Supercritical Fluid
And
Applications in Propulsion Systems

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Presentation at
6th International Conference and Exhibition
Mechanical and Aerospace Engineering
Atlanta, Georgia

Nov 7-8, 2018

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- Combustion instability (CI) in LRE
- Supercritical fluids
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  - *Non-reacting* coaxial jet & connection to multi-element LRE instability (coaxial, AFRL)
  - *Fired* single-element LRE instability (coaxial, DLR & PennState)
  - Impact of "d/V" ratio on dark core length & connection to LRE stability (Hewitt) (single & impinging jets)
  - Comparable preimpingement (for impinging jet in LRE) and dark core lengths (DLR, AFRL & PennState)
  - A proposed hypothesis
- *Unified Injector Sensitivity Theory*
- Supporting data and offered explanations by the theory (in brief)
- Conclusions

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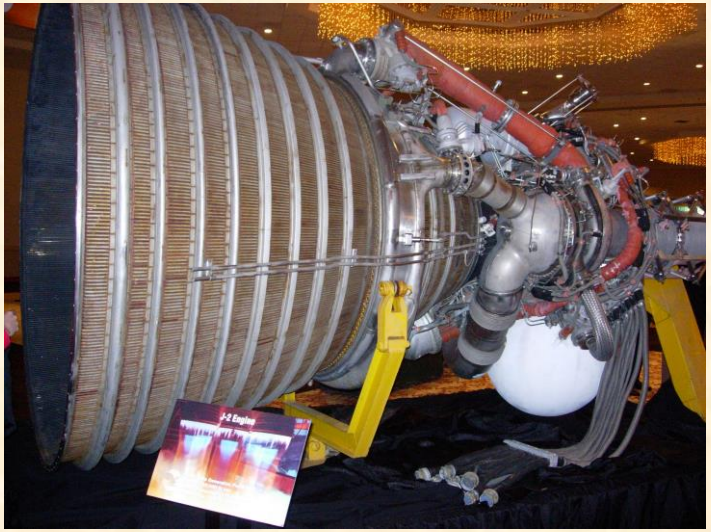
Motivation & Objectives

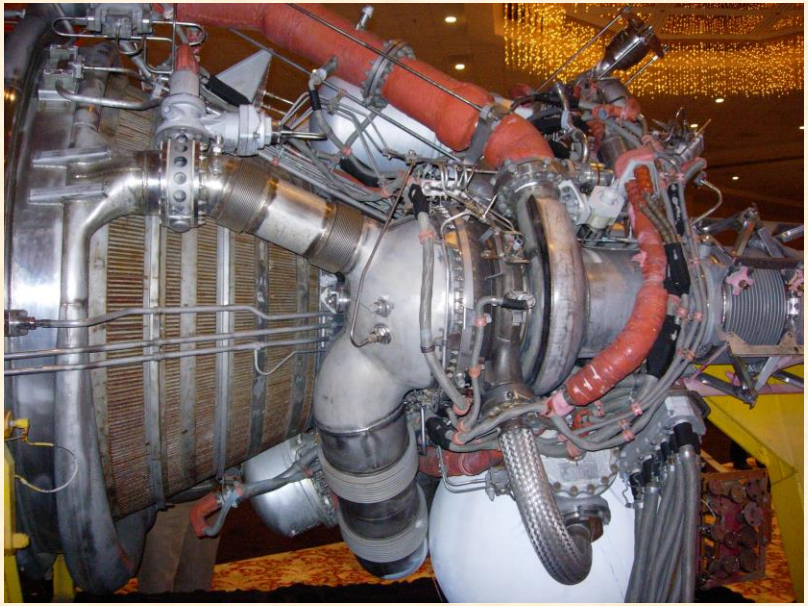
- High combustion chamber pressure and temperature generally reflect to high efficiency and/or thrust in diesel, gas turbine, and rockets.
- The Space Shuttle main engine thrust chamber pressure is about 22.3 MPa.
  - This is supercritical for the liquid H_2 (1.28/32.94) and liquid O_2 (5.04/154.6). (P_c in MPa / T_c in K)
  - The combustion chamber pressure for Vulcain (Ariane 5) with liquid H_2 /liquid O_2 can reach up to 10 MPa while a record pressure of nearly 28.2 MPa has been reported
- Limited information is available for jets injected under these conditions where injectant finds itself in a thermodynamic supercritical environment.
- Understanding mechanism of acoustic combustion instabilities under such a high pressure environment has been a challenge

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Rocket Engine









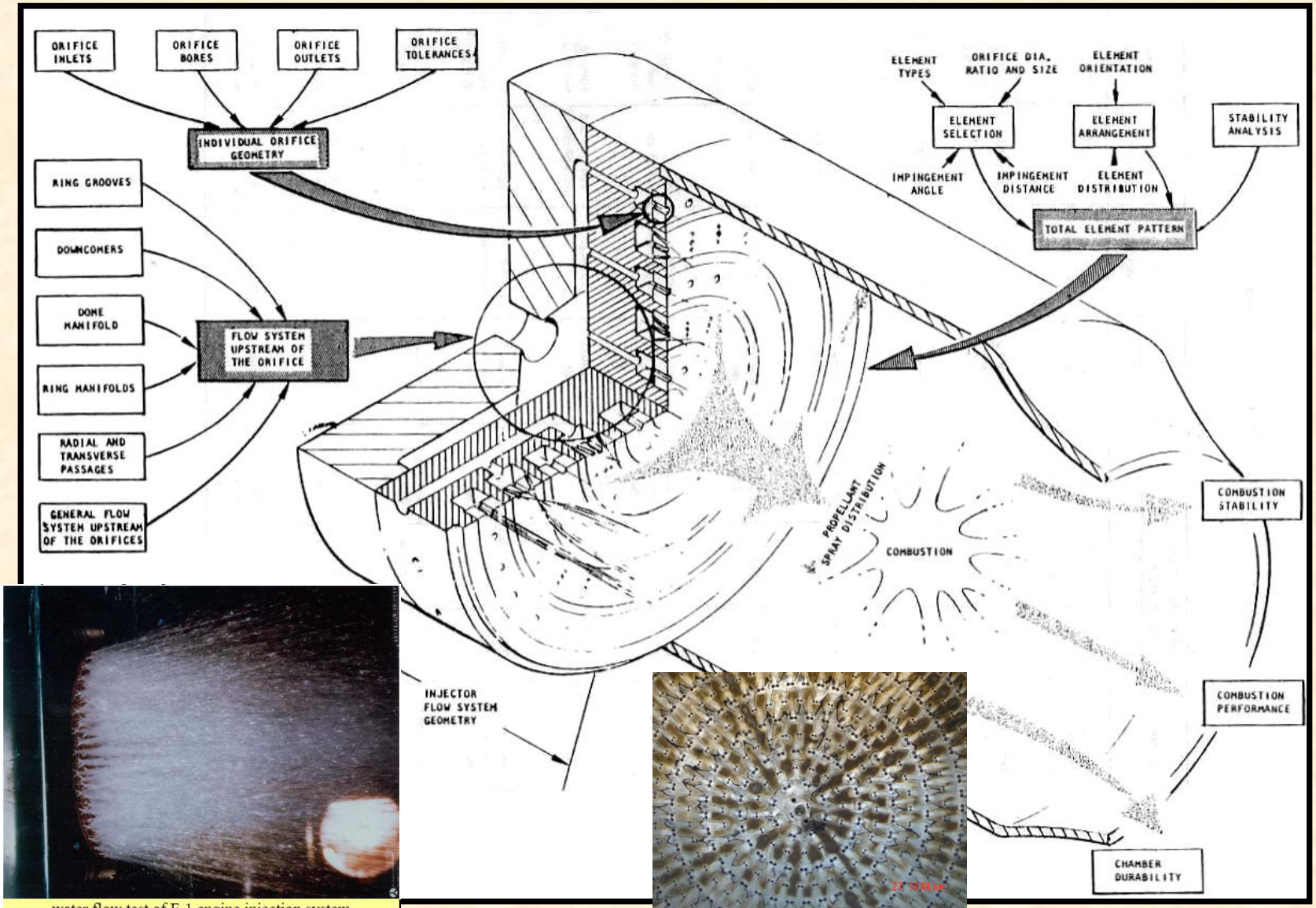
Overall Characteristics

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

- Diagnostics for combustion instability studies must then deal with the Following requirements
  - Deposits (soot, etc.) on the walls
  - High temperature
  - High pressure
  - Fast-response
  - Dense liquid spray

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Rocket Thrust Chamber



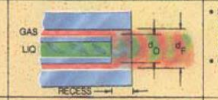
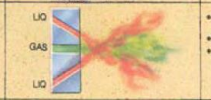
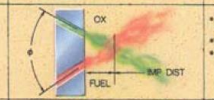
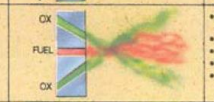
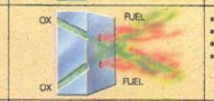
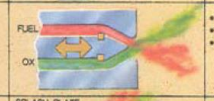
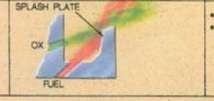
water flow test of F-1 engine injection system

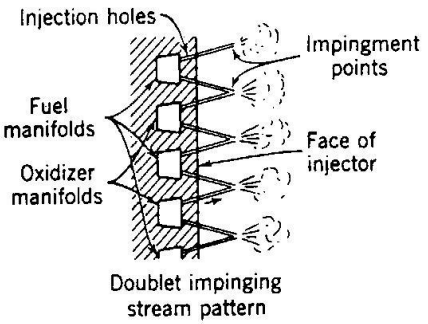
Rocket Engine Thrust Chamber

Bruce Chehroudi, Advanced Technology Consultants (www.AdvTechConsultants.com)

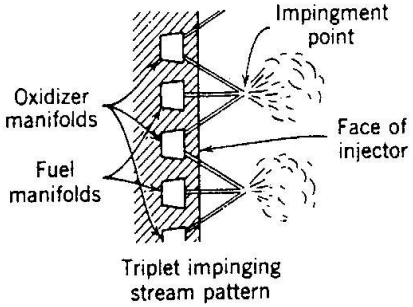
Major Kinds of Rocket Injectors

Common Injection Element Configurations

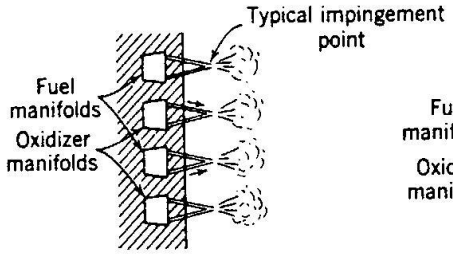
Element Designation	Element Configuration (Flow Direction)	Characteristics	Engine Application
Concentric Tube		• Very good wall compatibility • Very high performance with LOX/H_2 • Good stability characteristics with LOX/H_2 • Fuel is gas • Small annular gap requires care in fabrication and is sensitive to contamination	• Shuttle main and preburners • J-2 • Orbit Transfer Vehicle
Concentric Tube with Liquid Swirl		• Same as concentric tube except: • Improved mixing and atomization • More complex element • Stability characteristics in large engines unknown • Possible wall compatibility issue with some designs • Gas can also be swirled	• RL-10
Unlike Pentad (4 on 1)		• Applicable to very high or low mixture or density ratios • Good mixing and atomization • Difficult to manifold	• Experimental
Unlike Doublet (1 on 1)		• Good overall mixing and atomization (High Performance) • Simple to manifold • Subject to blowapart with hypergolic propellants	• LEM ascent engine • Delta launch vehicle • Almost all high response attitude control engines using storable propellants
Unlike Triplet (2 on 1)		• Good overall mixing and atomization (High Performance) • Symmetric spray pattern • Subject to blowapart with hypergolic propellants • Fuel can be gas • Pattern can be reversed	• Agena upper stage • Rocketdyne LEM descent engine design • LOX/RP-1 gas generators
Like Doublet (1 on 1)		• Easy to manifold • Excellent for chamber wall compatibility • Not subject to blowapart • Less effective atomization and mixing than unlike impinging elements	• Titan I and II first stage • Redstone, Jupiter, Thor, Atlas boosters • Shuttle OMES • H-1, F-1 engines
Showerhead		• Often employed for fuel boundary layer cooling of chamber wall • Easy to manifold • Poor atomization and mixing (Low Performance)	• Aerobee sustainer • X-15 • Pioneer
Variable Area (Pintle)		• Throttleable over wide range • Complex fabrication • Lower performance	• LEM descent engine • Lance sustainer
Splash Plate		• Less sensitive to design tolerances • Generally larger elements	• Lance booster (early version) • Saturn SIVB ullage control • Apollo CM RCS (SE-8) • Gemini SC maneuvering attitude control and reentry engines



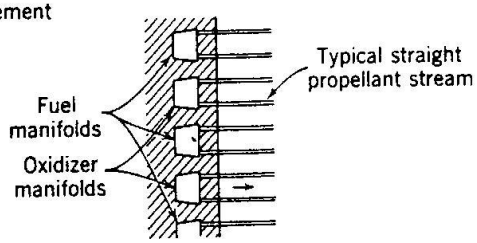
Doublet impinging stream pattern



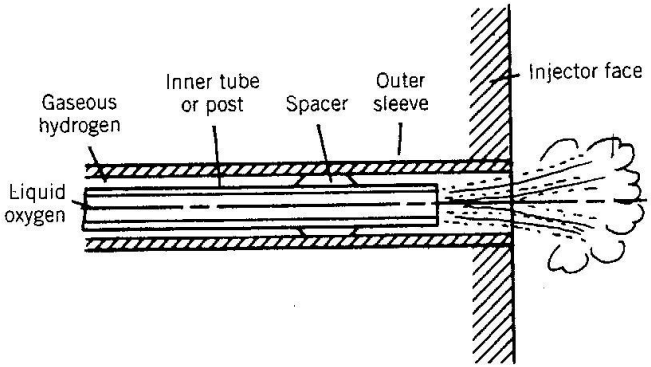
Triplet impinging stream pattern



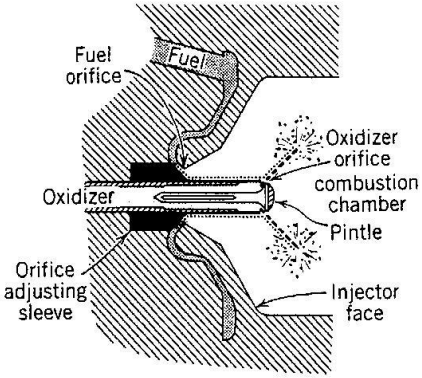
Self-impinging stream pattern



Shower head stream pattern



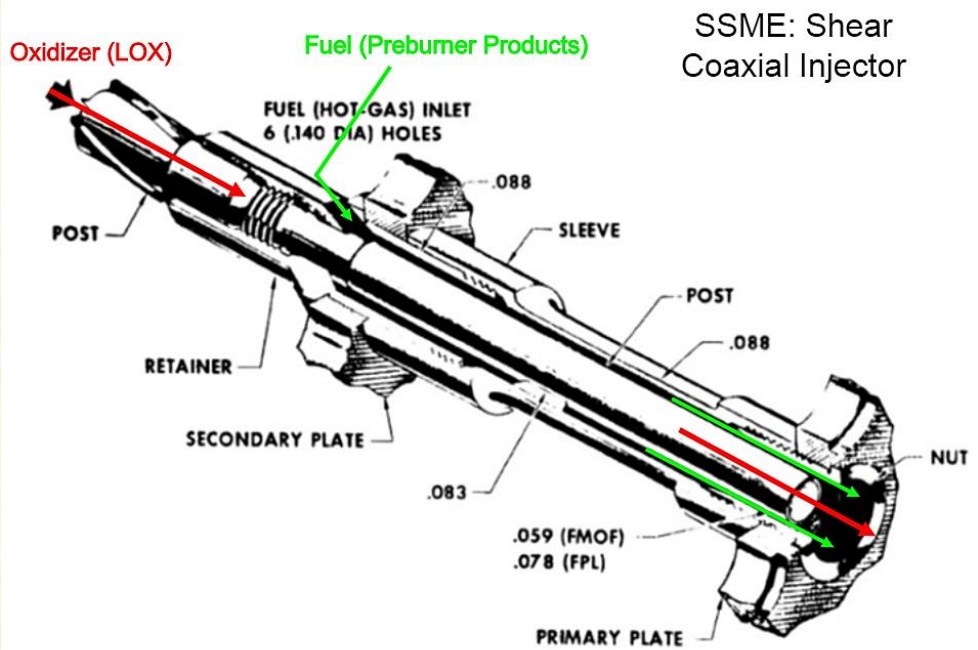
Hollow post and sleeve element



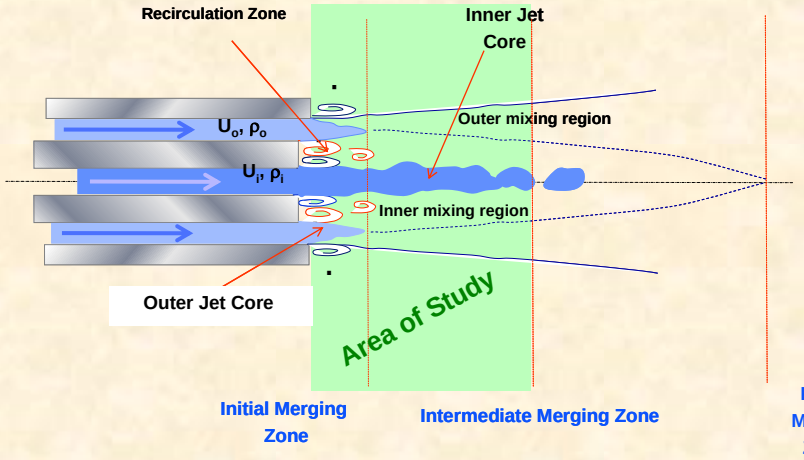
Variable injection area concentric tube injector

From Sutton, "Rocket Propulsion Elements," 6th ed., pg 299, Wylie 1992

SSME Coaxial Injector Element



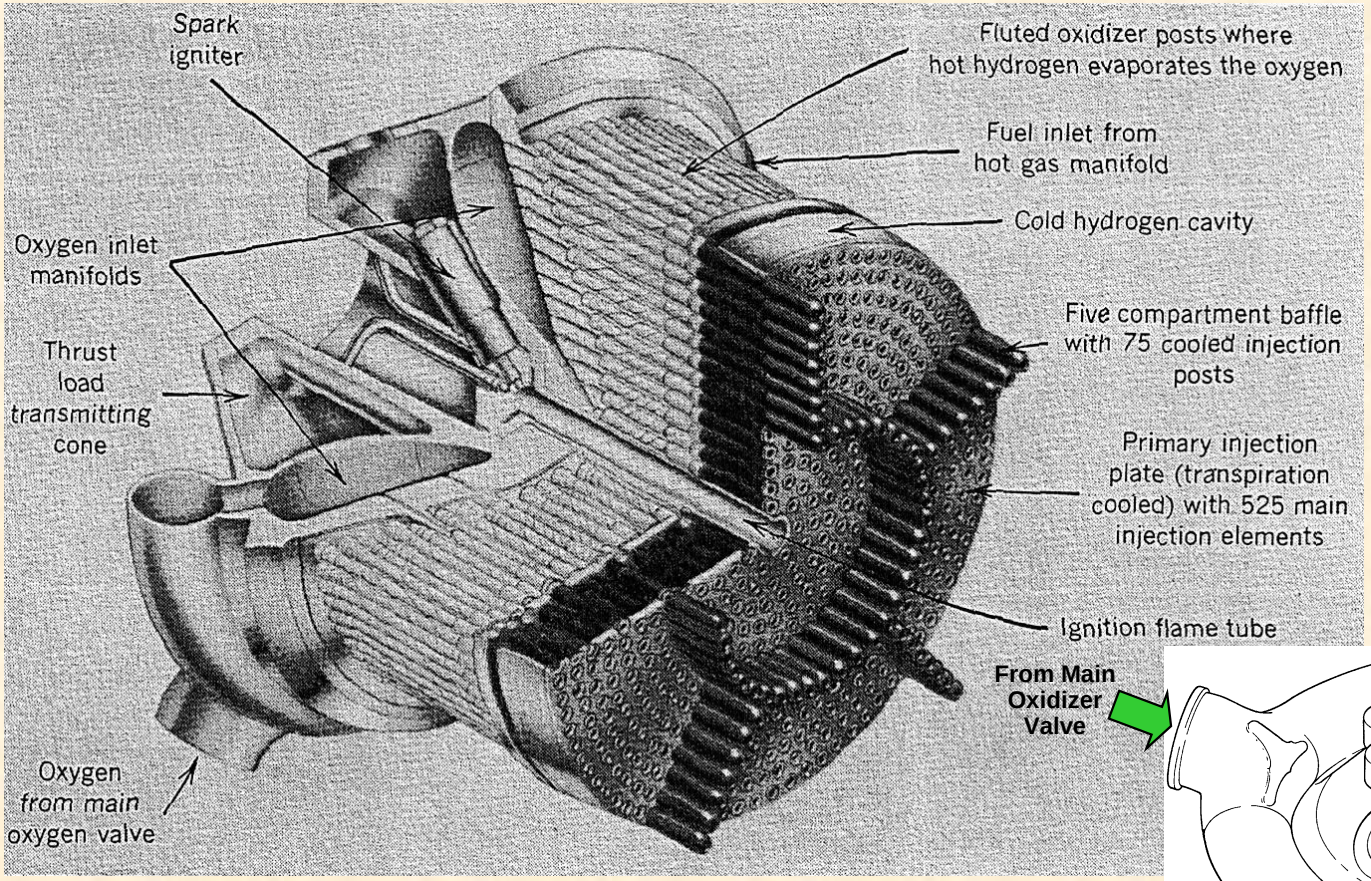
Lepore, Frank A., "Flow induced vibrations in the SSME injector heads," NASA CR-184209



AIAA 90-2186

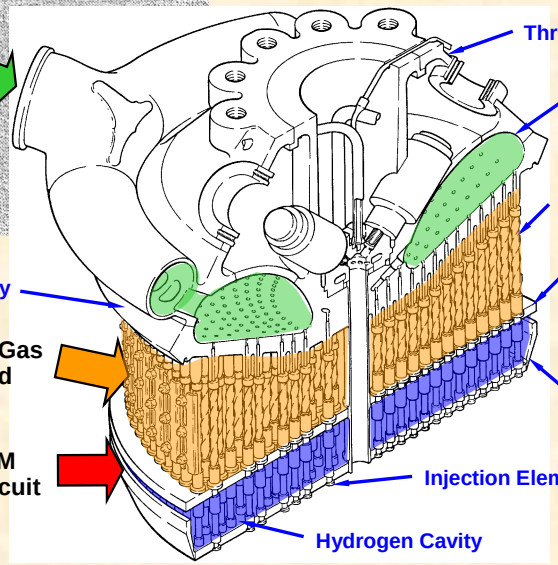
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Space Shuttle Main Engine Injector





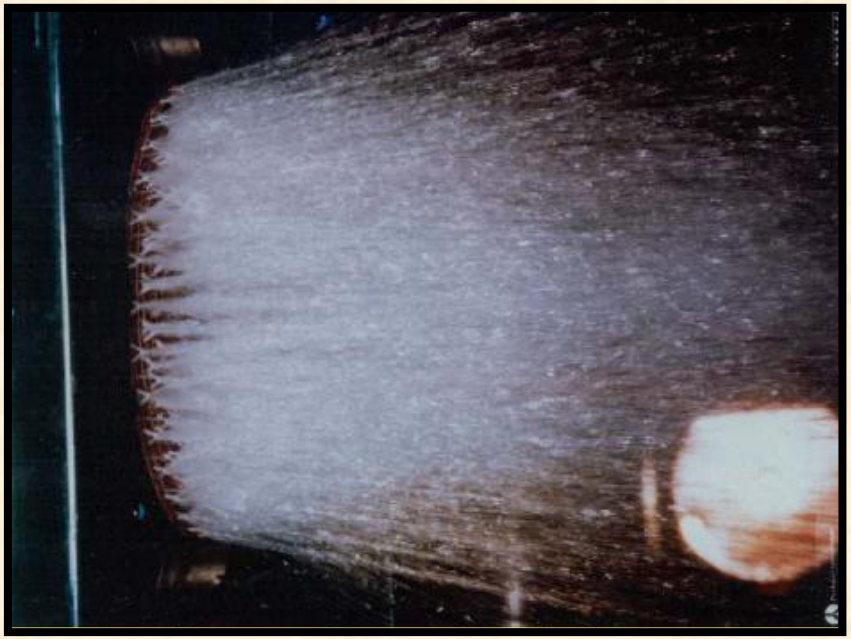
Coaxial Injector



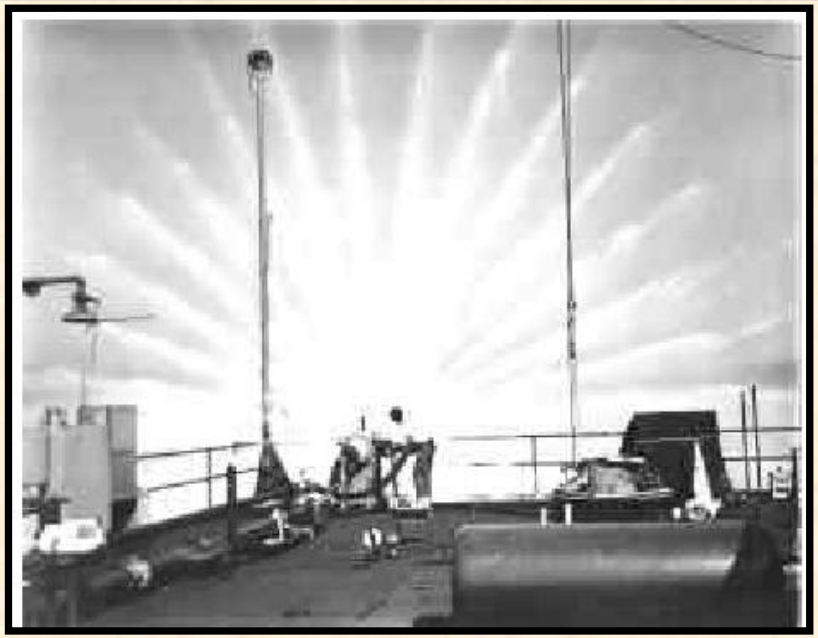
From Sutton, "Rocket Propulsion Elements," 6th ed., pg 277, Wylie 1992

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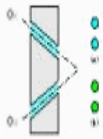
Water Testing Rocket Injectors

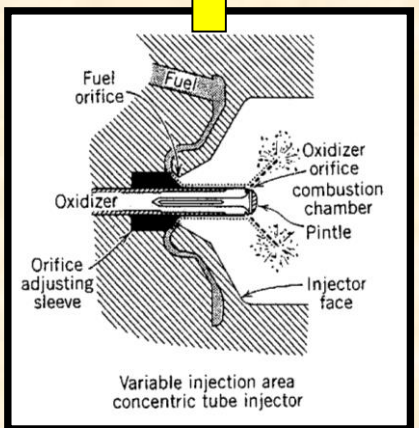


Water flow test of F-1 engine injector system



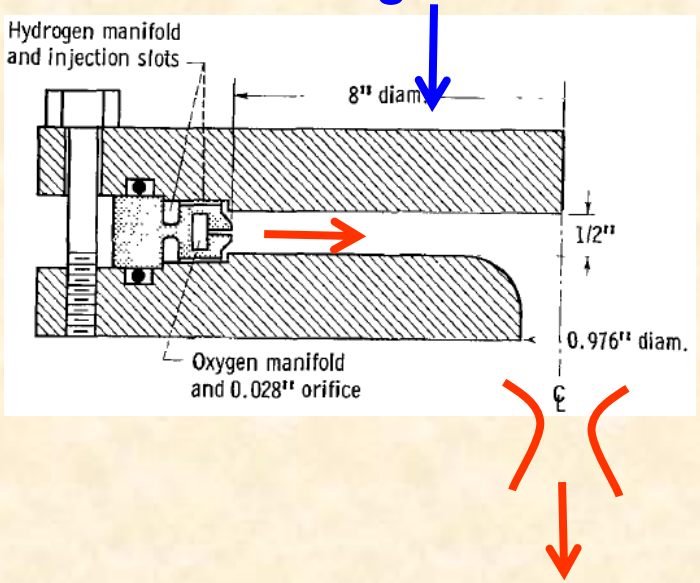
Water flow test of pintle injector for Air Force 250,000 lbf Engine

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

Combustion Instability in Liquid Rocket Engine (LRE)

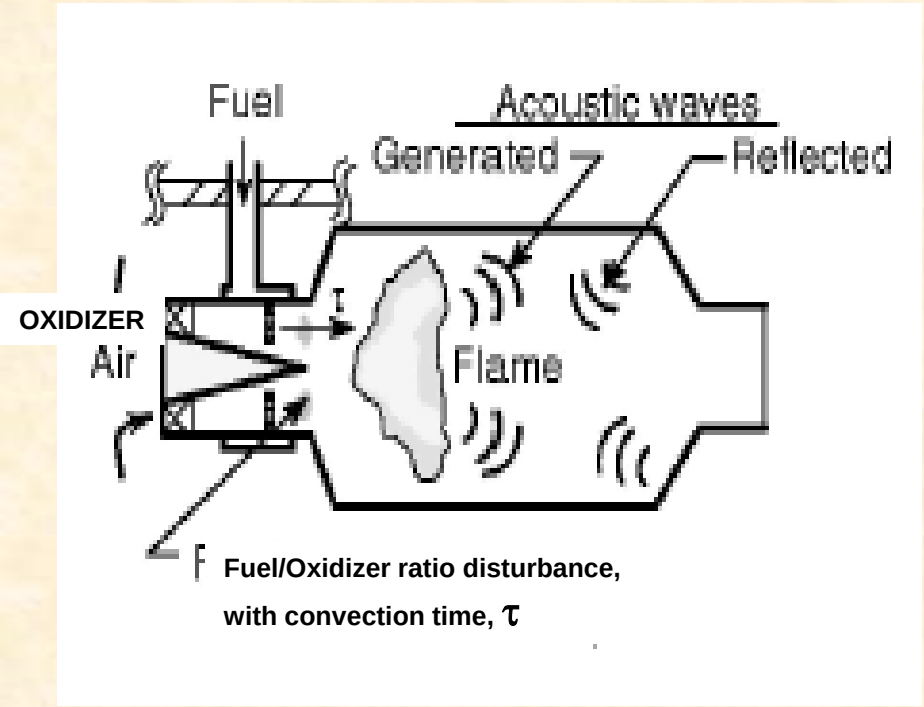


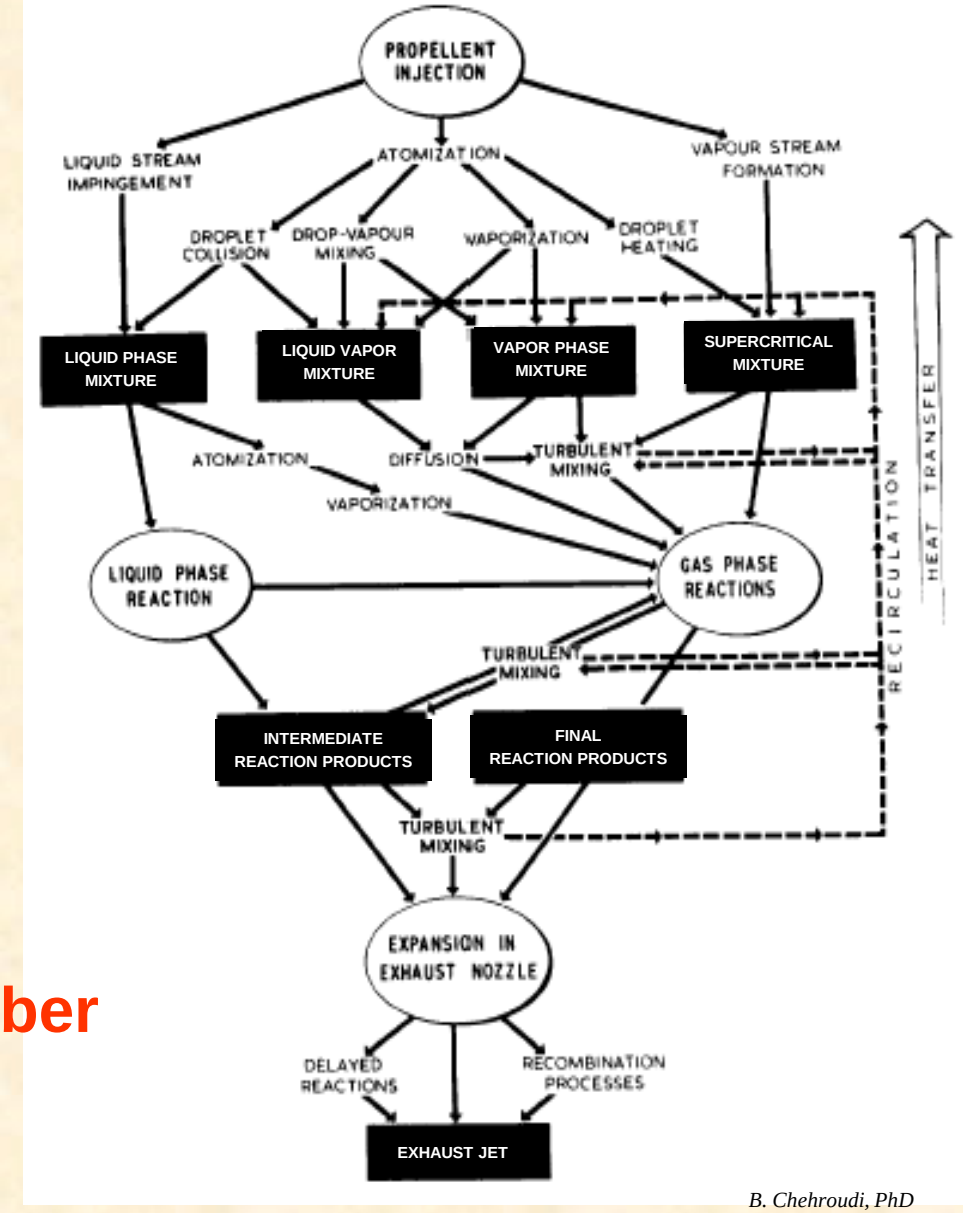


- The LOX core was found to decrease in length during a combustion instability event
- LOX core exhibits large-scale sinusoidal structure

Heidmann, NASA TN D-2725, 1965
NASA Lewis Film C-226, 1965

Combustion Instability:
Nature of the Problem





Rocket Engine Thrust Chamber

Combustion Instability:
Phenomenological Model (n-τ)

Amount of liquid converted to gas in the element dV in interval t to t+dt =

What was injected at the time t-τ in the interval d(t-τ)

$$w_l dV\ dt = \delta \dot{m}_i (t-\tau) d(t-\tau)$$

$$w_l = \overline{w}_l + w_l'$$

$$\tau = \overline{\tau} + \tau'$$

$$w_l' = \overline{w}_l n \left[\frac{p'(t)}{\overline{p}} - \frac{p'(t-\tau)}{\overline{p}} \right]$$

- $\dot{m}$ denotes the mass flow (mass/sec.) of the propellant.
- No distinction between fuel and oxidizer.
- The arguments based on the idea of a time lag are directed mainly to constructing a representation of the mass source term w_ℓ (mass/vol.-sec.) in the equation for conservation of mass.
- Intention: to express the rate of conversion of liquid to gas in a volume element of the chamber.
- No consideration of combustion processes in detail.
- Assumption:Combustion occurs instantaneously, a view that determines how the time lag model ought to be incorporated in the equations.

Mechanism of Acoustic Combustion Instability (CI) in Liquid Rocket Engines (LRE)

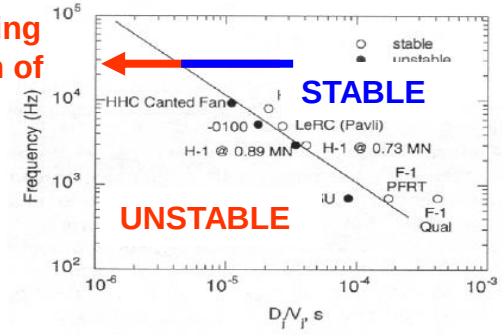
- **In LOX/H2 Engines (*Coaxial injector*; RL-10, J-2, J-2S; SSME). Conditions under which CI occurred more commonly (or inevitably):**
  - **Lower velocity ratio (VR) V_{H2}/V_{LOX}**
  - **Sufficiently low temperature of injected hydrogen (Temp Ramping)**
  - **Less recessed oxidizer tubes**
  - **Reduced injector pressure drop**
  - **True mechanism remains obscure**

- **In LOX/HC Engines (*Impinging jets injector*; mostly from F-1)**
  - **Sensitivity of jets and formation of spray fans to velocity fluctuations parallel to the injector face**
  - ***Hewitt correlation* suggests certain injector parameters (d/V)**
  - **Others (resurge, etc.)**

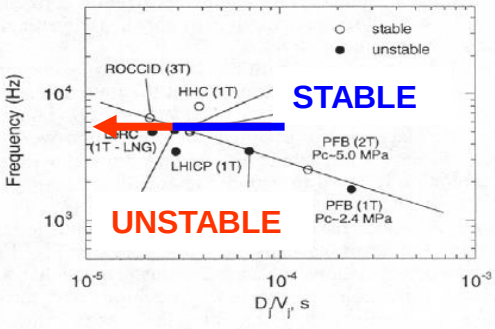
3.3 Mechanisms in LOX/HC Engines

- 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.

Decreasing direction of d/V



Like-doublet injector (LOX/HC)

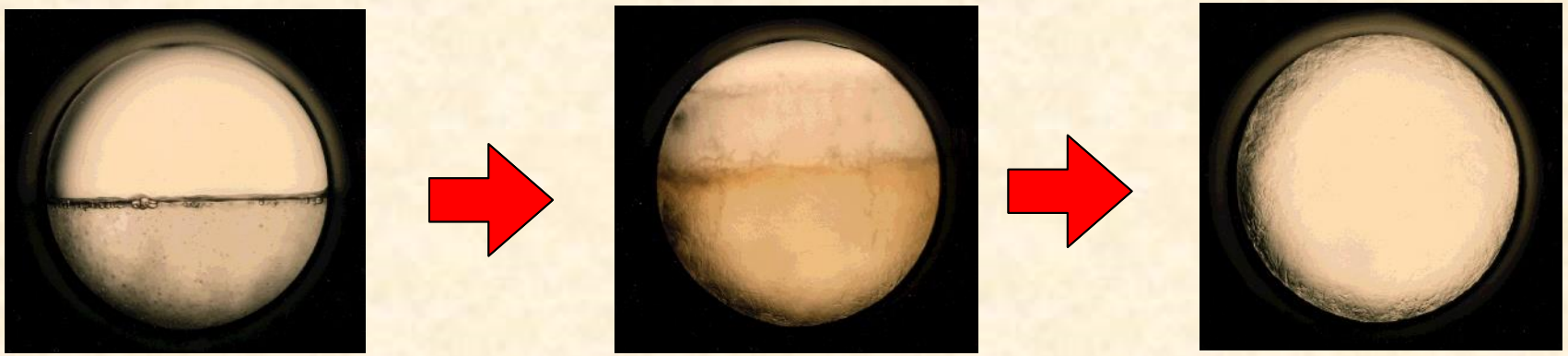


O-F-O injector (LOX/RP-1)

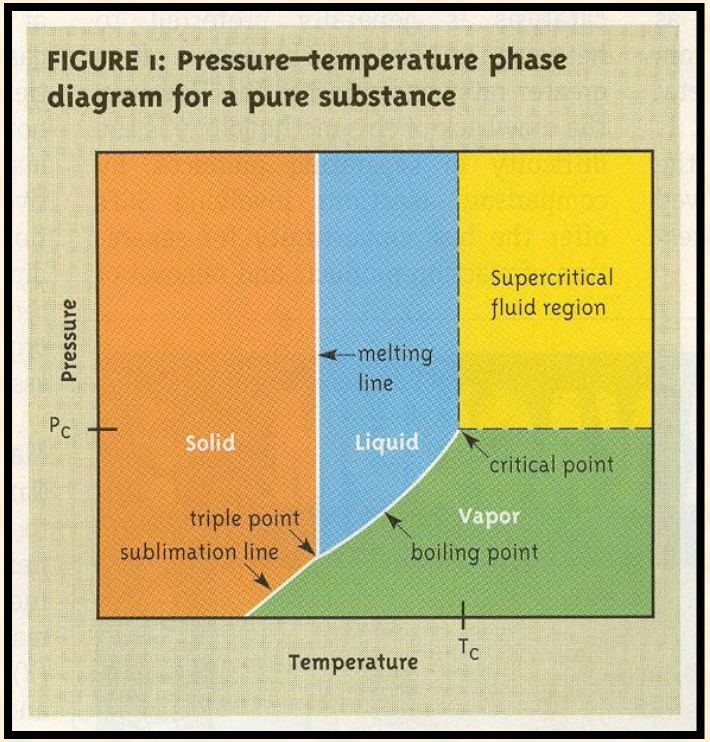
- These results are related to the dynamics of injectors but there is no associated modeling.

From Prof. F. Culick, CalTech

Thermodynamic Critical Point



- Very large C_p at Critical Point (CP)
- Surface tension vanishes
- Heat of vaporization vanishes above CP
- Distinction between liquid and gas phases disappears above CP
- For mixtures: Critical mixing T & P (critical lines for 2-component)



Chehroudi, B., 2006. Supercritical Fluids: Nanotechnology and Select Emerging Applications, *Invited Review Paper*, special volume dedicated to Supercritical Fluids, *Combustion Science and Technology*, Vol. 178, No. 1-3, January 2006, pp. 555-621(67).

More Information on Emerging Applications of Supercritical Fluids

Combust. Sci. and Tech., 178: 555–621, 2006
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ISSN: 0010-2202 print/1563-521X online
DOI: 10.1080/00102200500294247

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SUPERCRITICAL FLUIDS: NANOTECHNOLOGY AND SELECT EMERGING APPLICATIONS

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In this paper, a selected list of emerging applications of supercritical fluids (SCFs) are presented. In particular, demonstrated facts for the promise of the nanoscale science and technology and its overlap or interface with the SCFs technology are presented. It is argued that nanoengineered materials at the nanoscale have mechanical, optical, chemical, and electrical properties quite different from the bulk material. Examples of enhanced performance of many such materials when they are used in practical applications are given. SCFs, in particular carbon dioxide, on account of their special properties such as zero surface tension, low viscosity, and high solubility, enable them to play a critical role in many advanced technology applications. For example, as miniaturization efforts approach the nanoscale, surface tension forces become an important factor in many nanotechnology processes such as lithography in the electronic industry. In particular, the zero-surface-tension property of the SCFs presents them as a natural choice for nanotechnology

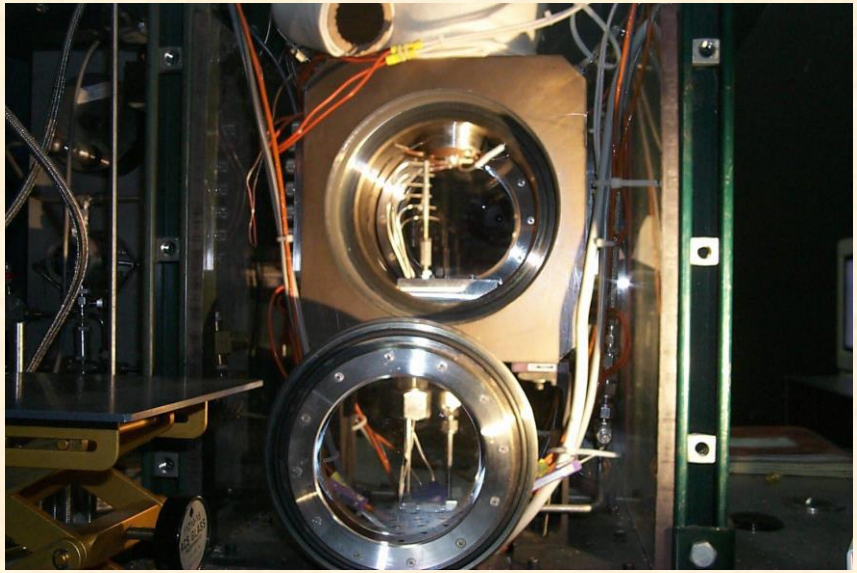


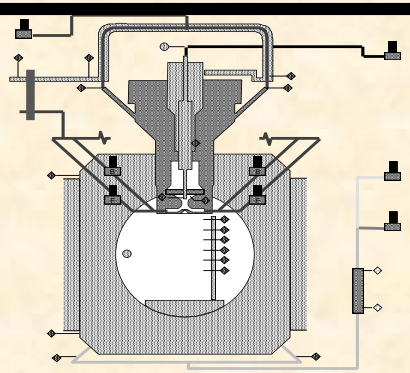
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http://www.informaworld.com/smpp/title~content=t713456315
SUPERCRITICAL FLUIDS: NANOTECHNOLOGY AND SELECT EMERGING APPLICATIONS
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[a] Engineering Research Consultants, Lancaster, California, USA

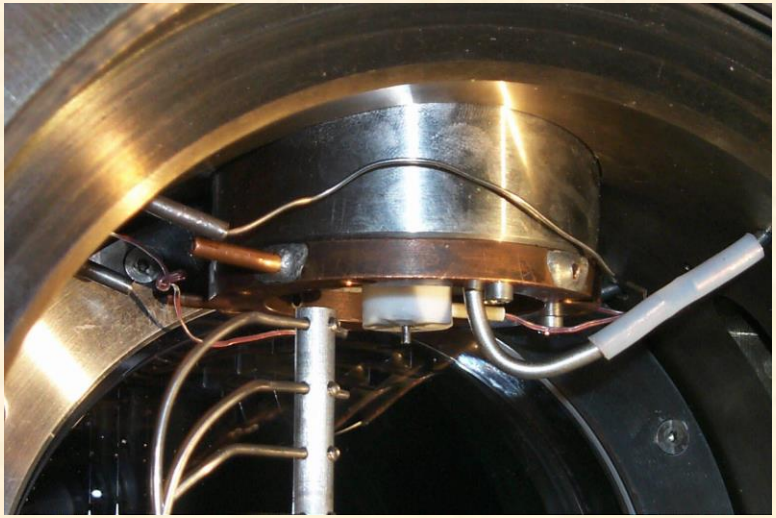
Online Publication Date: 01 January 2006
To cite this Article: Chehroudi, B. (2006) 'SUPERCRITICAL FLUIDS: NANOTECHNOLOGY AND SELECT EMERGING APPLICATIONS', Combustion Science and Technology, 178:1, 555 - 621
To link to this article: DOI: 10.1080/00102200500294247
URL: http://dx.doi.org/10.1080/00102200500294247

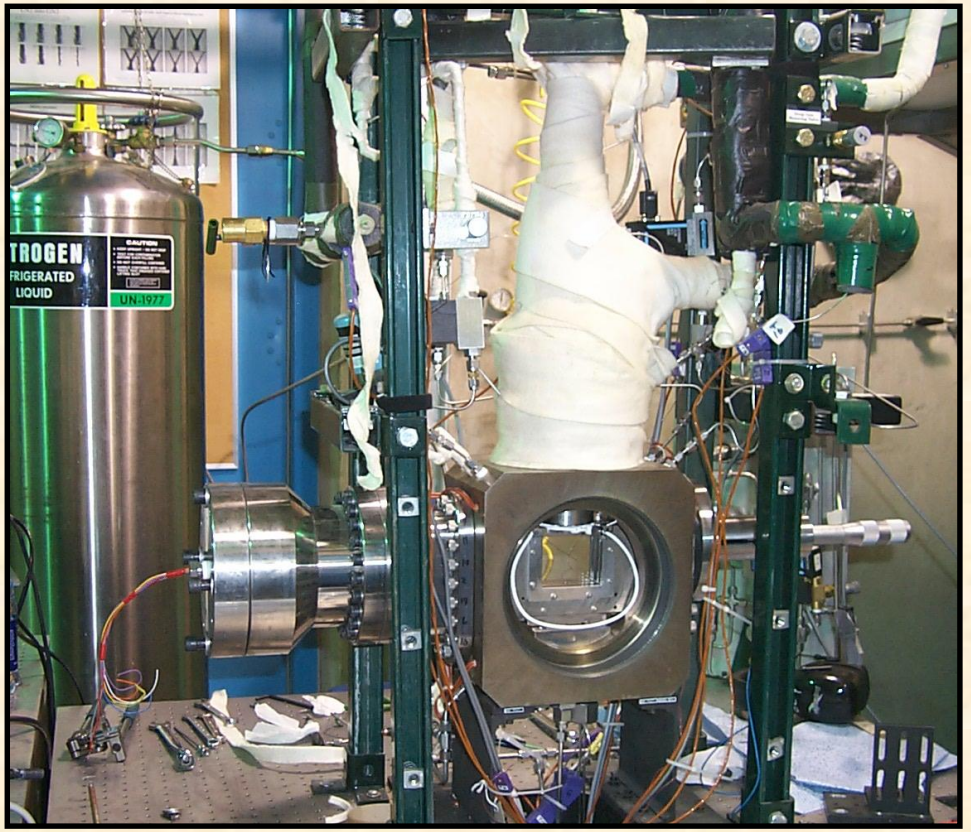
It is not just a "phenomenon", it is a "technology"

Injector Assembly and High-Pressure Chamber









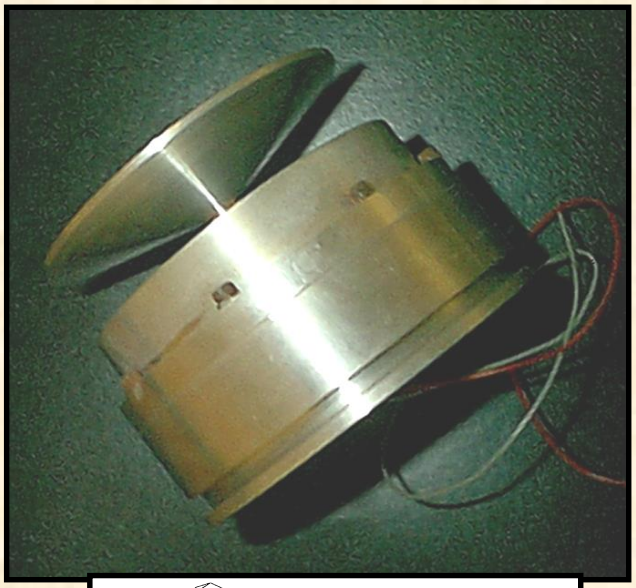
Bruce Chehroudi, Advanced Technology Consultants (www.AdvTechConsultants.com)

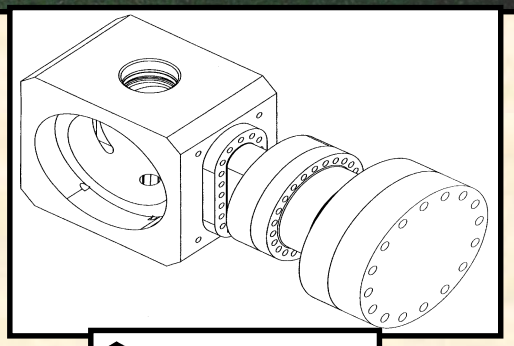
PiezoSiren for Acoustic Field Generation

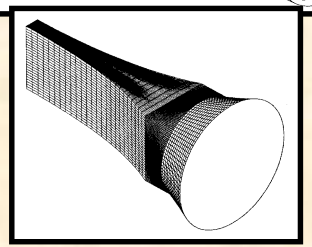
Circular-to-Rectangle Waveguide



PiezoSiren







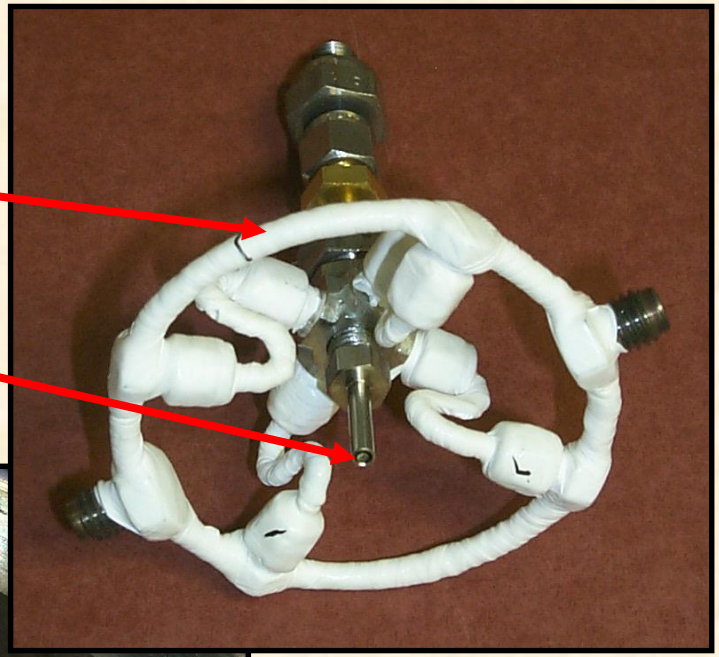
- PiezoSiren generates up to 180 dB SPL
- Designed to operate under high pressure
- Several resonance frequencies
- Most dominant are at ~ 2700 and ~4800 Hz
- The acoustic waves are channeled through a specially designed waveguide

Bruce Chehroudi, Advanced Technology Consultants (www.AdvTechConsultants.com)

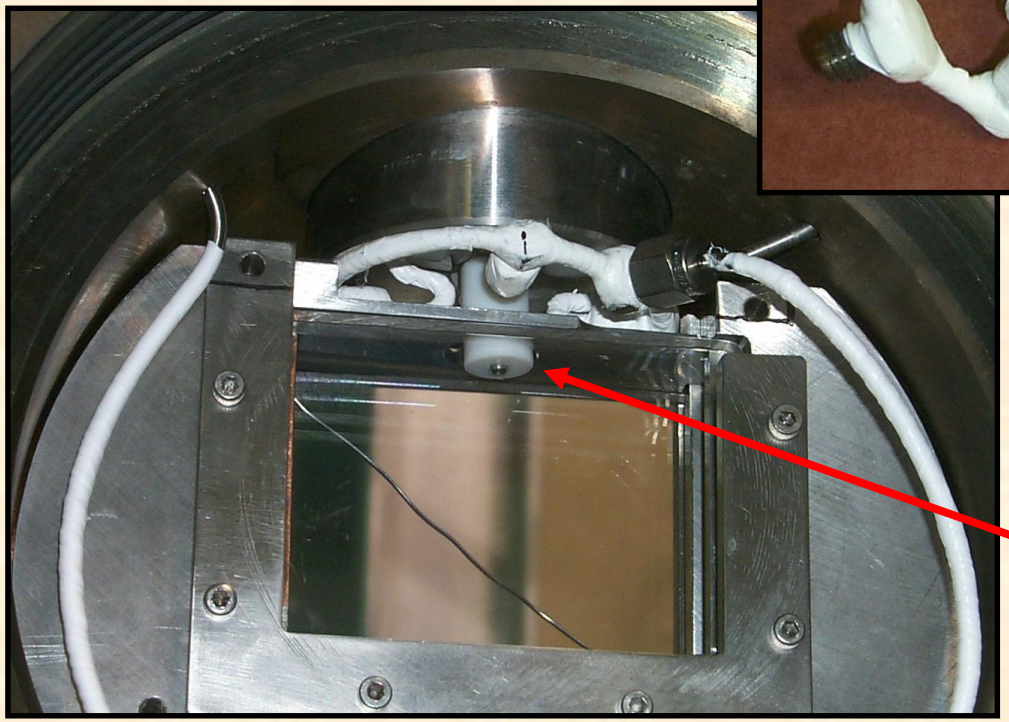
Coaxial Injector

Manifold for gaseous co-flow distribution

Injector tip

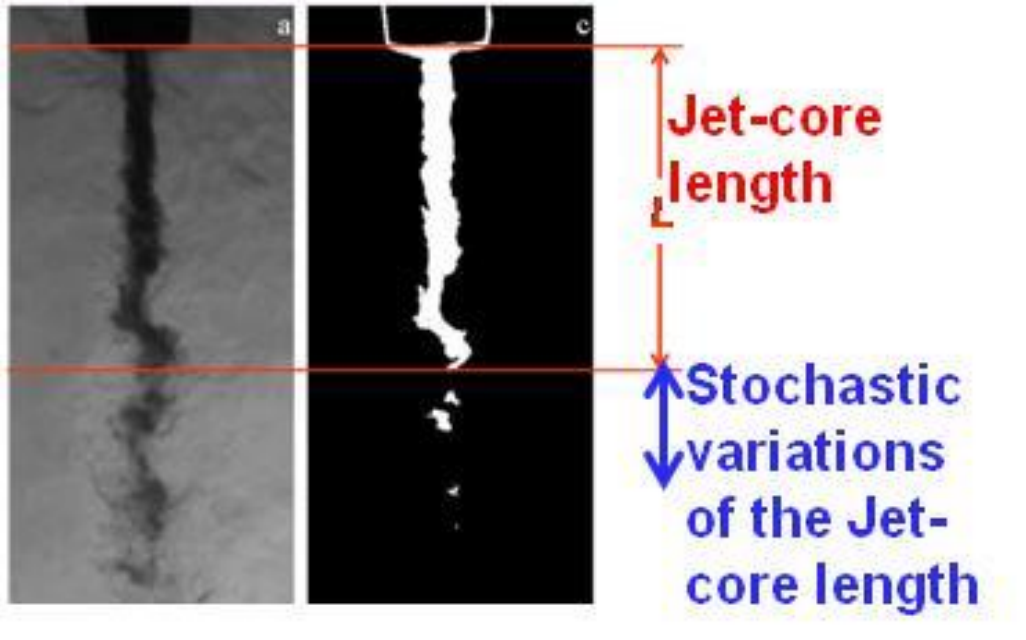






Injector and its holder inside the chamber

Dark Core Characteristics is the Key:
Physical Interpretation



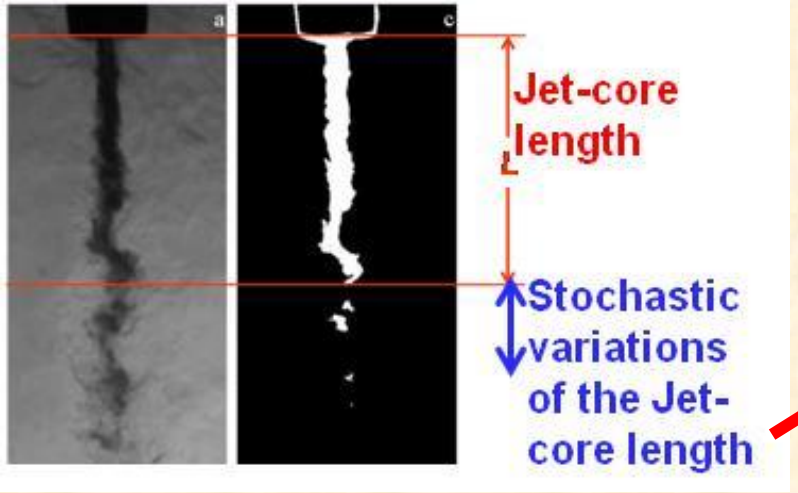
Root mean square (RMS) of the dark core length oscillations as

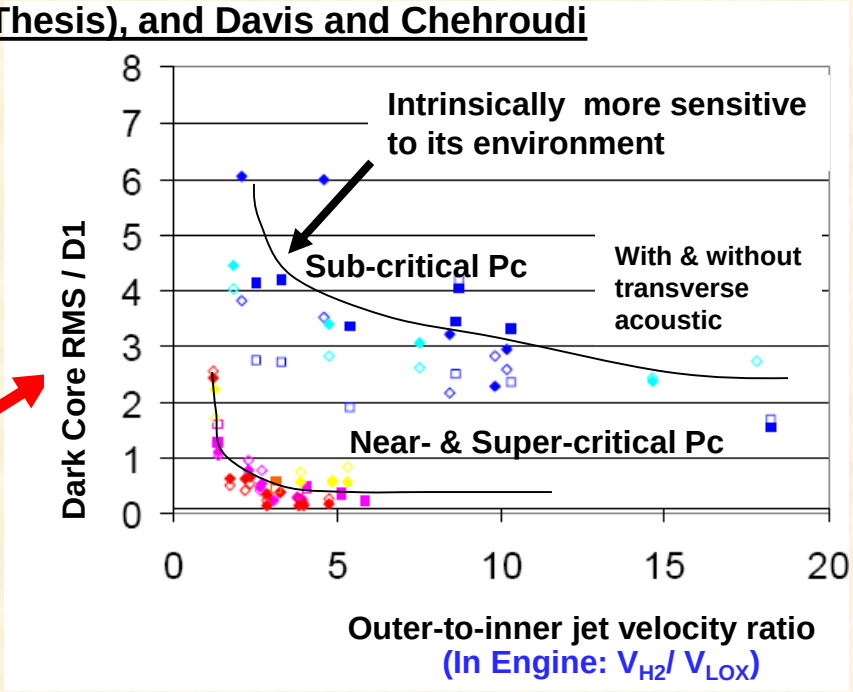
- **A reflection of mass fluctuations (first order approximation)**
- **Indication of *intrinsic sensitivity* of the injector**

Dark Core Characteristics is the Key

Non-reacting Coaxial Jet & Connection to Multi-Element LRE

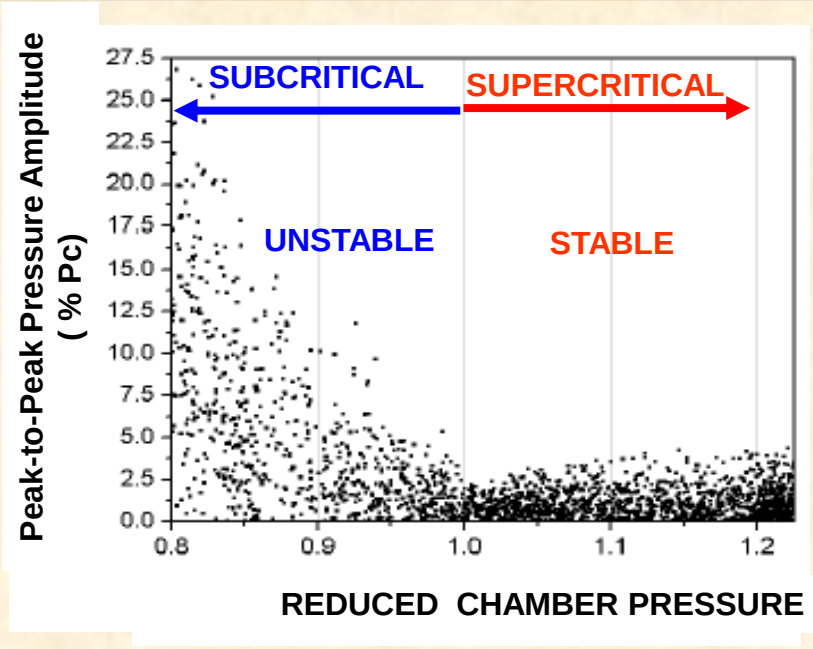
From AFRL & PennState: Davis (PhD Thesis), and Davis and Chehroudi





- **RMS of the core length variations is much higher at subcritical chamber pressure at all velocity ratios**
  - ***Intrinsic (higher) sensitivity* at subcritical**
- **Lower RMS at high velocity ratio offered a possible explanation for the enhanced stability observed in LRE** (at high V_{H2}/V_{LOX})
- **Temperature ramping** (for LRE stability rating) **was linked to its impact on the velocity ratio and hence core length RMS offered an explanation**

Dark Core Characteristics is the Key
Fired Single-Element LRE



From: DLR group, Germany

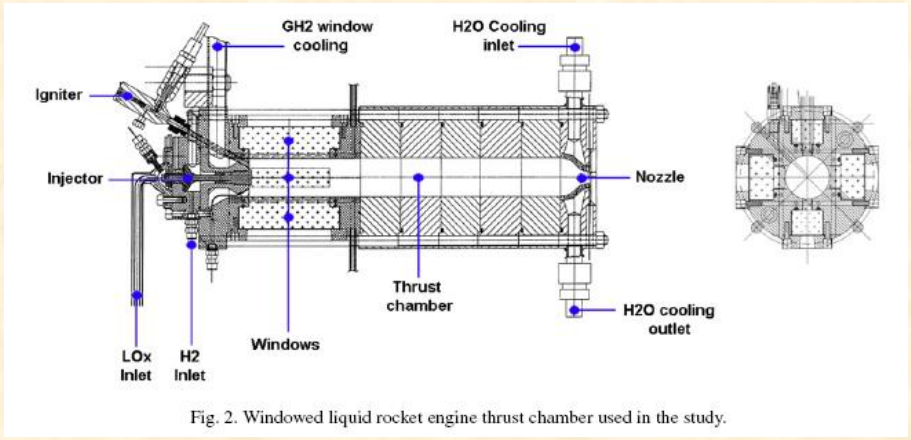


Fig. 2. Windowed liquid rocket engine thrust chamber used in the study.

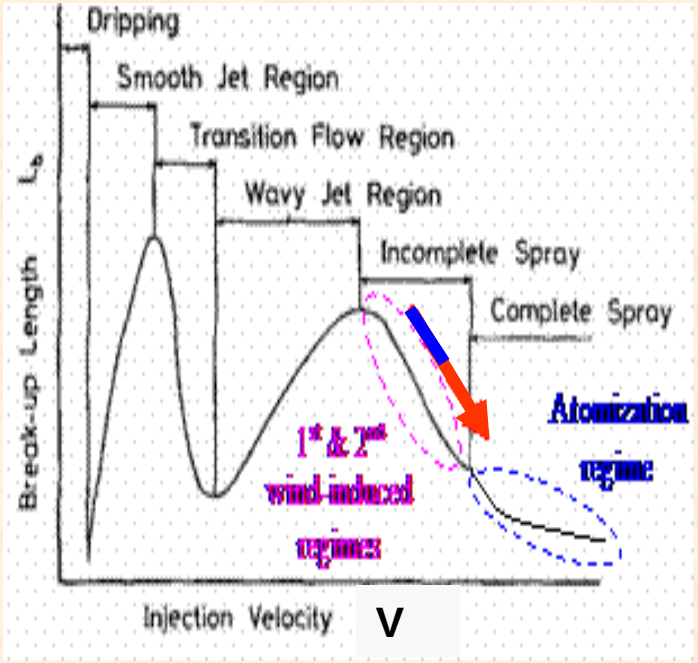
- **Under all conditions, no instability could be triggered when operating above or very close to the critical point of oxygen** (consistent with nonreacting jet's *intrinsic sensitivity* at subcritical)
- **Significantly different dynamic behavior for subcritical as compared to near- & super-critical**
- **Also, results from Santoro's group at Penn State (**Woodward et al.**) in *fired engine* are consistent with observations at AFRL (see paper for details)**

***Fired-engine* experimental observations consistent with Davis & Chehroudi (done in *non-reacting* supercritical facility at AFRL)**

Dark Core Characteristics is the Key

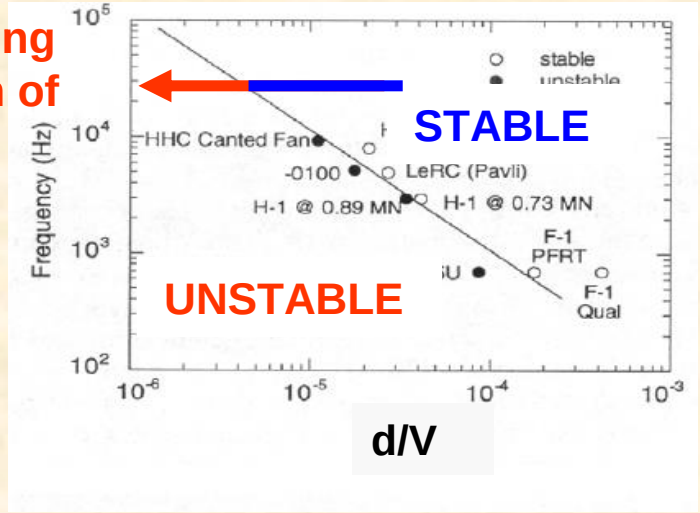
Impact of d/V on Dark Core & Connection to Multi-Element LRE Stability

REITZ & BRACCO AND HIROYASU BREAKUP (DARK CORE) LENGTH FOR SINGLE-HOLE NJECTOR



HEWITT STABILITY PLOT FOR IMPINGING JET INJECTORS in MULTI-ELEMENT ROCKETS

Decreasing direction of d/V



Single & Impinging Jets:

- **As "V" increases, the dark-core (or breakup) length decreases**
- **As "d" decreases dark core length decreases** ***(****not shown here, see Chehroudi et al. equation. See SAE Trans. Paper 850126****)***
- **As "d/V" declines (and engine moves into unstable regime by Hewitt), the dark core length for each jet (of the impinging jet) decreases & an impinging jet system becomes more sensitive**

Dark Core Characteristics is the Key

Intrinsic Sensitivity of Non-Reacting Impinging Jet Injector at Low d/V values

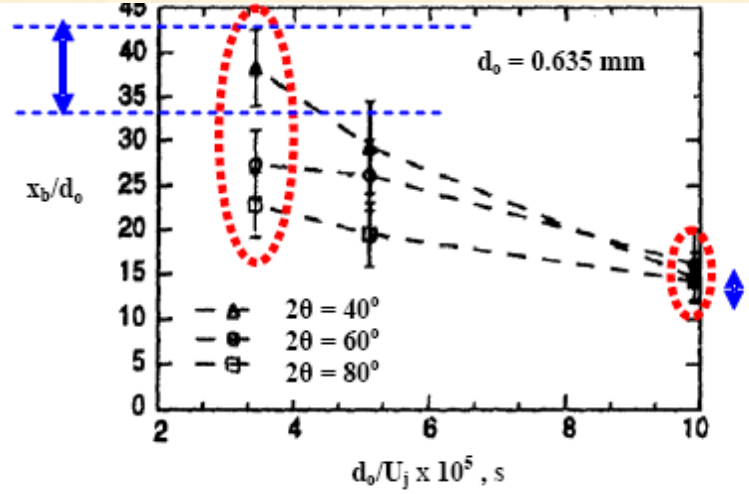


Figure 8. Shows *sheet breakup length* as a function of instability parameter at three different impingement included angles. Much higher sensitivity of the *sheet breakup length* is seen with included angle (2θ) at low dn/V (= d_o/U_j, in the original article) values. Anderson et al. [13].

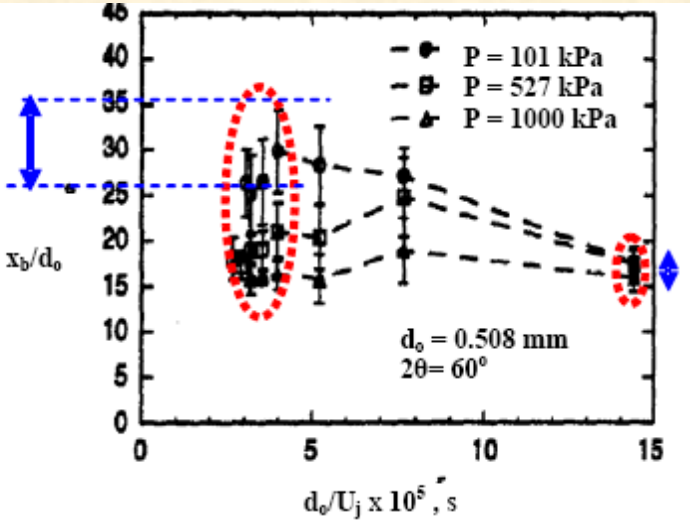
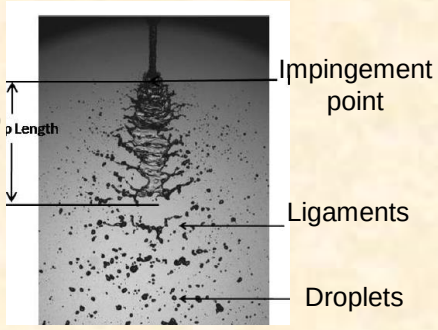


Figure 9. Shows *sheet breakup length* as a function of instability parameter at three different chamber pressures. Much higher sensitivity of the *sheet breakup length* is seen with chamber pressure at low dn/V (= d_o/U_j, in the original article) values. Anderson et al. [13].

Impinging Jets:

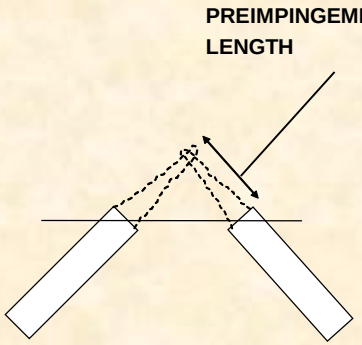
- **PennState work in non-reacting setup (*Anderson et al.)***
  - **Higher sensitivity at lower values of d/V**
  - **Higher sensitivity to chamber pressure at low values of d/V**
  - **Intrinsic stability of the impinging jet injector at low d/V values**
    (for more details see paper)



Dark Core Characteristics is the Key

Comparable Preimpingement Length and Dark Core Length

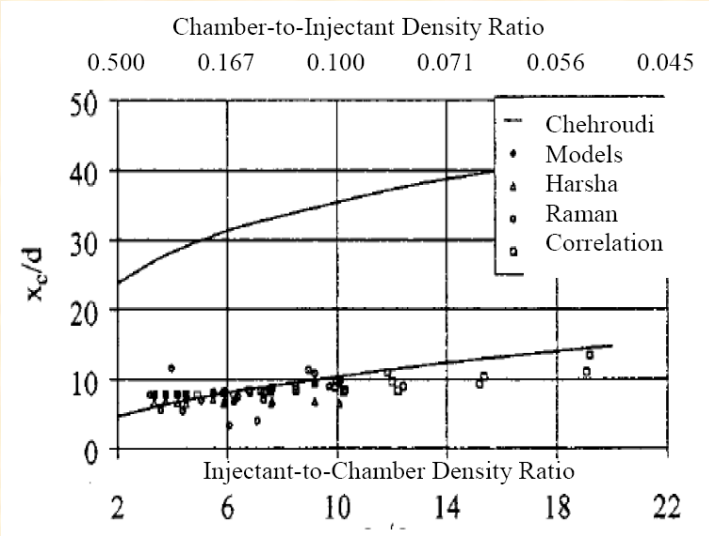
PREIMPINGEMENT LENGTH



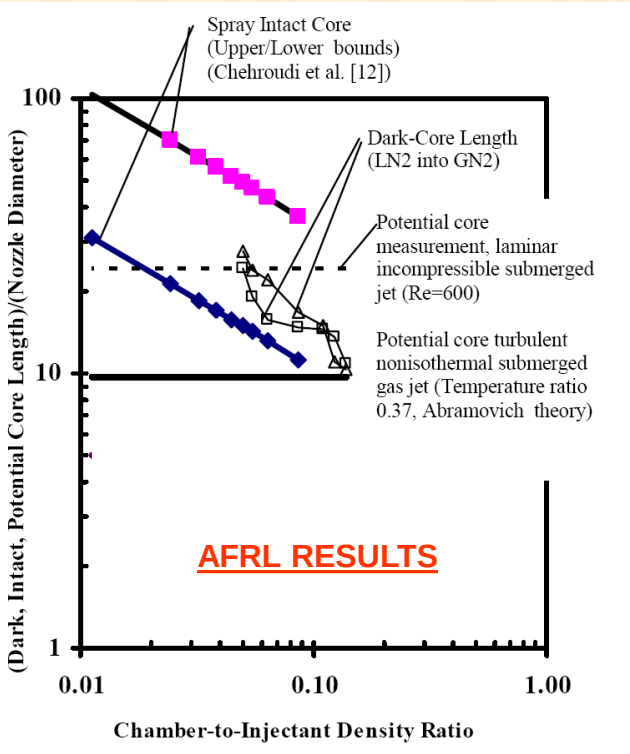
IMPINGING JETINECTOR LRE

DARK CORE LENGTH SINGLE-HOLE CRYOGENIC NJECTOR

(Single Jet)



DLR RESULTS



AFRL RESULTS

Single & Impinging Jets:

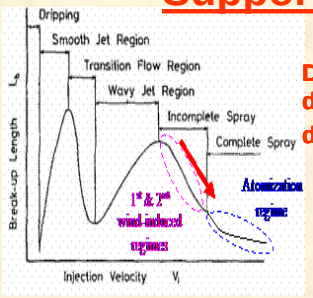
- **Cryogenic, sub- and super-critical conditions (AFRL data)**
- **Similar and comparable DLR data**
- **It is shown that the pre-impingement distance (for impinging-jets injectors) in production (LRE) engines is comparable to the measured dark core lengths (for cryogenic jets)**

Supporting Information for a Proposed Hypothesis

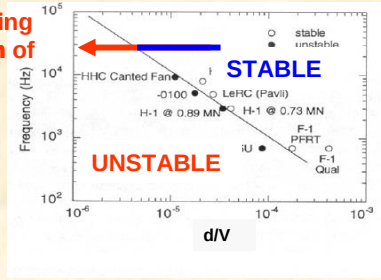
A Hypothesis:

The Hewitt stable-to-unstable transition point (or line) as d/V reduces is at or near where the dark core length reaches a critical value, being comparable to the distance from the holes exit plane (of the impinging injector) to the impinging point (i.e., the pre-impingement length).

Supporting Information



Decreasing direction of d/V



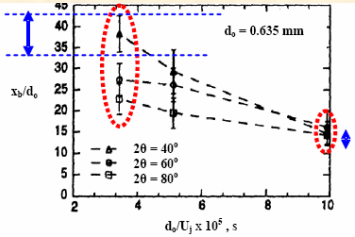


Figure 8. Shows *sheet breakup length* as a function of instability parameter at three different impingement included angles. Much higher sensitivity of the *sheet breakup length* is seen with included angle (2θ) at low dn/V (= d_o/U_j, in the original article) values. Anderson et al. [13].

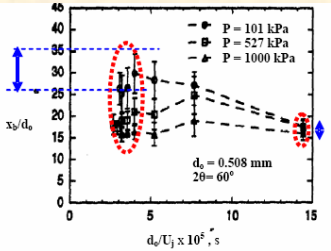
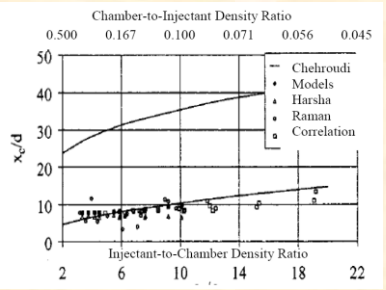
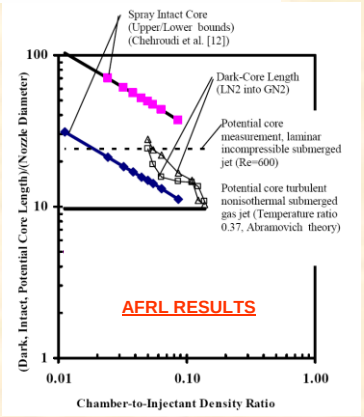


Figure 9. Shows *sheet breakup length* as a function of instability parameter at three different chamber pressures. Much higher sensitivity of the *sheet breakup length* is seen with chamber pressure at low dn/V (= d_o/U_j, in the original article) values. Anderson et al. [13].



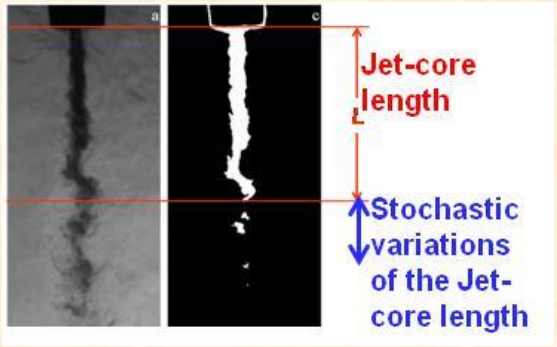
DLR RESULTS

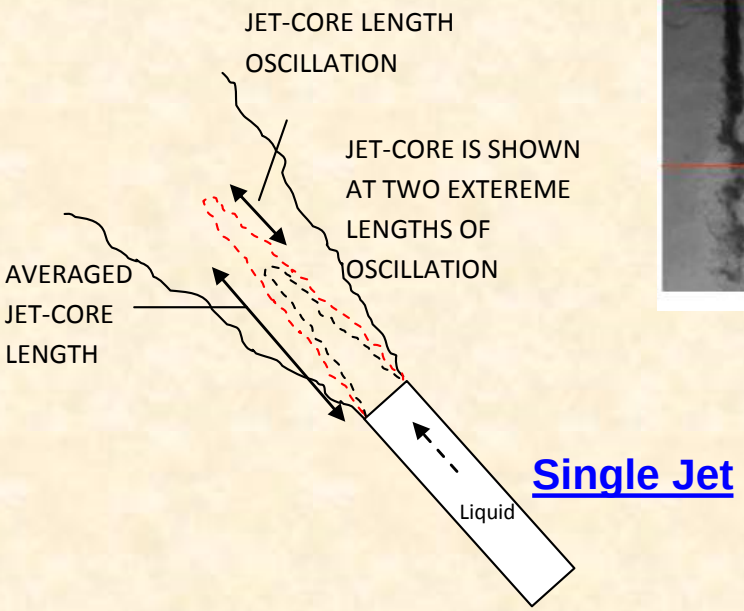


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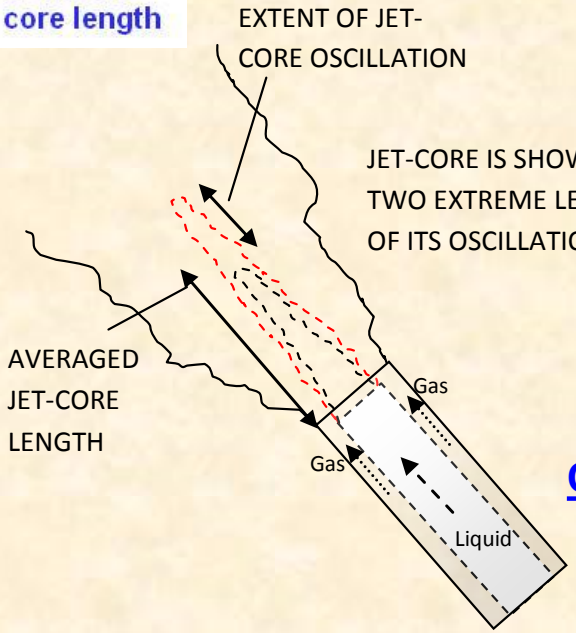
A Unified Injector Sensitivity Theory

Single Jet and Coaxial Jet Injectors





Single Jet

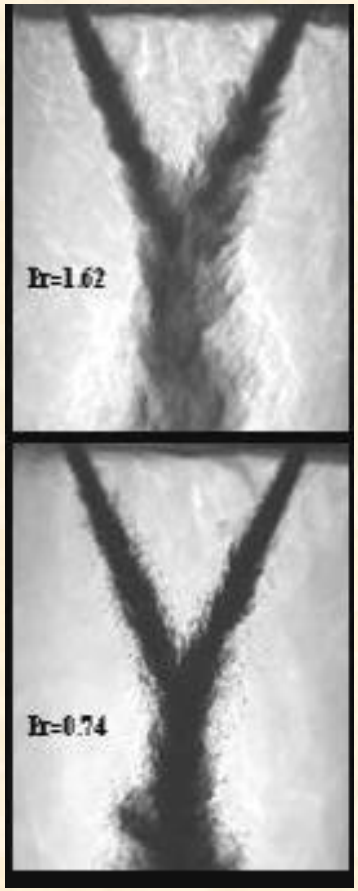


Coaxial Jet

Key Components of the *Unified Theory*

A Unified Injector Sensitivity Theory
Impinging Jet Injector

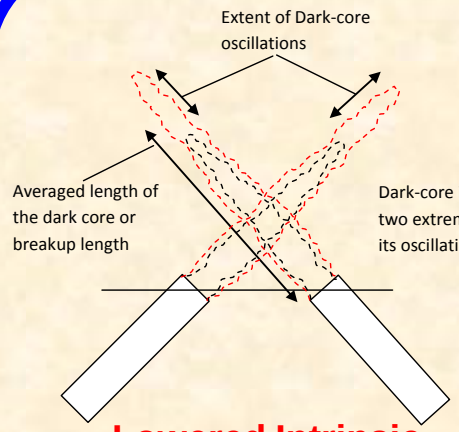
Key Components of the *Unified Theory*



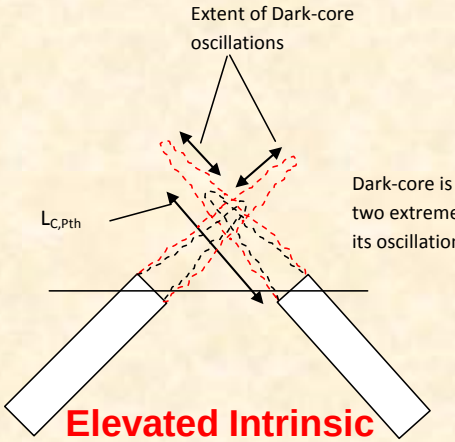
P_r = 1.62
SUPER-CRITICAL

P_r = 0.74
SUB-CRITICAL

The Hypothesis



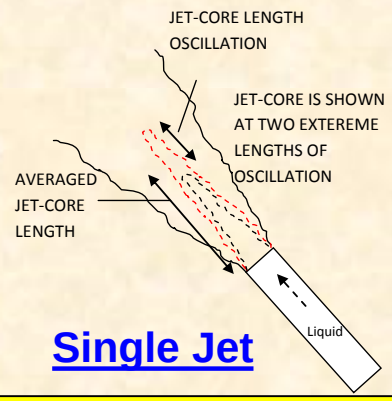
Lowered Intrinsic Sensitivity (e.g., for LOL)



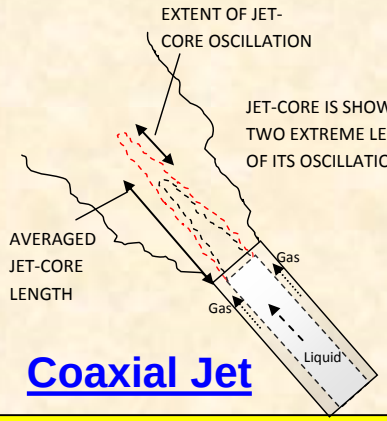
Elevated Intrinsic Sensitivity (e.g., for LOL)

Impinging Jets

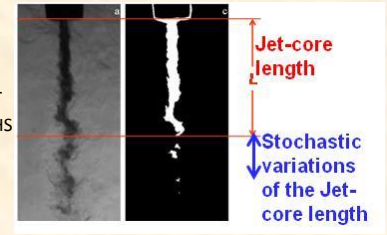
A Unified Injector Sensitivity Theory



Single Jet

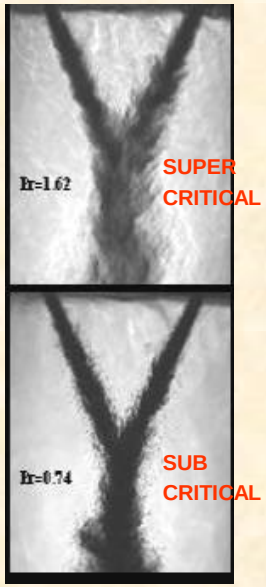


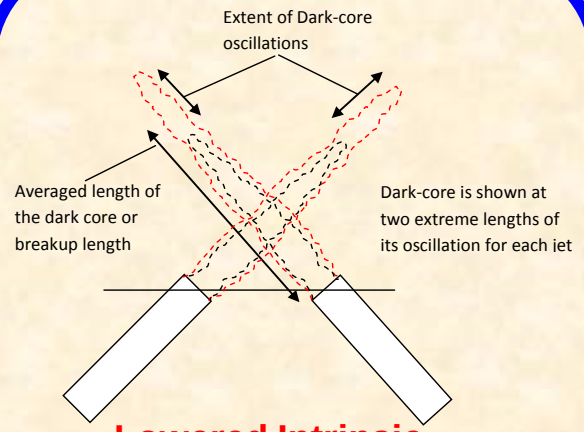
Coaxial Jet



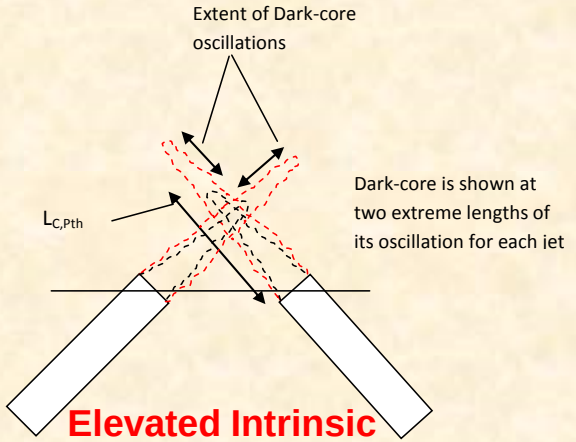
Key Components of the *Unified Theory*:

1. **All share a "dark core" with Mean & RMS, suggesting a unified approach for intrinsic sensitivity of the jet to its environment**
2. **When an important dynamic feature (dark-core or breakup zone) of an injector design becomes sufficiently sensitive to thermofluid parameters of its environment, it is highly likely that this could strengthen the feedback link thought to be critical in the amplification process and hence move the dynamic system into an unstable operating regime.**
3. **See schematic diagram of hypothesis**





Lowered Intrinsic Sensitivity (e.g., for LOL)

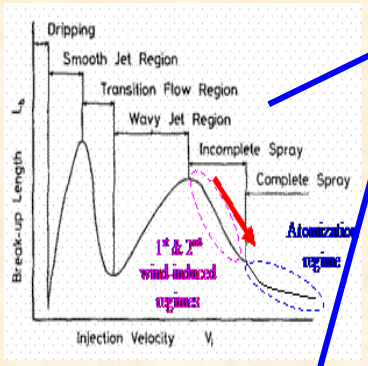


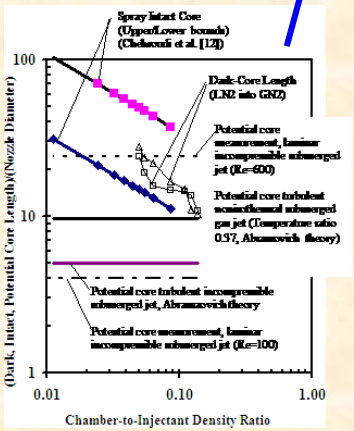
Elevated Intrinsic Sensitivity (e.g., for LOL)

Impinging Jets

Bruce Chehroudi, Advanced Technology Consultants (www.AdvTechConsultants.com)

Supporting Data and Offered Explanations by the Unified Injector Sensitivity Theory





SINGLE JET
Dark-core (Breakup) length
Hiroyasu

IMPINGING JET

Hewitt Stability plot for LOL impinging (d/V)

Comparable pre-impingement distance and Dark-core length

Observed Instability at high chamber pressures for some engine designs (J. Fang)

(Santoro' Group) Impinging jet increasing sensitivity at lower d/V (Anderson et al.)

Prediction for impinging jet rockets using the THEORY

Cavitation& Hydraulic Flip (Hiroyasu)

Dark Core length measurements by DLR and Chehroudi (AFRL)

COAXIAL JET

LRE Stability rating
- Temp Ramping
- Velocity Ratio

DLR work in single-element Rocket
Stable at near- & super-critical
Unstable at subcritical

Santoro's fired single-element Rocket

Unified Injector Sensitivity Theory
Dynamics of the Dark Core length

Physical interpretation of RMS and connection to instability (Culick)

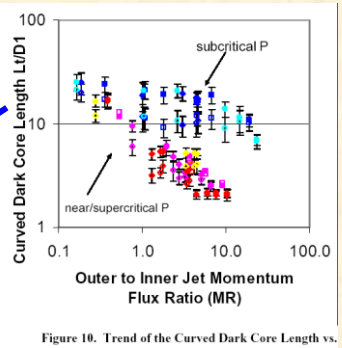
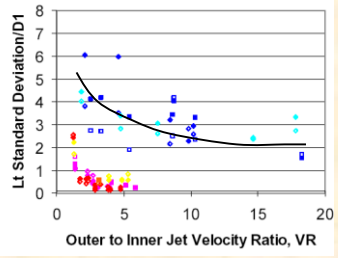


Figure 10. Trend of the Curved Dark Core Length vs.



MANY EXPERIMENTALLY OBSERVED TRENDS ARE CONSISTENT WITH THE THEORY

Bruce Chehroudi, Advanced Technology Consultants (www.AdvTechConsultants.com)

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Advanced Technology Consultants

AIAA Journal of Propulsion and Power

JOURNAL OF PROPULSION AND POWER

Physical Hypothesis for the Combustion Instability in Cryogenic Liquid Rocket Engines

Bruce Chehroudi
Advanced Technology Consultants, Laguna Niguel, California 92677

DOI: 10.2514/1.38451

In this work, the author would like to portray a sketch of a fluid dynamical picture to describe the coupling nature/strength between the chamber acoustics and the injectors. This new perspective is achieved through a physically intuitive argument combined with previously published test results for two popular injector designs, namely, coaxial and impinging jets. For the impinging-jet injectors, it is shown that the dynamic behavior of the dark-core (or breakup) zone for each jet, their lengths and thicknesses, has a profound impact on injector sensitivity to disturbances in its surrounding. This information is used to offer a possible explanation for the trends seen on the Hewitt stability plot in impinging-jet injectors.

Conclusions

- **A hypothesis is proposed to link observations made in cold flow injector studies, sub-scale fired engines, and full-scale production engines with an aim to offer a sketch of a *Unified Injector Sensitivity Theory* which is consistent with most observations pertaining to combustion instability.**
- **This is a unique and systematic approach based on dynamic behavior of the "Jet-core length" observed and characterized for single jets (showerhead), coaxial jets, and impinging jets**
- **This theory, *for the first time*, attempts to propose & unify the underlying mechanism responsible for the sensitivity of different liquid rocket injectors to acoustic field established inside the rocket thrust chamber**
- **Theory is able to offer plausible explanations for combustion instability observations in liquid rocket engines under sub- and super-critical conditions**

Acknowledgement

- Mr. Jay Levin (retired) and Doug Talley, AFRL_Edwards
- Financial support comes from Dr. Mitat Birkan, AFOSR
- The followings are thanked for review, comments, and suggestions:
  - Prof. R. Santoro, Penn State
  - Prof. F. Williams, UCSD
  - Prof. W. Sirignano, UC_Irvine
  - Prof. Vigor Yang, Georgia Tech