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Millimeter-Wave High Temperature Process Monitoring

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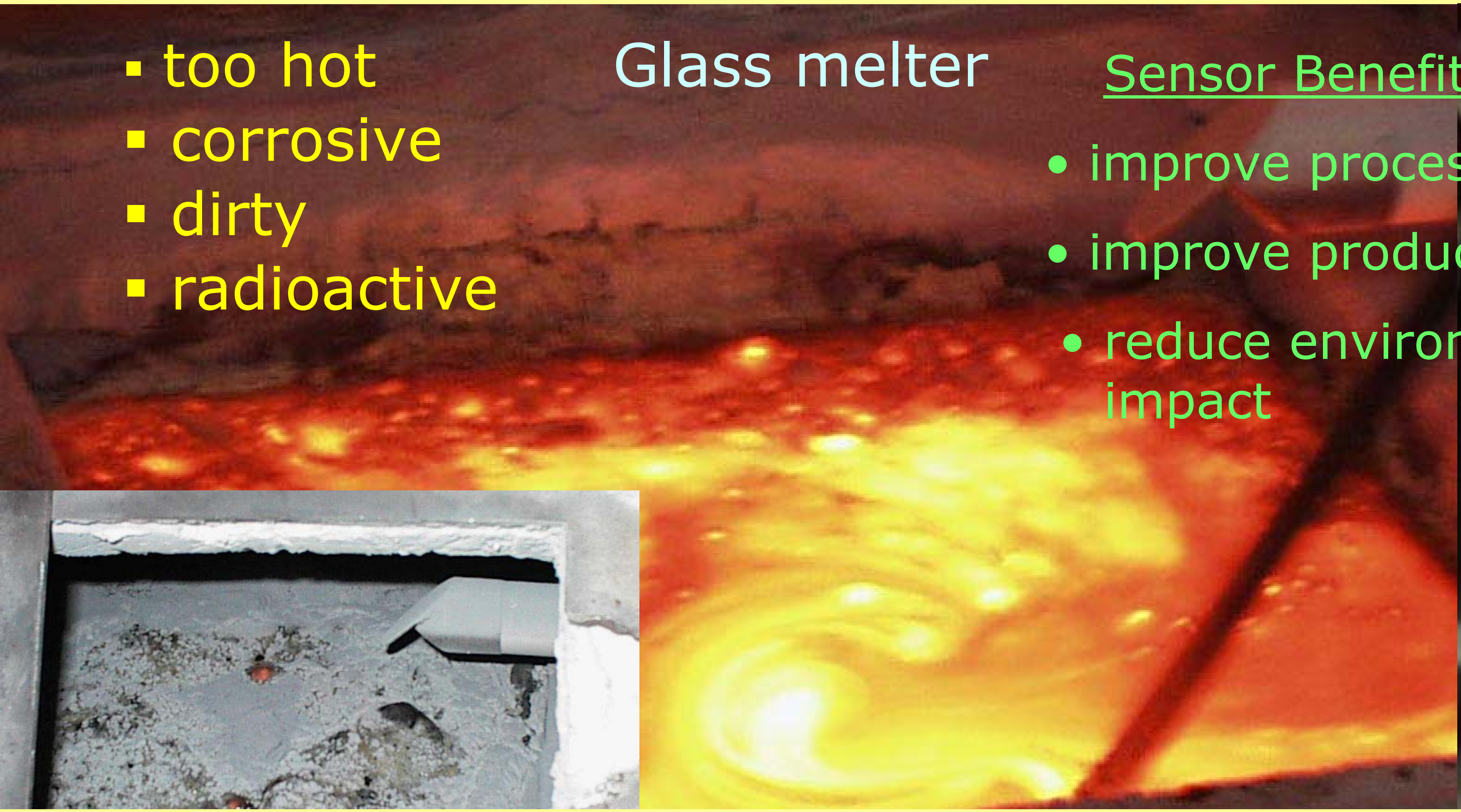
EMSP Environmental Management Science Program

High Temperature Process Monitoring Needs

- Many process environments inaccessible to conventional sensors
  - too hot
  - corrosive
  - dirty
  - radioactive



Glass melter

Glass pour

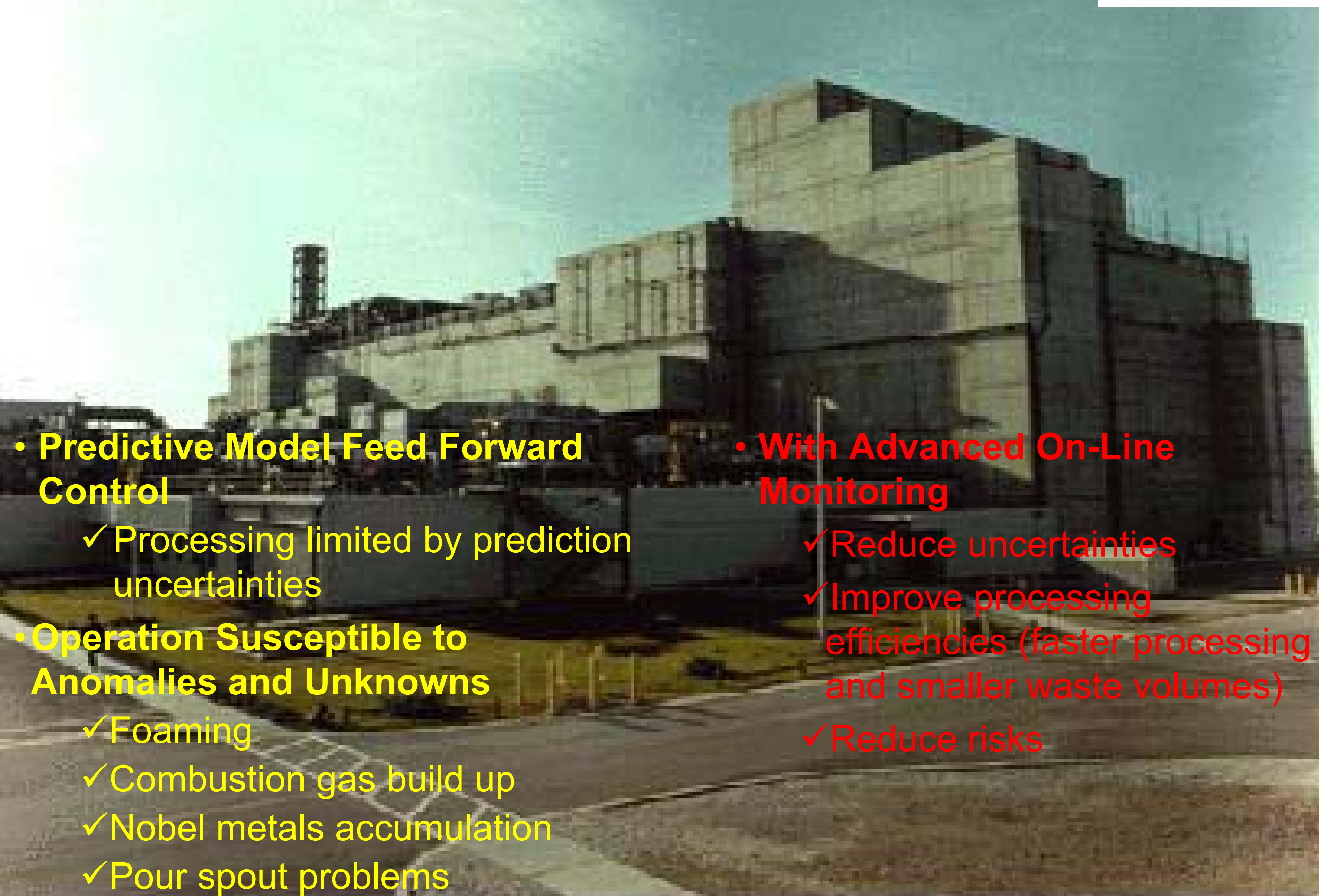
<u>Sensor Benefits</u>

- improve process efficiency
- improve product quality
- reduce environmental impact

- Many processes could benefit
  - metals refining, glass manufacturing, and waste remediation

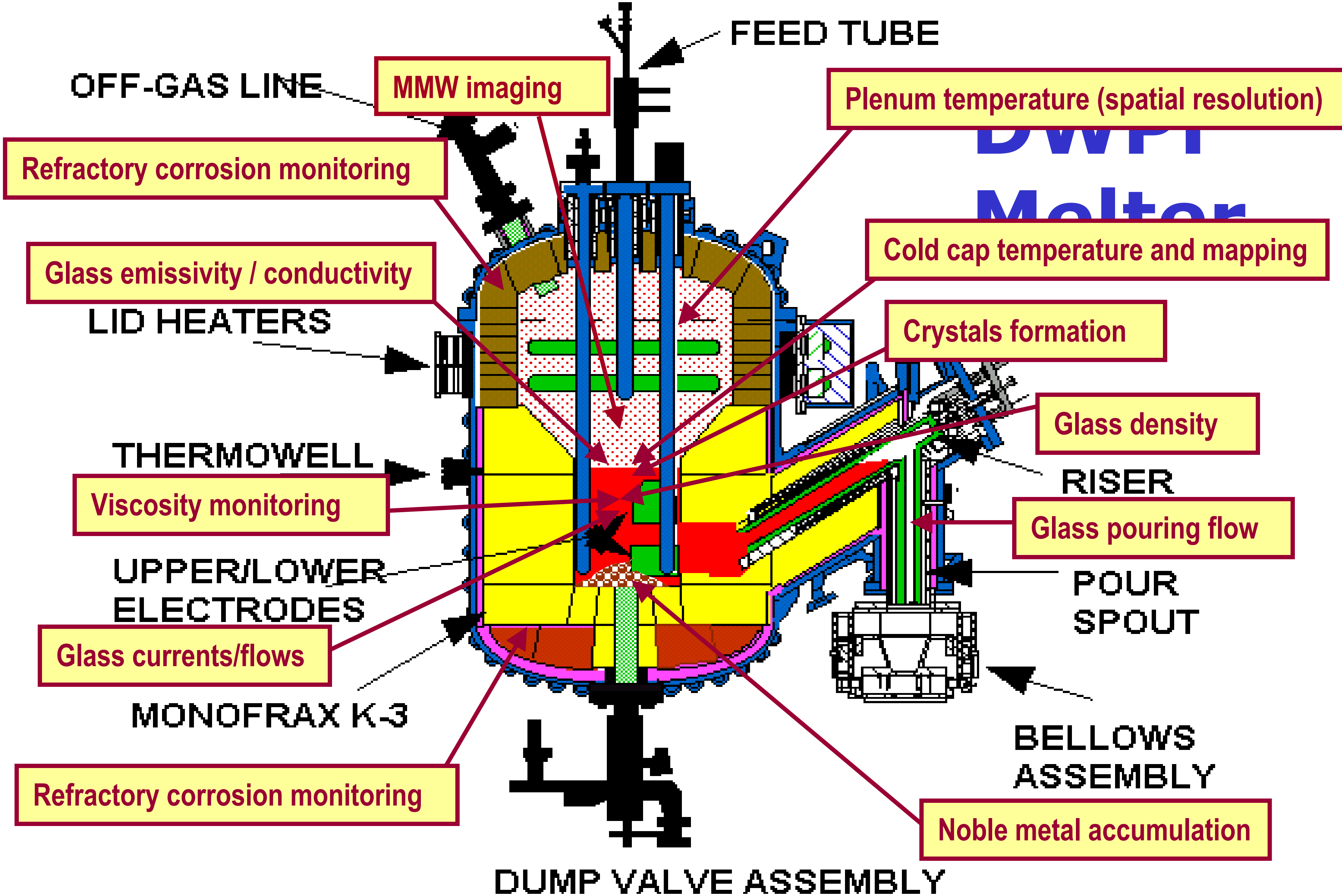
Defense Waste Processing Facility

Savannah River Technology Center



- **Predictive Model Feed Forward Control**
  - ✓ Processing limited by prediction uncertainties
- **Operation Susceptible to Anomalies and Unknowns**
  - ✓ Foaming
  - ✓ Combustion gas build up
  - ✓ Nobel metals accumulation
  - ✓ Pour spout problems
- **With Advanced On-Line Monitoring**
  - ✓ Reduce uncertainties
  - ✓ Improve processing efficiencies (faster processing and smaller waste volumes)
  - ✓ Reduce risks

A Vision of Millimeter Wave Diagnostics for DWPF

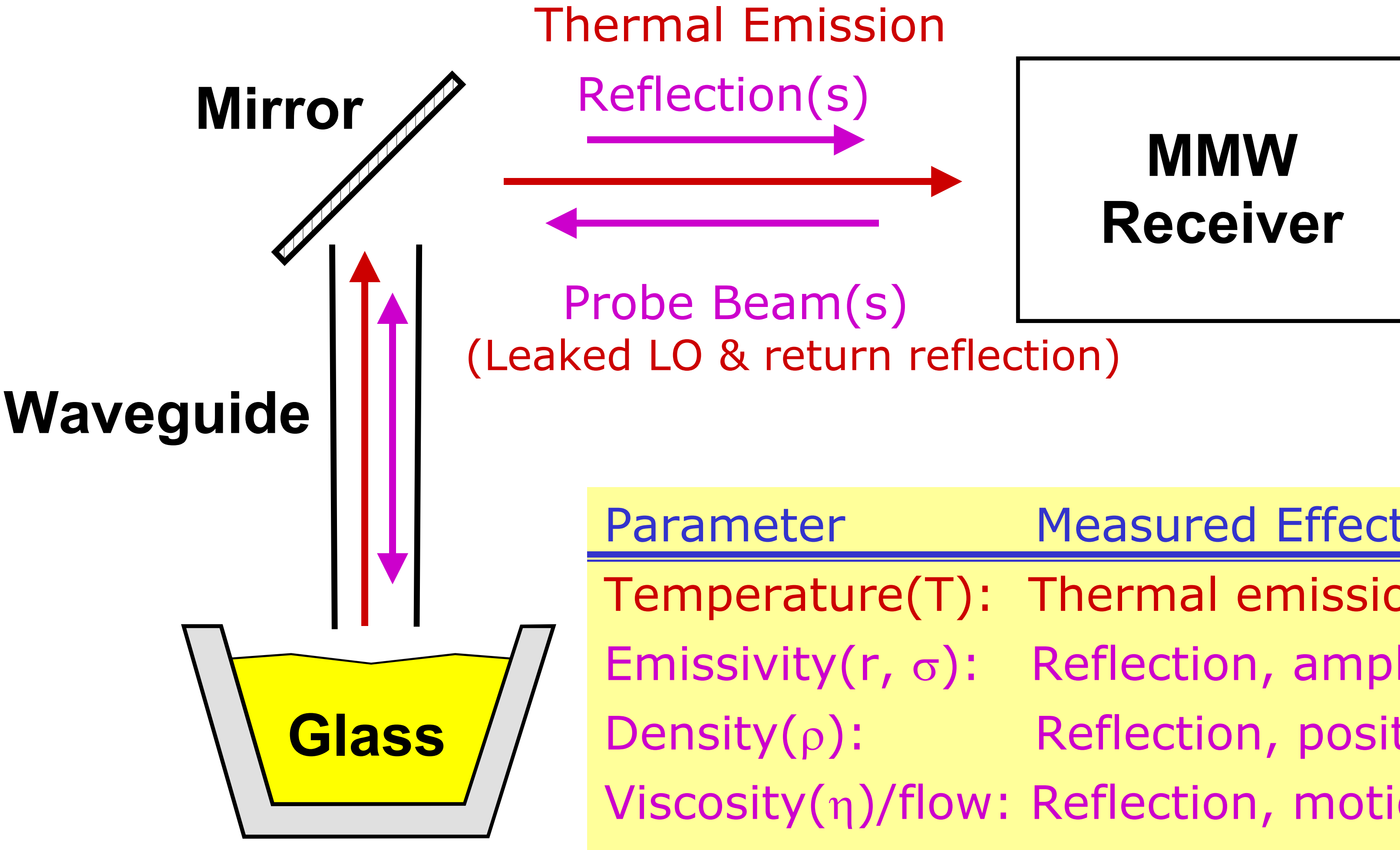


Millimeter-Wave Advantages

10-0.3 mm (30-1000 GHz)

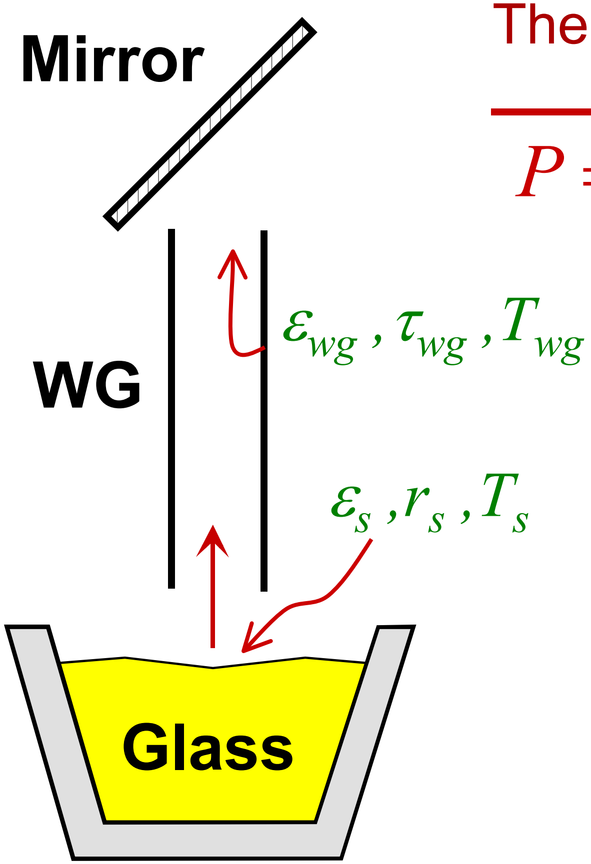
- Wavelengths are **long enough** to penetrate optical/infrared obscure viewing paths through dust, smoke, and debris
- Wavelengths are **short enough** for spatially resolved point measurements and profiles
- Robust **refractory material** melter interface and remote electronics

MMW Sensor Approach



Parameter	Measured Effect
Temperature(T):	Thermal emission
Emissivity(r, σ):	Reflection, amplitude
Density(ρ):	Reflection, position
Viscosity(η)/flow:	Reflection, motion
Fluctuations:	Reflection, fluctuations

Analytic Basis for Temperature Measurement



Need to consider all sources and losses of thermal radiation

$$T_{eff} = \varepsilon_{wg} T_{wg} + \tau_{wg} \varepsilon_s T_s + r_s \tau_{wg} \varepsilon_{wg} T_{wg}$$

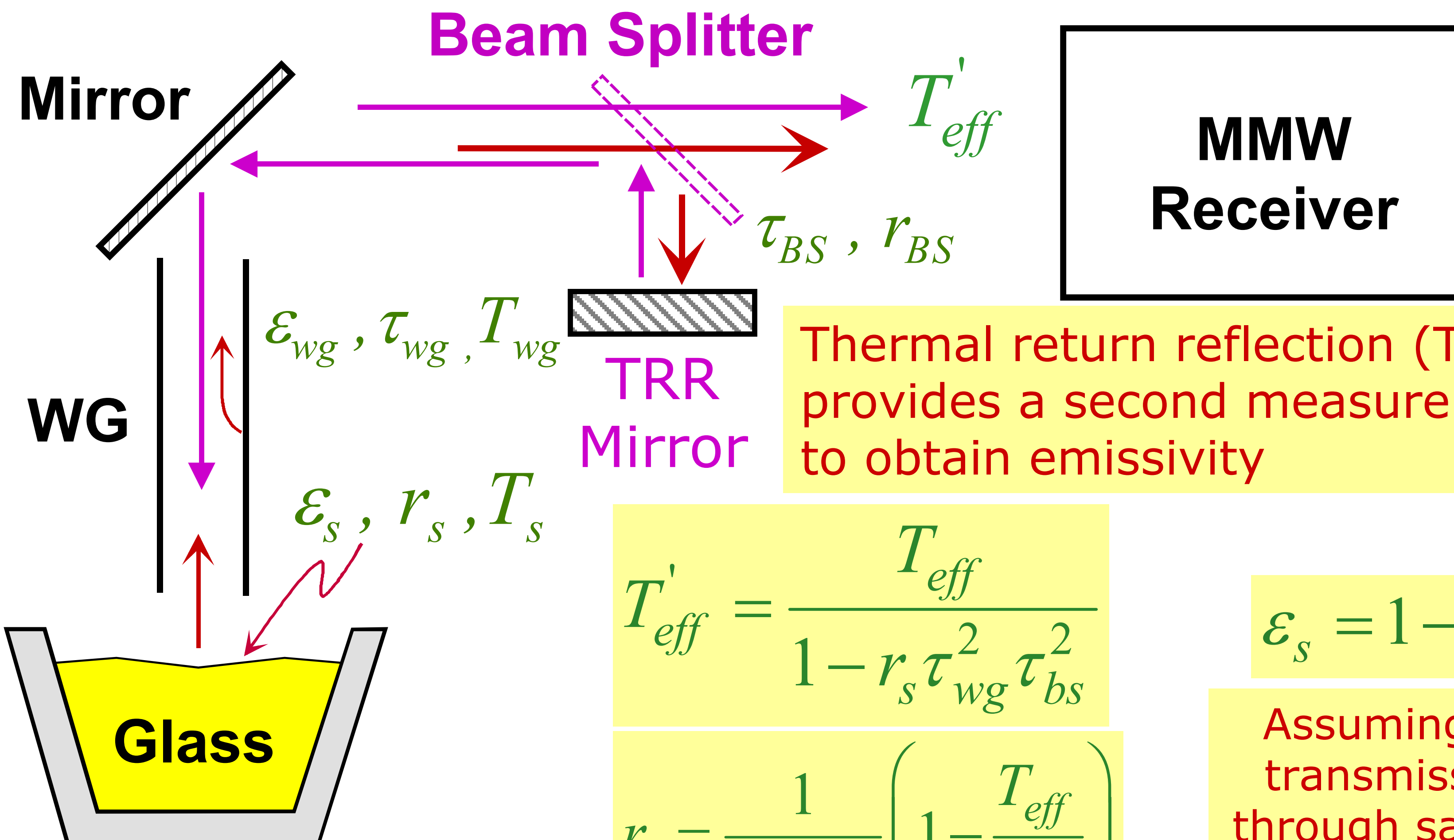
From waveguide

From sample

From waveguide reflected off sample

$T_{eff} = T_s$; when $\varepsilon_s = \tau_{wg} = 1 (\varepsilon_{wg} = 0)$

Analytic Basis for Emissivity Measurement



Thermal return reflection (TRR) provides a second measurement to obtain emissivity

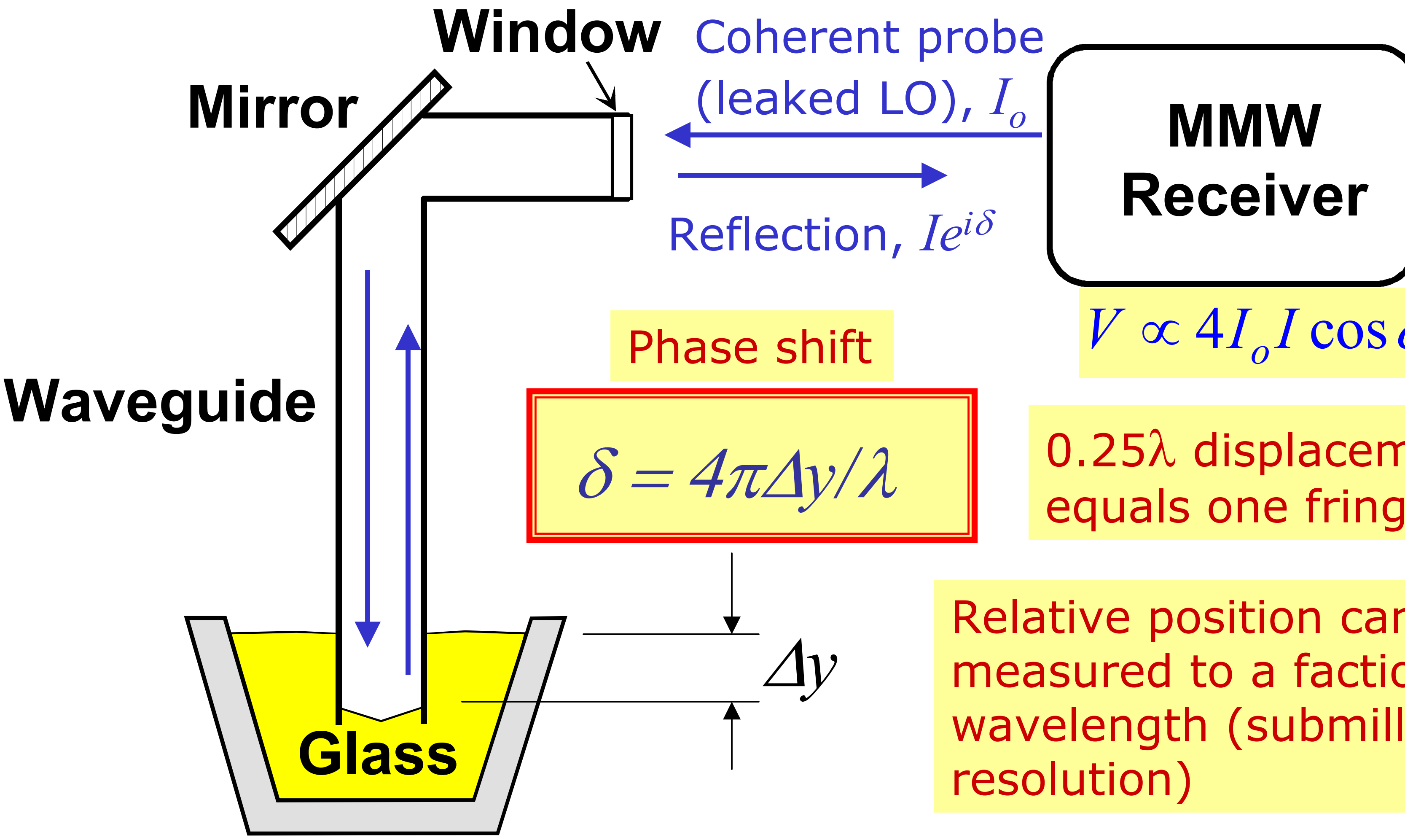
$$T'_{eff} = \frac{T_{eff}}{1 - r_s \tau_{wg}^2 \tau_{bs}^2}$$

$$r_s = \frac{1}{\tau_{wg}^2 \tau_{bs}^2}\left(1 - \frac{T_{eff}}{T'_{eff}}\right)$$

$$\varepsilon_s = 1 - r_s$$

Assuming no transmission through sample

Analytic Basis for Position and Flow Measurements



$V \propto 4 I_o I \cos\delta$

Phase shift

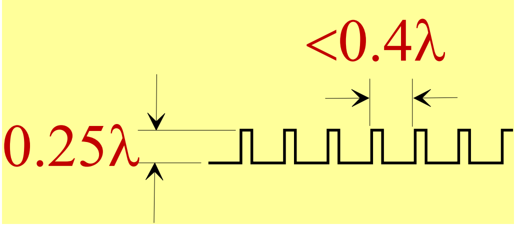
$$\delta = 4\pi \Delta y / \lambda$$

0.25λ displacement equals one fringe

Relative position can be measured to a faction of a wavelength (submillimeter resolution)

High-Temperature MMW Process Interface

- Refractory materials must be used for MMW interfacing components *(waveguides, mirrors)*
- Efficient waveguides can be fabricated from large diameter pipes *(propagating the HE_{11} mode)*
- Conducting materials *(Inconel, Graphite)* require corrugated walls



$$\alpha = 0.00767 \frac{R_s}{k^2 a^3}$$

0.026% loss/meter
Inconel at 140 GHz, 28 mm dia.

- Dielectric materials *(i.e. ceramics)* require smooth inner wall, dielectrics

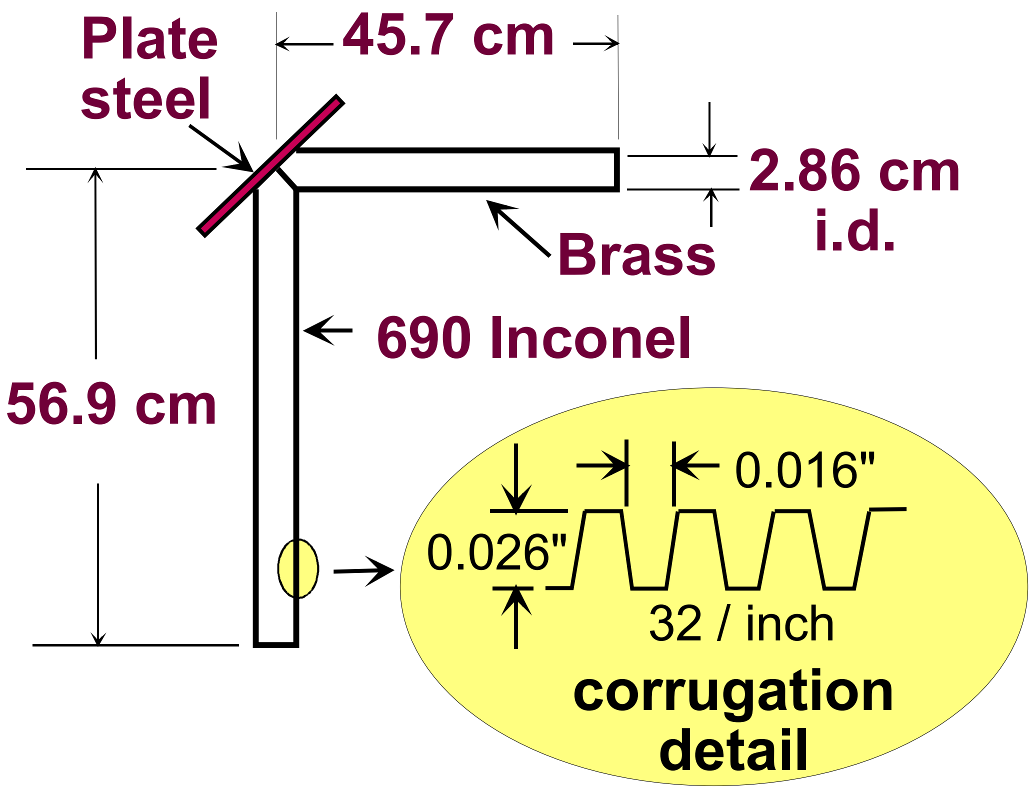
$$\alpha = \frac{2.892}{k^2 a^3} \frac{\left(n^2 + 1\right)}{\sqrt{n^2 - 1}}$$

32% loss/meter
(n=2.55) 140 GHz, 28 mm dia.

12% loss/m at 41 mm dia.

Composite Waveguides

- Transmission efficiency maximized by using refractory guide only in hot region and mating to conventional guide or optics



- For large diameter
  - ✓ propagation constants approach free space value
  - ✓ little mismatch between different waveguide types including ceramics and metals

Refractory Waveguides

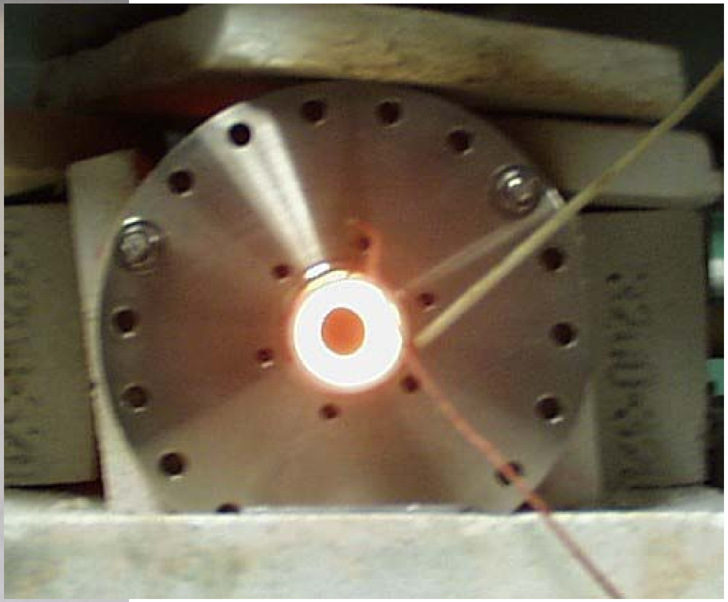
22”
(56 cm)

Coors Mullite

SiC

Vesuvius Mullite

Inconel 690



1200 °C Test

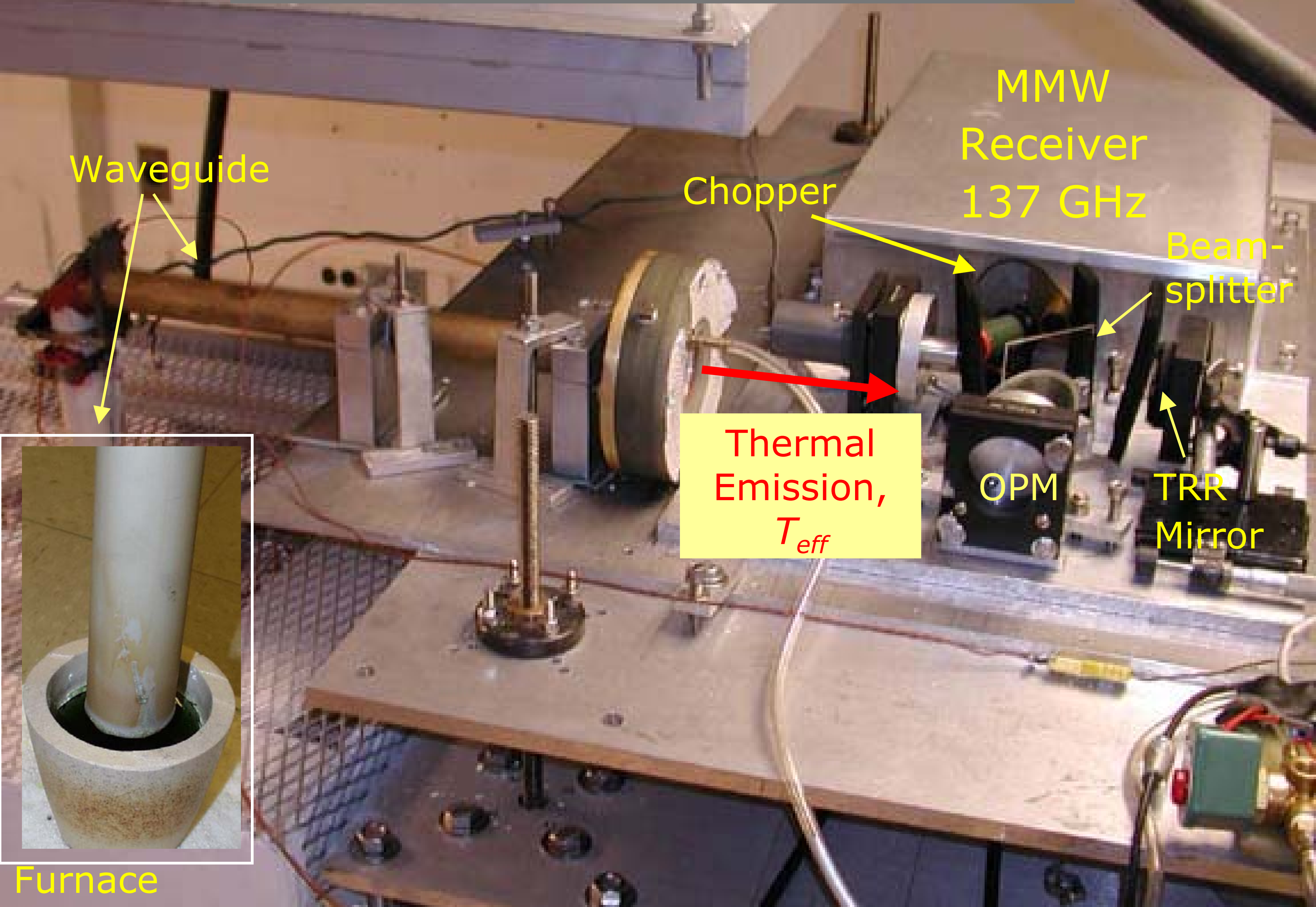
Room Temperature Performance at 137 GHz

Guide Material	Inside Surface	Inside Diameter	Wall Thickness	Measured Transmission
690 Inconel	Corrugated	28.6 mm	N/A	94.6%
690 Inconel *(after use to 1180 ^{o}C in Air)*	“	“	“	83.0%
Vesuvius Mullite	Smooth	41.3 mm	3.2 mm	97.6%
Coors Mullite	Smooth	41.3 mm	6.4 mm	87.5%
Silicon Carbide	Smooth	41.3 mm	12.7 mm	79.5%

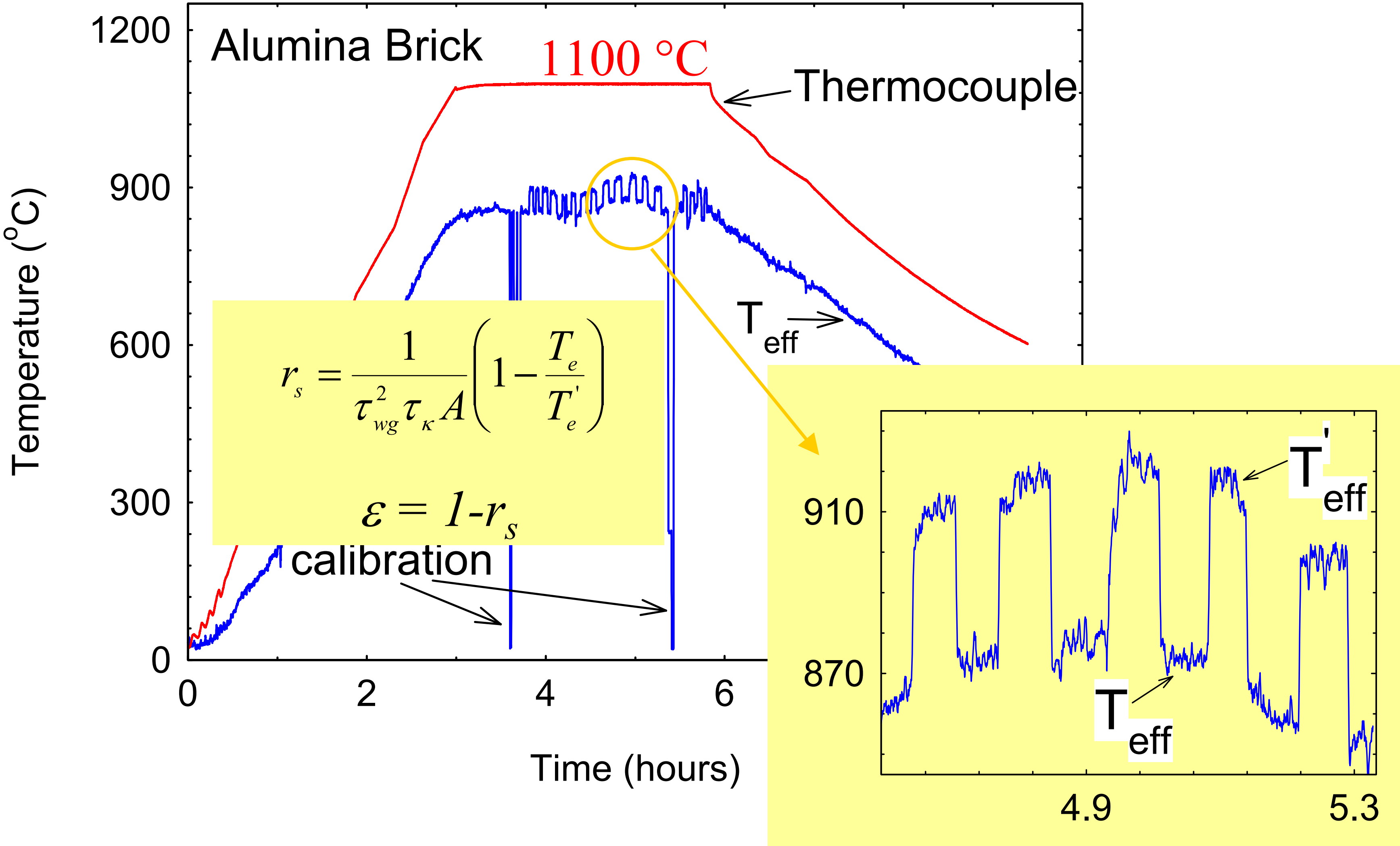
Transmission efficiency scales as $1/(\text{dia.})^3$ for a given material

- Refractory waveguides could be made large enough to transmit power into a melter for profile control

Laboratory Research Setup



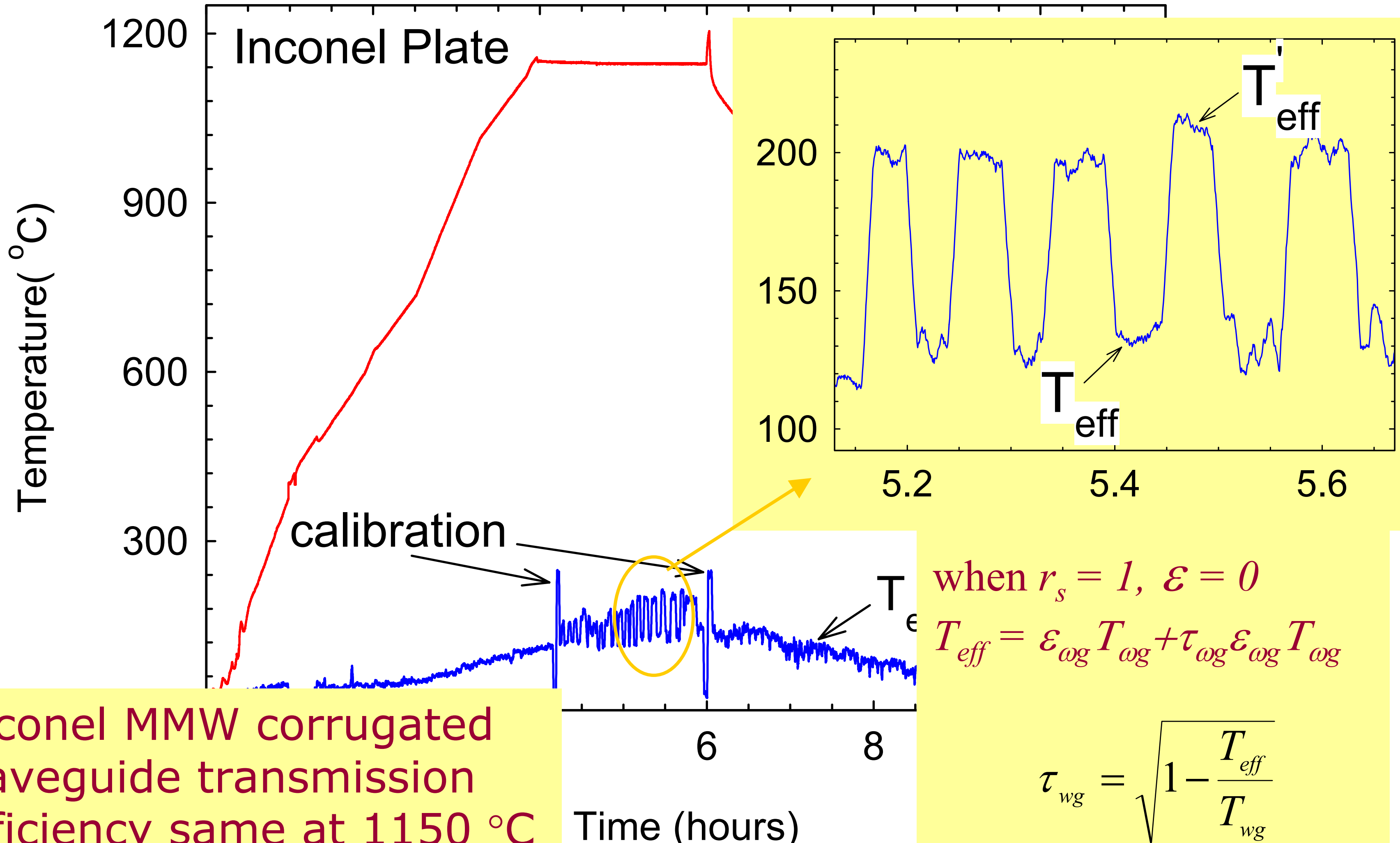
Measurements with Inconel Waveguide of Alumina Brick



$$r_s = \frac{1}{\tau_{wg}^2 \tau_\kappa A}\left(1 - \frac{T_e}{T_e'}\right)$$

$$\varepsilon = 1 - r_s$$

Inconel Waveguide Measurements at 1150 °C



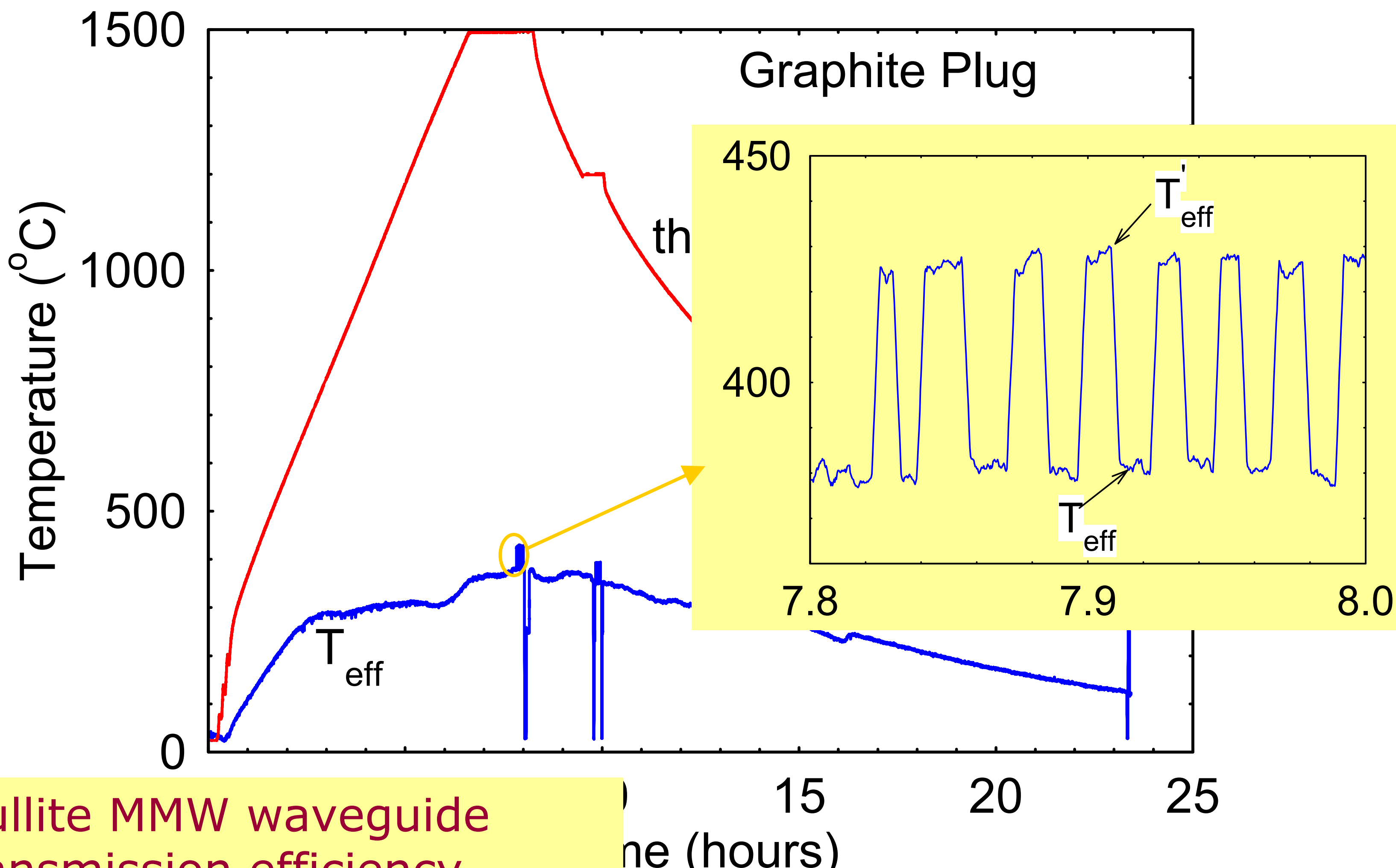
Inconel MMW corrugated waveguide transmission efficiency same at 1150 °C and room temperature ~95%

when $r_s = 1,\ \varepsilon = 0$

$$T_{eff} = \varepsilon_{\omega g} T_{\omega g} + \tau_{\omega g} \varepsilon_{\omega g} T_{\omega g}$$

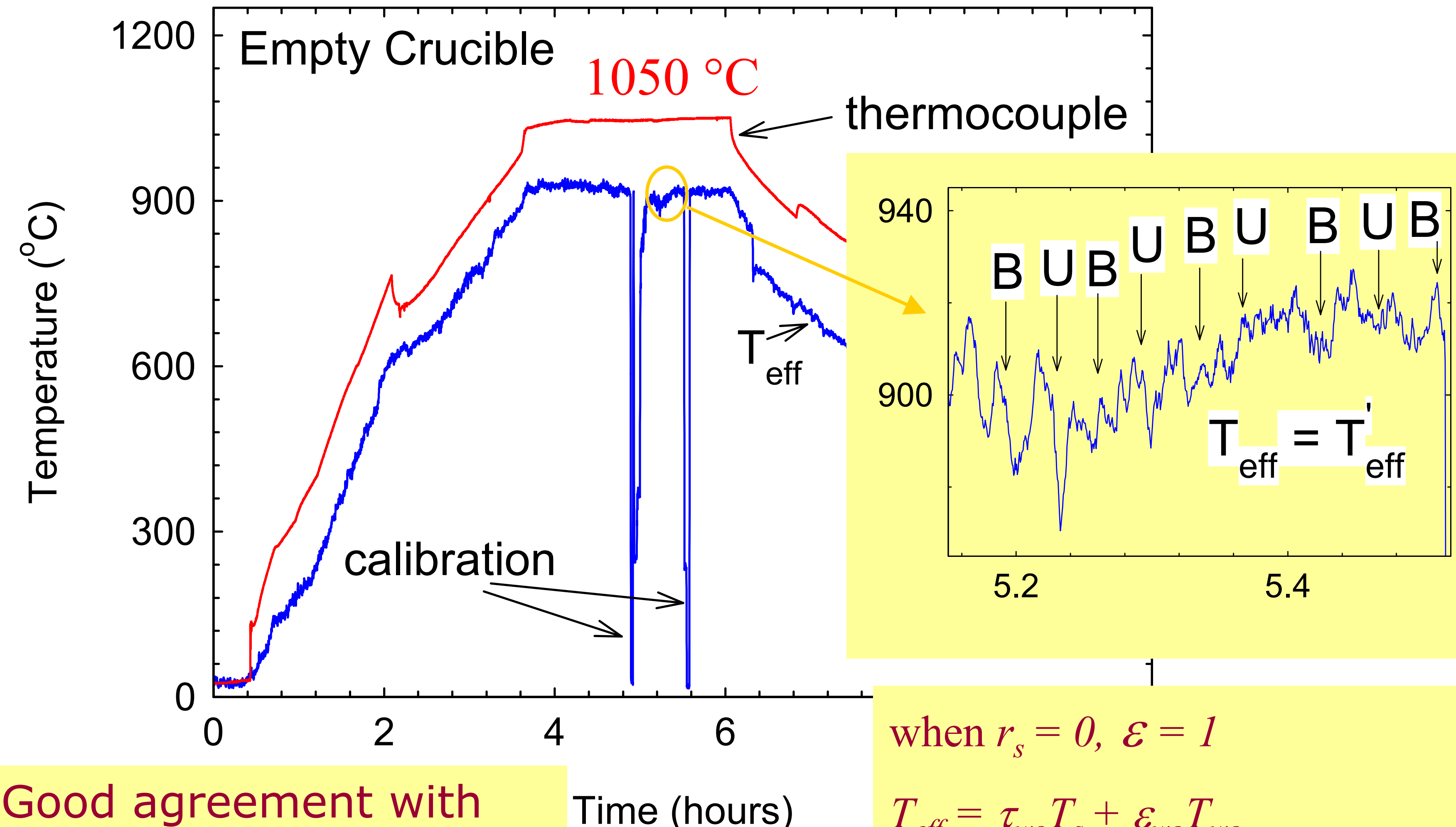
$$\tau_{wg} = \sqrt{1 - \frac{T_{eff}}{T_{wg}}}$$

Mullite Waveguide Measurements to 1500 °C



Mullite MMW waveguide transmission efficiency appears constant to 1500 °C ~90% for 1 5/8" diameter

Measurements of an Ideal Blackbody



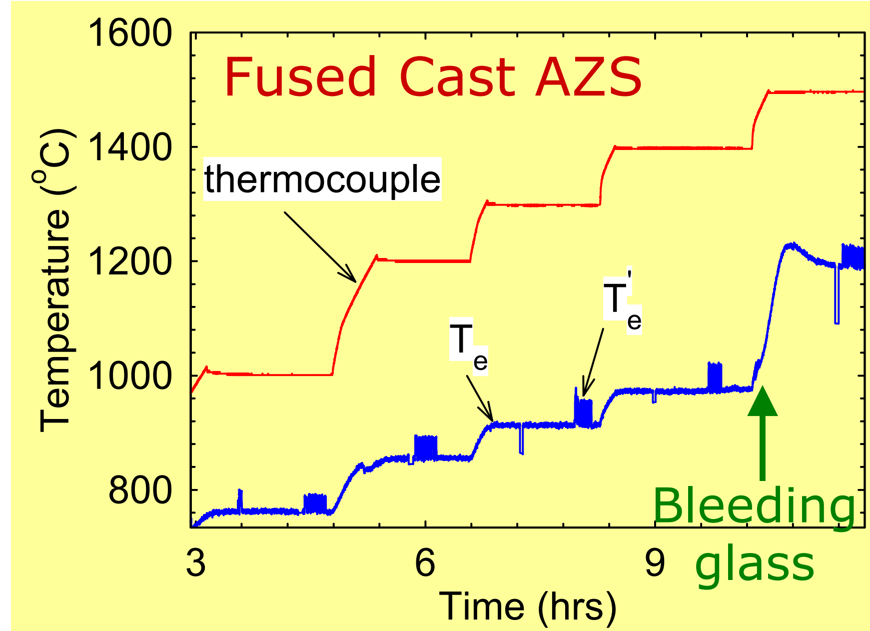
when $r_s = 0, \ \varepsilon = 1$

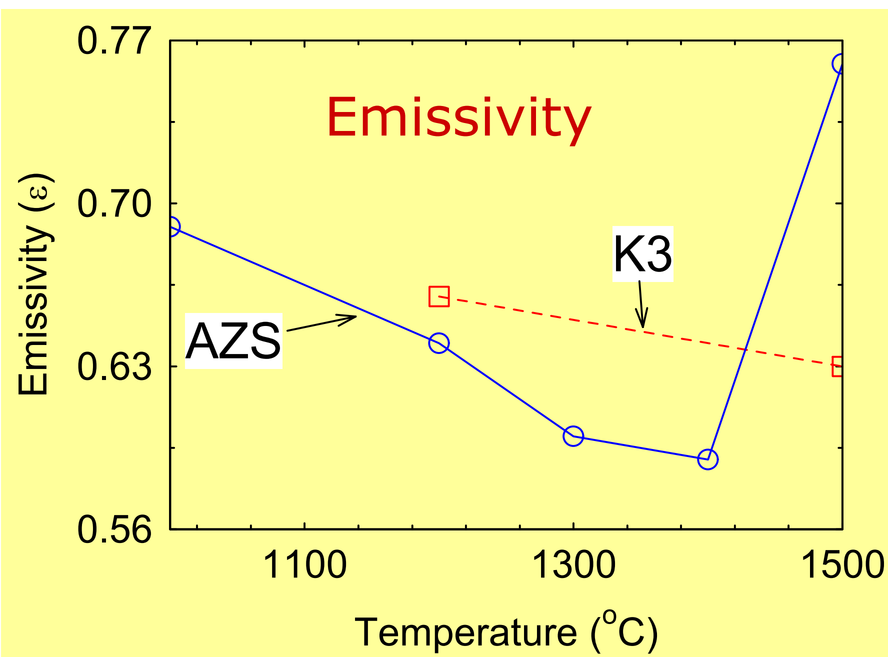
$$T_{eff} = \tau_{wg} T_s + \varepsilon_{wg} T_{wg}$$

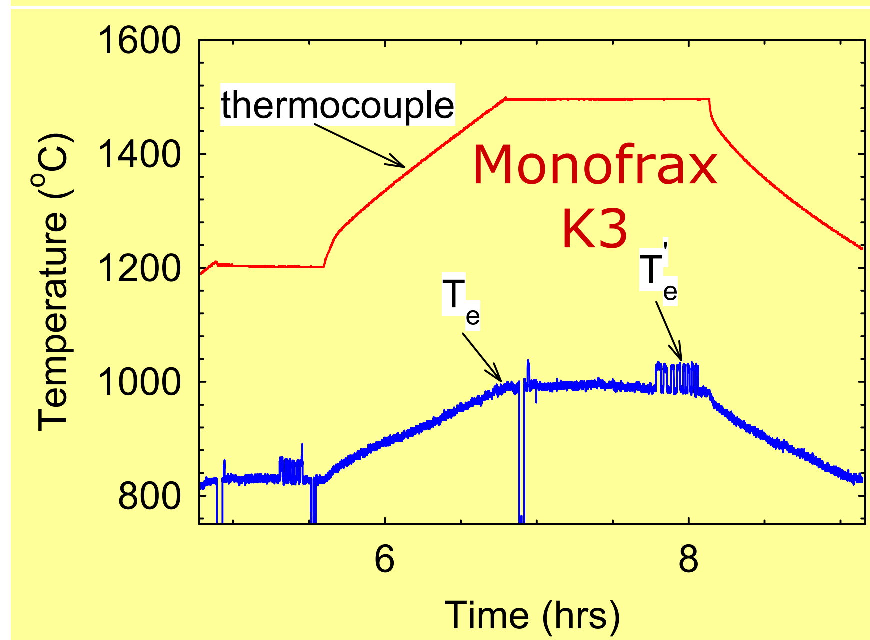
- Good agreement with thermocouple
- Typical case for cold cap melter measurements

Thermal Analysis of Materials

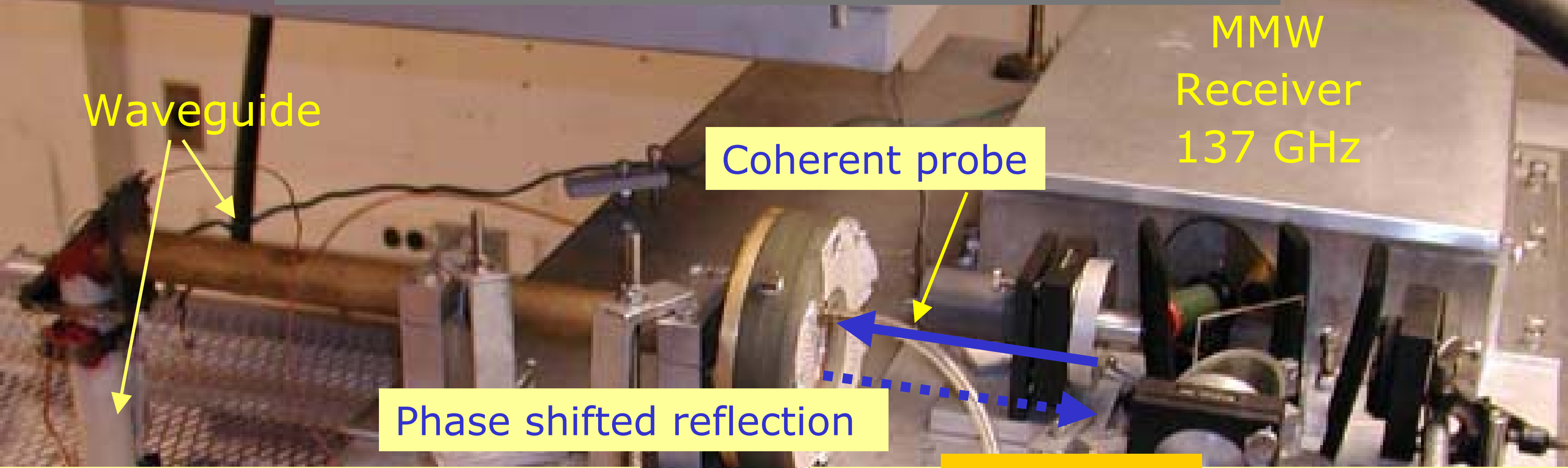
- Molten glass corrosion resistant materials studied
- Alumina-Zirconia-Silica (AZS) has unstable MMW properties
- Monofrax K3 more stable at MMW wavelengths

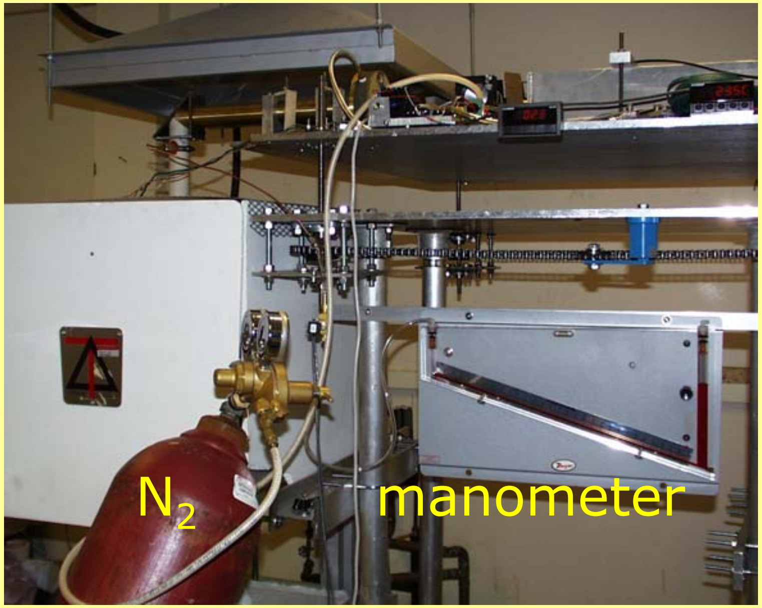


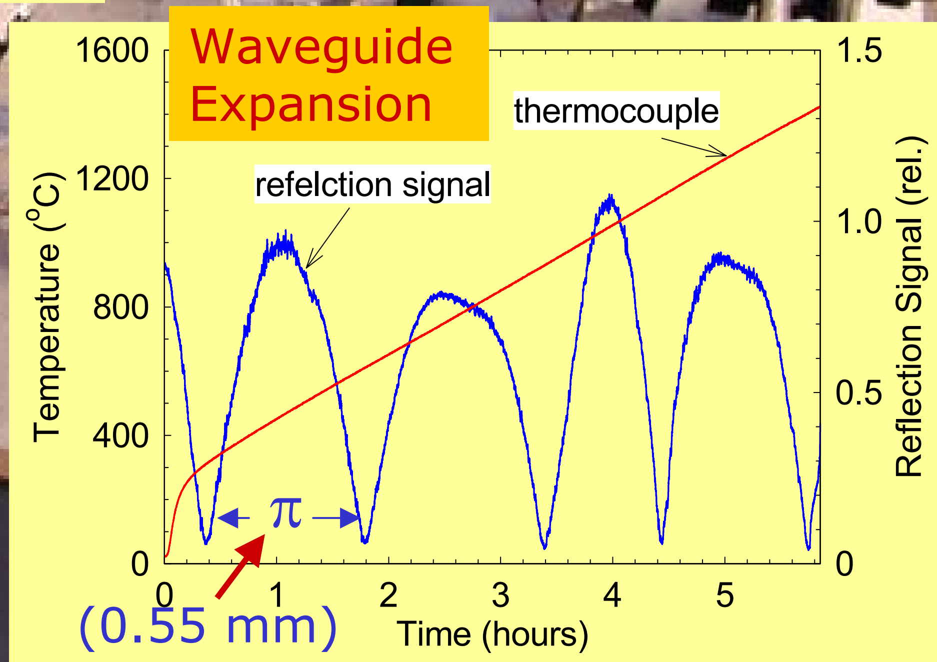




Laboratory Research Setup
Flow Measurements







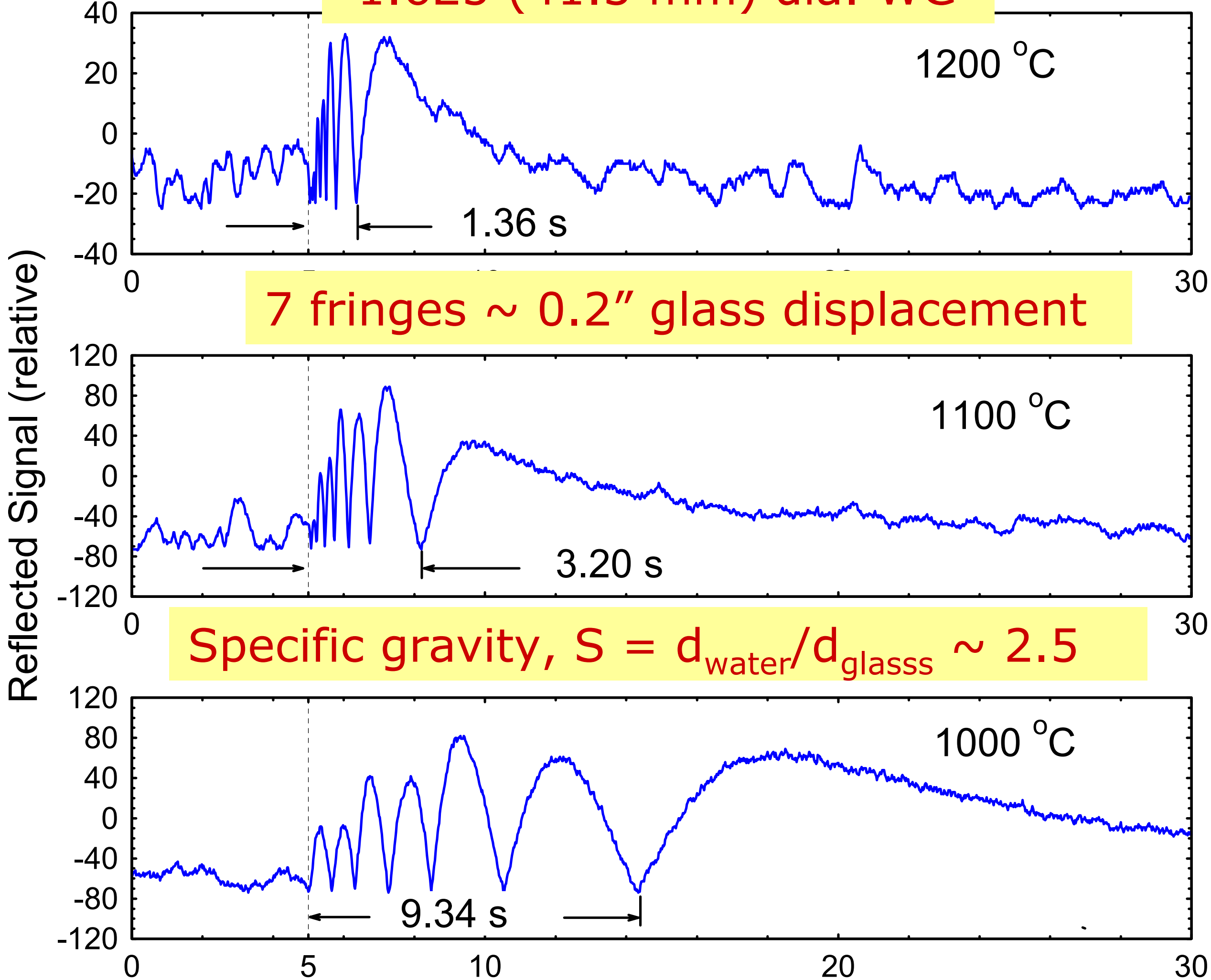
Hanford #7 Glass Flow in Waveguide for ~ 0.5" Water Pressure Displacement

1.625 (41.3 mm) dia. WG

From Corning Laboratory

7 fringes ~ 0.2" glass displacement

Specific gravity, $S = d_{water}/d_{glasss} \sim 2.5$



339 Poise (kg/m s)

868 Poise

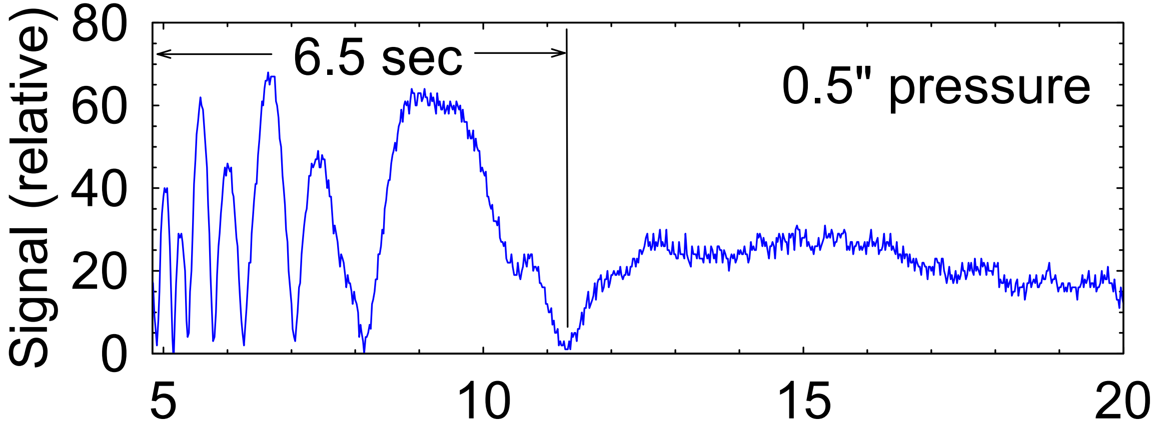
3,014 Poise

Glass density and flow velocity both determined simultaneously

100 Poise goal for pouring

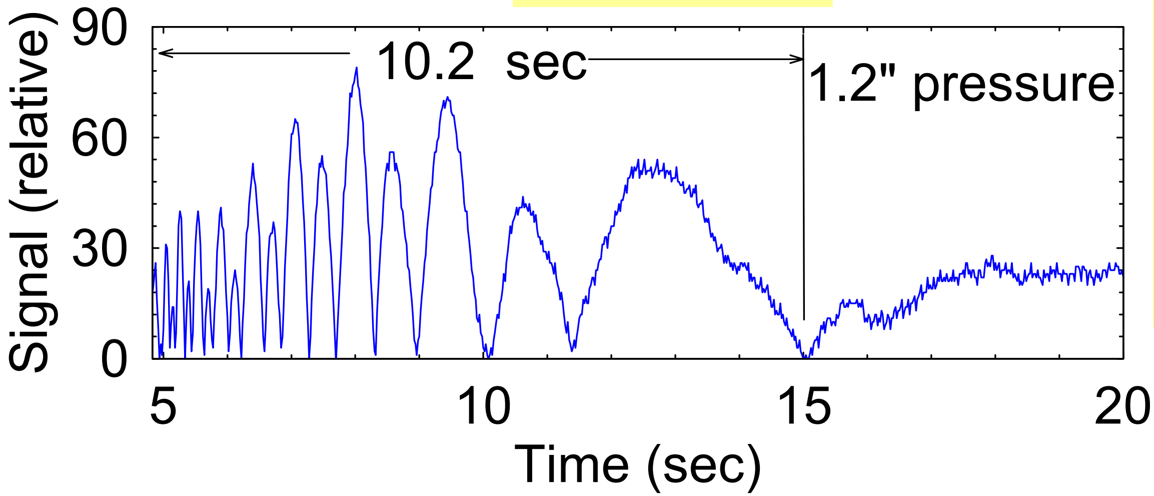
Hanford #8 Glass at 1000 ^oC and Two Pressures

Waveguide i.d. = 1.125” (28.6 mm)



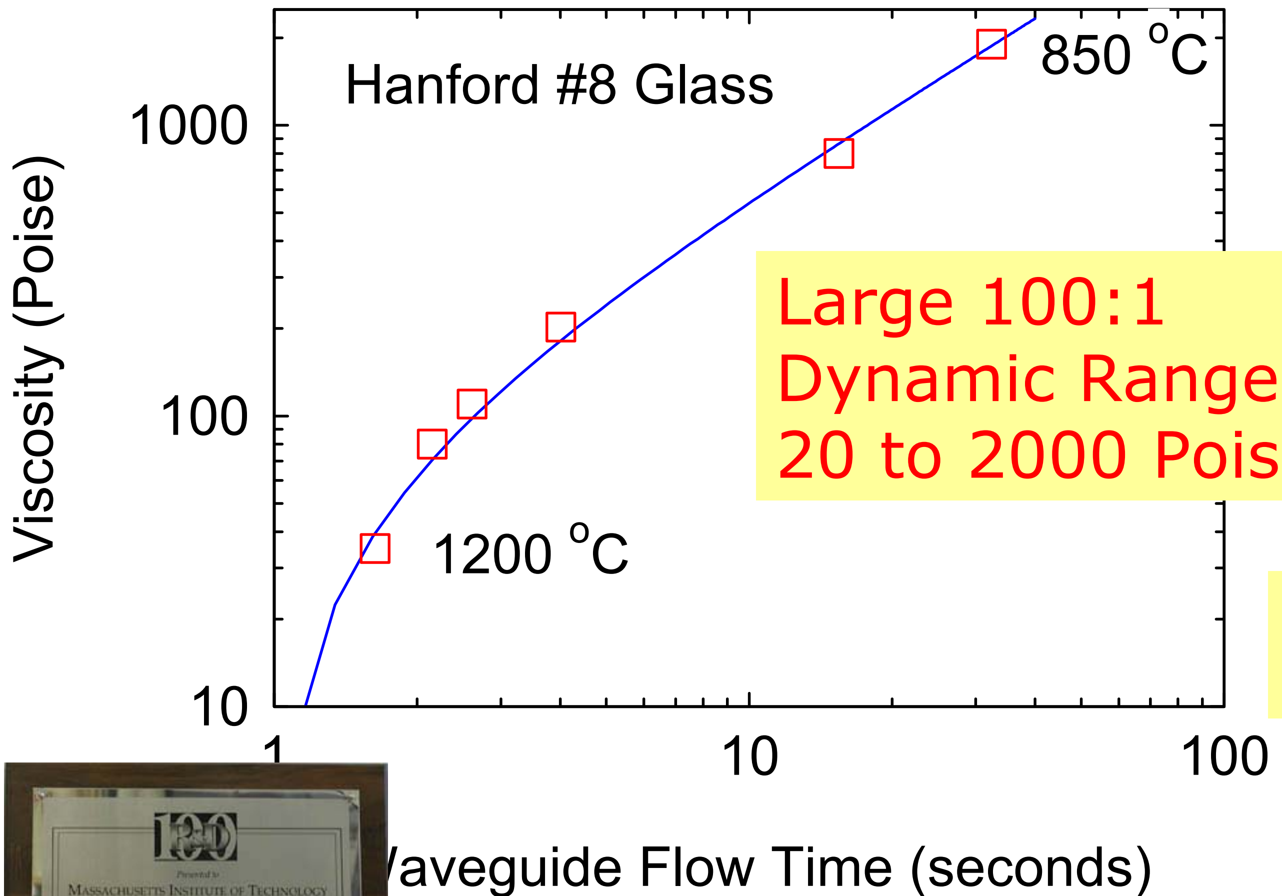
- smaller diameter waveguide reduces flow velocity as $1/a^2$

210 Poise



- Difference of two pressure displacements taken to eliminate surface tension effects

Good Correlation Between Viscosity and MMW Waveguide Flow Time Delay

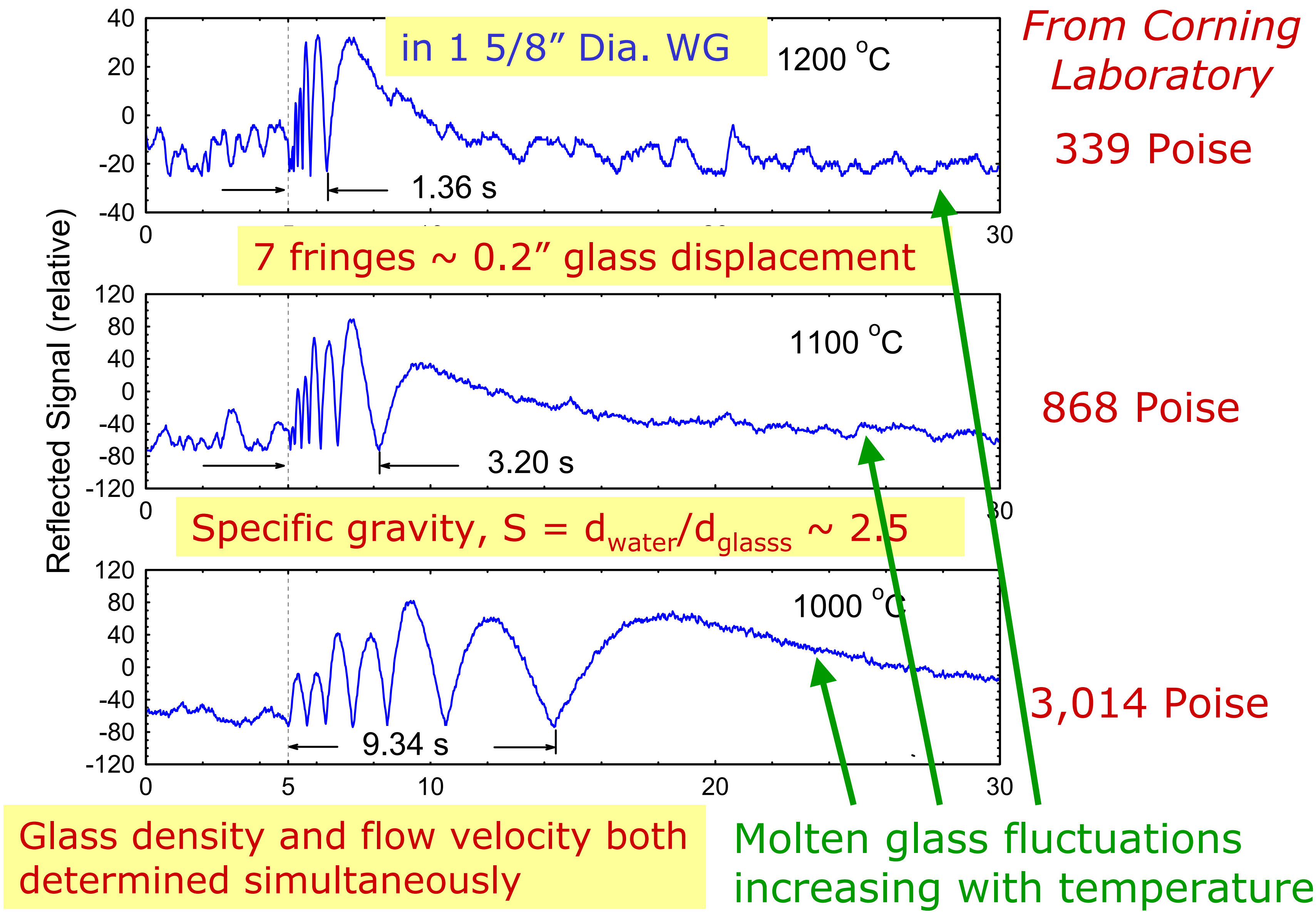


For 0.7" (17.8 mm) flow at 1 atmosphere

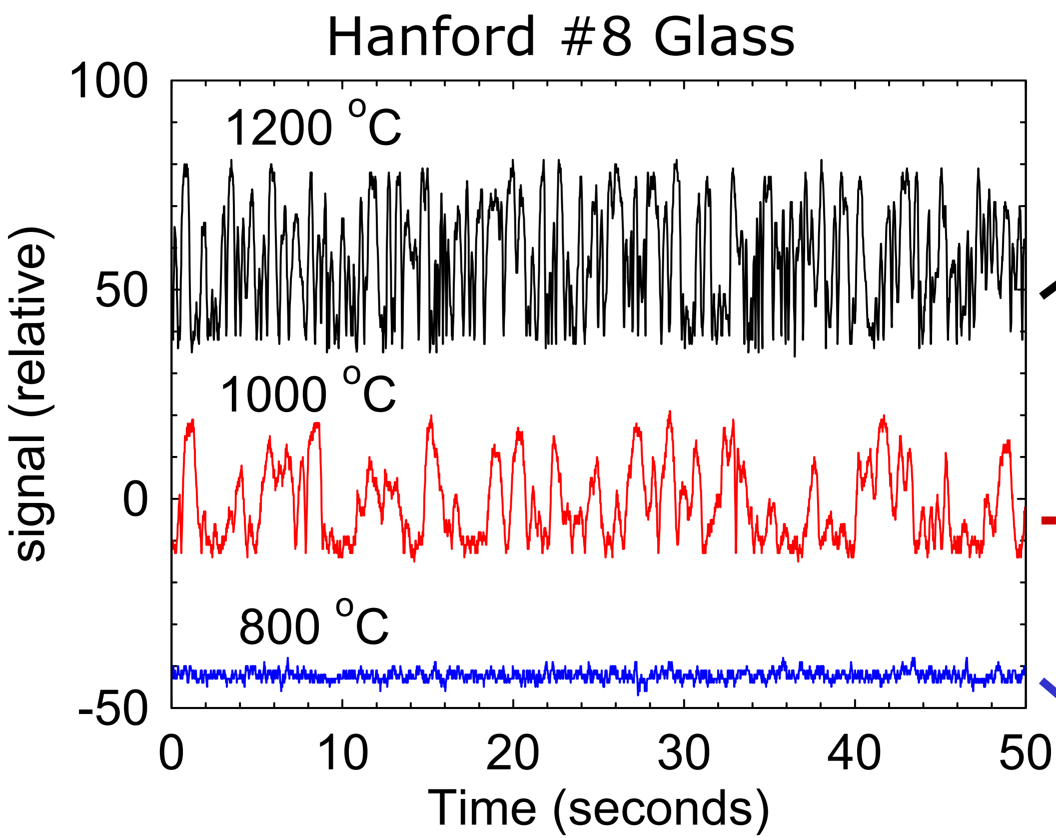
Large 100:1 Dynamic Range 20 to 2000 Poise

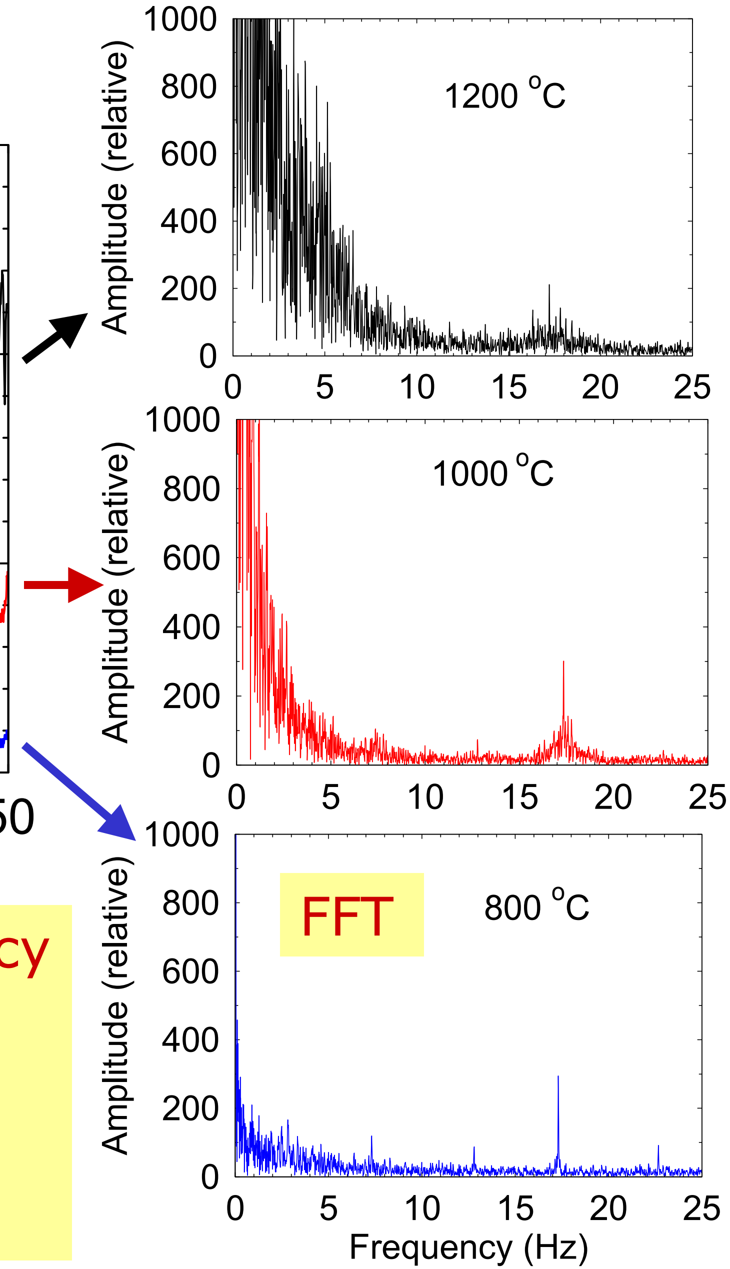
Waveguide i.d. = 1.125" (28.6 mm)

Hanford #7 Glass Flow in Waveguide for ~ 0.5" Water Pressure Displacement



Molten Glass Turbulence

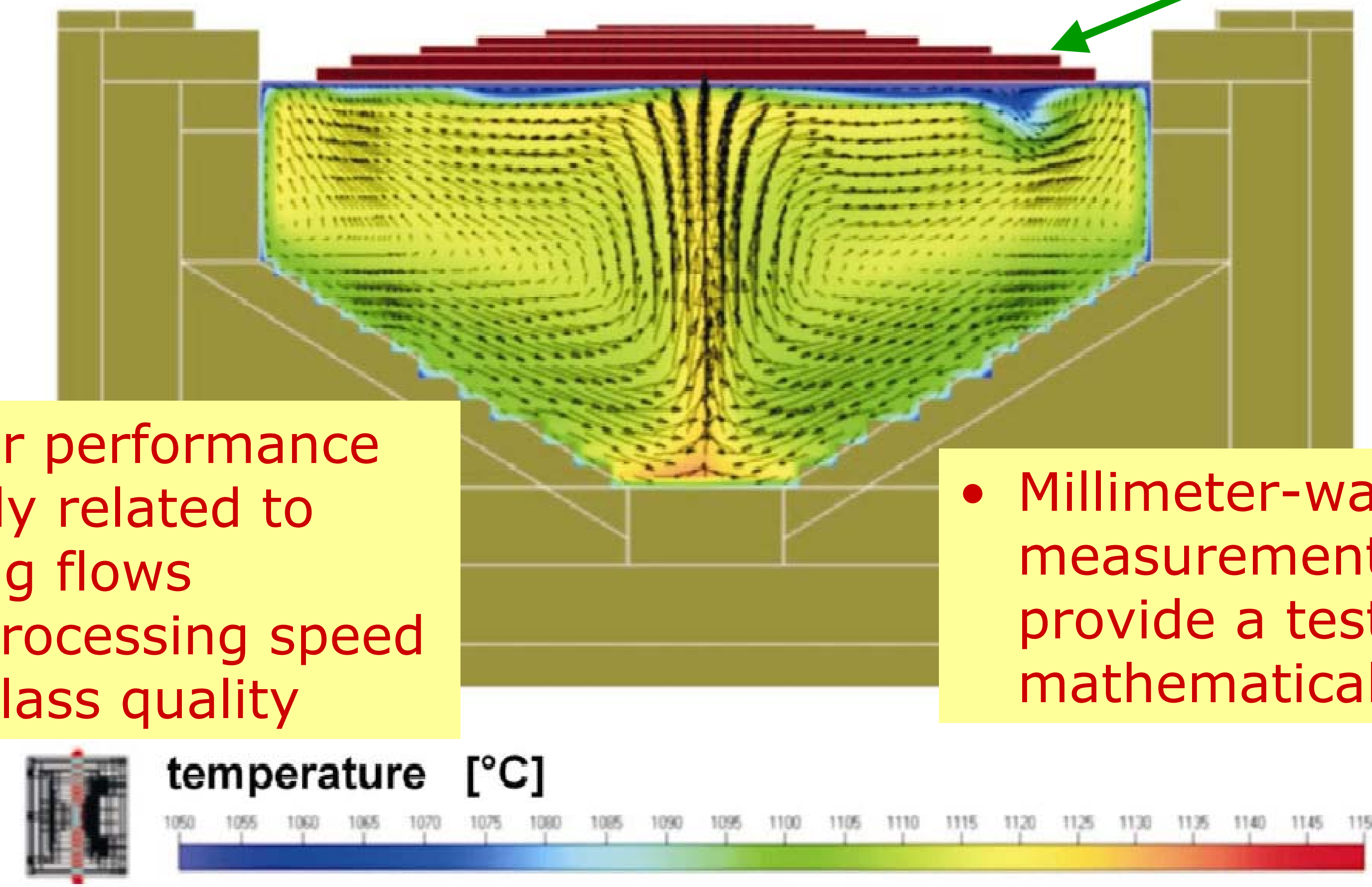




- Glass fluctuations increase in frequency and amplitude with temperature
- Could lead to instantaneous viscosity measurement and other fluid properties

Glass Flow Modeling

Temperature and velocity fields in a high level waste melter cross-section



- Melter performance closely related to mixing flows
  - ✓ processing speed
  - ✓ glass quality

- Millimeter-wave measurements could provide a test of mathematical models

Pavel Hrma, PNNL

Cold-Cap Monitoring

- Currently there is no proven technology to measure cold-cap temperature and profile it directly in a melter. Often plenum temperature is a good indicator.

- Cold-cap temperature and temperature distribution determine the cold-cap movement and dynamics in a melter, which in turn determine the productivity.

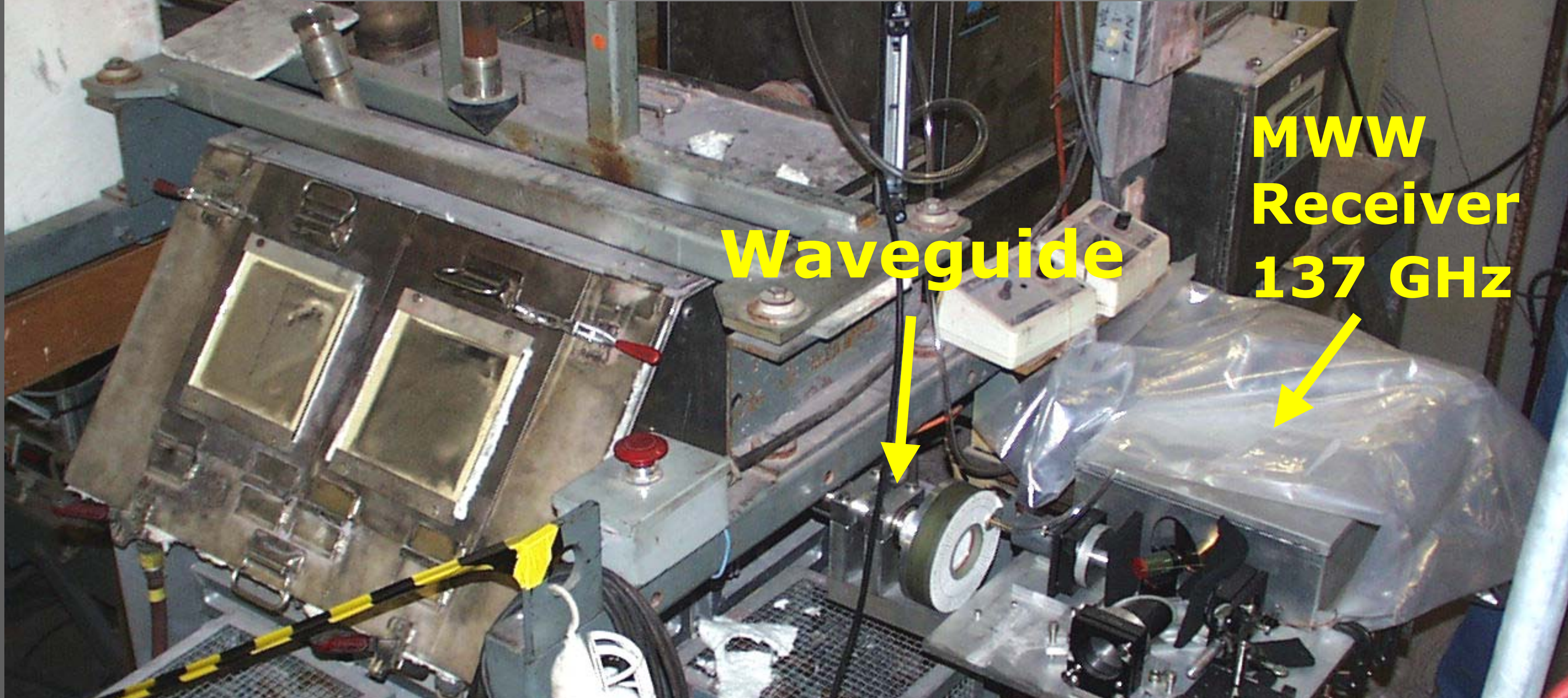
- A reliable on-line measuring and monitoring technology will help improve processability. Optical techniques do not work well (gases, steam, dust, particulates). Millimeter waves can penetrate smoke and dust.

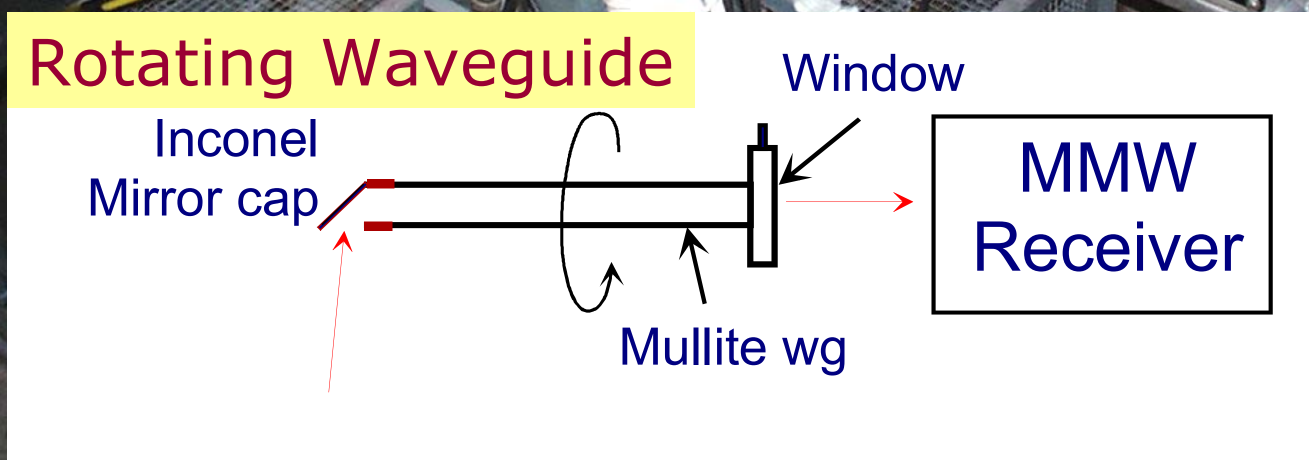
MMW Technology Field Tested
Cold Cap Profile Monitoring

- Engineering scale EV-16 Melter at Clemson Environmental Technologies Laboratory (CETL)
- Millimeter-wave temperature surface **profile** measurement capability implemented
- Millimeter-Wave monitoring technology operated reliably

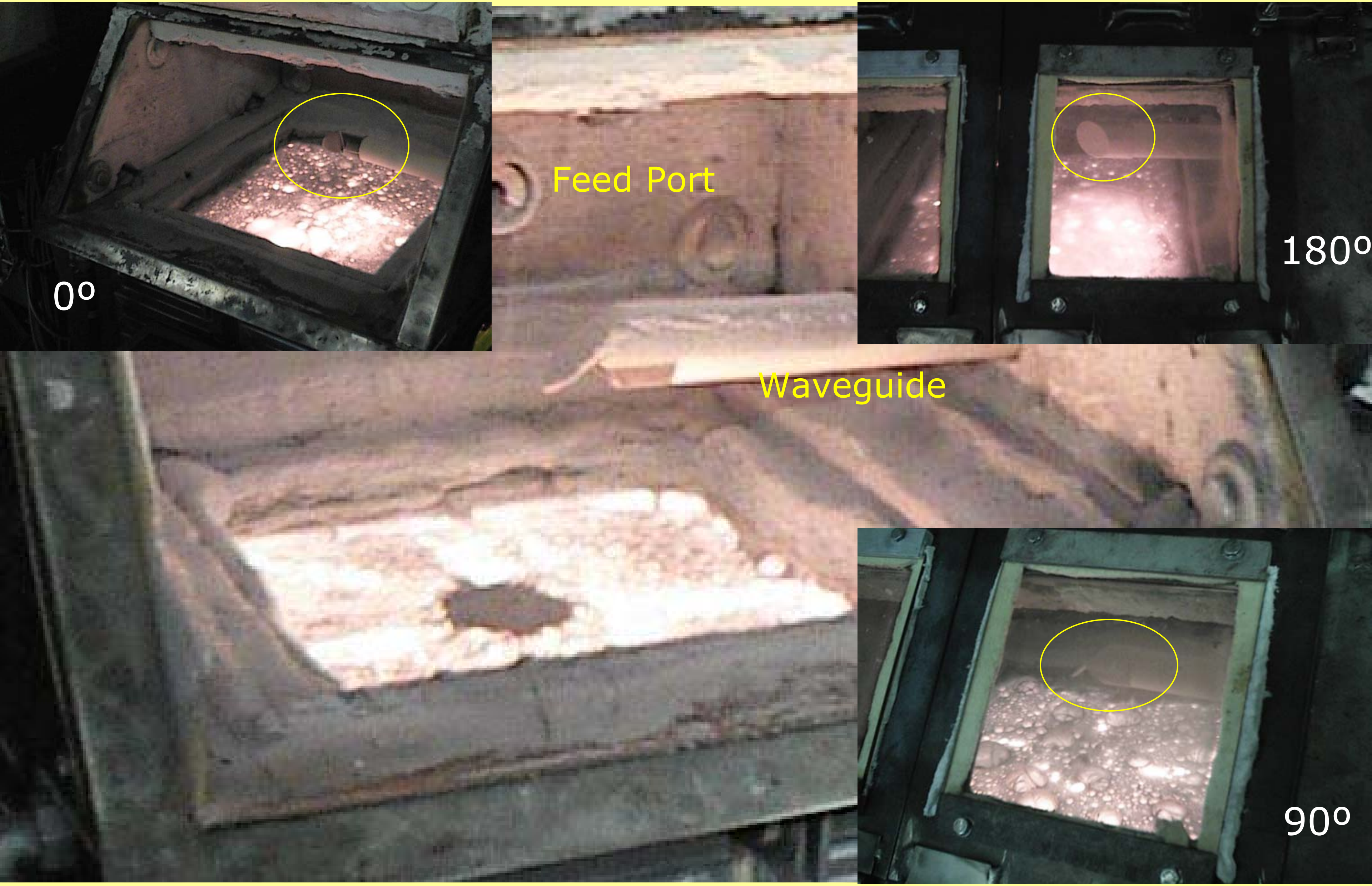
  → 24 hours a day over two week period

EV-16 Melter at CETL

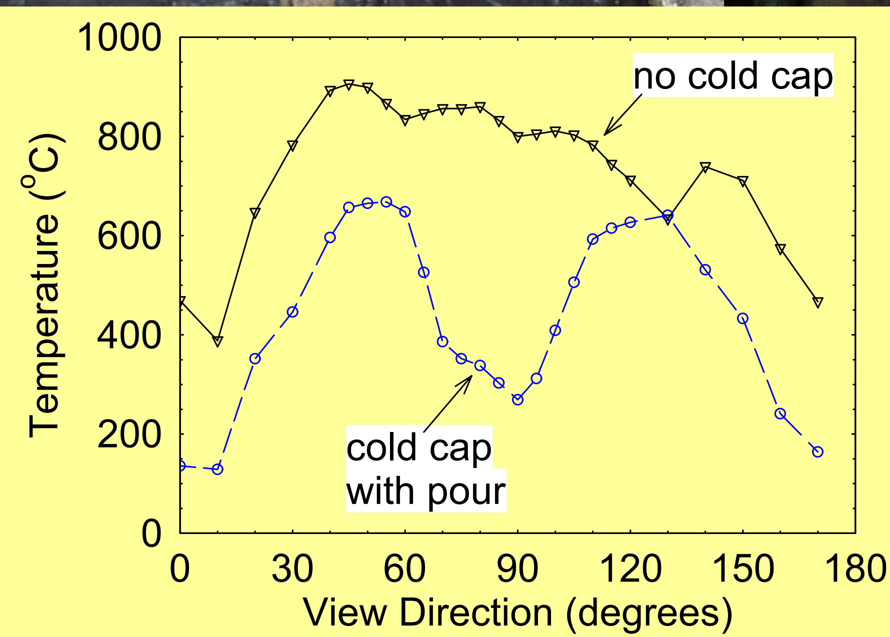


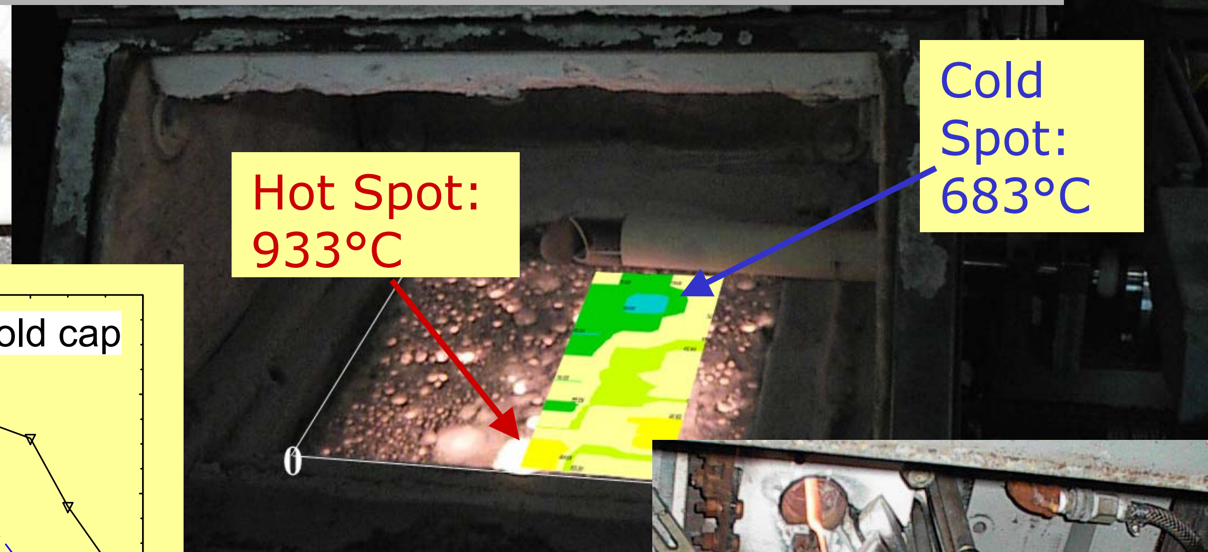


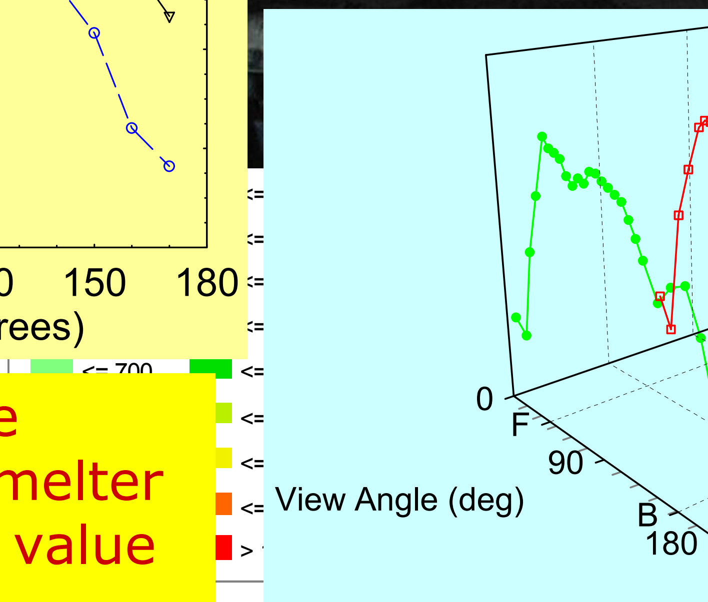
Inside Melter



Surface Temperature Profiles/Contours

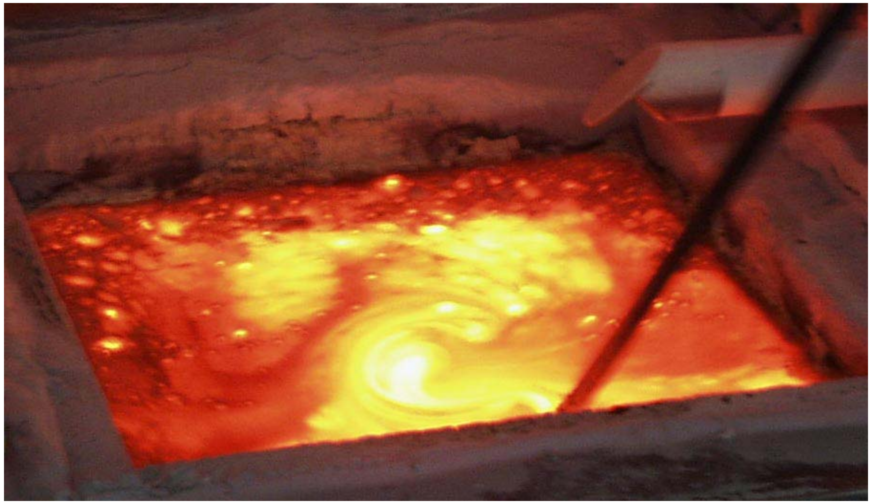


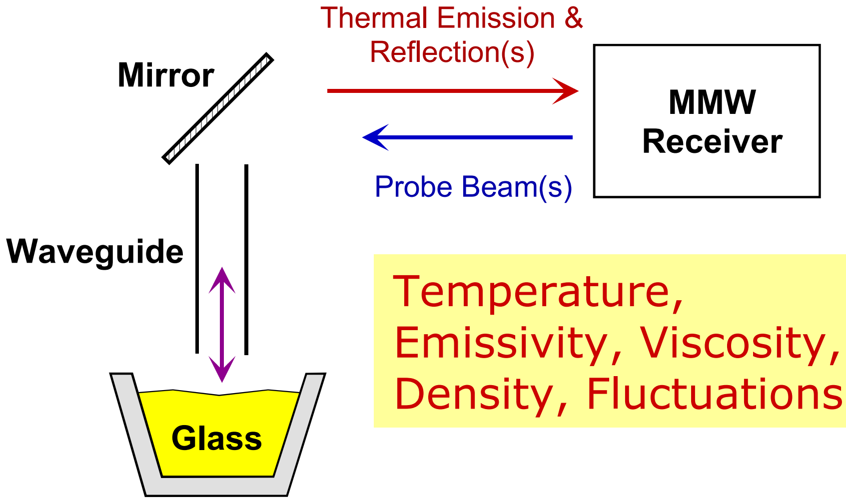




- Cold-cap temperature profiles indicative of melter process conditions of value to process control
- Potential to control plenum off gasses

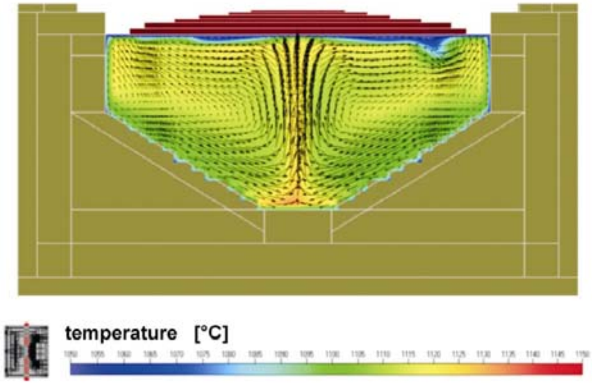
Summary



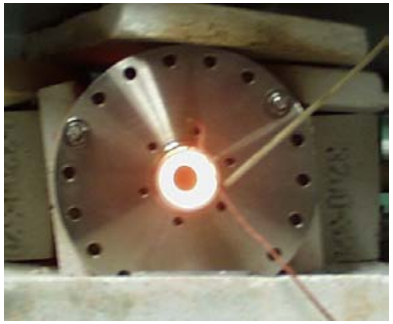


Temperature, Emissivity, Viscosity, Density, Fluctuations

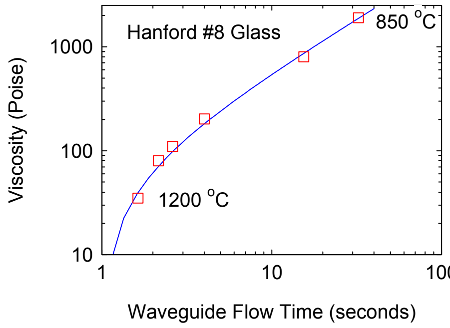
- **New High Temperature MMW Monitoring Capability Demonstrated**
  - ✓Improve process efficiencies
  - ✓Improve product quality
  - ✓Reduce environmental impact



Potential to test melter models



Efficient waveguides future potential for heating



Further Reading

"Millimeter-Wave Monitoring of Nuclear Waste Glass Melts – An Overview", *P. P. Woskov, J. S. Machuzak, P. Thomas, S. K. Sundaram, and W. E. Daniels, Jr.,* in Environmental Issues and Waste Management Technologies VII (*Ceramic Transactions, Volume 132*) pp. 189-201.

"Thermal return reflection method for resolving emissivity and temperature in radiometric measurements", *P. P. Woskov and S. K. Sundaram,* J. Appl. Physics, (to be published December 1, 2002).