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A Review of In-situ Temperature Measurements for Additive Manufacturing Technologies

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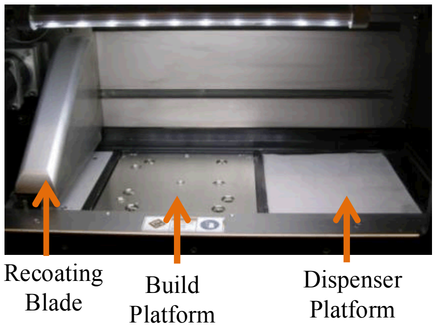
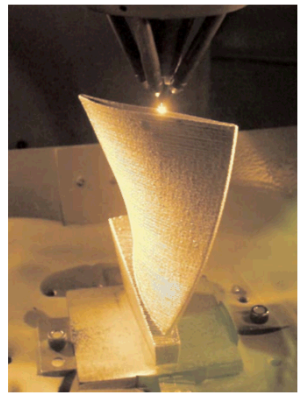
Additive Manufacturing

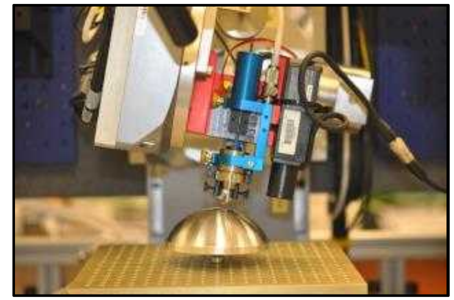
Powder Bed Fusion



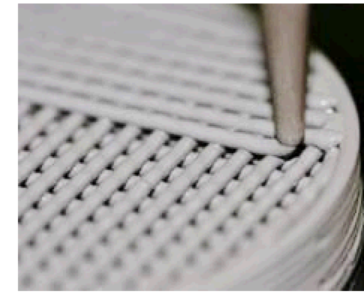
LENS



Metal Direct-Write



Ceramics



Pros

- Quick build times *(minutes – hours – days)*

  Why does traditional material assessment take months?

  Casting/forging/machining: 1 month (1 -12 months if using multiple vendors)

  Metrology: 1 month

- Tailored Properties *(graded density, graded alloys)*

Cons

- Build quality is often poor *(porosity, surface roughness, un-melted powder, warping)*.
- In-situ monitoring still uncommon.
- No in-situ monitoring means no feedback control *(poor run-to-run repeatability, waste light/heat, overheating)*.
- Extensive ex-situ characterization is often still needed *(electron microscopy, x-ray diffraction)*.

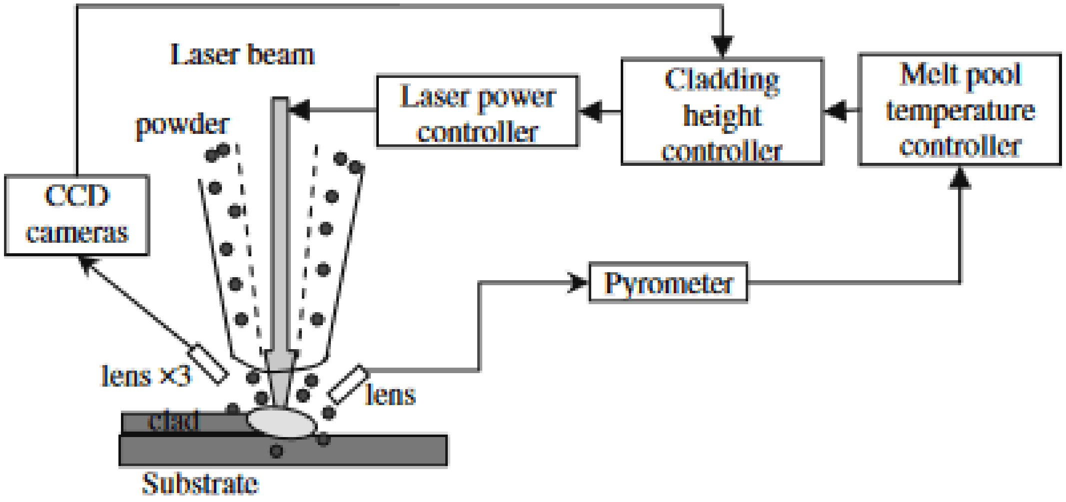
In-Situ Monitoring

Pros

- In-situ monitoring allows for feedback control.
- Feedback control provides greater control over process conditions and builds.
- Control of melt pool dimensions has been demonstrated.
- Dual melt pool dimensions and temperature control.

Cons

- In-situ monitoring is still not widely used or available.
- Challenging to develop.

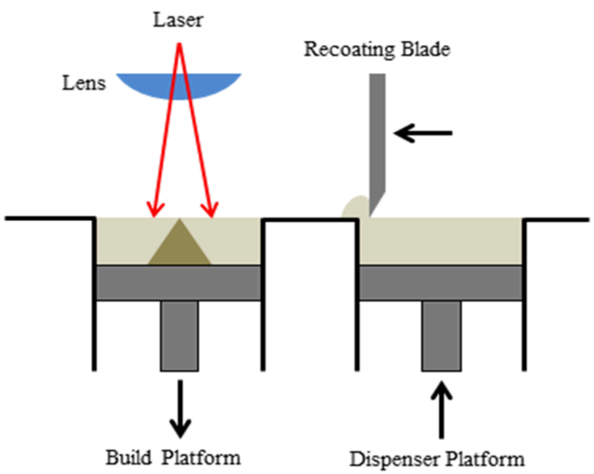


Control of melt pool temperature and deposition height during direct metal deposition process, *Int. J. Adv. Manuf. Technol.*, 2012.

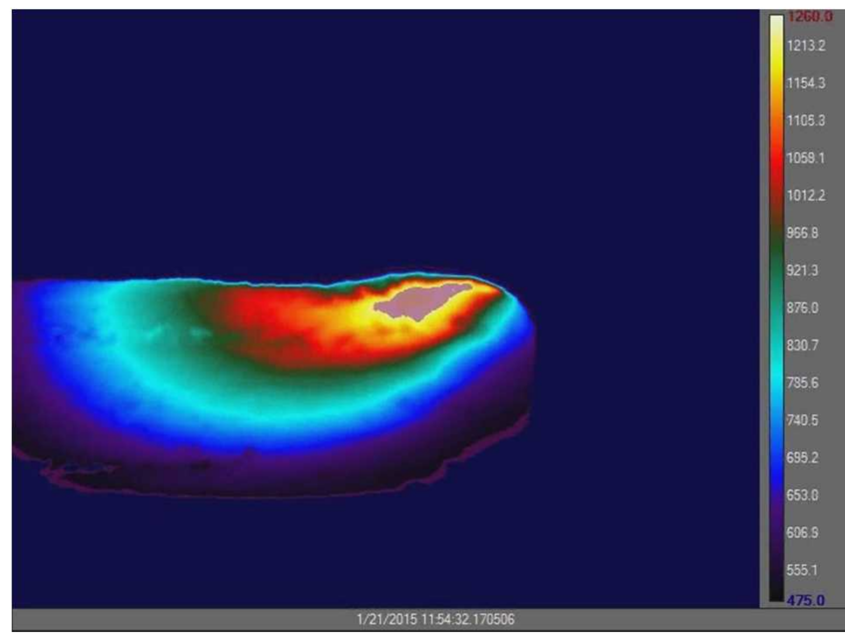
Temperature Measurements for AM

- Why temperature?
  - *The absolute temperature and rate both control the final stoichiometry of the part.*
  - *If you don't know the temperature you don't know much about your build!!!*

- Intensity can be easily measured during a build.



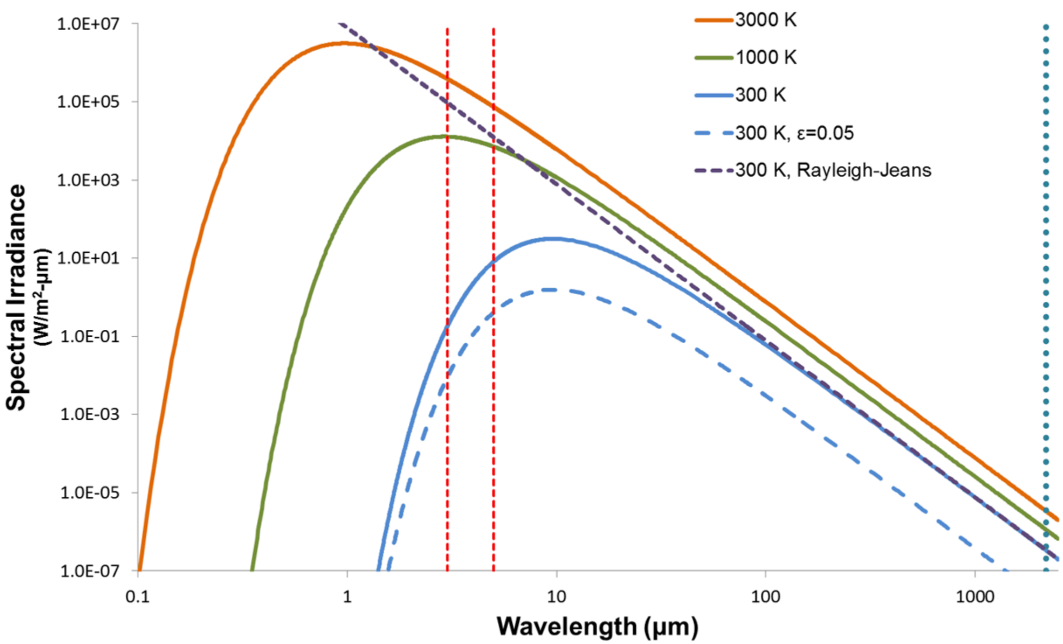
$$E\ (W/m^2) = \varepsilon \sigma T^4$$



thermal history during bi-directional metal deposition

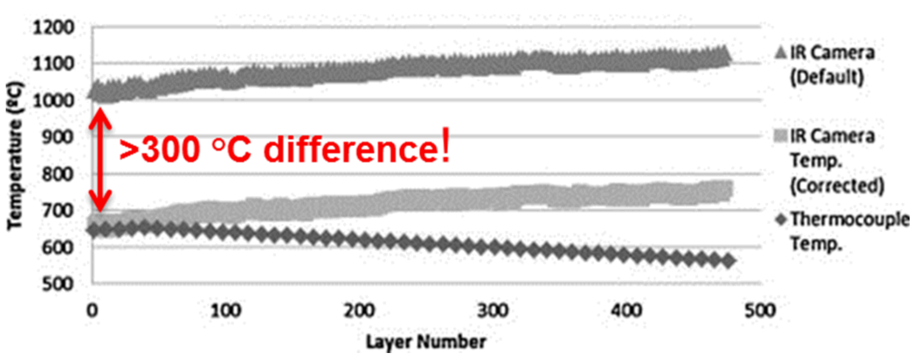
Intensity and Temperature

- *Planck's Distribution* for a Black Body: $I(\lambda, T) = \dfrac{2\pi hc^2}{\lambda^5[e^{hc/k_B T} - 1]}$
- Stefan-Boltzmann Law: $E(W/m^2) = \varepsilon\sigma T^4$



The Temperature Measurement Problem

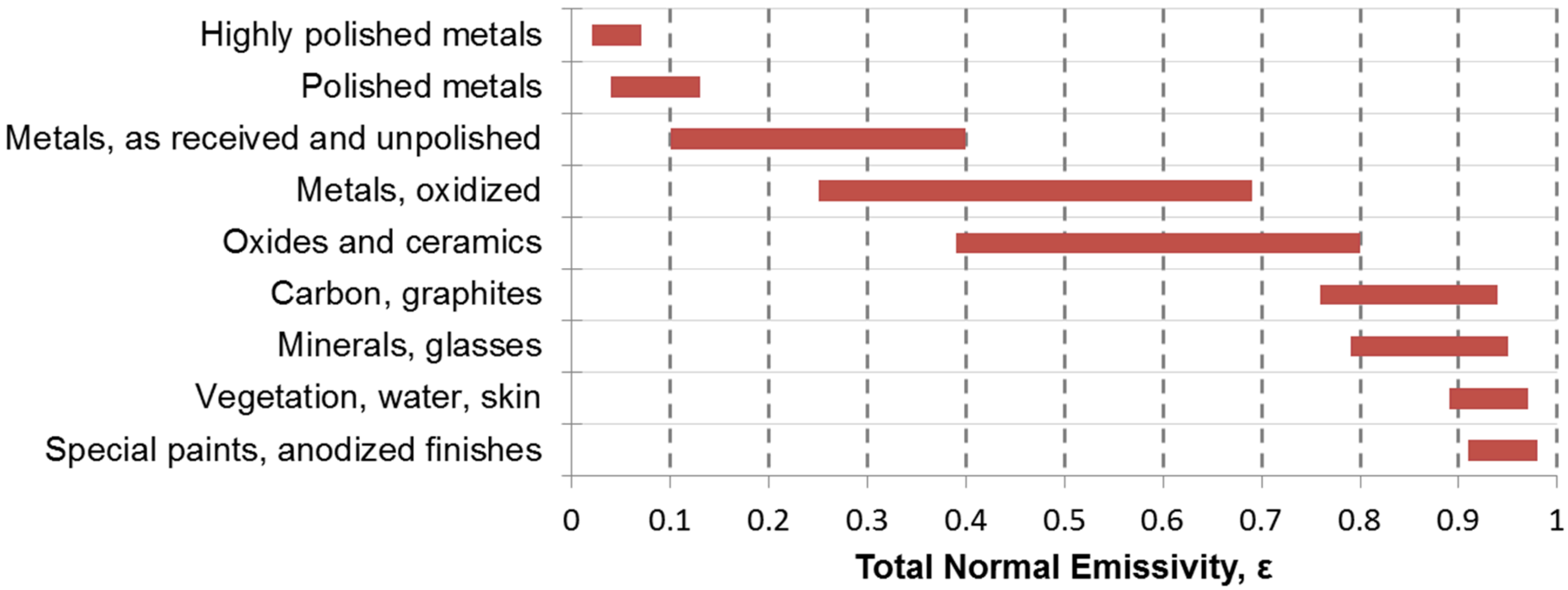
- ***Accurate*** determination of powder bed, melt pool, and part temperatures during build is critical for:
  1) ***Predicting*** performance and parameters such as residual stresses.
  2) ***Validating*** and verifying physics-based models.
  3) ***Feedback control*** for real-time AM process optimization.
- Layer-wise temperature measurement requires non-contact methods, but achieving accuracy a key challenge.



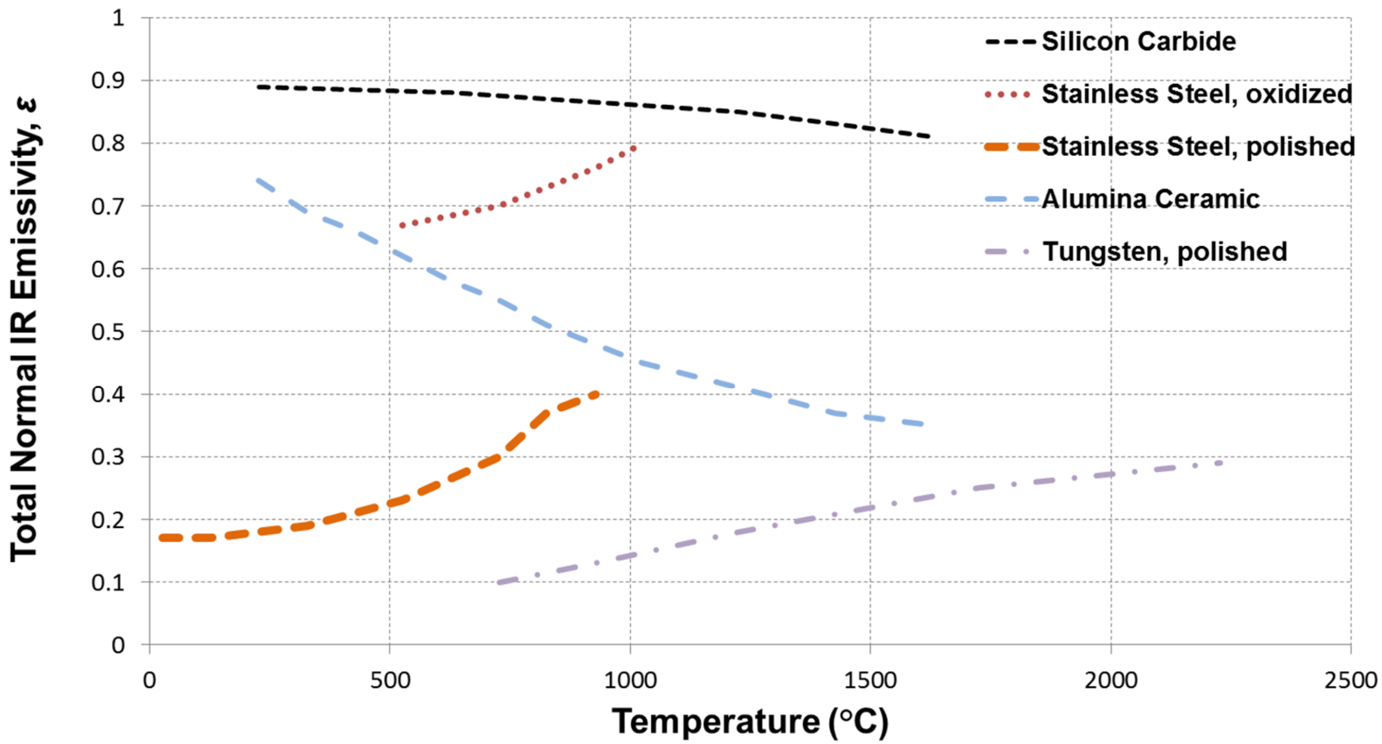
Observed temperature errors in powder bed process using IR Camera with factory calibration. *Rodriguez et al., Add. Mfg., 2015*.

The Temperature Measurement Problem

- ***Emissivity variation is underlying issue:***
  - Depends on material, temperature, wavelength, roughness, surface condition (oxidation, etc.), viewing angle…



Emissivity Changes with Temperature



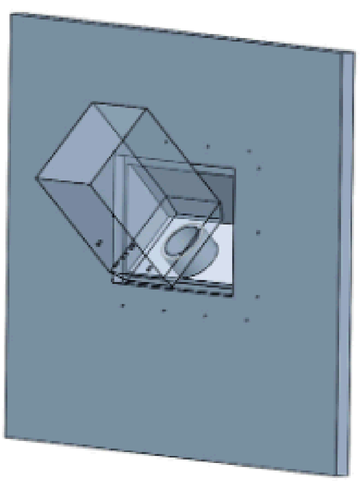
Existing Approaches

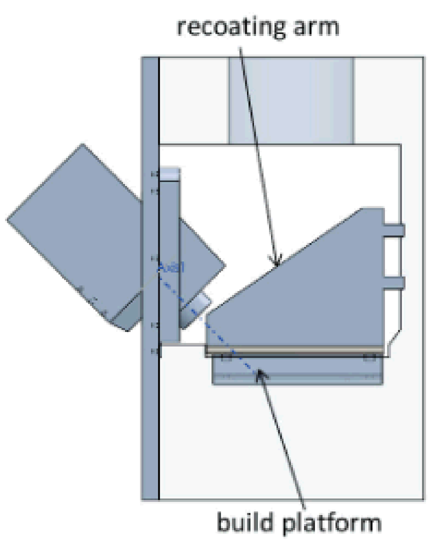
- Infrared Thermography (NIR, MWIR, LWIR)
  - Large field of view, good spatial resolution, high acquisition rate.
  - *Must* correct for emissivity.
  - Single-point black body correction *not* adequate.

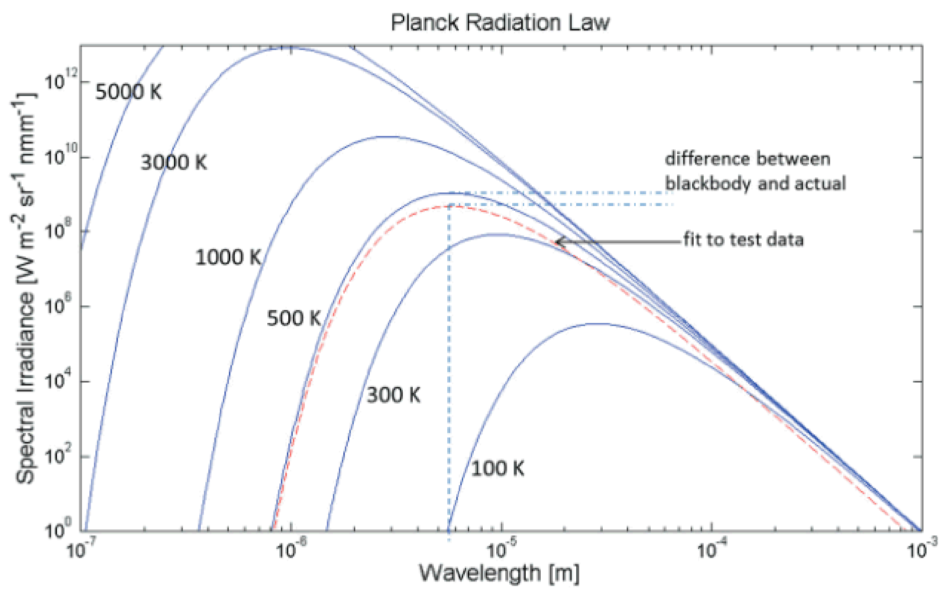
- Two-color Pyrometry (NIR or visible)
  - Ratio of intensities provides some correction for ε, assuming ε independent of wavelength.
  - For materials of interest visible pyrometers lead to ~ 10 °C accuracy
  - In IR, ε strongly dependent on λ **(errors of >50 °C)**.
  - 20 Hz frame rate

Hyperspectral Cameras

- Multiple wavelengths
- NIST is pursuing a custom, 11-wavelength IR camera.
  - Powder bed applications
  - Back-fit Planck's curve for gray body.
  - 80 x 80 pixel sensor array
  - 50 Hz acquisition rate



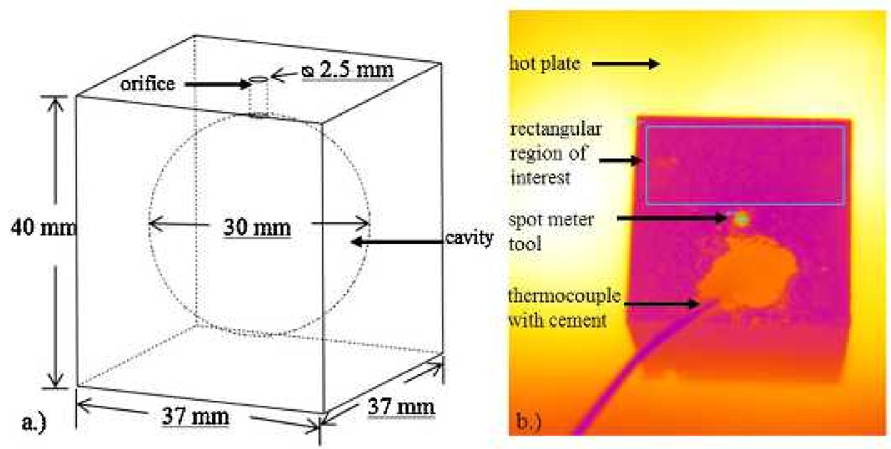


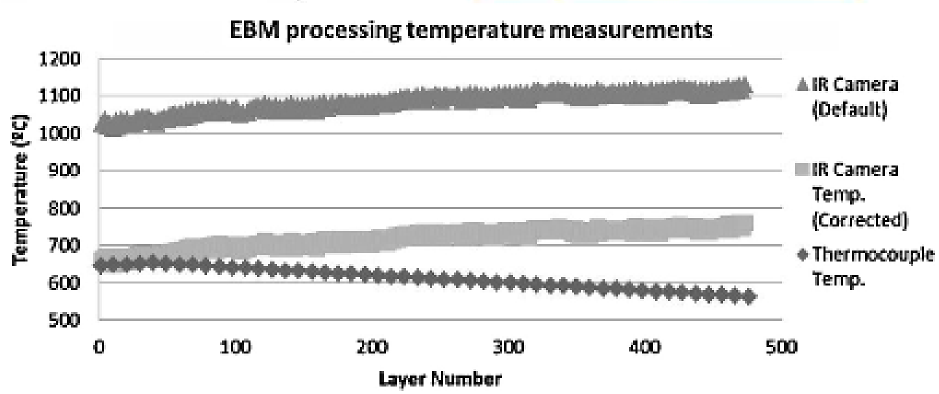


Infrared Thermography for Laser-Based Powder Bed Fusion Additive Manufacturing Processes, *40th Annual Review of Progress in Quantitative Nondestructive Evaluation*, 2014.

Printed Blackbody

- Blackbody emitter printed with powder bed fusion.
- Ti-6Al-4V build material
- Advantage is the blackbody printed from the material of interest.
- Emissivity is measured over a limited temperature range.
- Calibrated to 700 °C
- 3.7% temperature uncertainty

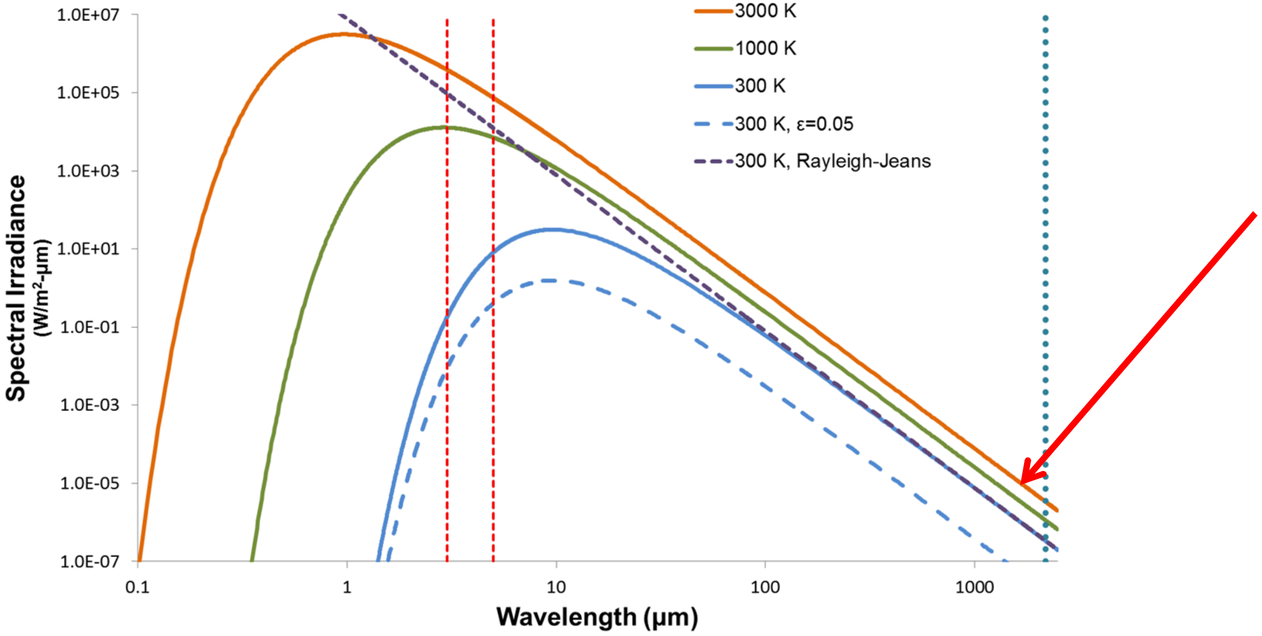




Approximation of absolute surface temperature measurements of powder bed fusion additive manufacturing technology using in situ infrared thermography, *Additive Manufacturing*, 2015.

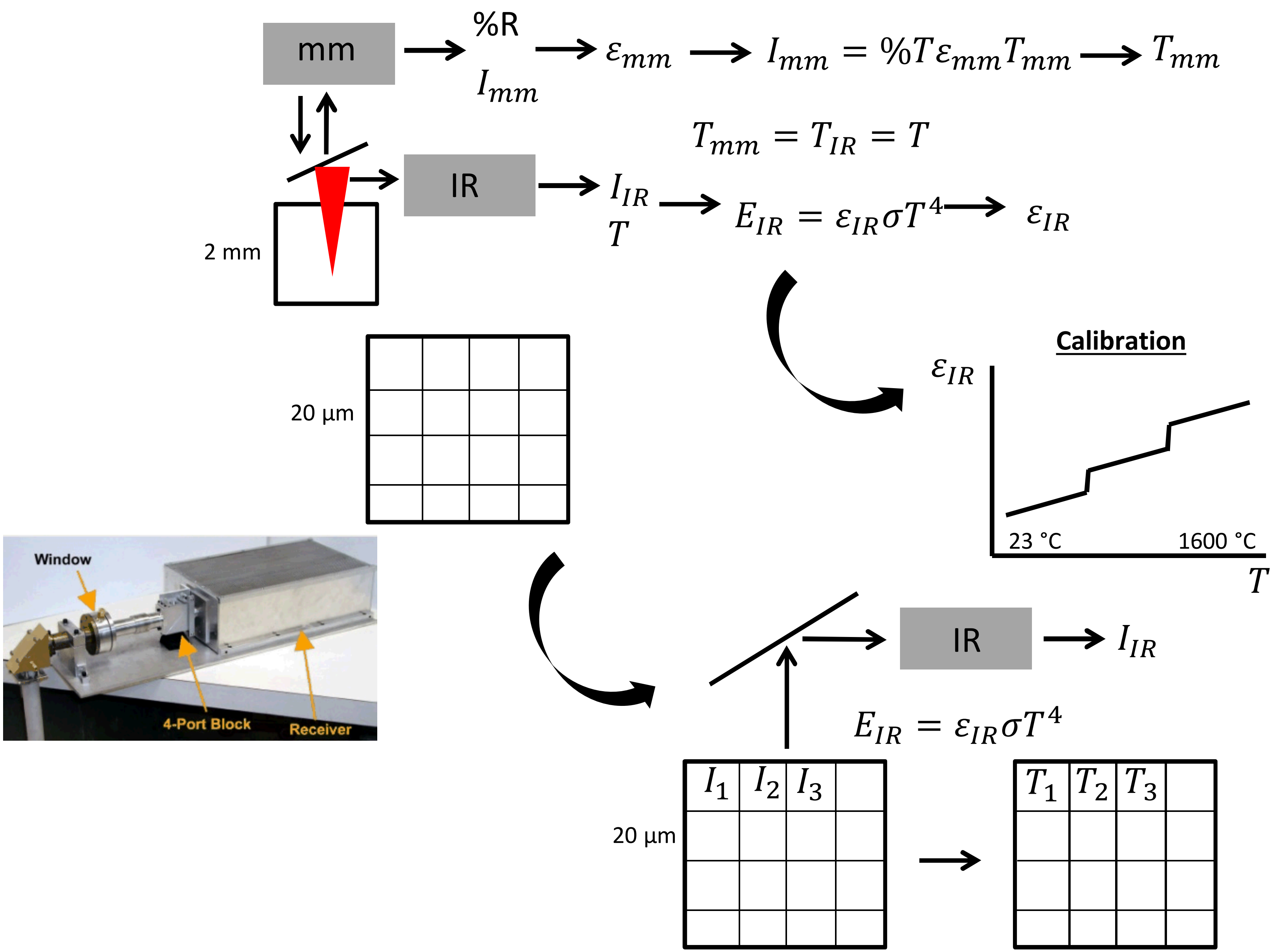
Ongoing Work

- Use mm-wave radiation to calibrate emissivity and temperature
- Intensity varies linearly (as opposed to T^4)
- 137 GHz (2.188 mm)
- 1 cm focused beam diameter
- Only one calibration point required

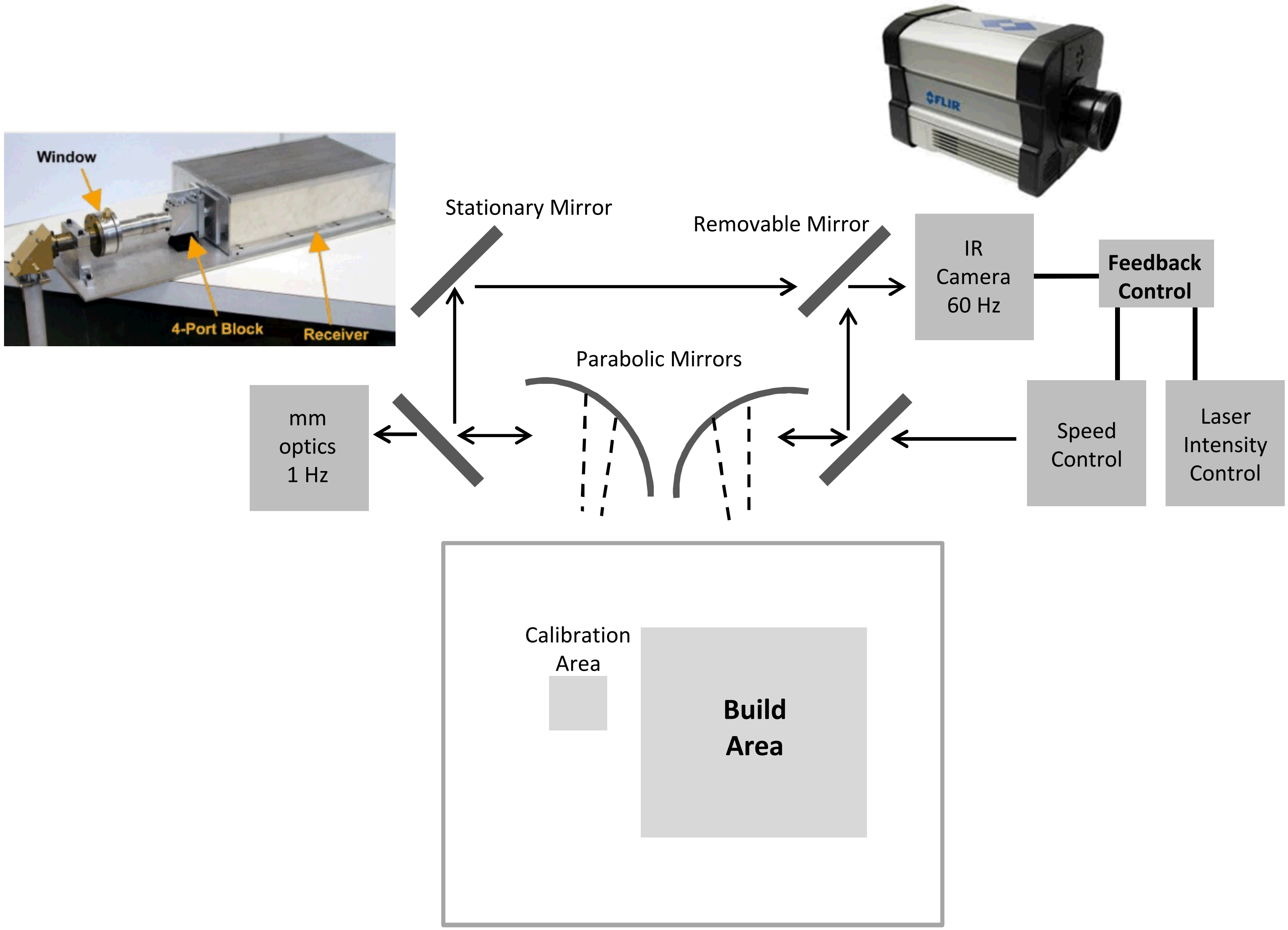


IR Camera Calibration

MM-wave radiation provides accurate T measurements over a large dynamic range with ~ 10 °C uncertainty

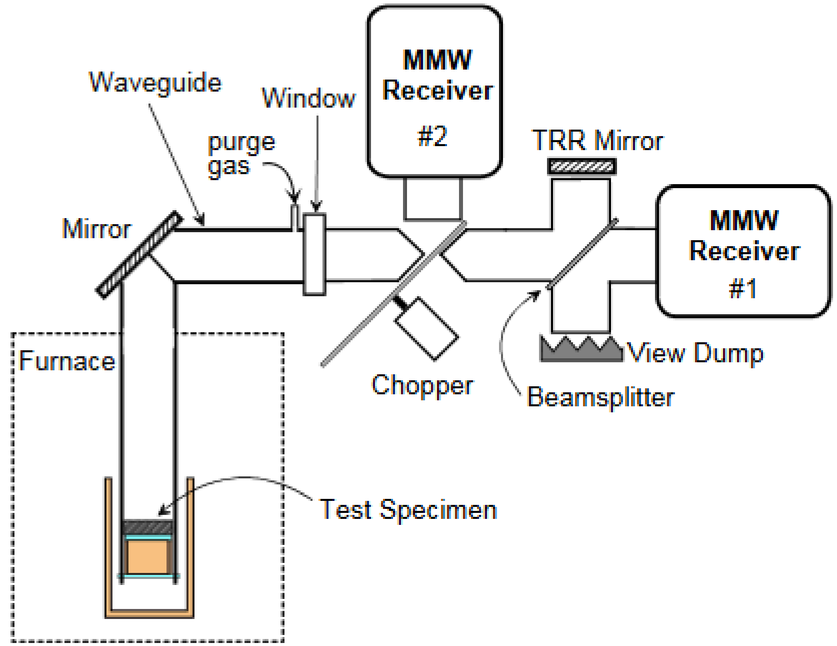


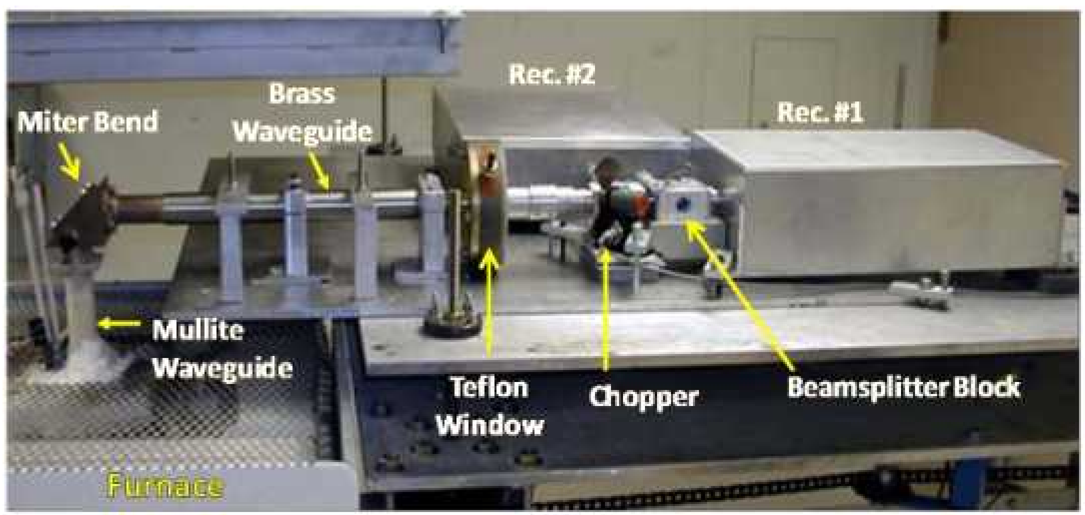
Feedback Control



Conclusions

- Additive manufacturing offers new opportunities for rapid prototyping.
- A major disadvantage is in-situ temperature monitoring and feedback control are typically not utilized during builds.
- In-situ temperature monitoring promises to improve additive processes.
- Non-contact temperature measurements are limited due to unknown material emissivity.
- Hyperspectral cameras offer the promise of full Planck's curve calibration.
- Blackbodies printed from the build material greatly lower the in-situ temperature uncertainty.
- Ongoing work with mm-wave radiation promises ~ 10 °C temperature uncertainty over a large dynamic range.





Millimeter-Wave Thermal Analysis Development and Application to GEN IV Reactor Materials, RC t RD&D Reactor, 2012.