AE 330 Rocket Propulsion

Thermochemistry

&

Liquid Rockets

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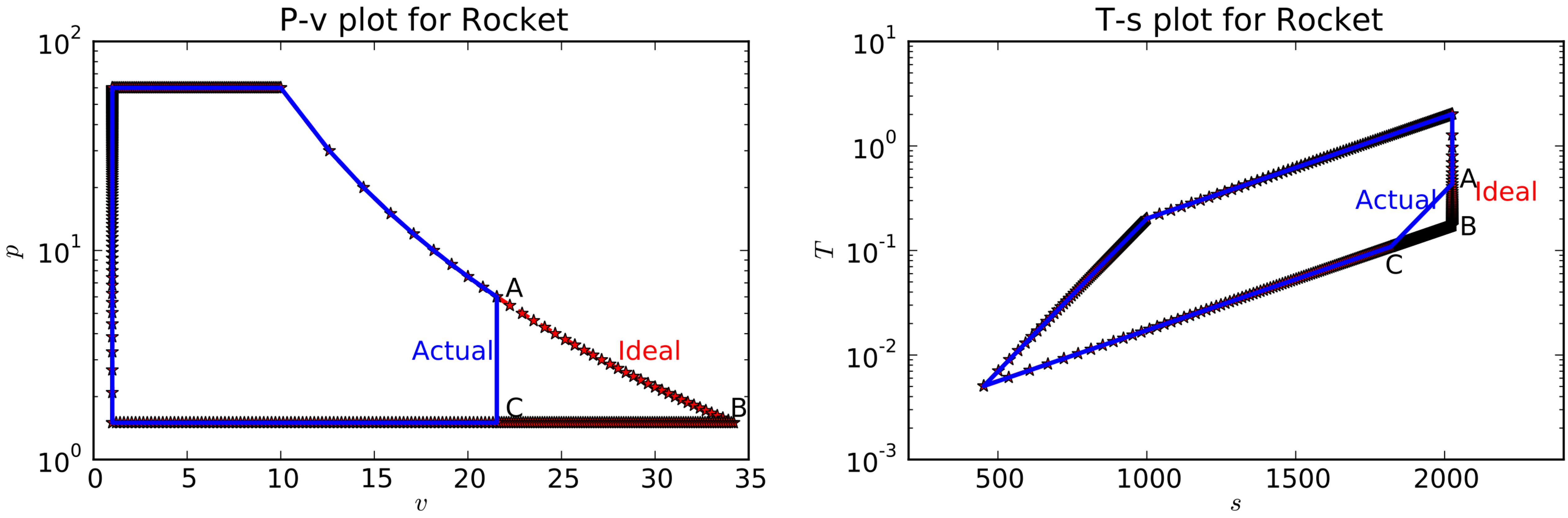
Rocket Thermodynamic Cycle



Thermodynamic Properties

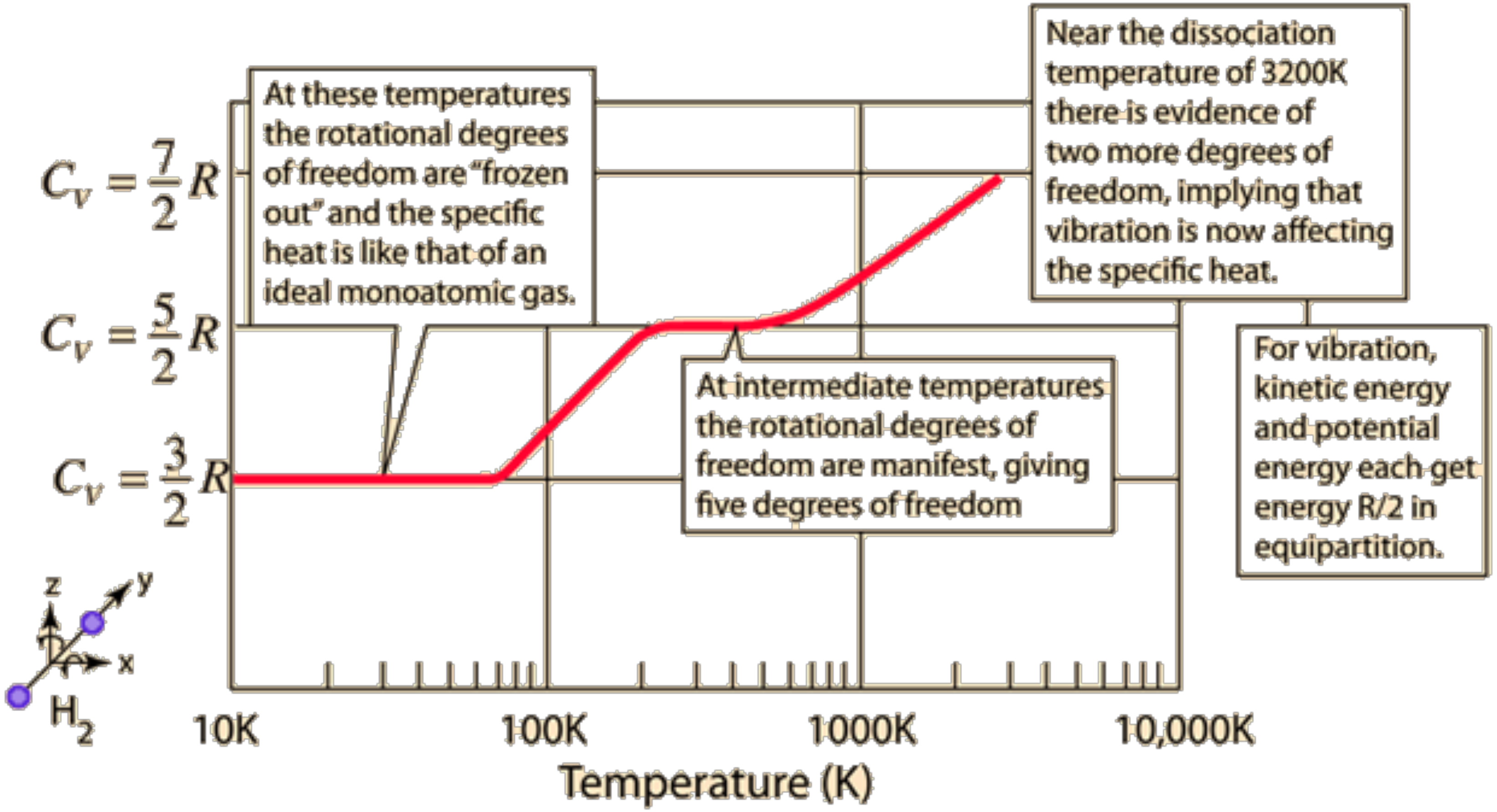
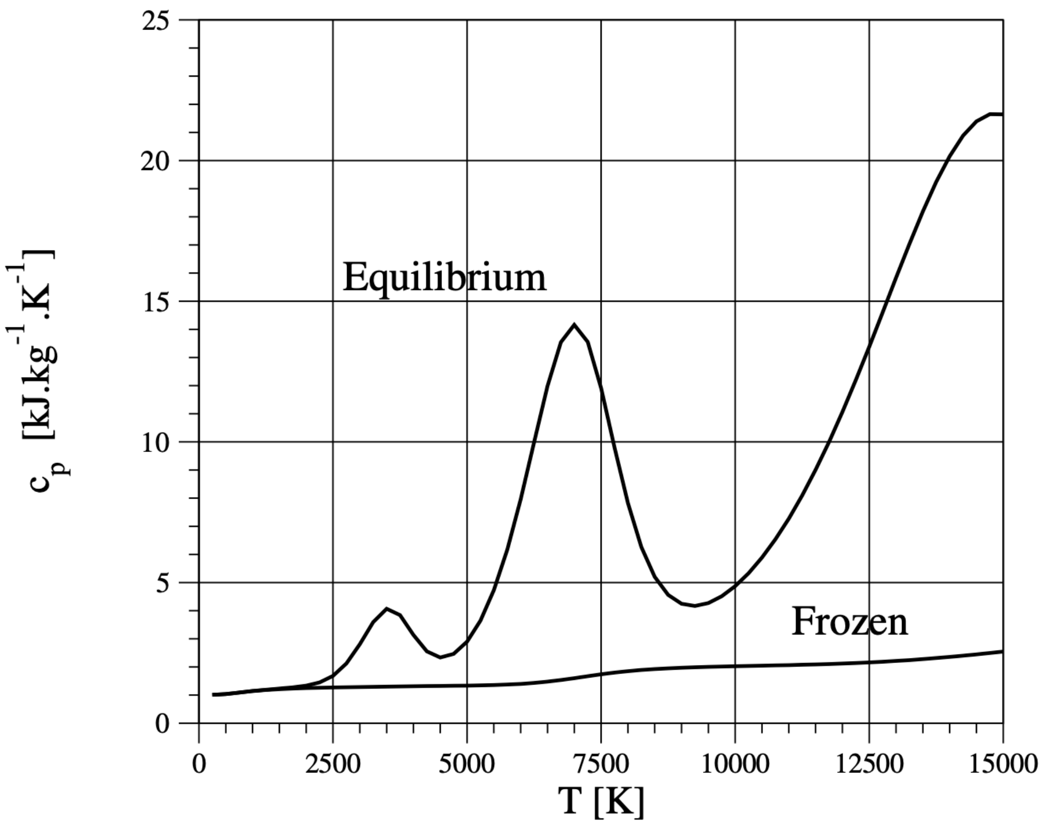
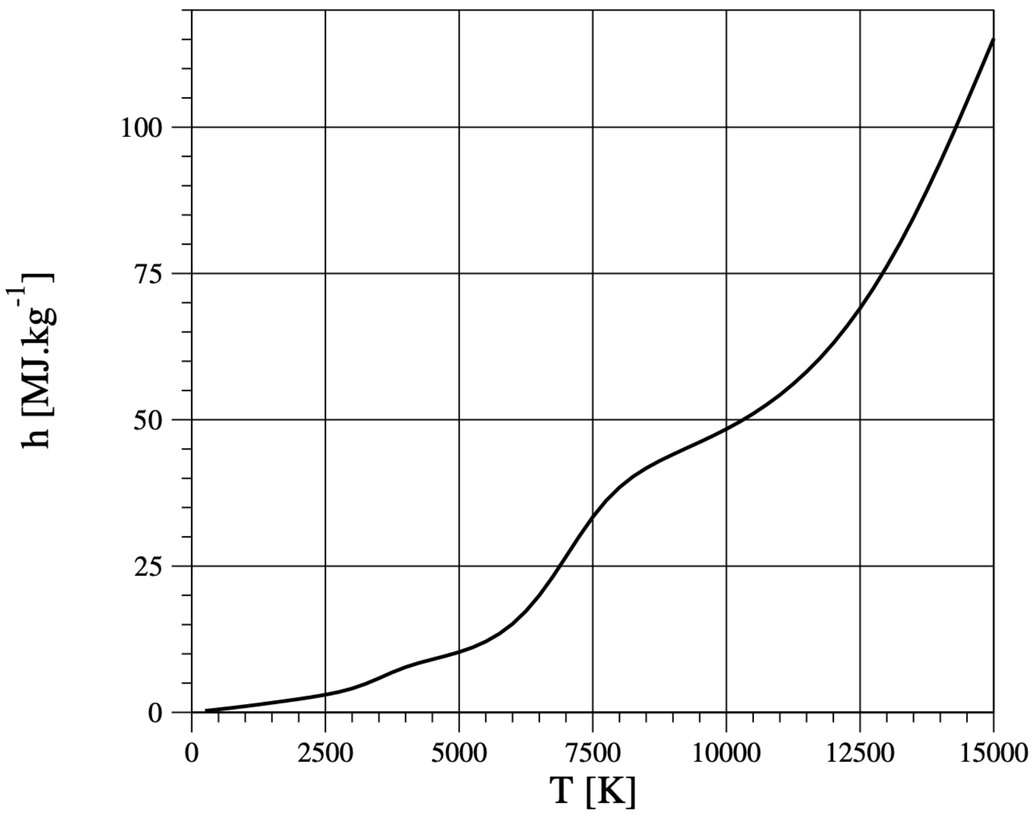


Image from hyperphysics.phy-astr.gsu.edu

Thermodynamic Properties

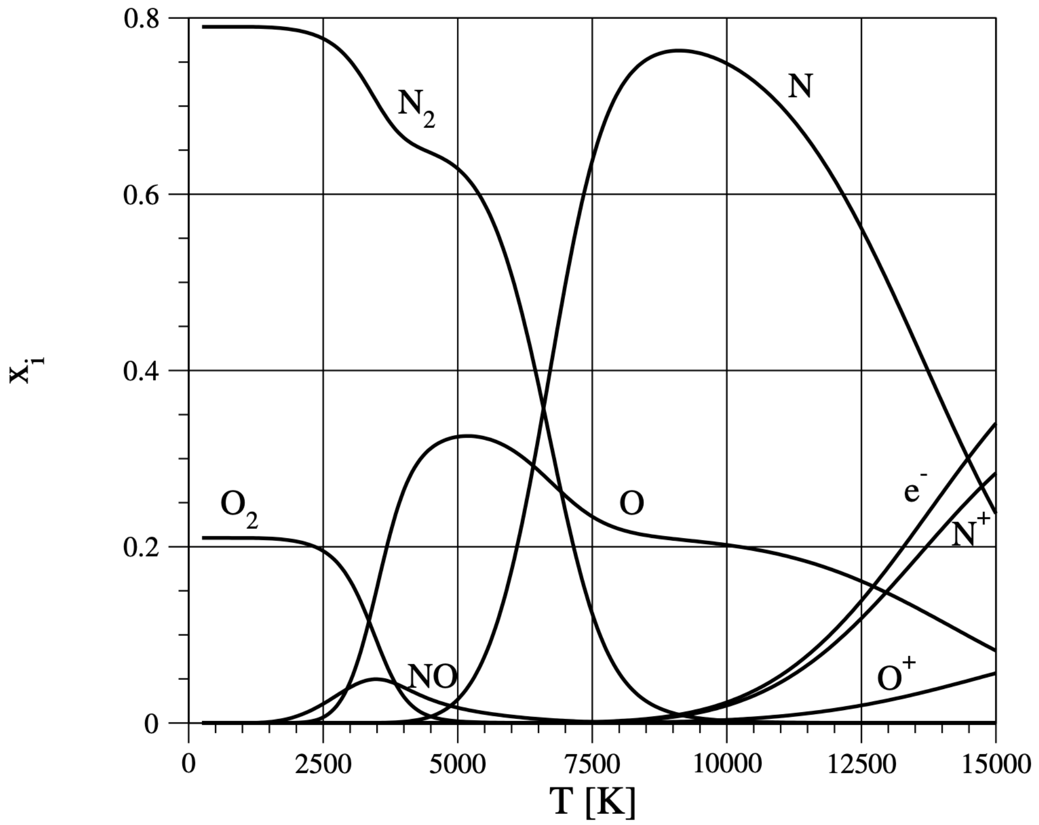


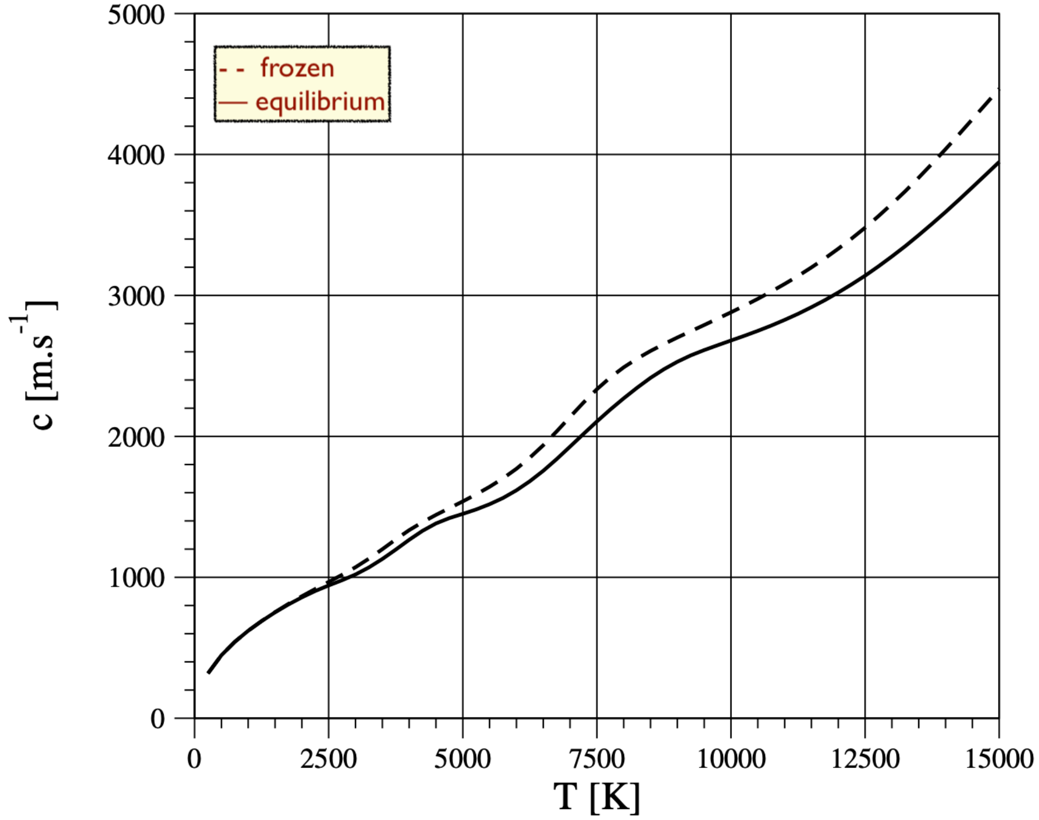


Air (1 atm)

Images from Babante & Magin

Thermodynamic Properties

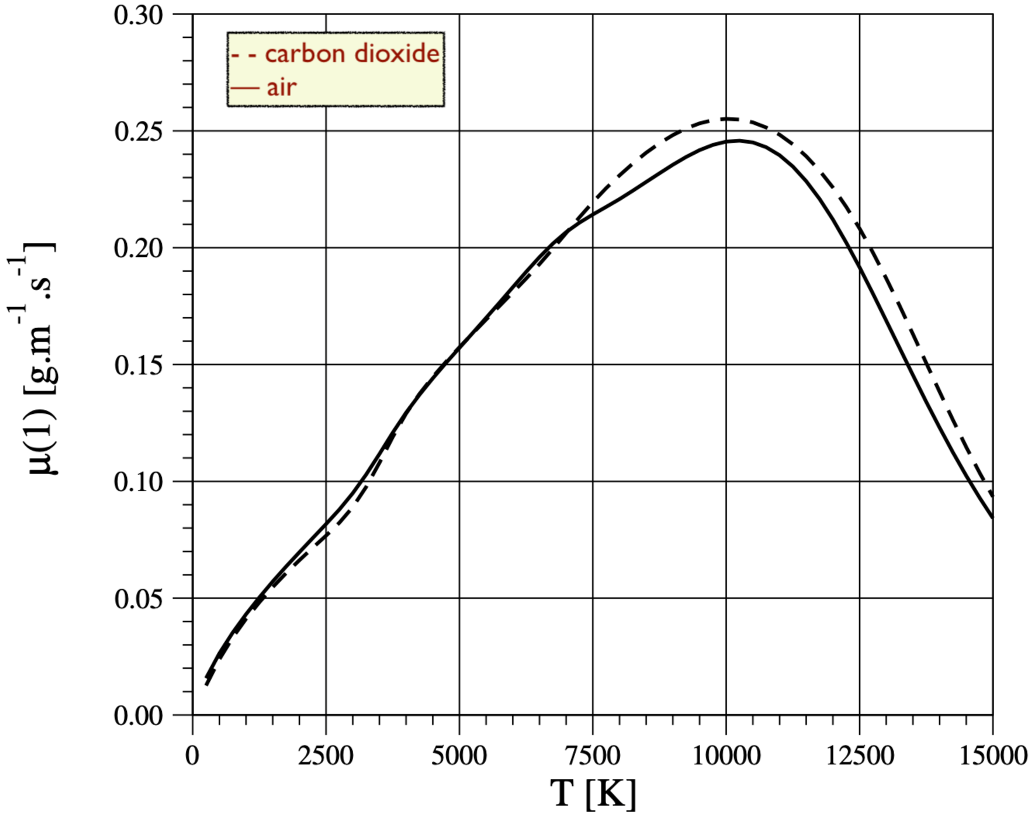


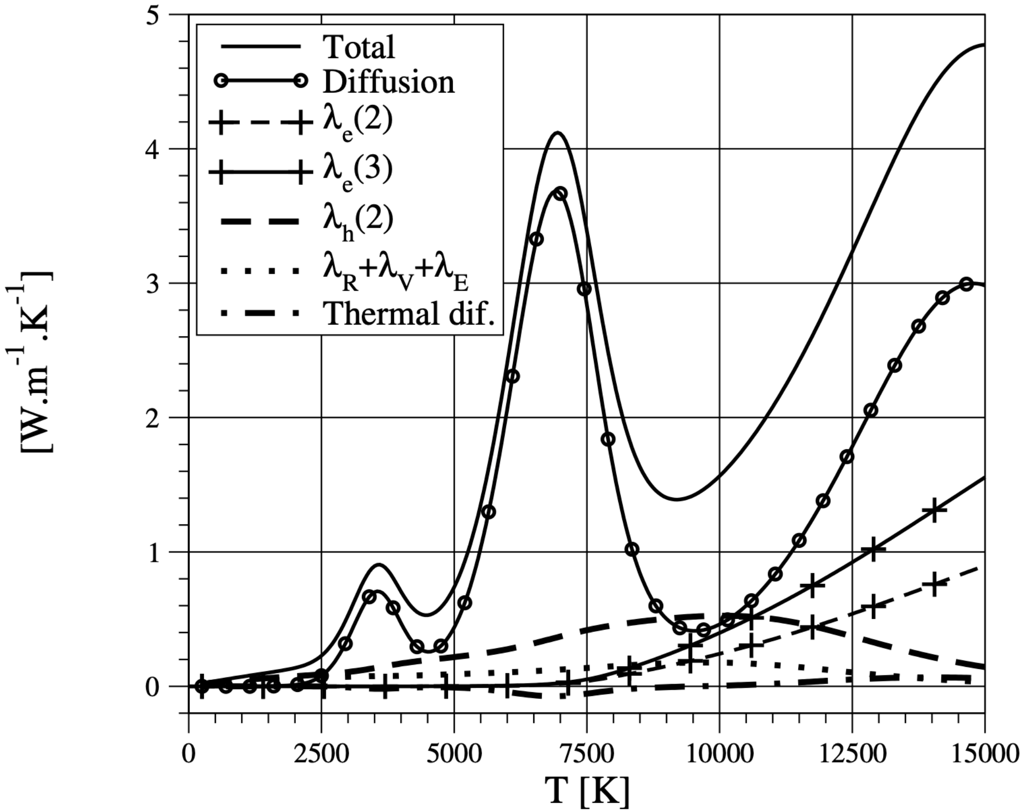


Air (1 atm)

Images from Babante & Magin

Thermodynamic Properties





Air (1 atm)

Images from Babante & Magin

Thermochemistry

Chamber pressure at injector 773.3 psia or 53.317 bar; $c^* = 2332.1$ m/sec; shifting equilibrium nozzle flow mixture ratio $O_2/H_2 = 5.551$; chamber to throat area ratio $A_1/A_t = 1.580$.

Parameters

Location	Injector face	Comb. end	Throat	Exit I	Exit II	Exit III	Exit IV
p_{inj}/p	1.00	1.195	1.886	10.000	100.000	282.15	709.71
T (K)	3389	3346	3184	2569	1786	1468	1219
$\mathfrak{M}$ (molec. mass)	12.7	12.7	12.8	13.1	13.2	13.2	13.2
k (spec. heat ratio)	1.14	1.14	1.15	1.17	1.22	1.24	1.26
C_p (spec. heat, kJ/kg-K)	8.284	8.250	7.530	4.986	3.457	3.224	3.042
M (Mach number)	0.00	0.413	1.000	2.105	3.289	3.848	4.379
A_2/A_t	1.580[a]	1.580[a]	1.000	2.227	11.52	25.00	50.00
c (m/sec)	*NA*	*NA*	2879[b]	3485	4150	4348	4487
v_2 (m/sec)	*NA*	*NA*	1537[b]	2922	3859	4124	4309
Mol fractions of gas mixture							
H	0.03390	0.03336	0.02747	0.00893	0.00024	0.00002	0.00000
HO_2	0.00002	0.00001	0.00001	0.00000	0.00000	0.00000	0.00000
H_2	0.29410	0.29384	0.29358	0.29659	0.30037	0.30050	0.30052
H_2O	0.63643	0.63858	0.65337	0.68952	0.69935	0.69948	0.69948
H_2O_2	0.00001	0.00001	0.00000	0.00000	0.00000	0.00000	0.00000
O	0.00214	0.00204	0.00130	0.00009	0.00000	0.00000	0.00000
OH	0.03162	0.03045	0.02314	0.00477	0.00004	0.00000	0.00000
O_2	0.00179	0.00172	0.00113	0.00009	0.00000	0.00000	0.00000

Table from Sutton

Liquid Rocket Engines

Type	Propellant	Energy Source	I_{sp} (s) Vacuum	F (lbs) Range	Specific Gravity	Advantages	Disadvantages
Liquid mono-propellant	H_2O_2 N_2H_4	Exothermic decomposition	150 200	0.01–0.1	1.46 1	Simple, reliable, low cost	Low performance, higher weight
Liquid bipropellant	RP-1/O_2	Chemical	270–360	$1–10^6$	1	High performance	Complicated
	H_2/O_2	Chemical	360–450	$1–10^6$	1.26	Very high performance	Cryogenic, complicated
	UMDH/ N_2O_4	Chemical	270–340	$1–10^6$	1.14	Storable, good performance	Complicated
	N_2H_4/F_2	Chemical	425	$1–10^6$	1.1	Very high performance	Toxic, dangerous, complicated

Table from Lee

Propellant Combinations

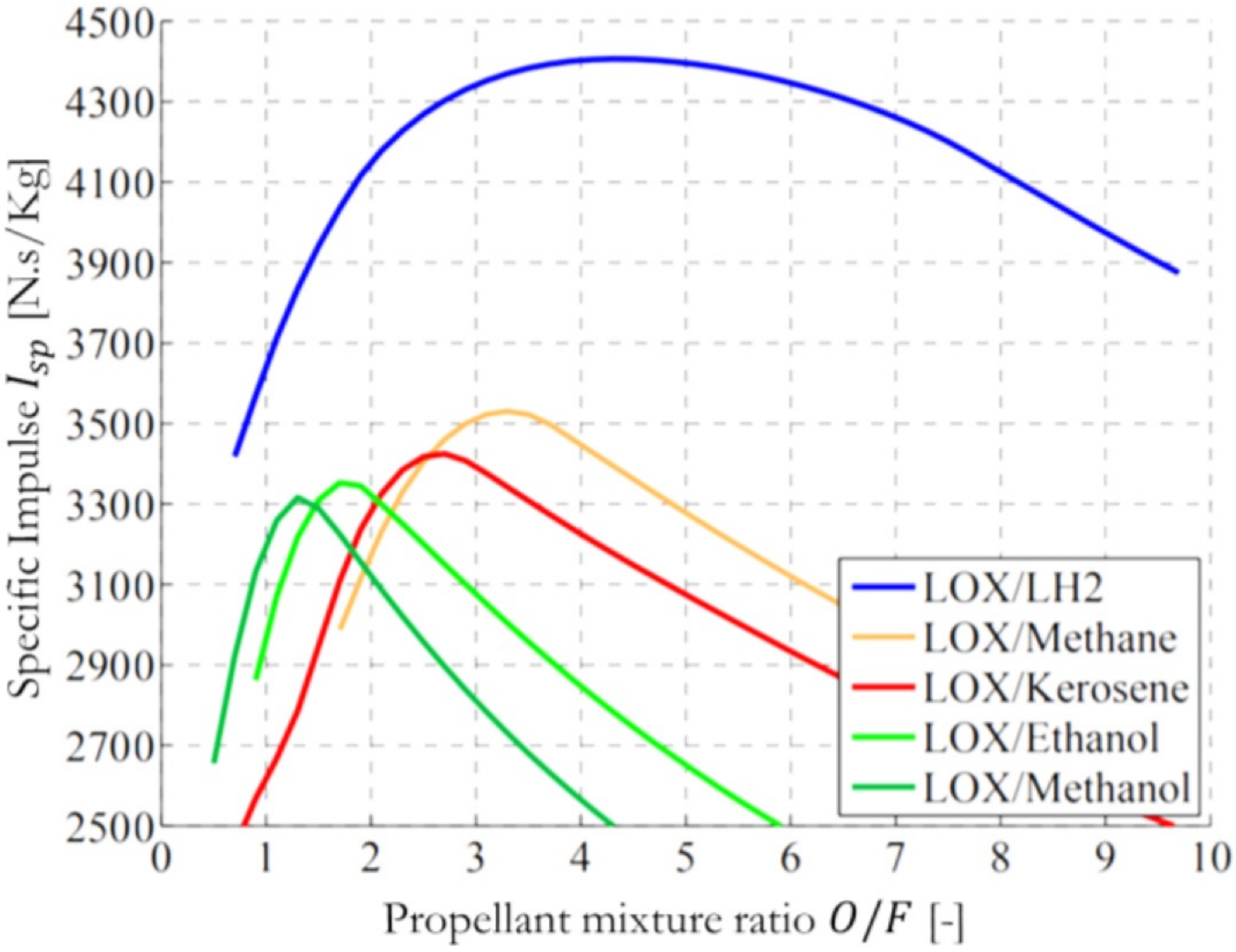
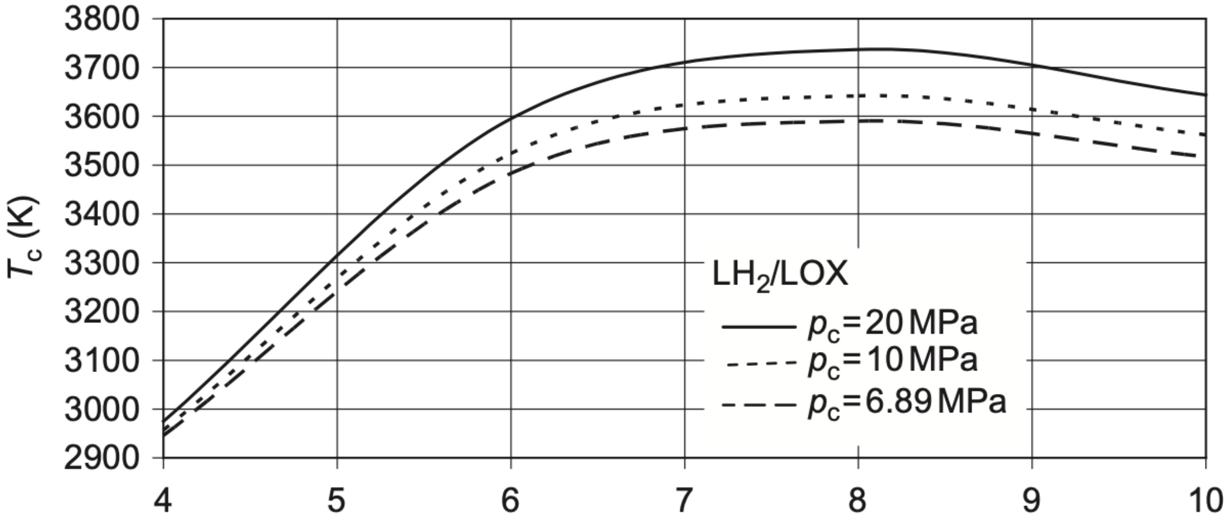
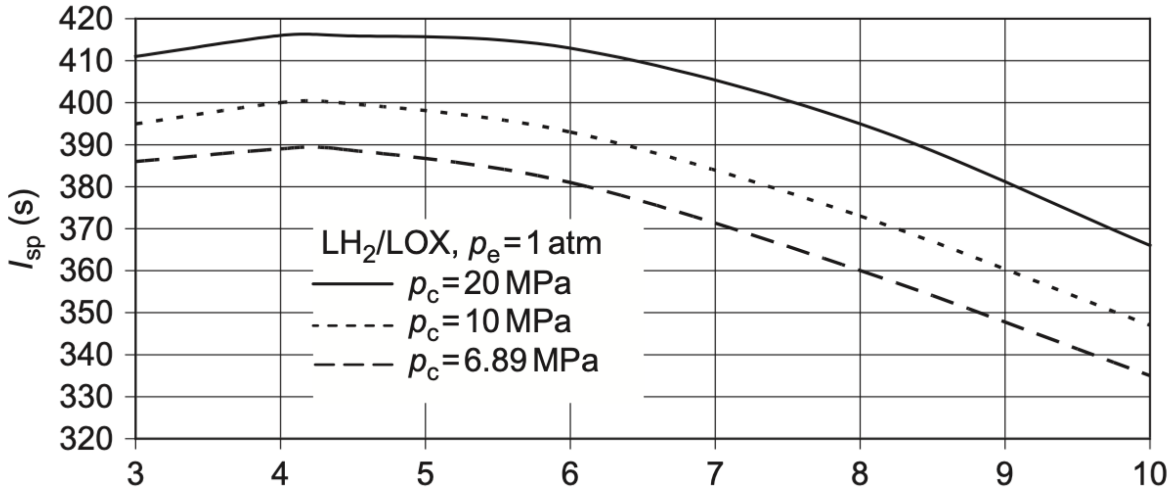
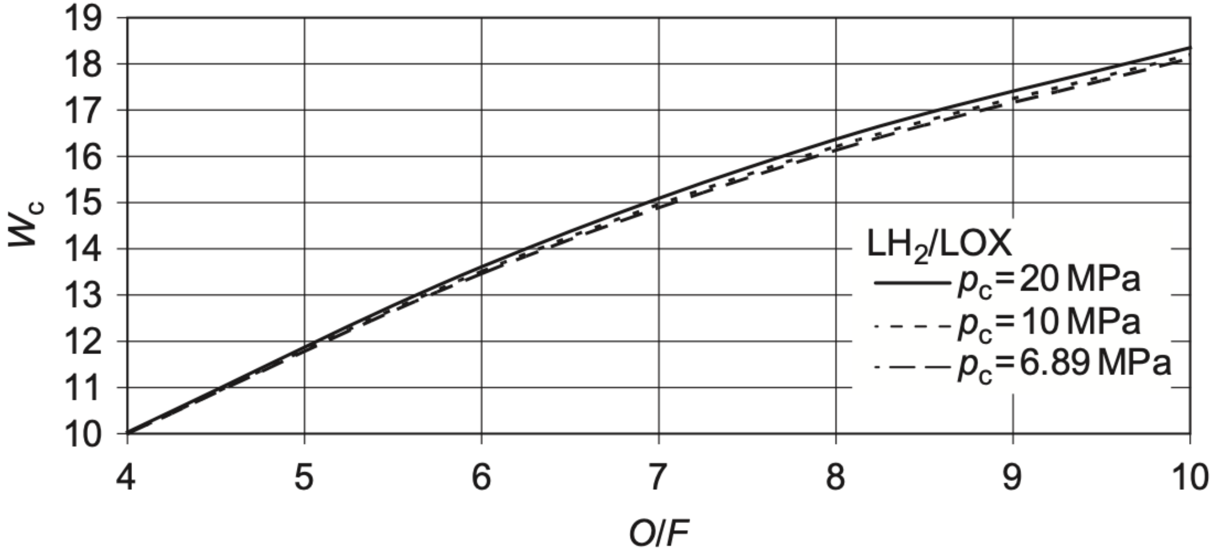


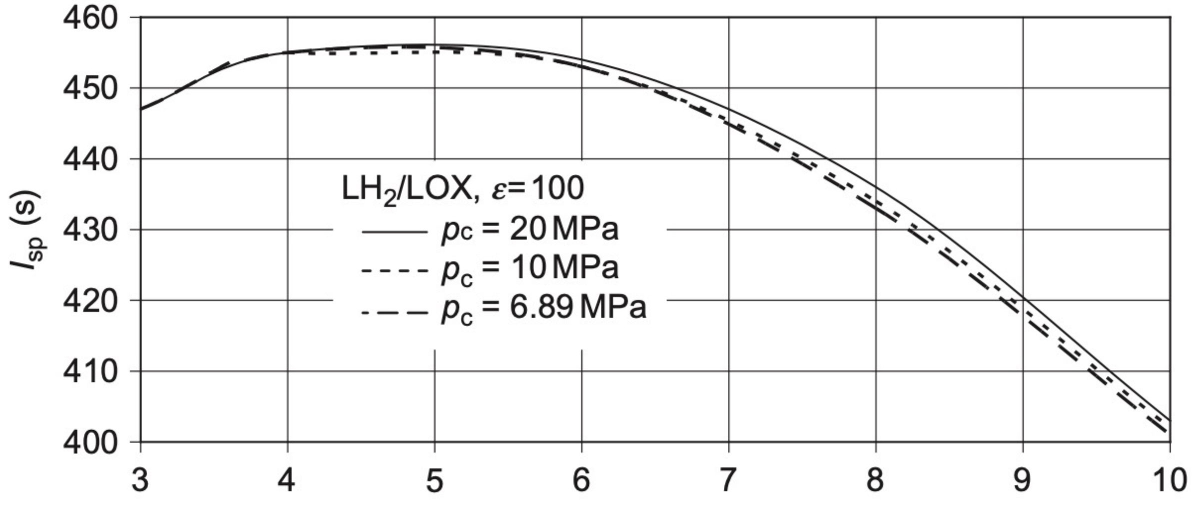
Image from Johnson

LOX-LH2: Effect of Mixture Ratio









Images from Sforza

LOX-LCH4: Effect of Mixture Ratio

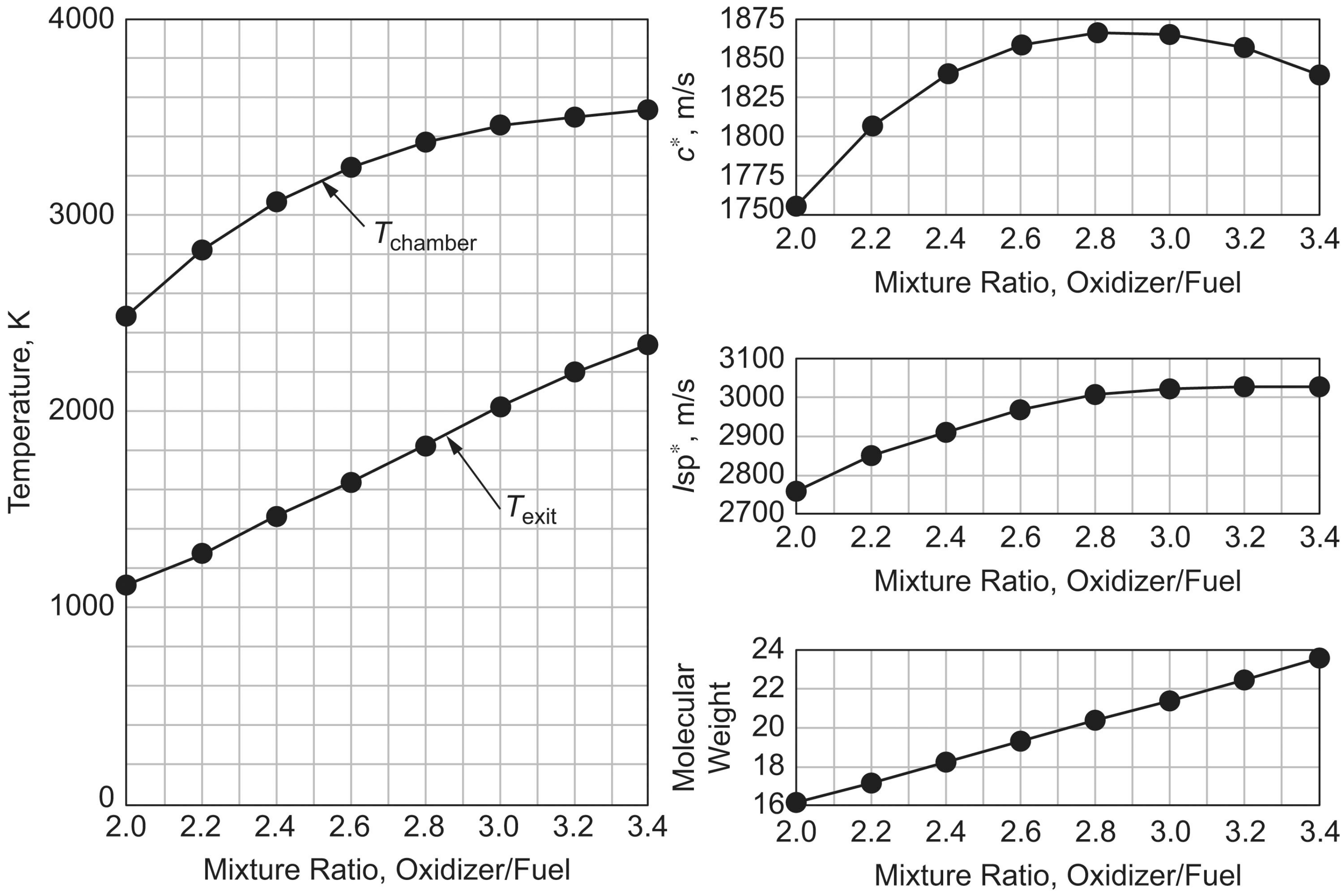


Image from Heister

Characteristic Length

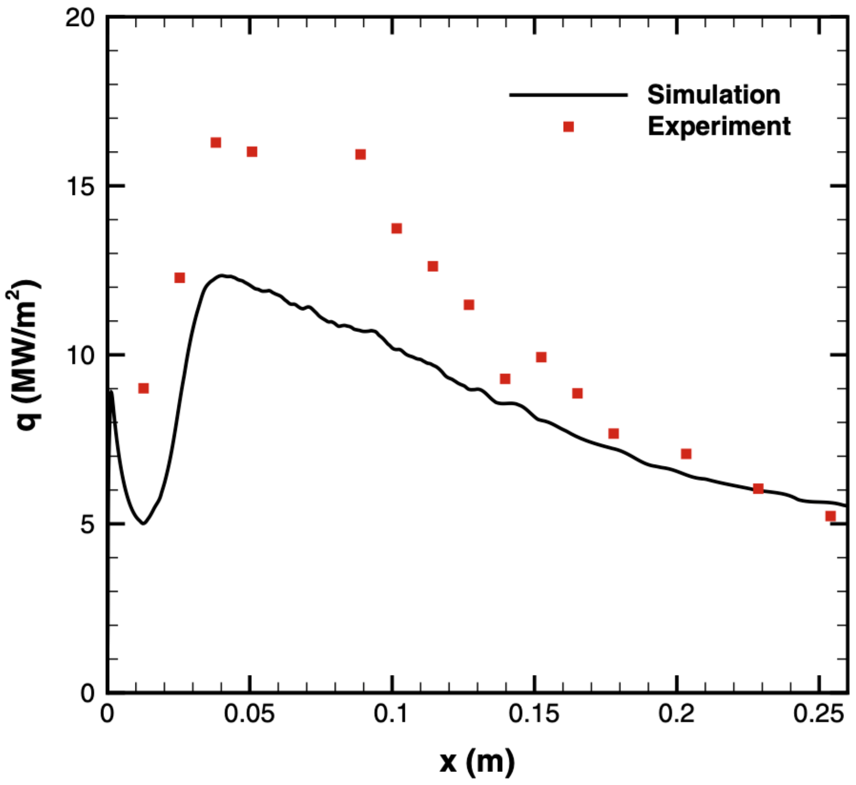
Propellant Combination	**L* (cm)**
HNO_3 / Hydrazine variants	76 – 89
N_2O_4 / Hydrazine variants	76 – 89
LO_2 / RP1	102 – 127
LO_2 / NH_3	76 – 102
LO_2 / LH_2 (gaseous H_2 injection) – Semicryogenic	56 – 71
LO_2 / LH_2 (liquid H_2 injection) – Cryogenic	76 – 102

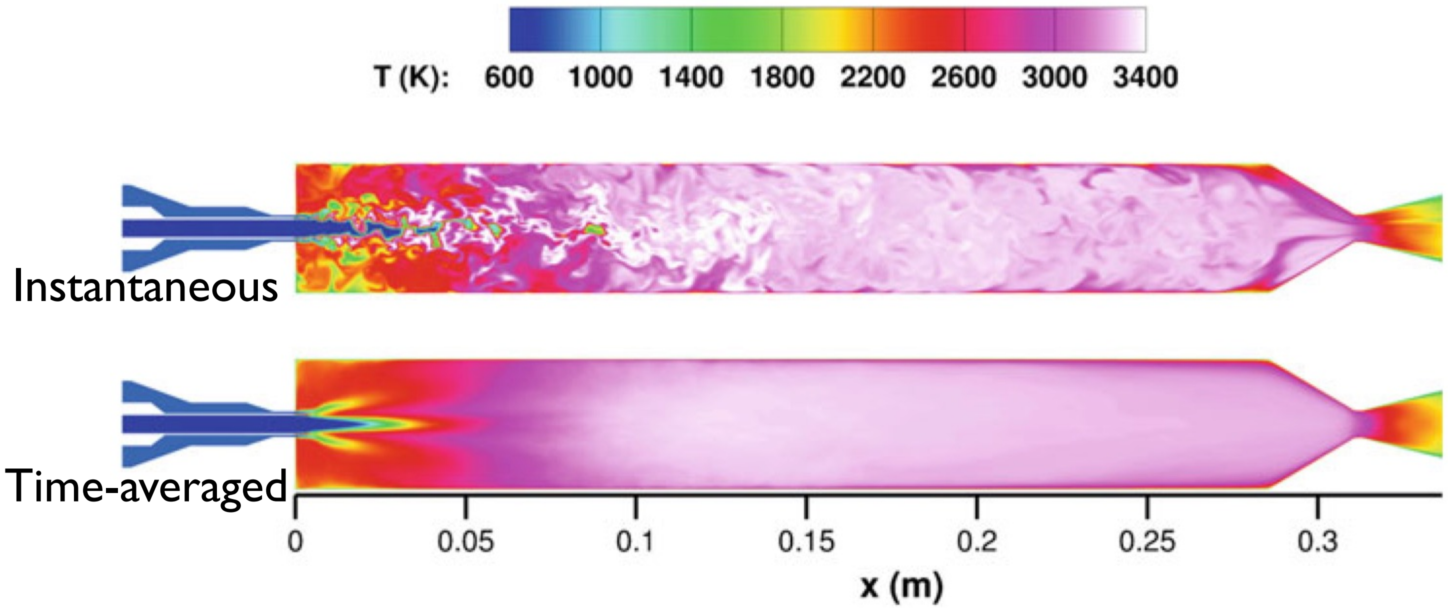
Propellant Combinations

	Merlin	RD-180	F-1	Raptor	BE-4	RS-25
Cycle	Open	Closed (LOX rich)	Open	Closed (Full Flow)	Closed (LOX rich)	Closed (Fuel Rich)
Fuel Type	RP-1	RP-1	RP-1	Methane	Methane	Hydrogen
Total Thrust	0.84 MN	3.83 MN	**6.77 MN**	2.00 MN	~2.40 MN	1.86 MN
Thrust : Weight	**198 : 1**	78 : 1	94 : 1	107 : 1	~80 : 1	73 : 1
Specific Impulse *(ISP)*	282 sl 311 vac	311 sl 338 vac	263 sl 304 vac	330 sl ~350 vac	~310 sl ~340 vac	**366 sl** **452 vac**
Chamber Pressure	97 bar	257 bar	70 bar	**270 bar**	~135 bar	206 bar

Image from EverydayAstronaut

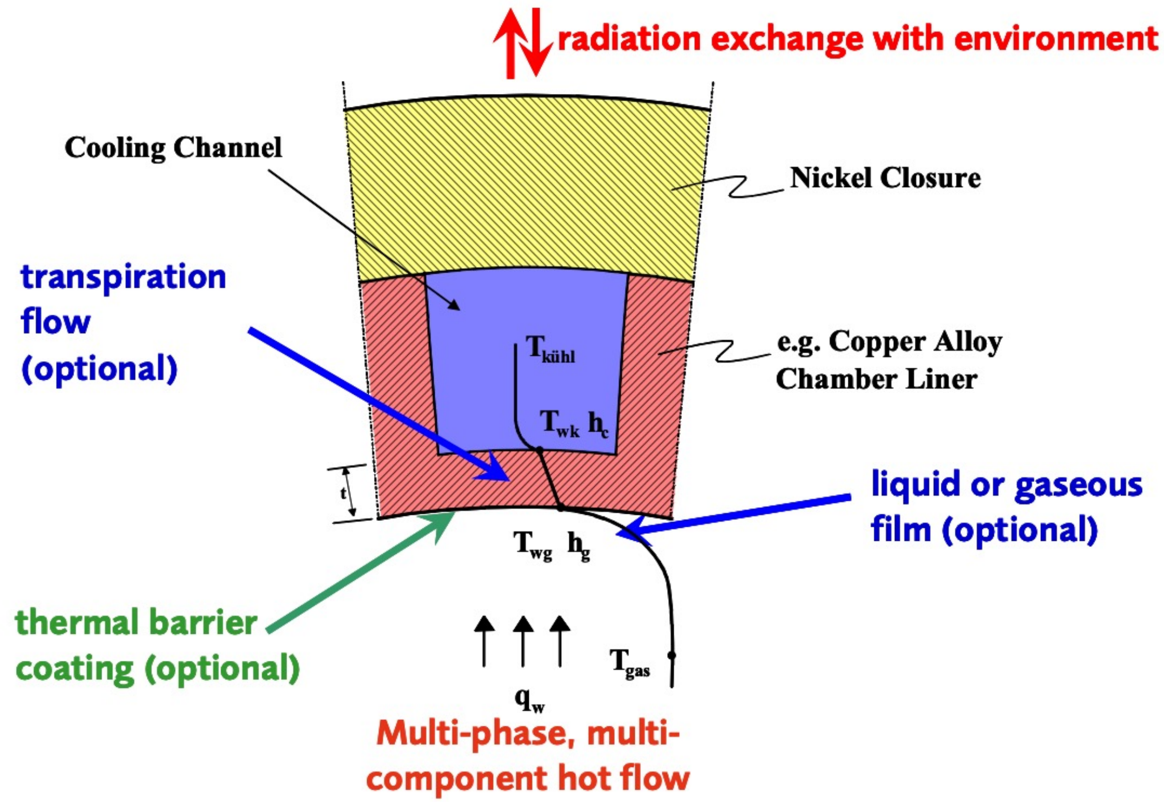
Thermal Loads

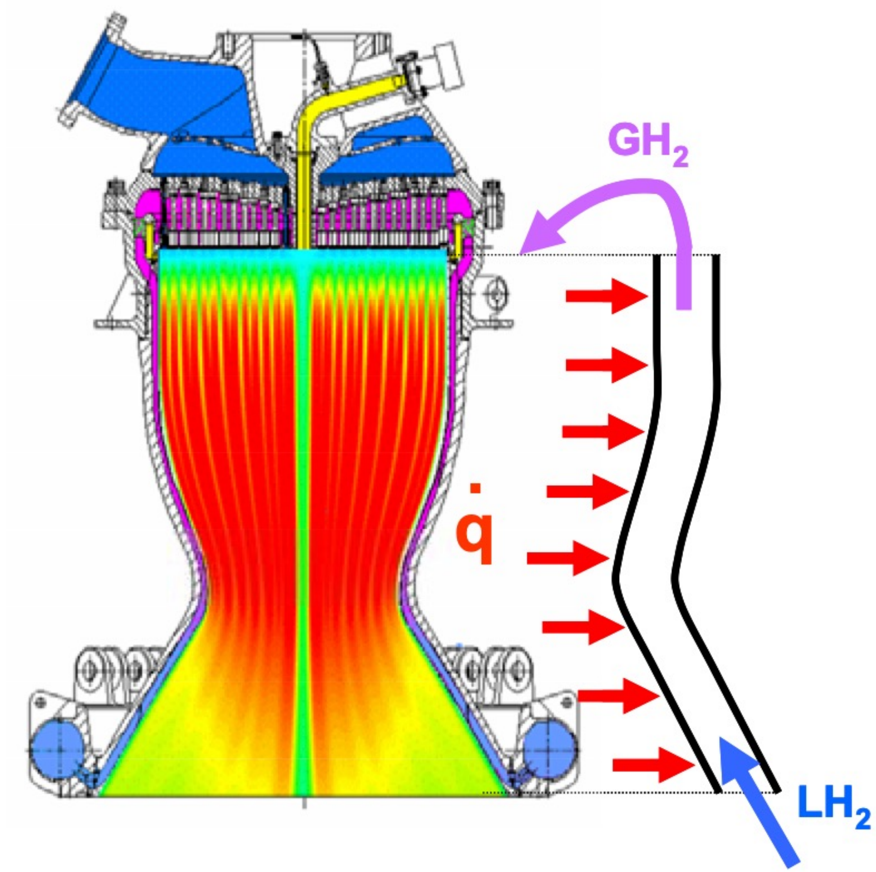




Images from Seiz

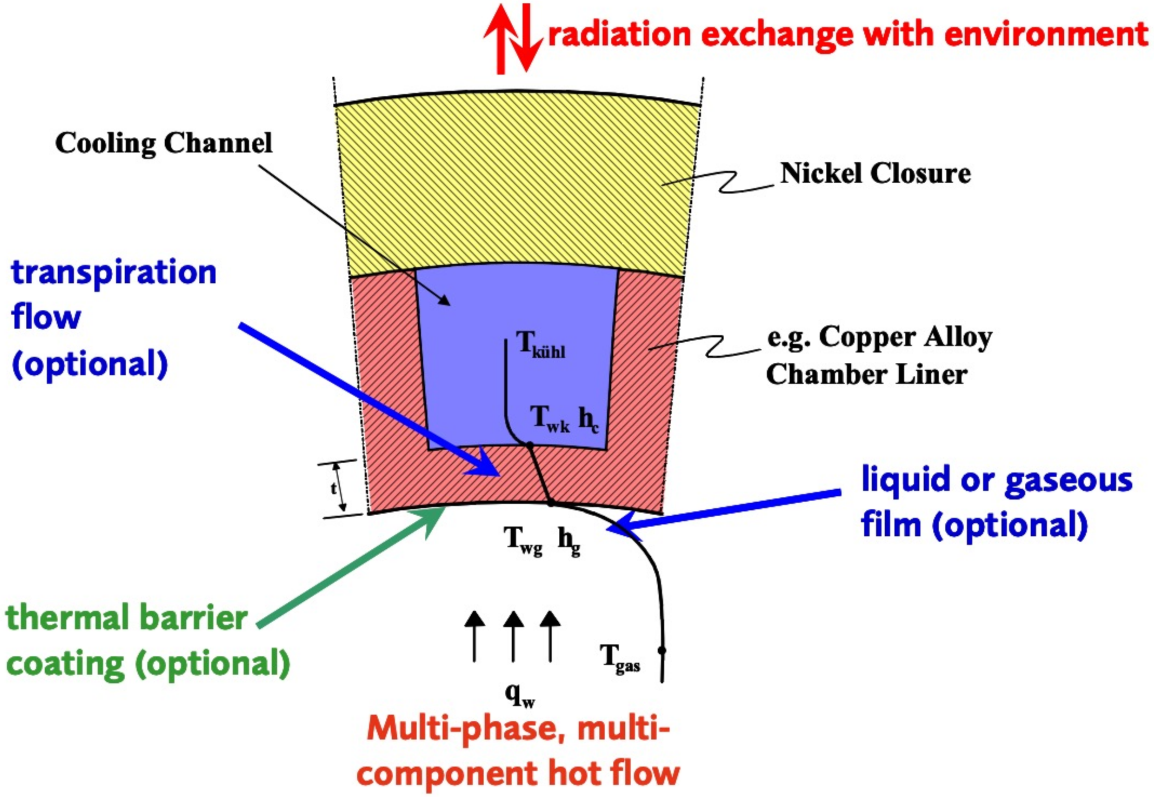
Thermal Loads

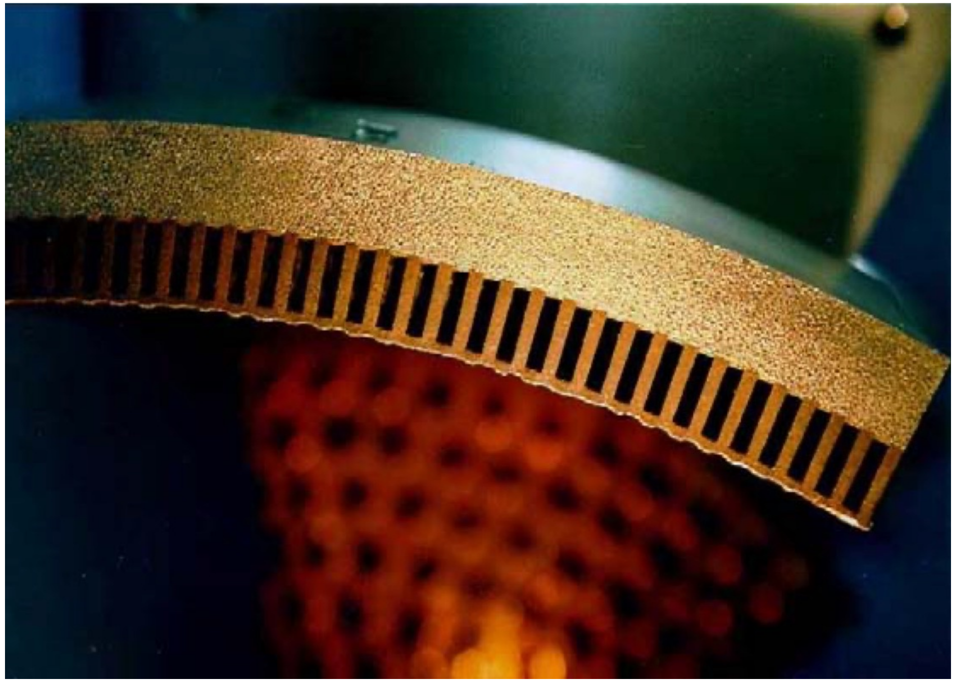




Images from Knab

Thermal Loads





Combustion Chamber Wall

Images from Knab, Haidn

Regenerative Cooling

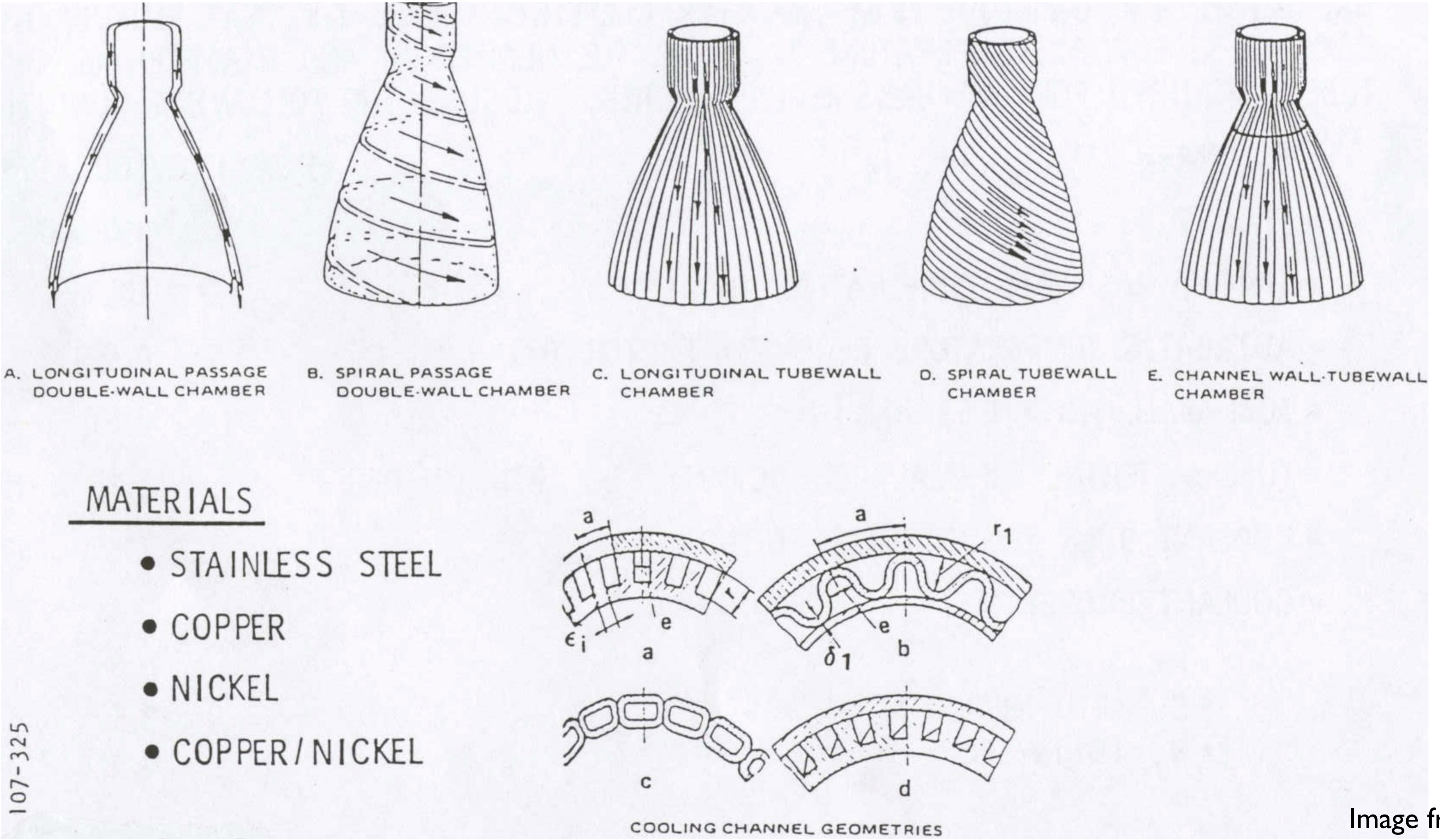
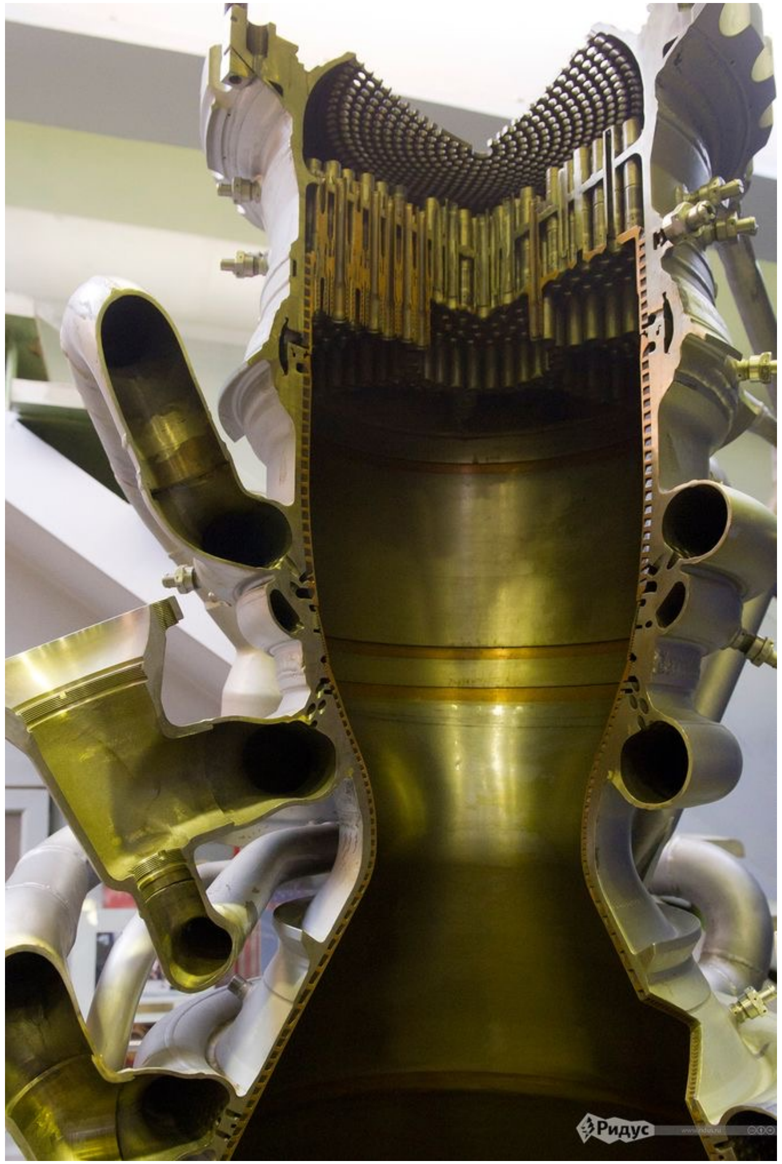


Image from Boeing

Combustion Chamber



Injectors

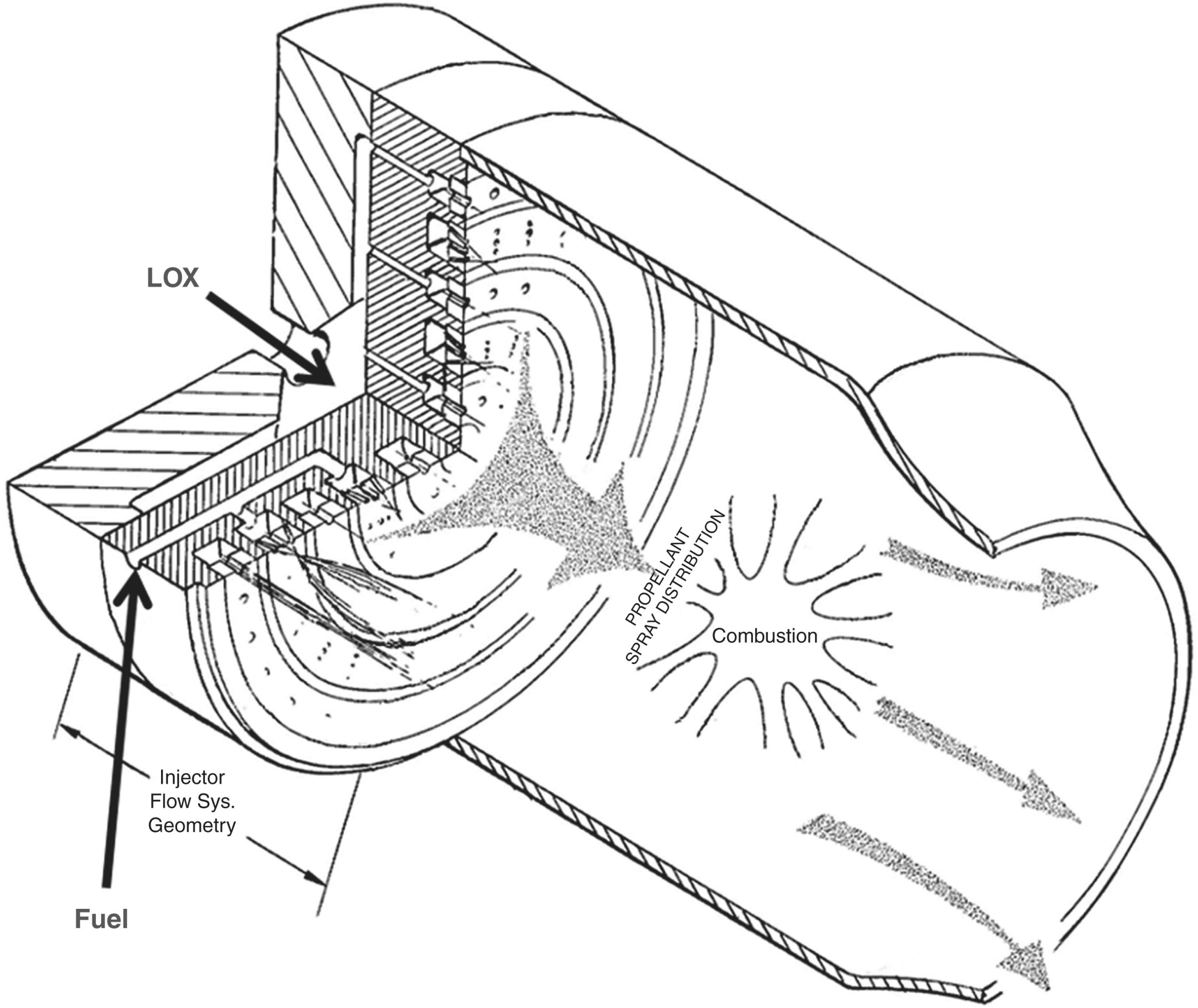


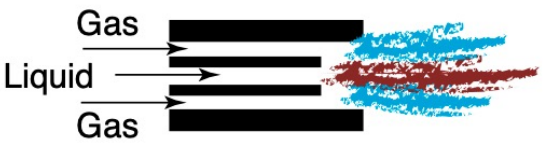
Image from Heister

Atomization

Image from ILASSEurope

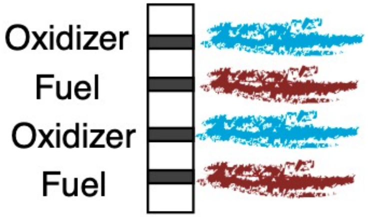
Injectors

Concentric tube



- High performance for LOX/H_2
- Fuel is gas
- Two options: Shear Coaxial and Swirl Coaxial
- Good wall compatibility
- Difficult to fabricate
- SSME, J-2, Orbit Transfer Vehicles

Showerhead

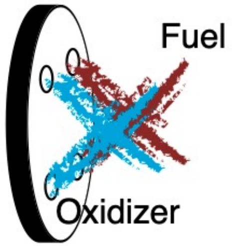


- Fuel injector for Chamber wall cooling
- Low performance: Poor atomization and mixing
- X-15, Pioneer

Images from Lee

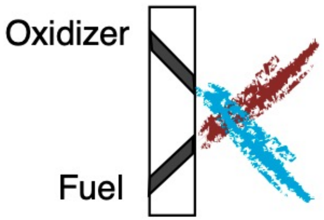
Injectors

Like doublet



- Easy to manifold
- Good wall compatibility
- Not subject to blowapart
- Less effective atomization and mixing than unlike injector elements
- Shuttle OMES, F-1, Titan I & II stages, Atlas Booster

Unlike doublet

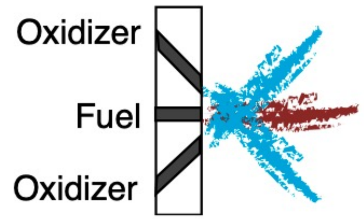


- Good mixing and atomization (high performance)
- Easy to manifold
- Subject to blowapart with hypergolic propellants
- LEM ascent engine, Most attitude control engines using storable propellants, Delta launch vehicle

Images from Lee

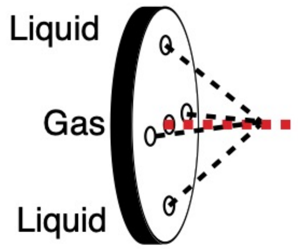
Injectors

Unlike triplet



- Good atomization and mixing
- Symmetric spray pattern
- Subject to blowapart with hypergolic propellants
- Fuel can be gas
- Pattern can be reversed
- Rocket LEM descent engine, LOX/RP1 gas generators

Unlike pentad

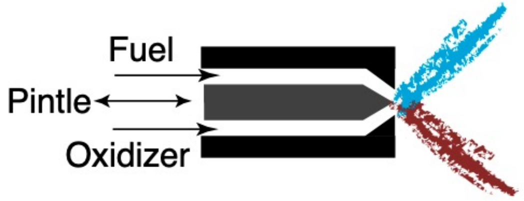


- Good atomization and mixing
- Applicable to very high or low mixture or density ratios
- Difficult to manifold
- Experimental

Images from Lee

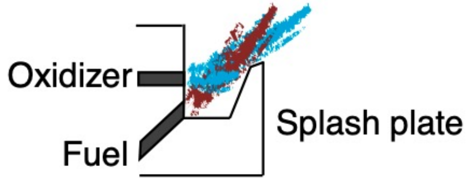
Injectors

Variable area (Pintle)



- Throttleable over wide range
- Complex fabrication
- Lower performance
- LEM descent engine

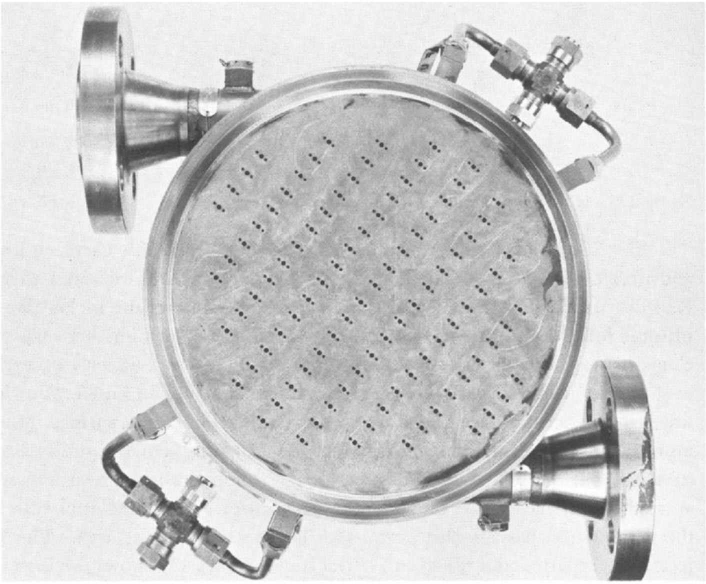
Splash plate



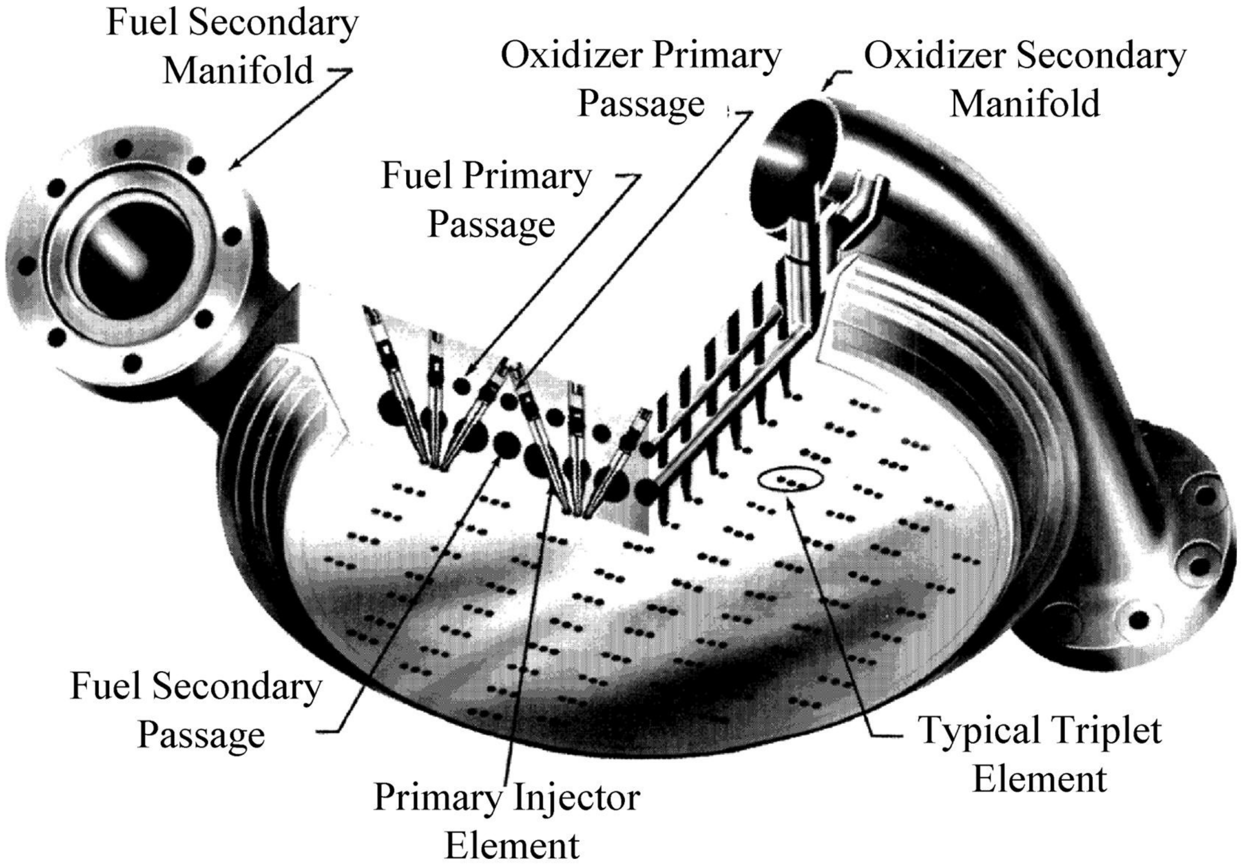
- Less sensitive to design tolerances
- Larger elements
- Apollo CM RCS, Gemini SC manoeuvring, attitude control and reentry engines

Images from Lee

Injector Manifold



a) Hardware photo



b) Schematic diagram

Images from Casiano

Liquid Rocket Engines

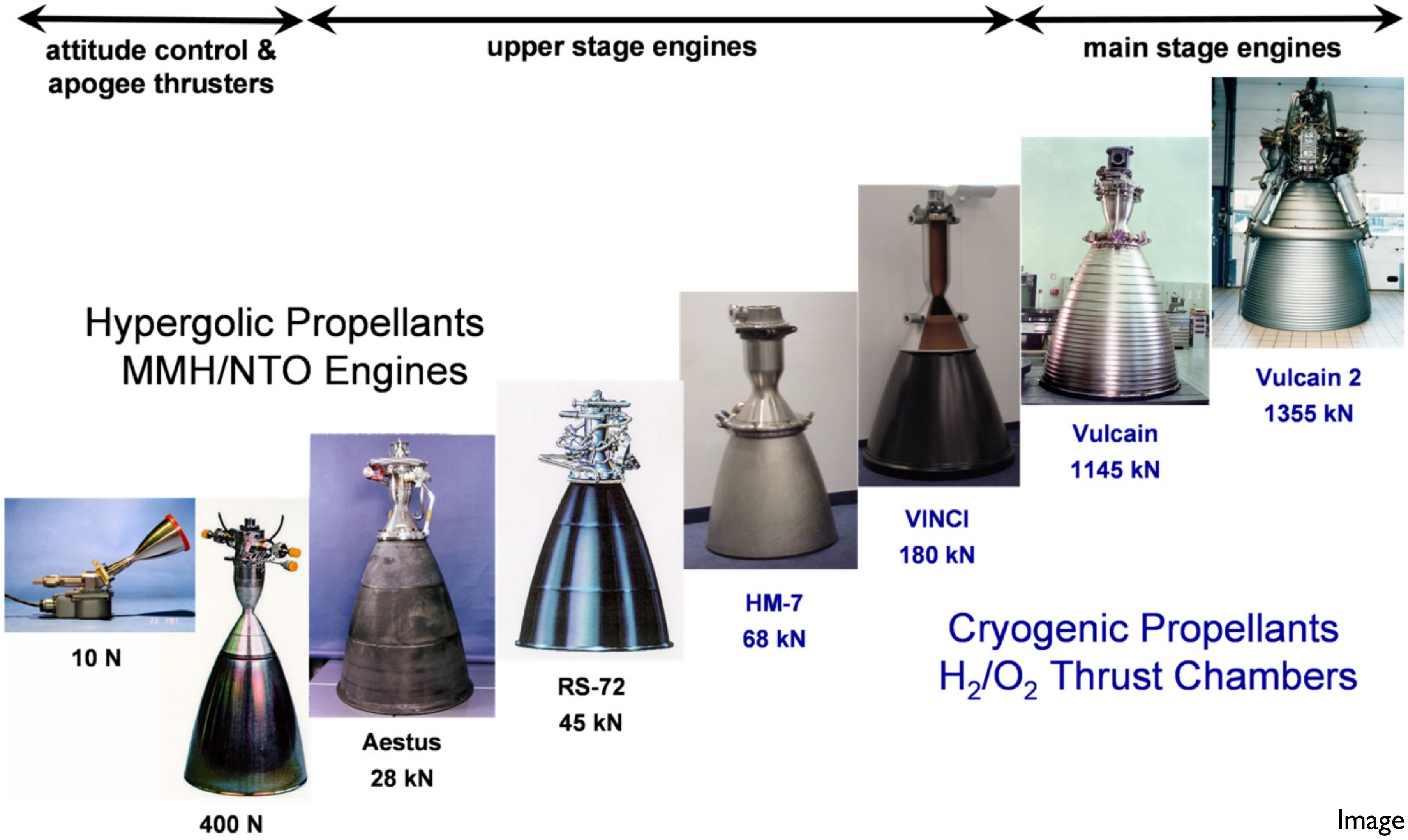


Image from Knab

Tank arrangements

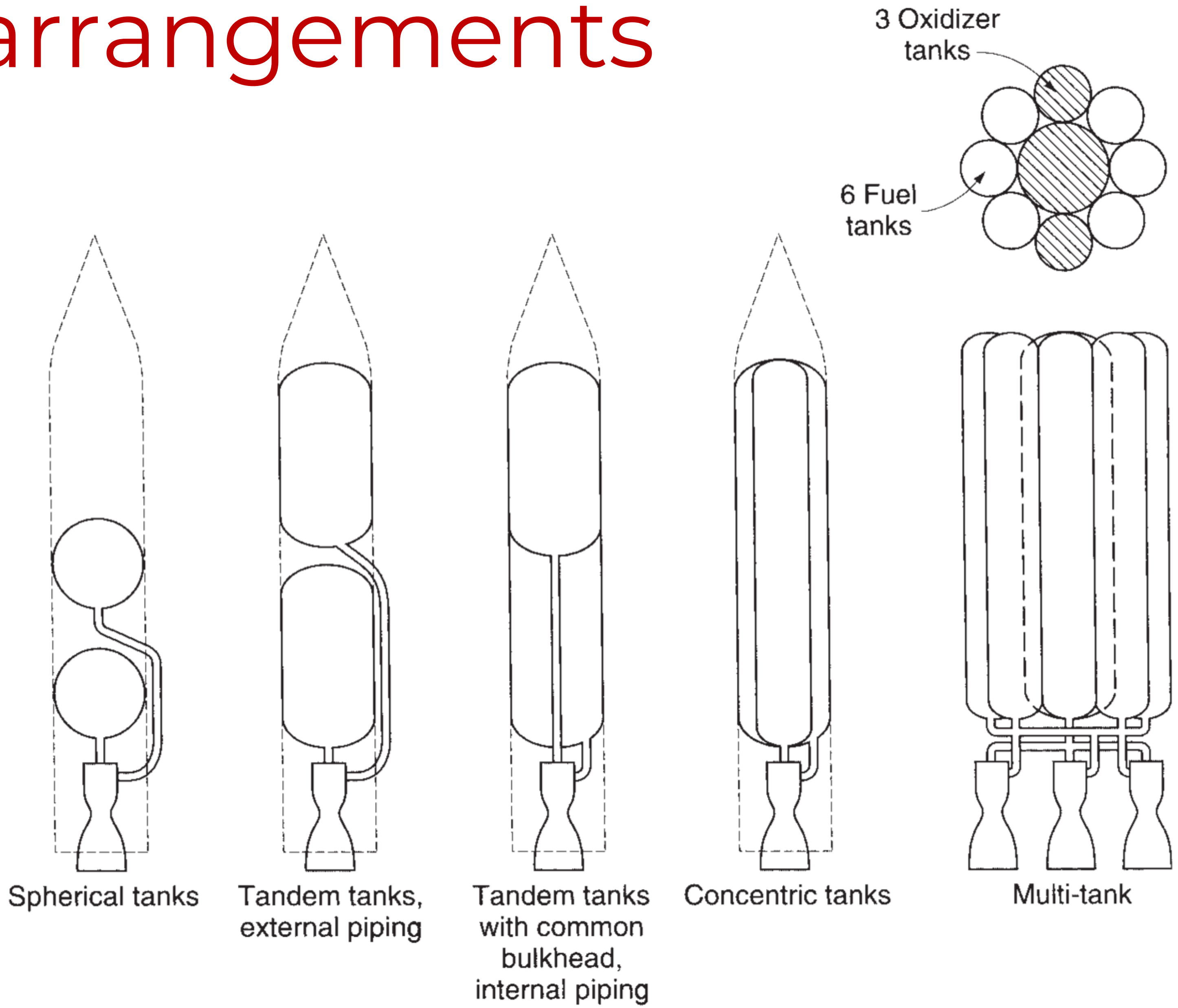
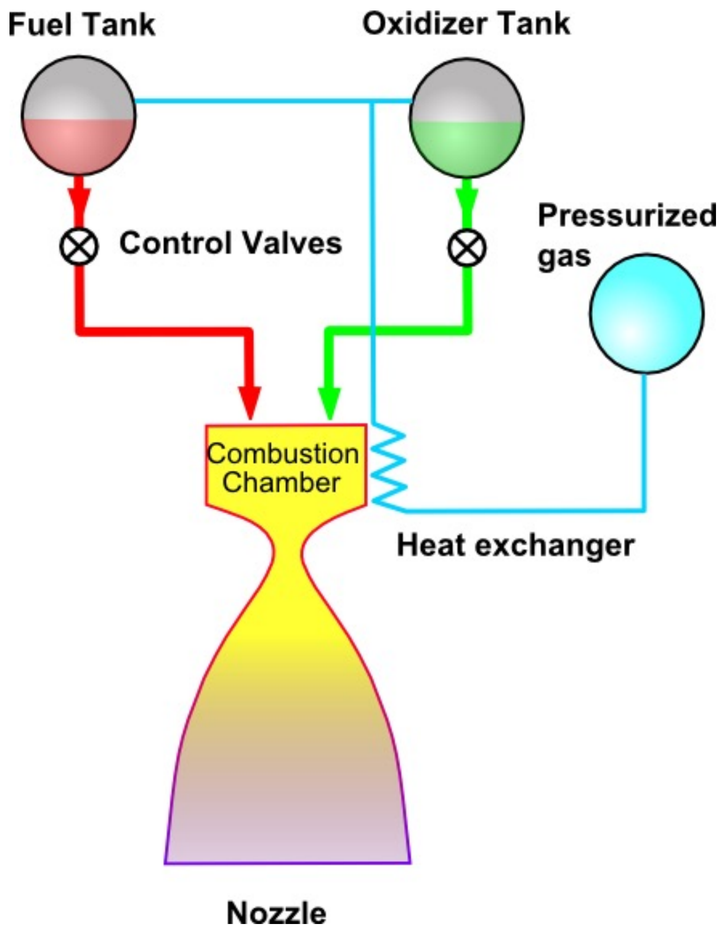


Image from Sutton

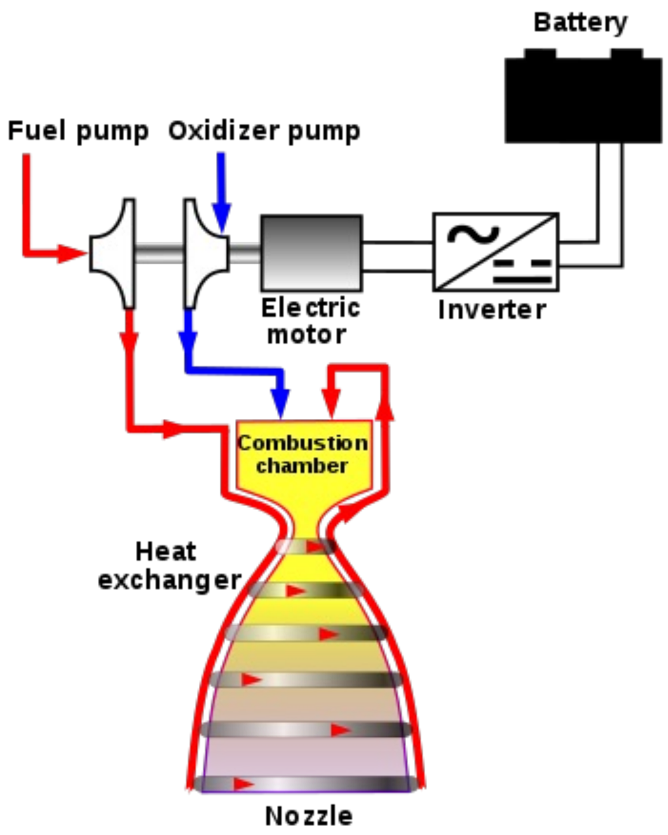
Pressure-fed Systems



- Upper Stage and Space-craft Engines
- Low pressures (< 2 MPa)
- Low thrust (< 40 kN)

Image from wikipedia

Pump-fed Systems

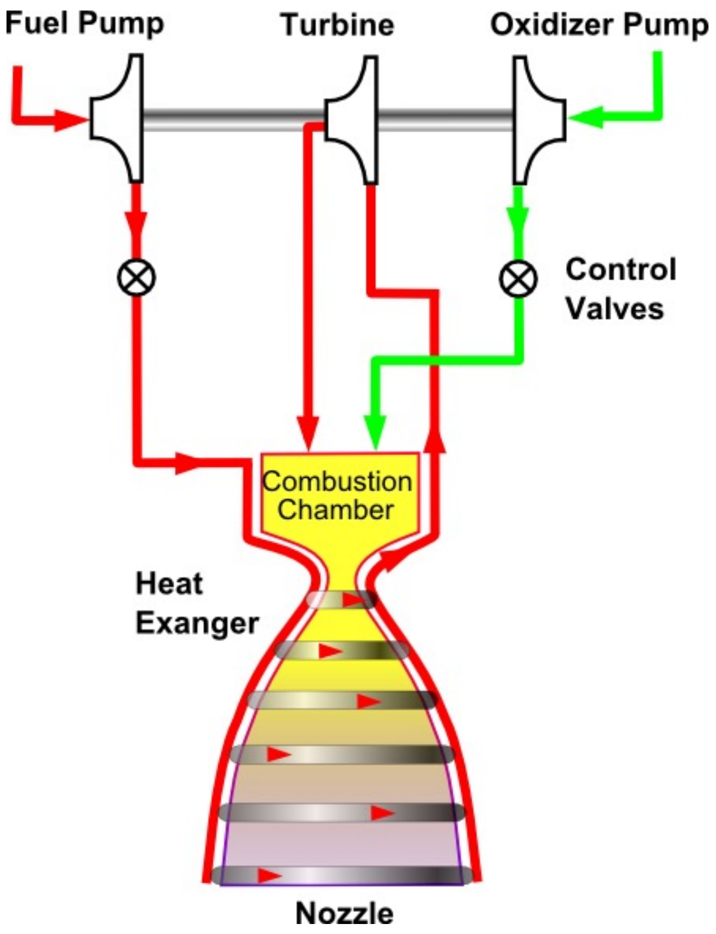


- Lower tank pressures
- SSME
  - Chamber pressure ~ 20 MPa
  - Tank pressure ~ 1 MPa
  - Pump exit pressures
    42 MPa (LH_2) & 50 MPa (LO_2)

- How to power the pump?
  - Extract power from a gas-generator

Image from wikipedia

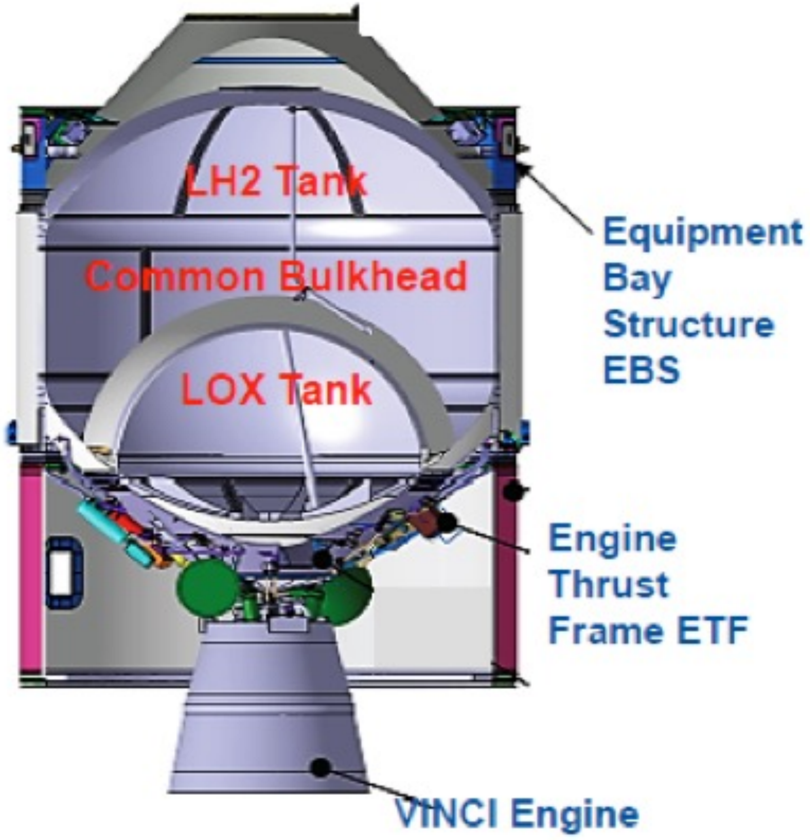
Expander Cycle



- Upper Stages
- Low-Medium Pressure (3 – 7 MPa)
- Small Thrust Range (80 – 200 kN)

Image from wikipedia

Vinci Engine



Thrust in vacuum	180 kN
ISP in vacuum	464 s
Mixture ratio	5.8
Chamber pressure	61 bar
LOX mas flow rate	33.69 kg/s
TPO rotational speed	18015 rpm
LOX pump discharge pressure	81 bar
LH2 mass flow rate	5.81 kg/s
TPH rotational speed	90127 rpm
LH2 pump discharge pressure	224 bar

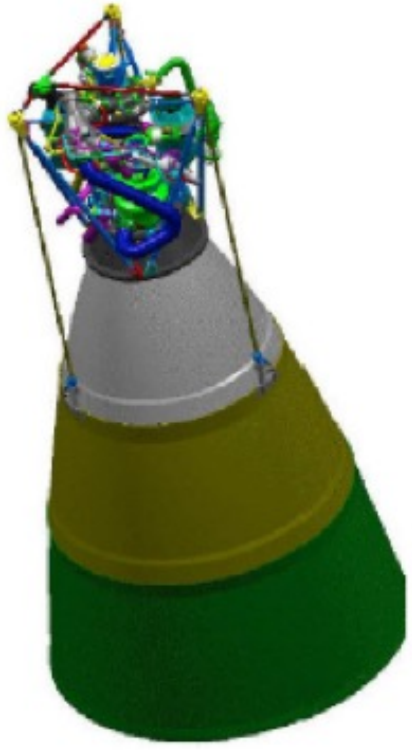
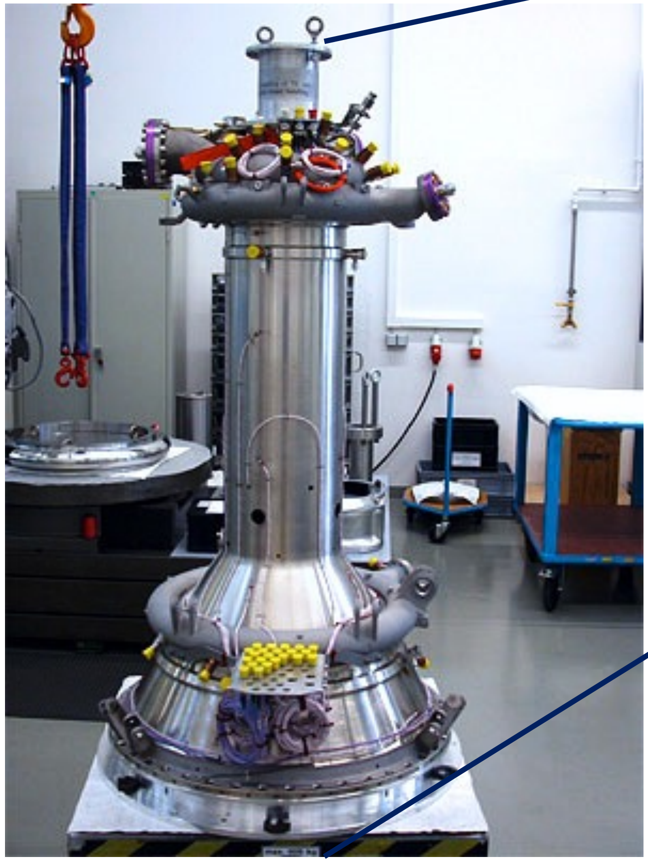
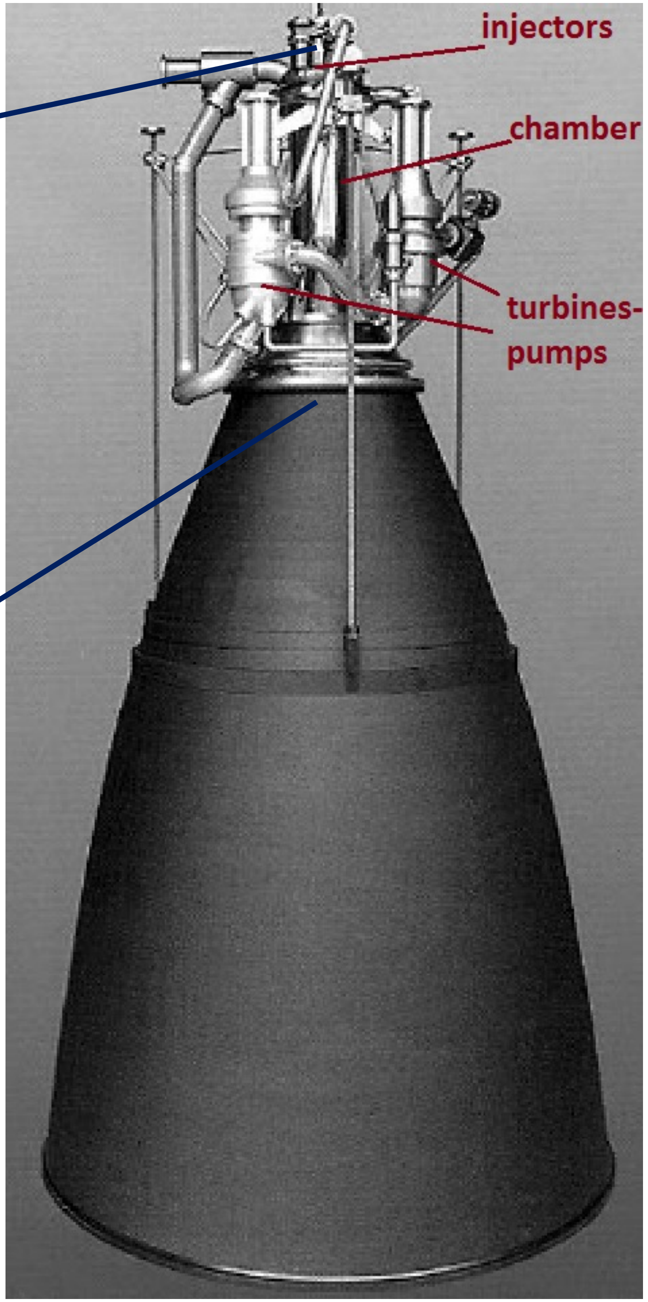


Image from ESA

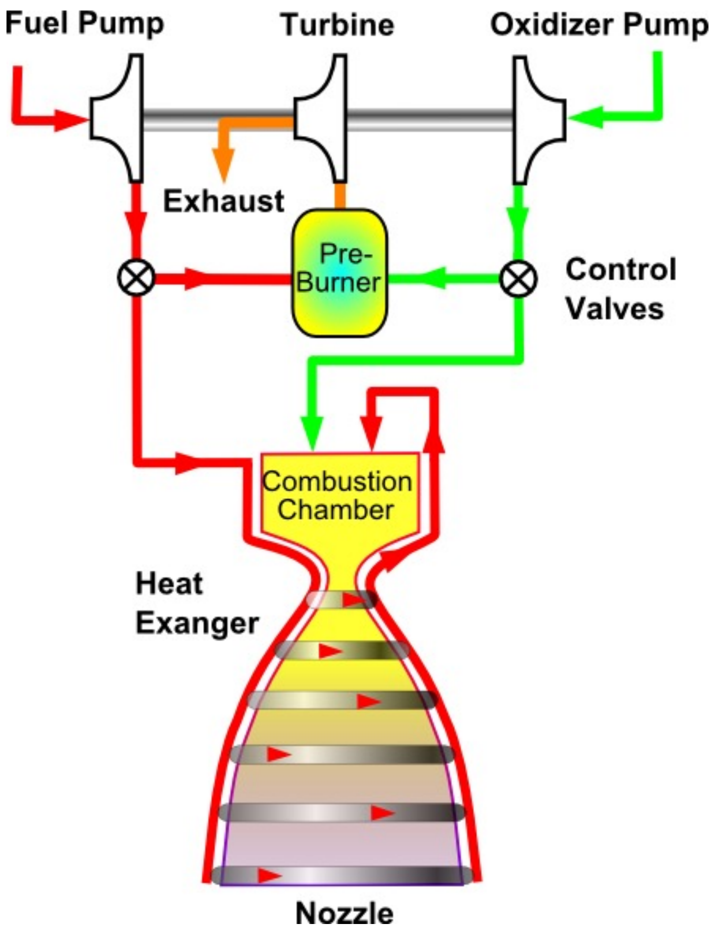
Vinci Engine





Images from [ESA](), [spaceflightnow]()

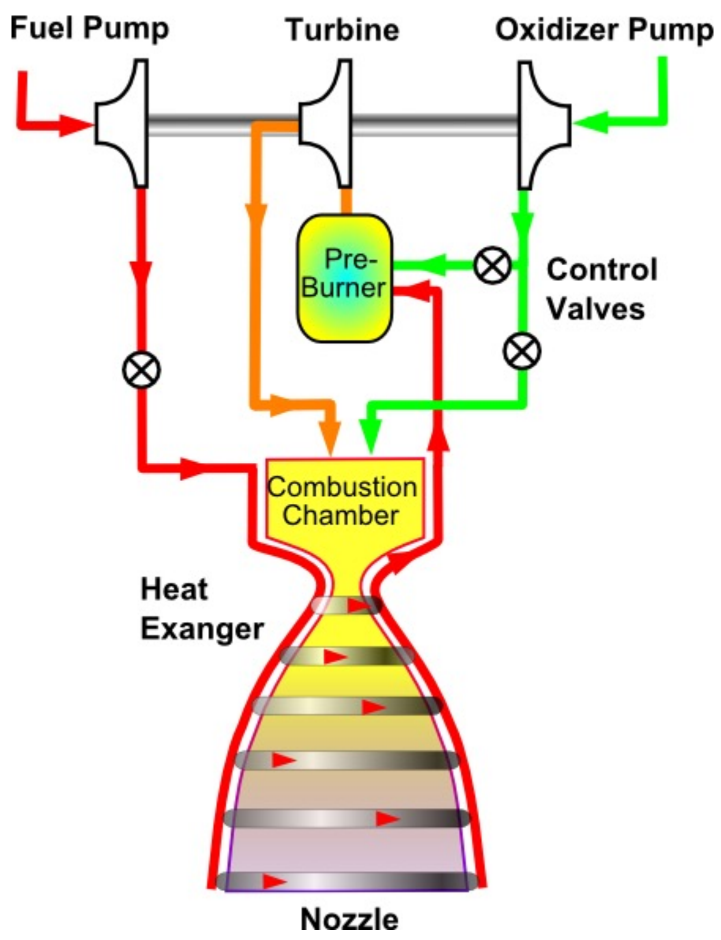
Gas-generator Cycle



- Booster, Core and Upper Stages
- Medium Pressure
  (< 15 MPa)
- Large Thrust Range
  (60 kN – 7 MN)

Image from wikipedia

Staged-Combustion Cycle



- Booster, Core and Upper Stages
- High Pressure
  (13 - 26 MPa)
- Large Thrust Range
  (80 kN – 8 MN)

Image from wikipedia

SSME

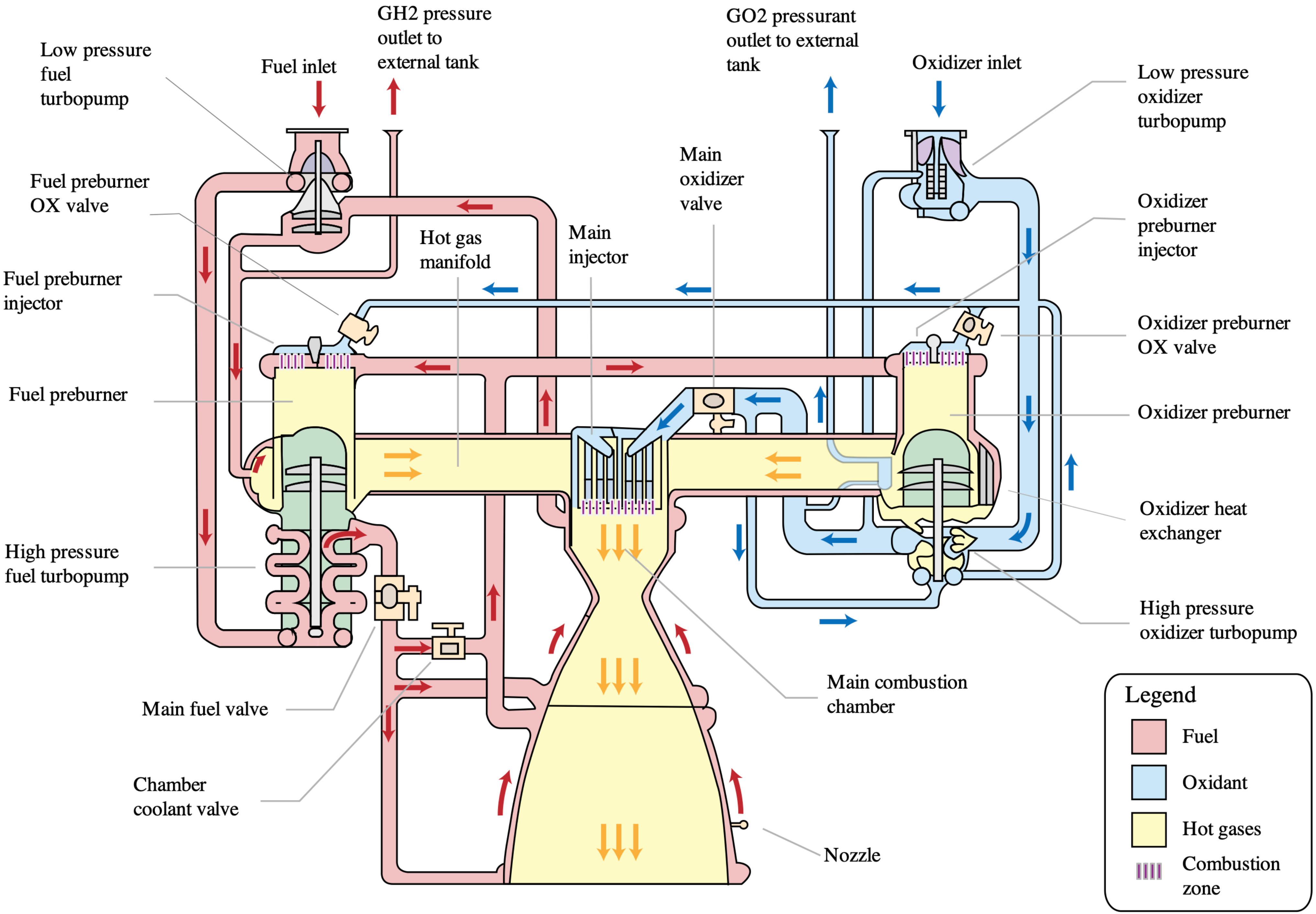


Image from wikipedia