$$\overline{E_k}$$

T

$$\overline{E_k} = \frac{3kT}{2}$$

k

×

$$10^{-23}$$

$$\frac{3kT}{2}$$

N

$$E_{\text{thermal}} = \frac{3NkT}{2}$$

$$E_{\text{thermal}} = \frac{3nRT}{2}$$

$$E_{\text{thermal}}$$

n

R

$$l = l_0(1 + \alpha\Delta T)$$

l

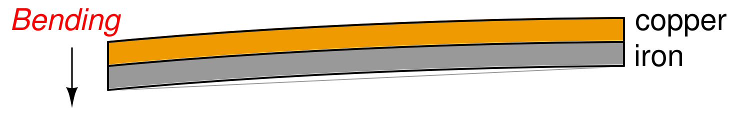
l_0

α

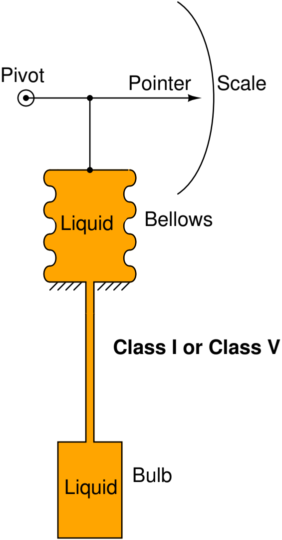
$$\Delta T$$

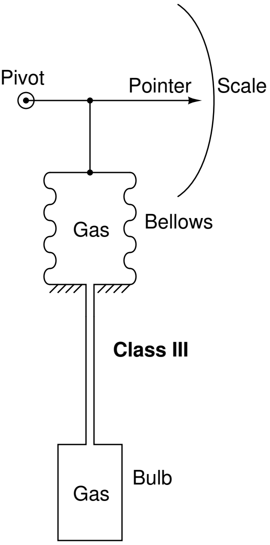
10^{-6}

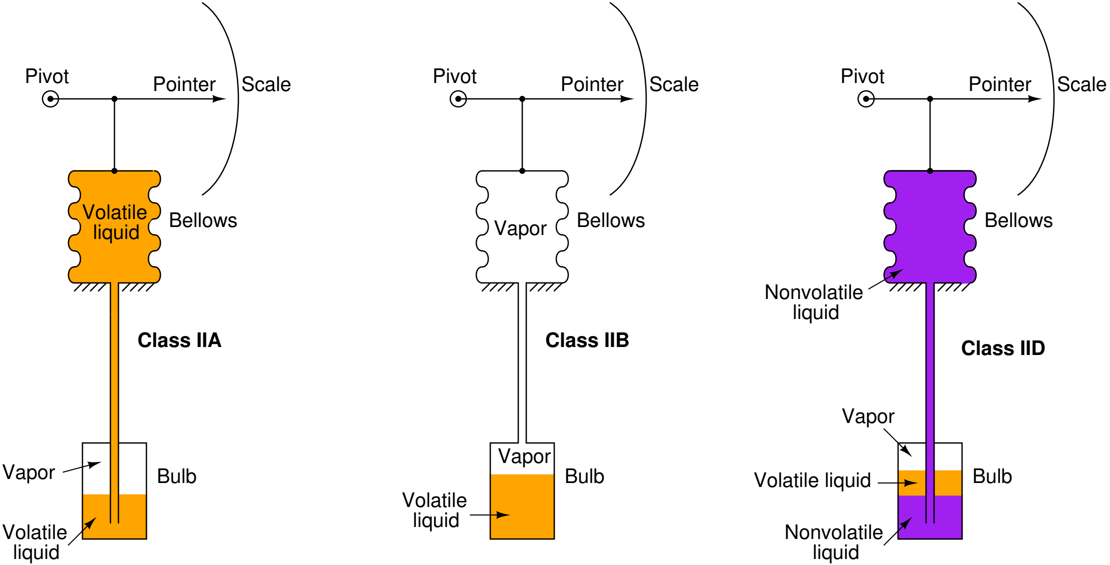

copper
Expansion
iron


Bending
copper
iron

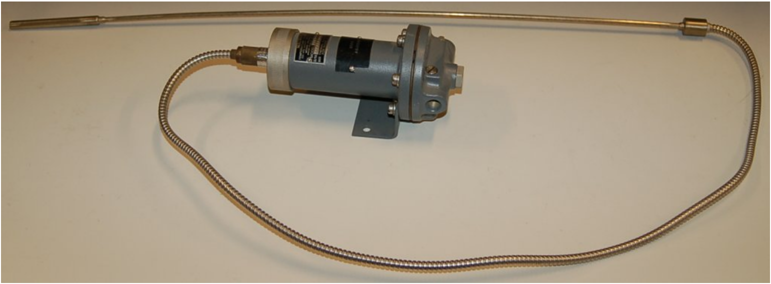
25
30
35
40
45
50
15
10
5
0
°C

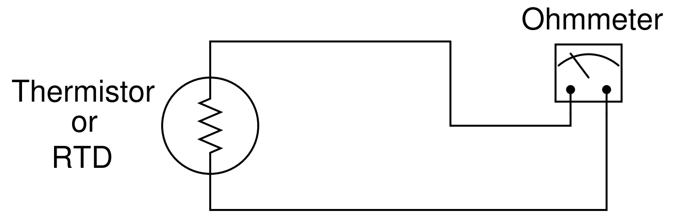

Pivot
Pointer
Scale
Liquid
Bellows
Class I or Class V
Liquid
Bulb


Pivot
Pointer
Scale
Gas
Bellows
Class III
Gas
Bulb



Pivot
Pointer
Scale
Volatile liquid
Bellows
Class IIA
Vapor
Bulb
Volatile liquid
Pivot
Pointer
Scale
Vapor
Bellows
Class IIB
Vapor
Bulb
Volatile liquid
Pivot
Pointer
Scale
Bellows
Nonvolatile liquid
Class IID
Vapor
Volatile liquid
Bulb
Nonvolatile liquid




Ohmmeter
Thermistor
or
RTD

$$R_T = R_{ref}[1 + \alpha(T - T_{ref})]$$

R_T

R_{ref}

T_{ref}

$$R_T = 100\ \Omega[1 + (0.00392)(35^o\ \mathrm{C} - 0^o\ \mathrm{C})]$$

$$R_T = 100\ \Omega[1 + 0.1372]$$

$$R_T = 100\ \Omega[1.1372]$$

$$R_T = 113.72\ \Omega$$

$$R_T = R_{ref}(1 + AT + BT^2 - 100CT^3 + CT^4)$$

-200

O

$< T <$

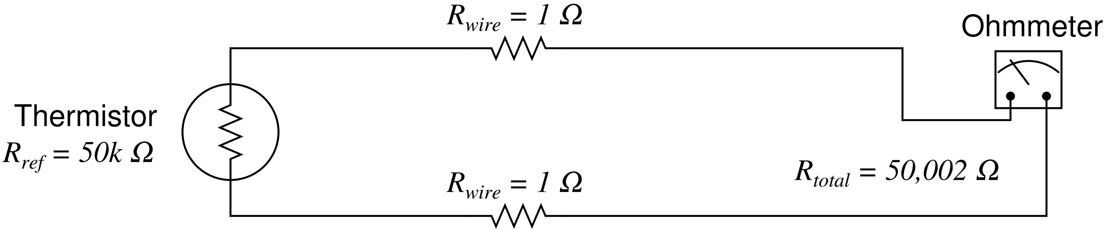
$$R_T = R_{ref}(1 + AT + BT^2)$$

A

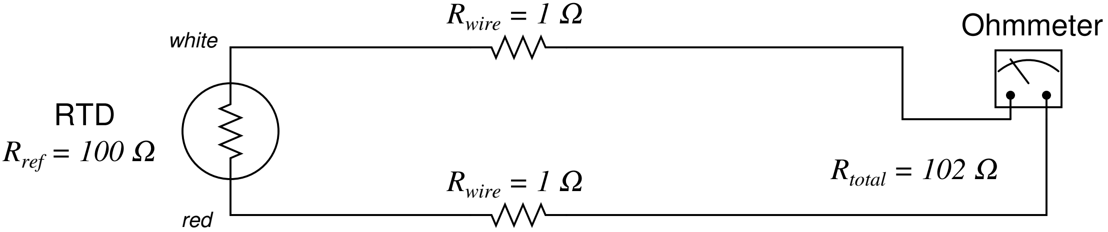
B

$\mathcal{C}$

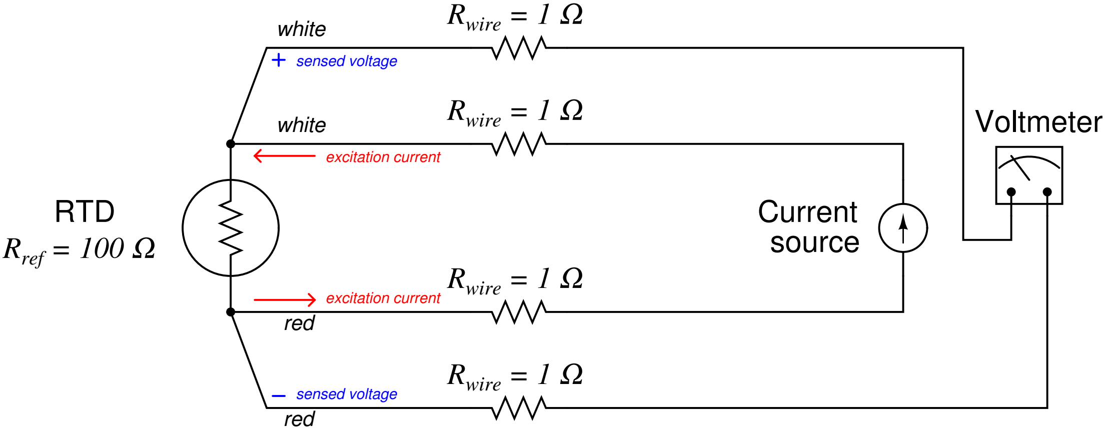
Ω



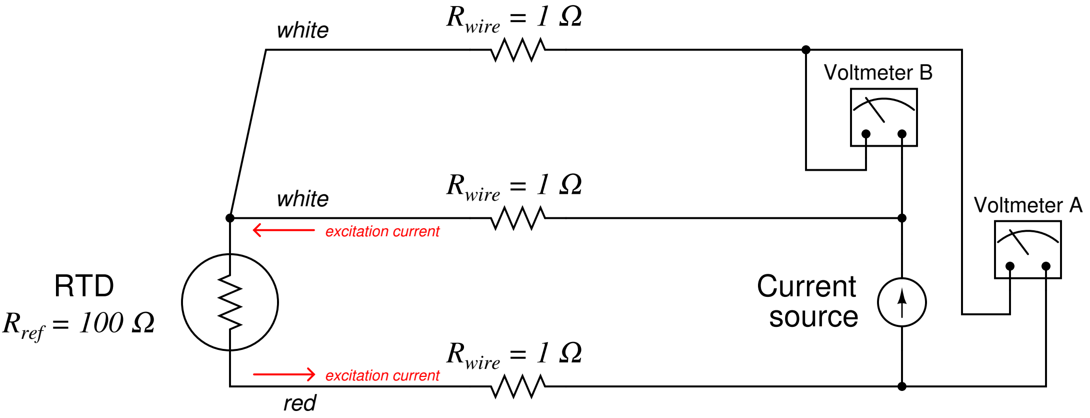
$R_{wire} = 1\ \Omega$
Ohmmeter
Thermistor
$R_{ref} = 50k\ \Omega$
$R_{total} = 50{,}002\ \Omega$
$R_{wire} = 1\ \Omega$



$R_{wire} = 1\ \Omega$
Ohmmeter
white
RTD
$R_{ref} = 100\ \Omega$
$R_{total} = 102\ \Omega$
$R_{wire} = 1\ \Omega$
red

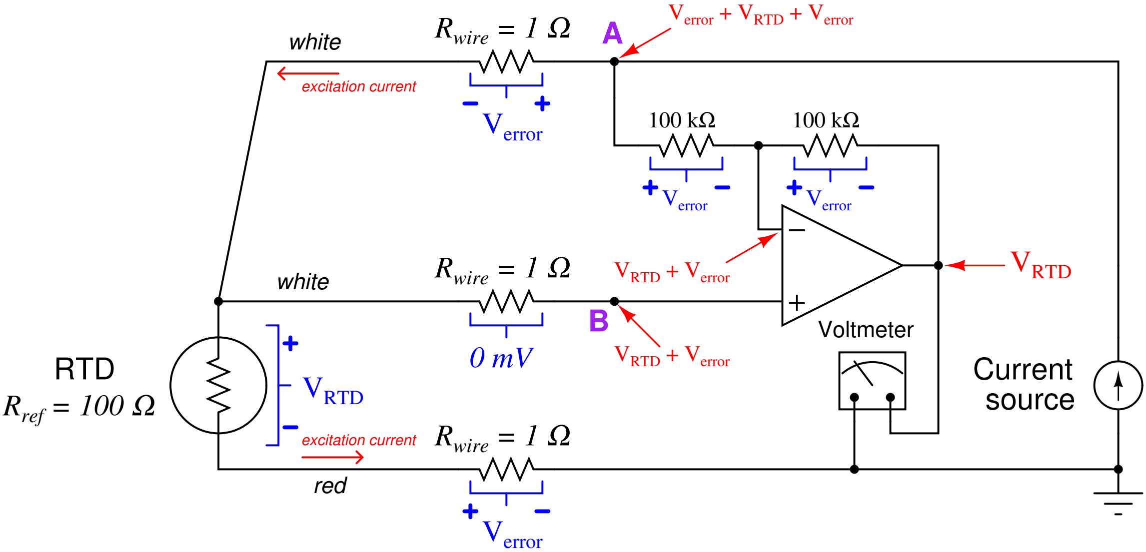


white
$R_{wire} = 1\ \Omega$
+ sensed voltage
white
$R_{wire} = 1\ \Omega$
Voltmeter
excitation current
RTD
$R_{ref} = 100\ \Omega$
Current source
excitation current
$R_{wire} = 1\ \Omega$
red
$R_{wire} = 1\ \Omega$
− sensed voltage
red



white
$R_{wire} = 1\ \Omega$
Voltmeter B
white
$R_{wire} = 1\ \Omega$
Voltmeter A
excitation current
RTD
$R_{ref} = 100\ \Omega$
Current
source
$R_{wire} = 1\ \Omega$
excitation current
red

$$V_{RTD} = V_{\text{meter(A)}} - V_{\text{meter(B)}}$$



white
$R_{wire} = 1\ \Omega$
A
$V_{error} + V_{RTD} + V_{error}$
excitation current
V_{error}
100 kΩ
100 kΩ
V_{error}
V_{error}
white
$R_{wire} = 1\ \Omega$
$V_{RTD} + V_{error}$
V_{RTD}
B
$V_{RTD} + V_{error}$
0 mV
Voltmeter
RTD
$R_{ref} = 100\ \Omega$
V_{RTD}
Current source
excitation current
$R_{wire} = 1\ \Omega$
red
V_{error}

$$V_{RTD} + V_{error}$$

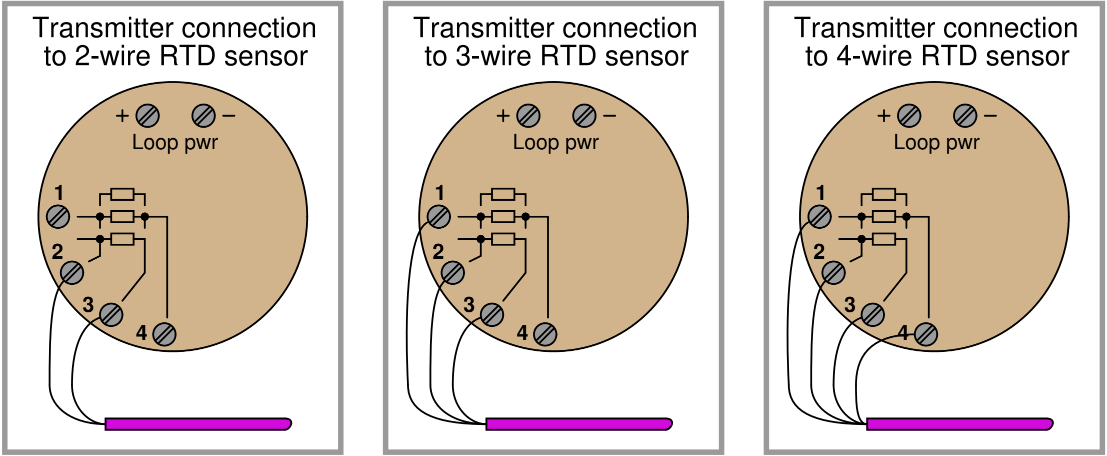
$$V_{error} + V_{RTD} + V_{error}$$

V_{error}

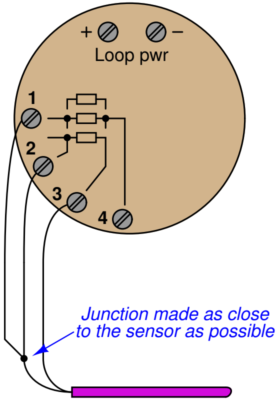
V_{RTD}


+
-
1
2
3
4

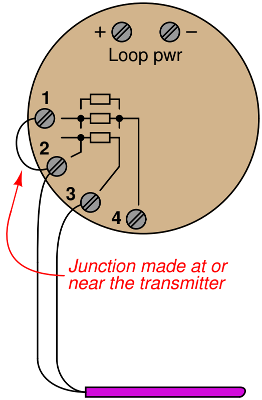
—


Transmitter connection to 2-wire RTD sensor
+
−
Loop pwr
1
2
3
4
Transmitter connection to 3-wire RTD sensor
+
−
Loop pwr
1
2
3
4
Transmitter connection to 4-wire RTD sensor
+
−
Loop pwr
1
2
3
4

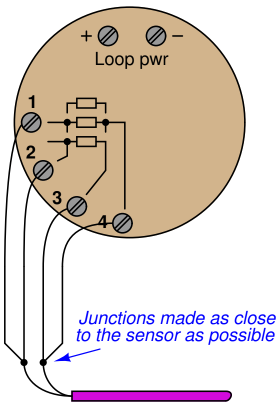
Correct way to use a 3-wire transmitter on a 2-wire RTD



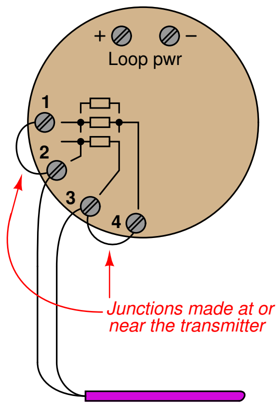
Incorrect way to use a 3-wire transmitter on a 2-wire RTD



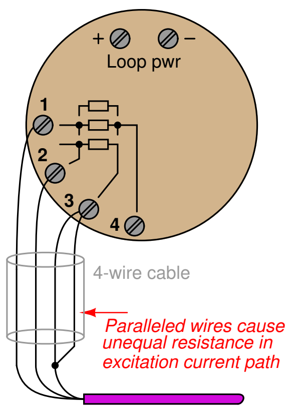
Correct way to use a 4-wire transmitter on a 2-wire RTD

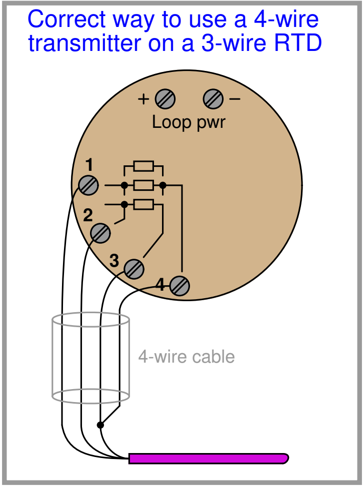


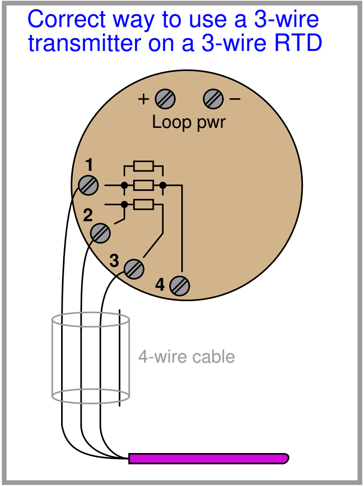
Incorrect way to use a 4-wire transmitter on a 2-wire RTD



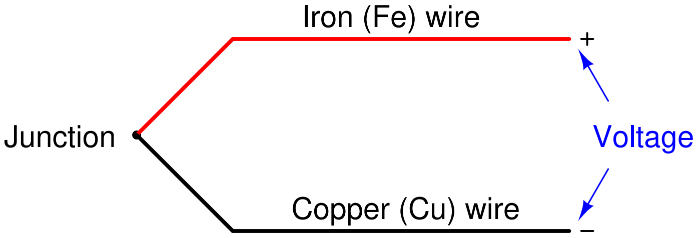
Incorrect way to use a 3-wire transmitter on a 3-wire RTD




Correct way to use a 4-wire transmitter on a 3-wire RTD
+
−
Loop pwr
1
2
3
4
4-wire cable

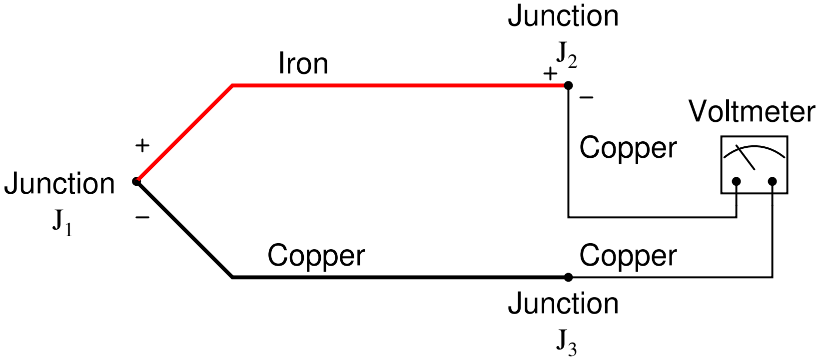

Correct way to use a 3-wire transmitter on a 3-wire RTD
+
−
Loop pwr
1
2
3
4
4-wire cable

$$P = I^2 R$$


Iron (Fe) wire
+
Junction
Voltage
Copper (Cu) wire
−

J_1

$$J_2$$



Junction
J_2
Iron
+
−
Voltmeter
Copper
+
Junction
J_1
−
Copper
Copper
Junction
J_3

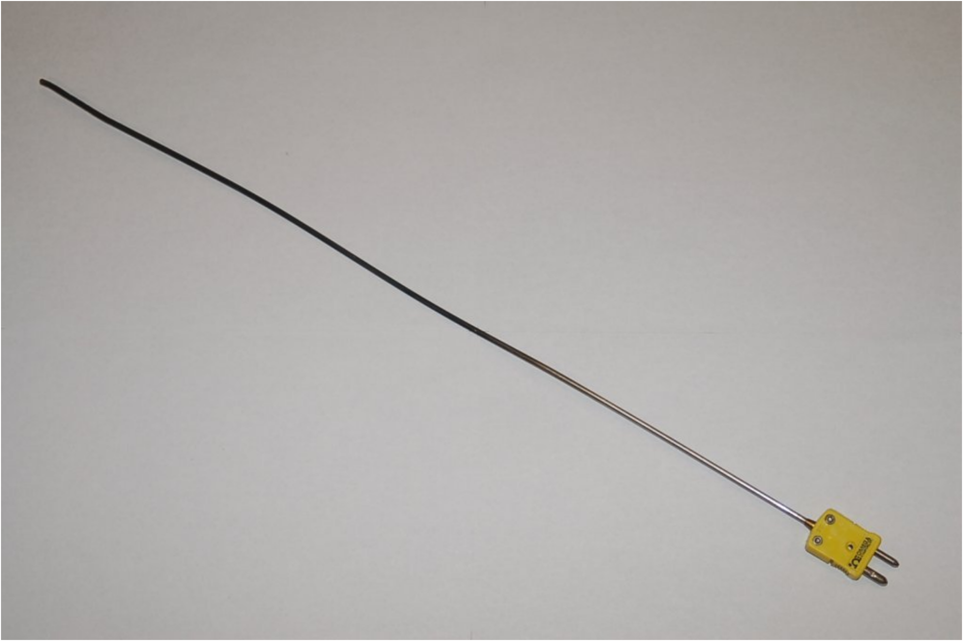
$$J_3$$

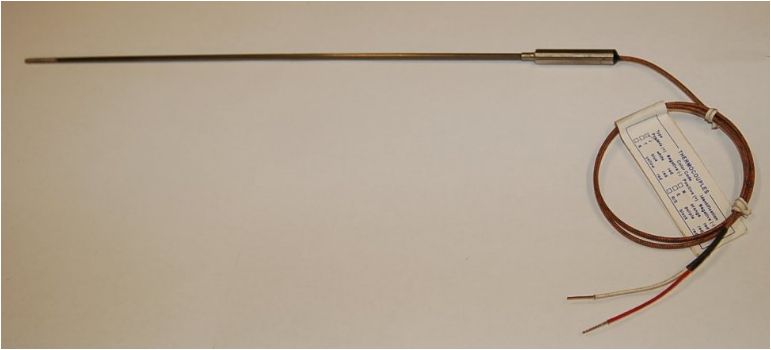
$$V_{meter} = V_{J1} - V_{J2}$$

$$V_{J1} - V_{J2}$$

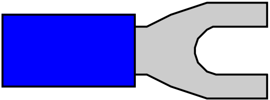
$$V_{meter} = V_{J1} - V_{J2}$$

Type	**Positive wire** *characteristic*	**Negative wire** *characteristic*	**Plug**	**Temp. range**
T	Copper (blue) *yellow colored*	Constantan (red) *silver colored*	Blue	–300 to 700 ^{o}F
J	Iron (white) *magnetic, rusty?*	Constantan (red) *non-magnetic*	Black	32 to 1400 ^{o}F
E	Chromel (violet) *shiny finish*	Constantan (red) *dull finish*	Violet	32 to 1600 ^{o}F
K	Chromel (yellow) *non-magnetic*	Alumel (red) *magnetic*	Yellow	32 to 2300 ^{o}F
N	Nicrosil (orange)	Nisil (red)	Orange	32 to 2300 ^{o}F
S	Pt90% - Rh10% (black)	Platinum (red)	Green	32 to 2700 ^{o}F
B	Pt70% - Rh30% (grey)	Pt94% - Rh6% (red)	Grey	32 to 3380 ^{o}F

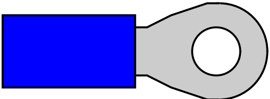


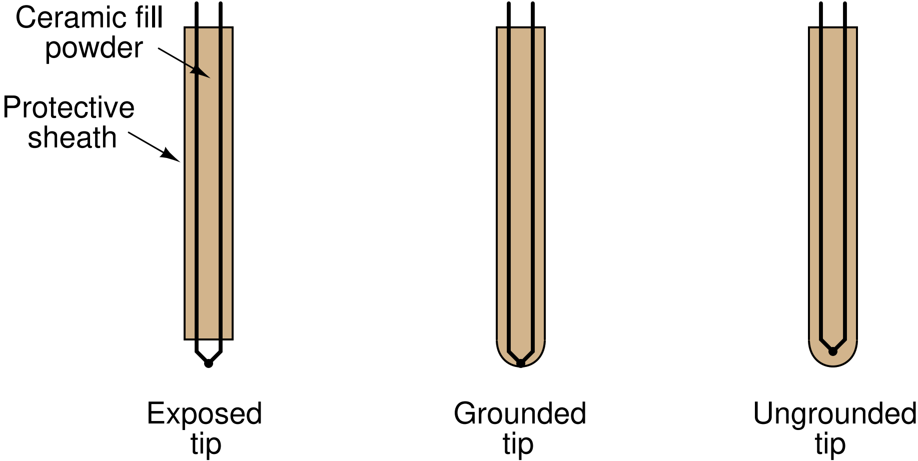

THERMOCOUPLES
Color Code Identification
Type
Positive (+) Negative (-) Positive (+) Negative (-)
white red
blue red
yellow red
orange
purple
black
R/S

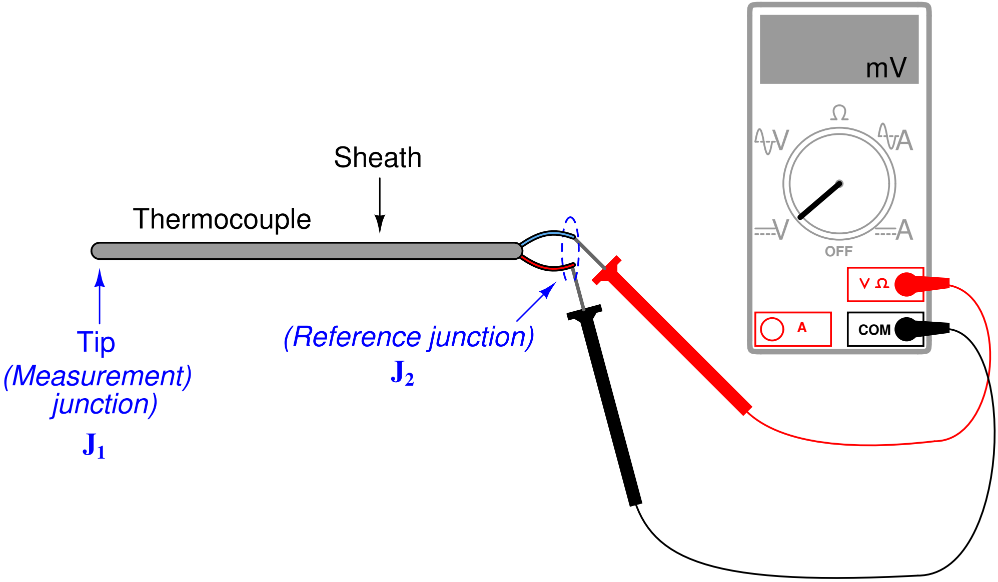
Fork terminal



Ring terminal




Ceramic fill powder
Protective sheath
Exposed tip
Grounded tip
Ungrounded tip

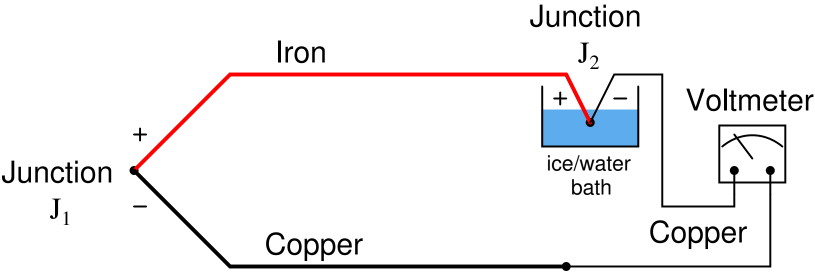

mV
Ω
V
A
V
A
OFF
V Ω
A
COM
Sheath
Thermocouple
Tip
(Measurement)
junction)
J1
(Reference junction)
J2

$$V_{J2}$$

V_{J1}

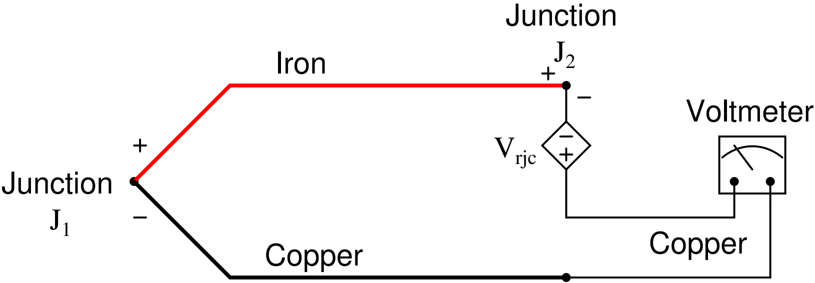
$$V_{J1} = V_{J2} + V_{meter}$$

2



Iron
Junction
J2
+
−
ice/water
bath
Voltmeter
+
Junction
J1
−
Copper
Copper

Compensating for the effects of J_2 using a "reference junction compensation" source to generate a counter-voltage



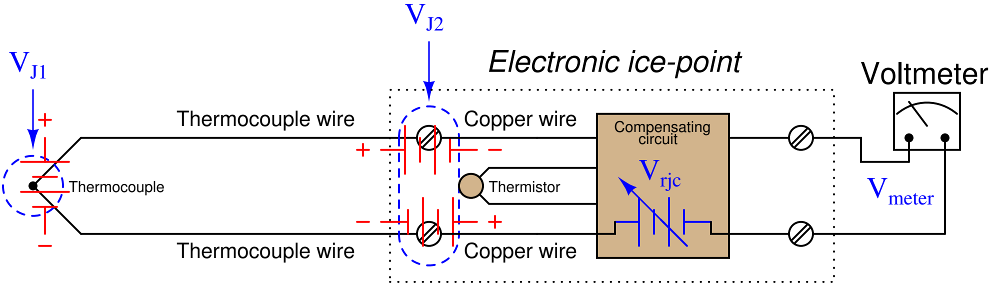
$$V_{rjc}$$

$$V_{rjc} = V_{J2}$$

$$V_{meter} = V_{J1} - V_{J2} + V_{rjc}$$

$$V_{meter} = V_{J1} + 0 \qquad (\text{If } V_{rjc} = V_{J2})$$

$$V_{meter} = V_{J1}$$



Example values:

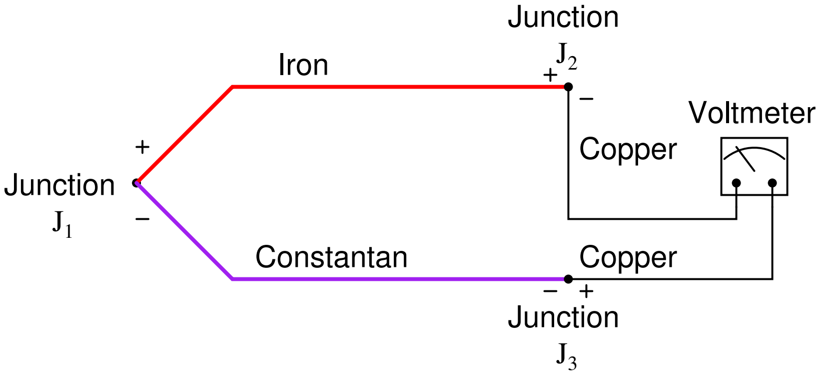
$T_{J1} = 570\ ^{o}\text{F}$ (type J) $\quad V_{J1} = 16.266$ mV

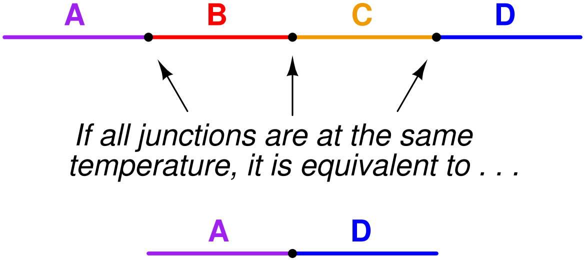
$T_{J2} = 69\ ^{o}\text{F}$ (type J) $\quad V_{J2} = 1.048$ mV $\quad V_{rjc} = 1.048$ mV

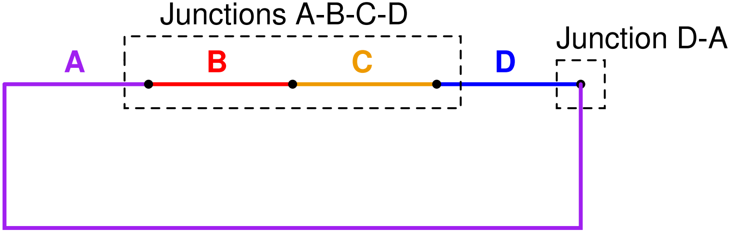
$$V_{meter} = V_{J1} - V_{J2} + V_{rjc}$$

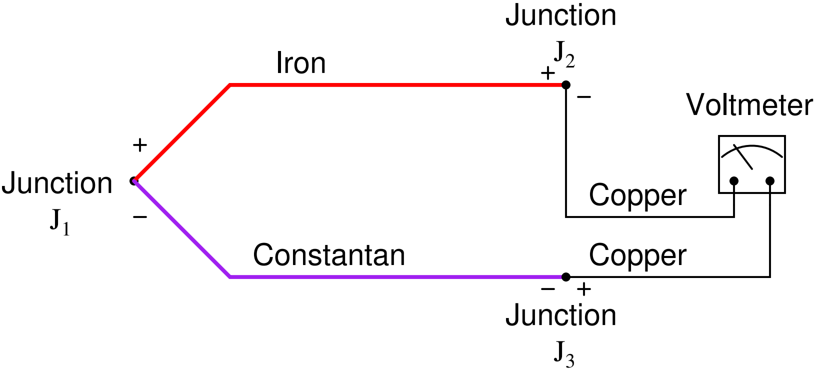
$$V_{meter} = 16.266 \text{ mV} - 1.048 \text{ mV} + 1.048 \text{ mV}$$

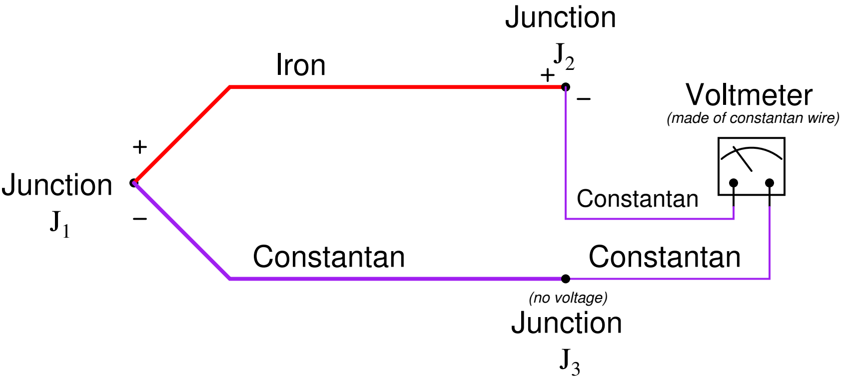
$$\mathbf{V_{meter} = 16.266 \text{ mV}} \text{ (equivalent to 570 } ^{o}\text{F)}$$

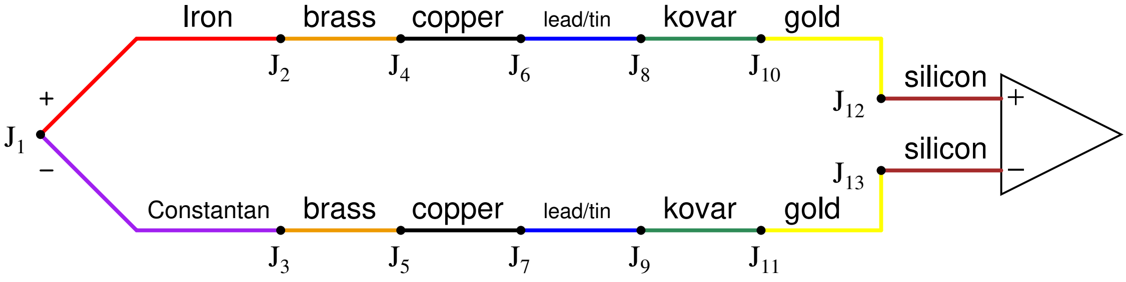

Junction
J_2
Iron
+
−
Voltmeter
Copper
+
Junction
J_1
−
Constantan
Copper
−
+
Junction
J_3


A
B
C
D
If all junctions are at the same temperature, it is equivalent to . . .
A
D


Junctions A-B-C-D
Junction D-A
A
B
C
D


Junction
J_2
Iron
+
−
Voltmeter
+
Junction
J_1
−
Copper
Constantan
Copper
− +
Junction
J_3


Junction
J_2
Iron
+
−
Voltmeter
(made of constantan wire)
+
Junction
J_1
−
Constantan
Constantan
Constantan
(no voltage)
Junction
J_3


Iron
brass
copper
lead/tin
kovar
gold
J2
J4
J6
J8
J10
+
J1
−
silicon
J12
+
silicon
J13
−
Constantan
brass
copper
lead/tin
kovar
gold
J3
J5
J7
J9
J11

$$J_{12}$$

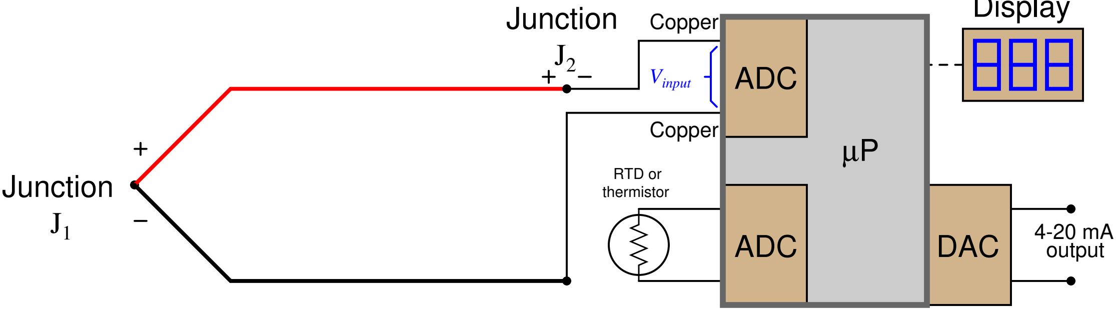
$$J_{13}$$

J_{10}

$$J_{11}$$

$$V_{meter} = V_{J1} + 0$$

Compensating for the effects of J_2 using a second input channel to sense ambient temperature and correcting mathematically in the computer



$$V_{input} = V_{J1} - V_{J2}$$

$$\text{Compensated total} = V_{input} + V_{rjc}$$

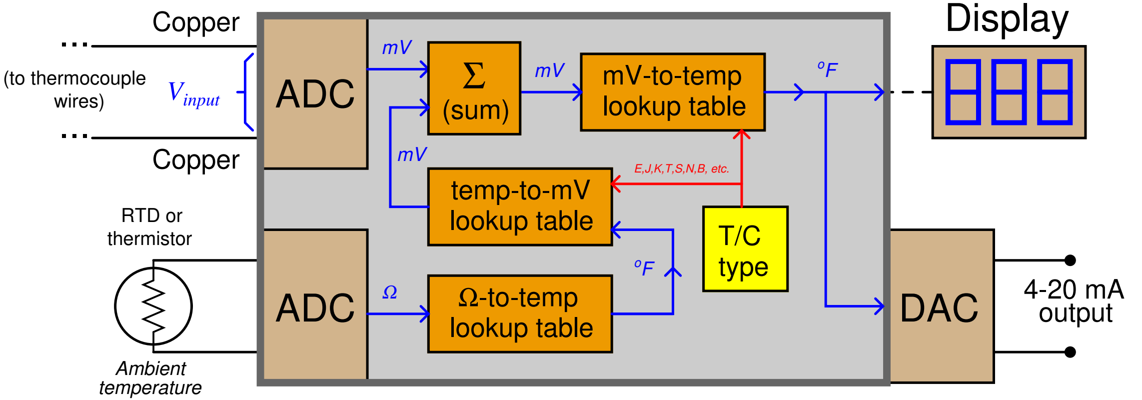
$$\text{Compensated total} = (V_{J1} - V_{J2}) + V_{rjc}$$

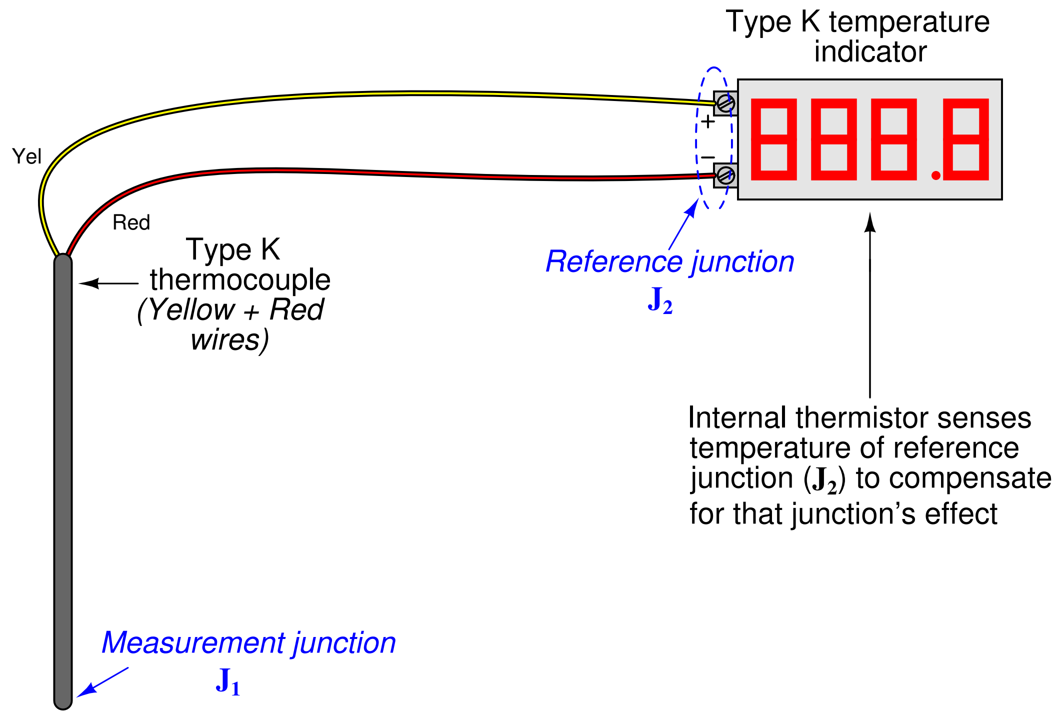
$$\text{Compensated total} = V_{J1} - V_{J2} + V_{rjc}$$

$$\text{Compensated total} = V_{J1} + 0$$

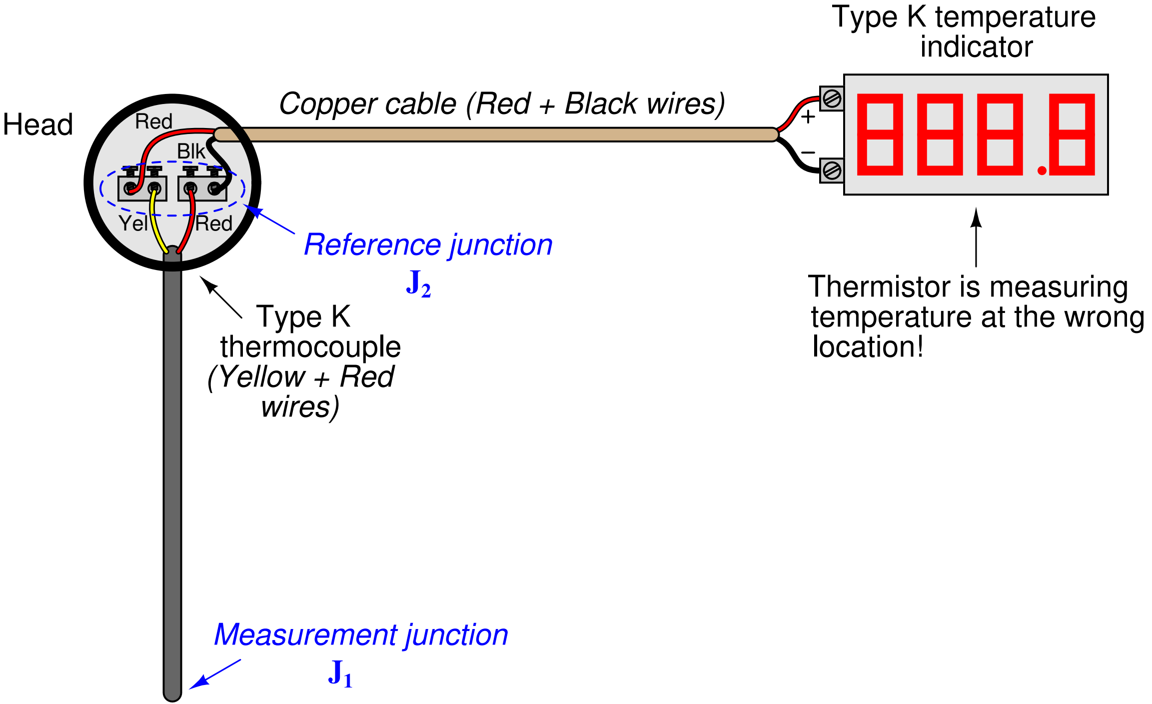
$$\text{Compensated total} = V_{J1}$$

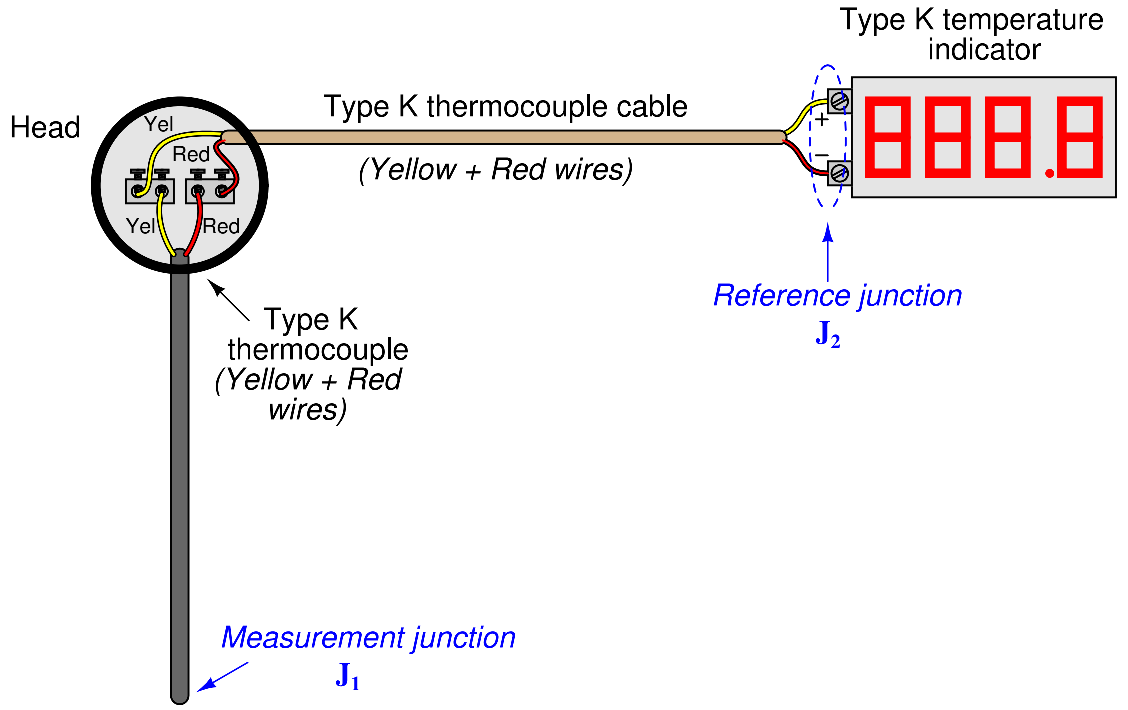
Digital ("smart") thermocouple temperature transmitter



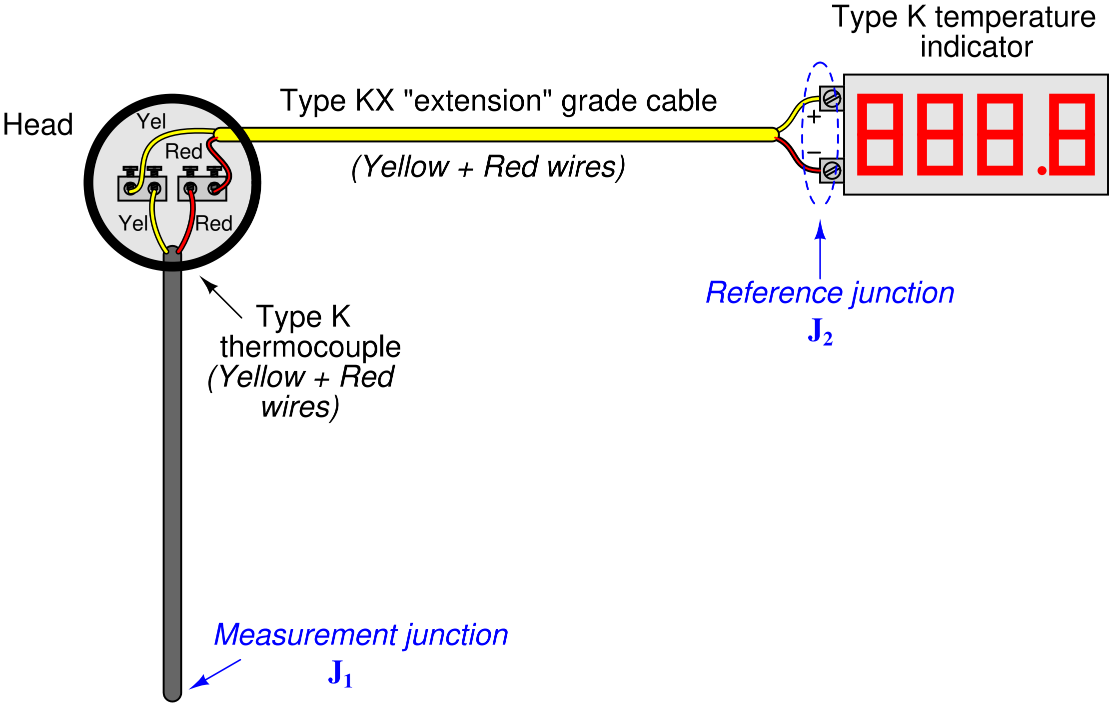


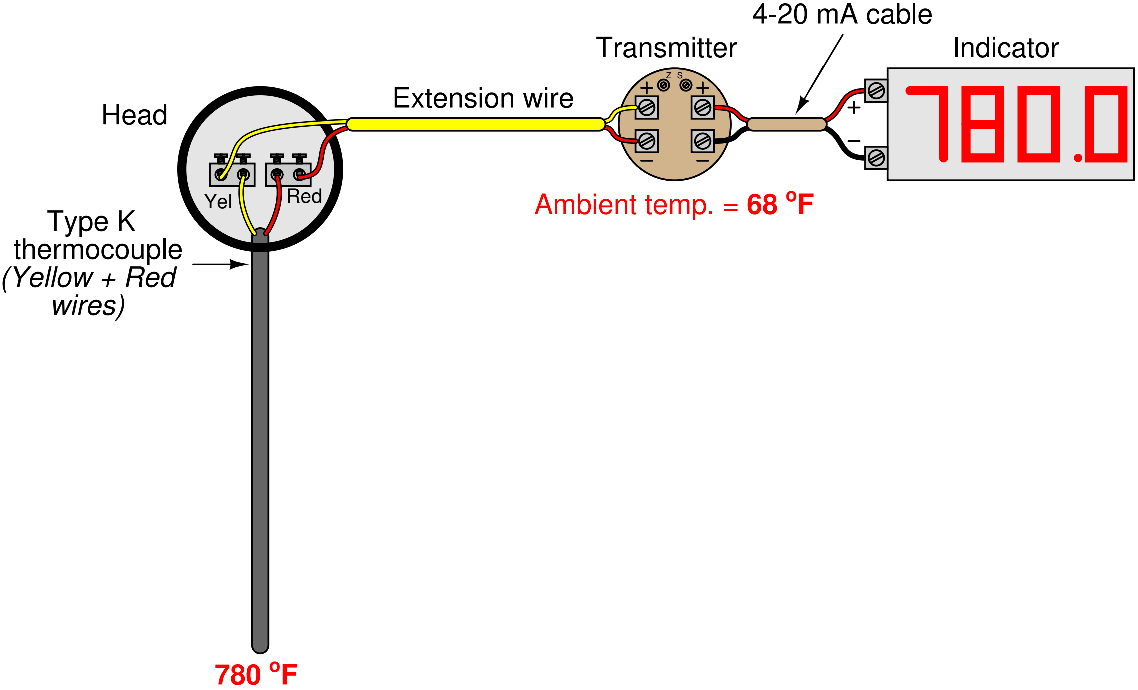
Type K temperature indicator
Yel
Red
+
−
888.8
Type K thermocouple (Yellow + Red wires)
Reference junction
J_2
Internal thermistor senses temperature of reference junction (J_2) to compensate for that junction's effect
Measurement junction
J_1

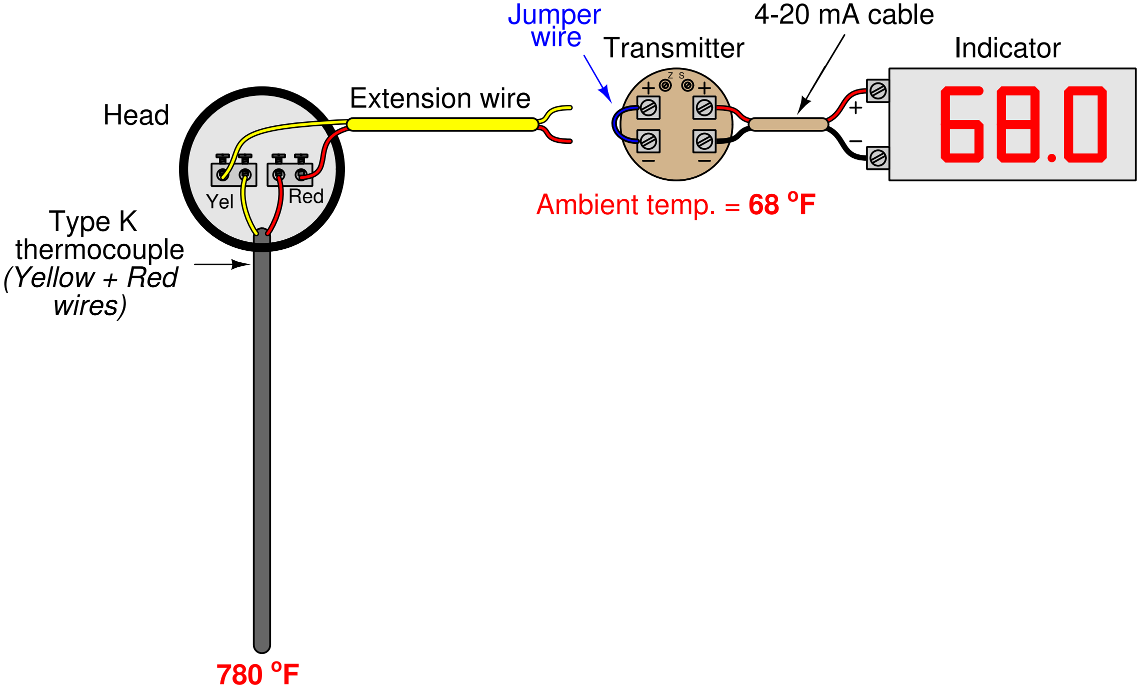

Type K temperature indicator
Copper cable (Red + Black wires)
Head
Red
Blk
Yel
Red
+
−
Reference junction
J_2
Type K thermocouple (Yellow + Red wires)
Thermistor is measuring temperature at the wrong location!
Measurement junction
J_1



Type K temperature indicator
Head
Type K thermocouple cable
(Yellow + Red wires)
Yel
Red
Yel
Red
+
−
Type K thermocouple (Yellow + Red wires)
Reference junction
J2
Measurement junction
J1


Type K temperature indicator
Type KX "extension" grade cable
Head
Yel
Red
Yel
Red
(Yellow + Red wires)
+
−
Reference junction
J_2
Type K thermocouple (Yellow + Red wires)
Measurement junction
J_1

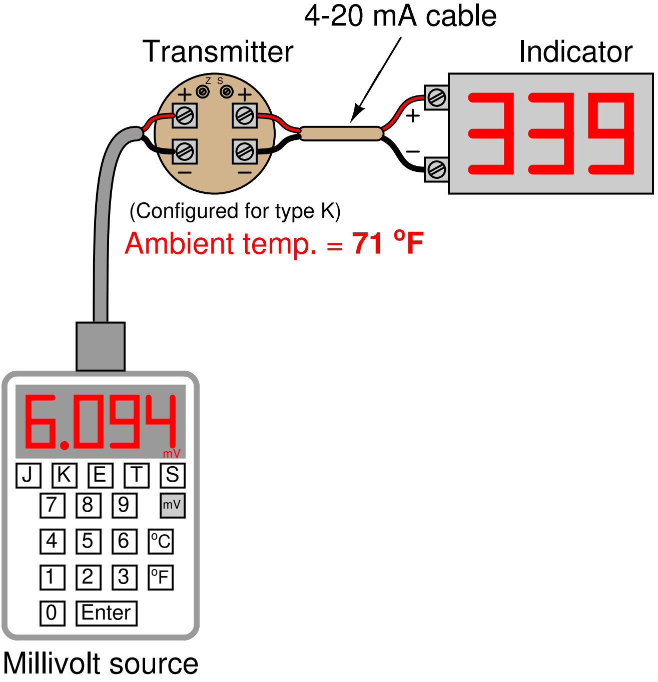

4-20 mA cable
Transmitter
Indicator
Z S
Extension wire
Head
780.0
Yel
Red
Ambient temp. = 68 °F
Type K
thermocouple
(Yellow + Red
wires)
780 °F



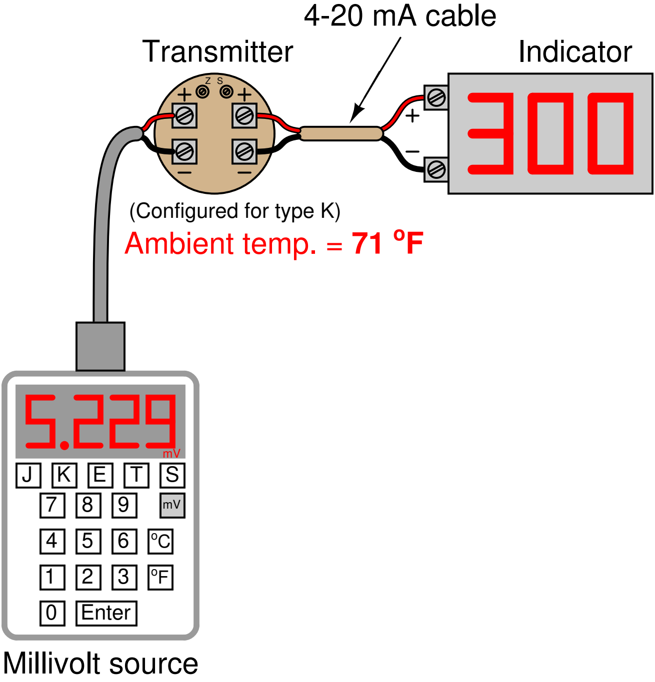
Jumper wire
4-20 mA cable
Transmitter
Indicator
Extension wire
Head
68.0
+
−
z s
Yel
Red
Ambient temp. = 68 °F
Type K thermocouple
(Yellow + Red wires)
780 °F

$$V_{meter} = 0 + V_{rjc}$$

$$V_{meter} = V_{rjc}$$

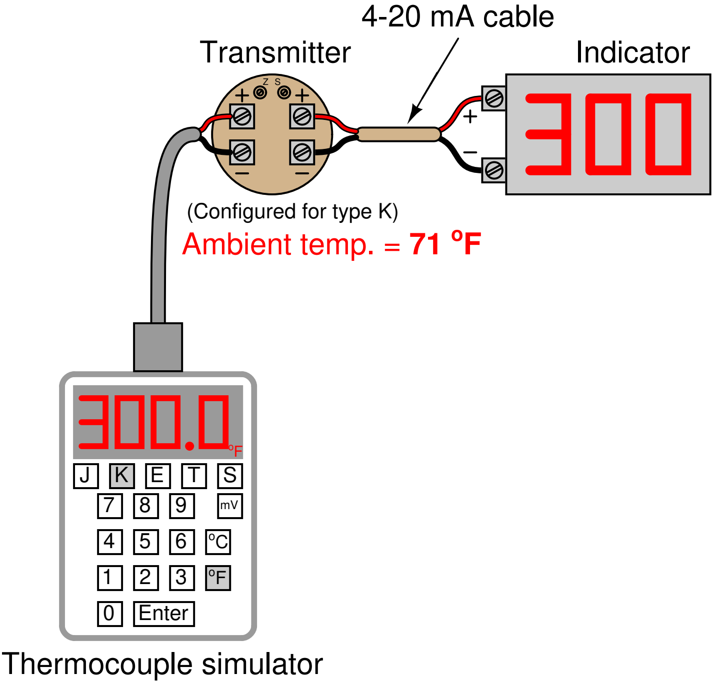


4-20 mA cable
Transmitter
Indicator
Z S
+ +
− −
+
−
339
(Configured for type K)
Ambient temp. = 71 °F
6.094
mV
J K E T S
7 8 9 mV
4 5 6 °C
1 2 3 °F
0 Enter
Millivolt source

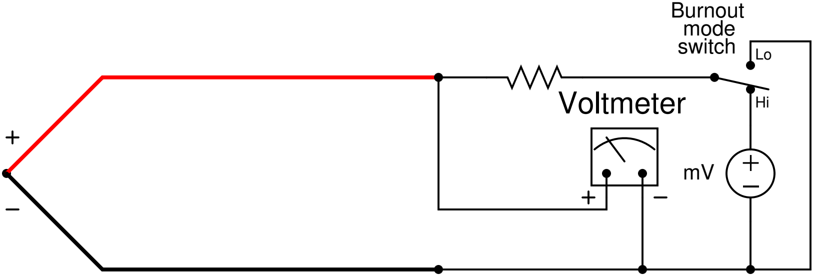

4-20 mA cable
Transmitter
Indicator
Z S
+
+
−
−
300
+
−
(Configured for type K)
Ambient temp. = 71 °F
5.229
mV
J K E T S
7 8 9 mV
4 5 6 °C
1 2 3 °F
0 Enter
Millivolt source


ELECTRICAL INSTRUMENT MAKERS
RUBICON COMPANY
PHILADELPHIA, PA., U.S.A.
OFF
ON
VOLTS
E.M.F.
S.C.
RUBICON COMPANY
PHILADELPHIA
SERIAL NO. 51791

SHEPPARD POTENTIOMETER
TO CALIBRATE
1. DEPRESS STANDARD CELL SWITCH.
2. ADJUST ABOVE CONTROLS TO OBTAIN ZERO GALVANOMETER DEFLECTION.
VOLTS
STANDARD CELL SWITCH
RANGE MULTIPLIER SWITCH
OFF
HIGH SENS.
LOW SENS.
UNITS
TENTHS
HUNDREDTHS


4-20 mA cable
Transmitter
Indicator
Z S
300
(Configured for type K)
Ambient temp. = 71 °F
300.0 °F
J K E T S
7 8 9 mV
4 5 6 °C
1 2 3 °F
0 Enter
Thermocouple simulator


SOURCE
TC Type S
2650.0°F
Int. Ref. 70.8°F ITS-90 14.910mV⎓



Burnout
mode
switch
Lo
Hi
Voltmeter
mV
+
−
+
−

$$\frac{dQ}{dt} = e\sigma AT^4$$

$$\frac{dQ}{dt}$$

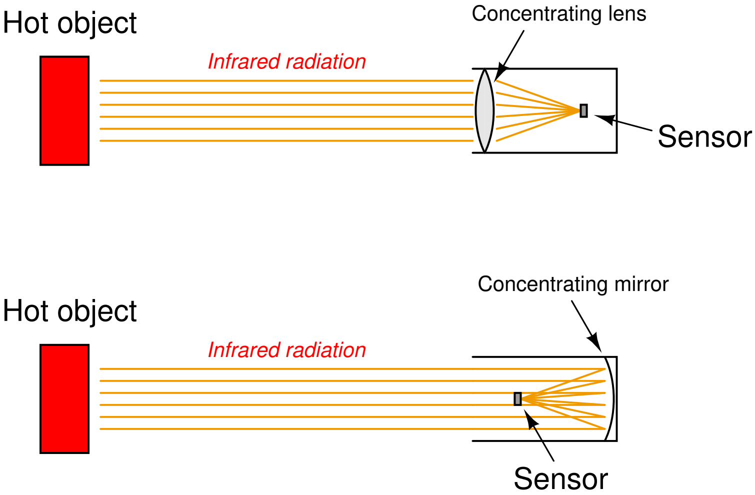
e

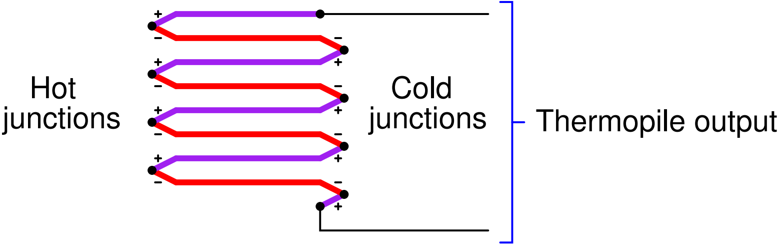
σ

$$10^{-8}$$

4

Two designs of non-contact pyrometer




Hot junctions
Cold junctions
Thermopile output

Target temperature (K)	**Millivolt output**
4144 K	34.8 mV
3866 K	26.6 mV
3589 K	19.7 mV
3311 K	14.0 mV
3033 K	9.9 mV
2755 K	6.6 mV
2478 K	4.2 mV
2200 K	2.5 mV
1922 K	1.4 mV
1644 K	0.7 mV

$$\frac{4144\ \text{K}}{3033\ \text{K}} = 1.3663$$

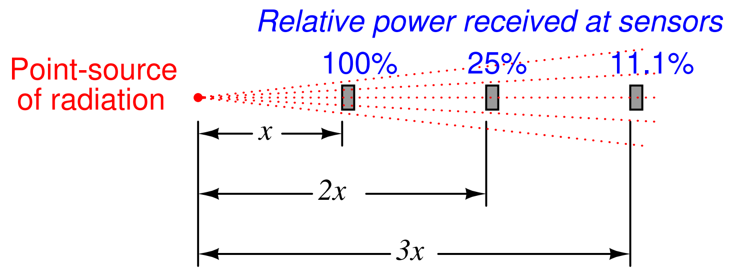
$$\left(\frac{4144\ \mathrm{K}}{3033\ \mathrm{K}}\right)^4 = 1.3663^4 = 3.485$$

$$(3.485)(9.9 \text{ mV}) \approx 34.8 \text{ mV}$$

x

$2x$

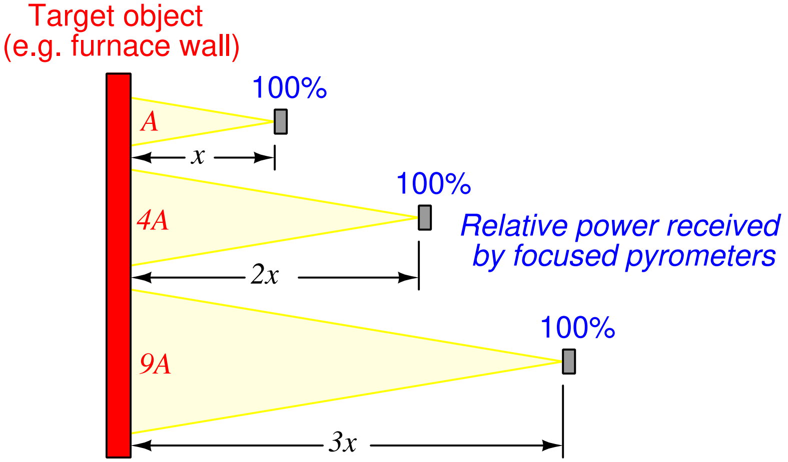
$$3x$$



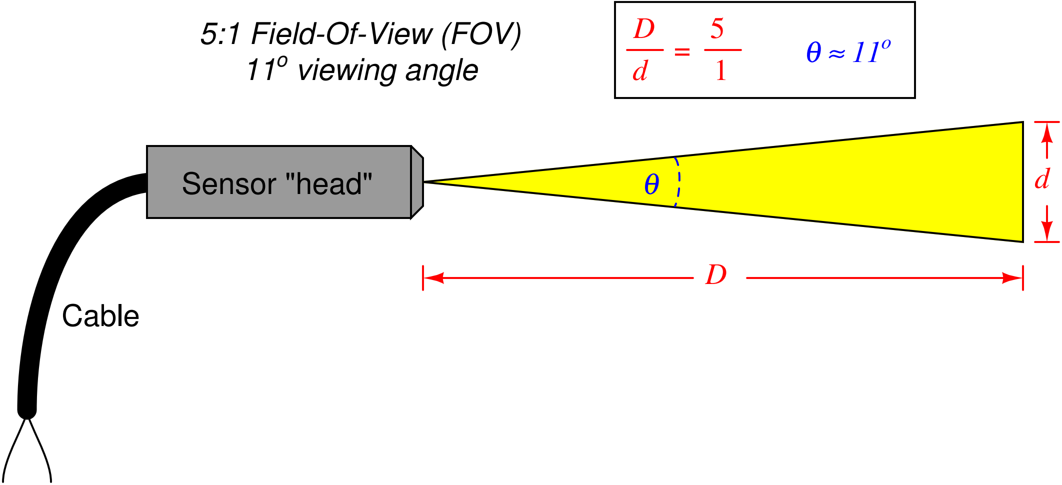
Relative power received at sensors
Point-source
of radiation
100%
25%
11.1%
x
2x
3x

$$A = \frac{\pi D^2}{4}$$

$$A = \pi r^2$$



Target object
(e.g. furnace wall)
100%
A
x
100%
4A
Relative power received
by focused pyrometers
2x
100%
9A
3x


5:1 Field-Of-View (FOV)
11° viewing angle
D/d = 5/1
θ ≈ 11°
Sensor "head"
θ
d
D
Cable

θ

D/d

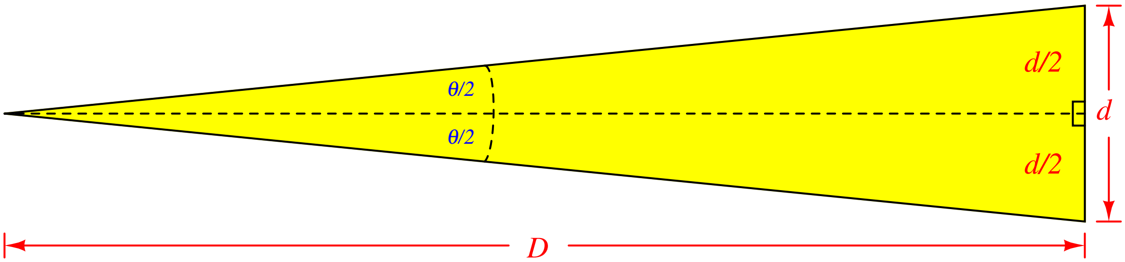
$$\frac{D}{d} = \frac{1}{2\tan\left(\frac{\theta}{2}\right)} \qquad \theta = 2\tan^{-1}\left(\frac{d}{2D}\right)$$

Distance ratio	**Angle** (approximate)
1:1	53^o
2:1	30^o
3:1	19^o
5:1	11^o
7:1	8^o
10:1	6^o

D

$d/2$

$\theta/2$



θ/2
θ/2
d/2
d
d/2
D

$$\tan\left(\frac{\theta}{2}\right) = \frac{d/2}{D} = \frac{d}{2D}$$

$$\tan\left(\frac{\theta}{2}\right) = \frac{d}{2D}$$

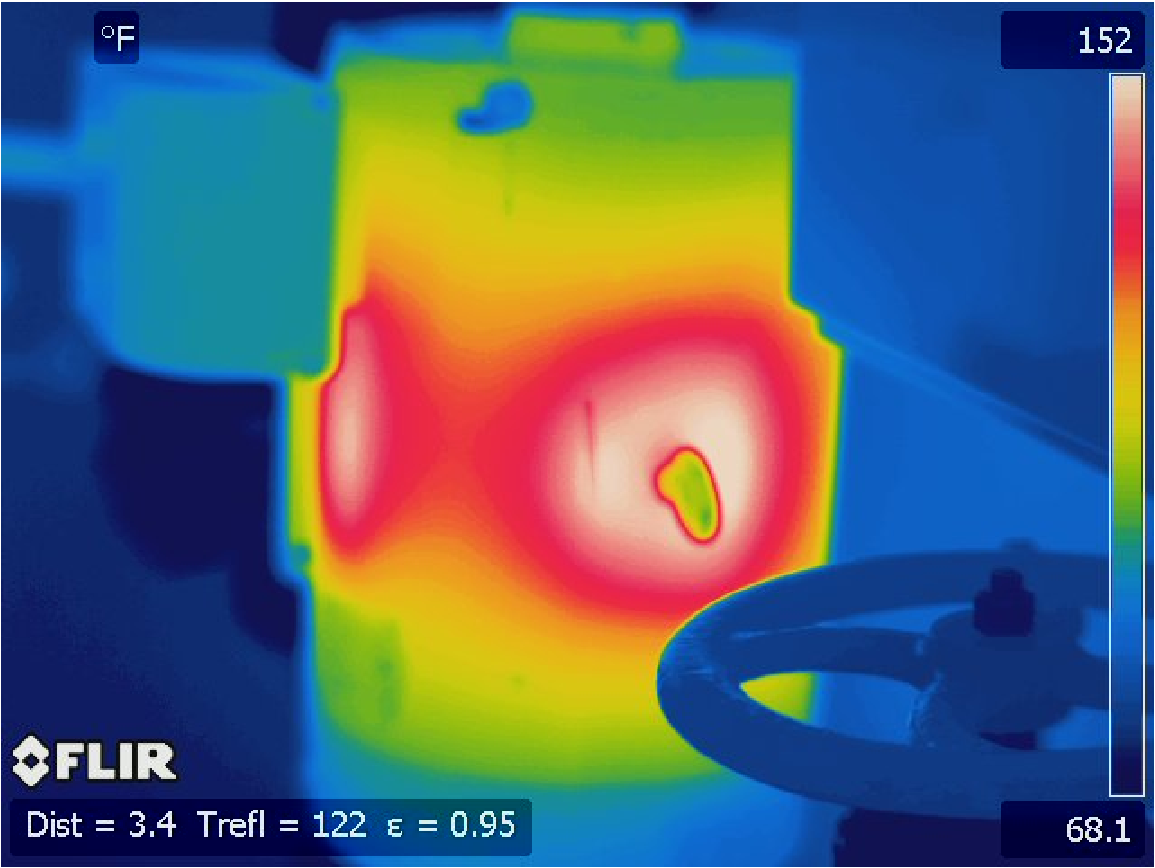
$$\frac{2D}{d} = \frac{1}{\tan\left(\frac{\theta}{2}\right)}$$

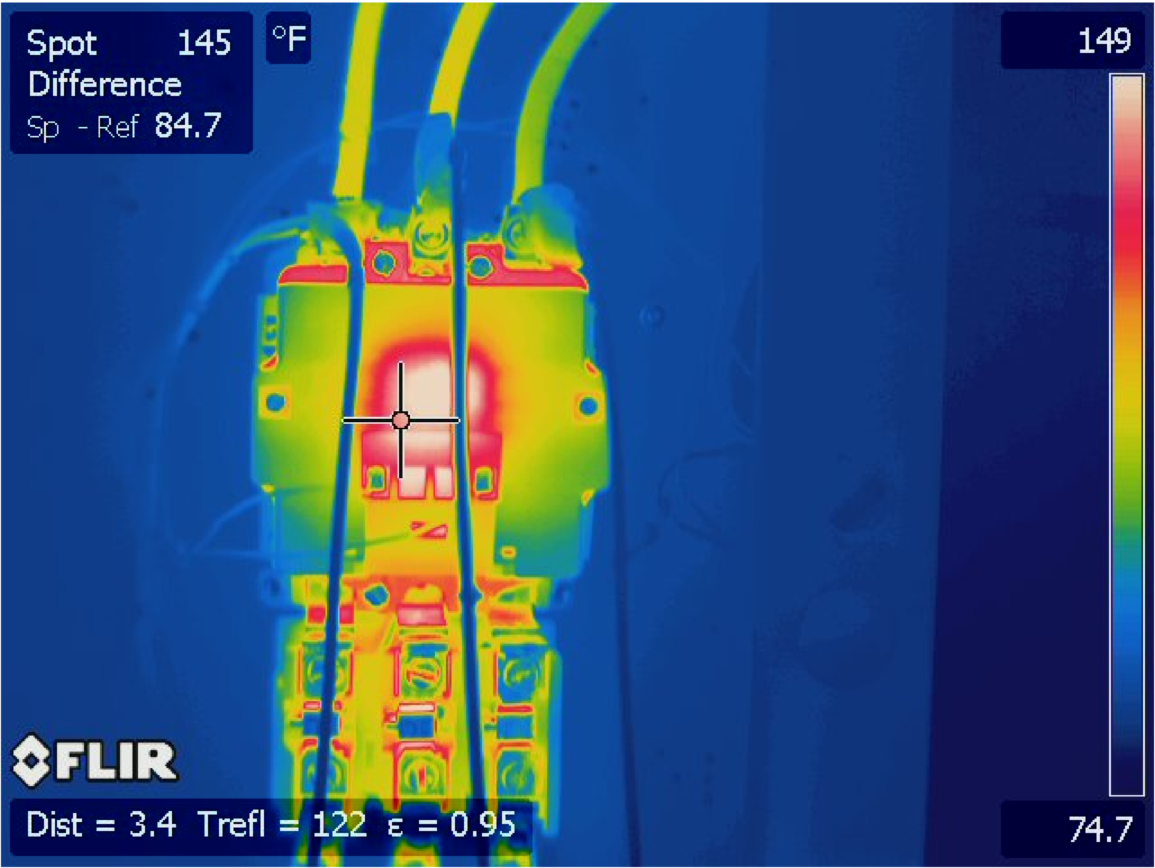
$$\frac{D}{d} = \frac{1}{2\tan\left(\frac{\theta}{2}\right)}$$

$$\tan^{-1}\left[\tan\left(\frac{\theta}{2}\right)\right] = \tan^{-1}\left(\frac{d}{2D}\right)$$

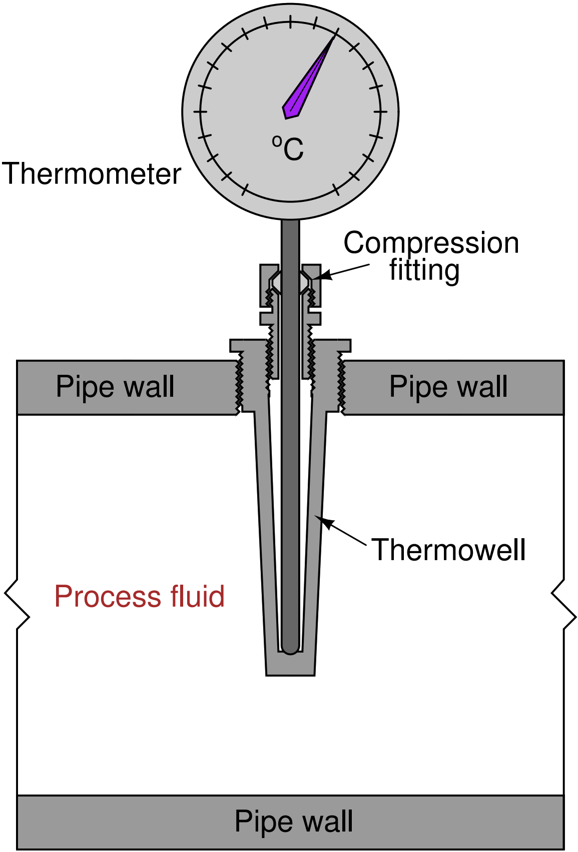
$$\frac{\theta}{2} = \tan^{-1}\left(\frac{d}{2D}\right)$$

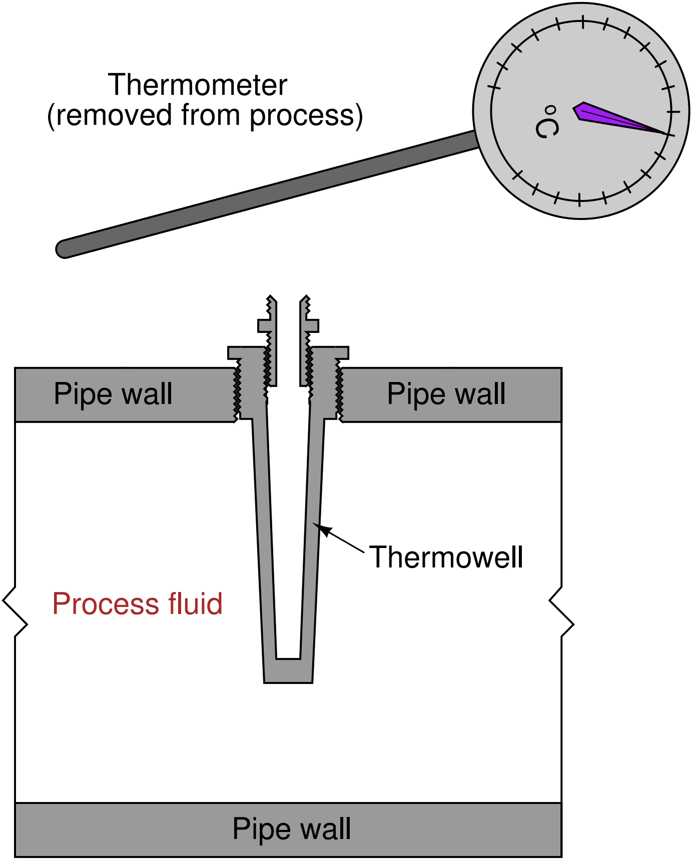
$$\theta = 2\tan^{-1}\left(\frac{d}{2D}\right)$$


°F
152
FLIR
Dist = 3.4 Trefl = 122 ε = 0.95
68.1


Spot 145
Difference
Sp - Ref 84.7
°F
149
FLIR
Dist = 3.4 Trefl = 122 ε = 0.95
74.7


Spot 68.4
°F
68.6
FLIR
Dist = 1.0 Trefl = 68.0 ε = 0.95
61.3


Thermometer
°C
Compression fitting
Pipe wall
Pipe wall
Thermowell
Process fluid
Pipe wall



Thermometer
(removed from process)
°C
Pipe wall
Pipe wall
Thermowell
Process fluid
Pipe wall


$$PV = nRT$$

$$\frac{dQ}{dt} = e\sigma AT^4$$

$\mathcal{T}$

5τ