

SENSING IN GLASS MANUFACTURING

Measuring the Extreme

Physics and Challenges of
High-Temperature Glass Sensing

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“The glass is at 1400 °C” ... or is it?

SAME TANK • SAME MOMENT



Both instruments can be calibrated...
and both can be correct.

Different:
spots measured • locations • depths • response times

Define the need before selecting a sensor

Consider the Possibilities



BULK MELT + HOT SPOT

Volume-average melt temperature -- and the hottest local region.



SURFACE + BATCH

Free surface, cold cap, or batch-blanket temperature.



REFRACTORY INTERFACE

Glass/refractory boundary temperature and the local gradient.



FOREHEARTH + DELIVERY

Forehearth, channel, feeder, moving gob, or stream temperature.



HEAD SPACE + FIELD

Combustion-space temperature -- or a full temperature distribution.

One furnace -- many areas of interest



Temperature variations (not just one number) can drive glass quality, furnace life, process control, and more.

Sensors turn interactions into information

Sensor: a device that receives and responds to a signal or stimulus

OPTICAL

radiance • absorption • image

ELECTRICAL

voltage • current • resistance

ACOUSTIC

velocity • attenuation • emission

ELECTROMAGNETIC

induction • microwave response

MECHANICAL

force • pressure • displacement

CHEMICAL

species • concentration • redox

P

Physical interaction

Energy, matter, or motion changes the sensing element.

T

Transduction

The interaction becomes an electrical or optical signal.

I

Inference

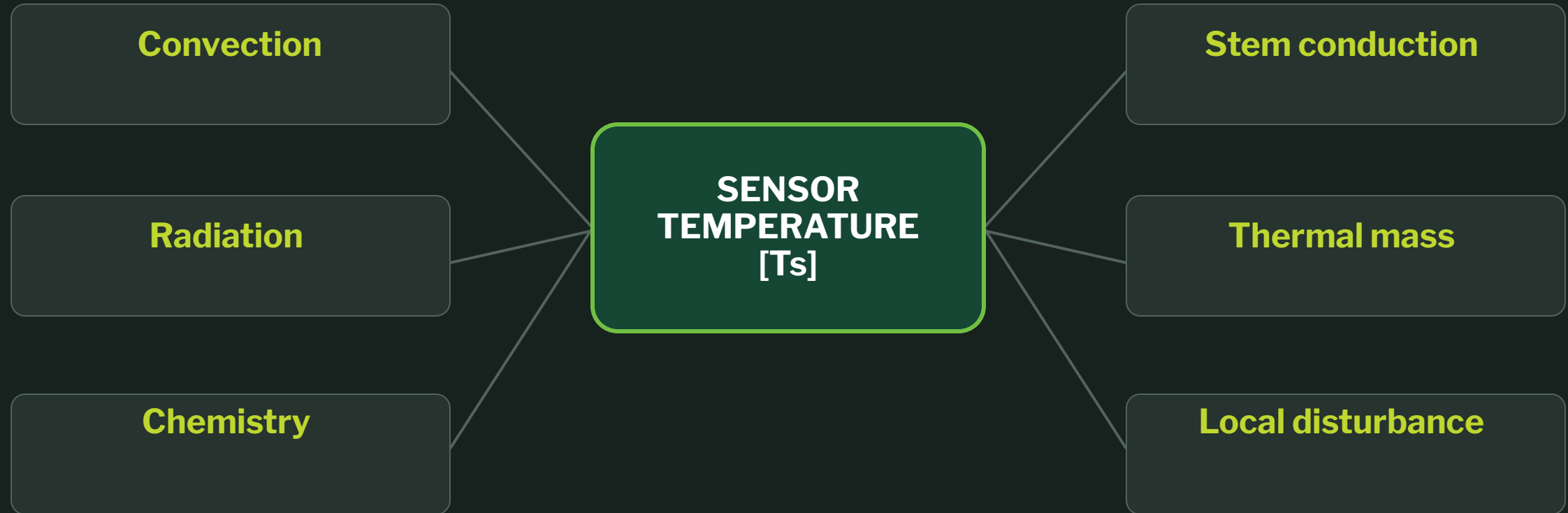
A model converts signal into the process variable to be used.

Contact and non-contact “see” different things

SENSOR FAMILY	ACCESS	TYPICAL VIEW / LIMIT
Thermocouple	Contact	Local bulk/interface; drift, sheath attack, stem conduction
Resistance Temperature Detector	Contact	Lower-temperature zones; limited by rated temperature
Embedded / optical fiber	Contact / coupled	Interface or remote optical point; installation-limited
Pyrometer / IR camera	Non-contact	Fast surface/depth-weighted radiance; emissivity and path
Spectroscopy	Non-contact	Path-average gas temperature/species; optical access

Contact engages the material --- Non-contact trades intrusion for inference.

A contact probe is part of the thermal circuit



Convection: heat transfers from moving glass to probe

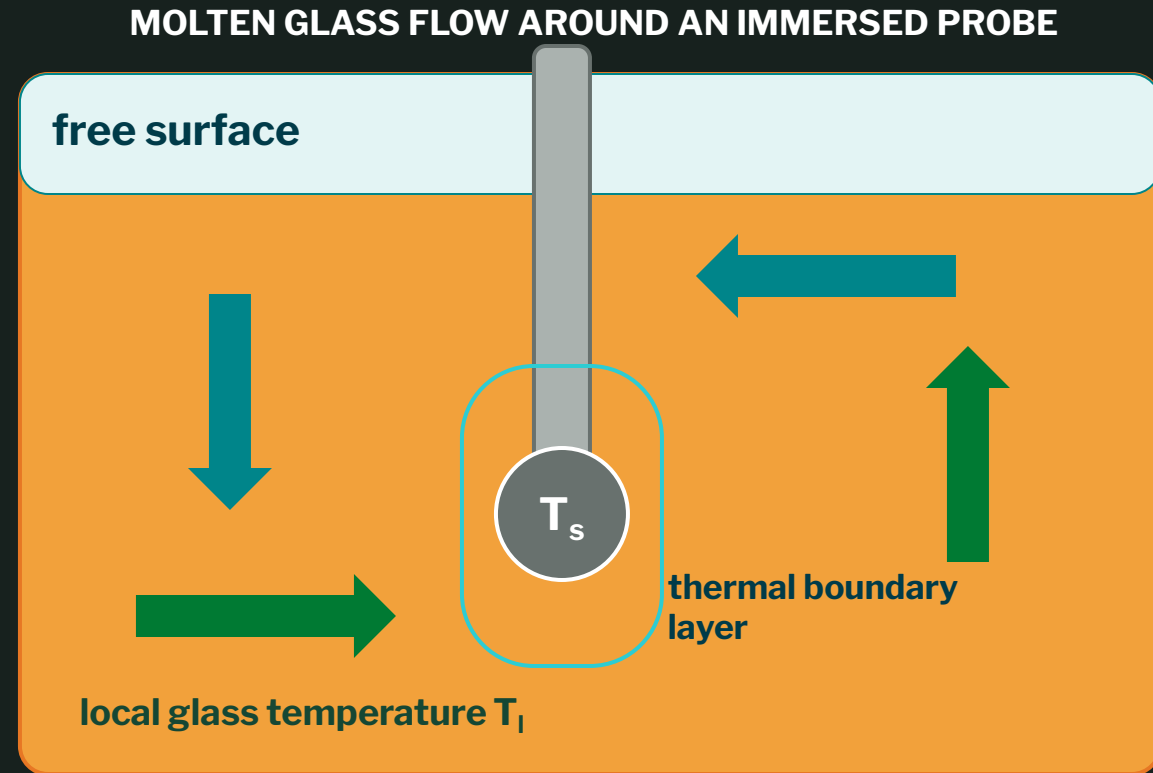
Convection

$$\dot{q}_{\text{conv}} = h A (T_l - T_s)$$

h depends on flow velocity, viscosity, probe diameter and orientation.

$$\eta = hD/k = f(\text{Re}, \text{Pr})$$

Higher local flow usually thins the boundary layer and increases heat transfer to the sensor.



A flow change can shift the reading even with minimal change in tank-average temperature

Radiation couples probe to furnace surroundings

Radiation

$$\dot{q}_{\text{rad}} = \varepsilon \sigma A F (T_{\text{sur}}^4 - T_s^4)$$

ε : surface emissivity

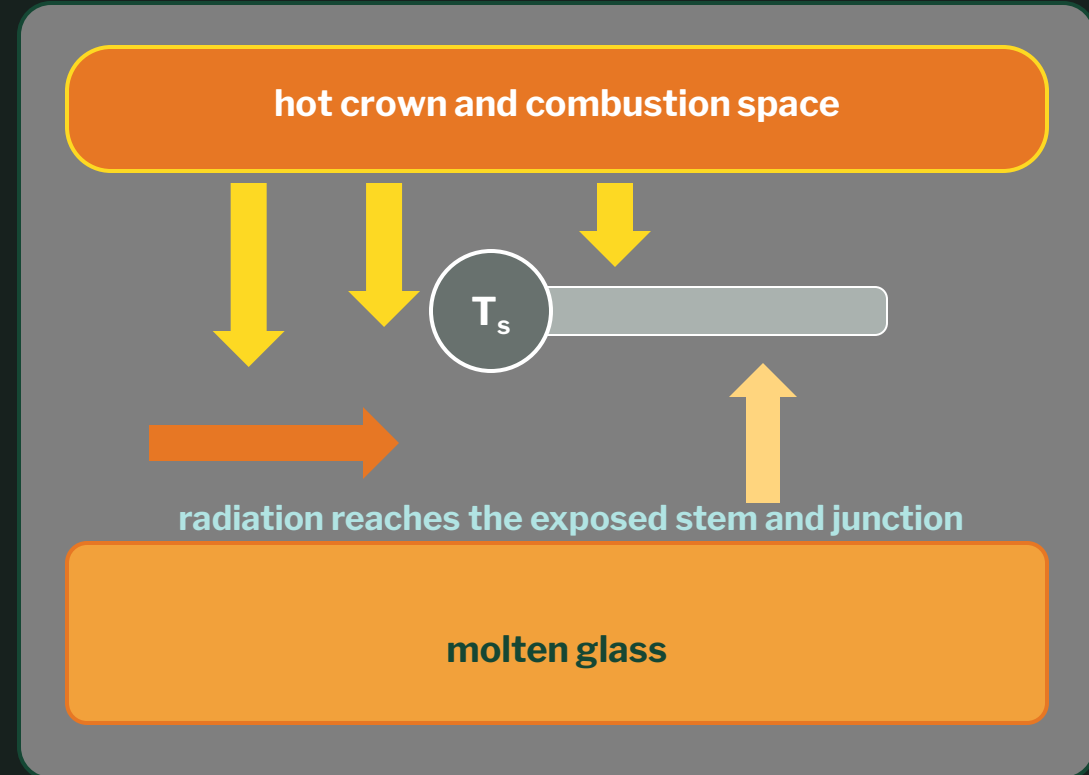
F : geometric view factor

T_{sur} : effective radiant surroundings

T_s : sensor temperature

σ : Boltzman's constant

The fourth-power term makes crown, wall and flame temperatures increasingly important at furnace conditions.



The probe responds to the radiant scene as well as the glass touching it.

Chemistry changes the sensor during service

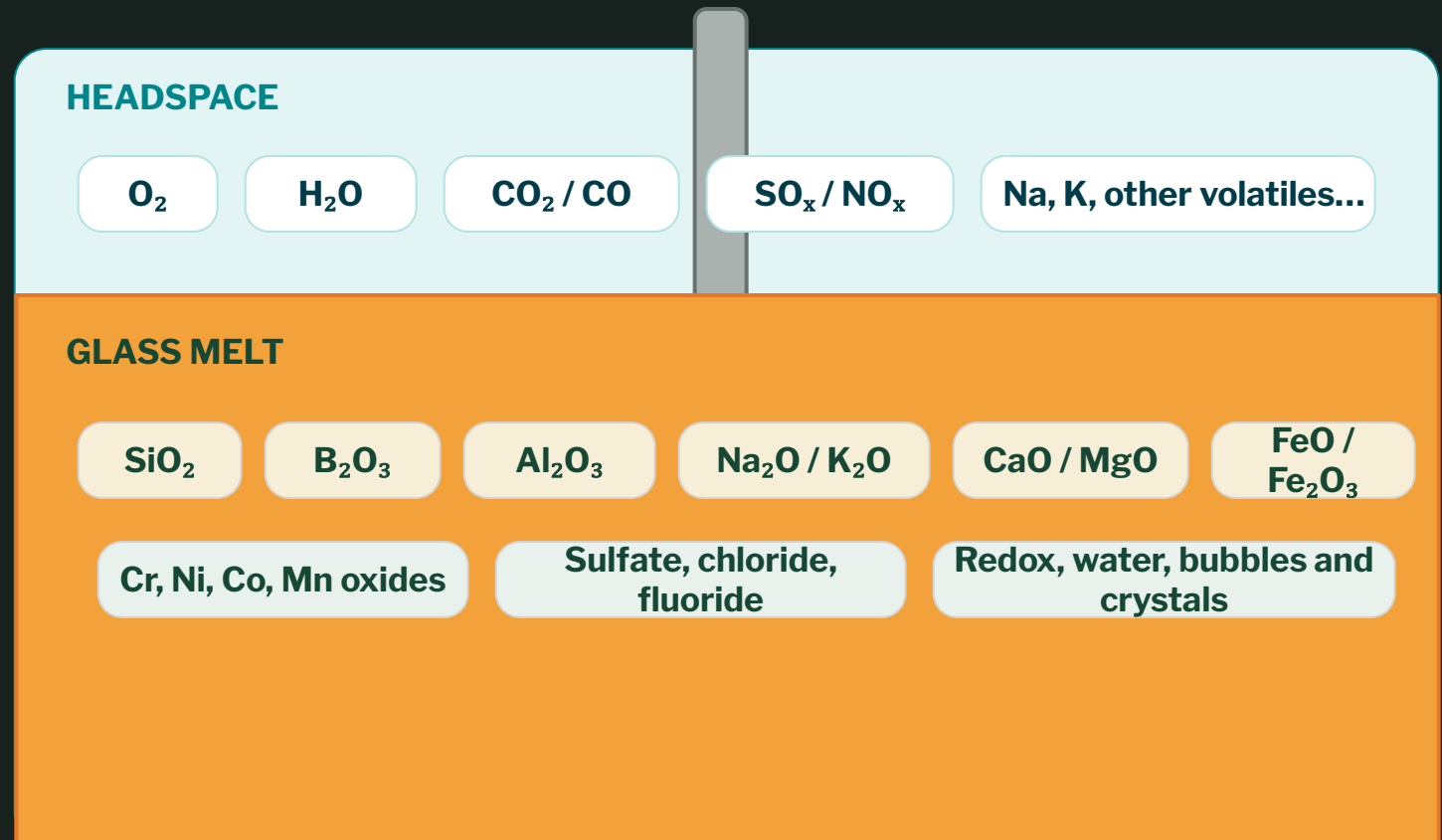
Chemistry

corrosion • dissolution • drift

Temperature and redox set reaction rates. Composition controls solubility, wetting and corrosivity.

Possible outcomes

sheath dissolution
junction contamination
selective oxidation
vapor deposition and electrical drift



Material compatibility and atmosphere history become part of the calibration history.

Stem conduction links the hot junction to the cool mount

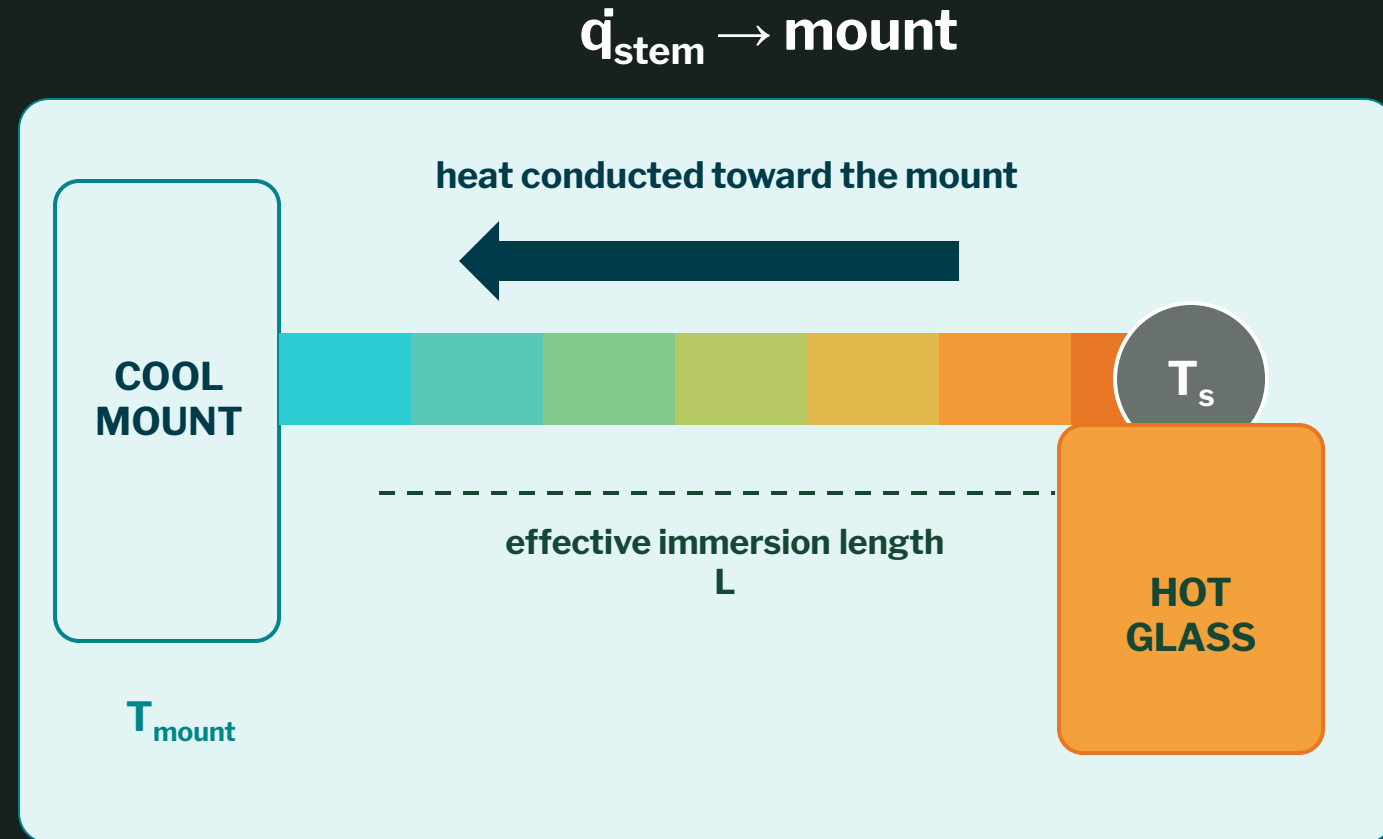
Stem conduction

$$\dot{q}_{\text{stem}} \approx kA_c (T_s - T_{\text{mount}}) / L$$

Large k_{stem} and cross-sectional area A_c increase the heat leak.

Longer effective immersion L reduces the influence of the mounting temperature.

If $T_{\text{mount}} < T_s$, the energy balance subtracts $\dot{q}_{\text{stem}}$.



Insufficient immersion can pull the indicated temperature toward the mount temperature.

Thermal mass sets the response time

Thermal mass

$$mc_p dT_s/dt$$

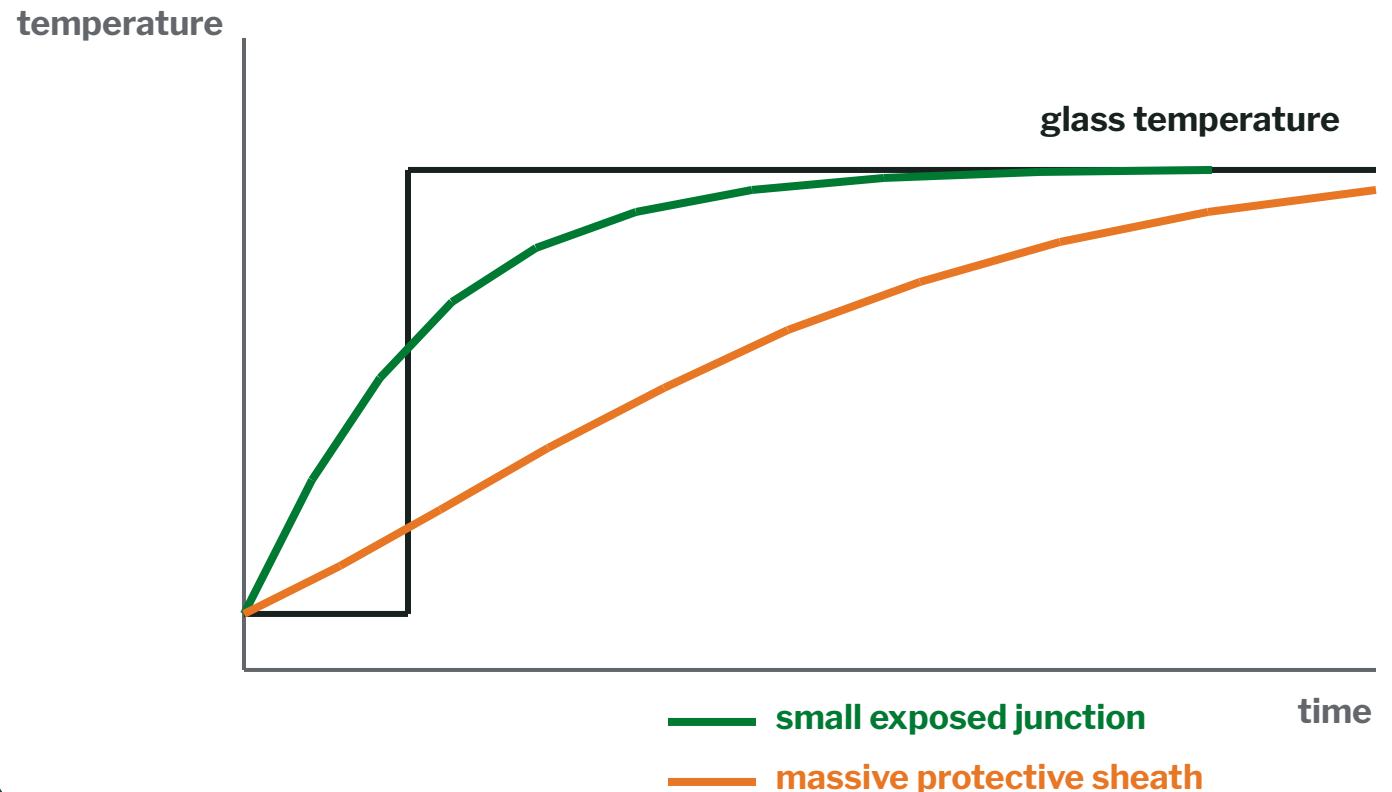
FIRST-ORDER RESPONSE

$$T_s(t) = T_\infty + (T_0 - T_\infty) e^{-t/\tau}$$

$$\tau \approx mc_p / (hA + 4\epsilon\sigma A\bar{T}^3)$$

More protective mass increases m^*c_p and usually increases τ .
The reading then averages more of the recent thermal history.

RESPONSE TO A STEP IN GLASS TEMPERATURE



A durable probe may miss rapid changes that a fast optical measurement captures.

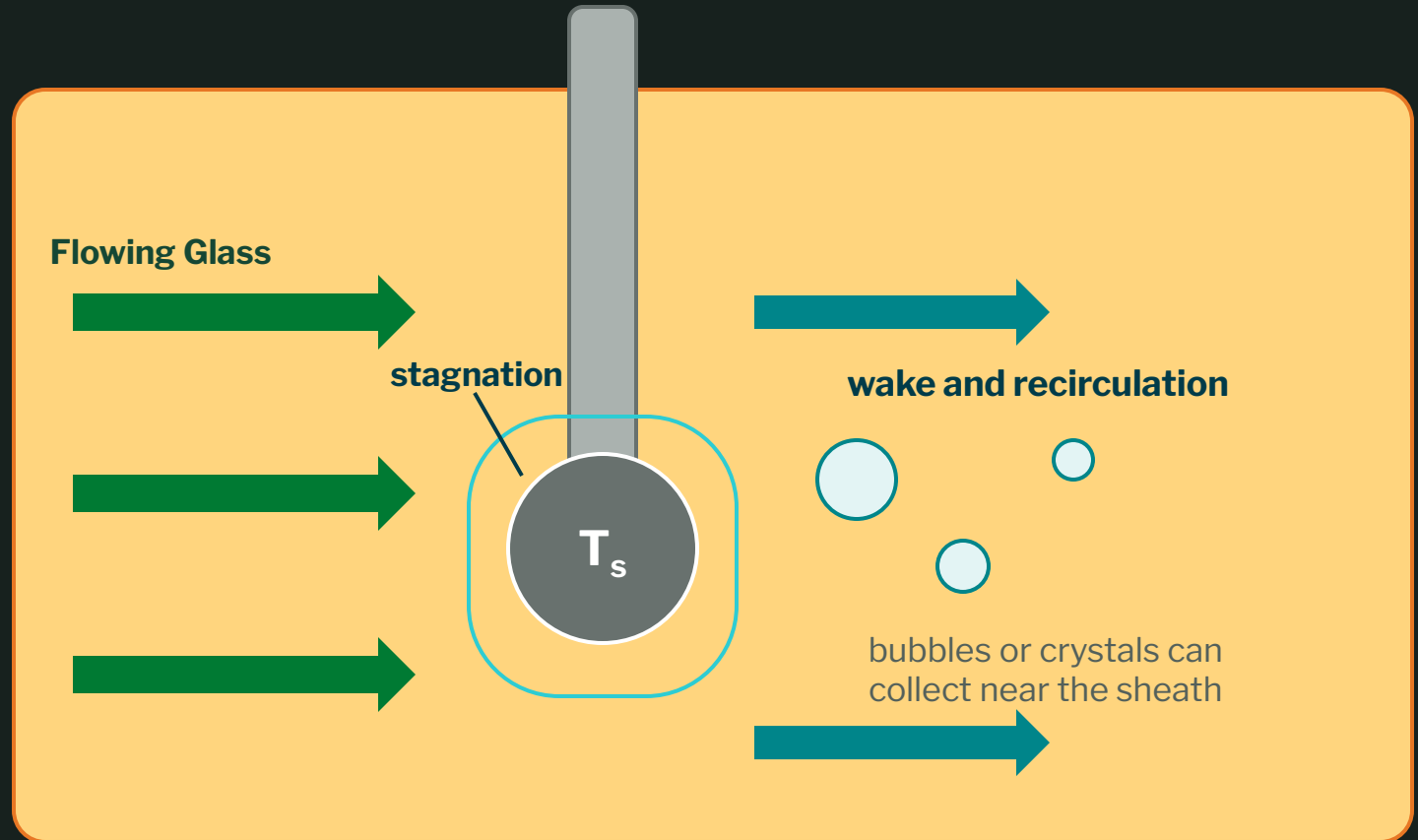
Local disturbance from an immersed probe

Local disturbance

$$Re = \rho v D / \mu \quad Pe = Re Pr$$

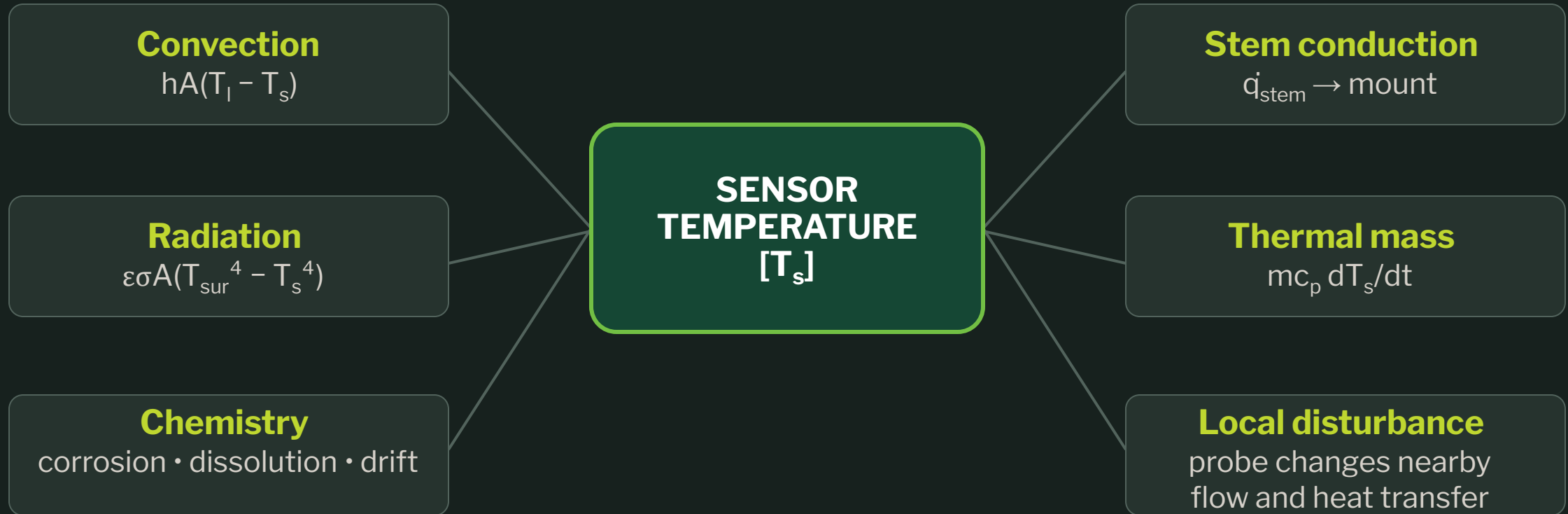
Probe diameter (D) changes blockage, boundary-layer thickness and wake size.

Nearby walls, bubbles, and steep gradients make the disturbed regions less representative of the undisturbed melt.



A calibrated probe can still report the temperature of a disturbed local field.

A contact probe is part of the thermal circuit



$$m c_p dT_s/dt = h A(T_l - T_s) + \epsilon \sigma A(T_{sur}^4 - T_s^4) - \dot{q}_{stem}$$

Pyrometry measures radiation... not temperature

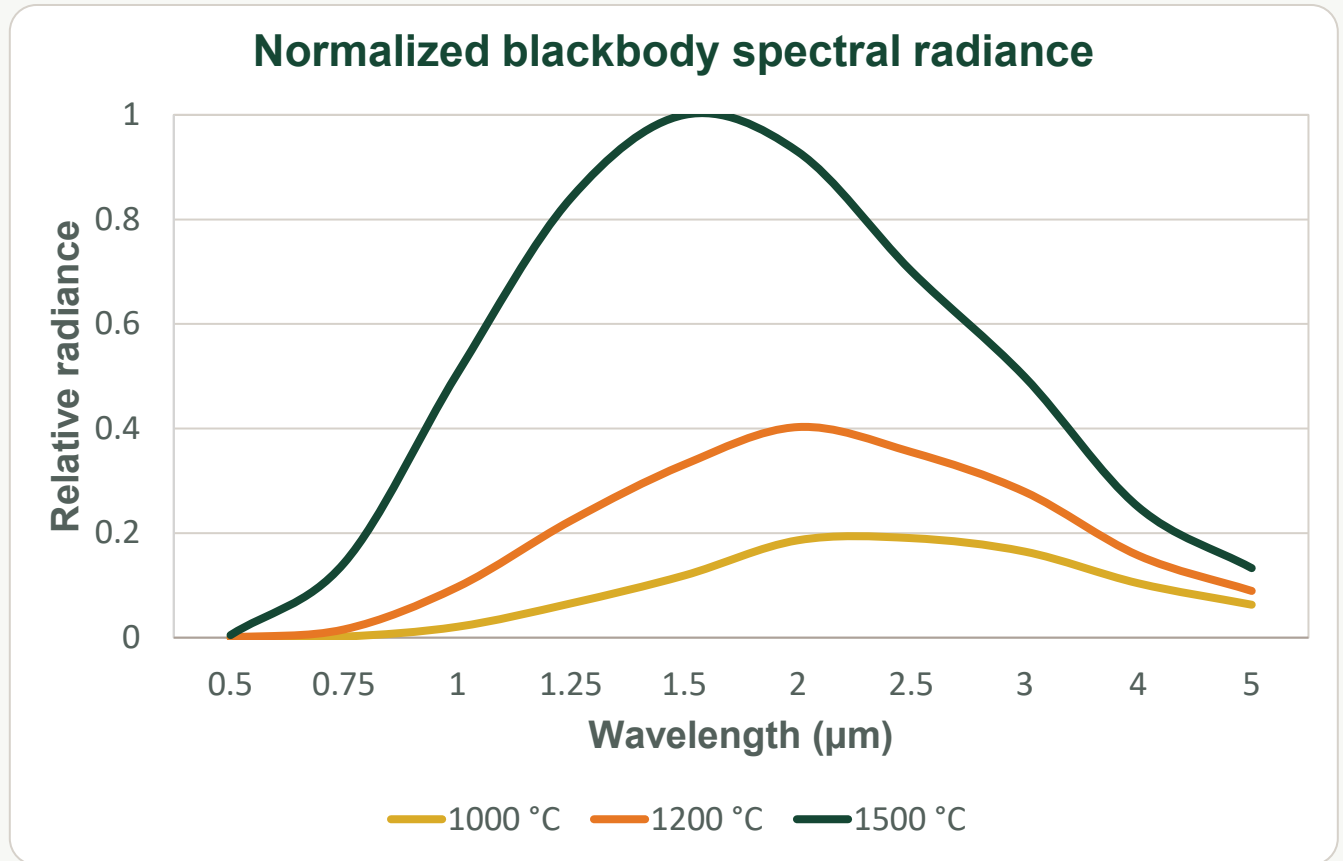
$$I_{\lambda} = \varepsilon \lambda B_{\lambda}(T)$$
$$B_{\lambda}(T) = \frac{2hc^2}{\lambda^5} \cdot [\exp(hc/\lambda kBT) - 1]^{-1}$$

Temperature changes the following:

total emitted radiance
spectral distribution and peak
wavelength

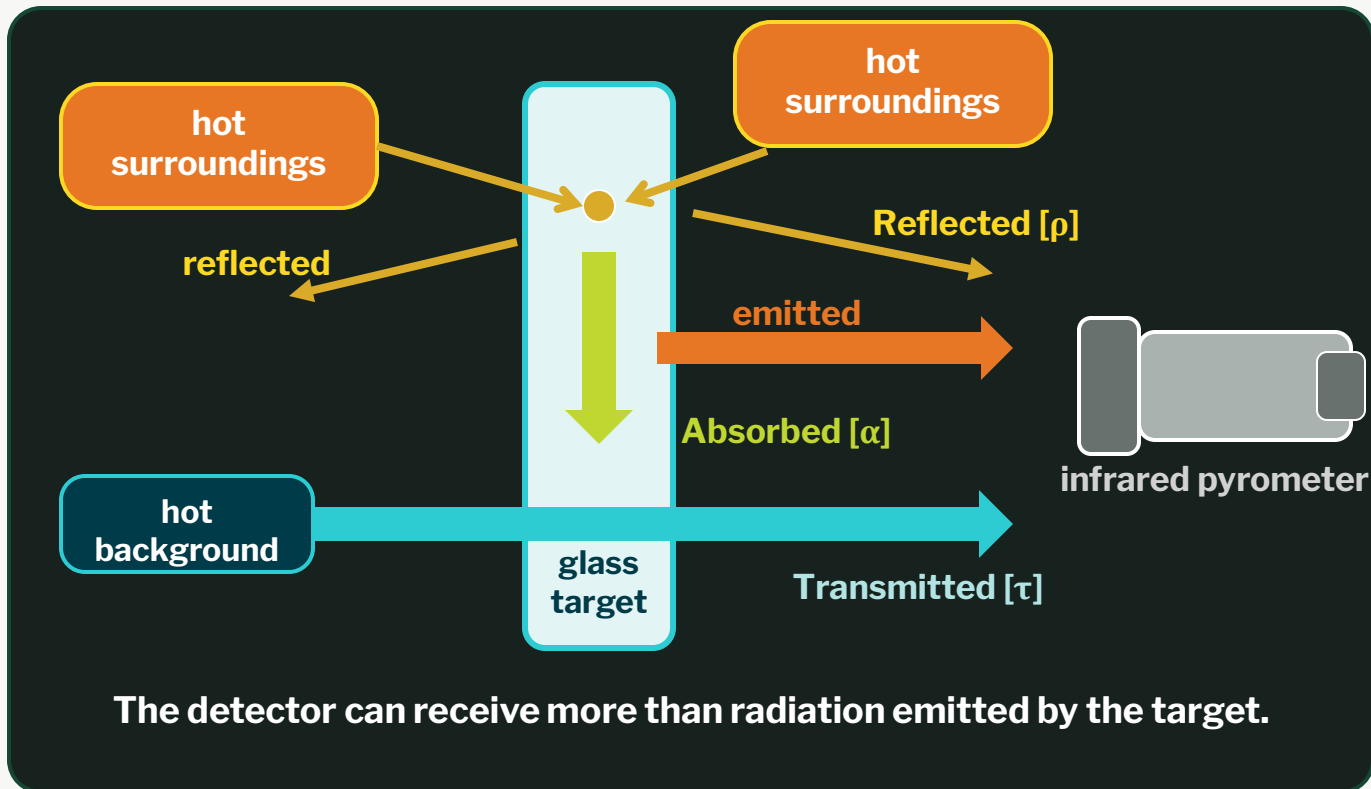
**The detector solves the inverse
problem:**

radiance + assumptions → temperature



What "emissivity" means

RADIANCE AT A SEMI-TRANSPARENT TARGET



SPECTRAL, DIRECTIONAL DEFINITION

$$\varepsilon_{\lambda,\theta}(T) = \frac{L_{\lambda,\text{target}}(T)}{L_{\lambda,\text{blackbody}}(T)}$$

POSSIBLE RANGE



RADIATION BALANCE

$$\alpha_{\lambda} + \rho_{\lambda} + \tau_{\lambda} = 1$$

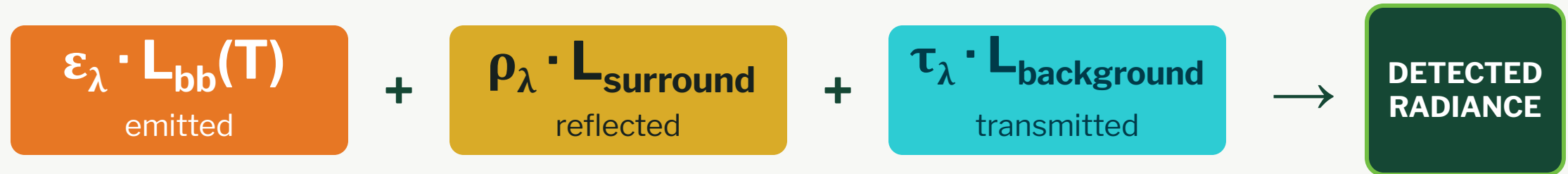
At thermal equilibrium: $\varepsilon_{\lambda,\theta} = \alpha_{\lambda,\theta}$

Opaque band: $\tau_{\lambda} \approx 0$, so $\varepsilon_{\lambda} \approx 1 - \rho_{\lambda}$

For glass, ε depends on wavelength, temperature, angle, composition, and surface condition.

Emissivity is the hidden variable

WHAT LEAVES THE TARGET



Why this causes error

- ❖ Emissivity varies with wavelength, temperature, composition, surface condition, and angle.
- ❖ Hot surroundings and optical-path emission can add radiance that the instrument assigns to the target.
- ❖ Two-color methods help only when the emissivity ratio and path attenuation behave as assumed.

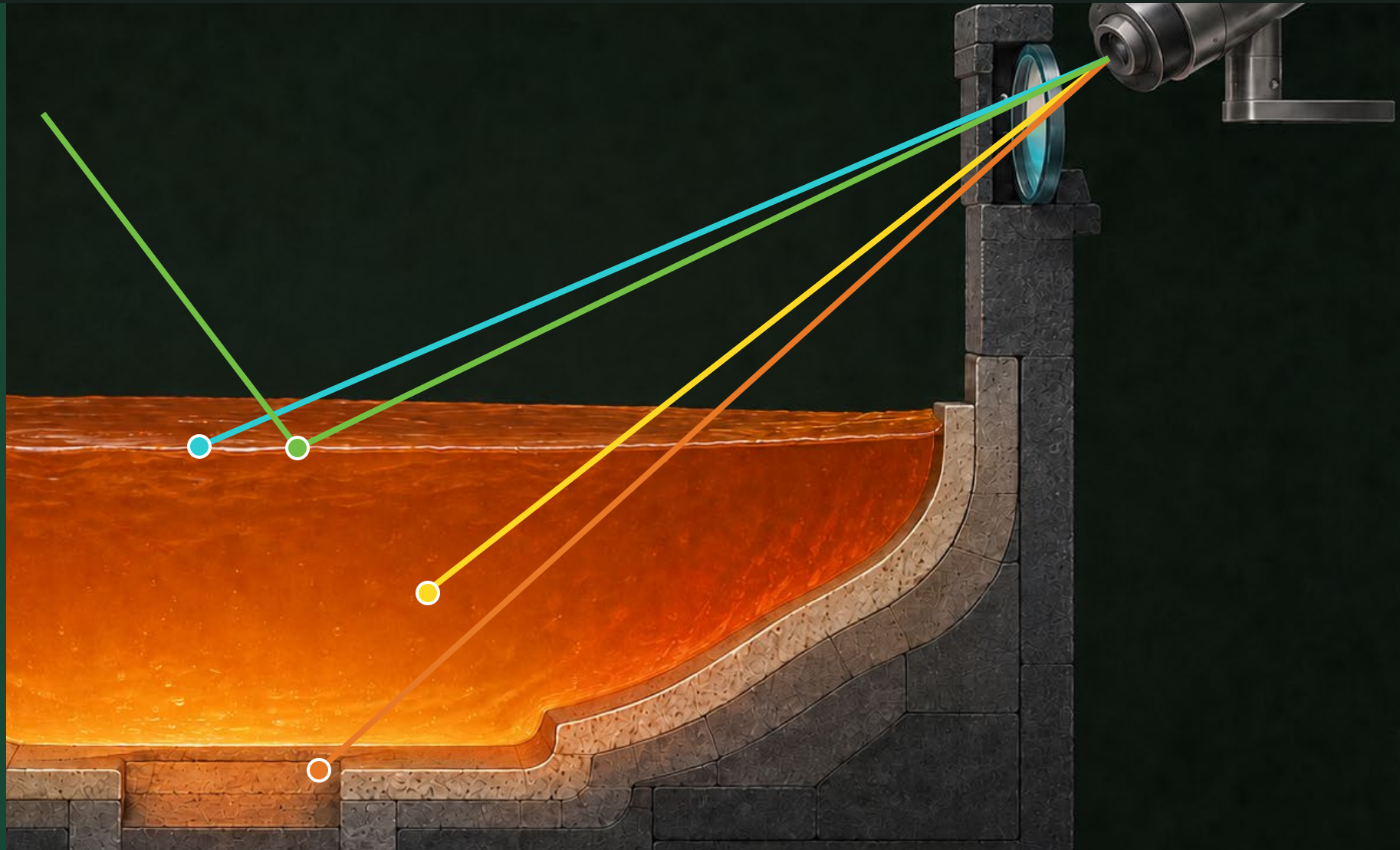
Calibration is necessary. A physically correct scene model is also necessary.

Hot glass is not an opaque surface

The detector may receive:

- surface emission
- emission from within the glass
- transmitted refractory background
- reflected furnace radiation

Composition, temperature, wavelength, thickness, and bubbles determine the weighting.



Glass optics are part of sensor design

1

SPECTRAL BAND

Transparency and absorption can change completely with wavelength.

2

CHEMISTRY + REDOX

Composition, colorants, transition metals, and oxidation state shift the spectrum.

3

TEMPERATURE + THICKNESS

Both set absorption, emission, and the optical depth sampled.

4

BUBBLES + PARTICLES

Bubbles, crystals, particles, and cords scatter or redirect radiation.

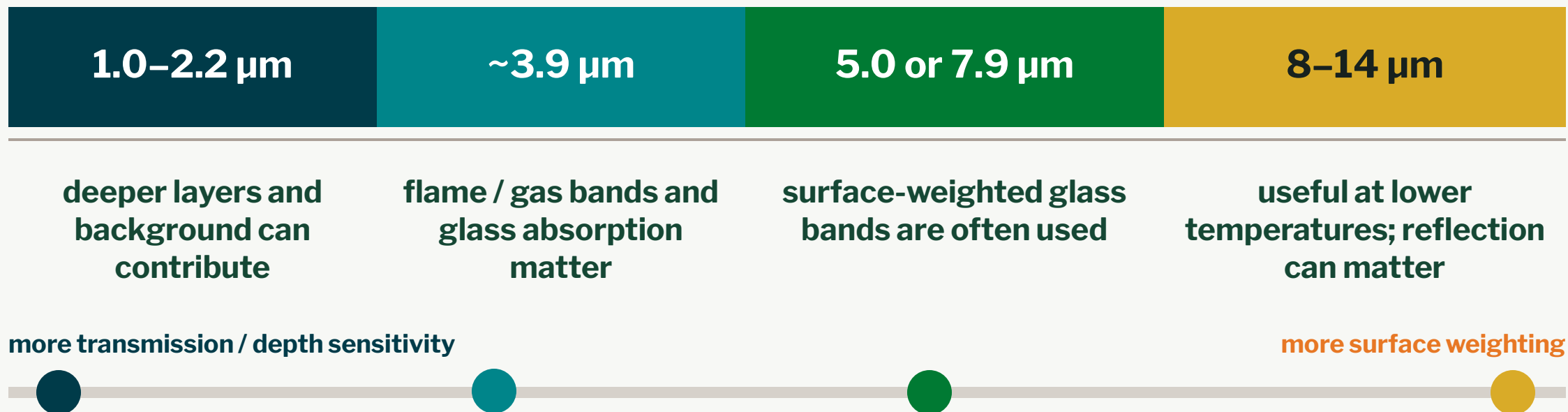
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SURFACE + ANGLE

Surface condition and viewing angle change reflection and emission.

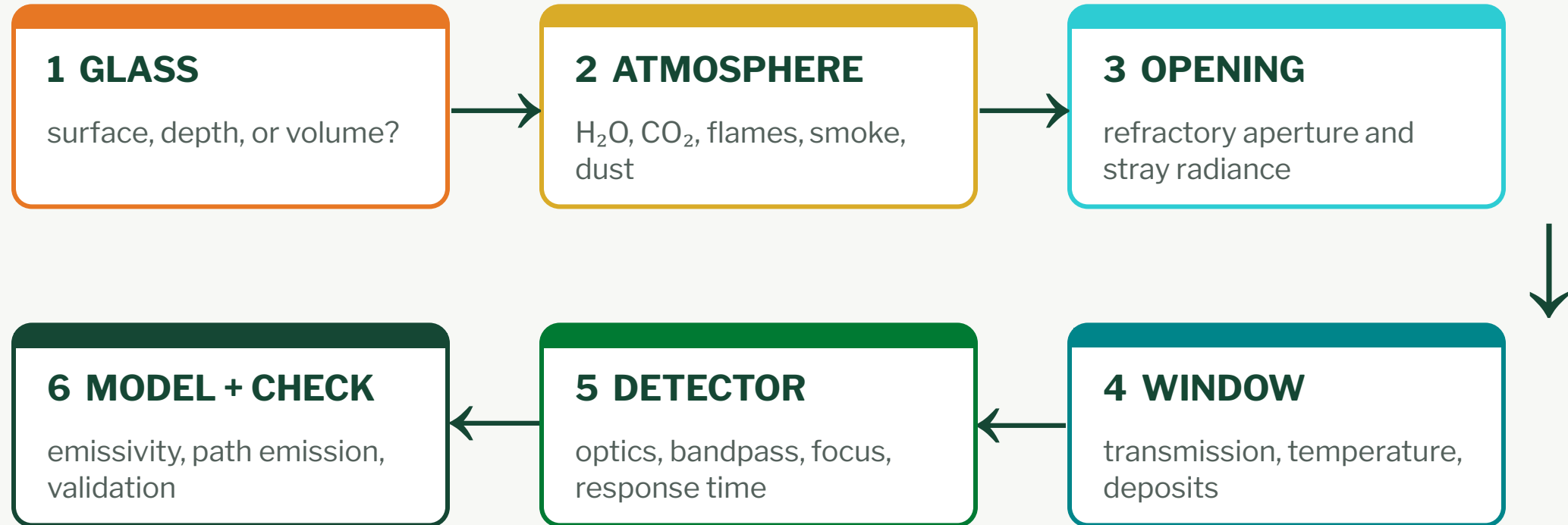
Wavelength decides what the pyrometer sees

TYPICAL INDUSTRIAL GLASS BEHAVIOR



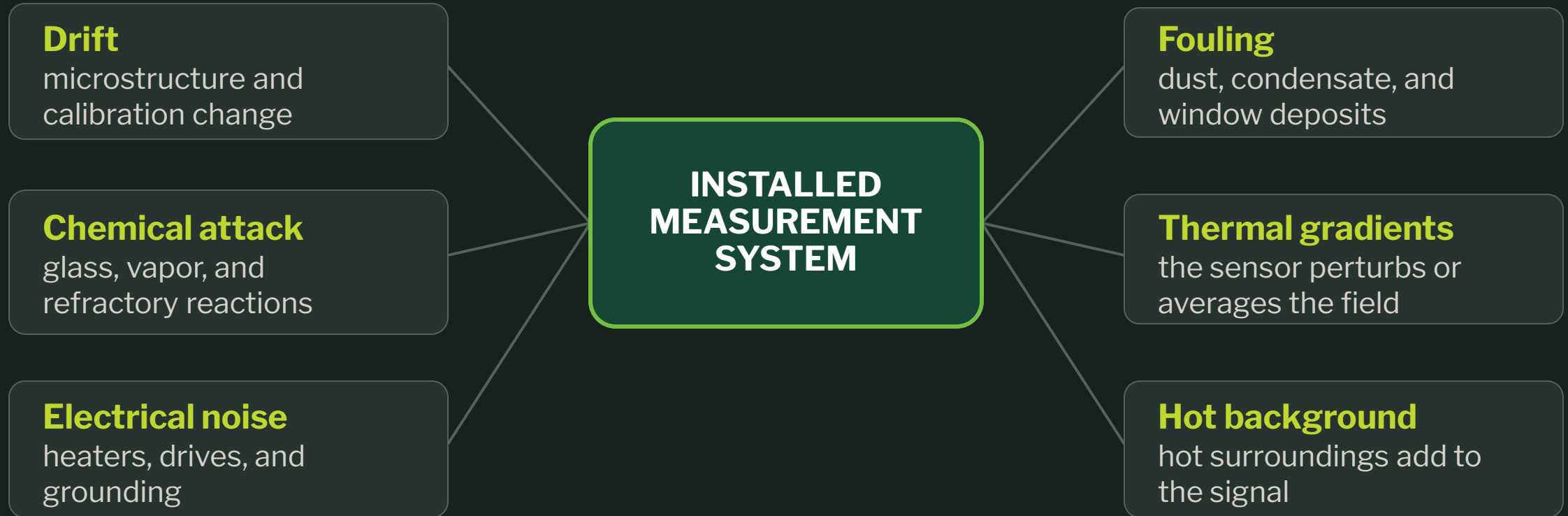
Choose the wavelength for the layer and decision that matter.

The optical path changes inferred temperature



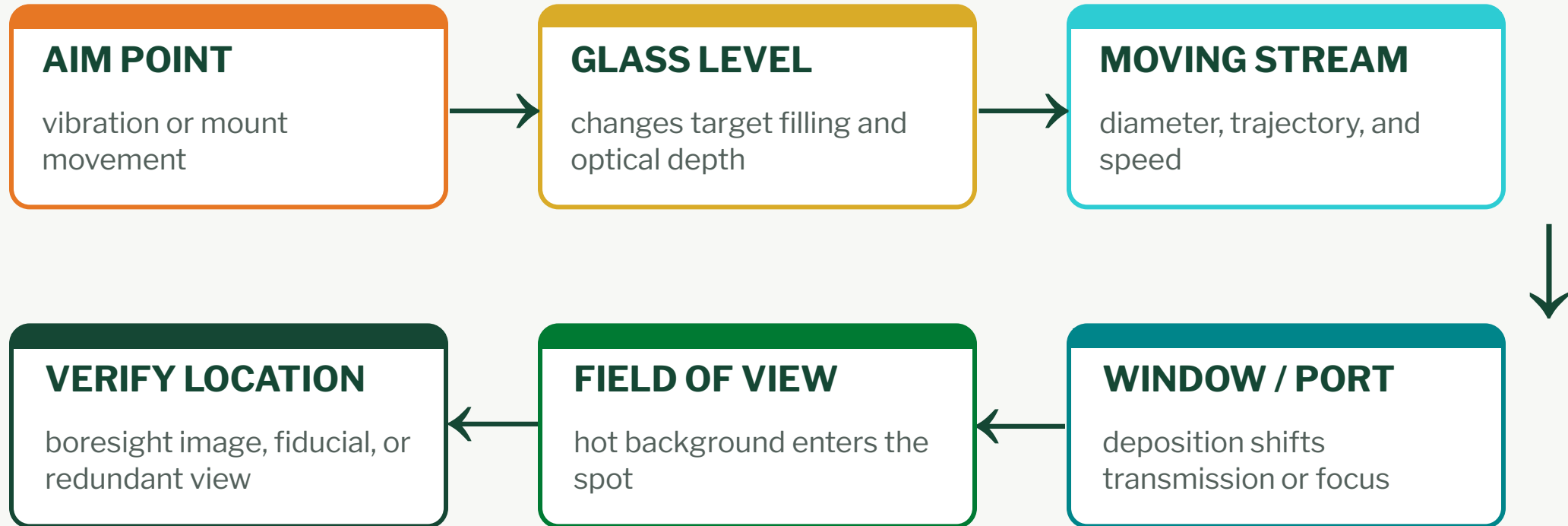
Important note:
Consider what your signal is passing through as you set up your sensors

Extreme heat becomes part of the measurement



The installed system (not the catalog specification) is the sensor.

The target can move inside the field of view



Track the scene geometry.... not only the signal value.

Dynamic processes force a four-way tradeoff

MORE ROBUST / SLOWER

FASTER / MORE INFERRED

Massive sheath

durable • slow

IR camera

fast • spatial

Spectroscopy

path average

Fine probe

fast • fragile

Pyrometer

milliseconds • one
spot

Soft sensor

fast estimate

DURABILITY

chemistry • cycling • mechanical
damage

RESPONSE + RESOLUTION

time constant • spot size • frame
rate

REPRESENTATIVENESS

point • surface • depth • path •
distribution

The process decides whether contact is practical

MORE PROCESS EXPOSURE

MORE REMOTE INFERENCE

Thermocouple

local contact

Waveguide

guided acoustic

Pyrometry

line of sight

Electrodes

in-melt response

Protected fiber

remote optics

Spectroscopy

path average

SURVIVABILITY

Can the sensing element and its sheath remain stable?

REPRESENTATION

Does the measurement represent the location or volume that matters?

MAINTAINANCE

Can it be inspected, calibrated, purged, or replaced safely?

One sensor rarely tells the whole process story

SENSOR FAMILY	BEST AT REVEALING	COMMON BLIND SPOT
Thermocouple	local material temperature	drift, sheath attack, conduction
Pyrometry / imaging	surface-weighted radiance and spatial patterns	emissivity, reflection, spot filling
Electrical / EM	level, conductivity, heating state	composition and geometry coupling
Acoustic	events, level, refractory condition	temperature- and path-dependent propagation
Spectroscopy / vision	gas species, bubbles, defects, flow	optical access, calibration, line-of-sight averaging

Sensor fusion works when the signals fail in different ways.

Sensor development and exploration helps inference to move closer to the process

SAPPHIRE / CRYSTAL FIBERS

temperature and strain beyond conventional silica-fiber limits

PHOSPHOR THERMOMETRY

surface temperature from calibrated luminescence lifetime or intensity

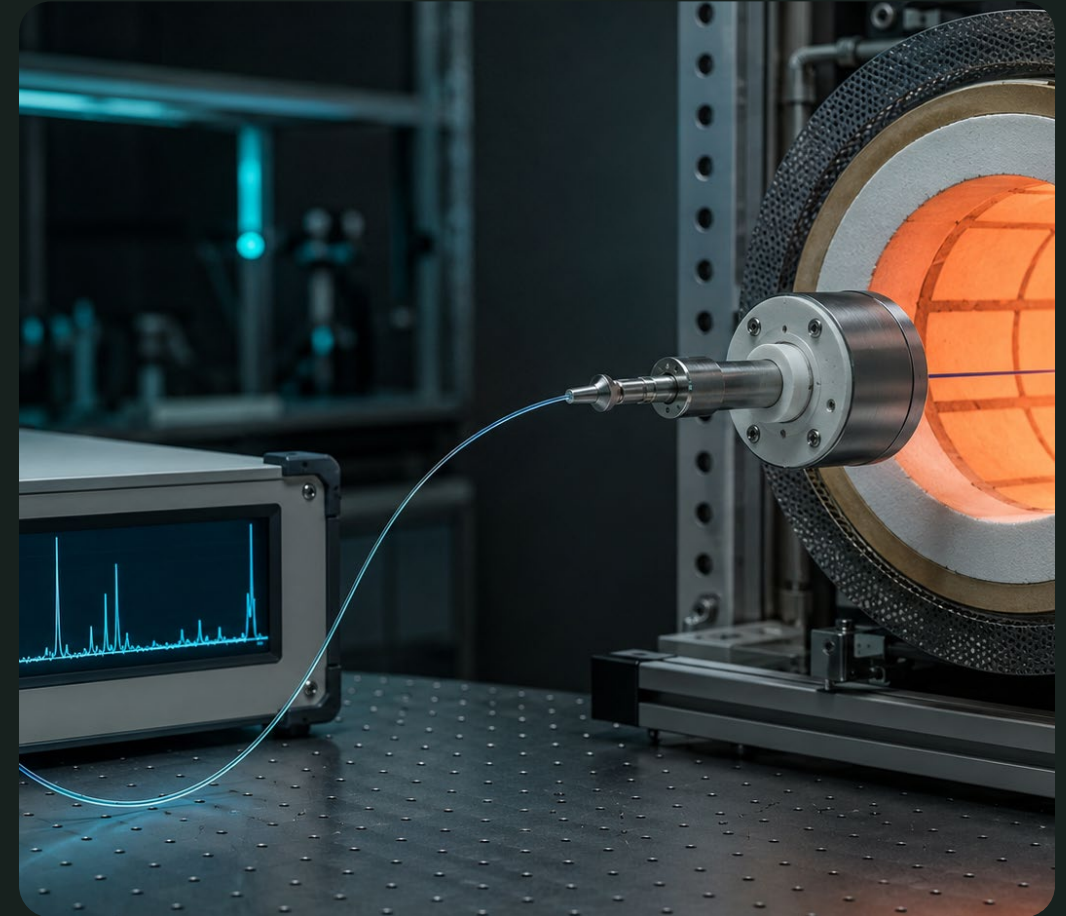
TUNABLE-DIODE SPECTROSCOPY

line-of-sight gas temperature and species in combustion space

SOFT SENSORS + DIGITAL TWINS

infer unmeasured states from sensors, physics, and process history

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Choose sensors by the decision they support

1

START WITH THE DECISION

What action will change if the value changes?

2

DEFINE THE MEASURAND

Temperature, level, flow, species, defect—or a proxy? Where and at what depth?

3

SET PERFORMANCE NEEDS

Allowable error, response time, spatial resolution, and useful range.

4

DESIGN FOR THE ENVIRONMENT

Temperature, corrosion, radiation, fouling, access, and maintenance.

5

PLAN VALIDATION

Independent evidence, redundancy, drift checks, and uncertainty.

ASK WHAT PRODUCED THE SIGNAL

- 1 A sensor measures an interaction, not the process variable directly.
- 2 At high temperature, installation and environment can dominate accuracy.
- 3 For glass, wavelength and optical depth define what “temperature” means.

Hopefully, this helps in future measurements!



QUESTIONS