Aerospace Combustion

Combustion Instabilities

Combustion Instabilities

Lecture Outline

- Introductory Remarks
- Combustion Chamber Processes
- Acoustics and Coupling
- Case Studies of Combustion Instabilities during Engine Development / Operation
  - F-1 (Saturn V)
  - RD-0110 (Soyuz)
  - Viking (ARIANE 1)
- Route Causes of Instabilities
  - Injector Design
  - Passive Control Devices

Combustion Instabilities

Definition

- Self-sustained oscillations of a dynamic system where the heat release of the chemical reaction outbalances the losses of the system
- The energetic source to maintain the pressure fluctuations come from the chemical reaction which is in itself stable (no explosions or chemical instabilities)
- Triggering and preservation of instabilities due to a coupling between chemical reactions and gas-dynamic processes (both phenomena are stable independently)
- Hence, the entire system which is the combination between, propellants, feed system, injection system, combustion process and combustion chamber is instable.

Combustion Instability = Pressure Fluctuations in a System preserved by Combustion

Combustion Instabilities

Frequency Levels

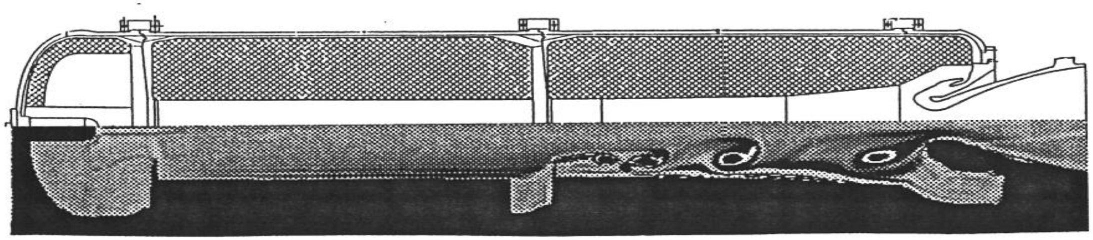
- Low-frequency (chugging) instabilities
  - arise from coupling between propellant feed system and combustion chamber
  - problems largely solved by adding POGO suppresser in propellant feed line and increasing pressure drop across injectors (20-45% of chamber pressure).
- Medium-frequency (buzz) instability
  - arising from entropy-wave induced instability due to poor mixing of propellant sprays and injector-wall interactions in confined regions.
  - problems largely solved by changing injector velocity, orientation and orifice size, as well as injector layout.
- High-frequency (intrinsic) instability
  - arising from interactions between oscillatory chamber flow and propellant combustion response.
  - vast experience in Russia with LOX/RP-1 staged combustion engines, none in Europe and US but recently in China

Combustion Instabilities

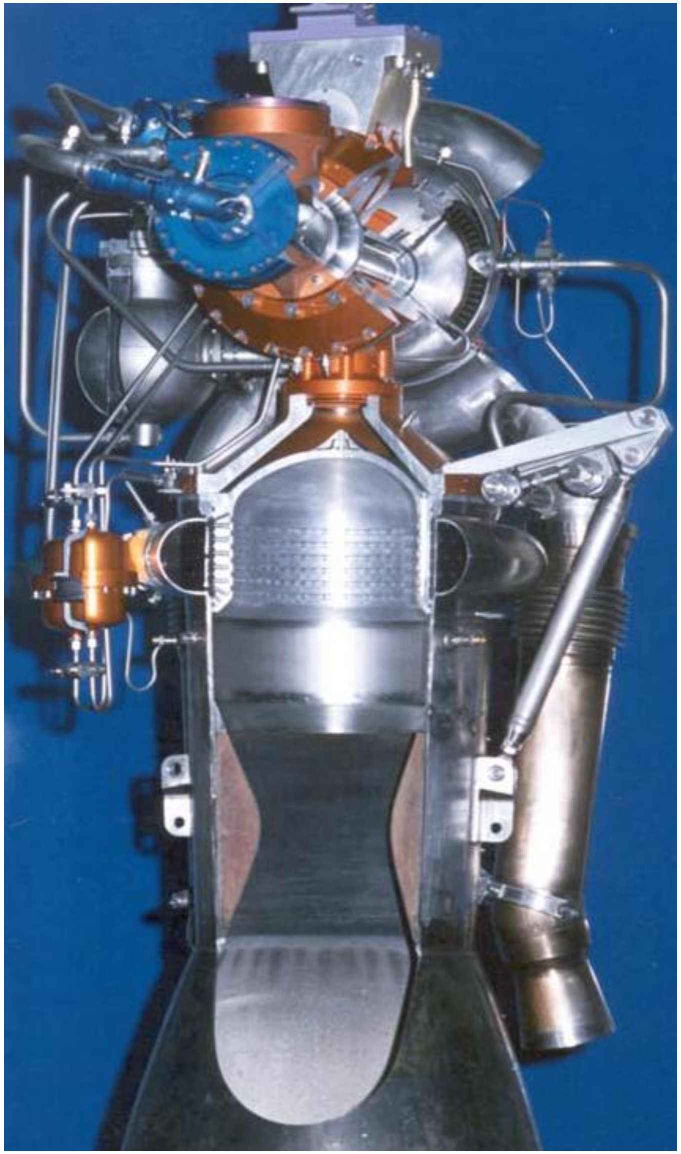
Low Frequency Instabilities

- Coupling of chamber pressure fluctuations with
  - test-rig structure
  - injector head structure
  - fluid supply system
- Flow induced pressure fluctuations (interaction of acoustic field with vortices)
  - Vortex shedding between segments of solid rocket boosters
  - Flow separation on injectors

$$f = \frac{c}{2L}$$



Sketch of a solid rocket motor and predicted flow field with vortex separation

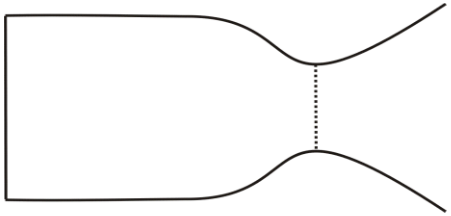


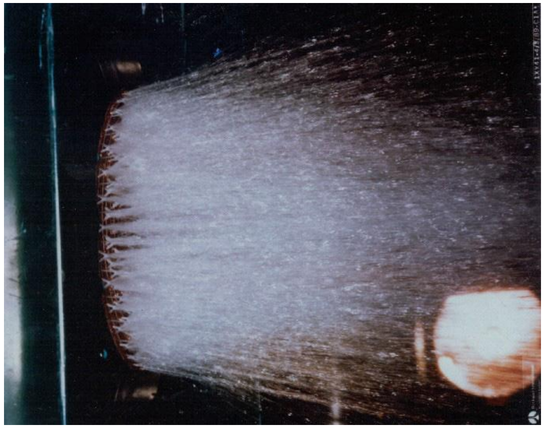
Viking engine

Combustion Instabilities

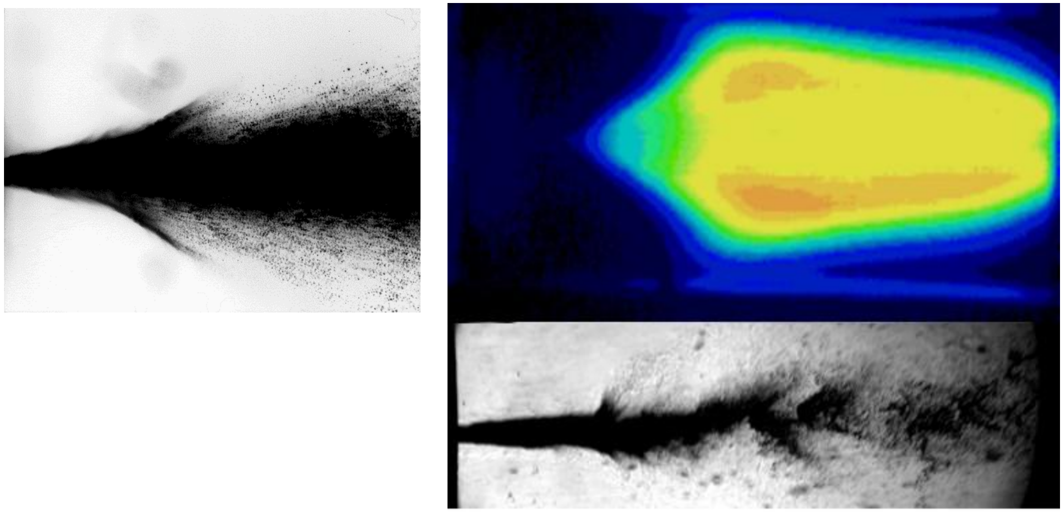
High Frequency Instabilities

- Coupling of chamber pressure fluctuations with combustion chamber acoustics
  - Various modes of a cylindrical volume
- Coupling with combustion chamber processes
  - Propellant injection
  - Propellant atomization
  - Propellant vaporization
  - Combustion kinetics





Spray pattern of F-1 injector water tests

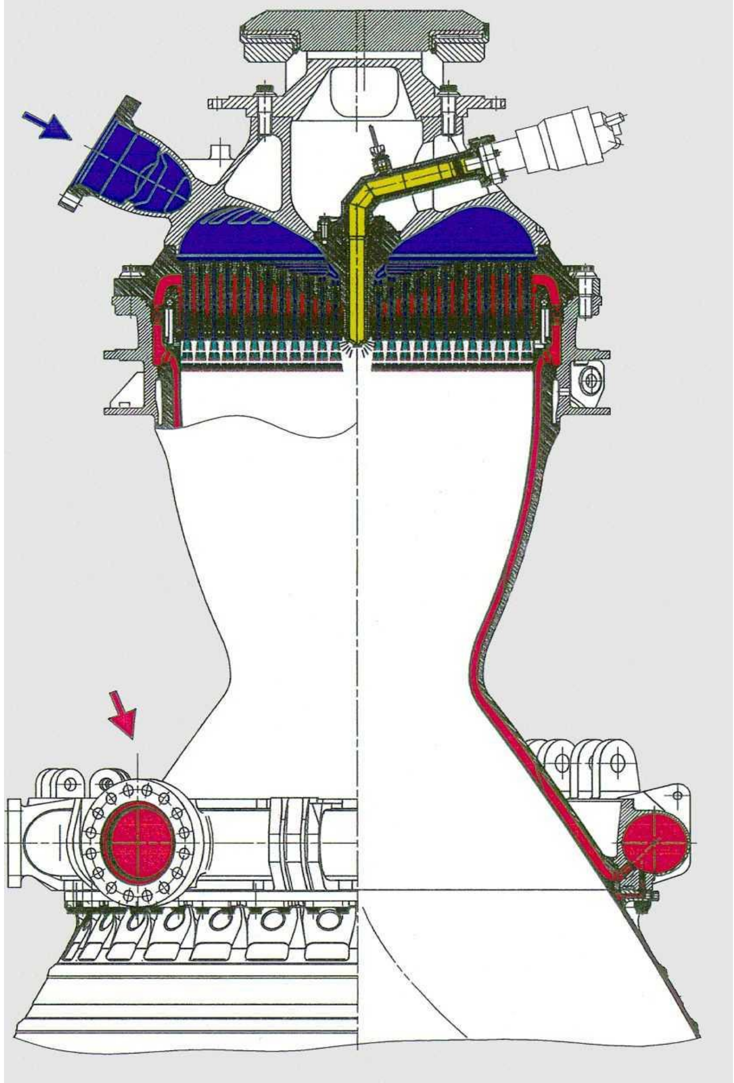


Spontaneous OH-emission and atomization pattern of a single injector LOX/CH4 combustor

Combustion Instabilities

Combustion Chamber Processes

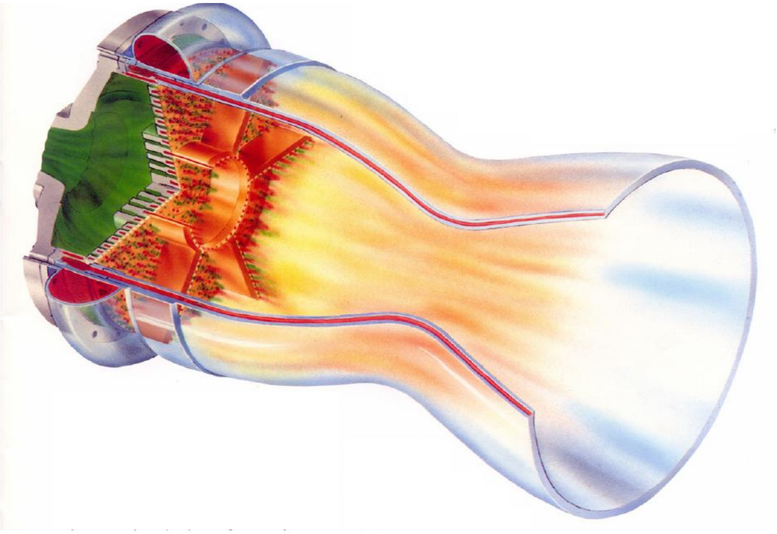
- Choked exit nozzle generally supports large amplitude pressure oscillations
- All internal processes which are capable to attenuate such unsteady motions are weak relative to driving energy
- Exceedingly small fraction of energy released during combustion is sufficient to generate severe unsteady motions



Assume a combustion chamber pressure $p_c \sim 200$ bar and a pressure fluctuation $\delta p \sim 20$ bar, → $< \varepsilon > = 4.2\text{x}10^4$ J/m3;

A typical volumetric heat release in a rocket engines is in the order ~ 10^7 J/m3

Combustion Chamber Processes



Injection

- Liquid Injection
- Gas Injection
- Heat Up
- Gasification

↓

Atomization

- Droplet Formation
- Liquid Jet Impingement
- Fan Formation
- Secondary Breakup
- Coalescence
- Liquid Mixing and Reaction

→

Vaporization

- Droplet Gasification and Diffusion

→

Mixing & Reaction

- Turbulent Mixing
- Chemical Kinetics
- Turbulence/Droplet Interaction
- Turbulence/Reaction Interaction

→

Expansion

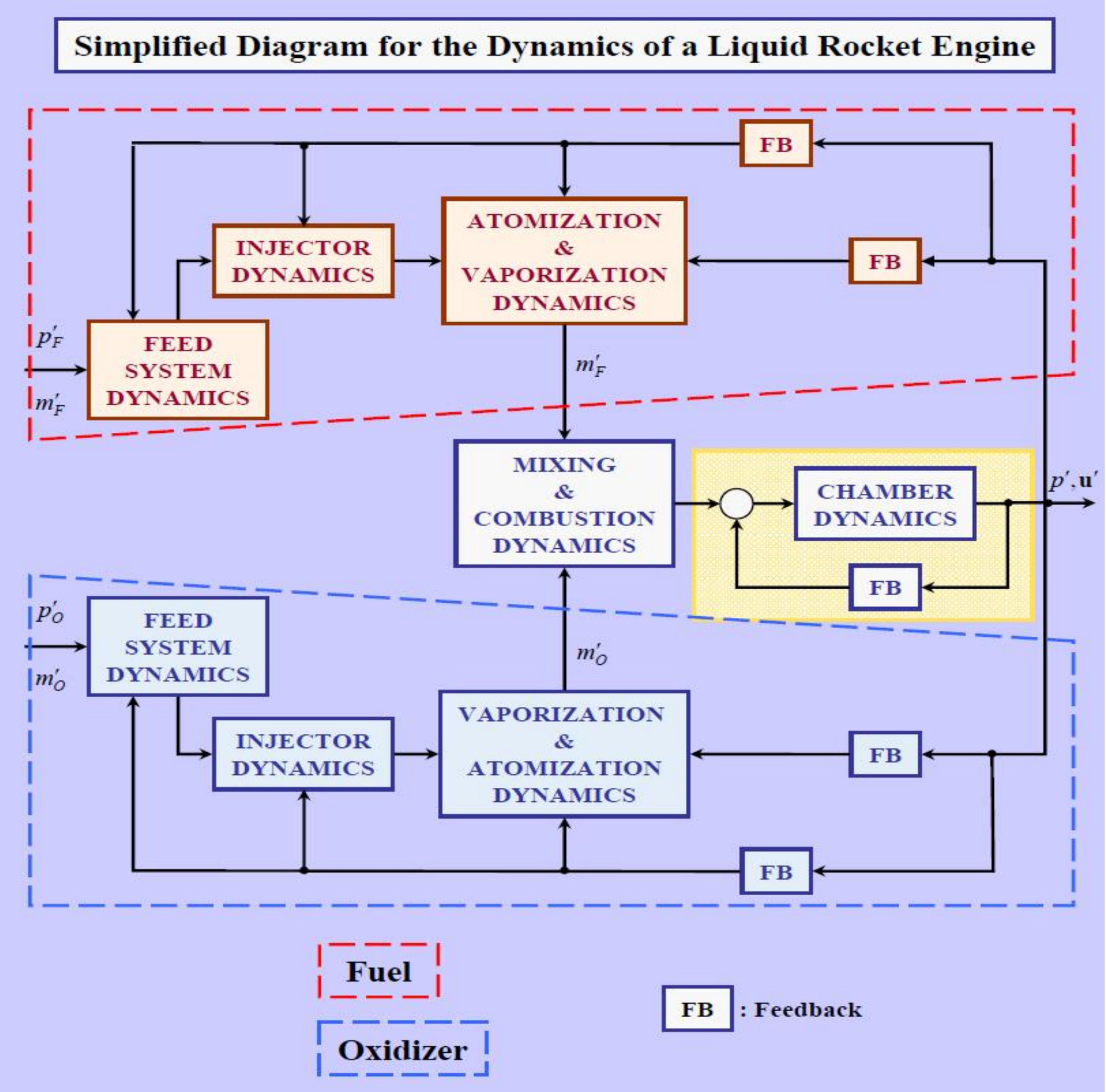
- Gas Dynamics
- Chemical Kinetics
- Flow Separation

© Courtesy of Vigor Yang (Georgia Tech)

Combustion Instabilities

Combustion Chamber Processes

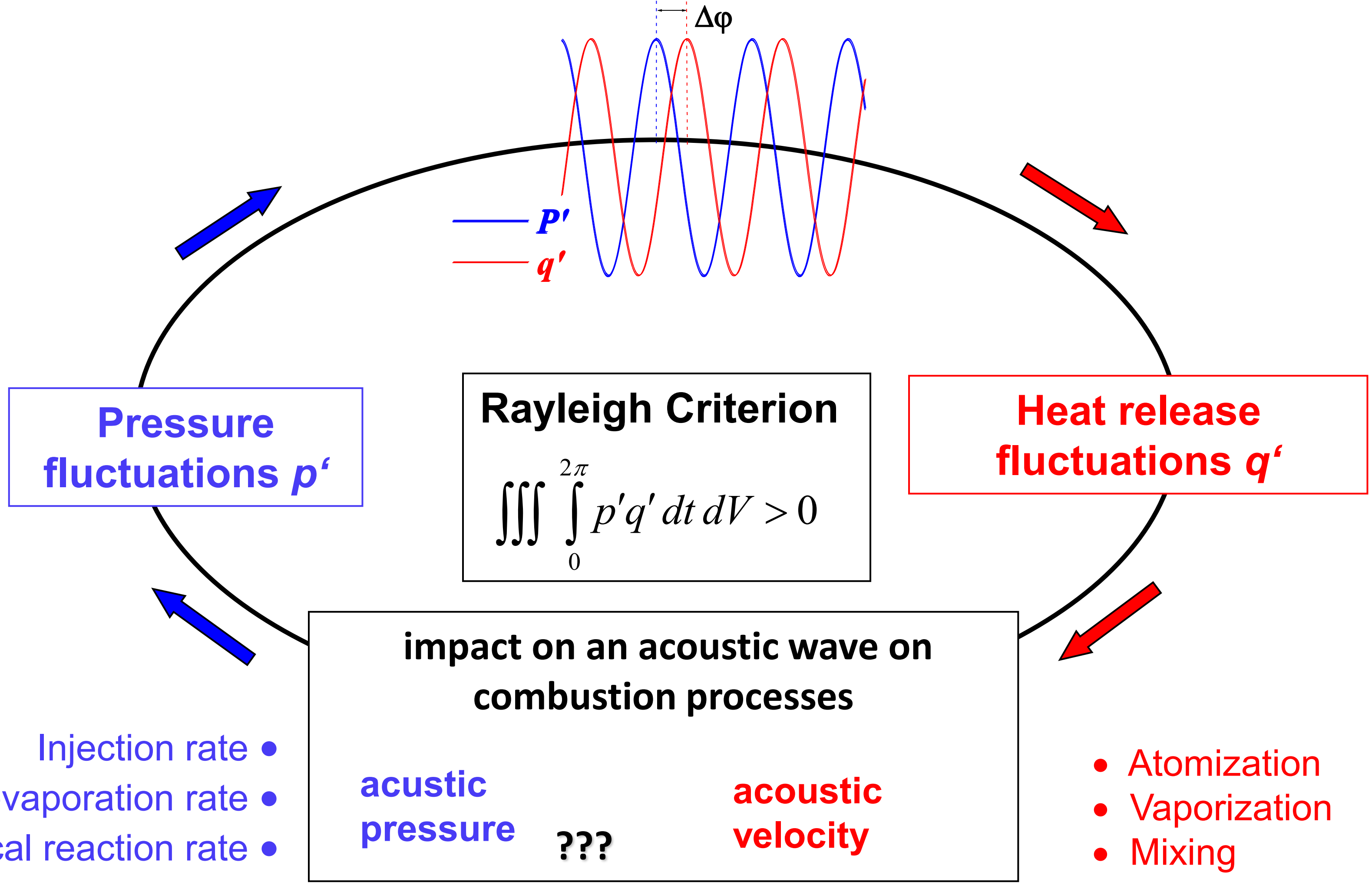
Scheme of possible linear and non-linear interaction and coupling of processes



F. Culick and V. Yang, Short Course on Combustion Instability, PSU, 2003.

Coupling of Acoustics and Combustion

Rayleigh Criterion



Pressure fluctuations *p‘*

Rayleigh Criterion

$$\iiint \int_0^{2\pi} p'q'\,dt\,dV > 0$$

Heat release fluctuations *q‘*

impact on an acoustic wave on combustion processes

acustic pressure

???

acoustic velocity

- Injection rate
- local evaporation rate
- Chemical reaction rate

- Atomization
- Vaporization
- Mixing

Coupling of Acoustics and Combustion

Rayleigh Criterion

$$N = \int_V \int_0^{2\pi} p' q' \, dt \, dV$$

- **Pressure coupling:**

$$\dot{q}' = n p'(t-\tau)$$

$$p'(x,t) = \bar{p}\left(e^{ikx} + e^{-ikx}\right) e^{i\omega t}$$

  - Interaction index n
  - time lag τ
  - Phase shift p', q': $\theta = \omega\tau$

- **algebraic equation for ω:**

$$\omega^2 + i\omega n(\kappa-1)e^{-i\theta} - \omega_0^2 = 0$$

$$\omega = -i\frac{(\kappa-1)ne^{-i\theta}}{2} \pm \sqrt{\left|\omega_0^2 - \left(\frac{(\kappa-1)ne^{-i\theta}}{2}\right)^2\right|}$$

$$e^{i\omega t} = e^{i(\mathrm{Re}(\omega)+i\,\mathrm{Im}(\omega))t} = e^{i\,\mathrm{Re}(\omega)t} e^{-\mathrm{Im}(\omega)t}$$

for θ = 0, 2π, ...:

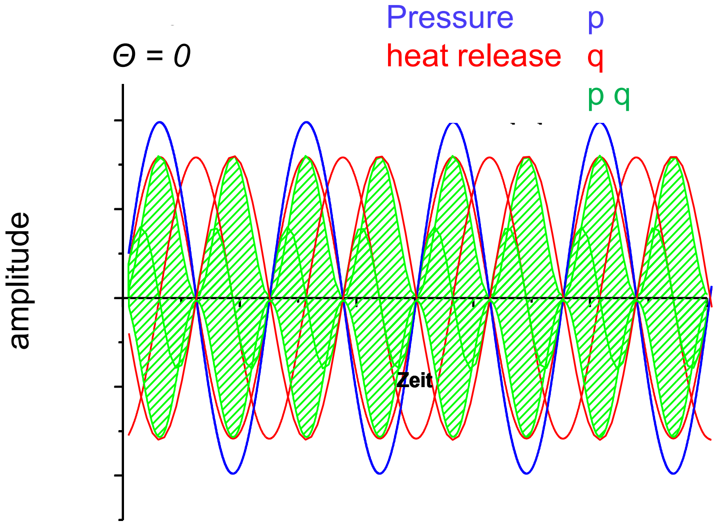
- Im(ω)<0 → amplification
- N>0

for θ = π/2, 3π/2, ...:

- Im(ω)=0 → neutral
- N=0

for θ = π, 3π, ...:

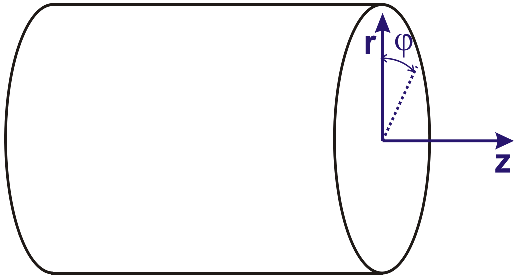
- Im(ω)>0 → damping
- N<0



Combustion Instabilities

Combustion Chamber Acoustics

eigenmodes of a cylinder



linear acoustics:

$$P(t) = \overline{P} + P'(t)$$

$$\nabla^2 P' - \frac{1}{c^2}\ddot{P}' = 0$$

eigenfrequencies:

$$\nabla^2 P' = \frac{\omega^2}{c^2} P'$$

boundary condition:

- chamber asumed as a closed volume → all surfaces $\frac{\partial P'}{\partial n} = 0$

Mode	n	m	α_{nm}
1T	1	1	1.841
2T	2	1	3.054
1R	0	2	3.832
1T1R	1	2	5.331

$$\omega = \frac{\alpha_{nm} c}{2\pi R}$$

$R \approx 0.1 m$

$c \approx 1500 m/s$

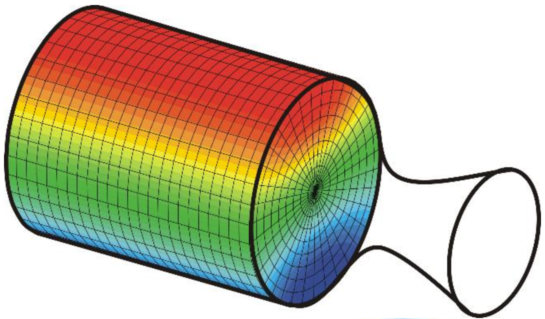
$\omega_{1T} \approx 4.4 kHz$

$$P'(z,r,\varphi,t) = P'_0 \cdot Z(z) \cdot R(r) \cdot \Phi(\varphi) \cdot e^{i\omega t}$$

$$P'(z,r,\varphi,t) = P'_0 \cdot \cos(kz) \cdot J_n(\alpha_{nm}\frac{r}{R}) \cdot \sin(n\varphi) \cdot \sin(\omega t)$$

Combustion Chamber Acoustics

Eigenmodes of a cylinder



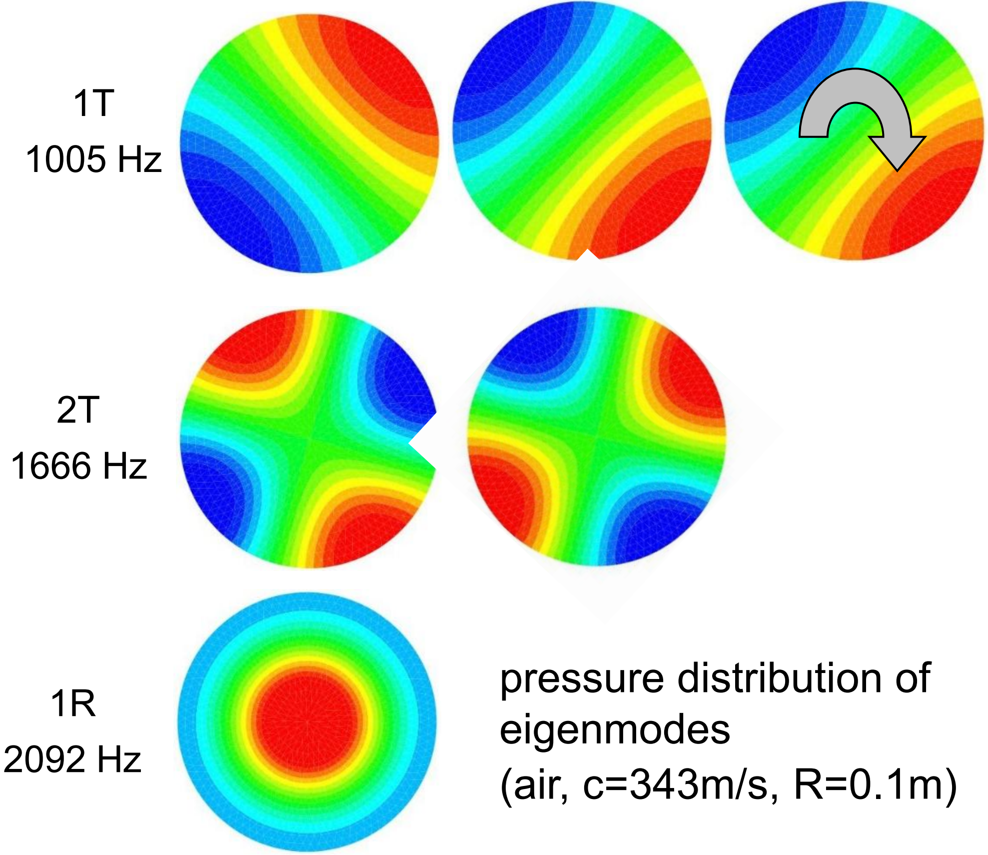
tangential modes

- dual degenerated modes
- spinning mode possible

radial modes

longitudinal modes

- less problematic for real engines (low frequencies)



pressure distribution of eigenmodes
(air, c=343m/s, R=0.1m)

Coupling of Acoustics and Combustion

Time lag model (Crocco)

$$\dot{q}' = n p'(t-\tau)$$

- n: interaction index
- τ: time lag

Basic idea: propellant injected reacts after a certain time τ_T:

$$\tau_T = \tau_J + \tau_A + \tau_H + \tau_V + \tau_M + \tau_R$$

τ_J : jet atomization

τ_A : droplet formation

insensitive to P_C

τ_H : droplet heating

τ_V : droplet vaporization

sensitive to P_C

τ_R : ignition delay

τ_M : propellant mixing

small compared to other τ

- time-lag has to be determined experimentally
- model performs good for specific hardware but is difficult to scale

Coupling of Acoustics and Combustion

Velocity coupling

Atomization

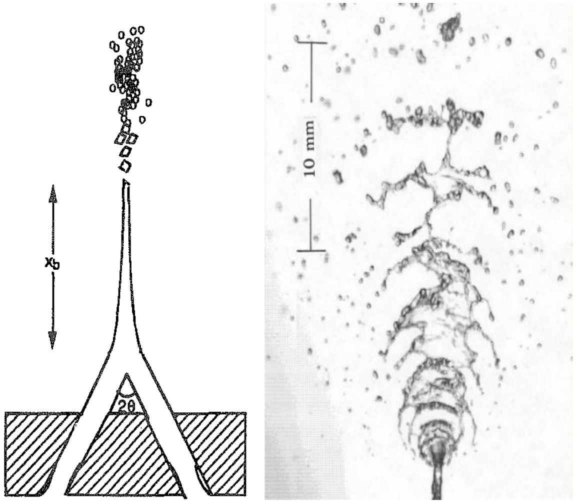
- periodic change of atomization
  - local atomization rate
  - droplet size distribution
  - propellant distribution
- continuous liquid jet/film length increases coupling possibility
- Secondary atomization

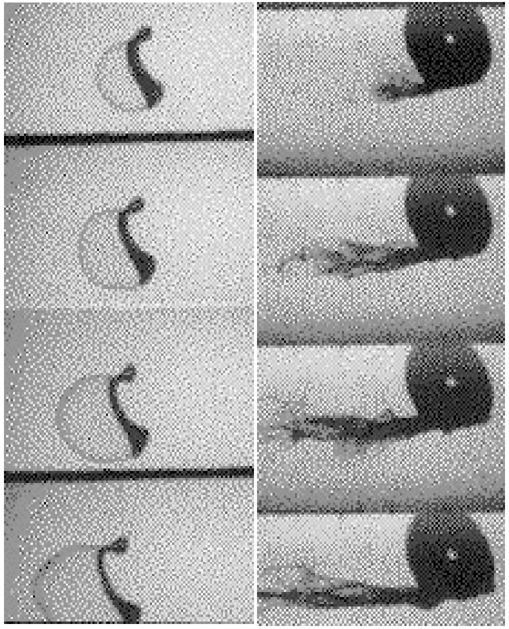
$$\frac{u'}{c} = \frac{1}{\gamma}\frac{P'}{P}$$

$$\frac{P'}{P} \approx 0.1$$

$$u' \approx 100 m/s$$

$$a' = \omega u' \approx 10^5 g$$





bag break-up   shear break-up

Combustion Instabilities

Coupling of Acoustics and Combustion

R.J. Priem, M.F. Heidmann: Propellant Vaporization as a Design Criterion for Rocket-Engine Combustion Chambers, NASA TR R-67, 1960

Pressure coupling

Droplet vaporization

- Order of magnitude for
  - adiabatic compression, p‘/p=0.1: T‘≈ 150 K
  - kinetics and vaporization strongly temperature dependent
- Model assumptions:
  - Droplet vaporization linear dependent on velocity:
    → coupling averages itself out
  - Droplet vaporization non-linear function on pressure:
    → coupling has net effect

$$\frac{u'}{c} = \frac{1}{\gamma}\frac{p'}{p}$$

$$T' = \frac{u'c}{c_p}\left(\frac{1}{V}\frac{\partial V}{\partial T}\right)\cdot T = \frac{u'c}{c_p}$$

$$w_{vap} \propto \rho\left|\Delta u\right|$$

$$w_{vap} \propto \left(Mp_C\right)^{1/2} \ln\frac{p_C}{p_C - p_L}$$

Coupling of Acoustics and Combustion

Nozzle Losses

Mass flow through throat generates losses

$$\dot{m}_t = A_t \rho_t c_t$$

$$-\frac{\dot{m}_t'}{\overline{\dot{m}_t}} = \frac{\gamma+1}{2\gamma}\frac{P_C'}{\overline{P_C}}$$

$$N = -\frac{\gamma+1}{2\gamma} = (-0.912)_{\gamma=1.2}$$

- Response factor of droplet vaporization has to compensate nozzle losses
- Maximum response factor according to Heidmann model *N*=0.8!.

Coupling of Acoustics and Combustion

Modeling

Conservation of

- mass $$\frac{\partial \rho'}{\partial t} + \overline{\rho} \nabla \cdot u' = 0$$
- momentum $$\overline{\rho} \frac{\partial u'}{\partial t} + \nabla \cdot p' = 0$$
- energy $$\rho c_P \frac{DT}{Dt} - \frac{Dp}{Dt} = \dot{q}$$
- species $$\rho \frac{DY_i}{Dt} = \omega_i$$

EOS $$\frac{\rho R T}{\left(\sum \frac{Y_i}{M_i} \right)^{-1}} = p$$

Linearization:

$$\frac{\partial^2 p'}{\partial t^2} - c^2 \nabla^2 p' = (\gamma - 1) \frac{\partial \dot{q}'}{\partial t}$$

Problem: Modeling of $\dot{q}'(t)$

- Different approaches to reduce complexity
  - linearize problem
  - neglect some coupling mechanisms
  - limit solution space
  - ….

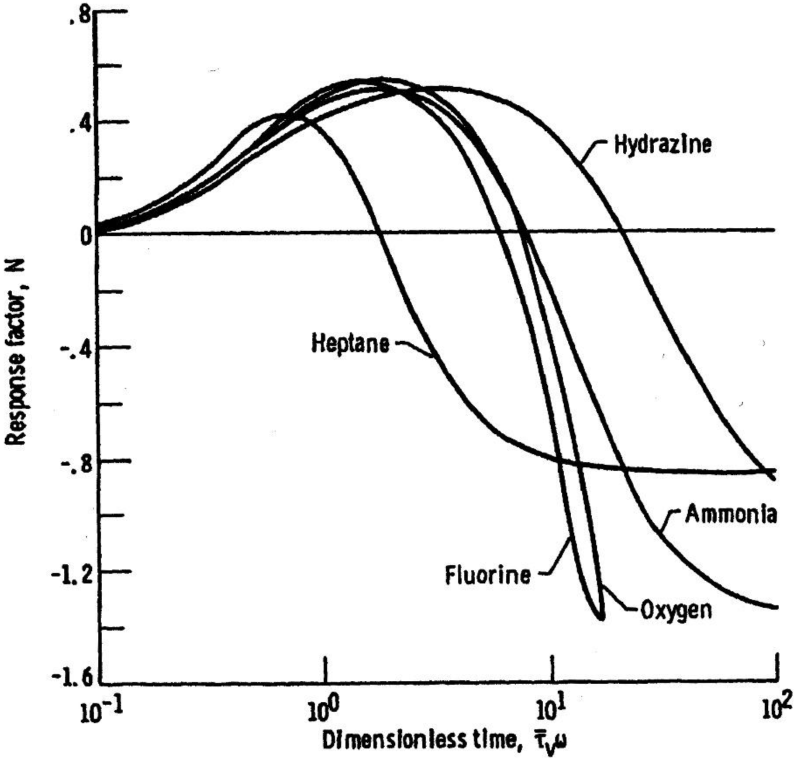
Combustion Instabilities

Coupling of Acoustics and Combustion

Response factor for a spinning T1-Mode

Heidmann et al.:

- Atomization not influenced by pressure and velocity fluctuations (Motivation: Vaporization is rate-limiting process)
- Vaporization model of Priem & Heidmann
- Investigation of single droplets and droplet ensembles
- Evaluation of results with response factor *N*



response factor *N*:

heat release rate *q‘* ~ vaporization rate *w‘*

$$N = \frac{\int_V \int_t q'(V,t)\,p'(V,t)\,dt\,dV}{\int_V \int_t \left[p'(V,t)\right]^2 dt\,dV}$$

Methods of Combustion Instability Suppression

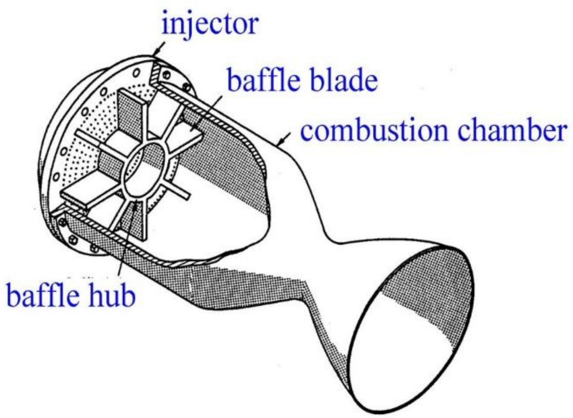
- Passive control by increasing acoustic losses in the combustion chamber:
  - baffles
  - acoustic cavities
  - injector acoustic tuning
- Passive control by the decrease of flame sensitivity on disturbances of inflow parameters:
  - more poor atomization and mixing of propellants
  - multi-stage combustion
- Active control of combustion instability
  - phase shift of secondary signal
  - changes in stationary parameters of propellant injection (O/F ratio, spray angle)
  - excitation of non-own frequency signal

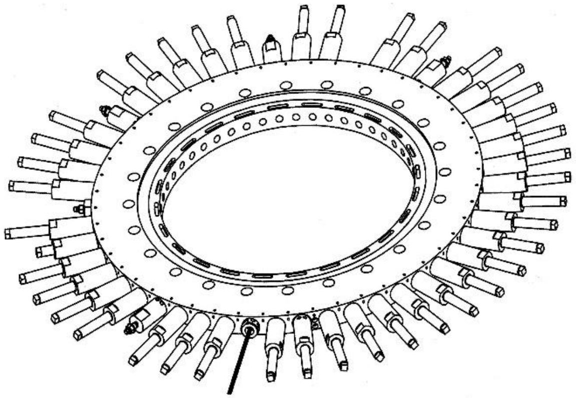
Methods of Combustion Instability Suppression

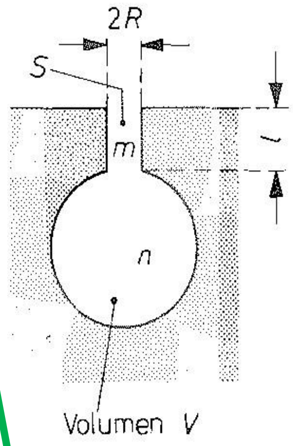
Baffles

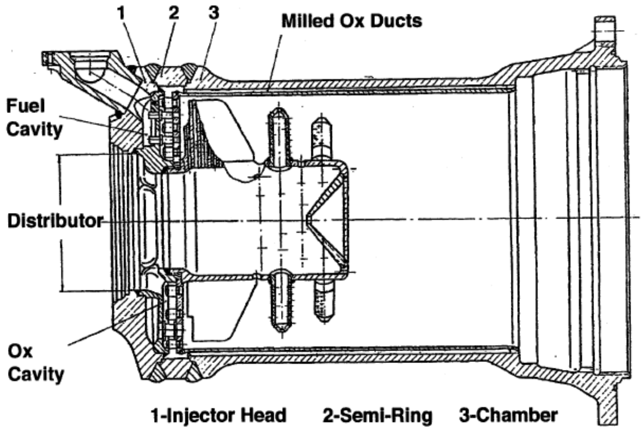
λ/4-Resonators

Helmholtz-Resonators

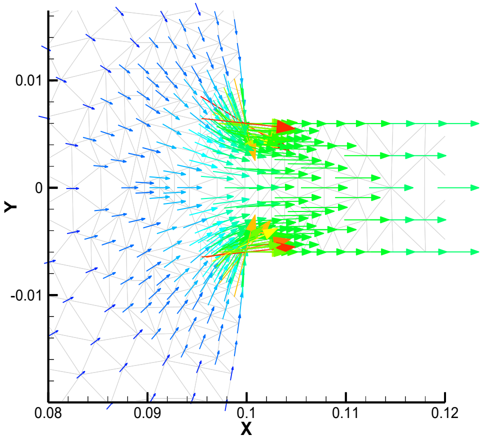


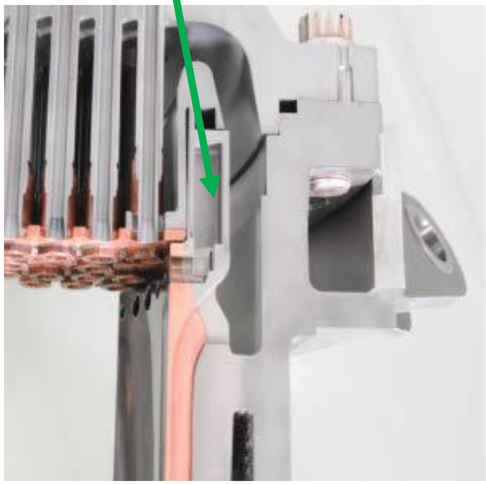






NK-33 preburner

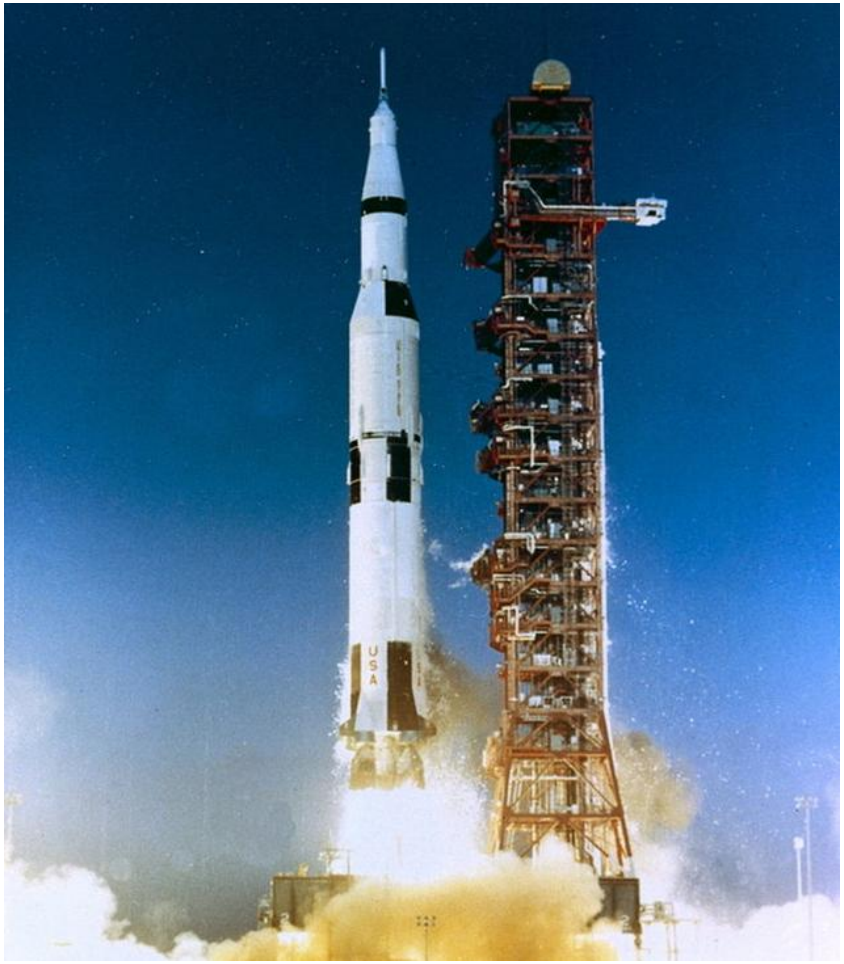




Vulcain 2 injector head

Combustion Instabilities

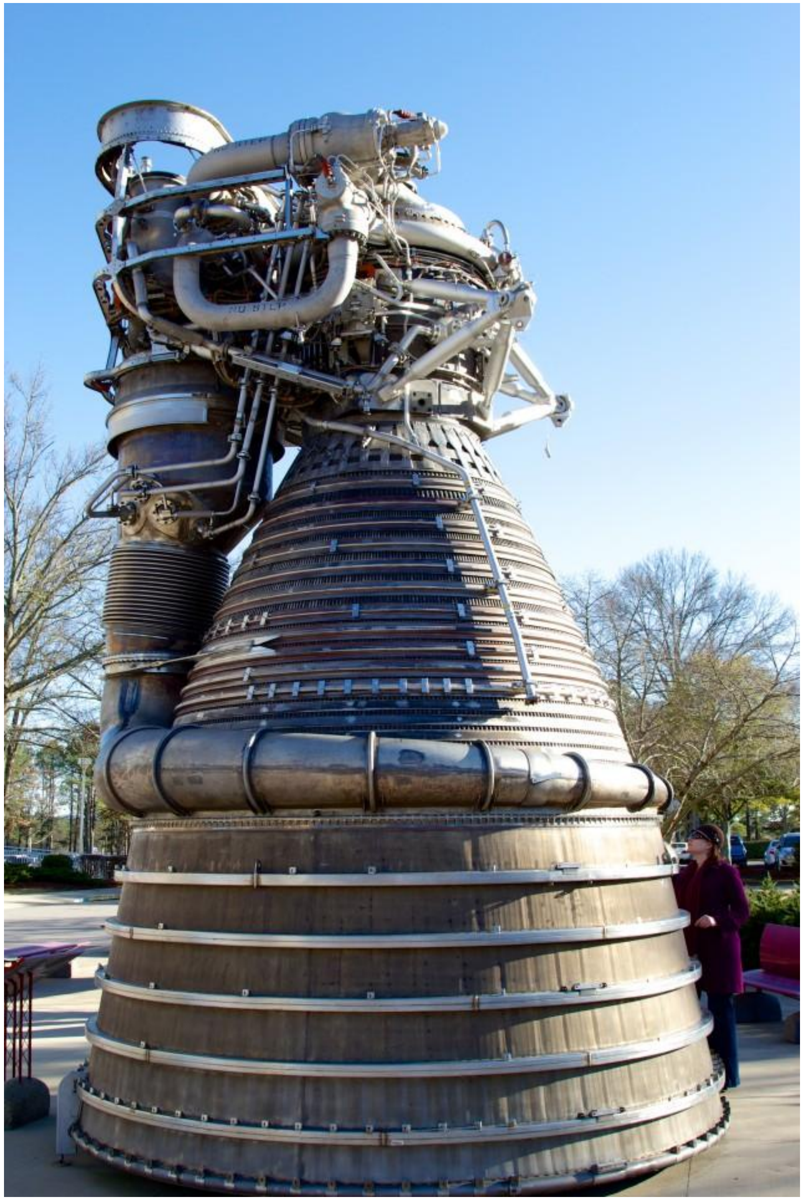
F-1 Engine Data



Saturn V launch

F-1 engine exhaust plume at launch; soot from turbine exhaust film cooling clearly visible as black curtain

Combustion Instabilities



Gas generator cycle engine with LOX / RP-1 operating at a chamber pressure of 70 bar and a mixture ratio of 2.27

•	Thrust	677 to (sl) 771 to (vac)
•	Isp	263 s (sl) 304 s (vac)
•	ε	16

Propellant mass flows rates:

- LOX = 1.79 t/s
- RP-1 = 0.79 t/s

Turbine exhaust inject at ε = 10 to cool the nozzle extension

Engine dry weight 8.4 t

Hypergolic assisted ignition (mixture of $B(C_2H_5)_3$ and $Al(C_2H_5)_3$ which reacts with oxygen

F-1 Development

Experienced combustion instabilities with engine failures in the period prior to 1962 led to special dedicated development program “First”

- Preliminary Flight Rating Tests (PFRT), October 1962 – June 1963
  207 full-scale tests with 11 injectors
- Flight Rating Tests (FRT), June 1963 – January 1965
  422 full-scale tests with 46 injectors
- Flight Qualification Tests (FQT), January 1965 – September 1966
  703 full-scale tests with 51 injectors

→ extremely large number of full scale engine tests (1332) performed at four different test facilities, Santa Susana (Rocketdyne), Marshall Space Flight Center (NASA), Stennis Space Center (NASA), Edwards AFB (Air Force)

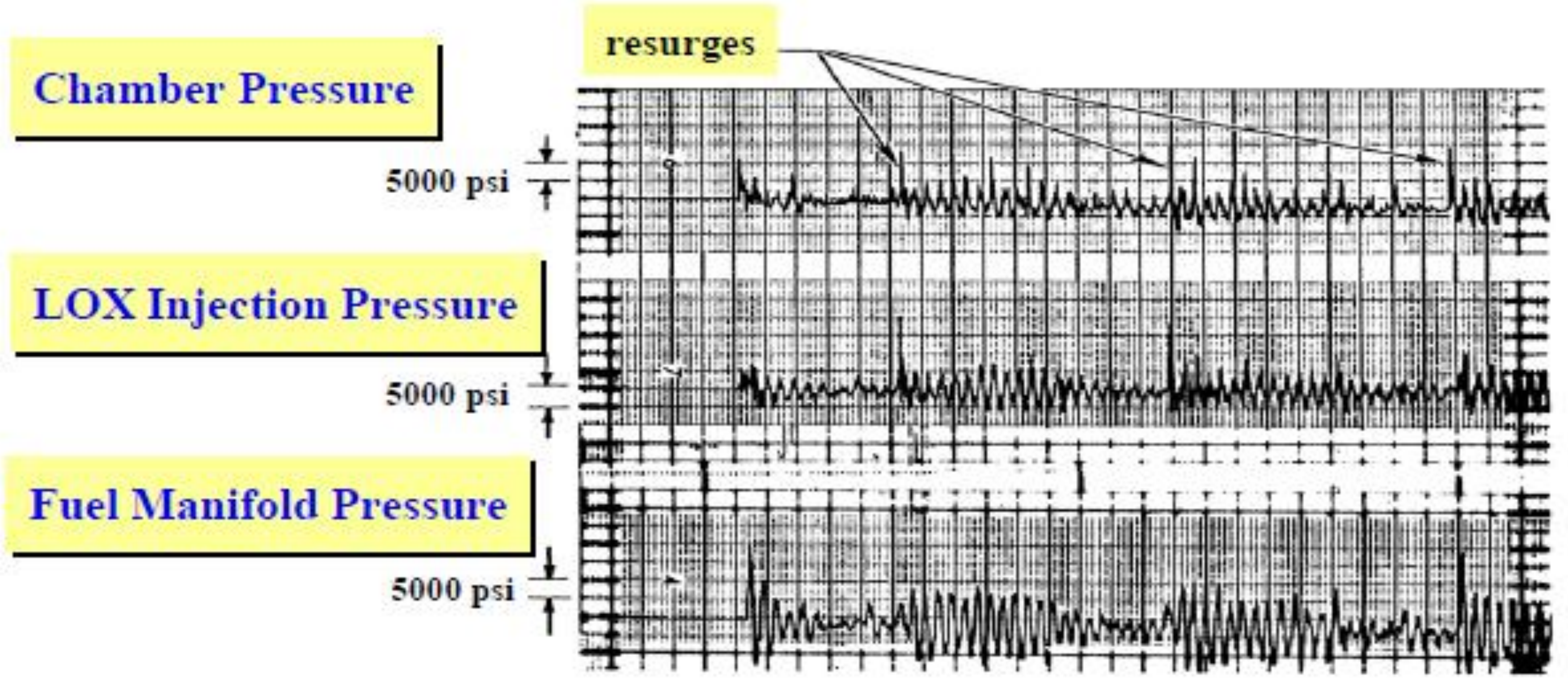
→ Significant number (1337) of components tests with more than 100 injectors and injector configurations.

F-1 PFRT Phase (1962-1963)

- All configurations exhibited spontaneous instabilities which persisted until cutoff of the propellant flow.
- Observed pressure peaks exceeded the average combustion chamber pressure by far.
- First tangential spinning mode was principal oscillation encountered.
- Baffled injectors exhibited oscillations with frequencies of 200 to 500 Hz with amplitudes approaching 100 percent of mean chamber pressure.
- Flat-face injectors exhibited oscillations with frequencies of 500 to 700 Hz with amplitudes always much higher than those observed for baffled injectors.
- In considering 5U baffled versus flat-face injector, a tradeoff clearly existed between engine reliability and incidence of self-triggering.

Combustion Instabilities

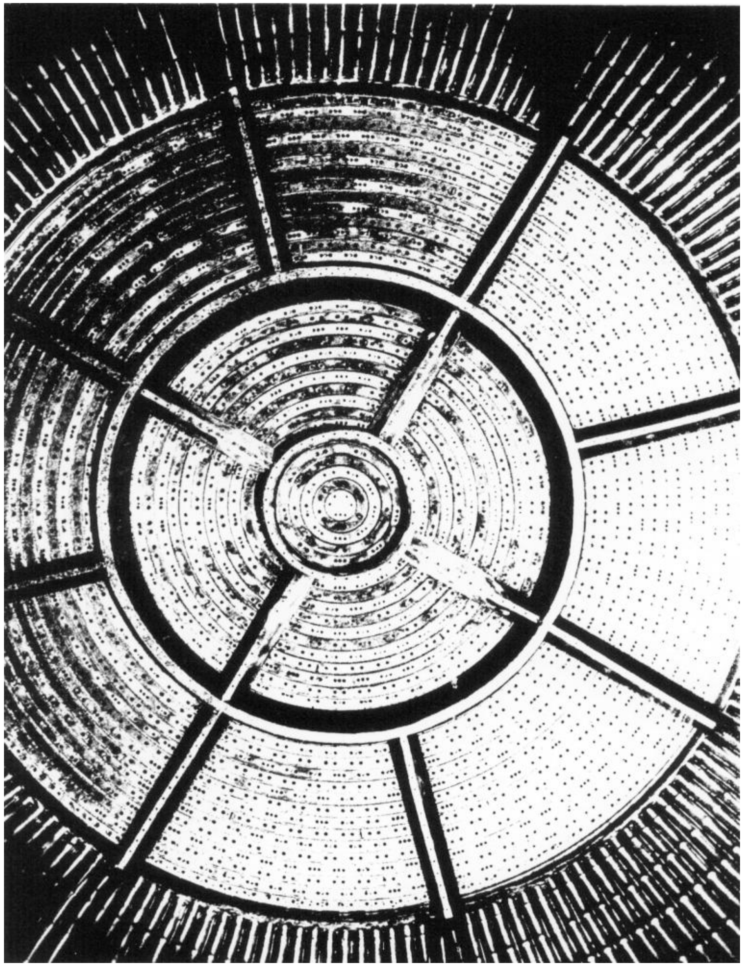
F-1 Extremely High Pressure Peaks

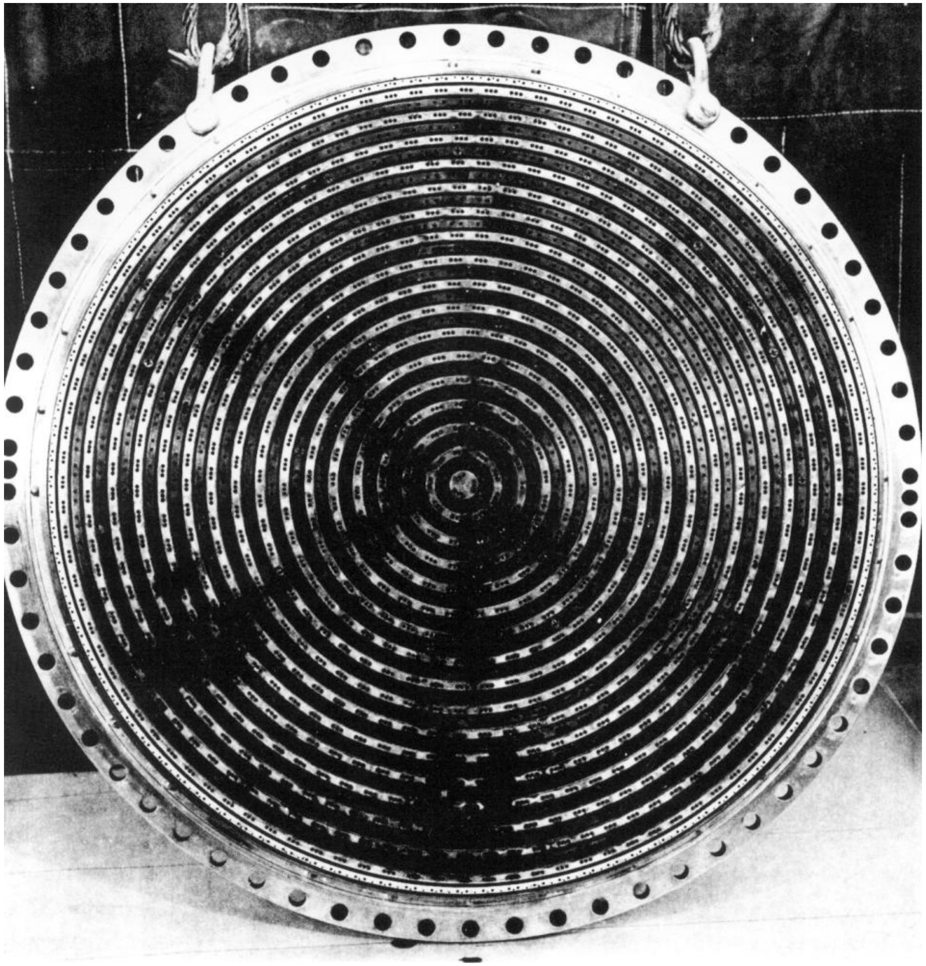


*Note that 5000 psi ~ 345 bar

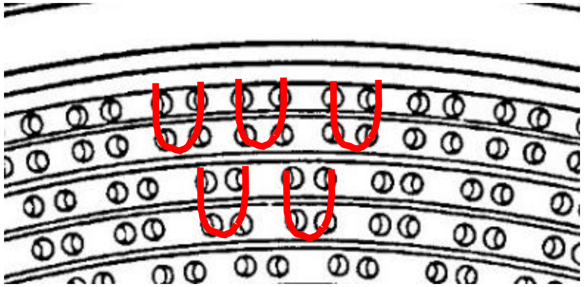
Combustion Instabilities

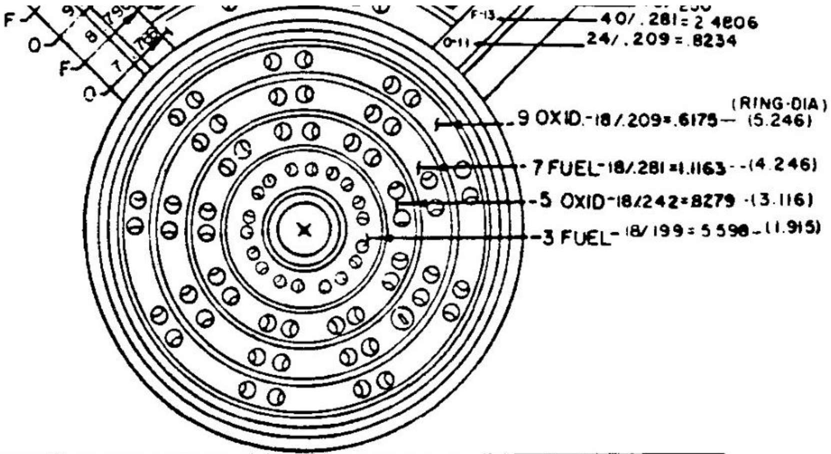
F-1: 5U Baffled ("Baseline") and Flat-Face Injectors





F-1 Injector (5U) Head Details

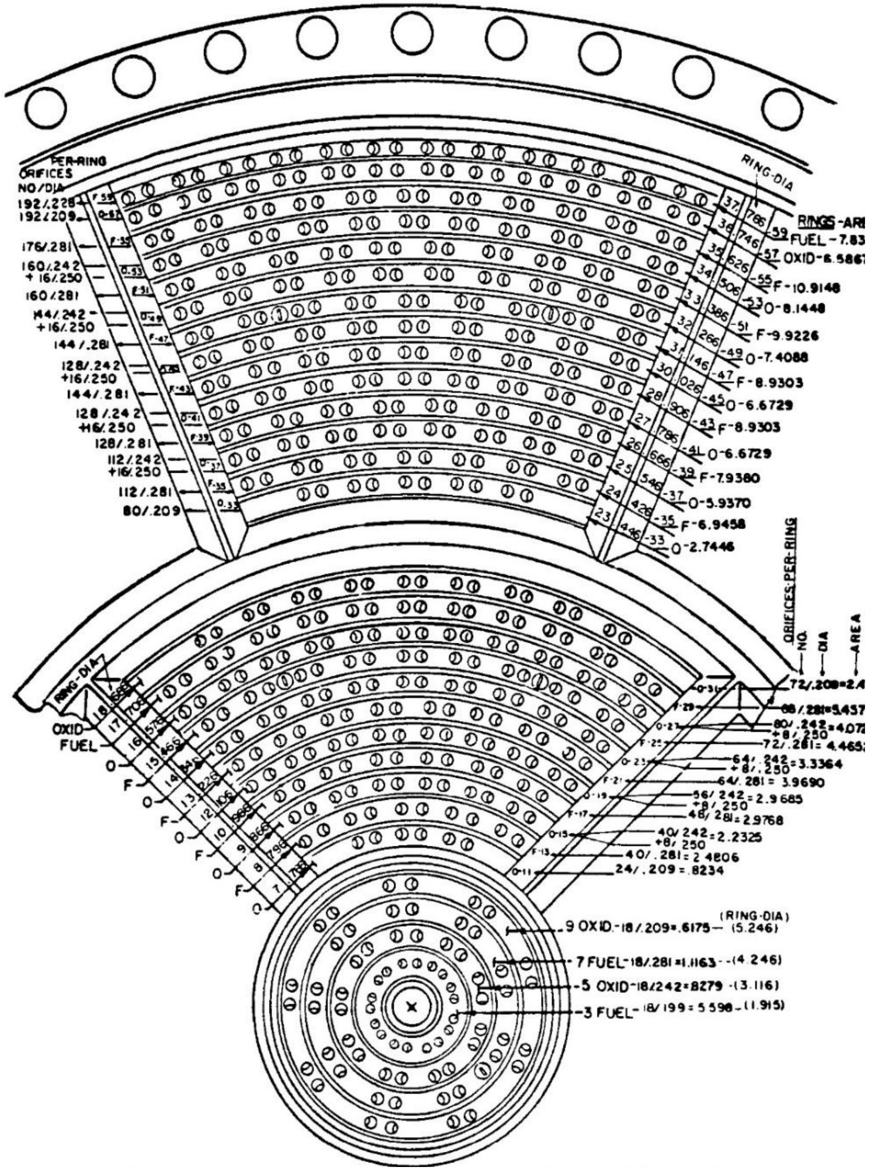




PATTERN GENERAL	FUEL	OXIDIZER
Orifice Area, cm²	548.4	396.8
Ring Groove Depth, cm	1.367	1.367
Wall Gap (Fuel Ring)	1.778	-
Injection Velocity, m/s	17.07	40.54
Wall Coolant, %	3.2	-
Flow to the -59 Ring, %	70	-
Baffle Coolant Area, cm²	15.23	-

Notes:

- Oxidizer doublets next to radial baffles are canted 28.2°/20.0°, and overlapped 6.325/6.147 mm diameter, respectively.
- Axial feed holes to -9, -15, -19, -23, -27, -31 oxidizer rings are restricted.



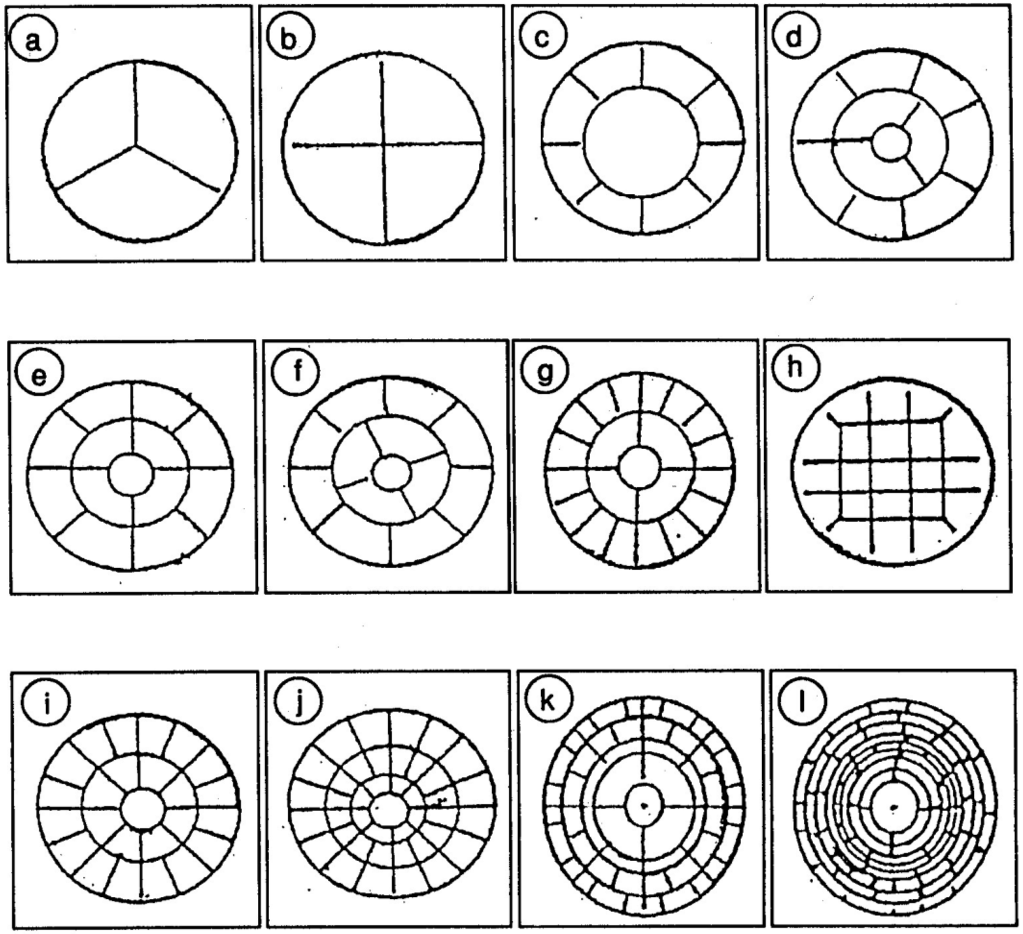
Combustion Instabilities

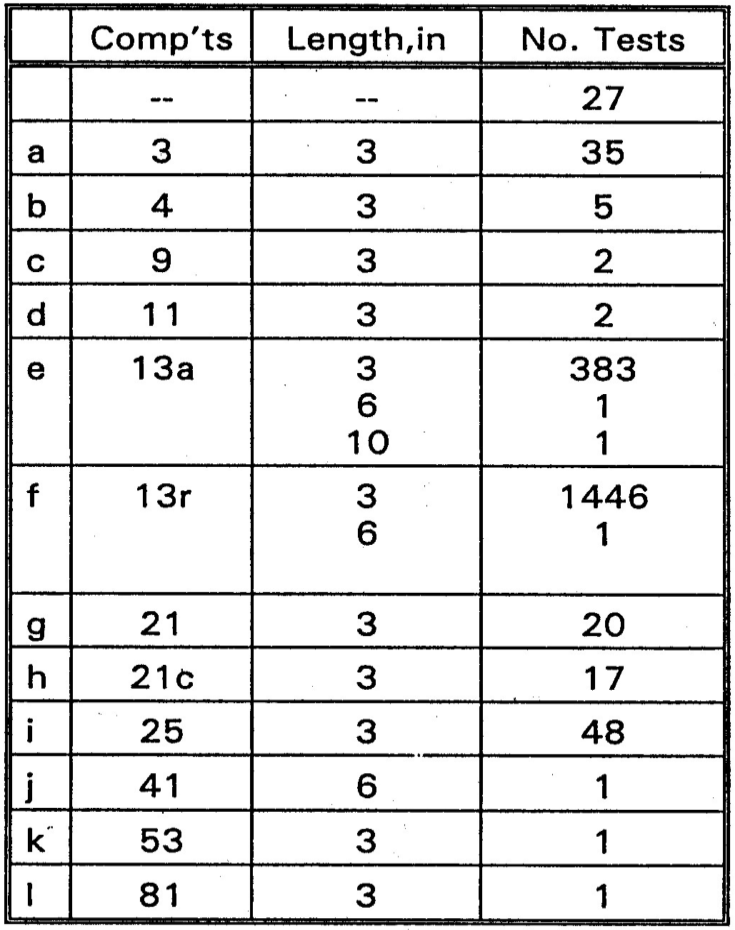
F-1 Program "First" Injection Head Studies

Injector pattern	Baffle configuration			Injection element		
	(a)	(b)	(c)	Fuel	Oxidizer	No. Tests
Modfied 5 U	-	-	-	Doublet	Doublet	4
	b	4	7.62	Doublet	Doublet	5
	c	9	7.62	Doublet	Doublet	2
	e	13	7.62	Doublet	Doublet	20
	f	13	7.62	Doublet	Doublet	1307
	f	13	15.2	Doublet	Doublet	1
	g	21	7.62	Doublet	Doublet	4
	k	53	7.62	Doublet	Doublet	1
5U	-	-	-	Doublet	Triplet	19
	a	3	7.62	Doublet	Triplet	35
	e	13	7.62	Doublet	Triplet	350
	e	13	15.2	Doublet	Triplet	1
	e	13	25.4	Doublet	Triplet	1
	f	13	7.62	Doublet	Triplet	101
Radially aligned	f	13	7.62	Doublet	Doublet	19
	g	21	7.62	Doublet	Doublet	1
	i	25	7.62	Doublet	Doublet	22
	i	25	7.62	Doublet	Triplet	7
Double-row cluster	e	13	7.62	Doublet	Triplet	5
	e	13	7.62	Shower-head	Triplet	2
Single fuel, double LOX	e	13	7.62	Doublet	Triplet	4
H-1	f	13	7.62	Shower-head	Triplet	4
Reverse 5U	e	13	7.62	Doublet	Triplet	2
Rotated fan	d	11	7.62	Doublet	Doublet	2
Spray nozzle	f	13	7.62	Nozzle	Nozzle	2
Double fuel, single LOX	f	13	7.62	Doublet	Doublet	13
	l	81	7.62	Doublet	Triplet	1
Splash ring	-	-	-	Shower-head	Triplet	2
Shielded stream	-	-	-	Doublet	Triplet	1
O-F-O Triplet	-	-	-	-	-	1
Coaxial	h	21	7.62	-	-	17

(a) baffle pattern,
(b) number of baffle compartments
(c) baffle length (cm)

F-1 Program “First” Injection Head Baffle Studies





	Comp’ts	Length,in	No. Tests
	--	--	27
a	3	3	35
b	4	3	5
c	9	3	2
d	11	3	2
e	13a	3 6 10	383 1 1
f	13r	3 6	1446 1
g	21	3	20
h	21c	3	17
i	25	3	48
j	41	6	1
k	53	3	1
l	81	3	1

F-1 Propellant Injection System

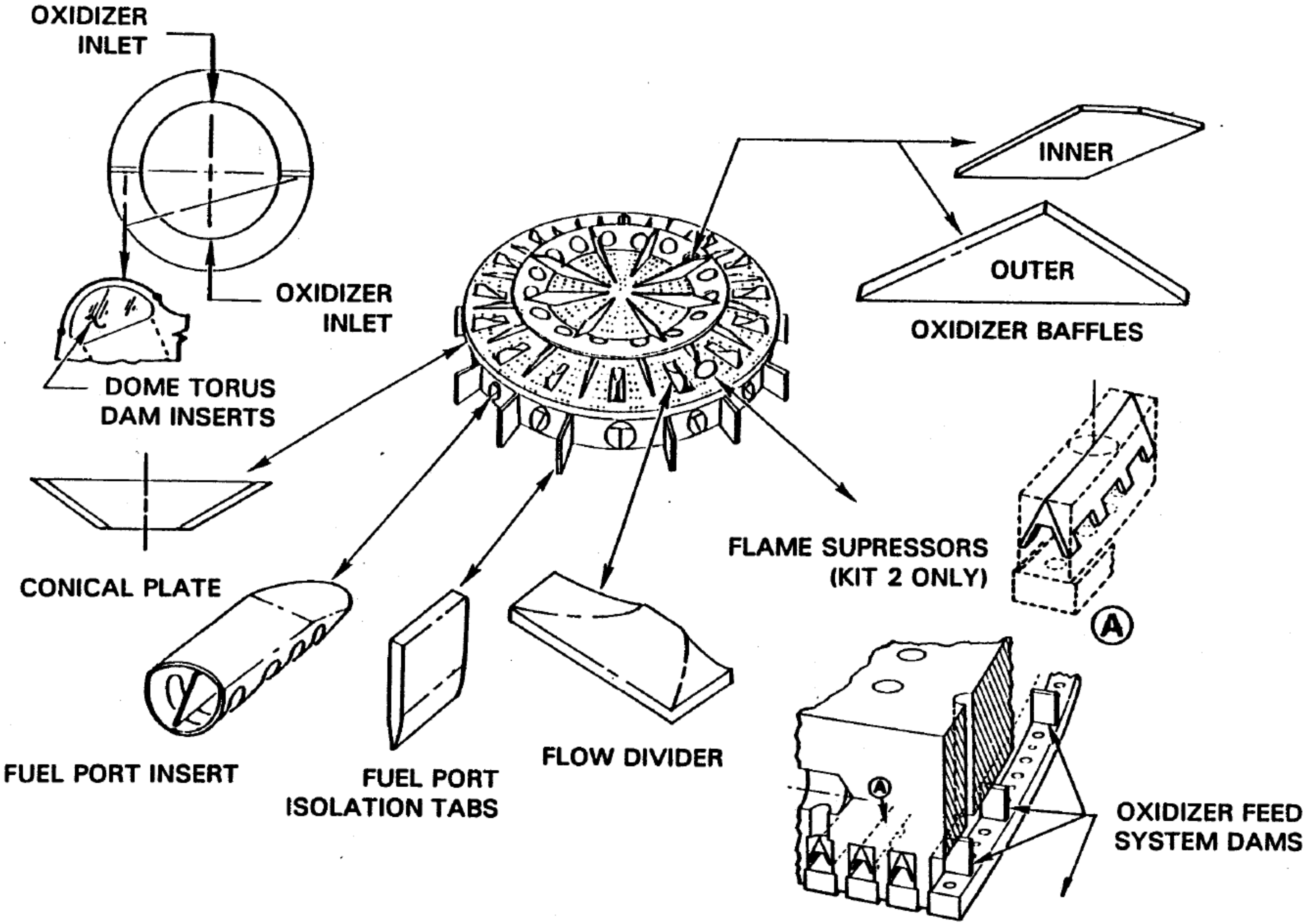
Objectives were to eliminate self-triggering of instabilities and achieve a tendency towards dynamic stability.

Principal design modifications:

- ❑ Hydraulic modifications to the injector body.
    - ○ Minimized oscillation amplitudes
    - ○ Eliminated low frequency acoustic paths
    - ○ Reduced occurrence of self-triggering
- ❑ Consideration of propellant spray displacement sensitivity by way of fuel element orifice modification.
    - ○ Promoted dynamic stability characteristics
    - ○ Produced decrease in performance
    - ○ Induced resurging phenomenon

Combustion Instabilities

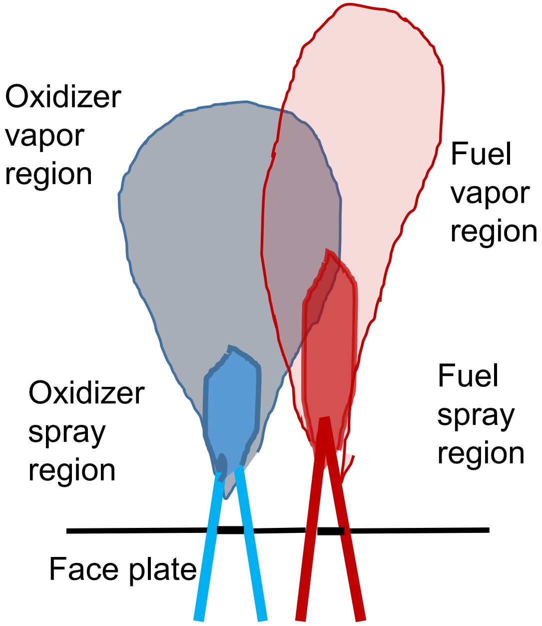
F-1 Modifications of Hydraulics of Injection System



F-1 Displacement Sensitivity Studies of Injection System

LOX will more readily vaporize than RP-1 which generates spray fans with different axial extension lengths

- Flow from O-F: Even for moderate velocities, oxidizer vapor will be blown to a region of high fuel droplet densities with a steep increase of the local heat release. However, too high velocities will blow the oxidizer vapor away from the fuel limiting heat release.
- Flow from F-O: Even for moderate velocities the oxidizer vapor is blown away from fuel yielding a steep decrease of local heat release but may increase the reaction rate with neighboring injector further downstream.



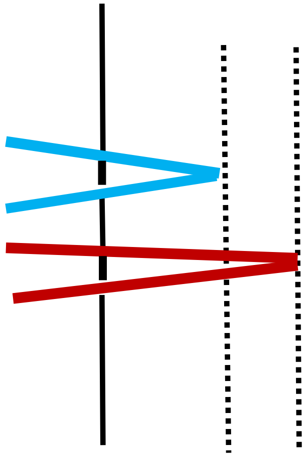
Final Findings

- Displacement sensitivity effects showed up when combustion zone was relatively close to injector face
- Sensitivity diminished as combustion zone was moved downstream by increase of fuel injector diameter and resulting larger fuel droplets.
- However, this measure provided proper conditions for a spinning mode instability.

Combustion Instabilities

F-1 Injector Bi-planar L-O-L Impinging Elements

Injector Modifications

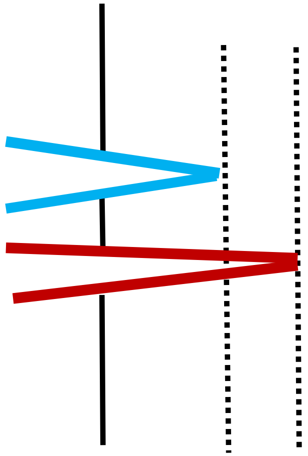


- Doubling of fuel injector diameter led to a decrease of RP-1 injection velocity and a reduced sensitive towards manufacturing precision
- Decreased RP-1 doublet impingement angle from 20° to 15 ° led to fuel spray fan generation downstream of LOX spray fan; oxygen will be readily available for combustion, no agglomeration of fuel
- Changed LOX triplets to doublets led to an increased oxygen velocity without change in LOX injection velocity led to a larger jet interaction area and a reduced sensitivity towards manufacturing precision
- Increased LOX doublet impingement angle from 20° to 28 ° generation of spray fan in the vicinity of face plate and oxygen-rich vapor in this region

Overall net effect: significant improvement of the damping characteristics

F-1 Injector Bi-planar L-O-L Impinging Elements

Injector Modifications



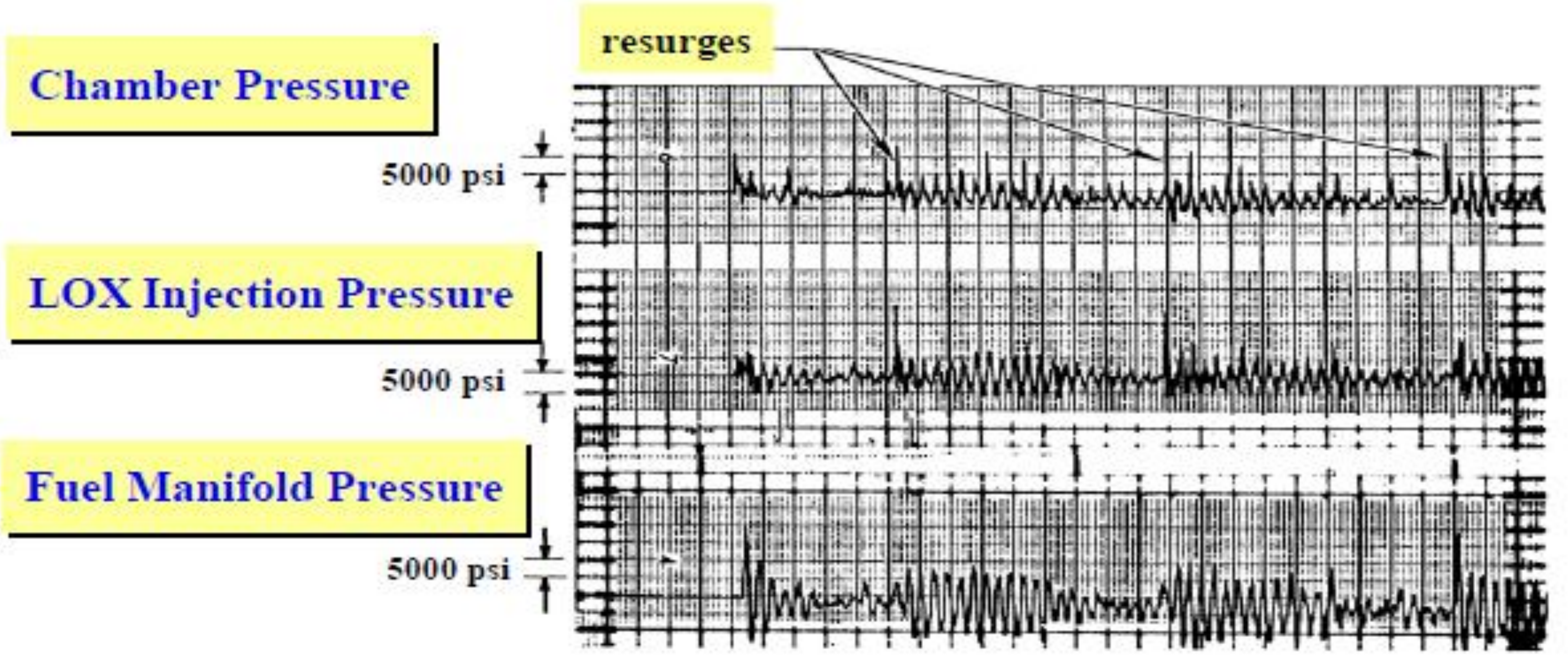
- Increasing of LOX injection velocity led to
  - Improved atomization with smaller drop size distribution and faster vaporization
  - Negative impact on performance since combustion zone was shifted downstream
- Simultaneous increase in LOX injector diameter and impingement angle yielded an improved performance
- However, a 500 Hz “buzz” limit cycle phenomenon appeared

Overall net effect: improvement of performance but 500 Hz buzzing

Combustion Instabilities

F-1 Resurge Phenomenon

Experimental evidence that resurges are result of spontaneous reactions of RP-1 which is sheared off in large junks (Klystron effect) from the chamber wall cooling film and entrained into the main reacting flow.

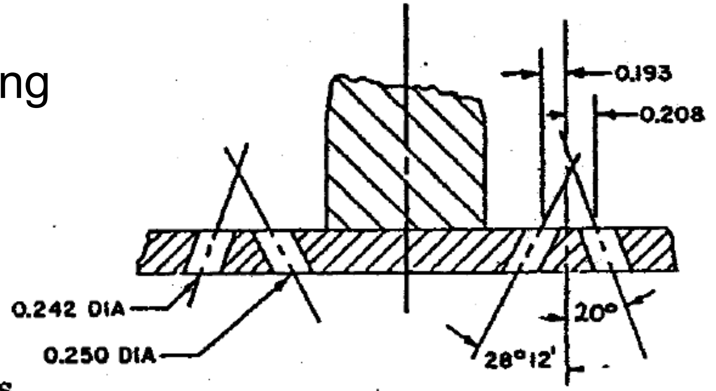


Reduction of film mass flow from 10.9% to 3.2 5 yielded a significant reduction of the number of incidents of this phenomenon

F-1: “Near Wall” Injection Element Modifications

Distortion of spray fans of injection elements adjacent to the baffle walls provided conditions favorable for the establishment of high amplitude pressure waves.

- Degree of reaction minimized by overlapping and canting of LOX fans through unequal diameter impinging orifices (increased wall side impingement angle)
- Modification consistently produced improved damping characteristics
- Single factor responsible for excellent damping characteristics of FRT injector.

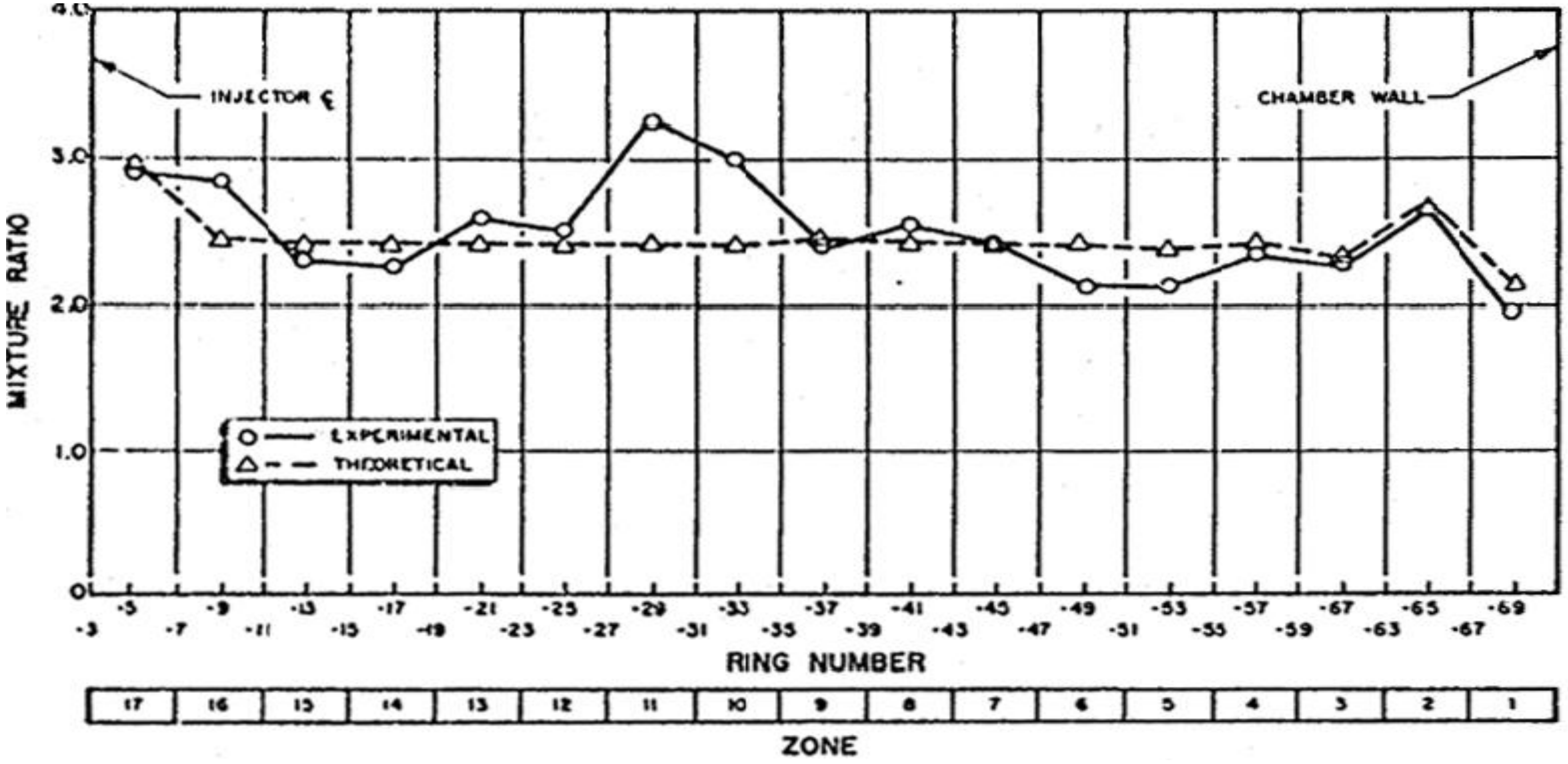


ORIFICE DIAMETERS
OUTER FUEL RING - 0.228 DIA.
REMAINING FUEL RINGS - 0.281 DIA.
OUTER LOX RINGS AND LOX RINGS
ADJACENT TO CANS - 0.209 DIA.
REMAINING LOX RINGS - 0.242 DIA.

SECTION A-A
TYPICAL FOR LOX DOUBLETS ADJACENT TO RADIAL BAFFLES EXCEPT OUTER LOX RING AND LOX RINGS ADJACENT TO BAFFLE CANS

F-1 Injection System

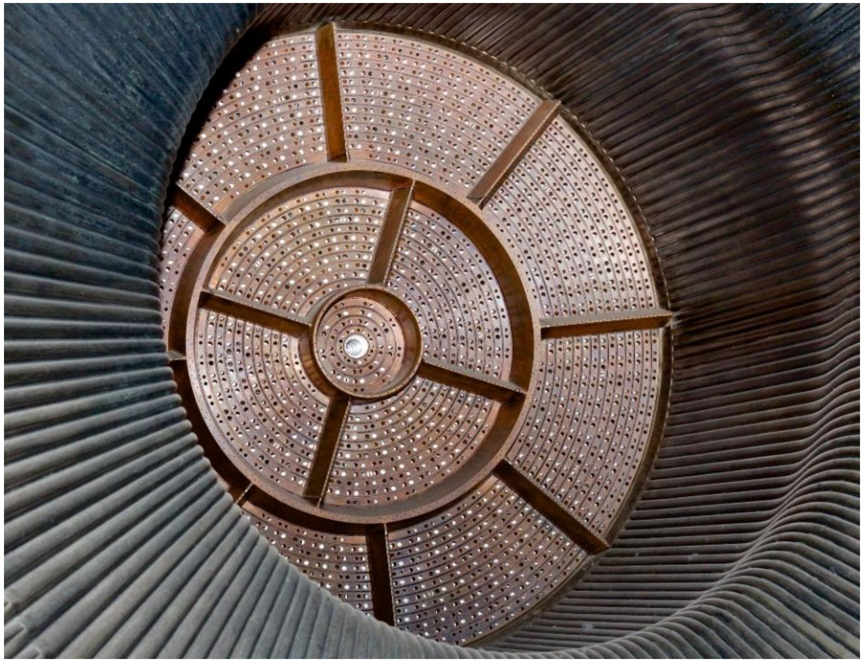
- Principal design modifications:
  - Evaluation of injection element conditions in vicinity of highly confined regions.
  - Improvement of mixture-ratio distribution across the injector face.
  - Consideration of the 500 Hz buzzing phenomenon.



Combustion Instabilities

F-1 Injectors: Initial and Final Configurations

Parameters	d_{RP1} mm	ΔP_{RP1} Bar	V_{RP1} m/s	d_{LOX} mm	ΔP_{LOX} Bar	V_{LOX} m/s	f Hz	Af/P %	Effici-ency %
Initial	3.66	24.5	51	4.04	24.5	46.2	538	400-65	93.194
Final	7.12	6.41	17.1	6.14	21.0	40.5	454	-	92.9



Final F-1 injector pattern and baffle arrangement

F-1 Program “First” Final Results and Conclusion

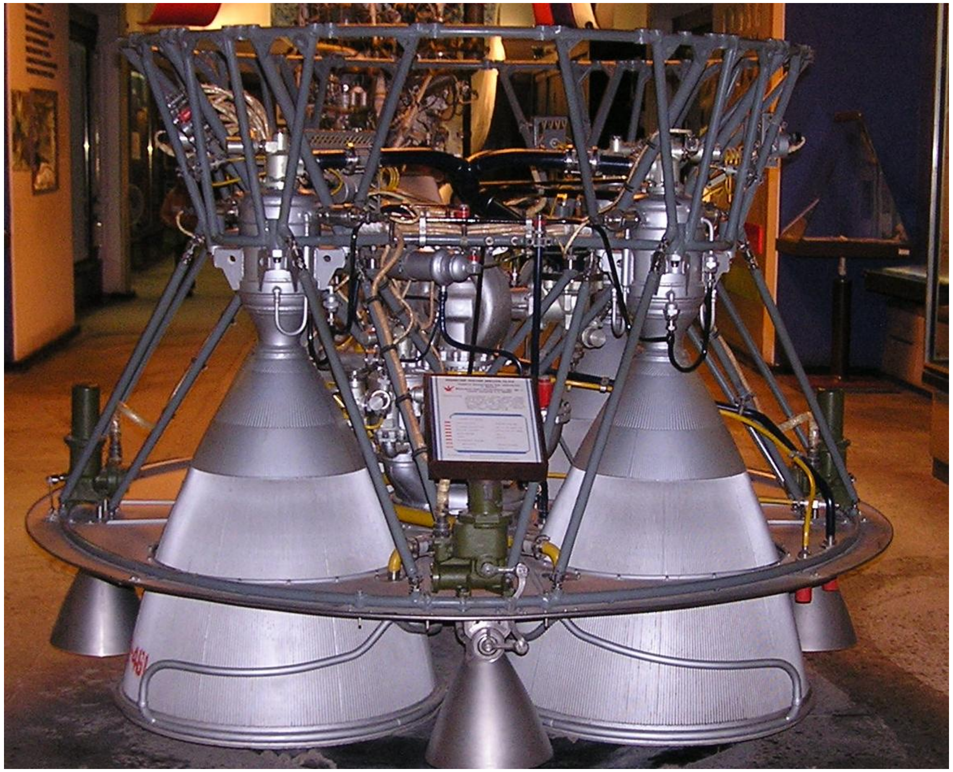
- Injector diameters play an important role in determining droplet spray fan characteristics:
  - Large diameters cause concentration of propellant in center of spray causing longitudinal spreading.
  - Small diameters generate smaller droplets that provide more concentrated area of energy release close to injector face.
- Injection velocities and impingement angles appear to be the controlling factor in the downstream regions:
  - Axial oxidizer velocity component affects performance,
  - Circumferential oxidizer velocity component affects stability.
- Method of injection near confining surfaces yields marked effects on stability characteristics.
- Local mixture ratio in regions of high confinement requires careful consideration to prevent wave amplification.

F-1 Program “First” Final Results and Conclusion

Considerable evidence suggests that three distinct regions exist in the combustion chamber:

- “Spray fan” region near injector face:
  - displacement of impinging fuel and oxidizer jets provide conditions for maintenance of 1T spinning mode,
  - sensitivity is minimized if combustion zone is moved downstream to point where oxidizer vapor concentration is uniform.
- RP-1 droplet vaporization (8-10 inches away from injector face)
  - Supercritical vaporization and droplet breakup by shear forces (LOX is essentially vaporized within the first 3-inches),
  - Fuel-lean/uniform-LOX environment promotes stability.
- 8-10 inch region
  - Axial striations of RP-1 LOX vapor exists which produce mixture ratio gradients.

RD-0110 Engine



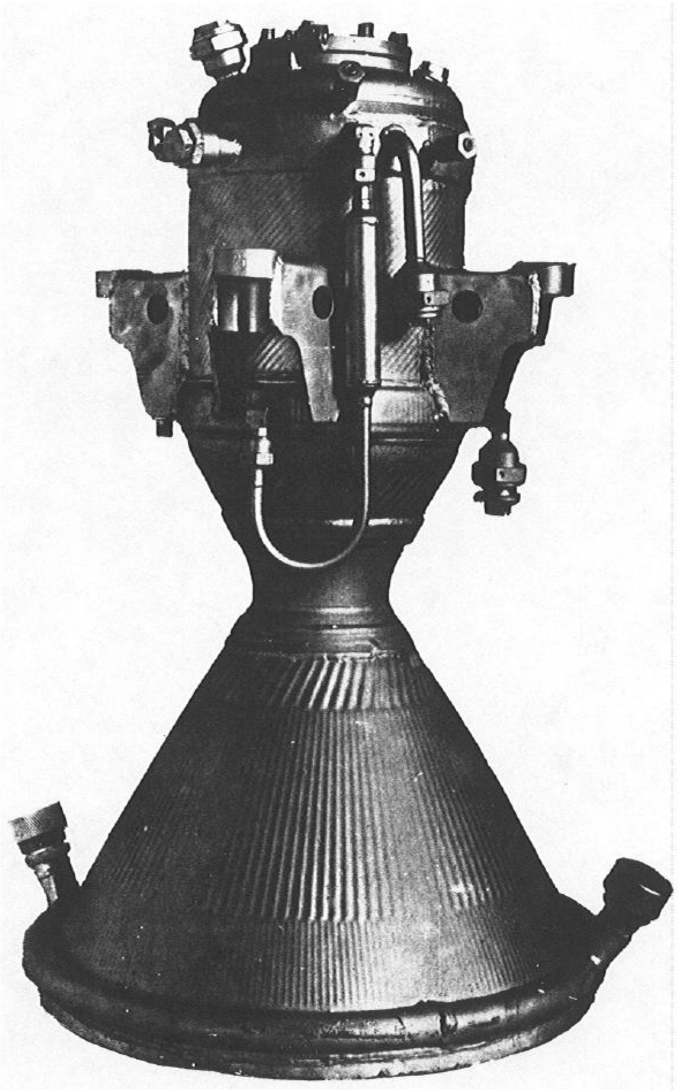
Gas generator cycle engine (4 chambers) design by CADB Voronezh running LOX / RG-1 operating at a chamber pressure of 70 bar and a mixture ratio of 2.2

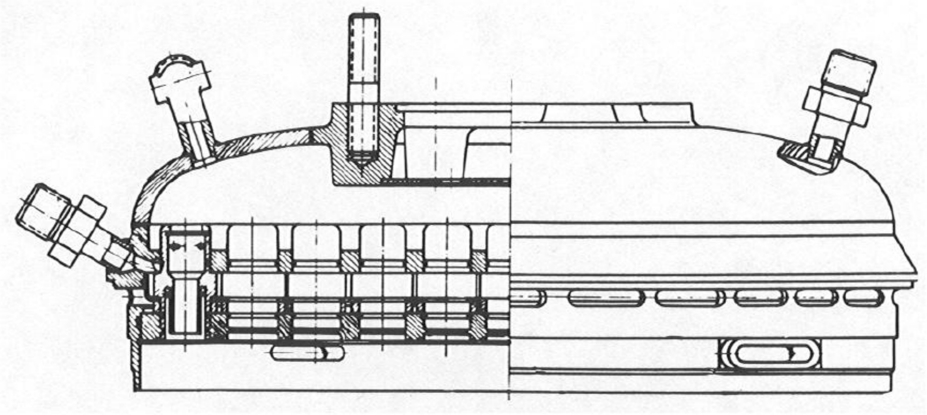
Thrust	30.4 to (vac)
Isp	326 s (vac)
ε	82

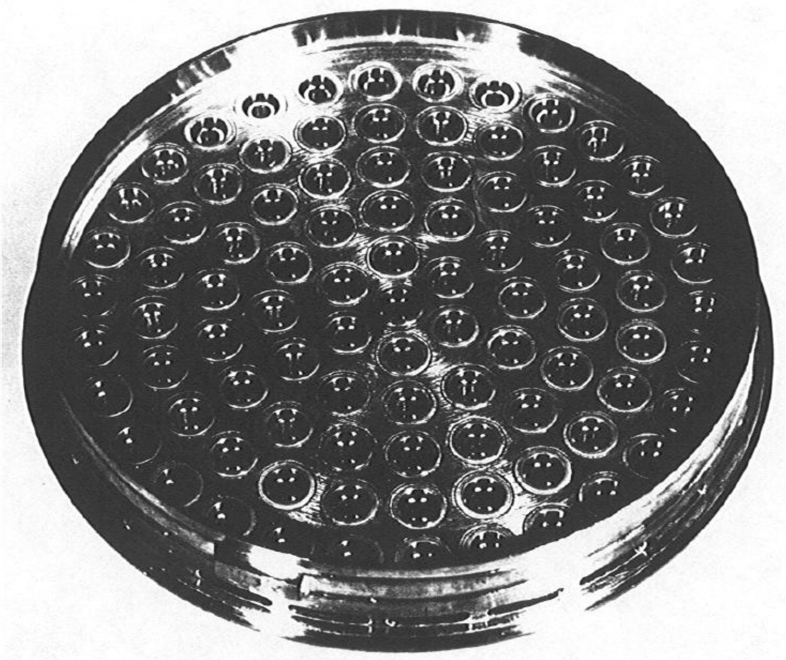
Engine derived from previous RD-0107/RD-108 for the Molniya-M Block and during development showed occasional combustion instabilities

Combustion Instabilities

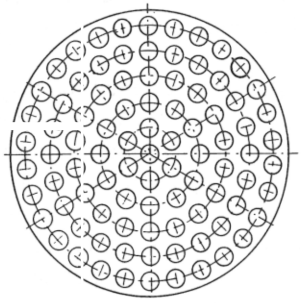
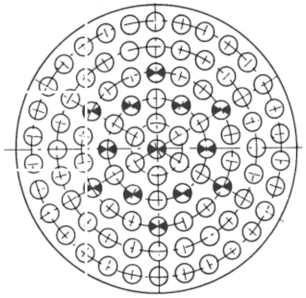
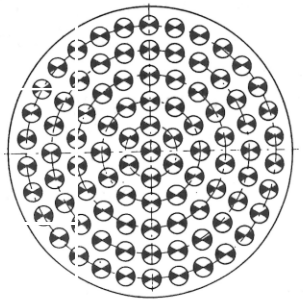
RD-0110 Engine







RD-0110 Injection System Investigations

Injector Index	**Injector Type**	**# of Injectors**	
C1, C2, C3, C4, C5	Swirl	91	
CS1	Swirl Quadruplet (3 on 1)	78 13	
S1	Quadruplet (3 on 1)	91	

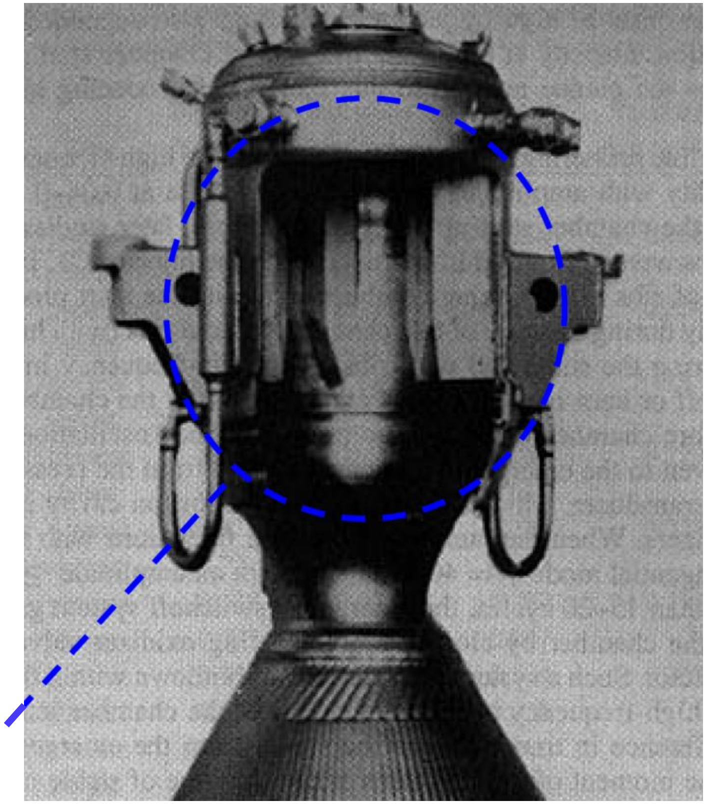
C1-C5 have different recess *L* and positions inside chamber (periphery / center ;(L_p / L_c) center).

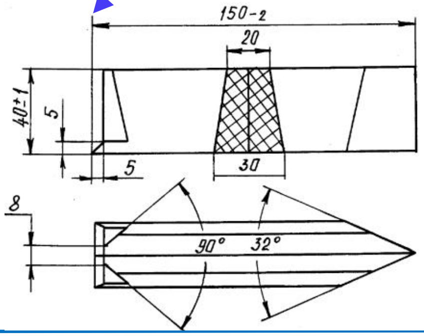
	L_P (mm)	**L_C (mm)**
C1	5.0	5.0
C2	2.5	2.5
C3	1.5	1.5
C4	5.0	1.5
C5	2.5	1.5

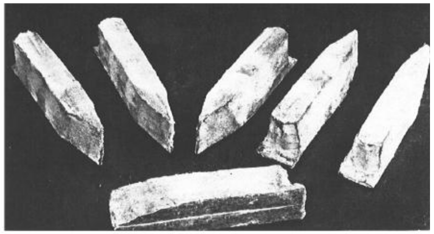
Only C3 and C5 were stable with C5 having superior performance. However, very rarely instabilities showed during transient start-up.

RD-0110 Injection System Investigation

- Combustion instabilities were all but totally eliminated with the properly designed C5 injector.
- Combustion instability occurred in 1-out-of-4 thrust chambers in every 70 to 80 engines or once in every 280 to 320 thrust chambers:
  - Damage occurred during 4000 Hz, 1T-mode instability,
  - Occurrence during start-up,
  - Investigations failed to discover a cause for the rare combustion instability,
- Combustion instability eliminated by installing baffle-like, soft-material ribs that burned away during start-up.





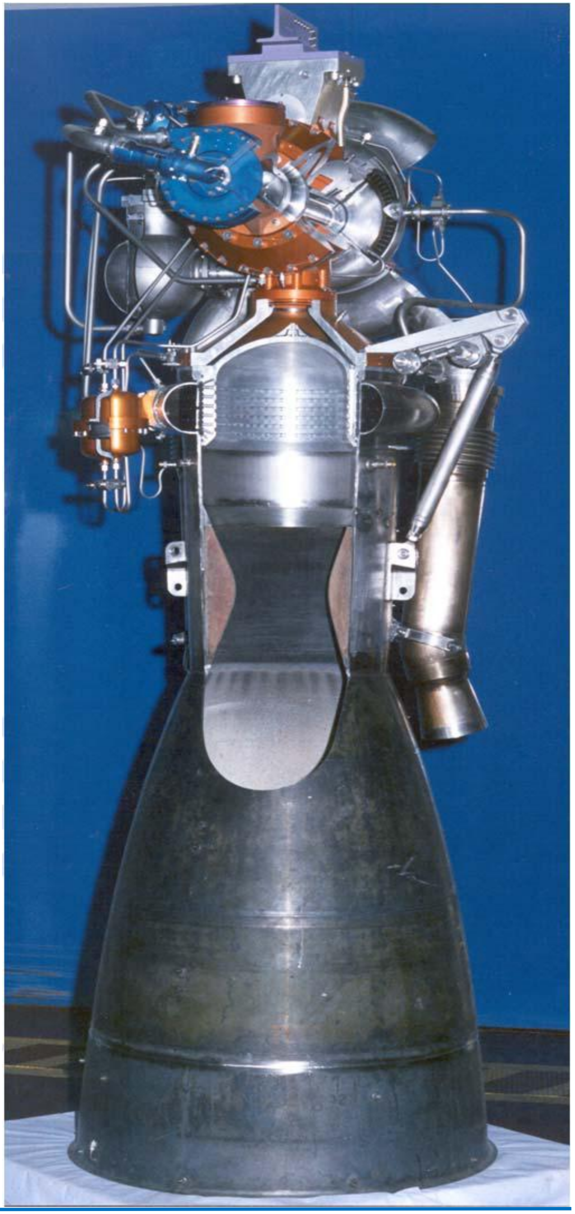


Combustion Instabilities

Viking engine failure

L02 Inquiry Results

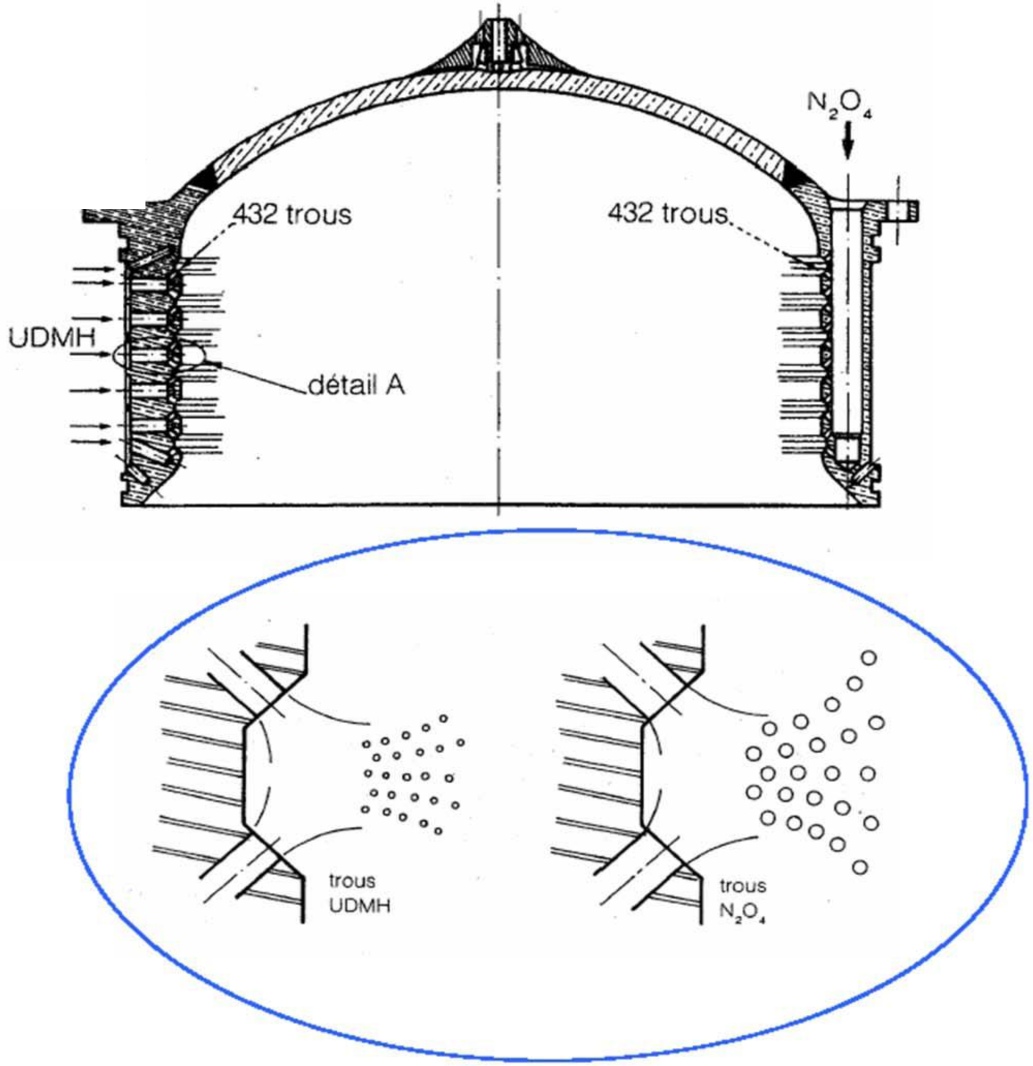
- The Viking injector, mounted in the chamber, can be unstable, with oscillations frequencies of 2.3 kHz and 2.7 kHz.
- Before L02, one instability case was encountered during one test only, but that was considered as a specific one due to special testing conditions.
- A considerable number of combustion instabilities have been met during ground tests after the L02 event.



Viking engine failure

L02 Inquiry Results

- The combustion instability within Viking was due to a dispersion of the vaporization zone of propellants, resulting from loose fabrication tolerances of the injector.



Détail A

Combustion Instabilities

Viking engine failure

L02 Inquiry Results

For L02 this instability has been very important during 0.3s, leading to:

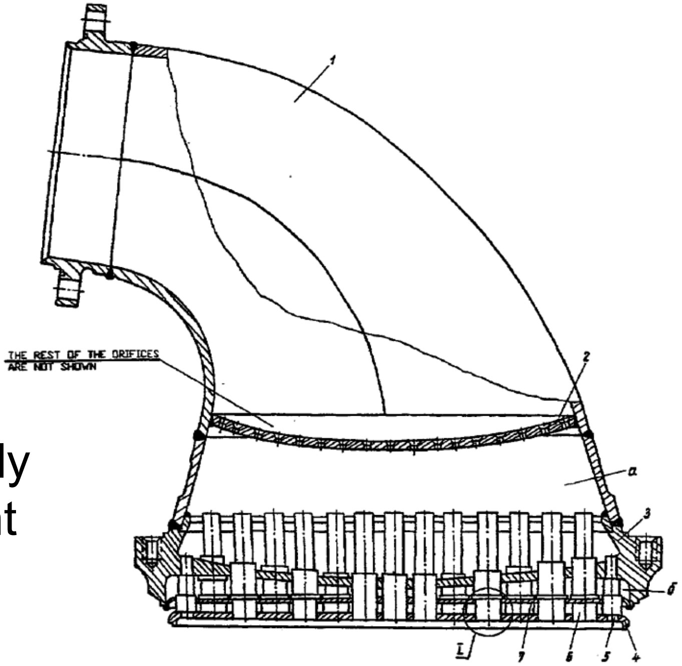
- An erosion of the injector bottom part (N2O4);
- A destruction of the UDMH coolant film cooling
- A wall temperature increase and a destruction of the nozzle extension

Combustion Instabilities

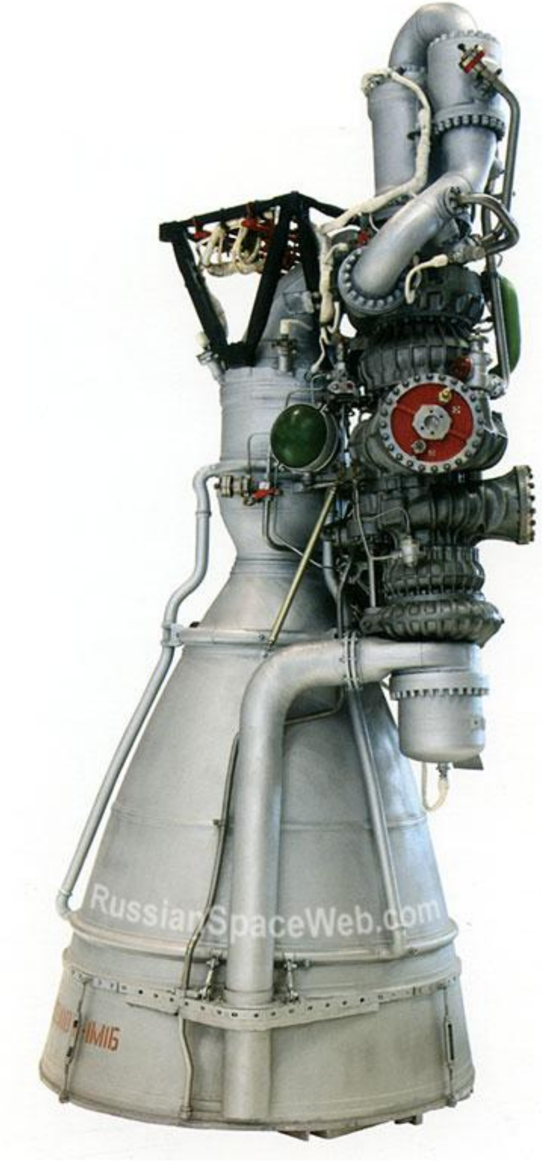
NK-33 LOX/Kerosene Engine
Injector Face Place

Injector Technology

- 183 gas-liquid coax elements without swirl
- Regenerative cooled face plate
- No baffles, no resonators



Example of an extremely well designed propellant injection system



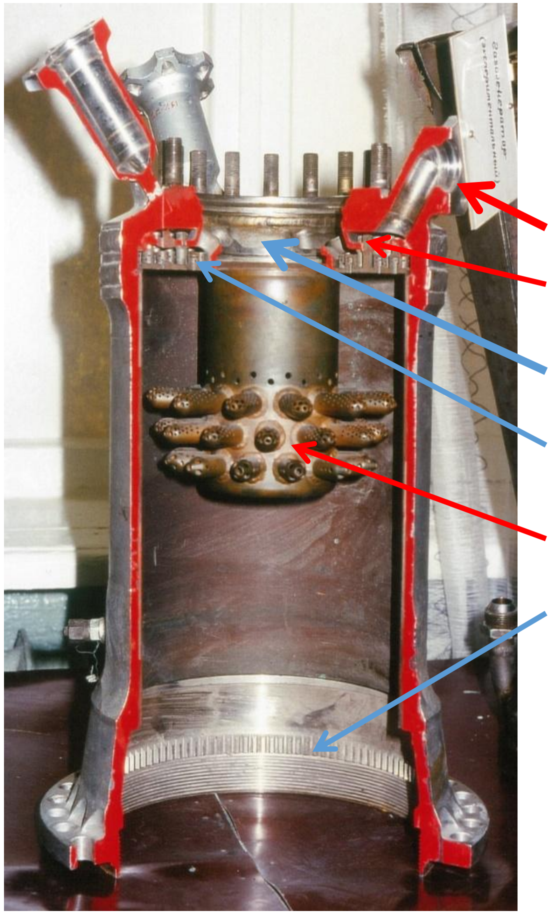
Combustion Instabilities

NK-33 Pre-burner Characteristics

Operating Conditions

- pressure: 320 bar
- temperature: 630 K
- mixture ratio: 58.2
- flow rate: 367 kg/s

- 214 Main injection elements (showerhead and swirl)
- 6 cooled baffles for instabilities suppression
- 24 drilled fingers with oxygen injection to improve oxygen distribution



Main kerosene inlet

Kerosene injection

LOX inlet

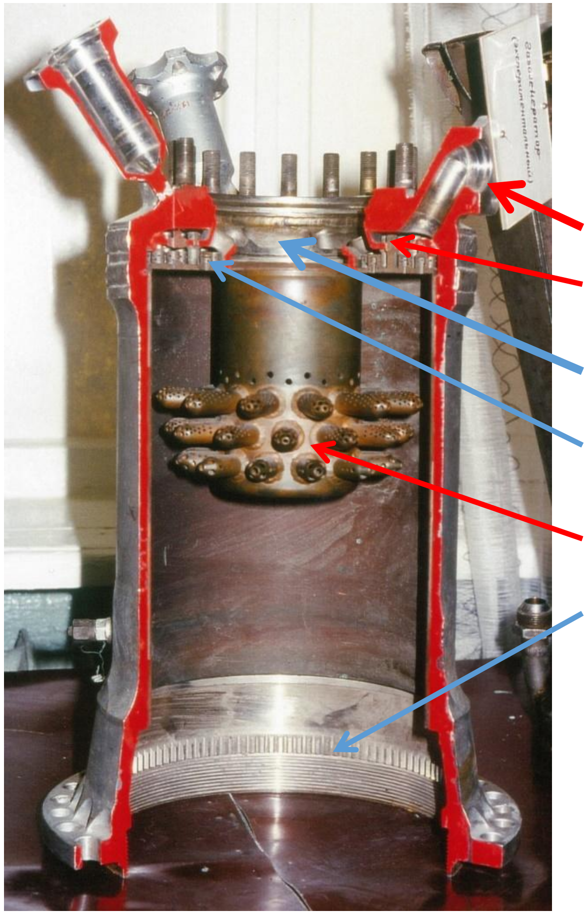
Secondary LOX injection (small mass flow rate)

Main LOX injection (even counterflow)

Cooling channel LOX outlet

Showerhead arrangement in an annular injection chamber with central LOX-cooled plug and walls)

NK-33 Pre-burner



Main kerosene inlet

Kerosene injection

LOX inlet

Secondary LOX injection (small mass flow rate)

Main LOX injection (even counterflow)

Cooling channel LOX outlet

Combustion Instabilities

RD-170: LOX/Kerosene Engine

Application: Energiya, Zenit 3

- Staged Combustion Cycle
- Propellant: LOX/Kerosene (2.63:1)
- Thrust: 7,6 / 8.1 MN (sl / v)
- Specific Impulse: 311 / 337 s (sl/v)
- Chamber pressure: 24.5 MPa
- Propellant flow rate: 2.5 Mg/s
- Dry weight: 11.8 to (73 T/W)

Injector Type:

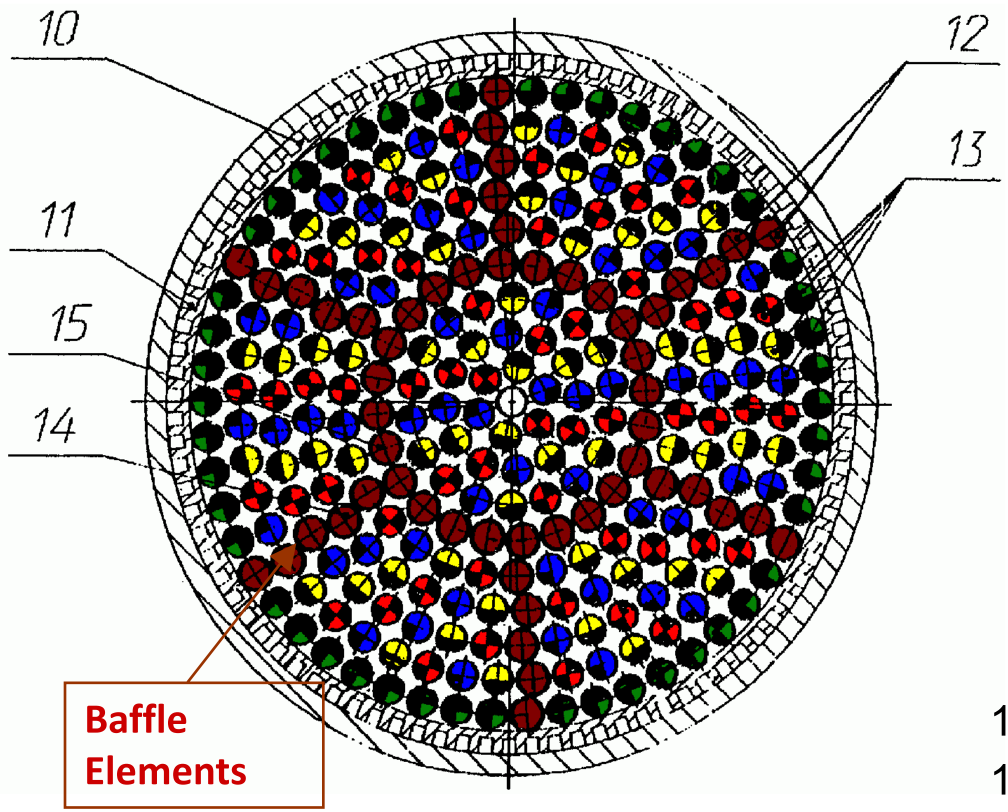
- Co-ax (4), gas (c), liquid (o), swirl
- Flow rate / element: 1.8 kg/s

Ox-rich Pre-burner (two):

- Flow rate: 1672 kg/s
- Mixture ratio: 54.7
- Chamber Pressure: 53.5 MPa
- Temperature: 772 K

RD-172 improved thrust (5%)

RD-170: LOX/Kerosene Engine Injector Face Plate



Baffle Elements

Reference: Chelkis 2003, RU2158841C2

- Three different types of injector elements with up 10% different mass flow rates
- Positioning of injector elements in three groups
- Baffled injectors in classical wagon wheel arrangement

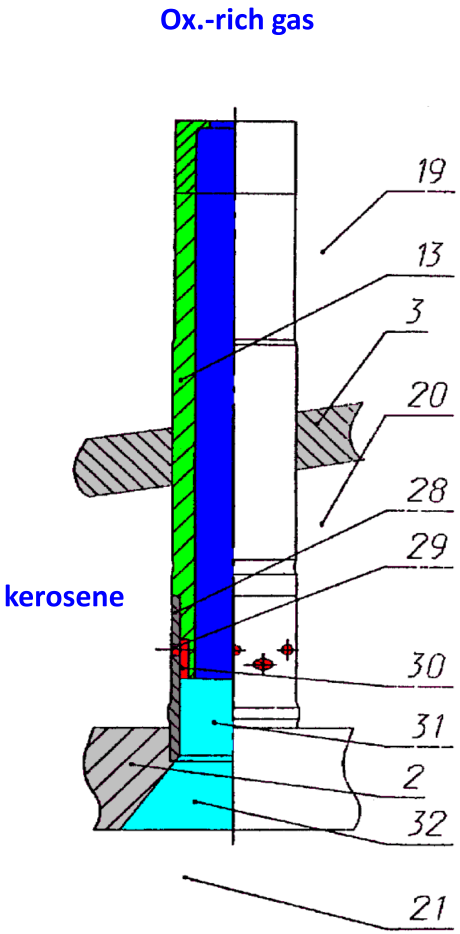
10	fins	13	Injector elements
11	cooling channel	14	Star-baffles
12	baffle-elements	15	Ring -baffles

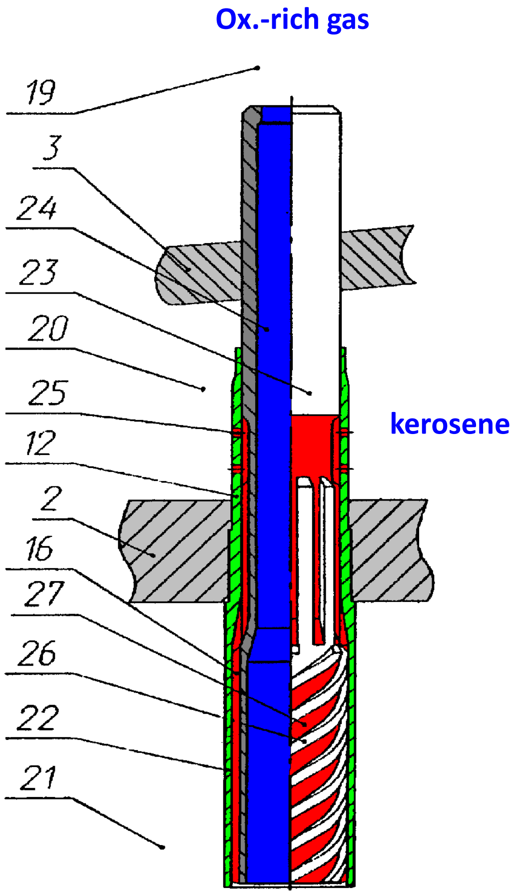
Combustion Instabilities

RD-170: LOX/Kerosene Injectors standard / baffle

2	faceplate
3	distribution plate
12	baffle element
13	injection element
16	pre-burner gas tube
19	ox.-rich gas
20	kerosene
21	thrust chamber
22	kerosene tube
23	Ox.-post
24	Ox.-gas channel
25	Kerosene inlet
26	rips
27	kerosene channels
28	kerosene tube
29	tangential inlets
30	kerosene manifold
31	pre-mixing zone
32	pre-mixing zone

Reference: Chelkis 2003, RU2158841C2





Combustion Instabilities

Lessons Learned

- Injectors are main component which influence combustion stability
- Stable flame anchoring is of key importance
- Distributed heat release inside the combustion chamber is favorable for stable combustion
- Hydrogen much more stable than any hydro-carbon fuel

What you shouldn‘t forget

- How are combustion instabilities typically characterized ?
- What are the main mechanisms which may generate combustion instabilities ?
- Which kind of means to cope with instabilities do you know ?
- What is the theory behind the $N - \tau$ model ?
- Which kind of injectors are more sensitive to trigger combustion instabilities and why ?
- Which propellant combination is less likely to develop such instabilities ?
- Do you know a LOX/Kerosene engine without damping devices ?