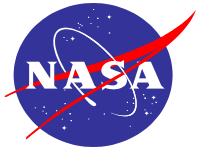


Hydrocarbon-Fueled Rocket Engine Plume Diagnostics: Analytical Developments & Experimental Results

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and

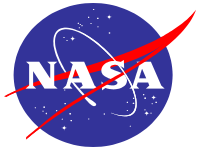
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Acknowledgments

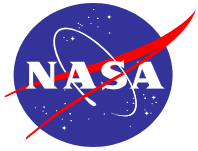
- RPTMBPO*
- John W. Bailey
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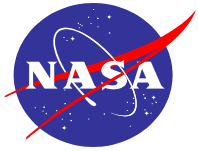
Outline

1. SSC Plume Diagnostics Background
2. Engine Health Monitoring Approach
3. Rocket Plume Spectroscopy Simulation Code
4. Spectral Simulation for 10 Atomic Species and for 11 Diatomic Molecular Electronic Bands
5. "Best" Lines for Plume Diagnostics for Hydrocarbon-Fueled Rocket Engines
6. Experimental Set Up for the Methane Thruster Test Program and Experimental Results
7. Summary and Recommendations



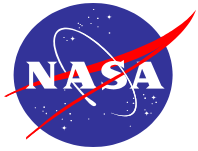
Background

- Plume Diagnostics has Unique Capabilities for the Engine Health Monitoring
 - Non-Intrusive
 - Remote Sensing
 - Extremely Sensitive
 - Highly Specific in Many Cases
 - Precursive
- Successful Application to the Space Shuttle Main Engine (SSME) Testing Program at SSC since 1989
 - High-Temperature Emission in the Mach Diamond Regions
 - Quantification of Atomic Species by using a Spectral Simulation Code
 - Identification of Effluent Materials by the Engine Diagnostics Control (EDC)
- Particularly Useful in the Alternate Turbopump Development (ATD) for High Pressure Fuel Turbopump (HPFTP) and High Pressure Oxidizer Turbopump (HPOTP)
- Numerous Successful Identifications of SSME Alloys in the Plume by the EDC. Many Quantification Results Validated
- Presence of CO₂, C₂, CH, CO, CN, and NO in addition to OH and H₂O in the Hydrocarbon-Fueled Rocket Engines



Engine Health Monitoring Approach

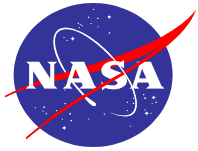
- Very Wide Spectral Range Coverage
 - High Resolution: 300 to 430 nm (for Ni, Cr, Fe, Mn, Co, Ag, Cu, Al, Ca, and Pd)
 - Low Resolution: 300 to 820 nm (Oxides, Hydrides and Hydroxides)
- Identify Metallic Elemental Species in the Plume
- Quantify Elemental Plume Contaminants
- Identify and Quantify the Alloy Combination on the Basis of Elemental Concentrations
- Most Probable Hardware Sources for Effluent Material(s)



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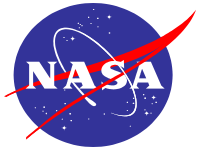
Spectral Simulation Code for Hydrocarbon-Fueled Engine Plumes

- Rocket Plume Spectral Simulation Code (RPSSC) is Based on SSC Line-by-Line (LBL) Code which itself is Based on NASA Ames LBL Code
- Voigt Line Profile
- Convolution with an Entrance Slit Function
- Optically Thin or Optically Thick Environment
- Non-Uniform Wavelength Computation Interval
- Multiple Layer Scheme for Radiance Computations
- All Significant Atomic Transitions for Ten SSME Elements: Ni, Cr, Fe, Co, Mn, Ag, Cu, Pd, Al, and Ca
- Eleven Electronic Band Systems for Six Diatomic Molecules



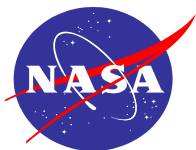
Rocket Plume Spectral Simulation Code

- Six Diatomic Species: OH, CH, C₂, CO, CN, and NO
- Eleven Electronic Band Systems (300 to 850 nm)
 - OH 3064 Å Band System
 - C₂ Swan Band System
 - CH 3900 Å Band System
 - CH 4300 Å Band System
 - CN Violet Band System
 - CO⁺ Comet-Tail Band System
 - CN Red Band System
 - C₂ Phillips Band System
 - CO Asundi Band System
 - NO Beta Band System
 - NO Gamma Band System



Atomic Emission Line Parameters

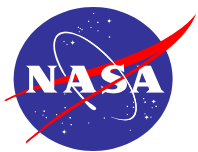
1. Doppler Broadened Linewidth at Half-Height
2. Pressure Broadened Linewidth at Half-Height
3. Electronic Multiplicity of the Upper State
4. Electronic Term Energy of the Upper State
5. Einstein Transition Probability Coefficient
6. Atomic Line Center



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Table 1. Molecular and Spectroscopic Parameters for C₂ Swan Band System

	Line Alternation Factor		Nuclear Spin for Homonuclear Molecules		Number of Electronic Levels		Reduced Mass in Atomic Weight Units	
	0.		0.0		10		6.00000000	
	Spin Coupling Constant	Electronic Angular Momentum Quantum Number	Rotational Constant, D _e (cm ⁻¹)	Rotational Constant, β _e (cm ⁻¹)	Dissociation Energy, D ₀ (cm ⁻¹)	Internuclear Distance at Equilibrium Position, r _e (cm)		
Upper State	-16.90	1	6.74x10 ⁻⁶	0.103x10 ⁻⁶	2.95x10 ⁴	1.2661x10 ⁻⁸		
Lower State	-16.40	1	6.44x10 ⁻⁶	0.0	4.89x10 ⁴	1.3119x10 ⁻⁸		
	Electronic Degeneracy	Electronic Term Energy (cm ⁻¹)	Vibrational Spectroscopic Constant, ω _e (cm ⁻¹)	Vibrational Spectroscopic Constant, ω _e x _e (cm ⁻¹)	Vibrational Spectroscopic Constant, ω _e y _e (cm ⁻¹)	Vibrational Spectroscopic Constant, ω _e z _e (cm ⁻¹)	Rotational Constant, B _e (cm ⁻¹)	Rotational Constant, α _e (cm ⁻¹)
Upper State	6	2.00225x10 ⁴	1788.22	16.440	-0.5067	0.0	1.7527	0.01608
Lower State	6	716.24	1641.35	11.67	0.0	0.0	1.63246	0.01661
	1	5.50347x10 ⁴	1671.50	40.02	0.248	0.0	1.7897	0.0387
	1	4.323944x10 ⁴	1829.57	13.94	0.0	0.0	1.8332	0.0196
	6	4.079665x10 ⁴	1106.56	39.260	2.8050	-0.1271	1.1922	0.0242
	2	3.42613x10 ⁴	1809.1	15.81	-4.02	0.0	1.7834	0.0180
	3	1.33121x10 ⁴	1961.6	13.7	0.0	0.0	1.87	0.0
	2	8391.00	1608.35	12.078	-0.01	0.0	1.61634	0.01686
	3	6434.27	1470.45	11.19	0.028	0.0	1.49852	0.01634
	1	0.0	1854.71	13.34	-0.172	0.0	1.81984	0.01765



Computational Results

- RP-1 Combustion at O/F Ratio of 2.0
- 3000 K
- 1 atm
- 10 cm Pathlength
- 300 to 430 nm for Atomic Emission

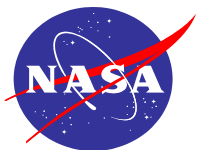
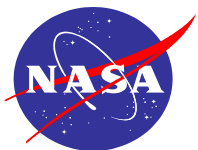


Table 2. Assumed Free Atomic Number Density for Atomic Species

Element	Free Atomic Number Density (in free atoms/cm³)
Ni	5.0×10^{12}
Fe	1.0×10^{12}
Cr	2.0×10^{11}
Co	1.0×10^{13}
Mn	2.0×10^{11}
Cu	1.0×10^{12}
Ag	1.0×10^{12}
Pd	1.0×10^{12}
Al	1.0×10^{12}
Ca	1.0×10^{10}



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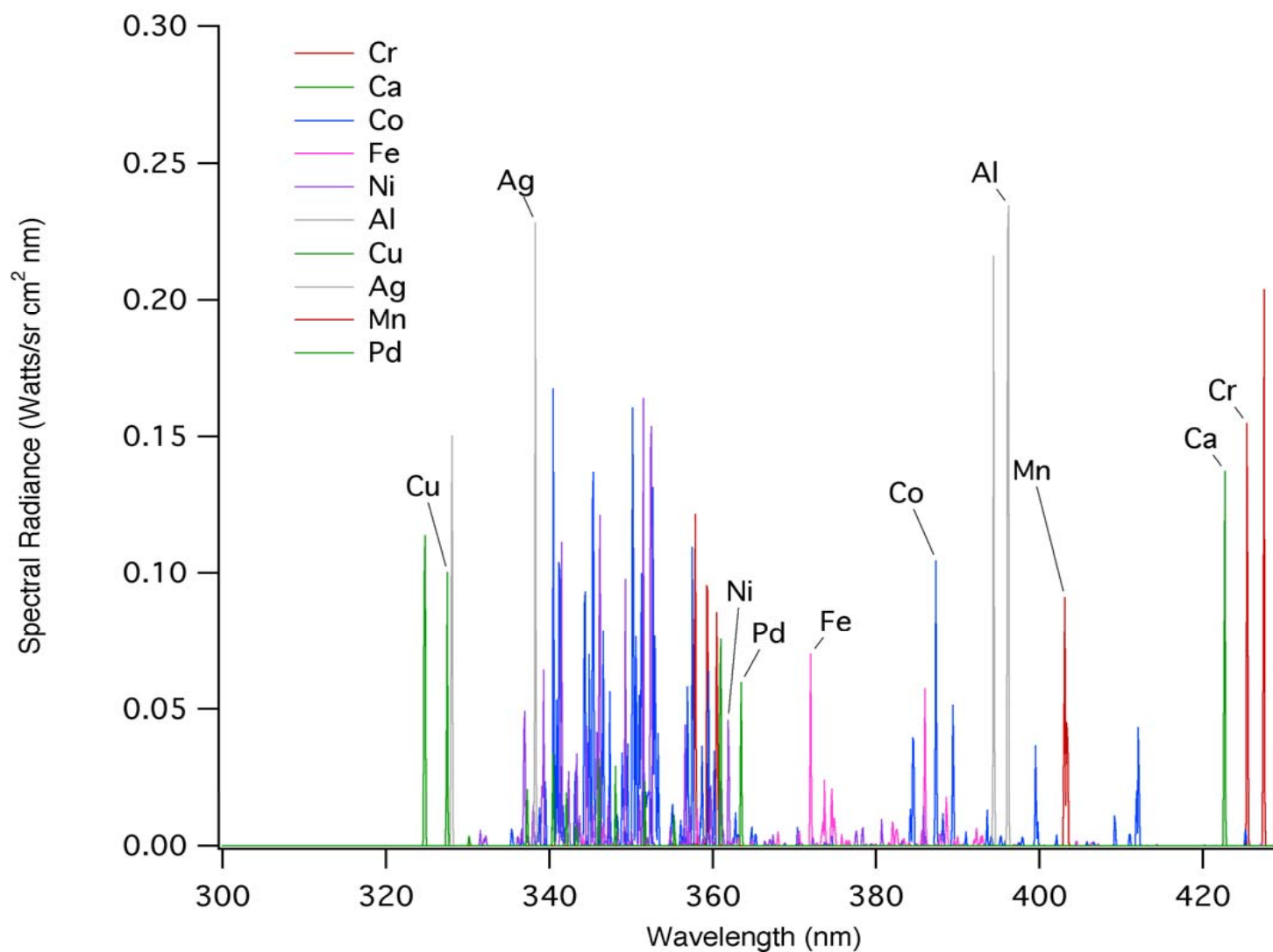
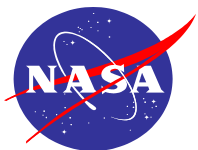
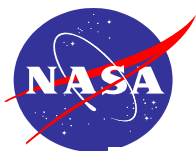


Figure 1. Computed Spectrum for Ni, Fe, Cr, Co, Al, Mn, Cu, Ca, Ag, and Pd at 3000 K for 10 cm Pathlength, 300.0 to 430.0 nm. Tagged Lines for All Ten Elements Correspond to the SSME EDC.



C₂ Swan Band System

- Present in All Hydrocarbon Combustion
- Bands Included: (0,0), (0,1), (0,2), (1,0), (1,1), (1,2), (1,3), (2,0), (2,1), (2,2), (2,3), (2,4), (3,1), (3,2), (3,3), (3,4), (3,5), (4,2), (4,3), (4,4), (4,5), (5,3), (5,4), (6,4), (6,5), (7,5), (7,6), (8,6), and (8,7)
- Spectral Emission Range: 422.9 to 619.7 nm
- Affected Elements/Lines: Cr (425.43, 427.48, and 428.97 nm)



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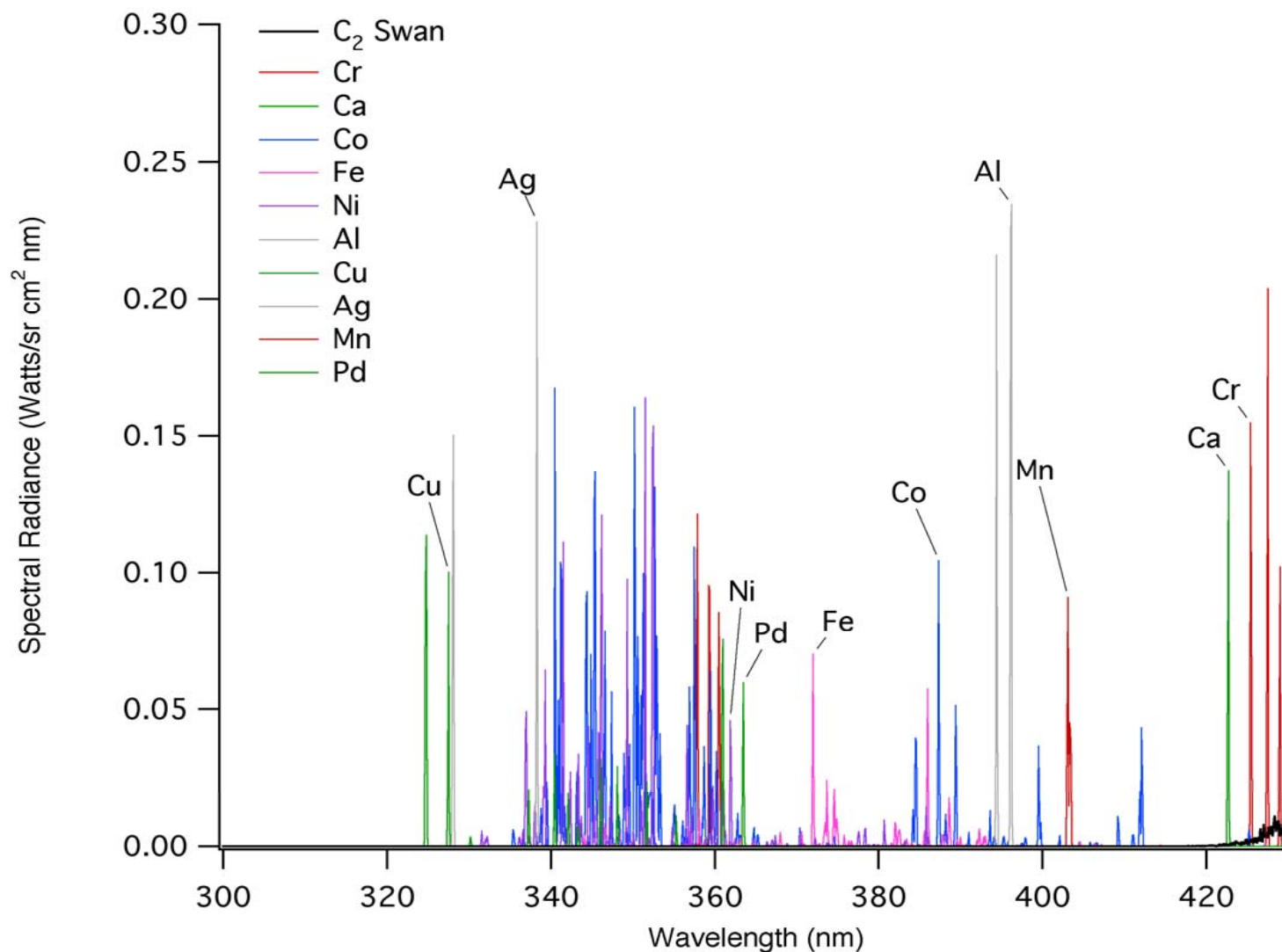
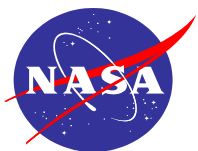


Figure 2. Computed Spectrum for Ni, Fe, Cr, Co, Al, Mn, Cu, Ca, Ag, Pd and C₂ Swan Band System at 3000 K for 10 cm Pathlength, 300.0 to 430.0 nm. C₂ Concentration in the Plume is 1×10^{14} Molecules/cm³.



CH 3900 Å Band System

- Common Intermediate Radical
- Bands Included: (0,0), (0,1), (0,2), (1,0), (1,1), (1,2), (1,3), (2,0), (2,1), (2,2), (2,3), (3,0), (3,1), (3,2), (3,3), (4,1), (4,2), and (4,3)
- Spectral Emission Range: 346.1 to 540.5 nm
- Strongest Emission: 386.6 to 413.4 nm
- Affected Elements/Lines: Al (394.40 and 396.15 nm)
Mn (403.08, 403.31, and 403.45 nm)
Ca (422.67 nm)
Co (387.31 nm)

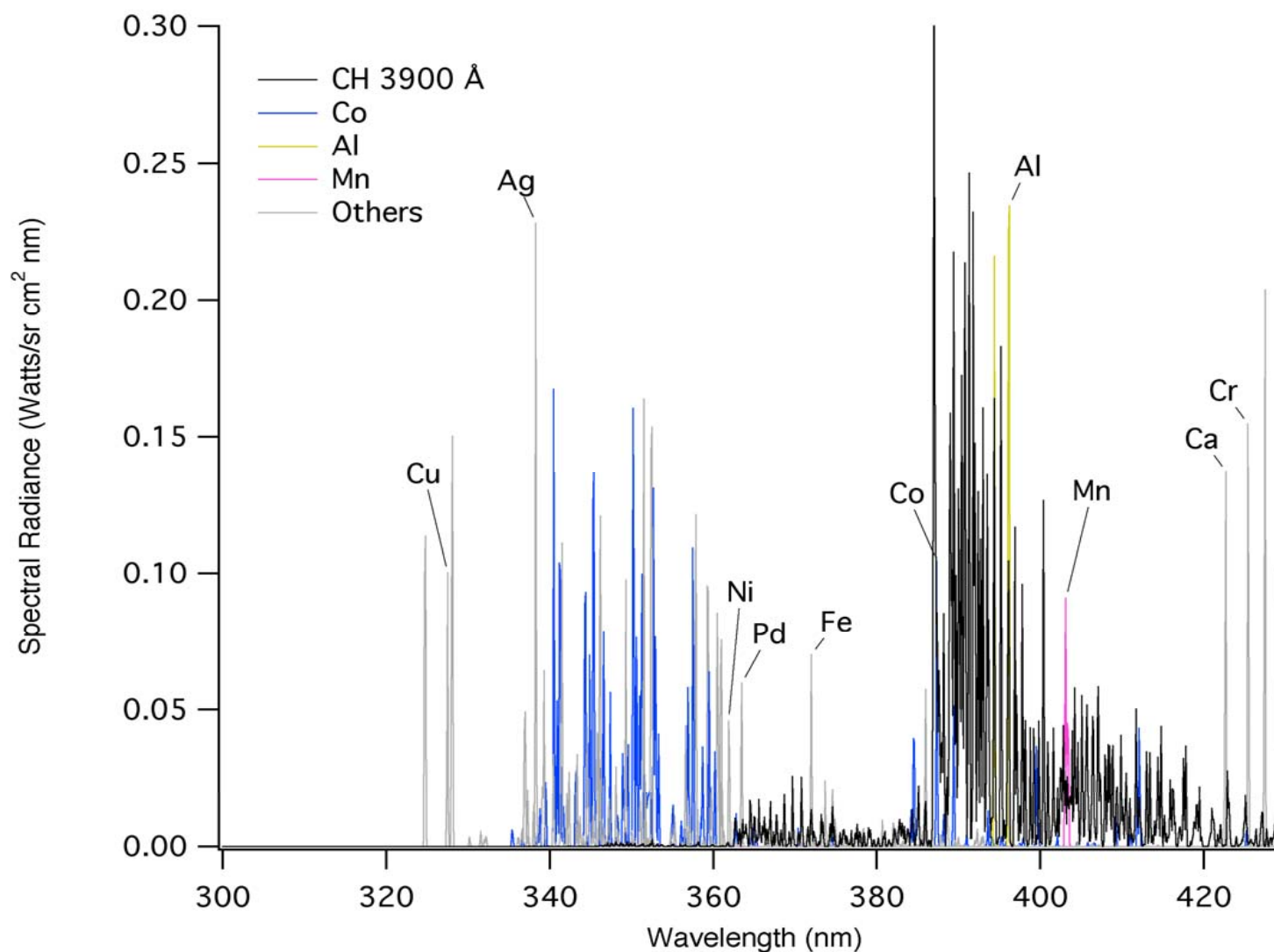
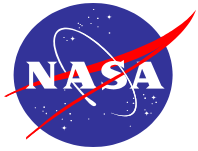


Figure 3. Computed Spectrum for Ni, Fe, Cr, Co, Al, Mn, Cu, Ca, Ag, Pd, and CH 3900 Å Band System at 3000 K for 10 cm Pathlength, 300.0 to 430.0 nm. CH Concentration in the Plume is 5×10^{14} Molecules/cm³.



CH 4300 Å Band System

- Bands Included: (0,0), (0,1), (0,2), (1,0), (1,1), (1,2), (1,3), (2,0), (2,1), (2,2), (2,3), (2,4), (3,1), (3,2), (3,3), (4,2), (4,4), (4,5), (5,3), (5,4), and (5,5)
- Spectral Emission Range: 409.2 to 453.6 nm at 3000 K
- Strongest Emission: 420 to 440 nm
- Affected Elements/Lines: Cr (425.43, 427.48, and 428.97 nm)

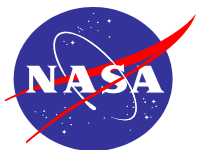
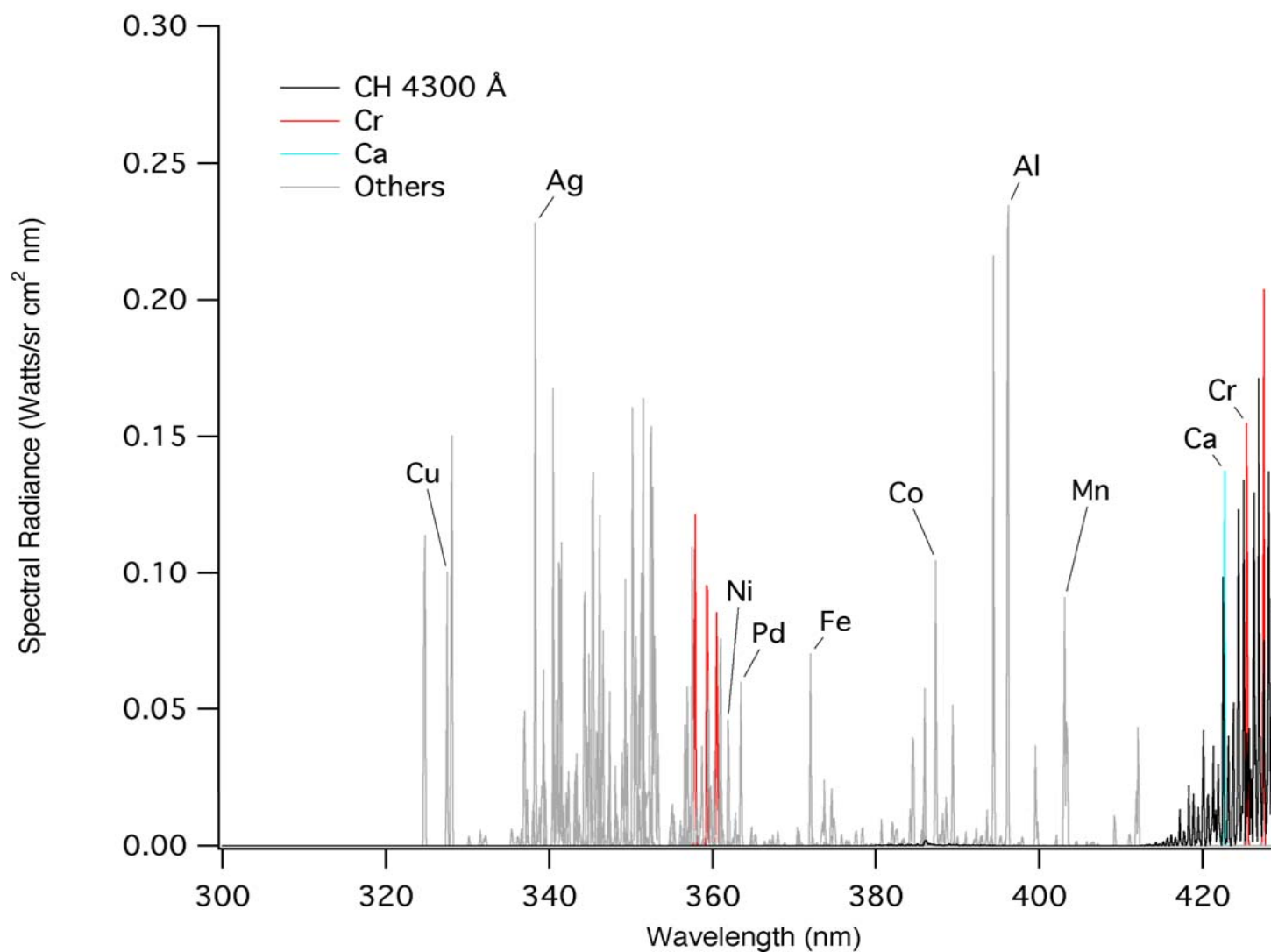
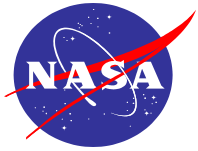
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Figure 4. Computed Spectrum for Ni, Fe, Cr, Co, Al, Mn, Cu, Ca, Ag, Pd, and CH 4300 Å Band System at 3000 K for 10 cm Pathlength, 300.0 to 430.0 nm. CH Concentration in the Plume is 1×10^{14} Molecules/cm³.



CN Violet Band System

- Free Radical in Mixing Layer
- Bands Included: (0,0), (0,1), (0,2), (0,3), (1,0), (1,1), (1,3), (2,1), (2,2), (2,3), (2,4), (3,1), (3,2), (3,3), (3,4), (3,5), (4,3), (4,4), (4,5), (4,6), (5,4), (5,5), and (5,6)
- Spectral Emission Range: 350.9 to 358.7 nm
373.9 to 388.0 nm
406.1 to 421.1 nm
- Strongest Emission: 380 to 388 nm
- Affect Elements/Lines: Co (387.31 nm)



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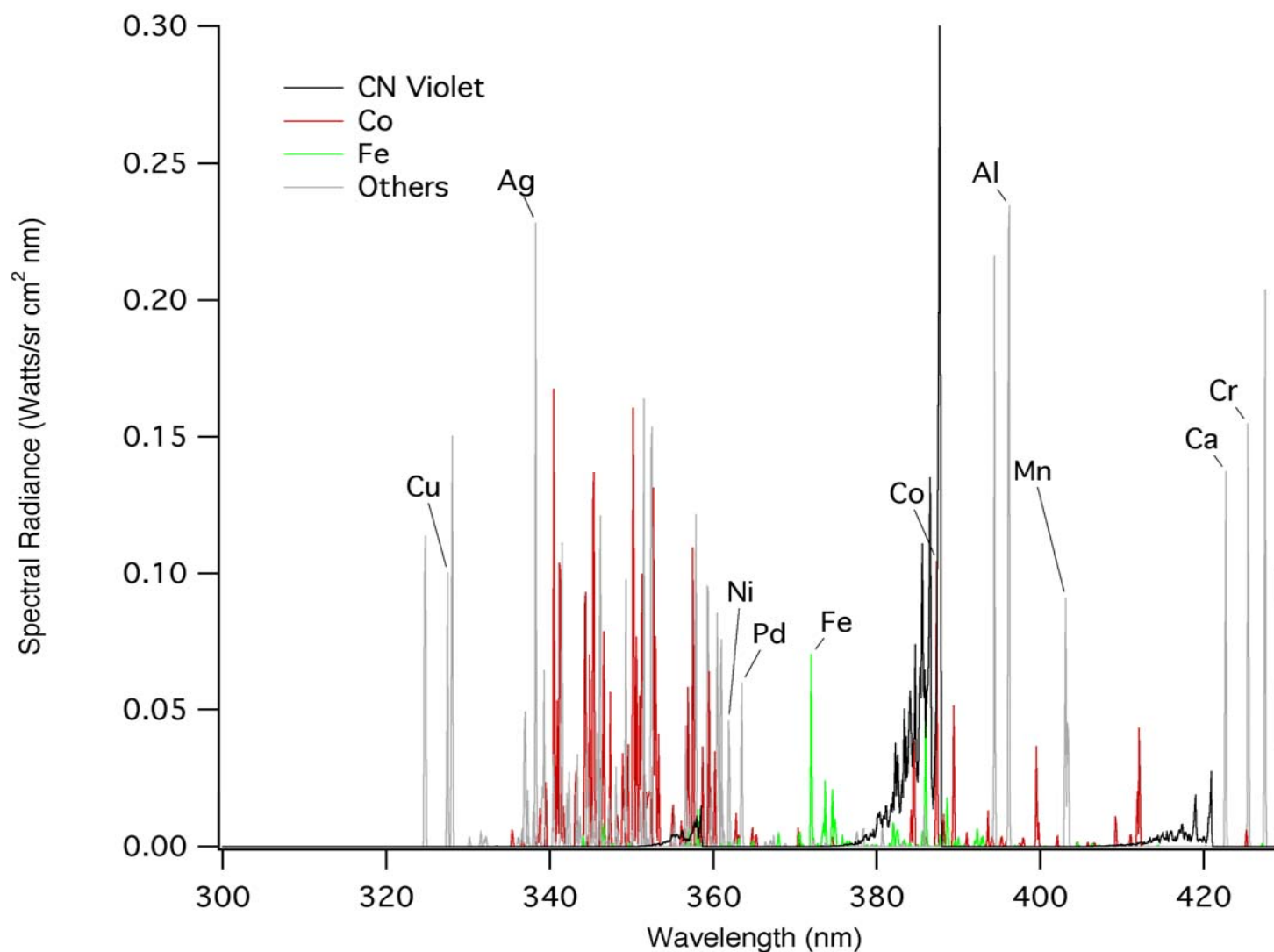
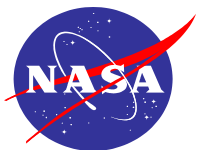
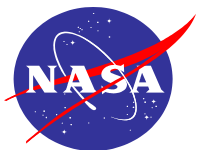


Figure 5. Computed Spectrum for Ni, Fe, Cr, Co, Al, Mn, Cu, Ca, Ag, Pd, and CN Violet Band System at 3000 K for 10 cm Pathlength, 300.0 to 430.0 nm. CN Concentration in the Plume is 2×10^{13} Molecules/cm³.



CO+ Comet-Tail Band System

- Product of Incomplete Combustion
- Bands Included: (0,0), (0,1), (0,2), (0,3), (0,4), (0,5), (1,0), (1,1), (1,2), (1,3), (1,4), (1,5), (2,0), (2,1), (2,2), (3,0), (3,1), (3,2), (3,3), (4,0), (4,1), (4,2), (5,0), (5,1), (5,2), (6,0), (6,1), and (7,1)
- Spectral Emission Range: 341.2 to 802.4 nm
- Strongest Emission: 400 to 430 nm
- Affected Elements/Lines: Mn (403.08, 403.31, and 403.45 nm)
Ca (422.67 nm)
Cr (425.43, 427.48, and 428.97 nm)



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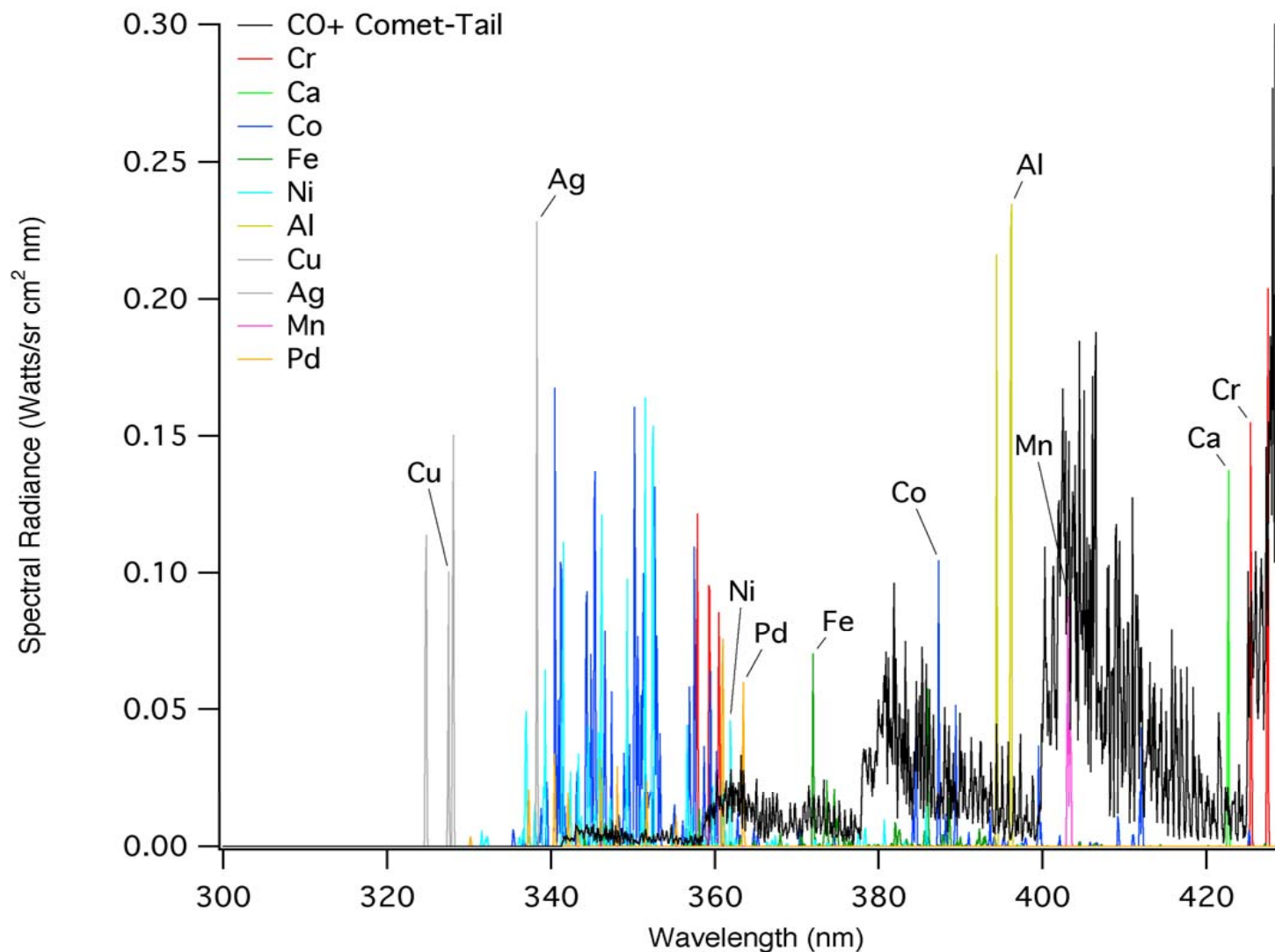
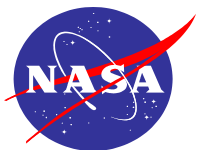
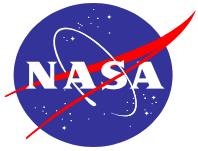


Figure 6. Computed Spectrum for Ni, Fe, Cr, Co, Al, Mn, Cu, Ca, Ag, Pd, and CO+ Comet-Tail Band System at 3000 K for 10 cm Pathlength, 300.0 to 430.0 nm. CO+ Concentration in the Plume is 4×10^{15} Molecules/cm³.



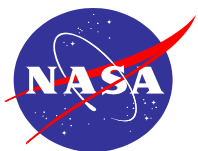
“Best” Atomic Lines for the Engine Health Monitoring

Element	Wavelength (nm)
Cu	327.40
Ag	338.29
Co	350.23
Ni	361.94
Pd	363.47
Fe	371.99
Al	396.15
Mn	403.08
Ca	422.67
Cr	425.43



Methane Thruster Test Program (MTTP) Features

- 50 lb Thrust Gaseous Oxygen/Gaseous Methane Thruster
- MTTP Operational since March 2006
- Spectral Instrumentation: High-Resolution OMA System, 310-436 nm
Broadband Spectrometer, 300-825 nm
- Optical System Details in the Paper
- O/F Ratio of 2.0 and 2.5 for Fuel-Rich Combustion



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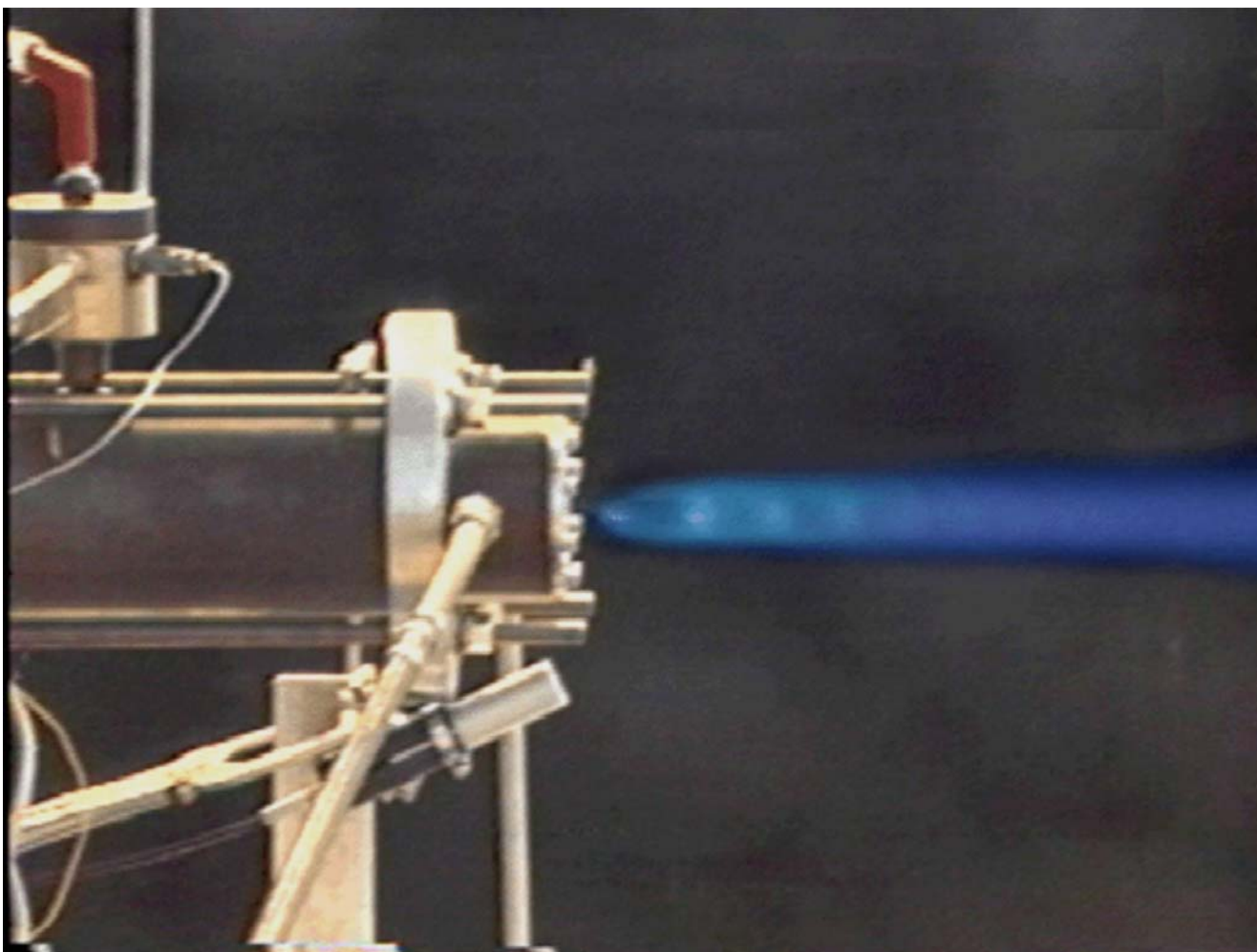


Figure 7. 50 lb Thrust Gaseous Oxygen/Gaseous Methane Thruster

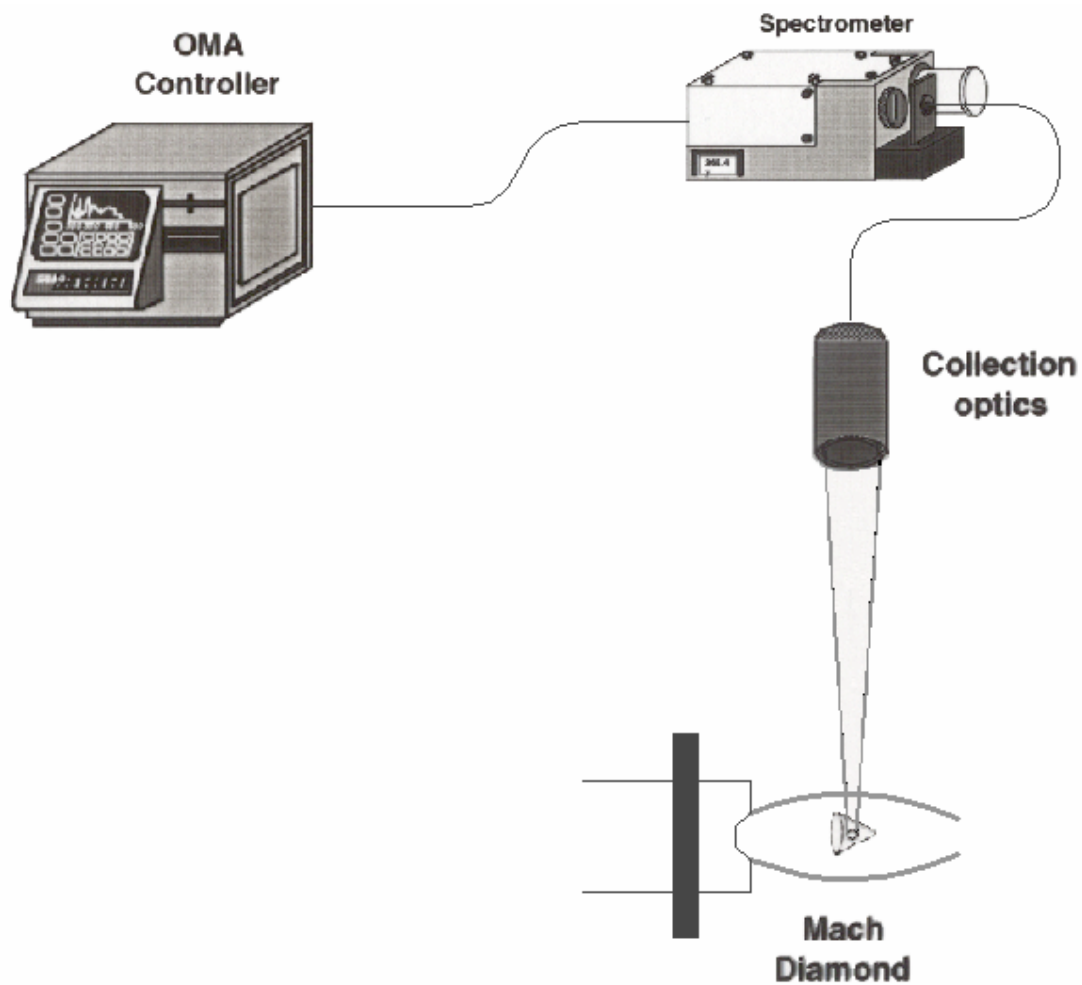


Figure 8. Atomic Emission Spectroscopic System Configuration

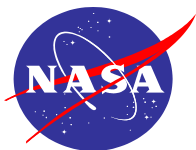
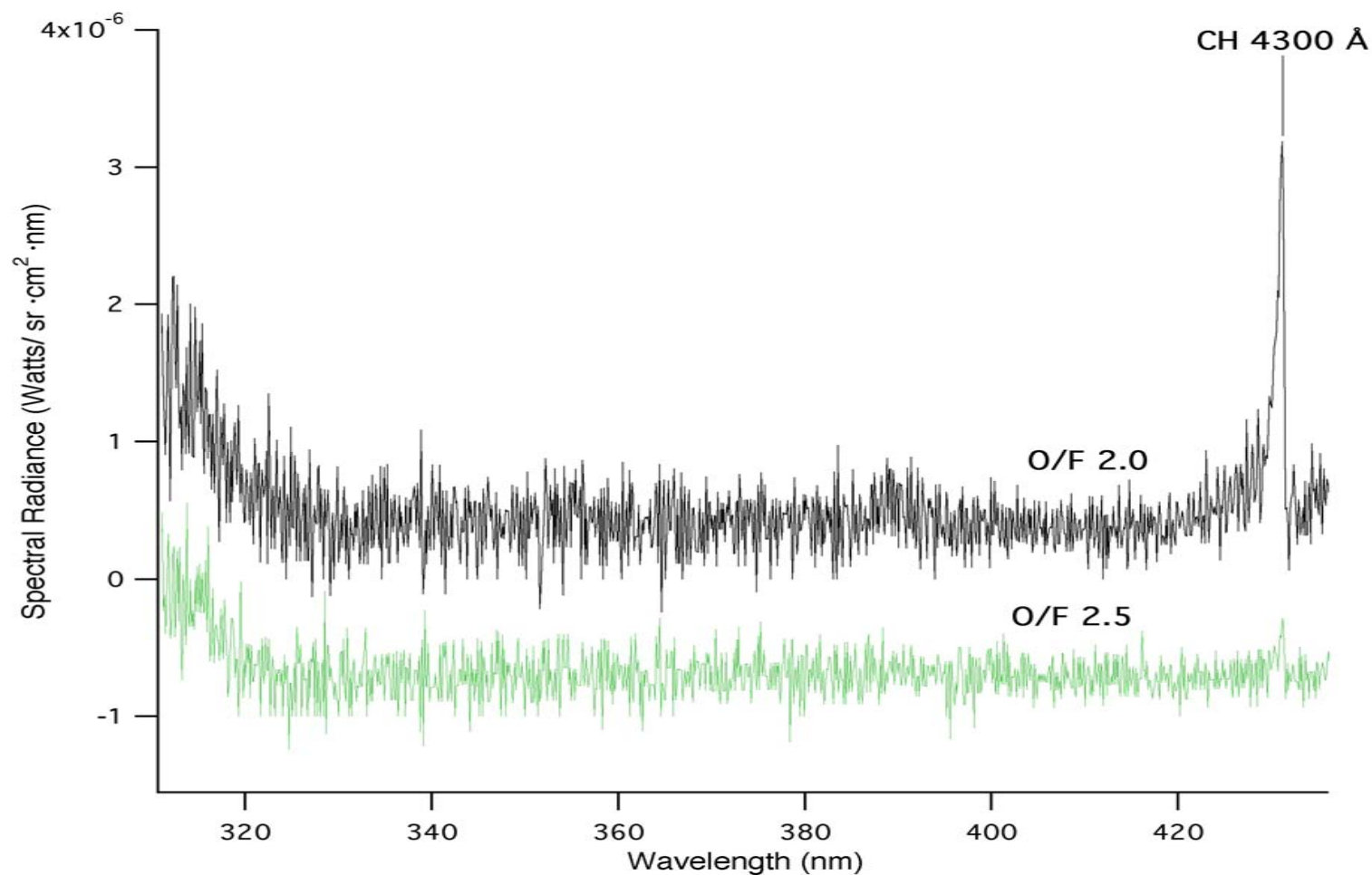
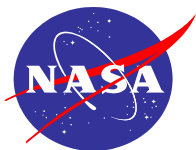
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Figure 9. High Resolution Spectra from Tests A and B showing CH 4300 Å Band System Emissions at O/F Ratios of 2.0 and 2.5, Respectively. Note the Weaker Signature of CH 3900 Å Band System Discernable for Test A in O/F 2.0 Spectra.



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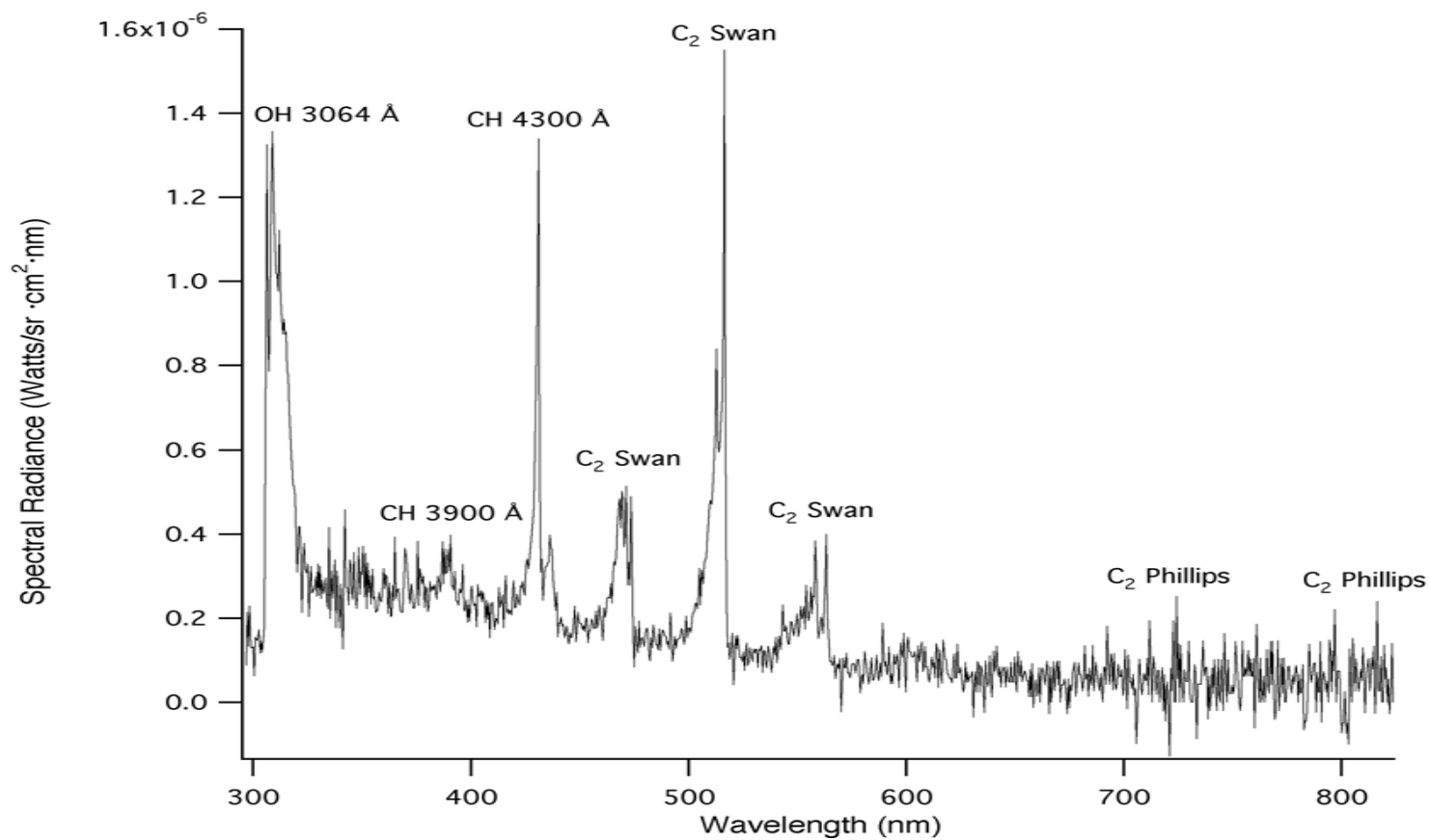
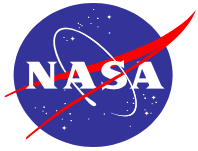


Figure 10. Broadband Spectra from Test A Displaying the Emission Band Systems of OH 3064 Å, CH 3900 Å, CH 4300 Å, C₂ Swan and C₂ Phillips.



Summary and Recommendations

1. RPSSC is Complete for Hydrocarbon Fuels
2. Tentative “Best” Lines for the Engine Health Monitoring for Fe, Ni, Cr, Co, Mn, Ag, Cu, Pd, Al, and Ca
3. MTTP is Operational
4. Future Work
 - a. Detection Sensitivity Limits
 - b. Broadband Spectral Region with all 11 Electronic Bands for Y and Ti Monitoring
 - c. MTTP Measurements with Metallic Dopants in the Combustion Chamber
 - d. Free Atomic Factor for the 10 Elements in the CH₄ and RP-1 Engine Exhaust Plume