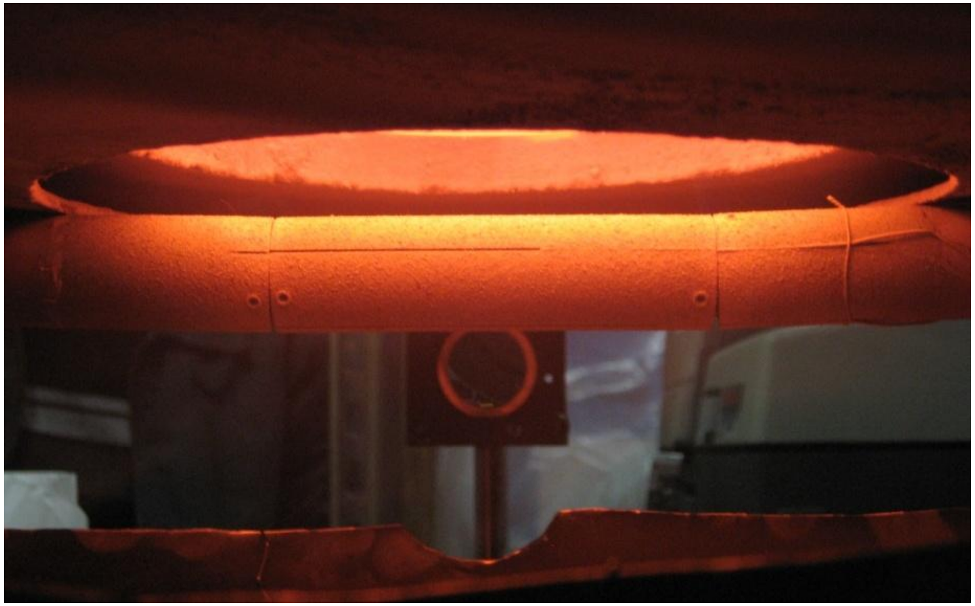
In Situ Measurement of the Spectral Emittance of Coal Ash Deposits

T. J. Moore, D. P. Cundick, M. R. Jones, D. R. Tree,

R. D. Maynes and L. L. Baxter



Coal as an Energy Source

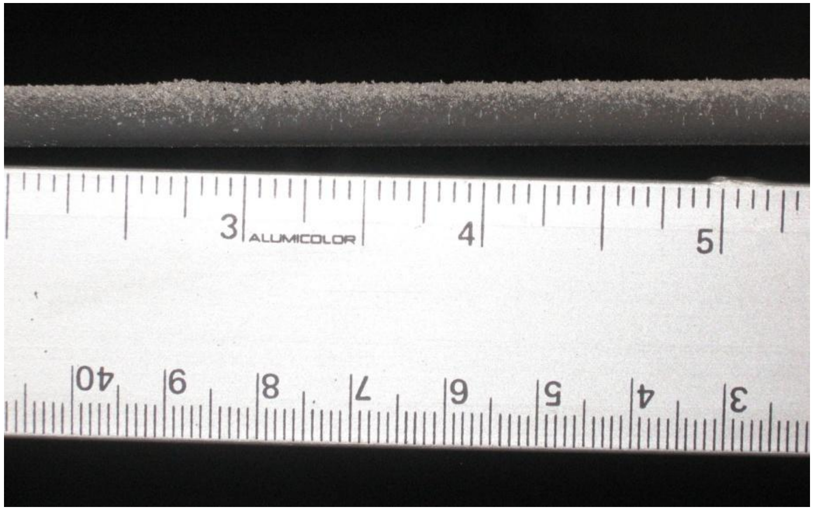
- The United States has more high quality coal than any country in the world (reserves to last 250 years)
- Presently, coal is used to power 57% of U.S. electrical generation
- By 2030, coal will account for 48% of the world’s electrical power

Pollutants from Coal-Fired Power Plants

- **Sulfur Dioxide**: causes acid rain
- **Unburned Hydrocarbons**: produces smog
- **Mercury**: contaminates rivers and lakes
- **Carbon Dioxide**: On April 17, 2009 the EPA announced that CO_2 may endanger public health or welfare.

Ash Deposits

In a coal fired reactor, ash is formed and accumulates on the walls of the combustion chamber. This deposited ash can significantly affect the thermal transport in the boiler.



(Zbogar et al)

Objectives

- Develop an experimental procedure to make accurate, *in situ* measurements of the emittance of the deposited ash.

- Measure the spectral and total emittance of ash deposits from both bituminous and subbituminous coals formed under oxidizing conditions.

Spectral Emittance of an Ash Layer

The spectral emittance of an object is defined as the ratio of the spectral emissive power of the object to the black body spectral emissive power at the object temperature.

$$\varepsilon_{\bar{\nu}}(\bar{\nu},T_s) \equiv \frac{E_{\bar{\nu}}(\bar{\nu},T_s)}{E_{b,\bar{\nu}}(\bar{\nu},T_s)}$$

The black body spectral emissive power can be calculated for any temperature using the Planck Function:

$$E_{b,\bar{\nu}}(\bar{\nu},T_s) = \frac{\pi\alpha_1\bar{\nu}^3}{\exp(\alpha_2\bar{\nu}/T_s)-1}$$

Spectral Emittance of an Ash Layer

$$\varepsilon(\bar{\nu},T_s)=\frac{E_{\bar{\nu}}(\bar{\nu},T_s)(\exp(\alpha_2\bar{\nu}/T_s)-1)}{\pi\alpha_1\bar{\nu}^3}$$

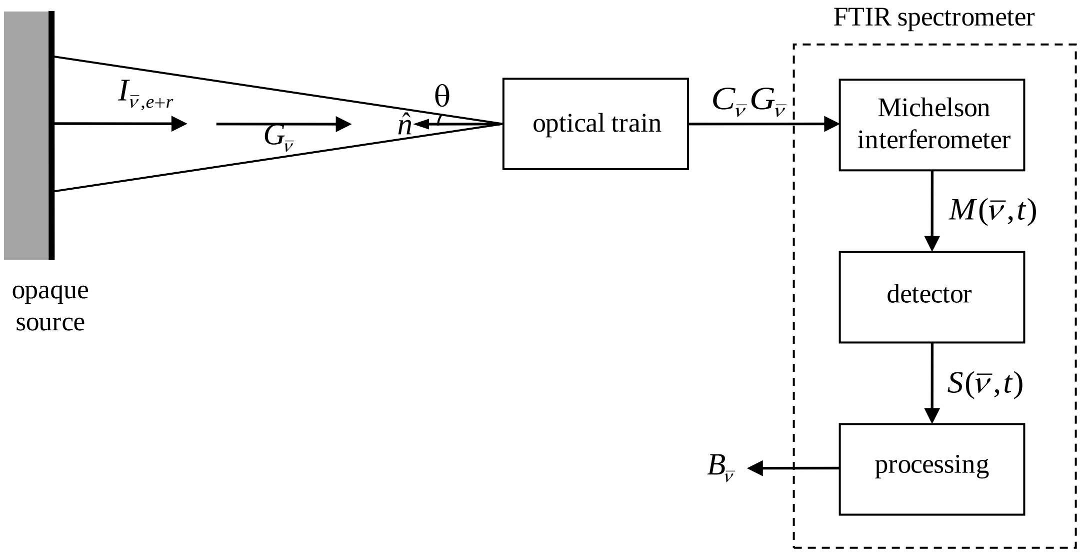
The only unknowns in the above equation are the spectral emissive power of the ash layer and the ash layer surface temperature.

Spectral emissive power of the ash layer: $\boxed{E_{\bar{\nu}}(\bar{\nu},T_s)}$

Surface temperature of the ash layer: T_s

Spectral Emissive Power of an Ash Layer

The basic measurement technique consists of directing the radiation from the ash layer into a detector via an optical system.

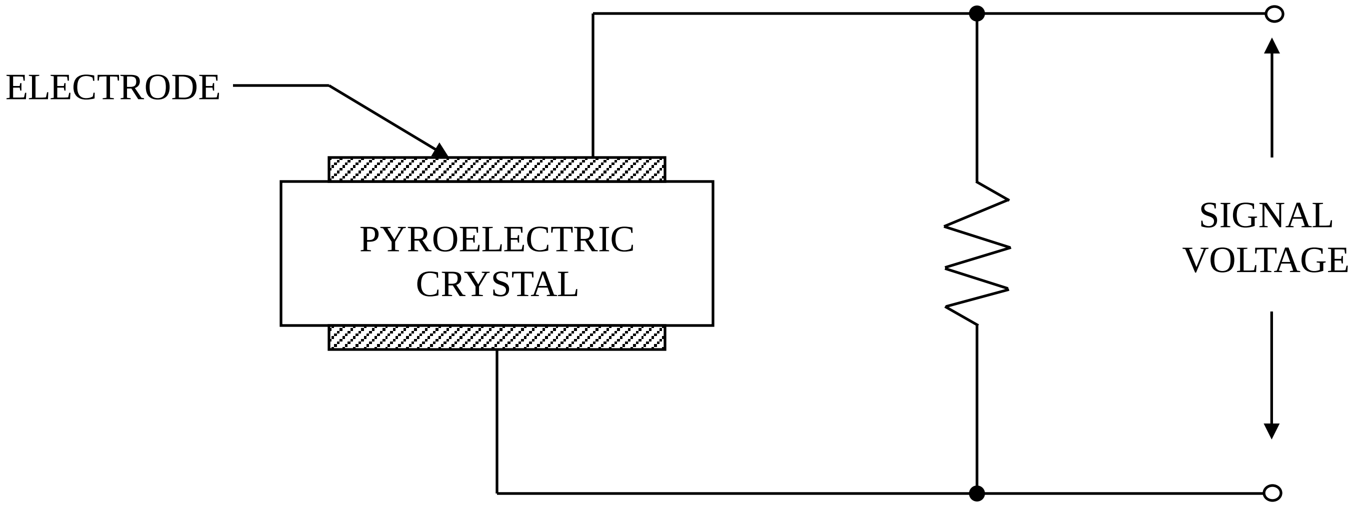


The objective is to find a relationship between the output signal and the spectral emissive power of the ash deposit according to:

$$E_{\bar{\nu}}(T_S) = f_{IR}(B_{\bar{\nu}})$$

Spectral Emissive Power of an Ash Layer

In order to relate the spectral emissive power of the ash deposit to the FTIR signal, we must know what the signal is.

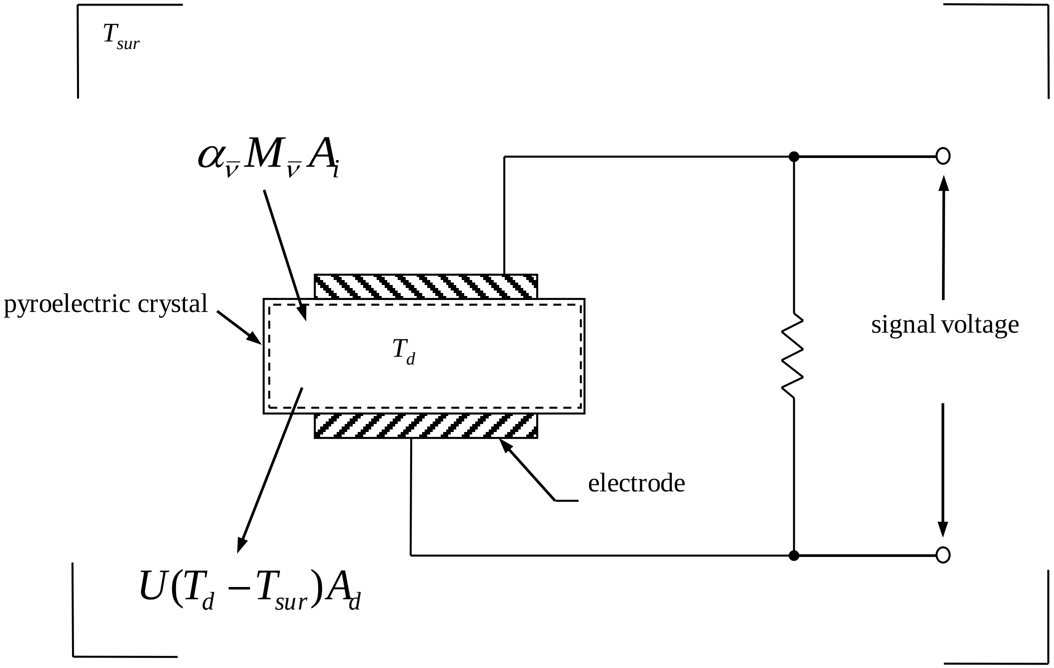


The signal voltage from the detector, $S_{\bar{\nu}}$, is proportional to the change in the detector temperature (T_d) with time.

$$\gamma_{\bar{\nu}} S(\bar{\nu}, t) = \frac{dT_d}{dt}$$

Spectral Emissive Power of an Ash Layer

$$\dot{E}_{in} - \dot{E}_{out} = \dot{E}_{st}$$



$$\dot{E}_{in} = \alpha_{\bar{\nu}} M(\bar{\nu}, t) A_i$$

$$\dot{E}_{out} = U(T_d - T_{sur}) A_d$$

$$\dot{E}_{st} = m_d c_p \frac{dT_d}{dt}$$

Spectral Emissive Power of an Ash Layer

$$\frac{dT_d}{dt} = \frac{\alpha_{\bar{v}} A_i}{m_d c_d} M(\bar{v},t) - \frac{UA_d}{m_d c_d}(T_d - T_{sur})$$

$$\frac{dT_d}{dt} = \gamma_{\bar{v}} S(\bar{v},t)$$

$$M(\bar{v},t) = f(E_{\bar{v}}(T_S),t)$$

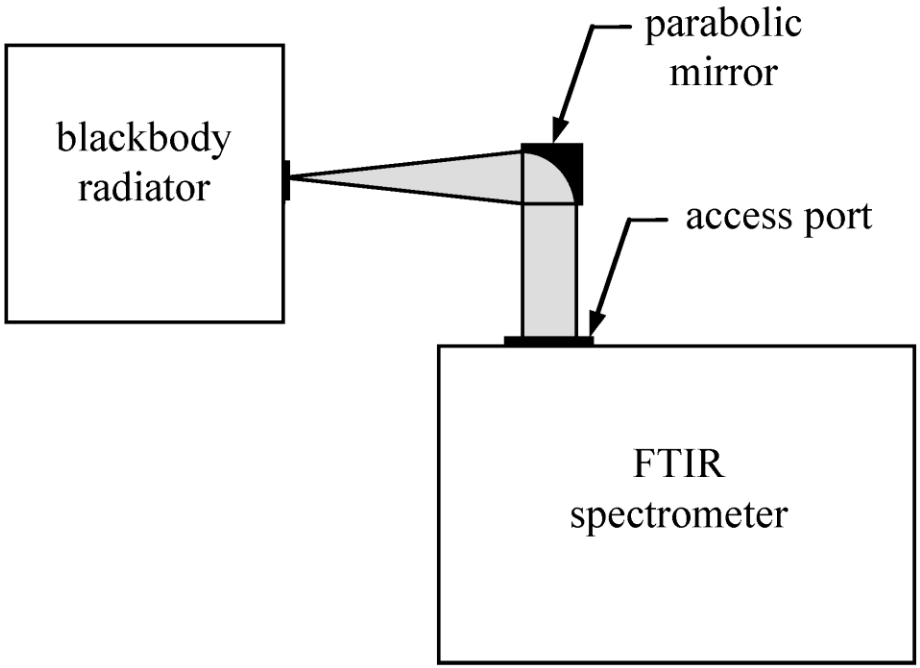
Instrument Response Function

$$\boxed{E_{\bar{v}}(T_S) = ga(\bar{v})B_{\bar{v}} + gb(\bar{v},T_d,T_{sur})}$$

Instrument Response Function

We can verify our derived relation by collecting spectra from an object with a known emittance and spectral emissive power, namely, a black body source.

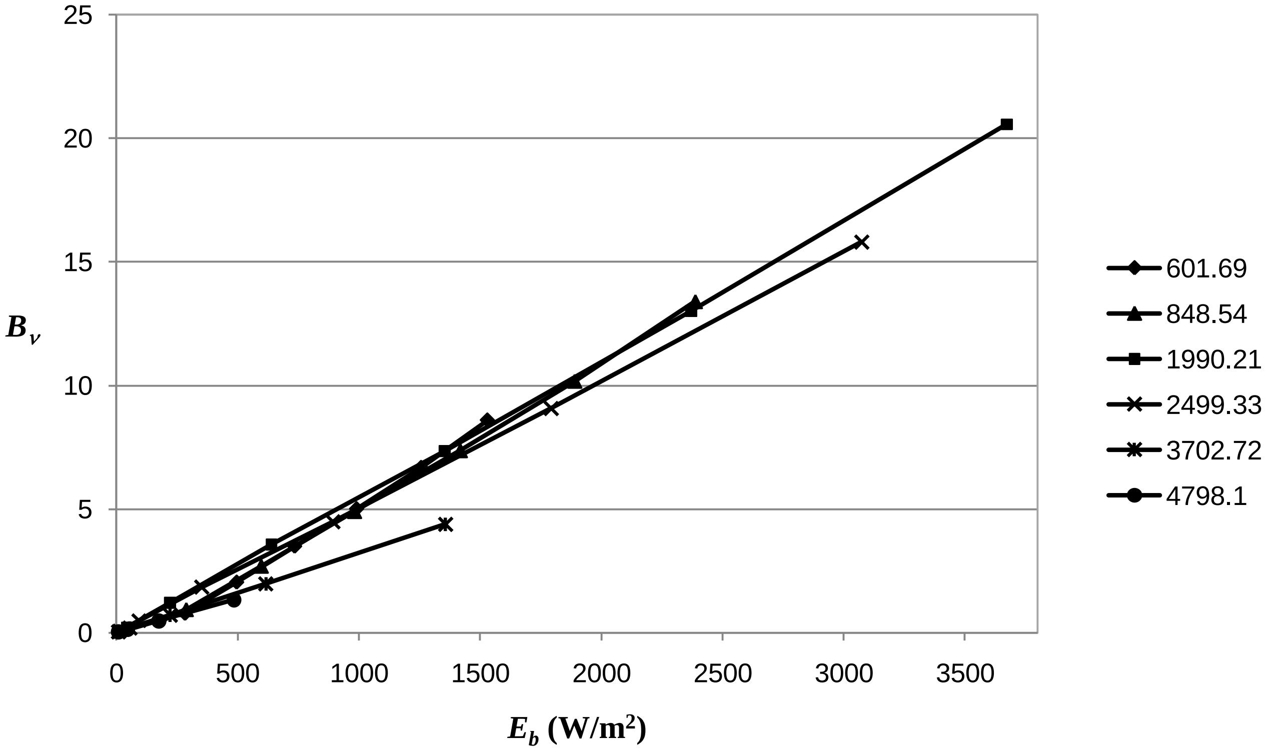
$$E_{\bar{\nu}}(T_S) = ga(\bar{\nu})B_{\bar{\nu}} + gb(\bar{\nu}, T_d, T_{sur})$$



Instrument Response Function

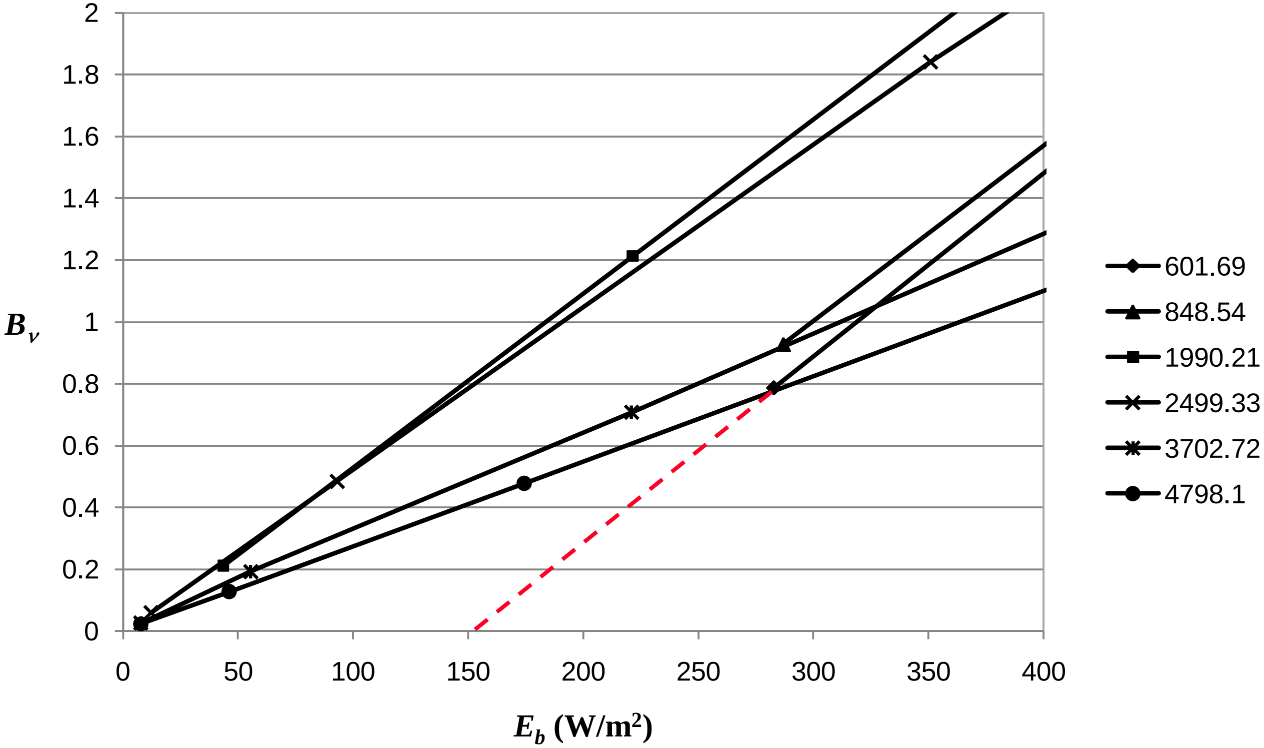
If we plot the FTIR output signal at any wavenumber as a function of black body emissive power, we see that the relation between the two is linear.

$$B_{\bar{\nu}} = a_{\bar{\nu}} E_{\bar{\nu}}$$



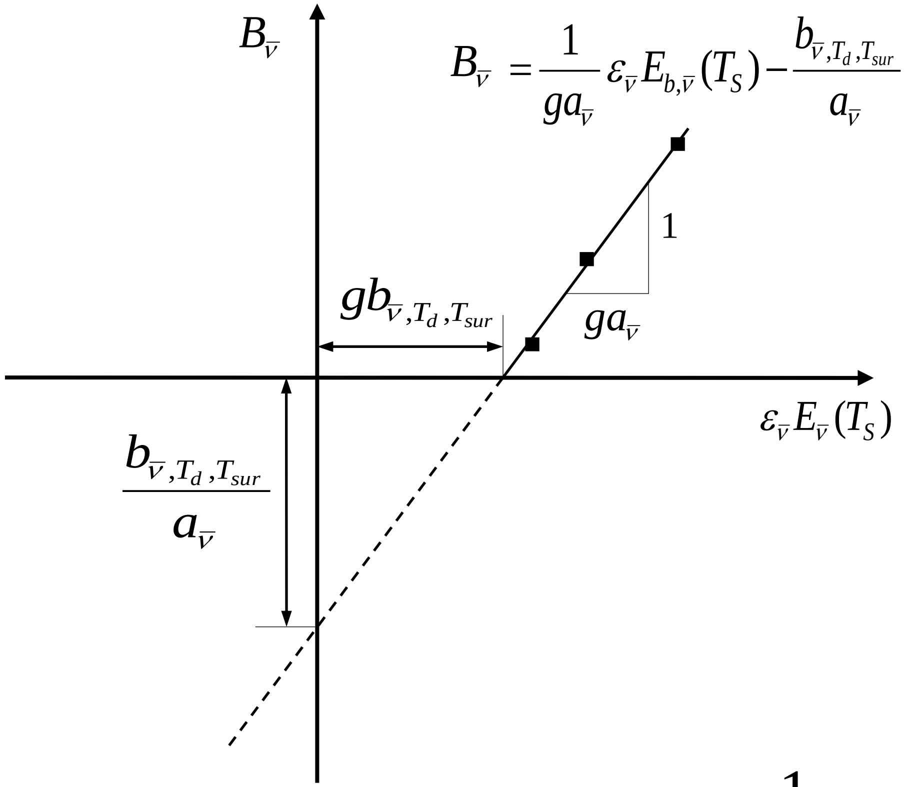
Instrument Response Function

However, a closer look reveals that these lines do not pass through the origin.



$$B_{\bar{\nu}} = a_{\bar{\nu}} E_{\bar{\nu}} + b_{\bar{\nu}}$$

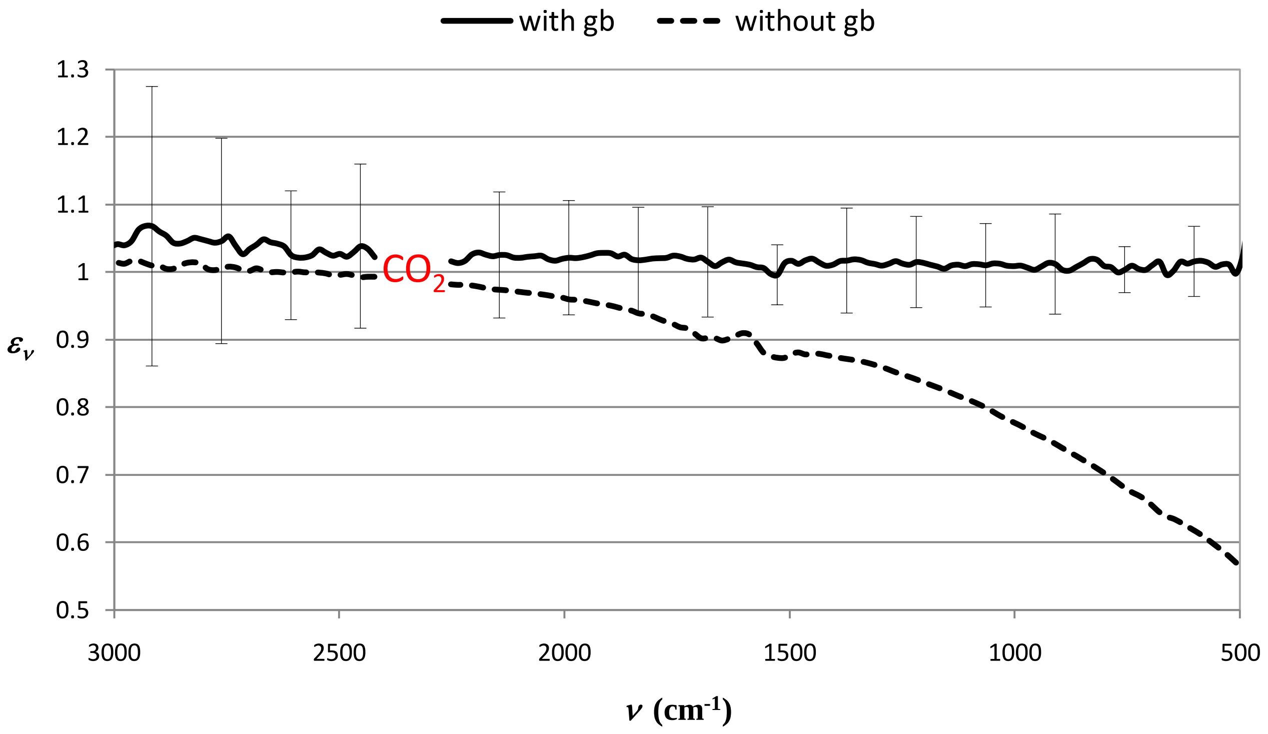
Instrument Response Function



$$E_{\bar{\nu}}(T_S) = ga(\bar{\nu})B_{\bar{\nu}} + gb(\bar{\nu},T_d,T_{sur}) \Longrightarrow B_{\bar{\nu}} = \frac{1}{ga_{\bar{\nu}}}E_{\bar{\nu}}(\bar{\nu},T_s) - \frac{b_{\bar{\nu},T_d,T_{sur}}}{a_{\bar{\nu}}}$$

The FTIR is calibrated to a given source by collecting spectra at a number of temperatures and finding *ga* and *gb* at each wavenumber using the geometry above.

Instrument Response Function



$$\varepsilon_{\bar{\nu}} = \frac{E_{\bar{\nu}}(T_{BB})}{E_{b,\bar{\nu}}(T_{BB})} = \frac{ga(\bar{\nu})B_{\bar{\nu}} + gb(\bar{\nu}, T_d, T_{sur})}{E_{b,\bar{\nu}}(T_{BB})}$$

Spectral Emittance of an Ash Layer

$$\varepsilon(\bar{\nu},T_s)=\frac{E_{\bar{\nu}}(\bar{\nu},T_s)(\exp(\alpha_2\bar{\nu}/T_s)-1)}{\pi\alpha_1\bar{\nu}^3}$$

The only unknowns in the above equation are the spectral emissive power of the ash layer and the ash layer surface temperature.

Spectral emissive power of the ash layer: $E_{\bar{\nu}}(\bar{\nu},T_s)$

Surface temperature of the ash layer: $\boxed{T_s}$

Surface Temperature Measurement

The ash surface temperature can be inferred from the spectral emissive power using two wavenumbers.

$$E_1(T) = \frac{\pi \varepsilon_1 \alpha_1 \bar{v}_1^3}{\exp(\alpha_2 \bar{v}_1 / T) - 1} \qquad E_2(T) = \frac{\pi \varepsilon_2 \alpha_1 \bar{v}_2^3}{\exp(\alpha_2 \bar{v}_2 / T) - 1}$$

$$\Downarrow$$

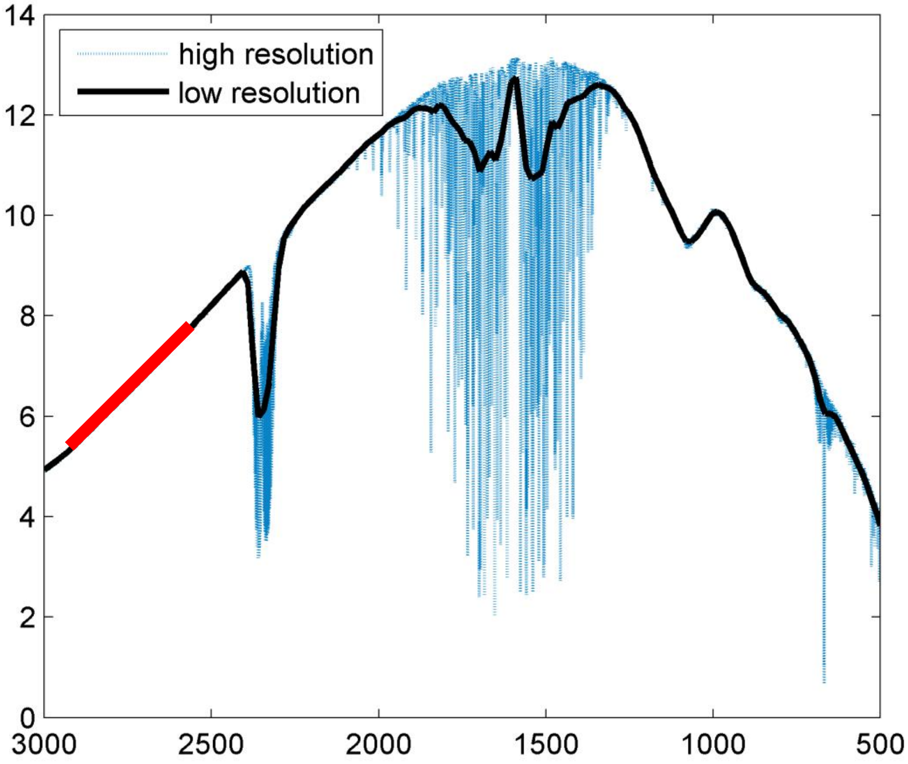
$$\frac{E_2}{E_1} = \frac{\varepsilon_2 \alpha_1 \bar{v}_2^3 / \exp(\alpha_2 \bar{v}_2 / T)}{\varepsilon_1 \alpha_1 \bar{v}_1^3 / \exp(\alpha_2 \bar{v}_1 / T)}$$

$$\Downarrow$$

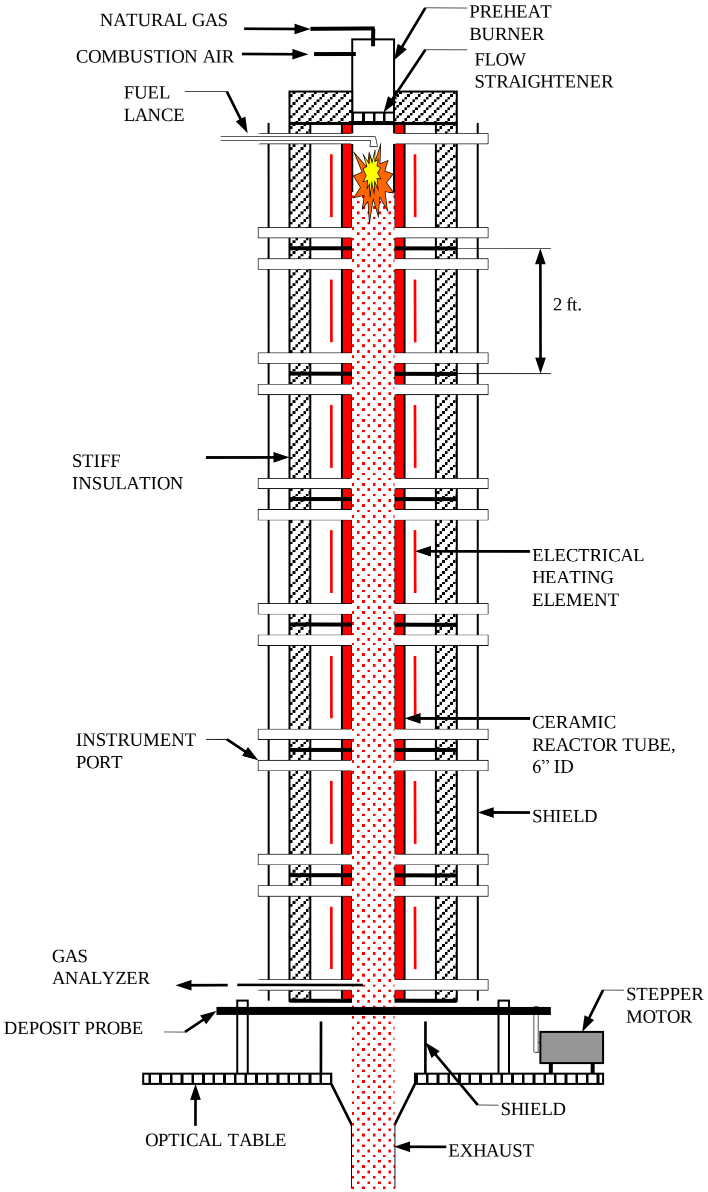
$$\frac{1}{T} = \frac{1}{\alpha_2 (\bar{v}_1 - \bar{v}_2)} \left[\ln(E_2 / E_1) - 3 \ln(\bar{v}_2 / \bar{v}_1) \right]$$

Surface Temperature Measurement

Instead of simply using two wavenumbers, we use all the points in a spectral band. The band must be gray for the emittance values to cancel out.

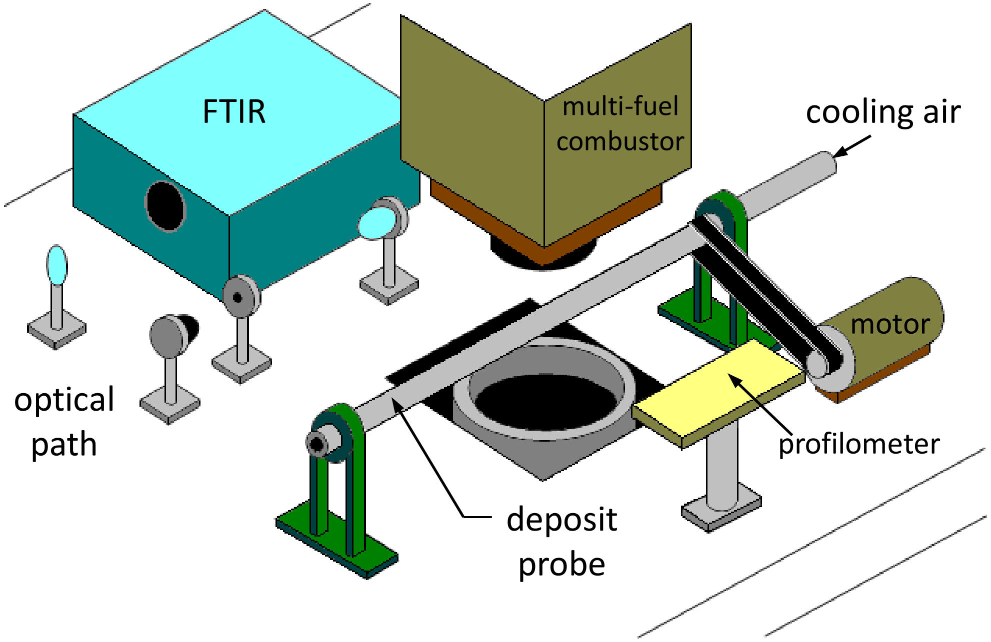


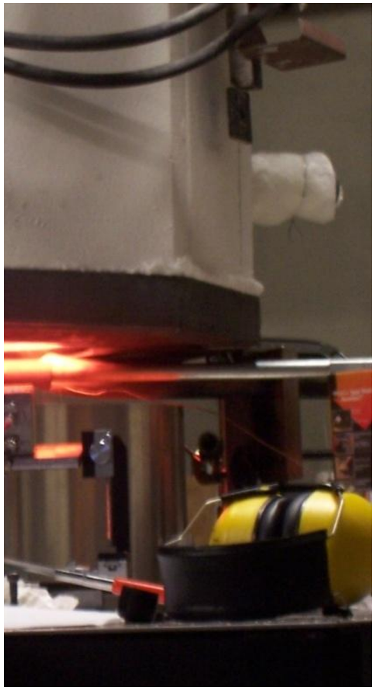
Ash Deposition Experiment



- A multi-fuel reactor (MFR) consists of seven vertically stacked sections.
- The drop tube has a 6 inch diameter and each section is 2 feet long.
- Each section is electrically heated.
- Fuel is injected into the top access port and burns out in the drop tube.
- The outlet is open to the atmosphere.

Ash Deposition Experiment

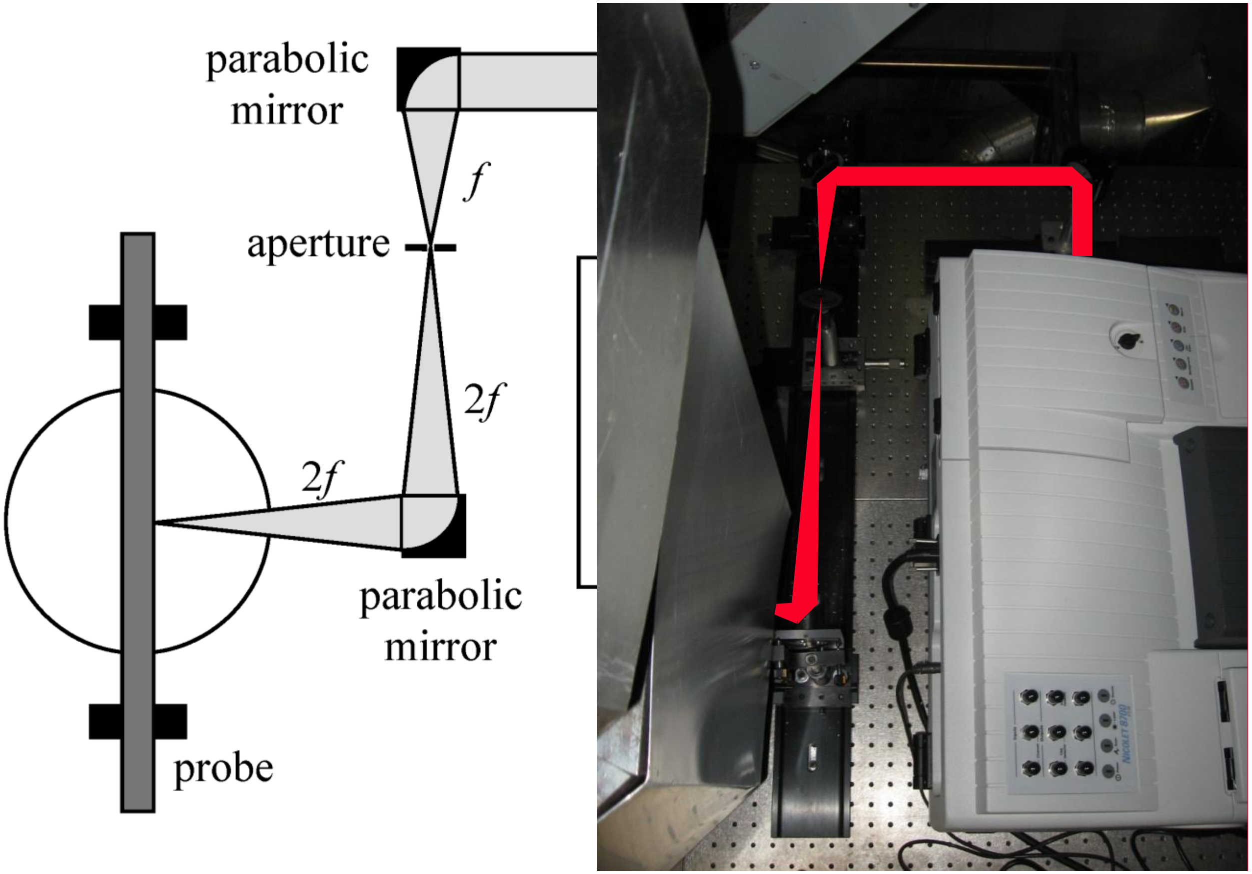




Method

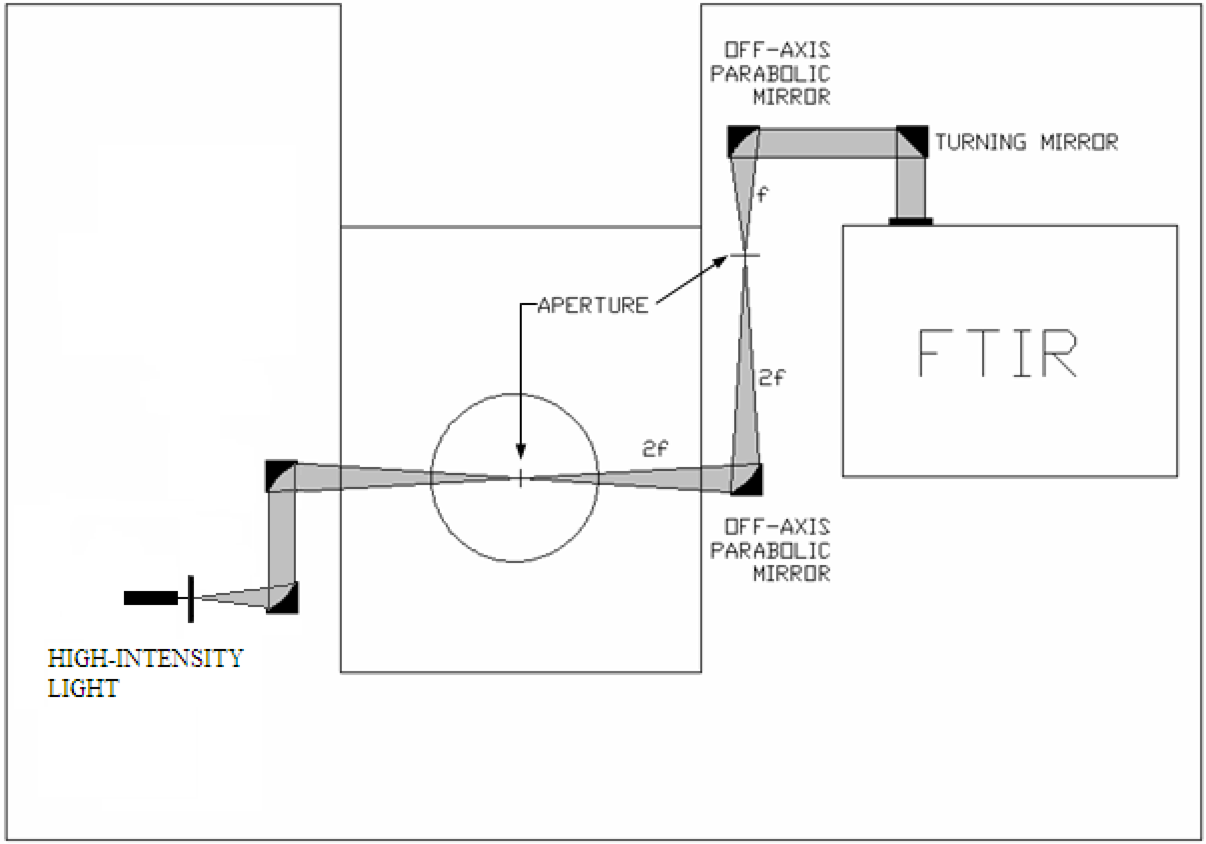
An air-cooled, circular steel probe is placed at the outlet of the multi-fuel combustor. Coal is injected into the top of the furnace and the noncombustible ash constituents accumulate on the probe. Various *in situ* measurements may be made on the deposited ash layer.

Optical Path



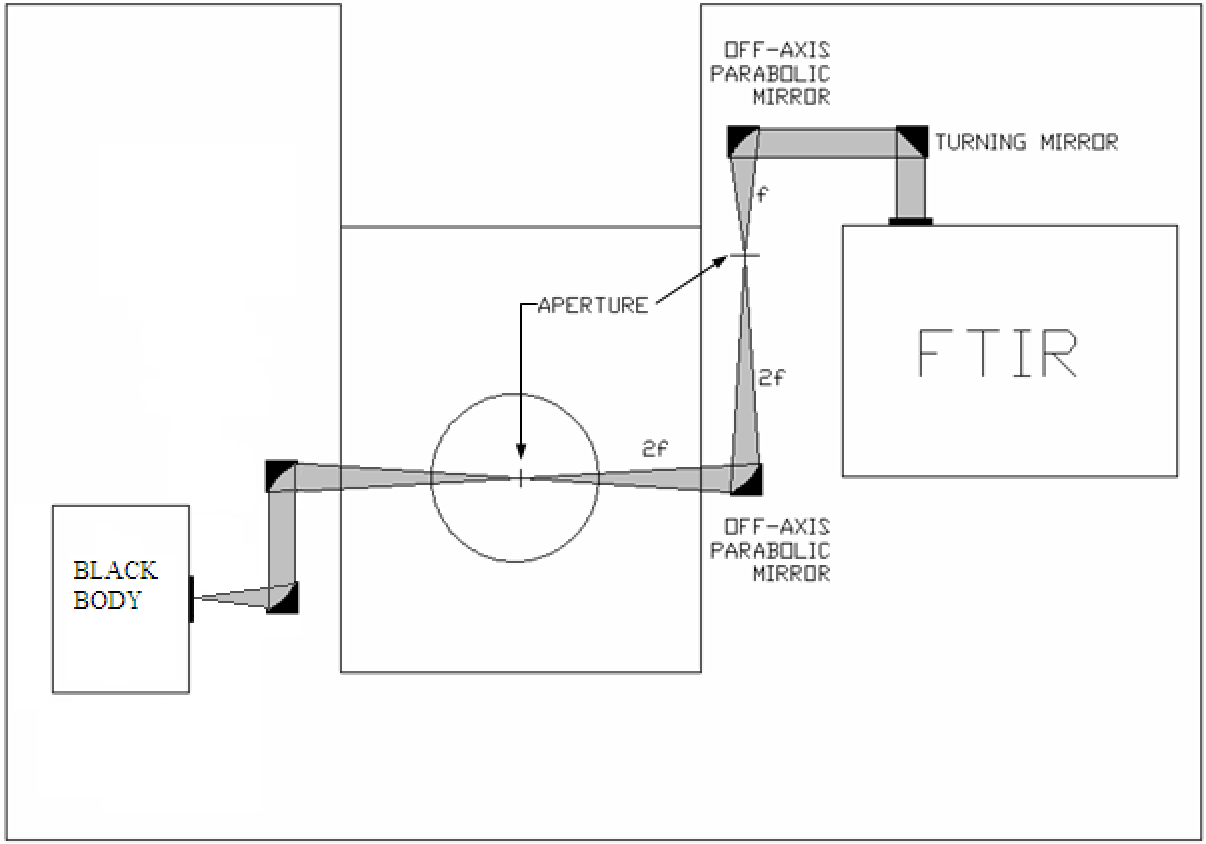
Optical path used to collimate the radiative energy from the deposited ash on the probe and direct it into the Fourier Transform Infrared Spectrometer (FTIR Spectrometer).

Alignment Procedure



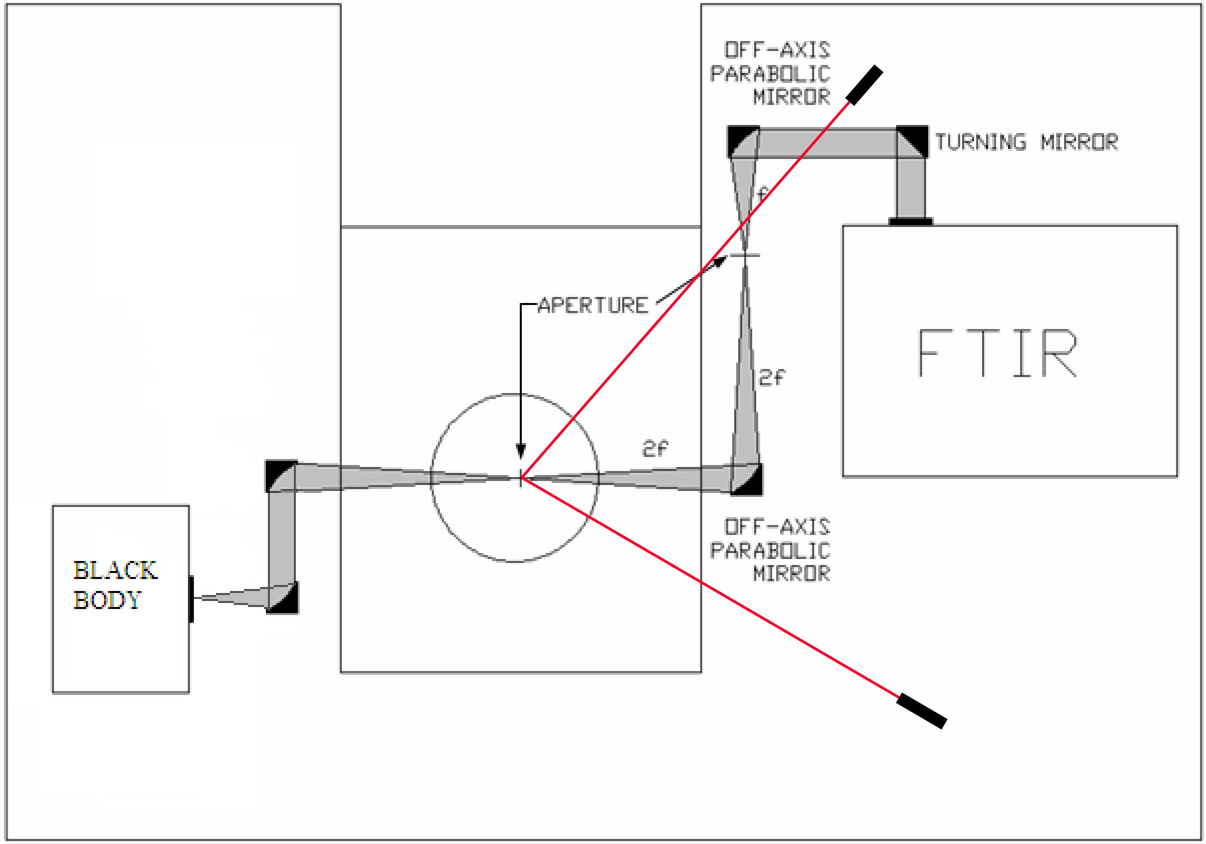
A high intensity fiber optics light is directed through the optical path for visible verification of correct alignment.

Alignment Procedure



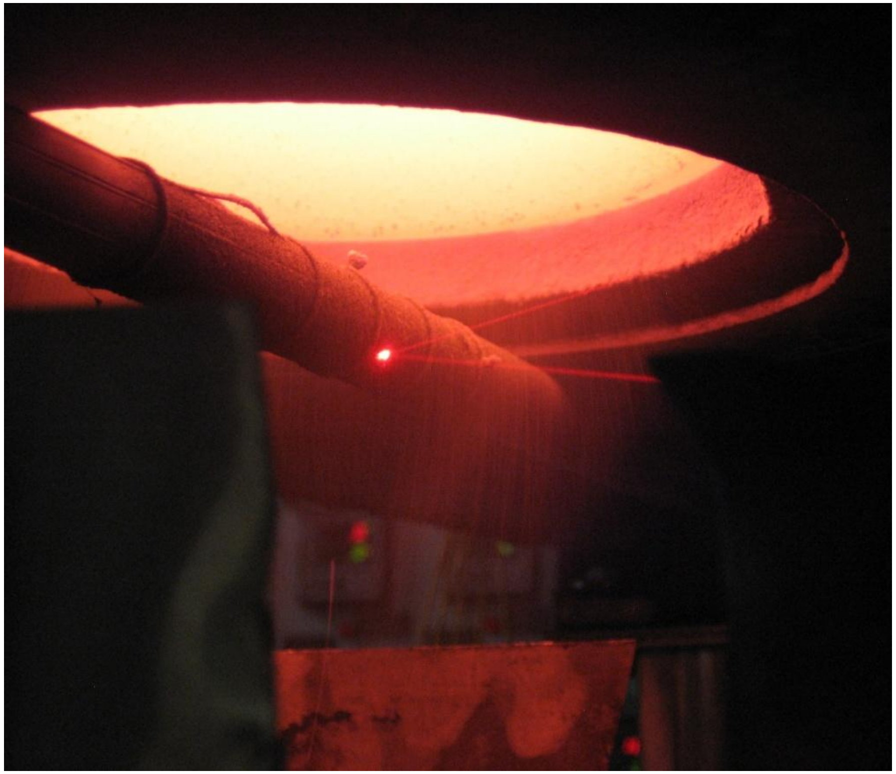
The light source is replaced by the black body radiator and the FTIR signal is maximized by fine tuning the optical path.

Alignment Procedure



Two intersecting lasers mark the point of interrogation.

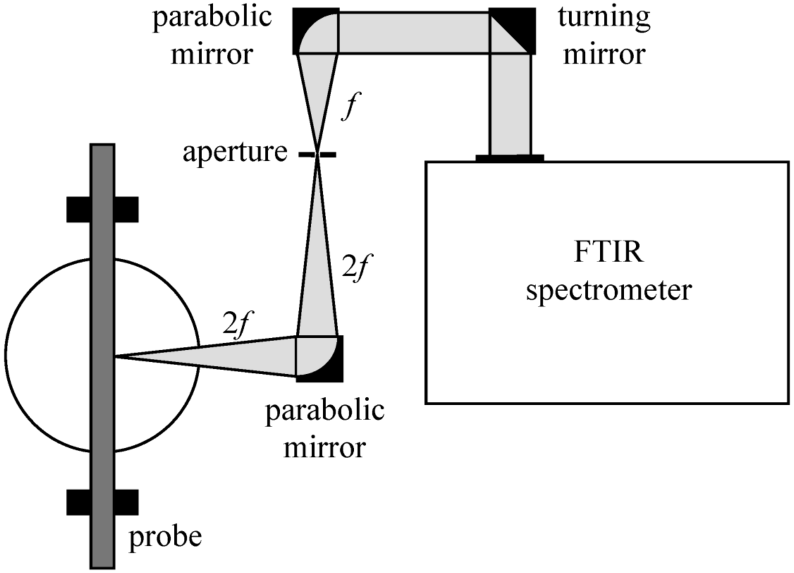
Alignment Procedure



Two intersecting lasers mark the point of interrogation.

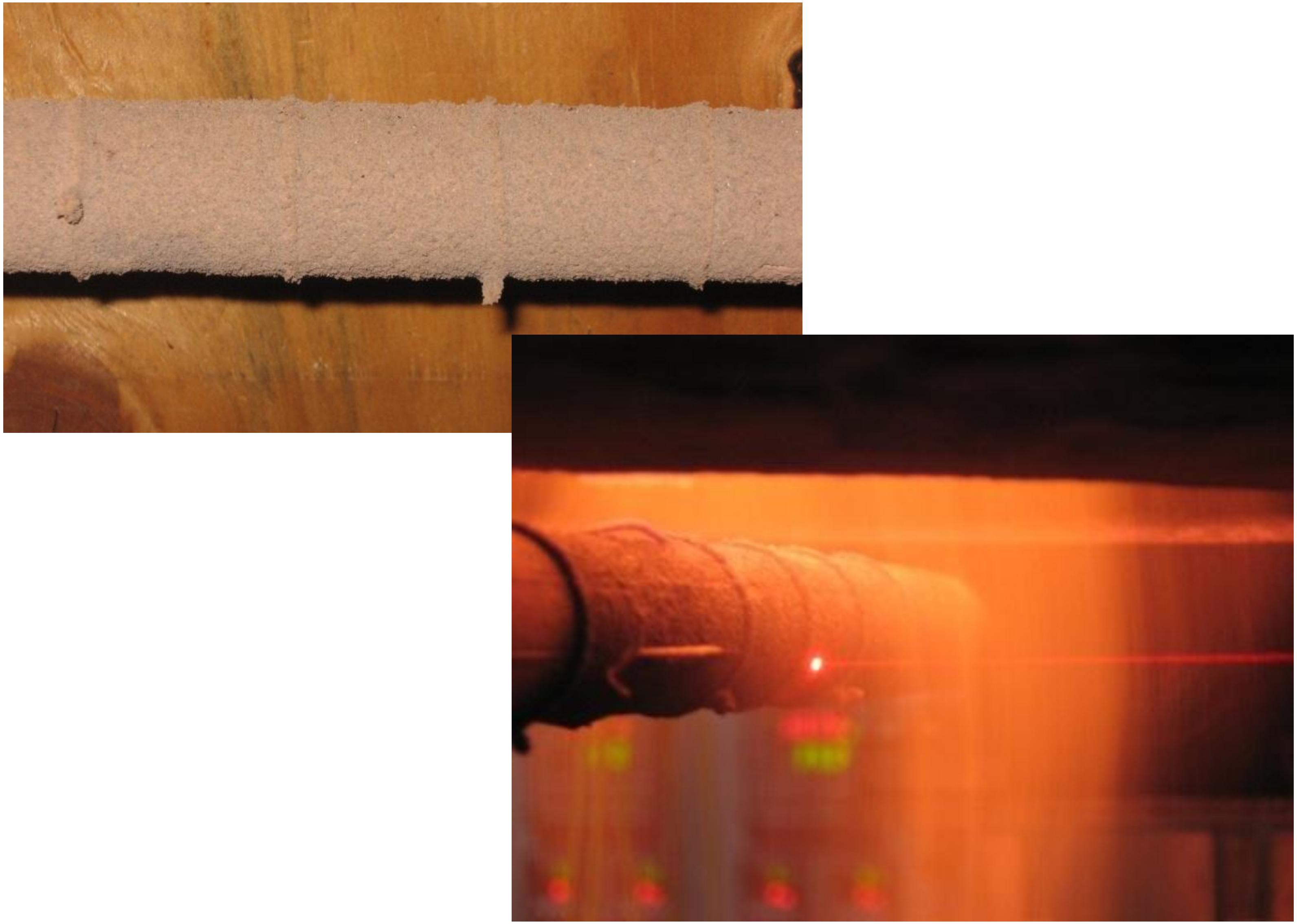
Instrument Calibration

As the cleaned, painted probe heats up in the reactor outlet, spectra are collected at a number of different temperatures to find *ga* and *gb* for the given geometry.



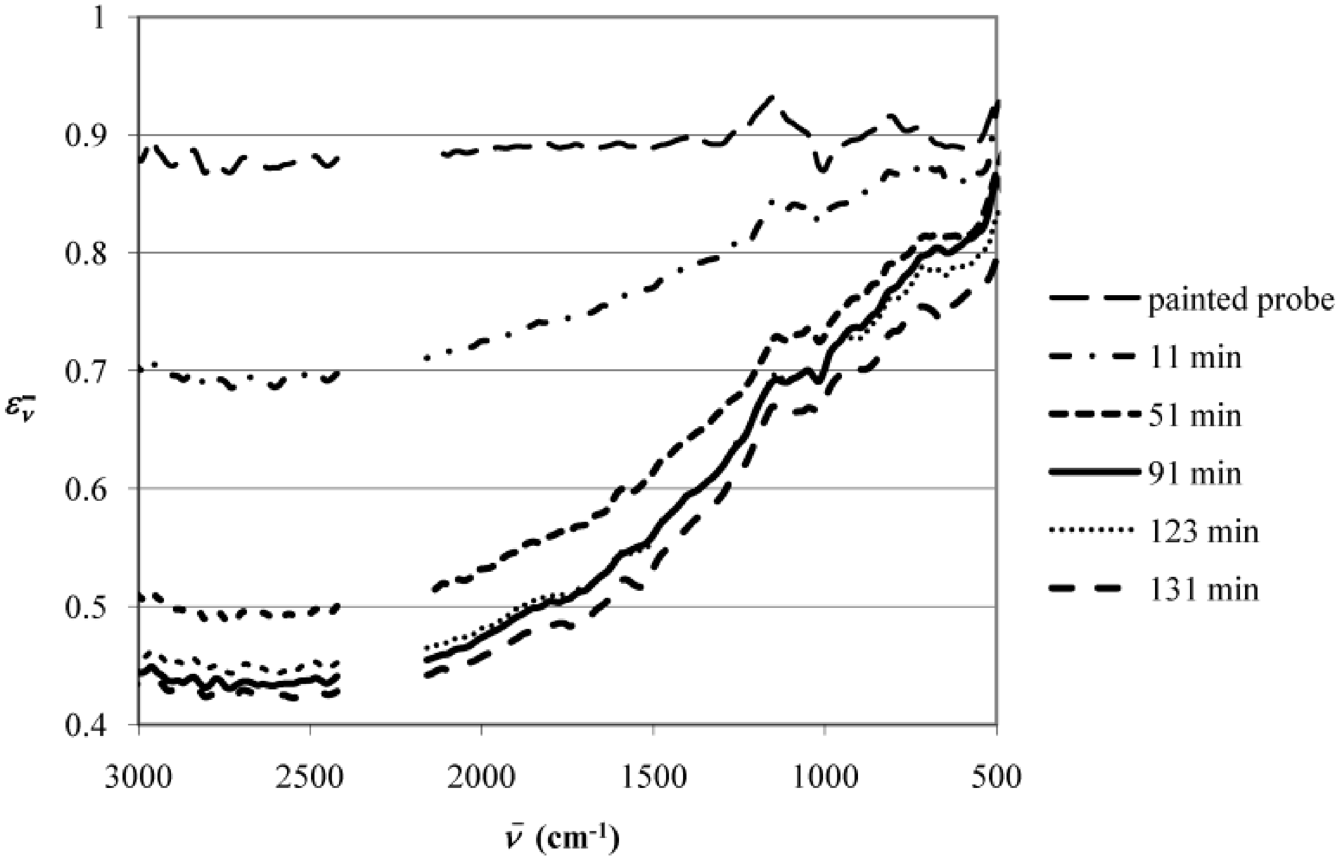
The interrogation point is positioned at one of the thermocouples on the probe surface.

Results



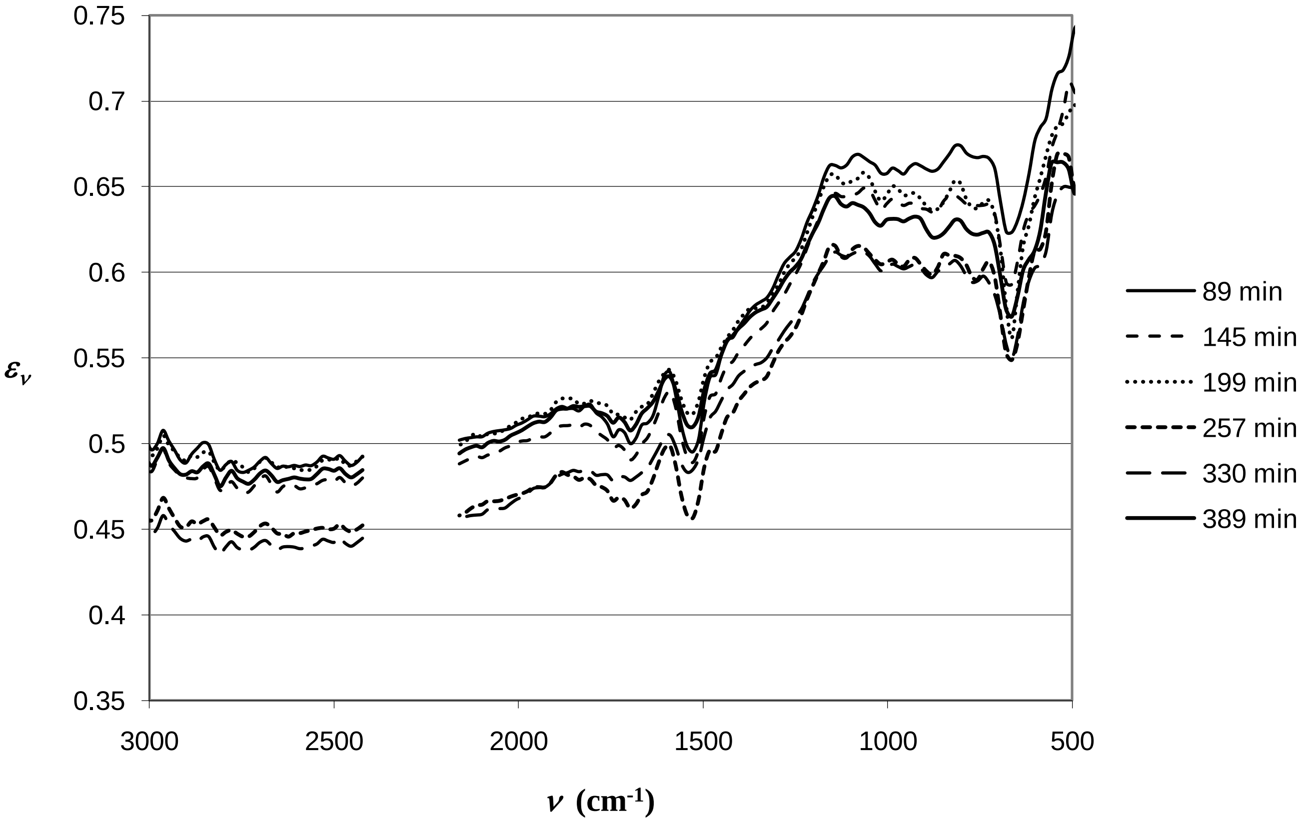
Bituminous Coal: Illinois #6

As a layer of ash accumulates on the painted probe, the spectral emittance changes.



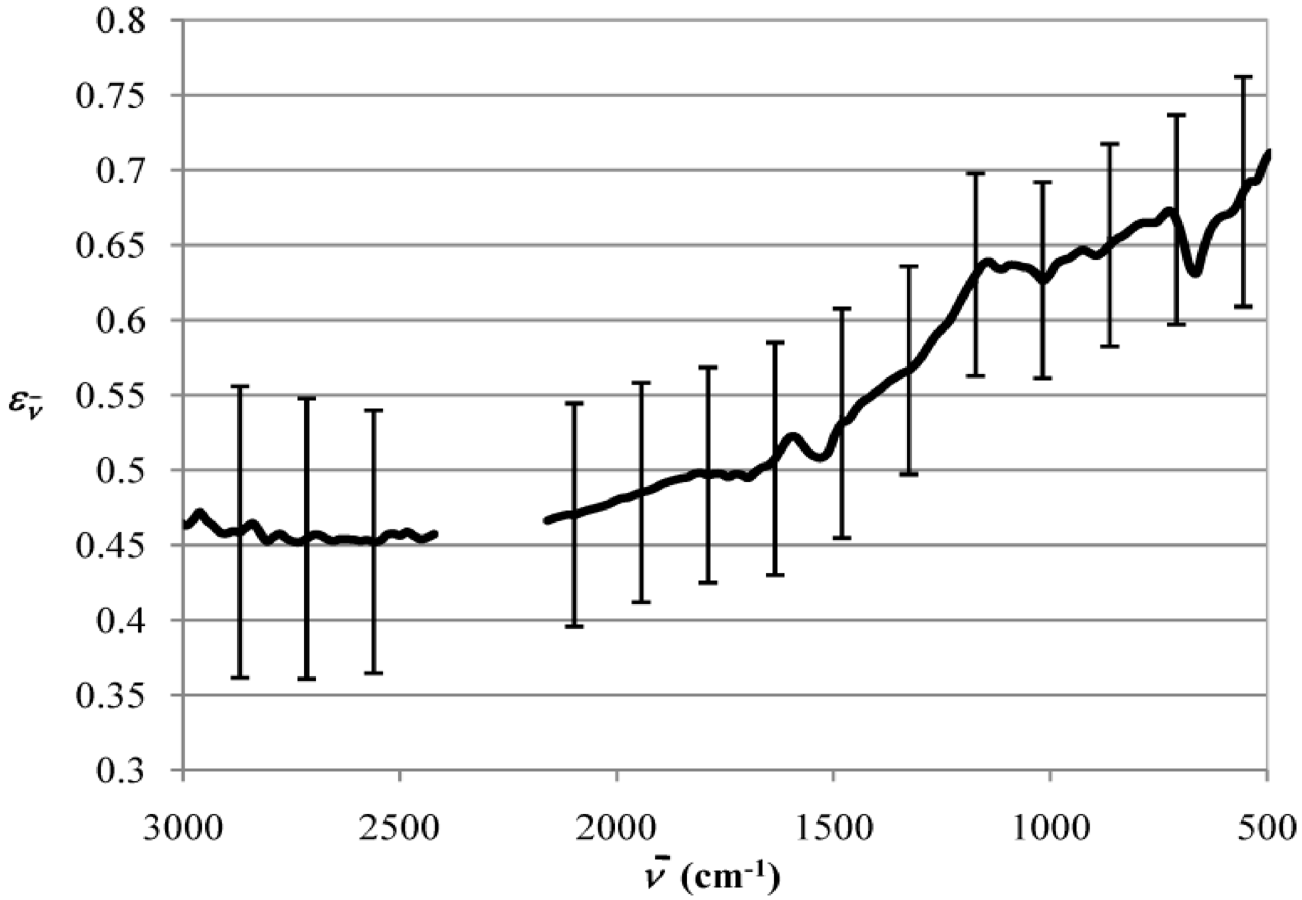
Bituminous Coal: Illinois #6

When the ash layer becomes opaque, any fluctuations in the spectral emittance are due to the continuously changing small scale structure of the particulate deposit and noise in the measurements.



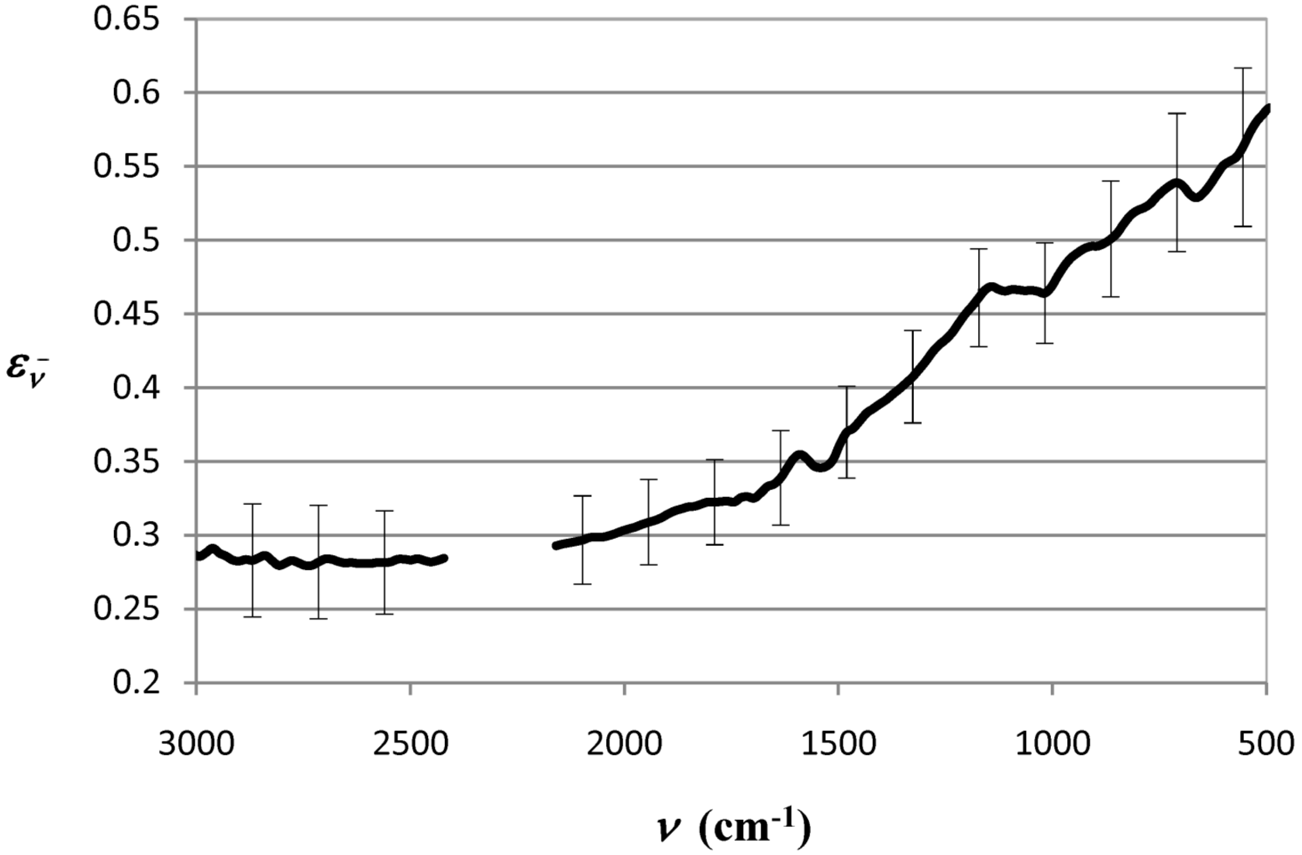
Bituminous Coal: Illinois #6

The average spectral emittance of 21 measurements of Illinois # 6 coal.



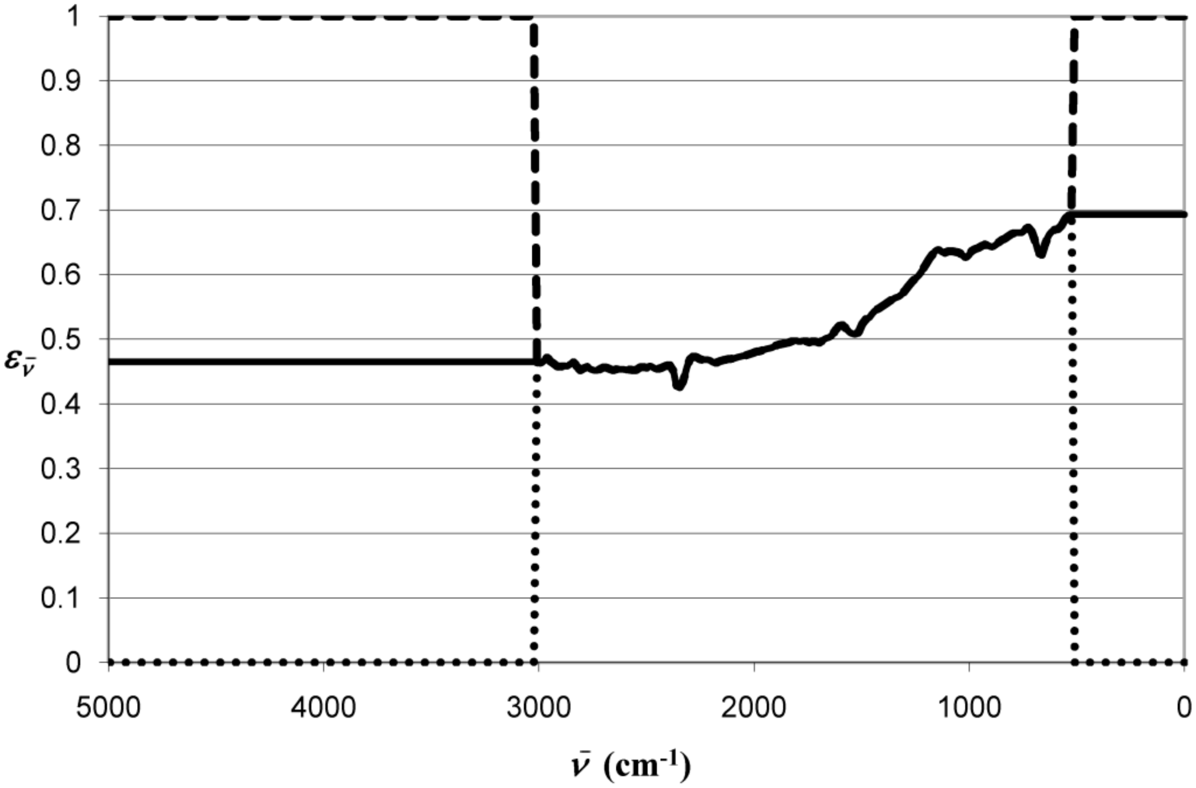
Subbituminous Coal: Wyoming

The average spectral emittance of 12 measurements of Wyoming coal.



Total Emittance

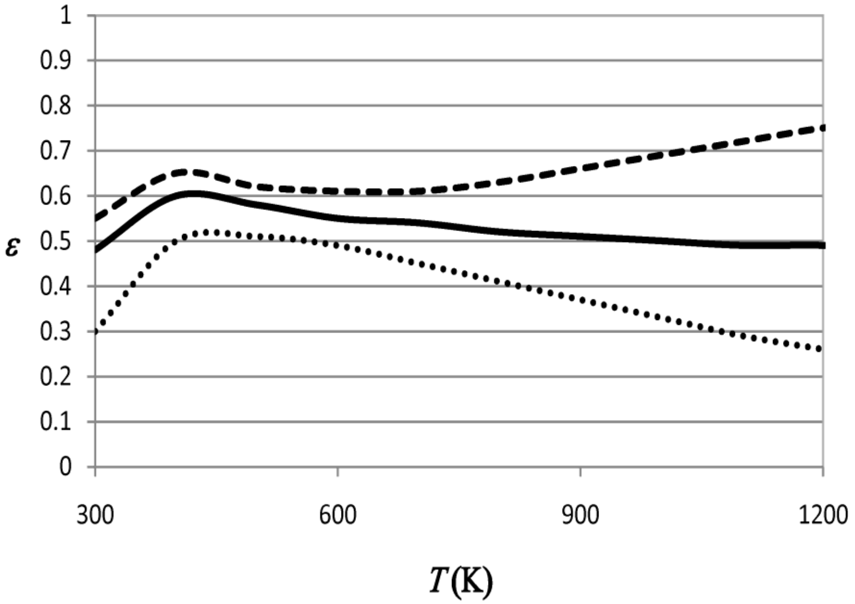
$$\varepsilon \equiv \frac{E(T)}{E_b(T)} = \frac{\int_0^\infty \varepsilon_{\bar{\nu}}(T) E_{\bar{\nu},b}(T)\, d\bar{\nu}}{E_b(T)}$$



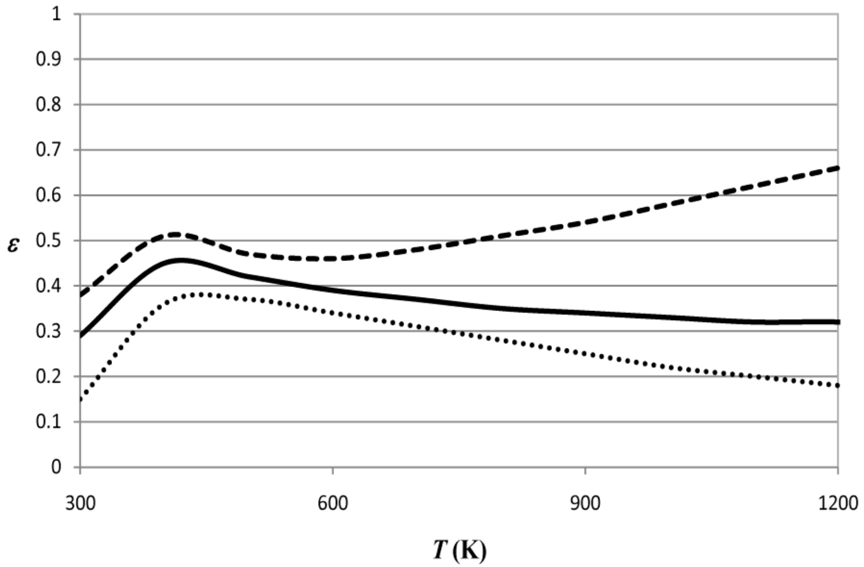
Total Emittance

$$\varepsilon \equiv \frac{E(T)}{E_b(T)} = \frac{\int_0^\infty \varepsilon_{\bar{\nu}}(T)E_{\bar{\nu},b}(T)d\bar{\nu}}{E_b(T)}$$

Illinois #6



Wyoming



Summary

For a bituminous coal (Illinois #6)

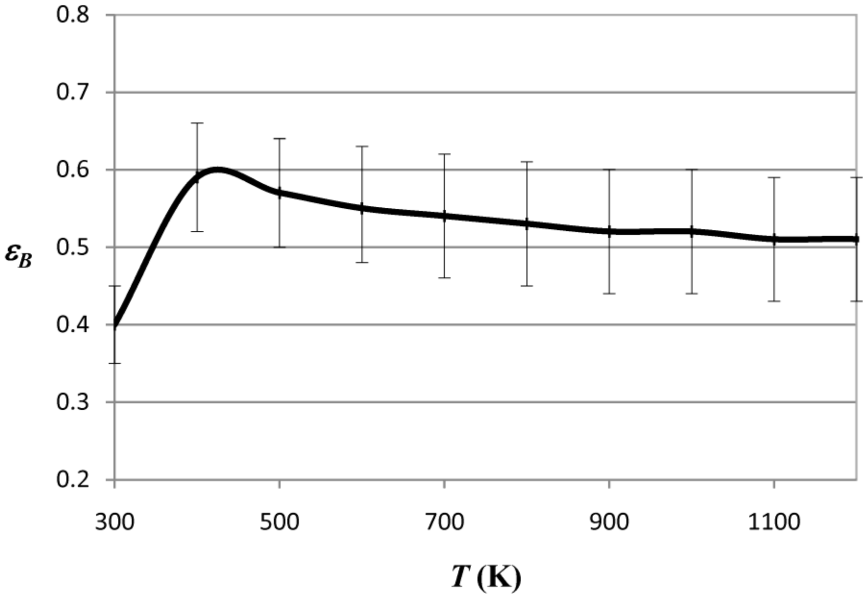
- The spectral emittance is relatively constant at 0.45 between 3000 and 2400 wavenumbers
- The spectral emittance increases from 0.46 to 0.72 between 2200 and 500 wavenumbers

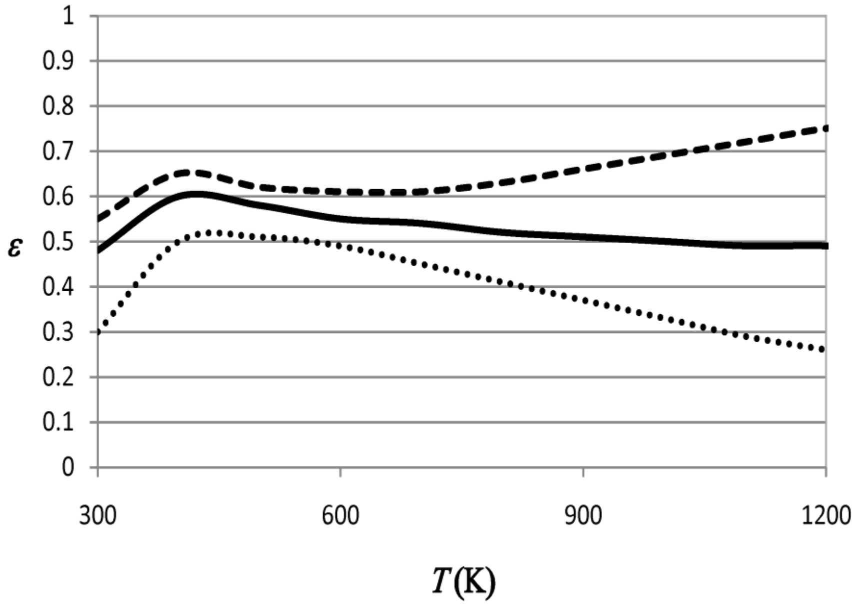
For a subbituminous coal (Wyoming)

- The spectral emittance is relatively constant at 0.29 between 3000 and 2400 wavenumbers
- The spectral emittance increases from 0.29 to 0.59 between 2200 and 500 wavenumbers

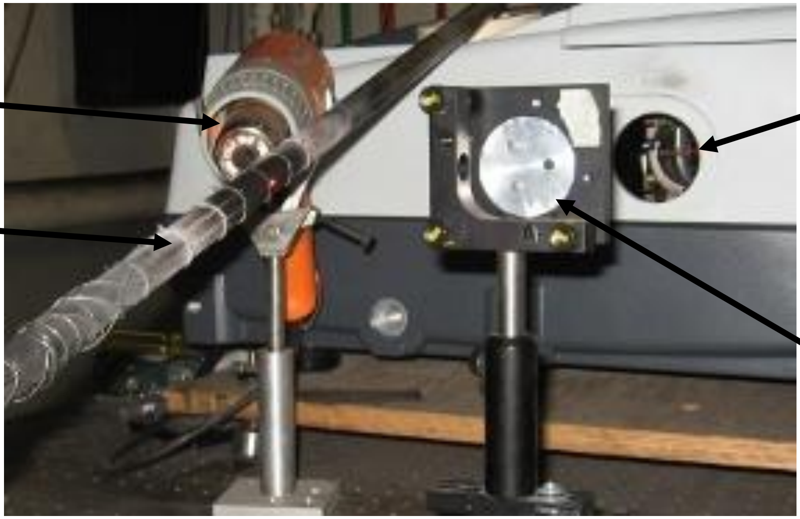

BYU

$$\varepsilon_B \equiv \frac{\int_{\bar{v}_1}^{\bar{v}_2} \varepsilon_{\bar{v}}(T) E_{\bar{v},b}(T)\,d\bar{v}}{\int_{\bar{v}_1}^{\bar{v}_2} E_{\bar{v},b}(T)\,d\bar{v}}$$





Emittance of Painted Probe

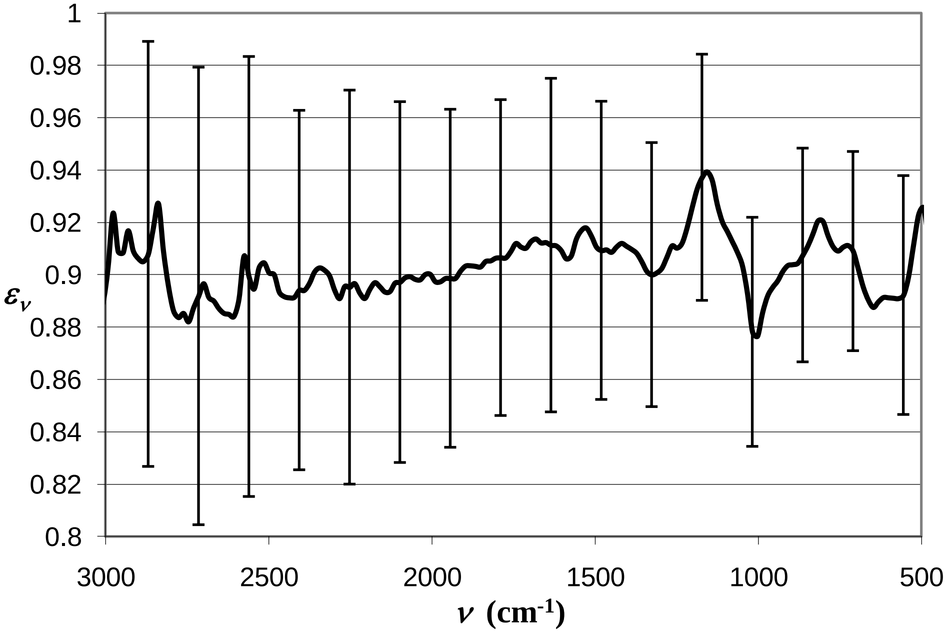


heat gun

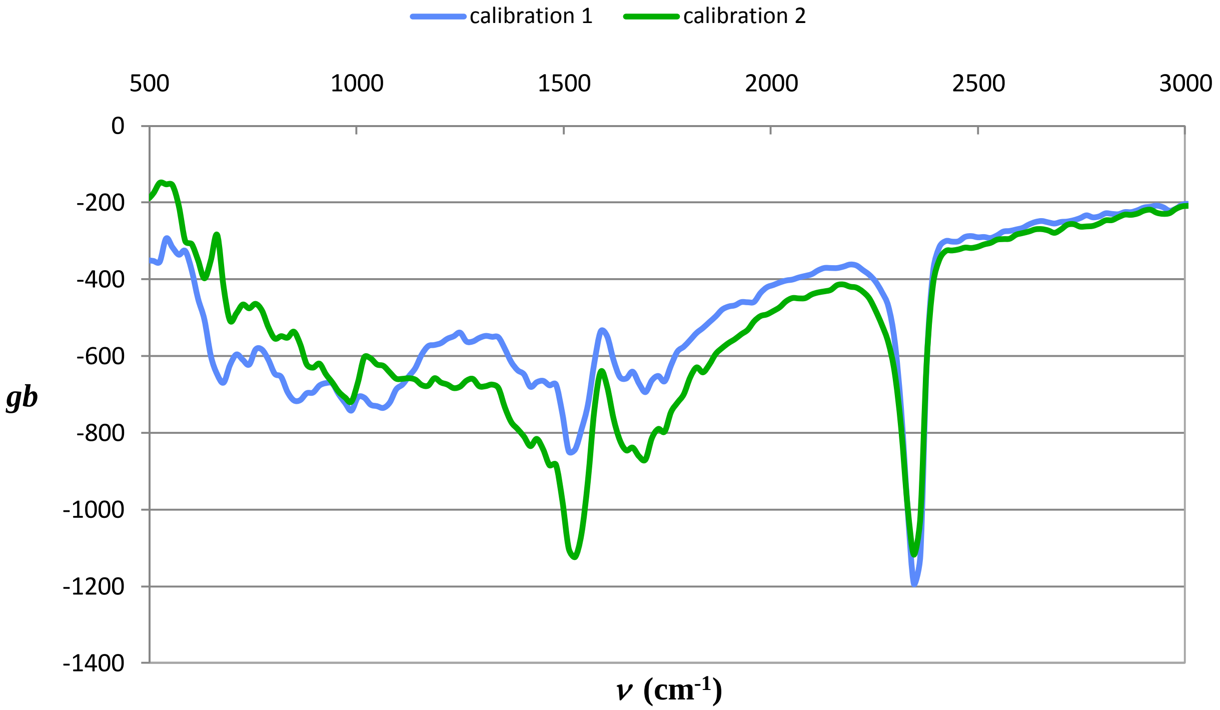
probe

FTIR access port

parabolic mirror



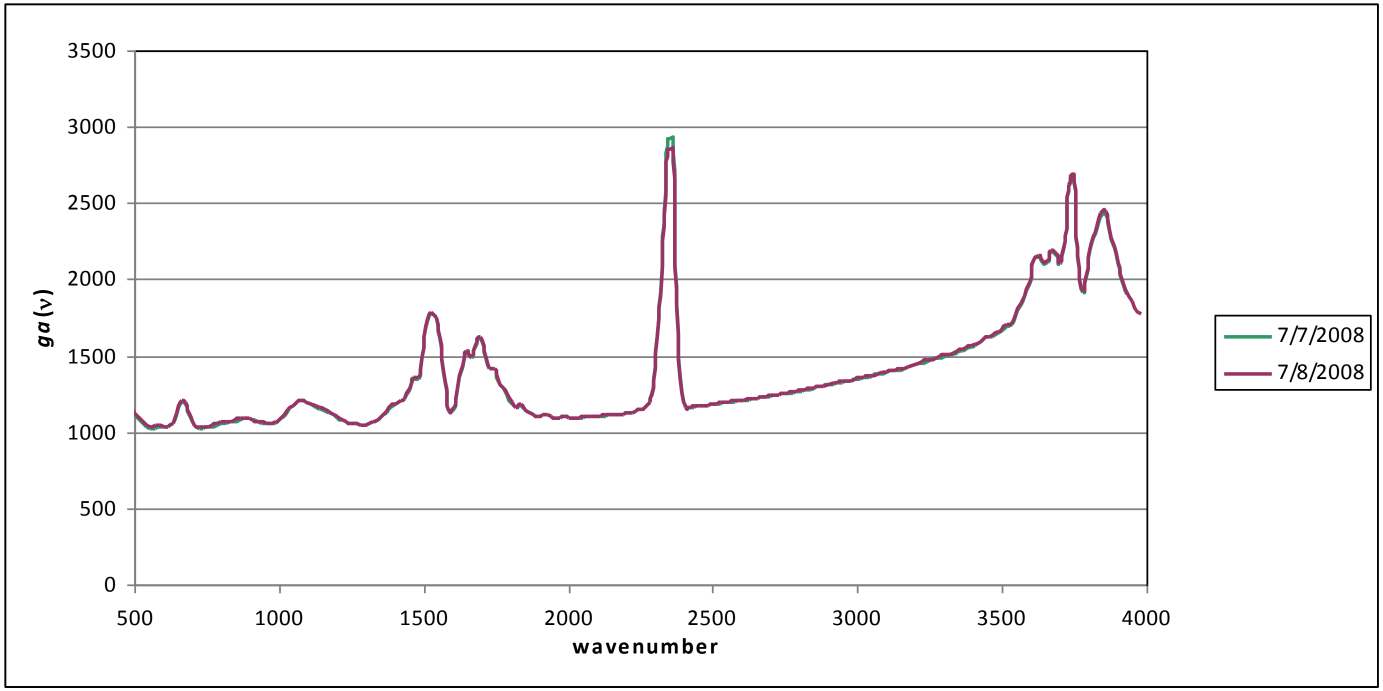
Instrument Response Function



$$E_{\bar{\nu}}(\bar{\nu},T_s)=g\left[a(\bar{\nu})B_{\bar{\nu}}+b(\bar{\nu},T_d,T_{sur})\right]$$

The *gb* term depends on the surrounding conditions and varies from day to day. This term is most important at low wavenumbers.

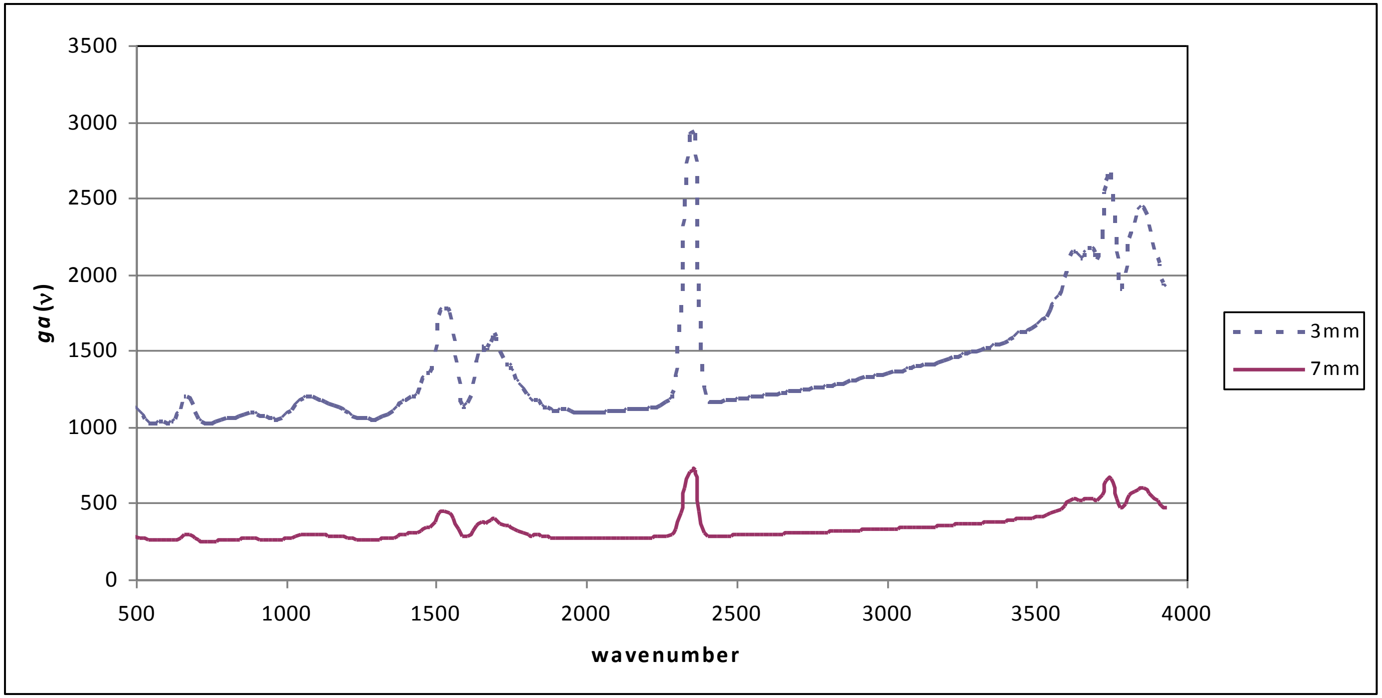
Instrument Response Function



$$E_{\overline{v}}(\overline{v},T_s) = g\left[a(\overline{v})B_{\overline{v}} + b(\overline{v},T_d,T_{sur})\right]$$

The *ga* term depends only on the wavenumber and on the geometry of the path from the FTIR spectrometer to the radiation source.

Instrument Response Function



$$E_{\bar{\nu}}(\bar{\nu},T_s)=g\left[a(\bar{\nu})B_{\bar{\nu}}+b(\bar{\nu},T_d,T_{sur})\right]$$

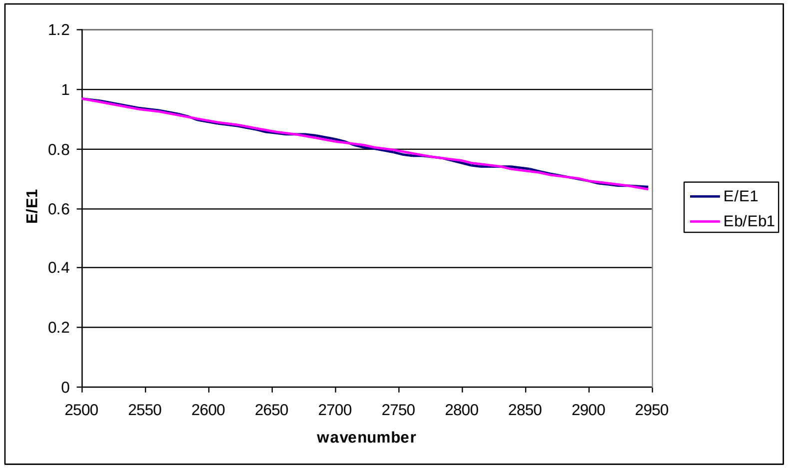
If any part of the geometry is changed, however, the geometric constant changes. This requires that the FTIR calibration be carried out with all of the components of the experiment in place.

Surface Temperature Measurement

The ratios of the spectral emissive power over the band are compared to ratios of the black body emissive powers. A least squares fit is used to find the temperature

$$\frac{E_{\bar{\nu}_i}(T_S)}{E_{\bar{\nu}_{ref}}(T_S)} = \frac{\varepsilon_{\bar{\nu}_i} E_{b,\bar{\nu}_i}(T_S)}{\varepsilon_{\bar{\nu}_{ref}} E_{b,\bar{\nu}_{ref}}(T_S)} \approx \frac{E_{b,\bar{\nu}_i}(T_S)}{E_{b,\bar{\nu}_{ref}}(T_S)}$$

$$\frac{\exp\{\alpha_2 \bar{\nu}_{ref}/T_S\}-1}{\exp\{\alpha_2 \bar{\nu}_i/T_S\}-1} \approx \frac{\bar{\nu}_{ref}^3[a(\bar{\nu}_i)B_{\bar{\nu}_i} + b(\bar{\nu}_i, T_d, T_S)]}{\bar{\nu}_i^3[a(\bar{\nu}_{ref})B_{\bar{\nu}_{ref}} + b(\bar{\nu}_{ref}, T_d, T_S)]}$$

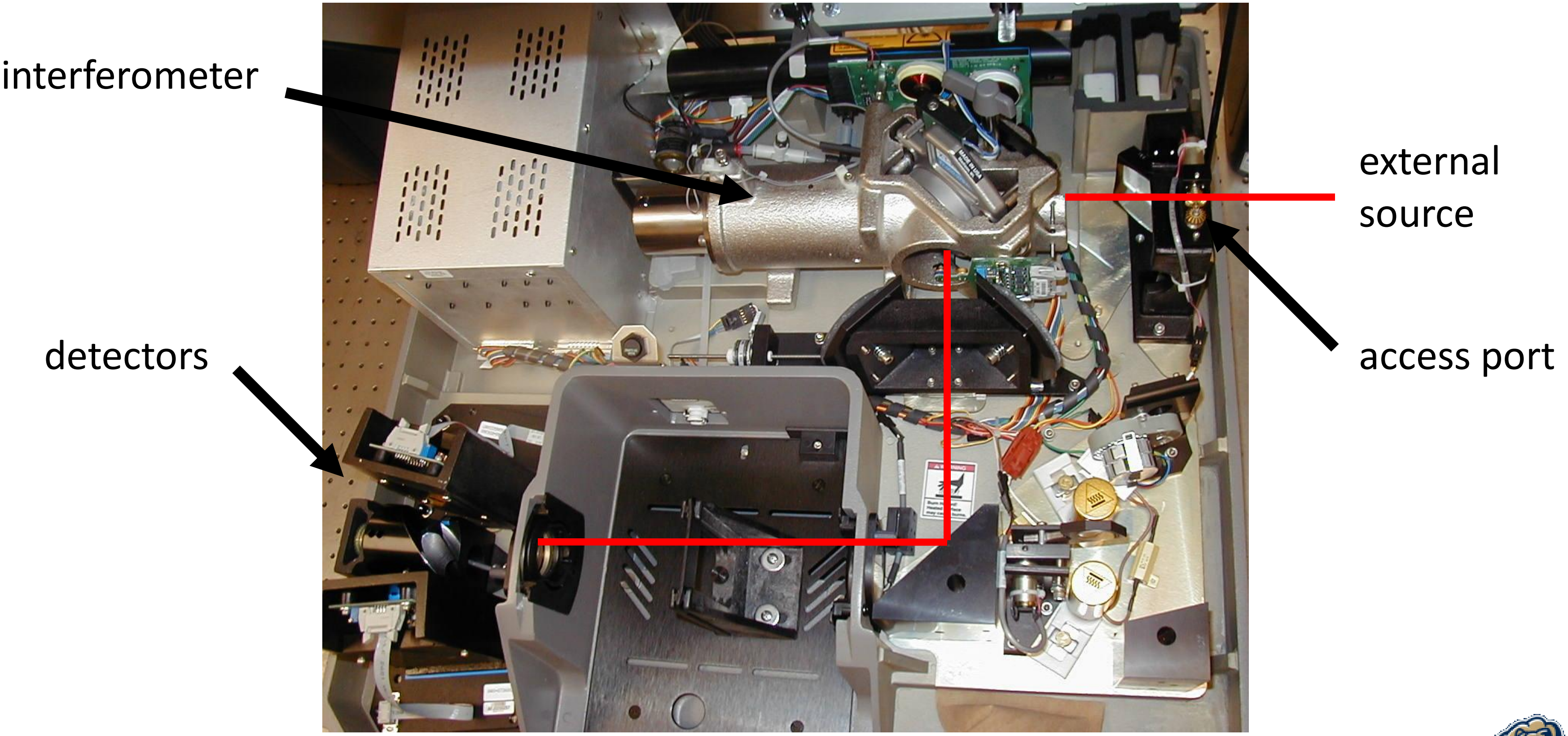


Thermocouple: 369.5 ºC

Temperature: 370.5 ºC

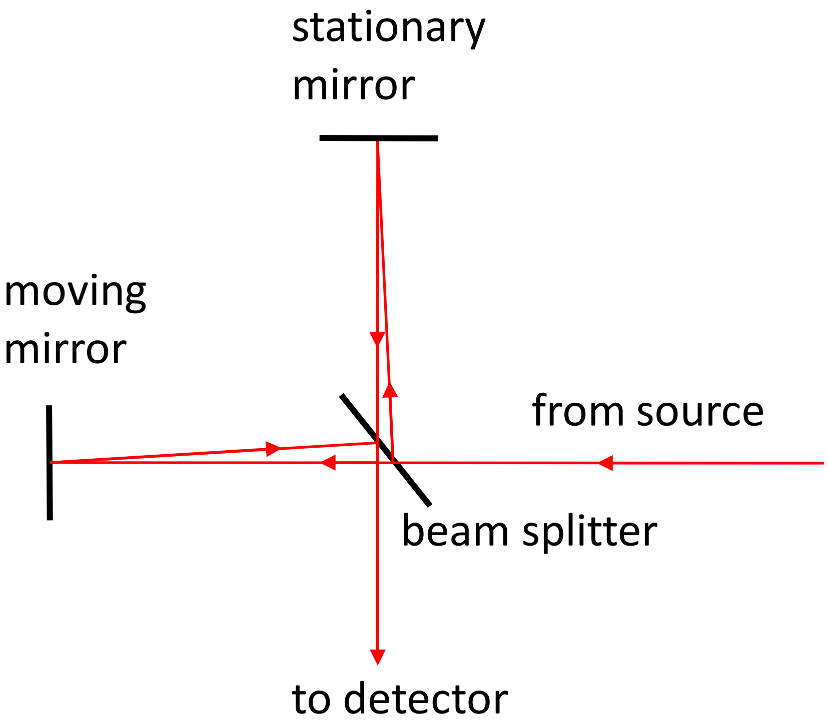
FTIR Spectrometer

Radiation from the ash deposit comes in through the access port, passes through the interferometer on the way to the detector.



FTIR Spectrometer

An interferogram represents the intensity of the recombined light as a function of the position of the moving mirror. The interferogram is the Fourier Transform of the light intensity as a function of wavenumber.



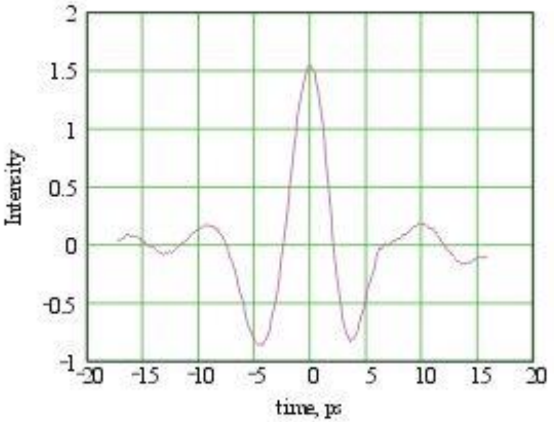
stationary mirror

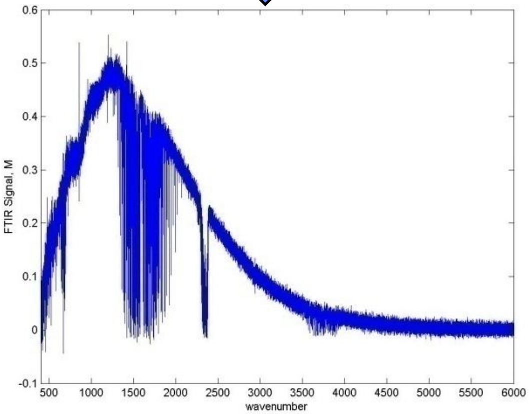
moving mirror

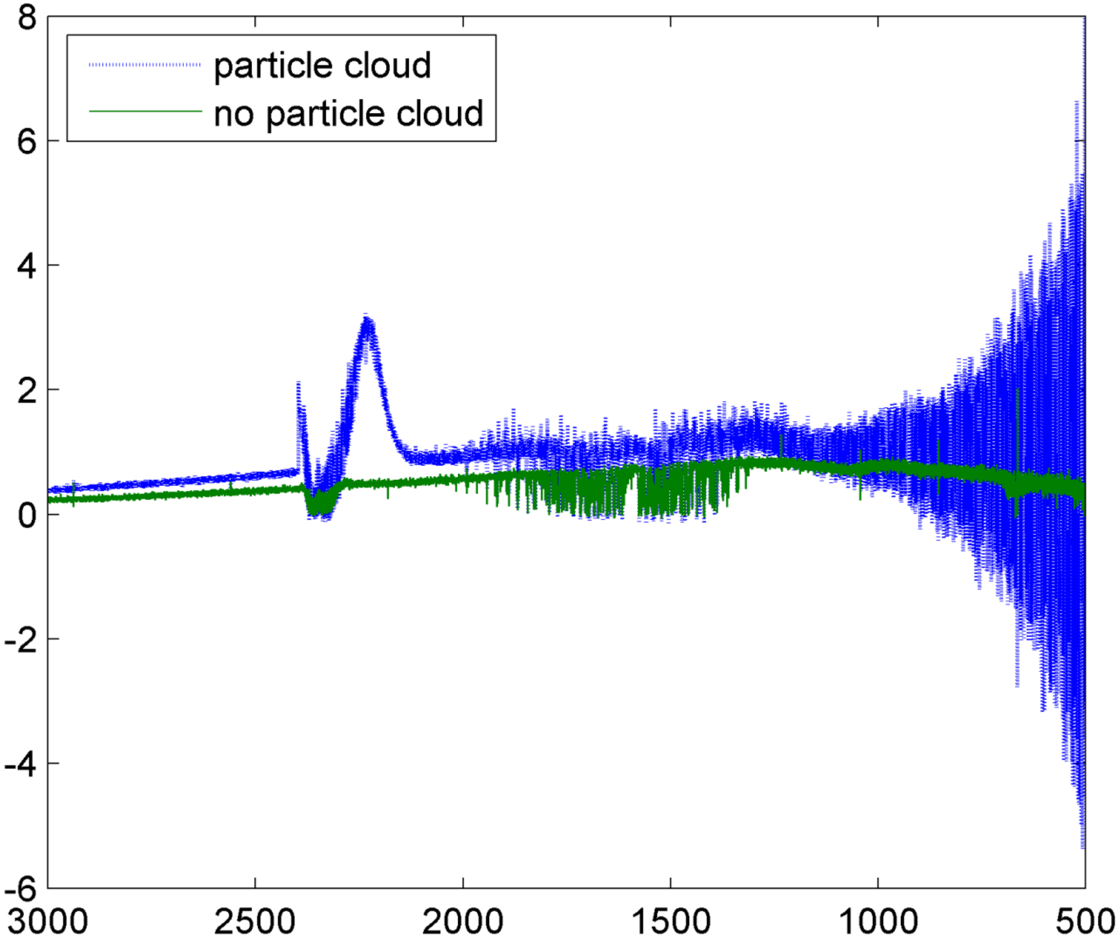
from source

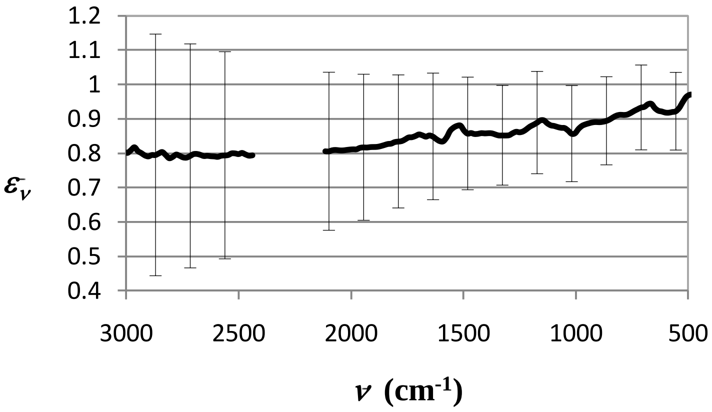
beam splitter

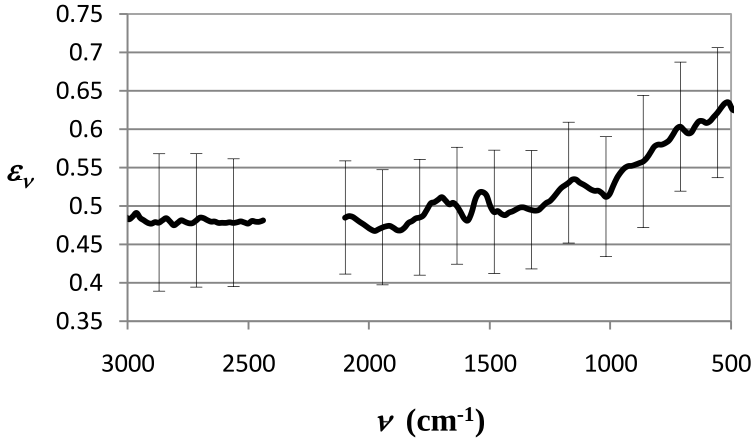
to detector

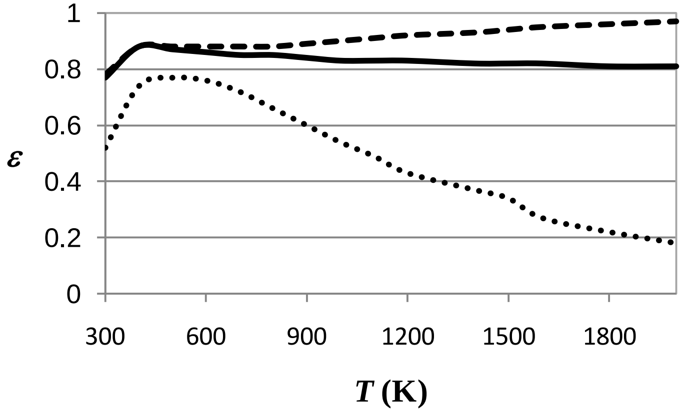


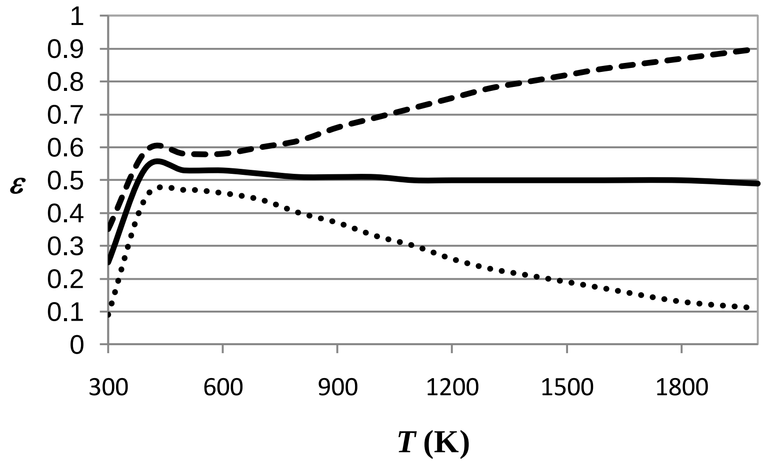



particle cloud
no particle cloud
8
6
4
2
0
-2
-4
-6
3000
2500
2000
1500
1000
500


1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
ε_{ν}
3000
2500
2000
1500
1000
500
ν (cm^{-1})


0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
ε_{ν}
3000
2500
2000
1500
1000
500
ν (cm^{-1})


1
0.8
0.6
0.4
0.2
0
ε
300
600
900
1200
1500
1800
T (K)


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
ε
300
600
900
1200
1500
1800
T (K)