Subscale Test Methods for Combustion Devices

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Outline

- Motivation for Scaled Experiments
- Brief Scaling History
  - Steady-State Combustion
  - Combustion Stability
  - Life Prediction
- Scaling Approaches Presently Used at Purdue

Background

- Stated goals for long-life LRE's have been between 100 and 500 cycles
  - Inherent technical difficulty of accurately defining the transient and steady state thermochemical environments and structural response (strain)
  - Limited statistical basis on failure mechanisms and effects of design and operational variability
  - Very high test costs and budget-driven need to protect test hardware (aversion to test-to-failure)
- Ambitious goals will require development of new databases
  - Advanced materials, e.g., tailored composites with virtually unlimited property variations
  - Innovative functional designs to exploit full capabilities of advanced materials
  - Different cycles/operations
- Subscale testing is one way to address technical and budget challenges
  - Prototype subscale combustors exposed to controlled simulated conditions
  - Complementary to conventional laboratory specimen database development
  - Instrumented with sensors to measure thermostructural response
  - Coupled with analysis

SSME Film Cooling Analysis

- Configuration
  - Propellant = LOX + LH2 with O/F = 6.02
  - M_dot_LOX = 64,000 liter/min
  - M_dot_LH2 = 178,000 liter/min
  - M_dot_coolant for regen cooling = 29.06 lb/sec
- Chamber condition
  - Pc = 3300 psi
  - Tc = 3500 K (5840 F)
  - D_throat = 10.88”
  - E = 77
- Cooling channel
  - Wall thickness = 0.03”
  - Width = 0.04 “
  - Height = 0.12 “
  - Pressure_throat = 3851 psi
- Thermal condition at throat
  - Heat flux = 80 Btu/in^2-s
  - hg = 58000 W/m^2-K
  - Twg = 1100 F
- Wall adiabatic temperature
  - Taw = Tr - η(Tr-Tco)

    Where Tr = recovery temperature

    η = film cooling efficiency

    Tco = initial coolant temperature
- Current near wall O/F ratio
  - q_dot = hg(Taw-Twg)

    Where q_dot = 80 Btu/in^2-s

    hg = 58000 W/m^2-K

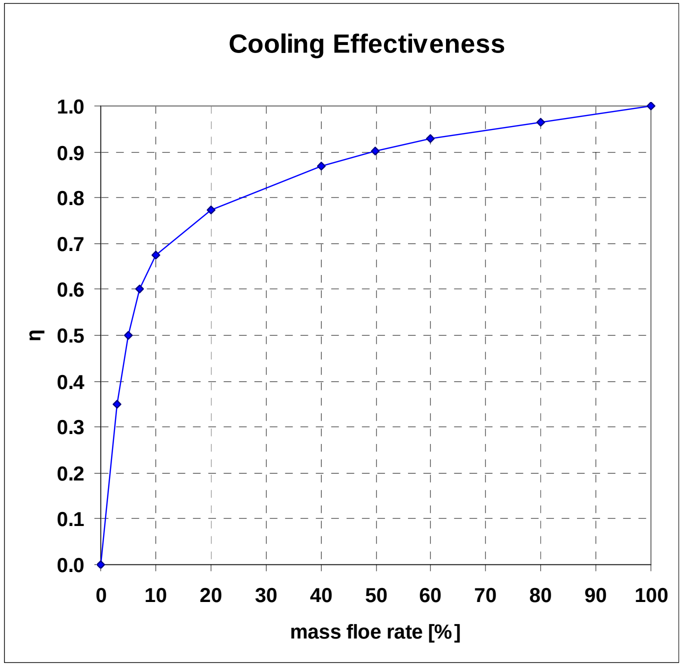
    Twg = 1100 F

    ➔ Taw = 3125 K

    η = 0.5

    ➔ Tco = 2750 K

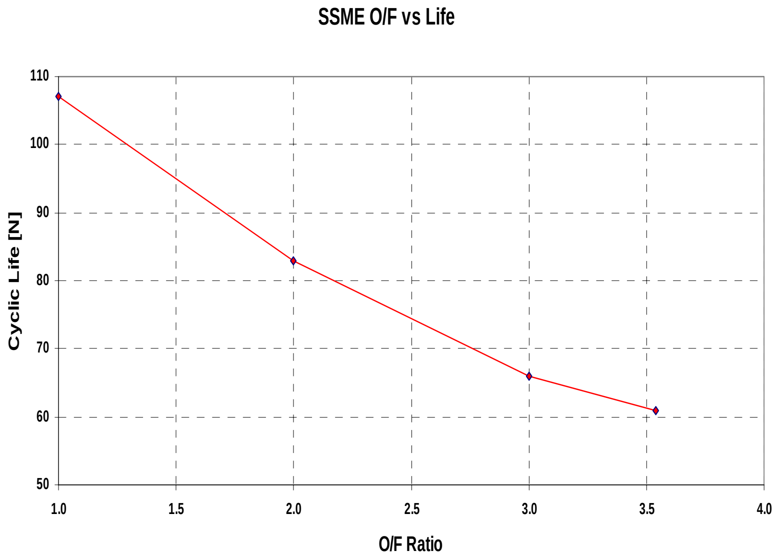
    ➔ O/F_nw = 3.54 from Flame temperature vs O/F ratio chart

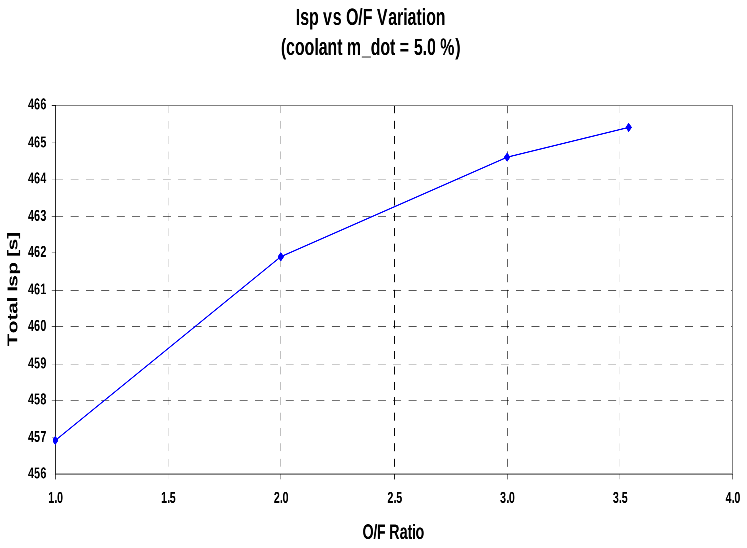


SSME Film Cooling Analysis

- Current film cooling condition
  - O/F_nw = 3.54
- Parametric study with fixed film flow rate (5 %)

  *Porowski et al. method (AIAA Journal Vol. 2 No. 2, 1985)
  - O/F_nw change = 3.54 → 1.0
  - Life change = 61 → 107 (75.4% increase)
  - Isp change = 465 → 457 (1.83 % decrease)

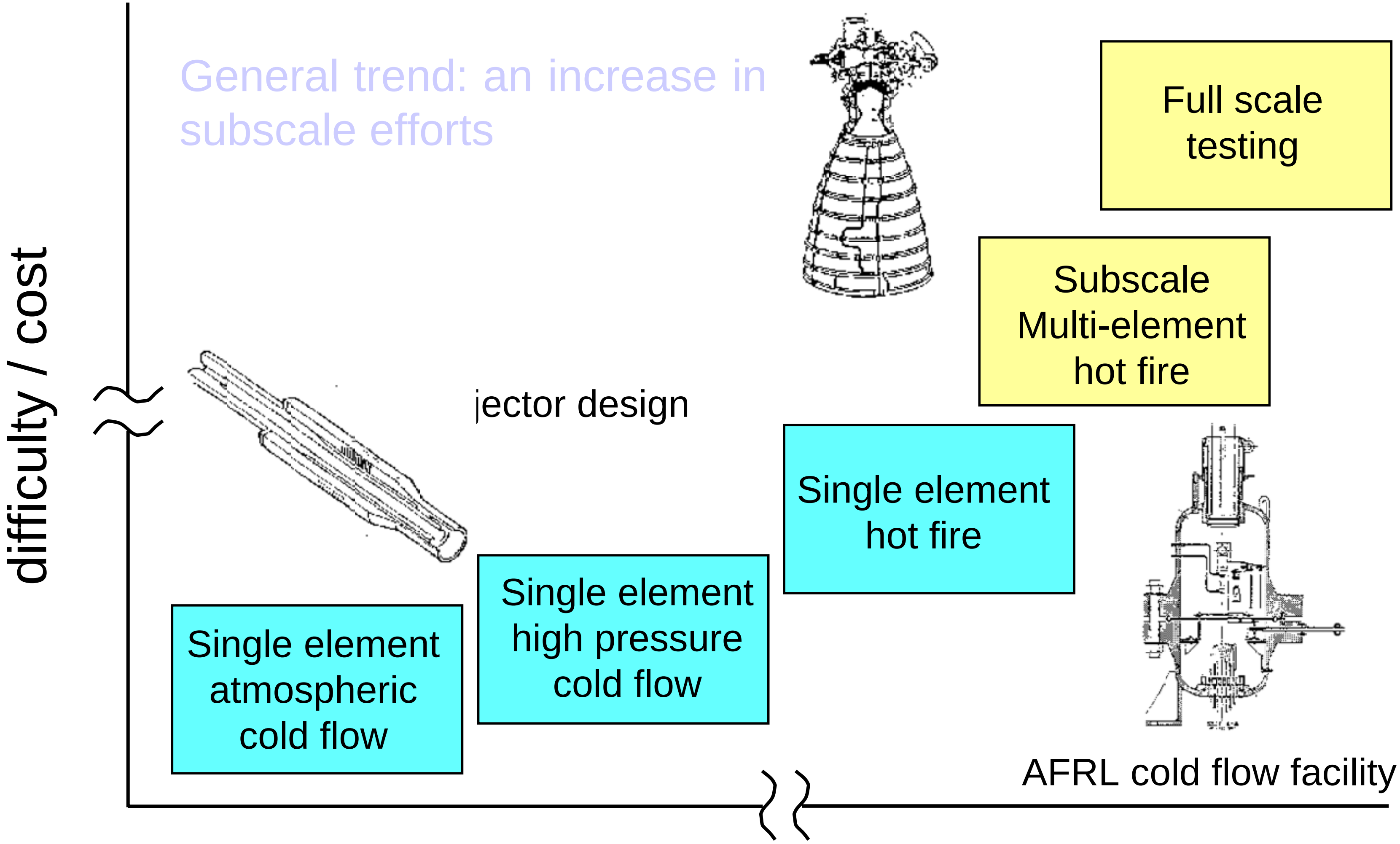

SSME O/F vs Life


Isp vs O/F Variation
(coolant m_dot = 5.0 %)

Scaling Objectives and Approaches

- Combustor characterization is goal
  - Validation data for design analysis models
  - Assess innovative functional design, materials, operation
  - Investigations into specific physics
- Single element, multi-element, 40K, 250K
- Cold flow and hot fire
- Performance, heat transfer, life, stability
- Experimental objective needs to define scaling approach and measurement
  - Well-instrumented combustors linked to analysis
  - Thrust level and number of elements
  - Element scaling and configuration

Hierarchy of injector experiments



General trend: an increase in subscale efforts

jector design

Single element atmospheric cold flow

Single element high pressure cold flow

Single element hot fire

Subscale Multi-element hot fire

Full scale testing

AFRL cold flow facility

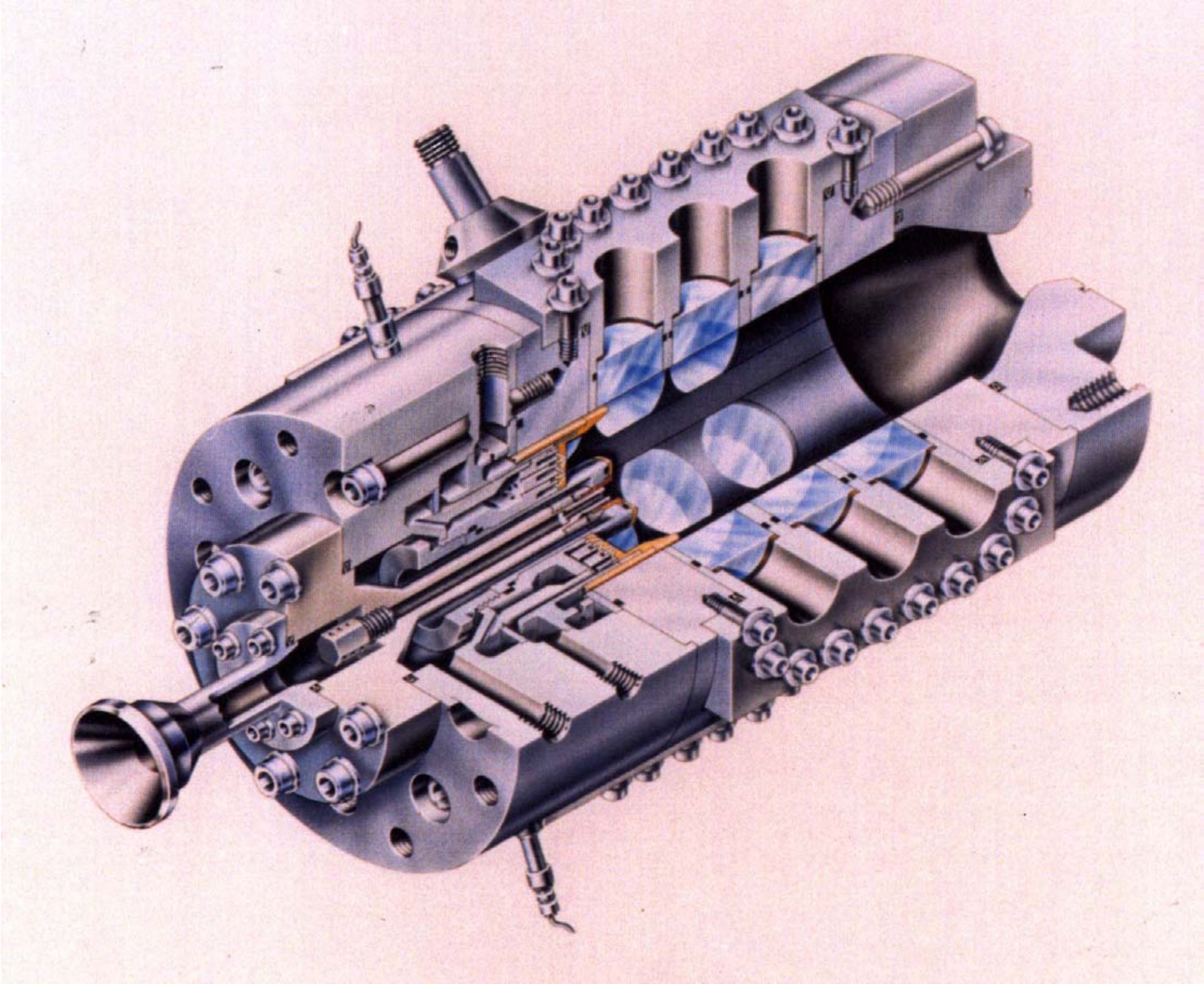
difficulty / cost

degree of simulation

Brief History of Scaling in the US – Steady State Combustion

- JPL studies of mixing efficiencies of impinging jets
- Bell Aerospace/AFRL holographic and shadowgraphic studies of combusting flows
- Rocketdyne development of LISP methodology for SDER
- Aerometrics development of PDPA
- Rocketdyne studies of flameholding behind LOX post
- PSU measurements of chemical species in HO combustors
- AFRL studies of supercritical jets

Single Element Test Chamber



Stability Scaling

- Simulation of chamber dynamics in subscale configuration is very difficult
  - Acoustic frequencies scale as ~ 1/d
  - Pressure *v* velocity sensitivity
- Scaling approaches
  - Wedges, T-burners, 2-d chambers
  - 1T = 3T scaling
- Single element rarely used in US, but is more typical in Russia

Experimental Approach of Bazarov

This facility screened Injector elements for Liq/liq and gas/liq Injectors for over 20 Years (1965-85)

Typical Pc = 750 psi, Total flowrate of 5 lb/s

‘self-oscillation’ and response to pulsations measured

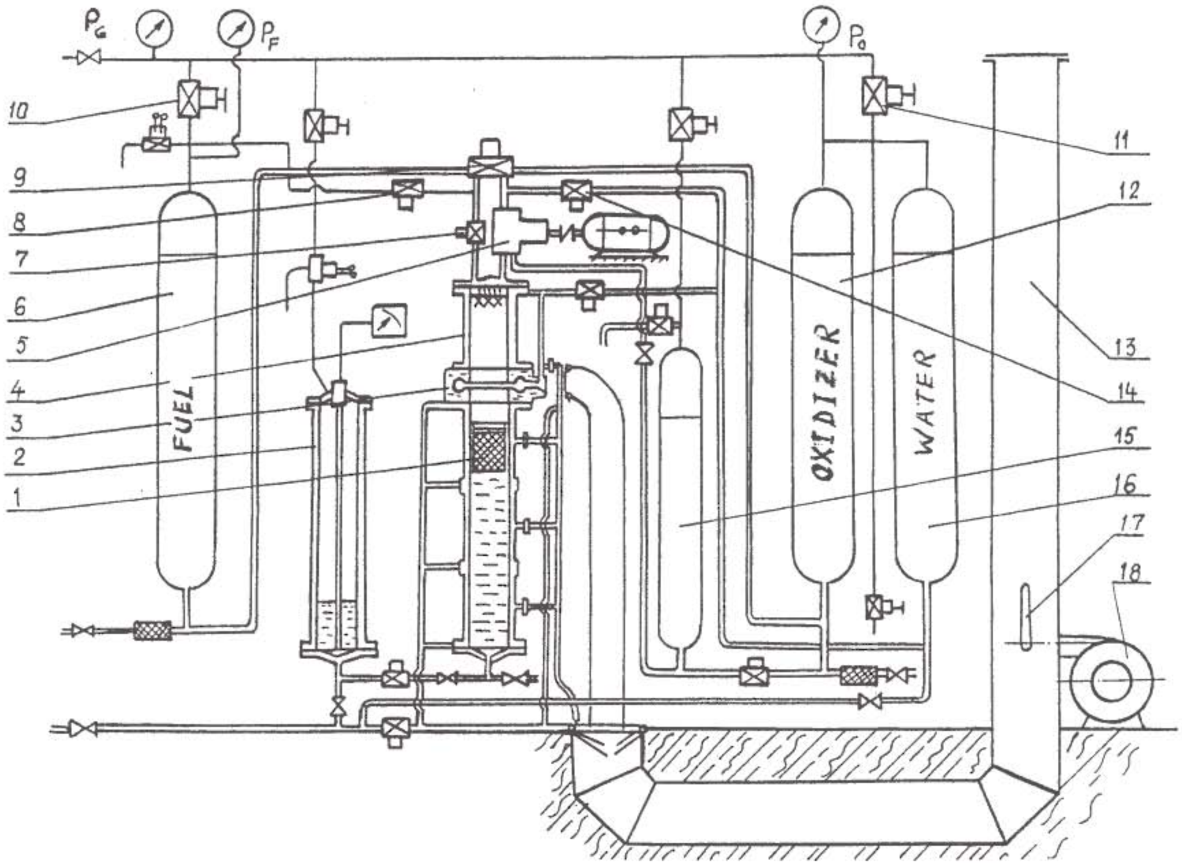


Fig.8 Pneumatic and hydroulic scheme of fire stand
1-piston, 2-measuring vessel, 3-nozzle collector, 4-combustion chamber, 5-pulsator, 6-fuel tank, 7-time delay valve, 8-blow through valve, 9-main bi-propellant valve. 10,11-pressurising gas reductors, 12-oxidizer tank, 13-exhaust tubes, 14-water valve, 15-oxidizer return tank, 16-pressurised water tank, 17-ejector, 18-air compressor

Experimental Approach of NIICHIMMASH

- Use full-scale injector elements
- Experiment designed to simulate controlling process - mixing
- Match equivalence ratio and volumetric flowrates using diluted gaseous propellants
- Combustor acoustics matched by using appropriately sized low-pressure chamber
- Stability boundaries determined by varying flowrates
- Relative boundaries indicate stability ranking

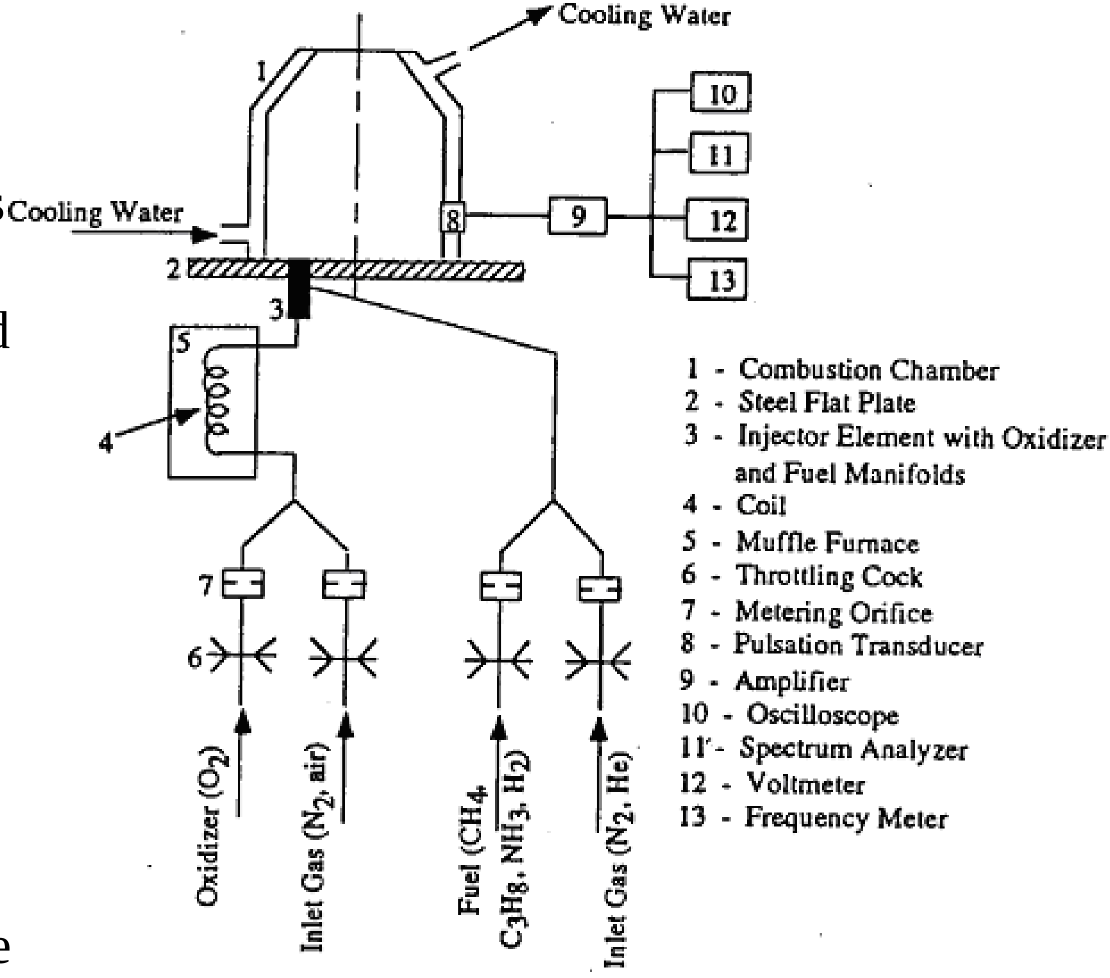


Figure 6. Schematic of Single Element Model Set-up and Instrumentation

Propellant Distribution Effects

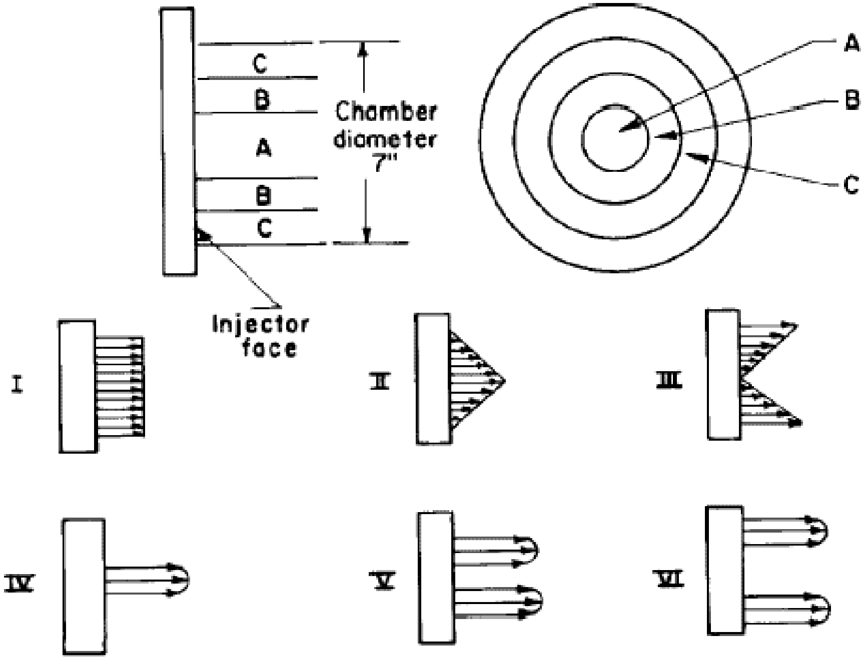


Figure 7.2.5a.—Injection radial profile comparison.

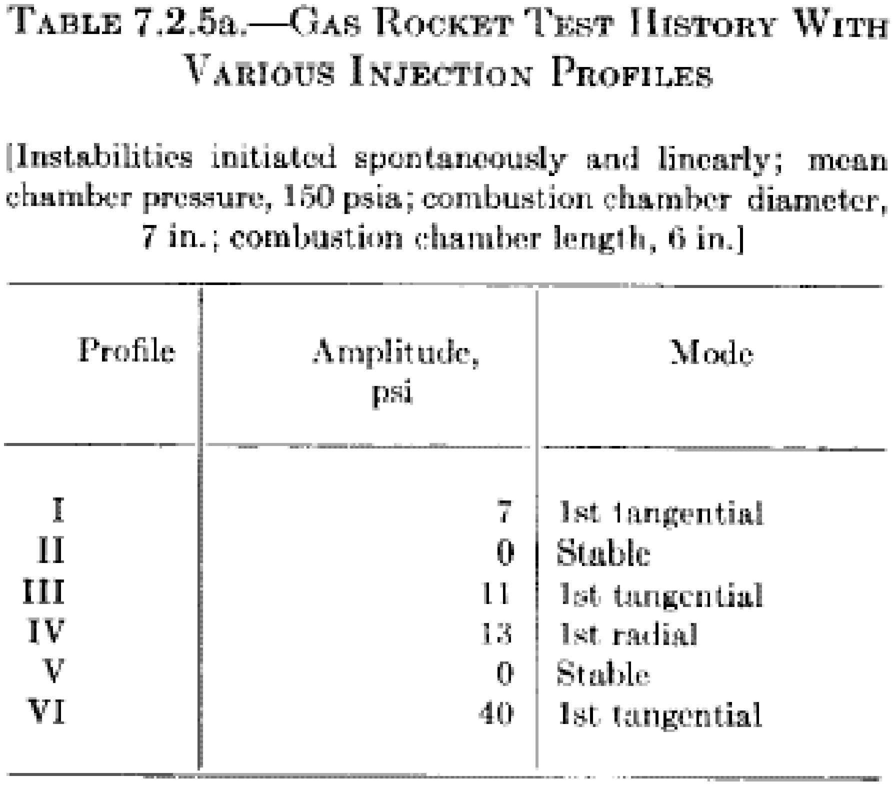
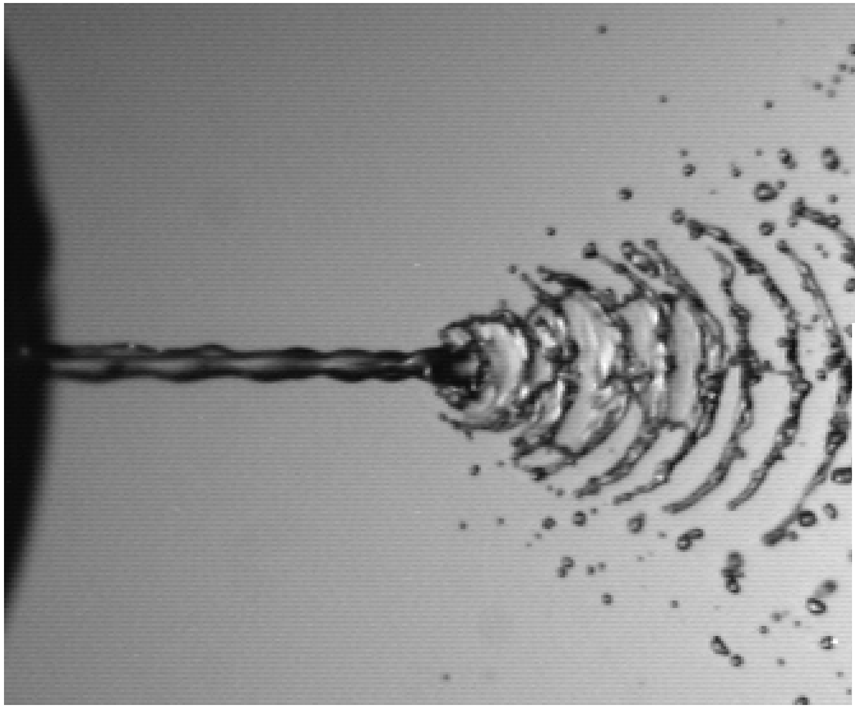


Table 7.2.5a.—Gas Rocket Test History With Various Injection Profiles

[Instabilities initiated spontaneously and linearly; mean chamber pressure, 150 psia; combustion chamber diameter, 7 in.; combustion chamber length, 6 in.]

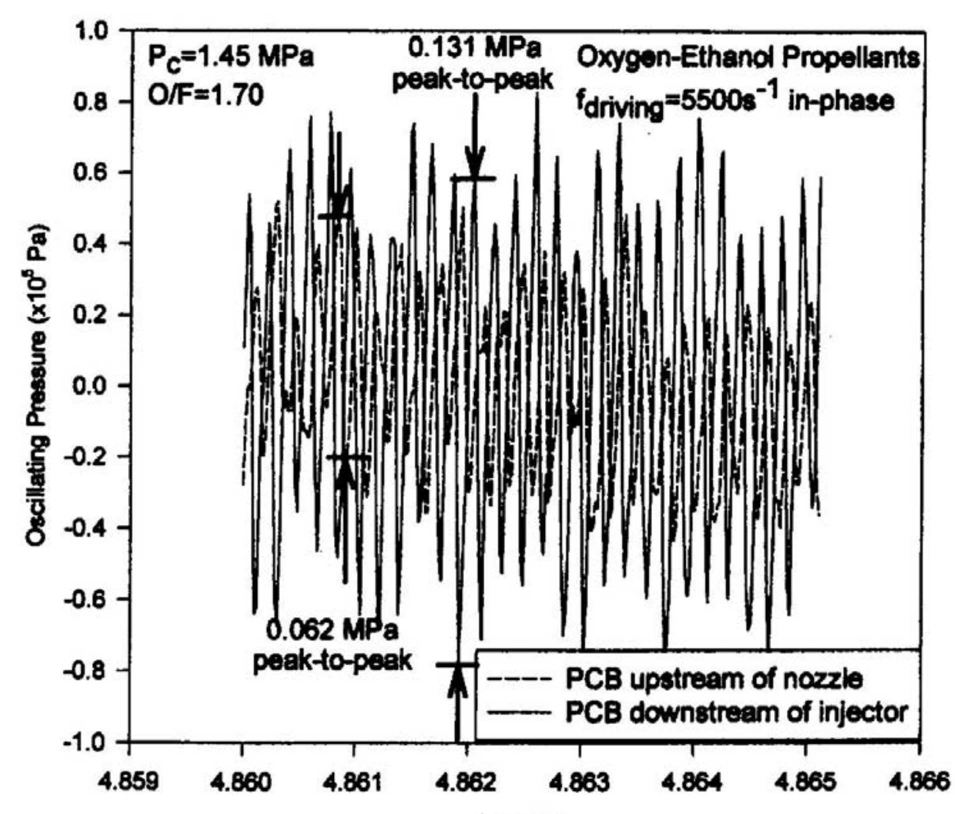
Profile	Amplitude, psi	Mode
I	7	1st tangential
II	0	Stable
III	11	1st tangential
IV	13	1st radial
V	0	Stable
VI	40	1st tangential

Single Element ‘Instability’

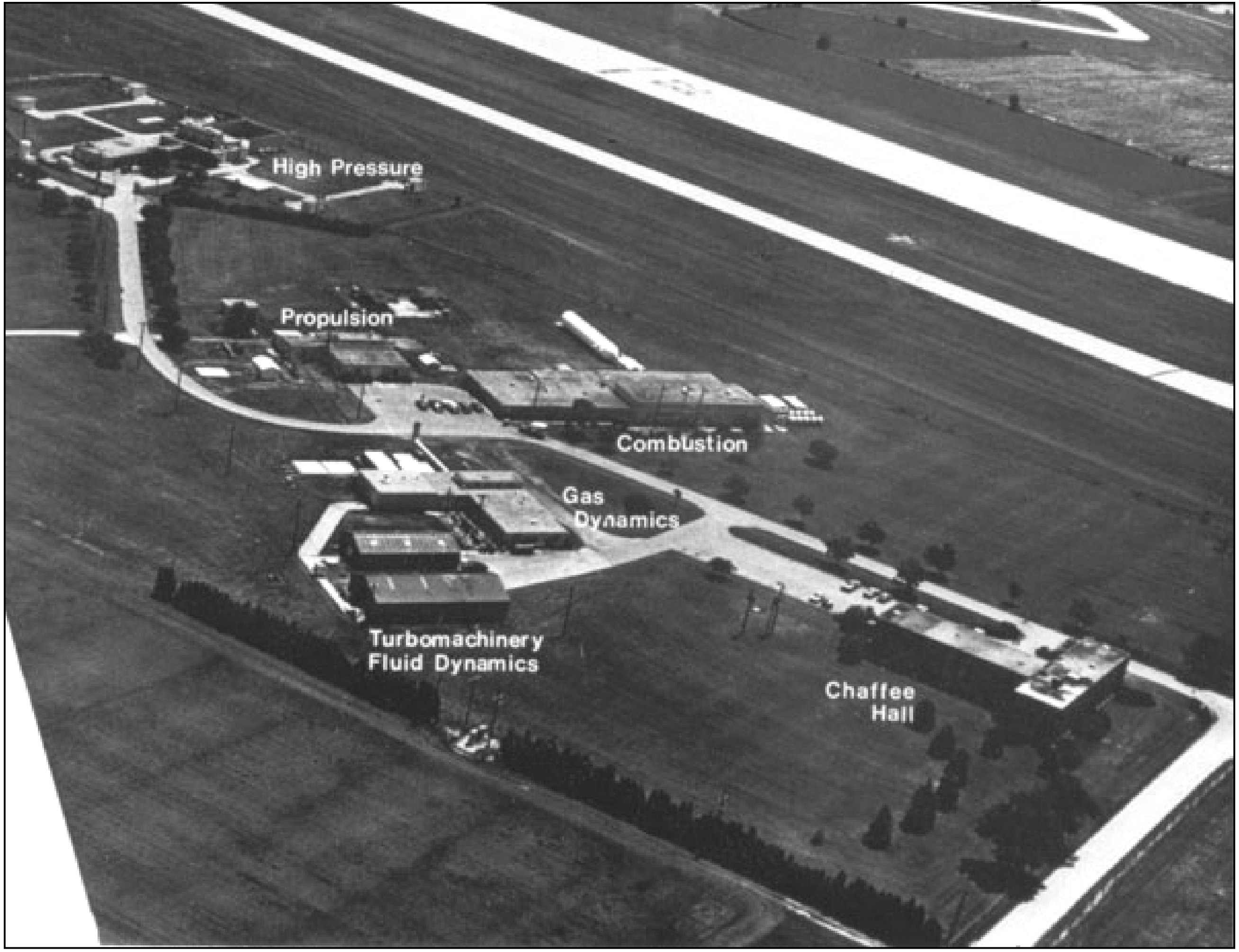


Impinging jets driven by piezoelectric actuator

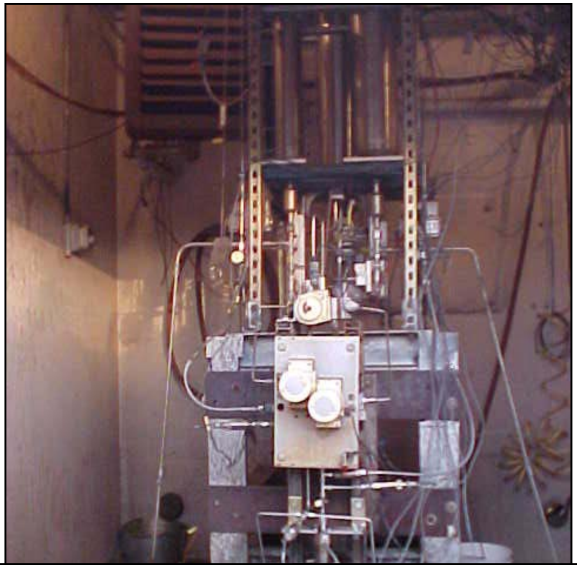
Combustor oscillations at driven atomization frequency



Subscale Test Activities at Purdue - Maurice Zucrow Laboratory



Advanced Propellants and Combustion Lab



- Two cells w/ 1 Klbf thrust stands
- Propellant supply of 1800 psia
- 2 - 4 gallon oxidizer tanks
- 1 & 4 gallon fuel tanks
- National Instruments hardware & LabView software
  - 32 channels pressure
  - 32 channels temperature

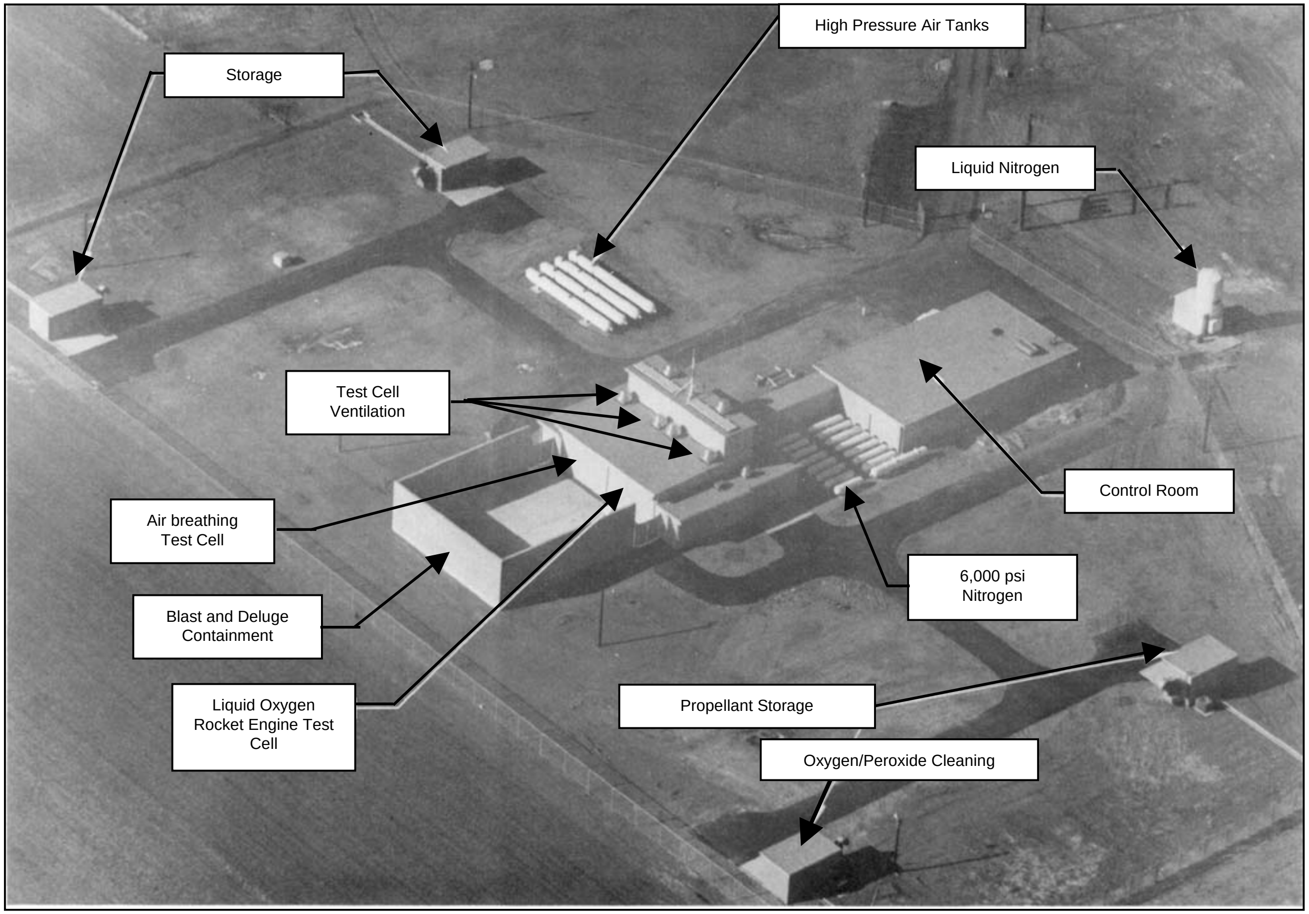
•All valves computer controlled

•Rapid test article installation

•Design/Build/Test course

High Pressure Lab

Renovation funded thru Indiana 21st Century R & T Fund –
Propulsion and Power Center of Excellence
Facility activated in May ‘03



6,000 psi Nitrogen System

- Pressurization, Actuation and Purge Gas
- 2,400 gallon Liquid Nitrogen Tank w/ 6,000 psi Pump
- 253 ft^3 6,000 psi Nitrogen Tube Trailer
- Computer Controlled Pressurization Systems

Propellant/Coolant Tanks

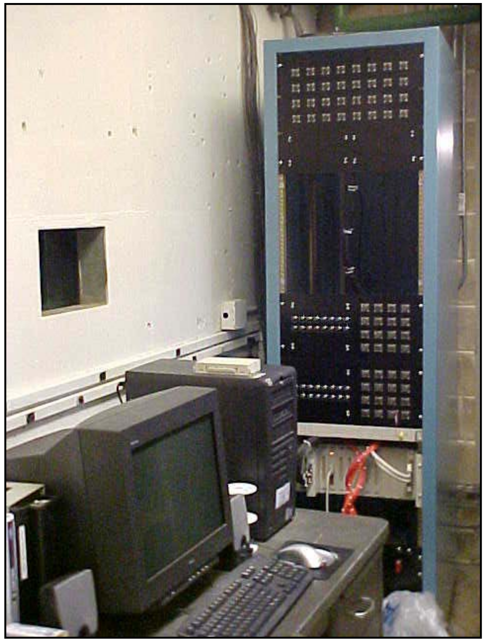
- 22 gal 5,000 psi LOx
- 16 gal 5,000 psi Fuel
- 220 gal 5,000 psi H_2O
- 400 gal 800 psi H_2O_2
- Hydraulic Control Valves

10,000 lbf Thrust Test Cell

- LabView 6.1-based DACS
- 10,000 lbf thrust measurement
- 64 channels pressure
- 96 channels thermocouples
- 18 channels analog control
- 32 channels on/off control

Control System Operation

- Data System Located Adjacent to Test Cell
- Operation Remoted to Control Room (KVM Extender) for Testing
- Video Recorded Directly to DVD



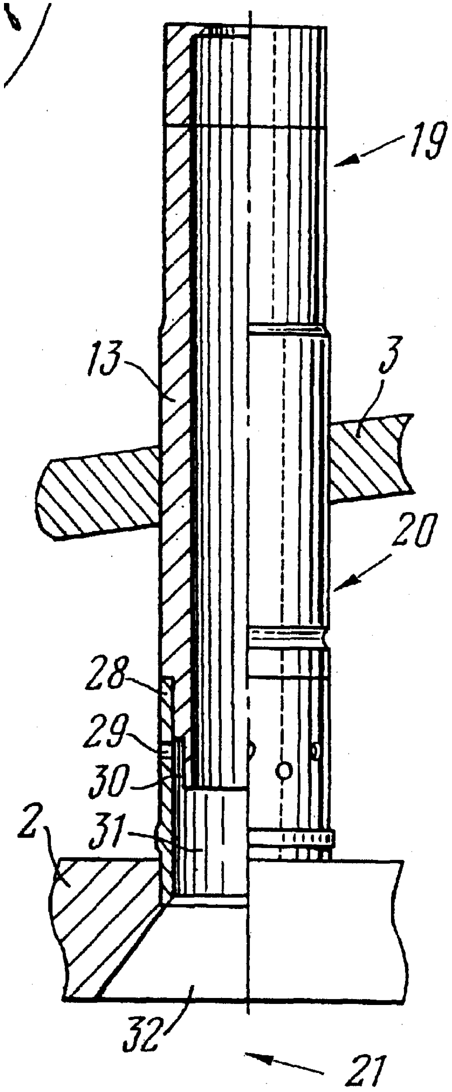
Test Cells

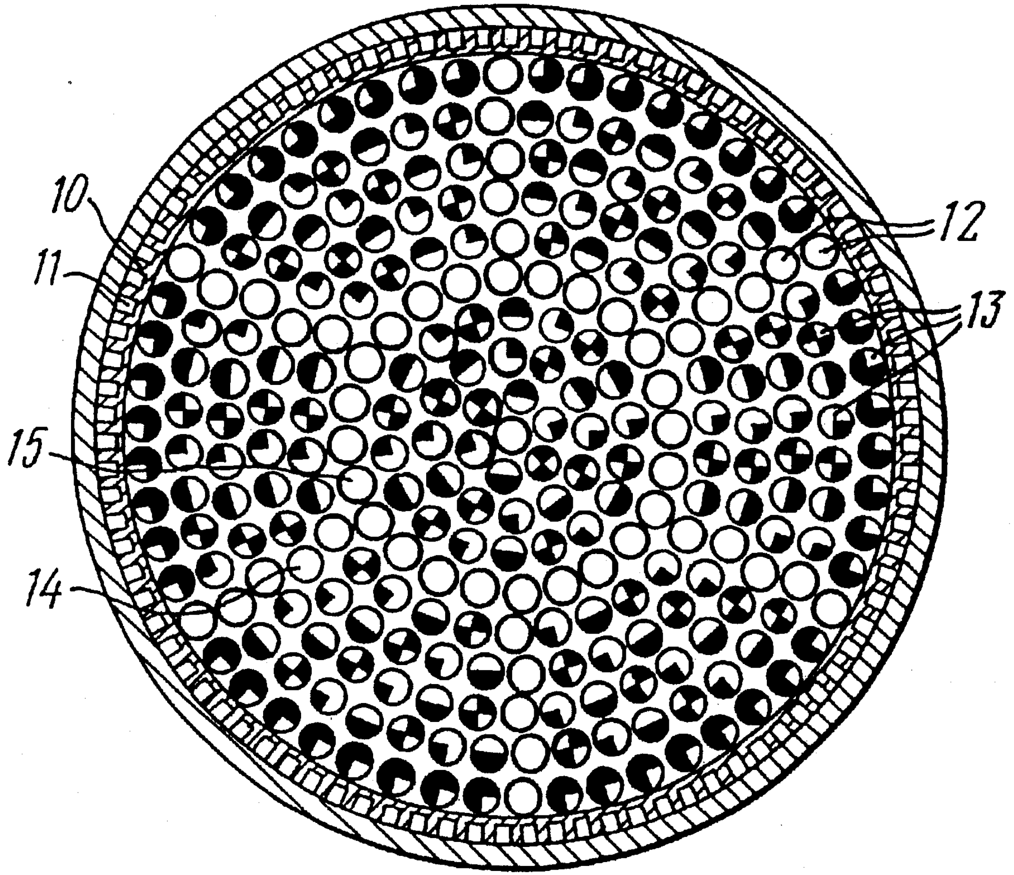
- 18” Thick Reinforced Concrete Test Cell Walls
- High Flow Capacity Test Cell Exhaust Fans
- Heated High Pressure Air Plumbed to Both Cells
- Walled Containment Area

Injector Characterization Scaling Approach

- Study Objectives
  - Steady state and dynamic characterization of ORSC MC injector elements
- Approach
  - Investigate full-scale elements at realistic operating conditions
  - No film cooling (if possible)
  - Evaluate different injector design configurations
  - Couple with analysis
- Measurements
  - Energy release profile from axial pressure gradient
  - Injector face and chamber wall thermal environments
  - Plume signature with IR tomography
  - Manifold, injector and chamber p’

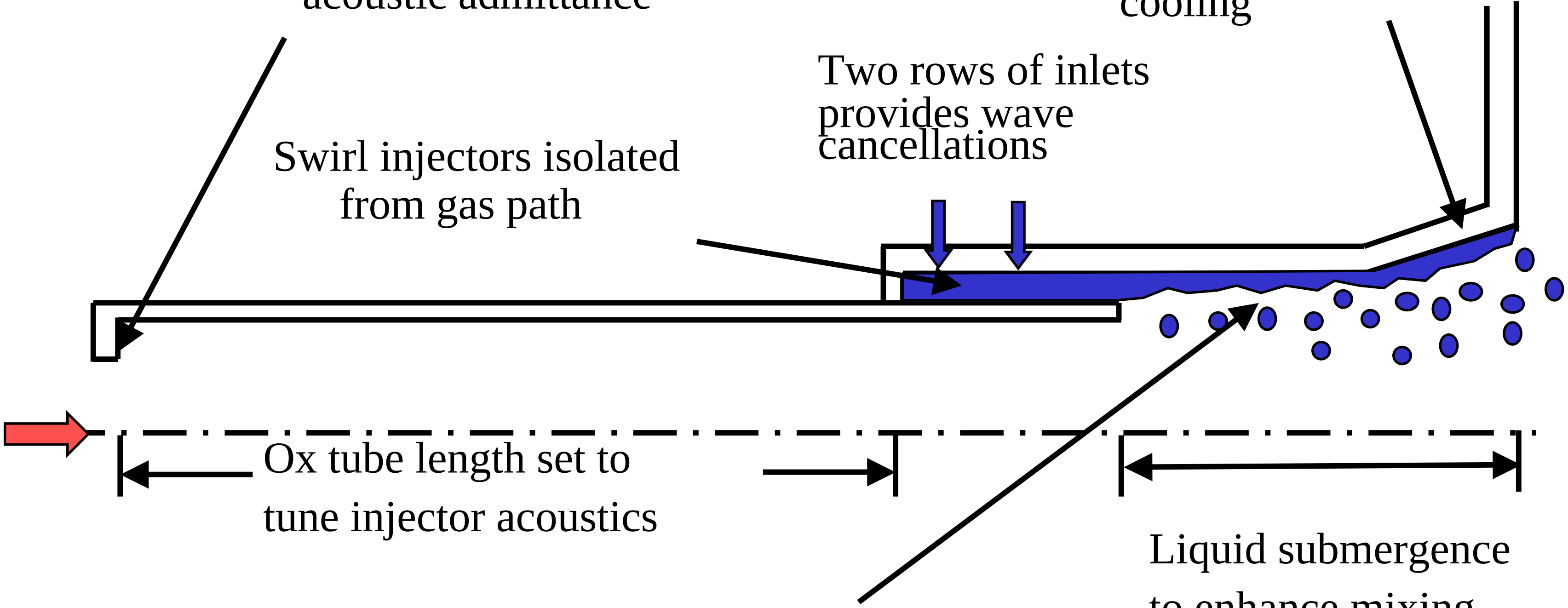
ORSC Main Combustor Components





271 elements, 1722 lb_f each, d = 0.5 in

Principle Design Features



Gasflow inlet lip to affect acoustic admittance

Swirl injectors isolated from gas path

Two rows of inlets provides wave cancellations

Beveled recess to provide injector face cooling

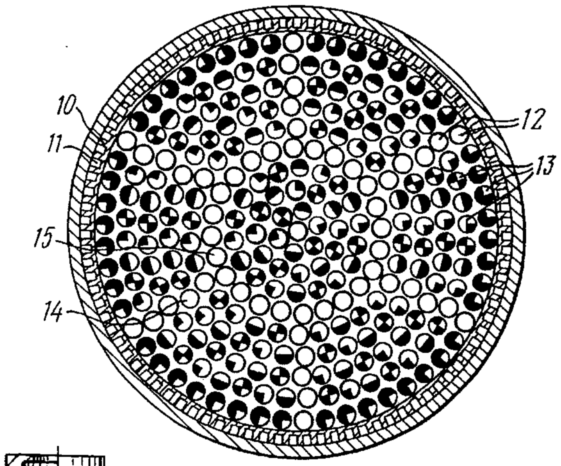
Ox tube length set to tune injector acoustics

Liquid submergence to enhance mixing, control face heating & promote stability

Atomization due to Kelvin-Helmholtz instability

Two-phase region enhances impedance

Single Element Sizing Exercise



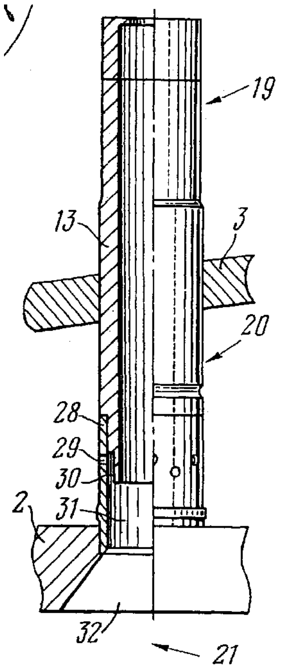
Approach

- use full scale F/element (1722 lb_{fvac})

  ➡ mox = 3.6 lb/s, mf = 1.2 lb/s
- test at ‘full’ Pc (2250 psia)

  ➡ At = 0.39 in^2, dt = 0.70 in
- match injection pressure drops (10%)

  ➡ dinj, ox = 0.43 in, dinj = 0.57 in



Possible scaling methods:

Contraction ratio (1.61) ➡ dc = 0.89 in

Element to chamber area ratio (0.30) ➡ dc = 1.04 in

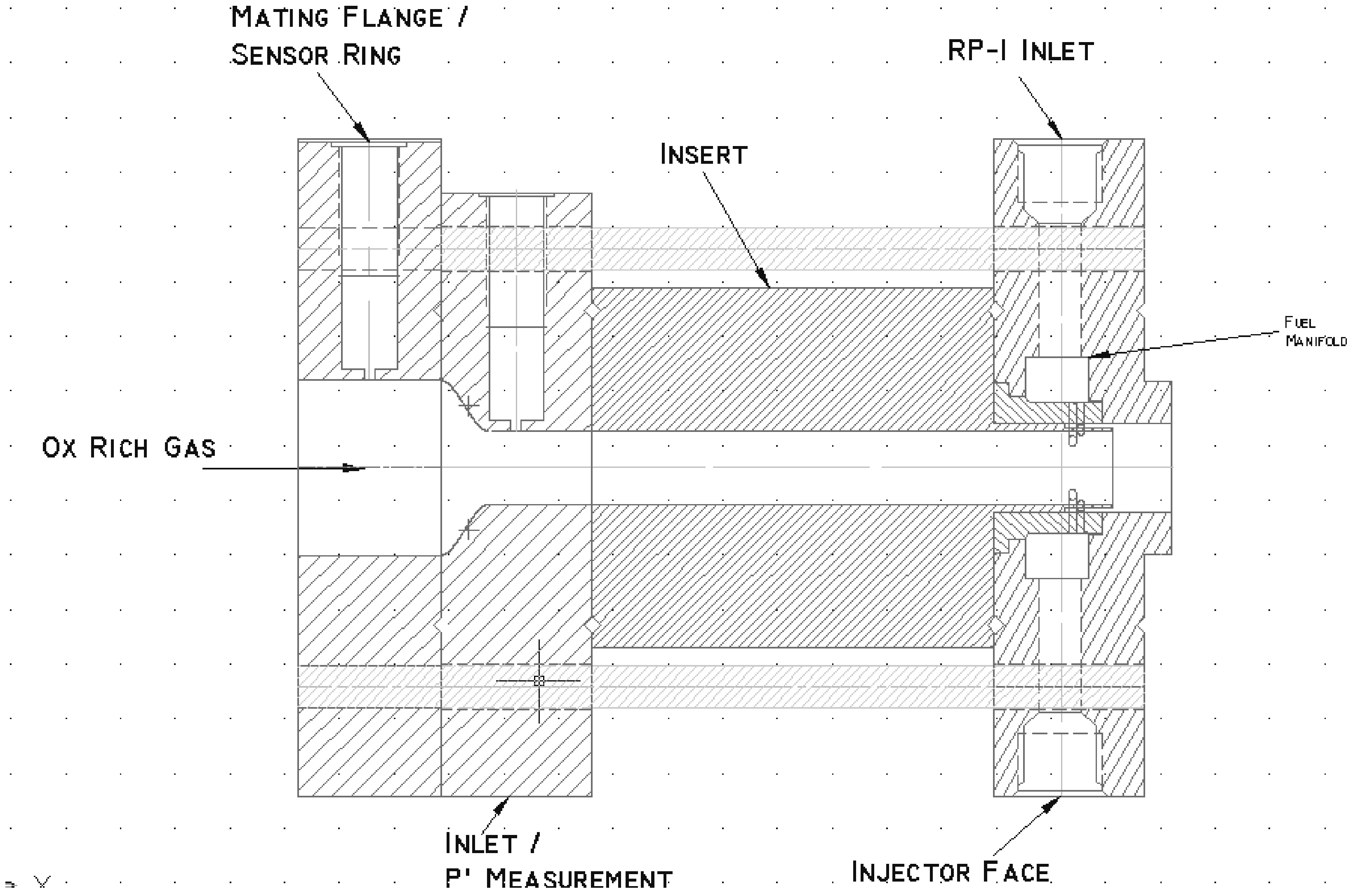
Element-element spacing (0.60d) ➡ dc = 0.91 in

Element-wall spacing (0.60d ?) ➡ dc = 0.91 in

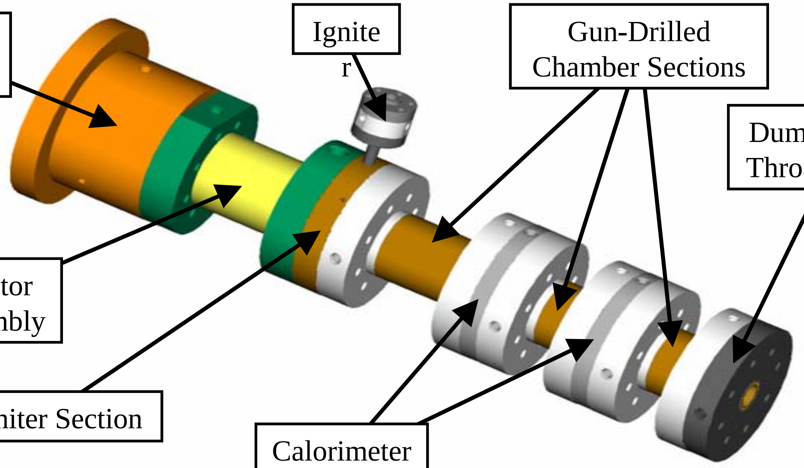
Element area (0.65 in^2) ➡ dc = 0.91 in

Chamber length based on L* ~ 30 in (??)

Baseline Injector Design



High-Pressure Chamber



Mating Flange

Igniter

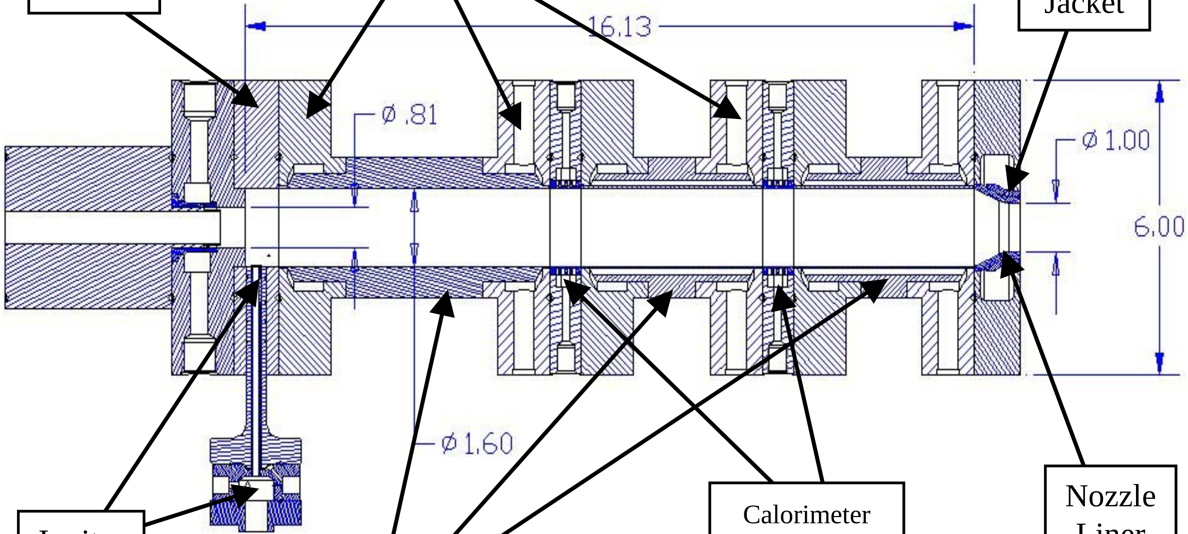
Gun-Drilled Chamber Sections

Dump-Cooled Throat Section

Injector Assembly

Igniter Section

Calorimeter Sections



Igniter Section

Flanges

Nozzle Jacket

Igniter

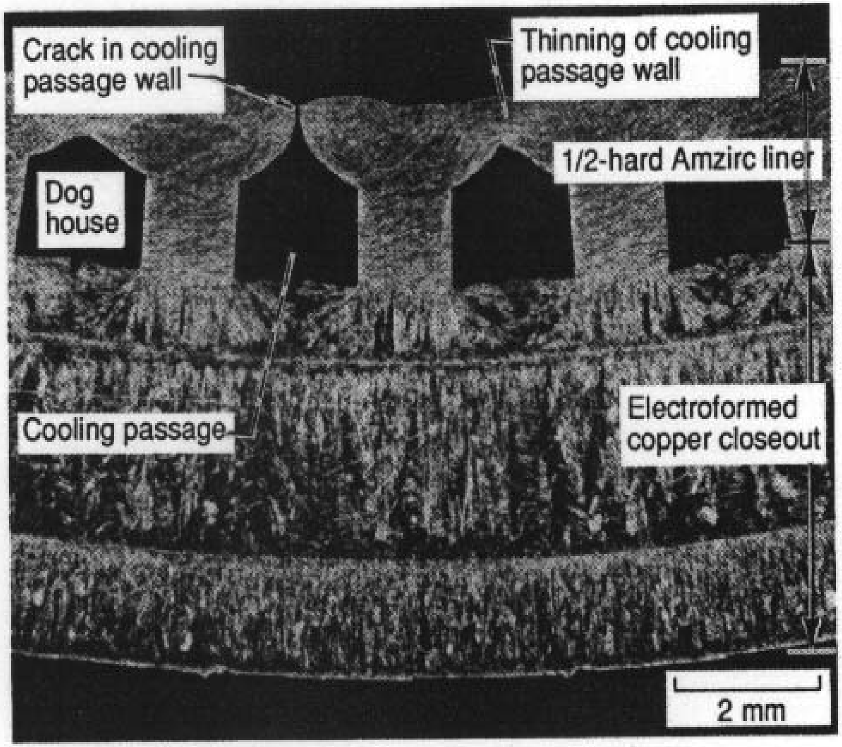
Gun-Drilled Chamber Sections

Calorimeter Sections

Nozzle Liner

Life Prediction - Background

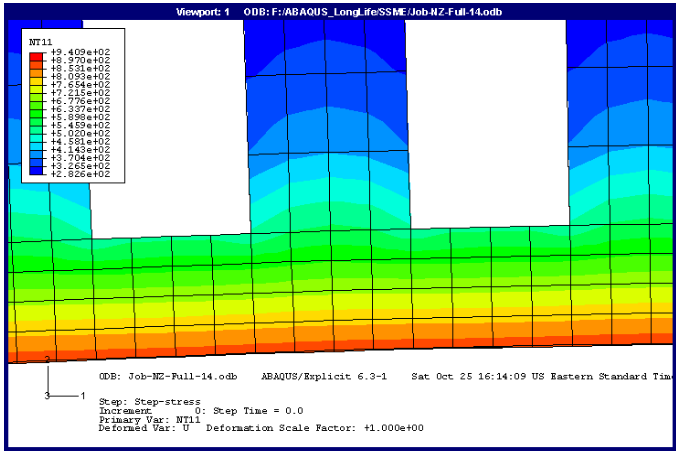
- Rocket combustor liner such as SSME operated at high temperature (6000F) and pressure (3000 psi) ranges as well as extreme heat flux (80 Btu/in^2-s) requires active cooling devices to prevent material failure.
- Combustor liner experiences high thermal structural stress (~100 MPa) during mission profile (SSME 8 min)
- Experiments by Quentmeyer and Jankovsky showed bulging and thinning of liner due to cyclic loading
- Kasper and Porowski developed analytical life prediction methods using simple fatigue and creep model
- Robinson, Arnold and Freed developed visco-plastic model for fatigue-creep interaction phenomena which is believed to be a main failure mechanism



Typical failure mode of combustor liner at throat so called "dog house effect" per Quentmeyer

Full Scale – Subscale Life Comparison

– Pc = 3300 psi, Tc = 3500 K



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ODB: Job-NZ-Full-14.odb    ABAQUS/Explicit 6.3-1    Sat Oct 25 16:14:09 US Eastern Standard Tim

Step: Step-stress
Increment       0: Step Time = 0.0
Primary Var: NT11
Deformed Var: U   Deformation Scale Factor: +1.000e+00
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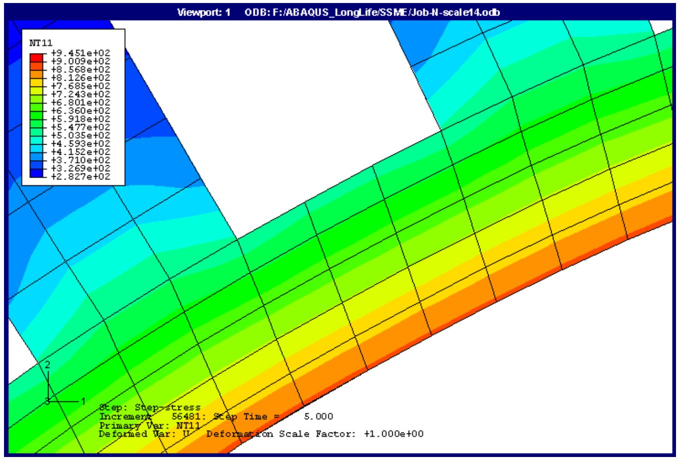

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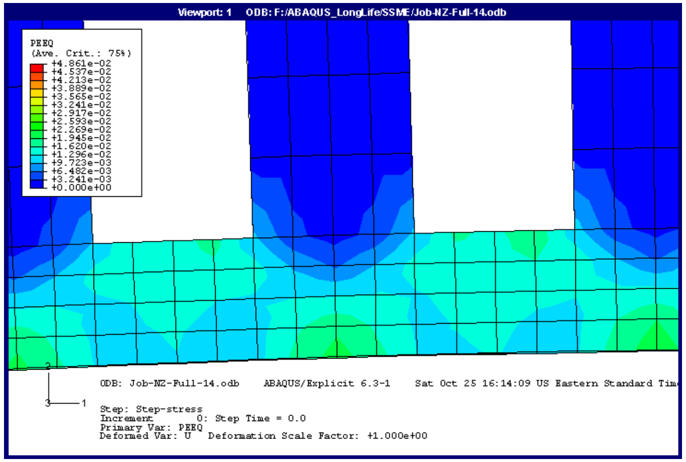

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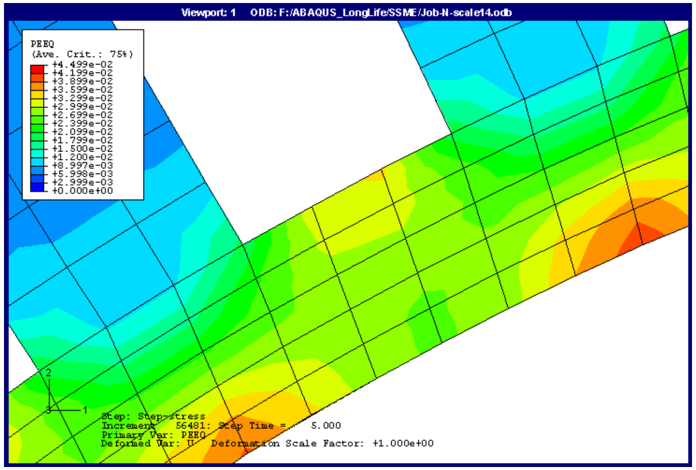

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Step: Step-stress
Increment    56481: Step Time =     5.000
Primary Var: PEEQ
Deformed Var: U   Deformation Scale Factor: +1.000e+00
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Full scale engine

Strain_max = 2.4

Life = 120

1/10 scale model

Strain_max = 3.94

Life = 48

Approach

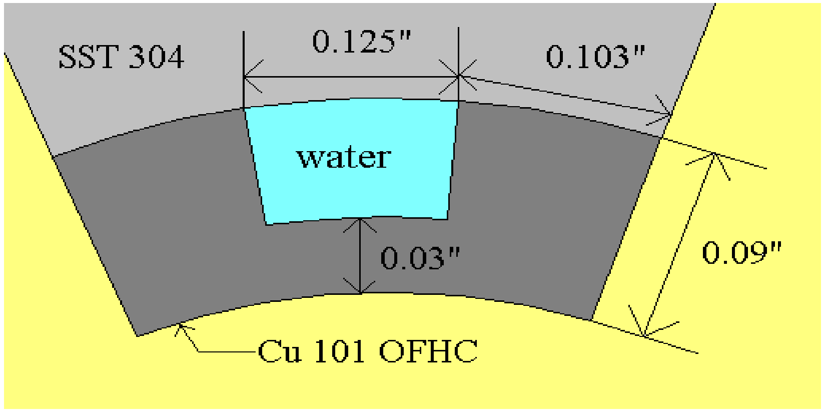
- Develop DBT course with life prediction as part of AAE curriculum
- Develop design requirements
  - Controlled hot-gas environments – use ‘pre-combustor’
  - Creep-fatigue interaction failure of cooled liner
  - Failure within reasonable number of cycles
- Life prediction analysis using conventional methods
  - Chemical equilibrium in pre-combustor
  - One-dimensional heat transfer analysis for initial design
    - critical heat flux and cooling requirements, duty cycle
  - FEM for stress and plastic strain
  - Strain-life curves for cycle life
  - More advanced life modeling by graduate student following project
- Cyclic testing of test article
  - Ten cycles per test
  - Validation of cooling analysis
  - Regular inspection
- Test-to-failure

Combustor Design Parameters

- Top level requirements
  - Less than 200 life cycle
  - Test should produce verifiable results
  - Liner has no melting prior to the LCF failure
  - All parts had to be manufactured in ASL at Purdue
- Under these requirements, the coolant pressure, flow rate and cooling channel aspect ratio (0.5) were determined.

Parameter	Value
Propellant	90% H_2O_2 + JP-8
Propellant mixture ratio (O/F)	4.0
Propellant flow rate	1.25 lb/s
Chamber pressure (P_c)	200 psia
Chamber temperature (T_c)	3440 °F
Characteristic velocity (C*)	4961 ft/s
Throat area (A_t)	0.915 in^2
Characteristic length (L*)	70
Test liner diameter	2.0 in
Test liner length	5.0 in
No. of cooling channel	30
$P_{coolant}$	110 psi
$M\_dot_{coolant}$	0.8 lb/s

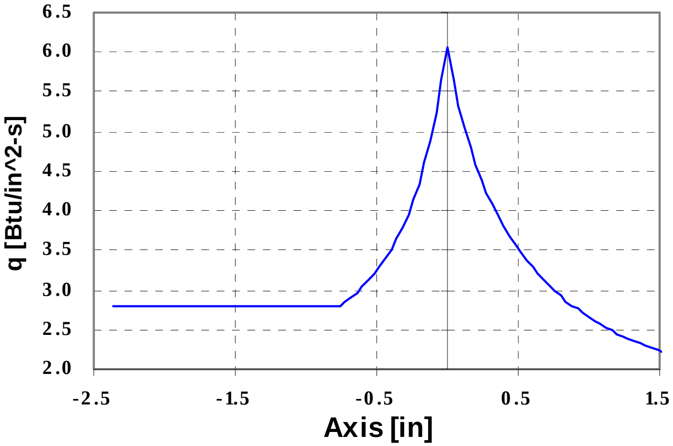
Table 1 : Combustor design parameters

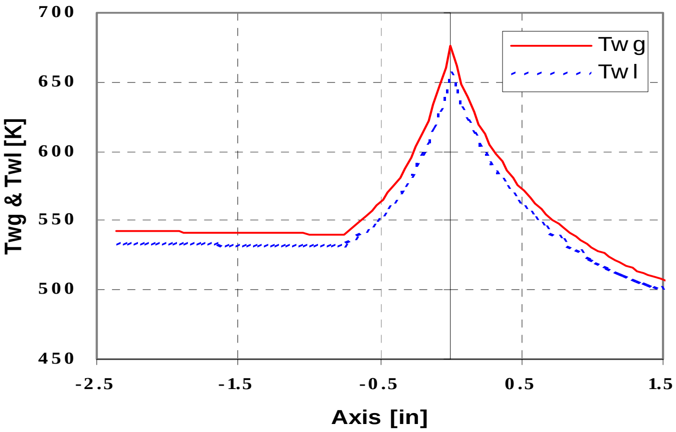


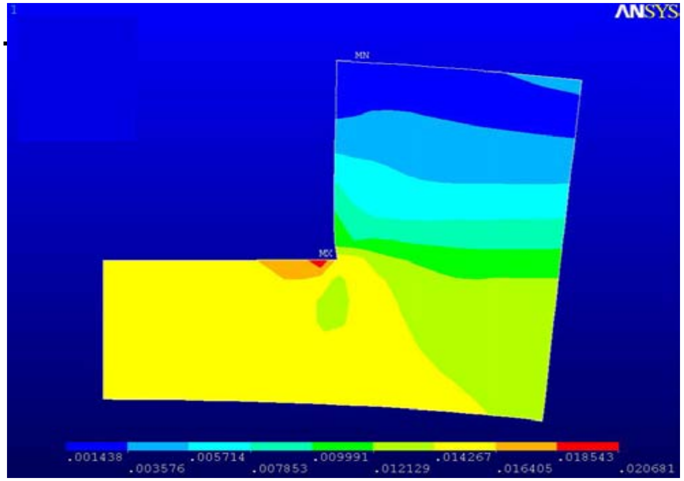
Thermal Structural Prediction

Thermal analysis

- Burn out heat flux --- 6.54 Btu/in^2-
- Max wall temp --- 670 K



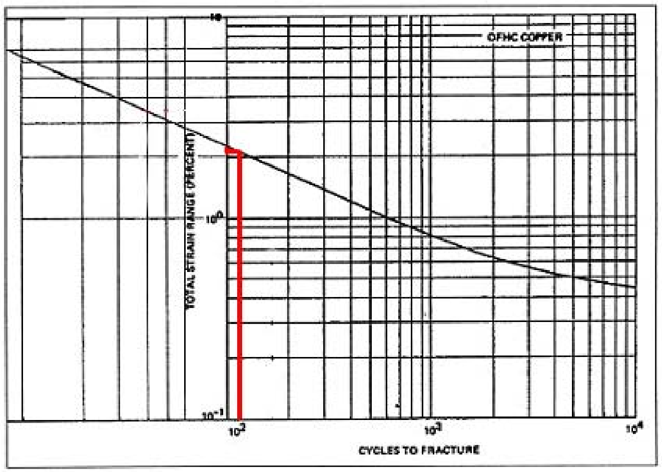




Total strain predicted by ANSYS around rectangular cooling channel.

-Total strain --- 2.0 %

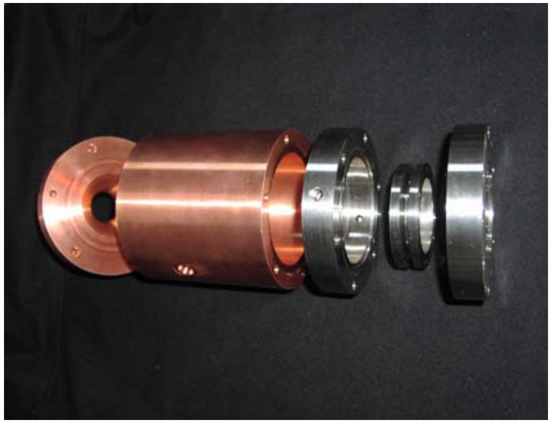
-Life expected --- 115 cycles

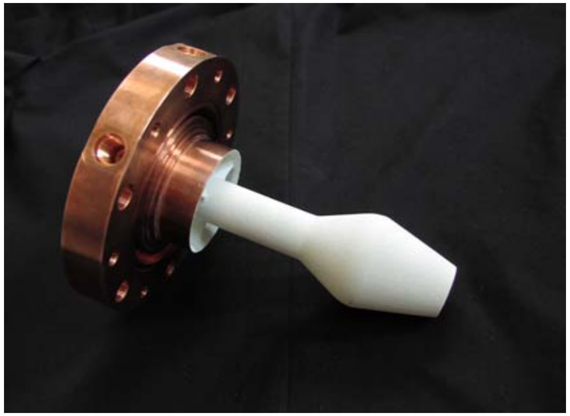


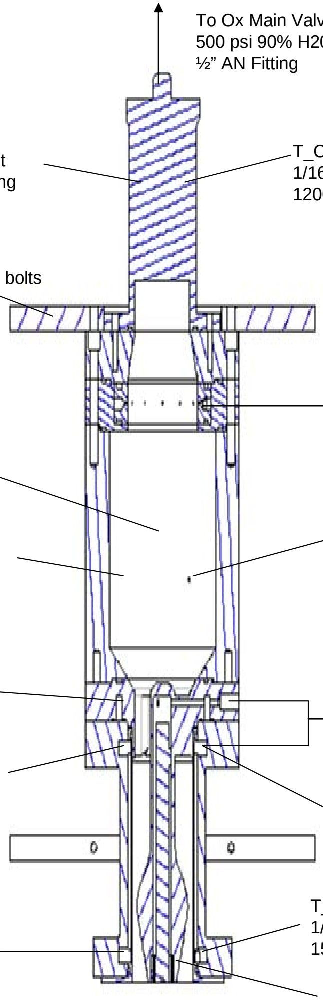
Strain-life curve for OFHC at 810 K from NASA CR-134806, 1975

Test Article

- Catalyst bed for decomposing H_2O_2
- Heat sink dump combustor for hot gas generation
- Chamber liner --- water cooling
- Center body --- water cooling with TBC (0.01” thick)







To Ox Main Valve
500 psi 90% H202
½” AN Fitting

P_Oxcatout
¼” AN Fitting
200 psi

T_Catout
1/16” Swagelok Fitting
1200 degrees F

Engine Mount Bolts to
(4) Unitstrut L-brackets
On Test Stand w/(4) ½” bolts

To Fuel Main Valve
250 psi RP-1
1/2” AN Fitting

T_Precombustor
Welded
260 degrees F

P_Chamber1
¼” AN Fitting
200 psi

P_Chamber2
¼” AN Fitting
200 psi

To Water Main Valve
200 psi H20
1/2” AN Fitting

P_CBin
¼” AN Fitting
100 psi

T_Jackin
1/16” Swagelok Fitting
71 degrees F

P_Jackin
¼” AN Fitting
100 psi

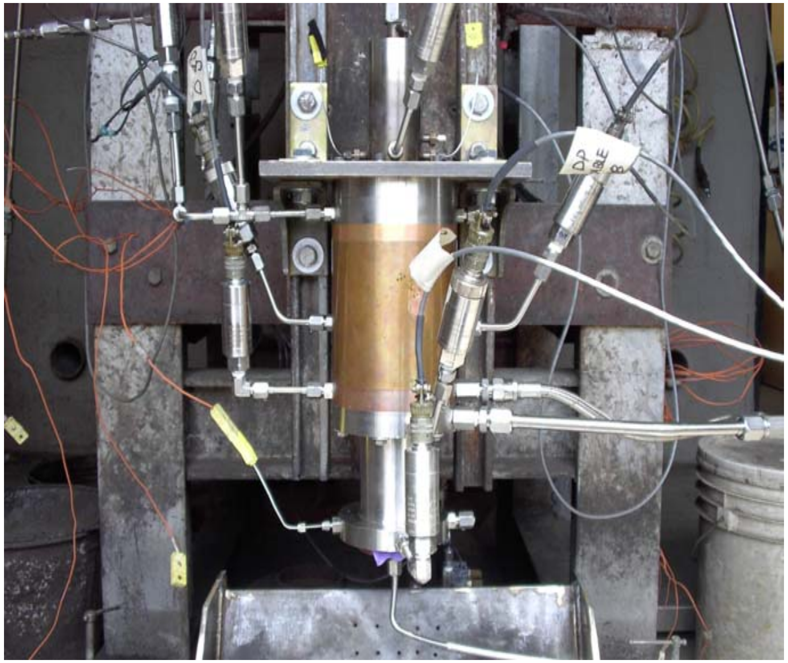
T_Jackout1
1/16” Swagelok Fitting
150 degrees F

P_Jackout
¼” AN Fitting
80-100 psi

T_Jackout2
1/16” Swagelok Fitting
150 degrees F

Testing

- Tests were conducted in the APCL at Purdue University
- Propellant flow timing sequence was automatically controlled by pneumatically actuated valve with LABVIEW system

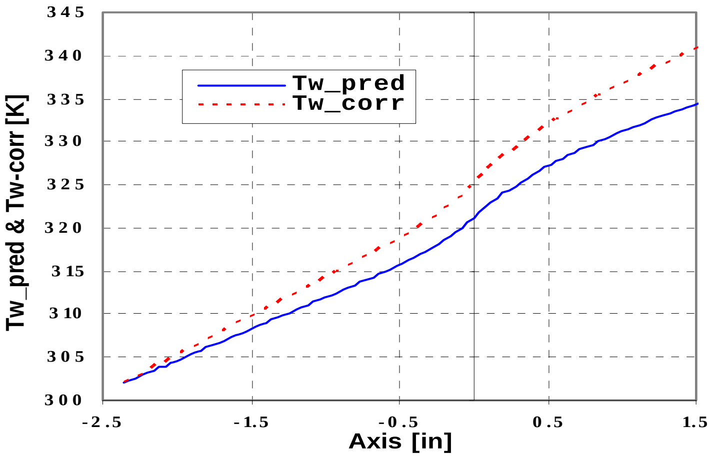


Test article assembly on test stand

Cyclic test

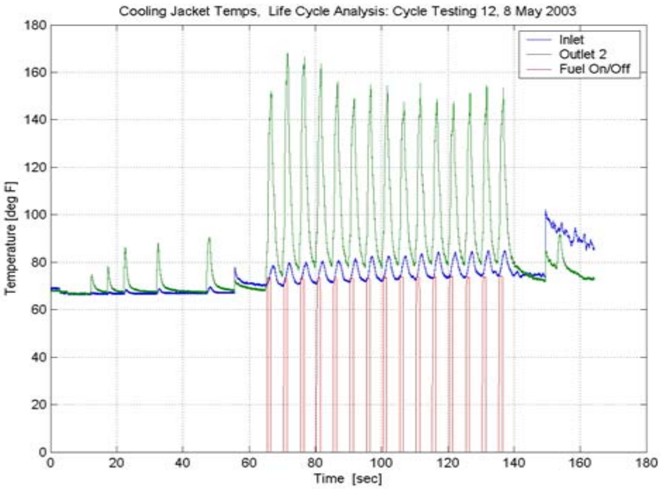
Test Results

- Chamber pressure, C* efficiency, propellant mass flow rate, coolant temperature and pressure were measured and calculated
- Data reduction was performed using in-house code written by students using MATLAB
- Validation procedure
  - Measure coolant ΔT, wall thinning rate
    - 2.15E-5 in/cycle (0.032”→0.029”)
  - Verify 1D thermal model
  - Compute updated thermo-structural environment
  - Make life prediction

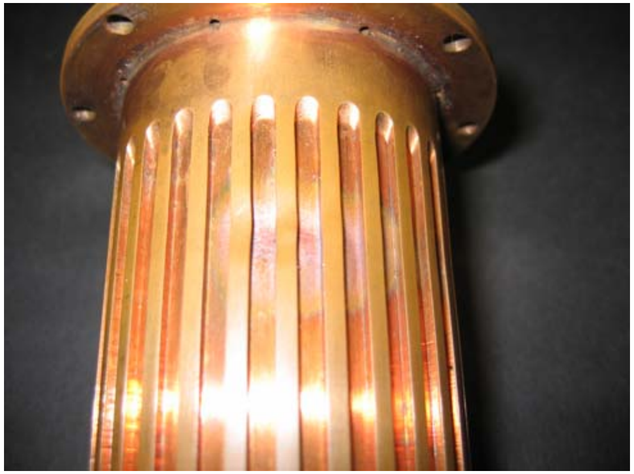


Predicted and measured coolant temperature

ΔT = 4.0K at throat



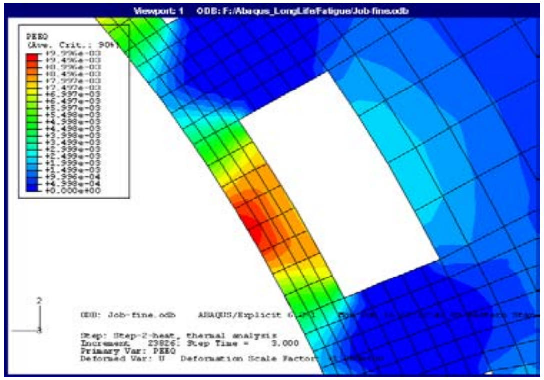
Coolant temperature



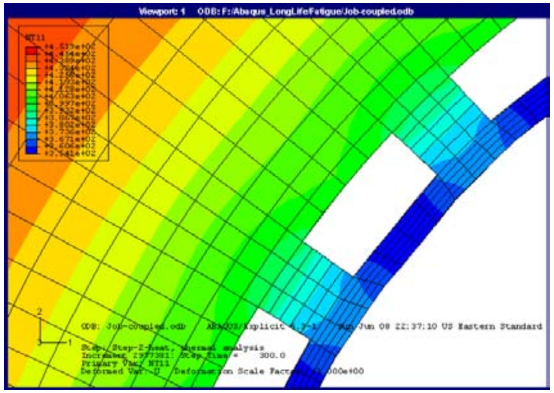
Discoloration and deformation at 90 cycles (1.5”×0.6”)

Updated Structural Analysis

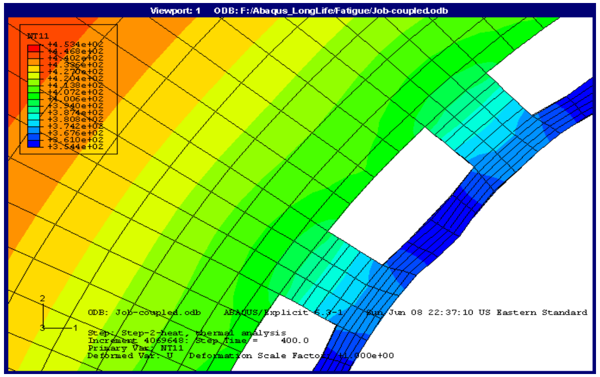
- Simulation of temperature, strain and deformation (bulging, thinning) using ABAQUS explicit module
- Maximum strain : 1.2 % at middle of ligament
- Only bulging of ligament was simulated



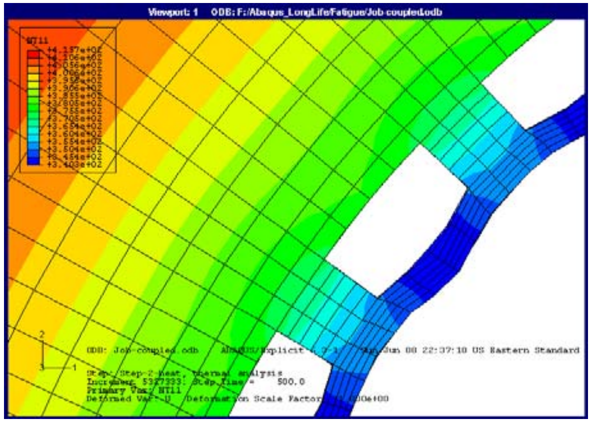
Plastic strain distribution



Deformation after 60 cycle



Deformation after 80 cycle



Deformation after 100 cycle

Summary and Conclusions

- Small-scale rocket combustor was designed and tested to verify life prediction models for low cycle fatigue and fatigue-creep interaction.
- Several life prediction methods were applied to predict combustor life and were compared with test results.
- Correlation data used to improve predictions.
- Improvements would include fixing the liner lands to the structural jacket, and testing at more severe conditions.

Prediction method	Estimated life cycle	Determined life cycle by experiment
Effective stress-strain	**115**	**270**
ANSYS	**115**	
Porowski	**51**	
Dai and Ray with Freed model	**260**	
ABAQUS	**320**	

Comparison of life prediction with test

Summary and Conclusions

- 100’s of cycle goal is very challenging and verification would be very expensive
  - Question of economic feasibility
- Improved life prediction methodology for expanding range of design and operational scenarios is needed
  - Probabilistic life prediction design analysis
  - Testing methodologies with *in situ* thermostructural response measurements
  - Environments definition
  - Improved material database and understanding of damage mechanisms

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