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Tri-Gas Thruster Performance Characterization

NASA Marshall Space Flight Center

2012 Propulsion Academy

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Agenda

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- Project Background
- Thruster Overview
- Test Operations
- Results and Analysis
- Conclusion

Project Background

Alternative Propellant Research

Purpose: develop and characterize “green” propellants for the following benefits:

- Reduced toxicity levels
- Improvements in health and safety management
- Cost reduction due to system simplification
- Wide range of applications in the Aerospace Industry
- Examples of “green” propellants:
  - Ammonium Dinitramide (ADN)
  - Hydrogen Peroxide
  - Tri-Gas

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Tri-Gas Overview

The proposed propellant consists of a mixture of hydrogen, oxygen, and an inert gas.

- Compared to traditional cold gas systems:

  -Safe and "green" alternative to cold gas propulsion systems

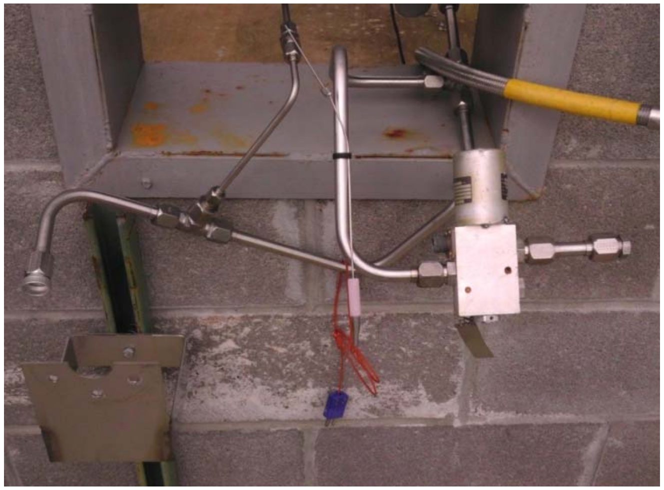
  -Potential performance enhancement at low additional cost

- Major application: reaction control systems (RCS thrusters)
- Project based off Rocketdyne's research in the 1960s
- Final mixture concentration: approximately 92% helium, and a stoichiometric mixture of hydrogen, and oxygen

The overarching goal of this project was to complete a technology demonstration of a 5lbf class thruster to demonstrate the feasibility of tri-gas as a propellant selection

Project Background

- **NASA Propulsion Academy 2010 Heritage**
  - Thruster design and manufacturing
  - Allocated bunker for testing
  - Majority of instrumentation
  - Palladium catalyst
  - In-house mixing of nitrogen based tri-gas

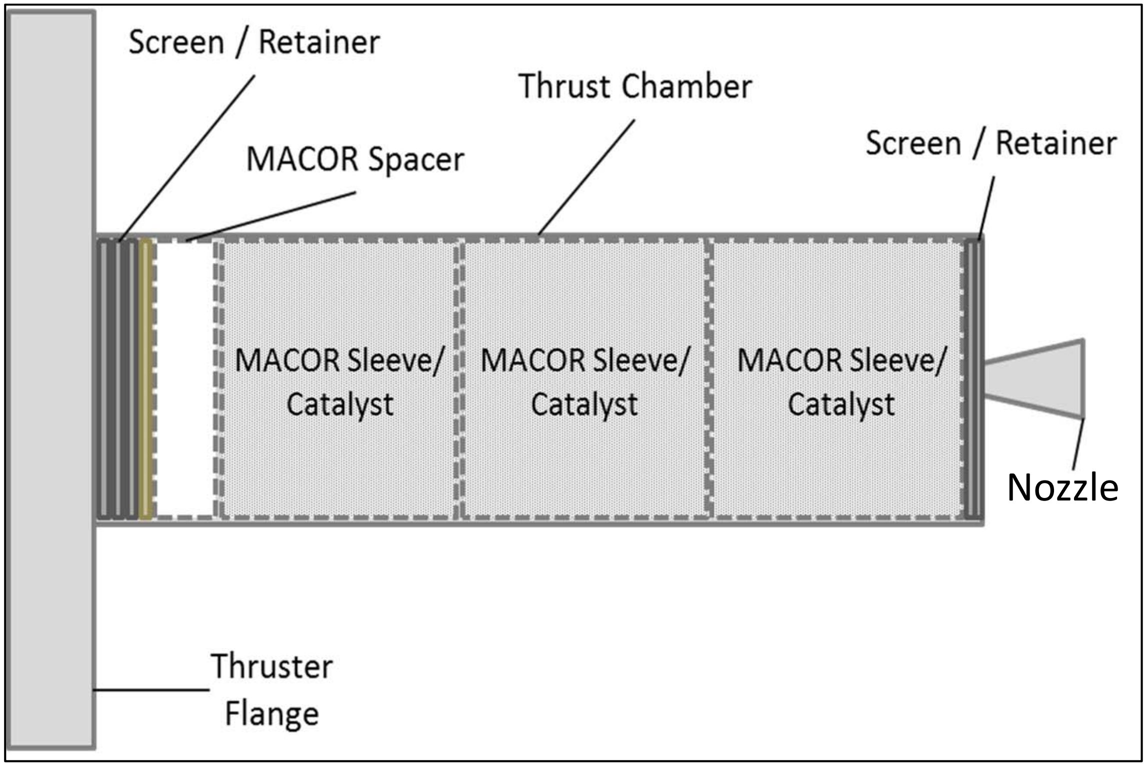


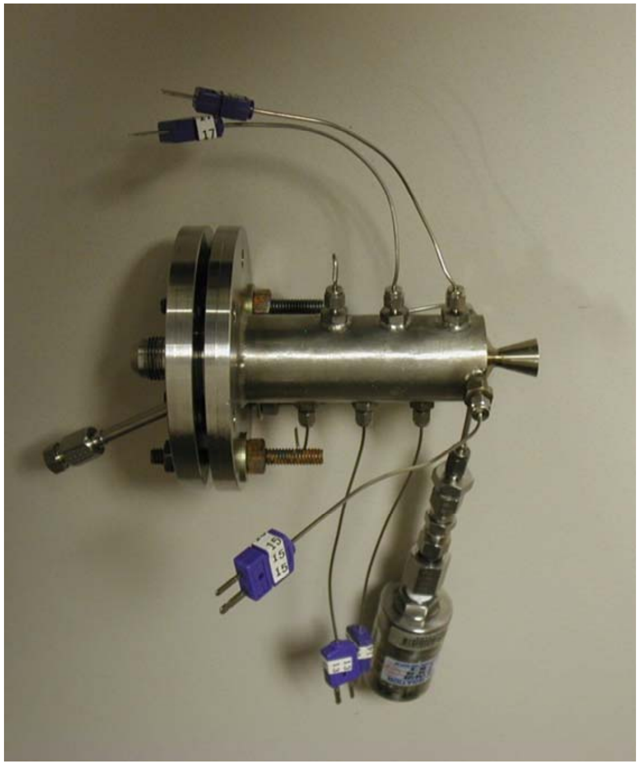
- **NASA Propulsion Academy 2012 Goals**
  - Continuation of 2010 research
  - Platinum catalyst
  - Helium based tri-gas
  - Predict and optimize the behavior of the catalytic reaction
  - Evaluate and decrease reaction times
  - Obtain and analyze thruster performance data for future reference

Thruster Overview

Thruster

- **Thruster design allowed for variable catalyst lengths using insulated Macor sleeves**
- **Perforated plates and screens included to prevent loss of catalyst pieces through nozzle**





Catalysts

- **Palladium catalysts in two forms: pelletized and substrate**
- **Pelletized catalyst**
  - Lengths: A (short), B (medium), C (long)
  - Initial temperatures: ambient, 350, 600, 800, 1100 °F
- **Substrate catalyst**
  - Lengths: D (short), E (long)
  - Same initial temperatures
- **Main configurations evaluated:**
  - C pelletized ambient
  - B pelletized ambient
  - A substrate ambient
  - C pelletized preheated to 1100 °F

B4

Heater

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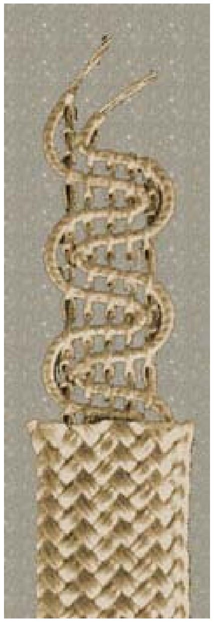
- **Estimated the adiabatic flame temperature with the selected Tri-Gas composition**
  - Based on heat of formation of H_2O in the stoichiometric reaction
  - Compared to observed maximum temperature
- **Established a feasible method of preheating the catalyst bed**
  - Electrical external heating tape
  - Incorporated fiber glass insulation during test



Slide 9

B4 Fiberglass insulation picture
Bryce, 7/8/2013

Test Operations

Test Matrix

Test No.	Catalyst Type	Configuration	Duration	Environmental Pressure (psi)	Initial Temperature (F)
1	Pelletized	C	Standard	Atmospheric	Ambient
2	Pelletized	C	Standard	Atmospheric	1100
3	Substrate	E	Standard	Atmospheric	Ambient
4	Substrate	E	Standard	Atmospheric	Ambient
5	Substrate	E	Pulsed	Atmospheric	Ambient
6	Pelletized	B	Standard	Atmospheric	Ambient
7	Pelletized	B	Standard	Atmospheric	1100
8	Substrate	D	Standard	Atmospheric	Ambient
9-12	Substrate	D	Pulsed	Atmospheric	Ambient
13	Substrate	D	Long Duration	Atmospheric	Ambient

Flow Schematic

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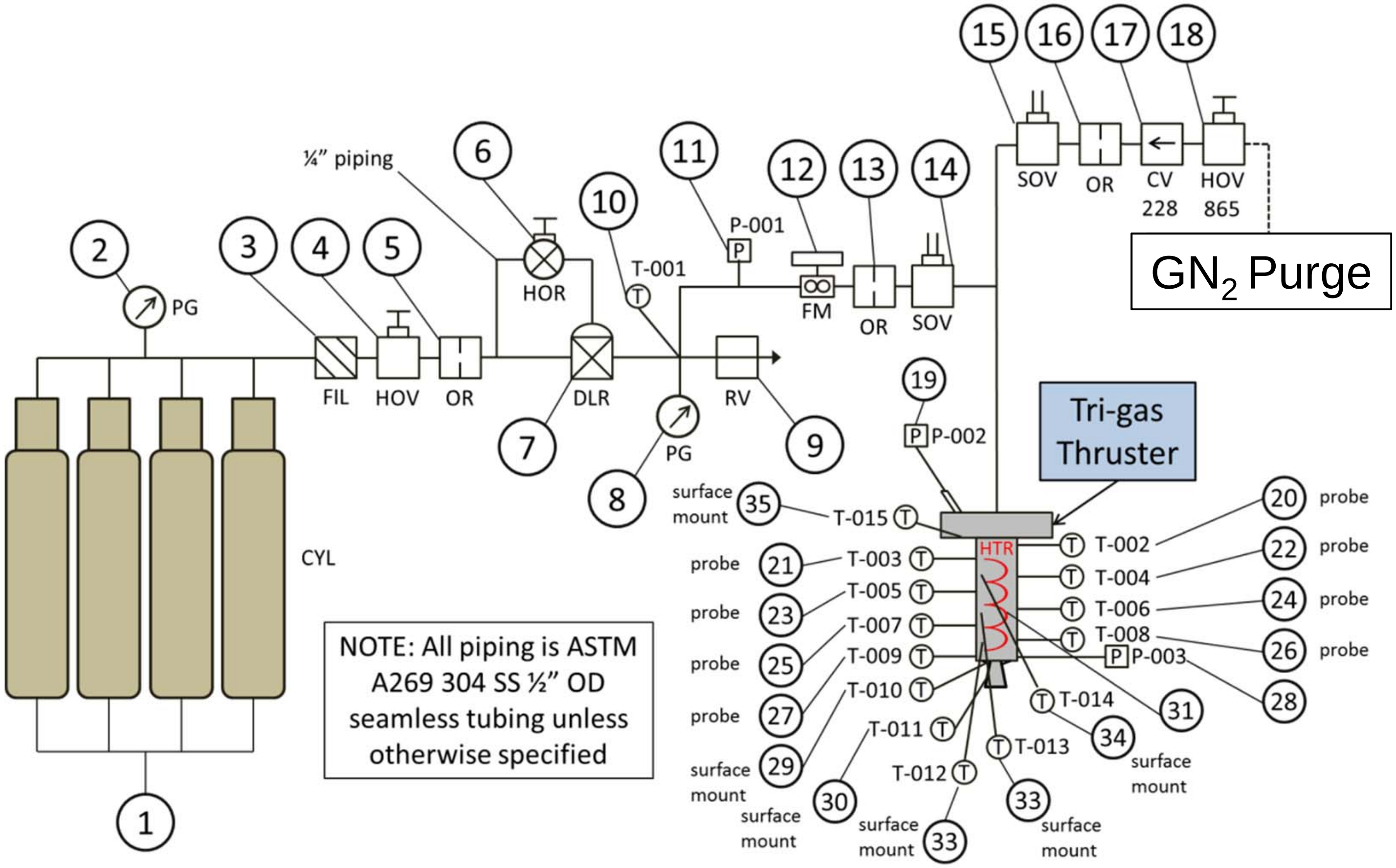
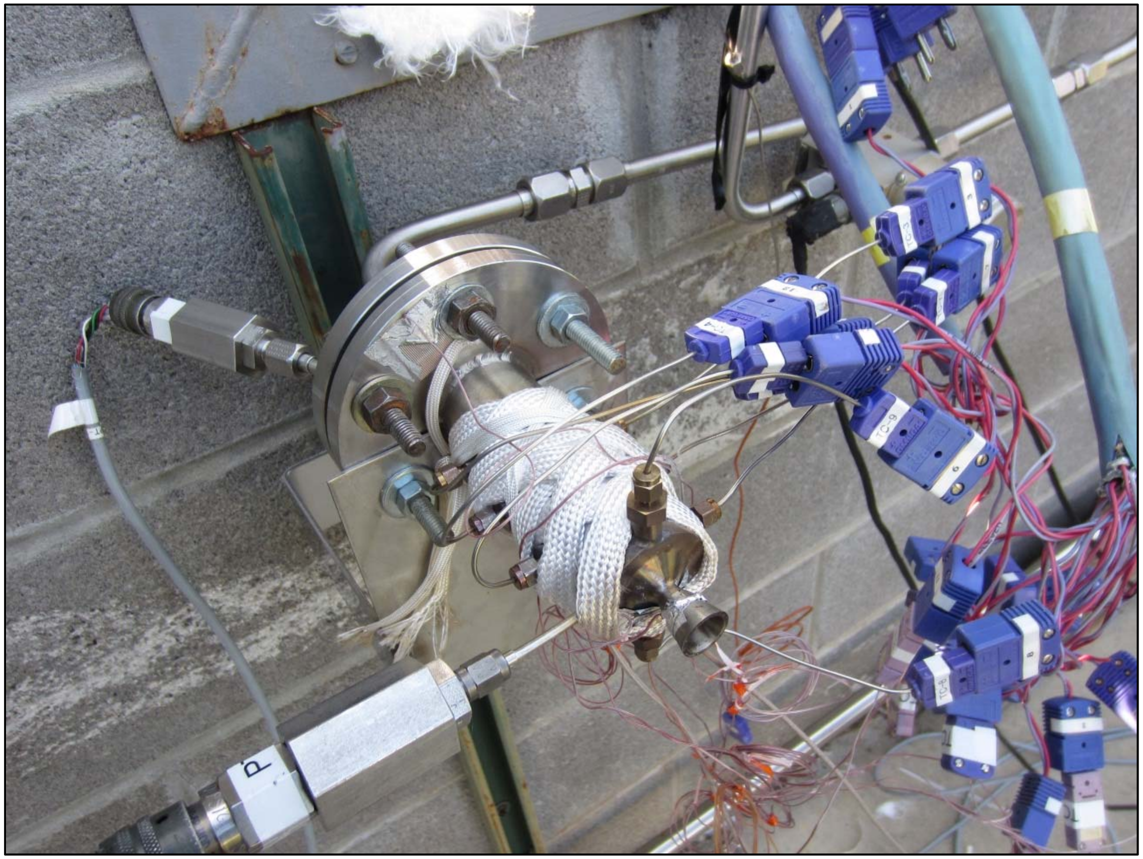
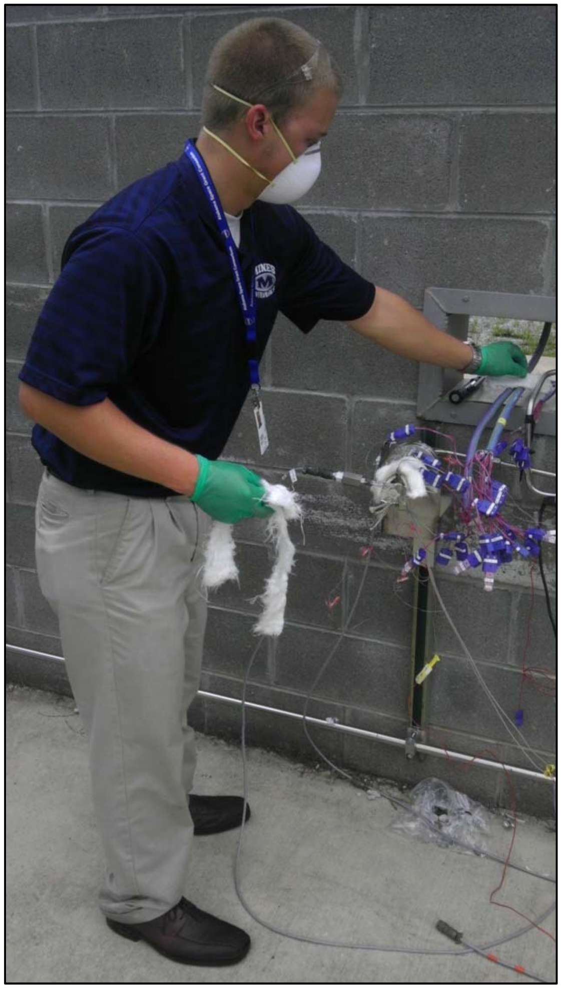


Instrumentation:
3 pressure transducers
15 thermocouples

Pics…



Thruster on Test Stand



Attaching insulation onto thruster with proper PPE

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Analysis

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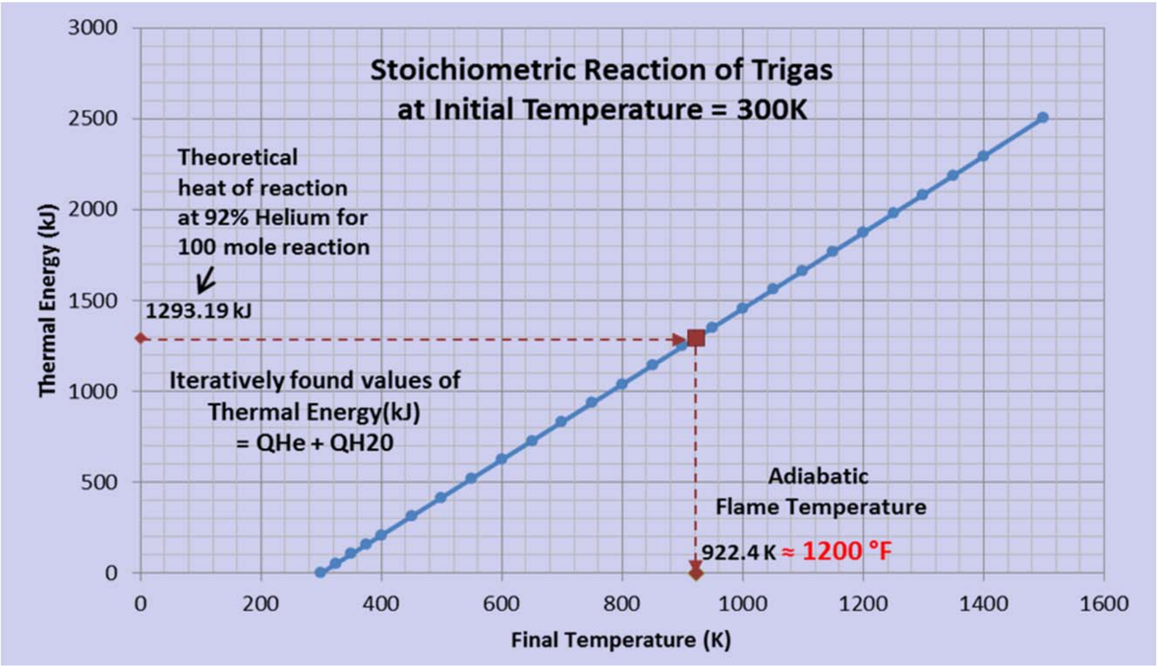
Thermal Reaction Analysis

- **Estimated the adiabatic flame temperature with the selected Tri-Gas composition**
  - Based on heat of formation of H_2O in the stoichiometric reaction
  - Compared to observed maximum temperature
  - Preheating of the catalyst bed was expected to reduce reaction delay
    - Heat losses were minimized with fiber glass insulation during testing



Pre-Heating Process

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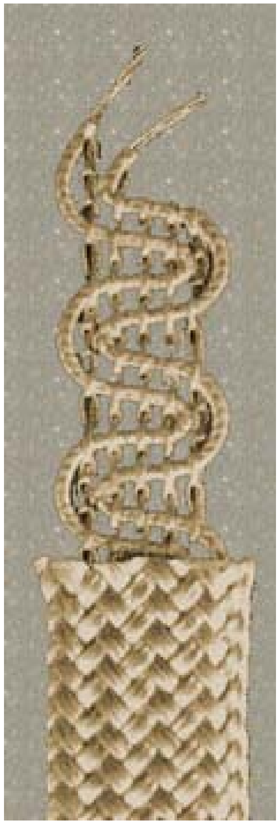
- **Method: analysis was performed with three types of heating in mind**
  - Convection of heat from the surface of the thruster to the surrounding air
  - Conduction through stainless steel thruster wall
  - Conduction through MACOR insulator sleeves
- **Total thermal resistance:**

$$R_{th} = \left(\frac{1}{h_\infty A_s}\right)_{air} + \left(\frac{\ln\left({r_2}/{r_1}\right)}{2\pi l k}\right)_{\substack{stainless\\steel}} + \left(\frac{\ln\left({r_3}/{r_2}\right)}{2\pi l k}\right)_{macor}$$

- **Electrical external heating tape**
  - High power density radial heat source
  - ON/OFF setting was modified by the use of a controller
  - Time dependent heat transfer profile:

$$T_{final} = -\frac{R_{total} \cdot Q}{t} - T_{initial}$$



System Pressure Drops

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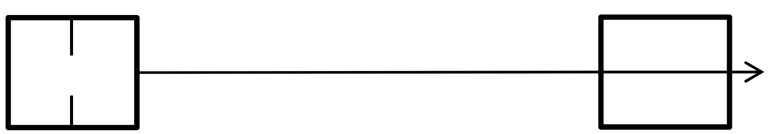
Predicting chamber pressure is imperative to estimating the performance of the thruster. Pressure drops are guided by analysis of the following components and equations:

Pressure drop through the catalyst bed (Ergun Equation):

$$\Delta P = \frac{150 L \mu V}{k g D^2} \frac{(1-\epsilon)^2}{\epsilon^3} + \frac{1.75 L \rho V^2}{k g D} \frac{(1-\epsilon)}{\epsilon^3}$$

Component Sizing:



$\dot{m}$ through the orifice $<$ $\dot{m}$ through the relief valve

$$C_d A_2 P_1 \sqrt{\frac{g_c}{R T_1} \gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} < \frac{6.32 \rho_1 A_1 C K P_1}{\sqrt{MTZ}}$$

Configurable components:

- Catalyst bed geometry
- Valve sizing
- Orifice Sizing
- Flow meter sizing
- Relief valve setting
- Regulator pressure

Performance

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- **Performance was predicted and measured based on both thrust and specific impulse**
- **Thrust:**

$$F = A_t P_c \gamma \left[\left(\frac{2}{\gamma - 1} \right) \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}} \left\{ 1 - \left(\frac{P_e}{P_c} \right)^{\frac{(\gamma-1)}{\gamma}} \right\} \right]^{\frac{1}{2}} + (P_e - P_a) A_e$$

- **I_{sp}:**

$$I_{sp} = \frac{F}{\dot{m} g_o}$$

- **Separation of flow through nozzle**
  - Necessary for cases using the substrate type catalyst due to decreased pressures and mass flow rates
  - Performance altered by assumption that flow separates approximately 30% of the way through the nozzle

Results

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Results: Baseline

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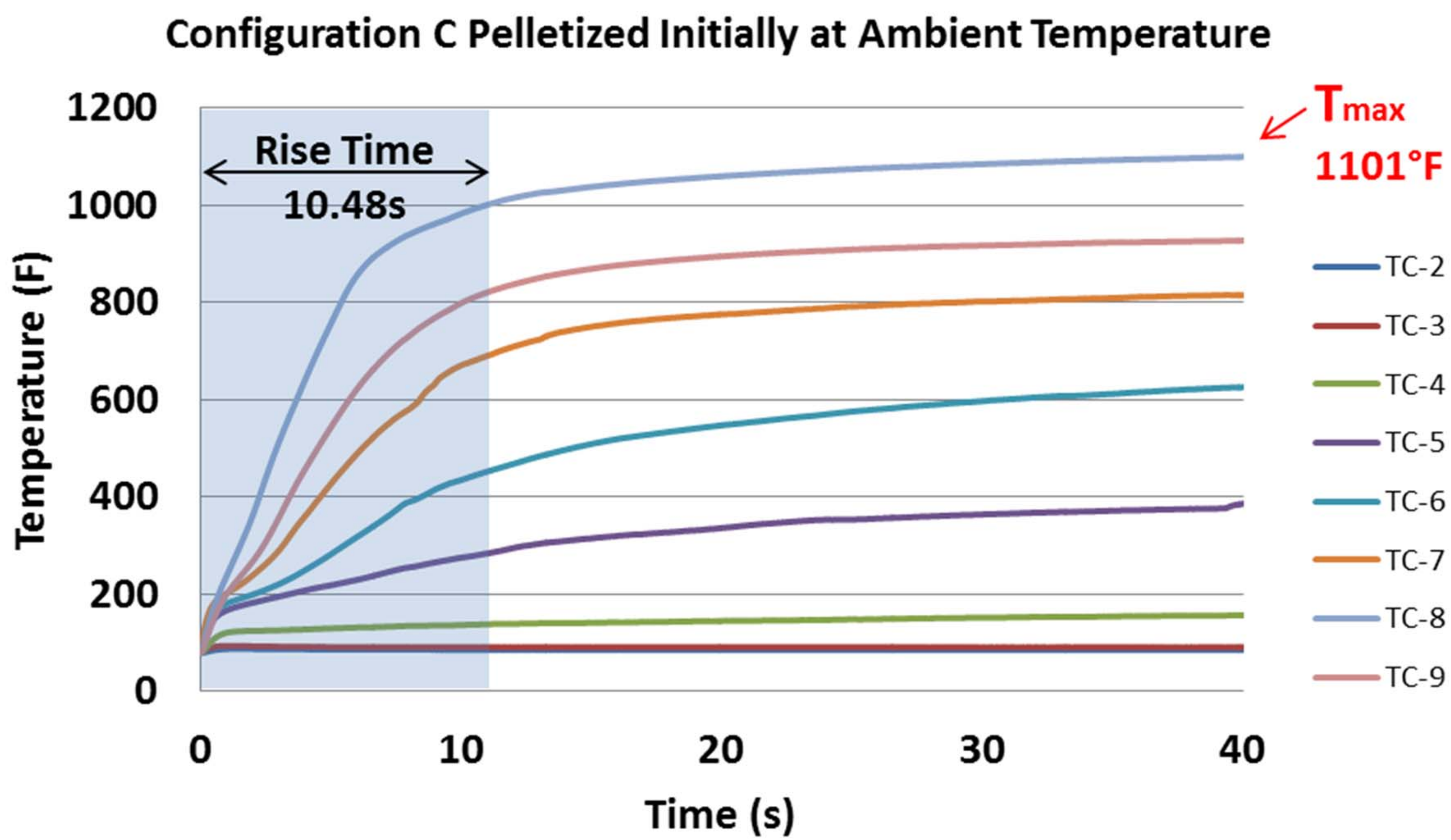
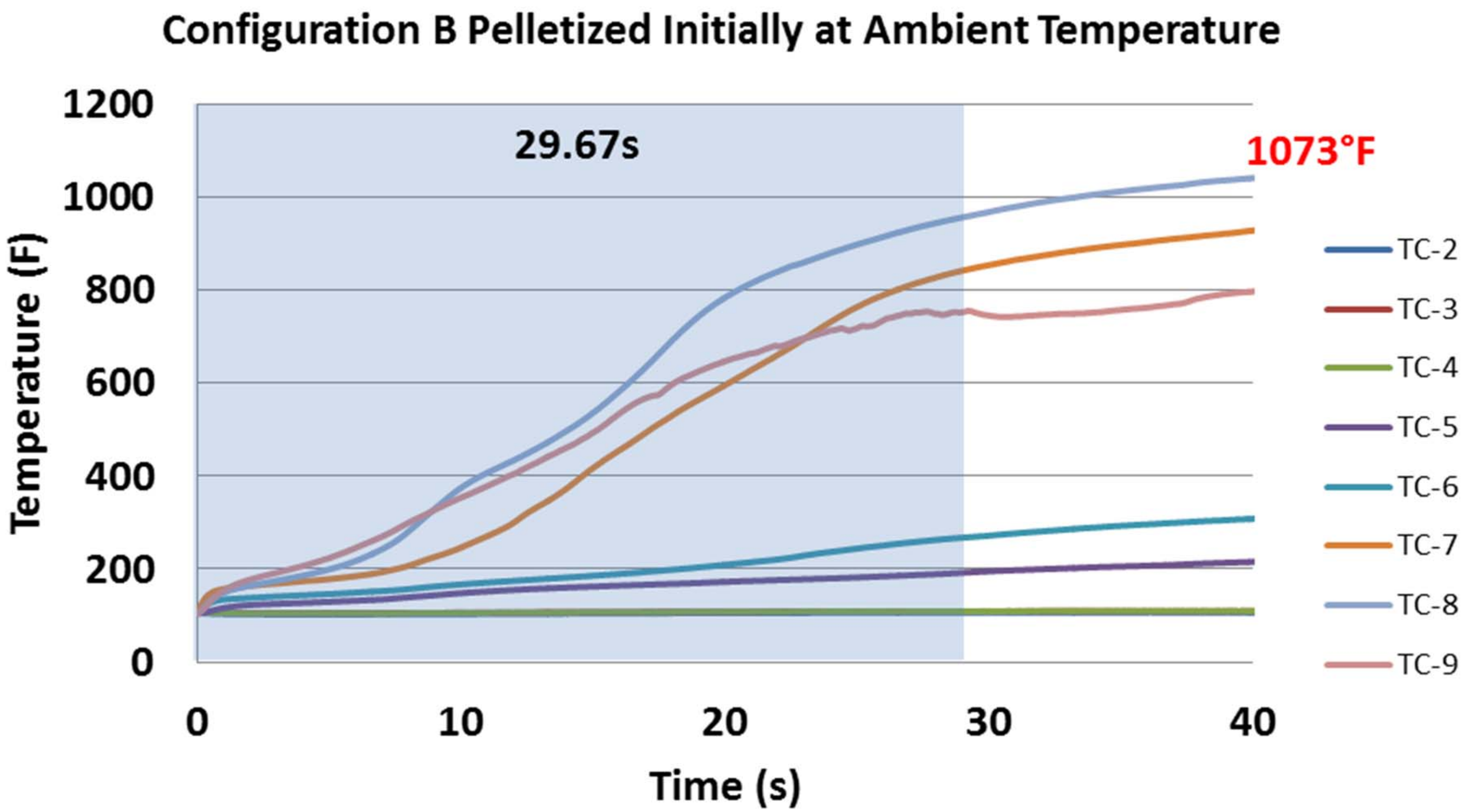


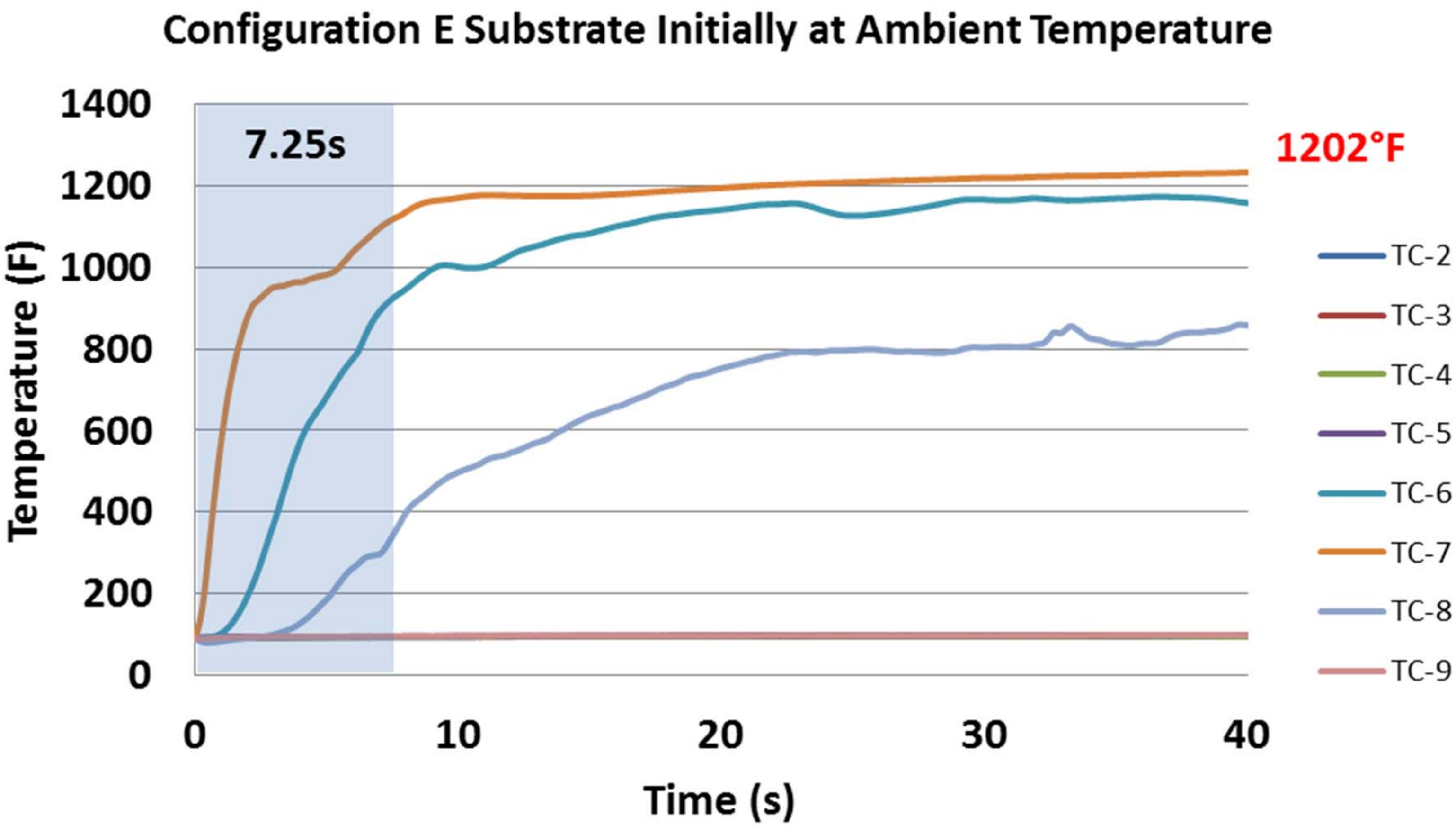
Max temp: 1101 °F; Max Thrust: slightly below predicted; Max I_{sp}: 195 s

Results: Effect of Catalyst Bed Length



Max temp: 1073 °F; Max Thrust: below predicted; Max I_{sp}: 180 s

Results: Effect of Catalyst Type



Max temp: 1202 °F; Max Thrust: below predicted; Max I_{sp}: 134 s; Catalyst crushed

Results: Effect of Heating

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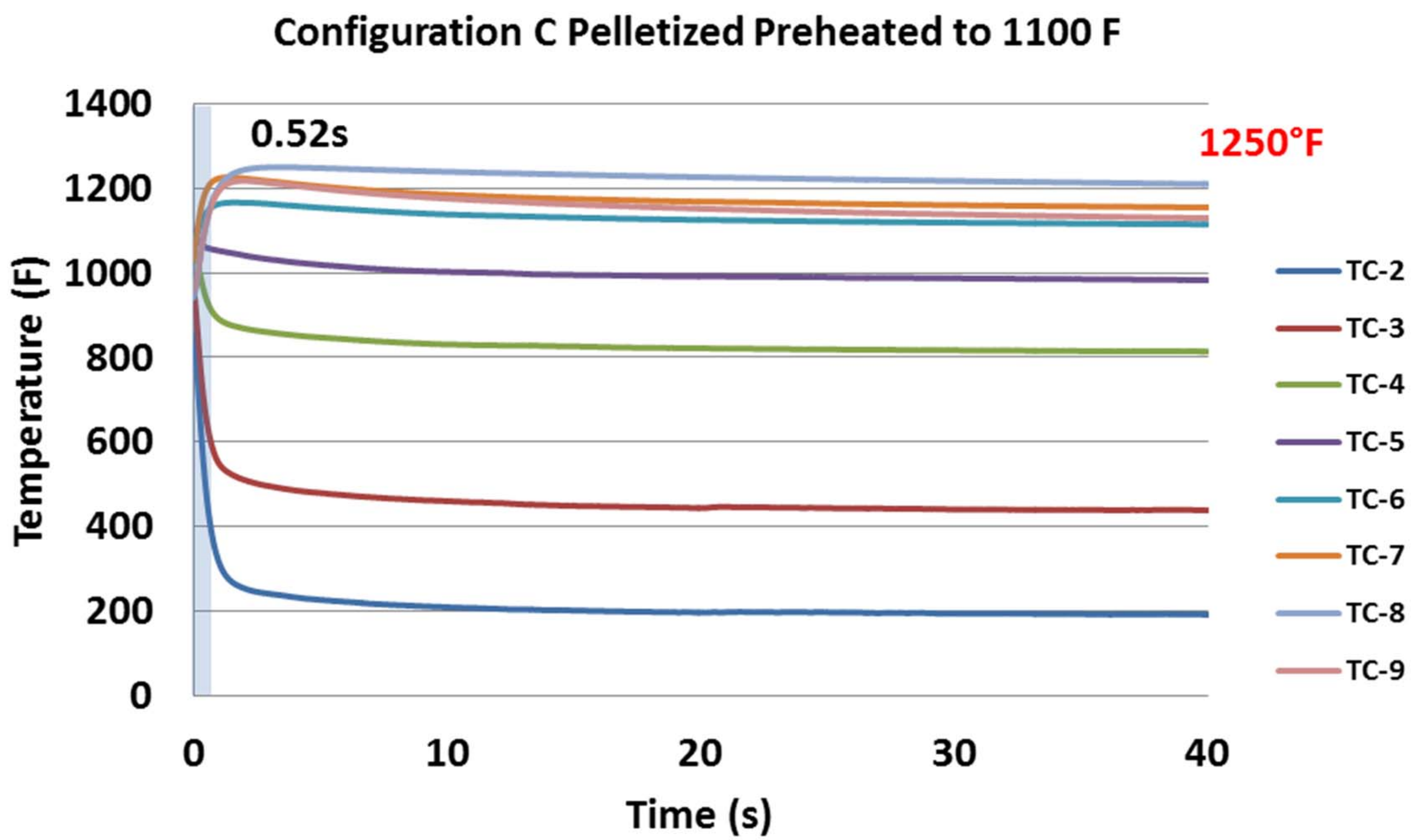

Max temp: 1250 °F; Max Thrust: nominal; Max I_{sp}: 221 s

Results: Specific Impulse vs. Time

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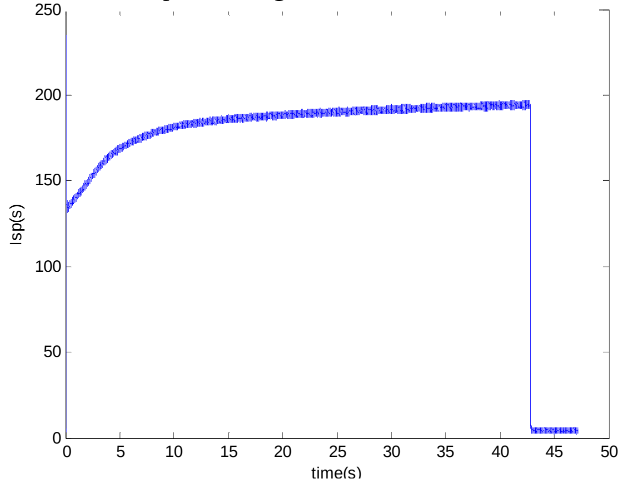
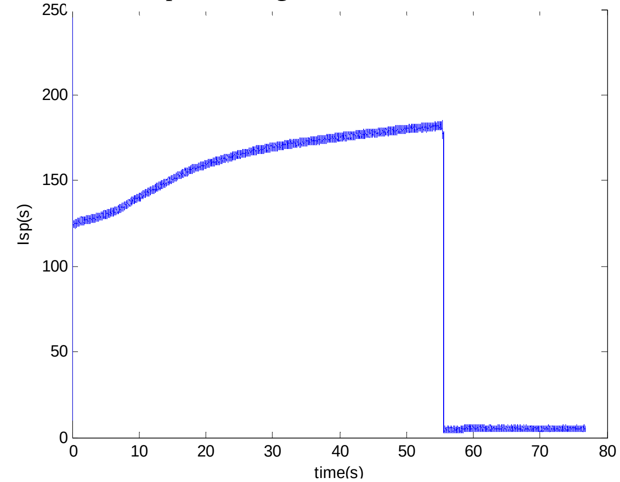
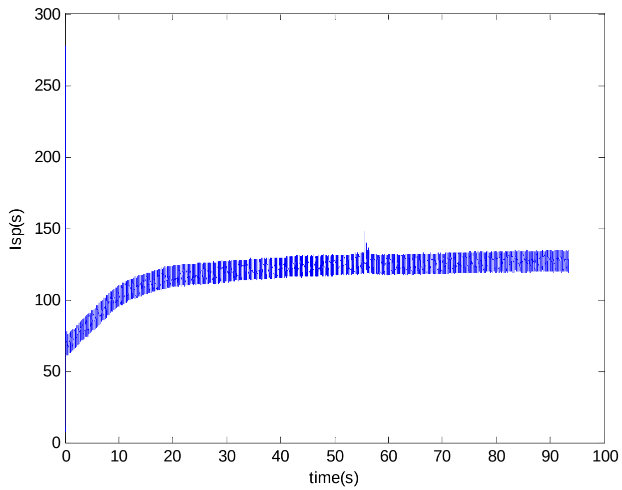
Isp of Configuration C, No Preheat



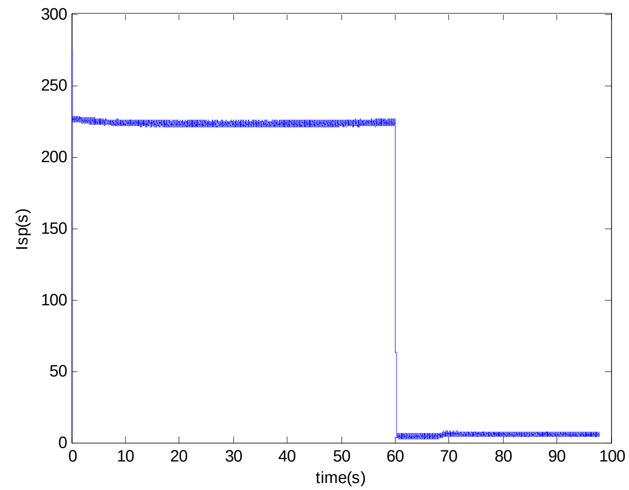
Isp of Configuration B, No Preheat



Isp of Configuration E, No Preheat



Isp of Configuration C, Pellets preheated to 1100 F



Results Summary

- **Catalyst bed length**
  - Larger catalyst beds provided highest thrust and I_{sp} levels
  - Catalyst bed length was limited by overall length of thruster
- **Catalyst type**
  - Substrate type catalyst had insufficient structural integrity
  - Limited by the manufacturer
- **Catalyst bed heating**
  - Heating the bed drastically reduced rise time and provided more uniform I_{sp}
  - Heater requires extra power from spacecraft
- **Optimal Configuration**
  - C, pelletized catalyst, pre-heated
  - Minimal rise time, nearly constant I_{sp}

Thank You!

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