Hybrid Rockets

Liquefying Solids – Enhanced Regression

Hybrids – Increasing Regression Rate

- Options

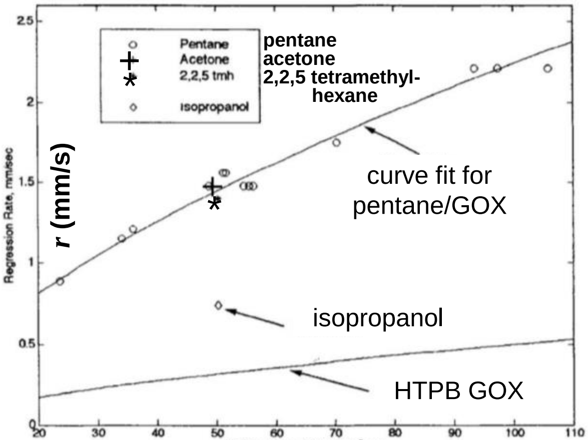
	Method	Basic Idea	Drawbacks
Increased heat transfer to solid surface	Add oxidizers or exothermic decomposing mat'ls.	Increase heat transfer by moving flame towards surface	• Reduced safety • Increased p dependence
	Add metal particles (micron sized)	Increase radiative heat transfer	• Small improvement
	Add metal particles (nano sized)	Move flame closer to surface and increase rad. heat transfer	• High cost • Complex processing
	Swirl injection for liquid	Increased mass flux near surface	• Increased complexity • Large motor scaling
More responsive material	Solid with low ΔH_{evap}	Lower heat transfer needed	• Limited options • Increased blowing

Cyrogenic Solid Hybrids

- Work at AFRL (Edwards) in the early-mid 1990’s to examine “frozen” solids
- Motivation
  - more flexibility on propellant selection (H_2, O_2, …) and possibility of adding metals to otherwise liquid propellants
  - retain nonexplosive, safe-handling features of the liquid propellants
- Worked on frozen organics (e.g., pentane) and GOx

Example AFRL Results

- Regression rate 3-5 × faster than “standard” (HTPB-GOx)
- Opens possibility of reduced burning area (A_b) for same thrust
  - single port
  - simpler manufacturing
  - higher volumetric efficiency
  - reduced sliver losses

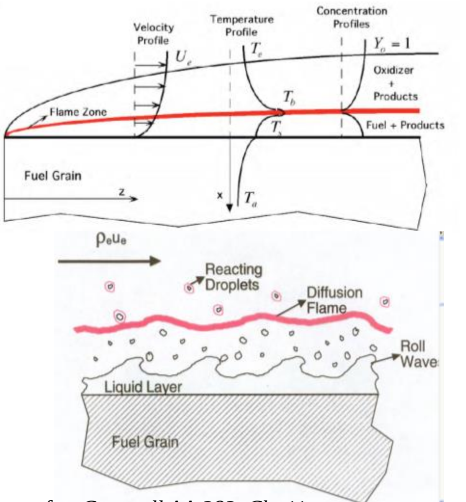


AIAA-95-2948, Carrick and Larson

“New” Mechanism for Regression

- Classical model (Marxman, 1965)
  - – vaporization of solid due to heat feedback from flame (usually diffusion limited)
- Modification
  - – melting surface layer
  - – formation of droplets that are entrained into gaseous flow

$$\dot{r} = \dot{r}_{evap} + \dot{r}_{entrainment}$$



after Cantwell AA 283, Ch. 11

Entrainment Mass Transfer

- Part of energy going to surface melts solid without vaporizing it
- Loss of mass from surface (thin film) due to entrainment given by

gas flow momentum flux

melt layer thickness

$$\dot{m}_{ent} \propto \frac{\left(\rho_g u_\infty^2\right)^\alpha \left(\Delta x\right)^\beta}{\sigma^\pi \mu_l^\gamma}$$

liquid surface tension

liquid viscosity

α~1-1.5
β~1-2
π~O(1)
γ~O(1)

Karabeyoglu, Altman and Cantwell, J Prop Power ***18*** *(2002), and Gater and L’Ecuyer, Intl J Heat Mass Trans* ***13*** *(1970)*

Other Changes to Hybrid Combustion Theory

- To include liquid layer effects
  - include reduced heating requirement to remove mass
  - reduce “blocking/blowing” effect (some of mass is initially denser, less of a pressure gradient produced)
  - increased surface roughness increases convective heat transfer coefficient to surface

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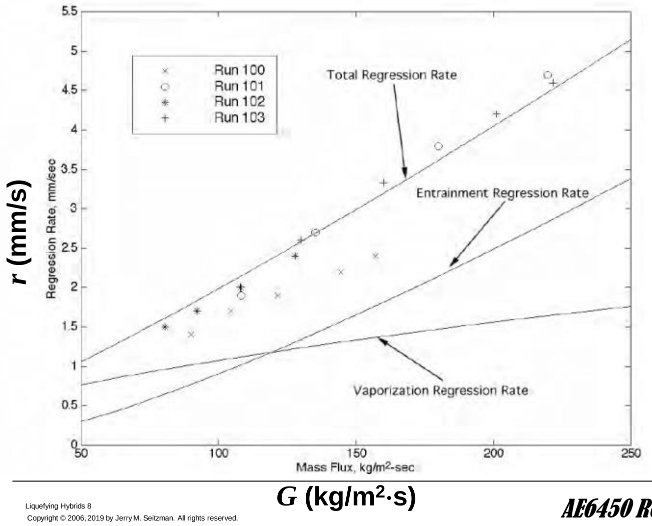
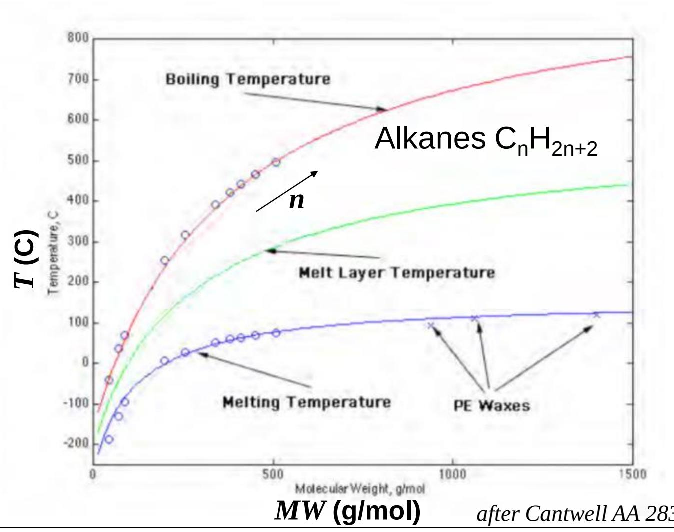
Example Results

- Pentane-GOX predictions and data comparison



Karabeyoglu, Altman and Cantwell, J Prop Power **18** *(2002)*

Energy Considerations



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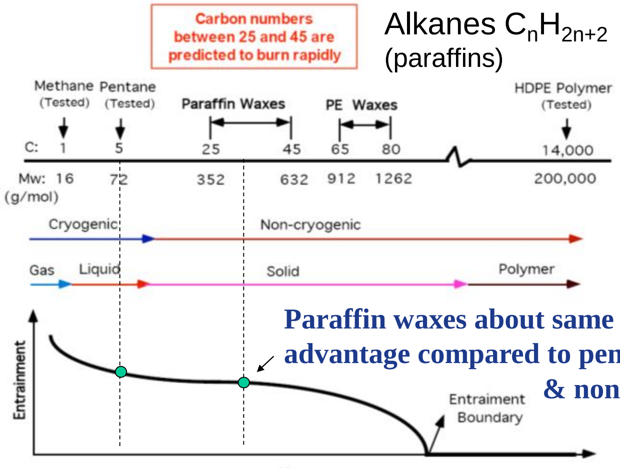
Fuel Choice: Entrainment

Alkanes C_nH_{2n+2}
(paraffins)



Paraffin waxes about same relative advantage compared to pentane & noncryogenic

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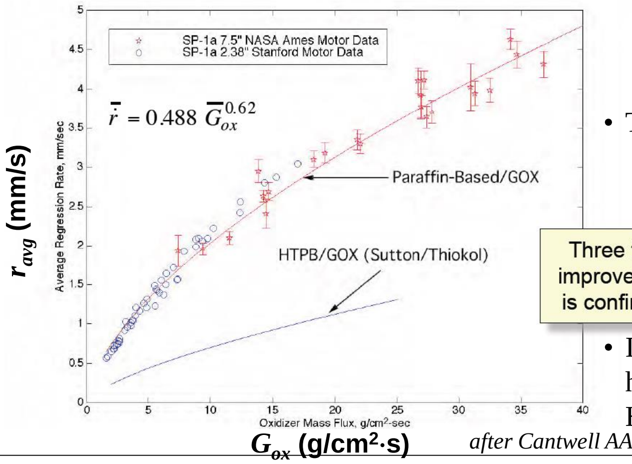
Experimental Results

- Stanford, NASA Ames



- Tested > 3000 lb_f, 8” grains

Three fold improvement is confirmed

- Isp_{theor} slightly higher than HTPB

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Comparison to Other Approaches

- To increase regression rate, the other major approach is adding metal particles to standard propellants (e.g., HTPB + oxidizer)
- In comparison, liquefying (paraffinic) fuels exhibit
  - significantly greater increase in regression rate
  - reduced efficiency and lower density specific impulse
  - reduced stiffness (without support structure)
- Optimum tradeoff depends on application specifics