Hybrid Propulsion In-Situ Resource Utilization Test Facility Results for Performance Characterization

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July 2016

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Government sponsorship acknowledged.

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Outline

- Motivation
- Test Facility
- Hotfire Results
- Data Reduction Methods
- Error Analysis
- Conclusion
- Future Work

Motivation

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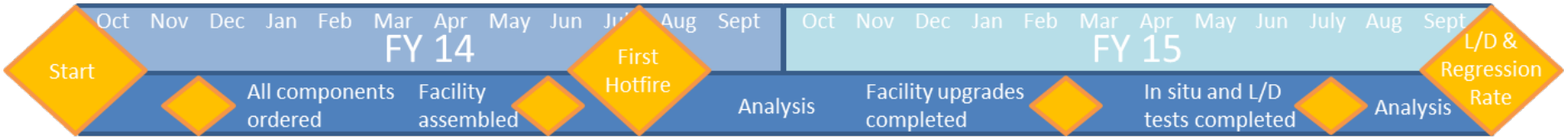
- Hybrid propulsion could be a potential game changing technology for in space applications
  - Long term fuel storage in cold temperatures
  - Oxidizer produced *In-Situ*
    (ex: O_2 with varying concentrations of CO and CO_2)
  - Single port solid grains with small length to diameter (L/D) ratio can be achieved using fast regression rate paraffin based fuels

At near optimum oxidizer to fuel (O/F) ratio, about 70% of the total propellant mass could be produced using In-Situ Propellant Production (ISPP)

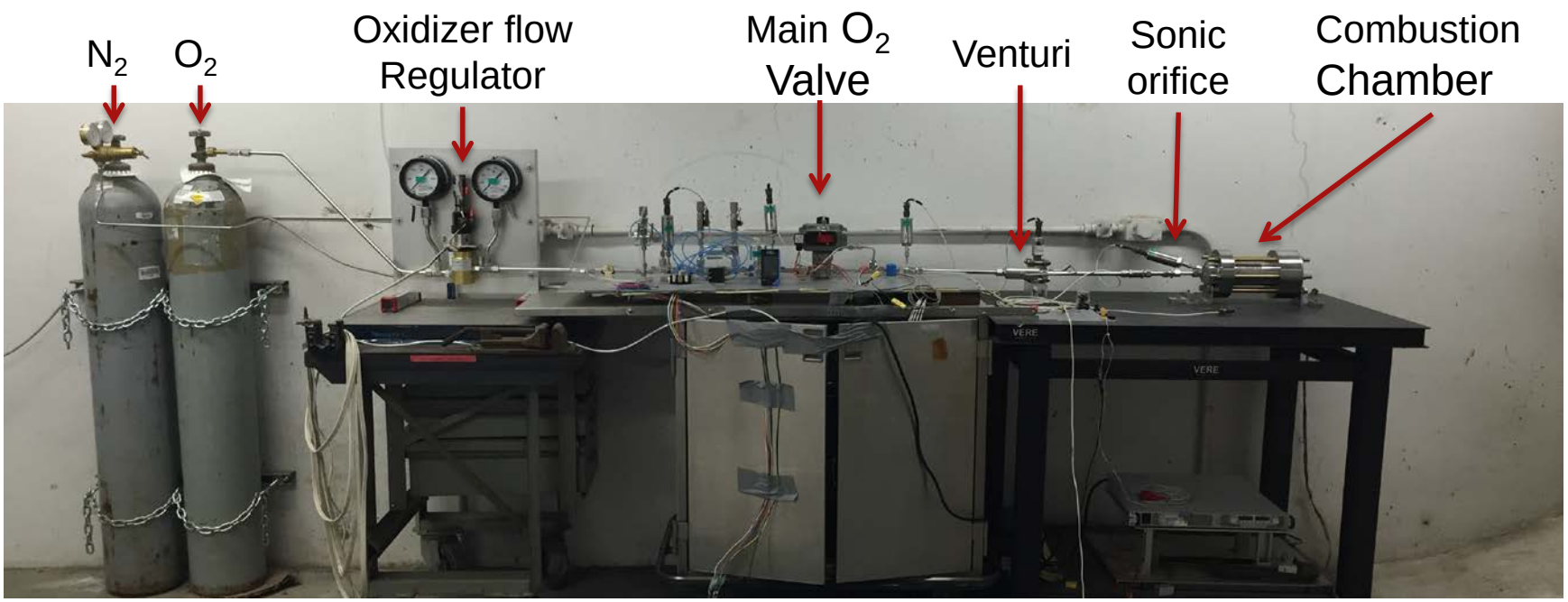
Motivation, cont.

- Crucial parameters in hybrid rocket preliminary designs:
  - Fuel regression rate
  - c* efficiency
- Test campaign objectives:
  - Support preliminary design studies with experimentally obtained data
  - Establish the fuel regression rate of hybrid fuels with ISRU Oxidizers
    - Two wax based fuels with GOx in different mass flux regimes
      - Compare paraffin/GOx with known data
    - Paraffin with GOx/CO_2 mixtures (not presented here)
  - Determine c* efficiency for different configurations
    - L/D effect
    - Associated uncertainty



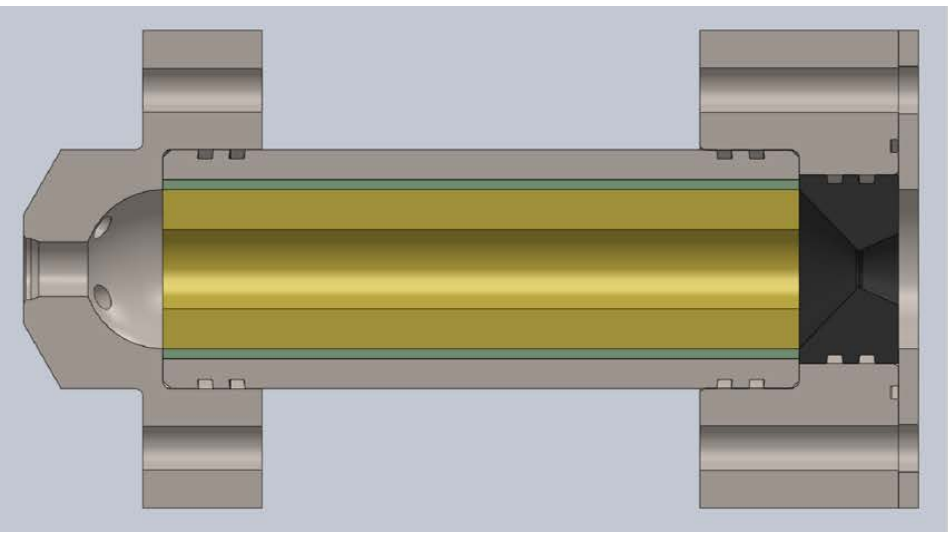
Test Facility

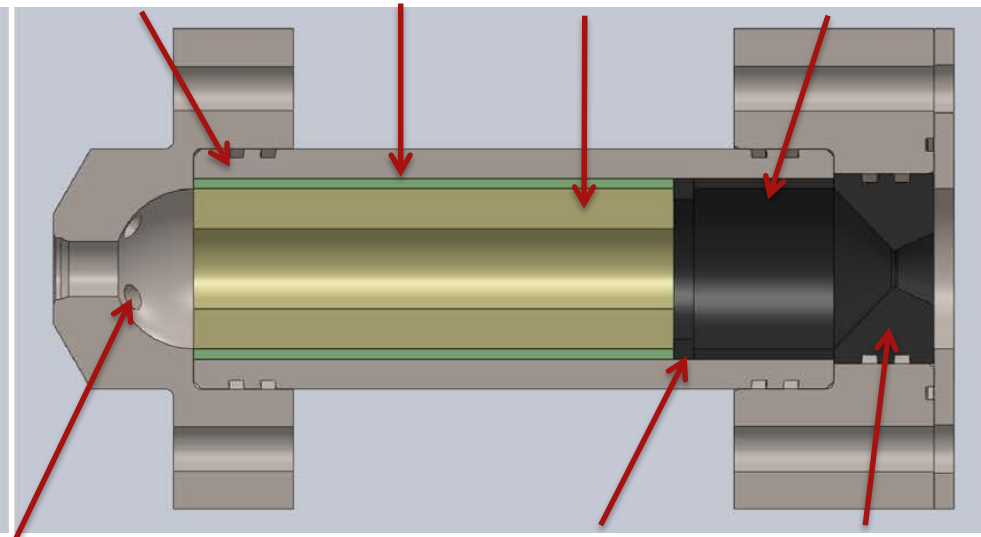
- Maximum thrust: 60 lbf (250 N)
- Fuel grain outer diameter: 2.0 in (5.1 cm)
- Maximum expected operating pressure: 250 psi (17.2 bar)
- Maximum oxidizer upstream pressure: 1000 psi (68.9 bar)

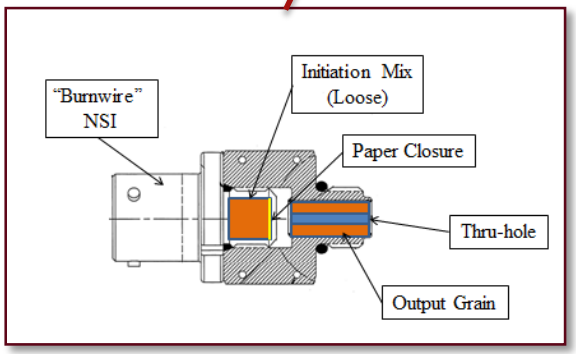


Test Facility, cont.

- Chamber length: 4.0 in (10.2 cm), 8.0 in (20.3 cm), 12.0 in (30.5 cm)
- 9-hole brass injector







Typical Hotfire Test

- Propellant Combination: SP1X/GOx
- $\dot{m}_{ox} \approx 70$ g/s
- O/F ≈ 2.3
- Chamber Pressure ≈ 130 psi (9 bar), supercritical for paraffin

Test Summary

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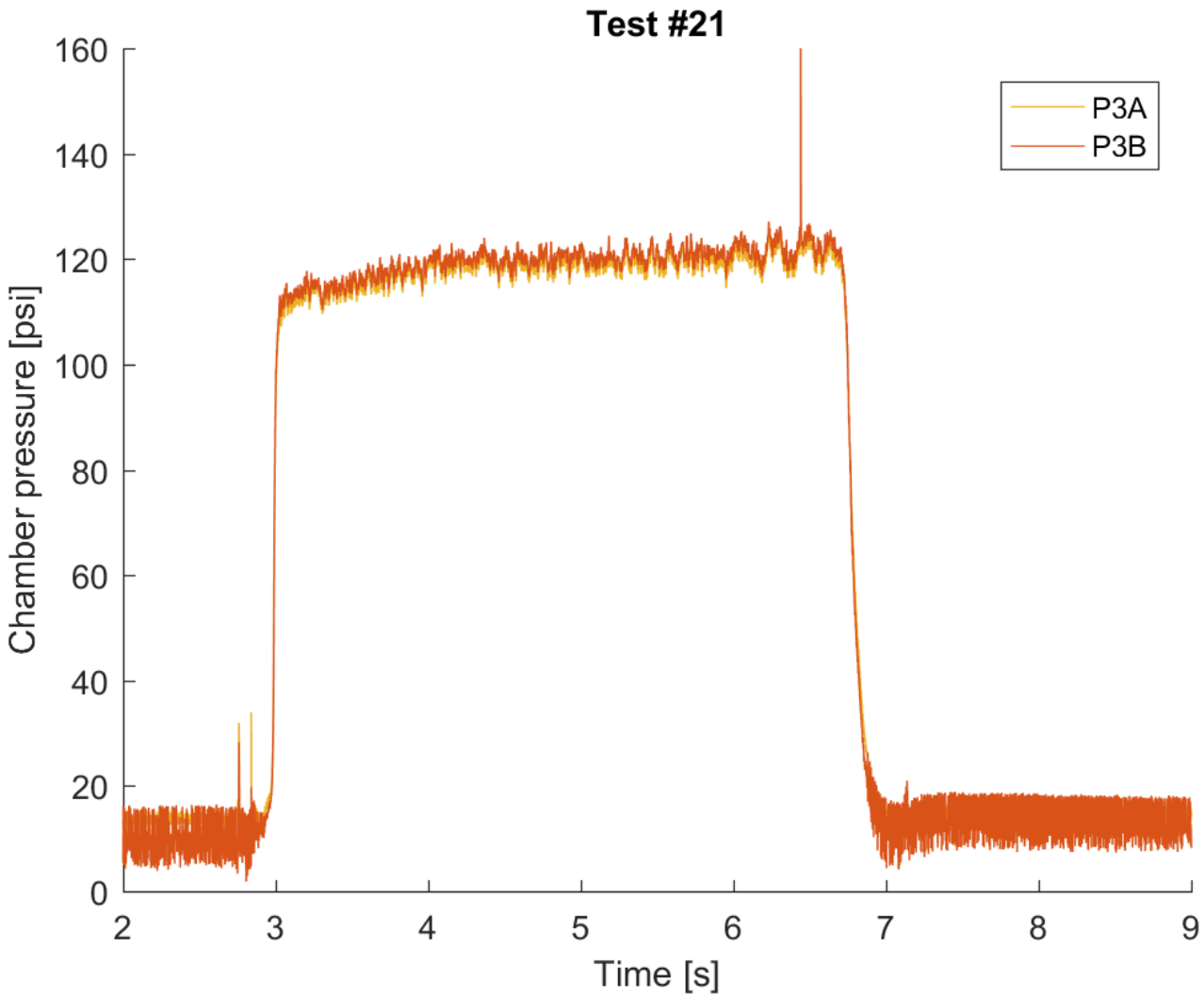
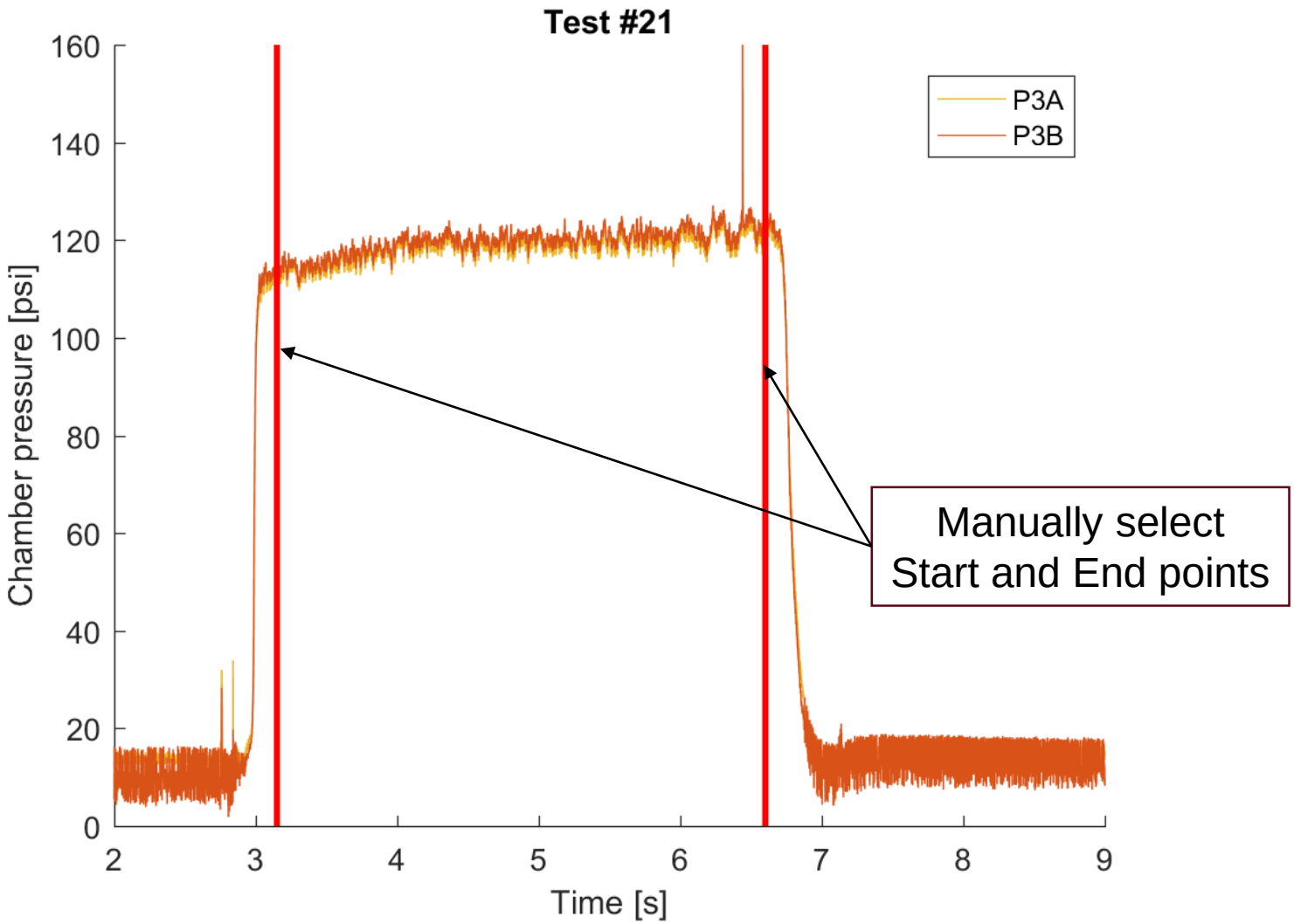
Test #	Fuel	Fuel length [in]	Burn time** [s]	$\dot{m}_{ox}$ [g/s]	OF**	Pc** [psi]
10	BP*	4.0	3.4	57	2.5	139
11	BP	4.0	3.7	51	2.6	127
12	BP	8.0	3.3	95	1.9	164
13	BP	8.0	3.3	105	2.0	176
14	BP	6.0	3.4	93	2.9	156
15	SP1X	6.0	3.0	79	2.8	127
16	SP1X	6.0	3.6	70	2.5	118
17	SP1X	6.0	3.0	69	2.4	124
18	SP1X	6.0	3.7	59	2.3	102
19	SP1X	6.0	2.6	49	2.6	115
20	SP1X	6.0	2.9	69	2.5	116
21	SP1X	6.0	3.7	69	2.5	117

** BP: Black Paraffin*
*** mean value obtained with six different reduction techniques*

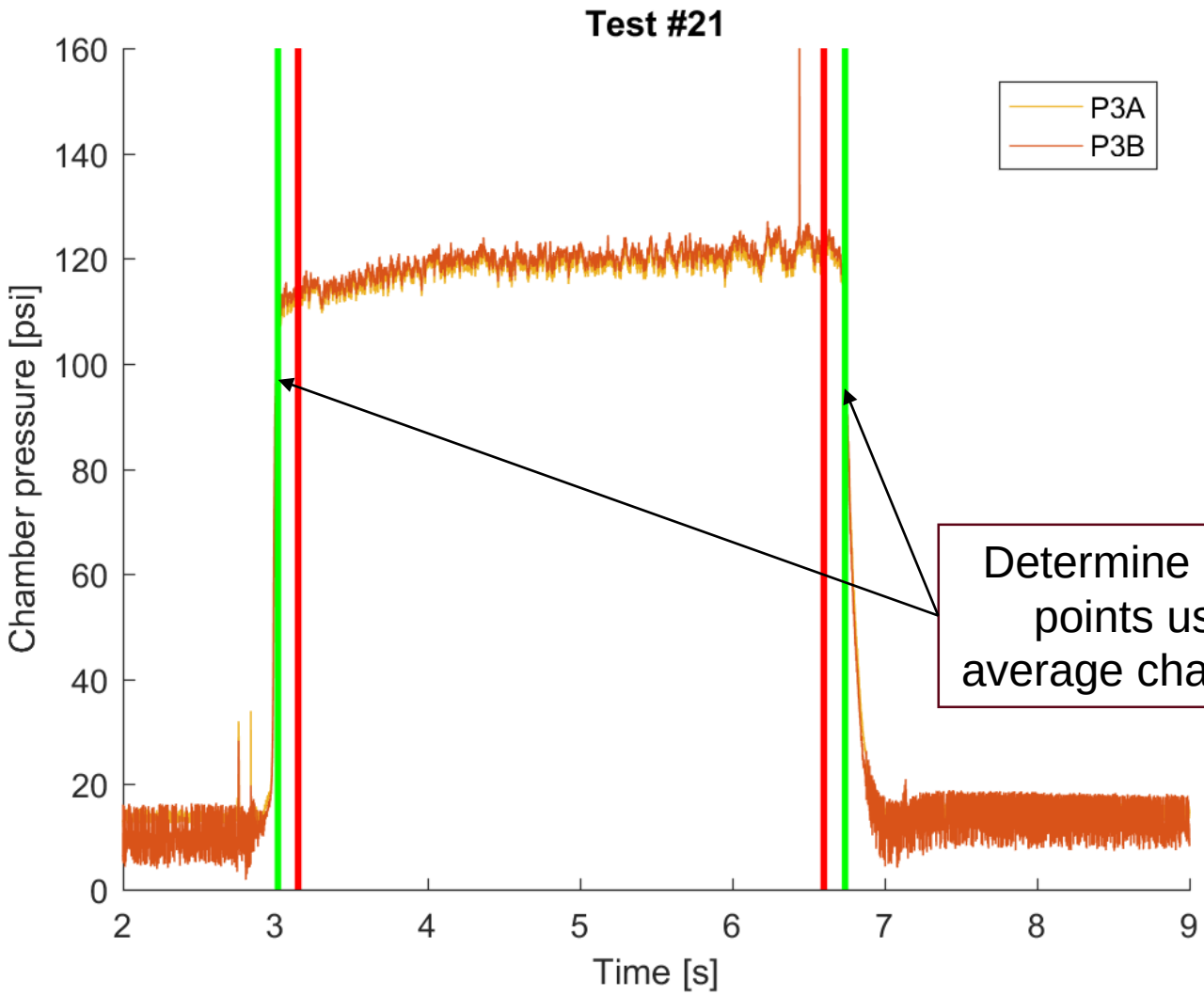
Burn Time and Chamber Pressure



Burn Time and Chamber Pressure

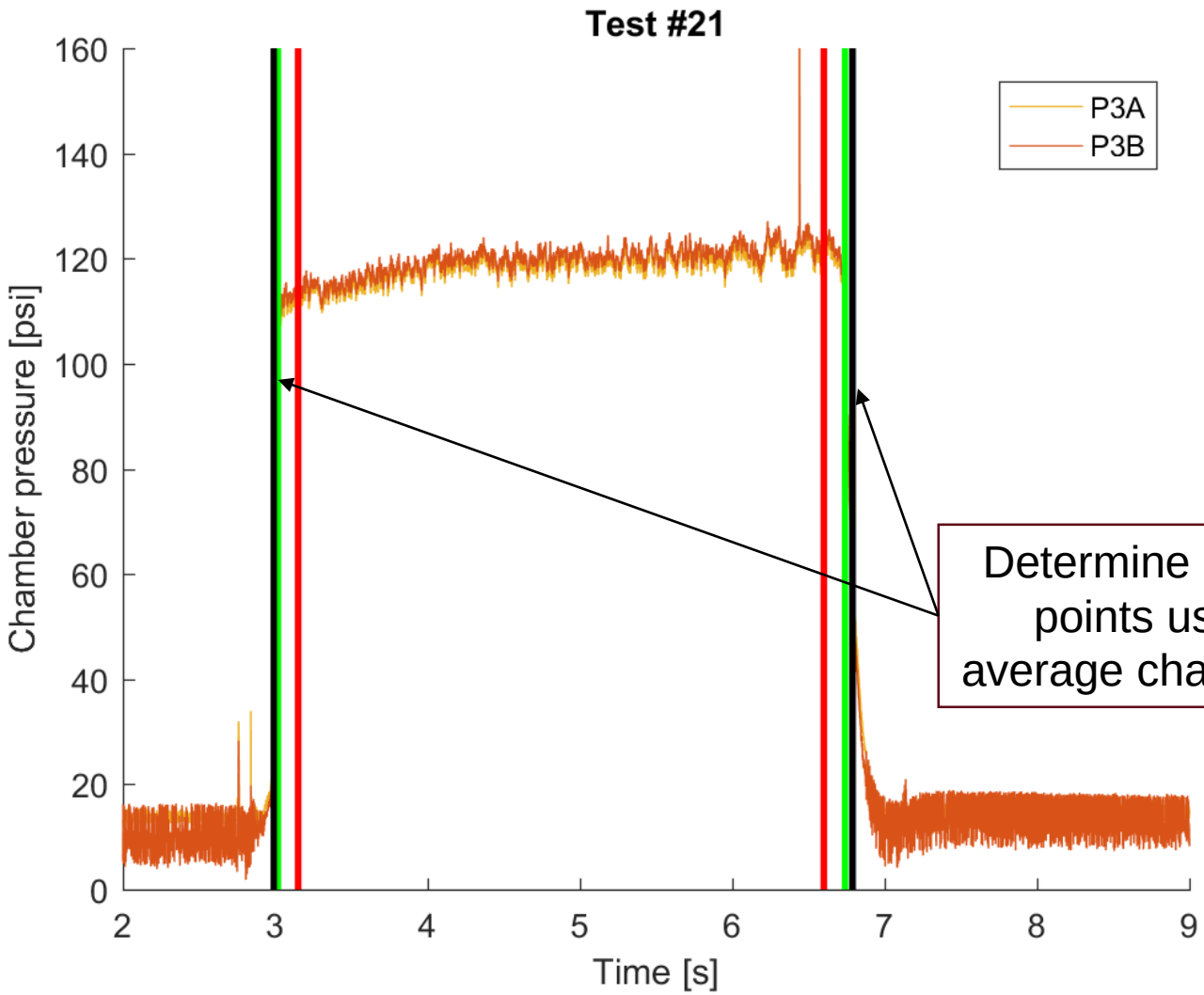


Burn Time and Chamber Pressure



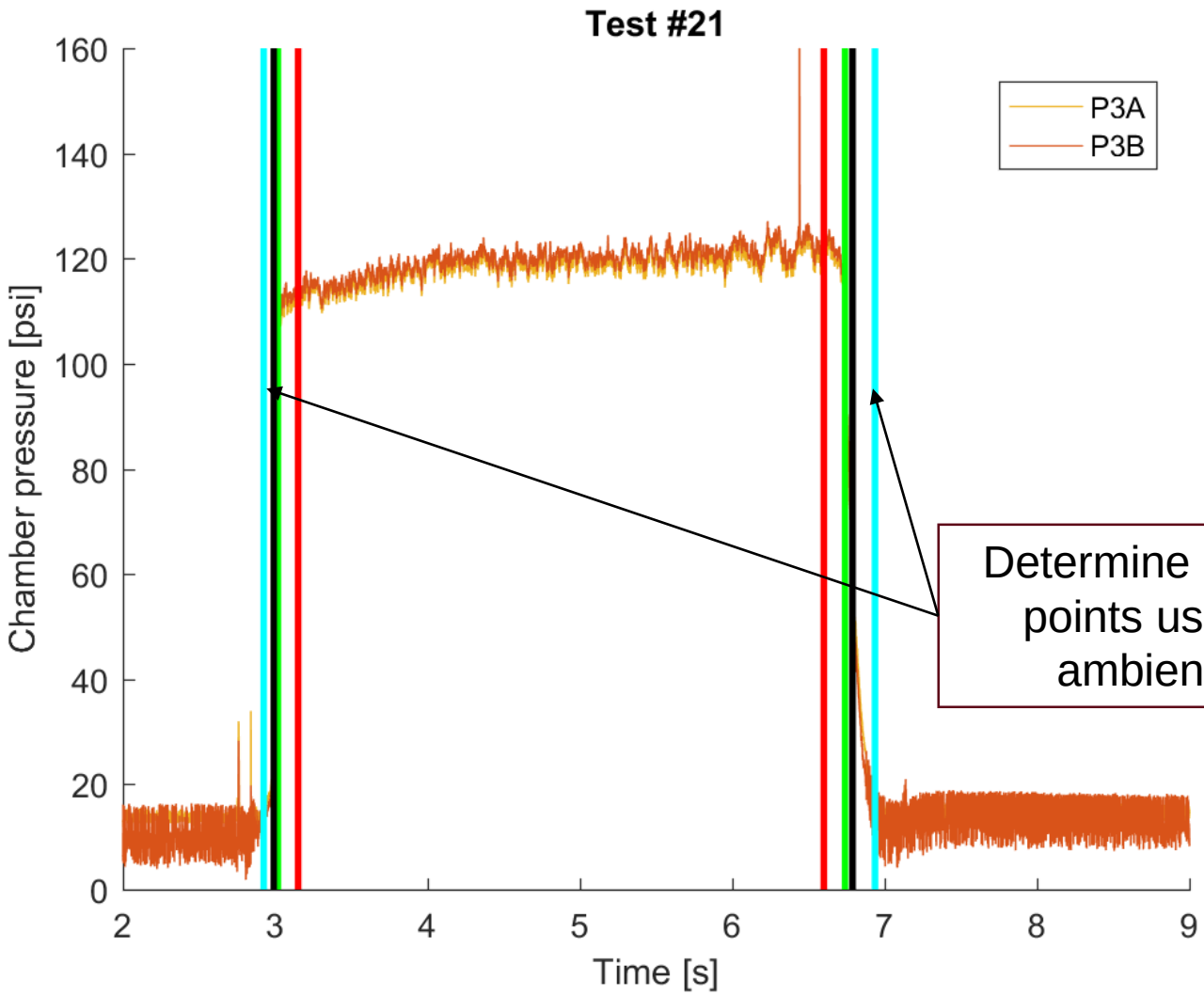
Determine Start and End points using 90% of average chamber pressure

Burn Time and Chamber Pressure



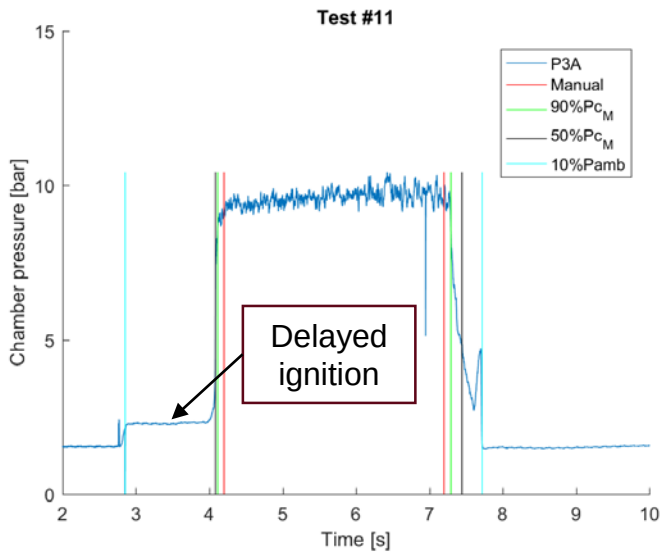
Determine Start and End points using 50% of average chamber pressure

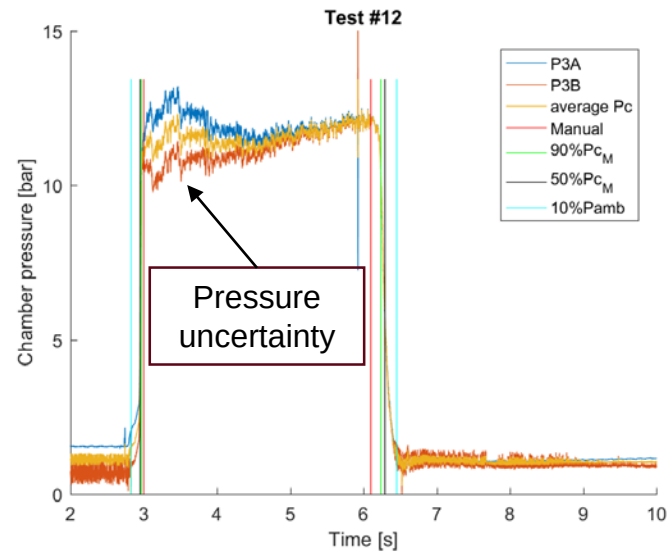
Burn Time and Chamber Pressure

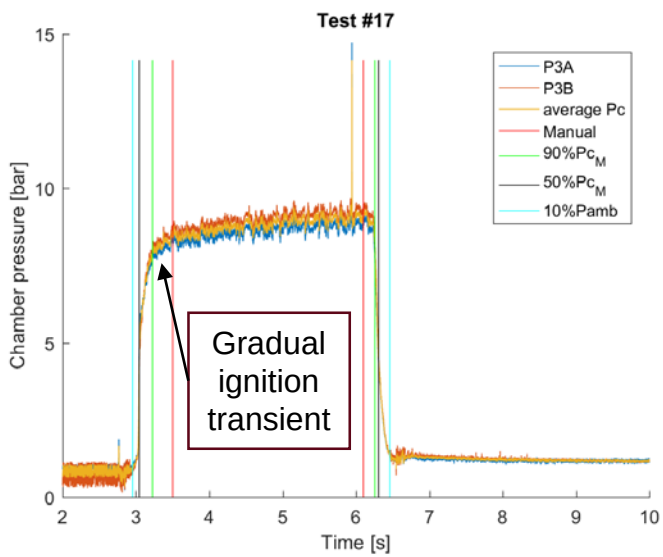


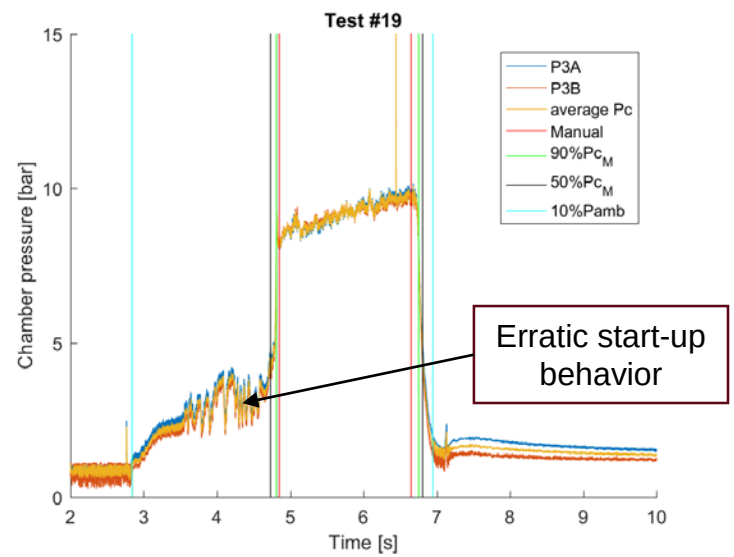
Determine Start and End points using 110% of ambient pressure

Challenges for Data Analysis







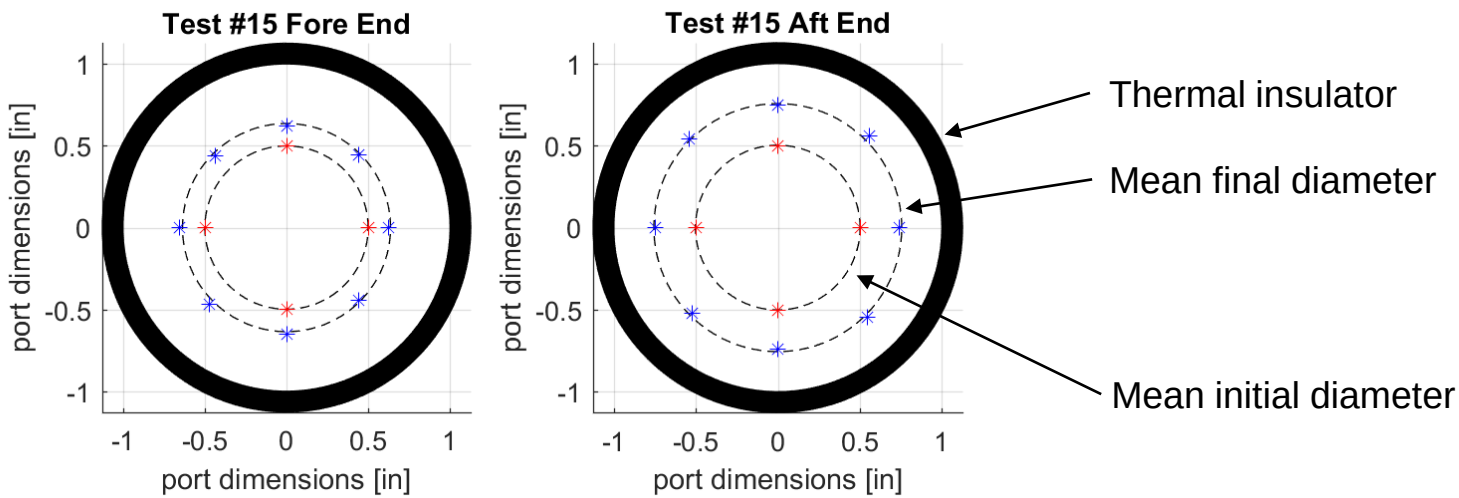


Oxidizer Mass Flux

- From Karabeyoglu at. al.*

$$\bar{G}_{ox} = \frac{16\bar{\dot{m}}_{ox}}{\pi(D_{p,i} + D_{p,f})^2}$$

- Insufficient data to calculate $D_{p,i}$ and $D_{p,f}$ from mass measurements
- $D_{p,i}$ and $D_{p,f}$ are calculated with thickness measurements



** AIAA 2005-3544*

Fuel Regression Rate

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- Space time averaged regression rate determined with fuel grain diameters and burn time

$$\bar{\dot{r}} = \frac{D_{p,f} - D_{p,i}}{2t_b}$$

- Karabeyoglu et. al. regression rate law for SP1-a/O_2*

$$\bar{\dot{r}} = 1.17e^{-4}\bar{G}_{ox}{}^{0.62}$$

- Preliminary regression rate law found in this study for SP1X/O_2**

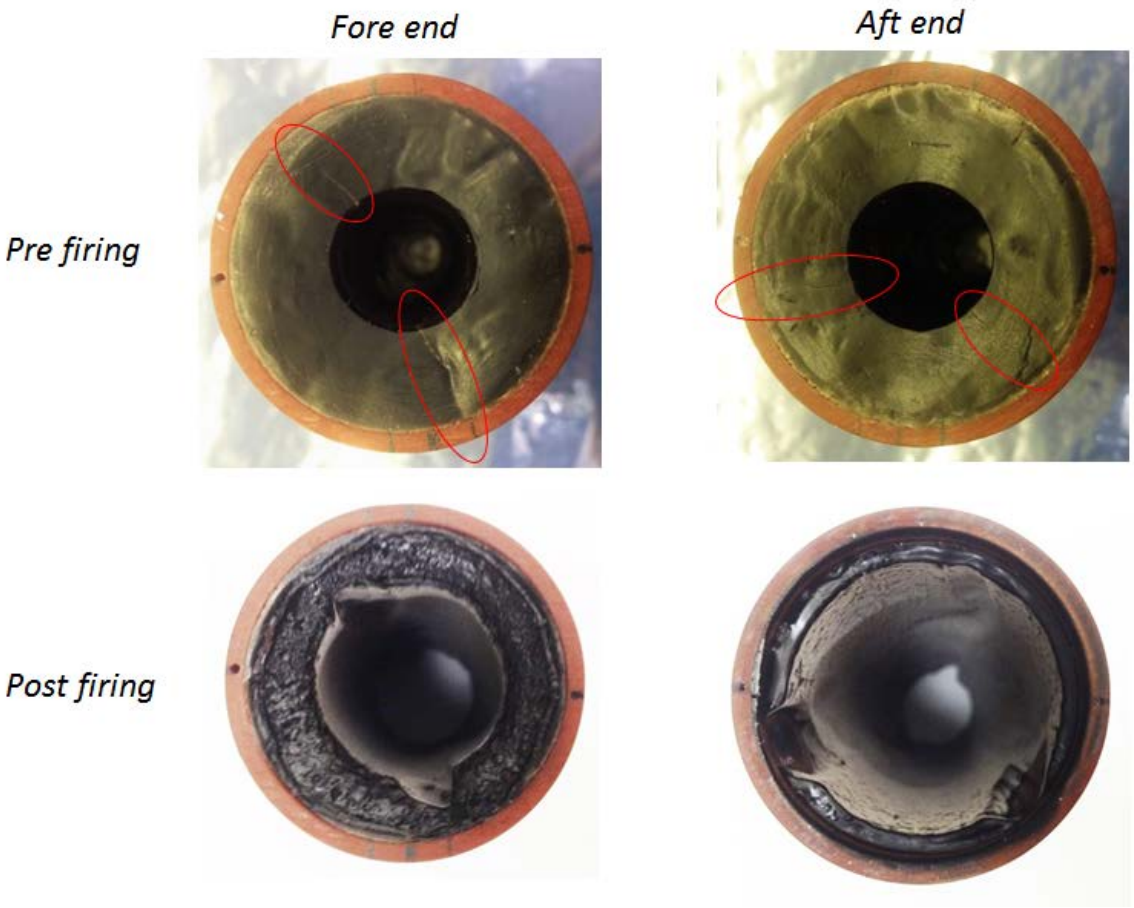
$$\bar{\dot{r}} = 1.22e^{-4}\bar{G}_{ox}{}^{0.62}$$

** AIAA 2003-1162. $\bar{\dot{r}}$ in m/s and $\bar{G}_{ox}$ between 70 and 370 kg.m^{-2}.s^{-1}*

*** Data from five tests. $\bar{\dot{r}}$ in m/s and $\bar{G}_{ox}$ between 80 and 110 kg.m^{-2}.s^{-1}*

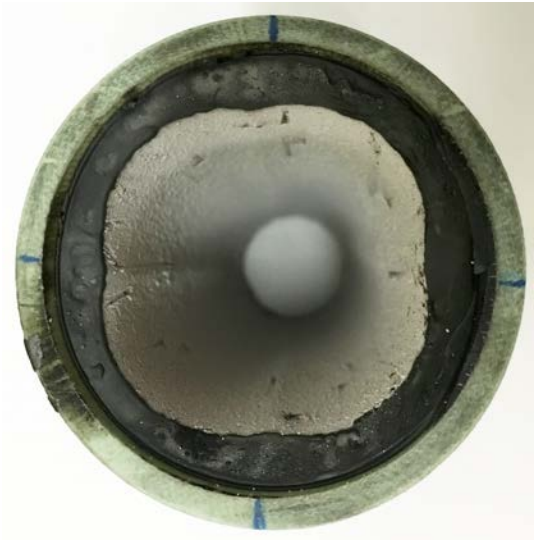
Non Uniform Regression

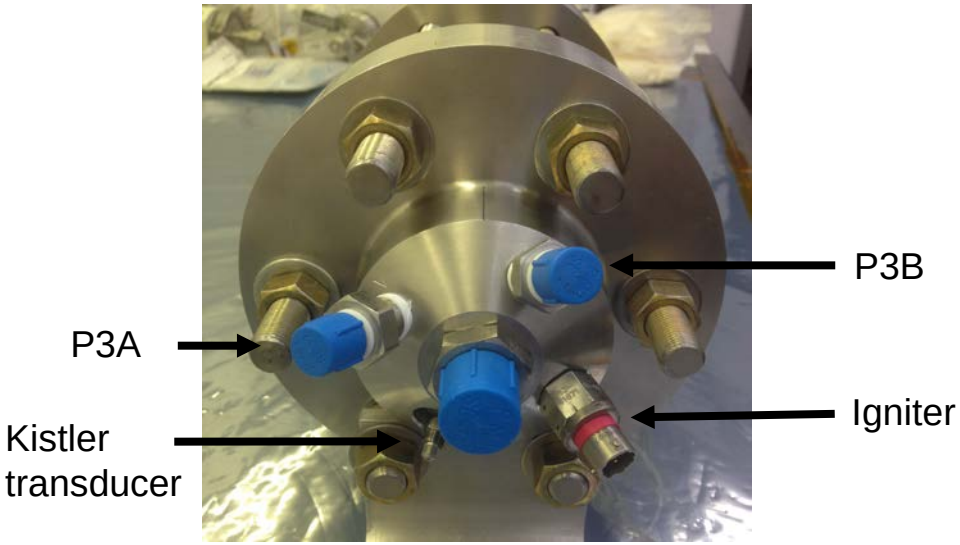
- Radial and axial cracks in centrifugally cast black paraffin wax grains propagate during burn due to increased surface area



Non Uniform Regression, cont.

- Significant outward coning of the fuel grain. Aft end regression rate is 80% higher than fore end recession
- A four lobe pattern was consistently observed on the fuel grains and is most likely due to the fore end geometry impacting the oxidizer flow in the port





c* Efficiency

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- c* is calculated using space time averaged values

$$\overline{c^*} = \frac{\bar{P}_c A_{nt}}{\bar{\dot{m}}_{ox} + \frac{m_{fuel}}{t_b}}$$

- Ideal c* is computed with NASA Glenn CEA code using average chamber pressure and O/F ratio

Test #	η_{c*M}	η_{c*90}	η_{c*50}	η_{c*ASM}	η_{c*MAE}	η_{c*A}	Mean	Std dev
15	84.0	86.8	87.1	83.1	84.7	84.0	**84.9**	1.5
16	83.6	86.1	86.3	83.7	84.2	84.4	**84.7**	1.1
17	86.3	90.2	91.2	88.0	86.2	89.0	**88.5**	1.9
18	83.1	85.0	85.2	83.4	83.6	84.1	**84.1**	0.8
19	79.4	80.6	79.8	66.4	77.8	68.2	**75.4**	5.8
20	83.4	85.8	86.1	83.7	83.6	84.2	**84.5**	1.1
21	84.3	86.6	86.8	84.8	84.5	85.2	**85.4**	1.0

Error Analysis

- Objective is to calculate upper bounds of the relative random error
- Spread in values using the different reduction methods is used to calculate the random relative error of burn time and chamber pressure

Parameter	Relative Error
E_{t_b}	9%
$E_{\dot{r}}$	21%
$E_{\dot{m}_{ox}}$	1.4%
$E_{G_{ox}}$	7.7%
$E_{O/F}$	9.2%
E_{P_c}	4.2%
E_{c^*}	6.5%

Conclusion

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- Structural additives in paraffin based fuels can reduce difficulties with centrifugal casting and are less prone to cracking
- Six different data reduction techniques were compared to determine random uncertainties
- Regression rate coefficients are in good accordance with previous SP1X/O_2 studies
- A large uncertainty is associated with burn time for short tests. This leads to a large uncertainty in O/F ratio
- For tests with short start-up and shut-down transients, c* efficiency can be determined with a small uncertainty (±2%)
- c* efficiency for this motor was found to be between 75 and 90%

Future Work

- Refine testing procedures and data analysis methods
- Test various mixtures of O_2 and CO_2 (completed ?)
- Use this facility to test slow burning fuels (HDPE, PMMA)

Acknowledgements

- This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

- The authors would like to thank the Jet Propulsion Laboratory for funding this research through its internal Research and Technology Development Program.

- Additional thanks go to Lawrence Harma, Matthew Devost, Alex Wolpe, Richard Webster, Alex Luna and William Gavid.

Thank you for your attention

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