Combustion Instabilities in Liquid Rocket Engines: Fundamentals and Control

Section III
Mechanisms of Combustion Instabilities in Liquid Rocket Engines

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28–29 October 2002

3. Mechanisms of Combustion Instabilities in Liquid Rocket Engines

- **Most extensive recent references:**

Harrje, D.T. and, Reardon, F.H. (Editors) (1997) *Liquid Propellant Rocket Combustion Instability*, NASA SP-194.

Yang, V. and Anderson, W. (Editors) (1995) *Liquid Rocket Engine Combustion Instability*, Vol. 169, AIAA Progress in Aeronautics and Astronautics.

Schoyer, H.F.R. (Editors) (1993) *Combustion Instability in Liquid Rocket Engines*, European Space Agency Report WPP-062.

Habiballah, M., Popp, M. and Yang, V. (Editors) (1995) *Liquid Rocket Combustion Devices*, Second International Symposium on Liquid Rocket Propulsion, ONERA, Châtillon, France.

Natanzon, M. (1999) *Combustion Instability*, published originally (1986) by Mashinostroyeniye, Moscow; translated electronically (1996); edited by F.E.C. Culick.

3. Mechanisms of Combustion Instabilities in Liquid Rocket Engines

- It seems that relatively little progress on CI in LRE has been achieved in the past decade.
- Hence the chief mechanisms remain those known for many years to be associated with:
    - propellant feed system
    - injection system
    - processes required for conversion of liquid to gas
    - combustion dynamics
- There seem to be no examples of CI in LRE caused by:
    - vortex shedding
    - mean flow/acoustic interactions
    - convective waves (entropy or vorticity)
- Identification of mechanisms, and especially their relative importance, rests on a combination of observations, physical reasoning and analysis.
- Most analysis (and therefore interpretation of observed behavior) has been directed to linear stability and small amplitude motions.
    - practically no data exist for the transient behavior of linear instabilities in full-scale motors;
    - data exists for decay of oscillations following injection of pulses, and for stability boundaries;
    - mechanisms and analysis of nonlinear behavior are poorly understood (nonlinear instabilities and limit cycles).
- First analyses of nonlinear behavior were done in the 1960s to early 70s at Princeton and Georgia Tech (Crocco, Sirignano, Mitchell, Zinn)
    - existence of limit cycles and nonlinear instabilities (triggering)
    - all based on n-τ model of combustion
    - difficult to extend and to relate to observed behavior

3. Mechanisms of Combustion Instabilities in Liquid Rocket Engines

INJECTION → **ATOMIZATION** → **VAPORIZATION** →

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 AND REACTION** → **EXPANSION**

MIXING AND REACTION

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

EXPANSION

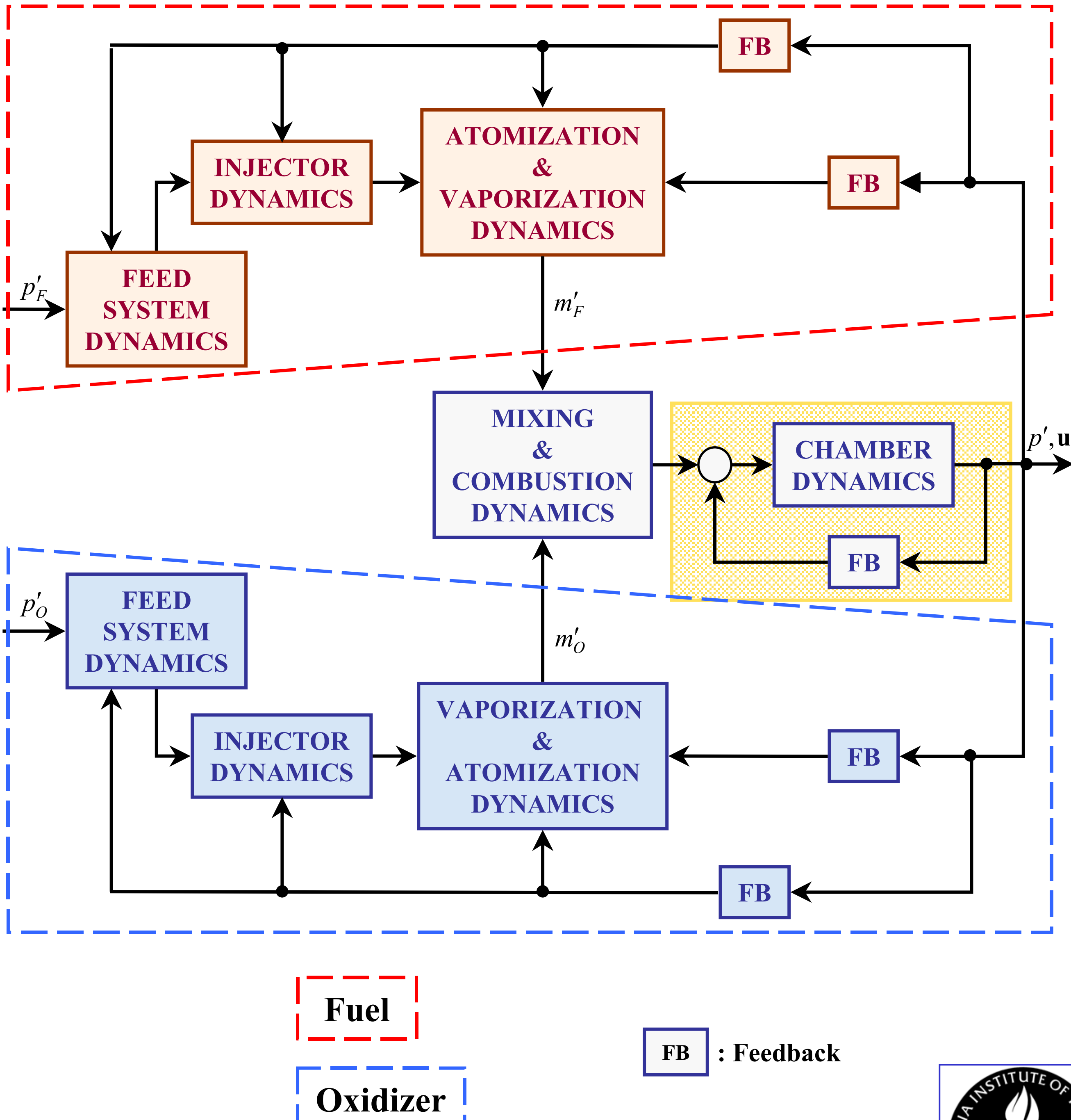
- Gas Dynamics
- Chemical Kinetics
- Flow Separation

- Each class of processes can be characterized by its dynamical behavior, interpreted in the linear limit by a transfer function.

- One approach to analyzing stability is based on combining the transfer functions and posing the problem in the manner of feedback control theory.

3. Mechanisms of Combustion Instabilities in Liquid Rocket Engines

Simplified Diagram for the Dynamics of a Liquid Rocket Engine



3. Mechanisms of Combustion Instabilities in Liquid Rocket Engines

Main Classes of Systems:

- Liquid Oxygen/Hydrogen (LOX/H)
  - e.g. RL-10, J-2, SSME, Vulcain

- Liquid Oxygen/Hydrocarbon (LOX/HC)
  - e.g. Apollo F-1, Atlas, RD-0110, Viking

- Storable: e.g. nitrogen tetroxide (oxidizer)
  - Fuels:
    - hydrazine (H)
    - monomethylhydrazine (MMH)
    - unsymmetrical dimethylhydrazine (UDMH)
  - NTO/H ; NTO/MMH ; NTO/UDMH
    - e.g. Lunar Descent Engine, TRW Pintle

Main Classes of Injectors:

- impinging jets
- shear coaxial
- swirl coaxial
- oxidizer showerhead
- oxidizer sheet/impinging jets

3. Mechanisms of Combustion Instabilities in Liquid Rocket Engines

Remarks:

- Identification of fundamental mechanisms is closely related to diagnostics.

- Principal methods of diagnostics:
    - pressure records
    - heat transfer
    - flow visualization
    - radiation spectra
    - tests at ambient temperature (notably jets and sprays)
    - changes of geometry of the injector and observed subsequent behavior (e.g. full-scale tests)
    - installation of baffles and observed effects on instabilities

- Most research and development effort has been spent on injectors and associated processes.

- Probably the dominant mechanisms have been identified, but accurate detailed models do not exist.

- Assessment of the relative importance of a mechanism requires an analytical/interpretive framework within which that assessment can be accomplished.

3.1 Summary of the F-1 Program

Reference: Olefein and Yang, (1993) *J. Propulsion and Power*, Vol. 9, No. 5, (pp. 657–677)

- LOX/HC (PR-1, kerosene)
- Summary of Development
  - Lineage E-1(1950s) → MA-2(Atlas) → H-1(Saturn I)
  - Experience with combustion instabilities in F-1

PERIOD	NUMBER OF TESTS	NUMBER OF CI	REMARKS
1959–1960	**44**	**20**	$(\Delta p)_{p-p} \geq \overline{p}$
1960–1960	—	—	• Linear or Nonlinear Instability identified: "self-triggering" • Baffles required for dynamic stability
1962–1965	**207**	—	• Preliminary Flight Rating Tests (PFRT): 11 injectors
	422	—	• Flight Rating Tests (FRT): 46 injectors
	703	—	• Qualification: 51 injectors
TOTAL	**1376**		**108 injectors**

3.1 Summary of the F-1 Program

- The F-1 program revealed many of the general characteristics of mechanisms for CI in LOX/HC engines
- **General 'Rule of Thumb'**
  - Engine with no baffles is prone to CI
  - With baffles and 'best injector', there are no self-excited oscillations and the engine is stable to finite disturbances
- **Global Observations**
  - Tangential modes are more unstable than longitudinal modes
    - First tangential most unstable
    - Nozzle attenuates longitudinal modes
- **Dominant Mechanisms**
  - **injection coupling**: sensitivity of motion in the injection element to oscillations in the chamber
  - **resurging**: periodic pulsed combustion of excess liquid fuel accumulated along the boundary, associated with film cooling
  - **transverse displacement** and sensitivity of fuel and oxidizer jets
  - **dynamics of jets and fans**
  - **droplet break-up and vaporization**
  - **strong influences of droplet size**

3.1 Summary of the F-1 Program

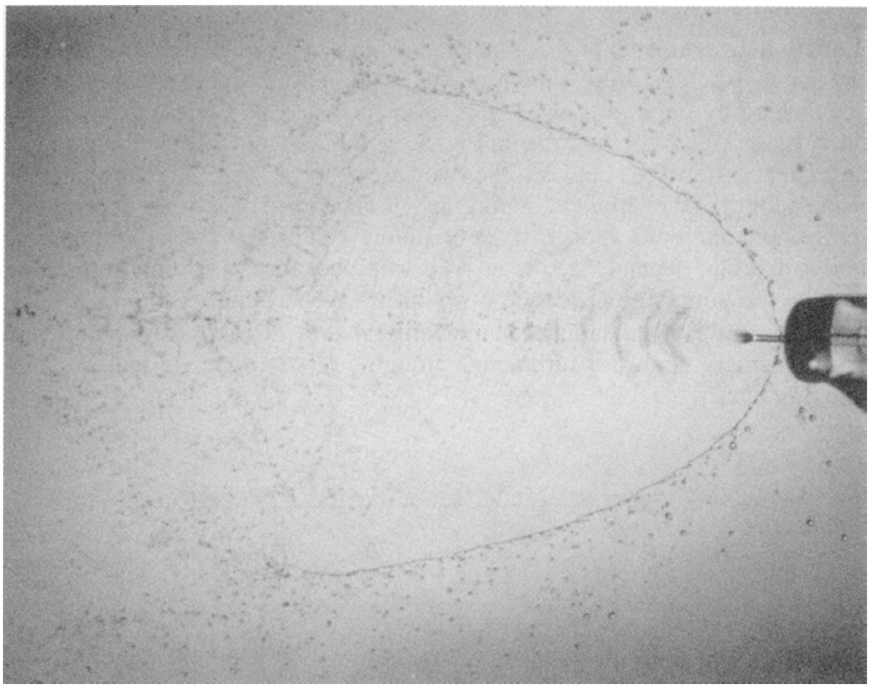
- Three Primary Regions of Activity

1)	$\lesssim$ 8 cm from injector face:	spray fans; all processes producing liquid drops
2)	~ 8–25 cm from injector:	vaporization of drops
3)	> 25 cm from injector:	combustion dynamics; extent of regions 2) and 3) sensitive to droplet size

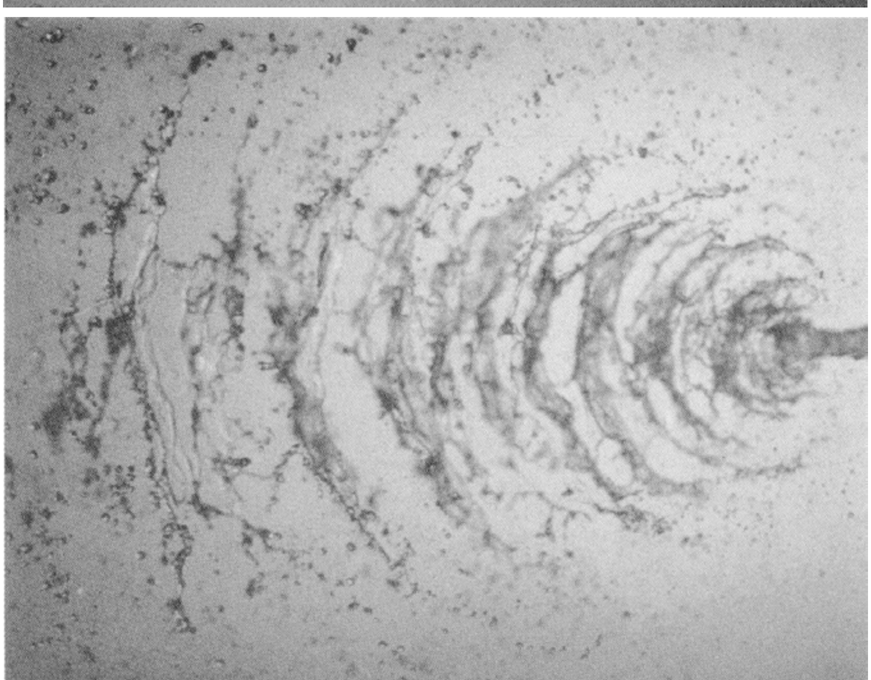
3.1 Summary of the F-1 Program

Illustration of Impinging Jets

Reference: Anderson et al., (1993) PSU Symposium, *Liquid Rocket Engine Combustion Instability*, (pp. 215–246).



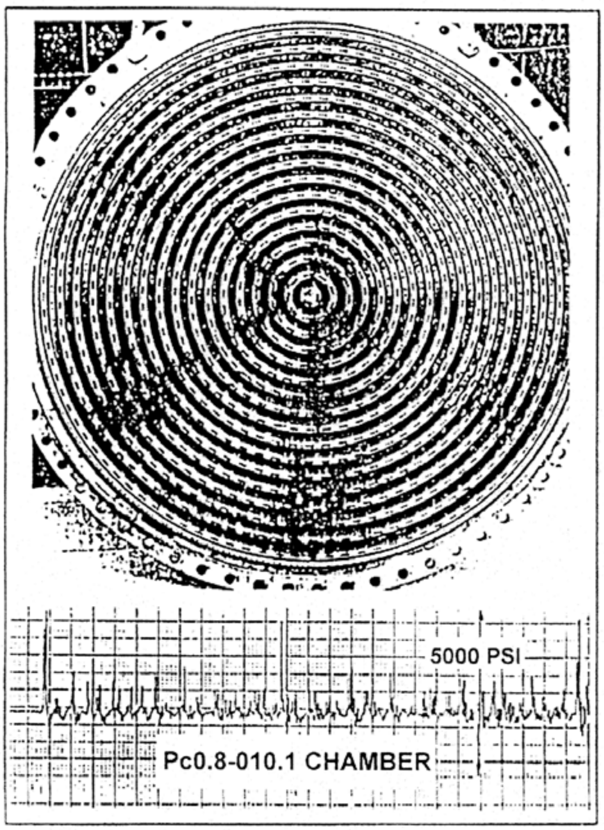
Jet ID = 0.51 mm
V = 14.8 m/s
Re = 7500



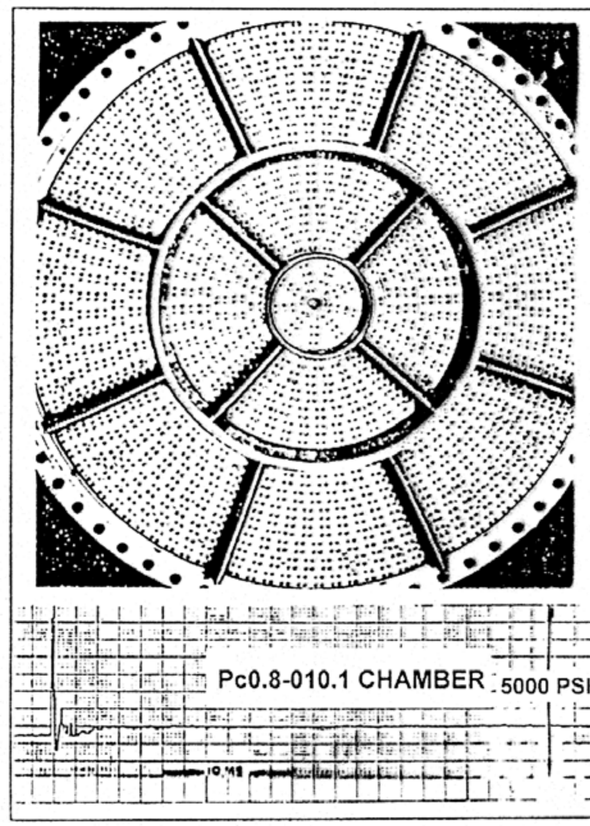
Jet ID = 1.45 mm
V = 12.2 m/s
Re = 12,400

3.1 Summary of the F-1 Program

IMPORTANCE OF BAFFLES WITH RESPECT TO DYNAMIC STABILITY IN F-1 ENGINE



WITHOUT BAFFLES

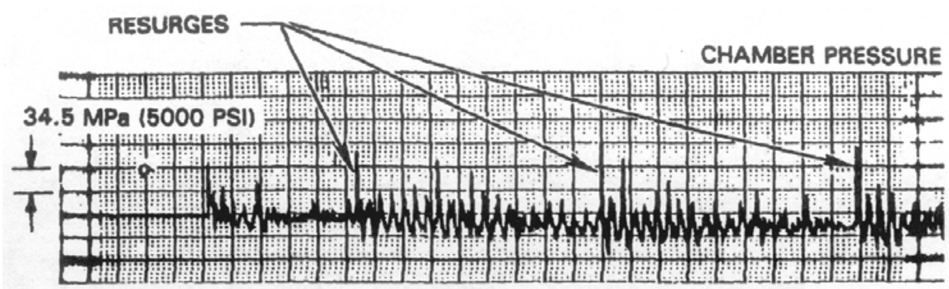


WITH BAFFLES

- Baffles act to shadow sensitive (responsive) regions of injection processes from transverse velocity disturbances

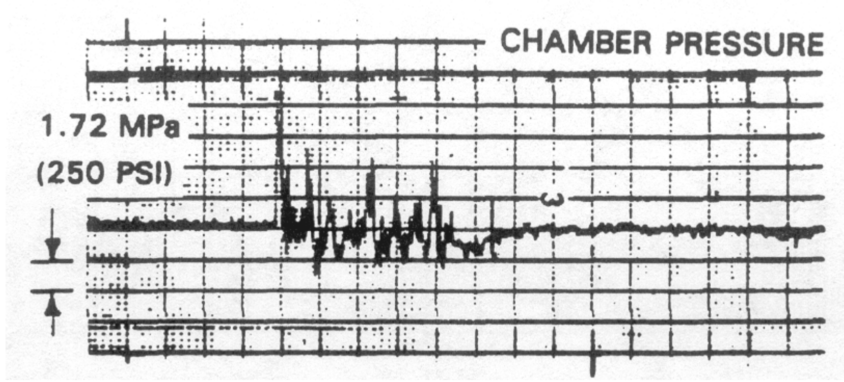
3.1 Summary of the F-1 Program

LOX/HYDROCARBON COMBUSTION OBSERVED IN F-1 ENGINES



Pressure trace exhibiting resurge phenomenon

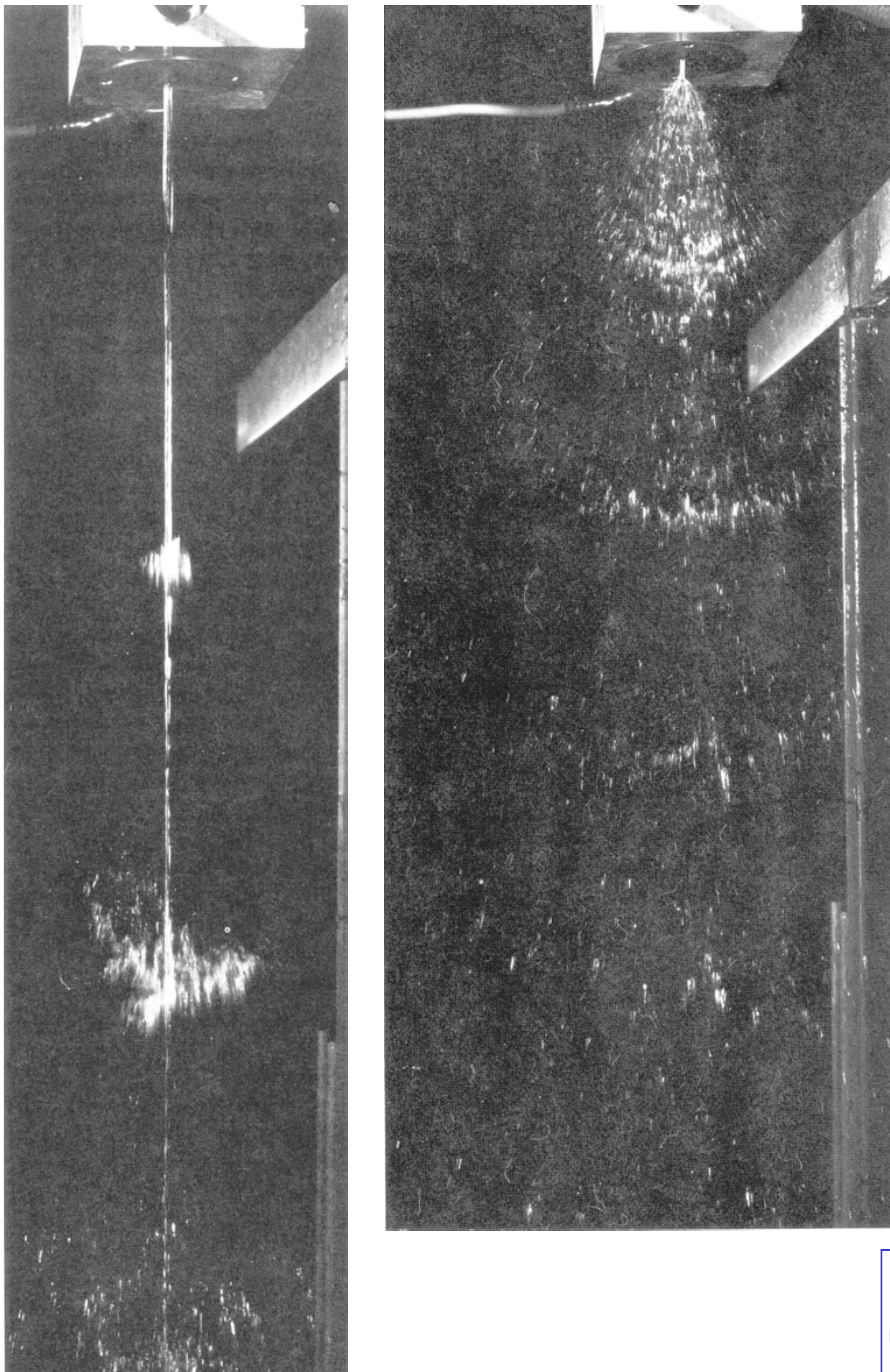
- Injection-coupled spontaneous instabilities minimized by:
  - eliminating low-frequency acoustic paths
  - reducing oscillation amplitudes within the injector body
- Resurging attributed to Klystron effect and overabundance of fuel film coolant:
  - minimized through optimization of fuel film coolant
- Velocity-coupled like-on-like element displacement sensitivity minimized by:
  - displacing combustion zone away from injector



Pressure trace exhibiting damping characteristics of FRT injector of F-1 engine

3.1 Summary of the F-1 Program

Illustrations of the Klystron Effect



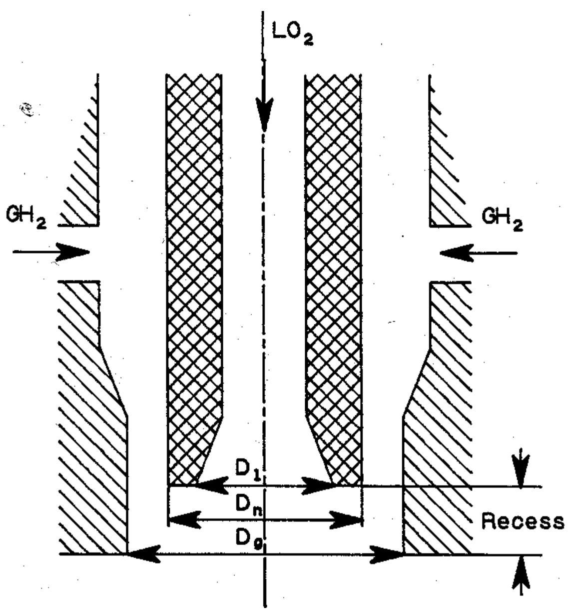
3.2 Mechanisms in LOX/H_2 Engines

<u>Reference</u>: Hulka and Hutt, (1993) PSU Symposium, *Liquid Rocket Engine Combustion Instability*, (pp. 39–71).

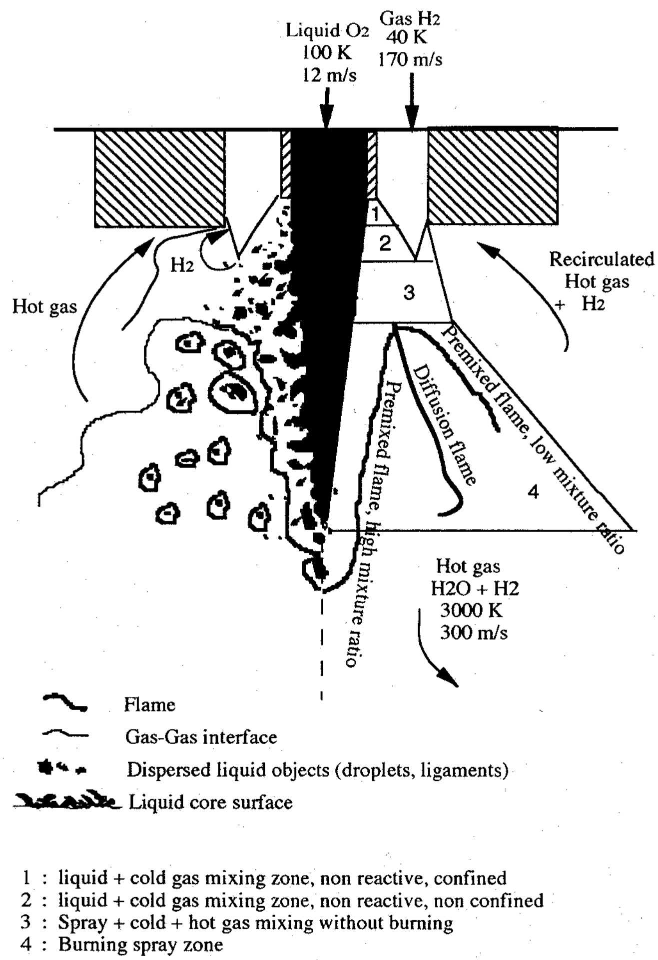
- Coaxial injector used in U.S. from 1940s and remains 'element of choice on all flight engine injectors' (LOX/H_2).
- Examples: RL-10; J-2; J-2S; SSME
- Conditions under which CI occurred more commonly or inevitably:
    - Sufficiently <u>**low temperature**</u> of injected hydrogen
    - <u>**Reduced**</u> pressure drop across injector
    - <u>**Lower**</u> velocity ratio $(V)_{H_2}/(V)_{LOX}$
    - <u>**Less**</u> recessed oxidizer tubes
    - <u>**Lower**</u> mass flow/element
- Data given in the reference may **suggest** mechanisms but are largely attempted correlation of observations with no basis in modeling.
    - Hence the true mechanisms remain obscure

3.2 Mechanisms in LOX/H_2 Engines

<u>Reference</u>: Vingert et al., (1993) PSU Symposium, *Liquid Rocket Engine Combustion Instability*, (pp. 145–189).



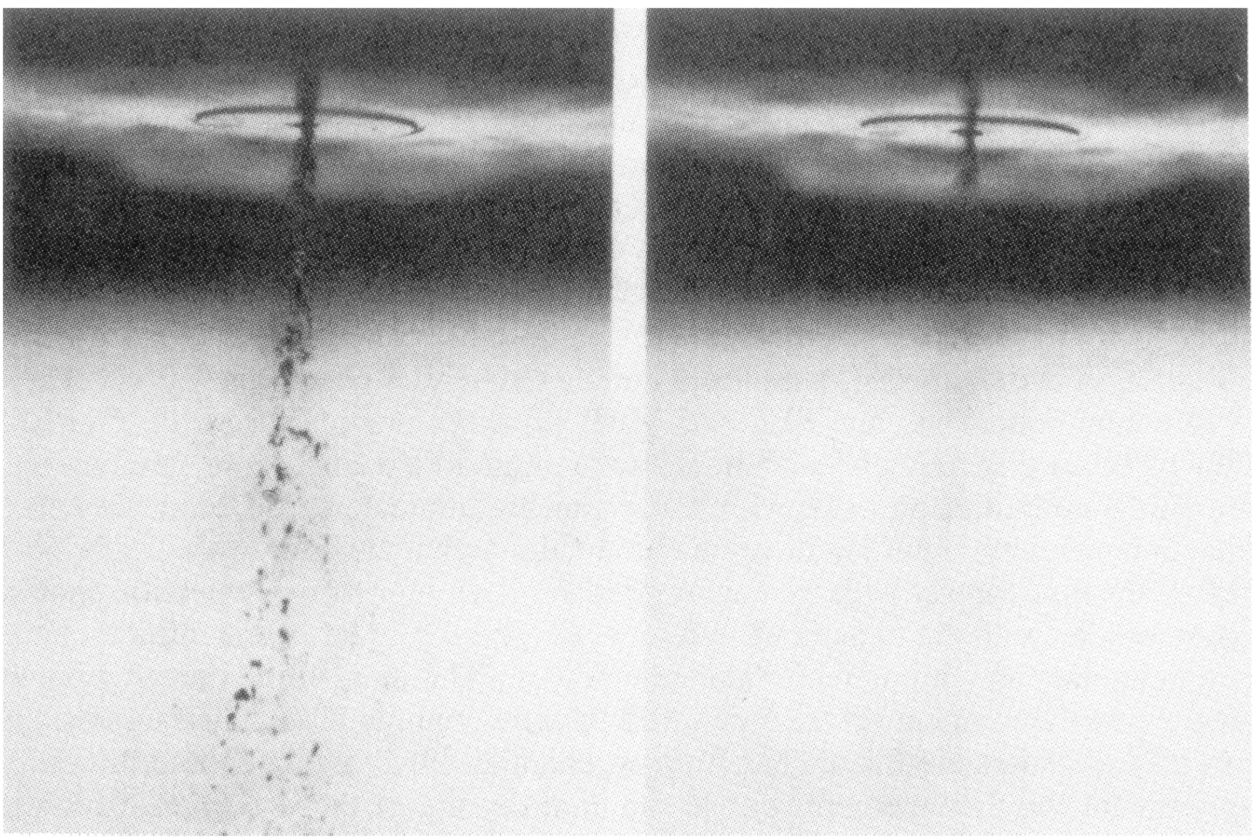
Typical coaxial injector



Coaxial injection flow phenomenon

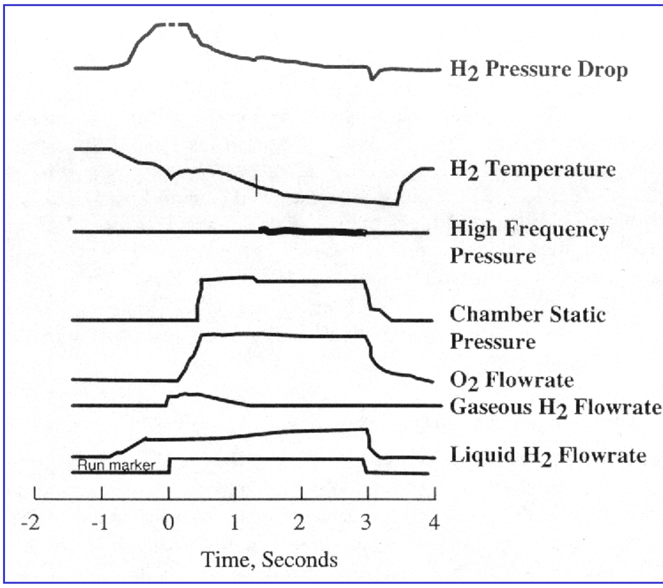
3.2 Mechanisms in LOX/H_2 Engines

Reference: Vingert et al., (1993) PSU Symposium, *Liquid Rocket Engine Combustion Instability*, (pp. 145–189).

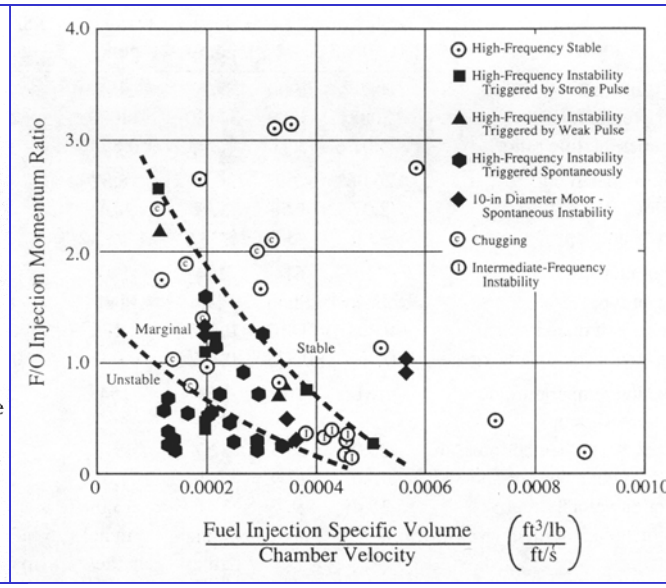


Comparison of poor and good atomization

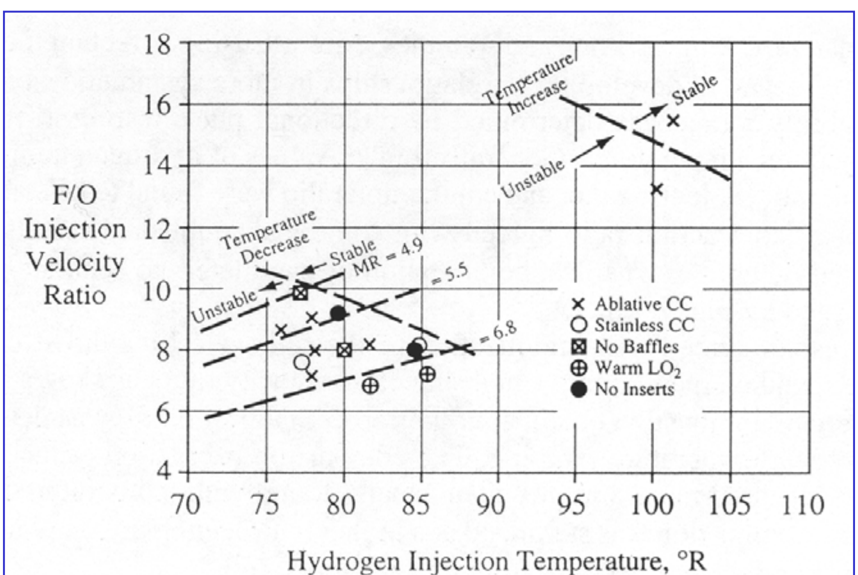
3.2 Mechanisms in LOX/H_2 Engines



Oscillograph from typical **temperature ramping** test



Correlation for shear coaxial elements



Influences of injection velocity ratio in stability

3.3 Mechanisms in LOX/HC Engines

Reference: Muss, (1993) PSU Symposium, *Liquid Rocket Engine Combustion Instability*, (pp. 73–88) (U.S. experience)
Harrje and Reardon, (1972) NASA SP-194 (U.S. experience).

- SP-194 covers ‘all’ U.S. work prior to 1972.

- One view (Muss, …): “… there were two major impediments to a fuller understanding of the relationship(s) between design features and combustion instability characteristics.”
    1) limited computational power;
    2) absence of “mechanistic models or even good correlations to describe the influence of injector elements and thrust chamber design features in the response characteristics of the combustion process.”

- Theory (e.g. Crocco and disciples) seriously limited by use of n-τ representation and intricate calculations often obscuring possible interpretations.

- Lack of ‘numeric models’ partly due to inadequate and limited detailed experimental results.
    - Test results (in U.S.) usually reported as correlations for ranges of various parameters not obviously guided by physical reasoning (?).

3.3 Mechanisms in LOX/HC Engines

'Causes' of CI as presented in SP-194

- Rayleigh's Criterion often cited as a representation of the 'cause'.
  - probably true almost always in LREs (as well as in other systems), but not by itself very helpful.

- Two classes of instabilities:
  1) **'nonascoustic'**: chugging, represented as low-frequency pulsations ($p \approx$ uniform) in a lumped-parameter system containing time lags, especially due to the propellant supply system.
  2) **'acoustic'**: high frequency, caused by coupling between the combustion processes and the unsteady motions.

- The experience with the F-1 engine is a canonical example and illustrates most of the understanding of the mechanisms for CI in LOX/HC engines.

- CI treated by:
  - modifications of injector elements.
  - installations of baffles.

- To what extent was the almost universal use of impinging-jet injector causing problems? (LOX/HC)
  - sensitivity of jets and formation of spray fans to velocity fluctuations parallel to the injector face.

3.3 Mechanisms in LOX/HC Engines

CI in U.S. after SP-194

- Several 'technology' programs were completed

- NASA (1978 – 1979): tests to investigate applicability (truth?) of the vaporization model development by Priem and Heidmann (NASA TR-67, 1960)
  - Apparently satisfactory results when combustion was vaporization limited.
  - Like-on-like injectors generally inferior to like-on-unlike injection elements.

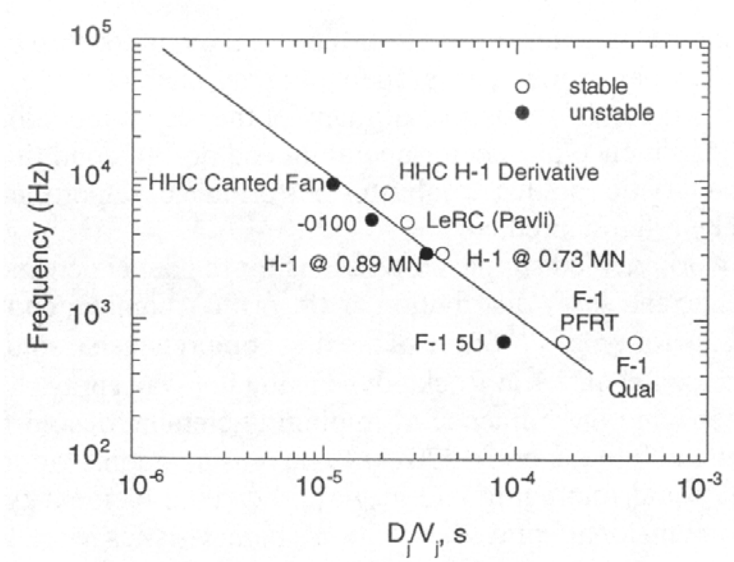
- LOX Injector Characterization Program (USAF, 1985–1991)
  - Observations and data with no basic progress
  - Aerojet: use of n-τ interpretation, no modeling.

- Design Methodology Development Program (NASA, 1988–1993)
  - Observations and data with no basic progress
  - Aerojet: development of program ROCCID
  - Goal to develop a triplet injector element having high performance apparently not reached

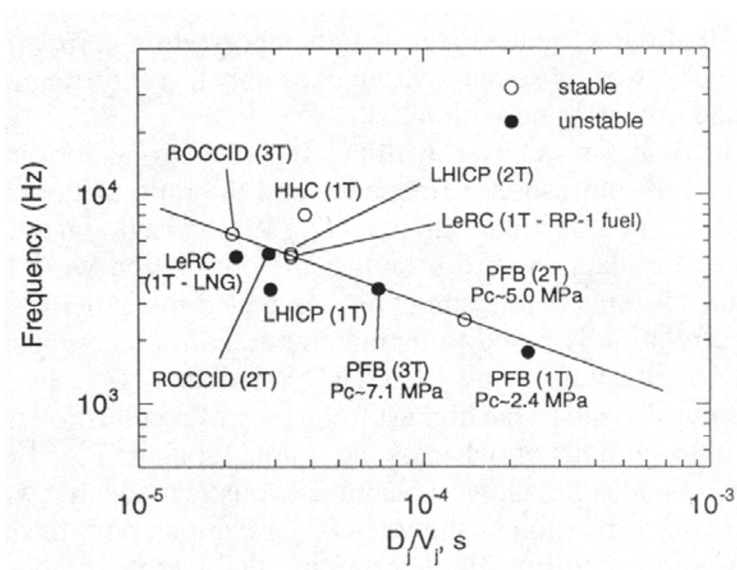
- Heavy Hydrocarbon Main Injector Program (NASA, 1986–1991)
  - Rocketdyne: various injectors evaluated experimentally (including an H-1 derivative)
  - Observations, data and 'correlations' using n-τ interpretation

3.3 Mechanisms in LOX/HC Engines

- Later developments at Aerojet and Penn State led to correlations with the parameter injector orifice diameter/injection velocity (D_j / V_j) to identify the peak injection response.



Like-doublet injector (LOX/HC)



O-F-O injector (LOX/RP-1)

- These results are related to the dynamics of injectors but there is no associated modeling.

3.4 An Example: The Russian RD-0110 Engine (LOX/HC)

Reference: Rubinsky, (1993) PSU Symposium, *Liquid Rocket Engine Combustion Instability*, (pp. 89–112).

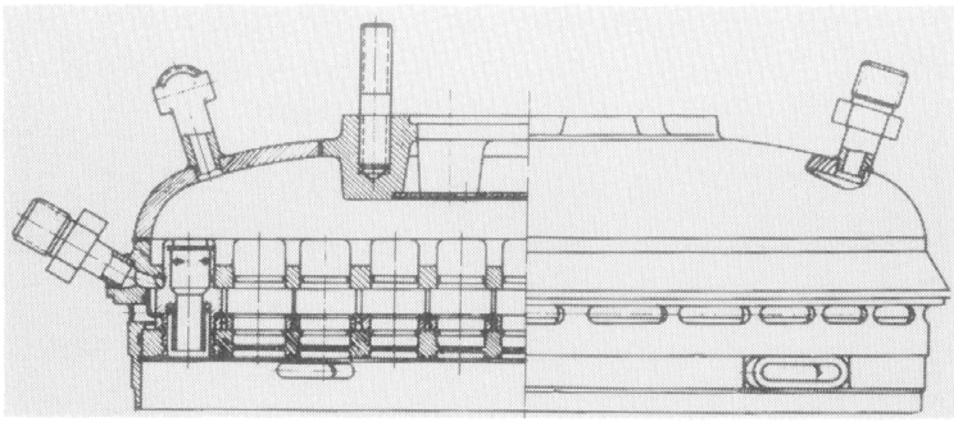
- Experience with the RD-0110 engine during the 1960s–1980s(?) first became known in the West with this reference.
- Four RD-0110s power the third stage of the Soyuz vehicle (1,200 kN, 300,000 lb total).
- Evidently, Russian experience with CI and approaches to treating the problem were qualitatively much like with those in the West, with some important differences in detail.
- Broadly the history of CI in the RD-0110 was:

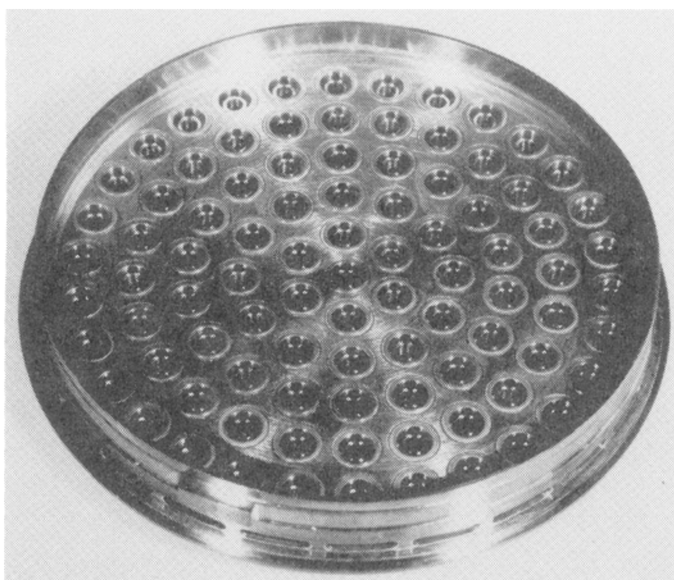
  1) During design of the injection system, attention was paid to minimizing the possibility for driving CI.
  2) Evidently the central idea of Rayleigh's Criterion (relative distribution of energy release and the mode shape) served as an important guide.
  3) Coaxial swirl injection elements were used, with emphasis on injector dynamics (Bazarov).
  4) CI was rare in the final design, but did occur 'randomly' during the ignition transient — observed during qualification tests.
  5) That behavior led to two important results:

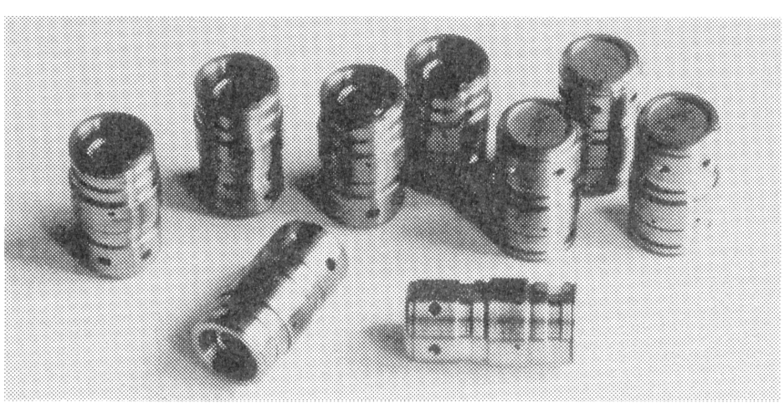
     a) cure by introduction of baffles.
     b) exploration (Natanzon) in terms of a fundamental hypothesis.*

* will be discussed in §9.

3.4 An Example: The Russian RD-0110 Engine (LOX/HC)

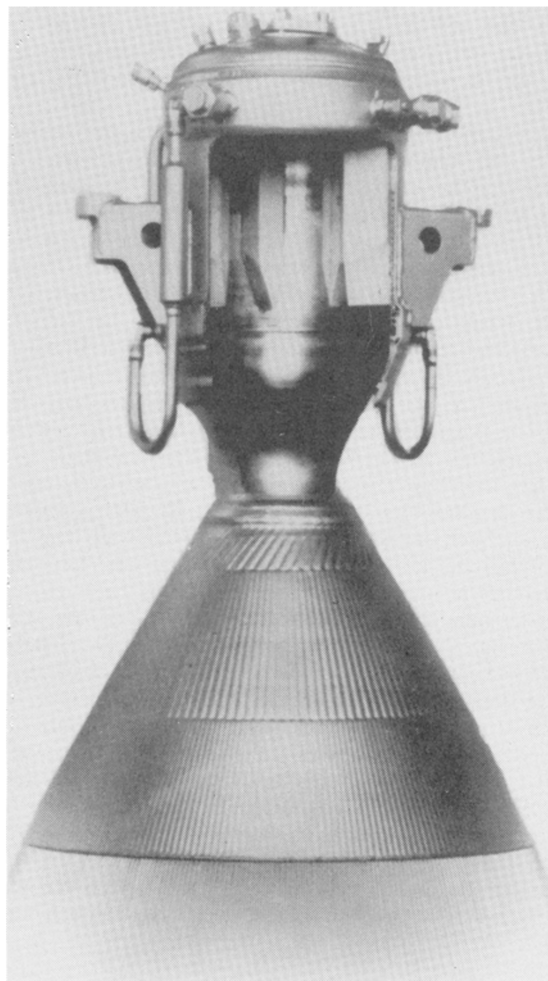






3.4 An Example: The Russian RD-0110 Engine (LOX/HC)

- The solution to the problem of CI involved installing combustible baffles (a unique solution ?).
- Because the oscillations were identified as transverse modes, baffles extending radially from the lateral surface were required.



- The ribs (baffles) were installed on > 10,000 chambers that successfully passed flight qualification tests at the factory.
- The cause of the random appearances of CI during the ignition period was identified with hysteresis associated with instability if recirculation zones formed at the injector elements (Bely, Natanzon, et al., discussed in §9).

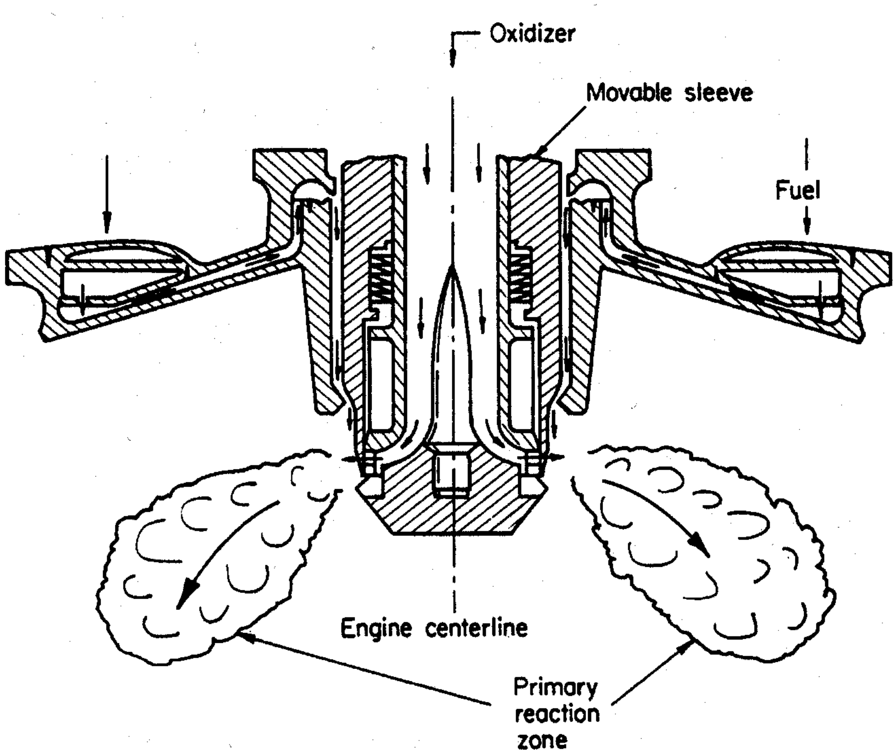
3.4 An Example: TRW Lunar Module Descent Engine

- Storable propellants: NTO/A-50

  NTO: nitrogen tetroxide
  A-50: 50/50 mixture hydrazine and UDMH
  UDMH: unsymmetrical dimethylhydrazine

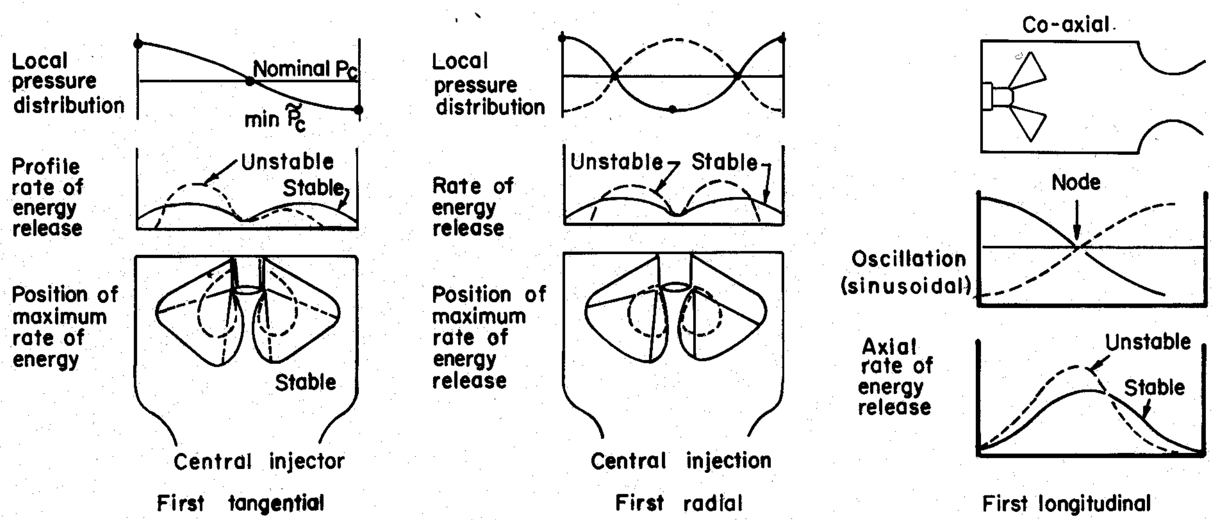
- Very stable with these propellants and under the required operating conditions.

- Explanation for stability based mainly on **qualitative** application of Rayleigh's Criterion, supported by pulsed tests for assessment of stability margins. Apparently no detailed analysis of gains and losses.

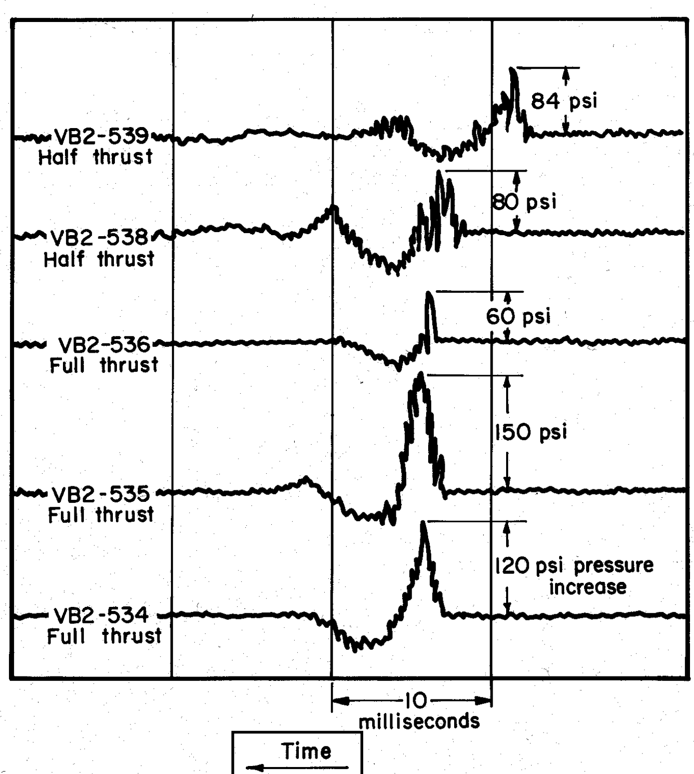


Pintle injector with cross section

3.4 An Example: TRW Lunar Module Descent Engine



Schematic comparison of resonant combustion and steady-state energy release patterns for central injection.

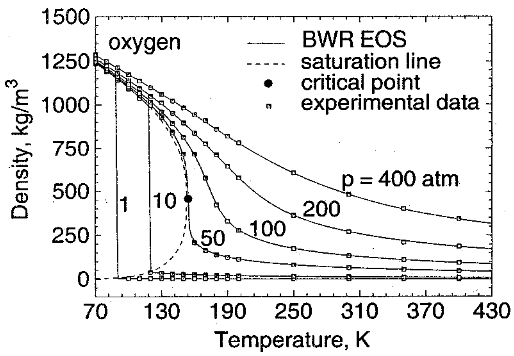


Typical pressure recovery for central injection design in LMDE engine.

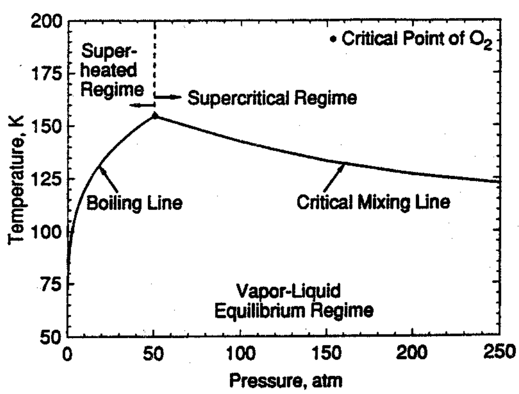
3.5 Dynamical Behavior Under Supercritical Conditions

- Fundamental physical behavior of a substance near its critical point has long been known to be highly sensitive to changes of state.

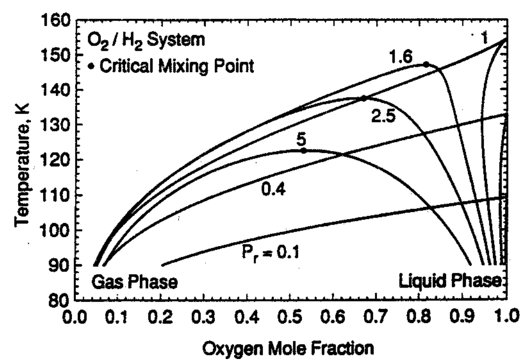
Density of Oxygen



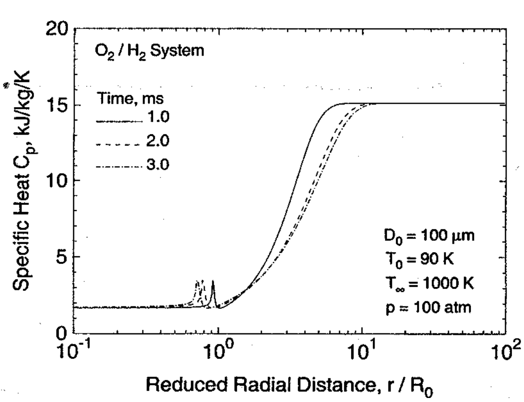
***p–T* Diagram for O_2/H_2**



Mixture Composition for O_2/H_2



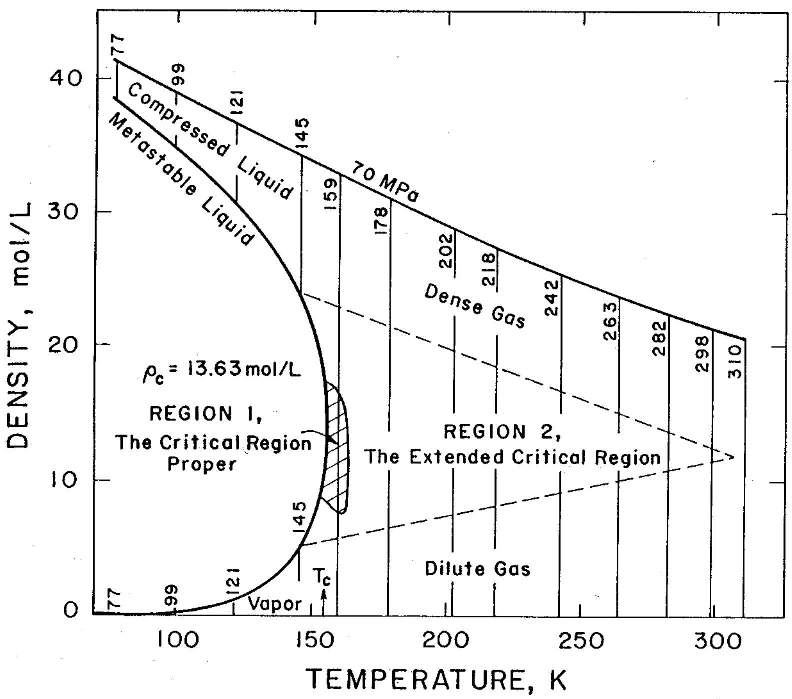
- In equilibrium, H_2 dissolves in O_2 forming a mixture (e.g. drops) whose properties vary strongly in both space and time.



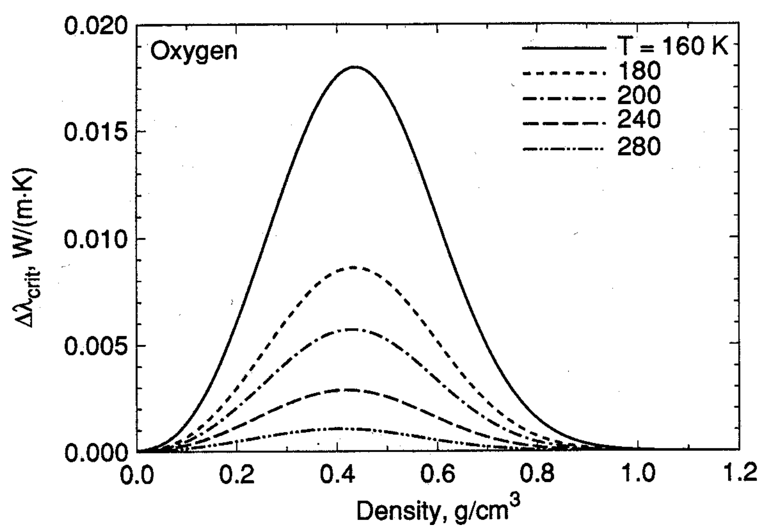
Specific Heat as a Function of Position for a Drop, O_2/H_2

3.5 Dynamical Behavior Under Supercritical Conditions

- Transport properties of pure substances also vary drastically near the critical point: values tend to diverge as the critical point is approached.



- Transport properties tend to vary more smoothly



- The dynamical behavior under supercritical conditions has not been identified as a mechanism for CI.

3.5 Dynamical Behavior Under Supercritical Conditions

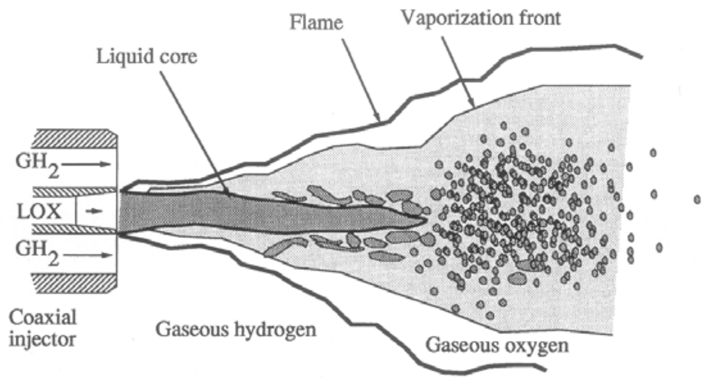
Some References:

1) Yang (2000) 28th Combustion Symposium, (pp. 925–942).
2) Chehrondi, Talley and Coy (2002) *Physics of Fluids*, Vol. 14, No. 2.
3) Chehrondi and Talley (2002) 40th AIAA Aerospace Sciences Meeting, AIAA-2002-0342.
4) Kendrick et al. (1999) *Combustion and Flame*, Vol. 111, (pp. 327–339).
5) Candel et al. (1998) *J. Prop. and Power*, Vol. 14, No. 5, (pp. 826–834).
6) Shuen et al. (1992) *Combustion and Flame*, Vol. 89, (pp. 299–319).
7) Yang et al. (1994) *Comb. Sci. and Tech.*, Vol. 97, (pp. 247–270).
8) Lafon, Yang and Habiballah (1995) 31st Joint Propulsion Conference, AIAA Paper 95-2432.
9) Oefelein and Yang (1998) *J. Prop. and Power*, Vol. 14, No. 5 (pp. 843–857).

1), 6), 7): **analysis and numerical simulations**
2), 3): **acoustics and cold jets**
4), 5): **steady combustion, cryogenic LOX in GH_2**
8): **response of droplets**
9): **mixing and combustion, coaxial injector**

3.5 Dynamical Behavior Under Supercritical Conditions

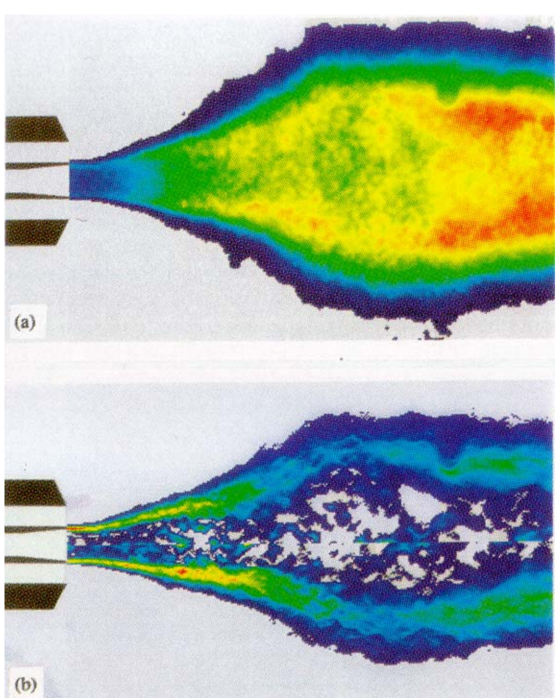
- Combustion of Supercritical Jets (École Centrale).



- Processes prior to combustion characterized mainly by two parameters:

$$J := \frac{\text{Gas momentum flux}}{\text{Liquid momentum flux}}$$

$$We := \frac{\text{Stresses due to relative motion}}{\text{Surface tension}} \qquad \left(\begin{array}{c}\text{Webber}\\ \text{number}\end{array}\right)$$



- OH-PLIF measurements
  - thin reactive layer stabilized near LOX tube, “shaped of a shell”

p = 10 bar
J = 6.5
We = 12.6 x10^{-3}

3.5 Dynamical Behavior Under Supercritical Conditions

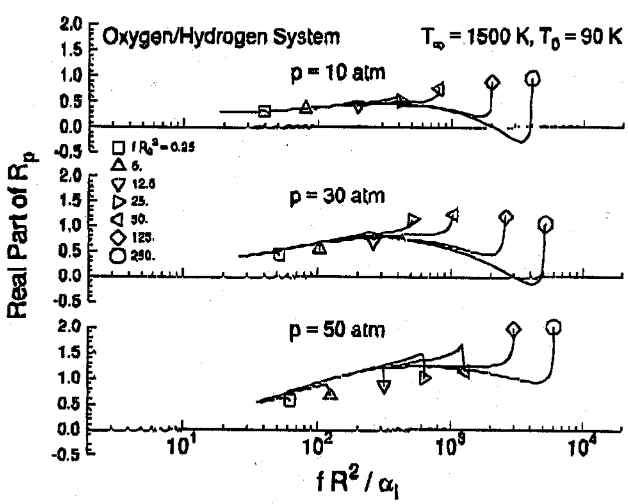
3.5.1 Combustion Response of LOX Droplets in H_2

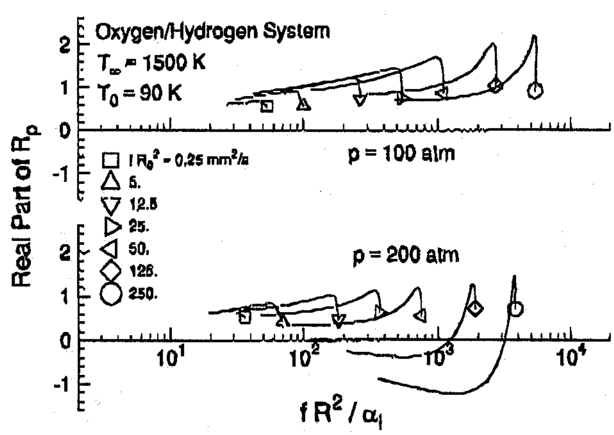
Reference: Lafon, Yang and Habiballah, (1995) 31st Joint Propulsion Conference, AIAA Paper 95-2432.

- Stationary droplet vaporizing and burning in a quiescent field and exposed to pressure pulsations.
- Calculation of the response,

$$R_p = \frac{\dot{m}'/\overline{m}}{p'/\overline{p}}$$

Note: Source terms in the wave equation require u', not $\dot{m}'$ (i.e. changing volume generates acoustic waves — e.g. a small pulsating sphere).

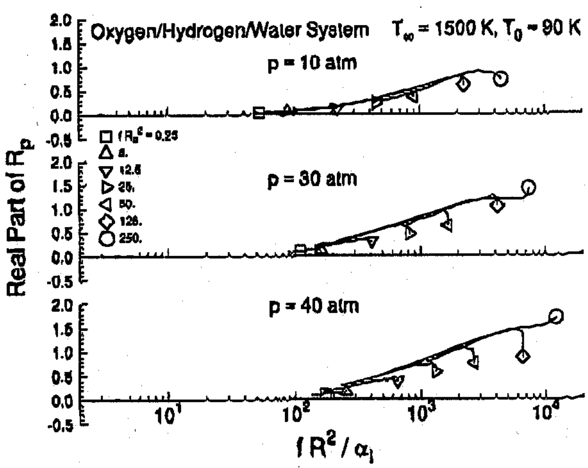


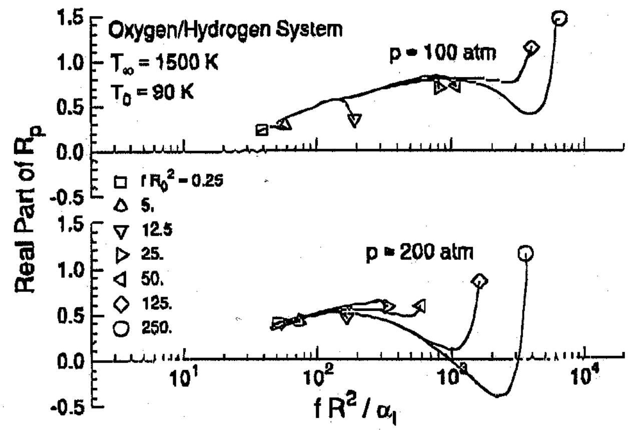


- The characteristic thermal relaxation time for a LOX droplet is of the same order as its lifetime. Unlike hydrocarbon droplets, the internal temperature field is non-uniform, significantly affecting the surface temperature and the vaporization response.
- Differences between behavior of LOX and liquid HC still controversial? (cf. works by Sirignano et al.)

3.5 Dynamical Behavior Under Supercritical Conditions

3.5.1 Combustion Response of LOX Droplets in H_2 (cont'd)





Conclusions

- vaporization response small
- 'gasification' (combustion?) response small
- responses smaller for supercritical conditions than for subcritical

3.5 Dynamical Behavior Under Supercritical Conditions

3.5.2 Mixing and Combustion, Coaxial Shear Injection Element

<u>References</u>: Olefein and Yang, (1998) *J. Propulsion and Power*, Vol. 14, No. 5, (pp. 843–857).
Mayer and Tamura, (1996) *J. Propulsion and Power*, Vol. 12, No. 6, (pp. 1137–1147).

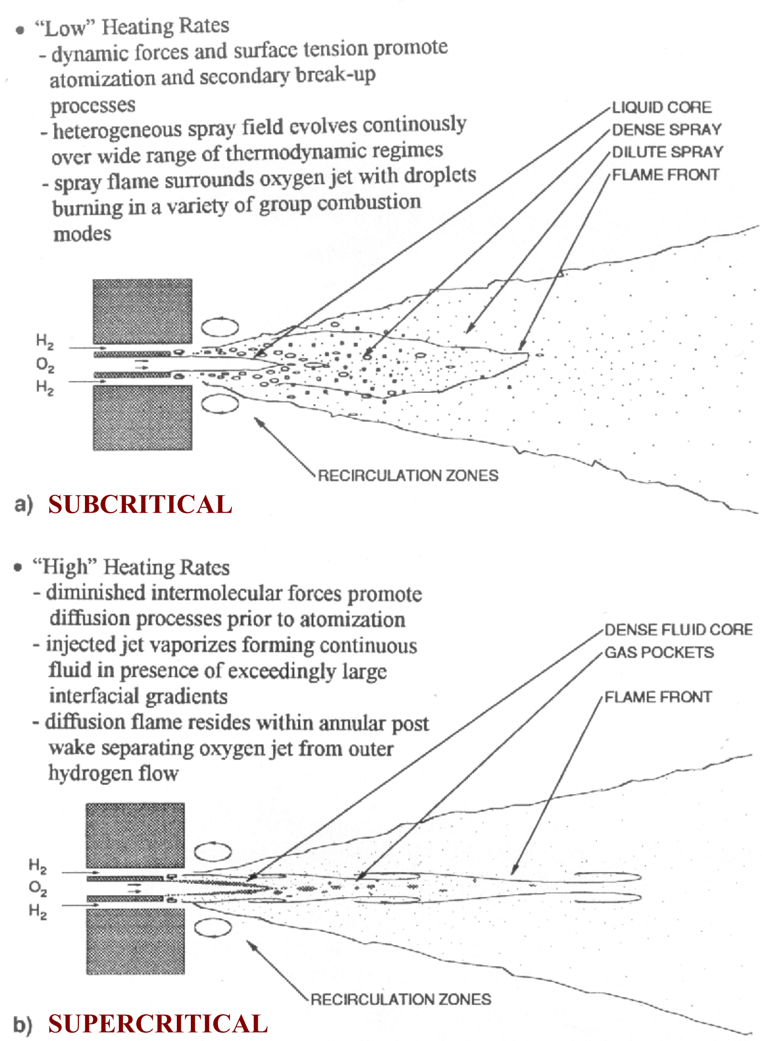
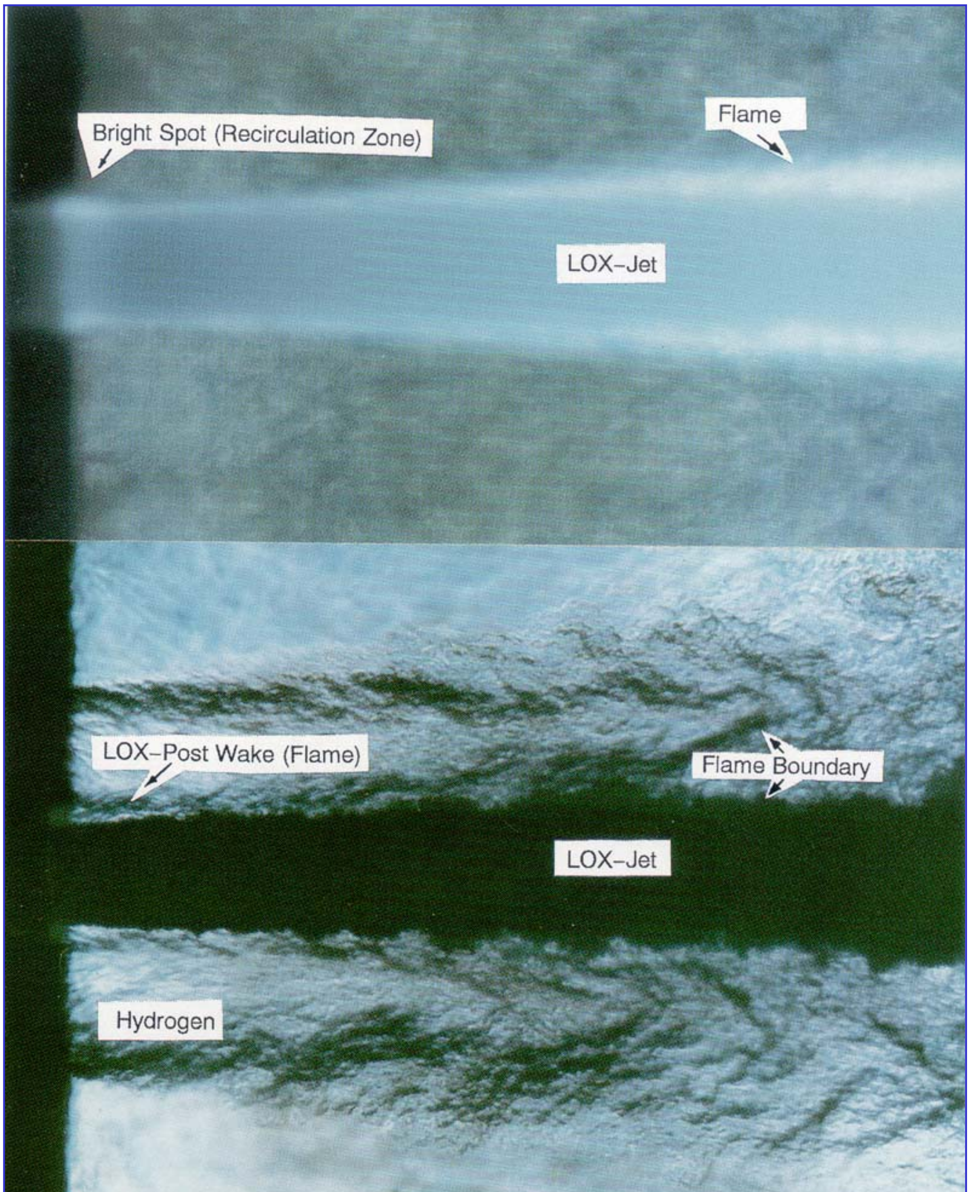


Fig. 1 Schematic diagrams illustrating the basic phenomena associated with a) low and b) high chamber pressures for the case of a liquid-oxygen–gaseous-hydrogen shear-coaxial injector element.

3.5 Dynamical Behavior Under Supercritical Conditions

3.5.2 Mixing and Combustion, Coaxial Shear Injection Element

Reference: Mayer and Tamura, (1996) (experimental).



Flame

Flow Field

$$V_{O_2} = 30 \text{ m/s} \qquad V_{H_2} = 300 \text{ m/s}$$

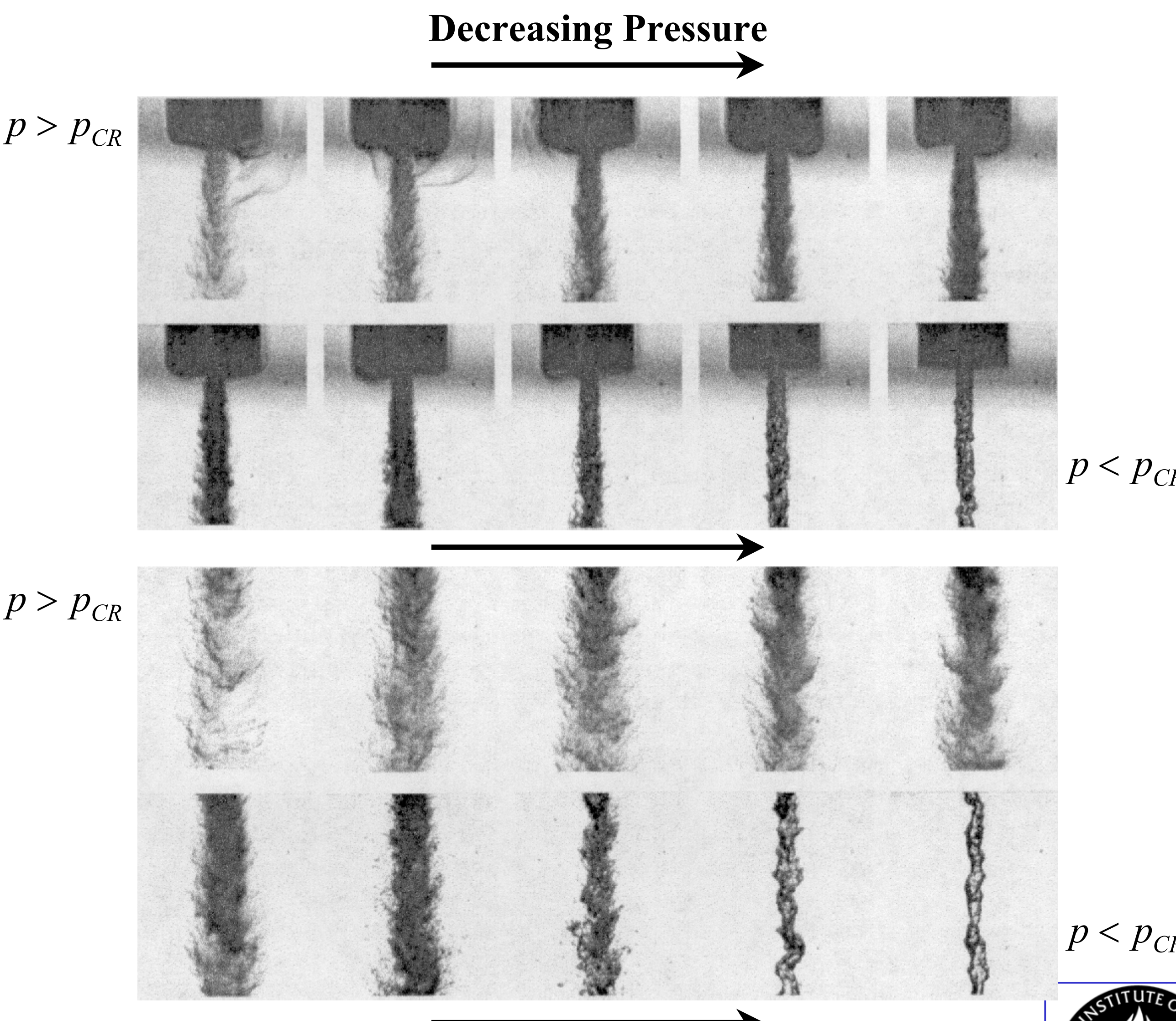
$$D = 1 \text{ mm} \qquad p = 4.5 \text{ MPa}$$

3.5 Dynamical Behavior Under Supercritical Conditions

3.5.3 Development of LN_2 and LOX Jets

Reference: Chehroudi, Talley and Coy (2002) *Physics of Fluids*, Vol. 14, No. 2.

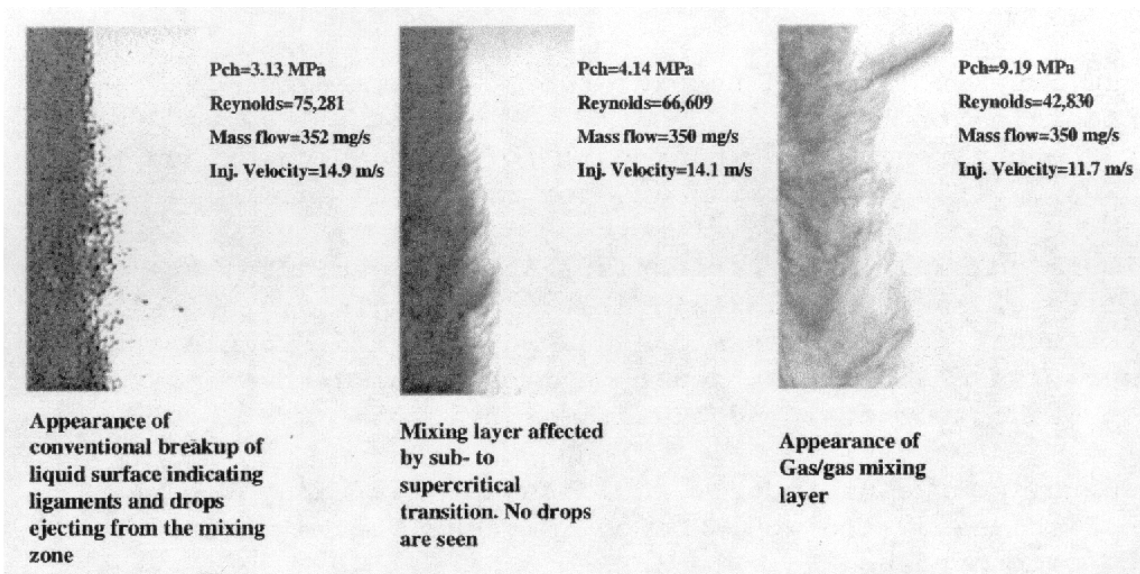
- Jets (LN_2, LOX) initially at subcritical temperature injected into region with $T > T_{CR}$ and various pressures (N_2, He, Ar, or CO + N_2).



3.5 Dynamical Behavior Under Supercritical Conditions

3.5.3 Development of LN_2 and LOX Jets

Reference: Chehroudi, Talley and Coy (2002) *Physics of Fluids*, Vol. 14, No. 2.



$p < p_{CR}$ TRANSITION $p > p_{CR}$

3.5 Dynamical Behavior Under Supercritical Conditions

3.5.3 Development of LN_2 and LOX Jets

Conclusions

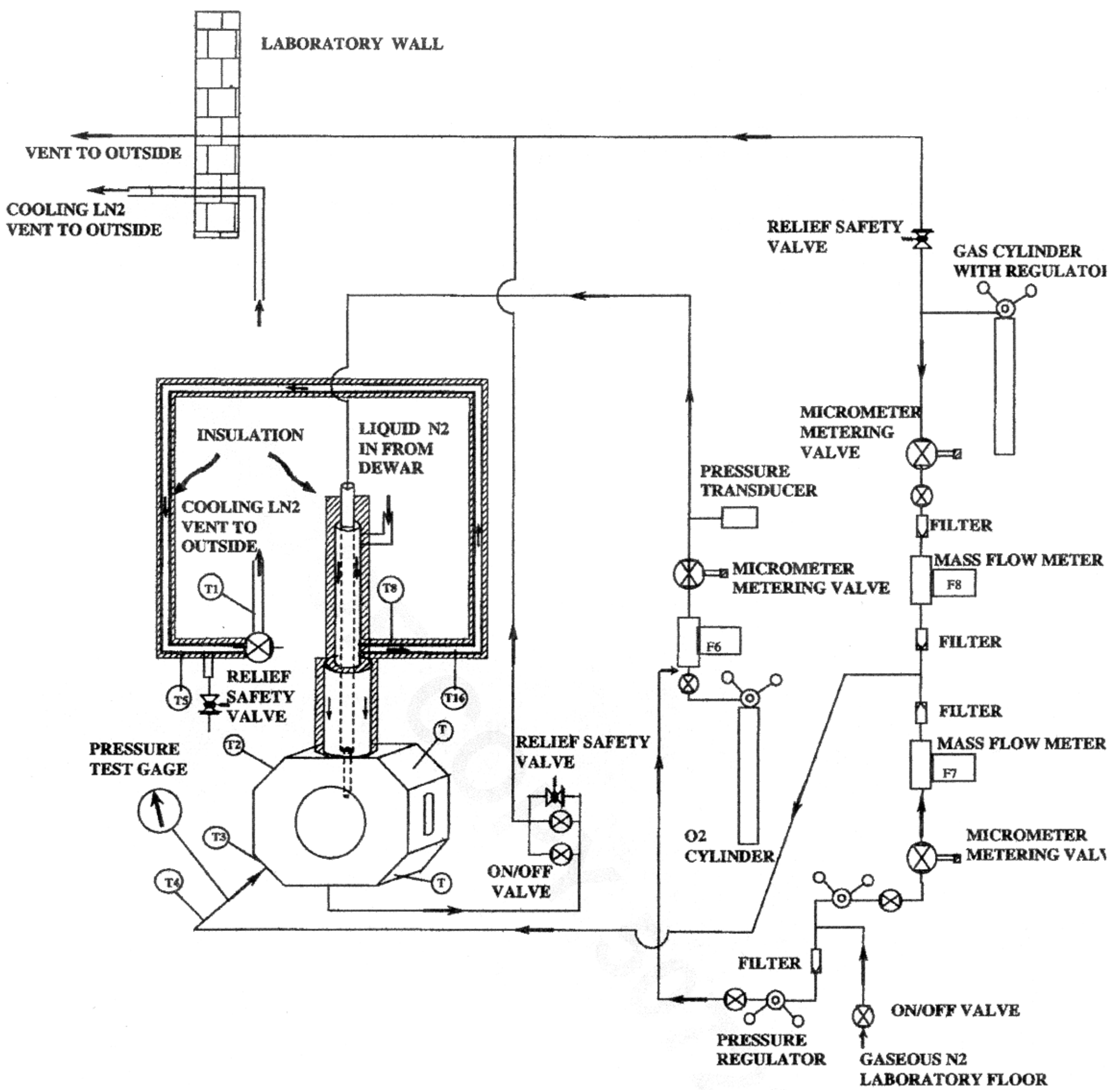
- Low subcritical pressures
  - shiny sinuous surface, some evidence of instabilities
- Increased pressure, near critical
  - small droplets produced, approaching full atomization
- Supercritical pressure
  - reduction of enthalpy of vaporization and surface tension produces a jet resembling a "turbulent jet with no detectable droplets"
- Growth rates agree with results for "incompressible but variable density gaseous mixing layers"

3.5 Dynamical Behavior Under Supercritical Conditions

3.5.4 LN_2 Jets Exposed to Acoustic Waves

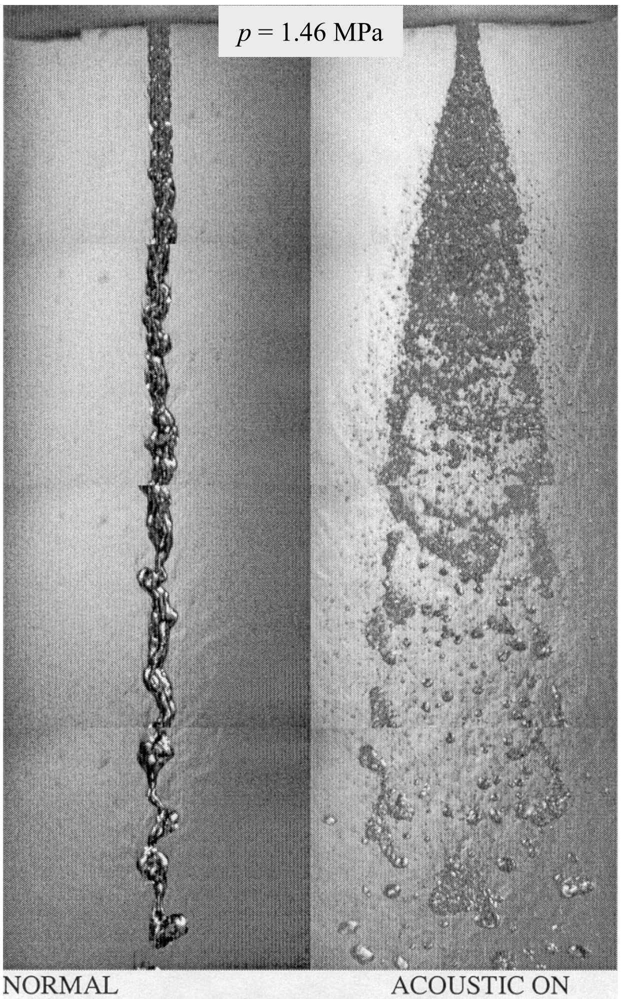
Reference: Chehroudi and Talley (2002) 40th AIAA Aerospace Sciences Meeting.

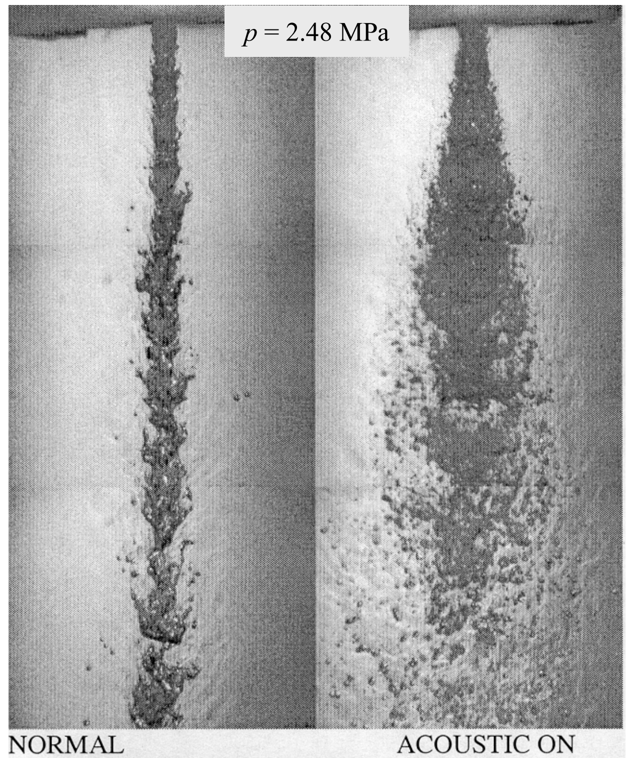
- Main conclusions
  - $p < p_{CR}$: acoustic waves have substantial effects on the behavior of the jet
  - $p > p_{CR}$: acoustic waves have no detectable effects



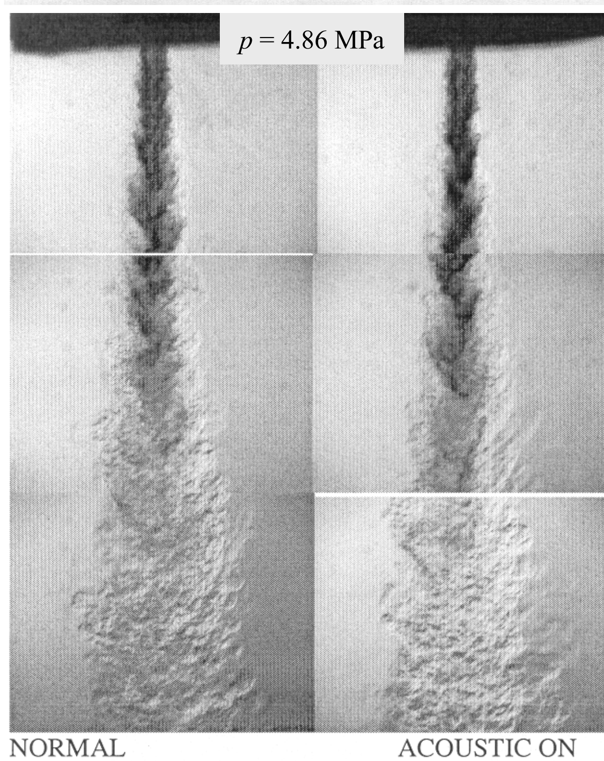
3.5 Dynamical Behavior Under Supercritical Conditions

3.5.4 LN_2 Jets Exposed to Acoustic Waves





$p < p_{CR}$



$p > p_{CR}$

End of Section

III