Reliability and Traceability of Electronic Thermometers

Dean Ripple
NIST Thermometry Group

contact: dean.ripple@nist.gov, or 301-975-4801

Overview of thermometer types

Discussion of thermocouples

Discussion of platinum resistance thermometers

Thermistors, digital thermometers, and other types

Traceability, including measurement assurance

Electronic Thermometer Types

Standard Platinum Resistance Thermometers (SPRTs)

(very accurate, but susceptible to shock)

–259.4 °C to 962 °C (–435 °F to 1764 °F)

Industrial Platinum Resistance Thermometers (IPRTs, PRTs, or RTDs)

–196 °C to 850 °C (–321 °F to 1562 °F)

Thermistors

–50 °C to 100 °C (–58 °F to 212 °F)

Thermocouples

–196 ° C to 2100 °C (–321 °F to 3810 °F)

Digital Thermometers (PRT, thermistor, or thermocouple in disguise)

–196 °C to 850 °C

Considerations in Selecting a Thermometer

Accuracy: Uncertainties range from < 0.001 °C (0.002 °F) to >1 °C (2 °F)

Cost of Thermometer: Range from $6 to $6000

Cost of Calibration: from $50 to $12,000

Temperature Range

Stability and Durability during use

- chemical contamination
- resistance to high temperatures, moisture, vibrations, and shock

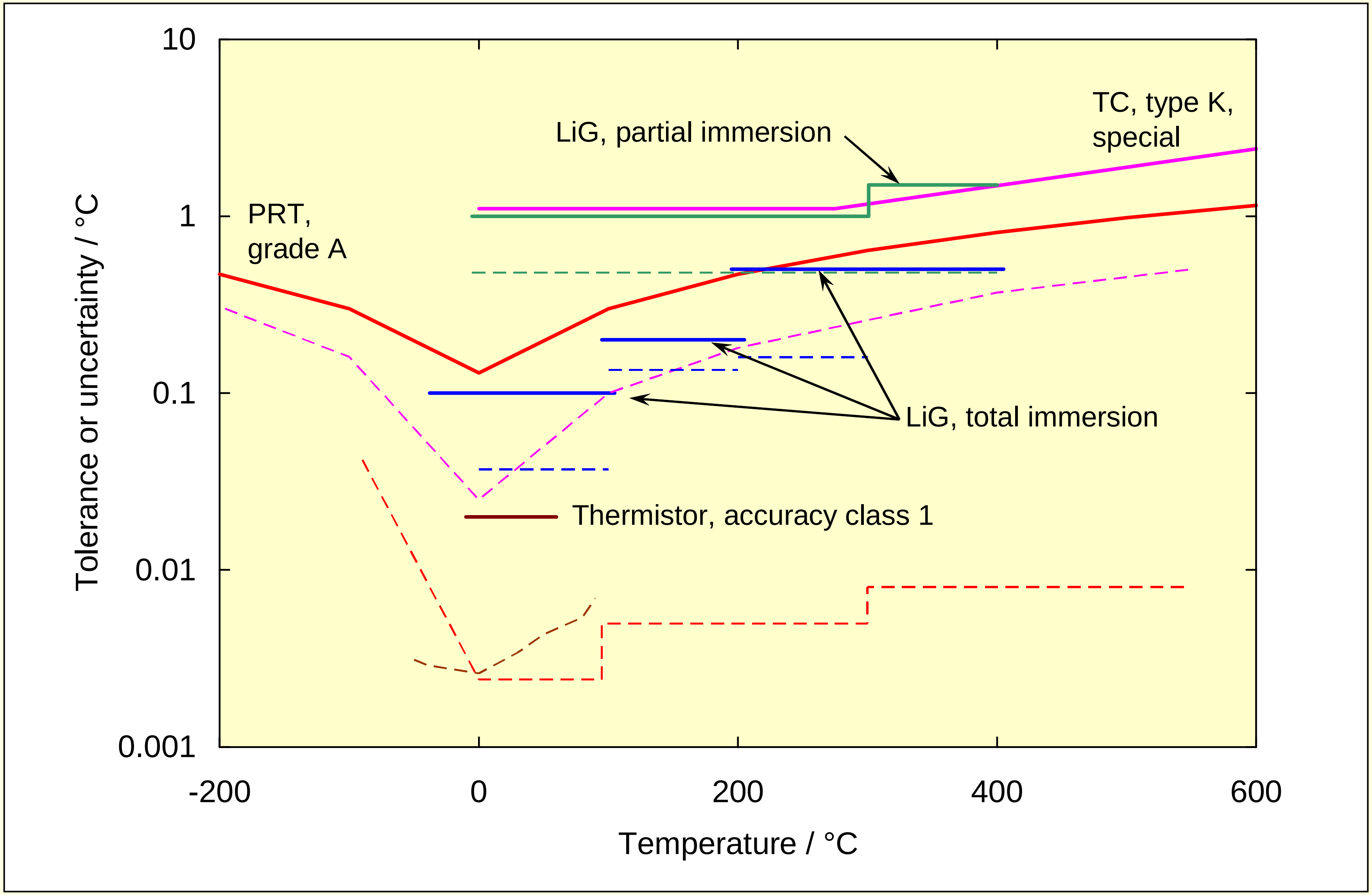
Compatibility with measurement equipment

- resistance thermometers, thermocouples easy to integrate to electronics
- liquid-in-glass, digital thermometers much easier for quick visual inspection

Compatibility with object being measured

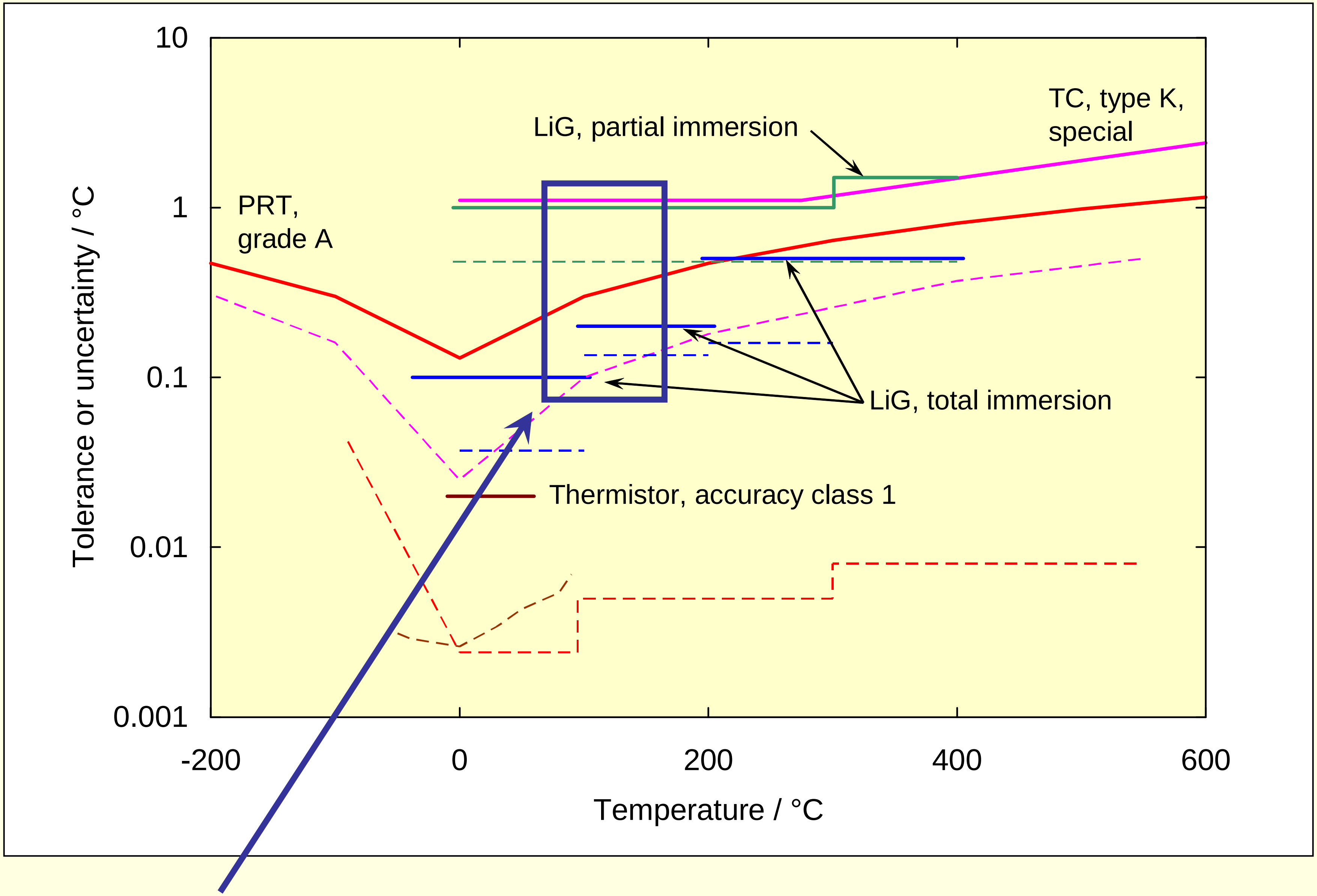
- sheath construction

Tolerances vs. Calibration Uncertainties



Colored lines: ASTM tolerances (ASTM E1, E1137, E230, and E879).
Dashed lines: NIST calibration uncertainties (*k*=2)

Tolerances vs. Calibration Uncertainties



Retort Applications

Tolerances vs. Calibration Uncertainties

Tolerance band: manufacturer’s guarantee that the instrument response will conform to a standard response function to within an error equal to the tolerance.

Calibrated thermometer: may or may not have a response close to the nominal response function for that thermometer type.

Response of individual unit is reported, along with uncertainties of the calibration process.

Individually calibrated thermometers cannot be considered directly interchangeable, unless the readouts or software are adjusted to incorporate the individual response function.

Measurement Uncertainty: MIG vs. electronic

Uncertainty component	**MIG**	**TC or PRT**	**Source**
Sensor tolerance or uncertainty	X	X	Cal certificate, manufacturer
Sensor drift	X	X	Literature; device history
Readout uncertainty	***N/A***	***X***	***Manufacturer***
Readout drift	***N/A***	***X***	***Manuracturer; device history***

Items in italics—examples of components generally not addressed with liquid-in-glass thermometers

Quick Guide to Uncertainty Terminology

An uncertainty is a statistical measure of how likely the result of a measurement agrees with the true answer.

Uncertainty at 68 % confidence (“standard uncertainty”) is denoted with lower case *u.* The difference between the true answer and the measured value will be less than ±*u,* 68 % of the time.

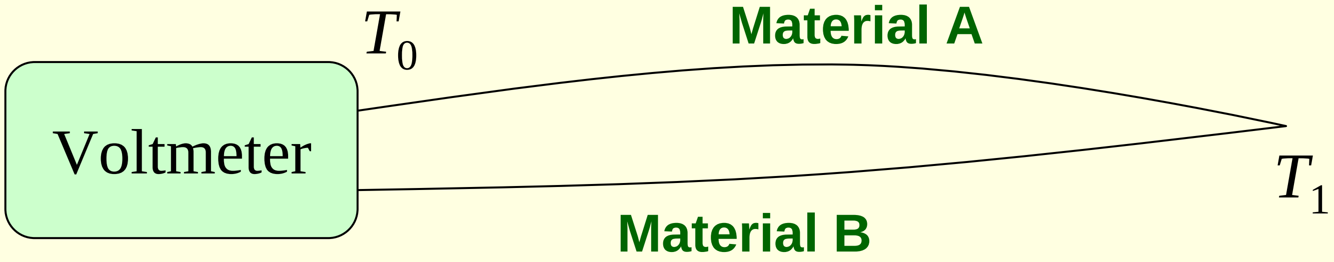
For higher confidence limits, *u* is multiplied by a coverage factor *k* to obtain the “expanded uncertainty” $U = k\,u$

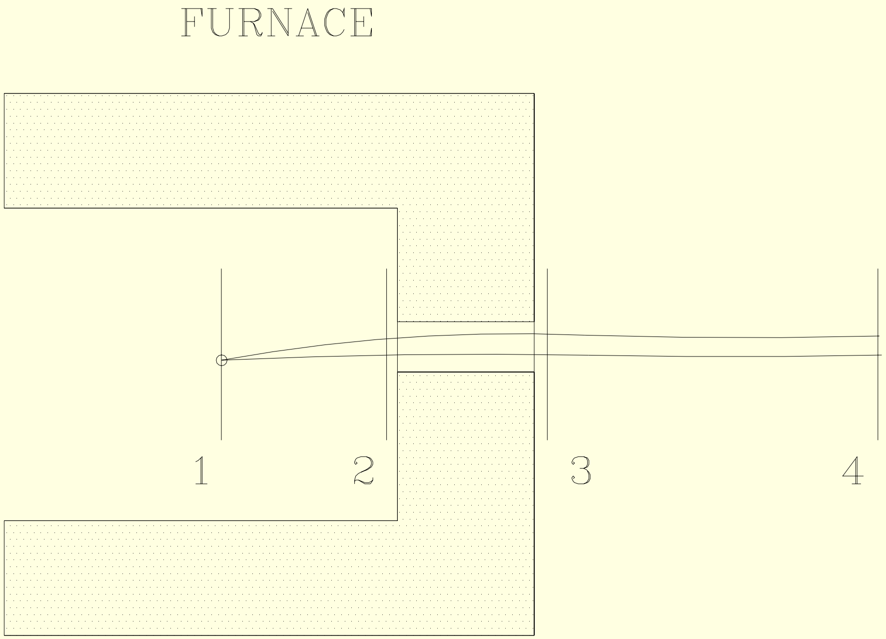
The default for calibration certificates is k=2, which for normally distributed uncertainties corresponds to a 95 % confidence limit.

When there are multiple uncertainty components, the combined uncertainty u_c is obtained by adding the components in quadrature:

$$u_\mathrm{c} = \sqrt{u_1{}^2 + u_2{}^2 + \cdots + u_n{}^2}$$

Thermocouples...any two dissimilar conductors, joined at one end





Although total signal depends on temperature of two ends (1 & 4), thermocouples generate signal primarily in regions of strong thermal gradients. (Region 2-3)

The junction itself does not generate a voltage!!

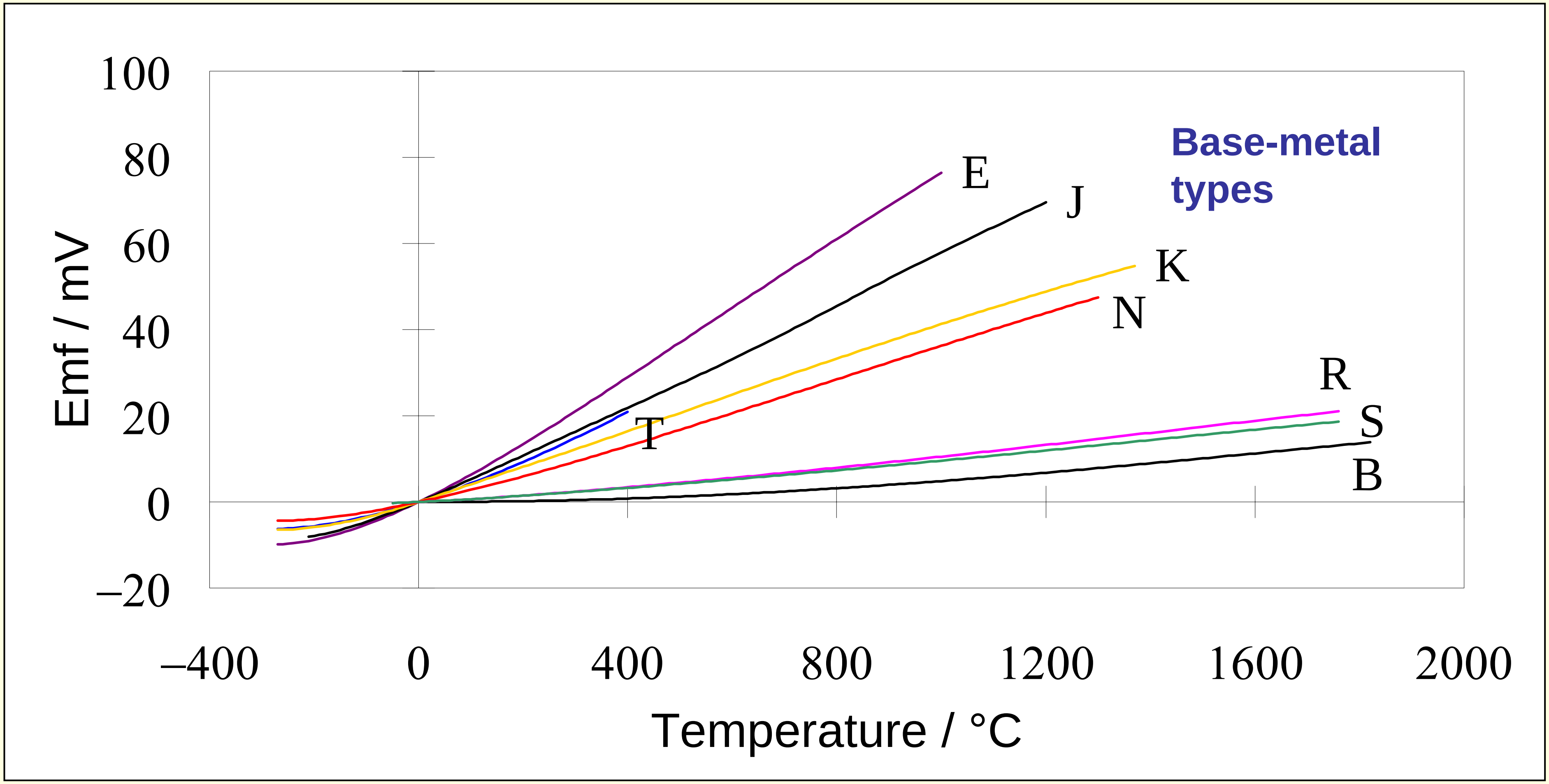
Advantages of Thermocouples

- Cheap
- Wide temperature range
- Small (down to 0.25 mm diameter)
- Easy to integrate into automated data systems

Disadvantages of Thermocouples

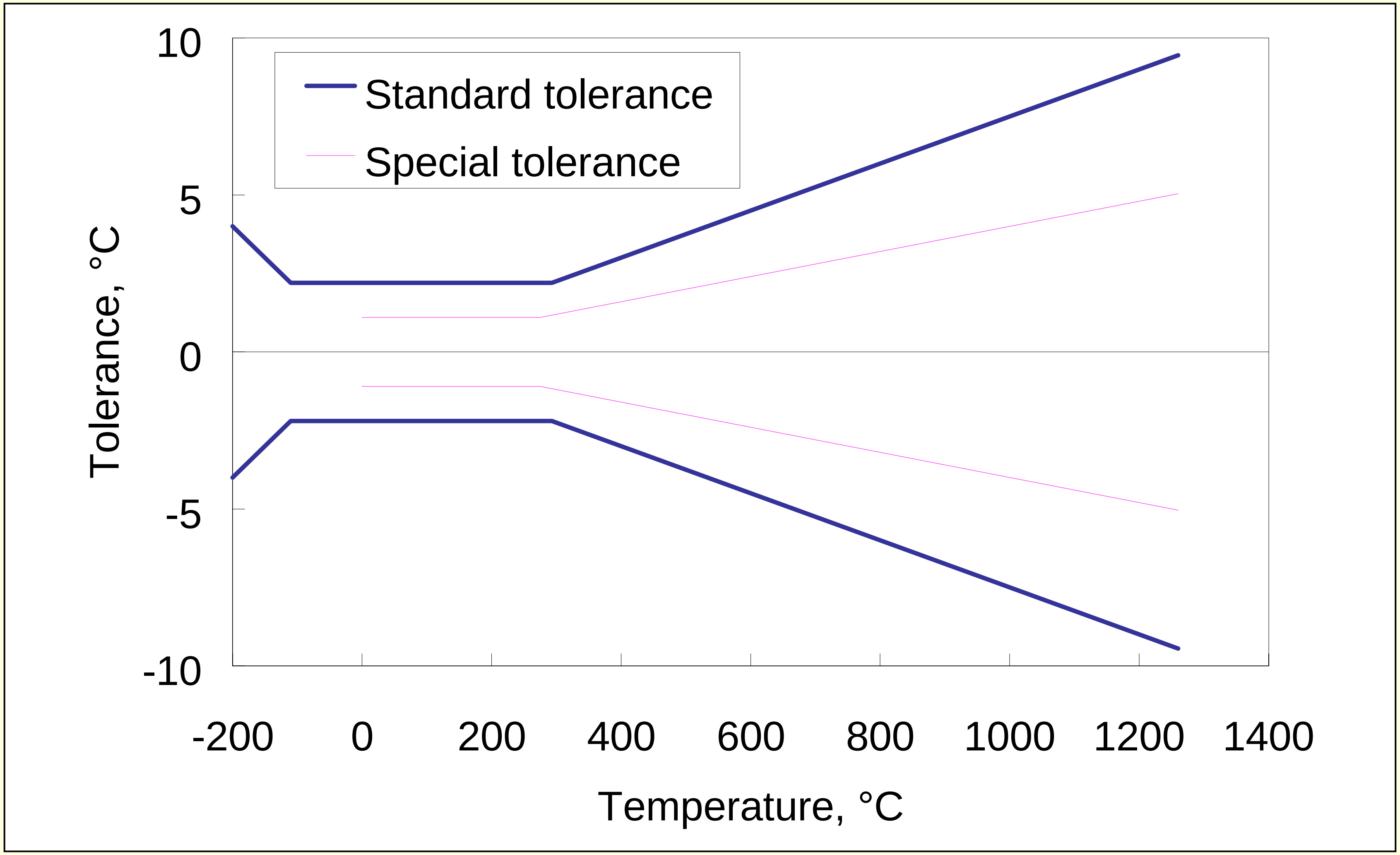
- Small signals, limited temperature resolution, typically 0.1 °C (0.2 °F)
- Thermocouple wires must extend from the measurement point to the readout. Signal generated wherever wires pass through a thermal gradient.
- At higher temperatures, thermocouples may undergo chemical and physical changes, leading to loss of calibration.
- Recalibration of certain types of thermocouples or in certain applications is very difficult.

Emf-Temperature Relationships for the 8 Letter-Designated Thermocouple Types



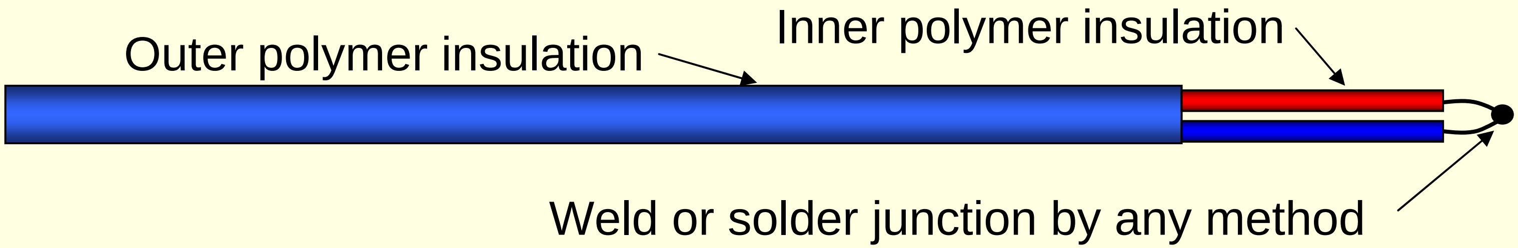
Notation: *E* = emf = Electromotive Force = Thermoelectric Voltage
S = *dE*/*dT* = Seebeck Coefficient = Sensitivity

ASTM E230 Tolerances for Type K and Type N Thermocouples



Note that even special tolerances does not meet goal of 0.5 °C (0.9 °F) uncertainty goal for retort applications: need calibration of wire !

Soft-Insulated Thermocouples



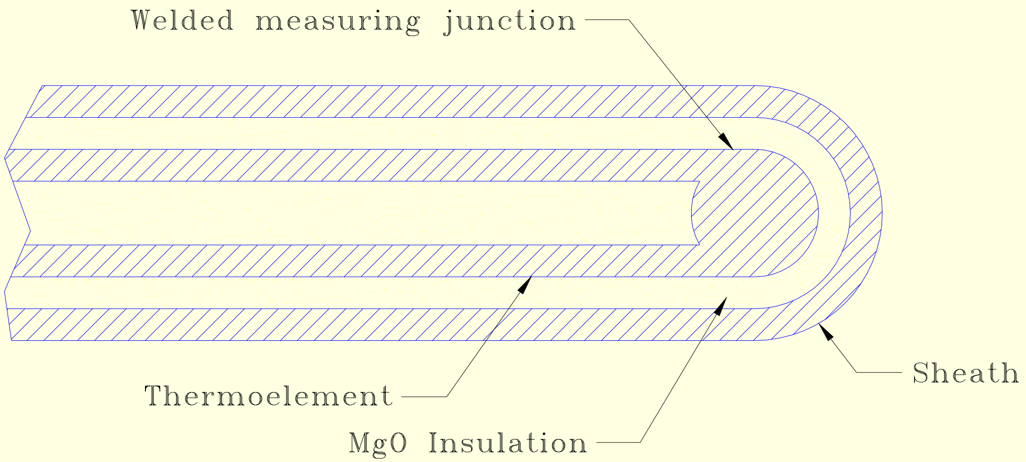
Outer polymer insulation

Inner polymer insulation

Weld or solder junction by any method

- Choose polymer insulation based on upper temperature limit
- Can mount soft-insulated TCs in metal sheath

Mineral-Insulated, Metal-Sheathed (MIMS) Thermocouples



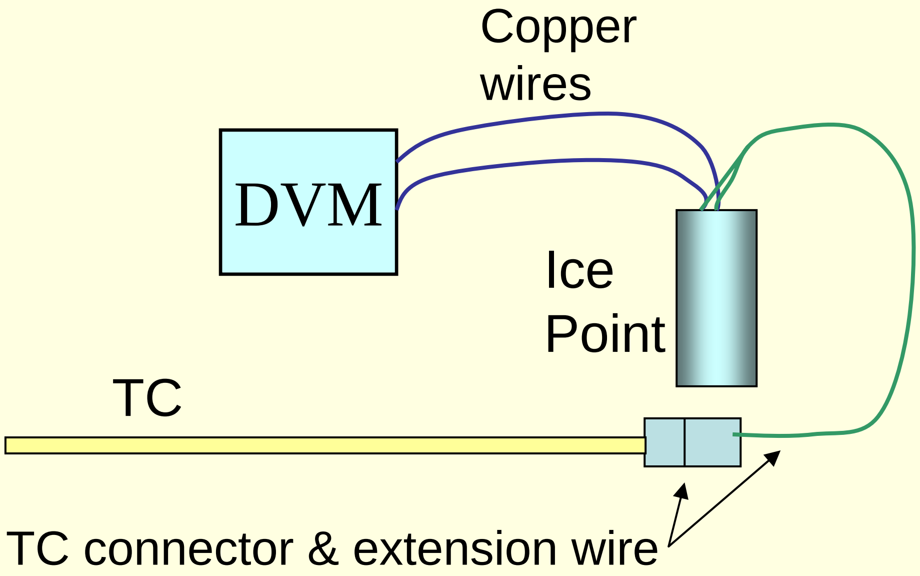
- MIMS thermocouples are available in small diameters (0.25 mm)
- Sheath protects thermoelements from contamination

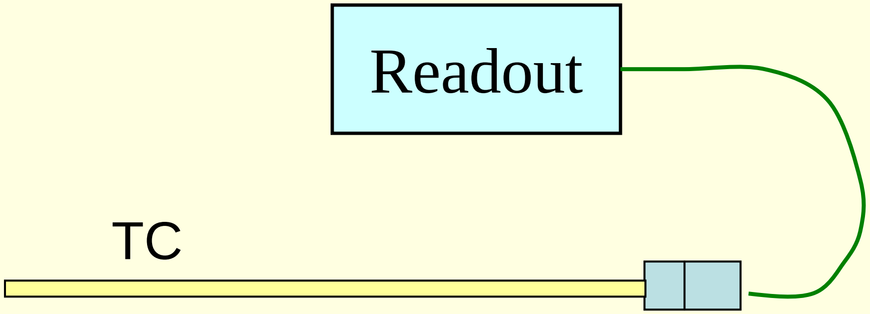
Emf Measurements

Dedicated Readout: equivalent to voltmeter + reference junction compensation + software.

Reference Junction Compensation (RJC)

- Tables assume 0 °C (32 °F) ref. junction temperature
- RJC mimics “missing” section of thermocouple when reference junction temperature is not at 0 °C
- Emf addition by hardware or software





Equivalent circuit, with internal RJC

Limitations on Thermocouple Performance

Unavoidable limitations:

- Metallurgical changes in wire. Rule of thumb for one year exposure at 200 °C (392 °C), for fixed immersion:

  U(type K) = 0.2 °C (0.4 °F)

  U(type E) = 0.4 °C (0.7 °F)

- Inhomogeneity of as-supplied wire. For base metal types:

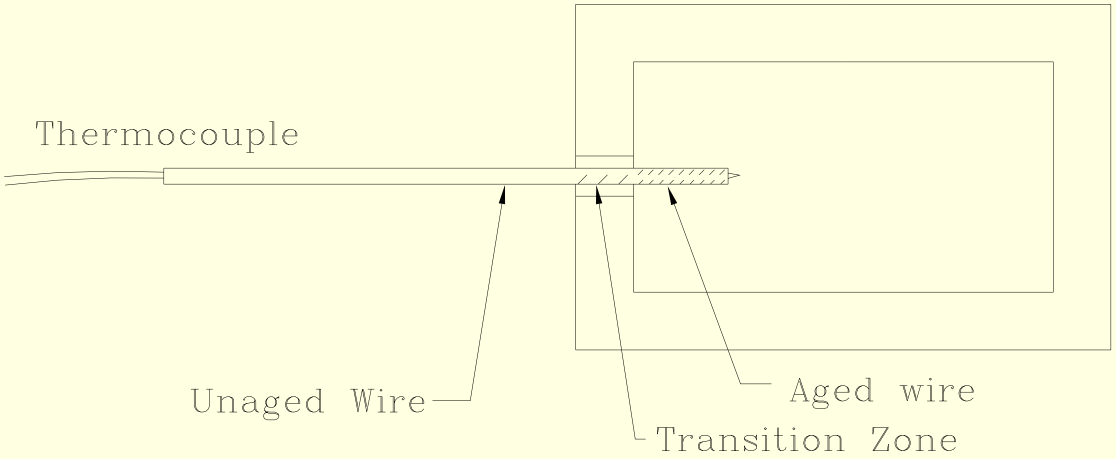
  U = 0.15 °C (0.3 °F) at 150 °C (300 °F)

Avoidable limitations:

- Chemical contamination
- Physical strain
- Extension wires, thermocouple connectors, feedthroughs (potentially large, but avoidable)

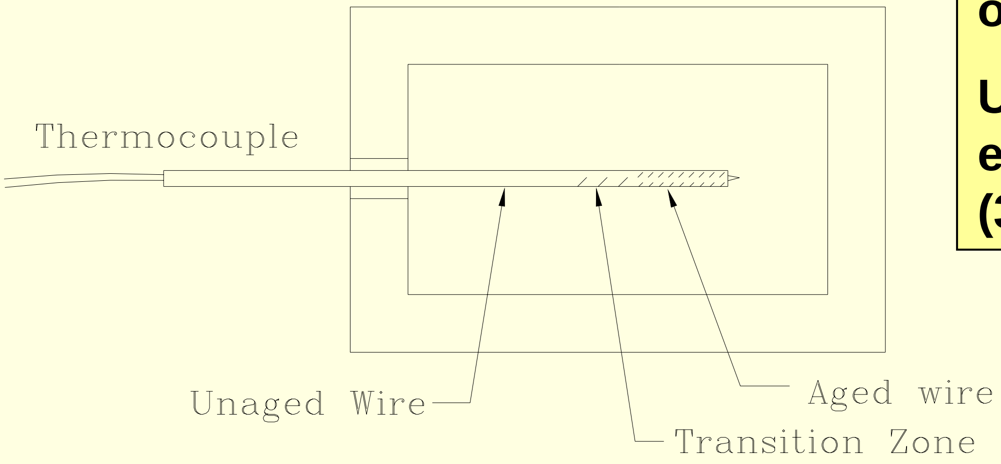
Recalibration of Used Thermocouples is Problematic!

TC As Used



If the furnace is isothermal, there will be NO difference between the original TC calibration and the recalibration.

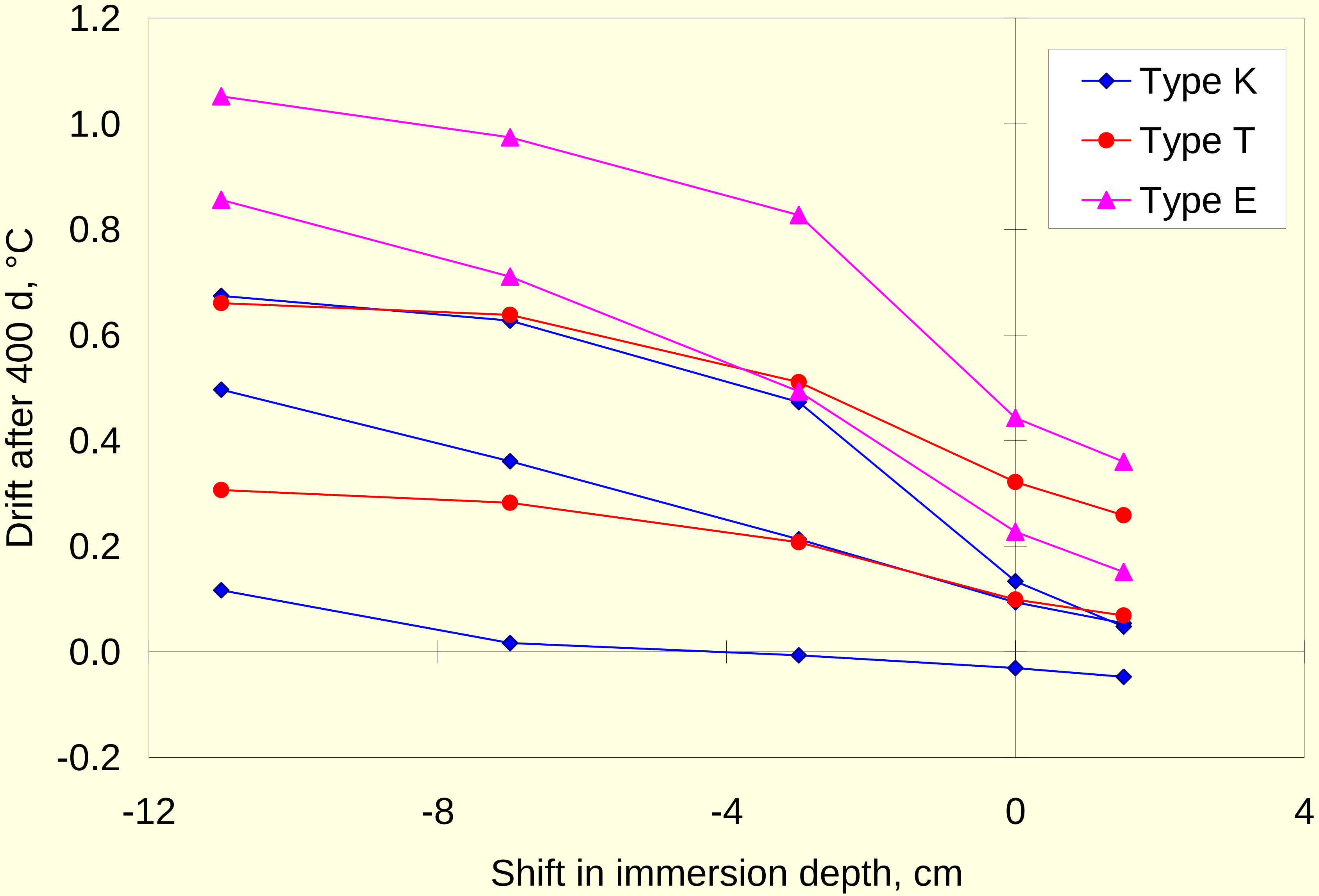
TC In Calibration Furnace



This is a known problem for *t* ≥ 200 °C or for strained TCs.

Unknown effects for exposure to 150 °C (300 °F)?

Drift of Base-Metal TCs after 400 d at 200 °C, fixed immersion



Thermocouple Recommendations

Type & calibration

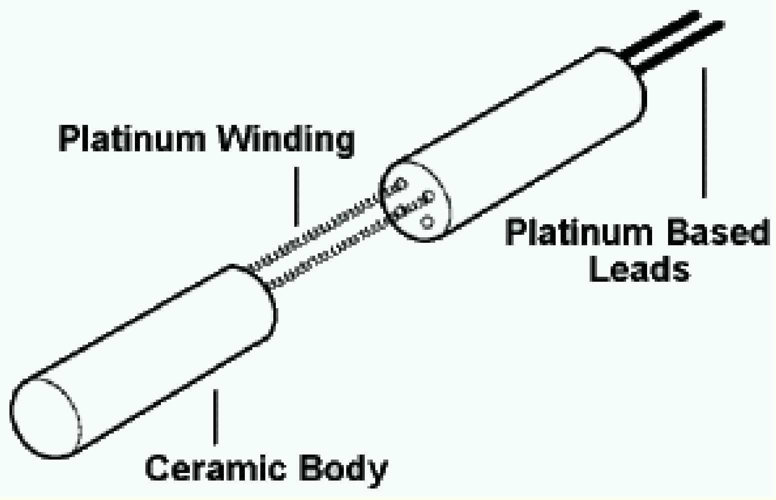
- Type K is a good match to retort applications
- Do a lot calibration of sensors (first & last of a small lot made from the same batch.)
- For each temperature environment to be measured, a new thermocouple should be made, and it should always be used at the same immersion.

Care and Feeding

- Protect from mechanical strain and kinks
- Protect from contamination using thermowell or sheath, or use mineral-insulated-metal-sheathed thermocouples.
- Recalibrate in situ, or recalibrate with variable immersion depth

What is an IPRT?

- **2, 3, or 4-wire resistance element – nominally 100 Ω @ 0 °C**
  - Wire wound
  - Thick film
  - Thin film
- **Resistance changes as a function of temperature**
- **Positive temperature coefficient**
- **Nominal temperature range of use:**
  - –200 °C to 850 °C (–328 °F to 1562 °F)
- **Nominal resistance at 0 °C**
  - 100 Ω wire wound, others for film



Pictures courtesy of SDI and Minco

Considerations in Selecting IPRTs

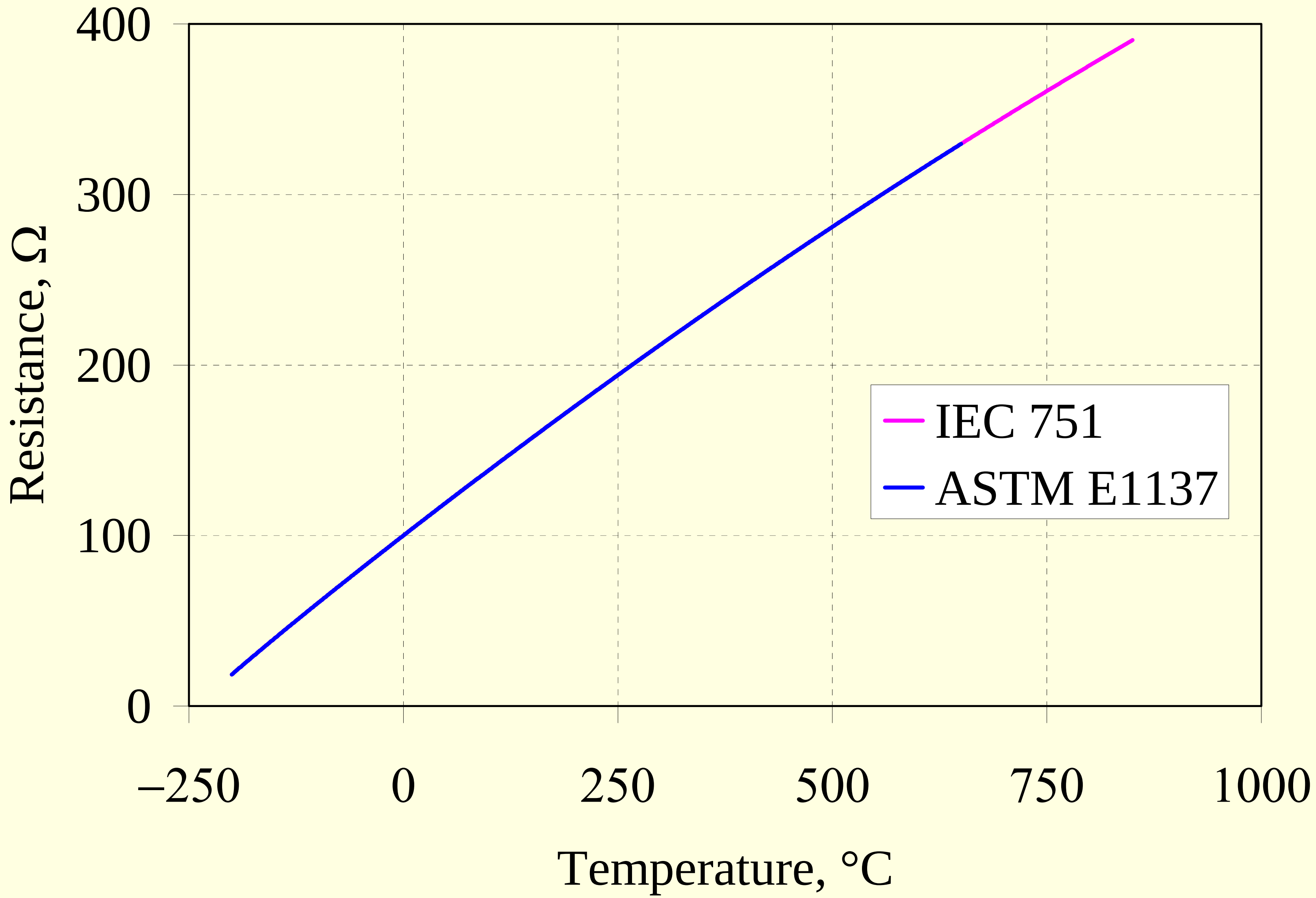
Advantages

- Temperature range is a good match to retort applications
- *R* vs. *T* is well characterized
- Available in different shapes and sized to meet most application requirements
- Can be used with a digital temperature read-out device

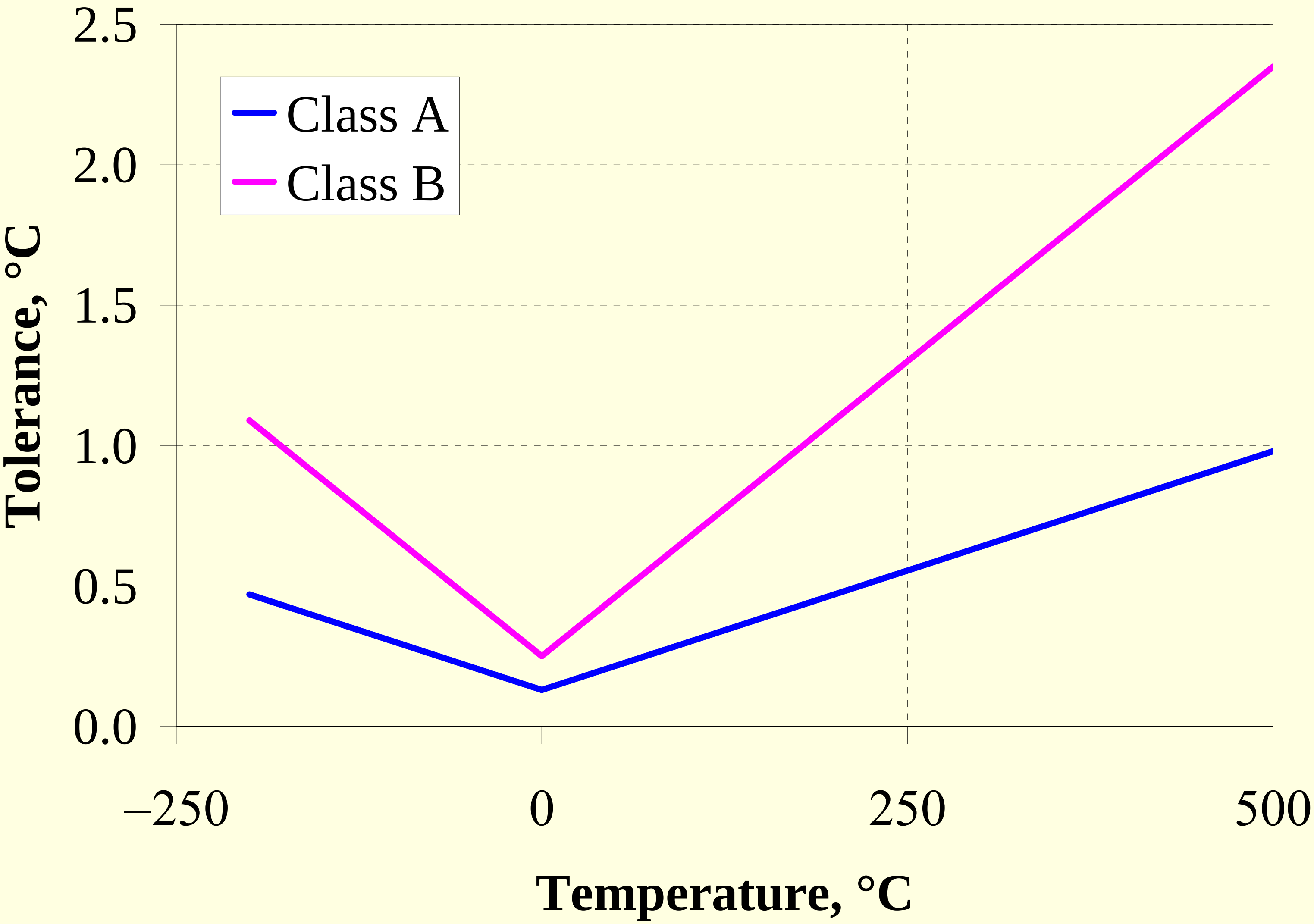
Disadvantages

- 2- and 3- wire devices need lead-wire compensation
- Non-hermetically sealed IPRTs will deteriorate in environments with excessive moisture
- Less rugged & more expensive than thermocouples

Nominal Resistance vs. Temperature Curve for an IPRT



ASTM E1137 “Off the Shelf” Tolerance and Uncertainty

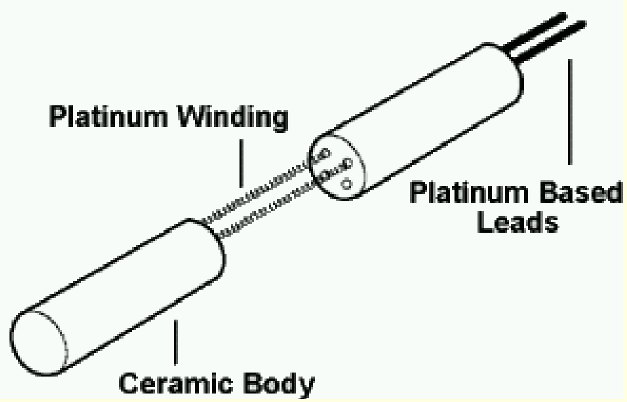


Calibrate individual units, or buy special manufacturer’s tolerances for lower uncertainty

Types and Construction of IPRT elements

Wire-wound element

- Alumina insulator: –200 °C to 850 °C
- Glass insulator: –200 °C to 400 °C
  (–330 °F to 750 °F)
- Often loose or compacted MgO powder for support
- Sometimes hermetic via glass compound
- Best accuracy with loose powder



2-wire IPRT element

Thick and Thin Film element

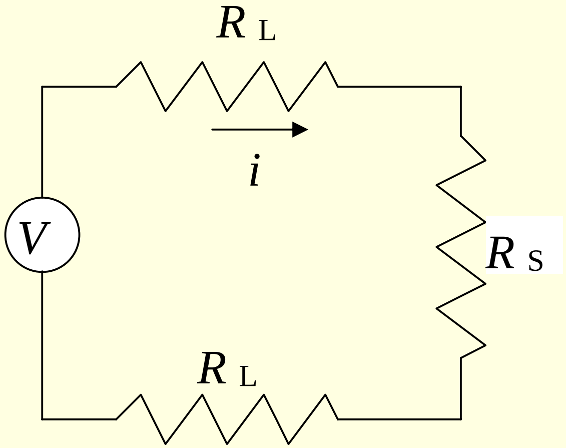
- Alumina substrate: –200 °C to 850 °C
- Polyimide: –200 °C to 200 °C
  (–330 °F to 390 °F)
- Small with fast time response

Thick Film IPRT element

Trade off between shock resistance and high accuracy

Pictures courtesy of SDI and Minco

IPRT Wiring Configurations



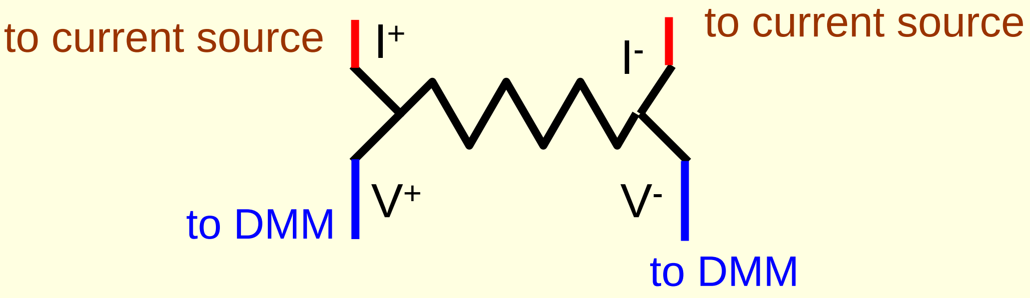
2-Wire: $R_{meas} = V/i = i(R_L + R_L + R_S)/i = 2R_L + R_S$

possible error of $(2\,R_L/R_S)(1/4\times10^{-3})$°C

- calibration will change if R_L changes

4-Wire: No current passes through voltage-sensing leads. Consequently, there is no extra voltage drop along these leads, and measured voltage is R_S.

- compensates for changes in R_L
- preferred method



2-wire for non-demanding applications (±5 °C, ±9 °F)
3-wire for ±1 °C, ±2 °F measurements, or ±5 °C, ±9 °F over long cables
4-wire for all high-accuracy measurements

Construction of IPRT Probe

MIMS IPRT Probe

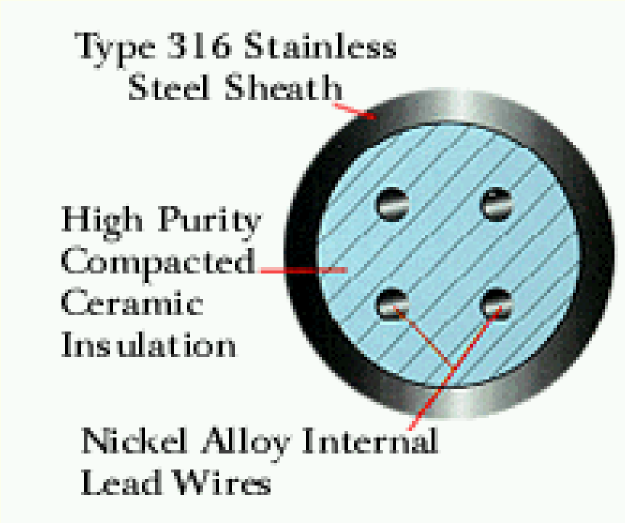
- –200 °C to 650 °C
  (–330 °F to 1200 °F)
- 2, 3, or 4-wire device
- Element is either wire-wound or film
- Specify length, fittings, element type

Support of winding

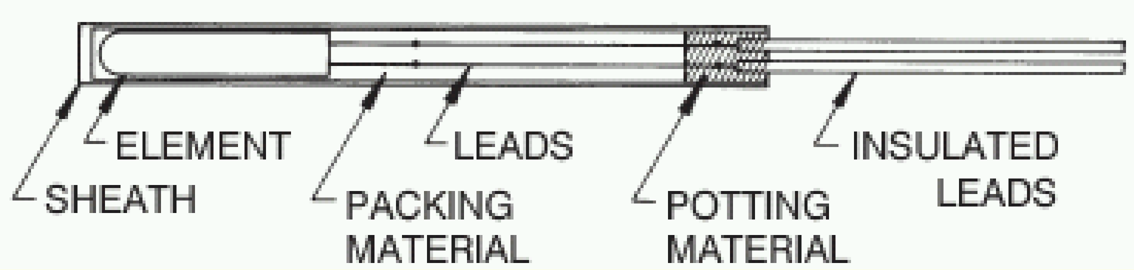
- Not strain free
- Thin film is bendable (strain sensor)

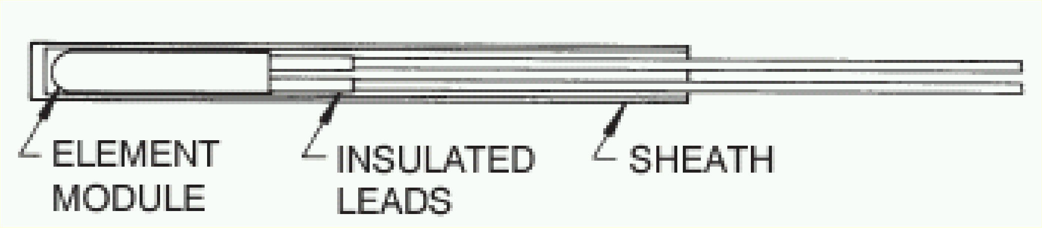
Sealing

- Element is usually hermetically sealed
- MIMS cable may not be sealed



MIMS





Pictures courtesy of Minco

Which IPRT Should I Use?

Probes vs. Bare Element: probes recommended unless element is permanently mounted

Film IPRTs: good time response, small size, shock resistant. Typical stability spec. of 0.25 °C/year

Wire-wound IPRTs with highly constrained coils: accuracy similar to film IPRTs, similar shock resistance

Wired wound IPRTs with slightly constrained coils: best accuracy (approaching ±0.01 °C over 400 °C span), sensitive to shock. Performance is highly variable with model.

Drift Mechanisms in PRTs

Water ingress into sensor through moisture seal

Moisture causing electrical short between lead wires in head, just outside of sheath seal. (Beware of effects of steam cleaning.)

Mechanical shock

Strain due to thermal cycling

Chemical contamination

User should minimize shock and exposure to moisture

Special care/validation/testing needed if thermometer head is exposed to steam

Case Studies of PRT Drift

N.P. Moiseeva, et al., 2003:

- Subjected IPRTs to 365 thermal cycles from 20 to 160 °C (70 to 320 °F).
- Of 65 thermometers tested, none obviously failed, but 3 drifted by 0.4 °C (0.7 °F) or more.
- In the worst case, the drift was 1.3 °C (2.3 °F) at a subsequent calibration temperature of 170 °C.
- In all cases of severe drift, the thermometers read too hot, so using the thermometers to set a process temperature would result in a process that was too cold.

B.W. Mangum, 1984:

- Subjected wire-wound IPRTs to 10 cycles to 235 °C.
- Several thermometers failed obviously. Of those that did not fail, 13 % had changes greater than 0.1 °C (0.2 °F).

Hashemian and Peterson, 1992:

- Tested 47 IPRTs up to 300 °C. In 6 cases, drift in the range 0.6 to 3.0 °C.

Thermistors (Thermal Resistor)

Semiconductors of ceramic material made by sintering mixtures of metallic oxides such as manganese, nickel, cobalt, copper, iron and uranium.

Temperature Range: –50 °C to 100 °C (–58 °F to 212 °F)

Standard Forms:

bead	300 Ω to 100 MΩ
probe	bead in glass rod
disc	0.5 cm to 1.3 cm thick, 5 kΩ to 10 kΩ
washer	2 cm diameter
rod	moderate power capacity, 1 kΩ to 150 kΩ

NTC: Negative Temperature Coefficient - The vast majority of commercial thermistors used as thermometers are in the NTC category.

Considerations for Using Thermistors

Higher sensitivity than PRTs

Excellent choice for environmental monitoring

Glass-coated beads or probes have best stability (better than 0.01 °C, 0.02 °F per year)

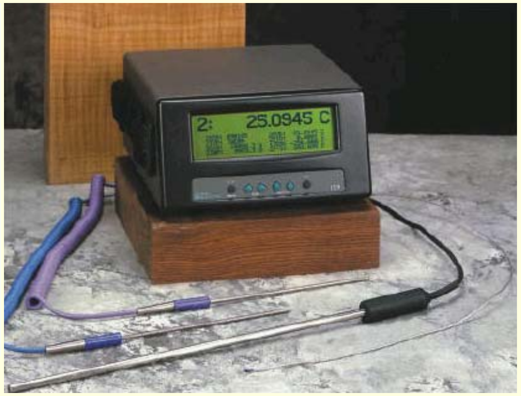
Do not expose thermistors above 100 °C (212 °F)

Mount thermistors in metal sheaths to avoid cracking glass-to-leadwire seal

Digital Thermometers: Sensor is a PRT, Thermocouple, or Thermistor in Disguise

What is a digital thermometer?

- An electronic measurement box that converts either resistance or emf of a thermometer to temperature



Pictures courtesy of Agilent, ASL, Brookstone, Hart Scientific, and Omega Engineering

Digital Thermometers

- Device displays temperature directly by using the calibration coefficients of the thermometer
- Uncertainty: 0.001 °C to 1 °C
- Resolution: 0.0001 °C to 1 °C
- Device may allow two thermometers to be connected directly to unit for differential thermometry
- Some have software that allow “real time” calibration
- SMART thermometers have electronics in the thermometer head for an RS232 (or similar) port connection
- Calibration as a system (probe + readout), or as components

Other Types of Thermometers

Band-gap thermometers

Commonly found in integrated circuit devices

No long track history on their stability (typical spec. of 0.1 °C/month)

Low cost, low accuracy with present state of technology

Liquid-in-glass thermometers filled with organic liquids

Partial-immersion versions are much more sensitive to stem temperature than mercury-filled versions

Performance is not equal to mercury thermometers

Overview of Traceability to NIST

Reference: http://www.nist.gov/traceability, especially the Supplemental Materials link

Only a *measurement*, not an instrument or artifact, is traceable.

Evaluation of traceability is the customer’s responsibility; NIST does not, in general, evaluate claims of traceability

Evaluation of traceability is one component of the laboratory accreditation process

Elements of Traceability

1. Unbroken chain of calibrations from NIST (or other National Metrology Institute) to final instrument; each calibration with documented uncertainty.

Traceability does imply known uncertainty to known national standards
does *not* imply that laboratories are NIST approved
does *not* imply that calibration is of high accuracy

2. A Measurement Assurance Program must be in place to assure continued validity of a calibration (i.e., you can’t keep using a thermometer calibrated in 1928 as your standard)

Examples periodic recalibration, with examination of instrument drift
comparison of retort control thermometer with process thermometer
comparison of calibrated thermometers between recalibrations
check of thermometers at the ice point or other convenient fixed point.

Examples of Subtle Device/Readout Failures

Long-term drift of readouts is expected, and addressed by periodic recalibration, but there are other risks:

Device loses calibration values in memory & reverts to default coefficients

Resistance bridge balances correctly, but circuitry to compensate for cable resistance is faulty

Incorrect entry of calibration coefficients into readout

Probes switched without updating coefficients (A common problem!)

Consequence: Greater need for measurement cross-checks / measurement assurance / check standards

Routine checks of performance

Checks at ice point

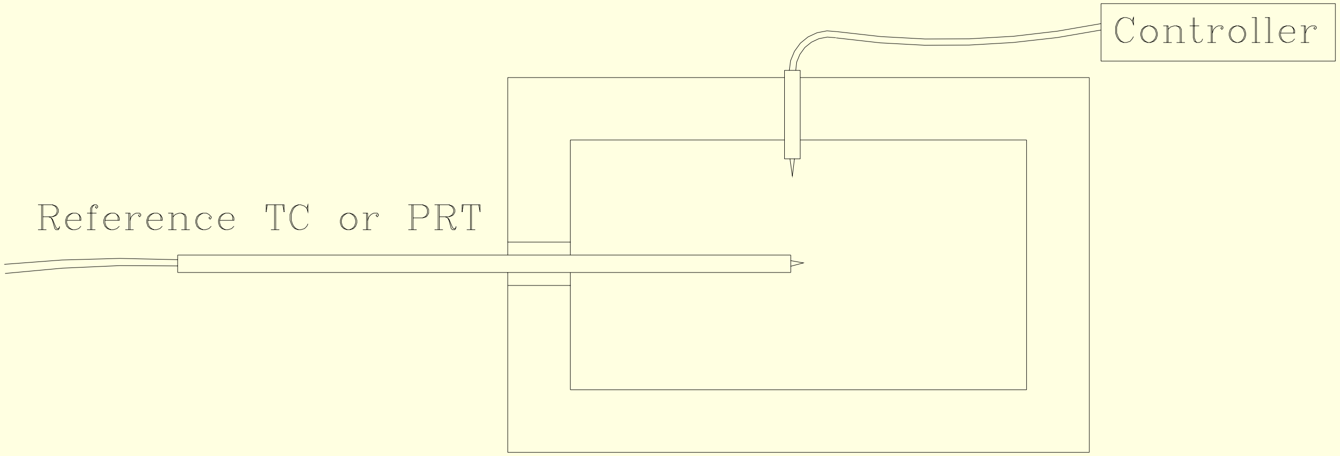
Comparison of readings of different thermometers

Measurement Assurance of Used Thermocouples

Option 1. Recalibrate thermocouples *in situ*.

Example: a reference thermocouple is inserted into a furnace with a control or process monitoring thermocouple. The process thermocouple may be recalibrated without removal.

Method also useful for establishing interval for periodic replacement program.



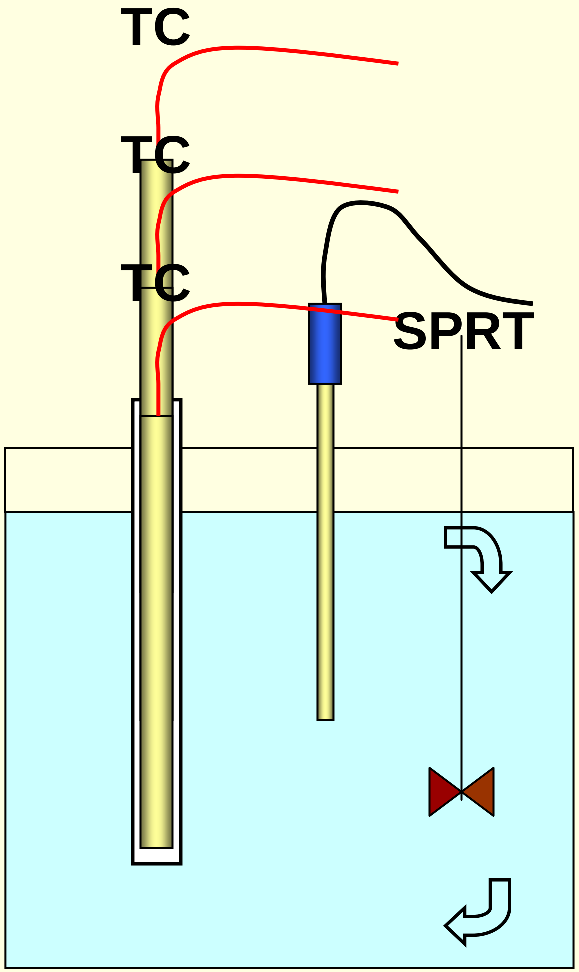
Recommended by ASTM Manual on the Use of Thermocouples (MNL-12)

Measurement Assurance of Used Thermocouples

Option 2. Recalibrate thermocouples in separate bath/furnace, but vary immersion depth to bracket immersion depth in use.

If TC agrees with original cal. at all depths, OK for service

If TC is out of tolerance, install a new TC



Recommended by ASTM Manual on the Use of Thermocouples (MNL-12)

Measurement Assurance for PRTs or Thermistors

Single-point validation of a PRT has value as a system check, but is generally not sufficient to identify all problems

Two-point validation (ice point and maximum usage temperature) may be used to determine if a probe is still within tolerance.

If probe is out of tolerance, replace or re-calibrate probe with a full set of points (3 points evenly spaced above 0 °C suffices for retort applications).

Conclusions

Good News: performance of electronic thermometers needed for retort applications is readily achieved

Caveat: a somewhat higher level of care is needed to insure against readout failures, mismatch of sensor and readout, etc.

Resources:

Traceable Temperatures, by J. Nicholas and D. R. White, Wiley, 2001

Dean C. Ripple and Gregory F. Strouse, “Selection of Alternatives to Liquid-in-Glass Thermometers,” *J. ASTM International* 2, JAI13404 (2005).