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Annual Users' Conference

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MIRION TECHNOLOGIES

Why Physics Matters in Infrared Imaging

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PLM: Imaging/Director, PLM: Defense, Security, and…

Mirion Connect | Annual Users' Conference 2024

Dallas, Texas

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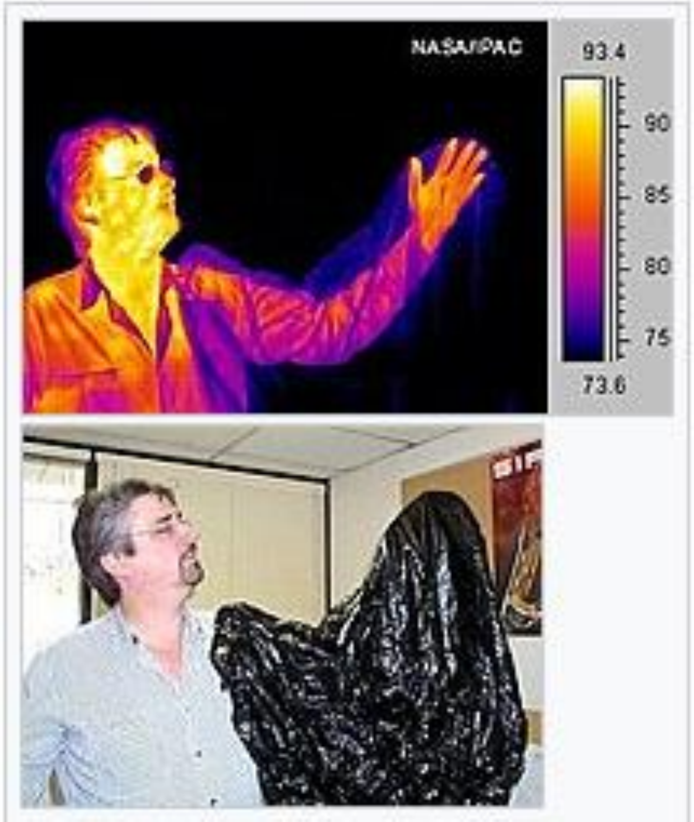
Why Physics Matters in Infrared Imaging

Most Industrial Imaging customers are well versed on visual imaging limitations and challenges, but most don't understand the benefits and limitations of Infrared Imaging, how to troubleshoot, and how to optimize. This breakout will discuss the differences between visible and infrared imaging with an emphasis on how using basic physics can aid in rapid selection and optimization.

Introduction

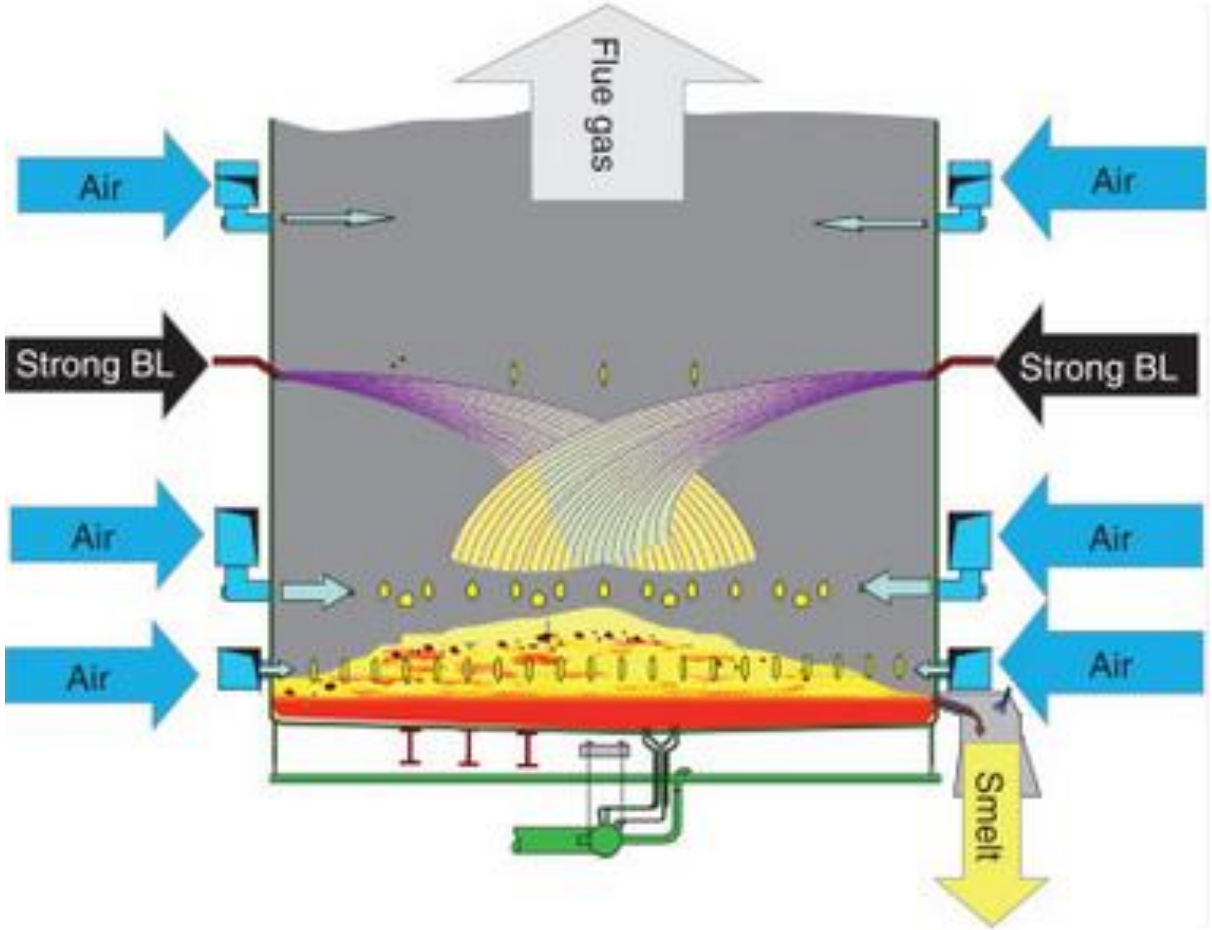
Visible v. Infrared



- What can we see with visible
- What can we see with infrared
- What can't we see

- The answers to these questions are the same that have to be considered for process monitoring cameras

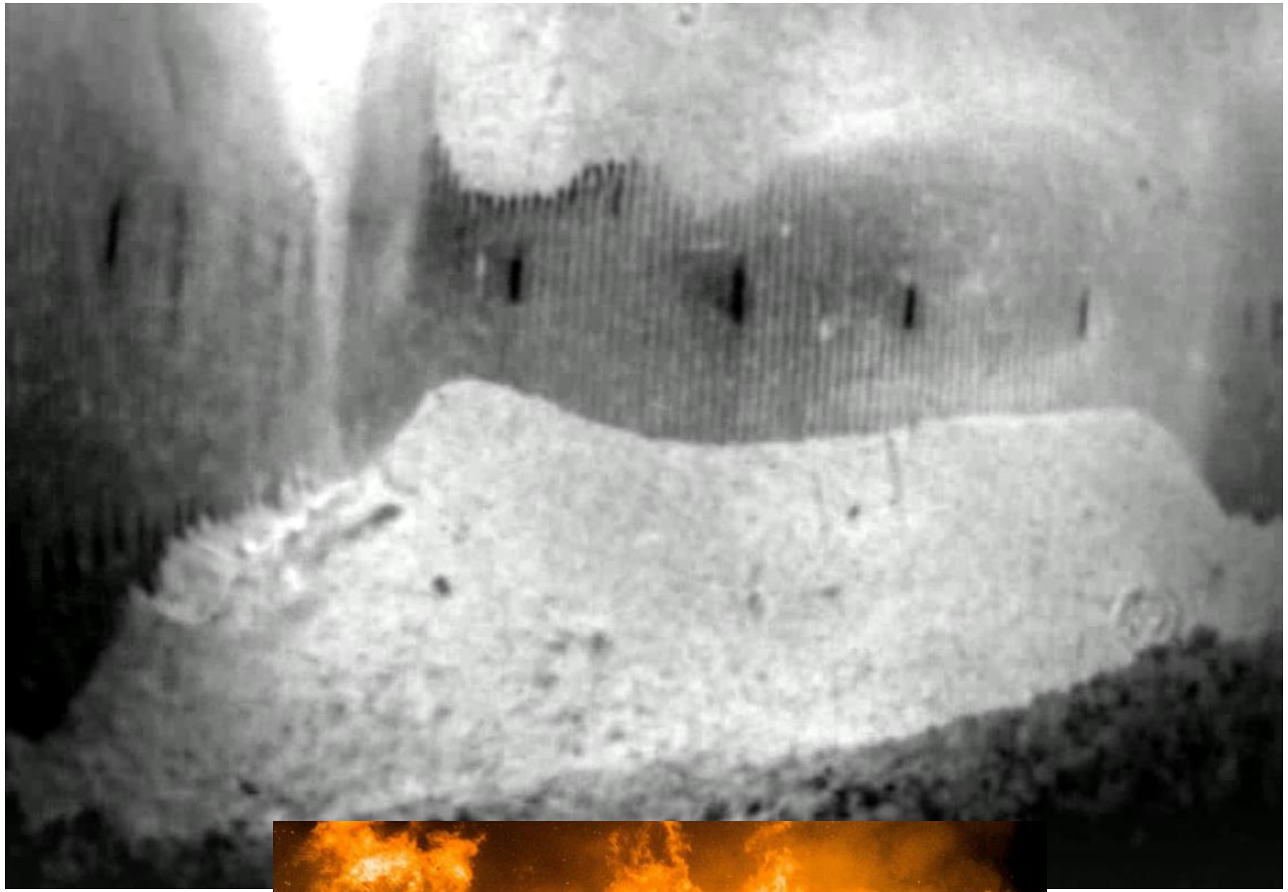
Typical Process Monitoring Application

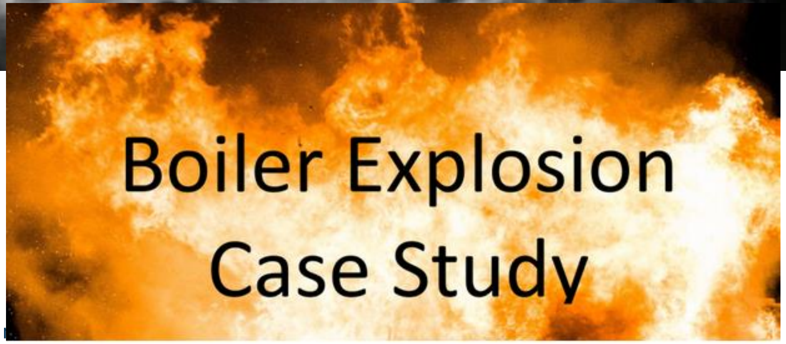


Recovery Boiler – What want to see

- Bed profile
- Slagging
- Primary air ports
- Secondary airports
- Fume circulation
- Fuel load
- Burn performance

Typical Process Monitoring Application





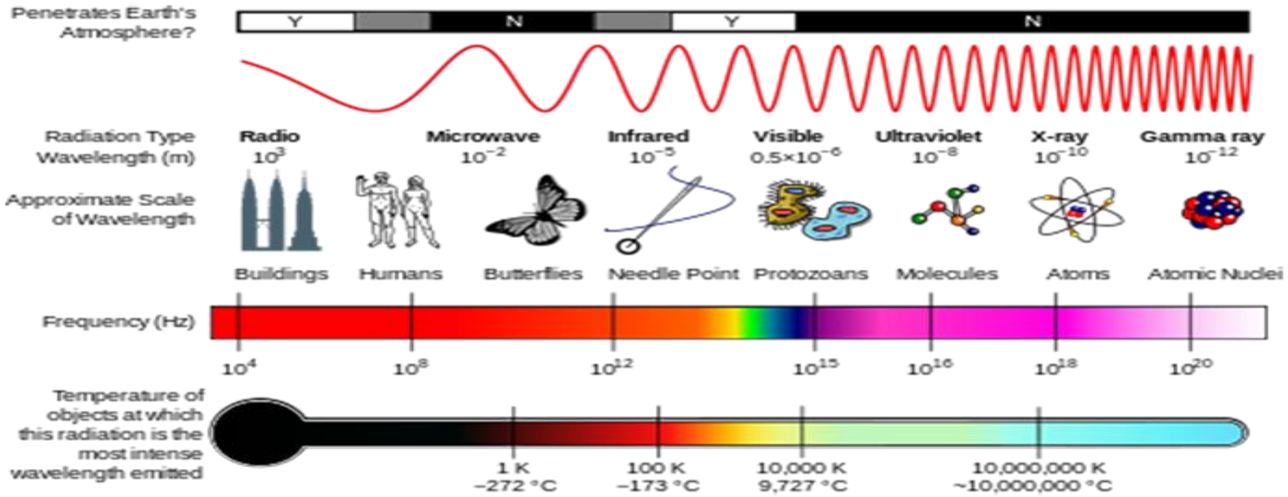
Recovery Boiler – What want to see

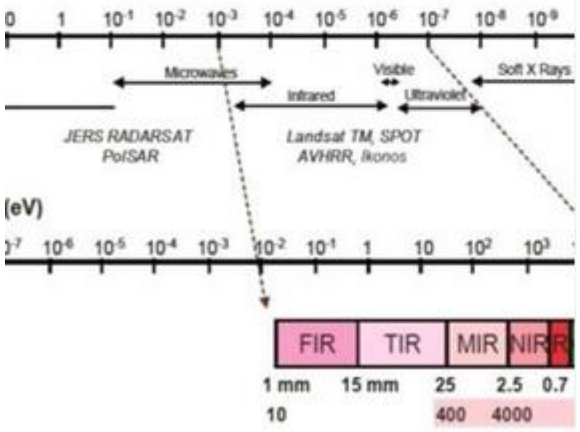
- Bed profile
- Slagging
- Primary air ports
- Secondary airports
- Fume circulation
- Fuel load
- Burn performance
- **No leaks/explosions**

Spectrum Overview

Stefan-Boltzman Law

- Don’t fall too deep into the equations as we’ll provide examples
- $M=\varepsilon\sigma T^4$ (Radiant exitance, emissivity, Stefan-Boltzman constant, temperature ˚K)
- $\varepsilon=5.670x10\text{-}8\ Wm^{-2}K^{-4}$
- Total emitted energy of a black body is equivalent to the 4th power of the absolute temperature





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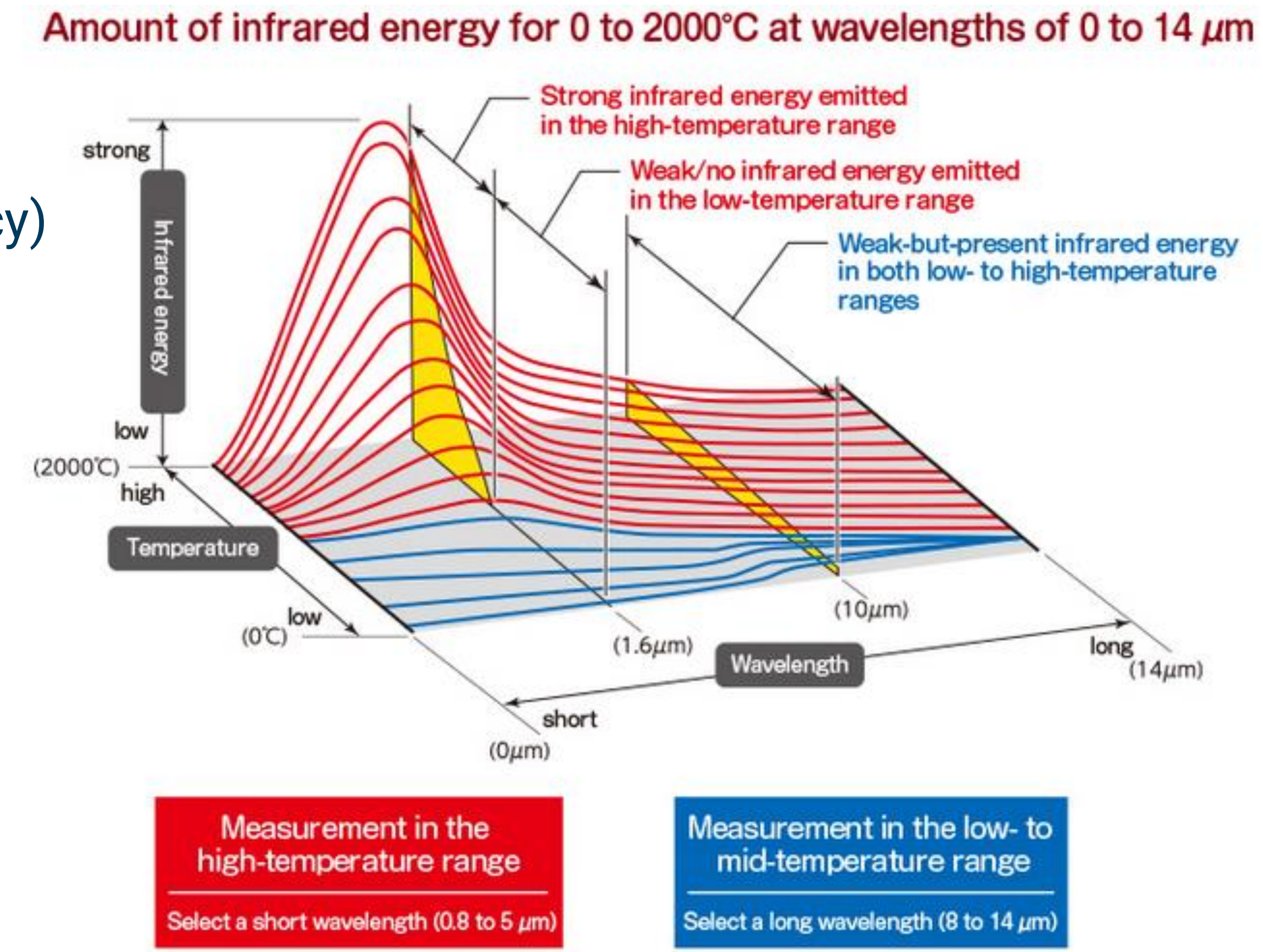
Spectrum Overview

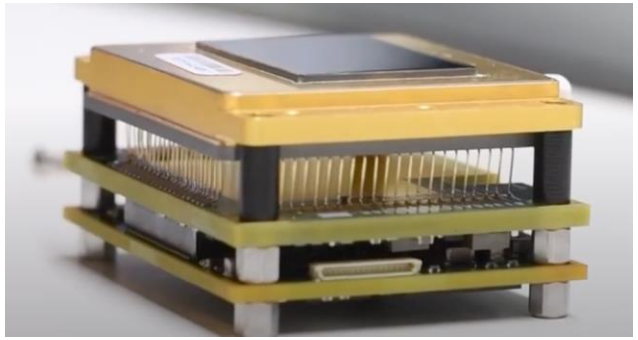
Planck's Law

- E=hf (Energy, Planck's Constant, frequency)
- 6.63×10^{-34} Joule seconds
- Photon energy is directly related to wavelength
- **Hotter objects have a shorter wavelength**
- **Cooler objects have a longer wavelength**
- **Imagers are sensitive to a window of wavelengths**



Detector Technologies

Typical Infrared Imagers



Needs for Imaging

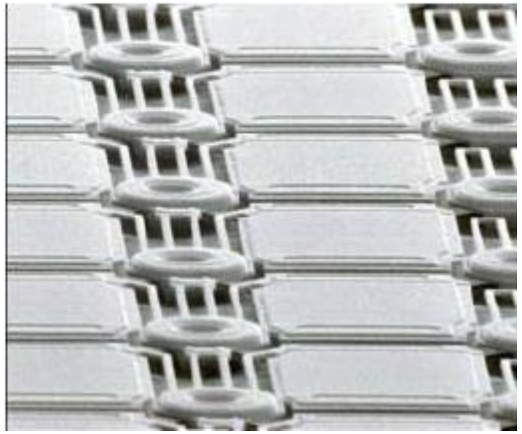
- Array matrix of pixels to form a picture
- Ability to correct for uniformity of response
- Frame rate high enough to demonstrate moving process
- Responsive to process wavelength (inclusive of any filtering/optics)

Typical Industrial Technologies

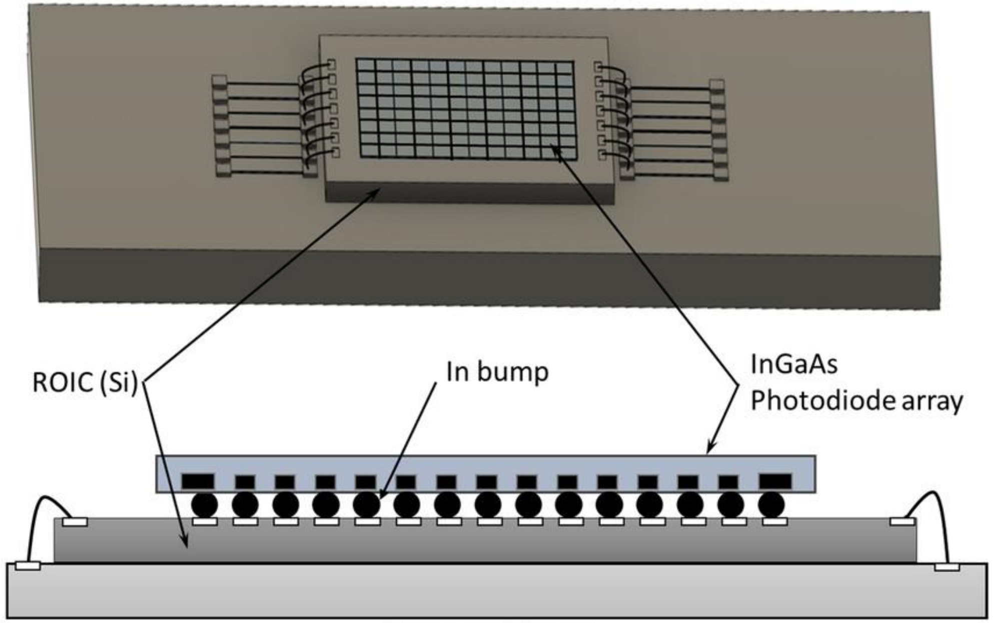
- Often described by material type:
  - InGaAs: Indium Gallium Arsenide
  - HgCdTe: Mercury Cadmium Telluride
  - a-Si: Amorphous Silicon
  - InSb: Indium Antimonide
  - PbS: Lead Sulfide
  - VO: Vanadium Oxide
  - Silicon photodiodes

We want to see through smoke, flame, and atmosphere – others have similar applications → results in review for ITAR and export restrictions

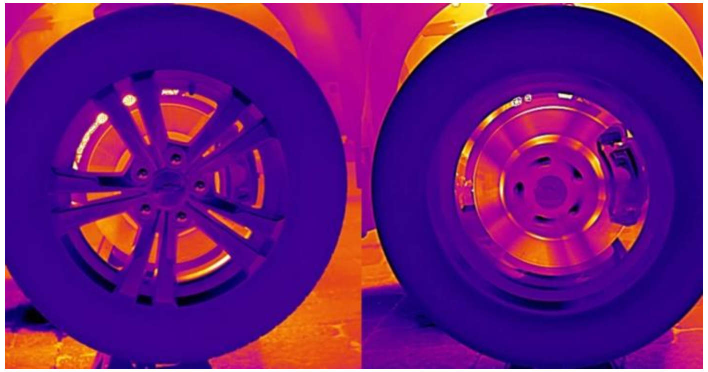
Infrared Imager Challenges

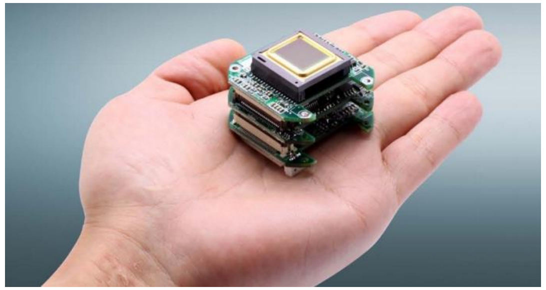


- Cooled v. Un-cooled
- NUC (single point and multi-point)
- Dynamic Range
- Sensitivity
- Thermal maintenance of Imaging Chain
- Dead Pixels
- Shutter v. shutterless
- Cost
- Technology restrictions



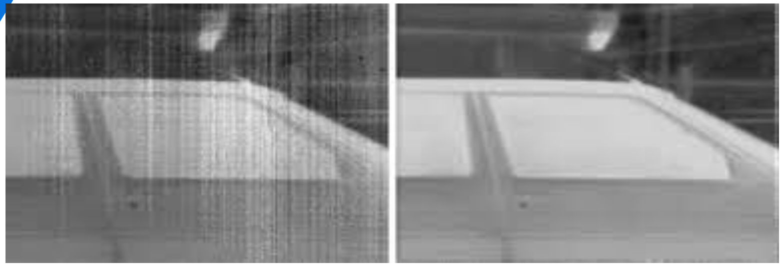
Cooled v. Un-cooled

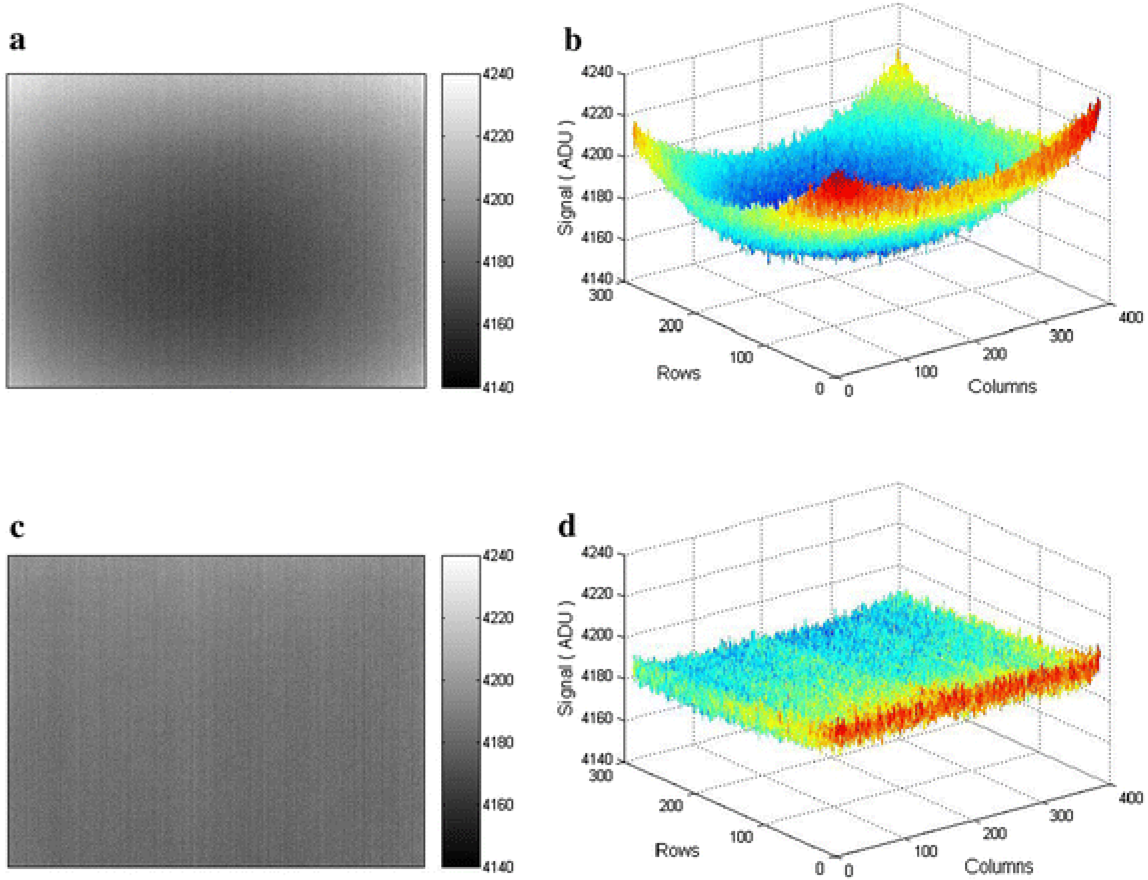




Minus	Plus
▪ Size	▪ Stable Image
▪ Complexity	▪ Enhanced Response
▪ Maintenance	▪ Reduced spectral noise
▪ Power Consumption	▪ Smaller temp differences
▪ Cooled Optics	
▪ Cost	

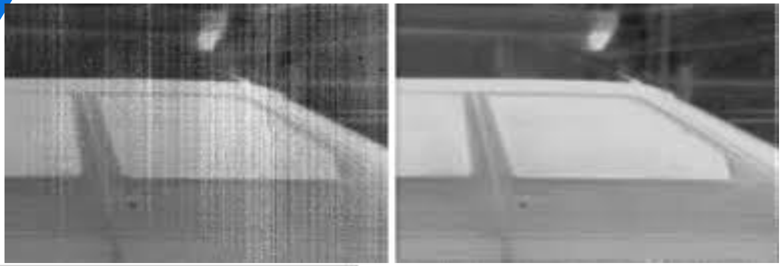
Non-Uniformity Correction

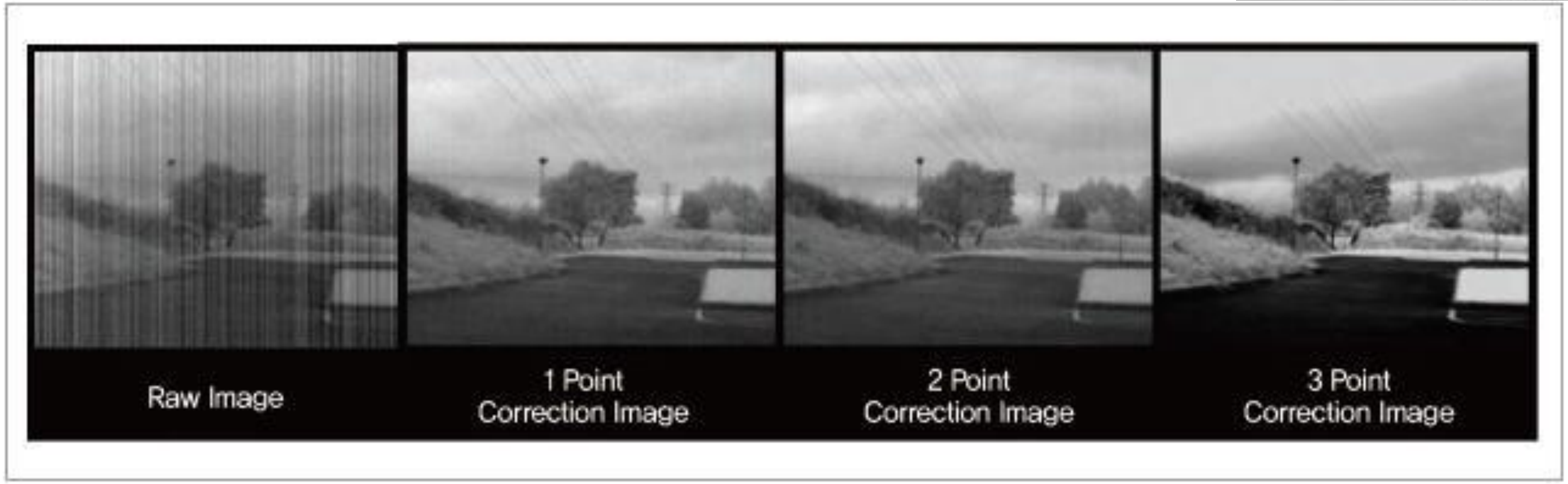




- Manufacturing differences
  - Pixel to pixel
  - Across the array
  - Electrical, optical, and geometry differences
- Imager based and/or entire capture path
- Adjust gain <u>and</u> offset for each pixel
- Some imagers will also include “dead pixel”
- Some imagers include auto-correct shutters

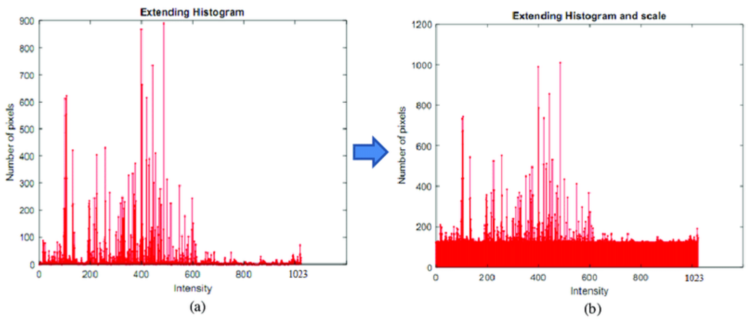
Non-Uniformity Correction

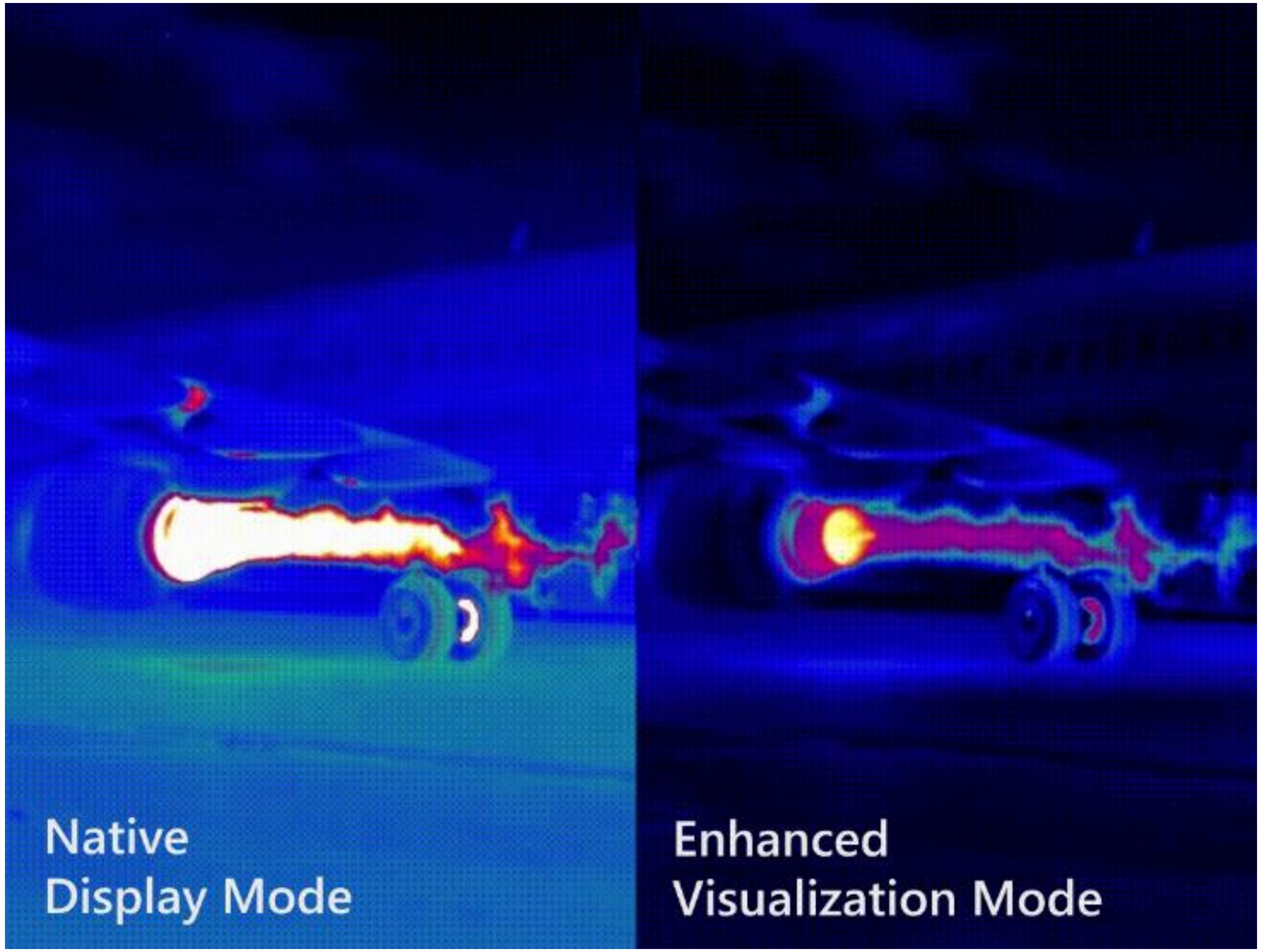




- Requires uniform planar sources of equal energy
  - Emissivity as close to 1 as possible
  - Across expected scene temperature (knowledge of end application)
  - Variations across calibration source minimized
- 1 point = center temperature of process, 2 point = 10%/90%, 3 point = 10%/50%/90%
- Ability to store in imager is required for most industrial applications

High Dynamic Range





- Critical for most industrial applications
- Compensate for variations in thermal load
  - During initial startup of process
  - Varying process levels
- Extends temperature range detectable
- Results in additional process monitoring capabilities
- Simultaneous monitoring of hot/cold objects

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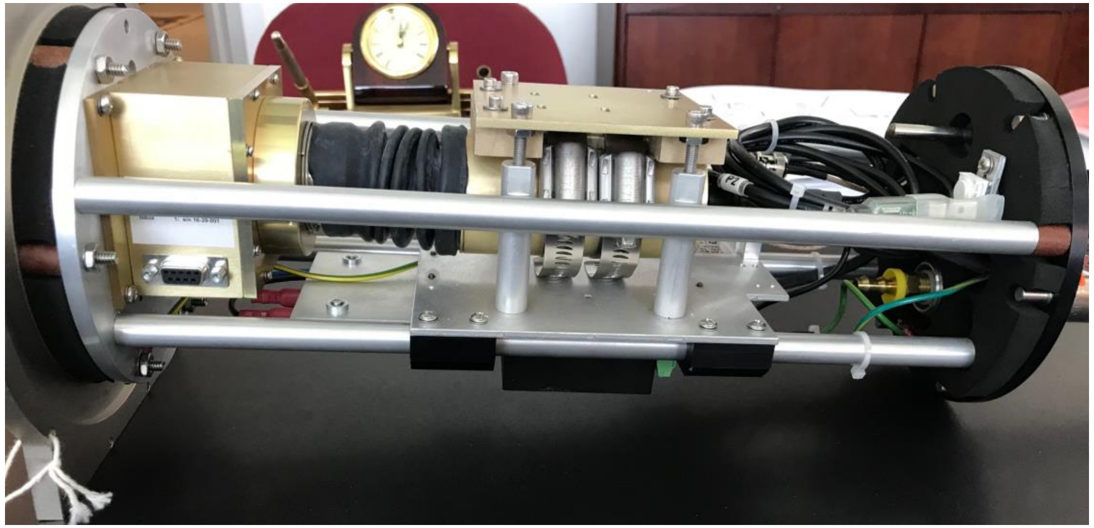
Anatomy of a Typical Industrial Camera



- Imager/detector is a key component, but only one part of the system for process monitoring
- Infrared camera is all about thermal paths
  - All components less than image of interest
  - Temperature stability
  - Isolation from process thermal energy
- Ultimate heatsink (often air or water)
- Adapt to customer process
- Include safety/protection of camera
  - Environmental (oil, water, dust)
  - Withdrawal from process (burnup)
  - Optical support

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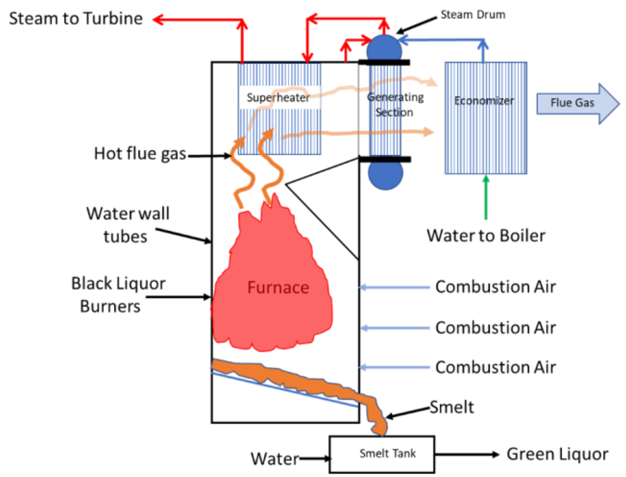
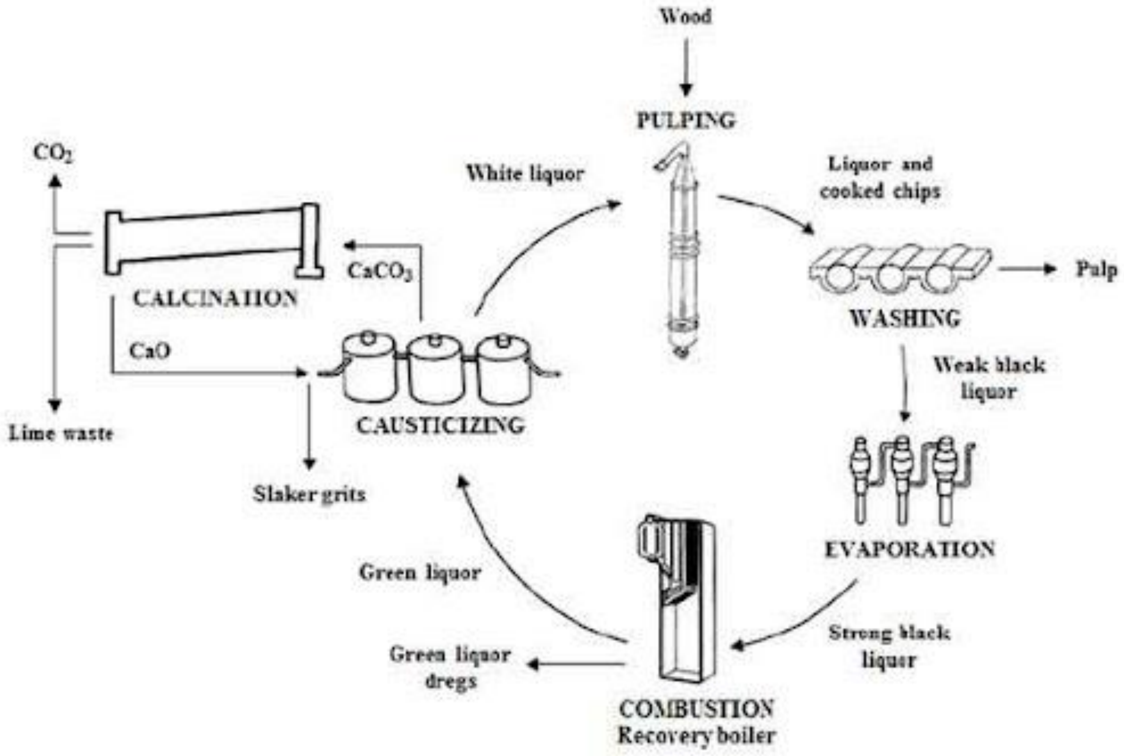
Chemistry, Physics, and Pass Bands

Recovery Boiler – Typical Application

- Process chemistry matters for imaging
- The plant wants
  - Pulp for making paper
  - Combustion heat for conversion and processing
  - Reduction of hazardous compounds
- Black liquor (wood lignins, organic materials, oxidized inorganic compounds and white liquor (H_20, Na_2SO_4, Na_2CO_3, Na_2S, NaOH)
- But, why do we care about chemistry…





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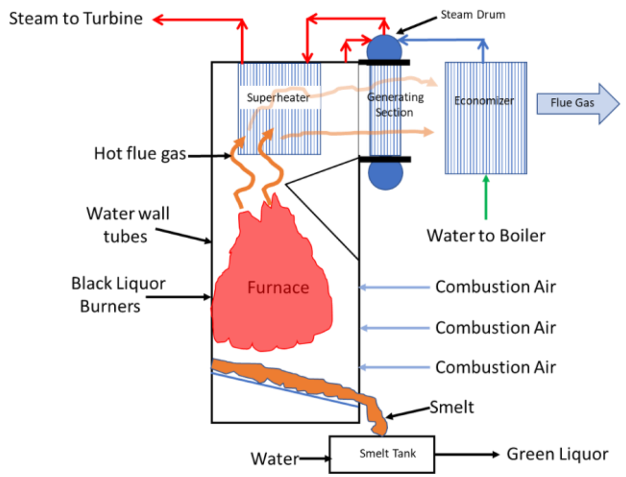
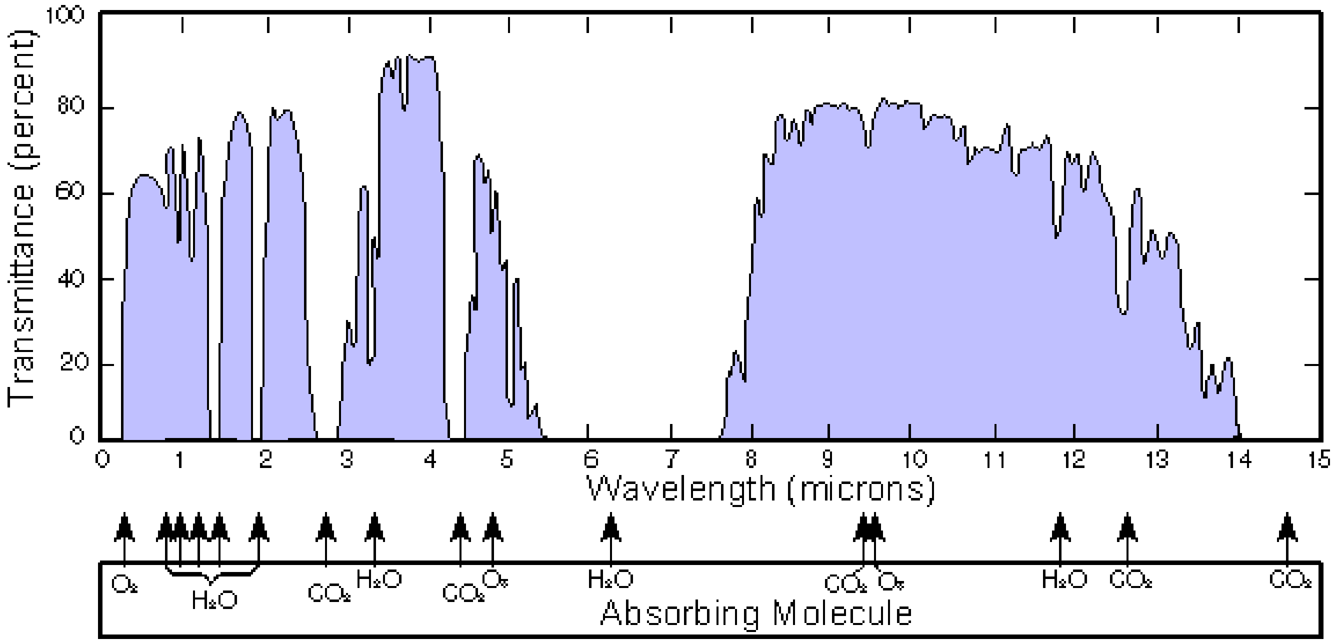
Recovery Boiler – Typical Application



- Why we care about chemistry…
- Some may recall their chemistry and IR spectroscopy
- Different functional groups absorb different frequencies of IR radiation
- There are three main processes by which a molecule can absorb radiation
  - Rotational transition
  - Vibrational transition
  - Electronic transition
- However, all will "block" the IR image



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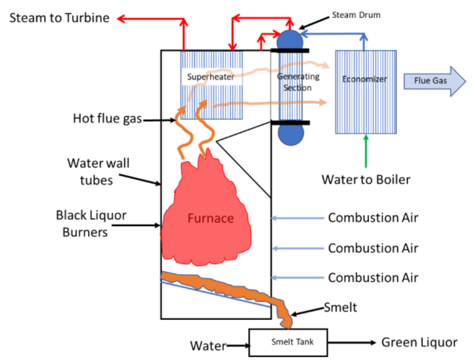
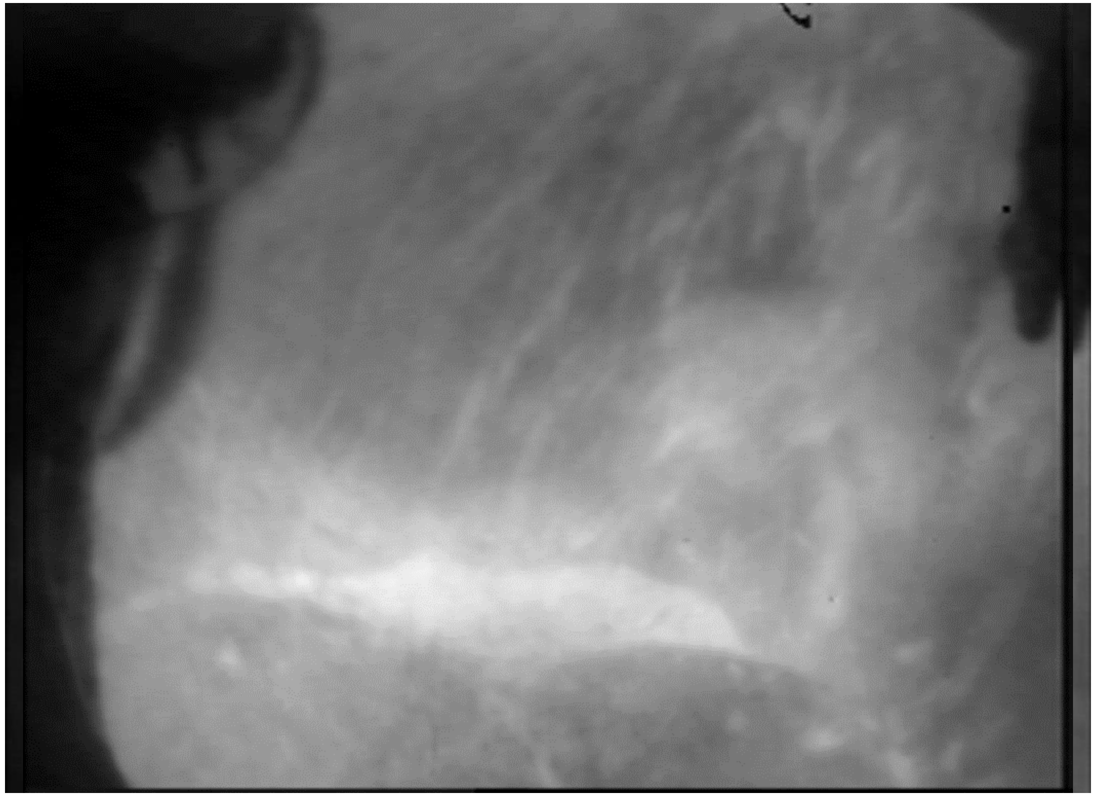
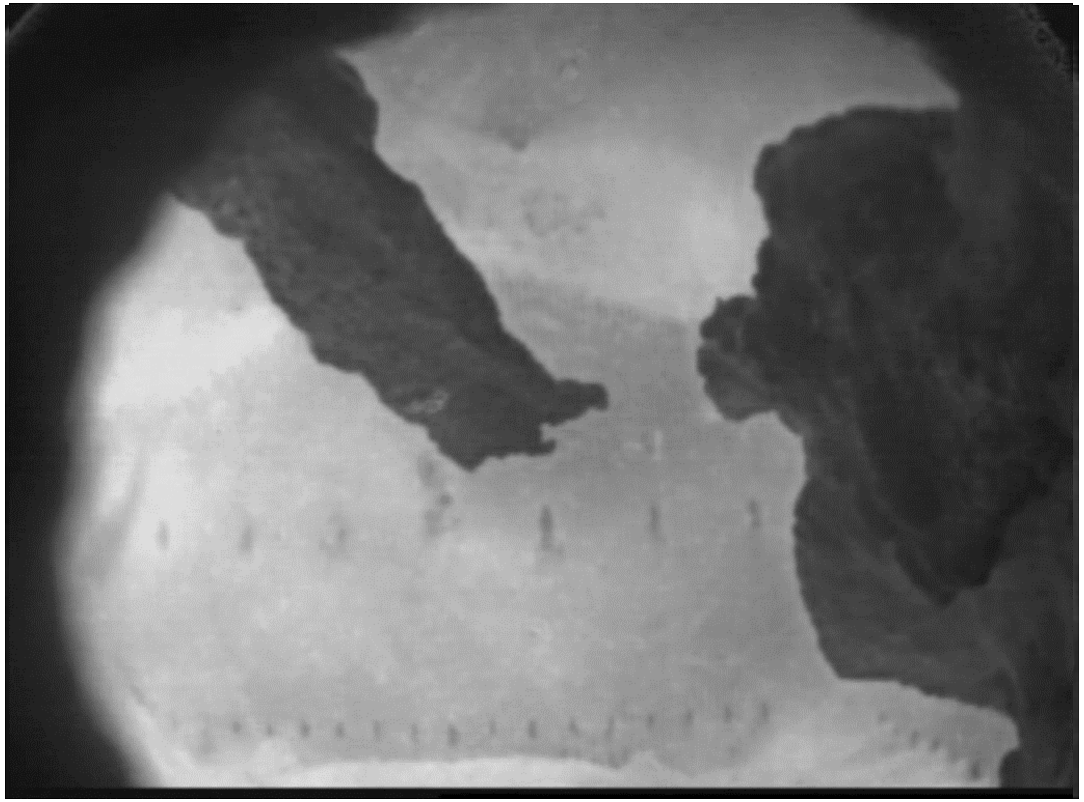
Recovery Boiler - Video



Typical of “blocked” IR radiation

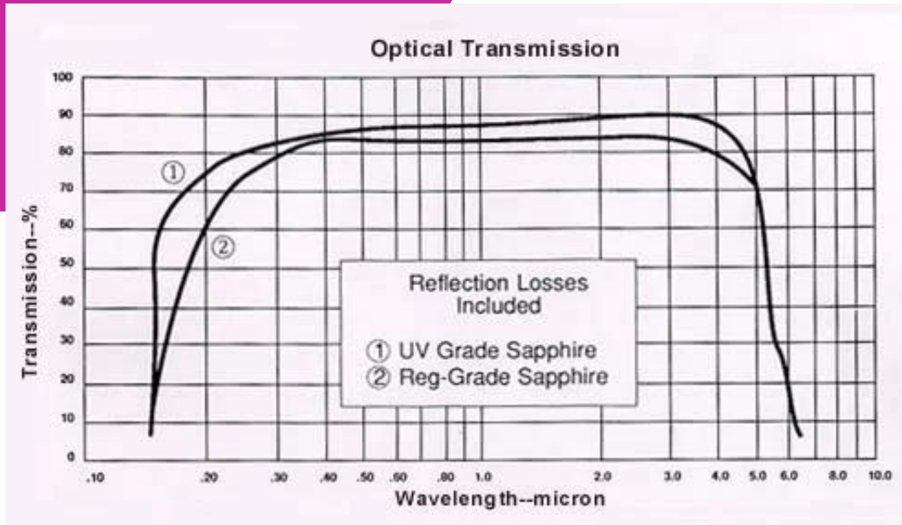


Typical of correct IR pass band



Additional Physics

The entire imaging chain matters



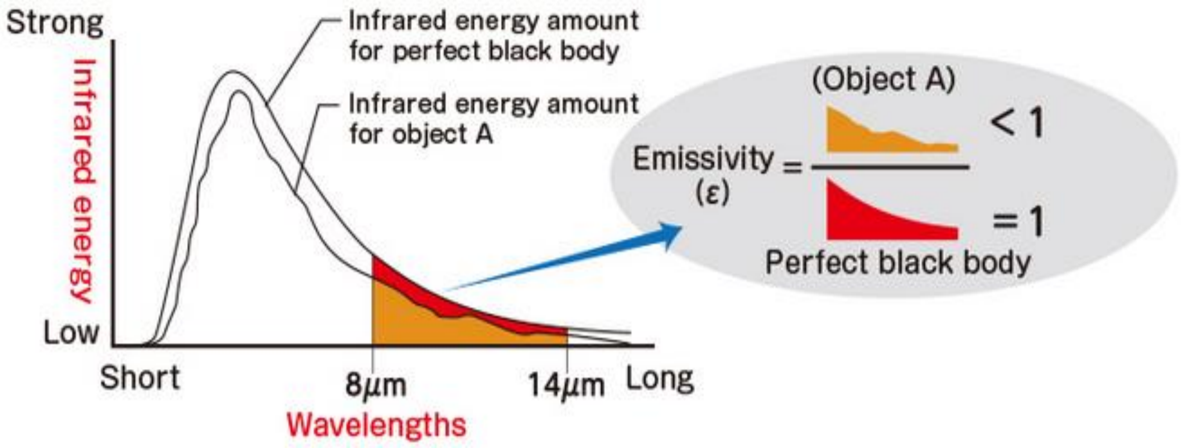
- Windows/entrance elements
  - Sapphire
- Lenses (relay and achromats)
  - Calcium Fluoride
  - Zinc Selenide
- Non-reflective coatings
- Sealing windows
  - Germanium

Recall our first page with the man's hand under the bag

What color were his glasses? Why?

Infrared Considerations

Emmissivity



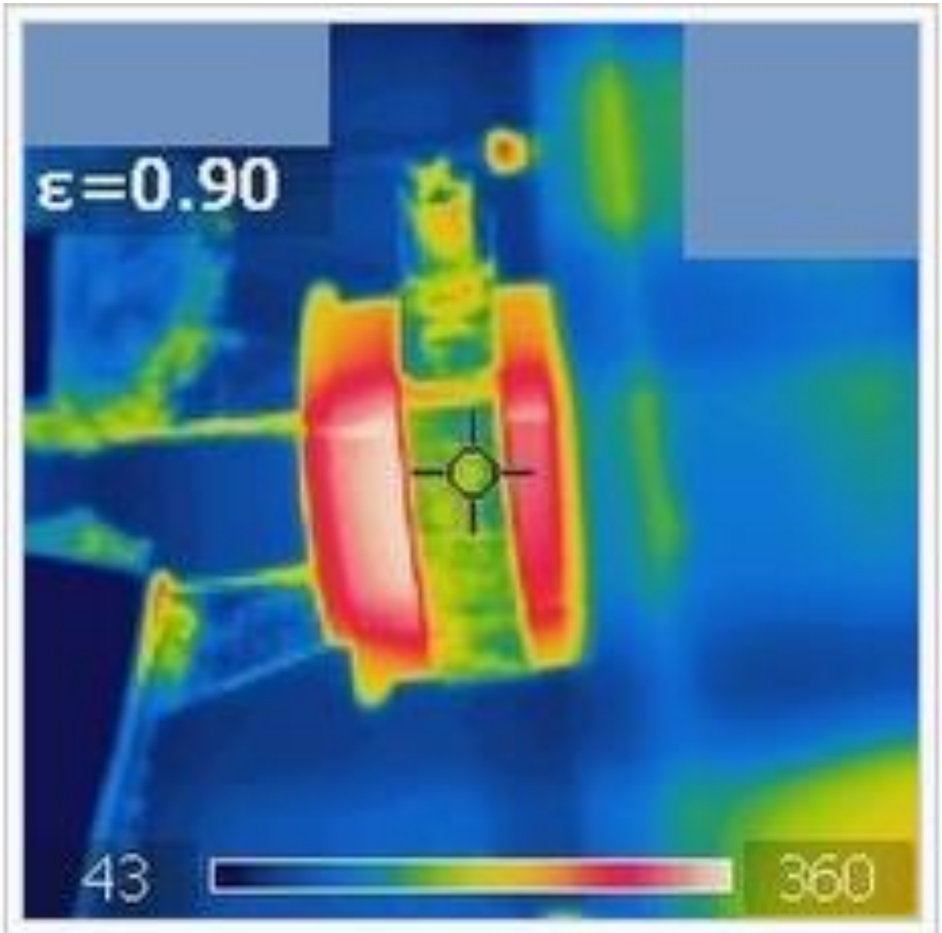
- Emissivity
  - Unitless value between 0 and 1
  - Measurement of effectiveness in emitting energy as thermal radiation
  - Compared to a perfect black body
- Most scenes are not homogeneous
- Important to understand the emissivity of all materials in a scene
- Impacted by wavelength

Emissivity – “false interpretation”

- **IF** goal is only to image, emissivity is not as critical
- **BUT** if process information derived from image this can be problematic

- We know from the previous slide that materials closer to an emissivity of “1” more closely approximate their true temp
- This image shows a ceramic cylinder in the center with silicon carbide on the sides

- **BOTH components are at the SAME temperature!**



Typical Emissivity Table

- Emissivity is unitless
- Emissivity is specified at varying wavelengths
- Surface quality of material impacts emissivity
- Scene emissivity can also guide wavelength choices for imaging
- What is a black body?

Emissivity table

		Emissivity		
Wavelength		1.0µm	5.1µm	8 to 14µm
Aluminum	Non-oxidized	0.1 to 0.2	0.02 to 0.2	0.02 to 0.1
	Polished	0.1 to 0.2	0.02 to 0.1	0.02 to 0.1
	Rough	0.2 to 0.8	0.1 to 0.4	0.1 to 0.3
	Oxidized	0.4	0.2 to 0.4	0.2 to 0.4
Iron	Non-oxidized	0.34	0.05 to 0.25	0.05 to 0.2
	Rusted		0.5 to 0.8	0.5 to 0.7
	Oxidized	0.7 to 0.9	0.6 to 0.9	0.5 to 0.9
	Casting/ Purified	0.9	0.9	0.9
	Fused	0.35		
Glass	Panel		0.98	0.85
	Fused		0.9	
Rubber			0.9	0.95

*Because emissivity varies depending on various conditions (such as temperature and surface shape), actual results may vary.

P550P

Transmittance

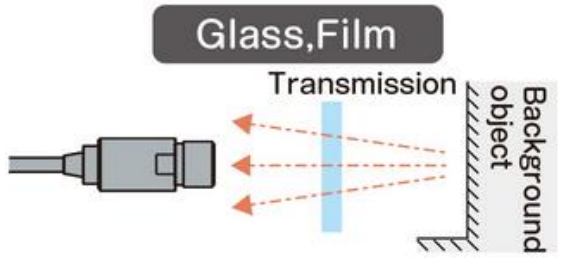
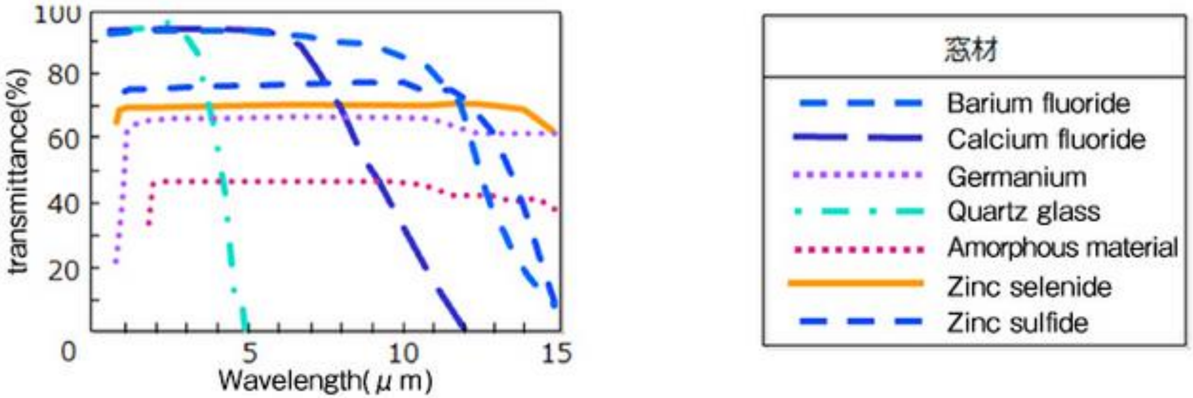
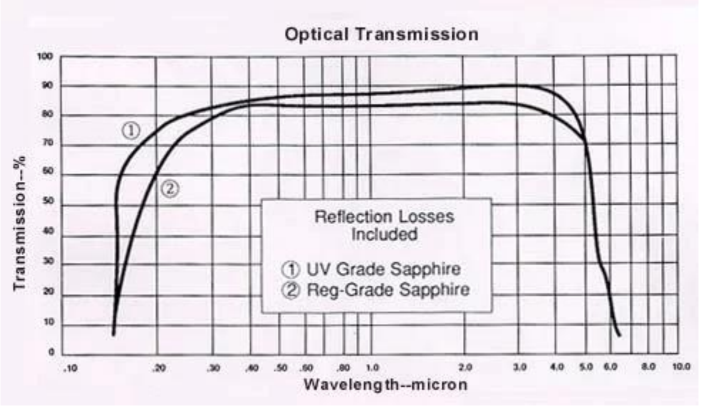


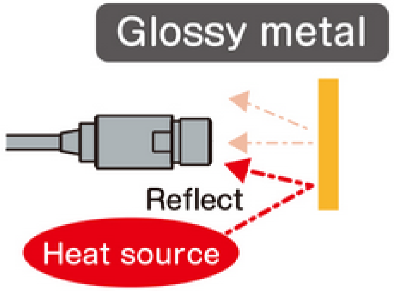
Table 1



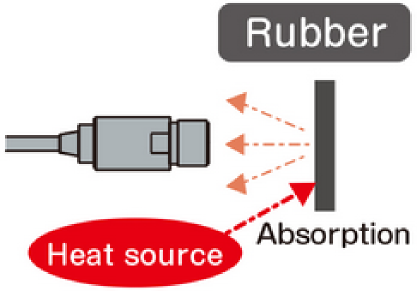


- Recall the camera construction included a number of lens elements and windows
- In order to transmit the scene of interest to the imager, <u>all</u> reduction to the transmission of the infrared energy must be considered
- This includes:
  - Pass bands highlighted earlier
  - Lens elements
  - Coatings
  - Apertures
  - Windows

Reflectance



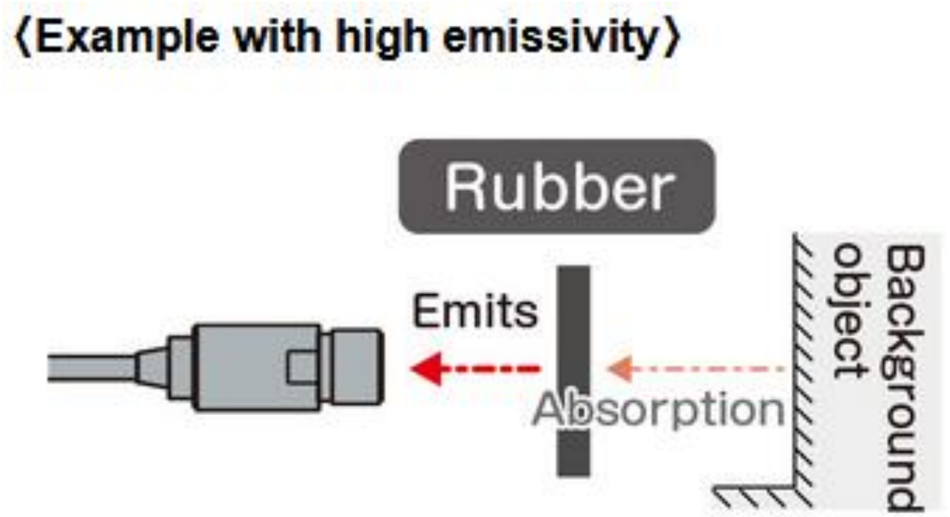
Glossy metal surfaces tend to reflect the infrared energy of other objects.
→ Measurement can be easily affected by nearby heat sources.



Rubber and other such objects absorb infrared energy, preventing that energy from being reflected.
→ Measurement is not likely to be affected by nearby heat sources.

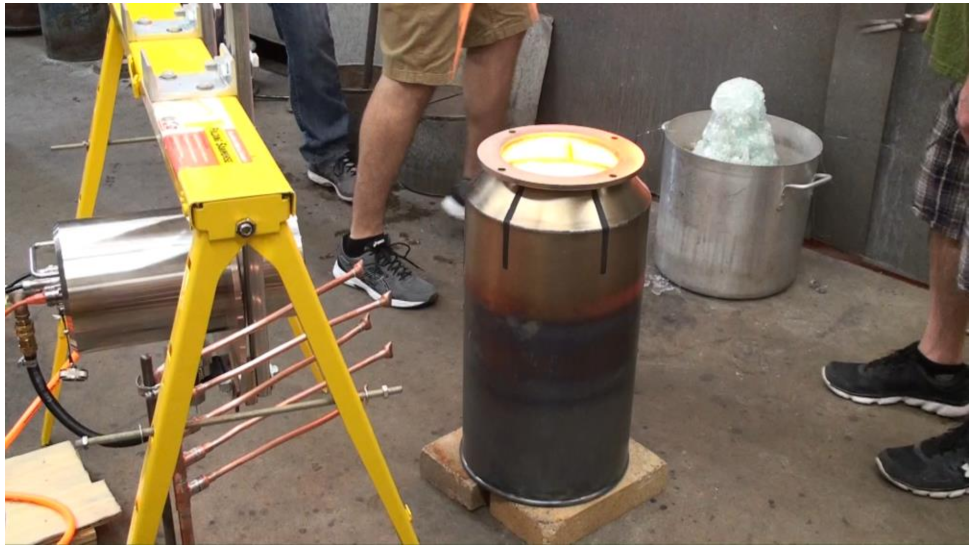
- Shiny smooth materials are more likely to reflect
- Some materials are reflective in the IR spectrum, but not in the visible
- Most materials reflective in the visible spectrum are reflective in the IR
- Metals are often both transmissive and reflective
- Careful shielding of non-interesting heat sources can be beneficial
- Changing angle of view can also be considered

Secondary Infrared Sources



- Special case of high emissivity and low transmission
- Used to understand temperature of material of interest beyond a protective covering
- Image secondary material, but recognize physics impacts from primary material
- To be effective primary material must be dominant source of energy (Stefan-Boltzman)
- Can make use of selective cooling and shielding to emphasize impact
- Can we think of useful examples?

Secondary Infrared Example



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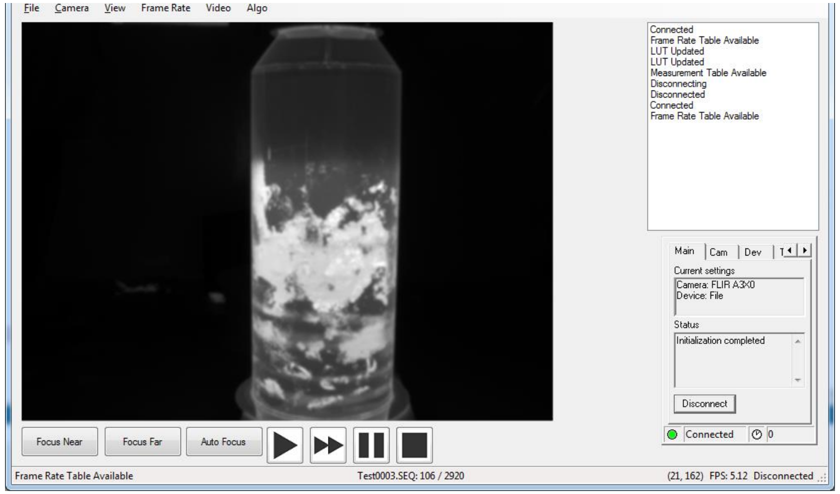
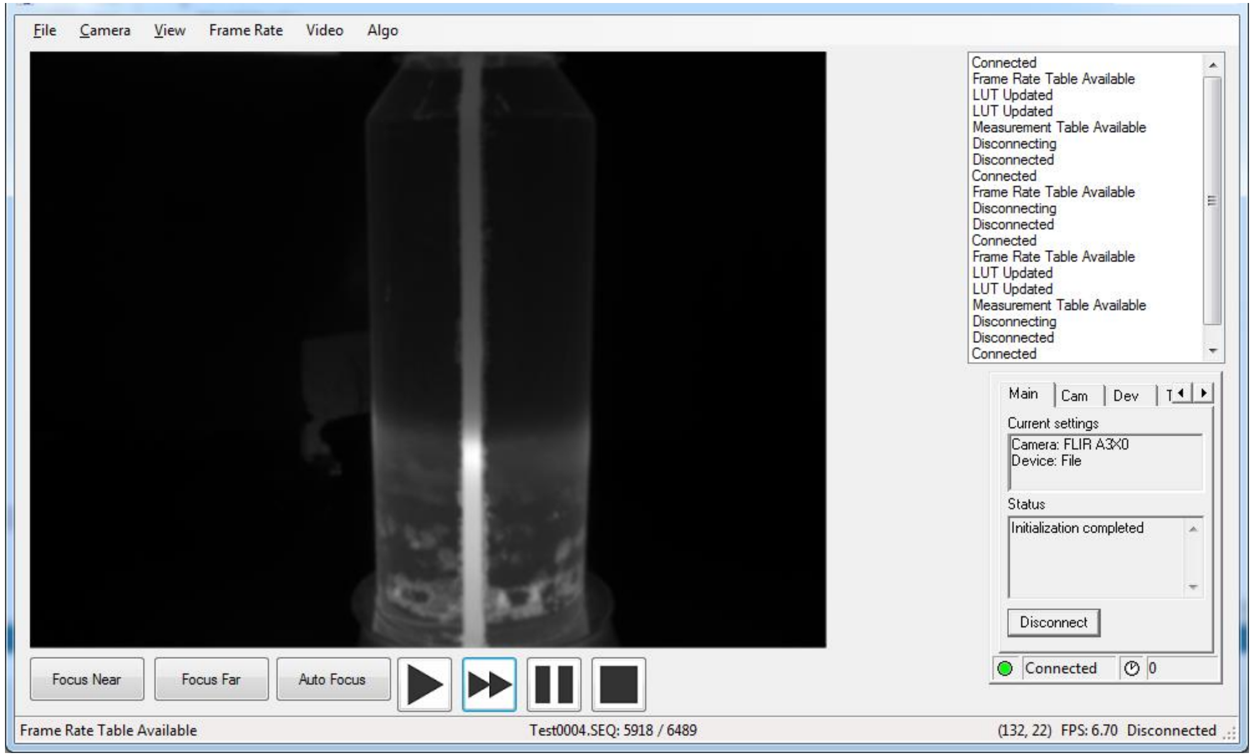
Secondary Infrared Example

Molten Glass Filling of Stainless Canister

- Primary material of interest is molten glass
- Stainless steel canister is material that can be imaged
- What challenges need to be addressed in this situation?
- Hint:
  - Utilize what we've learned about emissivity, transmittance, and reflectivity
- What other physical properties should be considered?

Secondary Infrared Example

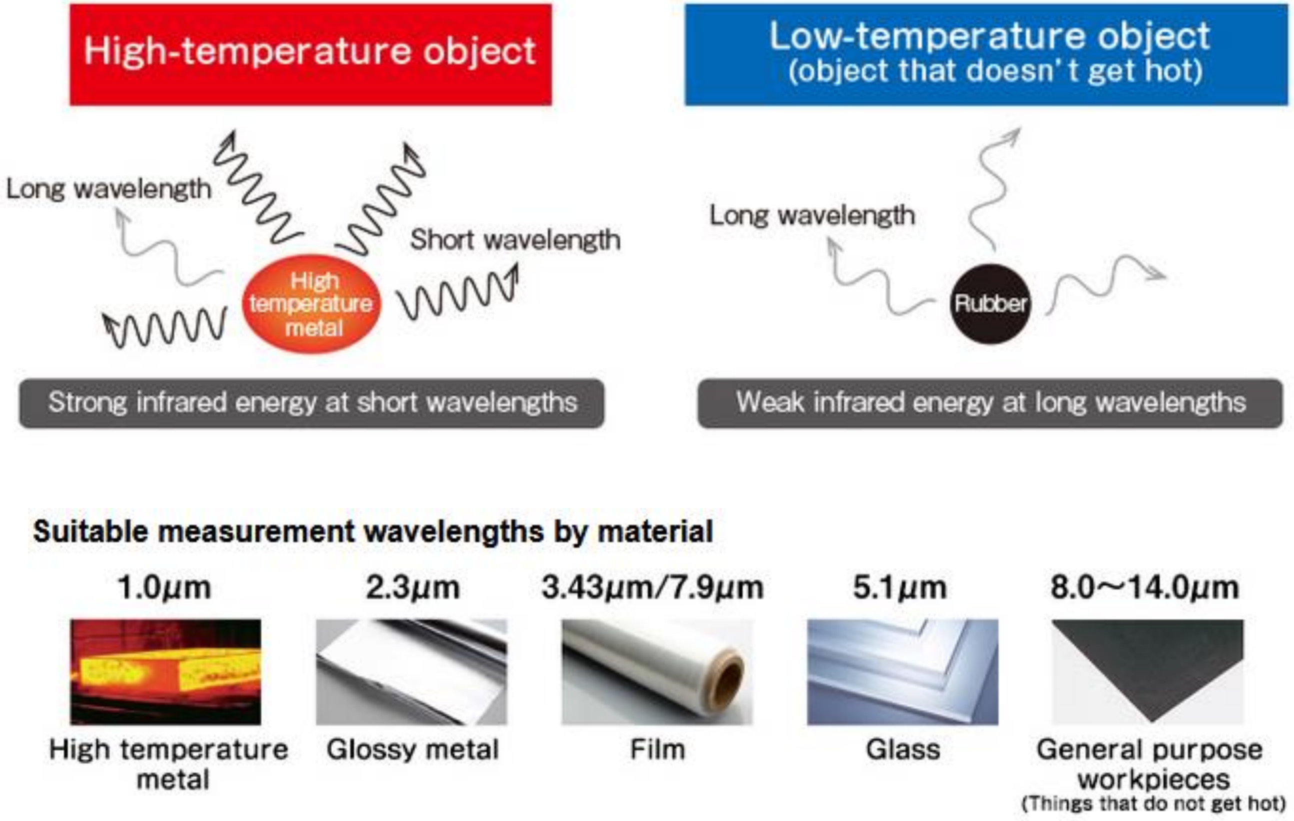




Challenges

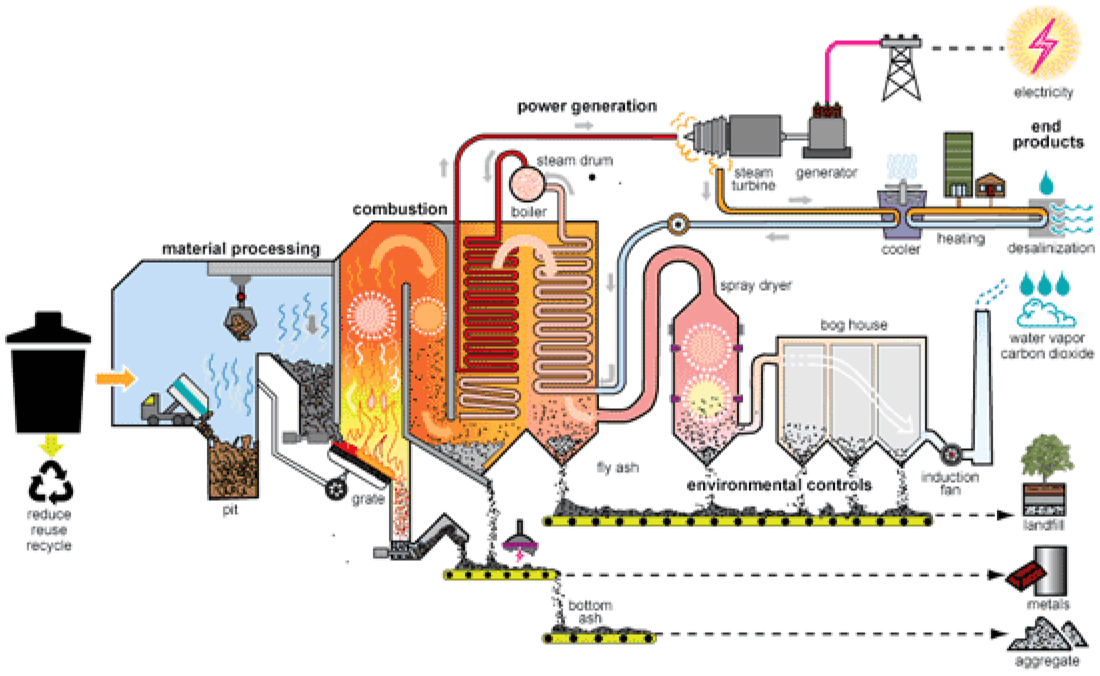
Challenges

- As is often the case, may have competing parameters to optimize
- The wavelength best suited for the material or process of interest may not be ideal for the physics
- Must always consider key parameters
  - Emissivity
  - Transmittance
  - Reflectance
- Remember what Planck's and Boltzman tell us



Challenges

- Instinctively we consider visual spectrum, but need to think about the physics
- Wide variation in process load and temperature can greatly impact energy (4th power of absolute temperature)
- Use of process variations (i.e. use of secondary fuel) with radically different chemistry
- Operations may require visualizing different aspects at different times



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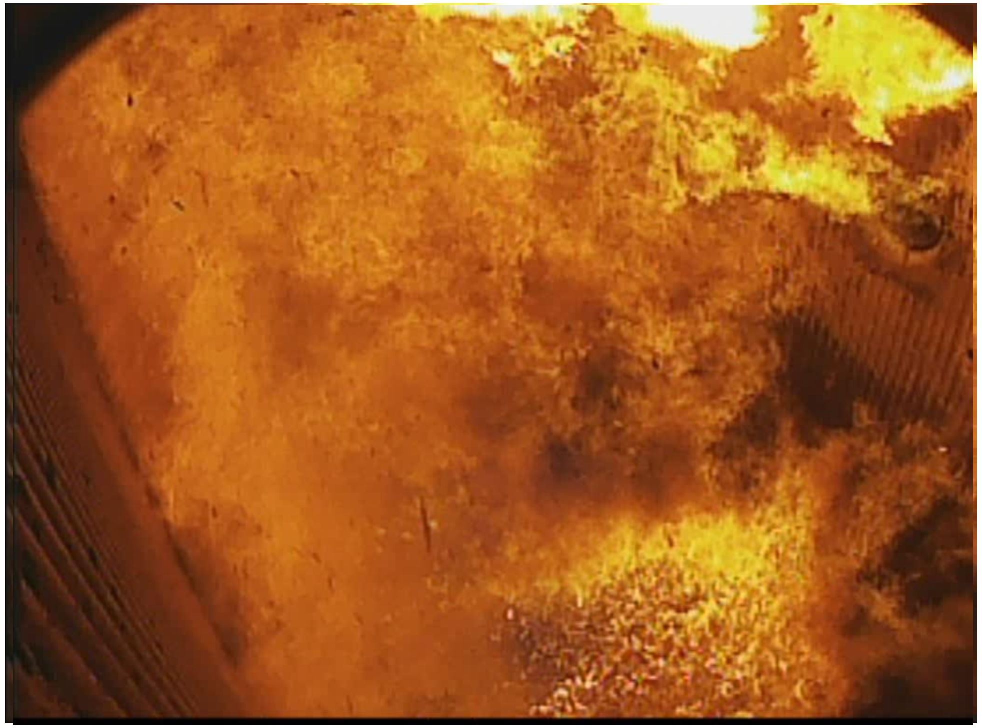
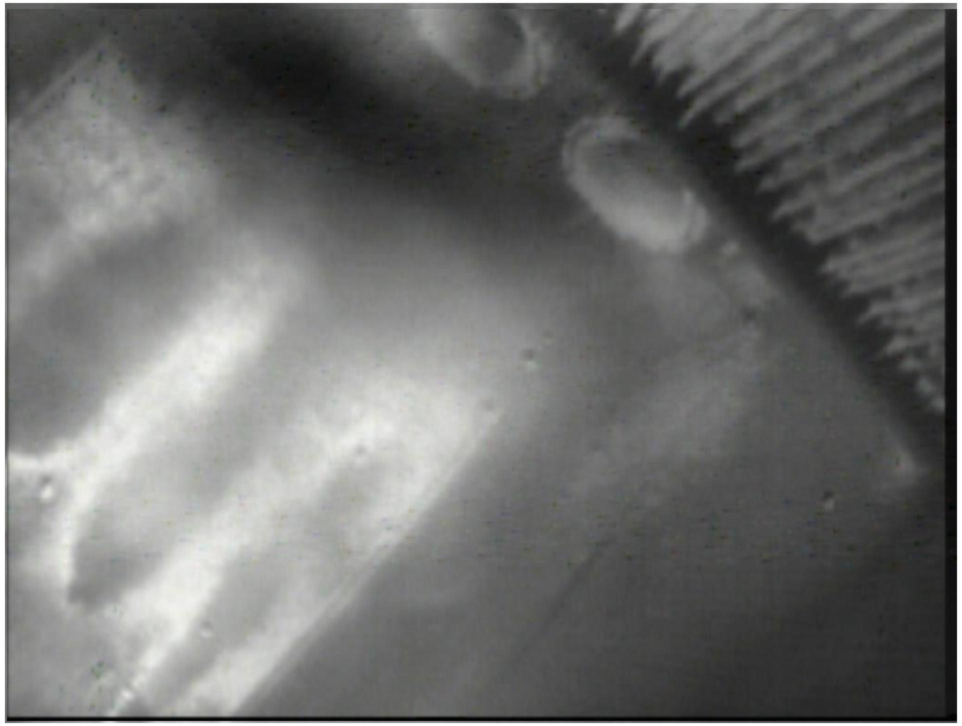
Challenges

Bark Boiler (visible spectrum)



Bark Boiler (infrared spectrum)



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Putting it all together…

Putting it All Together…

- Infrared is not the same as visual imaging
- Physics (and chemistry) can provide us with the base understanding
- Becomes an optimization and tradeoff challenge between the key parameters
- There is no substitute for testing
- Testing should be performed with an understanding of the possible parameters to optimize, however

Thank you