Transitioning from “Banned” Mercury Thermometers to Alternative Thermometers

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NIST Hg Reduction Activities

- **Over the last 6 years, NIST has actively participated in several national and international phase-out efforts to identify alternative thermometers for a broad range of measurement applications**
- **Several U.S. government and state agencies as well as international organizations are driving the removal of Hg thermometers as a means to reduce mercury in the environment**
  - NIST - Environment Compliance Group
  - EPA - Office of Pollution Prevention and Toxics
  - Northeast Waste Management Officials' Association (NEWMOA) - Interstate Mercury Education & Reduction Clearinghouse (IMERC)
  - American Petroleum Institute (API)
  - ASTM International
  - United Nations Environment Programme (UNEP) - UNEP Global Mercury Partnership

NIST Hg Reduction Activities

- **NIST stopped calibrating Hg thermometers on March 31, 2011**

  - The use of Hg thermometers has been virtually eliminated in routine hospital use, but a wide variety of regulations and test methods in the petroleum industry continue to specify mercury-in-glass thermometers.

  - NIST will continue to support our stakeholders by providing technical and scientific support to find suitable alternative thermometers that meet their measurement needs

  - ***NIST still calibrates all other types of thermometers***
    - ***Fees are at least 20% less than in 2010***
    - ***Increased automation = decreased turn-around time***

NIST Industrial Thermometer Calibration Services

Industrial Platinum Resistance Thermometers (IPRTs)

–196 °C to 550 °C

Thermistors

–50 °C to 100 °C

Thermocouples

–196 ° C to 2100 °C

Organic/Proprietary Liquid-in-Glass Thermometers

–196 °C to 200 °C

Digital Thermometers

–196 °C to 550 °C

Calibration fees are now 20% lower than in 2010 !!!

ASTM E20 Activities in Hg Thermometer Reduction

- **E20.05**
  - Hg Reduction Initiative
    - Chair, D. Cross

- **E20.09 – Standard Guide for Digital Contact Thermometers**
    - Chair, G. Strouse (NIST)
    - Task Group Chair, C. Meyer (NIST)

This Guide describes general-purpose, digital contact thermometers (hereafter simply called “digital thermometers”)… The different types of temperature sensors for these thermometers are described, and their relative merits are discussed. Nine accuracy classes are proposed for digital thermometers; the classes consider the accuracy of the sensor/measuring-instrument unit…

This Guide provides a number of recommendations for the manufacture and selection of a digital thermometer...

Interstate Mercury Education & Reduction Clearinghouse (IMERC)

- **Starting in 1999 the states in the Northeast and other parts of the country actively began to**
  - Pursue enactment of legislation focused on reducing Hg in products and waste
  - Provide ongoing technical and programmatic assistance to states that have enacted Hg education and reduction legislation
  - Provide a single point of contact for industry and the public for Hg education and reduction programs
  - promote consistency among the states in implementing product bans
  - provide a single point of contact for manufacturers.
- **The IMERC state members include**
  - California, Connecticut, Illinois, Louisiana, Maine, Massachusetts, Minnesota, New Hampshire, New Jersey, New York, North Carolina, Rhode Island, Vermont, and Washington.
- **Example of state law (New York – 1/08)**
  - **Cannot sell, offer for sale, or distribute mercury-added thermometers if a non-mercury alternative is available**; excludes mercury-added thermometers that are a component of a larger product in use prior to January 1, 2008 or resale manufactured before January 1, 2008; excludes if the use is a federal requirement

http://www.newmoa.org/prevention/mercury/imerc.cfm

United Nations Environmental Program - Hg

- **International Treaty on Hg**
  - Includes eventual elimination of Hg products
    - Reducing mercury in products may be the most effective means to control mercury in waste. Clear regulation can prompt manufacturers to produce mercury-free products.
- **Anticipated effective date of 2013**
- **United States of America is a contributing signatory**
  - Cooperative government agency effort
    - NIST representatives: D. Poster and G. Strouse

Why Replace Hg Thermometers ?

- **Mercury is a neurotoxin**
  - Everyone is at risk from ingestion exposure to mercury
  - Mercury poisoning symptoms include:
    - Tremors
    - Emotional changes
    - Insomnia
    - Neuromuscular changes
    - Performance deficits on tests of cognitive function
    - Increase exposure may cause kidney failure, respiratory failure and death
- **Broken thermometer can cost a significant amount of money**
  - Typical cost is $5K to $20K
  - Extreme cost is $1M
- **Several U.S. government, state agencies, and international organizations are driving the removal of Hg thermometers as a means to reduce Hg in the environment.**

Measurement Truths to Consider

- **Accuracy**
  - Hg thermometers are not more accurate than alternatives
  - ASTM standards give “out-of-the-box” tolerance specifications for Hg and alternative thermometers
    - Specifications can be used for interchangeability
- **Cost**
  - Hg thermometers are not cheaper when you consider clean up
- **Calibration**
  - All thermometers need calibration
    - All thermometers need verification – often
    - Verification for all industrial thermometers starts with the ice melting point
- **Range of use**
  - Digital thermometers cover the range from at least –200 °C to 500 °

General Issues with Replacing Mercury-in-Glass Thermometers

- **Hg-in-Glass thermometers are in widespread use:**
  - Food processing, laboratory use, health care, petroleum testing, etc.
- **New regulations strictly controlling either sales or use of instruments containing Hg and the high cost of mitigating mercury spills are driving the replacement of most Hg thermometers**
  - Interstate Mercury Education & Reduction Clearinghouse (IMERC)
  - Clean-up of mercury spills can cost from $2,000 to $10,000
- **The use of mercury thermometers is specified in government regulations (e.g., FDA) and in hundreds of documentary standards**
  - Over 800 ASTM standards incorporate a mercury-in-glass thermometer
- **Hurdles for the adoption of alternatives to Hg thermometers**
  - Existing regulations that mandate Hg thermometers
  - Alternative thermometer must be shown to have satisfactory performance for the application
  - User community needs assistance in the choice and use of the appropriate alternative technology.

Possible Replacement Thermometer Types

Analog Possibilities:

Organic Liquid-in-Glass Thermometers

–196 °C to 200 °C

Proprietary Liquid-in-Glass Thermometers

–196 °C to 300 °C

Digital Possibilities:

Digital Readout with Probe

–196 °C to 2100 °C

> Industrial Platinum Resistance Thermometers (IPRTs)

–196 °C to 500 °C

> Thermistors

–50 °C to 100 °C

> Thermocouples

–196 ° C to 2100 °C

Quick Tutorial on Electronic-Baseed Industrial Thermometer Sensors

Industrial Platinum Resistance Thermometers

Thermistors

Thermocouples

What is an Industrial Platinum Resistance Thermometer (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

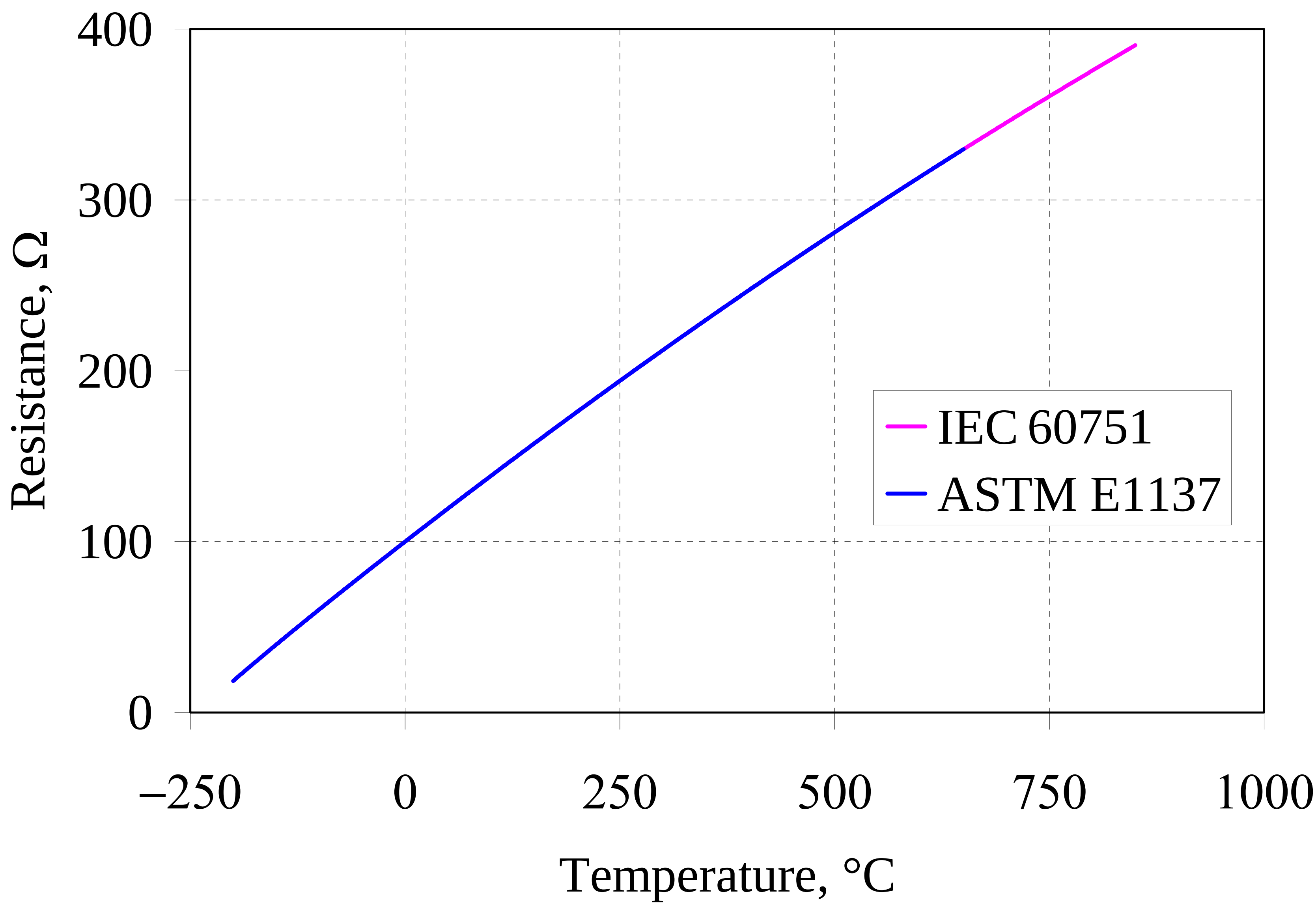
Nominal temperature range of use:

- –200 °C to 850 °C

Nominal resistance at 0 °C

- 100 Ω

Nominal Resistance vs. Temperature Curve for an IPRT



IPRT Reference Functions and Standards

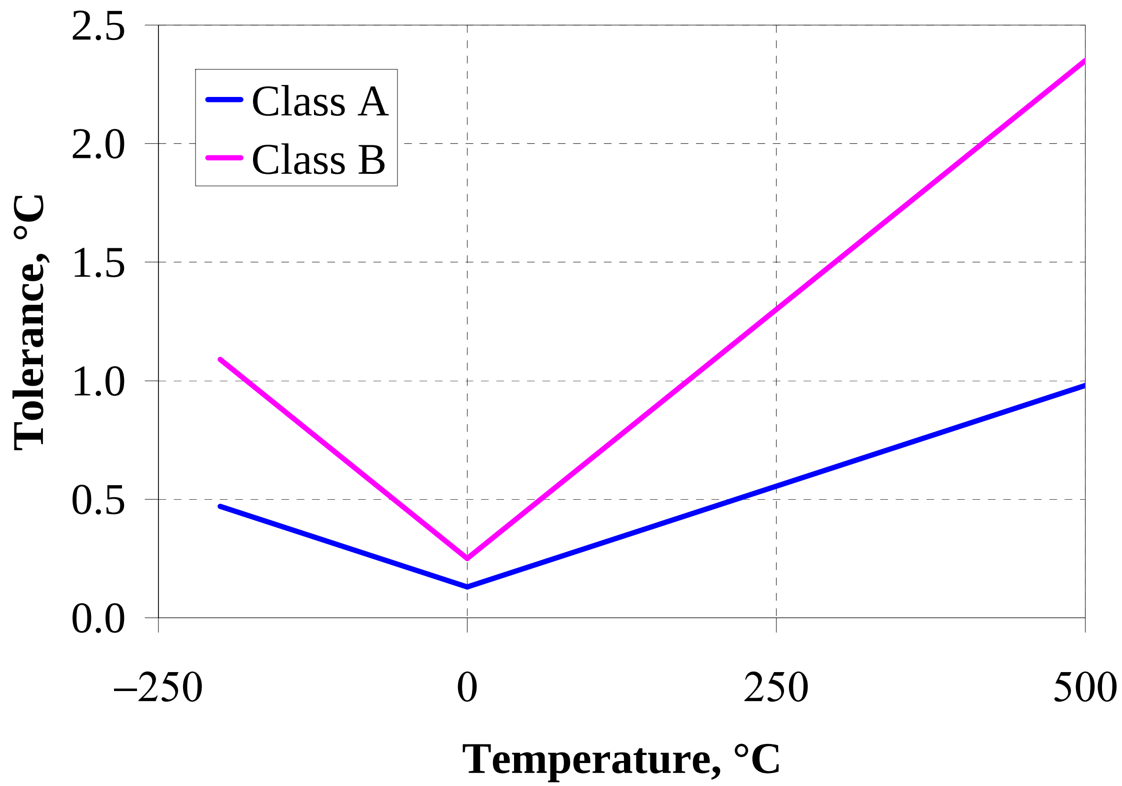
	R(0°C), Ω	alpha, Ω/Ω/°C	range, °C
IEC 60751			
class AA	100	3.85×10^{-3}	–200 to 250
class A	100	3.85×10^{-3}	–100 to 450
class B	100	3.85×10^{-3}	–196 to 600
ASTM E1137 – USA Standard			
class A	100	3.85×10^{-3}	–200 to 650
class B	100	3.85×10^{-3}	–200 to 650

IEC = International Electrotechnical Commission

ASTM = American Society for Testing and Materials

ASTM E1137 "Off the Shelf" Tolerance and Uncertainty

Class A	±[0.13 + 0.0017 |t|] °C	
Temperature °C	Tolerance Ω	Tolerance °C
–200	**0.20**	**0.47**
0	**0.05**	**0.13**
500	**0.33**	**0.98**
Class B	±[0.25 + 0.0042 |t|] °C	
Temperature °C	Tolerance Ω	Tolerance °C
–200	**0.47**	**1.1**
0	**0.10**	**0.25**
500	**0.78**	**2.4**



ASTM E1137 vs ITS-90

ITS-90 Equations may be used with IPRTs

No specific evidence that using ITS-90 equations is better than ASTM E1137 equations

- Use extra calibration points to determine uncertainty

Some measurement equipment may only allow for either ASTM E1137 or ITS-90 equations and not both

- End user must decide which works for their purpose

Measurement Uncertainties are a function of

- calibration uncertainty
- temperature range of use
- number of calibration points for ASTM E1137 equation
- mechanical vibration
- measurement system
- thermal environment

Types and Construction of IPRT elements

Wire-wound element

- Alumina insulator: –200 °C to 850 °C
- Glass insulator: –200 °C to 400 °C
- 2, 3, or 4-wire device

Support of winding

- None
- Loose MgO powder
- Compacted MgO powder

Sealing

- None
- Hermetic via glass compound

Types and Construction of IPRT elements

Thick and Thin Film element

- Alumina substrate: –200 °C to 850 °C
- Polyimide: –200 °C to 200 °C
- 2, 3, or 4-wire device

Support of winding

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

Sealing

- Hermetic via glass compound for alumina
- Hermetic via polyimide seal

Selecting an IPRT

Type – many shapes and sizes to meet most applications
- Bare element
- Probe

Application of use

Temperature range of use

Uncertainty in use
- Tolerance
- Interchangeability

Stability

Calibration
- Requirements
- Cost

Environment

Cost
- IPRT
- Measurement Equipment
- Calibration

“Simple” Questions to Consider in Buying an IPRT

Temperature Range

- probe, head, and wire compatibility

Specifications of probe

- Diameter
- Length
- Type of sensor and support
- Number of wires and insulation type
- Type of end seal

Uncertainty

- In use at your facility
- Stability – (e.g. 10 thermal cycles)

Environmental Conditions

- Pressure, vibration, moisture

Pt purity – α

- 385, 390, 392

Time Response

Calibration

- “Off the Shelf” – Tolerance and Interchangeability
- Actual calibration – Lower Uncertainty

Which IPRT Should I Use?

Probes recommended for Digital Thermometers

Film IPRTs: good time response, small size, shock resistant

Wire-wound IPRTs with constrained coils: low accuracy, but shock resistant

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.

Resistor configuration

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

"You get what you pay for – most of the time"

Commercial Measurement Equipment & Software

Digital Readout

- Accepts ASTM E1137 or ITS-90 coefficients
- Multiple IPRTs possible with scanner
- Differential temperature measurement
- Uncertainty is a function of cost, resolution, stability, and calculation of temperature

Multimeter

- 6.5 to 8.5 digit
- May accept ASTM E1137 or ITS-90 coefficients
- Uncertainty is a function of cost, resolution, stability, method of use, excitation current, and in some cases the calculation of temperature

Separate software available from various thermometer vendors

Important to validate the calculation of temperature of either the digital readout, multimeter, or software

Sources of Errors When Using IPRTs

Stability

- Repeatability at 0 °C or 0.01 °C

Immersion

- Check immersion characteristics of IPRT on insertion in thermal environment
- Critical for Dry Well Block Calibrators with only 6” immersion depth

Insulation Resistance

- R(22 °C) > 100 MΩ at 50 V dc is equivalent to 0.1 m°C error
- May degrade at t > 500 °C and high-moisture environments

Self Heating

- Calibration and measurement current must be the same (nominally 1 mA)
- Thermal contact with temperature of interest is important
- Air probe or fluid probe will influence calibration method

Mechanical Shock and Vibration

- Vibration or dropping the IPRT will cause the IPRT to drift or fail

Recalibration Interval for an IPRT

Widely varies by design

Widely varying performance based on use

- Thermal history
- Mechanical shock

Behavior is not as predictable as an SPRT

Drift at 0 °C or 0.01 °C may not always correlate well at other temperatures

Recommendation:

- Measurement at 0 °C or 0.01 °C as a minimum
- Measurement at highest temperature of use is better

Considerations in Selecting IPRTs

- **ADVANTAGES**
  - Wide temperature range
  - *R* vs. *T* is well characterized
  - Rugged construction
  - Cost is less than an SPRT
  - Available in different shapes and sizes – application specific
  - ***Can be used with a digital temperature read-out device***

- **DISADVANTAGES**
  - Mechanical shock and vibration will cause drift
  - Deterioration at elevated temperatures (e.g., >500 °C)
  - 2- and 3- wire devices need lead-wire compensation
  - Non-hermetically sealed IPRTs will deteriorate in environments with excessive moisture
  - Not as accurate as an SPRT
  - **Not a defining standard of the ITS-90**

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

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.

PTC: Positive Temperature Coefficient - Specialized use over very narrow temperature ranges, primarily as control and safety devices.

Applications for Thermistors

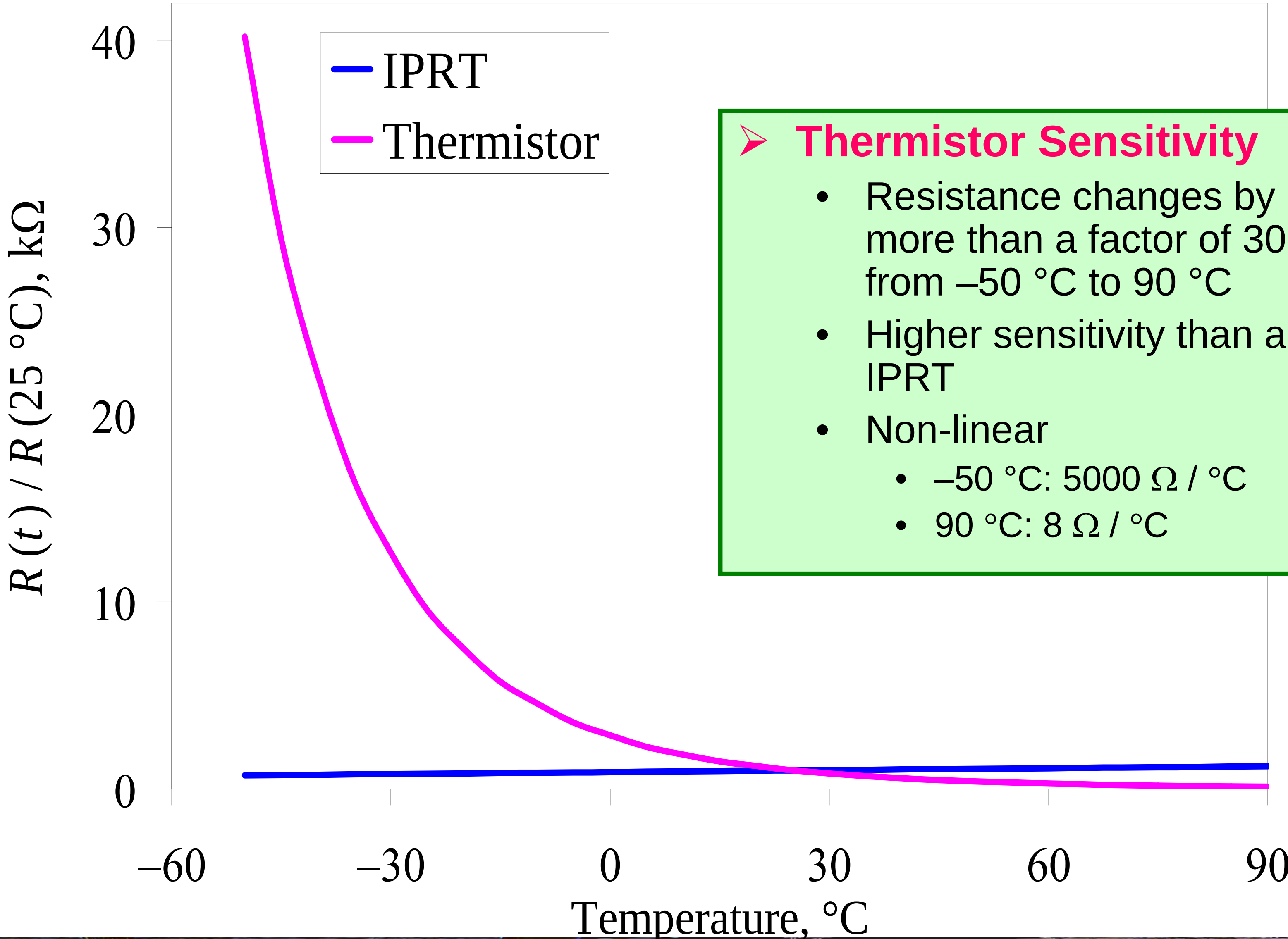
Application: temperature measurements, temperature compensation in electrical circuits, temperature control, liquid-level measurements, power measurements, thermal conductivity, biomedical applications and power level control

- High stability if used over a narrow temperature range of 0 °C to 50 °C
- Interchangeable to within 50 mK

- Glass-coated bead for use from 0 °C to 30 °C
- Uncertainties < 1 mK

- **Calibration**
  - Comparison with reference thermometer
  - Fixed-point cells (e.g. small NIST SRM cells or small commercial cells)

Sensitivity Comparison between Thermistors and IPRTs



Thermistor Sensitivity

- Resistance changes by more than a factor of 300 from –50 °C to 90 °C
- Higher sensitivity than an IPRT
- Non-linear
  - –50 °C: 5000 Ω / °C
  - 90 °C: 8 Ω / °C

Interchangeability of a Thermistor

Thermistors are interchangeable to within the manufacturer's tolerance band

Practical limits from –80 °C to 105 °C

- ±0.05 °C for a 50 °C span
- ±0.10 °C for a 75 °C span
- ±0.20 °C for a 100 °C span

For a greater accuracy than the tolerance band, then a calibration must be performed

- 0.001 °C for a 15 °C span
- 0.003 °C for a 70 °C span

Advantages and Disadvantages of Thermistors

ADVANTAGES

Easy to miniaturize
Rugged
Fast response time
Easy to use
Digital thermometer readout
Inexpensive
High sensitivity
Small-size beads may be used for point-sensing
Stability: 4000 h at 100 °C

bead-in-glass	0.003 °C to 0.02 °C
disc	0.01 °C to 0.02 °C

DISADVANTAGES

Small temperature range
Non-linear device
Needs frequent checks on calibration when exposed to $t > 100$ °C
Interchangeability is limited unless the thermistors are matched
Self-heating may be large

Cautions for Using Thermistors

Self-heating error may be large

- Use low current and match calibration and use current
- Calibrate air probe in air-filled glass tube

Epoxy coated thermistors are susceptible to degradation from moisture

Glass sealed thermistors are susceptible to degradation if the lead wires are bent apart at the base of the glass

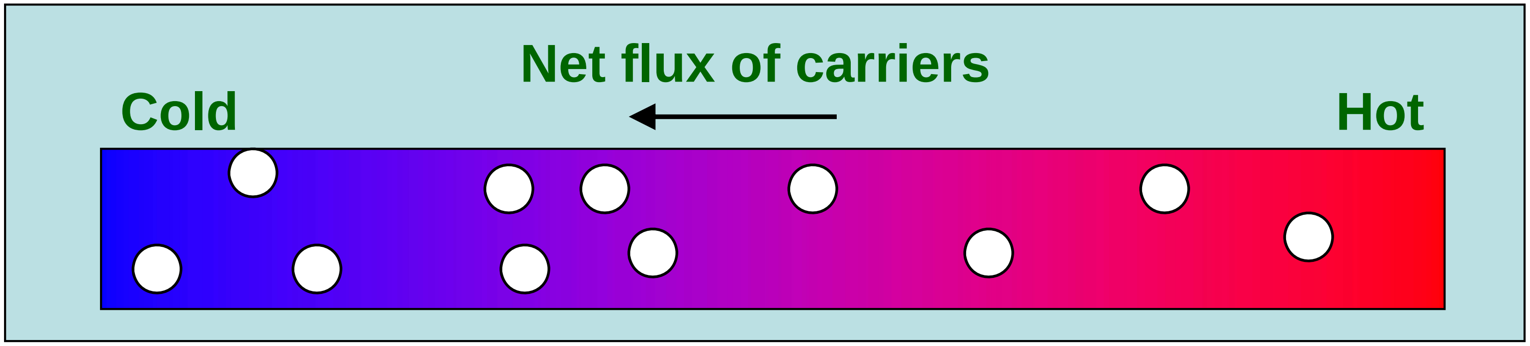
- Micro cracks can form in the glass

Heat sink the leads when making electrical connections with solder

Do not expose thermistors above 100 °C

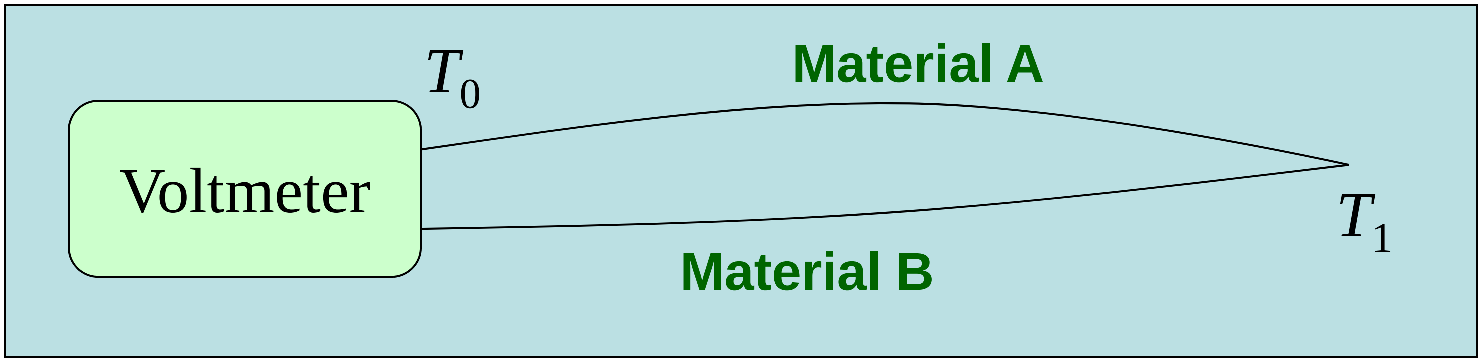
- Elevated temperatures will excessively age the thermistor and cause drift

What is a Thermocouple?



Hotter carriers travel farther before equilibrating with the crystal lattice than cold carriers.

Consequence: charge imbalance when crystal is in thermal gradient.

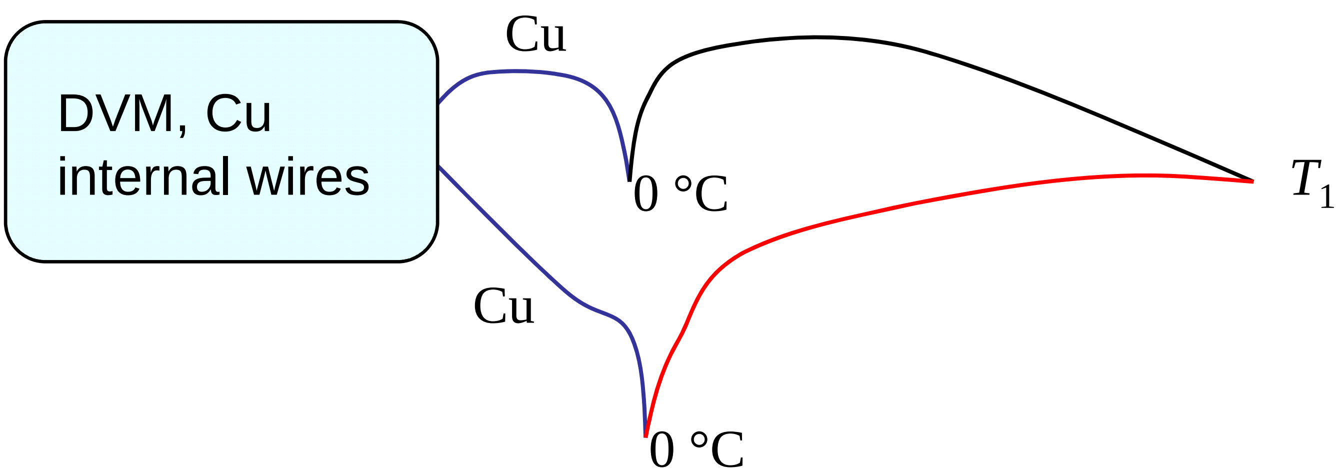


Net electromotive force = emf = $E = E_A(T_1, T_0) - E_B(T_1, T_0)$

Typical thermocouple circuit

Reference junctions maintained at 0 °C by

- Immersion into ice bath, made from water/ice slurry
- Electronic compensation (typical for Digital Thermometers)



Reference
junctions at 0 °C

Thermocouple Reference Functions

Sources:

- Reference functions for letter-designated TC types in ASTM E230, IEC 584, NIST Monograph 175

Reference functions for non-letter designated types in: ASTM E1751, E988

TC type	**Ref. func. range, °C**	**Nominal composition majority component in italics, % in mass**	
		Positive leg	**Negative leg**
B	0 to 1820	*platinum*-30% rhodium	*platinum*-6% rhodium
E	–270 to 1000	*nickel*-chromium alloy	*copper*-nickel alloy
J	–210 to 1200	iron	*copper*-nickel alloy
K	–270 to 1372	*nickel*-chromium alloy	*nickel*-aluminum alloy
N	–270 to 1300	*nickel*-chromium-silicon	*nickel*-silicon-magnesium
R	– 50 to 1768	*platinum*-13% rhodium	platinum
S	–50 to 1768	*platinum*-10% rhodium	platinum
T	–270 to 400	copper	*copper*-nickel alloy

Selecting a Thermocouple Type

type E: High Seebeck coefficient, homogeneous materials. Good for low temperatures.

type J: Cheap!

type K: Fairly cheap high temperature thermocouple.

type N: Good base metal thermocouple for high temperatures.

type T: Homogeneous materials. Direct connection of differential pairs to voltmeters.

Use type K, E, or T at room temp., type K up to 200 °C, type N in the range 300 °C to 600°C, type N or K above 600 °C

type R, S: Noble metal thermocouple for range 0 °C to1400 °C.

type B: Noble metal thermocouple used from 800 °C to 1700 °C.

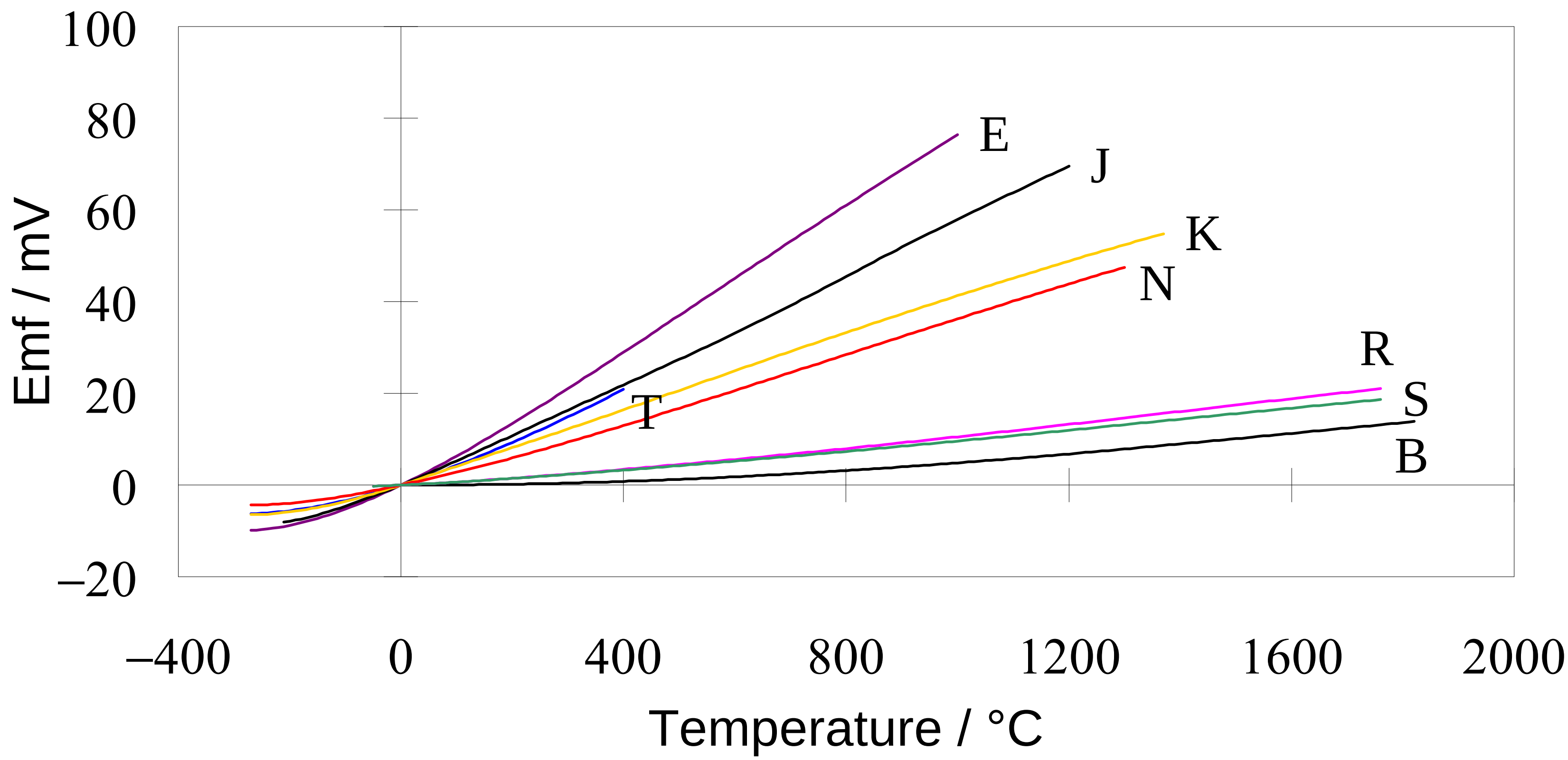
Use type R or S below 1300 °C, type B above 1300 °C.

Platinel: High Seebeck coefficient with some of the stability of types B, R, and S.

Au/Pt: The best accuracy from 0 °C to 1000 °C.

Pt/Pd: The best accuracy from 1000 °C to 1500 °C–not commercial

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



Thermocouple Construction Types

Bare wire with ceramic insulators

- the best performance for clean, high temp. environments

Soft-insulated wire

- polymer coatings excellent for use up to 200 °C
- fiber-glass insulation, woven ceramic sleeving–fine at moderate temperatures, not good protection at high temp.

Mineral-insulated, metal-sheathed construction (MIMS):

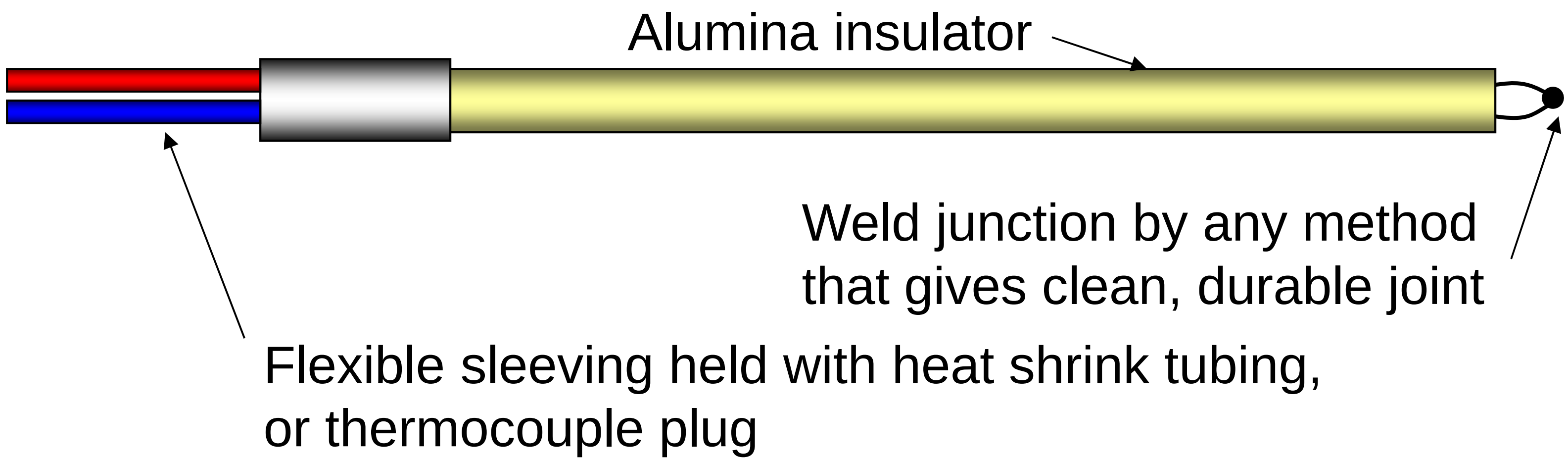
- excellent for base-metal thermocouples at high temperatures
- excellent for unclean environments
- can be bent to shape

Bare wire with ceramic insulators, and outer metal sheath

- not flexible
- better contamination resistance and less mechanical strain than MIMS construction for noble metal thermocouples

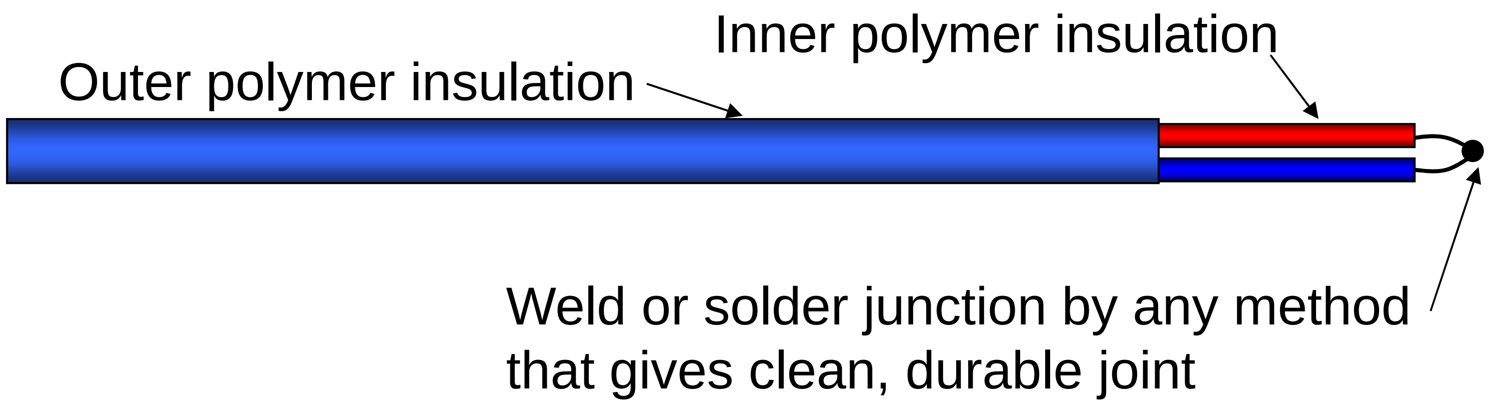
Thin-film thermocouples: research applications only

Bare Wire with Ceramic Insulators



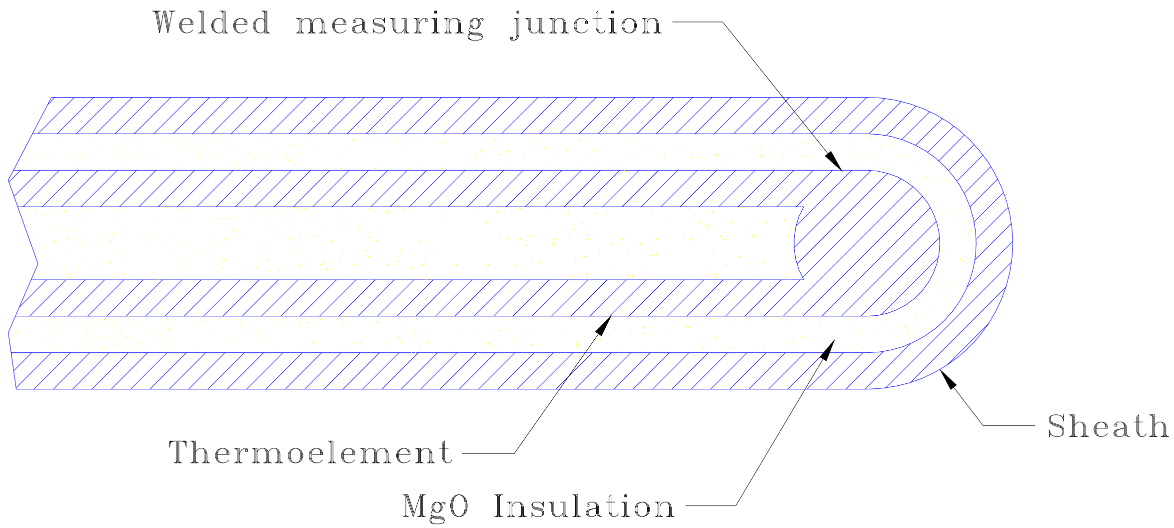
- For noble-metal alloys, use high-purity alumina (99 mass% for typical uses, 99.7 mass% for highest accuracy and stability).
- If old insulators are used, avoid cross contamination. e.g.: Pt wire into a bore that held Pt-Rh, or other base metals into bore that held iron
- Above 1300 °C, alumina insulator itself is a source of impurities.
- Use single, unbroken lengths of ceramic, to prevent contamination and loss of volatile alloy components
- Pt-Rh alloys annealed pre or post assembly for best performance

Soft-Insulated Thermocouples



- Choose polymer insulation based on upper temperature limit
- Woven ceramics are popular in semiconductor applications
  - Always bake out binders to avoid contamination
  - Contamination of thermocouples by ceramic has not been studied well
  - Use single lengths of alumina in high-gradient zone, if possible

Mineral-Insulated, Metal-Sheathed (MIMS) Thermocouples



- At high temperatures, choice of sheath material is critical
  - for types K and N, sheath material dominates performance
- MIMS thermocouples are available in small diameters (0.25 mm)
- Sheath protects thermoelements from contamination

Thermocouple Color Codes

TC Type	IEC Positive Cond., Extension Sheath	ASTM Extension Sheath	ASTM Positive Conductor
B	—	Gray	Gray
E	Violet	Purple	Purple
J	Black	Black	White
K	Green	Yellow	Yellow
N		Orange	Orange
R,S	Orange	Green	Black
T	Brown	Blue	Blue

IEC: Negative Conductor is **White** for all Types

ASTM:

- Negative Conductor is **Red** for all Types
- For base metal types, duplex insulated thermocouple wire has identical color codes, but with brown overall insulation.

Thermocouple Drift Estimates

Base Metal Thermocouples

- **type E, J, N, T:** <0.5 °C after 10,000 h at 200 °C

- **type J:** <0.5 °C after 1,000 h at 430 °C
  2 °C after 1,000 h at 650 °C

- **type K:** <0.2 °C after 10,000 h at 200 °C
  <1 °C after 1,000 h at 650 °C (bare wire, 8 ga)
  up to 4 °C hysteresis, on heating well past 400 °C and then cooling
  3 °C after 24 h at 1250 °C (bare wire, 8 ga)

- **type N, bare 8 Ga:** <1 °C after 24 h at 1250 °C

- **“Stabilized” type K & E:** <1 °C after 3200 h at 540 °C in air

Advantages of Thermocouples

- Cheap
- Wide temperature range (–270 °C to 2100 °C)
- Small (down to 0.25 mm diameter)
- Easy to integrate into automated data systems
- Adapts easily for use as a Digital Thermometers

Disadvantages of Thermocouples

- Small signals, limited temperature resolution (1 mK to 1 K)
- Thermocouple wires must extend from the measurement point to the readout.
- At higher temperatures (>500 °C), thermocouples may undergo chemical and physical changes, leading to loss of calibration.
- Recalibration for use above 200 °C is difficult

What is a Digital Thermometer ?

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

- *IPRT, Thermistor, or Thermocouple*

Digital Thermometers

- **Electronic Display + Probe = Digital Thermometer**

- **Easy to use**
  - Measurement system adapts to different probe types (e.g., IPRT, thermistor, TC)
  - Hand held, battery operated
  - Connected to a computer
  - Large temperature range

- **Device displays temperature directly by using the ASTM coefficients or calibration coefficients of the thermometer**
  - ASTM E20 Standards
  - ITS-90

- **Device may allow two thermometers to connected directly to unit for differential thermometry**

- **Some have software that allow “real time” calibration**

- ***Cost of purchase, training in use, and maintenance are a serious consideration***

Non-Mercury Liquid-in-Glass Thermometers

- **Organic liquids generally have inferior performance to mercury,** but are a reasonable alternative if uncertainty requirements are modest (ASTM standard just begun)
- **Beware of drainage of organic liquid down capillary wall on cooling**
- **"Next-generation" proprietary liquids under development** (Existing ASTM standard E2251); good accuracy, but check for separation of liquid column
- **For all non-mercury LiG thermometers,** capillary and bulb dimensions will be different, with different time response and immersion characteristics!!!
- **Uncertainties are not well understood – so far**
  - NIST Thermometry Group (Dawn and Wyatt) are measuring **organic** LIGs to determine uncertainty
    - Both **calibration** and **repeatability in use** uncertainties

Choice of a LiG Thermometer

Advantages of LiG thermometers

- Relatively inexpensive
- When used at moderate temperatures (<150 °C), recalibration at the Ice MP suffices
- Damage to thermometer is usually visually apparent (!!!)

Disadvantages of LiG thermometers

- Very difficult to automate
- Total immersion require adjustment of immersion with changing temperature/Partial immersion not too accurate
- Hg is banned in some circumstances; prohibitively expensive to clean up in other instances

Replacement Roadmap

1. **Identify the level of uncertainty needed**
2. **Identify the temperature range**
3. **Identify unique aspects of the test apparatus or method**
   (e.g., inherent temperature non-uniformity)
4. **Identify adequacy of presently specified Hg thermometer**
   (anywhere from overkill to just adequate)
5. **Make judgments on**

   how tightly to prescribe the thermometer

   whether to require calibration, measurement assurance

   what tests/round robins are needed to validate the revised standard

- When in doubt, call for assistance:
  - How to select what type of device should work for your application.
  - How to maintain traceability
  - How to validate accuracy and re-calibration

Considerations in Selecting a Thermometer

Digital or Analog: Compliant with ASTM E20 standards, internal measurement procedures, and training in use

Accuracy: Uncertainties range from 0.01 °C to >1 °C

Cost of Thermometer: Range from $6000 to $6

Cost of Calibration: from $1,000 to $50

Temperature Range of measurement: varies by thermometer type

Stability and Durability during use

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

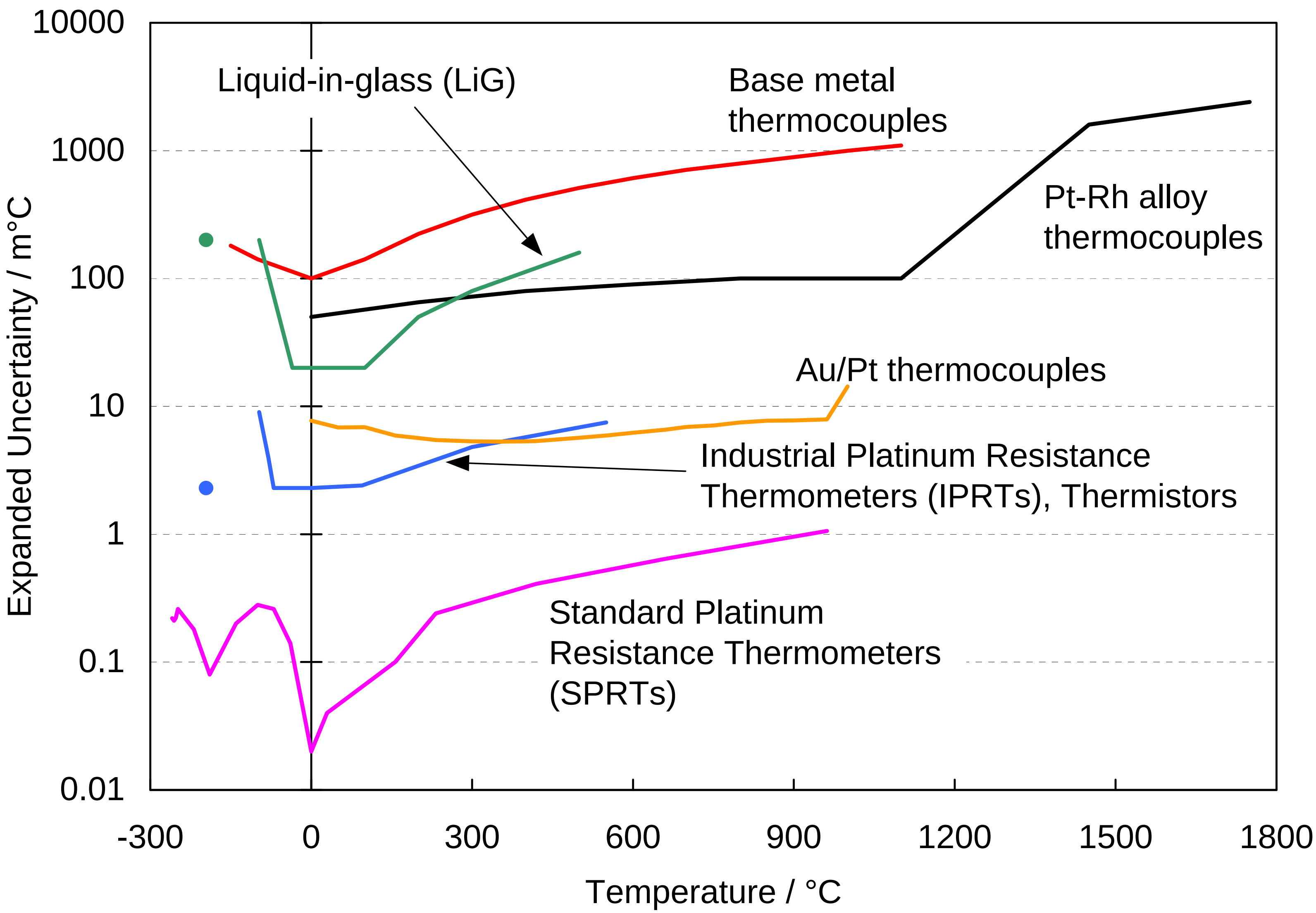
Compatibility with measurement equipment

- **Digital probes easy to integrate to electronics**
- **liquid-in-glass, digital thermometers much easier for quick visual inspection**

Compatibility with object being measured

- **sheath diameter, length chosen for good thermal equilibrium**

Thermometer Types:
Calibration Ranges and Uncertainties



Comparative Thermometer Types: Calibration Methods, Uncertainties, and Costs

Thermometer Type	Probe Type	Nominal Cost, $	Temperature Range, °C	Calibration Method	Measurement Uncertainty, °C
Digital	IPRT	5 to 1,000	–196 to 500	Comparison	0.01 to 1
	Thermistor		–50 to 100		0.005 to 0.01
	TC		–196 to 2100		0.1 to 1
Analog	Organic LiG	30	–196 to 200	Comparison	1 to 3
	Proprietary LiG	50 to 200	–196 to 300		?

Tolerances vs. Calibration Uncertainties

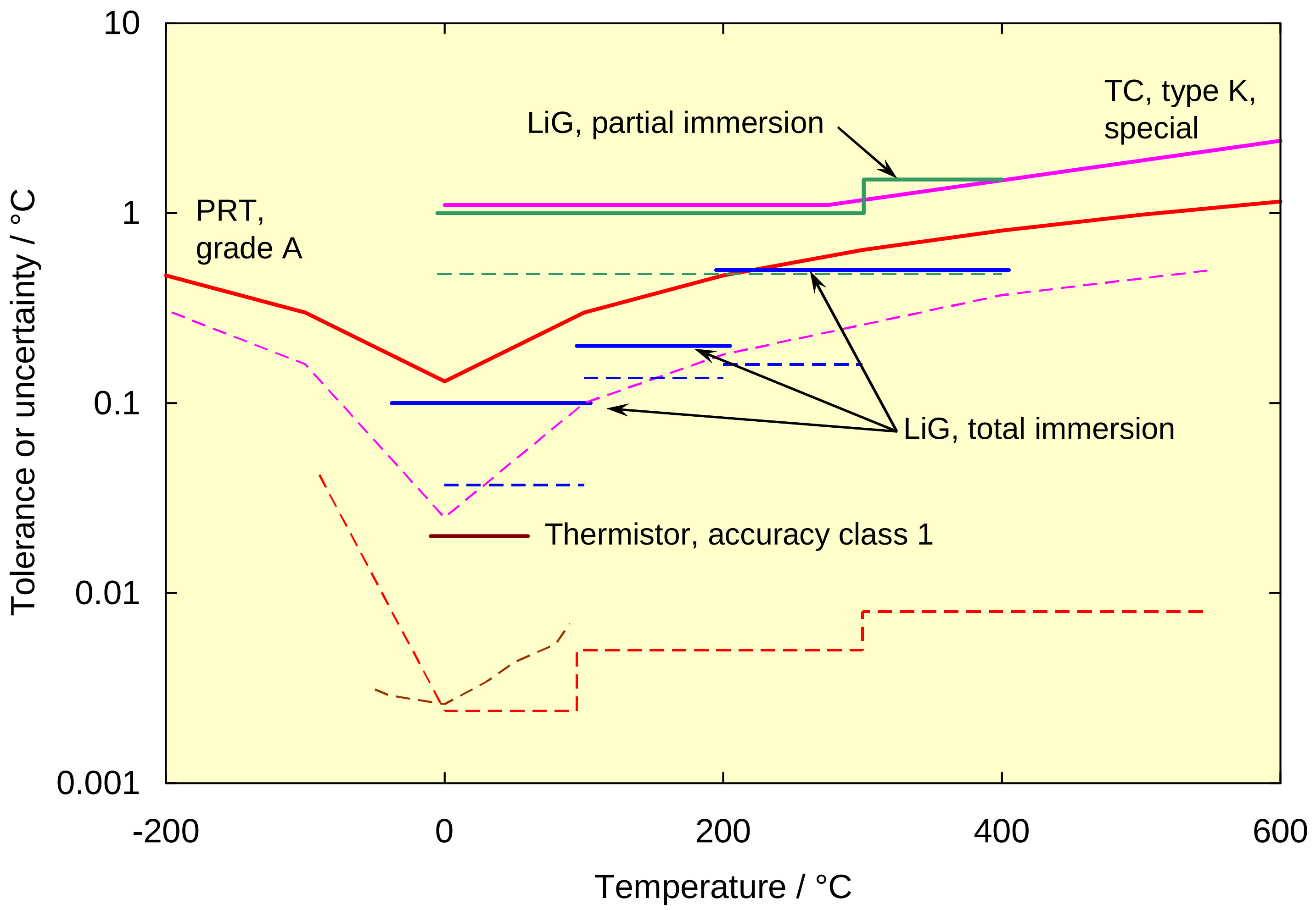
Tolerance band: manufacturer's guarantee that the instrument response will conform to a standard response function to within an error equal to the tolerance.

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.

Tolerances vs. Calibration Uncertainties



Colored lines: ASTM tolerances (ASTM E1, E1137, E230, and E879).

Dashed lines: NIST calibration uncertainties (*k*=2)

Measurement Aspects to Consider During the Transition Phase

- Measurement Bias
- Temperature Non-Uniformity
- Measurement Uncertainty
- Device Display Issues
- Non-Hg thermometers
- Validation or Re-calibration

Bias of Liquid-in-Glass Thermometers

1. For a partial immersion thermometer, if the **stem temperature during use differs significantly from the ASTM E 1 stem temperature** specified in Table 4 of E 1 and a correction is not applied, there will be an error (see ASTM E 77).

2. **Total-immersion thermometer is used at a fixed, partial immersion, with no correction applied.** Extreme care must be taken in selecting an alternative thermometer for these applications, because use of a different thermometer type, while reducing the measurement error, may cause changes in the bias of the standard.

3. **If the thermometer is not in good thermal contact with the body being measured**, there may be significant errors due to thermal conduction along the thermometer sheath. Temperature reading biased even though the precision is acceptable.

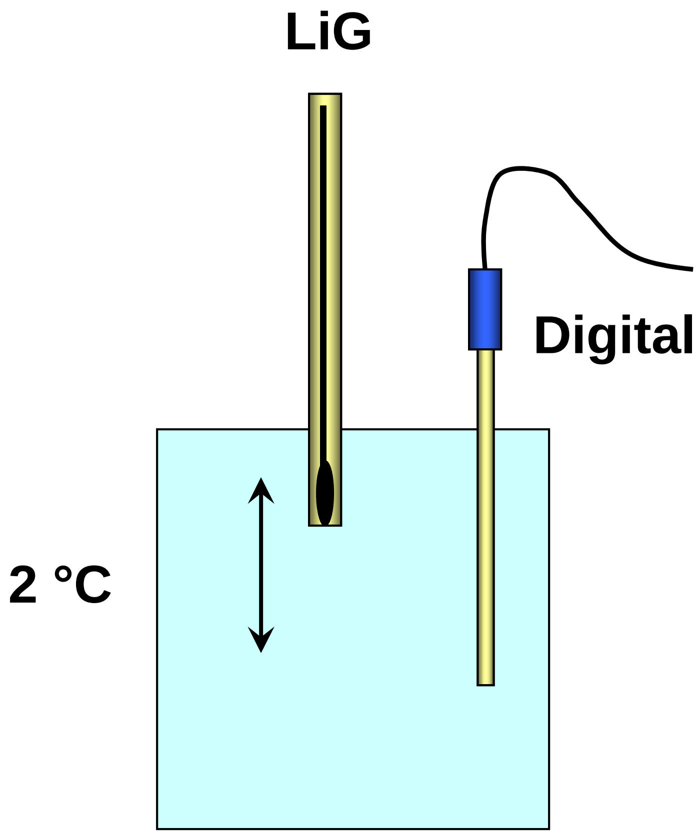
Temperature Non-Uniformity

Total-Immersion Liquid-in-Glass Thermometer: Immersion depth varies with temperature

Partial-Immersion Liquid-in-Glass Thermometer: Immersion depth specified on thermometer

Digital Thermometer: Placing thermometer at a fixed depth may introduce a bias, due to temperature variations in apparatus

Adequate immersion is often 10 times the sheath diameter
(e.g., ¼” sheath = 2.5 “ immersion



Typical Measurement Uncertainty Budget: Digital Thermometer

Component	Method of evaluation
Calibration uncertainty or tolerance	Manufacturer or calibration laboratory, or ASTM E 230 tolerance
Thermocouple drift	Results from literature, or in situ comparisons
Reference junction uncertainty	Manufacturer or independent evaluation
Readout uncertainty	Manufacturer or independent evaluation
Readout drift	Manufacturer or independent evaluation

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

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
- Incorrect entry of calibration coefficients into readout
- Probes switched without updating coefficients
- Low battery

Consequence: Measurement cross-checks / assurance / check standards

- Routine checks of performance
- Checks at ice point
- Comparison of readings of different thermometers

EPA Activities

Webpages &
Using Alternative Thermometers in the Field

Permission granted by the EPA

Note of thanks to Dody, EPA Chemical Engineer

2010: A Year in Review

EPA Deliverables in FY2010

- **Web-based user-friendly guidelines**
  - Replacement of Mercury Thermometers
  - Selecting Alternatives to Mercury-Filled Thermometers
  - Verification Methods to Alternatives to Mercury-Filled Thermometers, Including Research on Ice and Steam Points
  - Non-Mercury Thermometers for Validating Autoclave Operating Temperatures
  - What is Traceability?
- **Web-based videos**
  - Alternative Thermometers
  - Ice Melting Point
  - Steam Point
  - Traceability

Alternatives to Hg Thermometers cc

- **Testing of alternative thermometers**
  - Site visit to a petroleum distribution center
  - Develop field-test protocol
  - Select and test alternative thermometers for accuracy and repeatability

Permission granted by the EPA
Note of thanks to Dody, EPA Chemical Engineer

Petroleum Distribution Center Thermometers

4 Phase Project

EPA sponsored - 2010

- Phase I Repeatability of thermometers at NIST
- Phase II Field-testing of protocol and thermometers
- Phase III "Closing-the-Loop" Measurements at NIST

Note of thanks to those companies who donated thermometers (analog and digital) for this work

Permission granted by the EPA
Note of thanks to Dody, EPA Chemical Engineer

Phase I
Repeatability of Thermometers

Petroleum Distribution Center visit to understand measurement issues

Thermometer selection

- ASTM Hg thermometers
  - 59F, 12F, 63F
- ASTM Organic thermometers
  - S59F
- Intrinsically-safe digital thermometers
  - 5 models

Repeatability testing protocol performed at NIST

- Thermometers cycled through full calibration cycle 3 times
- Measurements performed by two NIST metrologists
- Temperature range of –21 °C to 99 °C

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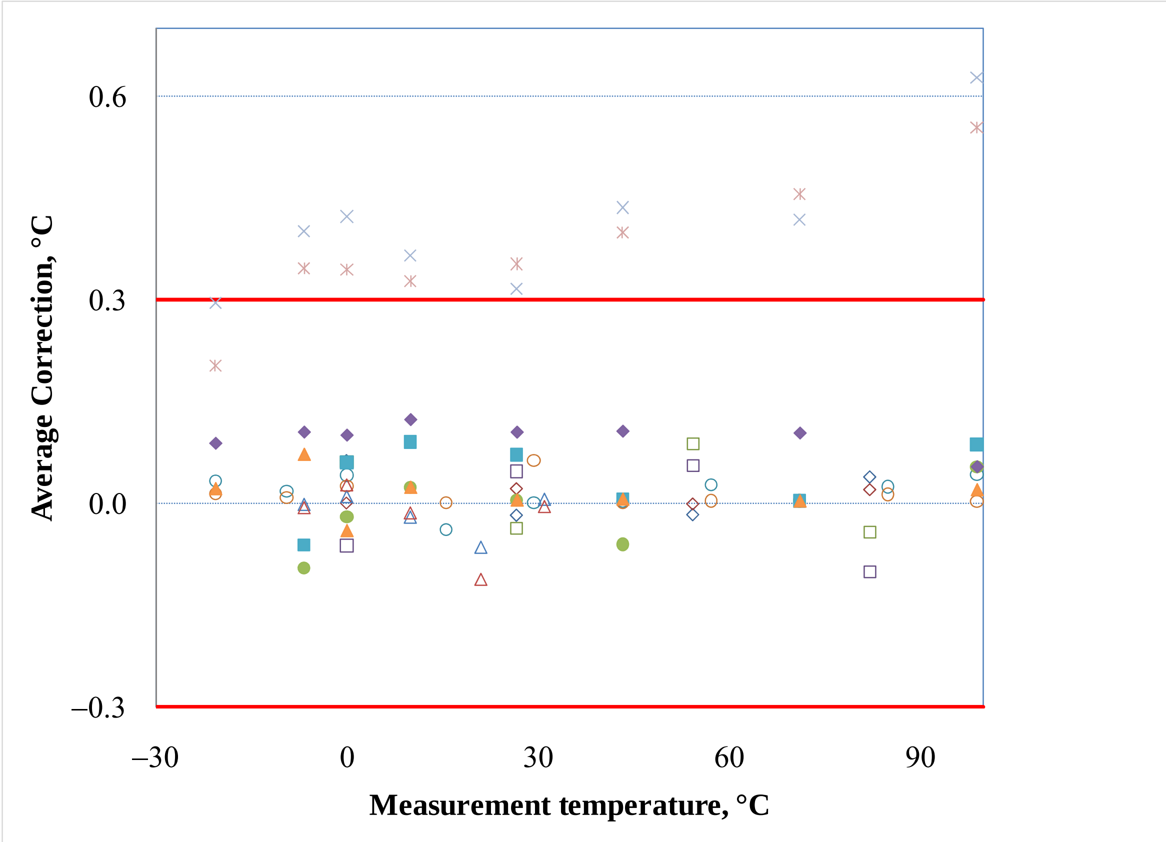
Phase I NIST Laboratory Results



One digital thermometer model did not meet the requirement of ±0.3 °C

- **Manufacturer instructions used to adjust thermometers within manufacture tolerances before retesting – EASILY FIXED in lab !!!**

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Note of thanks to Dody, EPA Chemical Engineer

Phase II
Field-Testing of Protocol and Thermometers

Simple protocol developed for use at a Petroleum Distribution Center

- Based on information from exploratory trip to the Petroleum Distribution Center
  - Measurement instructions
  - Feasibility of technicians measuring several thermometers
  - Survivability of transfer standards (e.g. thermometers)
  - Data-collection worksheets

Five transfer standards delivered to a Petroleum Distribution Center

– 1 ASTM Hg with cupcase	59F
– 1 ASTM Organic with cupcase	S59F
– 3 Digitals	DT1-3, DT1-4, DT2-1

8 measurements (once per week) by onsite staff

- Petroleum Distribution Center reference thermometer included

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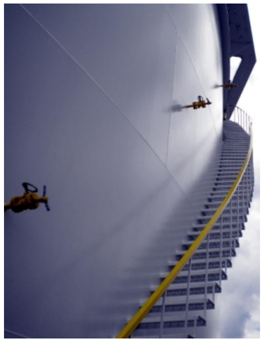
Note of thanks to Dody, EPA Chemical Engineer

Field Testing at a Petroleum Distribution Center

8 measurement sets performed once per week

- 4 different technicians
- Different measurement conditions
  - Time of day / night
  - Gasoline and Ethanol
  - Weather conditions

Last set performed with EPA staff, API staff, and NIST metrologists



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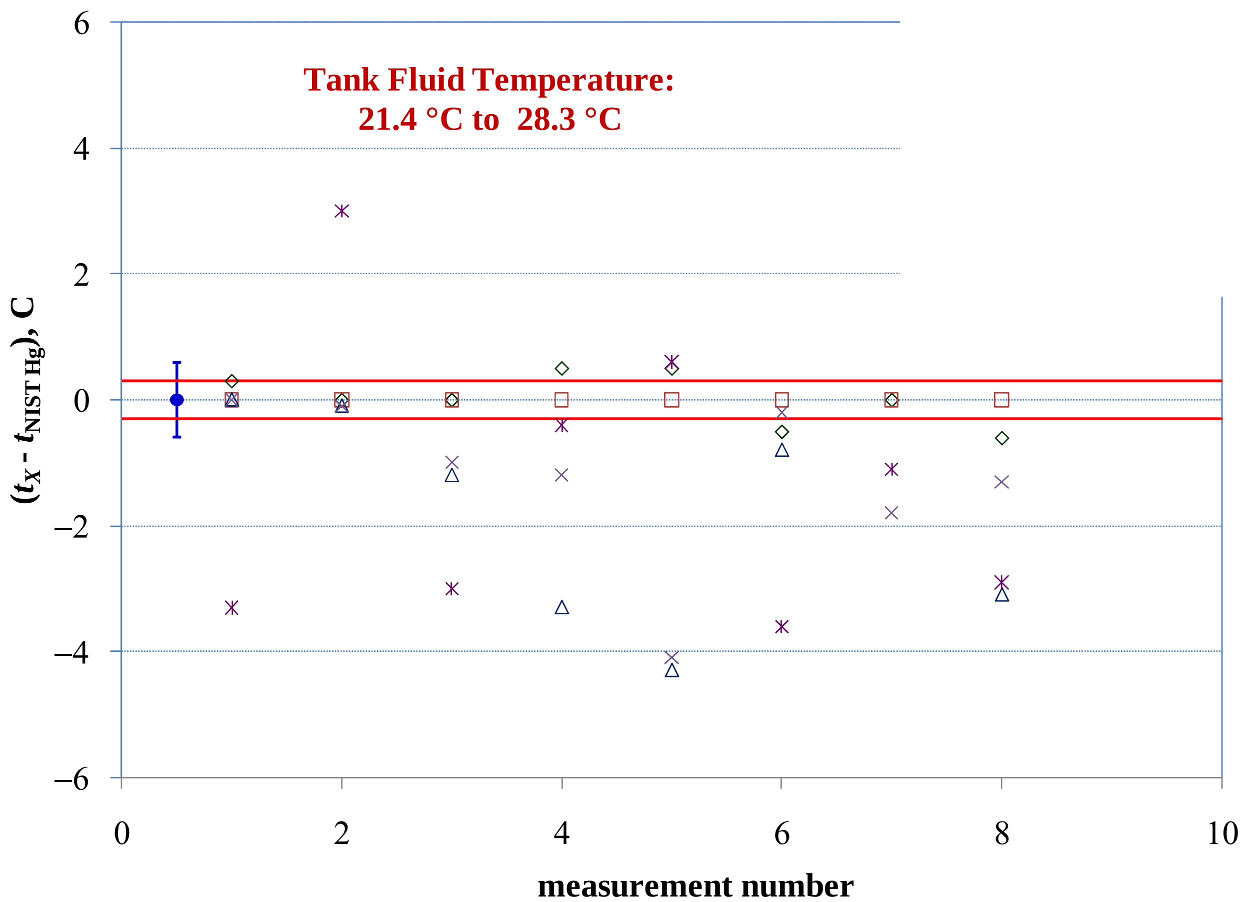
Phase II Results in the Field



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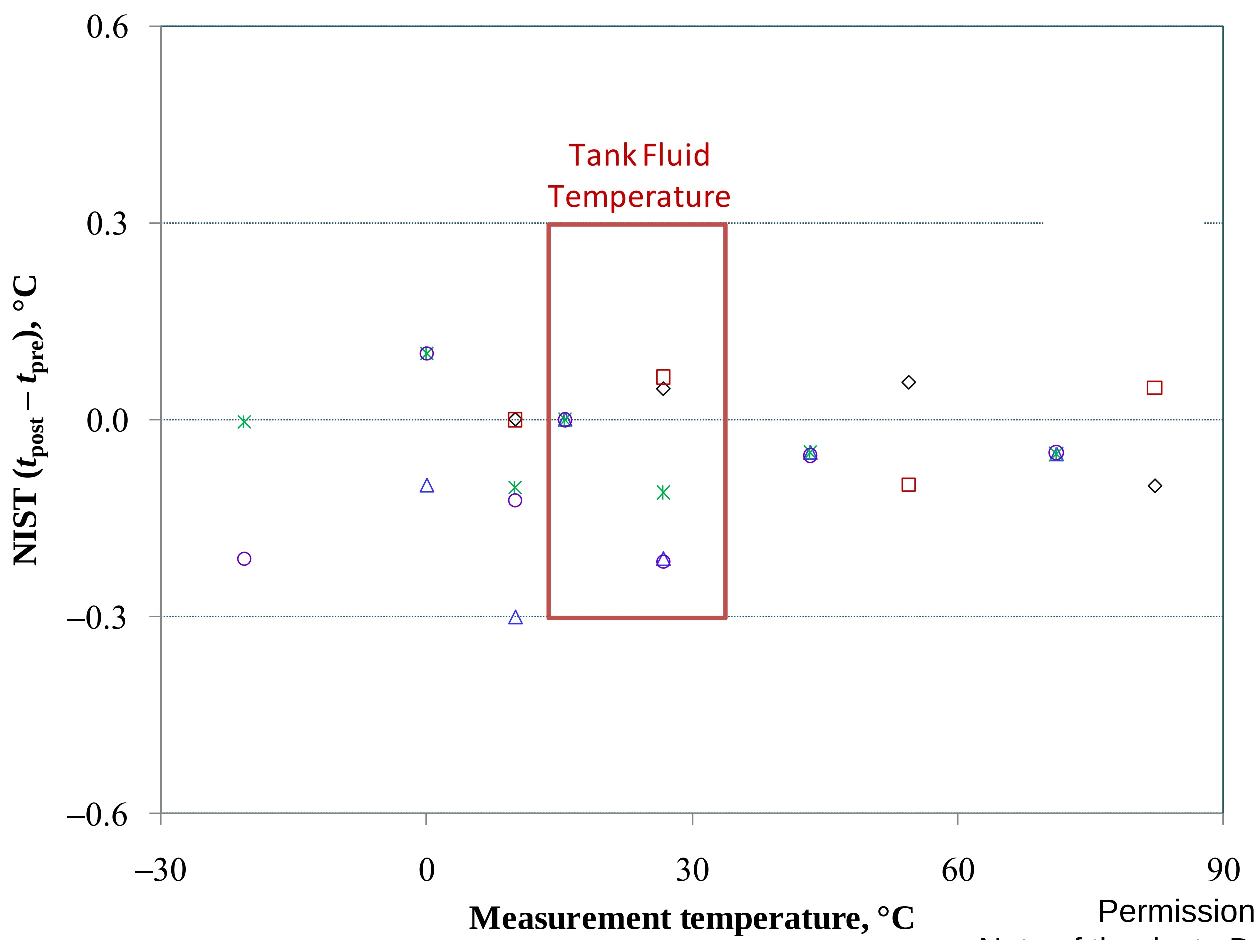
Phase III "Closing-the-Loop" Measurements at NIST

On return, thermometers did not significantly change

- All still met ±0.3 °C requirements over tank fluid temperature



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Note of thanks to Dody, EPA Chemical Engineer

Phase II Notes from the Field

Analog thermometer measurement resolution needs improvement

– ±0.6 °C resolution negatively impacts the field results

Learning curve to overcome in using digital thermometers in the field

Better Training Needed !!!

Digital thermometer manufacturers need to work closer with Petroleum End-Users to solve various issues

– Ergonomics
– EMI
– Confidence in measurement results
– Training tutorials – online videos

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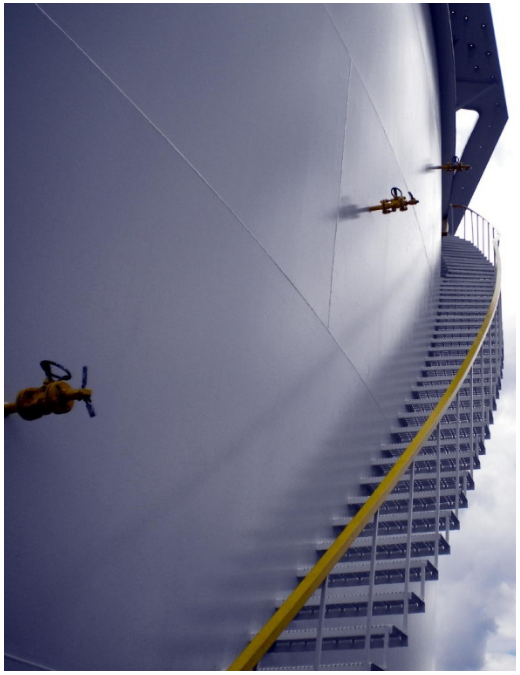
Note of thanks to Dody, EPA Chemical Engineer



Questions ?