Combustion Processes in Hybrid Rocket Engines

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In recent years, there has been a resurgence of interest in the development of hybrid rocket engines for advanced launch vehicle applications. Hybrid propulsion systems use a solid fuel such as hydroxyl-terminated polybutadiene (HTPB) along with a gaseous/liquid oxidizer. The perfomance of hybrid combustors depend on the convective and radiative heat fluxes to the fuel surface, the rate of pyrolysis in the solid-phase and the turbulent combustion processes in the gaseous-phase. These processes in combination specify the regression rates of the fuel surface and thereby the utilization efficiency of the fuel. In this paper, we employ computational fluid dynamic techniques in order to gain a quantitative understanding of the physical trends in hybrid rocket combustors.

The computational modeling is tailored to ongoing experiments at Penn State that employ a 2D slab-burner configuration. The co-ordinated computational/experimental effort enables model validation while providing an understanding of the experimental observations. Computations to date have included the full-length geometry with and without the aft-nozzle section as well as shorter-length domains for extensive parametric characterization. HTPB is used as the fuel with $1,3$ butadiene being taken as the gaseous product of the pyrolysis. Pure gaseous oxygen is taken as the oxidizer. The fuel regression rate is specified using an Arrhenius rate reaction, while the fuel surface temperature is given by an energy balance involving gas-phase convection and radiation as well as thermal conduction in the solid-phase. For the gas-phase combustion, a two-step global reaction set is used. The standard $k - \epsilon$ model is used for turbulence closure. Radiation is presently treated using a simple diffusion approximation which is valid for large optical path lengths, representative of radiation from soot particles.

Computational results are obtained to determine the trends in the fuel burning or regression rates as a function of the head-end oxidizer mass flux, $G = \rho_e U_e$, and the chamber pressure. Furthermore, computations of the full slab-burner configuration have also been obtained for various stages of the burn. Comparisons with available experimental data from small-scale tests conducted by General Dynamics-Thiokol-Rocketdyne suggest reasonable agreement in the predicted regression rates. Future work will include: (1) a model for soot generation in the flame for more quantitative radiative transfer modeling, (2) parametric study of combustion efficiency and (3) transient calculations to help determine the possible mechanisms responsible for combustion instability in hybrid rocket motors.

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Presentation Outline

- Introduction
  - Research Issues
  - Penn State Slab Burner Configuration

- Physical Modeling
  - Gas/Surface Coupling
  - Radiation

- Computational Results
  - Representative Solutions
  - Characterization of Regression Rates

- Conclusions

Introduction

- Advantages of Hybrid Propulsion
  - Reduced Cost
  - Safety
  - Improved Reliability
  - Thrust Tailoring
  - Environmentally Friendly

- Hybrids Development
  - Intermittent Testing Since 60's
  - JIRAD
  - AMROC
  - France & Japan

- Small-Scale Testing
  - JPL/Strand *et al.*
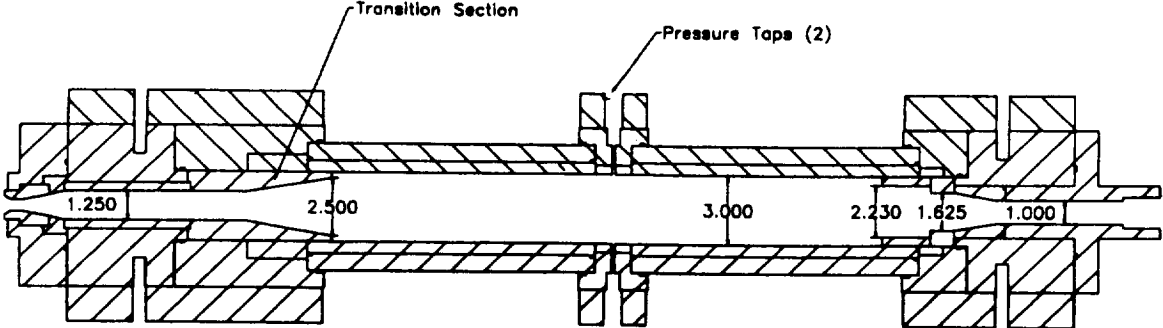 - ONERA
  - UAH
  - Penn State

Research Issues

- Characterization of Fuel Surface Regression
  - Fuel Pyrolysis and Surface Chemistry
  - Heat Fluxes - Convection and Radiation

- Combustion Efficiency

- Combustion Instability

- Modeling Issue:
  - Boundary Layer vs. Navier-Stokes

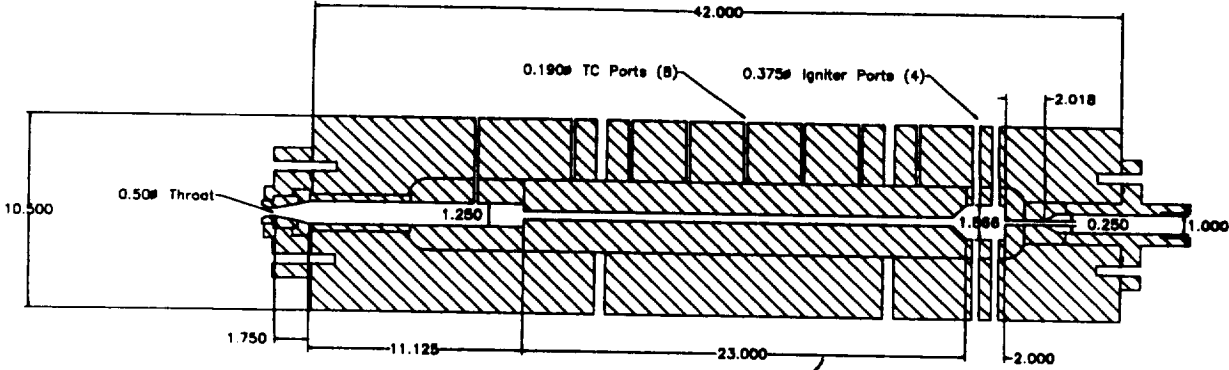# Schematic of Hybrid Rocket Motor

Edge of Boundary Layer

Station ①

Temperature

Station ②

Temperature

Temperature

Velocity

Diffusion Flame Zone

Velocity

Injected Reactant Concentration

Injector

Velocity

Grain Reactant Concentration

Solid Grain

Injected Reactant Concentration   Grain Reactant Concentration
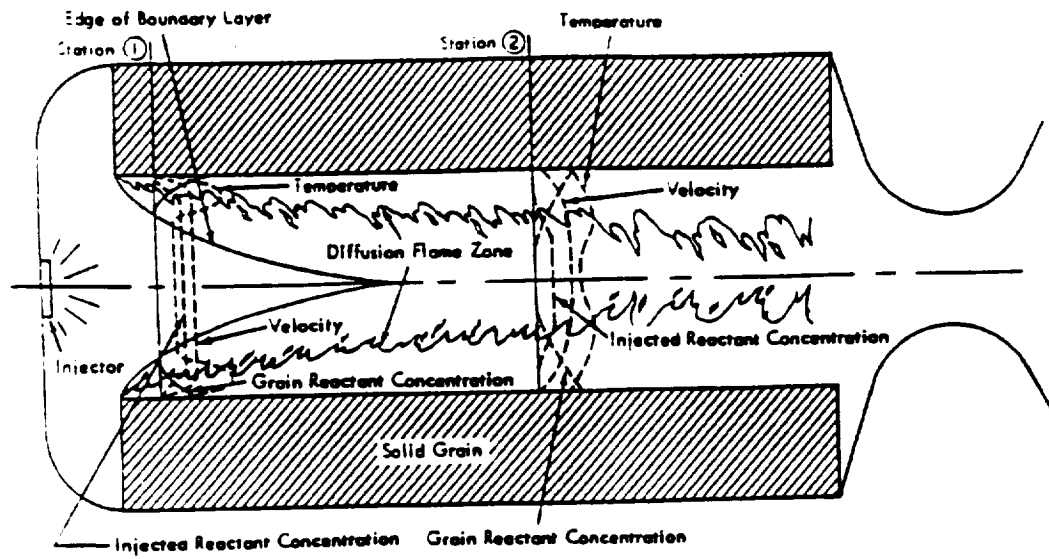
Experimental Configuration

Top View

Transition Section

Pressure Taps (2)

1.250   2.500   3.000   2.230 1.625   1.000

Profile View

42.000

0.190ø TC Ports (8)   0.375ø Igniter Ports (4)

2.018

10.500   0.50ø Throat   1.250   1.868   0.250   1.000

1.750   11.125   23.000   2.000

Experimental Configuration

- Test Conditions
    - — Fuel - HTPB
    - — Oxidizer - GOX
    - — Pressures - 300 to 900 psi
    - — GOX Flow Rates - 0.2 to 0.8 lbm/s
    - — GOX Mass Flux $(G = \rho U)$ - ~~0.15~~ 0.1 to 0.5 $lbm/in^2 - s$

Physical Modeling

- Gas-Phase Navier-Stokes Equations
  — Standard $k - \epsilon$ Model

- Gas-Phase/Combustion Model:
  — Butadiene—Product of Pyrolysis
  — Two-Step Global Kinetics Model

$$C_4H_6 + 3.5O_2 \longrightarrow 4CO + 3H_2O$$

$$CO + 0.5O_2 \longleftrightarrow CO_2$$
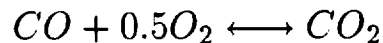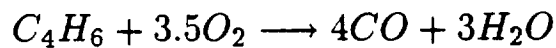
- Solid-Phase/Pyrolysis:
  — Arrhenius Pyrolysis Rate

$$\rho_s r_b = A_s \exp\left(\frac{-E_s}{R_u T_s}\right)$$

Solid/Gas Coupling

- Surface Mass Balance

$$\rho v = -\rho_s r_b$$

- Surface Energy Balance

$$-\lambda \frac{\partial T}{\partial y} + Q_{rad} + \rho v h - \sum_{i=1}^{N} \rho \mathcal{D}_{im} \frac{\partial Y_i}{\partial y} h_i = -\lambda_s \left(\frac{\partial T}{\partial y} \right)_s - \rho_s r_b h_s$$

Radiation Modeling

- Gaseous Molecular Radiation
  - Optically Thin Approximation

$$Q_{rad,k} = \sum_{i,j} \frac{4\sigma k_{i,j} T_{i,j}^4}{J_{i,j}} \mathcal{F}_{i,j \to k}$$

- Particulate (Soot) Radiation
  - Optically Thick Approximation

$$Q_{rad,k} = -\lambda_R \frac{\partial T}{\partial y}$$

, where $\lambda_R = \frac{4}{3}\pi \frac{C}{k} T^3$
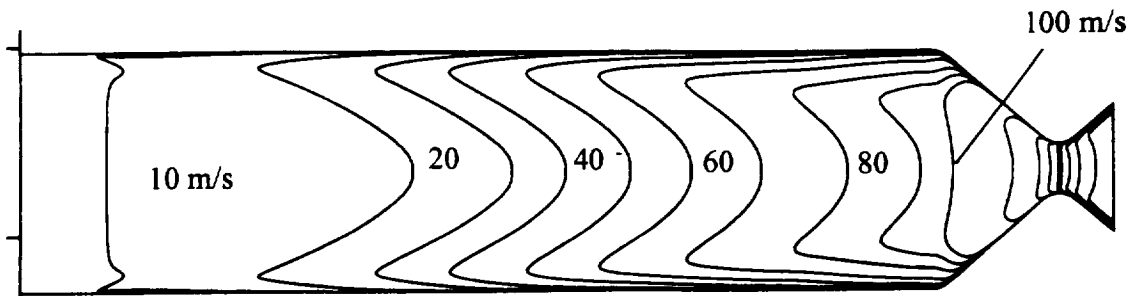
Representative Solution

Grid Geometry

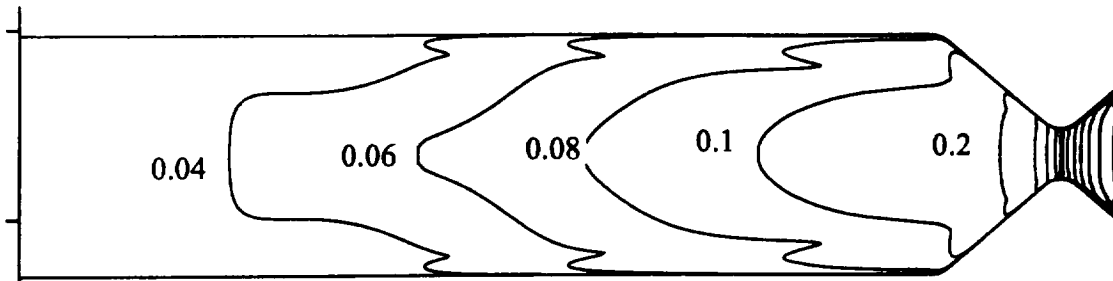.00   .30   .60   .90

Temperature Contours

$T_s \times 1000 K$

3500K

500 K
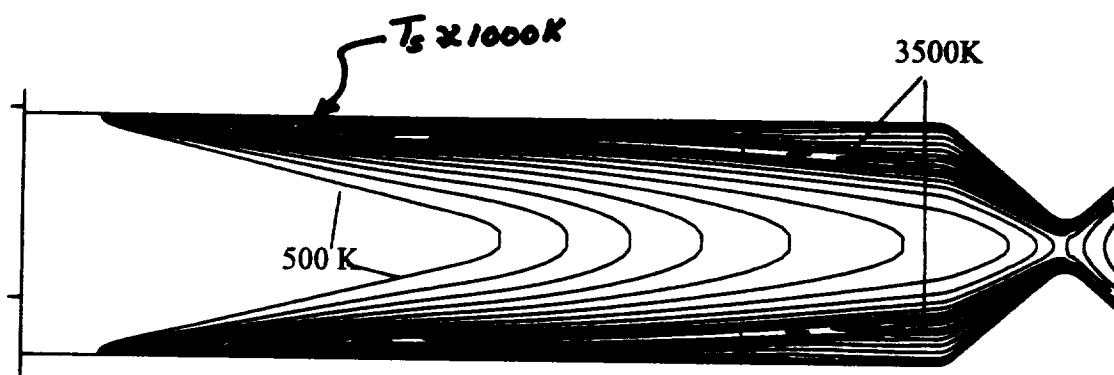
Representative Solution
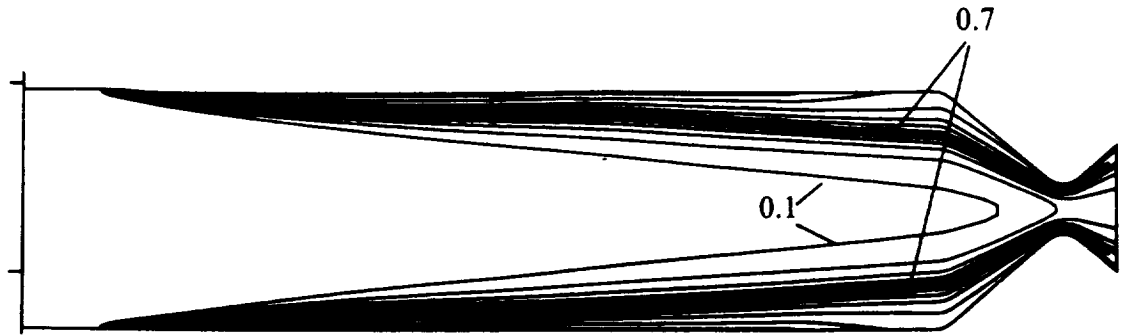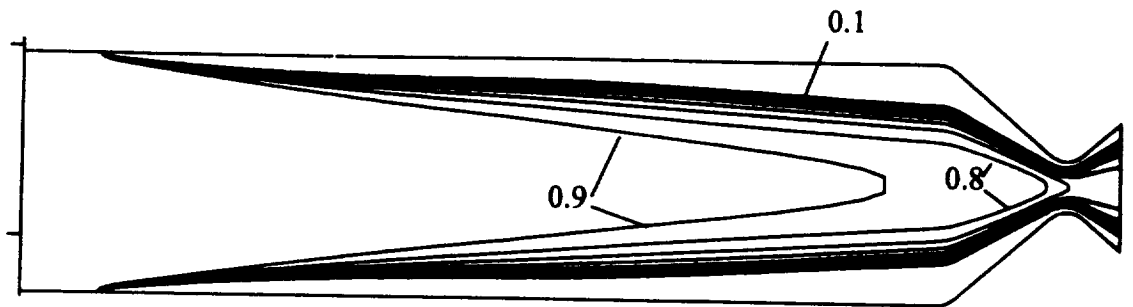
Axial Velocity

Mach Number Contours

Representative Solutions

Carbon Dioxide Mass Fraction

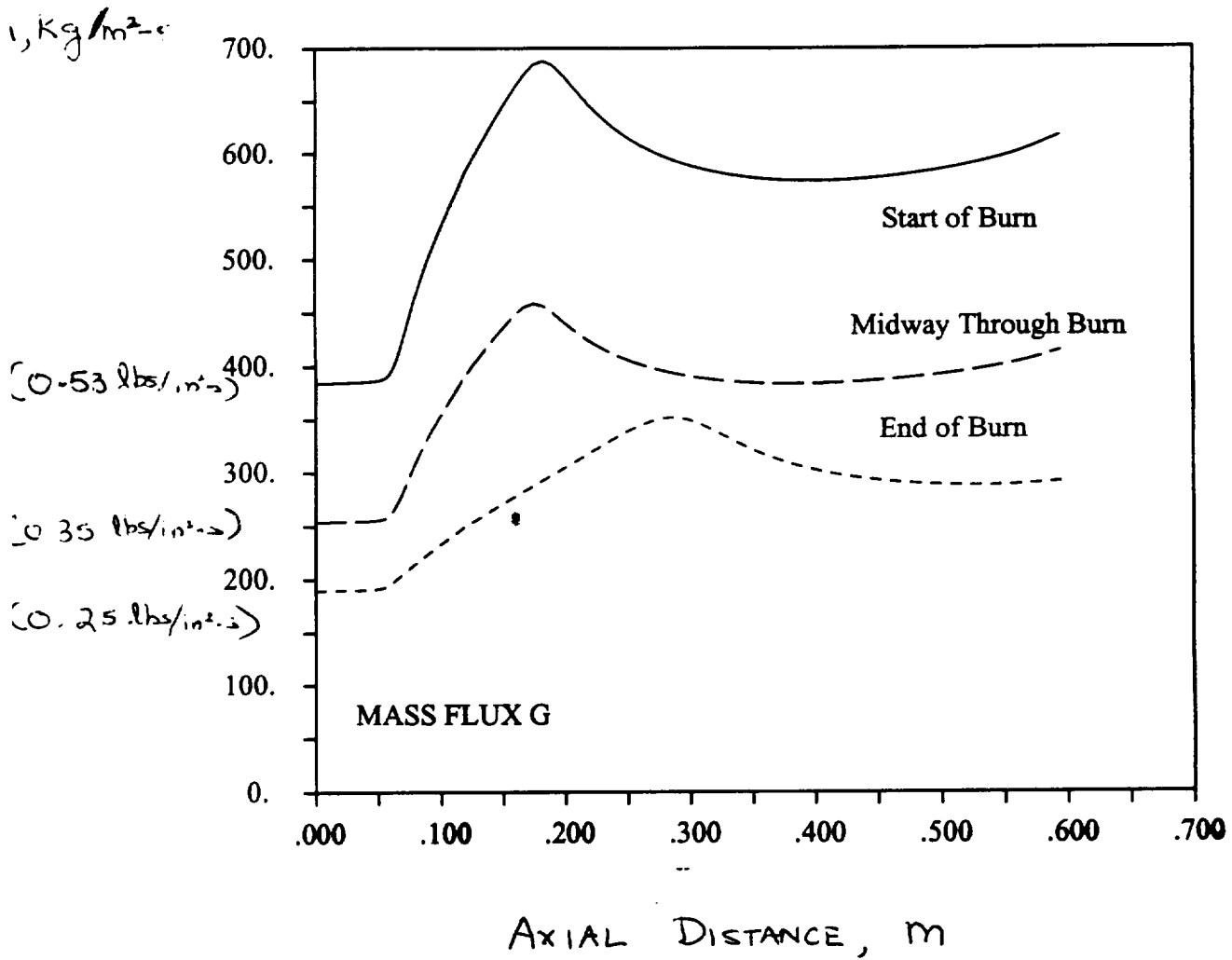## GOX Mass Fraction

Representative Results

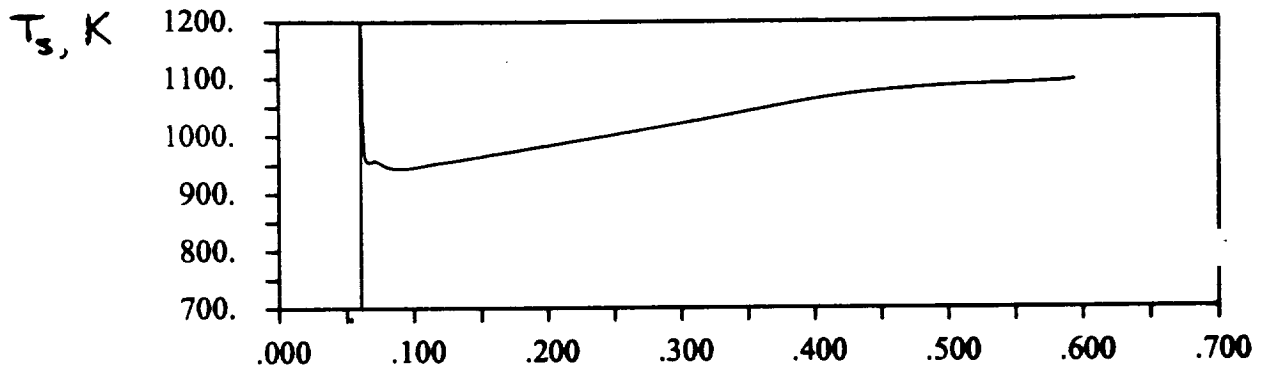# Centerline Variation of Mass Flux (G)

$, Kg/m^2-s$

700.

600.

Start of Burn

500.

Midway Through Burn

$(0.53 \ lbs/in^2-s)$ 400.

End of Burn

300.

$(0.35 \ lbs/in^2-s)$

200.

$(0.25 \ lbs/in^2-s)$

100.

MASS FLUX G

0.

.000   .100   .200   .300   .400   .500   .600   .700

AXIAL DISTANCE, m

Representative Results

Surface Regression Rate

$\dot{r}_b$, in/s

.100	
.080	
.060	
.040	
.020	
.000	

.000   .100   .200   .300   .400   .500   .600   .700

Fuel Surface Temperature

T_s, K

1200.
1100.
1000.
900.
800.
700.

.000   .100   .200   .300   .400   .500   .600   .700

Wall Heat Fluxes

q_w, W/m^2

.500E+07
.400E+07
.300E+07
.200E+07
.100E+07
0.

CONVECTIVE HEAT FLUX

RADIATIVE HEAT FLUX

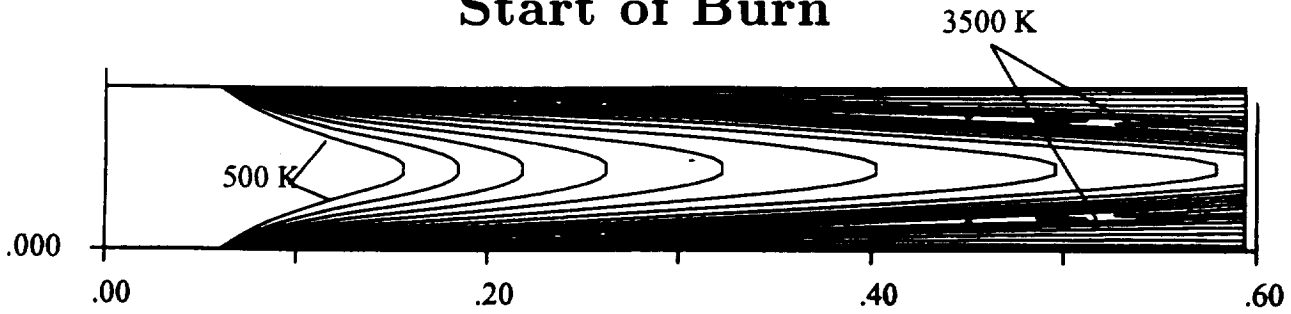.000   .100   .200   .300   .400   .500   .600   .700
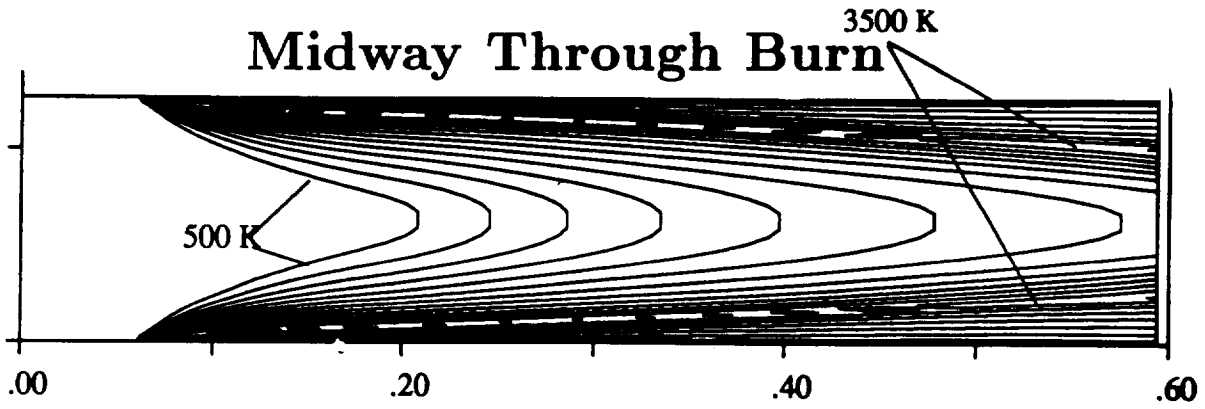
AXIAL DISTANCE, m

1328
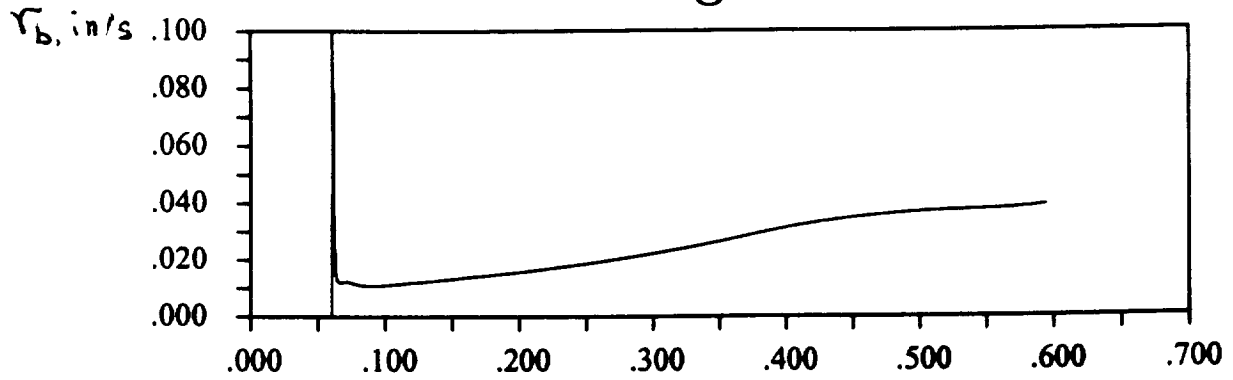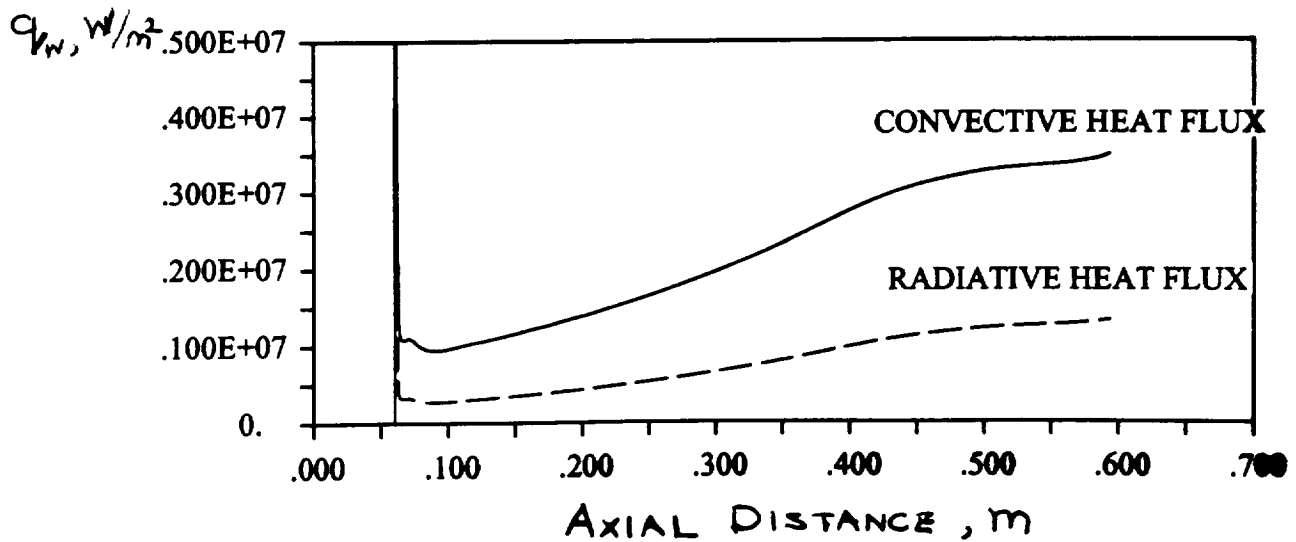
Parametric Studies
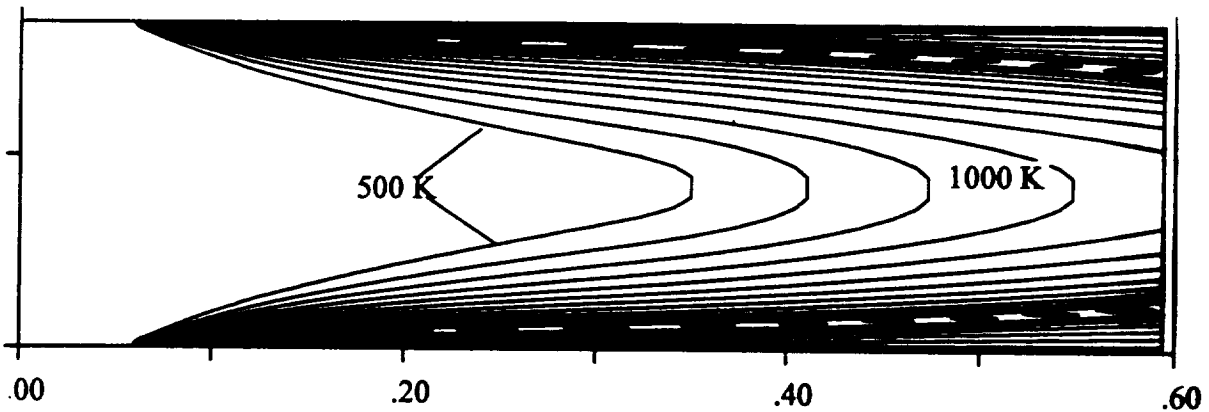## Different Stages in Burn

Start of Burn

Midway Through Burn

End of Burn

Parametric Studies
Different Stages in Burn

W/O Radiation

Surface Regression Rate

r_b, in/s

G =

0.53 lbs/in²-s

0.35

0.25

Convective Wall Heat Fluxes

q_c, W/m²

0.53 lbs/in²-s

0.35

0.25

AXIAL DISTANCE, m
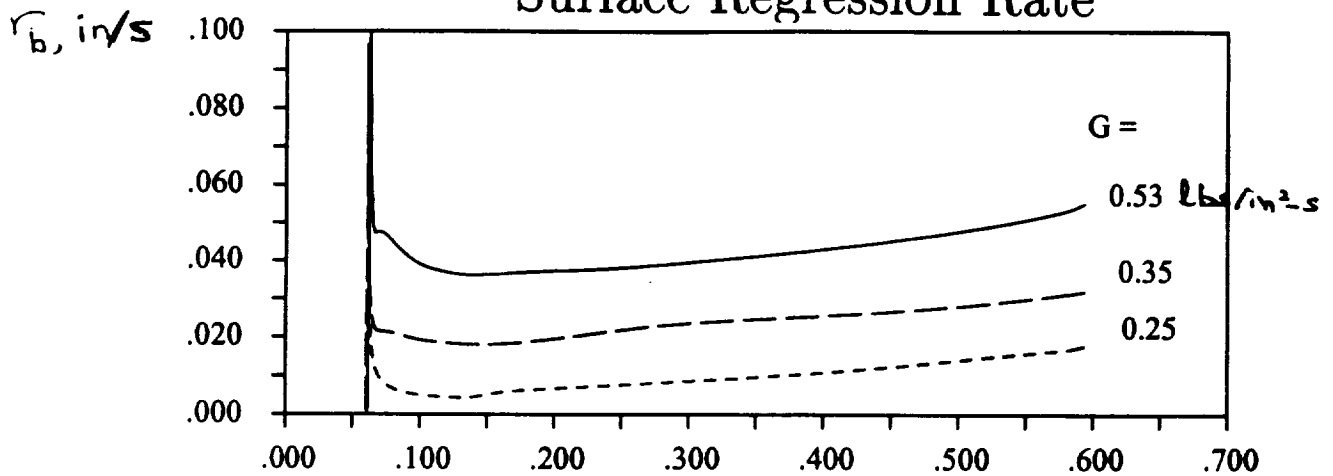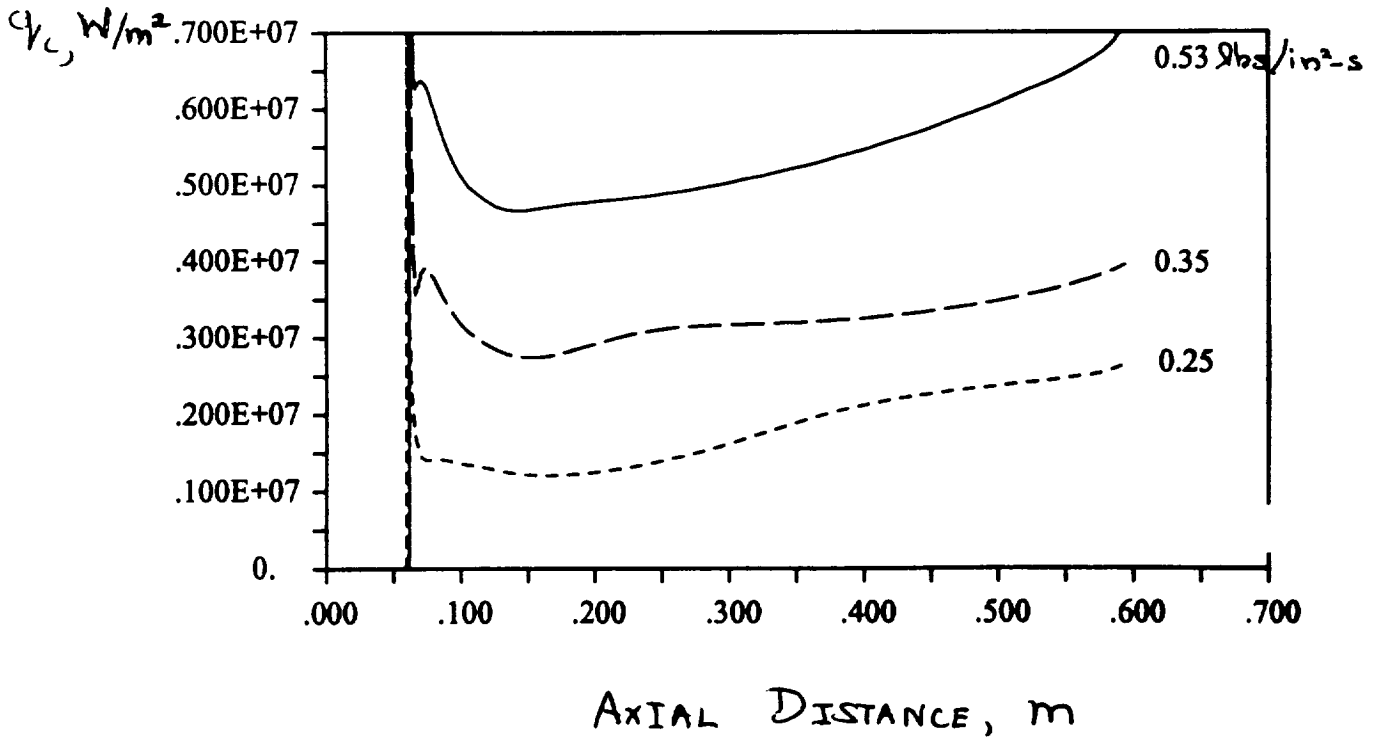
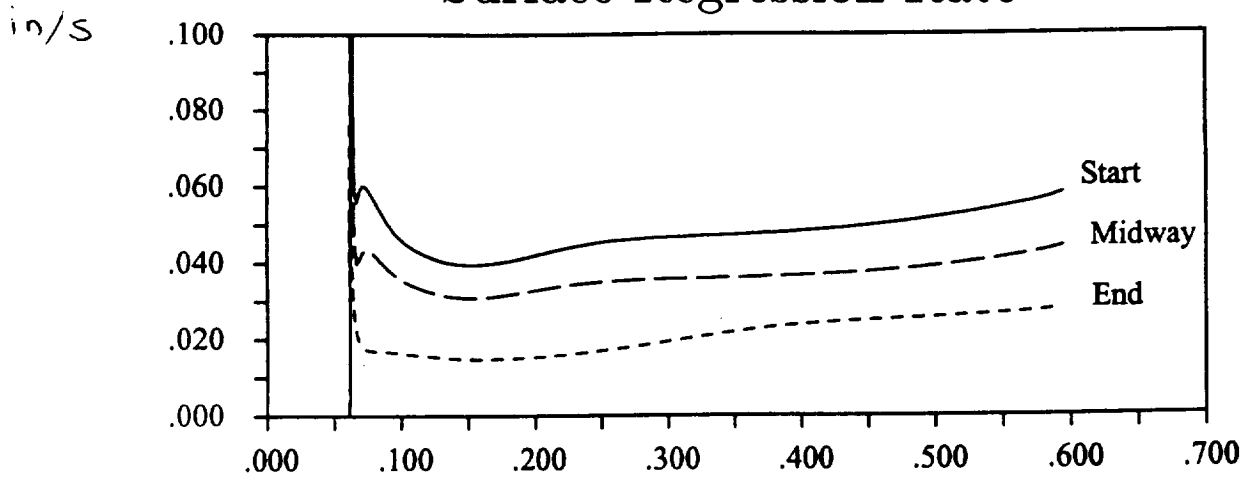# Parametric Studies
Different Stages in Burn

With Radiation/Optically Thick

Surface Regression Rate

in/s   .100

.080

.060   Start

.040   Midway
                                        End
.020

.000
   .000   .100   .200   .300   .400   .500   .600   .700

Radiative Wall Heat Fluxes

√/m² .500E+07

.400E+07

.300E+07

.200E+07   Start
                                        Midway
.100E+07   End

0.
   .000   .100   .200   .300   .400   .500   .600   .700

Axial Distance, m

1331
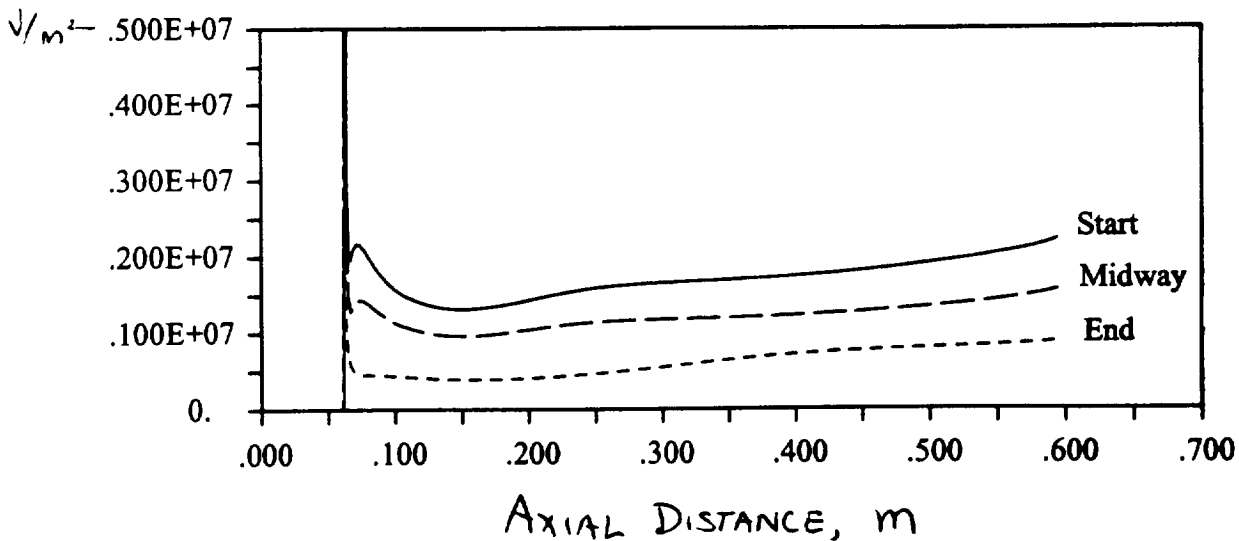
Parametric Studies
Effect of GOX Flow Rate

Temperature Contours

3500 K

500 K

.00   .20   .40   .60

Temperature Profiles

x=0.3 m

r/R_0

G
0-35
0.17
0.08

1000   2000   3000   4000
Temperature, K

x=0.45 m

r/R_0

1000   2000   3000   4000
Temperature, K

x=0.6 m

r/R_0

1000   2000   3000   4000
Temperature, K
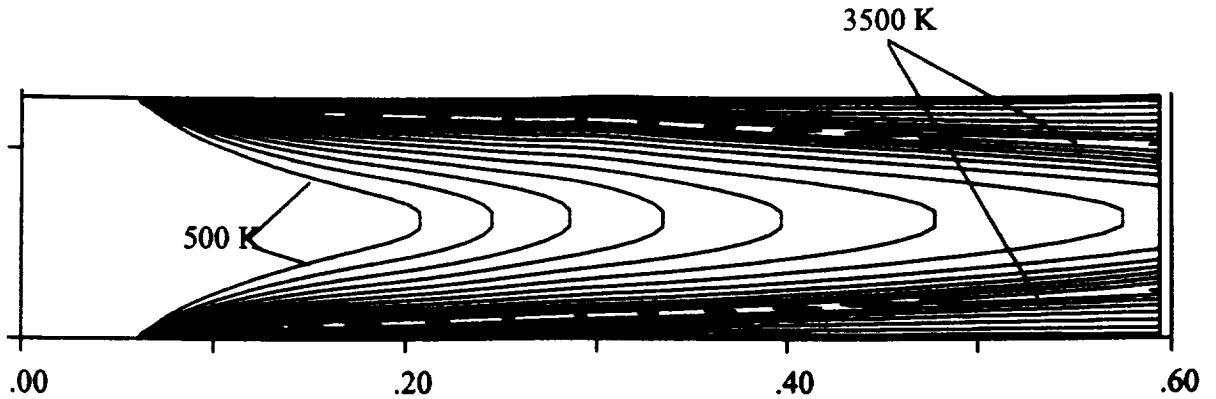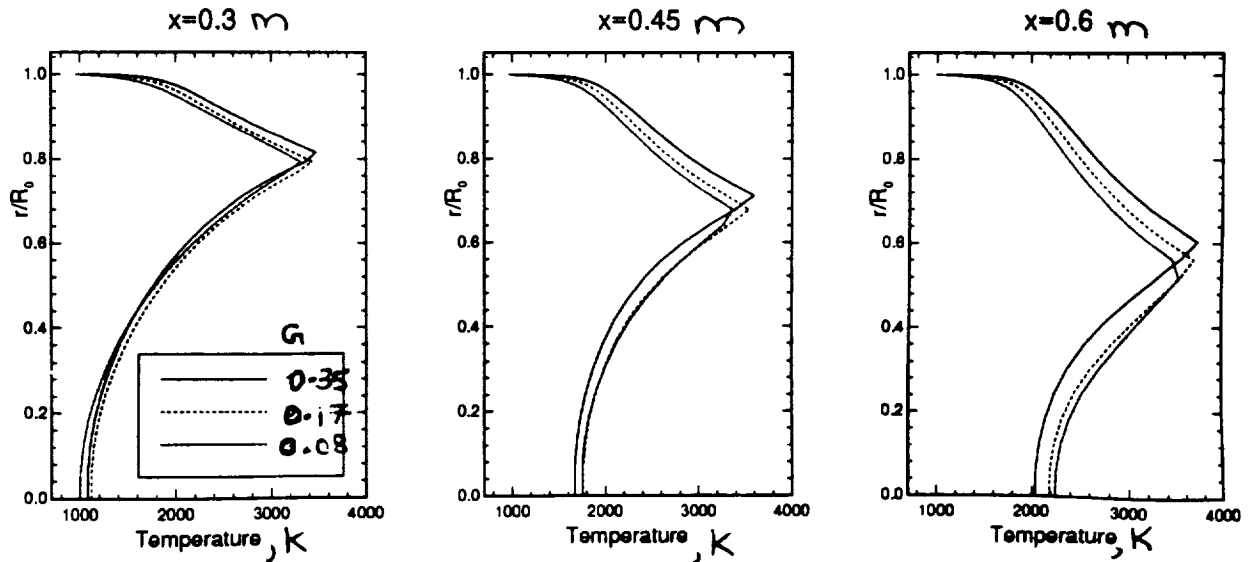
Parametric Studies
Effect of GOX Flow Rate

W/O Radiation

Surface Regression Rate

$\dot{b}, in/s$

Mass Flux G

0.35 lbs/in^2-s

0.17

0.08

.100
.080
.060
.040
.020
.000

.000 .100 .200 .300 .400 .500 .600 .700

Convective Wall Heat Fluxes

J/m^2

G

0.35 lbs/in^2-s

0.17

0.08

.500E+07
.400E+07
.300E+07
.200E+07
.100E+07
0.

.000 .100 .200 .300 .400 .500 .600 .700

AXIAL DISTANCE, m

1333
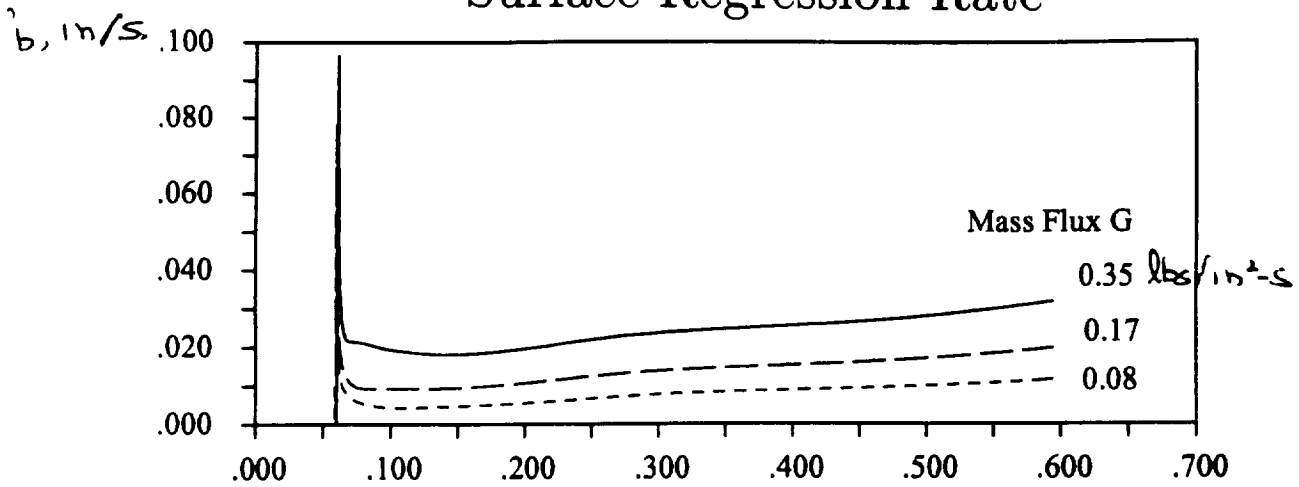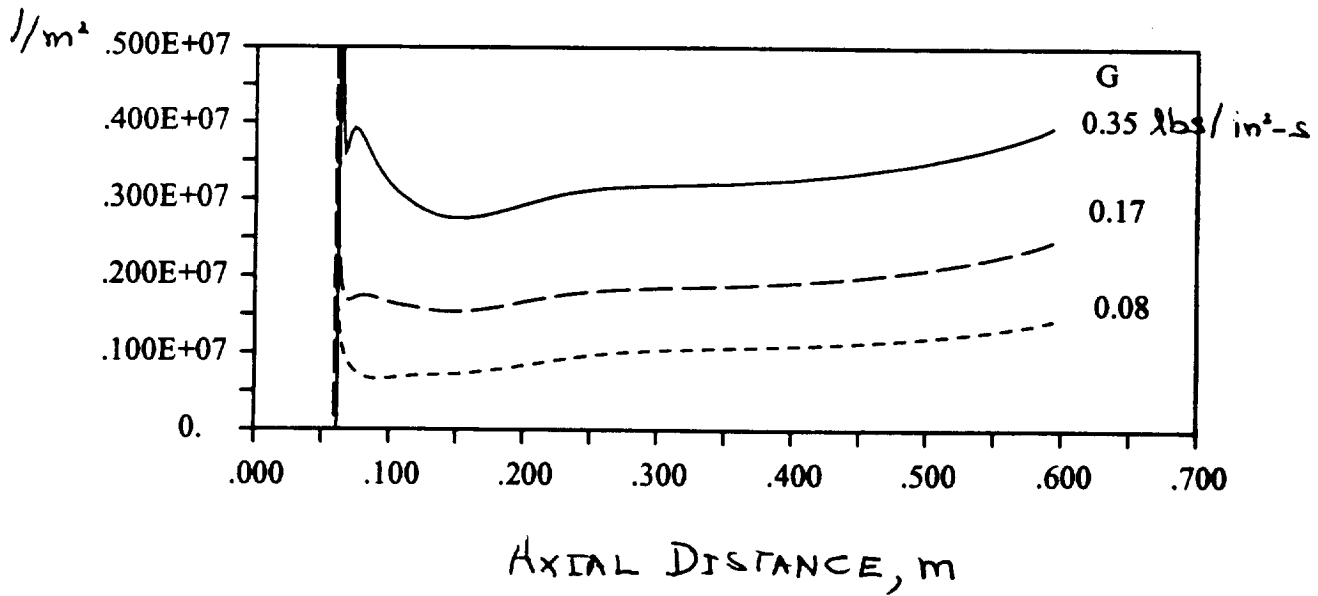
Parametric Studies
Effect of GOX Flow Rate

With Radiation/Optically Thick

Surface Regression Rate

Mass Flux G

0.35 lbs/in²-s

0.17

0.08

in/s axis: .100, .080, .060, .040, .020, .000

x-axis: .000, .100, .200, .300, .400, .500, .600, .700

Radiative Wall Heat Fluxes

W/m² axis: .500E+07, .400E+07, .300E+07, .200E+07, .100E+07, 0.

G =

0.35 lbs/in²-s

0.17

0.08

AXIAL DISTANCE, m

x-axis: .000, .100, .200, .300, .400, .500, .600, .700
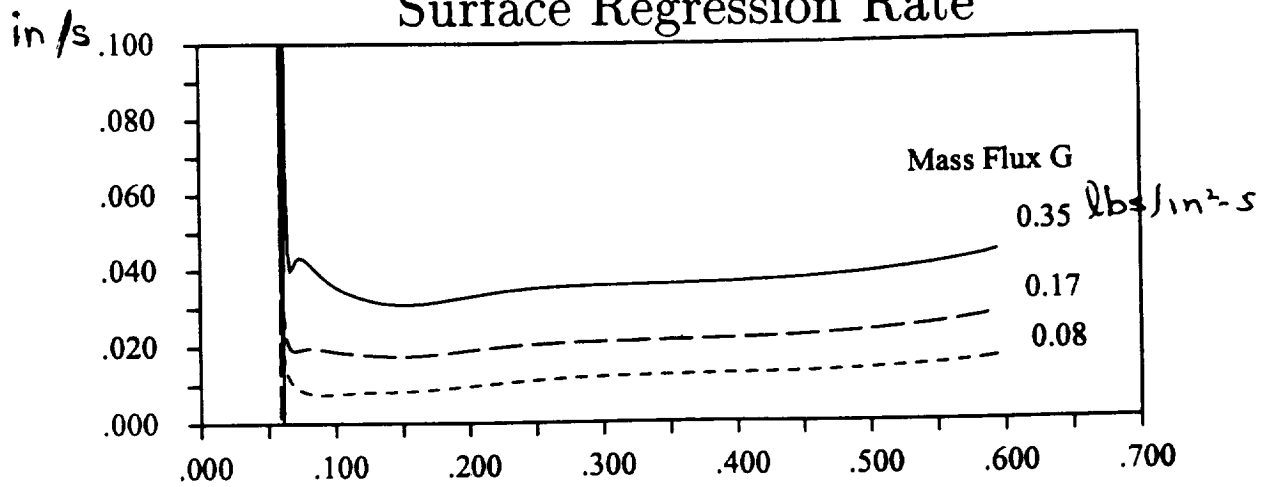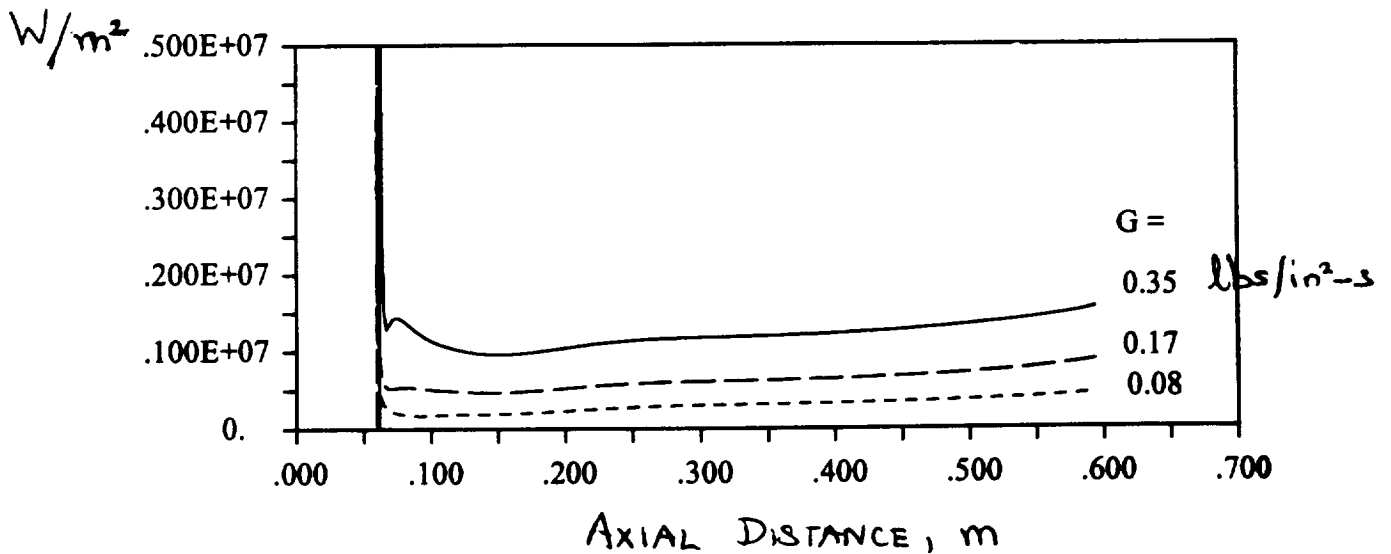
Parametric Characterization of
Fuel Surface Regression
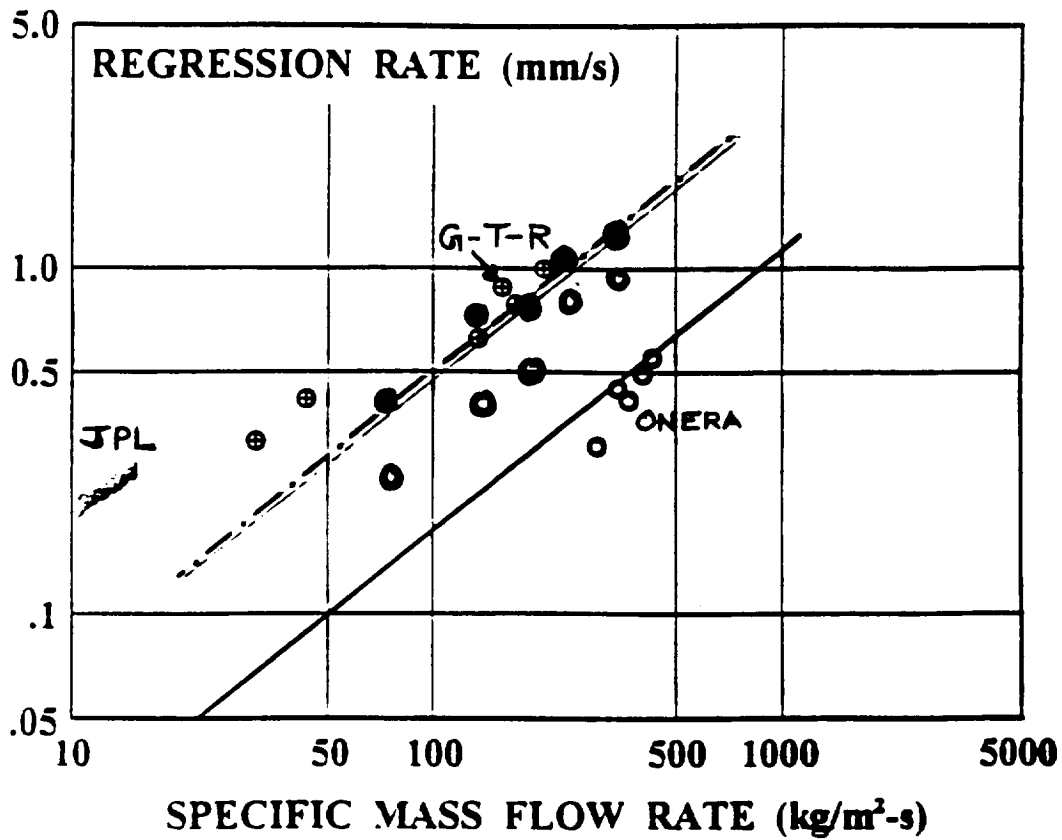
● Current Results With Radiation

○ Current Results W/o Radiation

Conclusions

- Navier-Stokes Analysis of Hybrid Motor
  - Planar Slab Burner Configuration
  - Arrhenius-Rate for Pyrolysis
  - Global Chemistry
  - Turbulence Model
  - 'Thick/Thin' Radiation Model

- Computational Results
  - Parametric Characterization
  - Fuel Surface Temperatures 900 to 1100 K
  - Regression Rates of 0.01 to 0.07 in/s
  - Radiative Fluxes - Significant Contribution

- Ongoing/Future Work:
  - Radiation Properties - Soot Concentration
  - Combustion Efficiency - Downstream Mixing
  - Combustion Instability - Transient Calculations