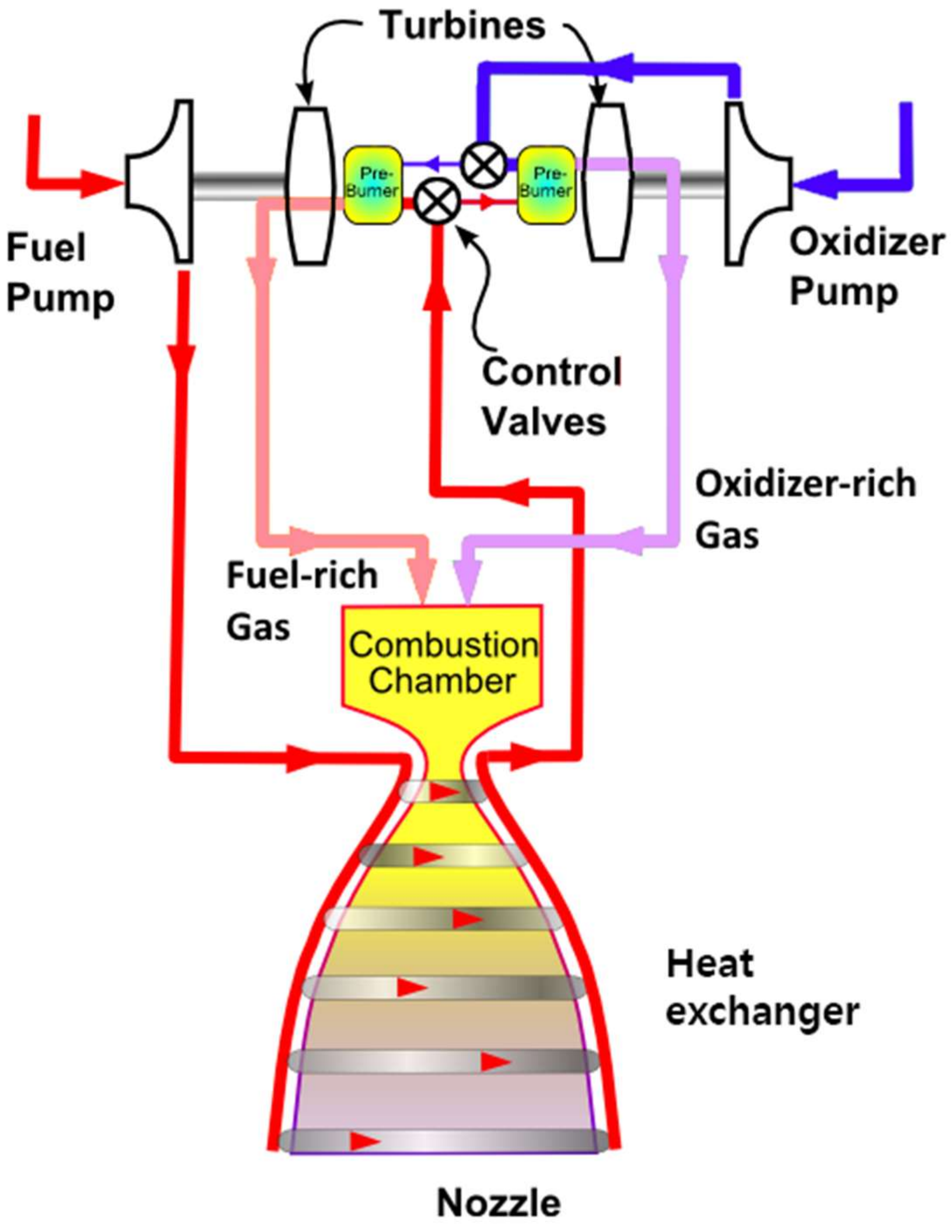
- Pump-fed staged combustion cycle:
  - Several variants of the staged combustion cycle exist
  - Pre-burners that burn a small portion of oxidizer with a full flow of fuel are called fuel-rich, while pre-burners that burn a small portion of fuel with a full flow of oxidizer are called oxidizer-rich
  - When both oxidizer-rich and fuel-rich pre-burners are used on a single engine, the cycle is called full-flow staged combustion.
  - Staged combustion designs can be either single-shaft or twin-shaft.
  - In the single-shaft design, one set of pre-burner and turbine drives both propellant turbo-pumps

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed staged combustion cycle:
  - In the twin-shaft design, the two propellant turbopumps are driven by separate turbines, which are in turn driven by the outflow of either one or separate pre-burners
  - Relative to a single-shaft design, the twin-shaft design requires an additional turbine (and possibly another pre-burner) but allows for individual control of the two turbo-pumps
  - In addition to the propellant turbopumps, staged combustion engines often require smaller boost pumps to prevent both pre-burner back-flow and turbo-pump cavitation

Stage Combustion Cycle – Full Flow



Turbine gas :

By preburner

All propellant usage

High effective V

High thrust

Highest-performance cycle

Pre-burner system with 2 chambers

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed full flow staged combustion cycle:
  - Full-flow staged combustion (FFSC) is a twin-shaft staged combustion cycle that uses both oxidizer-rich and fuel-rich pre-burners
  - The cycle allows full flow of both propellants through the turbines
  - The fuel turbo-pump is driven by the fuel-rich pre-burner, and the oxidizer turbo-pump is driven by the oxidizer-rich pre-burner
  - Benefits of the full-flow staged combustion cycle include turbines that run cooler and at lower pressure, due to increased mass flow, leading to a longer engine life and higher reliability

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

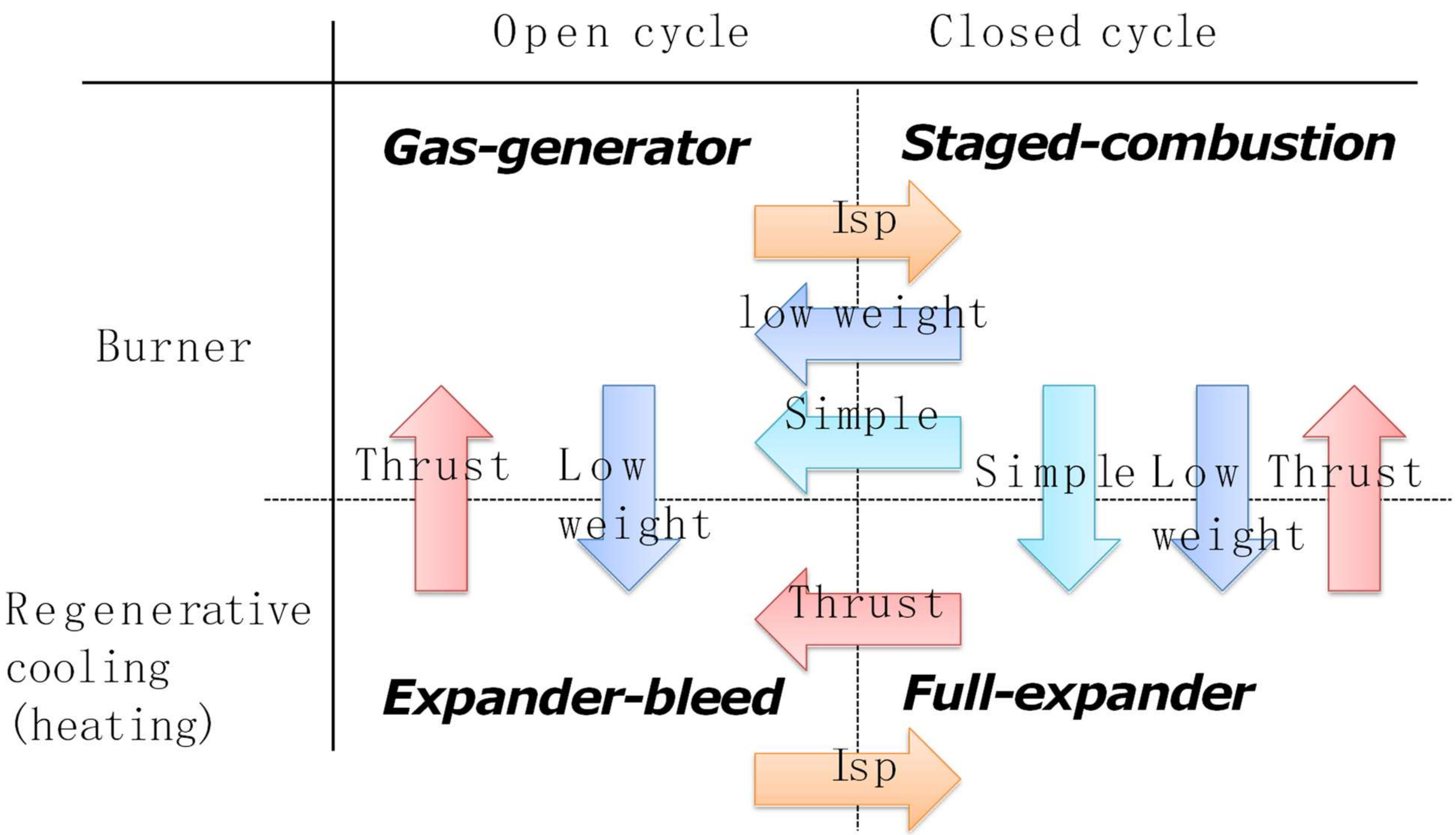
- Pump-fed full flow staged combustion cycle:
  - Further, the full-flow cycle eliminates the need for an inter-propellant turbine seal normally required to separate oxidizer-rich gas from the fuel turbopump or fuel-rich gas from the oxidizer turbo-pump, thus improving reliability
  - Since the use of both fuel and oxidizer pre-burners results in full gasification of each propellant before entering the main combustion chamber, faster chemical reactions are given in the combustion chamber, allowing a smaller combustion chamber

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pump-fed full flow staged combustion cycle:
  - This in turn makes it feasible to increase the chamber pressure, which increases efficiency
  - Potential disadvantages of the full-flow staged combustion cycle include increased engineering complexity of two pre-burners, relative to a single-shaft staged combustion cycle, as well as an increased parts count

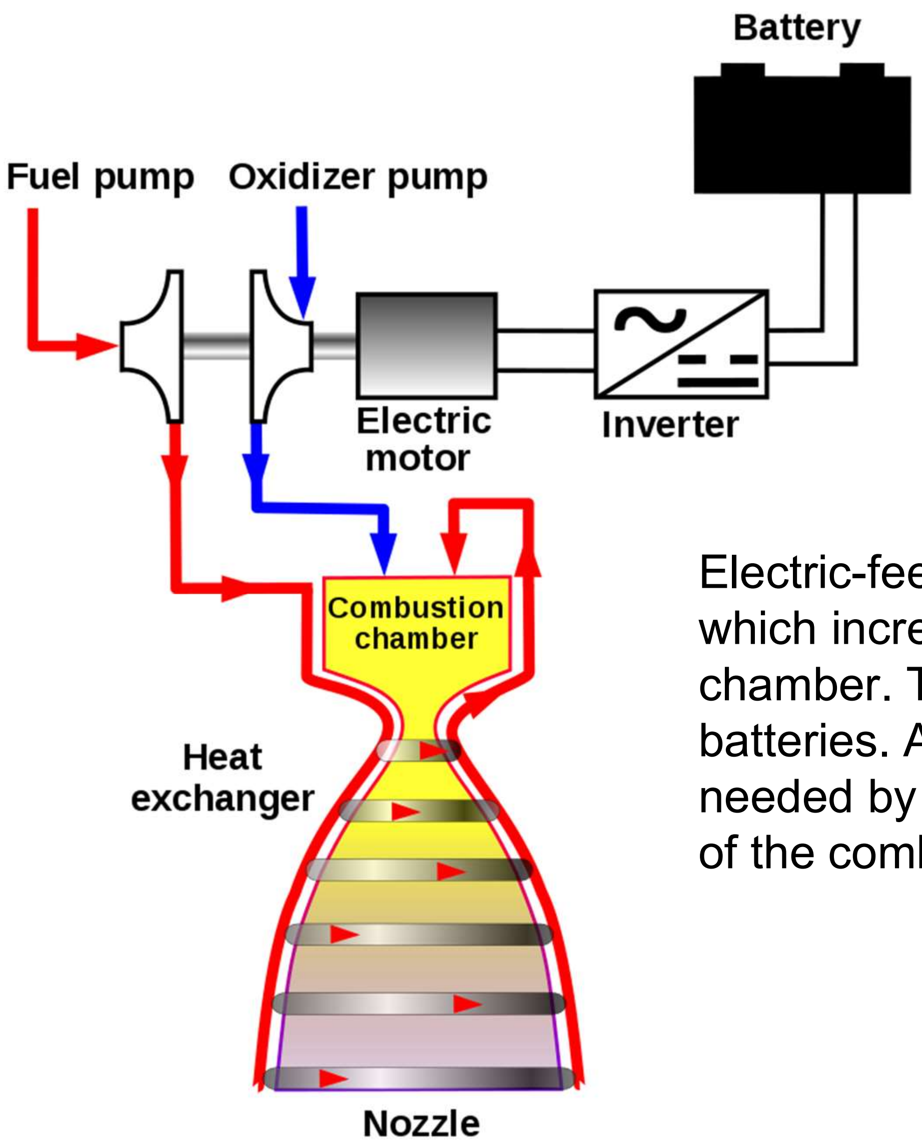
Engine Cycles



Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- But one could also use an electric pump…



Electric-pump Cycle

Electric-feed rocket cycle – The oxidizer and fuel are fed to the pump which increases the pressure before injecting it into the combustion chamber. The pumps are actuated by an electric motor powered by batteries. An inverter converts the batteries' DC electricity to the AC needed by the motor. The fuel is also circulated around the outside of the combustion chamber and nozzle to prevent it from overheating

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Electric pump-fed system:
  - The electric pump-fed engine is a bi-propellant engine cycle in which the fuel pumps are electrically powered, and so all of the input propellant is directly burned in the main combustion chamber, and none is diverted to drive the pumps
  - This differs from traditional engine cycles, in which the pumps are driven by a portion of the input propellants.
  - An electric cycle engine uses electric pumps to pressurize the propellants from a low-pressure fuel tank to high-pressure combustion chamber level

Which Liquid Bi-propellant Propulsion Systems exist?

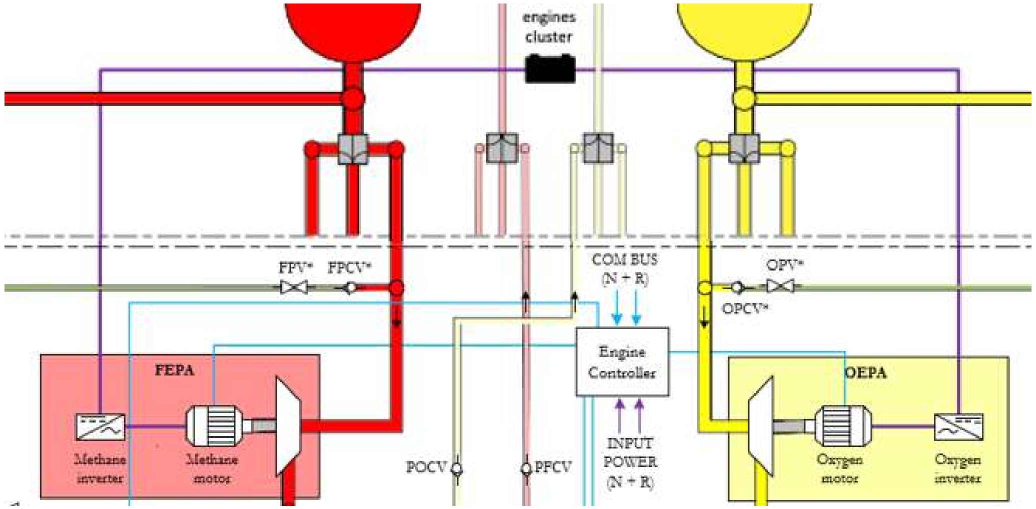
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Electric pump-fed system:
  - The pumps are powered by an electric motor with electricity from a battery bank
  - Example: Rutherford engine from the Electron launch vehicle from Rocketlab
  - In comparison to turbo-pumped rocket cycles such, an electric cycle engine has potentially worse performance due to the added mass of the batteries but may have lower development and manufacturing costs due its mechanical simplicity, its lack of high temperature turbomachinery, and its easier controllability

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Electric pump-fed system:
  - Example: Huracan engine from The Exploration Company



Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pressure Vessels Types (including vessels for pressurant gas storage but also propellant storage)
  - Type I – Full metal: Cylinder is made entirely from metal
  - Type II – Hoop wrap: Metal cylinder, reinforced by a belt-like hoop wrap with fibre-reinforced resin
  - Type III – Fully wrapped, over metal liner: Diagonally wrapped fibres form the load bearing shell on the cylindrical section and at the bottom and shoulder around the metal neck. The metal liner is thin and provides the gas tight barrier

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pressure Vessels Types (including vessels for pressurant gas storage but also propellant storage)
  - Type IV – Fully wrapped, over non-metal liner: A lightweight thermoplastic liner provides the gas tight barrier, and the mandrel to wrap fibers and resin matrix around. Only the neck which carries the neck thread and its anchor to the liner is made of metal, which may be lightweight Aluminum or sturdy stainless steel

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pressure Vessels Types (including vessels for pressurant gas storage but also propellant storage)
  - Type V - Compared to Type I, II and III tanks using metal, and Type IV tanks using a plastic liner, Type V pressure vessels offer the lightest weight, featuring a fully composite construction reinforced primarily with carbon fiber but without a liner. However, because the liner serves as a barrier to prevent gases and cryogenic liquids from permeating into the composite laminate at high pressures building liner less tanks that can perform reliably for potentially thousands of pressurization cycles is no easy feature

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pressure Vessels Types (including vessels for pressurant gas storage but also propellant storage)
  - Polar mounted or equatorial mounted

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pressure Vessels Types

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Pressure Vessels Considerations
  - Propellant / pressurant leakage
  - Leak before burst - Leak before burst describes a pressure vessel designed such that a crack in the vessel will grow through the wall, allowing the contained fluid to escape and reducing the pressure, prior to growing so large as to cause fracture at the operating pressure
  - Liquid propellant control

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Liquid Propellant Control
  - Positive Expulsion Device – Bladder, Diaphragm (metallic or plastic)
  - Surface Tension Device – Capillary forces
  - Piston Device – Pressure force
  - Pre-acceleration + Collector – Acceleration forces
  - Damping – Baffles
  - Zero-sloshing Tank – De-orbitation for small spacecraft

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Liquid Propellant Control:
  - Example: Stage separation

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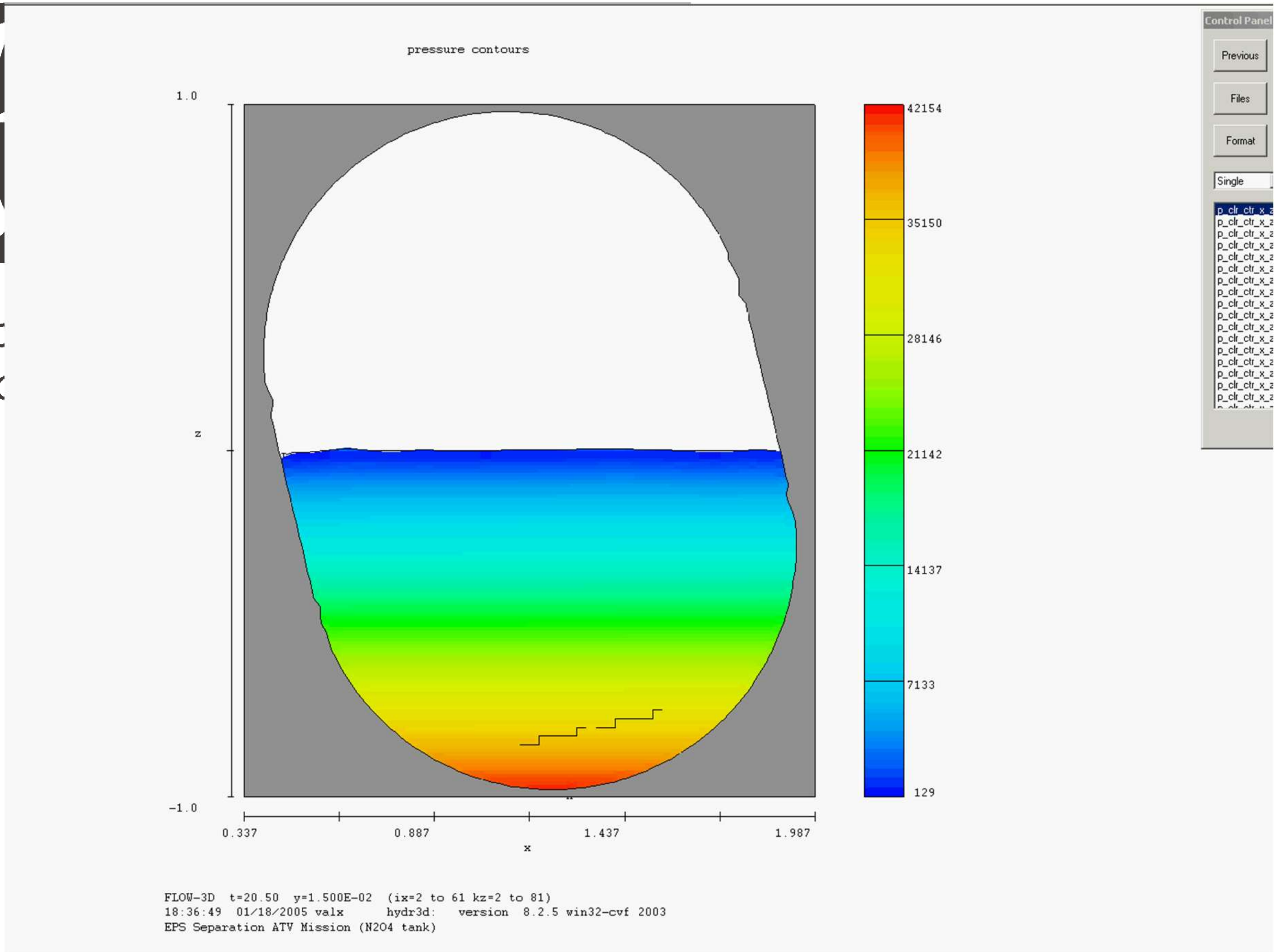
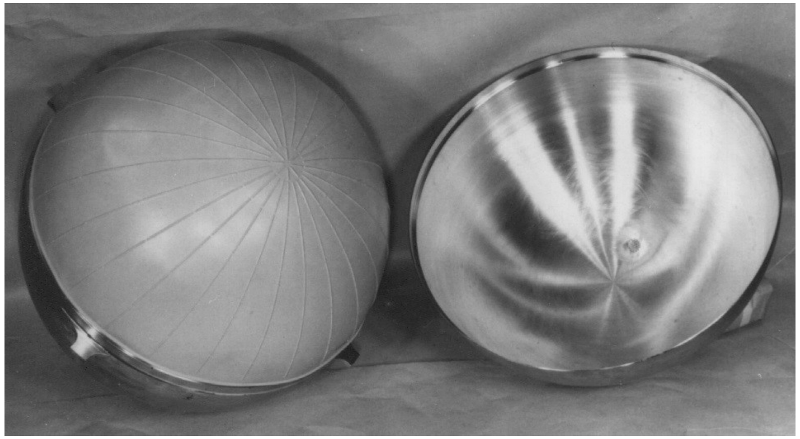


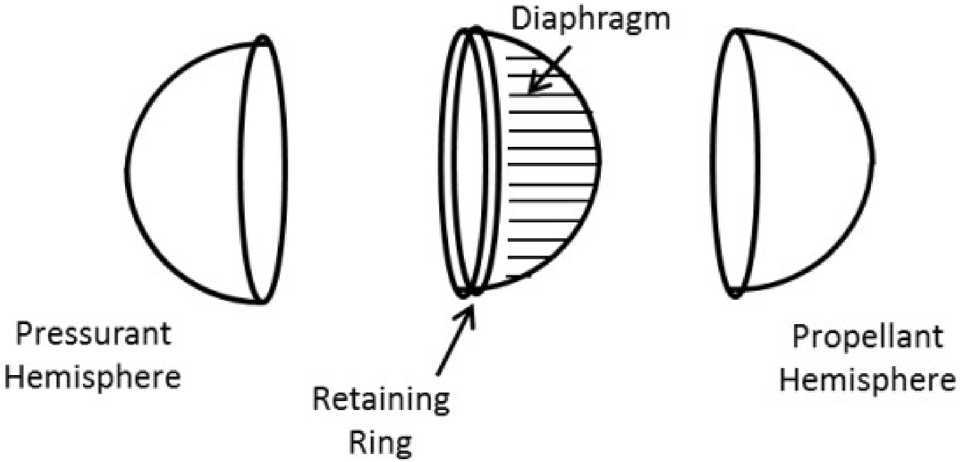
pressure contours
1.0
z
-1.0
0.337
0.887
1.437
1.987
x
42154
35150
28146
21142
14137
7133
129
FLOW-3D t=20.50 y=1.500E-02 (ix=2 to 61 kz=2 to 81)
18:36:49 01/18/2005 valx hydr3d: version 8.2.5 win32-cvf 2003
EPS Separation ATV Mission (N2O4 tank)
Control Panel
Previous
Files
Format
Single

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Liquid Propellant Control
  - Positive Expulsion Device – Plastic diaphragm

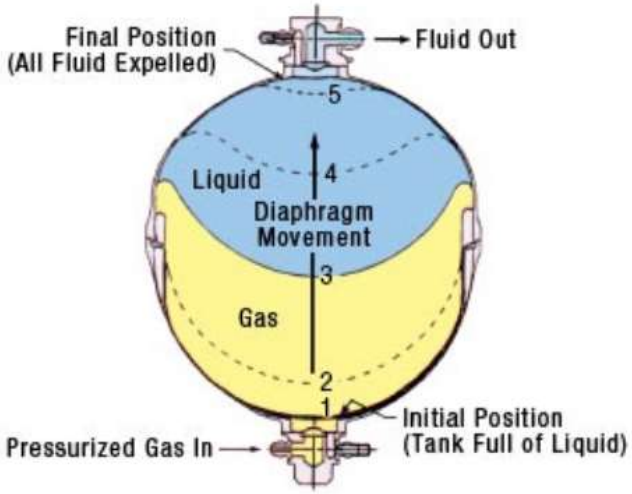


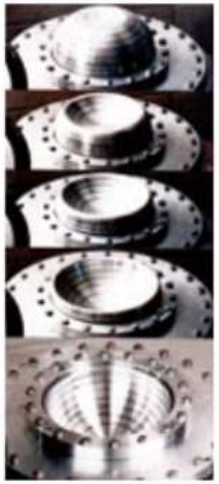


Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Liquid Propellant Control
  - Positive Expulsion Device – Metallic diaphragm



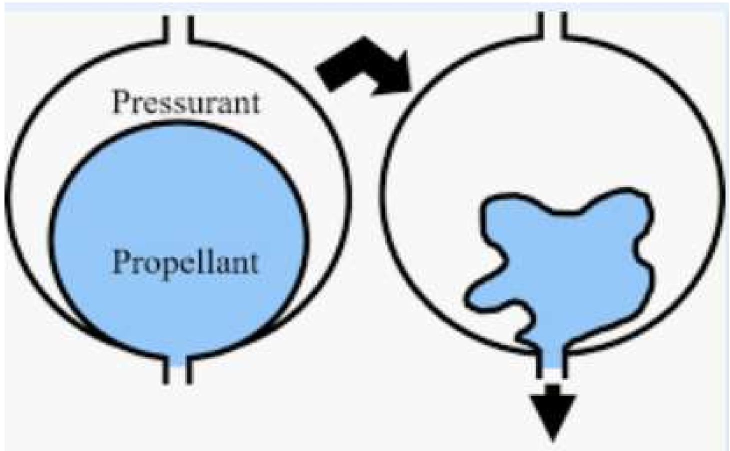


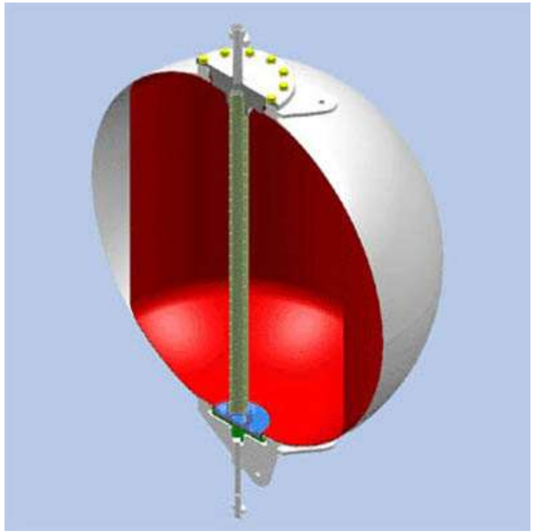
EPFL

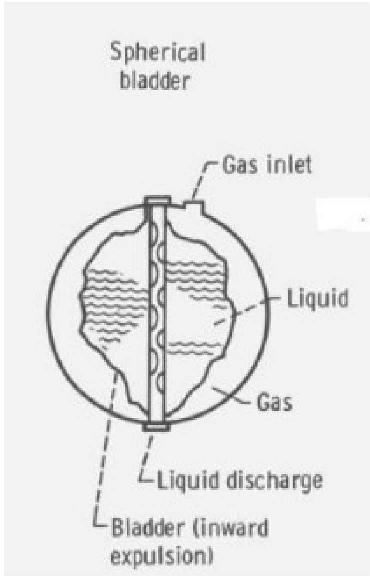
Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Liquid Propellant Control
  - Positive Expulsion Device – Bladder



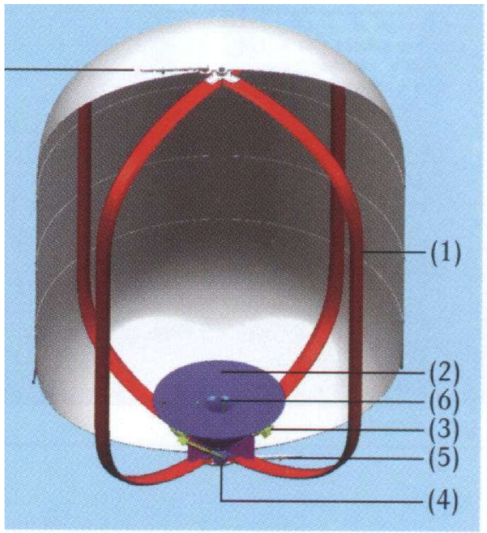




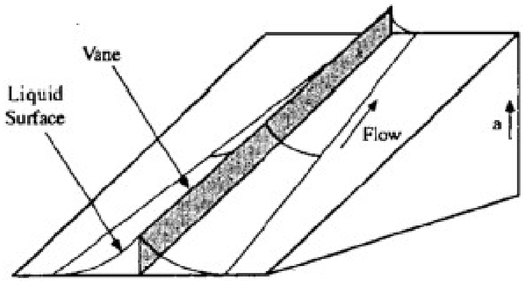
Which Liquid Bi-propellant Propulsion Systems exist?

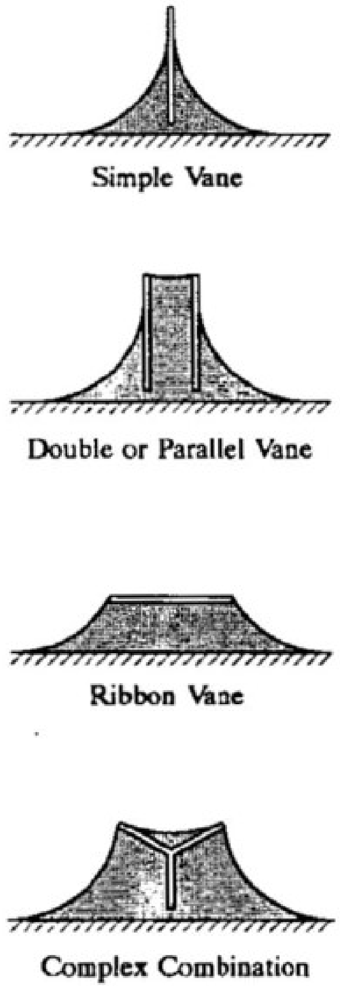
Objective: To develop the basics of chemical L/L combustion propellant propulsion

- Liquid Propellant Control
  - Surface Tension Device – Capillary forces



(1) Prop. Aquisition Vanes
(2) Prop. Refillable Reservoir
(3) Upper Screen
(4) Lower Screen
(5) Propellant Port
(6) Venting Tube
(7) Gas Port

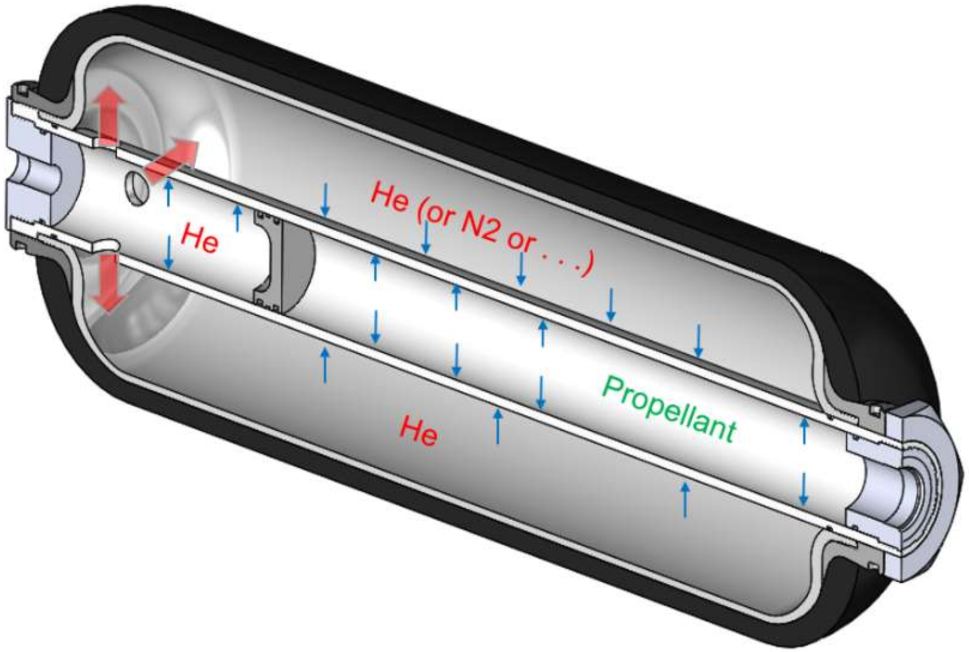




Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

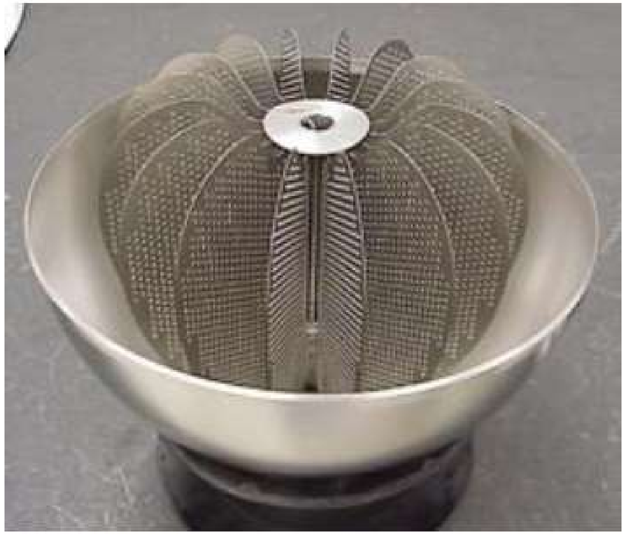
- Liquid Propellant Control
  - Piston Device – Pressure force



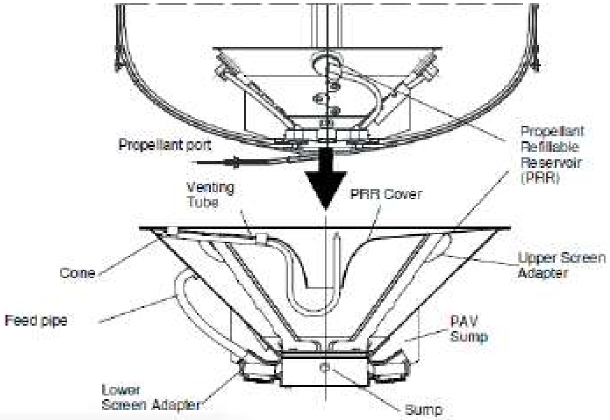
Which Liquid Bi-propellant Propulsion Systems exist?

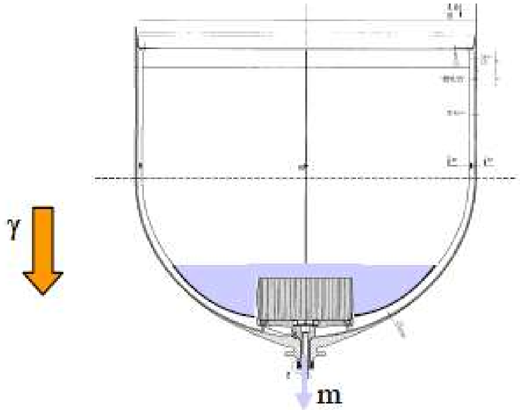
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Liquid Propellant Control
  - Pre-acceleration + Collector (Sponge) – Acceleration forces



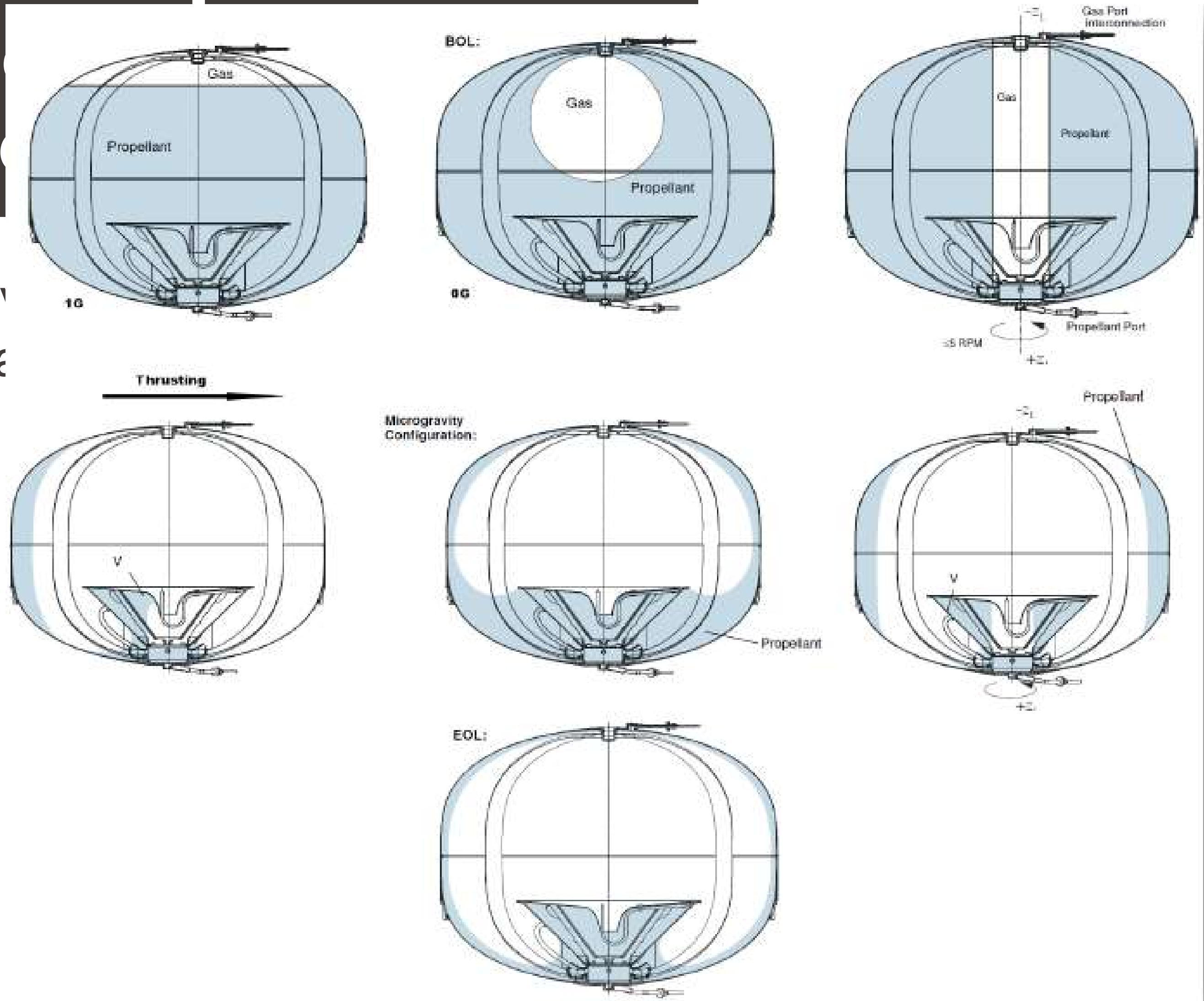
Which Liquid Bi-propellant Propulsion Systems exist?





Which Liquid Bi-prop… Syst…

Objecti… …n bi-propella…



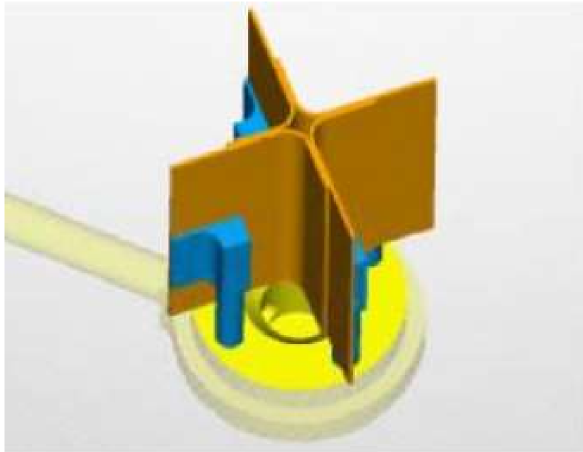
EPFL

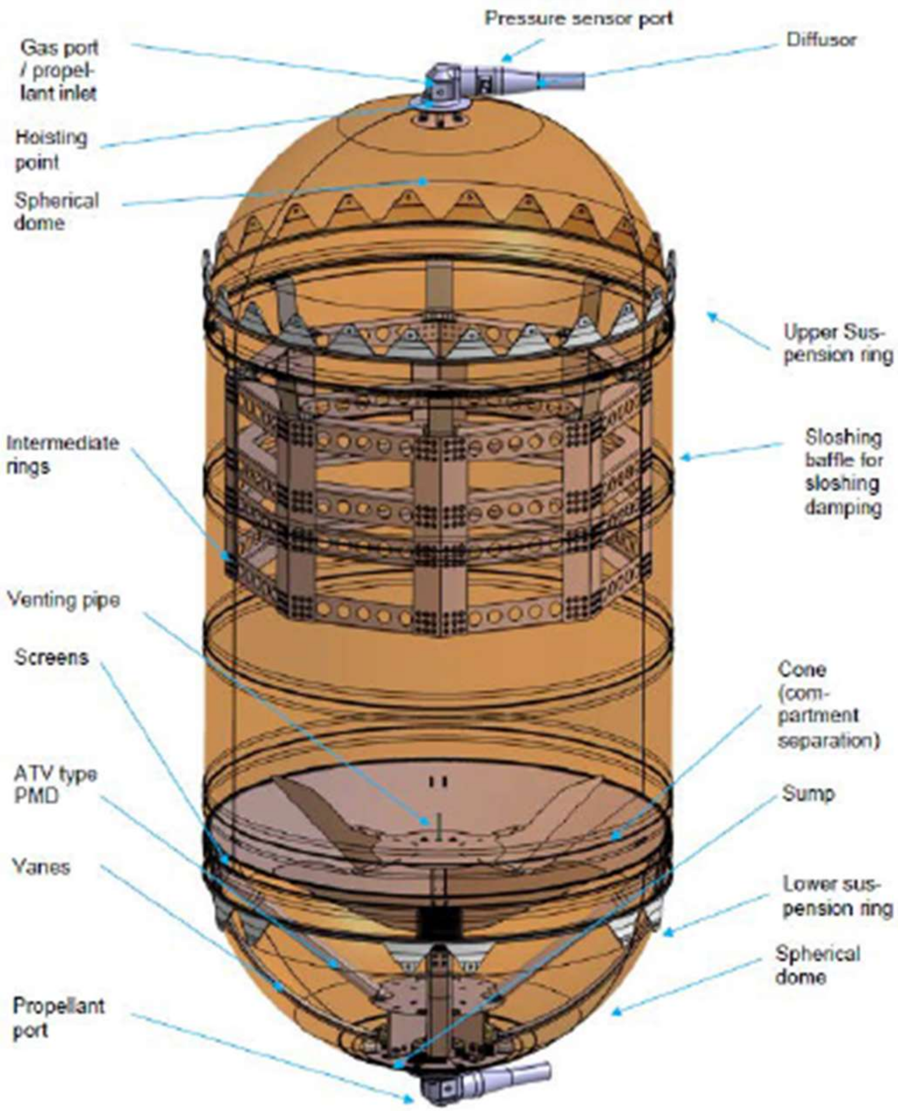
L4 – Propulsion Systems

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of propellant propulsion

- Liquid Propellant Control
  - Damping (Sloshing, Vortex) – Baffles





Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Liquid Propellant Control
  - Zero-sloshing Tank – De-orbitation for small spacecraft
  - Potentially Piston…
  - Or N2O in supercritical state…

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Functions
  - Fill & Drain
  - Isolation
  - Regulation
  - Flow control
  - Throttling
  - …

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types
  - Pyro Valves (N/O – normally open – or N/C – normally closed)
  - SMA Valves (Shape Memory Alloy)
  - Check Valves
  - Monostable Valves (Solenoid valves) – Flow Control Valves
  - Bistable Valves (Latch valves)
  - Pneumatic Valves
  - Electric Valves

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types
  - Ball Valves
  - Fill & Drain Valves
  - Burst Disk + Relief Valve

Which Liquid Bi-propellant Propulsion Systems exist?

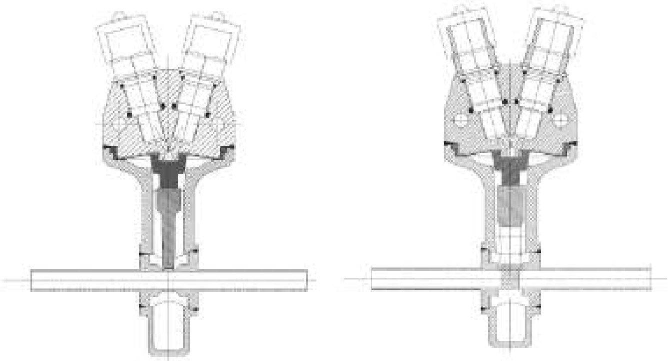
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types
  - Pyro Valves (N/O – normally open – or N/C – normally closed): Redundancy
    - PVs are a one shot deal
    - Explosive charges are fired to open the valve (normally closed type) or to close the valve (normally open type
    - PVs are used to permanently change the flow paths within the propulsion system
    - Better leakage rate than latch or solenoid valves
    - Cost effective

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types
  - Pyro Valves (N/O – normally open – or N/C – normally closed): Redundancy



NO before activation

NC before activation

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types
  - SMA Valves (Shape Memory Alloy): Low shock but duration for temperature increase

Which Liquid Bi-propellant Propulsion Systems exist?

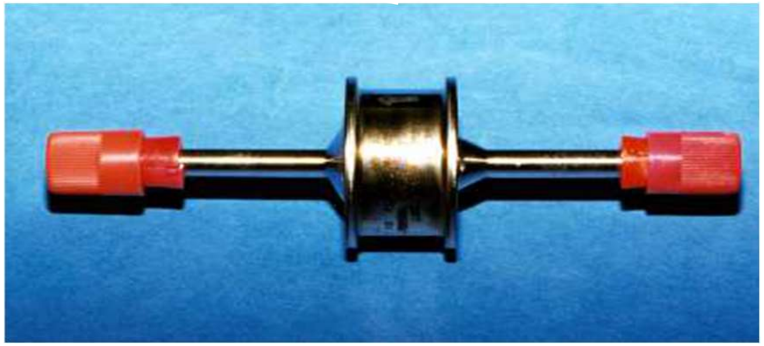
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types
  - Check Valves: Never tight + oscillations
    - Non return valves prevent the mixing of oxidiser and fuel vapour in the pipes
    - No electronic parts
    - Valves allow the flow of gas in one direction only
    - Valves can exert a high pressure drop in the system (especially when series redundant)
    - Good reliability

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types
  - Check Valves: Never tight + oscillations



Which Liquid Bi-propellant Propulsion Systems exist?

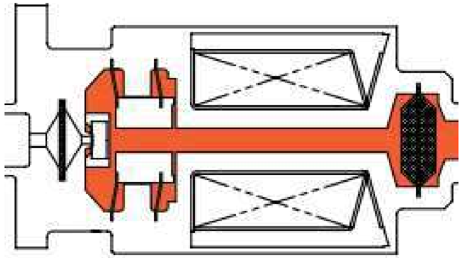
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types:
  - Monostable Valves (Solenoid valves): Pressure assisted or not + force balance (also in dynamic case) + heating
    - Solenoid valve is a monostable valve
    - "Normally closed" version will only remain open whilst powered, where after they
      return to closed position
    - "Normally open" versions are also available
    - As with the latch valve, they are used to control propellant flow around the system

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types:
  - Monostable Valves (Solenoid valves):



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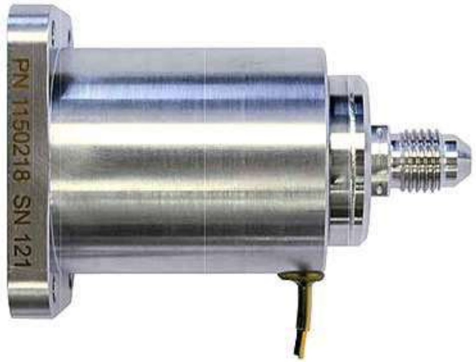


Which Liquid Bi-propellant Propulsion Systems exist?

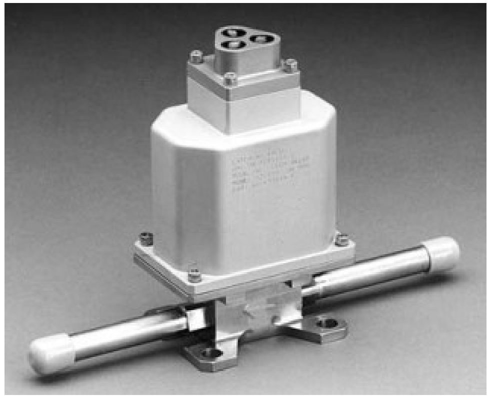
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

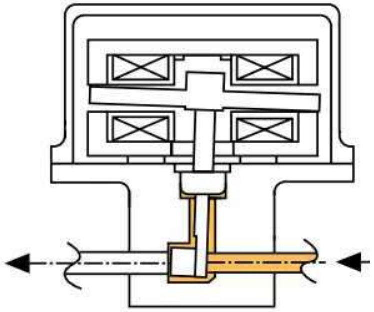
- Valve Types
  - Bistable Valves (Latch valves): Force balance (also in dynamic case) + power need
    - Latch valve is a bistable valve
    - The position open/closed is controlled by a short electrical pulse on demand
    - Most examples contain an internal position indicator to determine valve position
    - The function of the valve is to control propellant (sometimes gas) flow around the propulsion system

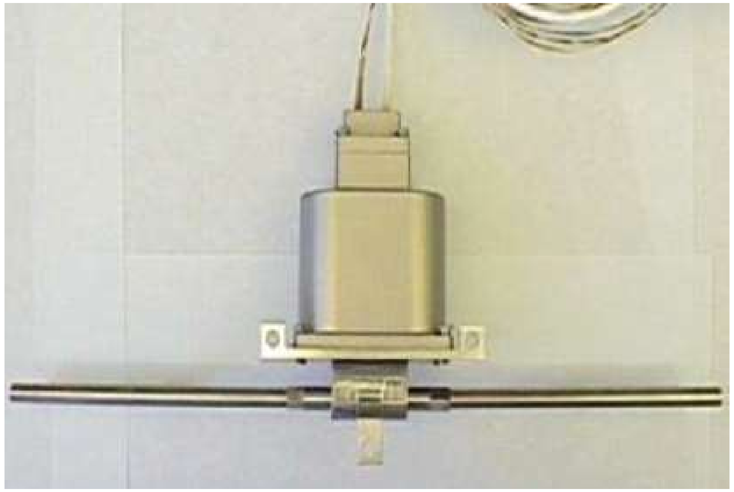
Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types
  - Bistable Valves (Latch valves): Force balance (also in dynamic case) + power need







Which Liquid Bi-propellant Propulsion Systems exist?

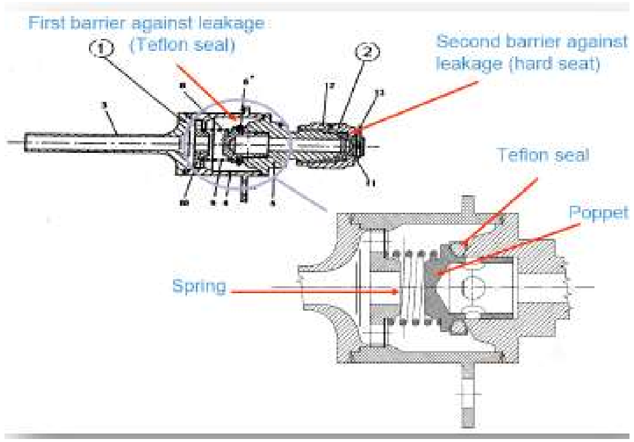
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types
  - Test Ports, Fill and Drain Valves or Fill and Vent Valves (FDV, FVV or TP)
    - The name determines the function, but all are fundamentally the same valve
    - They are used on ground to enable fluids to be put into the system, or to perform tests on ground
    - The valves are operated using a counterpart called a ground half coupling
    - Often called Mechanical Valves, Service Valves or Flight Half Couplings

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types
  - Test Ports, Fill and Drain Valves or Fill and Vent Valves (FDV, FVV or TP)



Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types
  - Burst Disk & Relief Valves:
    - Pressure relief valve will be set to a pre-determined "cracking pressure"
    - If the pressure gets too high within the system the relief valve vents gas to prevent over pressurisation (particularly tanks)
    - Burst discs work in the same way, but once opened, they cannot be closed
    - They are not particularly desirable as the reliability of the system can be impaired – analytical design solutions are better

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types
  - Burst Disk & Relief Valves:

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Valve Types
  - And everything can be a little bit smaller…

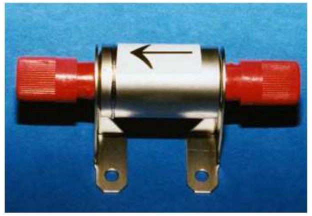
Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

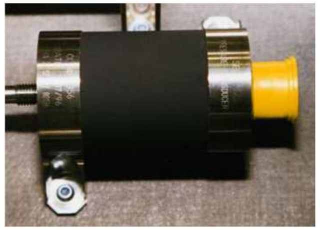
- Other propulsion equipment
  - Transducer (Pressure, Temperature, Flow rate, Position indication, Acceleration)
  - Filter (Liquid and Gaseous)
  - Heater
  - Heat exchanger
  - Electrolyzer
  - Sabatier Reactor
  - Compressor
  - …

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion



He - Filter



Pressure Transducer

Propellant Filter

Pressure Transducer High Accuracy

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Other propulsion equipment
  - Transducer (Pressure, Temperature, Flow rate, Position indication, Acceleration)
    - Pressure transducers convert physical pressure into an equivalent electrical signal
    - PTs are typically powered continuously through life
    - PTs are used to monitor pressure which is used to determine
    - Correct function of the system (Propellant gauging calculations, Thruster performance)
    - The PTs come in various low and high pressure ranges and are calibrated during supplier testing

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Other propulsion equipment
  - Transducer (Pressure, Temperature, Flow rate, Position indication, Acceleration)

Which Liquid Bi-propellant Propulsion Systems exist?

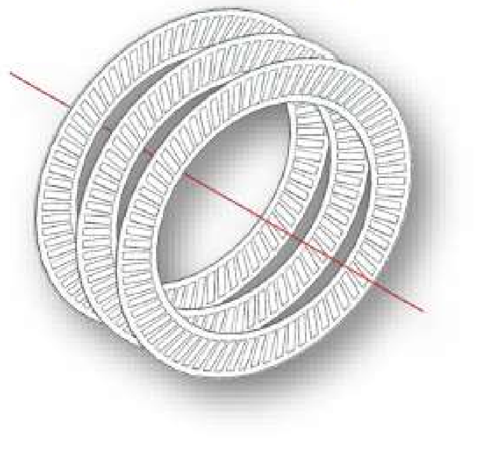
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

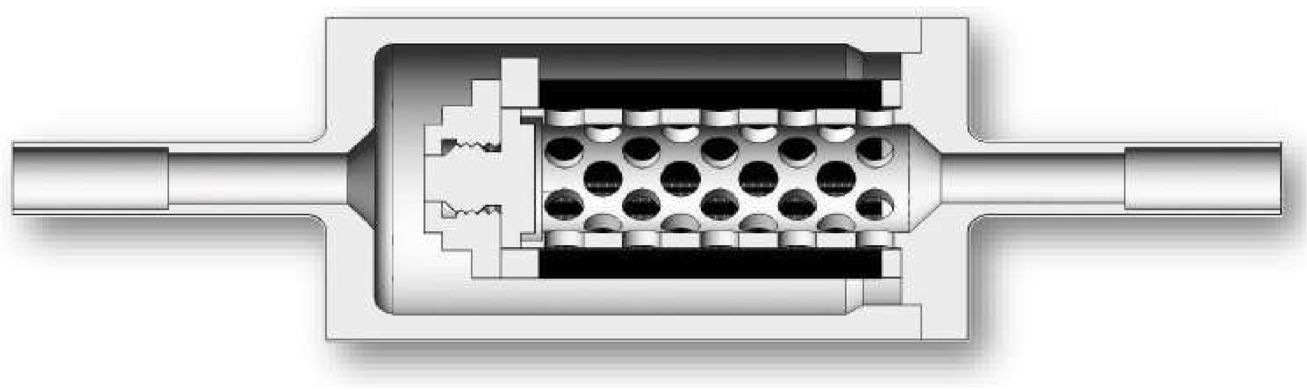
- Other propulsion equipment
  - Filter (Liquid and Gaseous)
    - Filters are used to filter particulate from gas or propellant to protect downstream components
    - The propulsion systems are precision cleaned during assembly, however residual particulate and debris created from pyro valves can damage valves
    - Filters will exert a pressure drop at high flow rates, which must be taken into account

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Other propulsion equipment
  - Filter (Liquid and Gaseous)





Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- And thruster for sure…

10N RCT

200N RCT

400N LAE

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Bi-propellant thruster definitions:
  - Steady State
    - Refers to the configuration where the thruster valves are fully open
    - Continuous thrust is produced (provided conditions remain stable)

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Bi-propellant thruster definitions:
  - Pulse Mode
    - At the same pressure, a net lower thrust can be produced by cycling the valve producing a series of impulsive pulses for more accurate positioning
    - The Impulse bit is the equivalent thrust which can be produced for a given pulse
    - Minimum Impulse bit is the smallest possible amount of thrust which can be produced by a thruster for given operating conditions

Which Liquid Bi-propellant Propulsion Systems exist?

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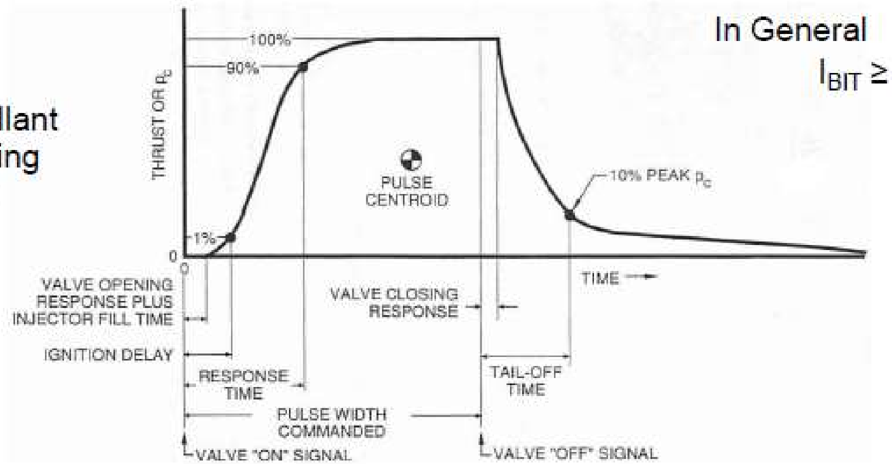
ring

Objective: To develop the basics of che
propellant propulsion

- Bi-propellant thruster definitions:
  - Pulse Mode
    - Duty cycle
  - Transient Phases
    - Thrust rise time
    - Thrust decay time



$$\text{Duty Cycle (\%)} = \frac{t_{ON}}{t_{ON} + t_{OFF}}$$

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Bi-propellant engines

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

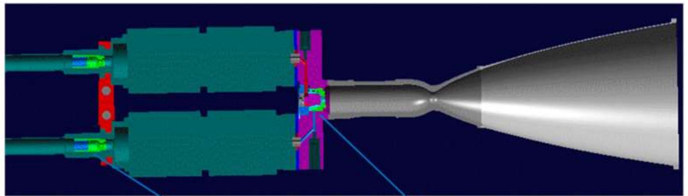
- Bi-propellant thrusters / engines
  - Injection method for propellants (e.g. spin, showerhead, …)
  - Cooling of engine
  - Trimming of engine
  - Ignition of propellants

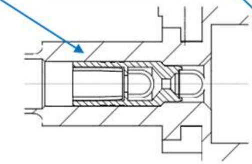
Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

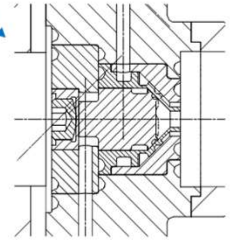
- Bi-propellant thrusters / engines
  - Trimming / calibration of engine
    - Orifice (passive)
    - Throttling valve / injector (active)

22N Zweistoff-Triebwerk

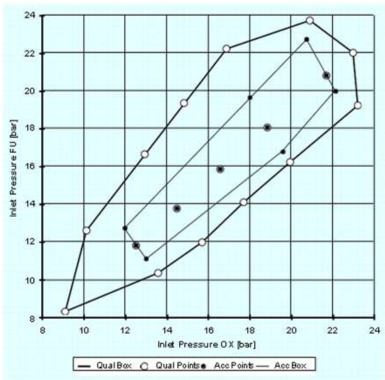


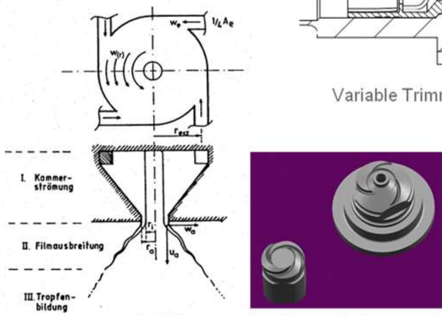


Variable Trimmblende



Doppeldrall-Einspritzsystem





Funktionsmechanismen bei Dralleinspritzdüsen

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Bi-propellant thrusters / engines
  - Cooling of engine (Combustion Chamber, Throat, Nozzle Extension)
    - Radiative cooling
    - Capacitive cooling (Phase change material)
    - Film cooling
    - Vortex cooling
    - Regenerative cooling
    - Ablative cooling
    - Transpiration cooling

Which Liquid Bi-propellant Propulsion Systems exist?

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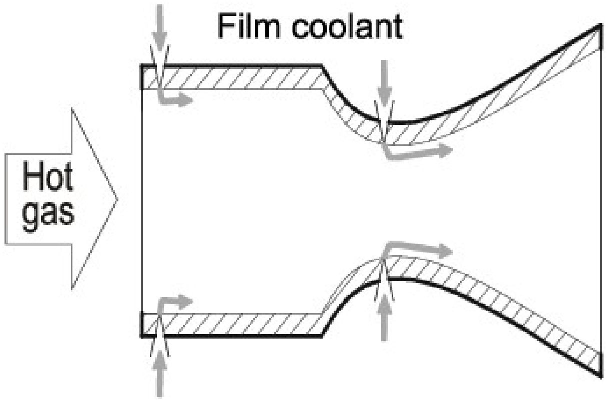
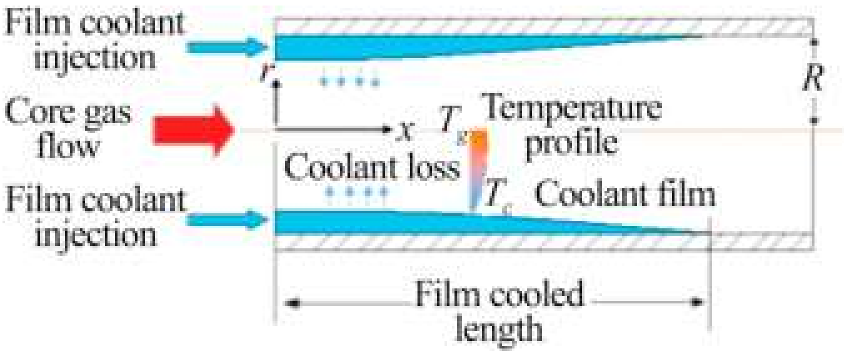
- Bi-propellant thrusters / engines
  - Cooling of engine (Combustion Chamber, Throat, Nozzle Extension)
    - Film cooling

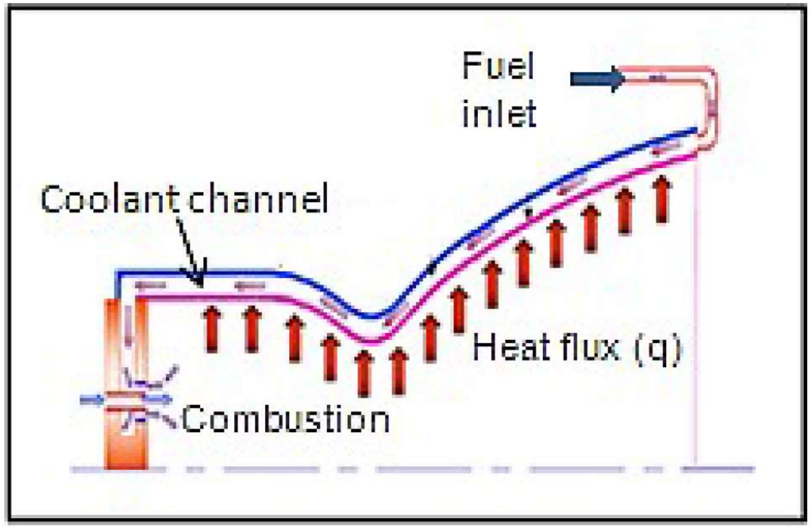




Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Bi-propellant thrusters / engines
  - Cooling of engine (Combustion Chamber, Throat, Nozzle Extension)
    - Regenerative cooling



Which Liquid Bi-propellant Propulsion Systems exist?

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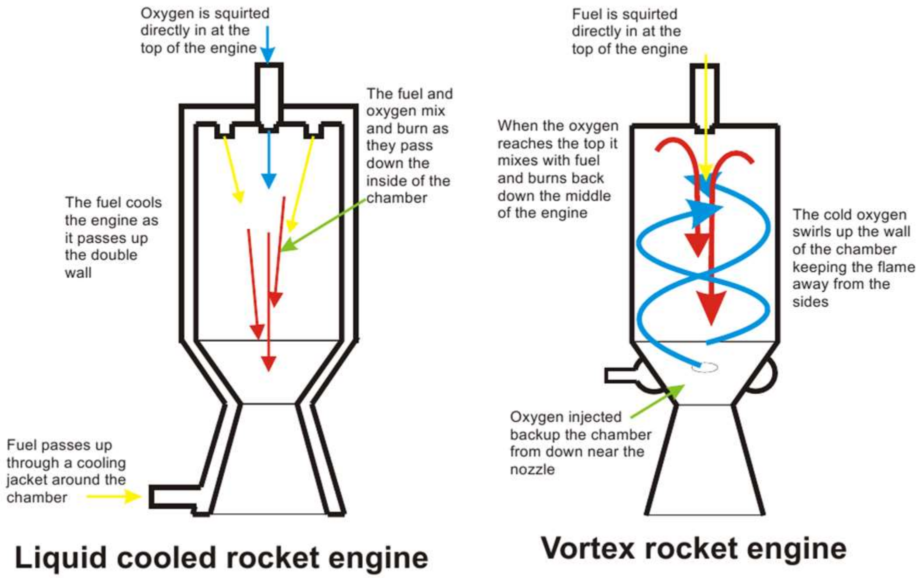
- Bi-propellant thrusters / engines
  - Cooling of engine (Combustion Chamber, Throat, Nozzle Extension)
    - Vortex cooling

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: ustion bi-
propellant

- Bi-prope
  - Cooli Extension)
    - V



Which Liquid Bi-propellant Propulsion Systems exist?

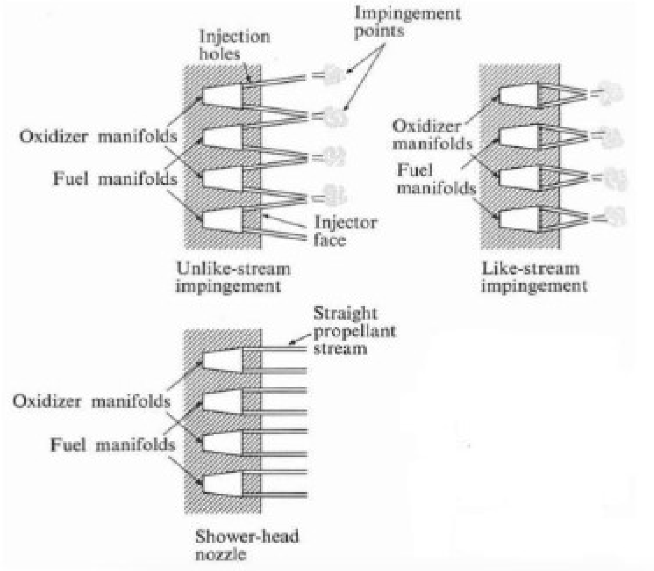
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Bi-propellant thrusters / engines
  - Injection method for propellants (e.g. spin, showerhead, …)
    - Impingement
    - Showerhead
    - Concentric tube (with or without swirl)
    - Splash plate

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L propellant propulsion

- Bi-propellant thrusters / engines
  - Injection method for propellants (e.g. spin, showerh



Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Bi-propellant thrusters / engines
  - Ignition of propellants
    - Hypergolic ignition
    - Catalytic decomposition
    - Thermal decomposition
    - …

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Bi-propellant thrusters / engines
  - Ignition of propellants
    - Spark plug
    - Glow plug
    - Laser ignitor
    - Resonance acoustic ignition
    - Thermal wire
    - …
    - Torch ignitor (Different propellant or same propellants with smaller amount)

Which Liquid Bi-propellant Propulsion Systems exist?

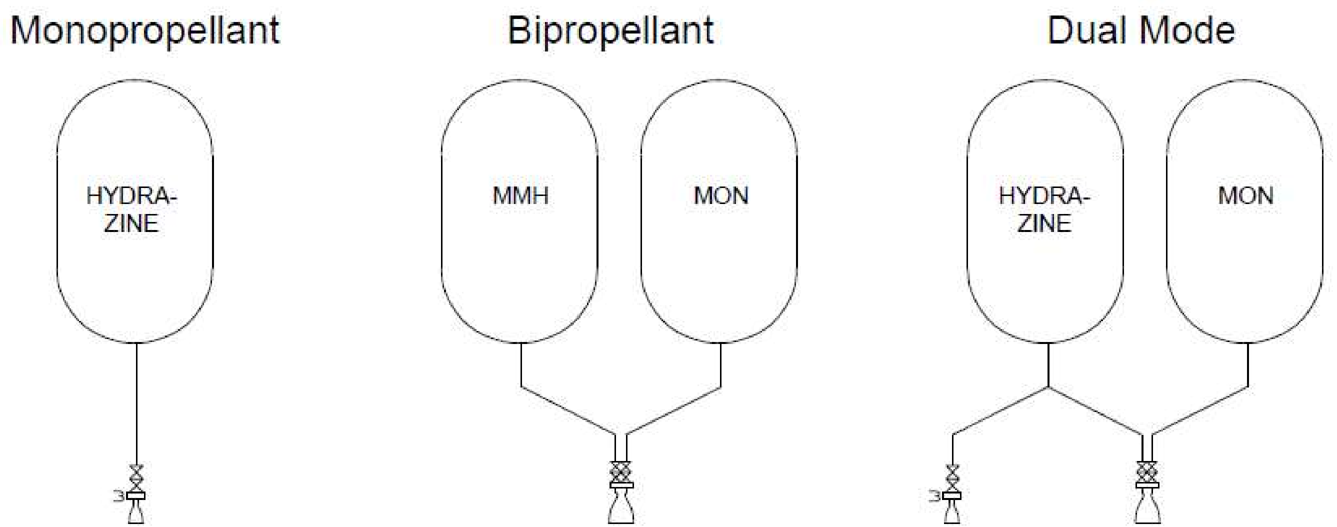
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Dual Mode Propulsion
  - Dual Mode systems combine elements of monopropellant and bipropellant systems
  - Dual mode propulsion system can have a high thrust bipropellant engine and small precise monopropellant engines
  - Or resistojets or arcjets may be used instead of catalytic hydrazine thrusters

Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Dual Mode Propulsion



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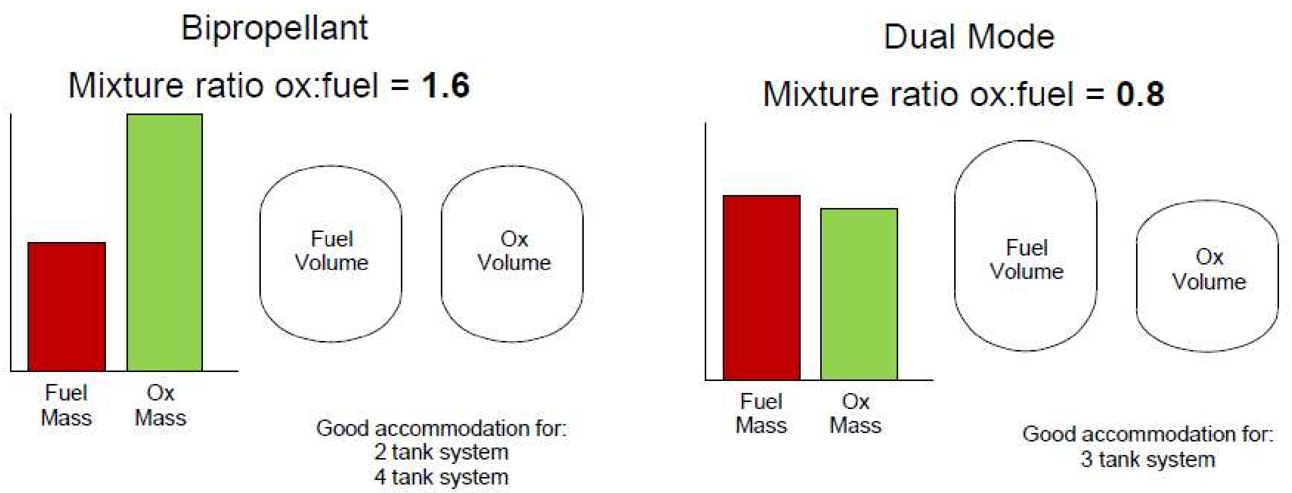
Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

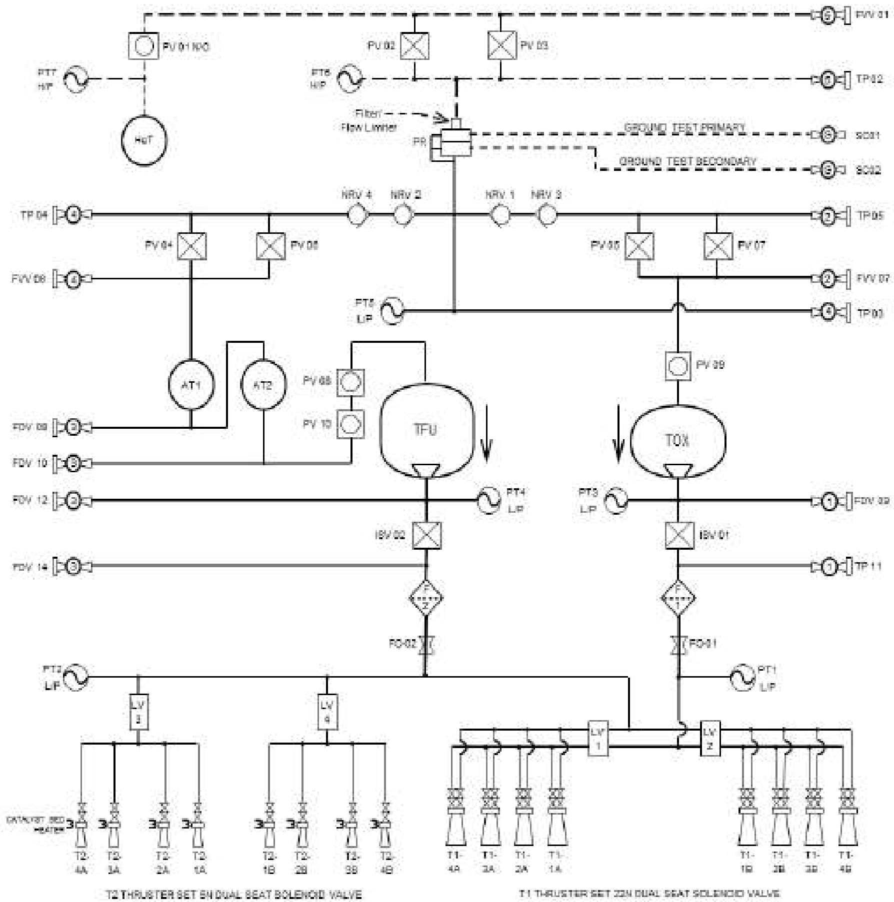
- Dual Mode Propulsion



Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basic propellant propulsion

- Dual Mode Propulsion
  - Example: Bepi Colombo



Which Liquid Bi-propellant Propulsion Systems exist?

Objective: To develop the basics of chemical L/L combustion bi-propellant propulsion

- Mixed Mode Propulsion
  - Mixed Mode propulsion refers to the use of different propellant types with one thruster:
    - Cold gas, mono-prop or bi-prop operation of a thruster
    - Small flow (igniter flow) or full flow

Back-up

Brief overview on all space propulsion systems