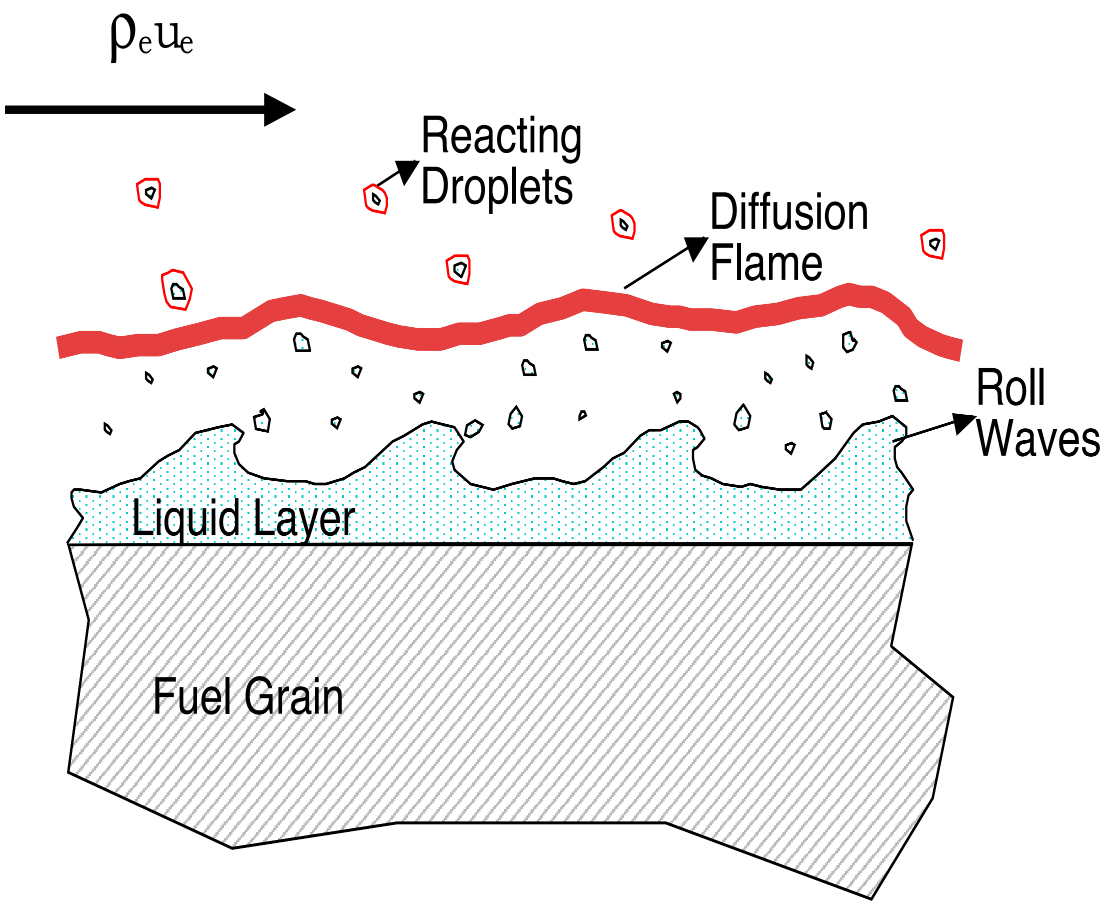
AA 284a
Advanced Rocket Propulsion

Lecture 9
Hybrid Rocket Propulsion
Liquefying Fuels

Prepared by
Arif Karabeyoglu

Department of Aeronautics and Astronautics
Stanford University
and
Mechanical Engineering
KOC University

Entrainment Mass Transfer Mechanism



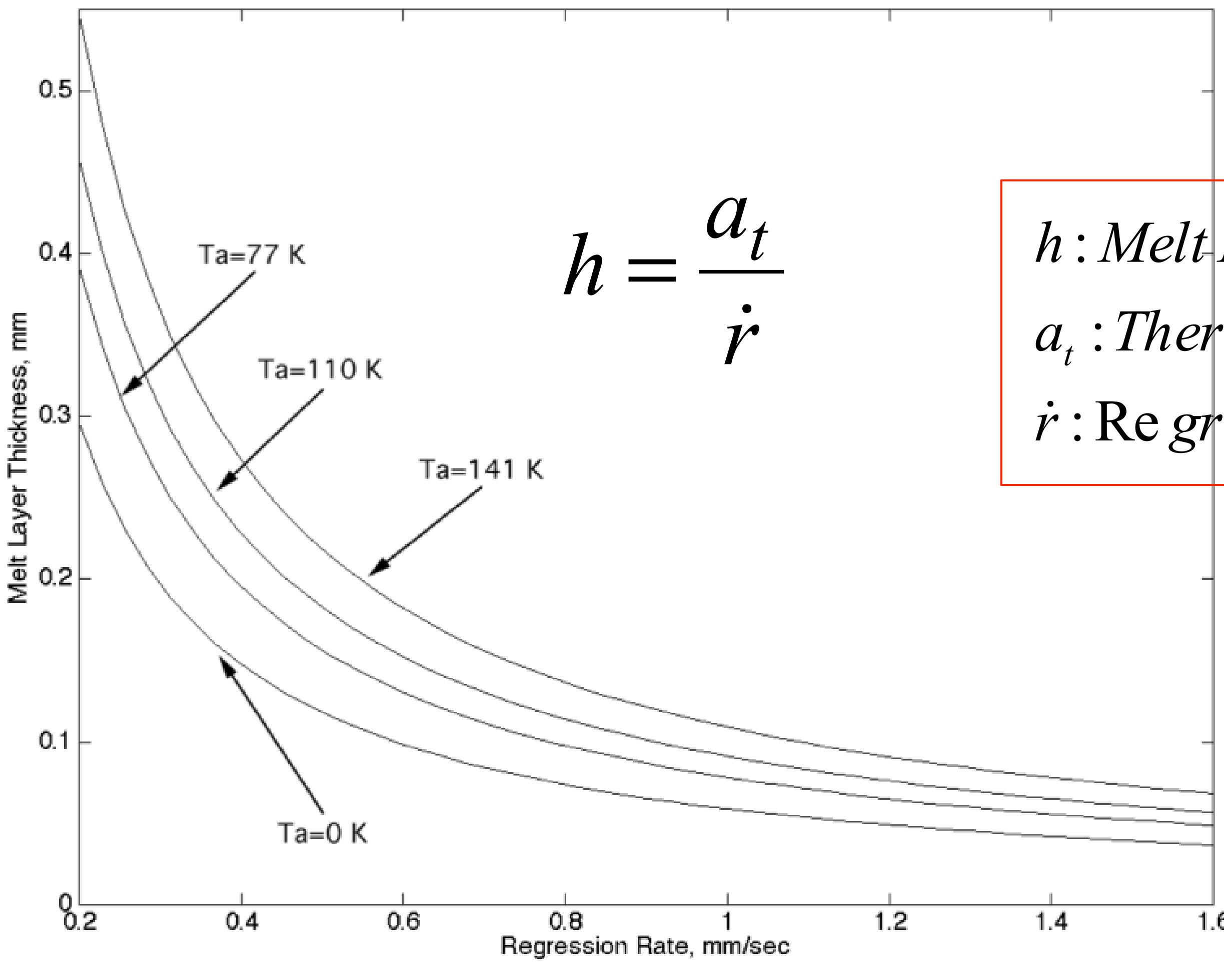
- A new transfer mechanism:
  - Certain fuels form a liquid layer
  - If the conditions are right, mechanical entrainment of liquid droplets occur
- Enhanced mass transfer due to the new mechanism
- Effective use of energy since vaporization is not required for entrained mass
- Liquid Layer Hybrid Combustion Theory (Stanford - 1997)

Regression Rate = Entrainment + Vaporization

Liquid Layer Hybrid Combustion Theory Outline

- Steps of the Theory Development
  - Estimate film thickness
  - Stability of the liquid film
  - Scaling for the entrainment mass transfer
  - Modify "Diffusion Limited Model" for the existence of entrainment.

Film Thickness Model-Pentane



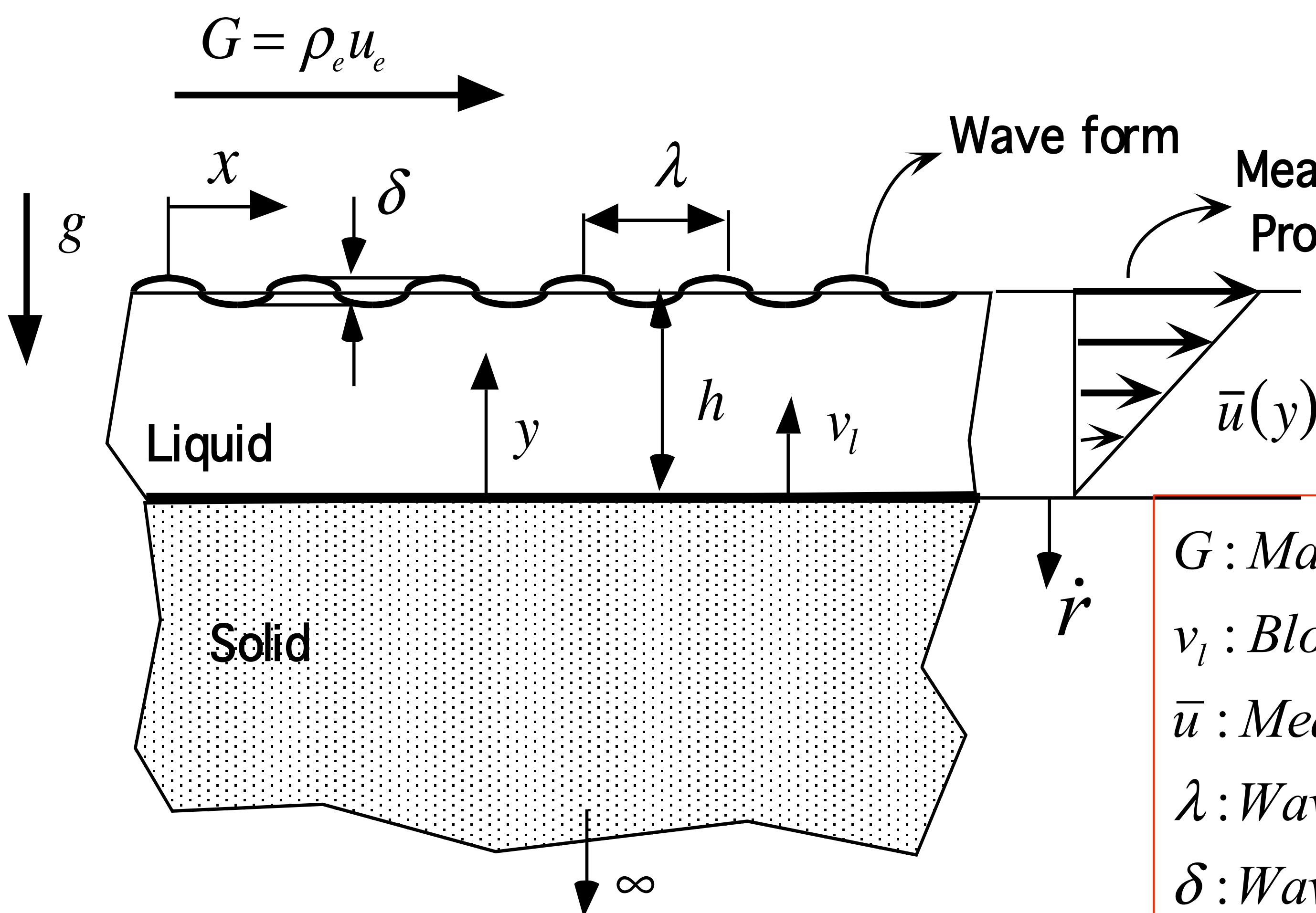
$$h = \frac{a_t}{\dot{r}}$$

h : *Melt Layer Thickness*

a_t : *Thermochemical Parameter*

$\dot{r}$: *Regression Rate*

Film Stability Model



G : *Mass Flux*

v_l : *Blowing Velocity*

$\bar{u}$: *Mean Axial Velocity*

λ : *Wave Length*

δ : *Wave Amplitude*

g : *Acceleration*

Orr-Sommerfeld Equation

- $\tilde{u}$: *Axial Velocity Disturb.*
- $\bar{v}$: *Transverse Velocity Disturb.*
- φ : *Stream Function*
- c : *Amplification*
- α : *Wave No*

- Stream function

$$\tilde{u} = \varphi_y \qquad \tilde{v} = -\varphi_x$$

- Form of Solution - (Surface disturbance)

$$\varphi(x, y, t) = \phi(y) e^{i\alpha(x-ct)} \qquad \left(\eta = \varepsilon\, e^{i\alpha(x-ct)}\right)$$

- Stability equation (Nondimensional)

$$\phi^{IV} - 2\alpha^2\phi'' + \alpha^4\phi - b\left(\phi''' - \alpha^2\phi'\right) = i\alpha \mathrm{Re}(y - c)\left(\phi'' - \alpha^2\phi\right)$$

Re : *Film Reynolds No.* $\qquad$ b : *Blowing Parameter*

Perturbation Solution

- Follow Craik (b=0, *JFM* 1966)
- Consider power series solution (N=6)

$$\phi(y) = \sum_{n=0}^{N} A_n y^n$$

- Rapid convergence for

$$\alpha^2 << 1 \qquad \mathrm{Re} < O(1) \qquad b < O(1)$$

$\tilde{P}_g / \eta$: Pressure Disturbance
$\tilde{\tau}_g / \eta$: Shear Disturbance
T : Surface Tension Parameter
G : Acceleration Parameter

- Solution for eigenvalue problem

$$T\alpha^2 + G - \tilde{P}_g / \eta + \frac{3i\tilde{\tau}_g / \eta}{2\alpha} = (1-c)\left[\frac{3}{2}(1-c) - 1 + \frac{(3 + 3b + 6\alpha^2)}{i\alpha \mathrm{Re}}\right]$$

Exact Solution

- Solution for Orr-Sommerfeld equation

$$\phi_1(y) = e^{\alpha y}$$

$$\phi_2(y) = e^{-\alpha y}$$

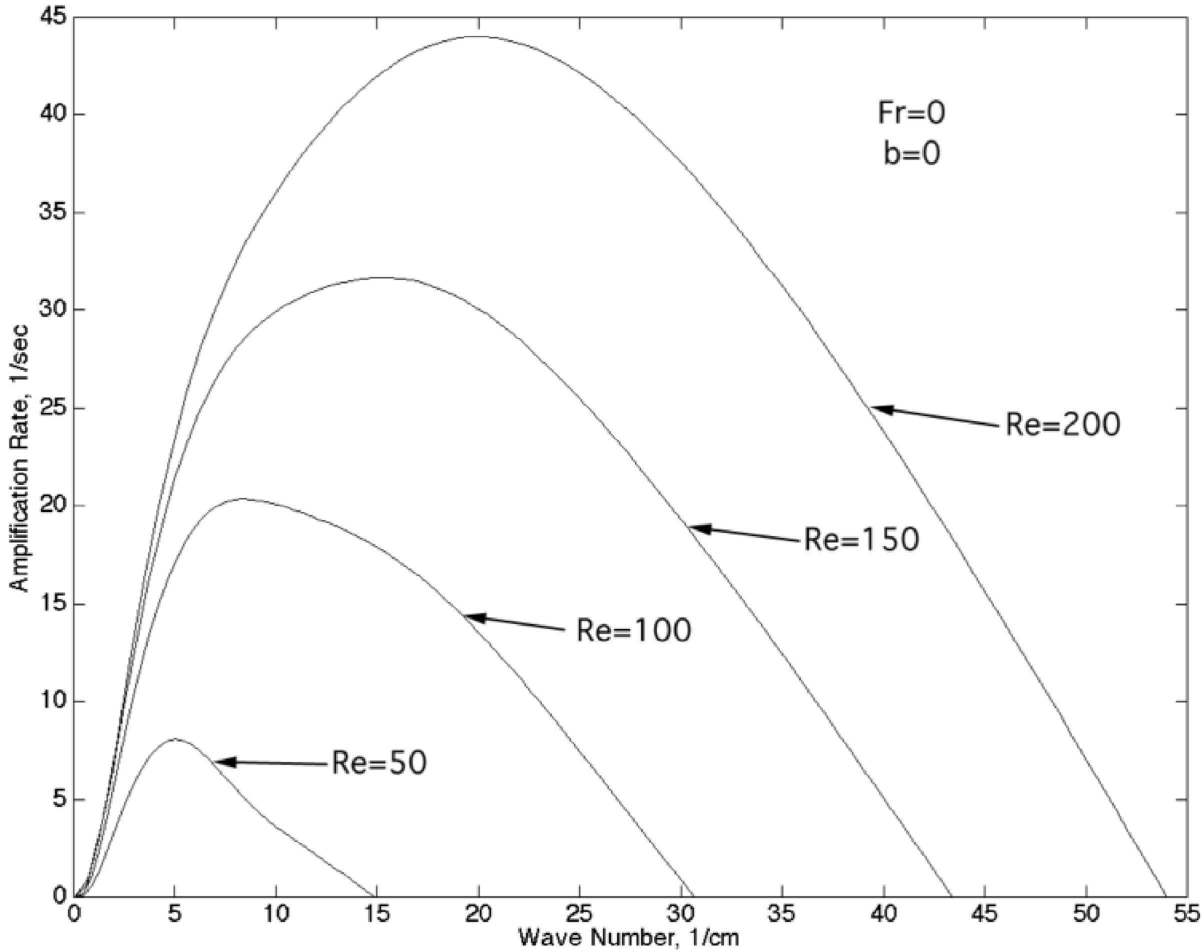
$Ai, Bi : Airy\ Functions$

$$\phi_3(y) = \frac{1}{\alpha}\int_{y_o}^{y} \sinh[\alpha(y-\hat{y})]\ e^{-(B/2)z(\hat{y})} Ai\left[z(\hat{y}) + B^2/4\right] d\hat{y}$$

$$\phi_4(y) = \frac{1}{\alpha}\int_{y_o}^{y} \sinh[\alpha(y-\hat{y})]\ e^{-(B/2)z(\hat{y})} Bi\left[z(\hat{y}) + B^2/4\right] d\hat{y}$$

where $B = -ib/(\alpha \mathrm{Re})^{1/3}$

Film Stability-Pentane Film



$$Re = U_l h \rho_l / \mu_l$$

Entrainment Mass Transfer

- Scaling for entrainment mass transfer

$$\dot{m}_{ent} \propto \frac{P_d^{\bar{\alpha}} h^{\beta}}{\sigma^{\pi} \mu_l^{\gamma}}$$

Numerator ← Operational Parameters: (Pressure, Oxidizer Flux)

Denominator ← Material Properties: (Viscosity, Surface Tension)

- Gater & L'Ecuyer (1970)- RP1, methanol

$$\bar{\alpha} = 1.5 \qquad \beta = 2$$

P_d : Dynamic Pressure

σ : Surface Tension

μ_l : Liquid Viscosity

$\bar{\alpha}, \beta, \pi, \gamma$: Exponents

Liquid Layer Hybrid Combustion Theory

- Modification on the classical Hybrid Combustion Theory
  - Reduced heating requirement for the entrained mass.
  - Reduced "Blocking Effect" due to two phase flow.
  - Increased heat transfer due to the increased surface roughness.

Liquid Layer Hybrid Combustion Theory

- Mass balance

$$\dot{r} = \dot{r}_v + \dot{r}_{ent}$$

$\dot{r}_v$: *Vaporization Regression Rate*

$\dot{r}_{ent}$: *Entrainment Regression Rate*

$\dot{r}$: *Total Regression Rate*

a_{ent} : *Entrainment Parameter*

F_r : *Surface Rougness Coefficient*

R_{he}, R_{hv} : *Energy Parameters*

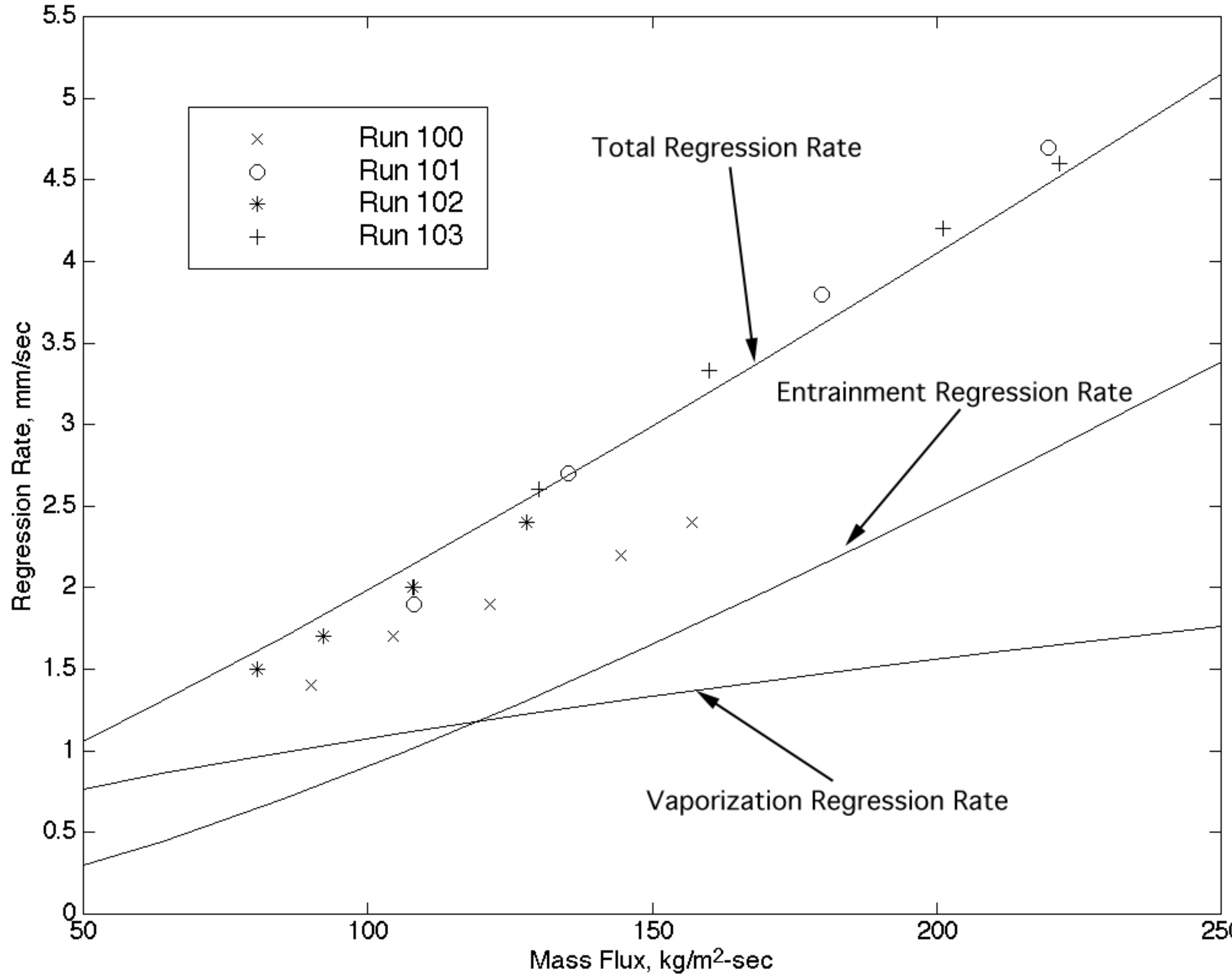
- Energy balance

$$\dot{r}_v + \left[R_{he} + R_{hv}\left(\dot{r}_v / \dot{r}\right)\right]\ \dot{r}_{ent} = F_r \frac{0.03\mu_g^{0.2}}{\rho_f}\left(1 + \dot{Q}_r / \dot{Q}_c\right) B \frac{C_H}{C_{Ho}} G^{0.8} z^{-0.2}$$

- Entrainment regression rate

$$\dot{r}_{ent} = a_{ent} \frac{G^{2\alpha}}{\dot{r}^{\beta}}$$

Theory-Pentane Predictions



Theory Effect of Melt Layer Properties

Propellant	Pentane C_5H_{12}	Acetone C_3H_6O	2,2,5 tmh	HFI	Isopropanol C_3H_8O
Melt Layer Viscosity	1	1.1	0.9	5.4	10.8
Melt Layer Surface Tension	1	1.3	0.8	1.1	1.1
Entrainment Parameter, a_{ent}	1	0.7	1.3	0.17	0.09
Observed Regression Rate	1	~1	~1	0.56	0.5

Homologous Series of n-Alkanes (C_nH_{2n+2})

- Normal Alkanes: Fully saturated, straight-chain hydrocarbons
- Examples:

Methane (CH_4):
C

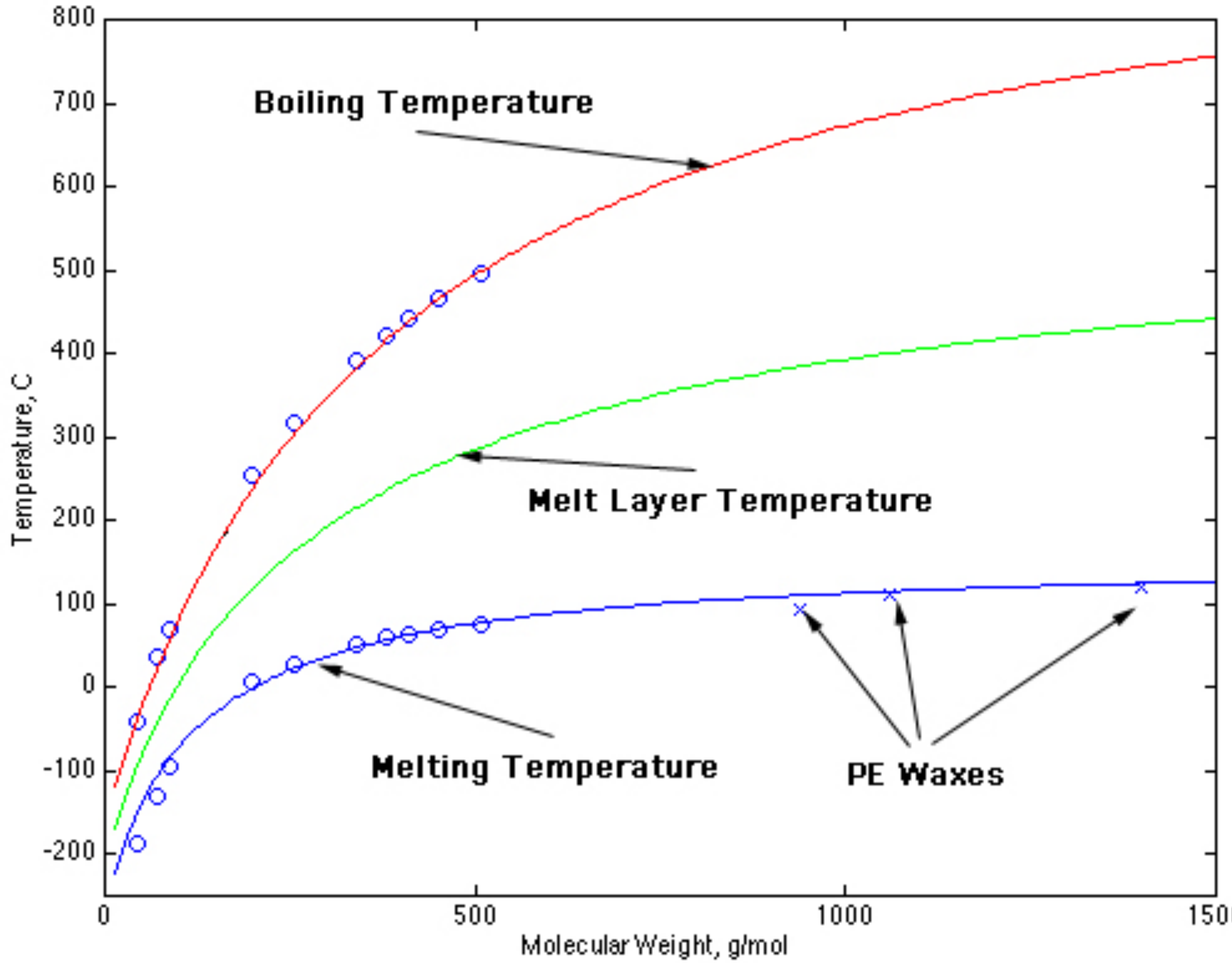
Ethane (C_2H_6):
C-C
:

Pentane (C_5H_{12}):
C-C-C-C-C
:

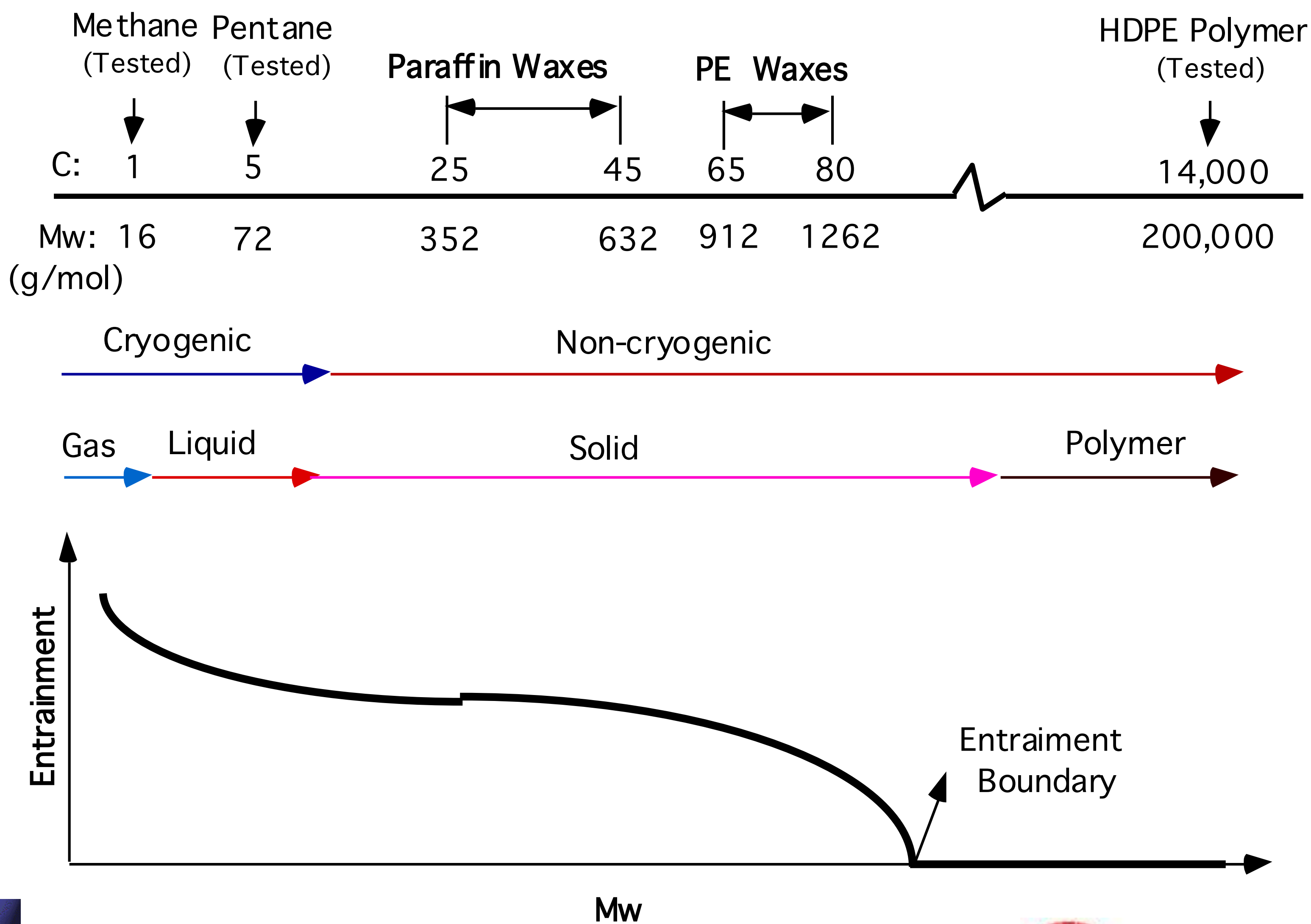
"Wax" ($C_{32}H_{66}$):
C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C-C

A number of practical fuels (pure form or mixtures):
Methane, Kerosene (n~10), Paraffin Waxes (n=16-45),
PE waxes (n=45-90), HDPE Polymer (n in thousands)

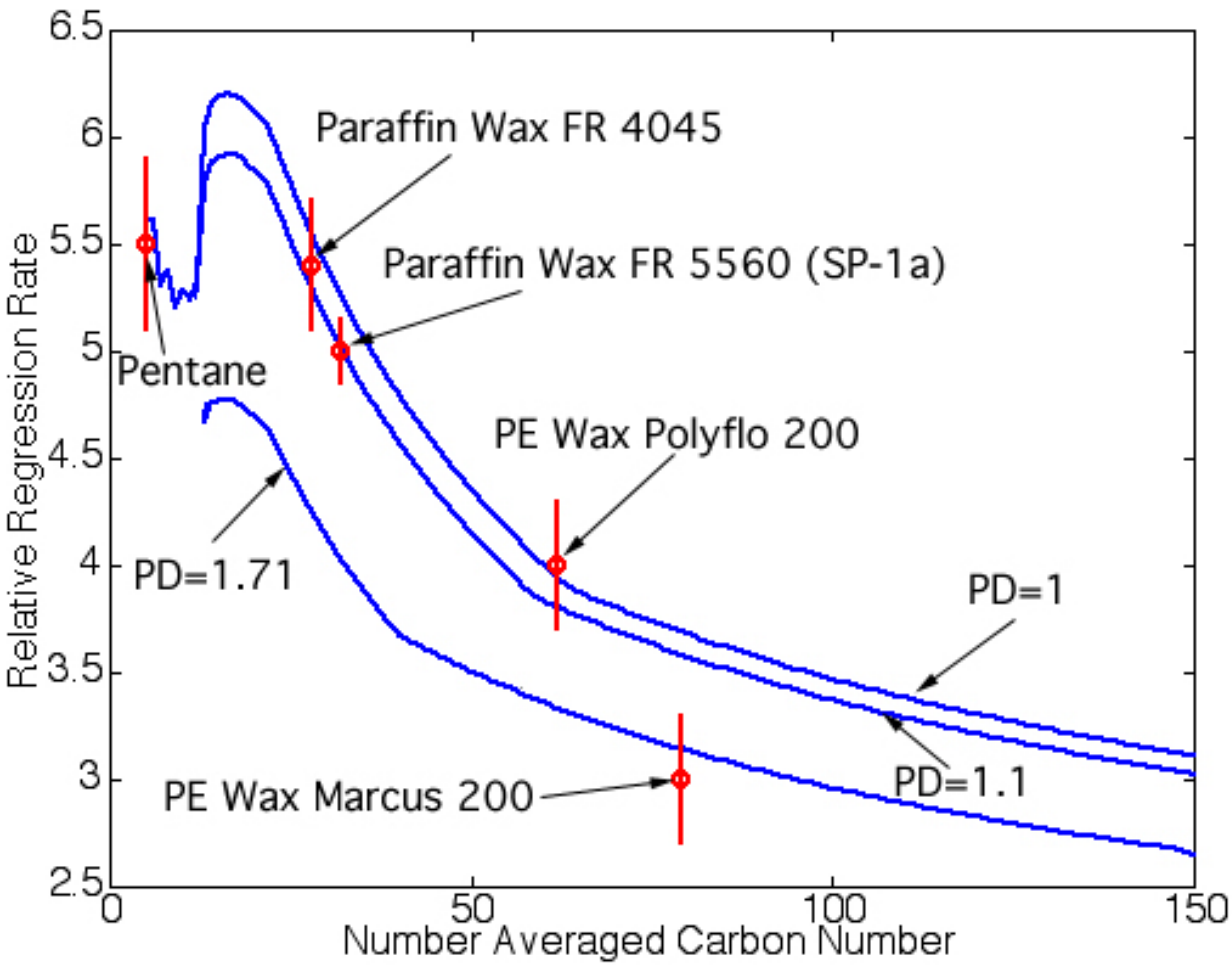
Melt Layer Temperatures for C_nH_{2n+2} Series



Entrainment for C_nH_{2n+2} Series



Theory Prediction and Motor Test Data for C_nH_{2n+2}



Regression rate increase over the classical value is as high as 6.1

Paraffin waxes burn 5-5.5 times faster than the HDPE polymer

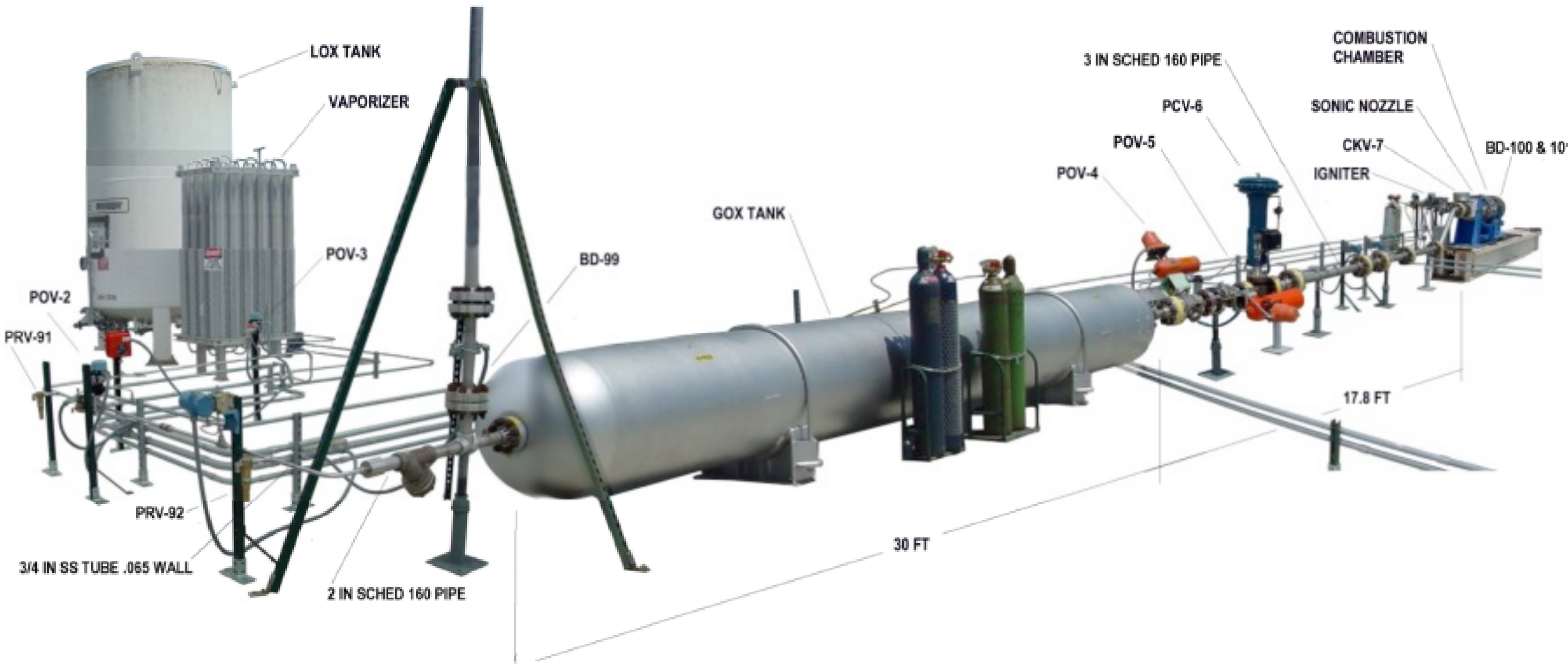
Theory prediction is fairly accurate

Stanford Motor Tests

- Formulated paraffin-based fuel SP-1:
  - Melting temperature: 70 C
  - Structural and optical additives

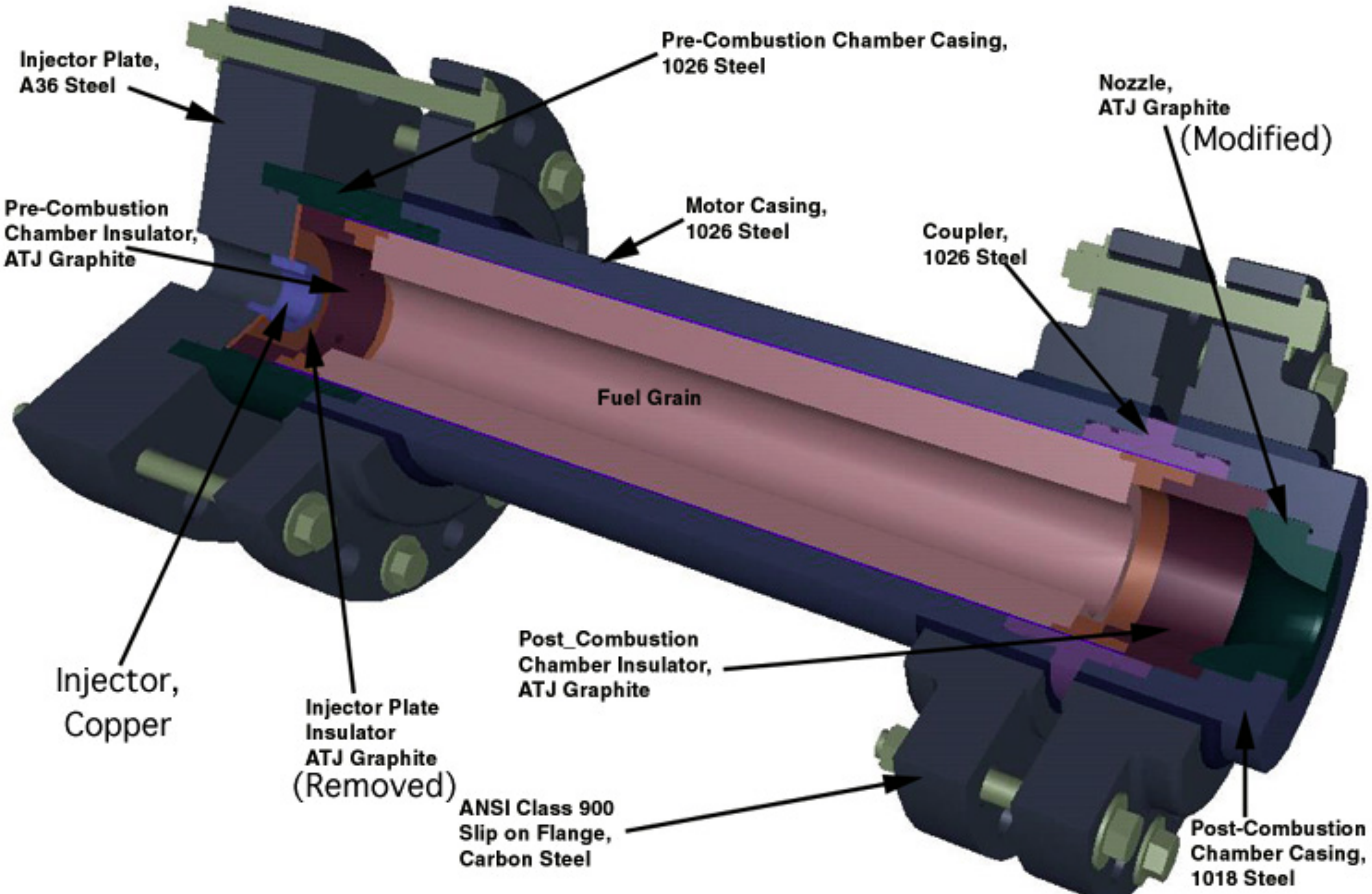
- Stanford lab-scale tests confirmed the prediction
  - Low oxidizer mass flux (< 15 g/cm^2-sec)
  - Low chamber pressure (~150 psi)
  - Small physical scale (i.e. 2.38" OD)

NASA Ames Hybrid Combustion Facility (HCF)

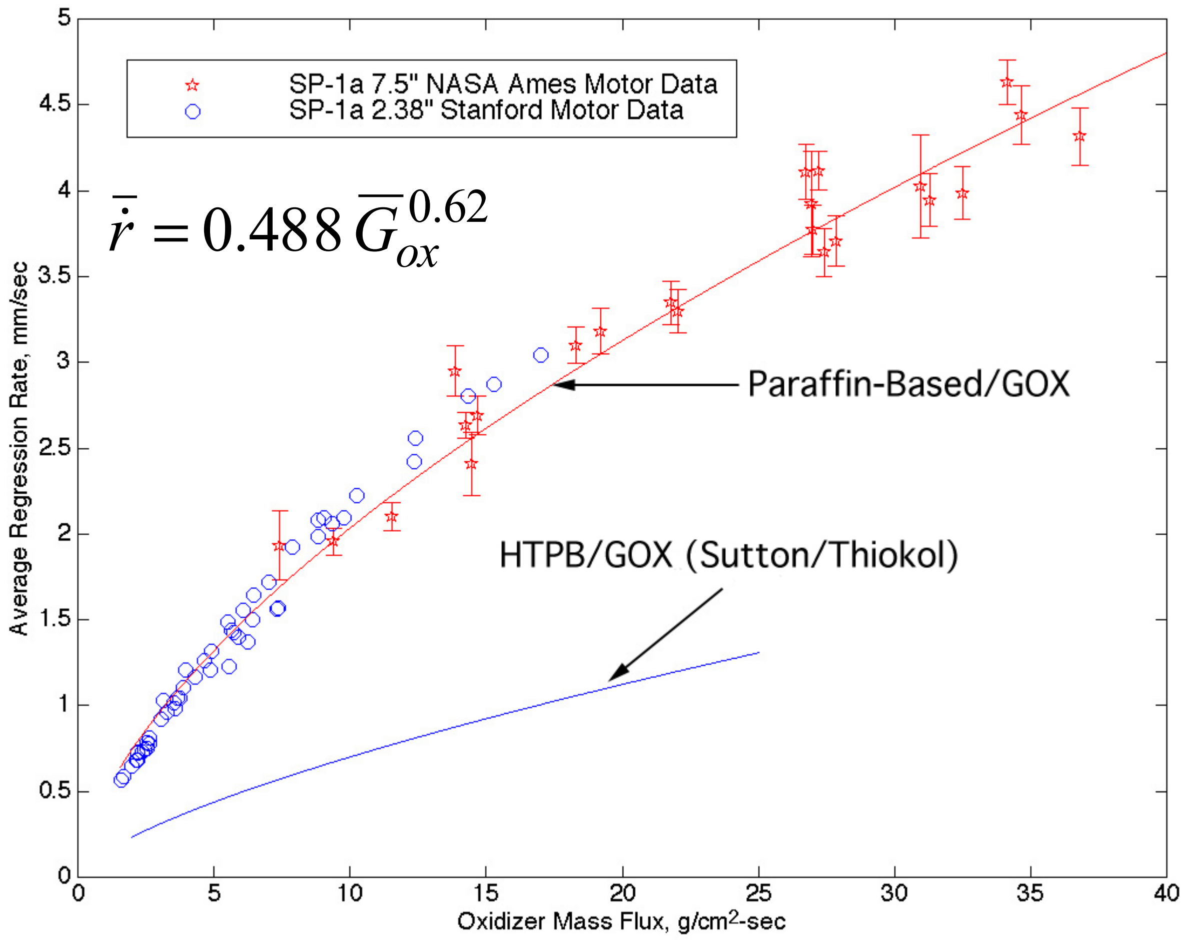


- Oxidizer: Gaseous oxygen up to 16 kg/sec
- 10” OD steel test section.
- Cartridge loaded 7.5” OD grains up to 45” in length.
- 41 motor tests since September 2001.

Test Motor Configuration

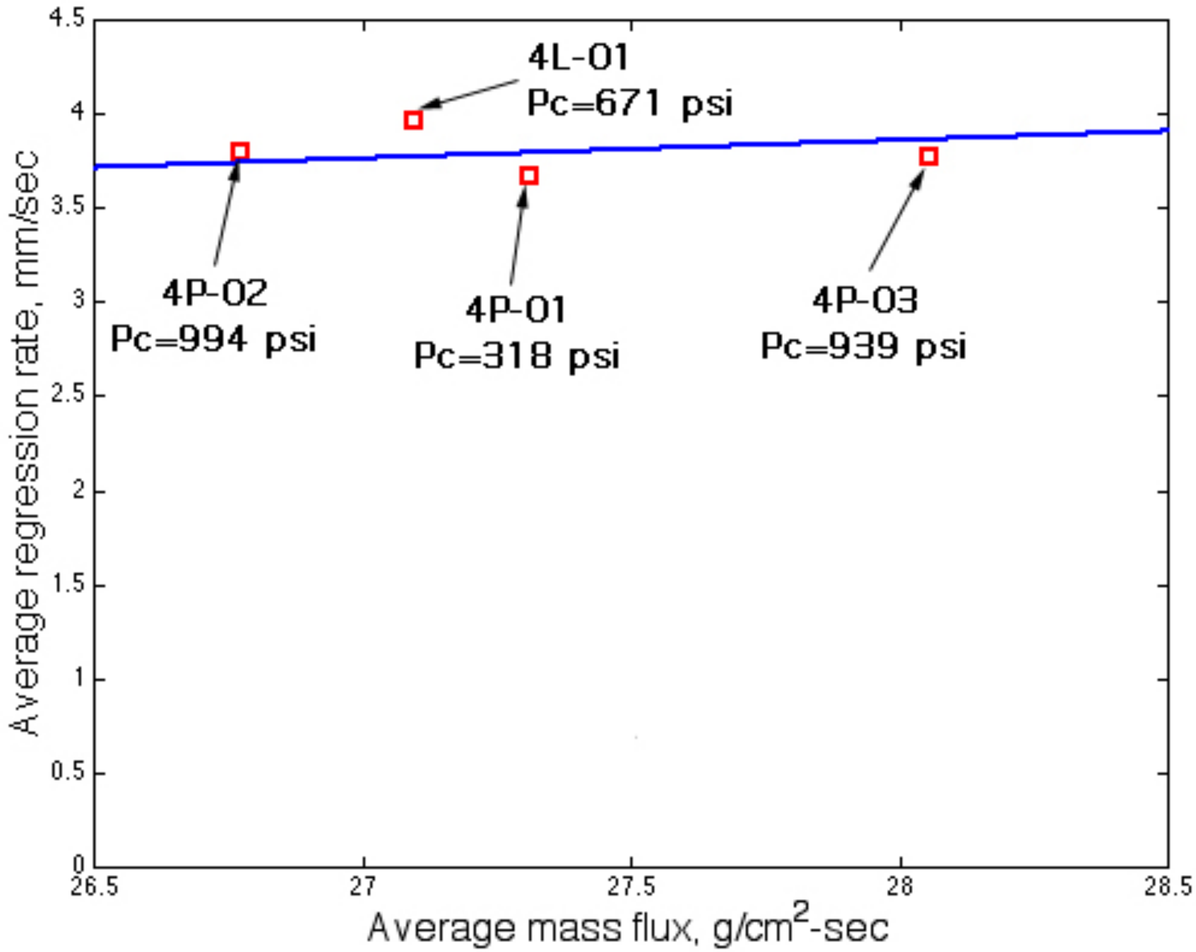


Regression Rate Law for Paraffin-Base Fuel, SP-1a



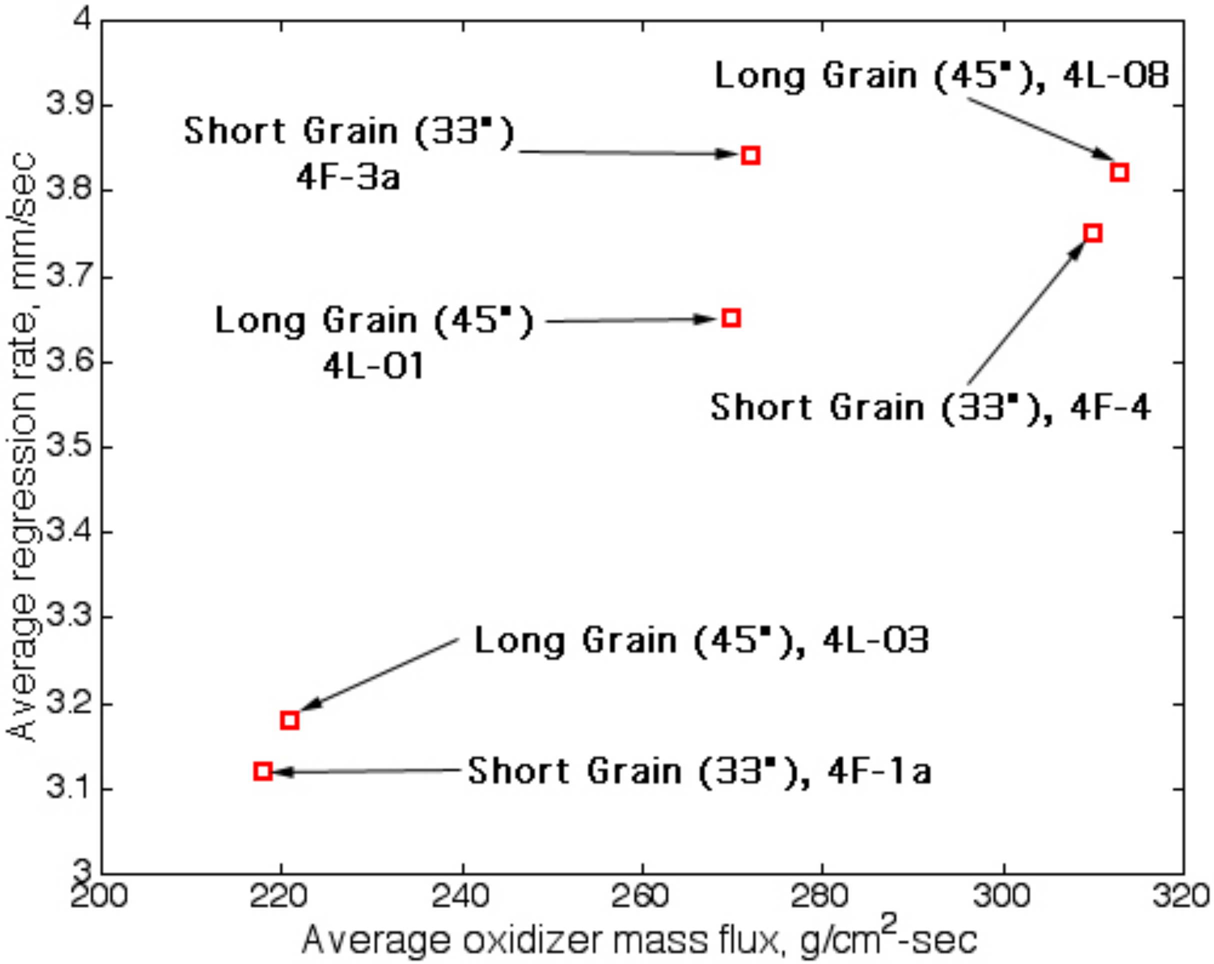
Three fold improvement is confirmed

Effect of Chamber Pressure on the Regression Rate



No Pressure Effect

Effect of Fuel Grain Length on the Regression Rate

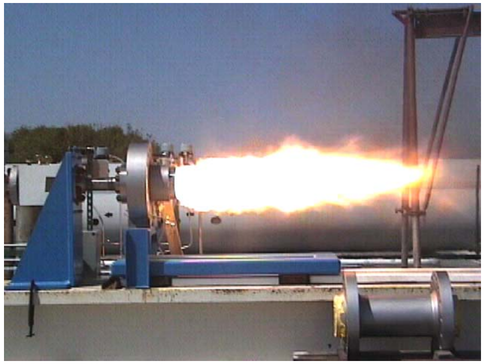


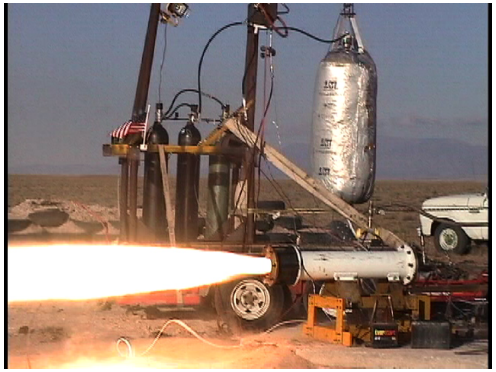
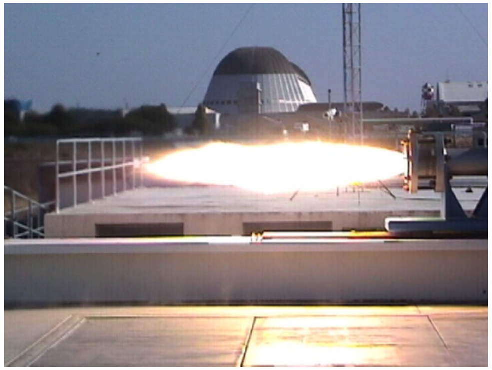
No Length Effect

Motor Test Experience

- Small Scale(i.e. 50-100 lbf): >1000 tests
- Scale-up (i.e. 900-3500 lbf): >125 tests
- Oxidizers: GOX, LOX, N2O





Advanced Hybrid Rockets

Hybrid Propulsion –Technical Challenges

Technical Challenges

- *Low regression rates for classic hybrid fuels*
  - *Results in complicated fuel grain design*
- *Low frequency instabilities*
  - *Instabilities are common to all chemical rockets*
  - *They need to be eliminated*
  - *Expensive and long process*

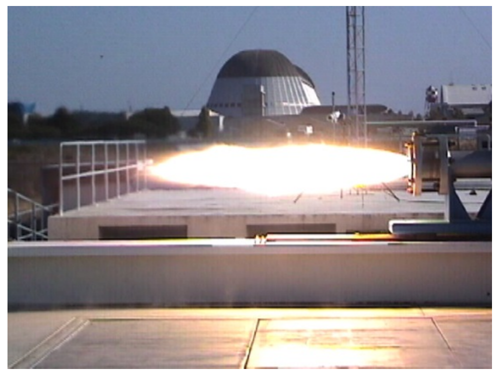
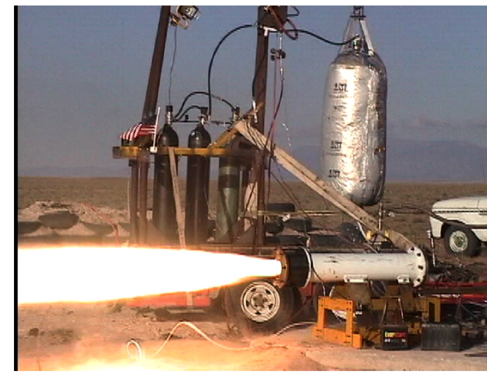
Solution Strategy

- *Solutions to these technical issues should be such that they do **NOT** compromise the simplicity, safety and cost advantages of hybrids.*
- *Comparable or better performance compared to liquids and solids.*

Paraffin-Based Fuels Technology Progress

Motor testing experience (SPG/Stanford/NASA Ames)

- *Small Scale(i.e. 50-100 lbf): ~1,000 tests*
- *Scale-up (i.e. 900-15,000 lbf): ~125 tests*
- *Oxidizers: Liquid Oxygen, Gaseous Oxygen, Nitrous Oxide, Nytrox*

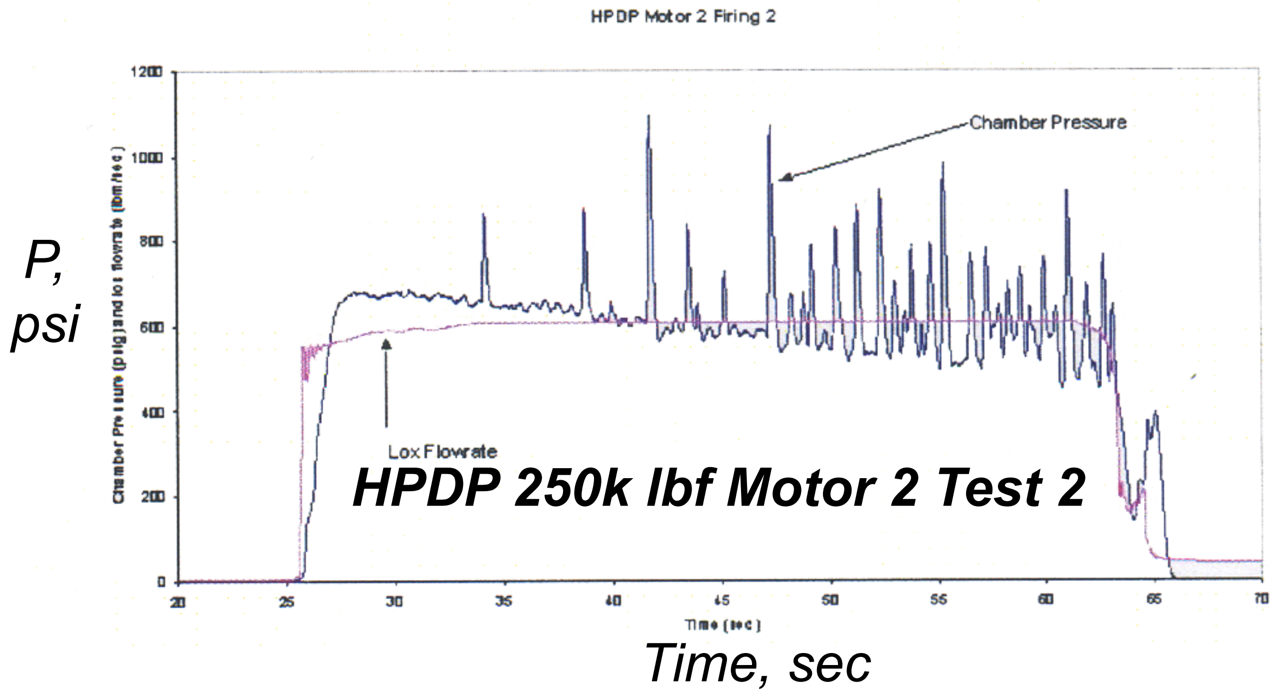




SPG work on paraffin-based fuel technology

- *Formulation (Keep cost ~ 1 $/lb)*
- *Processing (22 inch OD fuel grains – 700 kg)*
- *Structural testing and modeling*
- *Internal ballistic design of single circular port hybrids*
- *Scale up motor testing (in 2012 35,000 lbf class motors)*

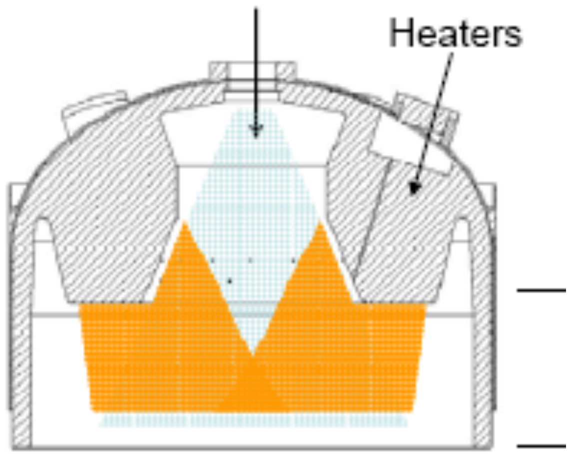
Large single circular port hybrids are feasible

Low Frequency Instabilities



- Hybrids are prone to low frequency instabilities (2-100 Hz)
- High amplitude spiky combustion
- Especially common in liquid oxygen (LOX) based systems
- A number of mechanisms

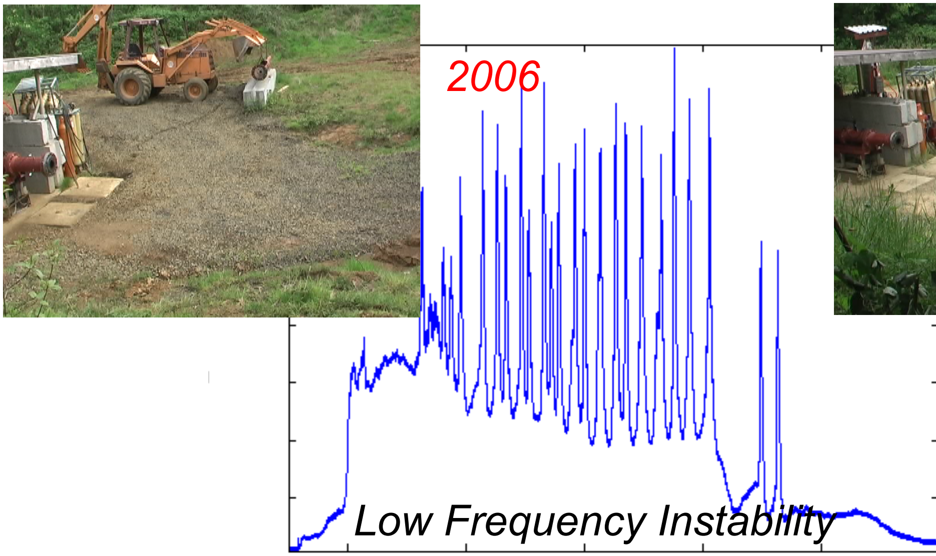
Low Frequency Instabilities - Remedies

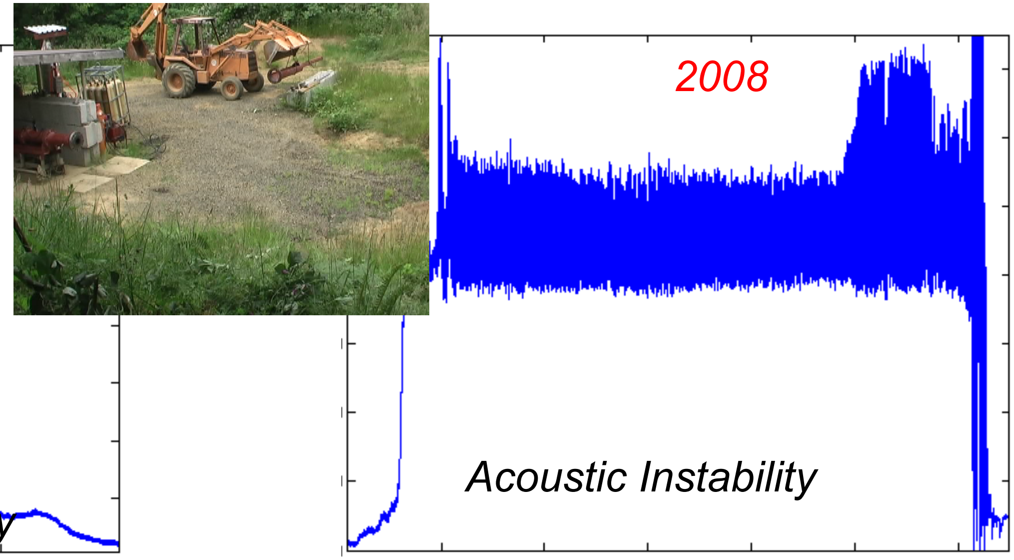


- We believe that a LOX motor can be made stable
  - Without the use of heaters or TEA injection
  - By advanced injector and combustion chamber design
- Demonstrated in 11 inch and 22 inch LOX/Paraffin-based motors

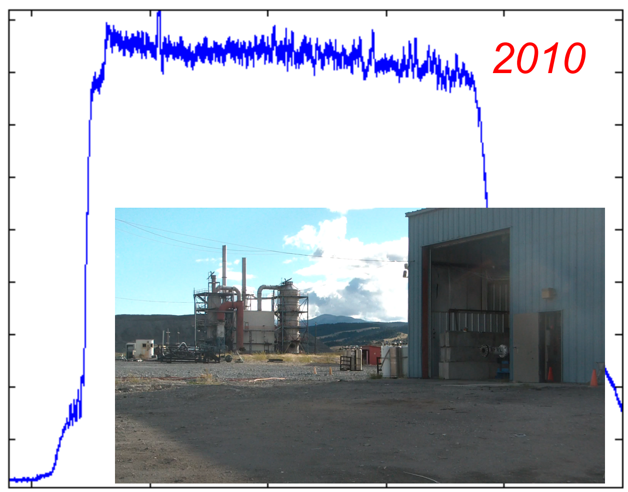
- Solutions used in the field
  - Lockheed Martin –Michoud and HPDP used hybrid heaters to vaporize LO_2
  - AMROC injected TEA (triethylaluminum) to vaporize LOX
- Both solutions introduce complexity minimizing the simplicity advantage of hybrids
  - Heaters- extra plumbing
  - TEA – extra liquid, hazardous material

Low Frequency Instabilities – 11 Inch LOX Motor





- All three tests have the same
  - Oxidizer flow rate
  - Fuel formulation
  - Port diameter
  - Nozzle diameter



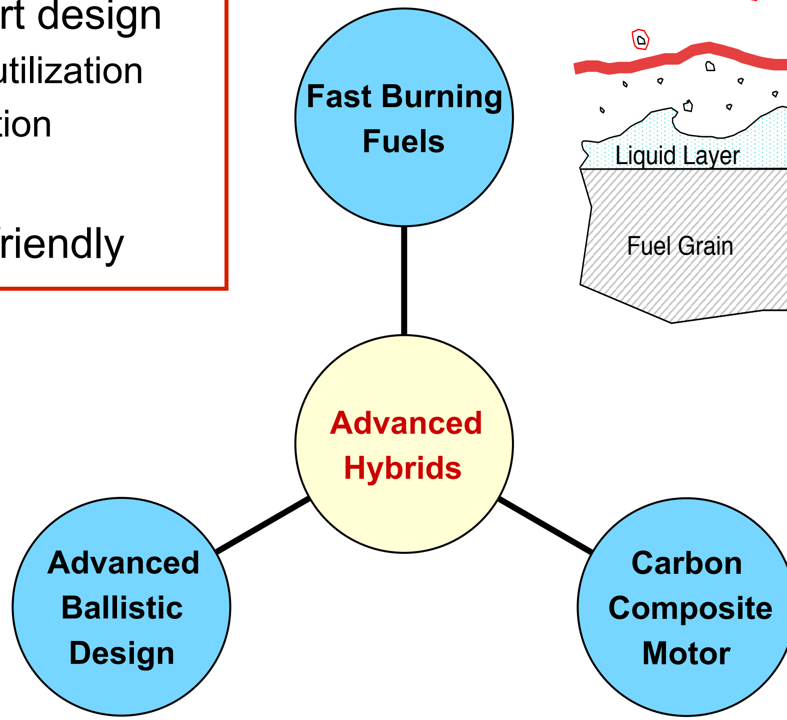
Stable Motor (c* efficiency > 95%)

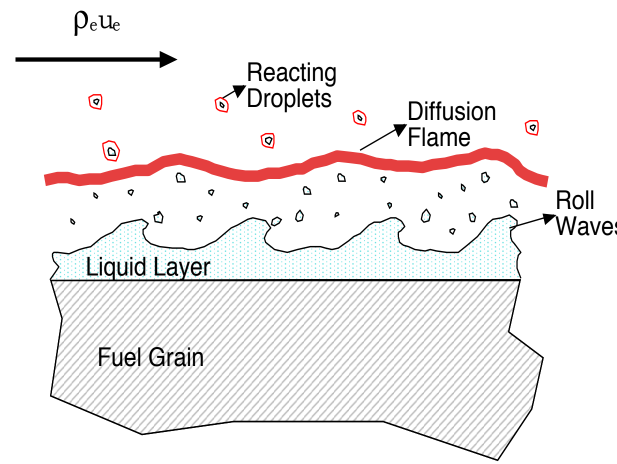
- Solution requires NO
  - Active heating
  - Injection of a pyrophoric liquid (i.e. TEA)
  - Active control
  - Moving parts
  - Complicated parts or exotic materials

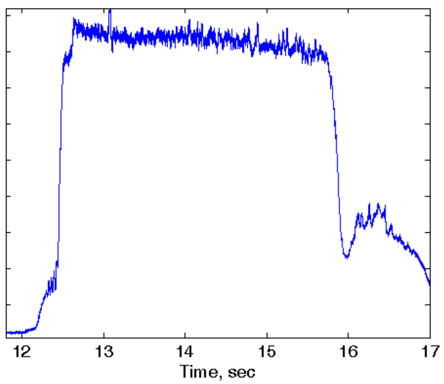
AA284a Advanced Rocket Propulsion

Advanced Hybrid Rockets

- Single circular port design
  - Excellent fuel utilization
  - Simple fabrication
- Low cost fuel
- Environmentally friendly







- Light weight construction
- Low cost
- All in house manufacturing

- Stable operation with NO
  - External heating
  - Pyrophoric liquid injection
- High combustion efficiency (>95%)

Technology Details

Composite Fabrication

- ***Winding Machine Specifications***

Filament Winder Specification Summary:

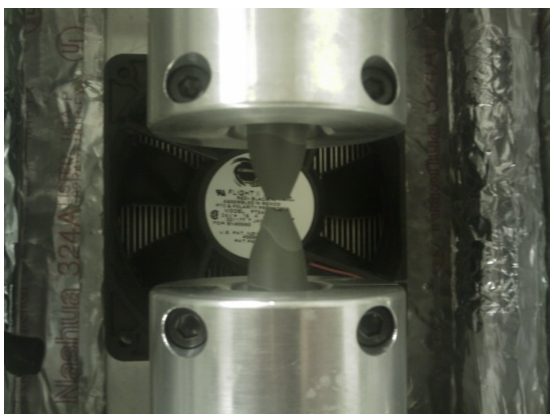
- *Machine: 4 axes CNC Fil. Winding Machine*
- *Max Part Dimensions: 60in x 15.1ft*
- *Weight capacity: 6,600 lbs (3,000 kg)*
- *Machine Control: Siemens industrial computer*
- *Winding software purchased: CADFIL*

Machine Use

- *Winding of three 22 inch motors has been completed*
- *Winding of numerous 10 inch flight weight motors has been completed.*

Fuel Formulation

Formulations with extreme elongation capability are feasible

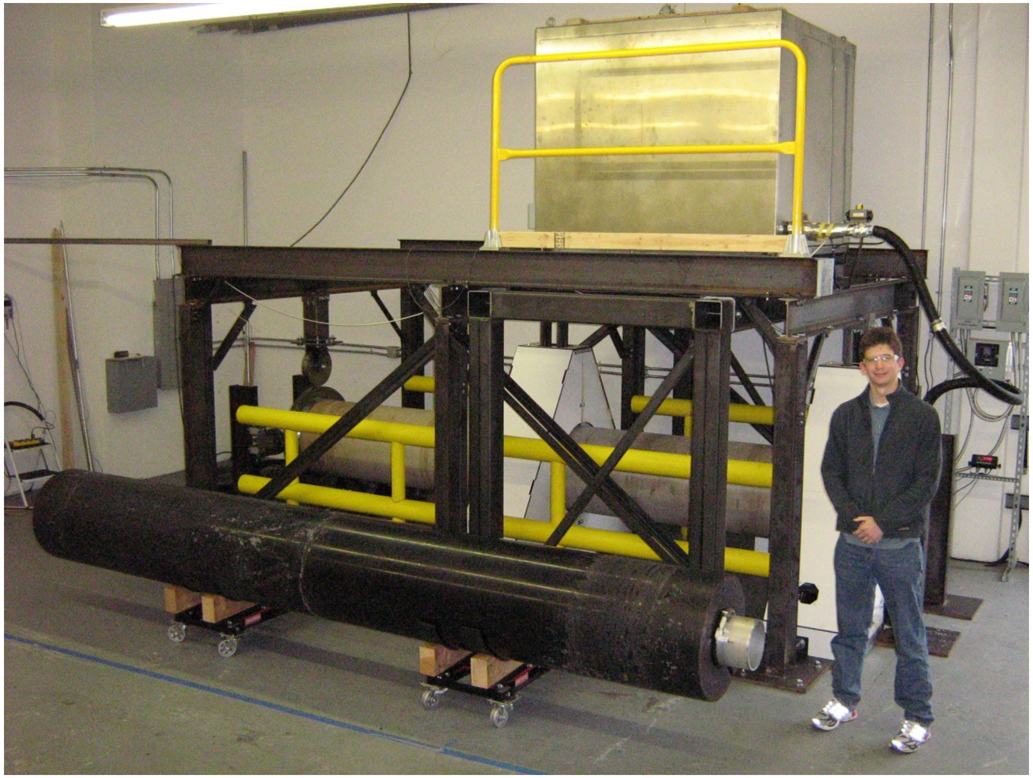


Progress - Formulation

- *Formulation and characterization of paraffin-based fuels with a wide range of ballistic properties.*
- *Fuel cracking problem has been solved by formulation and advanced structural design of the fuel grain/ motor case system*
- *New fuel capable of operating from -80 C to 60 C has been formulated to be used in Mars applications*

Fuel Processing

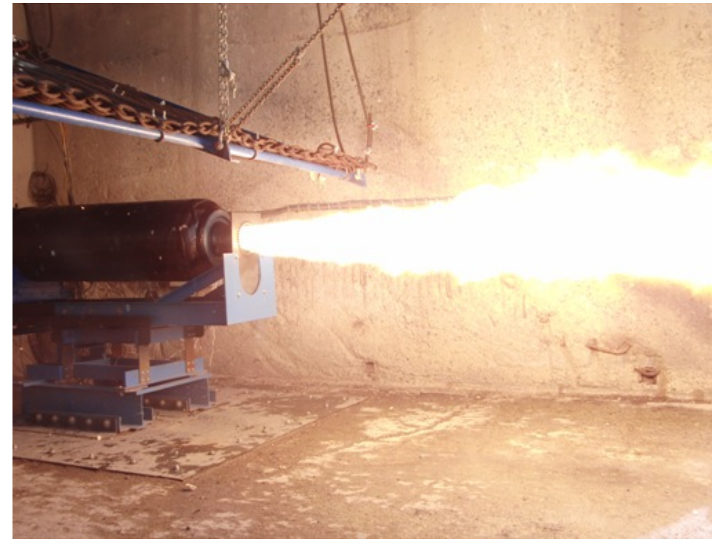
- **Progress - Fuel Processing Technologies**
- *SPG has now capability to cast grains up to 36 inches in diameter*



- *Developed 3 alternative casting technologies*
- *High quality and consistency is achieved*
- *Successfully produced 22 inch OD paraffin-based fuel grains*
  - *Each weigh 700kg*
  - *Largest monolithic wax piece ever built*

22 Inch Flight Weight Motor

- ***22 Inch Flight Weight System***
  - *Development is ongoing*
  - *Up to 35,000 lb of thrust*
  - *Booster Mode:25 seconds of burn time*
  - *Upper stage mode burns for 100 sec.*
  - *Stable/efficient LOX/paraffin-based motor (upper stage version)*
  - *Motor length/regression rate can be adjusted for a specific mission*
  - *Carbon composite motor case*
  - *Cost effective motor*



Summary and Potential Applications of the Technology

Key Virtues of the Technology

- *High performance for the LOX/Paraffin-based system*
  - *Delivered vacuum Isp value of ~340 sec for a nozzle expansion ratio of 70*
    - *High combustion efficiency (97-98%)*
    - *Motor operating at the optimal average O/F of 2.8*
    - *Low O/F shift*
  - *Low fuel sliver fraction: < 1%*
- *Simplicity and fault tolerance of hybrids is retained*
  - *No external heating is required for stability*
- *Safe (Zero TNT equivalency and reduced fire hazard)*
- *Affordable (Both development and recurring)*
  - *No exotic materials*
  - *No parts with tight machining tolerance*
  - *No active cooling*
- *Mission flexibility*

Applications

- *Launch vehicle – Booster or upper stage*
- *Tactical or strategic missile propulsion, target drones*
- *In space, in orbit*
- *Sub-orbital space tourism*
- *Sounding rocket*
- *Aircraft thrust augmentation*

Hybrid Combines the Worst of the Two Worlds?

Some claim that hybrids combine the low performance of a solid rocket and the complexity of a liquid engine

- This could certainly be true for a poorly designed hybrid
- However a well designed hybrid would
  - Deliver Isp performance much better than a solid (up to 35 seconds of improvement)
  - Be much simpler than a liquid
    - Fault tolerance
    - No active cooling
    - Half the plumbing
    - Simple injector design
- Inherent safety, easy throttling and environmental cleanliness are the added benefits.