

# LIQUID PROPULSION SYSTEMS

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# Indian Space Research Organisation

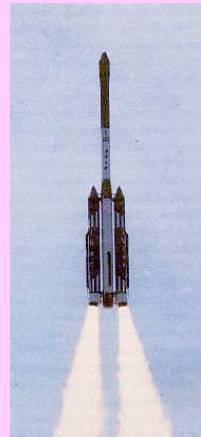
## - LAUNCH VEHICLES -



**SOUNDING  
ROCKETS**



**SLV**



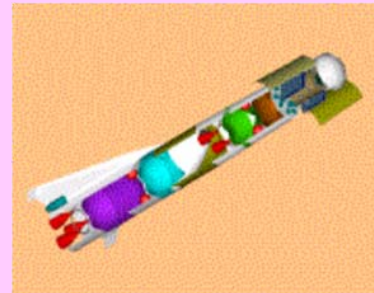
**ASLV**



**PSLV**



**GSLV**



**THE FUTURE**

# GSLV



# *I INTRODUCTION*

Space as we all know has always been charming to mankind and provide inspiration and imagination. It had its beginnings in fiction, the product of fertile human mind. In Indian epics, 'Pushpaka Vimanam' is widely referred. In 1865, Jules Verne, wrote about spaceship having minimum velocity to escape earth's gravity. The transformation of fiction to fact was done by the scientific work of Copernicus, Keppler, Galileo and Newton.

Apart from Chinese in 970 AD, Tippu Sultan in India developed high performance rockets of 2.4 km range for effective use in the war against the British. But rational theory on propulsion was attributed to Konstantin Tsiolkowsky who devised the famous rocket equation in 1903.

- Herman Oberth proposed novel design aspects of liquid propellant rockets in mid 1920s.
- Robert Goddard experimented with rockets in the second half of 1920.
- Tsiolkowsky brought out the concept of multistage rockets in 1924.
- Werner Van Braun, developed functional liquid propellant rockets burning liquid oxygen & alcohol in A4 engine for V2 missiles in early 1940.

## ***II ROCKET SYSTEM***

- Popularly known use of the name 'Rocket' is a complex space transportation system capable of transcending the atmosphere and beyond into near earth space and deliver the 'payload' into defined orbit. Among the many subsystems of the rocket, propulsion system is the power plant which provides kinetic energy conversion. This is the backbone of the total system and therefore, the entire launcher is referred to as 'rocket' though many other subsystems are necessary for successful functioning.

They are the following.

## **1. Guidance & Control:**

In order to achieve the orbit, the trajectory of the vehicle has to be optimally shaped to reach the end condition / state vector in space and the guidance system works out this path in the three dimensional space. The steering of the vehicle along the desired path is performed by the vehicle attitude control system which continuously orients the thrust vector as required to achieve the trajectory. Both guidance & control are closed loop systems autonomously managed by on board computers.



## 2. Navigation:

To arrive at the desired end condition, viz. payload injection point in space, the vehicle has to keep track of its current position and velocity vector & attitude and the on board navigation system provides & updates this input data to on board computer on a continuous mode. These systems are based on inertial sensors, viz. gyroscopes & accelerometers, housed on the top of the vehicle in equipment bay.

### **3. Staging & Separation:**

In general the rocket comprises multiple propulsion system / stages. The inert stages which have performed their functions i.e. fully burnt out their propellants are jettisoned sequentially as flight progresses through staging/ separation system which are essentially pyro/ explosive based systems that effect, clean, disturbance free disconnection of hardware as per on-board command.

The vehicle also has provision for premature termination of flight through ground terminated telecommand which activates certain onboard explosives to break-up the rocket in flight if there are gross deviation in flight path/behaviour endangering people & property on ground.

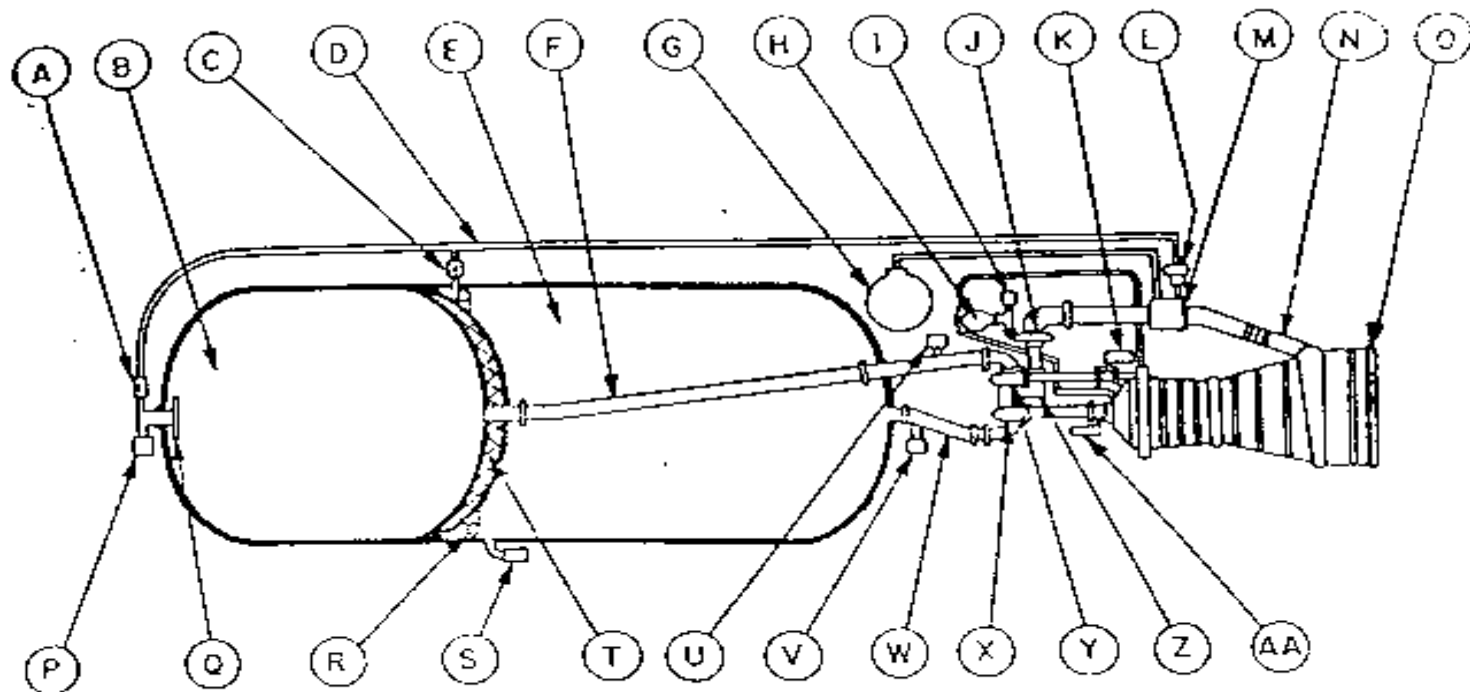
## 4. Vehicle Avionics:

This comprises mainly electronic packages & systems which implement

- Sequencing & pyro initiation functions
- Control command & feed back
- Telemetry of on-board requirements
- Tracking & telecommand during flight.

The avionics packages are concentrated in vehicle equipment bay and are also distributed throughout the vehicle inside interstage compartments

Success in space demands perfection. Many of the brilliant achievements made in this vast, austere environment seem almost miraculous. Behind each apparent miracle, however, stands the flawless performance of numerous highly complex systems. All are important. The failure of only one portion of a launch vehicle or spacecraft may cause failure of an entire mission. But the first to feel this awesome imperative for perfection are the propulsion systems, especially the engines. Unless they operate flawlessly first, none of the other systems will get a chance to perform in space. Perfection begins in the design of space hardware, with quality & reliability.



A Check valve

B Fuel tank

C Check valve

D Pressurizing gas line

E Oxidizer tank

F Fuel duct

G High pressure helium bottle

H Gas generator and valve assembly

I Turbine starting spinner

J Gas turbine

K Main fuel valve

L Pressure regulator

M Heat exchanger

N Turbine exhaust duct

O Thrust chamber assembly

P Fuel tank vent and relief valve

Q Pressurizing gas diffuser

R Pressurizing gas diffuser

S Oxidizer tank vent and relief valve

T Inter-tank insulation (required for cryogenic and non-

cryogenic propellant combination)

U Fuel tank fill and drain valve

V Oxidizer tank fill and drain valve

W Oxidizer duct

X Oxidizer pump

Y Fuel pump

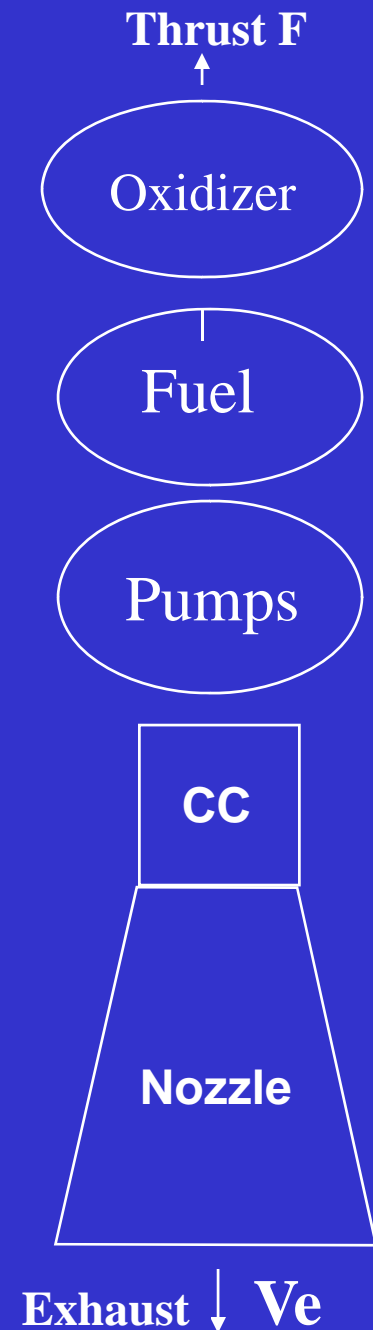
Z Gear box

AA Main oxidizer valve

*Typical turbopump feed liquid propellant rocket engine system.*

### ***III CONCEPTS & DESIGN EQUATIONS***

The function of a chemical rocket engine system is to generate thrust through combustion by release of thermal energy derived from the chemical energy of the propellants. These combustion gases are ejected through a nozzle at high velocity.



## WHY LIQUID ENGINE ?

1. Higher Specific Impulse
2. Longer Burning duration
3. Stop & restart capability
4. Lower System Weight
5. Testability in ground



# SELECTION OF LIQUID PROPELLANTS

- High Energy release per unit mass. Combined with low molecular weight of combustion products.
- Stable Combustion
- High density to minimize size & weight of propellant tanks
- Effectiveness of thrust chamber cooling
- High thermal & shock stability
- Non corrosiveness & non toxicity
- Cost & availability.

1.  $V_e dm = -m dv$

2.  $\Delta V = V_e \ln (m_o / m_i)$

3. Thrust Coefficient  $C_f = F / A_t P_c$

4. Characteristic exhaust velocity

$$C^* = A_t p_c / \dot{m} = C / C_f$$

5. Thrust  $F = C_f \cdot A_t \cdot p_c = \dot{m}^* \cdot C_f \cdot C^*$

6. Specific Impulse  $I_{sp}$

= Thrust / mass flow rate of propellant

$$= F / W = F / \dot{m} \cdot g = C^* \cdot C_f / g$$

$$\propto \sqrt{T_c / m}$$

# Propellant Chemistry & Performance Calculations

The temperature  $T_c$  of the reaction in combustion chamber & the molecular weight  $M$  and the specific heat ratio  $\gamma$  of the exhaust are essential parameters in performance calculation. Various simplified assumptions such as frozen composition or the absence of shock waves & discontinuities may not be valid. Application of first principles for reliable estimation of the system performance is often necessary on the following simultaneous consideration.

Chamber condition.

- Mass balance
- Enthalpy balance (conservation of energy)
- Pressure balance (Dalton's law)
- Chemical equilibrium ( minimization of Gibbs free energy)

## Rocket Performance:

- Equation of state (Ideal gas law)
- Continuity equation (Conservation of mass)
- Conservation of momentum
- Conservation of energy ( first law of thermodynamics)
- Isentropic expansion (second law of thermodynamics)

Considerable numerical computations are thus necessary. Sophisticated computer modelling & simulation are to be done exclusively for accurate prediction of performance.

## ***IV DESIGN IMPLEMENTS***

1. Thrust levels
2. Performance
3. Burn time
4. Propellant mixture ratio
5. Burnout mass.
6. Envelope/Size
7. Reliability
8. Cost
9. Schedule.

# 1. Thrust Level.

- Lift off weight
- Minimum & maximum acceleration allowed.
- Single engine or multiple engine.
- Variable thrust.

# 2. Performance

- Specific Impulse
- Theoretical
- Tested
- Flight

### 3. Burn duration

- Tank capacity
- Pressurant storage
- Nozzle cooling
- Thrust build up
- Shut down

### 4. Mixture Ratio

- Stoichiometric ratio -(max. temp & heat)
- Exhaust velocity - (gas properties)
- Optimum ratio - (Residence time in combustion chamber; Chamber wall cooling)

## 5. Burnout Mass

- Dry mass + residual propellants
- Burn out mass
- Wet mass – CG & MI
- Wet gimbal mass.

## 6. Envelope/Size

- Vehicle Structure
- Handling
- Servicing
- Realisation
- Expansion Ratio



## 7. Reliability

- Unmanned/manned mission
- Review of design, calculation & drawing
- Paintaking execution of the above
- Familiarizing with correct application of accepted, prior design standards & procedures
- Written statements & instruction
- Simplicity, Redundancy & Safety
- Test condition vs. Flight condition
- FMECA

## 8. Cost

- Design Phase
- Engineering Phase
- Programme phase.

## 9. Schedule.

- Availability of subsystems
- Design Quality
- System Analysis
- Materials, Fabrication, Handling.

# V *THRUST CHAMBER & COMBUSTION DEVICES*

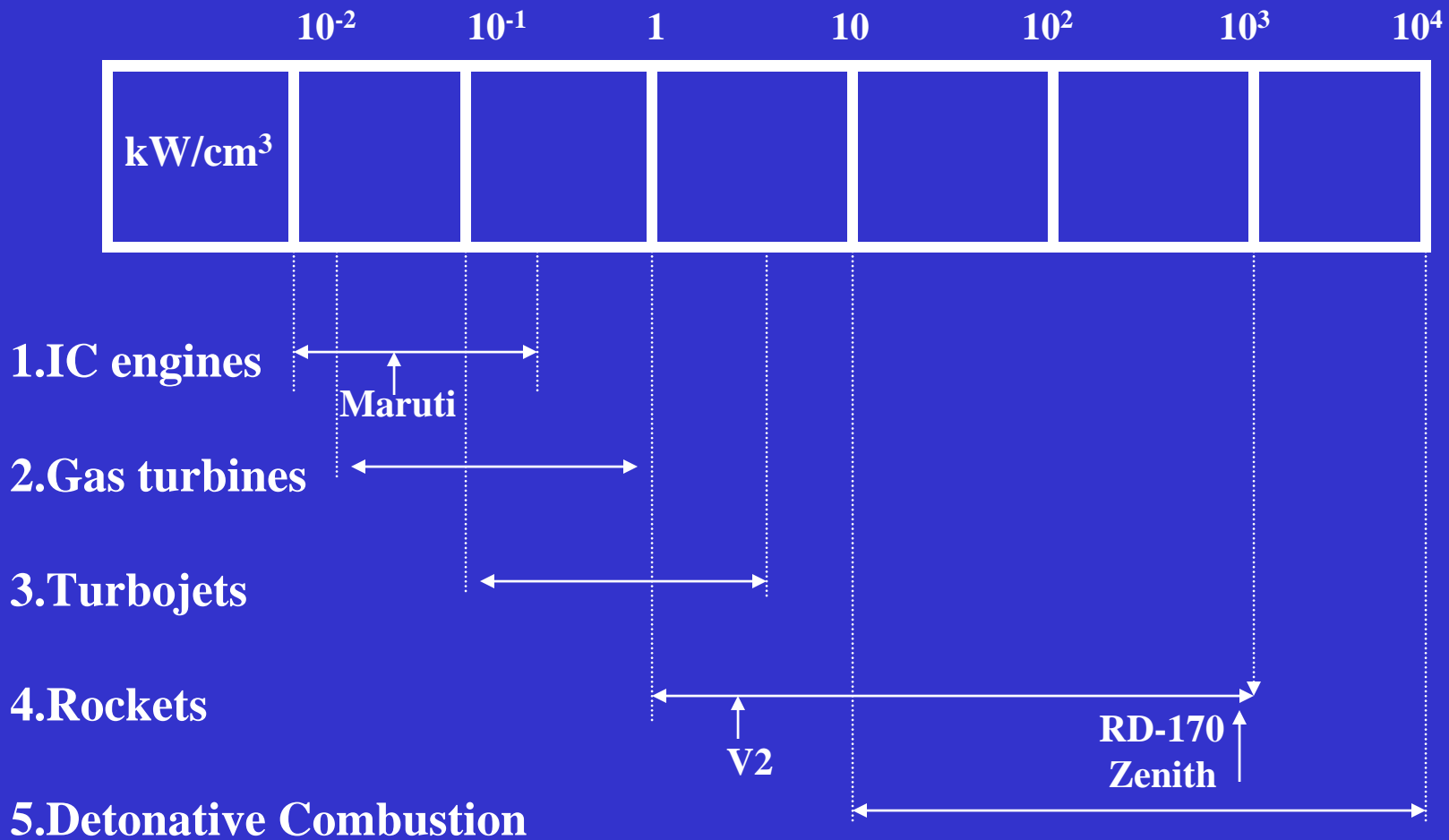
Thrust chamber assembly undeniably embodies the essence of rocket propulsion: the acceleration and ejection of matter, the reaction of which imparts the propulsive force to the vehicle.

The design goals are

- maximum performance
- stability & durability
- minimum size, weight & cost.

Basic Elements are

1. Combustion process
  - droplets spray
  - Evaporation by surrounding gas
  - Mixing & reaction
  - High speed diffusion
  - Stability of mixing process



**Power Density of energy release of different propulsion devices**

## 2. Performance parameters

- Characteristic velocity

$$C^* = f(\gamma, R, T_c)$$

- Thrust coefficient  $C_f$

$$C_f = f(\gamma, \varepsilon, p_a)$$

## 3.1 Configuration and Layout

$$\text{Throat Area } A_t = F / C_f \cdot p_c$$

$$\text{Chamber volume } V_c = m \cdot V \cdot t_s$$

$$\text{Characteristic length } L^* = V_e / A_t$$

$$= m \cdot V \cdot t_s / A_f$$

3.2 Shape: a) Long one:

gas flow pressure losses

b) Short one:

Vaporization zone – excessive

Combustion zone - inefficient

## Conical nozzle Vs. Bell Nozzle

- c) Spherical: Less mass & cooling surface  
Difficult to produce & poor performance
- d) Cylindrical: Design Flexibility & easy to produce  
Heavy mass & more cooling surface
- e) Conical Nozzle: non axial component of velocity leads to performance losses but easy to fabricate
- f) Bell Nozzle: Shorter length & increased performance starting from fast expansion flow to uniform axial flow at exit

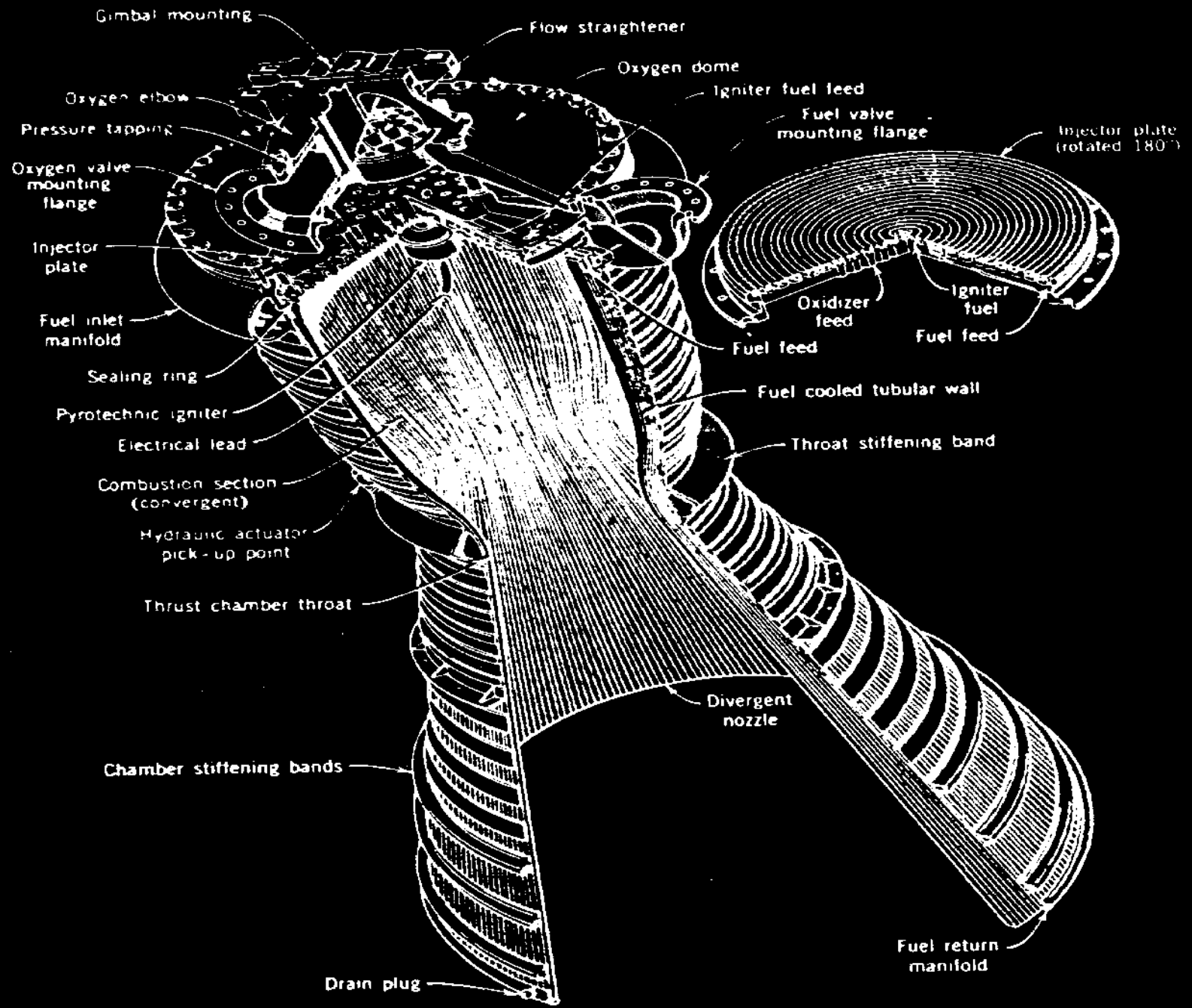
## 4. Cooling Techniques

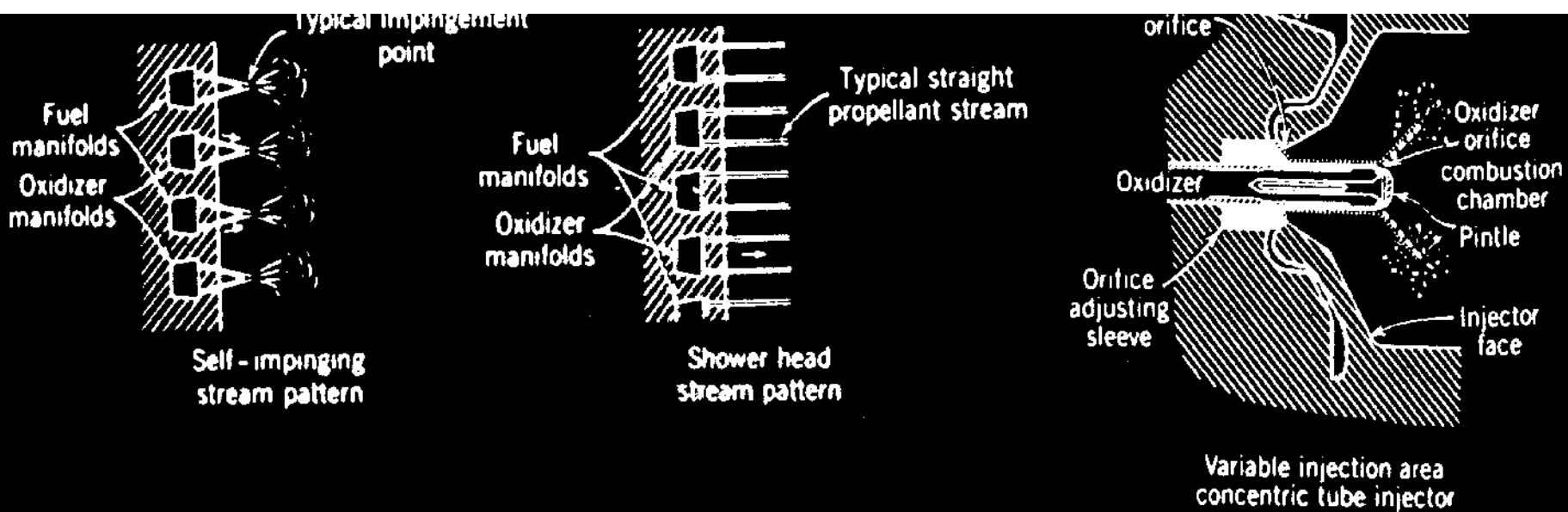
- (i) Regenerative cooling : widely used
- (ii) Dump Cooling : limited use
- (iii) Film Cooling : used in high heat flux
- (iv) Transpiration cooling: special type
- (v) Ablative Cooling : mainly solid motors, low  $P_c$  liquid system
- (vi) Radiation Cooling : Used in nozzle extension/  
low heat flux.



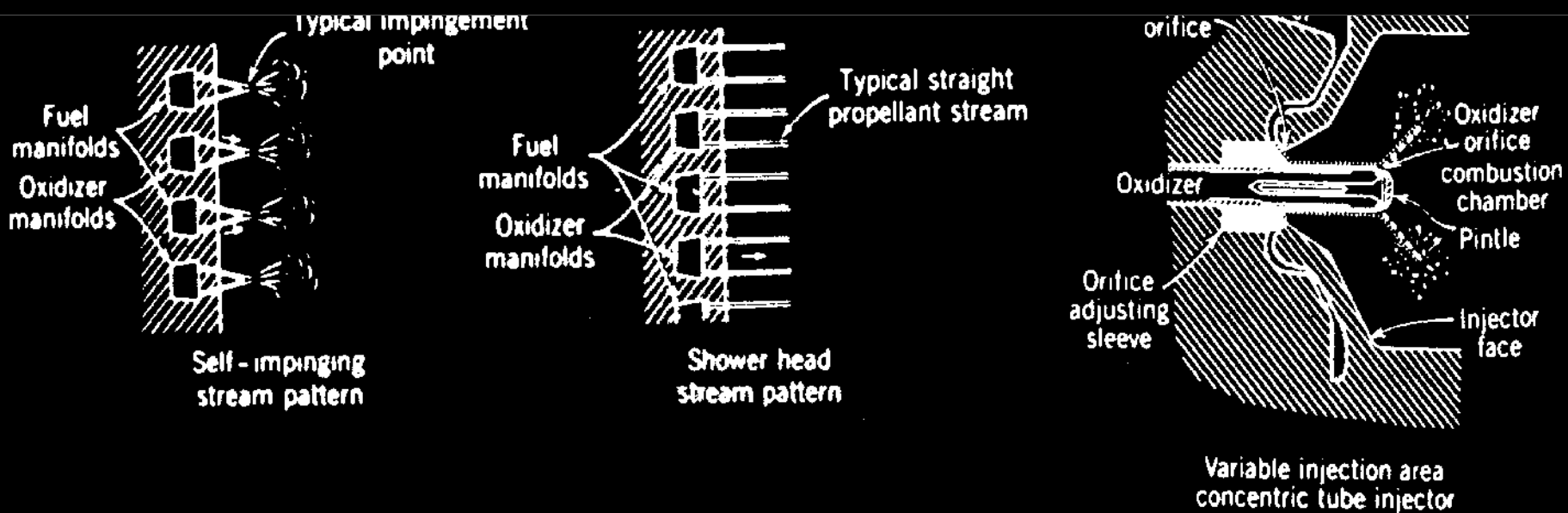
## 5. Injector Design:

- Combustion stability
- Performance
- Structural integrity
- Hydraulic characteristics
- Combustion chamber heat protection
- Special requirements





Schematic diagrams of several injector types.



Schematic diagrams of several injector types.

## ***VI PROPELLANT TANKS & FEED SYSTEM***

### **1. General Categorization:**

- a) Booster stage system**
- b) Upper stage system**

#### **a) Booster Stage System**

- Large volumes**
- Pump- fed system**
- Self supporting walls reinforced by skin stringers**
- Independent designer**

## b) Upper Stage System

- Smaller volumes
- Pressure-fed system
- Waffle / Isogrid walls
- Most likely engine designer

## 2. Design consideration:

- Propellant properties & Compatibility
- Operating pressure & temperature
- Thrust level from engines to vehicle
- Manufacturing easiness.

### 3. Pressure – fed system

- Pressurant gas is used
- Tank pressure higher than engine chamber pressure
- Flow rate governed by feed line resistance
- For higher engine thrusts above 220 kN, not effective

#### (i) Stored gas system

- High pressure storage gas bottles are used
- Pressure & flow rate are regulated for a specified tank pressure
- Helium gas is the most common gas

## ii) Blow down system:

- No continuous feeding of gas.
- Pressurant gas expands in the ullage volume
- Continuously decreasing the tank pressure
- Not in common use

## iii) Hot gas system:

- Gases produced in gas generator are used
- System mass is less but highly complicated
- Not in general use.

#### iv) Propellant evaporation system:

- Propellants after cooling thrust chamber, are vapourised
- These vapours are fed back to tanks as pressurant
- Mainly used in cryogenics in fuel tanks.

#### 4. Pump fed system


- Used in high thrust engines requiring high propellant flow rate
- Larger pressurant flow rate & larger tank volume make tank weight highly non-optimal




- Tank pressures are kept at low pressure levels just sufficient enough to meet NPSH requirements of pumps (0.4-0.5 MPa)
- Classified into either open or closed system depending on the way the power is supplied to turbine and how the energy of the working fluid is dumped from turbine exhaust.
- Open Cycle has 3 types & closed cycle has 2 types.

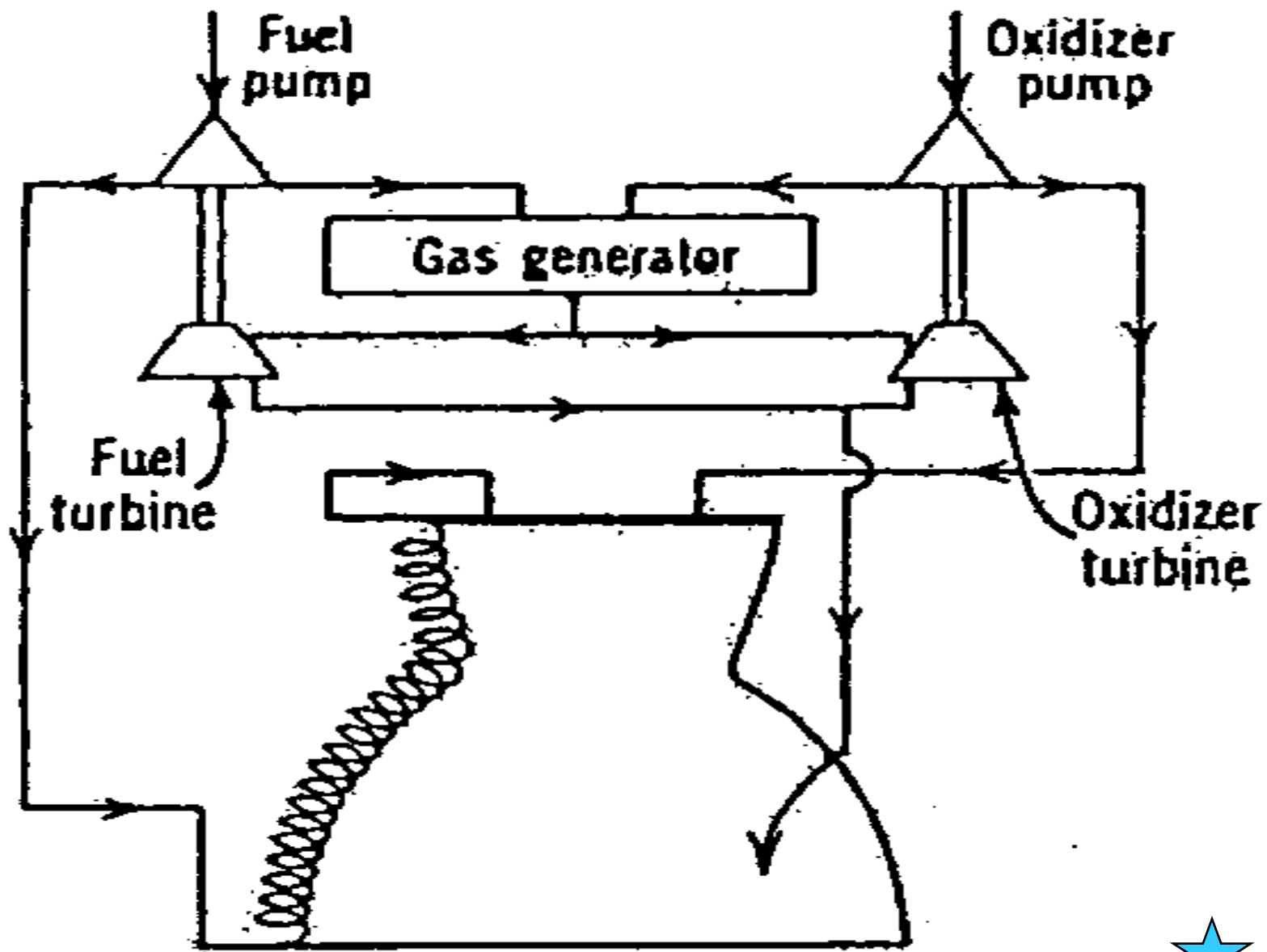
4.1 Open cycle: Turbine exhaust is directly discharged in a separate nozzle or into main thrust chamber nozzle at some point near exit where pressure levels are compatible.

## (i) Gas Generator cycle

- Propellants are burnt partially in a separate combustion chamber called gas generator.
- The gaseous product is used to drive the turbine of the pump 

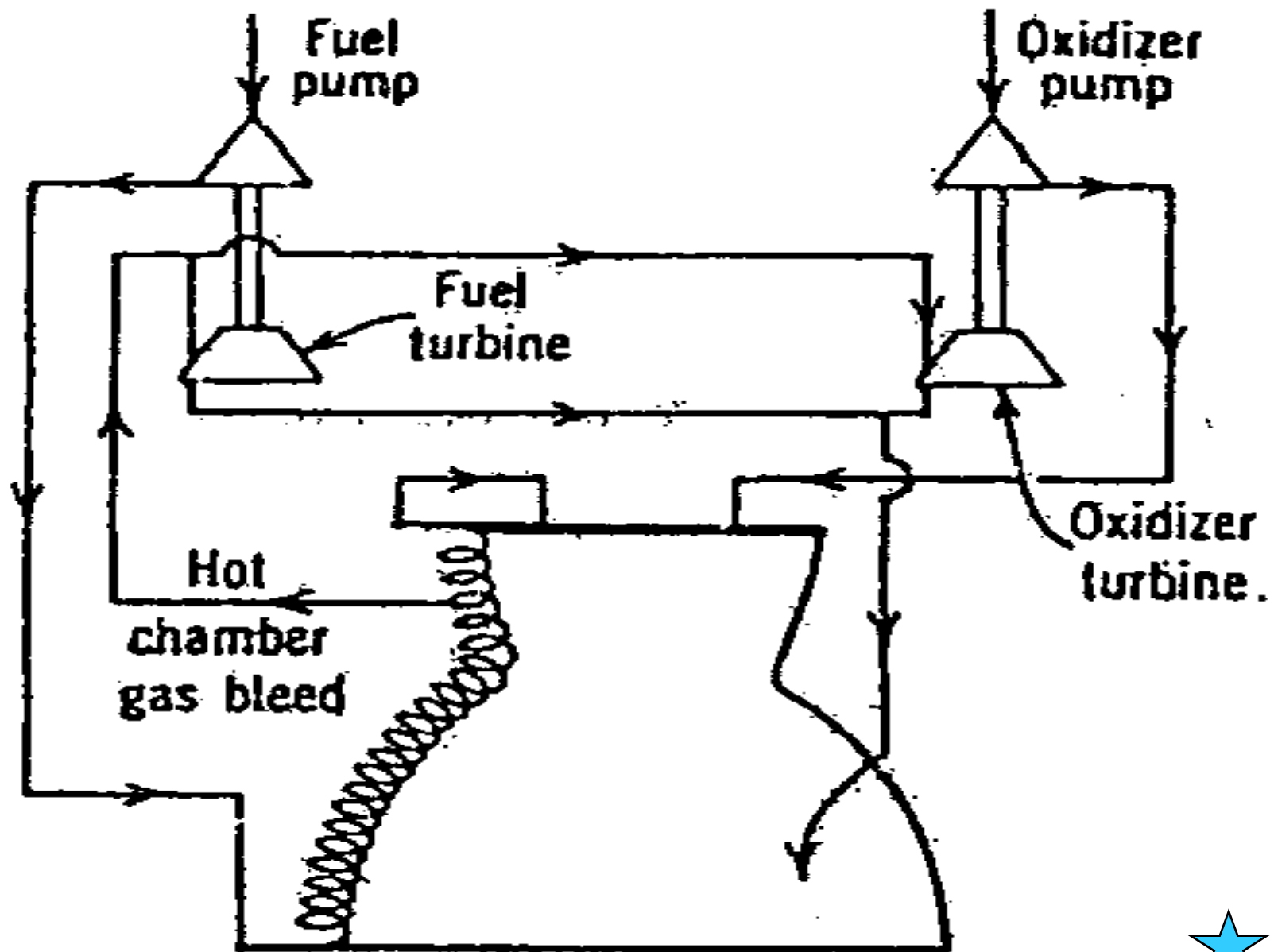
## (ii) Combustion tap off:

- No need for a separate gas generator
- Hot gas stream are bled from main thrust chamber itself, at a point where the temperature is low enough for turbine operation. 



**GAS GENERATOR CYCLE**






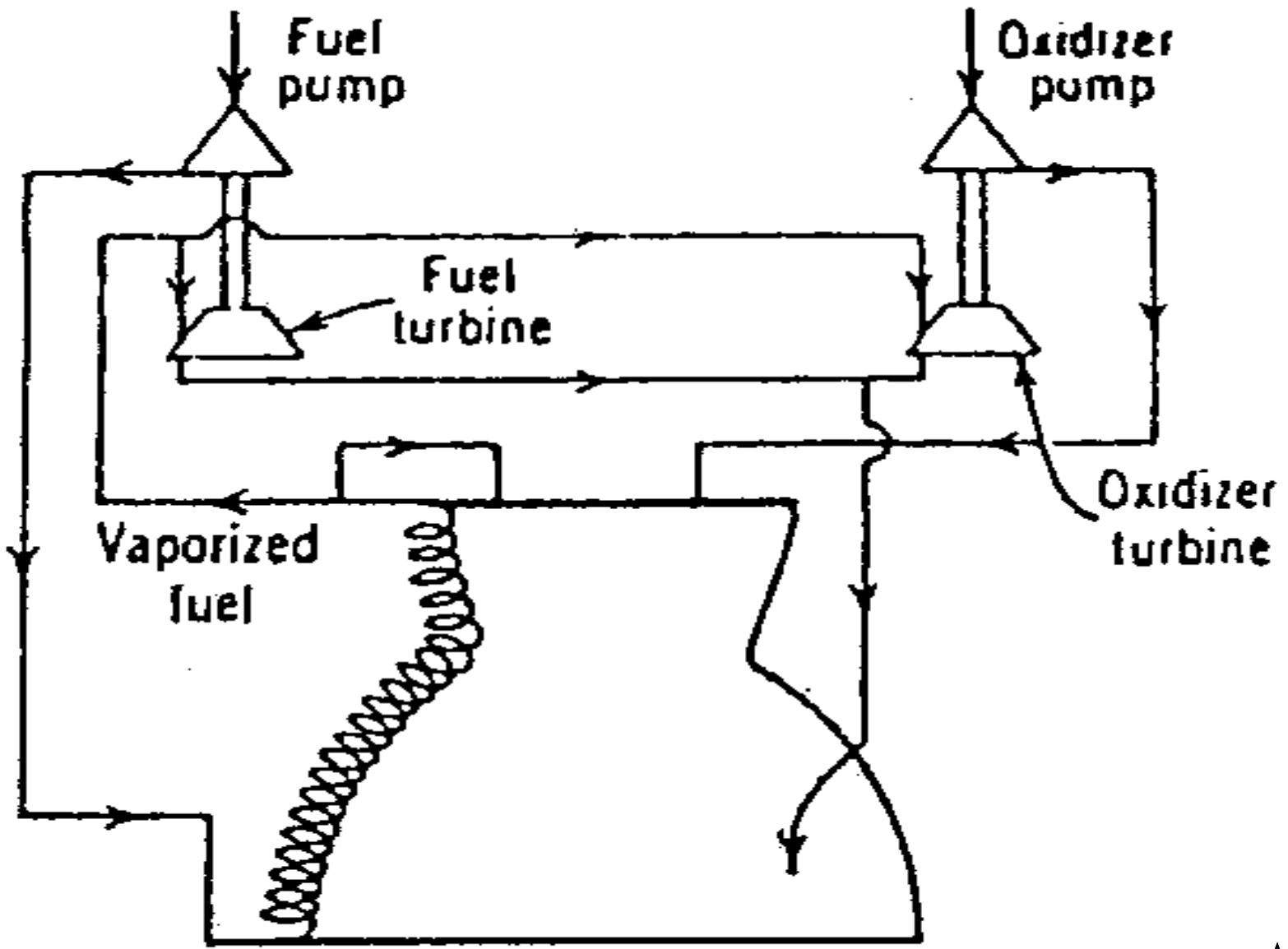
**COMBUSTION TAP-OFF CYCLE**



### (iii) Coolant Bleed cycle

- No need for a separate gas generator
- Hot gas stream to drive turbine is taken from part of the vapour from cooling jacket of the main thrust chamber 

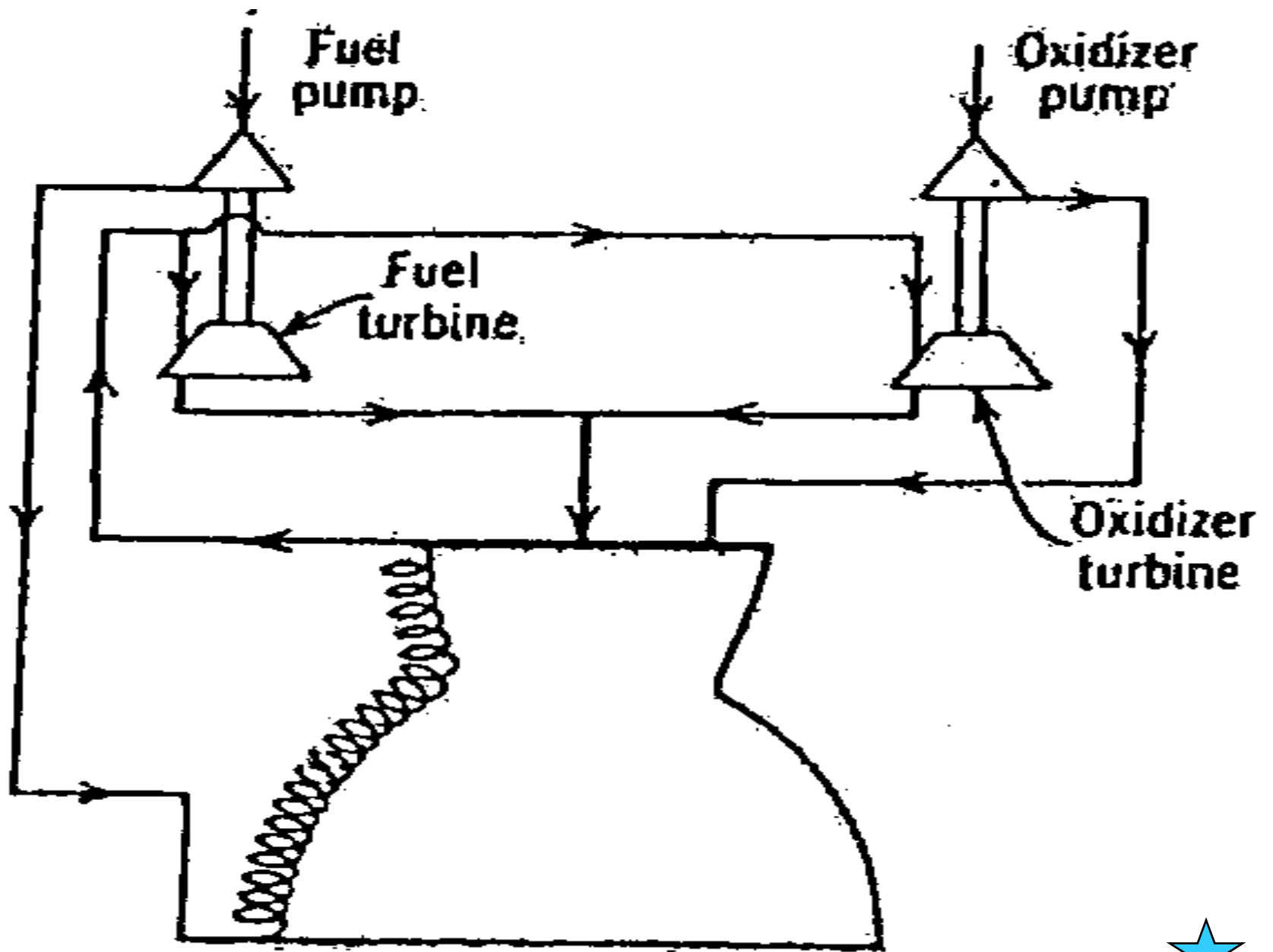
4.2 Closed cycle: Partially burnt turbine gas is introduced into main thrust chamber for complete burning. Very effective due to maximum energy conversion of propellants and therefore a complex system.



COOLANT BLEED CYCLE



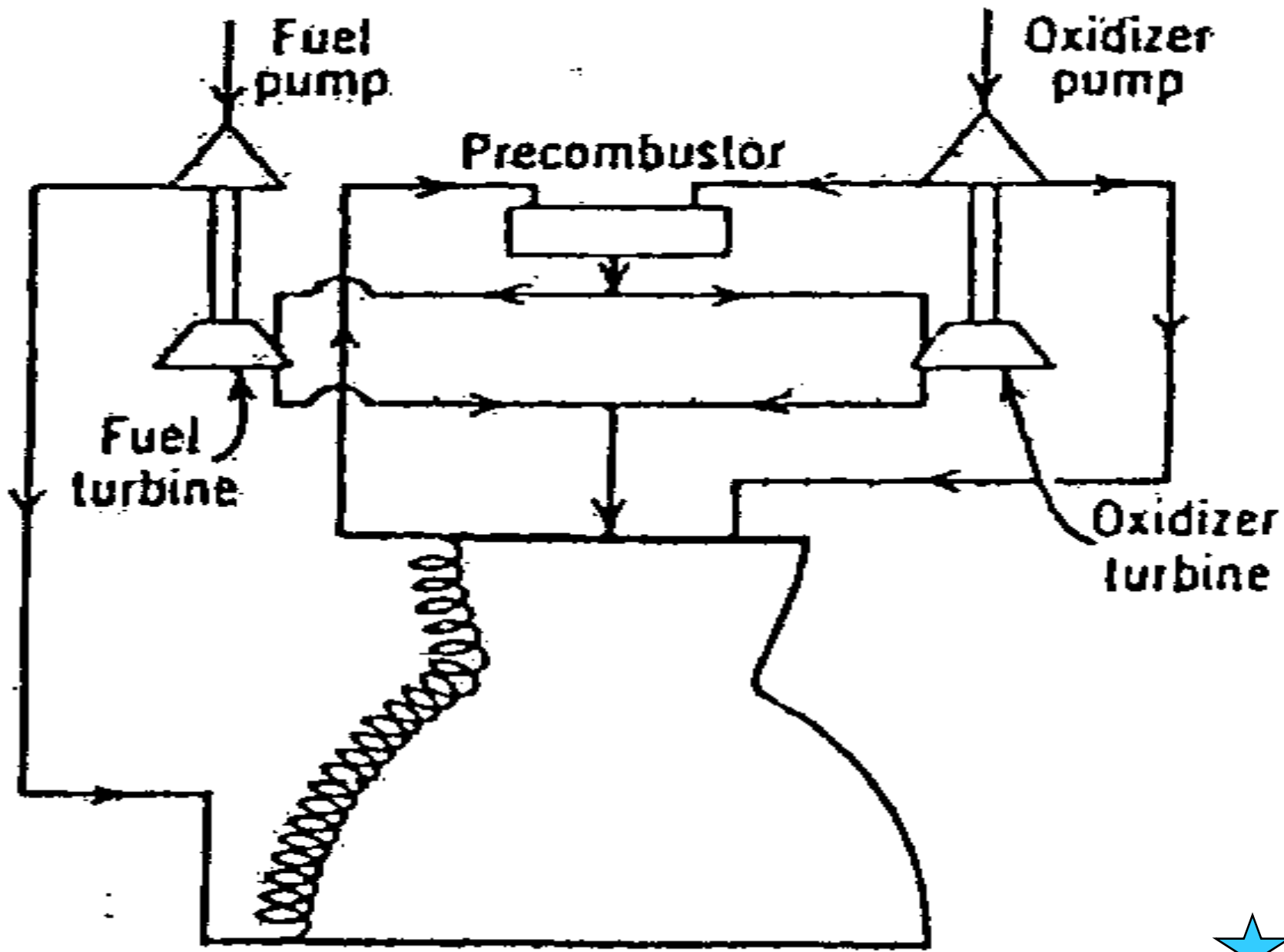
- (i) Expander cycle: ★
- Thrust chamber coolant liquid is evaporated into hot gas; this is used to drive turbine and gets injected into combustion chamber
  - Used in low thrust engines as the energy demands are not high
- ii) Staged Combustion cycle: ★
- The cooling liquid from main engine coolant passage evaporates into hot gas; this is burnt in a pre-burner with small amount of oxidiser.
  - The partially burnt combustion product is used to drive the turbine.
  - After driving the turbine, the gases are injected into main thrust chamber for complete combustion.
  - This enhances the specific impulse.



**EXPANDER CYCLE**







**STAGED-COMBUSTION CYCLE**



## ***VI CONTROL SYSTEM & VALVES***

A The propulsion system has the following control systems:

1. Engine gimbal system
  - Main engine gimbal
  - Steering engine gimbal
2. Thrust regulation system
3. Mixture Ratio (O/F) control system.
4. Orientation & Stabilization system.

# 1. Engine Gimbal System:

- a) Main engine can be moved about its thrust axis by providing 2 actuators at 90 deg. apart in order to steer the rocket in the pre determined trajectory based on control system feed back from on-board computers.
- b) Alternately 2 smaller engines can be configured at 180 deg. apart and keeping the main engine at fixed position. Each of these 2 steering engines is configured with 2 actuators each at 90 deg. apart so that combined action of these 2 engines can steer the rocket in the pre-determined trajectory based on closed loop control system feed back from on board computers.

## 2) Thrust control system:

It is essential to control the thrust of the engine by careful regulation of the propellant mass flow rate.

There are number of techniques deployed depending on the expertise available & system optimization. This becomes all the more important in upper stage systems where higher burn time and velocities are involved.

### 3) Mixture ratio control system:

In ideal condition, mixture ratio is to be kept constant; but the flight operating condition due to various constraints, a control system is necessary to ensure mixture ratio within a close tolerance for optimum engine performance and complete utilization of propellants loaded.

#### 4) Orientation & Stabilization System:

The system generally employs an autonomous mini thrust system based on

- Monopropellant system
- Bipropellant system
- Cold gas system.

This is required during non-propulsive phase of the propulsion system to impart axial velocity prior to ignition or interval between multi start or tumbling of the upper stage away from satellite path.

## ***VII CONTROL SYSTEM COMPONENTS/VALVES***

Liquid systems are more complex and less reliable mainly on account of large number of active functional components/valves. Typical types are listed below:

- Propellant flow control valves
- Electro pneumatic valves
- Pneumatic valves
- Electric motors for driving actuators of control system

- Hydraulic system for actuating gimbal Engines
- Pyro-initiated valves for critical systems.
- Diaphragm type valves.
- Vent valves for pressure control.
- Safety relief valves for passive pressure control
- Check valves
- Filters.



## ***VIII INTEGRATION & ENGINEERING***

1. Engine Thrust frame
2. Gimbal mount assemblies
3. Interstages housing equipment packages
4. Necessary cutouts for last minute checks
5. Instrumentation scheme scheme
6. Propellant Feed lines
7. High pressure pump outlets
8. Mounting on high pressure gas bottle
9. Turbine exhaust, Hot gas ducts
10. Repairs, replacement provision

## ***IX MATERIALS***

1. Rocket engines must be built as light as possible and propulsion system should be of maximum efficiency. This can be accomplished only through the most sophisticated use of all the available materials and advanced fabrication techniques.  
“Moderate increase in velocity and range can be achieved switching from ‘ordinary’ to high energy propellants, large increases are achievable by reduction of the dead weight fraction. Mathematically, velocity at burnout becomes infinite as empty weight tends to zero. It is therefore, sometimes possible for the structural design engineer to produce performance benefits greater than the propulsion engineer can produce”.

# Examples of Materials used in LPS

	<u>Material</u>	<u>Type</u>	<u>Application</u>
1.	Al. Alloys	2219, 6061, 7075	Propellant Tanks Pump Housings
2.	Austenite Stainless steel	321,316 347	Nozzle tubing ducts
3.	Martensite Stainless steel	440C	Bearings, Balls Races
4.	PH Stainless steel	174PH 15.5 PH	Valve parts stem, poppets
5.	Cobalt Alloys	Stellite 21	Injection ports Turbine blades

	<u>Material</u>	<u>Type</u>	<u>Application</u>
6.	Iron base super alloys	903, 909	Duct, Bellows
7.	Titanium Alloys	Ti-6Al-4V	Gas bottles Gimbal blocks
8.	Silica	Composite	Engine throat
9.	Carbon-carbon	Composite	Vanes, seals
10.	Alumina Zirconia	Protection coatings	Nozzles, turbine blade
11.	Fluorocarbon Polymer	KEL-F PTFE, FEP	Gaskets O rings, seals
12.	Elastomers	Nitrile Silicone	Sealants gaskets

# ***X TEST PROGRAMME***

Testing alone ensures validation of design

A There are different types of tests

1. Development tests
2. Qualification Tests
3. Functional tests
4. Acceptance tests
5. Flight Tests.

B There are different levels of tests

1. Components levels
2. Subassembly levels
3. Subsystem level
4. System level.

C. There are different test conditions.

1. Simulated tests for flight environment like vibration, acoustics, thermal
2. Hot tests of engines in sea level.
3. Hot test of engines in High Altitude condition in vacuum chamber (100 m bar)

D. Stage Hot Test.

## ***XI POGO & SLOSH***

The longitudinal vibrations caused by an instability arising from interaction of the vehicle structure with propulsion system is called POGO. The vibration begins spontaneously, intensifies, and then dies away. These vibrations can overload vehicle structure as well as lead to loss of propulsion performance.

Two basic kinds of propulsion-system behaviour cause Pogo.

1. Engine coupled pogo – from the action of the tank - to - engine propellant feedlines and the engine itself. This leads to oscillations in engine thrust.

To overcome engine coupled POGO, close coupled accumulators in the engine feed line should be incorporated as close to the engine as possible.



2. Ullage coupled pogo – from the longitudinal vibration of the vehicle which causes ullage pressure oscillations. This forces the regulator to produce oscillatory flow of pressurant.

Ullage coupled instability can be overcome by alteration of regulator characteristics or additional accumulator in the feedline.

- Sloshing is the periodic motion of the free surface of the liquid in partially filled tank.
- It can be induced by changes in vehicle acceleration or in response to control & guidance commands.
- Free sloshing of liquids can produce lateral motions of the accelerating vehicle resulting in closed loop with control system, leading to instability.
- Such instability can lead to structural failures, propellant flow disturbances, engine shutdown etc.
- Usually anti-slosh baffles are used to damp the liquid motion and prevent instability.

## ***XII FLIGHT PERFORMANCE***

In order to ensure a successful flight, the performance related activities are initiated years ahead. The activities are:

- Ensuring correct data based on system characteristics & validation tests.
- Carrying out results of flight performance
- Statistical analysis covering full boundary condition.
- Large number of computer simulation.

The main flight of few minutes duration will validate the years of effort in design, fabrication & testing. The first flight alone gives the real performance in the “space” environment. Extensive instrumentation of the rocket provides the necessary data on the performance of all the systems. Exhaustive analysis of the data is done for full understanding to ensure reliable performance.

# PERFORMANCE OF TYPICAL LIQUID PROPULSION SYSTEMS

Sl.No	Fuel - Oxidization	Mixture Ratio	Combust. Temp.(K)	Specific Impulse (s)
1	UDMH - N2O4	2.6	3140	285
2	UDMH 50% } Hydrazine 50% } N2O4	2.0	3090	290
3	MMH - N2O4	2.2	3110	288
4	Kerosene - LOX	2.7	3425	300
5	Ammonia - LOX	1.4	2815	260
6	Ethyl alcohol - LOX	1.8	3135	285
7	LH2 - LOX	5.0	2738	440
8	LH2 - LF2	8.0	3594	420
9	Ammonia - LF2	3.5	4285	360

# PERFORMANCE DATA FOR LIQUID BOOSTER ENGINES

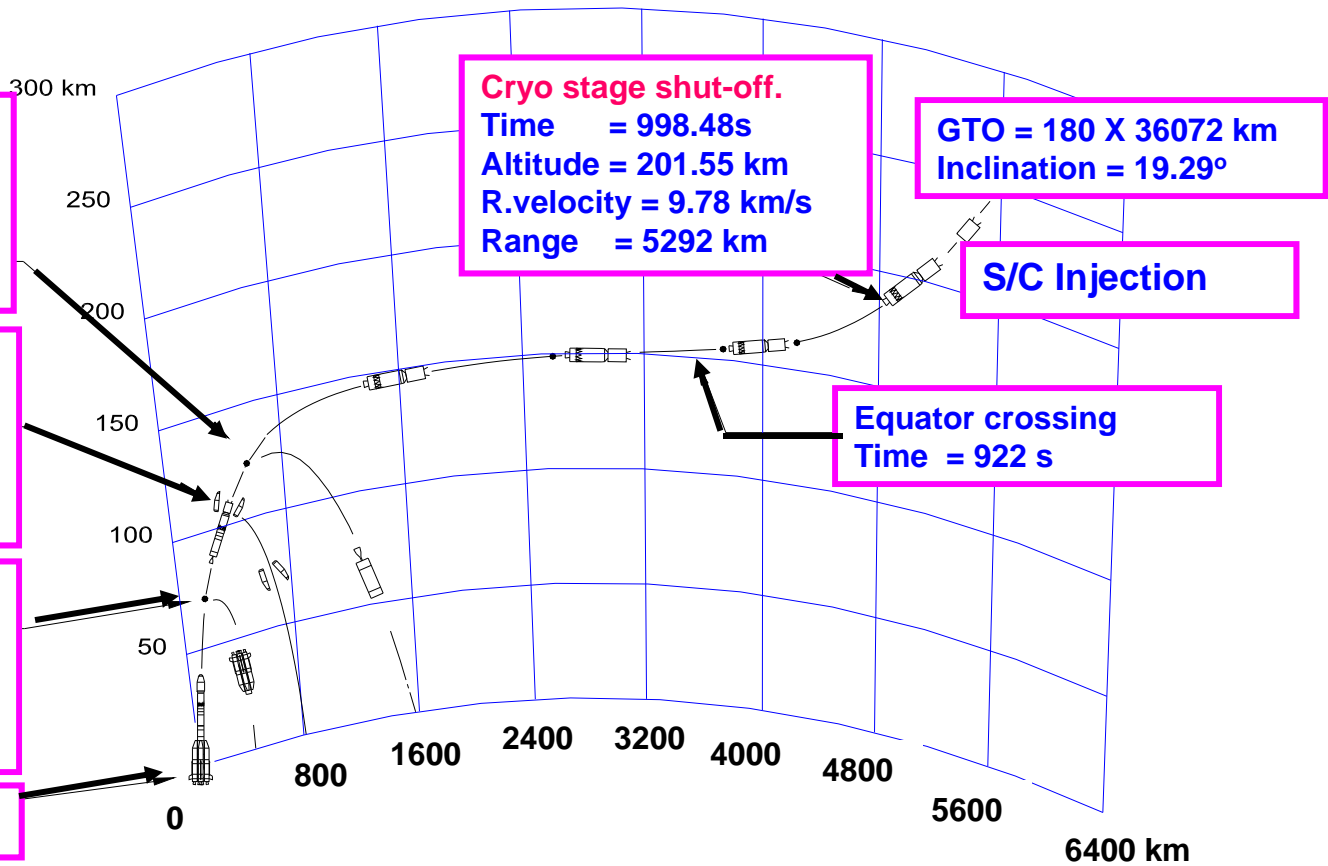
Engine	RD-270	RD-253	LR-87-A55	Viking
Rocket	N-1/UR-700	Proton	Titan	Ariane
Thrust SL    kN	6272	1570	1913	678
VAC            kN	6713	1745	2347	725
Mixture Ratio	2.67	2.88	1.91	1.7
Chamber Pressure. (MPa)	26.6	15.7	5.83	5.8
Isp    SL (s)	301	285	259	243
Vac (s)	322	316	281	278
Cycle	SC	SC	GG	GG

**Cryo stage Ign.**  
Time = 291.82s  
Altitude = 131.180 km  
R.velocity = 4.967 km/s  
Range = 596 km

**H.S Sep.**  
Time = 227.24s  
Altitude = 115.03 km  
R.velocity = 3.432 km/s  
Range = 332 km

**4L40Hs Shut-off**  
Time = 147.64s  
Altitude = 70.32 km  
R.velocity = 2.390 km/s  
Range = 114 km

**Vehicle lift-off**



**TYPICAL MISSION PROFILE**