File name

Rocket 101

What unique characteristics make rockets different than gas turbines?

B. Chehroudi, PhD

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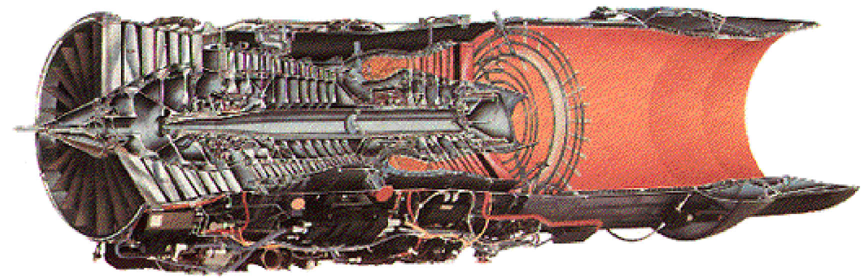
April 10, 2009

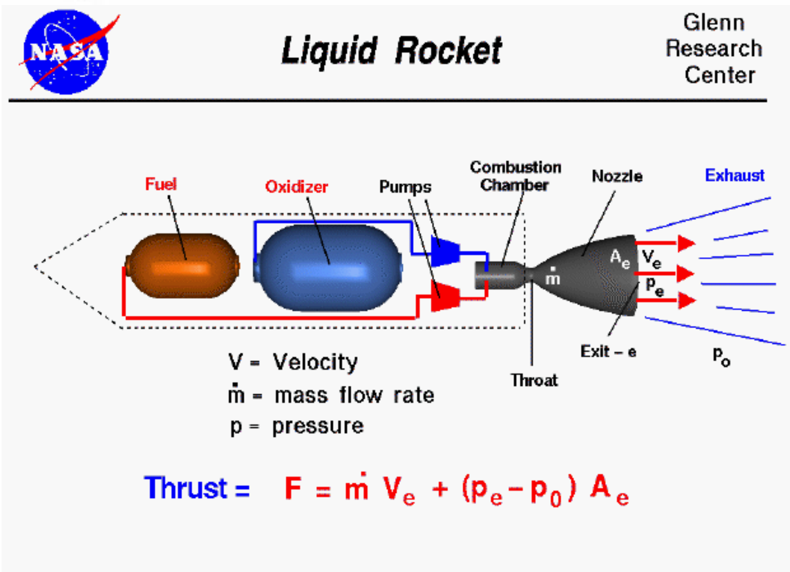
File name

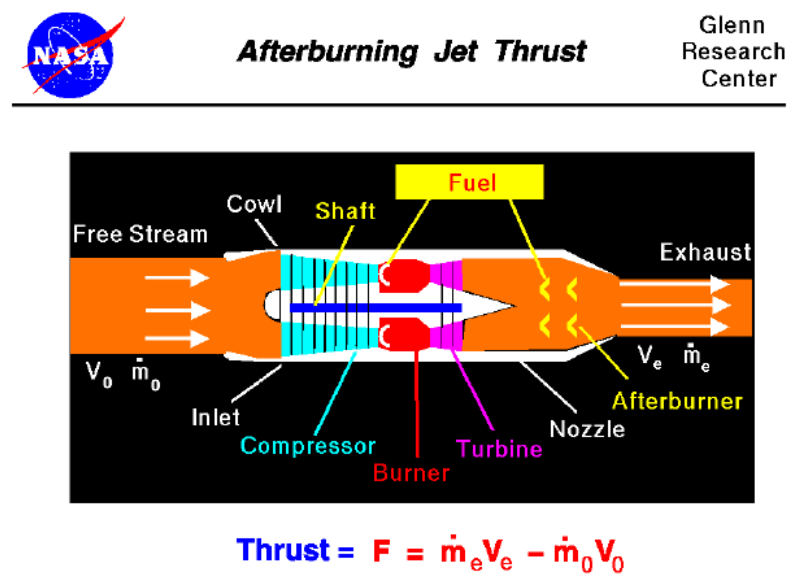
What unique characteristics make rockets different than gas turbines?

Rocketdyne SSME

Pratt & Whitney F100-PW-229







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Gas Turbine Combustion Chamber

Gas Turbine Engine Combustor

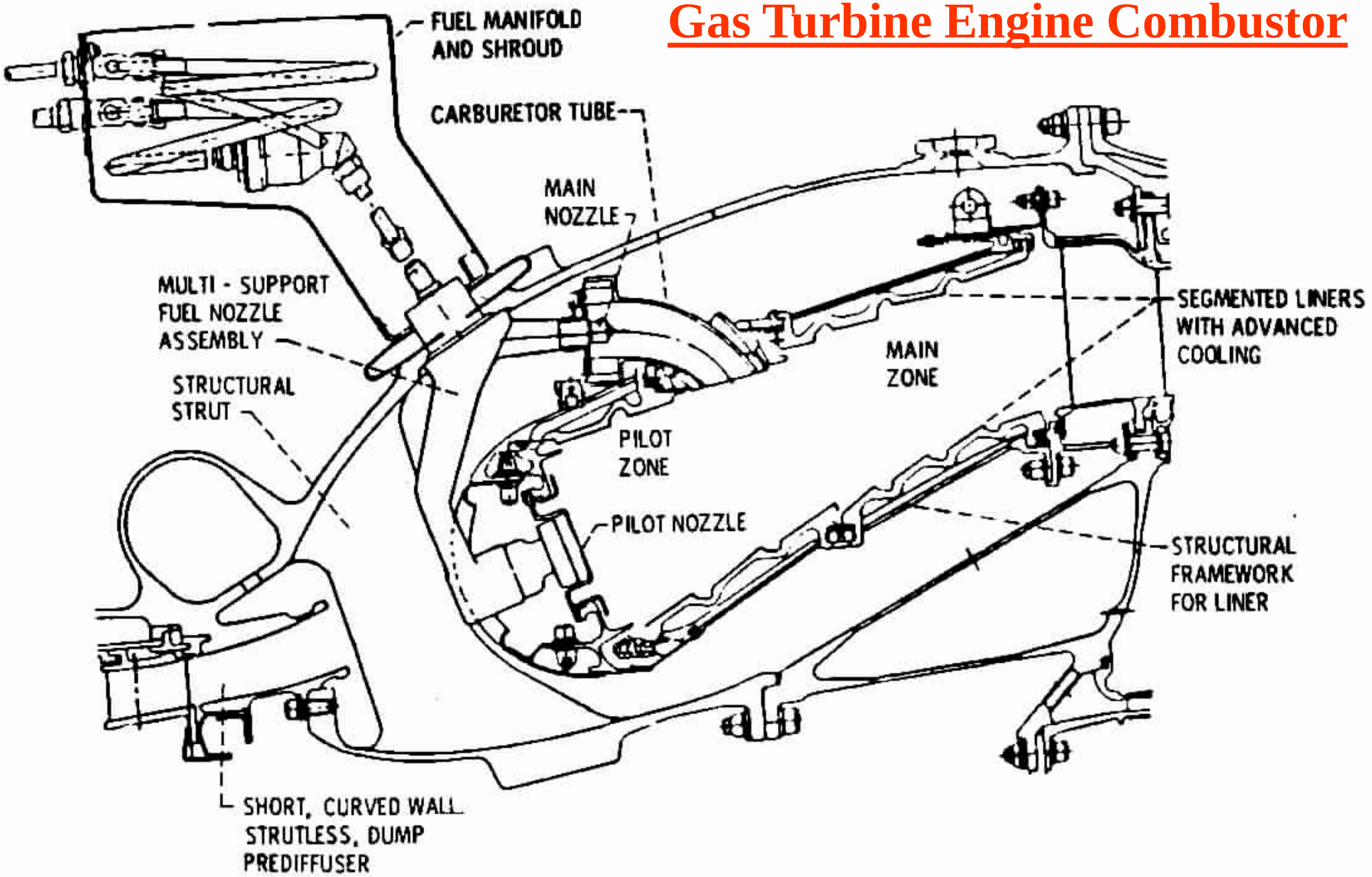
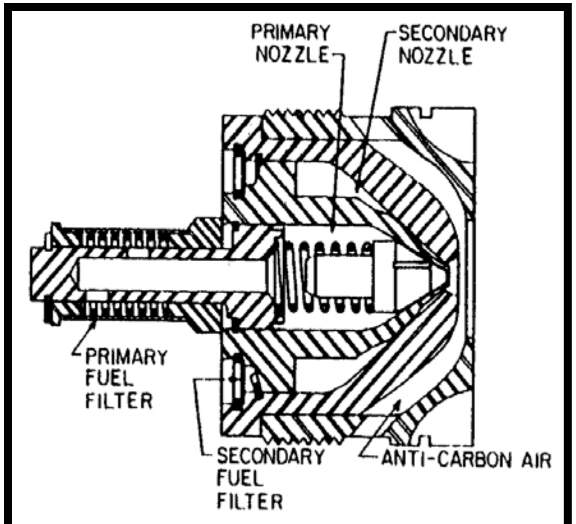


Figure 8.4 P&W E^3 combustor design and features (Sokolowski and Rhode 1981). *Copyright © AIAA 1981. Used with permission.*

Gas Turbine Fuel Injectors



Dual orifice atomizer

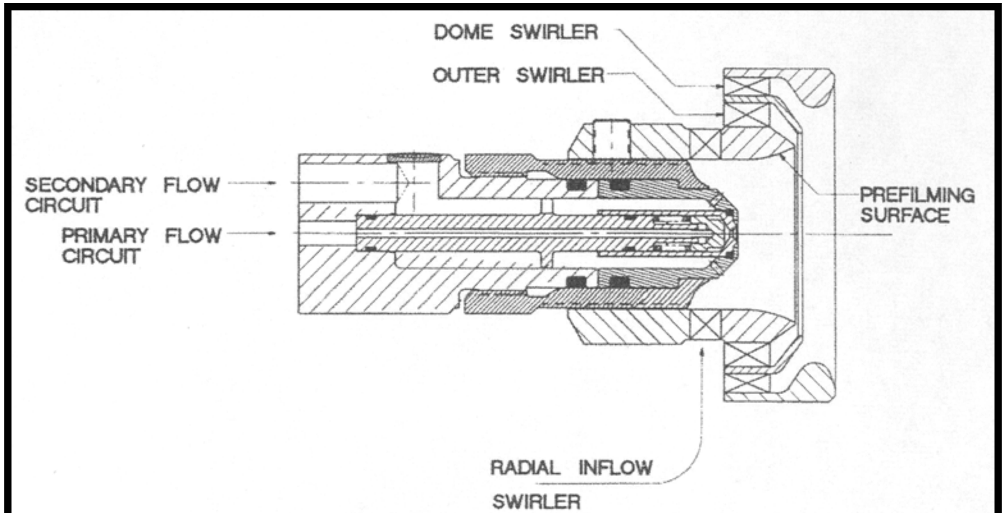
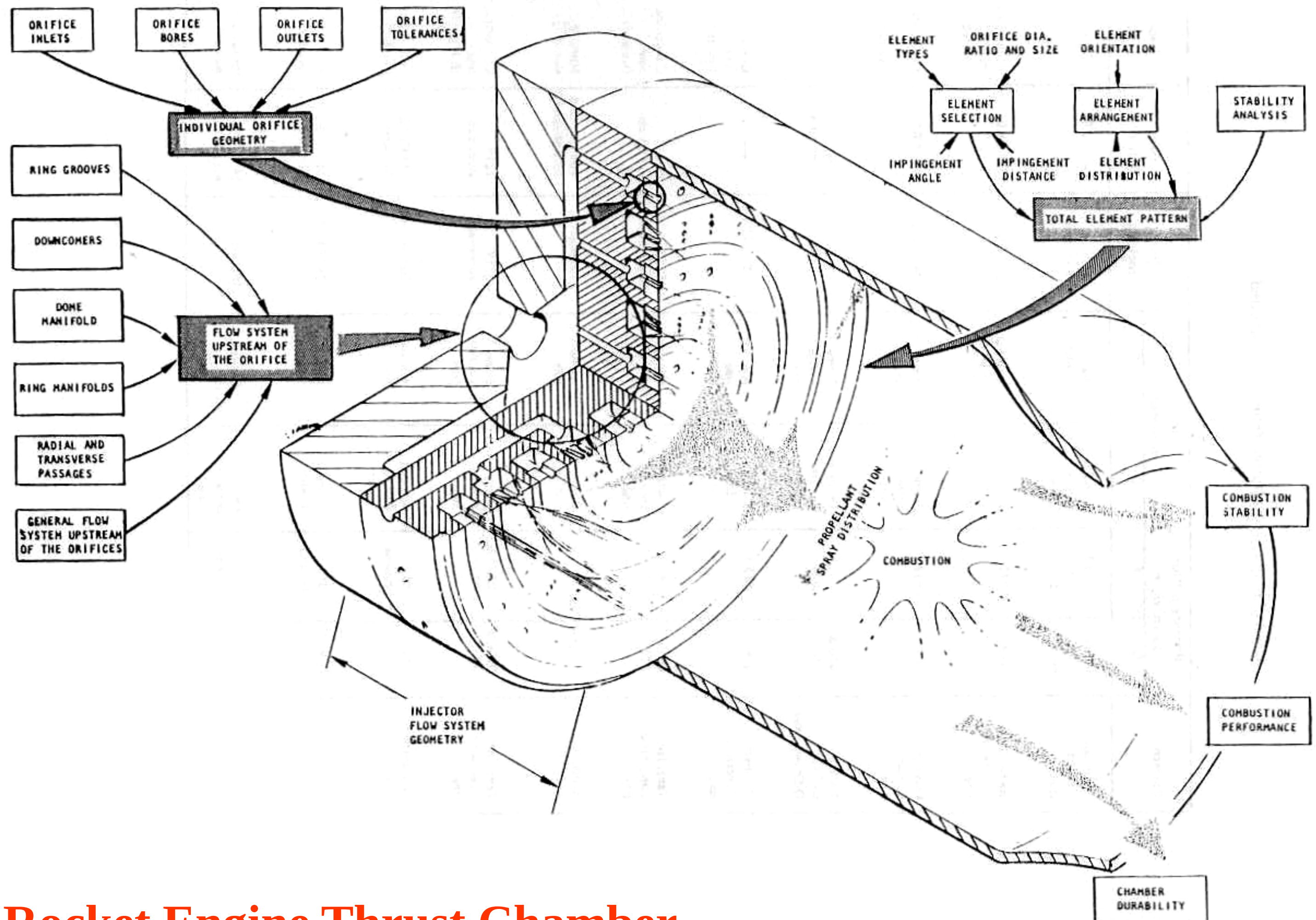


Fig. 1 General configuration of Parker Hannifin's hybrid air-blast fuel nozzle (patent pending).

Hybrid airblast fuel injector

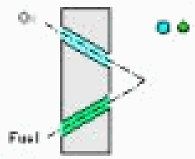
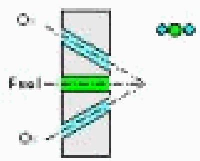
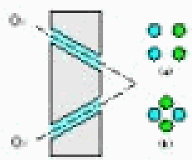
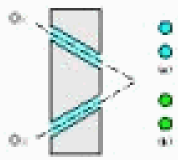
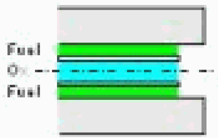
Rocket Thrust Chamber



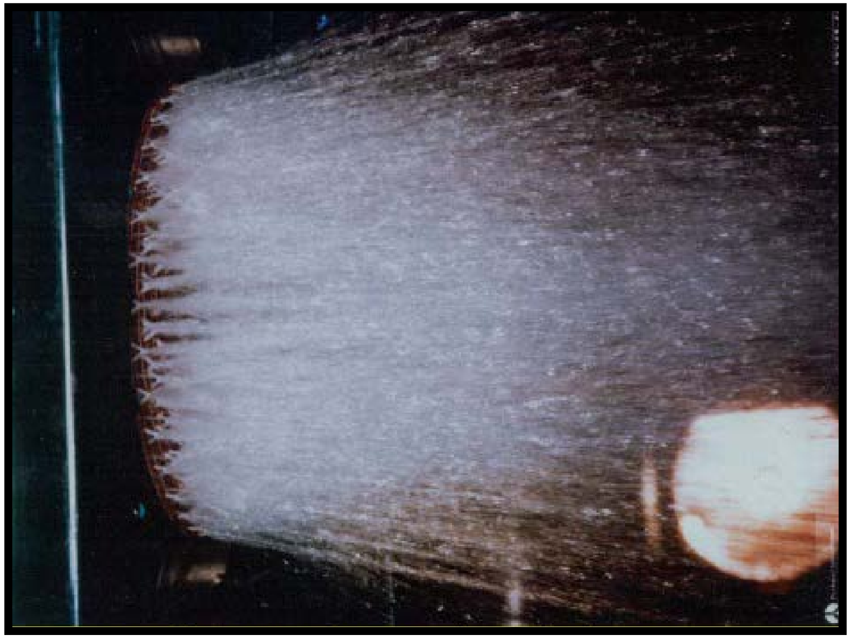
Rocket Engine Thrust Chamber

File name

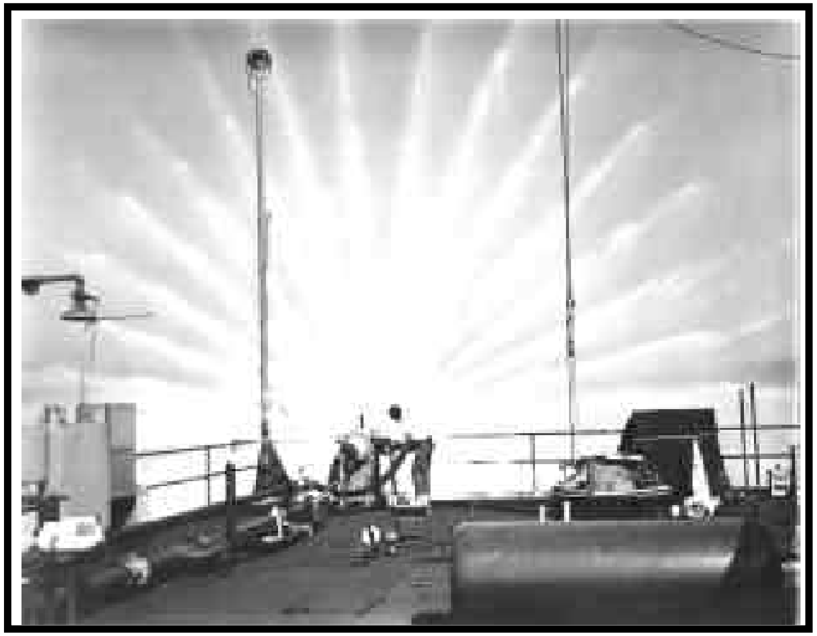
Liquid Rocket Injectors

Type	Element Configuration	Advantages	Disadvantages	Engine Application
Unlike Doublet (1 on 1)		• Proven dependability • Good overall mixing • Simple to manifold • Extensive studied	• Subject to blowapart with hypergolic propellants • Wall compatibility problems due to mixture-ratio gradients	• LEM ascent engine • Delta launch vehicle
Unlike Triplet (2 on 1)		• Good overall mixing • Resultant spray direction is axial • Proven dependability	• Subject to blowapart with hypergolic • Wall compatibility is good only when fuel is used in outer orifices	• Agena upper stage, Gemini
Unlike Quadlet (2 on 2)		• Can be used near wall • Resultant spray direction is axial • Proven dependability	• Subject to blowapart with hypergolic propellants • Difficult to manifold • Not well characterized	• Titan III first, second stage • Titan II, second stage
Like Doublet (1 on 1)		• Easy to manifold • Good mixing, Very stable • Not subject to blowapart • Well understood	• Requires increased axial distance to mix • Sensitive to design tolerances	• Titan I,II first stage • Jupiter, Thor, Atlas • H-1, F-1 engines
Concentric Tube		• Very good wall compatibility • Low pressure drop	• Poor mixing • Difficult to fabricate • Tends to become unstable when throttled	• Russia use extensively

Water Testing Rocket Injectors

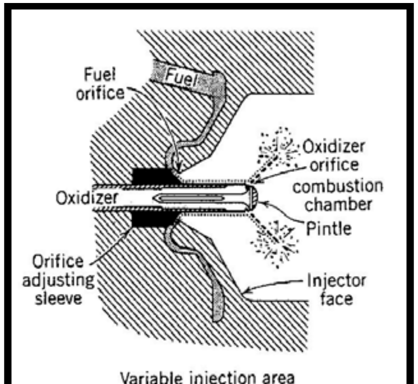


Water flow test of F-1 engine injector system



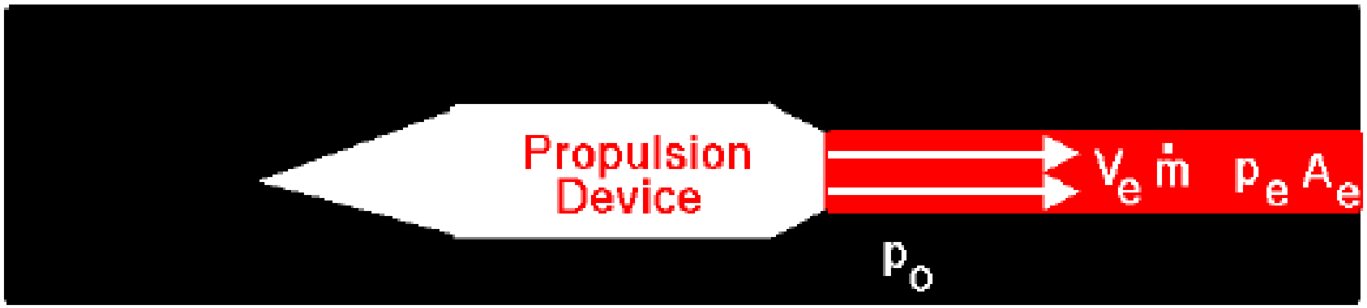
Water flow test of pintle injector for Air Force 250,000 lbf Engine

Like Doublet (1 on 1)		•Easy to manifold •Good mixing, Very stable •Not subject to blowapart •Well understood	•Requires increased axial distance to mix •Sensitive to design tolerances	•Titan I,II first stage •Jupiter, Thor, Atlas •H-1, F-1 engines



Variable injection area concentric tube injector

Rocket Equations - I



Rocket Thrust Equation $F = \dot{m} V_e + (p_e - p_o) A_e$

where p = pressure, V = velocity, A = area, $\dot{m}$ = mass flow rate, F = thrust

Define:

Equivalent Velocity: $V_{eq} = V_e + \dfrac{(p_e - p_o) A_e}{\dot{m}}$ $\quad F = \dot{m} V_{eq}$

Define:

Total Impulse: $I = F \Delta t = \int F\, dt = \int \dot{m}\, V_{eq}\, dt = m\, V_{eq}$

Define:

Specific Impulse: $\dfrac{\text{Total Impulse}}{\text{Weight}}$ $\quad Isp = \dfrac{I}{m\, g_o} = \dfrac{V_{eq}}{g_o}$ $\quad$ units = sec

$$\boxed{Isp = \frac{F}{\dot{m}\, g_o}}$$

Rocket Equations - II

$$F = (\text{mdot})\, V_{eq}$$

$$F = (\text{mdot})\, g\, I_{sp}$$

$$I_{sp} = V_{eq} / g$$

$$\boxed{I_{sp} = c^* C_f / g}$$

$$\boxed{V_{eq} = c^* C_f}$$

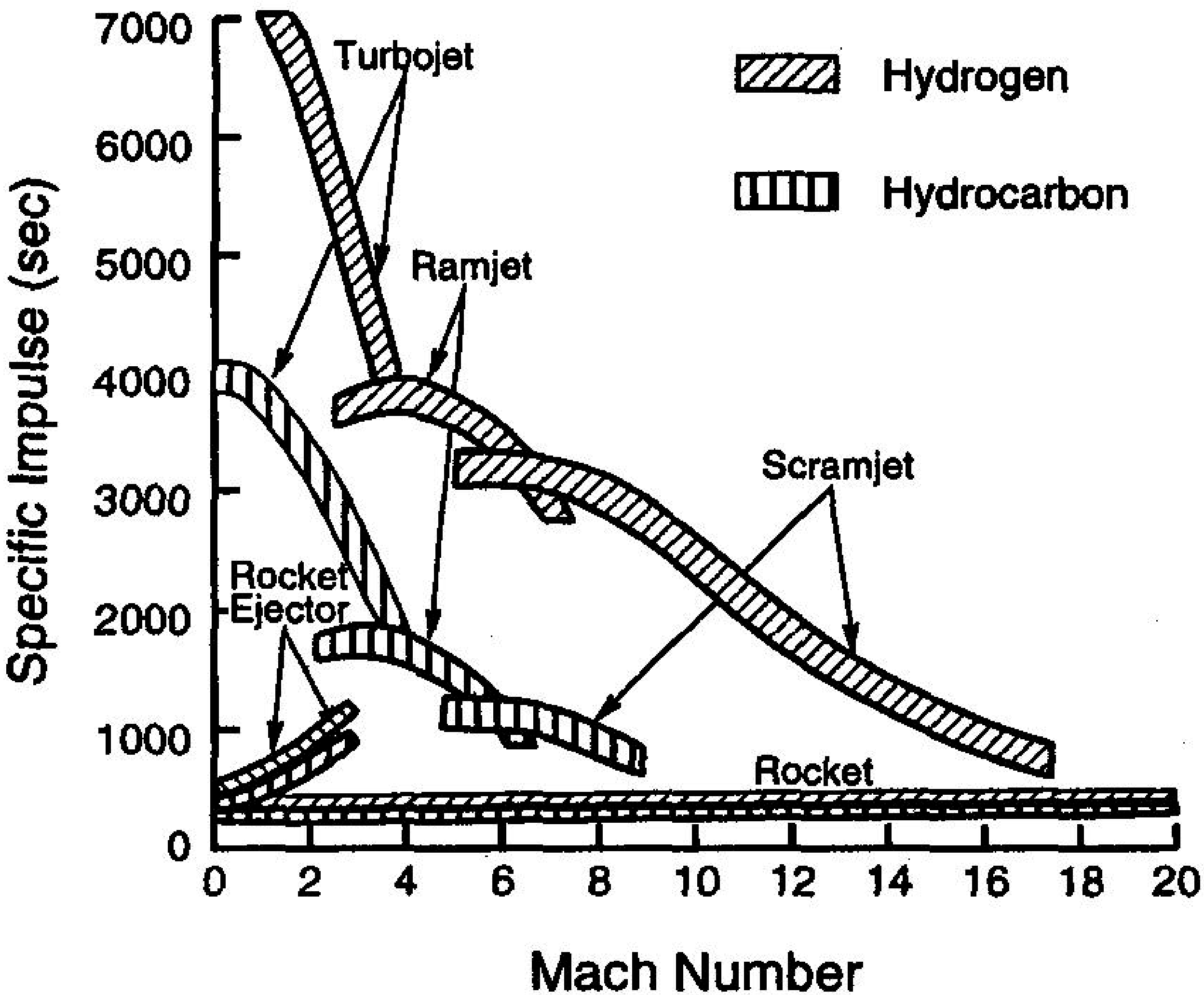
Define C-Star: $c^* = (P_{ch} A_{throat}) / (\text{mdot})$

Define Thrust Coefficient: $C_f = F / (P_{ch} A_{throat})$

$$\boxed{F = C_f\, (\text{mdot})\, c^*}$$

- C_f shows contribution of the divergent part of the nozzle to the total thrust (1.6 to 2)
- c* evaluates the combustion efficiency of the thrust chamber: A function of propellant characteristics and combustion chamber design. It is independent of nozzle characteristics. It is used as a figure of merit in comparing propellant characteristics and combustion chamber design.
- c* -efficiency is the ratio of actual valve of c* , as determined from the measurements, and the theoretical value, and typically has a value 92 to 99.5%. It is used to express the degree of completion of the energy release and the creation of the high temperature, high pressure gas in the chamber

Specific Impulse



Overall characteristics - I

Rockets, Turbojets, and Ramjets

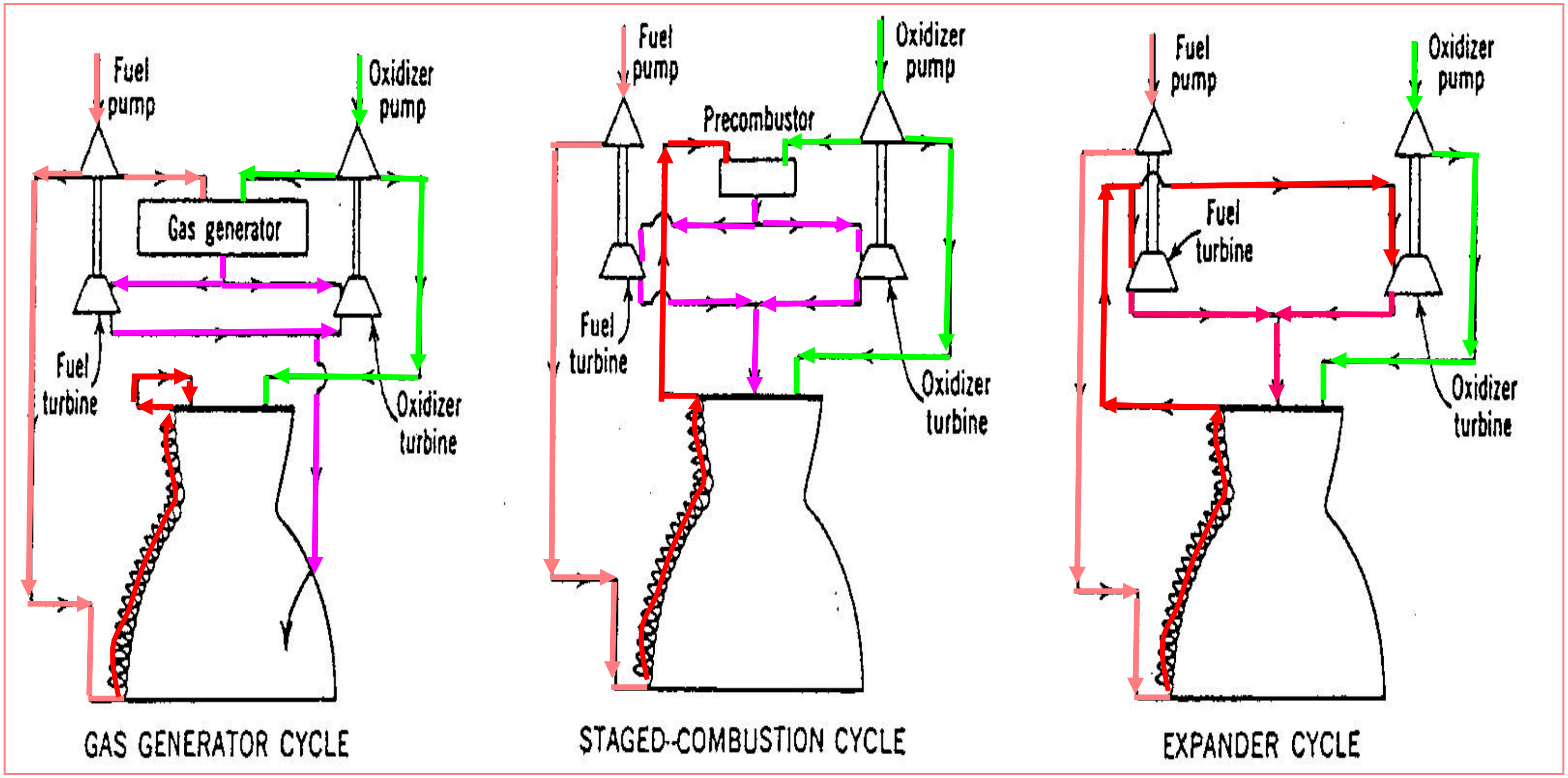
Feature	Rocket	Turbojet	ramjet
Thrust-to-Weight, typical	75:1	5:1, turbojet and afterburner	7:1 at Mach 3 at 30,000 ft
Specific fuel consumption (lb/h)/(lbof thrust)	8-14	0.5-1.5	2.3-3.5
Specific thrust (lb thrust)/(ft2 frontal area)	5000 to 25,000	2500 (Low Mach at sea level)	2700 (Mach 2 at seas level)
Thrust change with altitude	Slight increase	Decreases	Decreases
Thrust vs. flight speed	Nearly constant	Increases with Speed	Increases with speed
Thrust vs. air temperature	Constant	Decreases with temperature	Decreases with temperature
Flight speed vs. exhaust velocity	Unrelated, flight speed can be greater	Flight speed always less than exhaust velocity	Flight speed always less than exhaust velocity
Altitude limitation	None; suited to space travel	14,000 – 17,000 m	20,000 m at Mach 3 30,000 m at Mach 5 45,000 m at Mach 12
Specific impulse typical (lbf per unit propellant or fuel weight flow per sec)	270 sec	1600 sec	1400 sec

Overall characteristics - II

ROCKET vs. TURBINE ENGINES	
TURBINE ENGINES	ROCKE ENGINES
Internal operating pressure ~ 300 psi	Internal operating pressures ~ 6000 psi
Turbine temperature ~ 3300F	Turbine temperatures ~ 1250 F
T/W ~ 6 AT T ~ 40,000 lbf	T/W ~ 65 AT T ~450,000 lbf
Room Temperature propellant	Cryogenic propellants (-280F to -423F)
Mission time at max thrust ~25%	Mission time at max thrust ~ 95%
Idle to max thrust time <~ 5s	Idle to max thrust ~ 1s

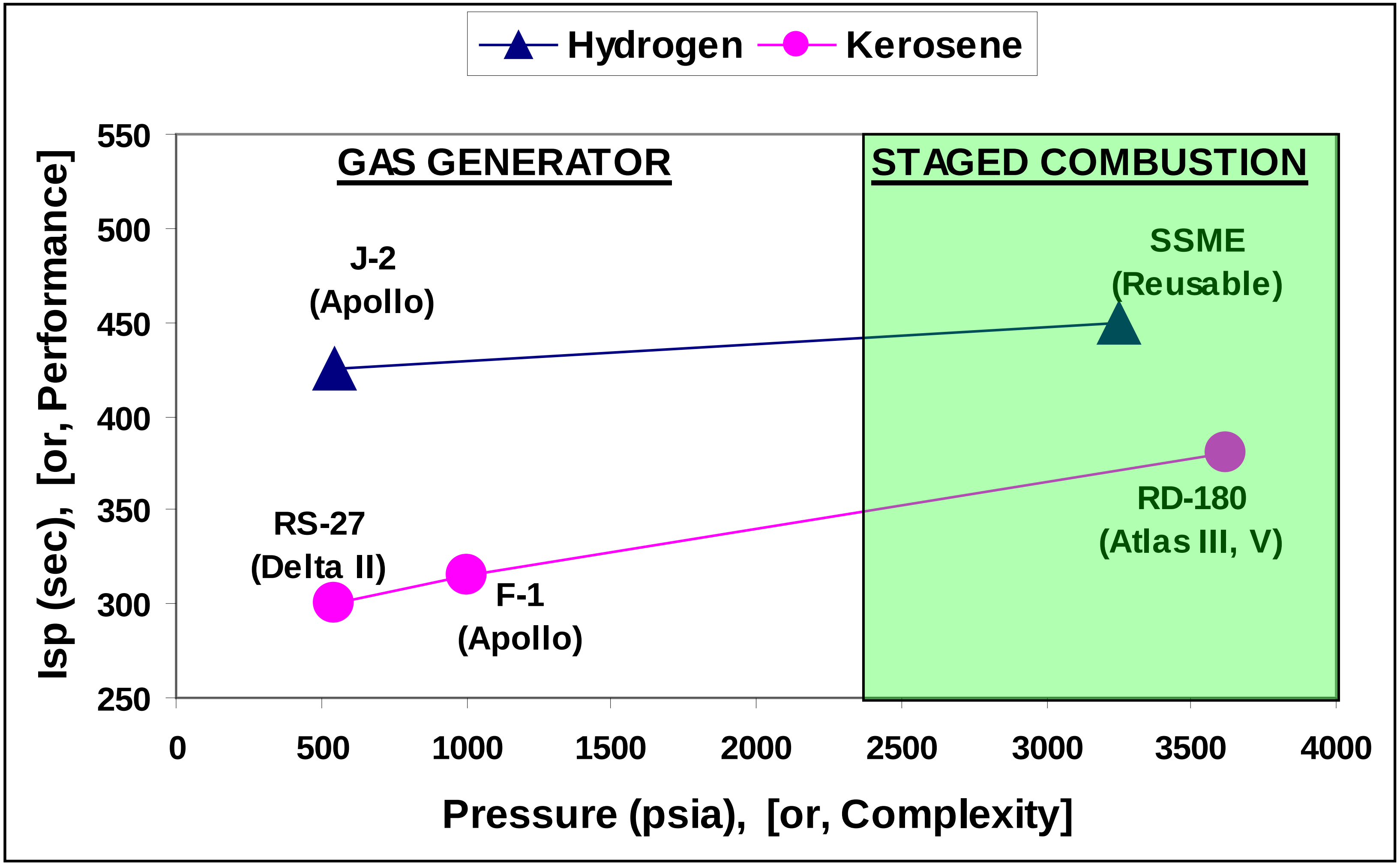
File name

Engine Cycles



Different engine cycles used for liquid rocket engines

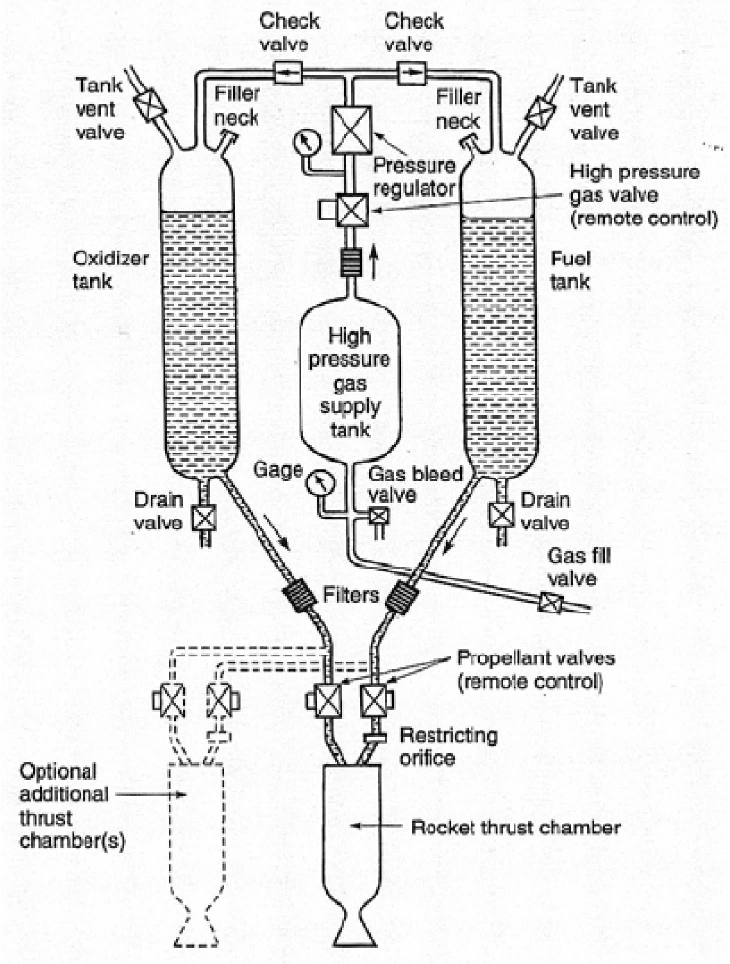
Performance of Different Types of Engines



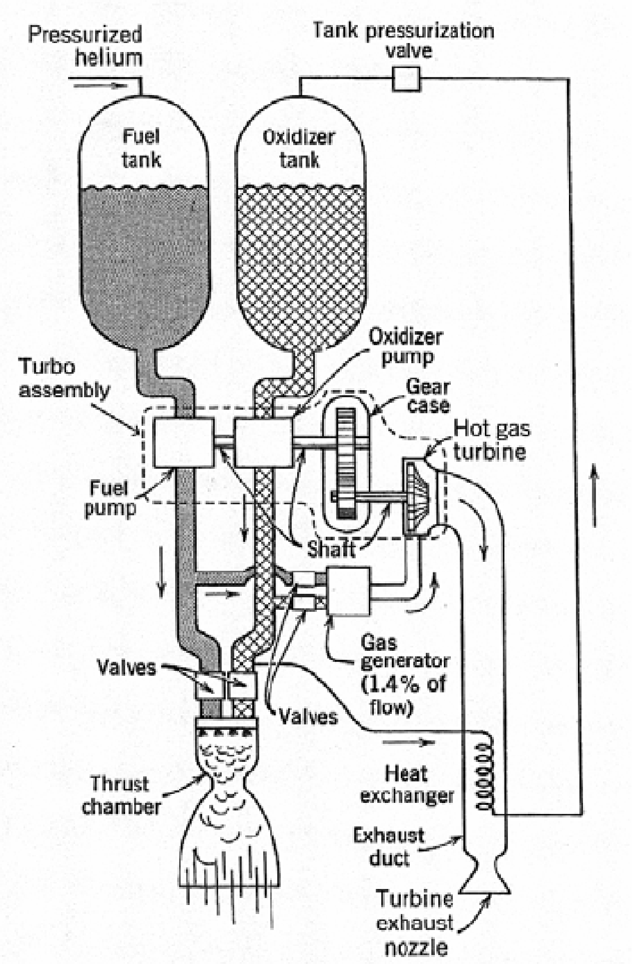
B. Chehroudi, PhD

Feed System: Pressure-Fed vs. Turbopump

- Liquid propellant rocket engine with gas pressure feed system.



- Liquid propellant rocket engine with a turbopump feed system.



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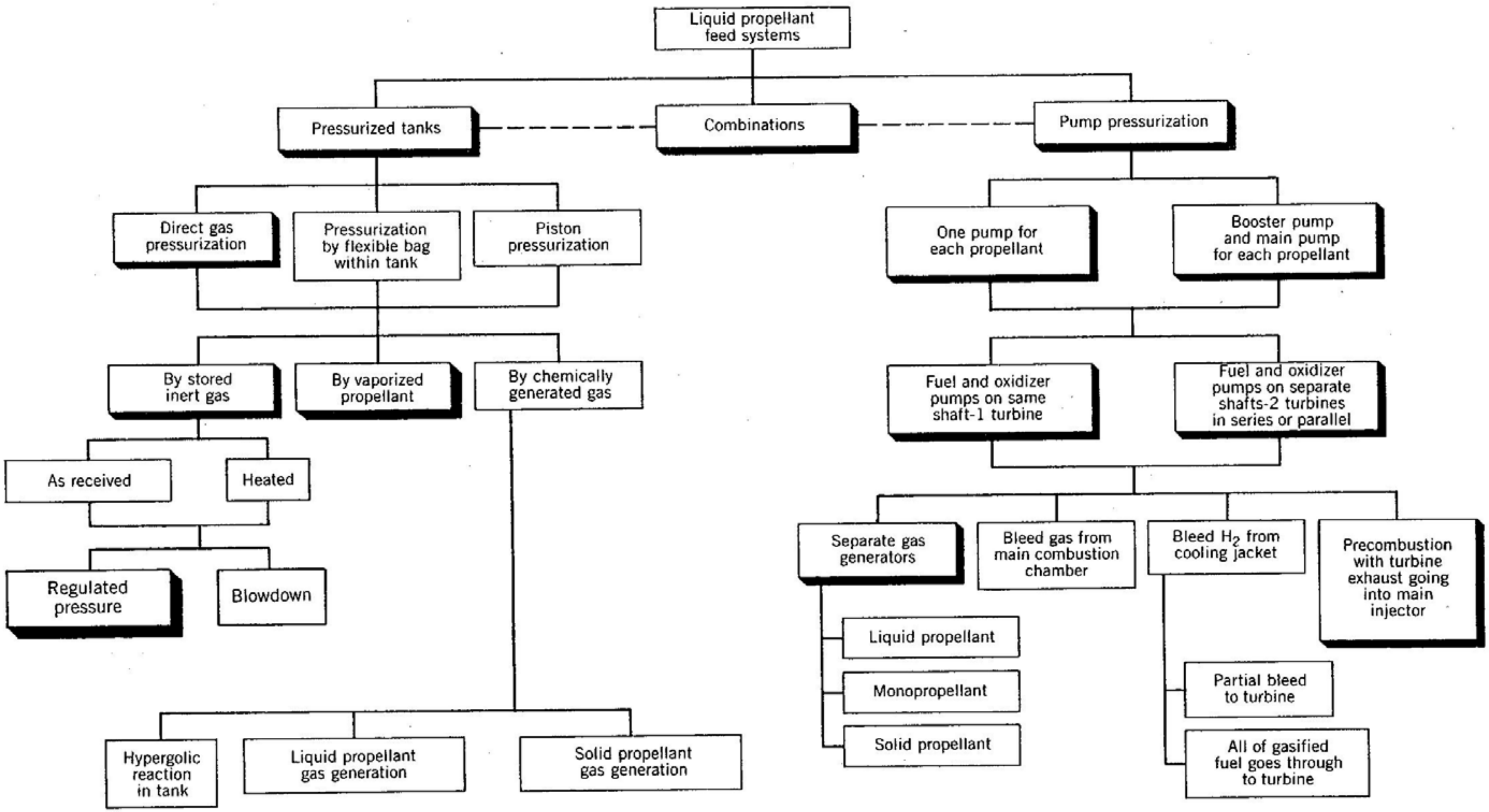
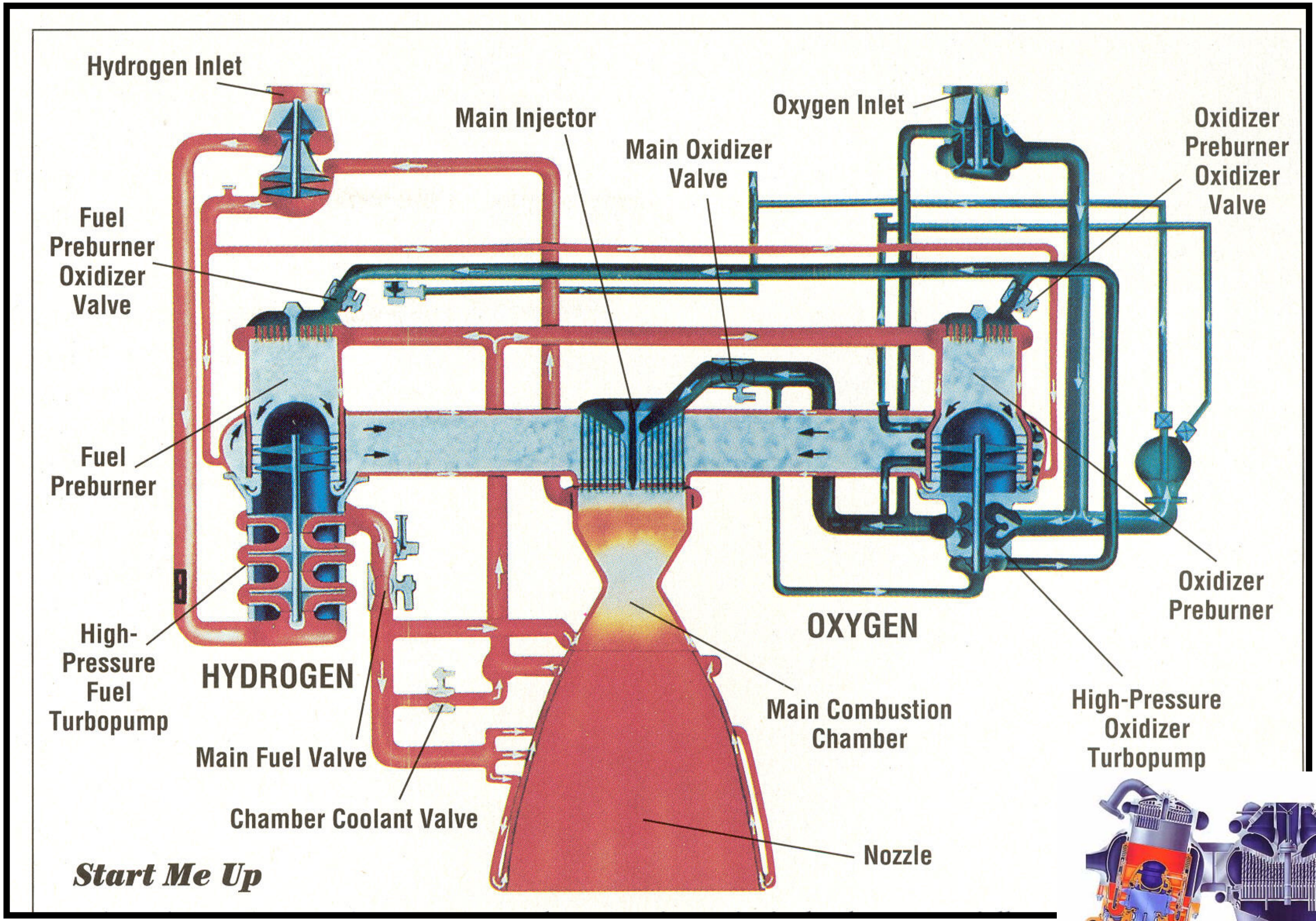
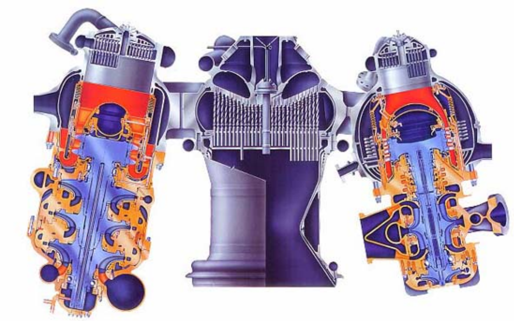
Feed System: Pressure-Fed vs. Turbopump



Space Shuttle Main Engine (SSME)

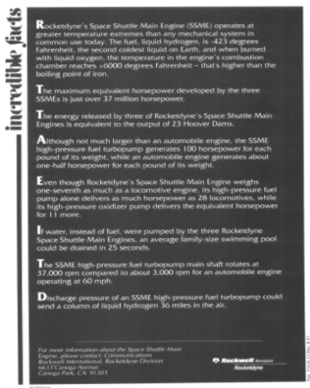




Special Features of SSME Engine

- Rocketdyne's Space Shuttle Main Engine (SSME) operates at greater temperature extremes than any mechanical systems in common use today. The fuel, liquid hydrogen, is -423 degrees F, the second coldest liquid on earth, and when gurned with liquid oxygen, the temperature in the engine's combustion chamber reaches +6000 degrees F – That's higher than the boiling point of iron
- The maximum equivalent horsepower developed by the three SSMEs is just over 37 million HP.
- The energy released by three Rocketdyne's SSMEs is equivalent to the output of 23 Hoover Dams
- Although not much larger than an automobile engine, the SSME high-pressure fuel turbopump generates 100 HP for each pound of its weight, while an automobile engine generates about one-half HP for each pound of its weight

- Even though Rpcketdyne's SSME weighs one-seventh as mush as a locomotive engine, its high-pressure fuel pump alone delivers as much horsepower as 28 locomotives, while its high pressure oxidizer punp delivers the equivalent horsepower for 11 more
- If water, instead of fuel, were pumped by the three Rocketdyne SSMEs, an average family-size swimming pool could be drained in 25 seconds
- The SSME high-power fuel turbopump main shaft rotates at 37,000 rpm compared to about 3,000 rpm for an automobile engine operating at 60 mph.
- Discharge pressure of an SSME high-pressure fuel turbopump could send a column of liquid hydrogen 36 miles in the air.



incredible facts

Rocketdyne's Space Shuttle Main Engine (SSME) operates at greater temperature extremes than any mechanical system in common use today. The fuel, liquid hydrogen, is -423 degrees Fahrenheit, the second coldest liquid on Earth, and when burned with liquid oxygen, the temperature in the engine's combustion chamber reaches +6000 degrees Fahrenheit – that's higher than the boiling point of iron.

The maximum equivalent horsepower developed by the three SSMEs is just over 37 million horsepower.

The energy released by three of Rocketdyne's Space Shuttle Main Engines is equivalent to the output of 23 Hoover Dams.

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Discharge pressure of an SSME high-pressure fuel turbopump could send a column of liquid hydrogen 36 miles in the air.

For more information about the Space Shuttle Main Engine, please contact: Communications
Rockwell International, Rocketdyne Division
6633 Canoga Avenue
Canoga Park, CA 91303

Rockwell Aerospace
Rocketdyne

B. Chehroudi, PhD

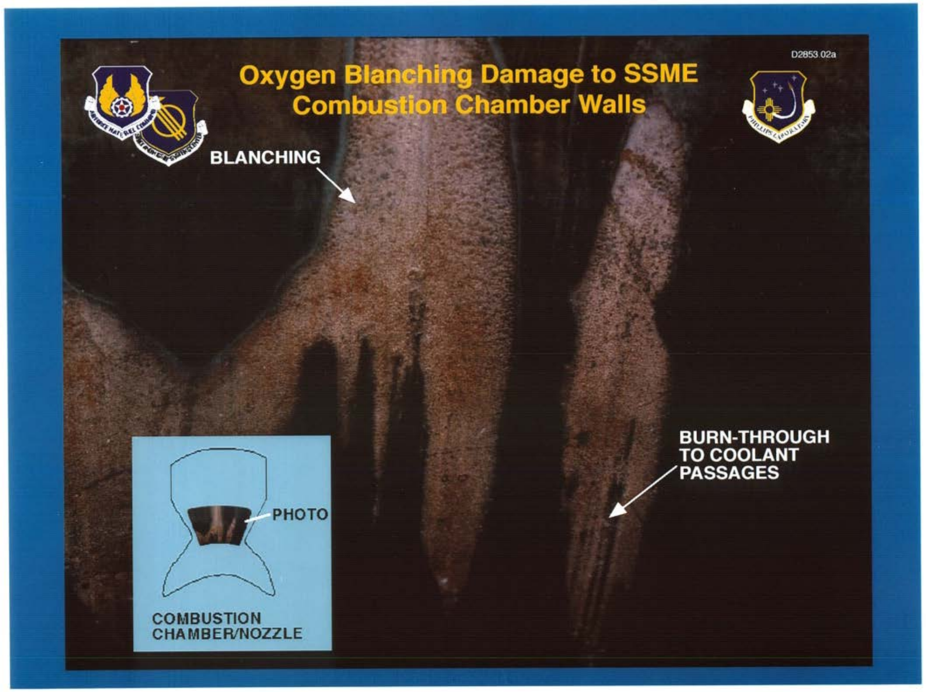
Special Features of SSME Engine

- **Liquid Rocket Engines (LRE) can use a wider range of oxidizers**
  - **Not limited to oxygen**
- **LRE's burn hotter**

Combustion temperatures

(K)	**Air**	**O2**
H2	2376	3078
CH4	2224	3053

  - **Derivative consequence: harsher materials environment**
    - **Oxygen blanching (wall corrosion due to hot oxygen)**

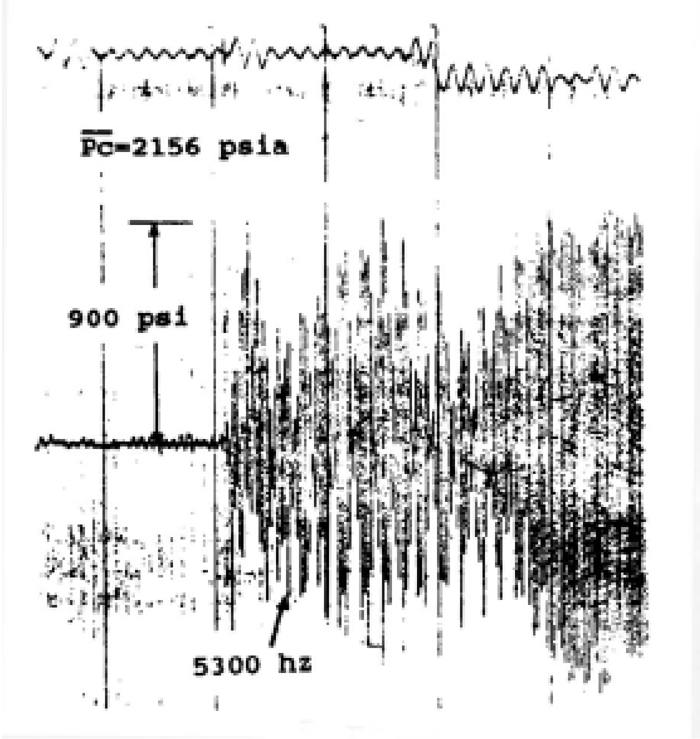


Combustion Instability

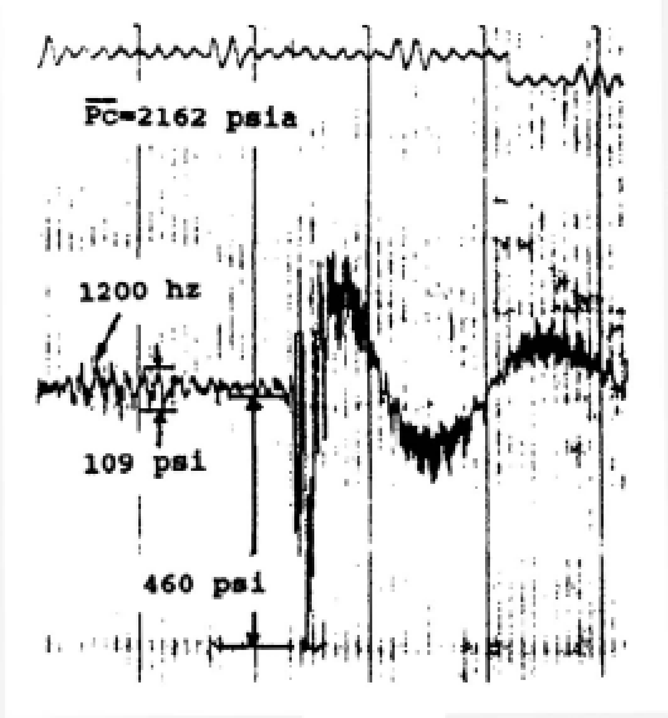
File name

Combustion Instability: Nature of the Problem

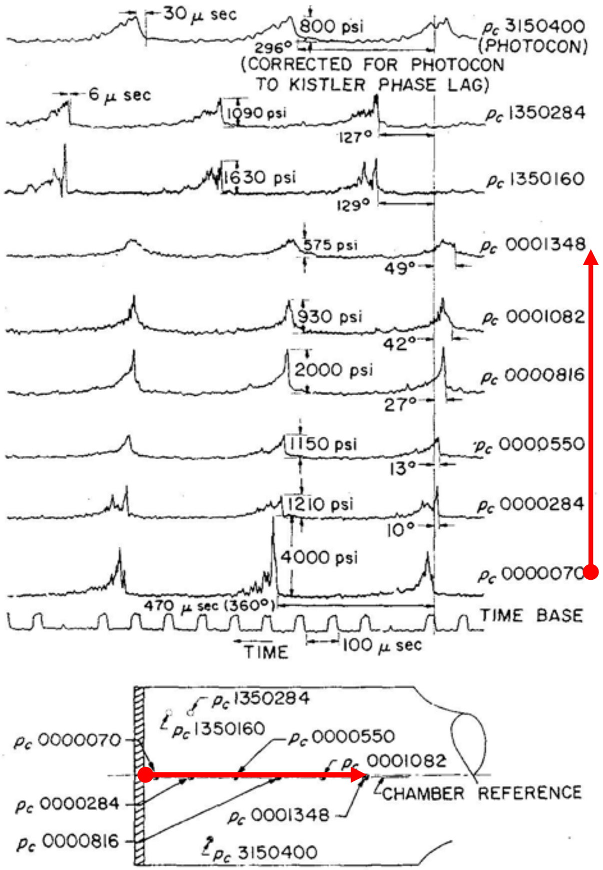
"Like Doublet Injector with a Monotuned 1T Resonator" without Baffles



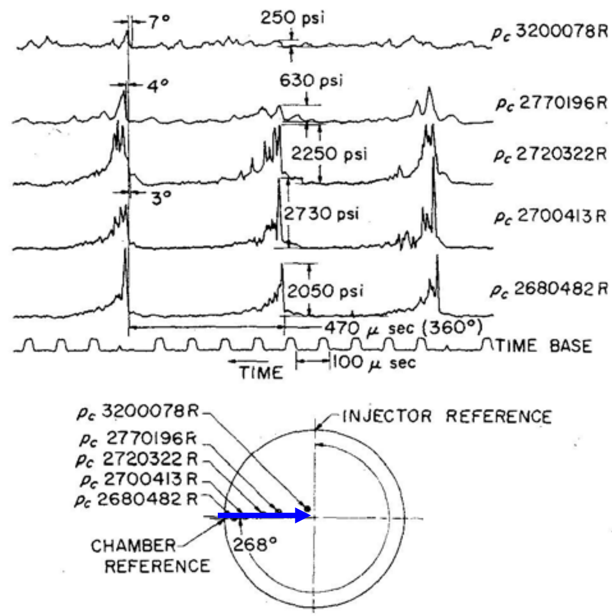
"Like Doublet Injector with a 16 cm High Baffle" without 1T-mode Acoustic Cavities



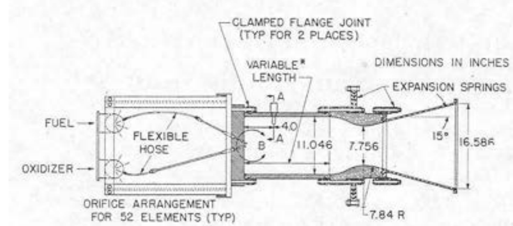
Combustion Instability: Nature of the Problem

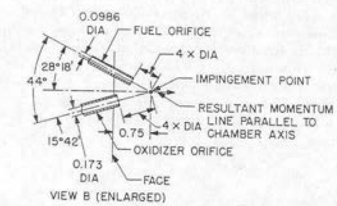


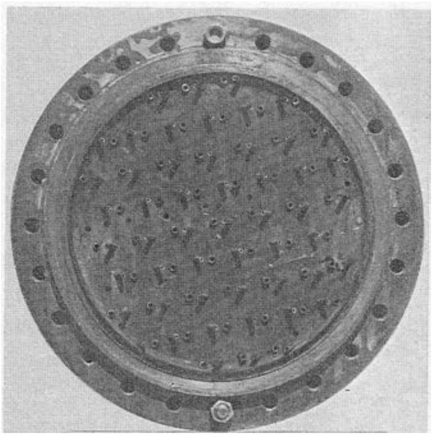
Pressure distribution along the chamber wall vs time during resonant combustion – Standard chamber. These records obtained ~25 ms from bomb pulse



Pressure distribution across the injector radius vs time during resonant combustion – Standard chamber. These records obtained ~25 ms from bomb pulse







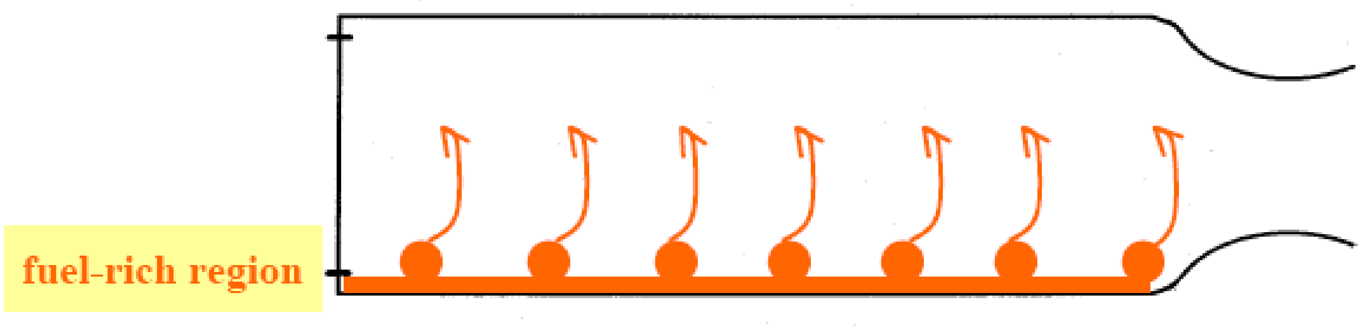
- A steep-fronted, high amplitude pressure wave sweeping about the combustion chamber axis during a destructive liquid rocket resonant combustion mode leads to the consideration of a rotating detonation-like wave concept to explain the phenomenon
- The observed pressure ratio across the wave front varies from in excess of 20:1 near the injector to 4:1 near the nozzle entrance. The nonsymmetrical wave exhibits a shock-like transient at certain chamber locations

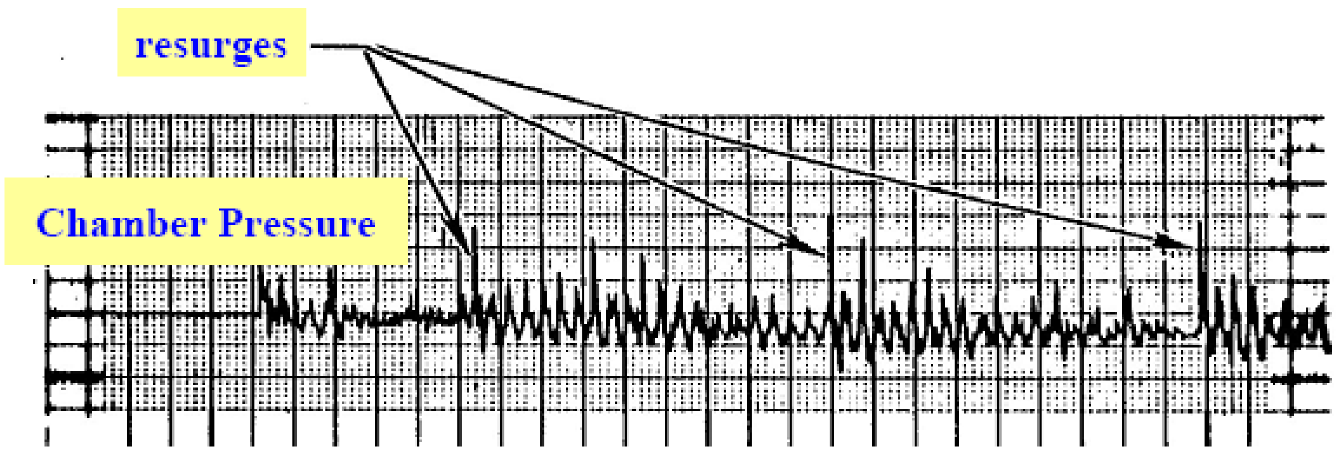
Possible Mechanisms (F-1 Engine)

- **Coupling between oscillations in the chamber and unsteady motions within the injection elements (Injection coupling)**
- **Periodic pulsed combustion of excess liquid propellant accumulations on boundary surfaces accompanying film cooling (*Resurging*: frequently observed following explosion of a bomb for rating dynamic stability. It is cause by the pulsed combustion of liquid fuel detached from the liquid layer produced with the film cooling)**
- **Transverse displacements of the injected fuel and oxidizer jets when exposed to oscillations of velocity parallel to the injector face (critical nearest the injector where processes forming liquid drops are most important)**
- **If the fuel and oxidizer are not uniformly mixed due to injector design and near-injector processes, interactions with oscillations in the flow can cause fluctuations of the mixture ratio and, therefore, of the burning rate**
- **Processes within the combustion zone or factors affecting the location of the combustion within the chamber**
- **Transient fluctuations can be amplified by the large fluctuations of thermodynamic properties (such as pressure fluctuations, brining instantaneous pressure near the critical pressure)**

Oefelein and Yang (1993). Comprehensive review of liquid propellant combustion instabilities in F-1 Engines. Journal of Propulsion and Power, Vol. 9, No. 5, Sept.-Oct.

Possible Mechanisms (F-1 Engine)





Resurging Phenomenon

File name

A Living List of Research Areas for Fundamental Understanding of Combustion Instabilities

1. Flame acoustic wave interaction
2. Flame shock wave interaction
3. Injector stream – acoustic wave interaction (both transverse and longitudinal)
4. Heat release before and during the acoustic instability
5. The nature of flame stabilization and impact of instability on stabilization
6. Impact of characteristic combustion time on instability
7. Effects of mean drop size, size distribution, and atomization periodicity/unsteadiness on instability
8. Is vaporization the rate-controlling mechanism under supercritical condition?
9. Nature of interaction between adjacent injector flames
10. Near-wall heat transfer augmentation as a result of transverse flow oscillation
11. Heat transfer from acoustically resonating flames
12. Interaction of acoustic field/waves with vortex shedding
13. Mechanism of energy transfer from chemical reaction in the flame zone to acoustic motion/field
14. Role of equivalence ratio fluctuations as a possible mechanism for driving combustion instability
15. Investigation of detailed flame dynamics at scales sufficient to resolve the energy transfer processes
16. Impact of swirling flow on combustion instabilities
17. Fundamental understanding of flame/flow interaction
18. Acoustic wave – shear layer interaction (vortex shedding)
19. Acoustic waves – jet core interaction
20. Flame flashback issues as it pertains to instabilities
21. Role of vorticity in the shear layer and its interaction (resonance) with acoustic field in a chamber
22. Linear and nonlinear interaction of sound and flame
23. The impact of fuel properties on combustion instabilities
24. Flame impingement with solid boundaries (rapid destruction of flame area leading to intense sound radiation)
25. Flame-flame collision (Rapid destruction of flame area leading to intense sound radiation)
26. …
27. Effects of supercritical condition on relevant items listed. The nature of stability under supercritical condition
28. Wave steepening and unsteady detonation wave phenomena
29. Shock / injector interaction
30. Surface effects including heat transfer computations
31. Modeling of the bombing tests in computational terms
32. …