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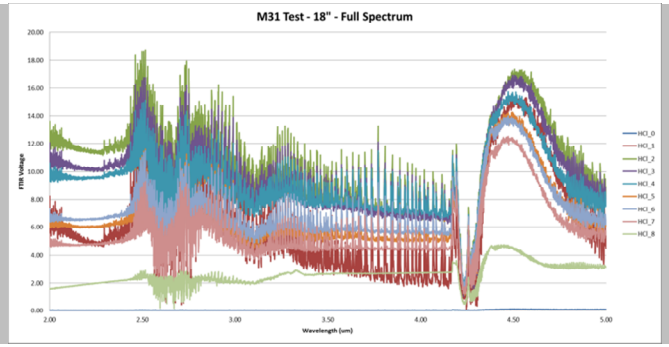
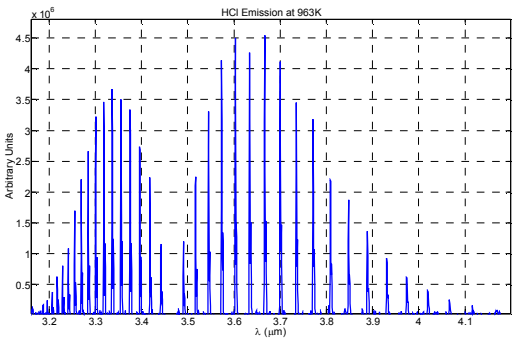




Temperature Calculations from FTIR Measurements of HCl

Alvaro Cruz-Cabrera

January 18, 2017

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Motivation & Introduction

Accident Scenario During Launch

Motivation

During the launch of radiological payloads (e.g. RTGs) using solid propellants:

- There is the risk of an accident with the consequent rupture of the solid propellant
- The radiological container could be breached by the propellant plume with the possible vaporization and dispersion of the radiological material

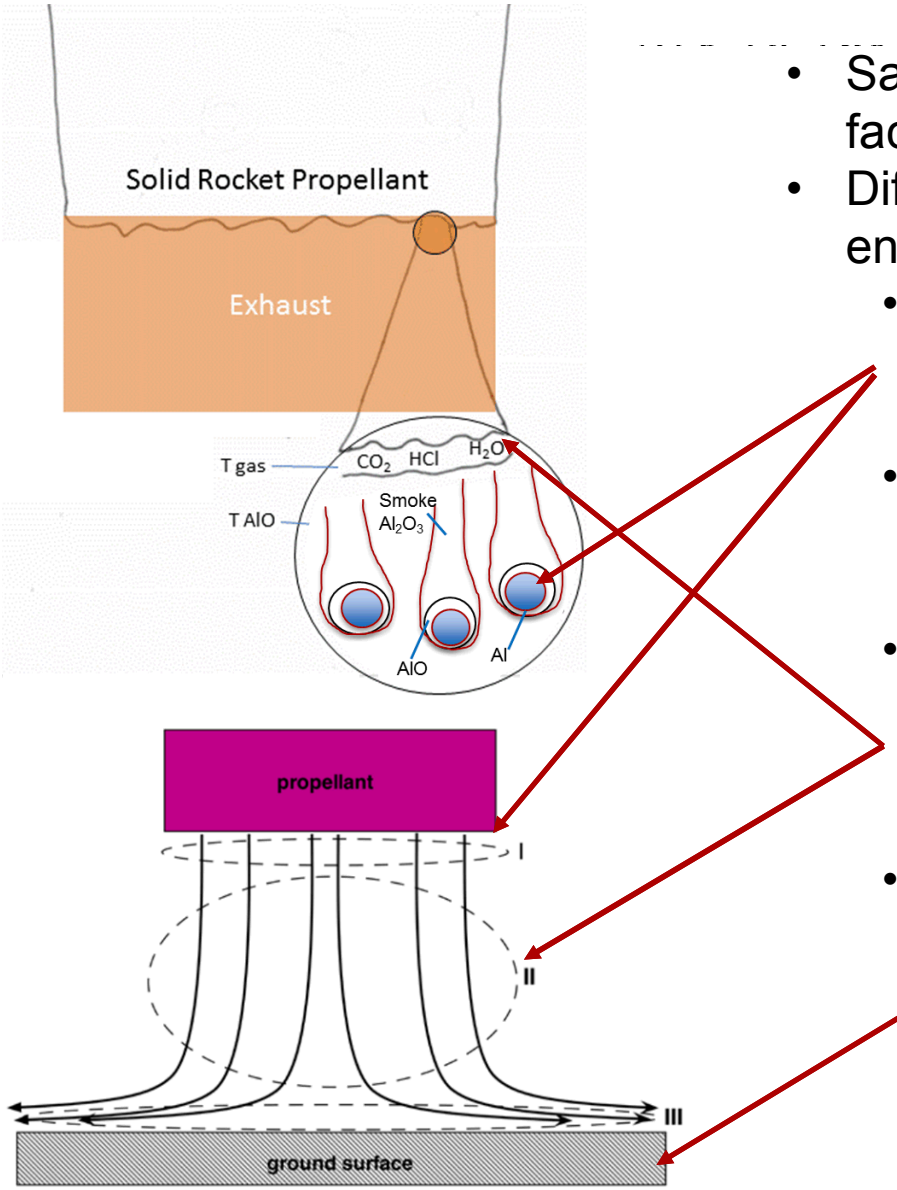
To be able to launch planetary probes with RTGs, a political decision must be made at the highest level of the government.

Part of the decision making involves the previous understanding of the temperatures affecting the RTG during an accident scenario.

While the desire parameter is a single temperature, the environment inside the plume consist of multiple temperatures forged by different reactions. One of those is the gas temperature which we try to measure by collecting spectra from HCL (hydrogen chloride) gas.

RTG: Radioisotope thermoelectric generator

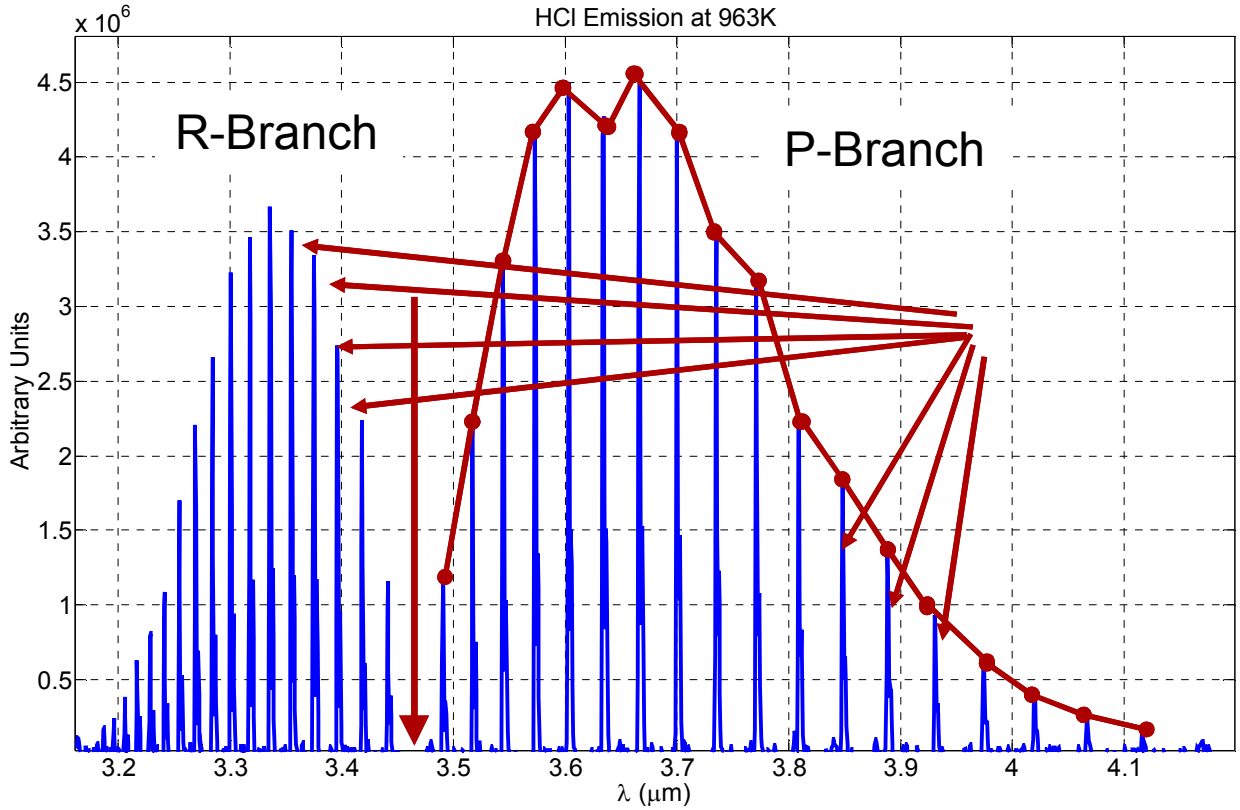
Condition During Propellant Test

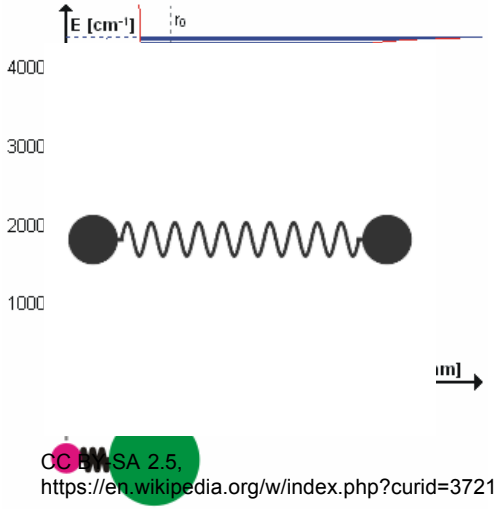


- Sandia performed tests at the old flame facility face up and face down burns
- Different temperatures are measured in this environment:
  - Burning metal (if propellant is aluminized – narrow band emission) is used in the radiation model
  - "Continuum Spectrum" temperature (Black body, grey body, 1/λ, or other model)
  - Gas Temperature (H_2O, CO_2, HCl, etc.) – Related to "Continuum Spectrum" temperature is used in the convection model
  - The radiation and convection models are used in the calculation of the overall temperature seen by the thermocouples at the surface.

Introduction

- Measure temperature of one of the gases using the spectral emission of hydrogen chloride (HCl) gas
- HCl is a diatomic molecule with a vibrational-rotational emission spectrum centered at 3.46μm with multiple emission lines between 3 μm and 4.2 μm
- Temperature is measured by linearizing and fitting the envelope of the emission lines

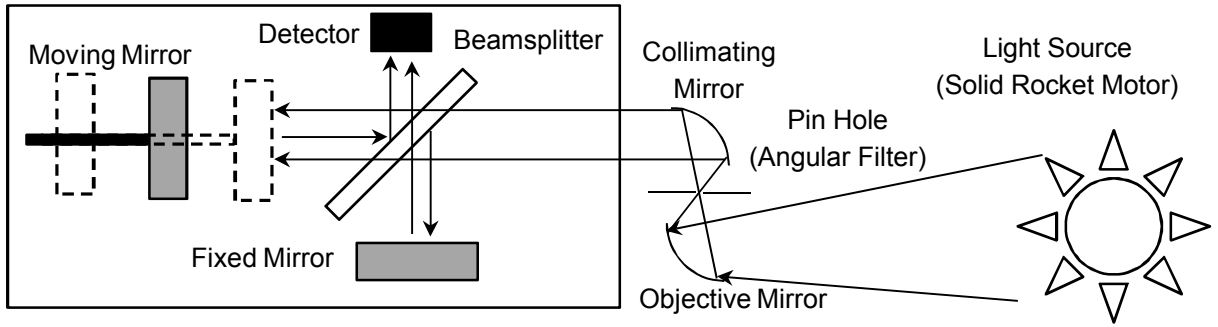




Experimental Setup: FTIR

Sandia National Laboratories

Modified Michelson Interferometer

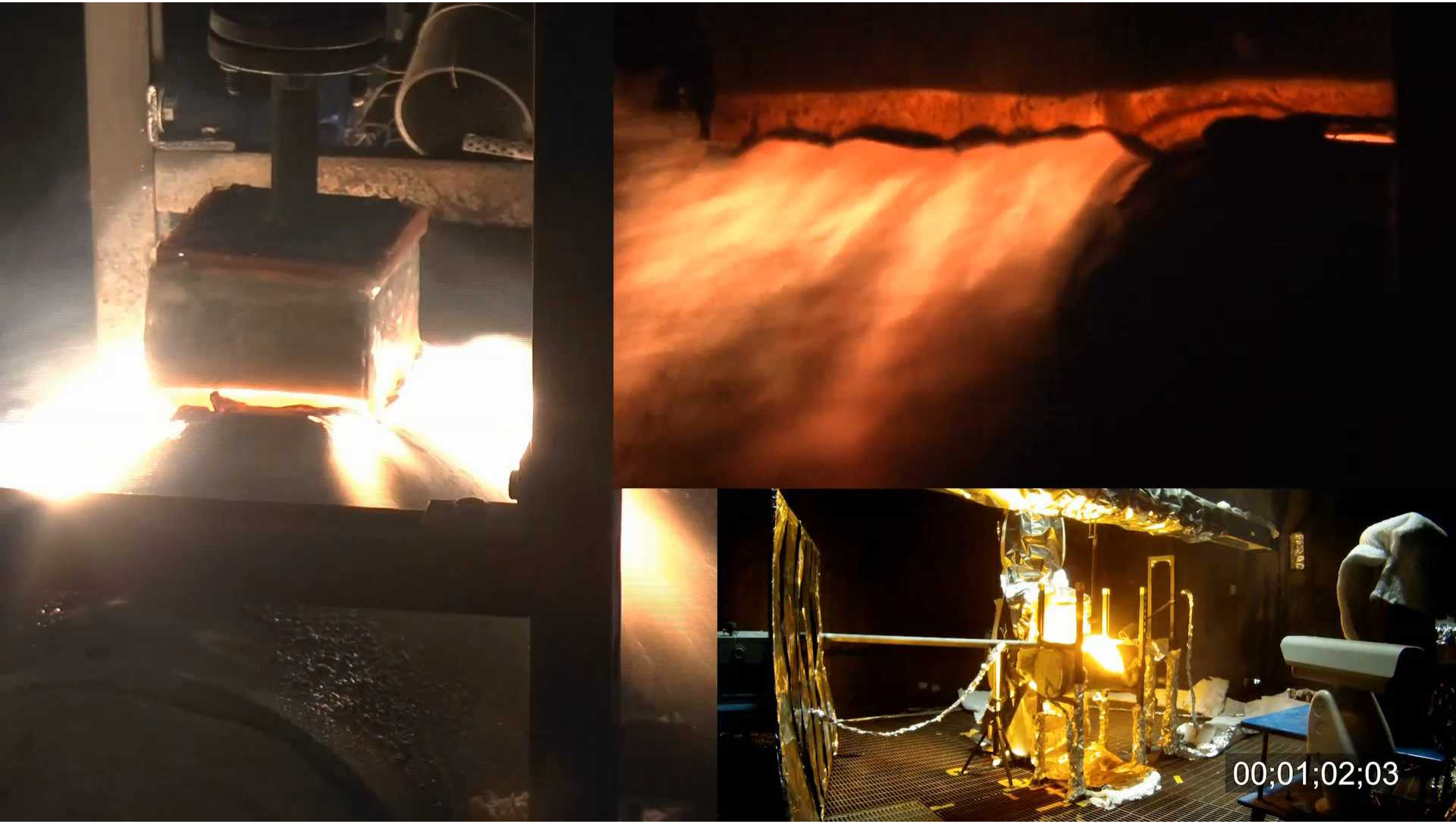


- HCl is considered a target of opportunity to measure gas temperature
- The FTIR is not a fast instrument but provides an excellent SNR
- 3 to 5 seconds per measurement
- Spectral Response: 2.5-4.5μm
- Noisy data was captured, when loss of sight of the flame due to:
  - Propellant inhibitor failure
  - Extremely small gaps
  - Large amount of particles

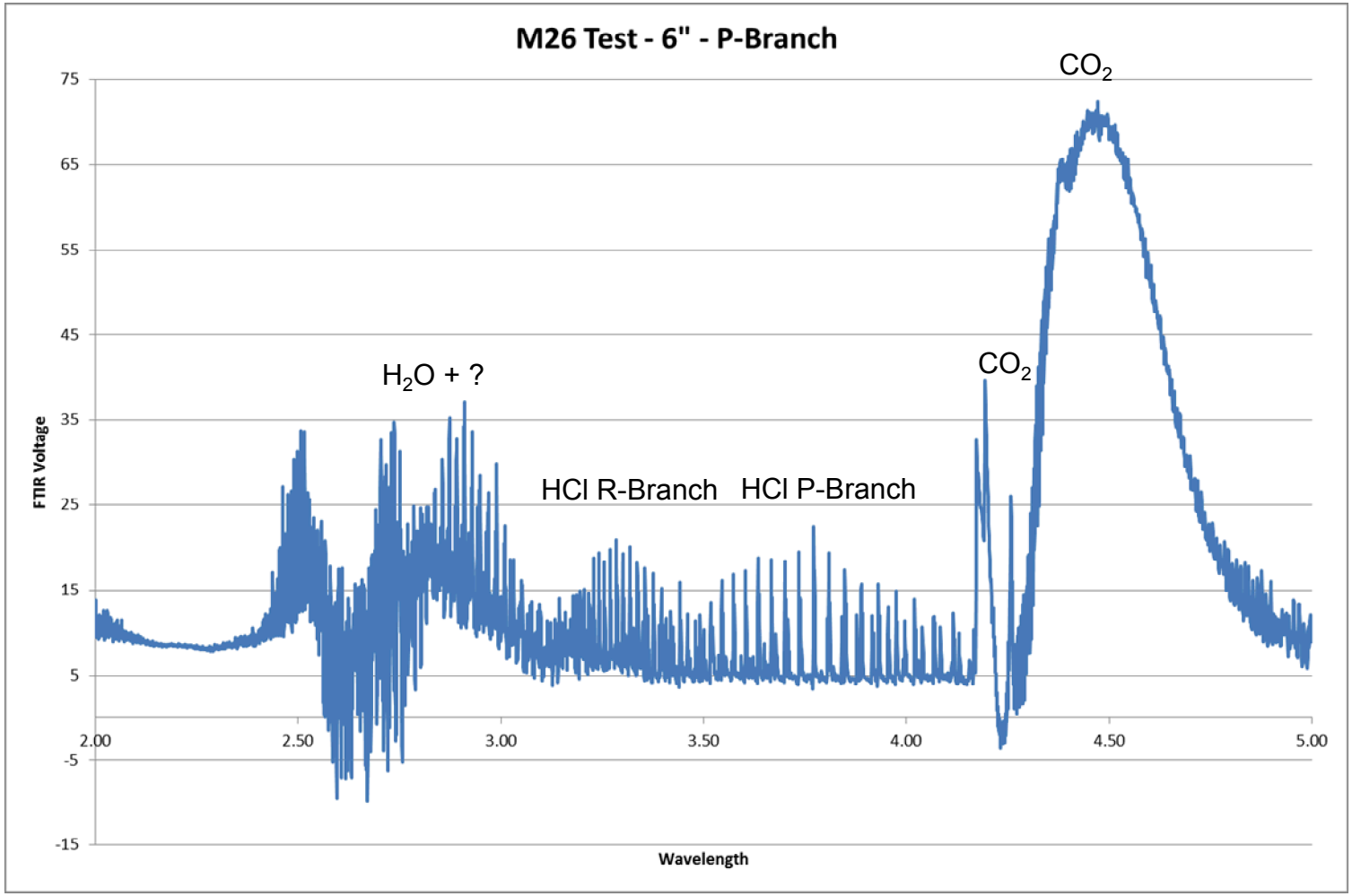
Large Test: 1207C

Large Test: VTQ-3

Large Test: MG841



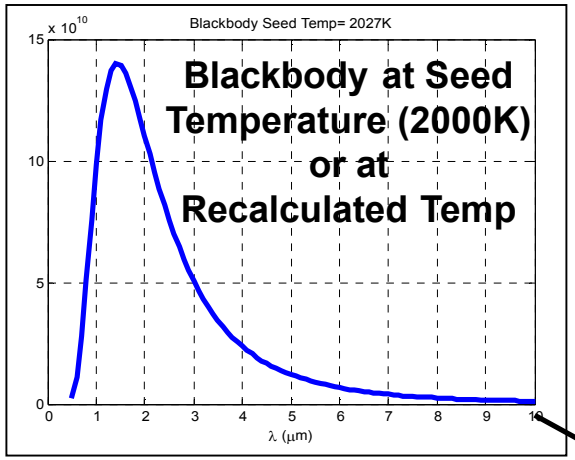
Example of Spectrum

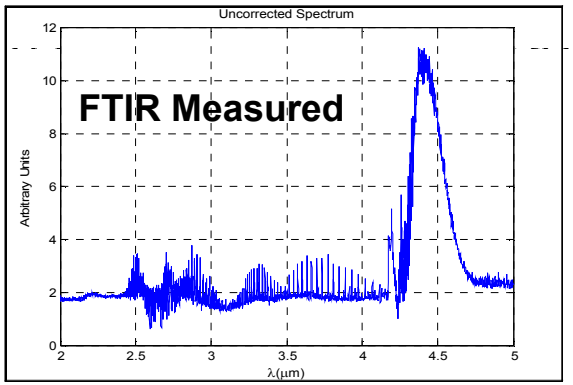


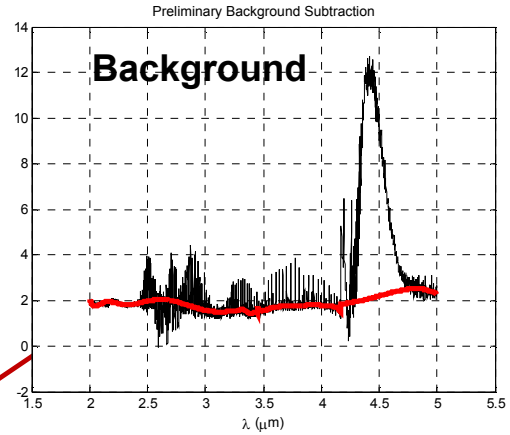
- Star 48 Propellant
- Devcon Inhibitor
- 6” Diameter
- 40 Sample Averaged
- Graphite

Temperature Calculation Method

Basic Algorithm

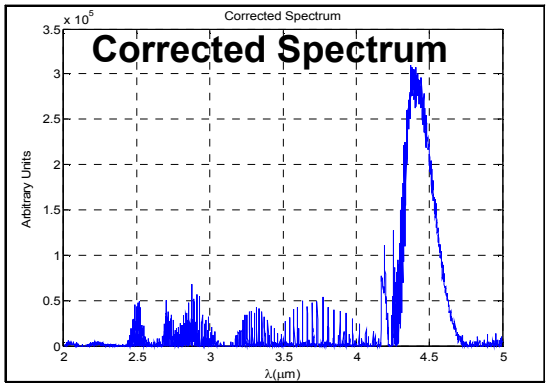






Background Subtraction

9 degree polynomial robust bi-square weights

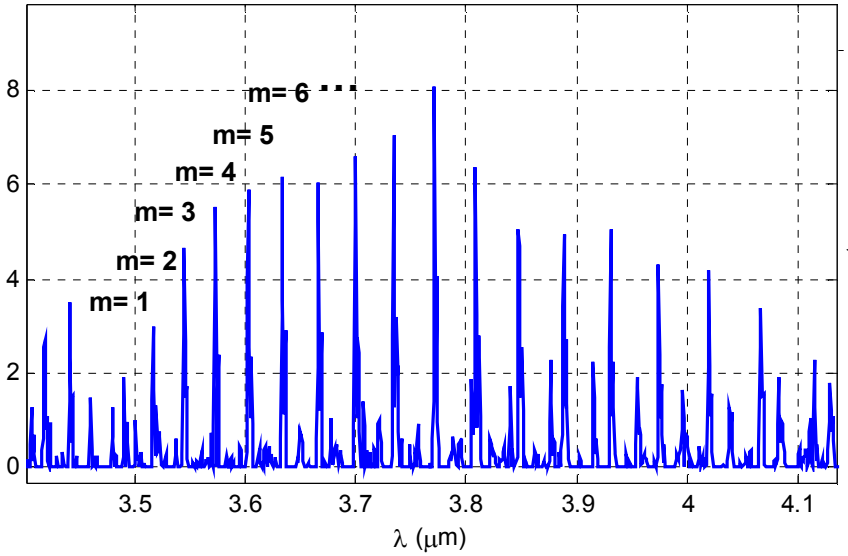


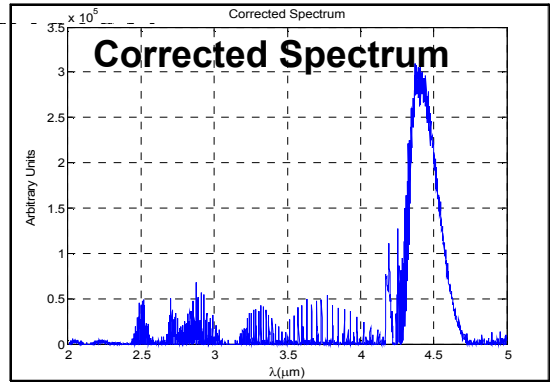
Recalculated Temperature

1- L. Zhang, L. Zhang, Y. Li, B. Liu, J. Wang, "Study of Combustion Properties of a Solid Propellant by Highly Time-Resolved Passive FTIR," Propellants, Explosives, Pyrotechnics 31,No . 5 (2006)

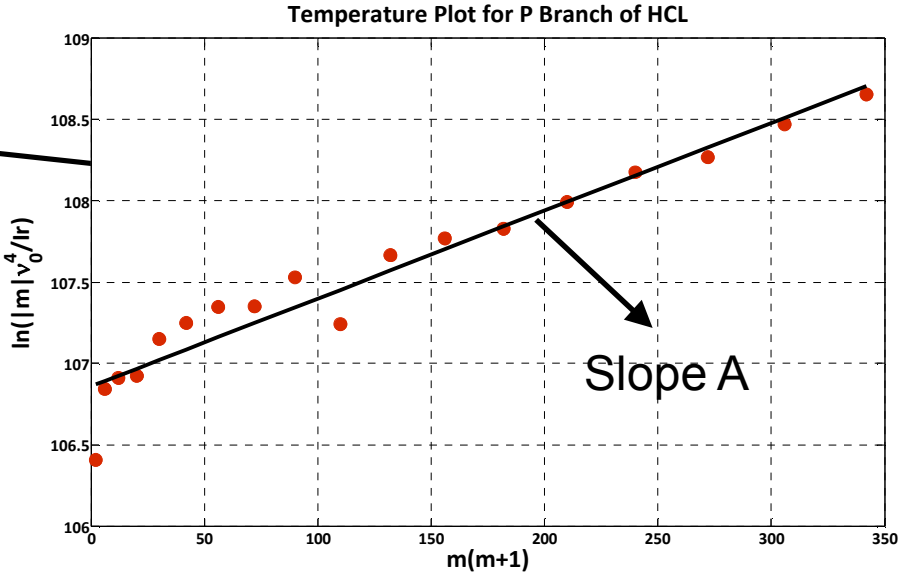
2- Flame Spectroscopy – ed. part II by H. Boiteux – Ch 21, John Wiley & Sons, Inc. (1965).

Basic Algorithm – Part 2





Linearize



Recalculated T
Use to
Calculate New
Blackbody T
Until ΔT is
Small

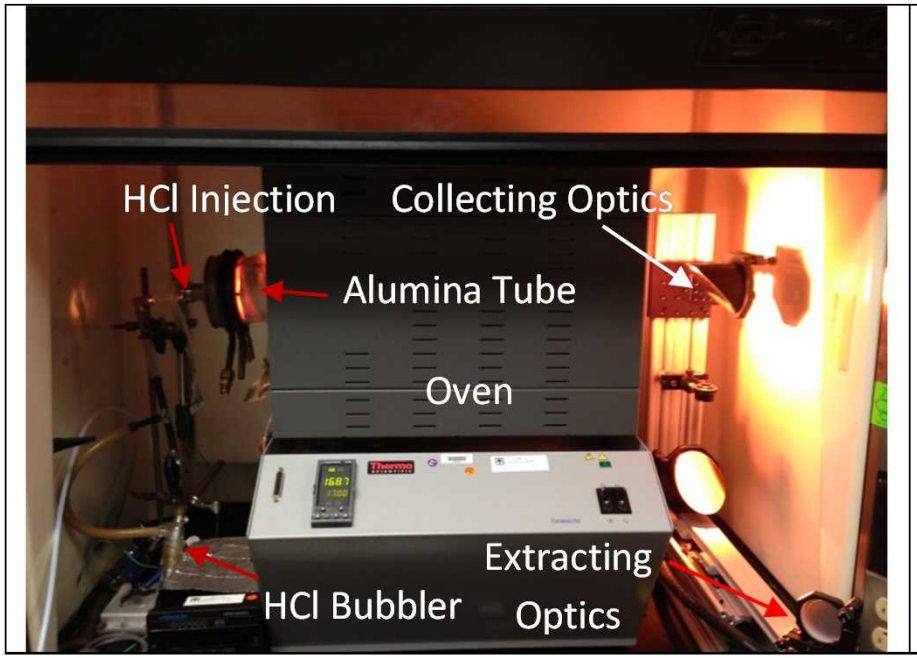
$$T = \frac{B_\vartheta hc}{kA}$$

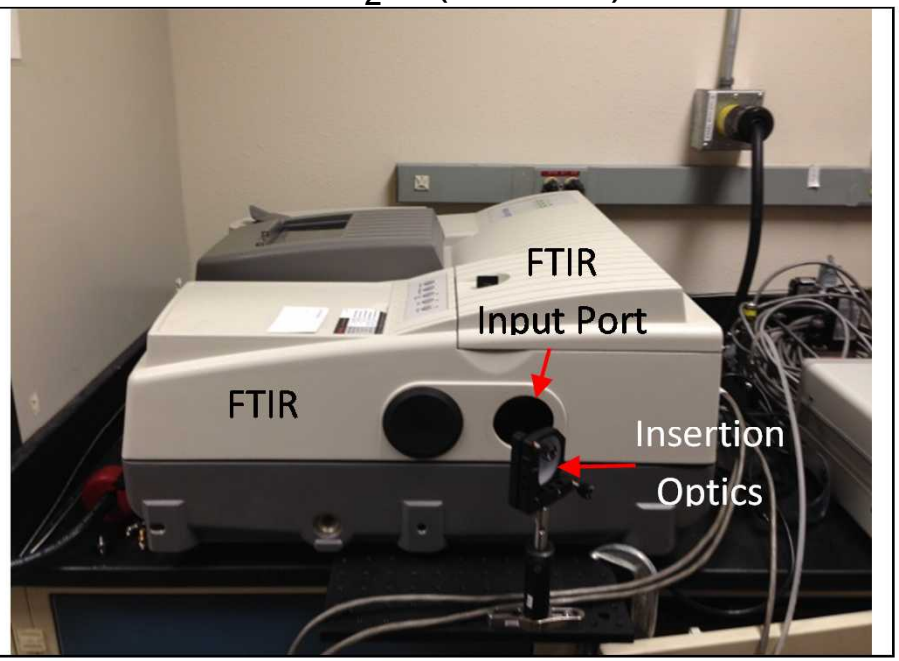
Report Temperature

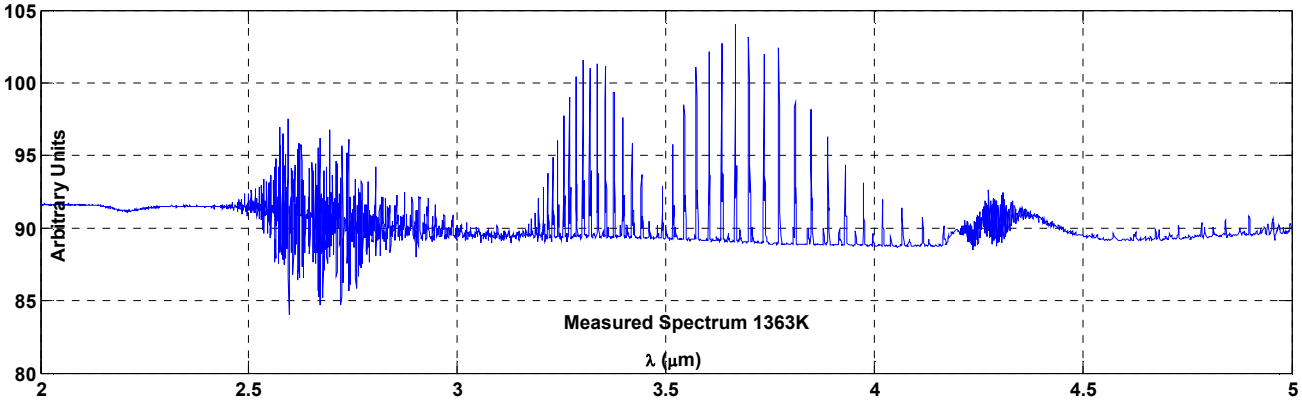
Laboratory Experiment - Calibration

Calibration Experiment Setup

Experiments were done at a laboratory where HCl was heated at well known temperatures. The measured spectrum contained HCl, H_2O (bubbler) and Ar

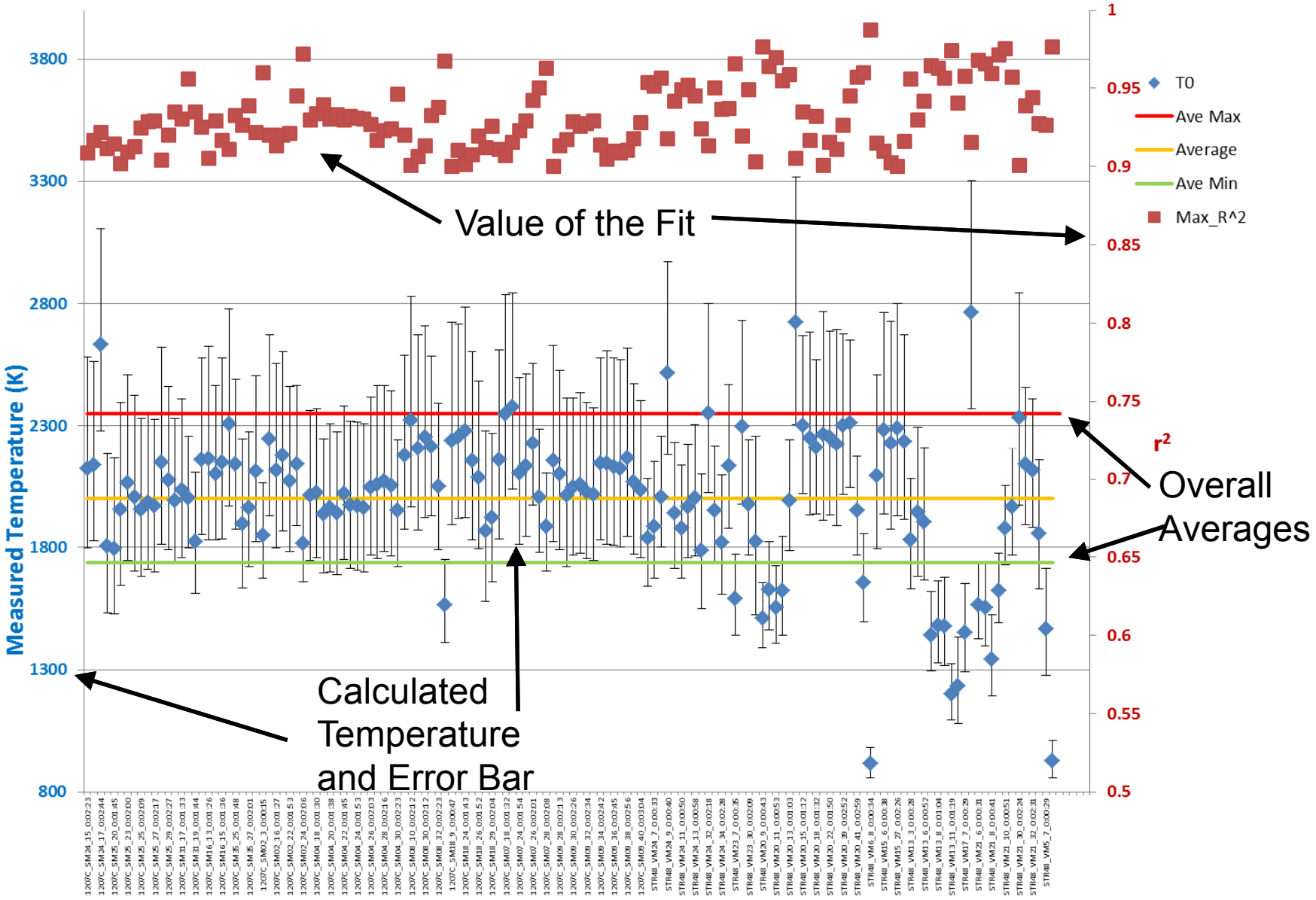




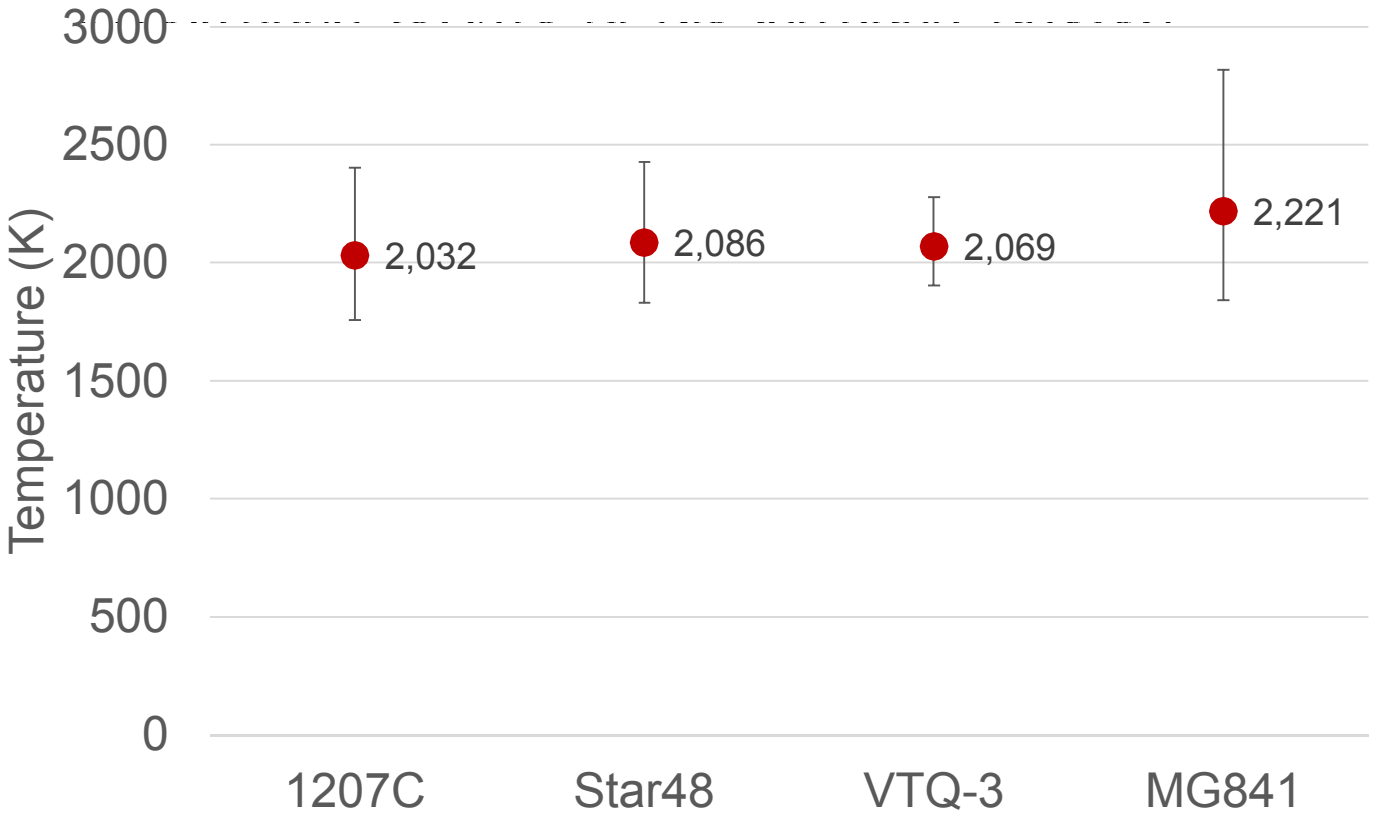


HCI Temperatures from SM and SV Tests

HCl Temperature for NASA Tests



HCl Temperatures for Large Tests

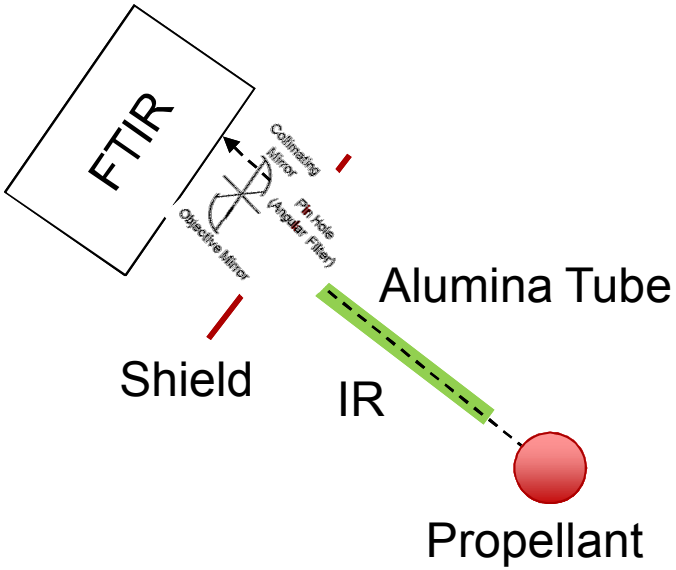


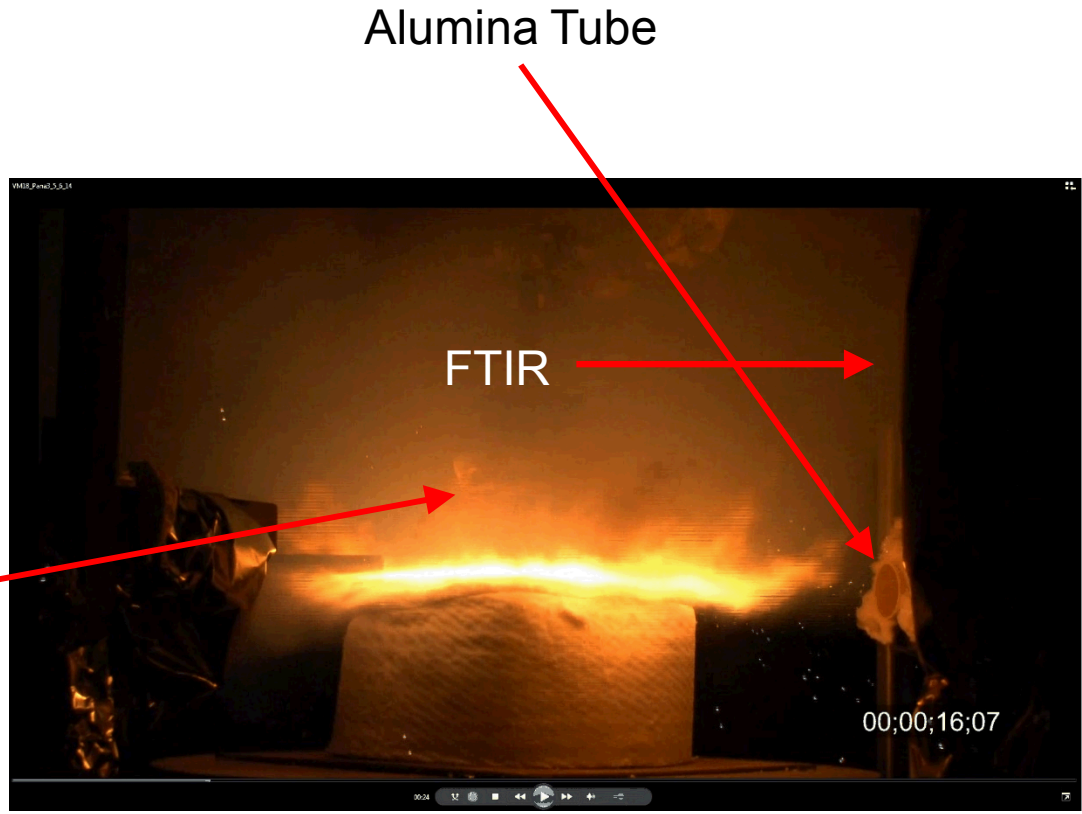
Propellants:

1207C: Aluminized AP - 12 Tests – 2 to 4 minutes duration
Star 48: Aluminized AP - 12 Tests – 2 to 4 minutes duration
VTQ-3: Aluminized AP – 3 Tests – 15 to 20 minutes duration
MG841: Non Aluminized AP – 4 Tests – 2 to 3 minutes duration

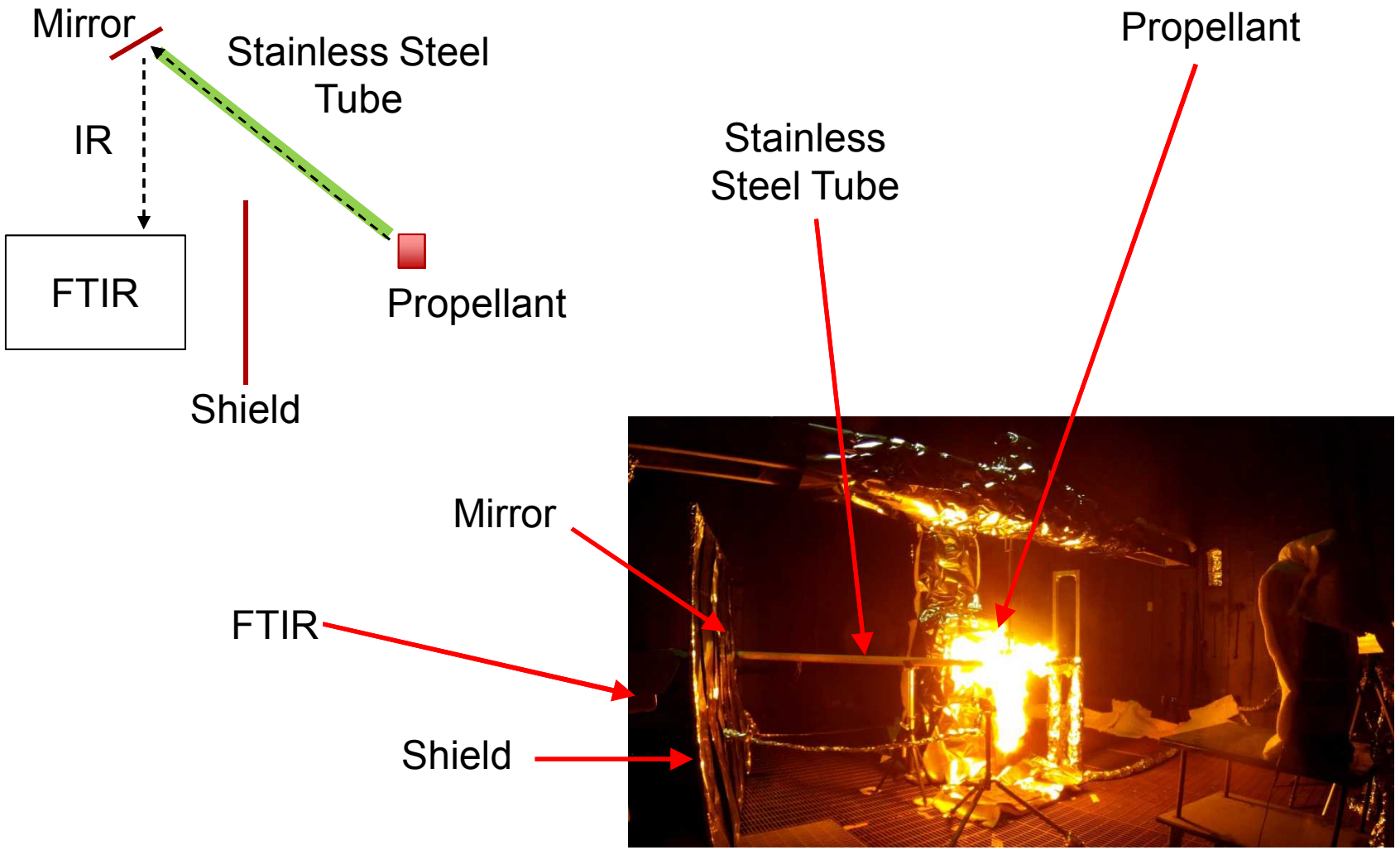
Closer to the Flame

Direct Sight With Alumina Tube

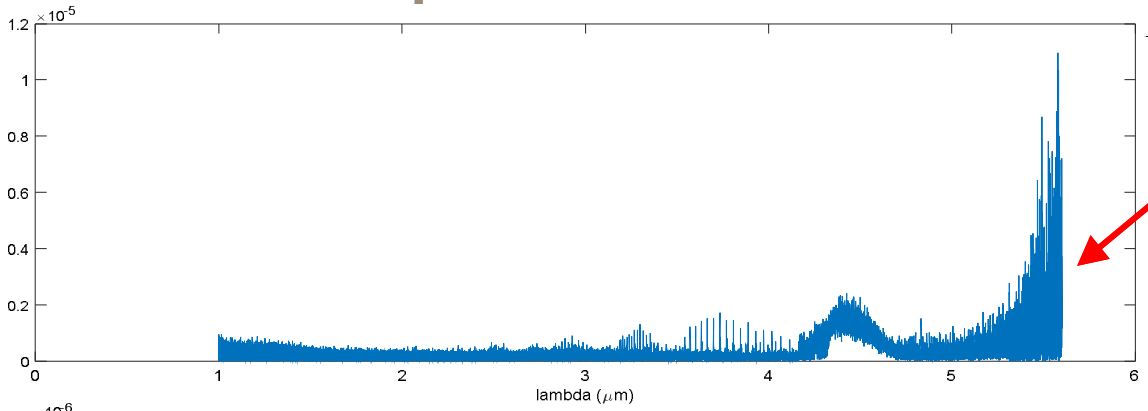




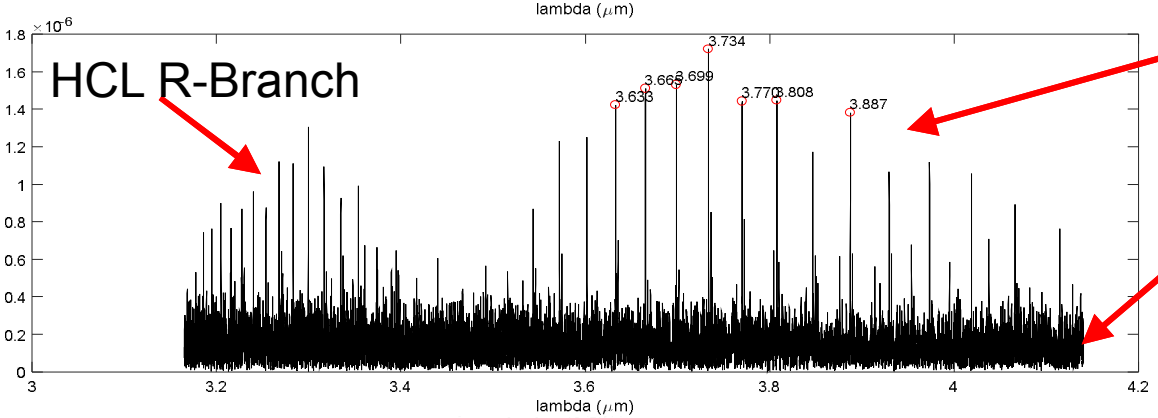
Indirect Sight With Steel Tube



IR-Fiber Spectrometer



Atlas Propellant Spectrum
1-5 μm



HCL R-Branch

HCL P-Branch

There is concern with SNR
by looking at the signal floor

Signal was gathered with an IR Fiber

Conclusions

- HCl (gas) temperature from the Star 48 verification tests were used in the convection model at the same time that AlO temperatures were used on the radiation model to get an overall temperature of 2650K.

- These results closes the loop on the overall model that includes the temperatures measured at the surface (region III) with the thermocouples.

- The 2650K is close to the vaporization temperature used in the radiological element used in the RTG, it is lower temperature than previous believed temperatures for these conditions.

- Similar tests were performed with other aluminized and non aluminized AP propellant with similar temperatures for HCl.

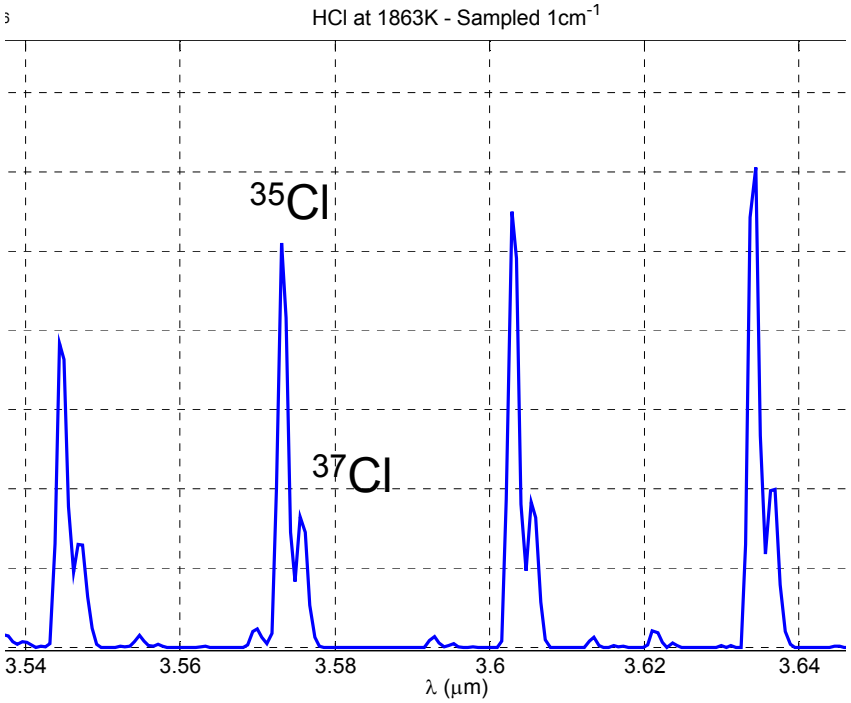
Thanks and Questions

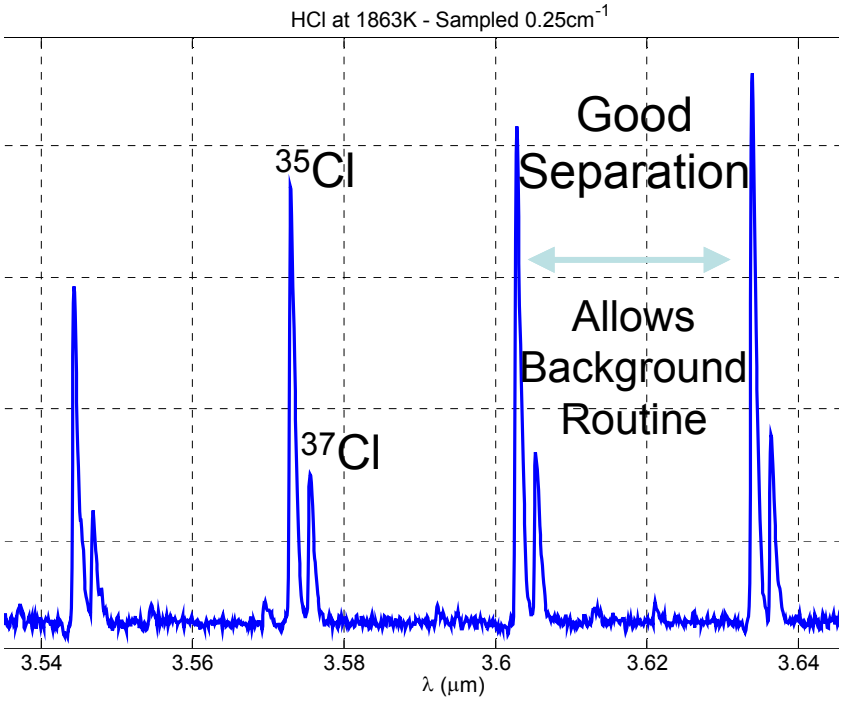
Thanks to
- Walt Gill (1532) for technical details on propellant burn
- Richard Simpson (01384) for the videos
- Edward Bystrom (01535)
- Michael Montoya (01535)

Back Up Slides

HCl Measurements: Isotopes

- The FTIR can pickup enough details at 1cm^{-1} resolution including the Chloride Isotopes
- Laboratory measurements at 0.25cm^{-1} shows that we can separate ^{35}Cl and ^{37}Cl

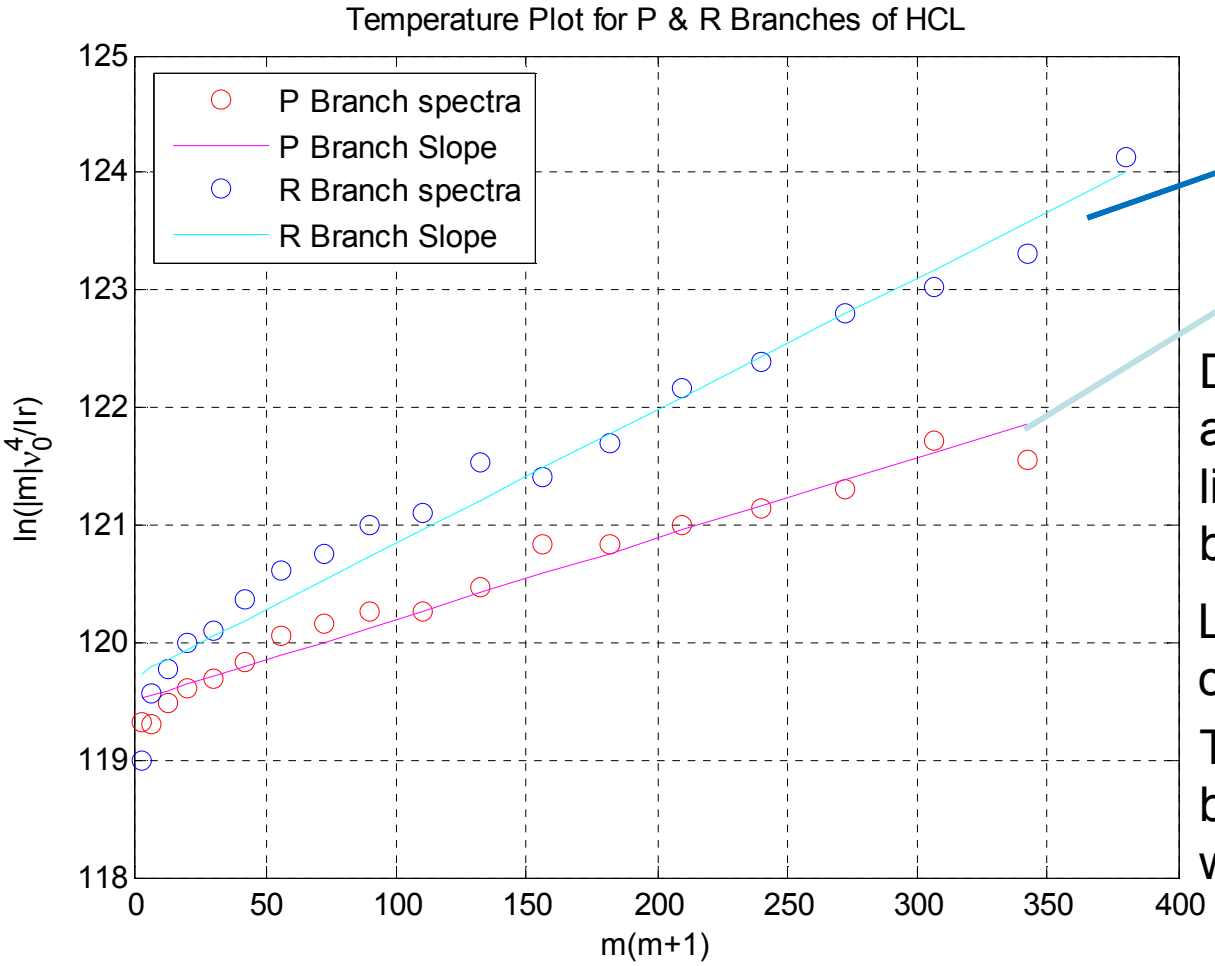




The 1cm^{-1} resolution was chosen as a compromise for resolution and measurement speed

P & R Branches Slopes

$$\ln\left(|m|\frac{\vartheta^4}{I_r}\right) = \frac{B_\vartheta hc}{kT} m(m+1) + b$$



$$T_R = \frac{B_\vartheta hc}{kA_R}$$

$$T_P = \frac{B_\vartheta hc}{kA_P}$$

Different efficiencies absorbing heat and emitting light between the P and R branches

Laboratory measurement correction applied

The P branch is used because R-branch overlaps with H2O spectra

Star 48 Temperatures