Laboratory 6: Using Strain Measurements to Measure the Pressure Inside of a Full Soda Can

- ***Lab Objectives:***

  -- Understand Stress / Strain Relationships

  -- Strain Gauge Installation and Bonding

  -- Use of Wheatstone Bridge for Strain Gauge Conditioning

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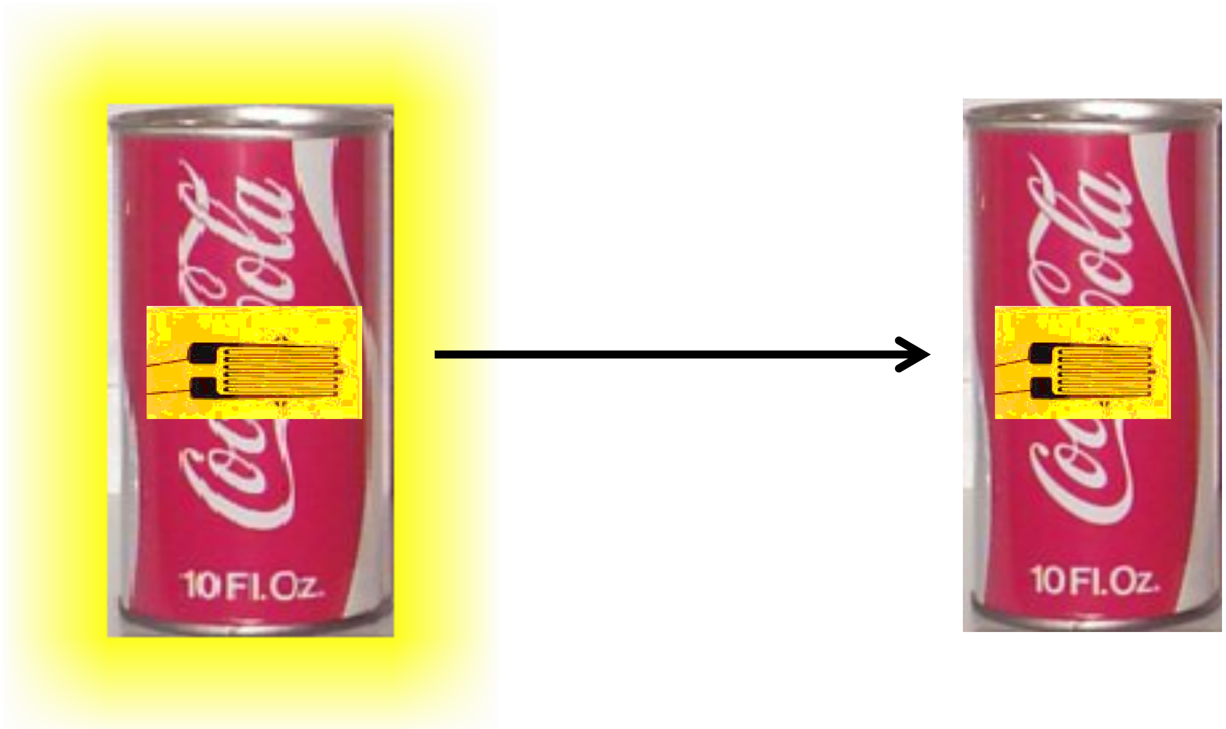
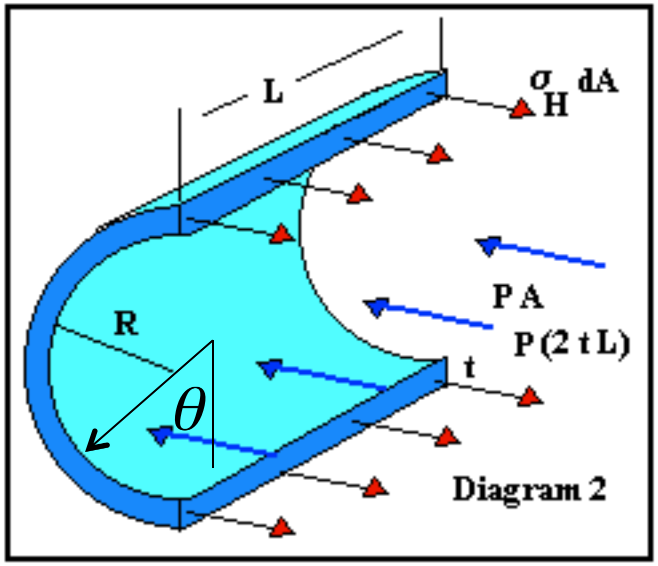
You are going to use strain measurements to infer the pressure in the Soda can



Full   Empty

- Soda can contracts as pressure is released

Circumferential Stress on a Cylindrical Thin-Walled Pressure Vessel (1)



Pressure force on wall →

$$\int_0^{\pi}\left[p_{internal} - p_{external}\right]R\sin\theta d\theta =$$

$$-\left[p_{internal} - p_{external}\right]\cdot R\cdot\cos\theta\Big|_0^{\pi} = \left[p_{internal} - p_{external}\right]\cdot 2R\cdot L$$

force balance across section →

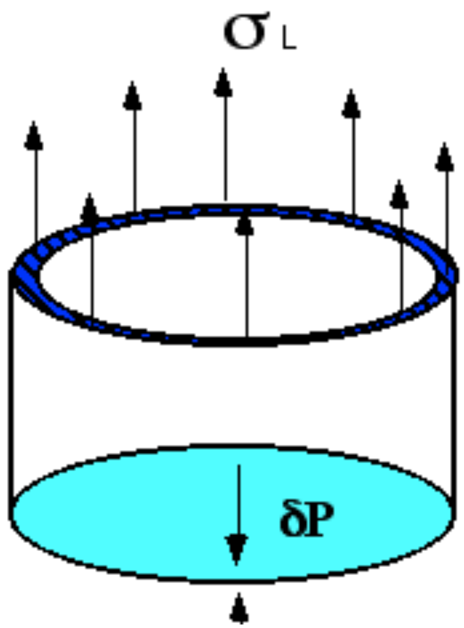
$$\left[p_{internal} - p_{external}\right]\cdot 2R\cdot L = 2\cdot\sigma_H\cdot t\cdot L$$

$$\rightarrow \sigma_{Hoop} = \left[p_{internal} - p_{external}\right]\cdot\frac{R}{t} \rightarrow \boxed{\sigma_H = \delta p_{wall}\cdot\frac{R}{t}}$$

- ***Circumferential Stress Calculated by equating the force due to internal gas/fluid pressure with the force due to the Circumferential stress:***

$$\delta p_{wall} \rightarrow \text{"gauge pressure"}$$

Longitudinal Stress on a Thin Walled Can (1)



Area at can end ***Area of "cut" wall***

$$\delta p_{end} \cdot \pi \cdot R^2 = \sigma_L \cdot 2\pi \cdot R \cdot t \rightarrow \sigma_L = \frac{\delta p_{end} \cdot \pi \cdot R^2}{2\pi \cdot R \cdot t}$$

$$\rightarrow \sigma_L = \frac{\delta p_{end} \cdot R}{2 \cdot t} \rightarrow \delta p_{end} = \delta p_{wall} \rightarrow \boxed{\sigma_L = \frac{1}{2}\sigma_H}$$

- ***Longitudinal Stress***

Calculated by equating the force due to internal gas/fluid pressure with the force due to the longitudinal stress:

$$\delta p_{wall} \rightarrow \text{"gauge pressure"}$$

Strain Measured by “this” gauge (1)

$$\varepsilon_H = \frac{\sigma_H}{E} - \nu \frac{\sigma_L}{E}$$

- For an aluminum can assume …

E: Elastic Modulus ~ 70 gigapascals

V: Poisson Ratio: ~ 0.35

$$\varepsilon_H = \frac{\sigma_H}{E} - \nu \frac{\sigma_L}{E} \rightarrow \sigma_L = \frac{1}{2}\sigma_H$$

$$\rightarrow \varepsilon_H = \frac{\sigma_H}{E} - \frac{\nu}{2}\frac{\sigma_H}{E} = \frac{\sigma_H}{E}\left(1 - \frac{\nu}{2}\right)$$

Strain Measured by "this" gauge (2)

$$\sigma_H = \delta p \cdot \frac{R}{t} \rightarrow \delta p = \frac{t}{R} \cdot \sigma_H \rightarrow \sigma_H = \frac{E}{\left(1 - \frac{\nu}{2}\right)} \cdot \varepsilon_H$$

$$\delta p = \frac{t}{R} \cdot \sigma_H = \frac{t}{R} \cdot \frac{E}{\left(1 - \frac{\nu}{2}\right)} \cdot \varepsilon_H \rightarrow \boxed{p_{soda} = 2 \cdot \frac{t}{D} \cdot \frac{E}{\left(1 - \frac{\nu}{2}\right)} \cdot \varepsilon_H}$$

$\rightarrow \varepsilon_H$ = *compressive strain on empty can*

$\rightarrow p_{soda}$ *is the "gauge" pressure reading*

$\rightarrow D$ = *soda can diameter(full)....nom* = 6.553*cm*

$\rightarrow t$ = *soda can wall thickness...nom* = 0.0109*cm*

$\rightarrow E$ = *Elastic modulus*

$\rightarrow \upsilon$ = *Poisson Ratio*

Strain Measured by “this” gauge (3)

$$p_{soda} = 2 \cdot \frac{t}{D} \cdot \frac{E}{\left(1 - \frac{\nu}{2}\right)} \cdot \varepsilon_H$$

What can we expect here?

…. Lets go with a range from … 35-60 psi (~240 – 415 kPa)….. Depending on the soda)as bottled with CO_2 concentrations) and room temperature

- For an aluminum can assume …

E: Elastic Modulus ~ 70 gigapascals

V: Poisson Ratio: ~ 0.35

Students …. You! do the calculation to predict the range of expected strain to be measured!

Typical Soda Can Dimensions … ***t = 0.01 cm***
D = 6.0 cm

http://en.wikipedia.org/wiki/Beverage_can#Standard_sizes

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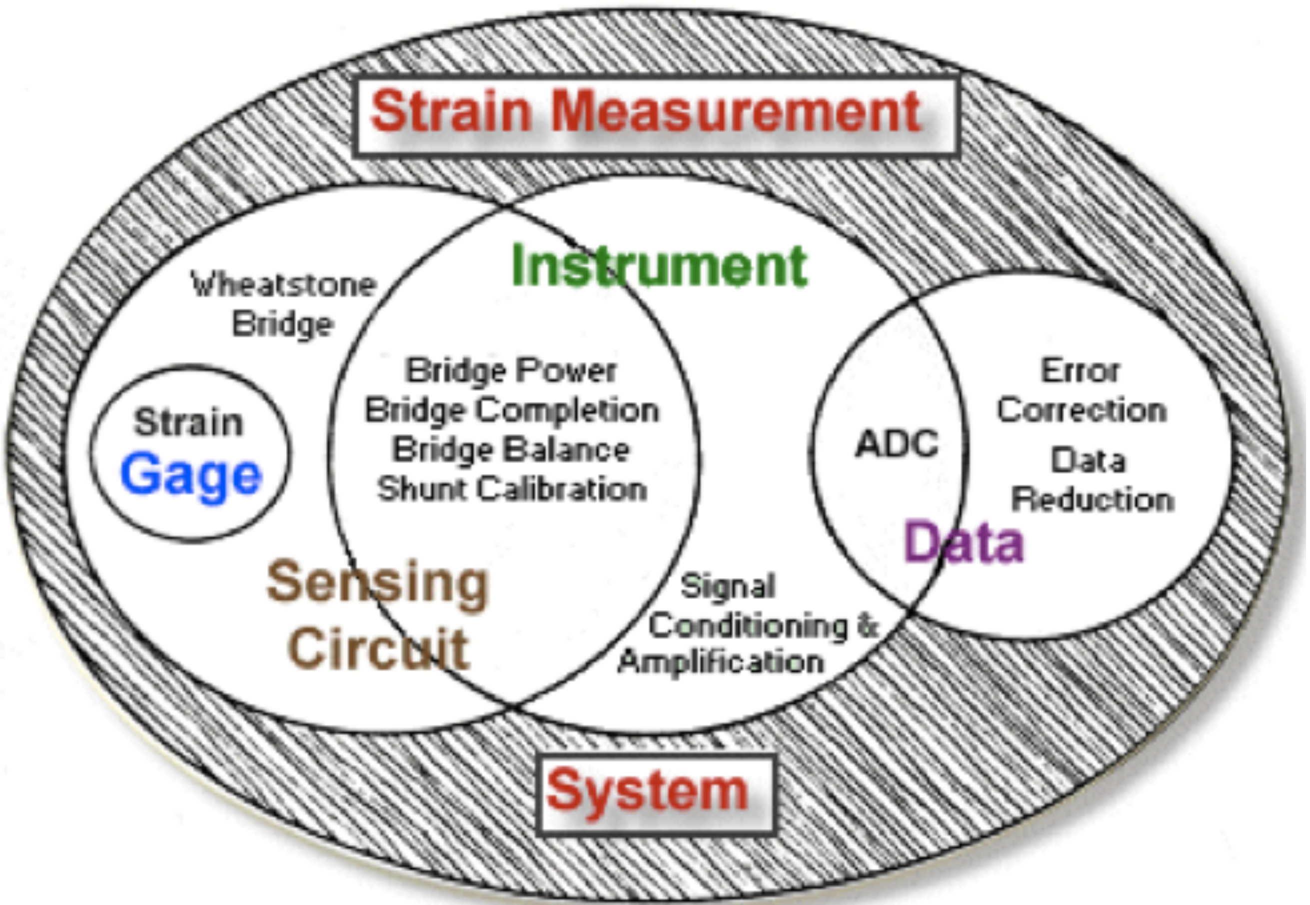
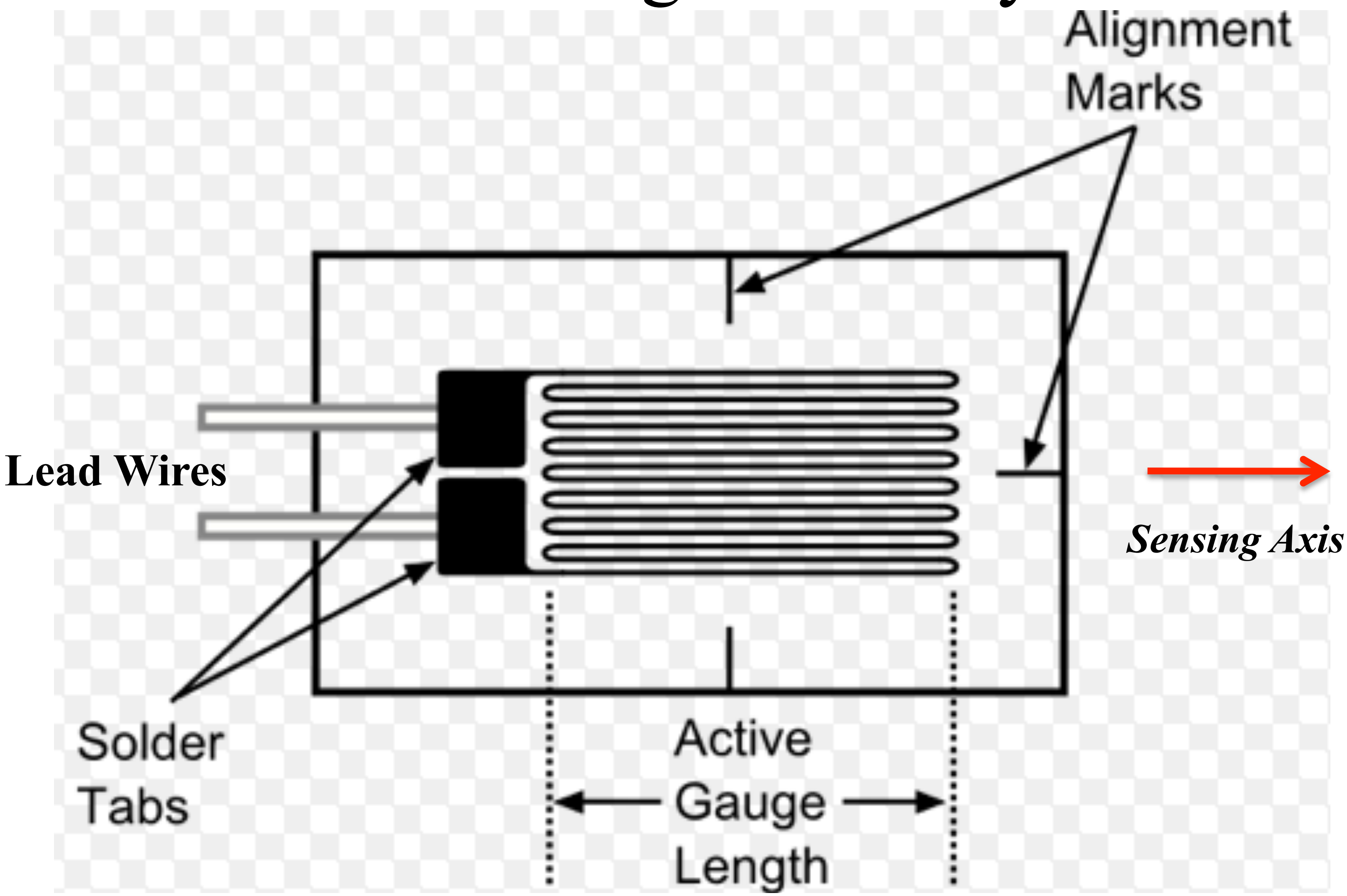
Some Reference Examples

Bibliographic Entry	Result (w/surrounding text)	Standardized Result
Kimmey, R. Pepsi Brooklyn Bottling Center. Fax. 25 May 2000	"At 60 F, the gauge pressure in the container is approximately 40 psi"	276 kPa
Murphy, P., E. Klages & L. Shore. *The Science Explorer: Family Science Experiments from the World's Favorite Hands-On Museum*. 5.	"A refrigerated can of 7UP® has an internal pressure of about 30 pounds per square inch."	207 kPa
Bates, Paul W. History of the Beverage Can. The Museum of Beverage Containers and Advertising.	"A much sturdier container than that used for food products was required to withstand the 80 to 90 psi pressure of pasteurization, In contrast to the 25 to 30 psi used in food processing."	< 550 ~ 620 kPa
Sowell, Jeff. Consumer Affairs Specialist. Coca-Cola Company. Letter. 31 May 2000.	"For example, the table shows a typical can of Coca-Cola classic with 3.7 volumes of carbon dioxide dissolved in the product at a temperature of 75F has an internal pressure of about 55 psi."	380 kPa
Kieran, Kelly. Re: what is the average pressure in a 12 oz. soda can? Mad Scientist Network. 3 February 2000.	"To give you a quick example, let's say that the soda was carbonated to 3.0 volumes of CO2 and it has been sitting in your refrigerator so it's around 40 degrees F. The pressure inside the can will be roughly 17 psig (pounds per square inch, gauge) above atmospheric pressure. If you let the can warm up on the counter so its temperature increases to 70 F or so, the pressure inside the can will have increased to about 36 psig."	117 kPa (4 °C, when canned) 248 kPa (21 °C, at room temperature)

Making Strain Measurements



Strain Gauge Anatomy



Bonding Strain Gauge to the Soda Can (1)

- Be Sure your strain axis is Aligned along Circumferential Direction

- For reliable strain measurement you Need to be sure that the gauge is securely Bonded to the can so that any movement In the sidewall is faithfully transmitted to the gauge

- Detailed bonding instructions listed Starting on page 17 in *"Student Manual for Strain Gage Technology"*

- *PDF file is linked on section 9 web page*

Bonding Strain Gauge to the Soda Can (2)

- ***M-Bond 200 …*** Costs $85 a bottle .. We can't afford this .. Soooo we are using a cheap "super glue" substitute! … good luck!

  - *methyl -2-cyanoacrylate compound.*

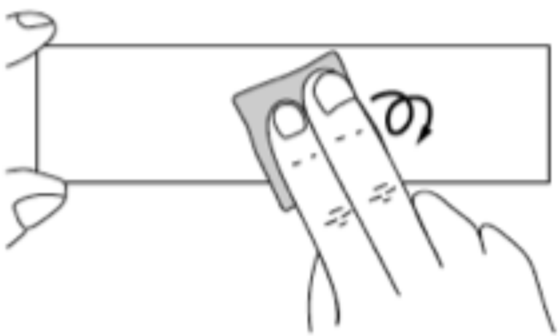
See Appendix I for the Industry Standard Procedure for Bonding Strain Gauges to Test Specimens

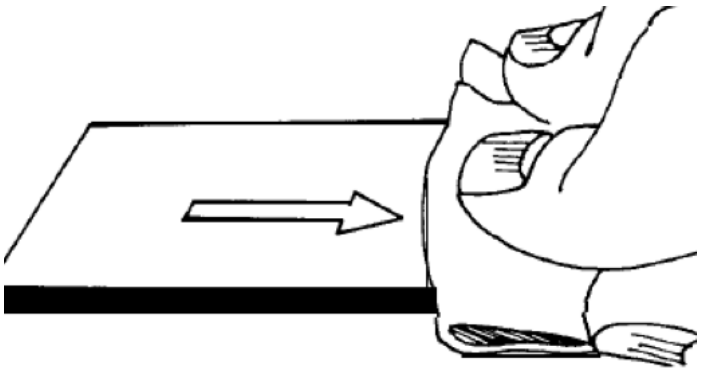
As a cost and time saving measure, we are going to follow a more simple"expedited" process for installing and connecting the gauges

The strain gauges used for this lab will be "pre-wired" with lead wires.

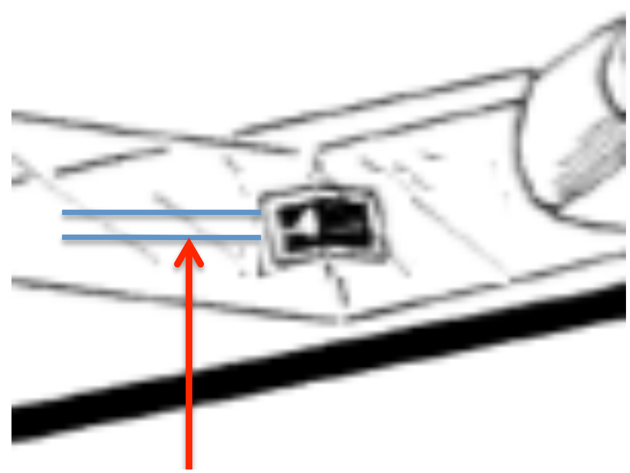
Application of the gauges is pretty straightforward .. see procedure on following pages

Bonding Strain Gauge to the Soda Can (3)



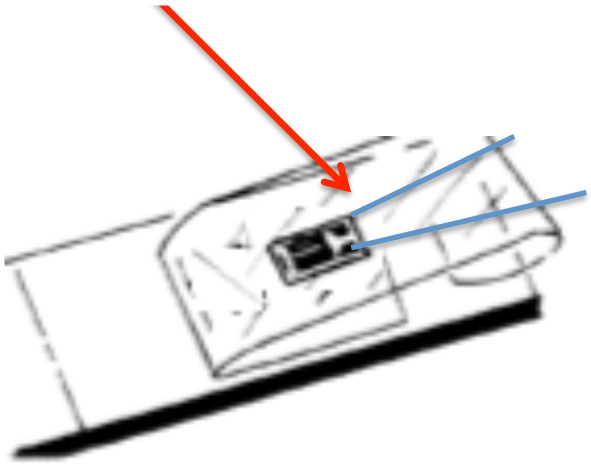


1. **Polish the installation area well with the provided fine-grit sand paper.**
2. **Clean the area using cotton swap and isopropyl alcohol**
3. **Place strain gauge "bonding surface" down (lead wires up) on table top**
4. **Place clear adhesive tape over gauge, edges parallel to gage main sensing axis**

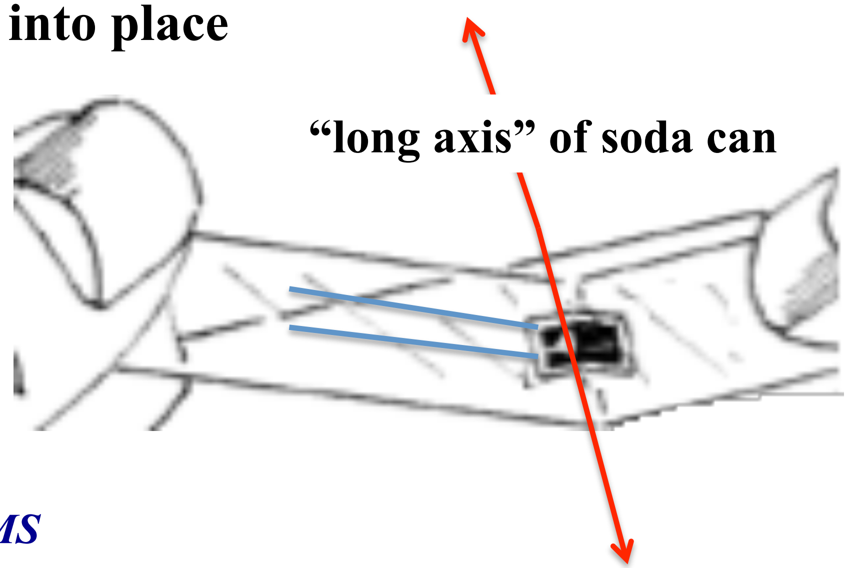


Bonding Strain Gauge to the Soda Can (4)

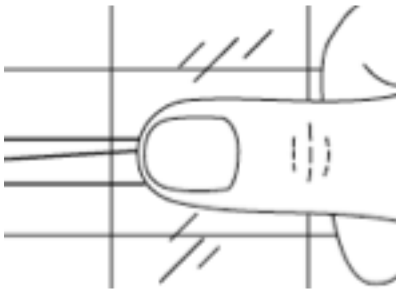
Lead Wires



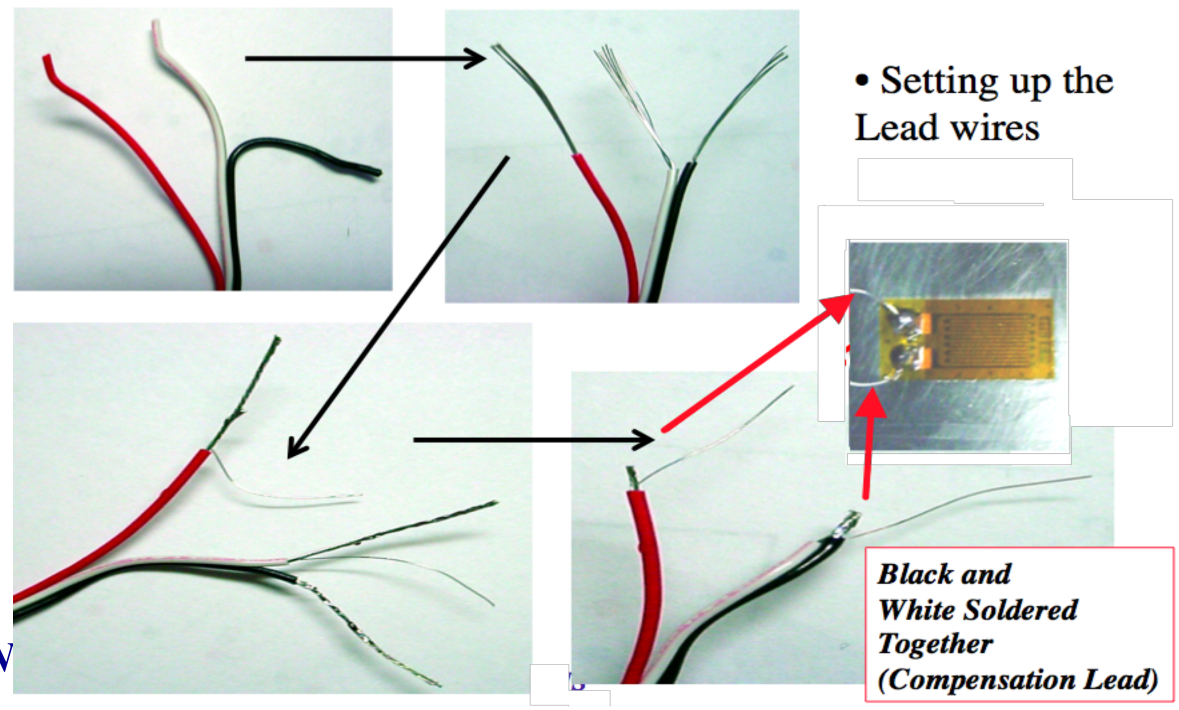
5. **Pull back tape exposing lower bonding surface**
6. **Apply a "tiny amount" of adhesive (super glue) … a lot less than you are inclined to use!**
7. **Carefully align tape edges perpendicular to "long axis" of can, press the "glue-side" of the gauge down, and smooth into place**



Bonding Strain Gauge to the Soda Can (5)



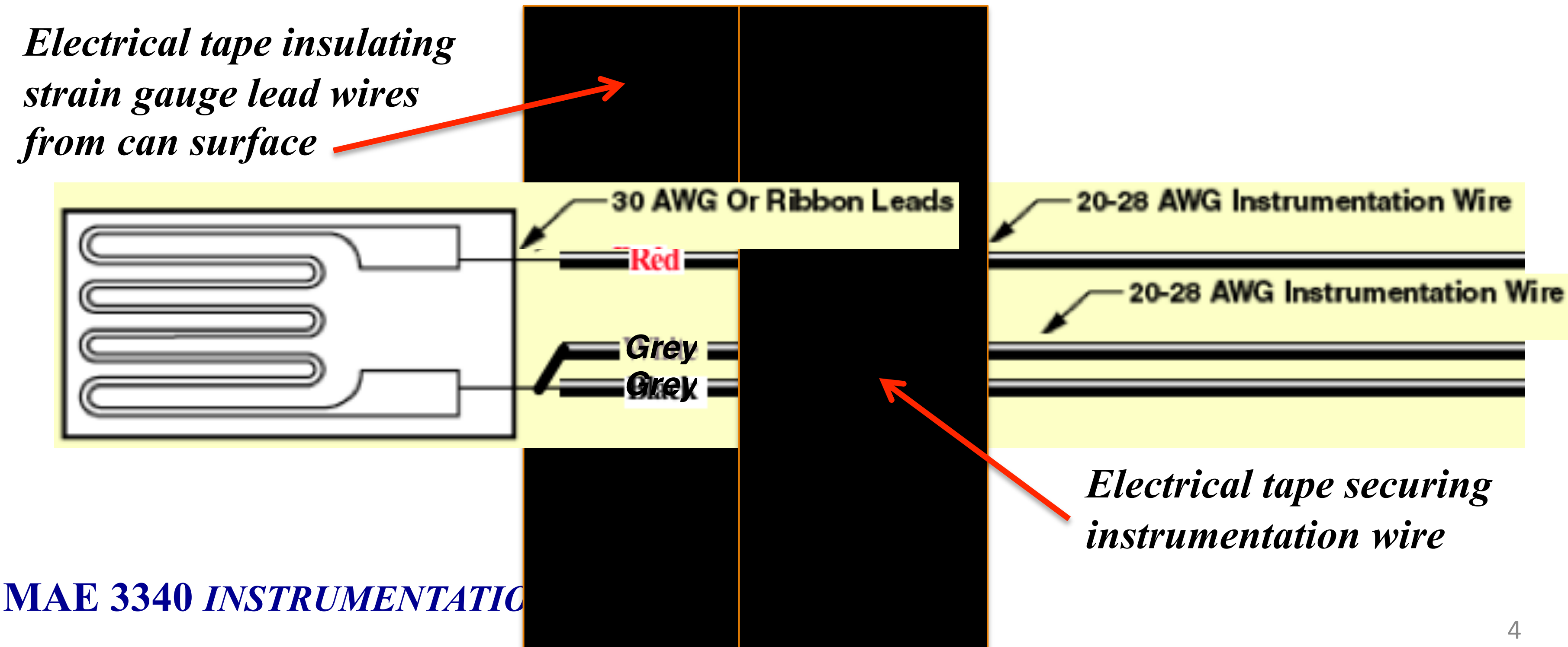
8. **After glue has set appropriately! Gently but firmly pat the gauge ! into place!**
9. **Carefully! Pull back the tape exposing the non-bonded gauge with sensing axis perpendicular to the "long axis" of the can.**
10. **Solder the three lead wire connections to the two strain gauge leads as shown below**



Bonding Strain Gauge to the Soda Can (6)

11. **Place TWO layers of black electrical tape on can, under the exposed (un-insulated) strain gauge lead wires. Tape acts as electrical insulator from soda can's metallic surface**

12. **Secure wire leads to can using additional runs of electrical tape. Do NOT pull strain strain gauge lead wires tight .. Should be considerable "slack" in the lead wires. …. This installation provides "strain relief" to gauges.**



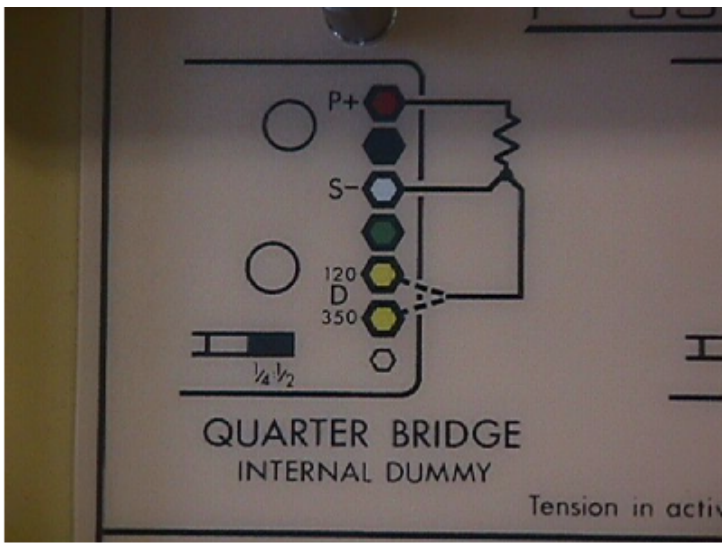
Bridge Completion for Strain Gauge

- Will Use Vishay Model P-3500 Portable Strain Indicator

For these measurements

http://www.vishay.com/

- Quarter-Bridge setup

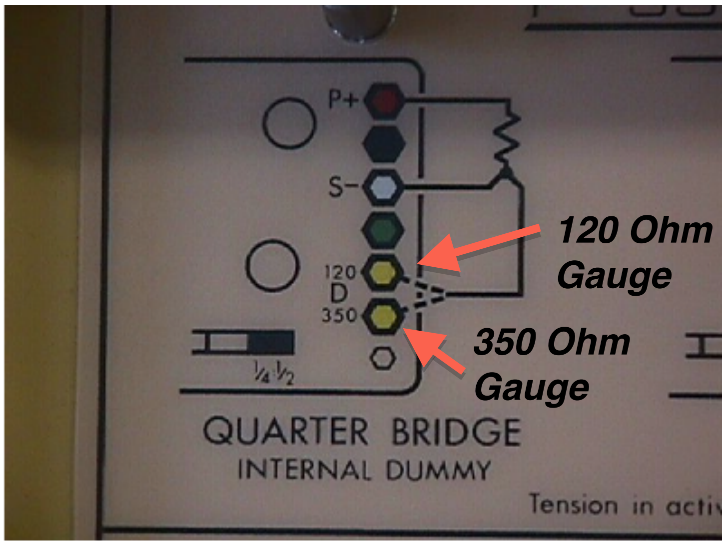


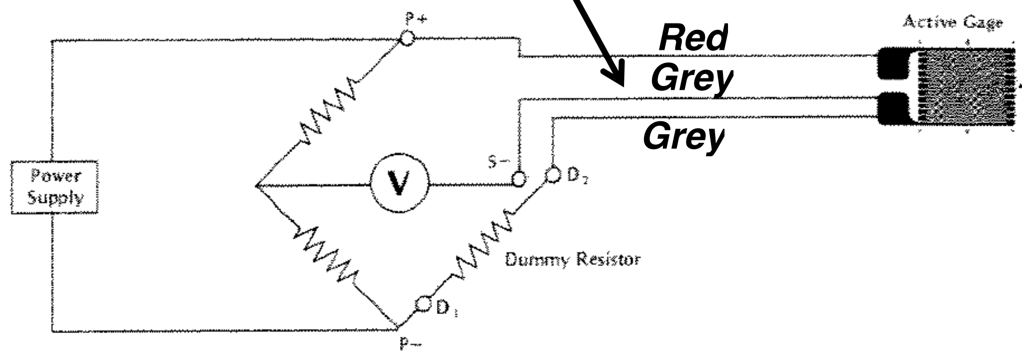
for 120 Ohm Strain Gauges …

Connect the red lead wire from the gage to the P+ terminal on the strain indicator, the white lead wire to the S- terminal and the black leadwire to the D120 terminal. These connections create a quarter bridge circuit by pairing the gage with a internal "dummy" resistor. Make sure that the bridge switch indicates a quarter bridge arrangement.

Bridge Completion /Signal Conditioning (2)

- Quarter-Bridge setup
- Two wires for wire resistance compensation





Three-wire circuit for single active gage (quarter bridge)

Connect the red lead wire from the gage to the P+ terminal on the strain indicator, the ~~white~~ **Grey** lead wire to the S- terminal and ~~the black~~ **Other Grey** leadwire to the D120 **Or D350** terminal. These connections create a quarter bridge circuit by pairing the gage with a internal "dummy" resistor. Make sure that the bridge switch indicates a quarter bridge arrangement.

Bridge Completion /Signal Conditioning (2)

- **Quarter-Bridge setup**
- **Bridge excitation is 2 Vdc**
- **Analog Output:**

Linear ±2.50V max. Adjustable from 40 μV/με to 440 μV/με, nominal.

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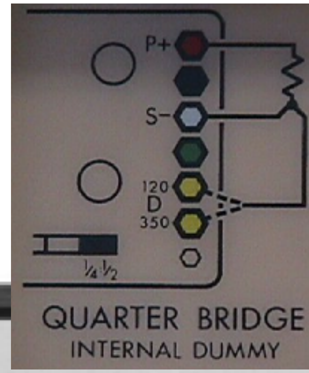
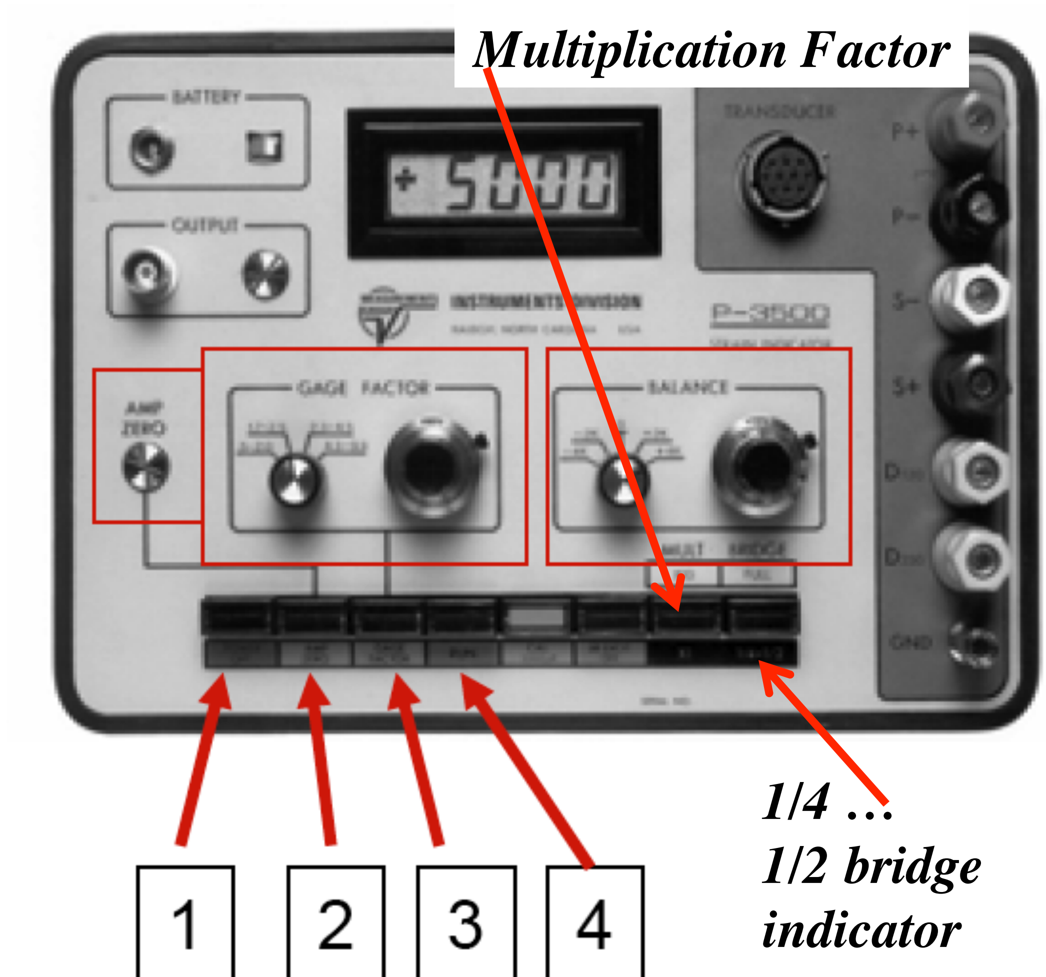
Vishay P-3500 Control Panel



Reading the Strain Indicator

1. Turn on P-3500 strain measurement system
2. Push in and check Amp Zero setting; if it is off from zero adjust using silver knob
3. Push in Gage Factor pushbutton and dial in gage factor; lock the settings.
4. Set instrument to run and zero instrument
5. Output is in Microstrains



Amplified Analog Strain Output from Vishay

Adjustable from 40 μV/με to 440 μV/με, nominal.

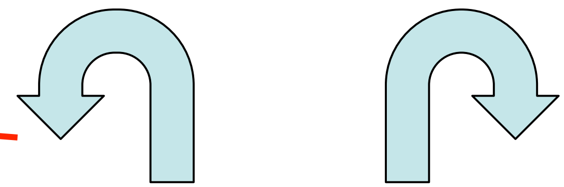
Analog Output: ***Page 3 of Vishay Manual***

Linear ±2.50V max. Adjustable from 40 μV/με to 440 μV/με, nominal. Output load 2 KΩ min. Bandwidth, DC to 4 kHz, -3 dB nominal. Noise: Less than 400μV rms at 40 μV/με output level.

Analog Output from the *Vishay Box (2)*

- **Amplified Analog Output:**

Adjustable from 40 µV/µε to 440 µV/µε, nominal.



40 µV/µε **440 µV/µε**

- **Analog Output (AO):**
Linear ±2.50V max.
Adjustable from 40 µV/µε to 440 µV/µε, nominal.

- ***Set AO for for maximum sensitivity***

3.15 ANALOG OUTPUT

The ANALOG OUTPUT is accessible via the front panel BNC connector. See Section 2.0 for output specifications.

3.16 ANALOG OUTPUT Level Control

The ANALOG OUTPUT level is variable over an 11:1 range by the fingertip adjustable level control. The control is operated by pressing lightly with the fingertip and rotating until the desired level is obtained.

Analog Output from the *Vishay Box (3)*

- **Amplified Analog Output:**

At maximum sensitivity ….. V_{out} = 440 μV/με, nominal.

±2.5V output from Vishay AO →

$$-2.5V = -2.5\times10^{6}\mu V \rightarrow \frac{-2.5\times10^{6}\mu V}{440\mu V/\mu\varepsilon} = -5682\mu\varepsilon_{(conpression)}$$

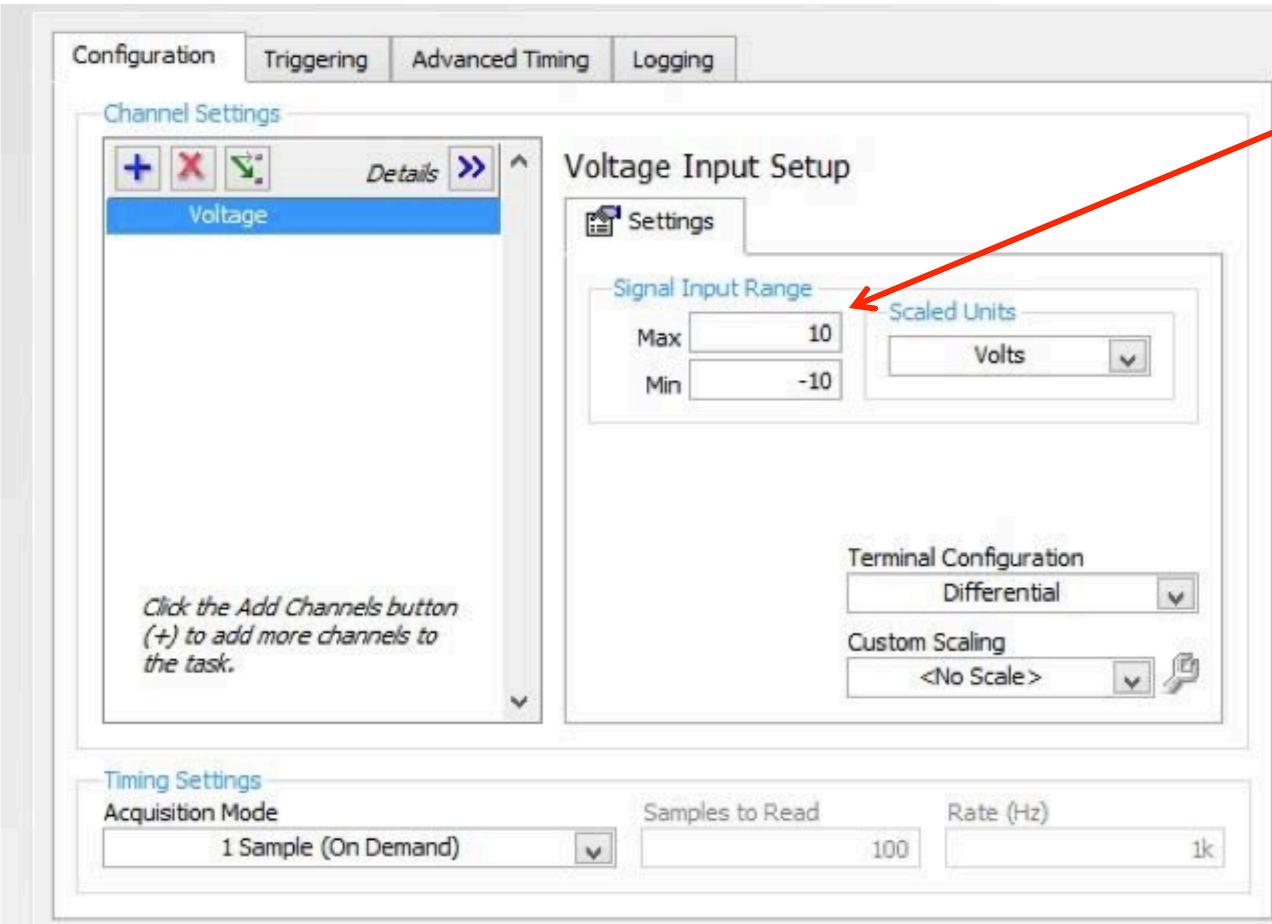
$$2.5V = 2.5\times10^{6}\mu V \rightarrow \frac{2.5\times10^{6}\mu V}{440\mu V/\mu\varepsilon} = 5682\mu\varepsilon_{(tension)}$$

$$\boxed{\mu\varepsilon = 2272.73\cdot\left(V_{out} - V_0\right)} \rightarrow V_0 = zero\ reading\ with\ no\ strain$$

Analog Output from the *Vishay Box (4)*

- **Amplified Analog Output:**

…. Modify your VoltMeter VI from Lab 2 to Set up MyDAQ to read Vishay Box Output on ACH0 … Create a new task .. Select MyDAQ from Menu

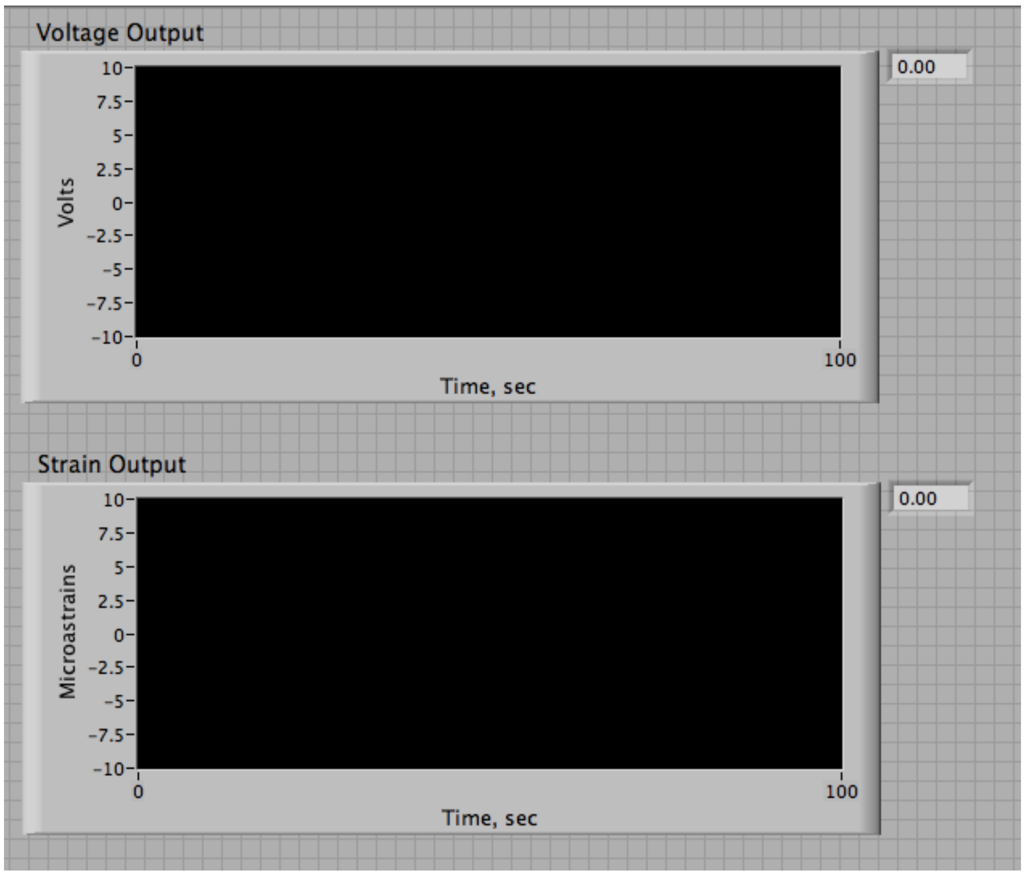


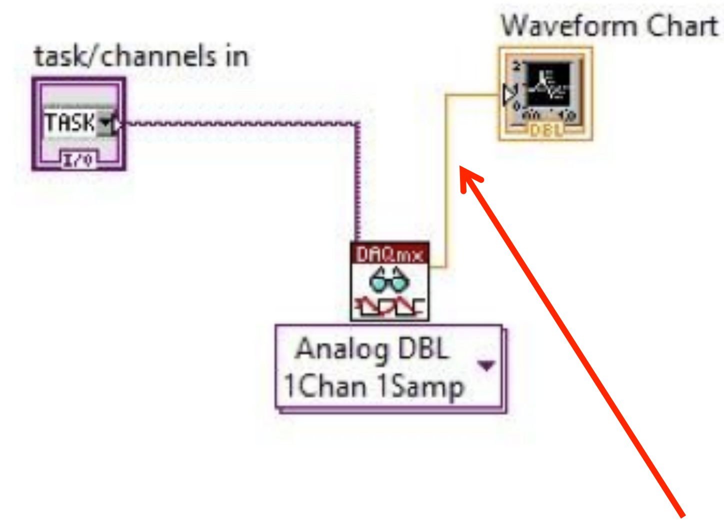
Set min/max voltage range to $\pm$ 2.5 V dc

You will need to modify your to VI to select the MyDAQ ACH0

Analog Output from the *Vishay Box* (5)

- **Modify your Volt Meter VI from Lab 2 …. To also display microstrains based on conversion from previous slide … add strip chart indicator to front panel to also display microstrains strains ….**



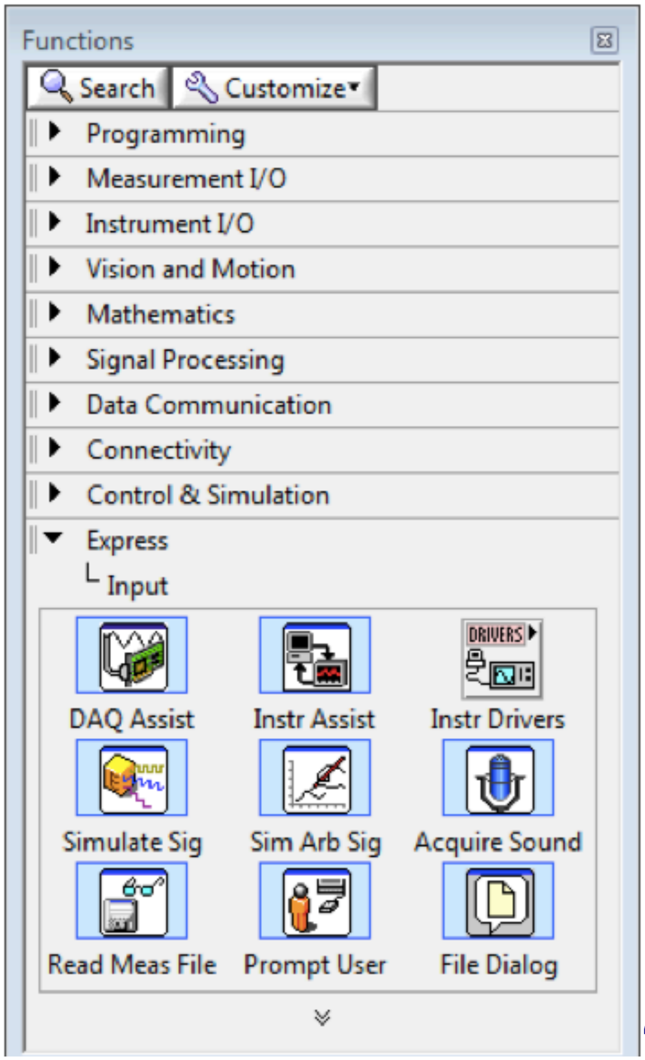


Insert Appropriate Multiplier Here

You will need to modify your VI to select the MyDAQ ACH0 … easiest method is to use DAQAssistant

VI Programming Procedure (1)

- Modify VI from lab 2 to acquire Analog In CHANNELS from the MyDAQ
- Easiest method is to use the DAQ assistant



- The DAQ Assistant Express VI can be found on the Functions palette by going to Express » Input.

- Place the DAQ Assistant on the block diagram by dragging and dropping it from the Functions palette.

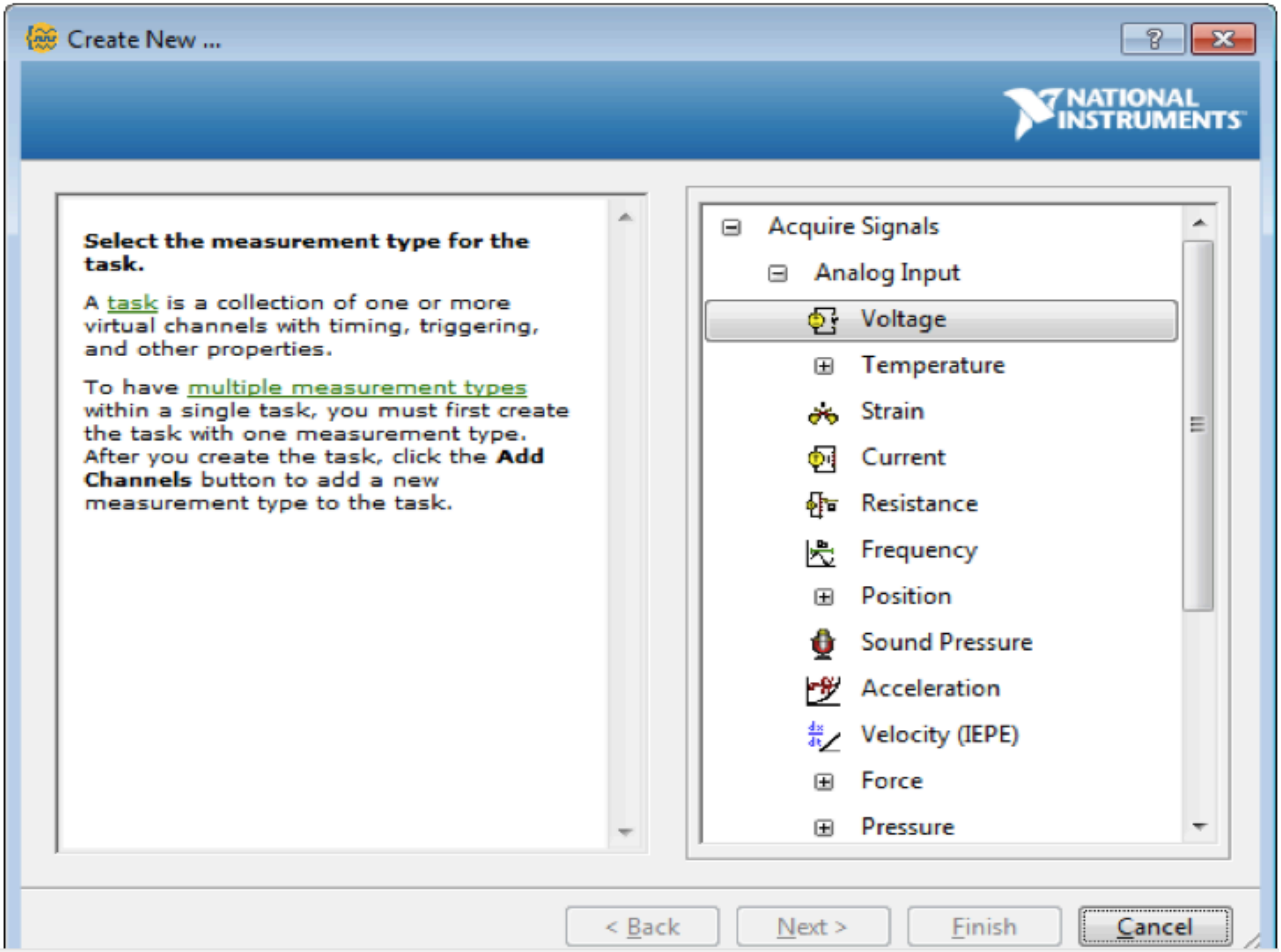
- The Assistant should automatically launch when you drop the VI on the diagram.

- **Create the Task**

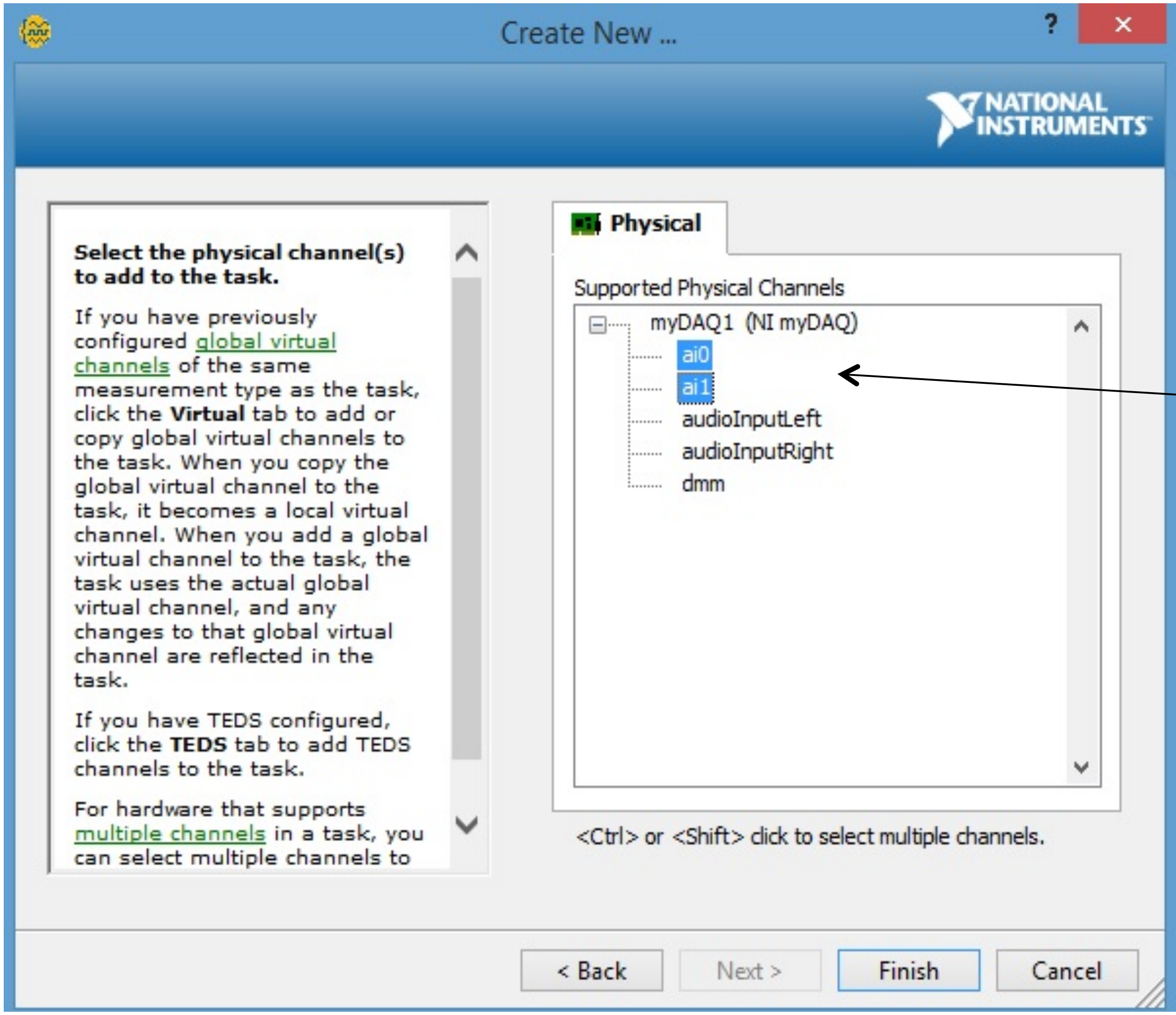
  -- Select **Acquire Signals** and then **Analog Input** for your Measurement Type.

  -- Next, select **Voltage.**

VI Programming Procedure (2)



VI Programming Procedure (3)



- Will show "MyDAQ"
- and available channels

Select a0

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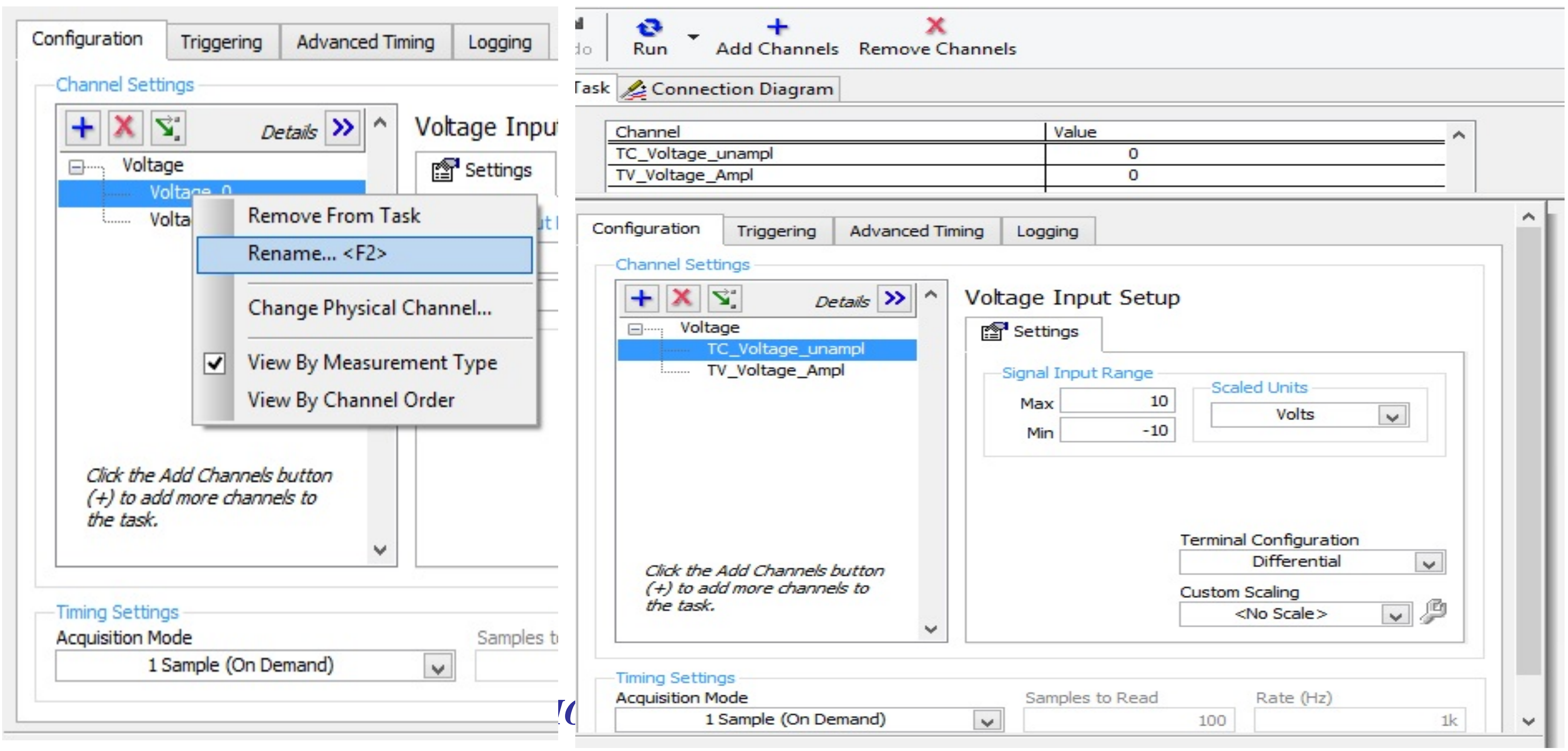
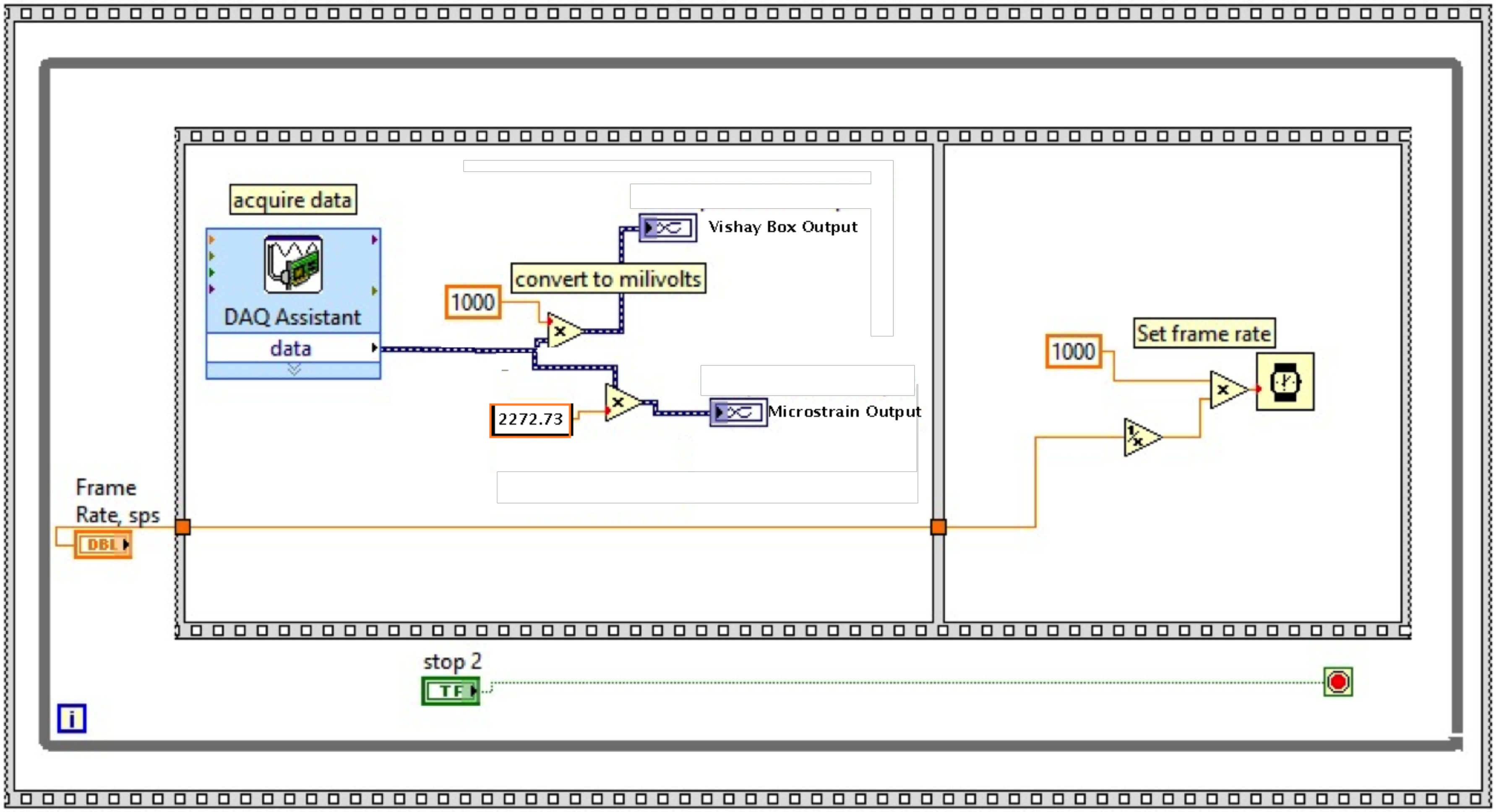
VI Programming Procedure (4)

- ***Rename Channels (right click on channel)***
  - ACH0 → Vishay Box Voltage

- ***Set Acquisition Mode: 1 Sample (On Demand)***
  - 1-sample, On demand
- **Set Voltage Range for Both Channels:** +- 10 Volts (Default for MyDAQ)



VI Programming Procedure (6)



• Wite output to two separate strip charts; 1) for Vishay Box millivolts output, and 2) for Vishay Box microstrains

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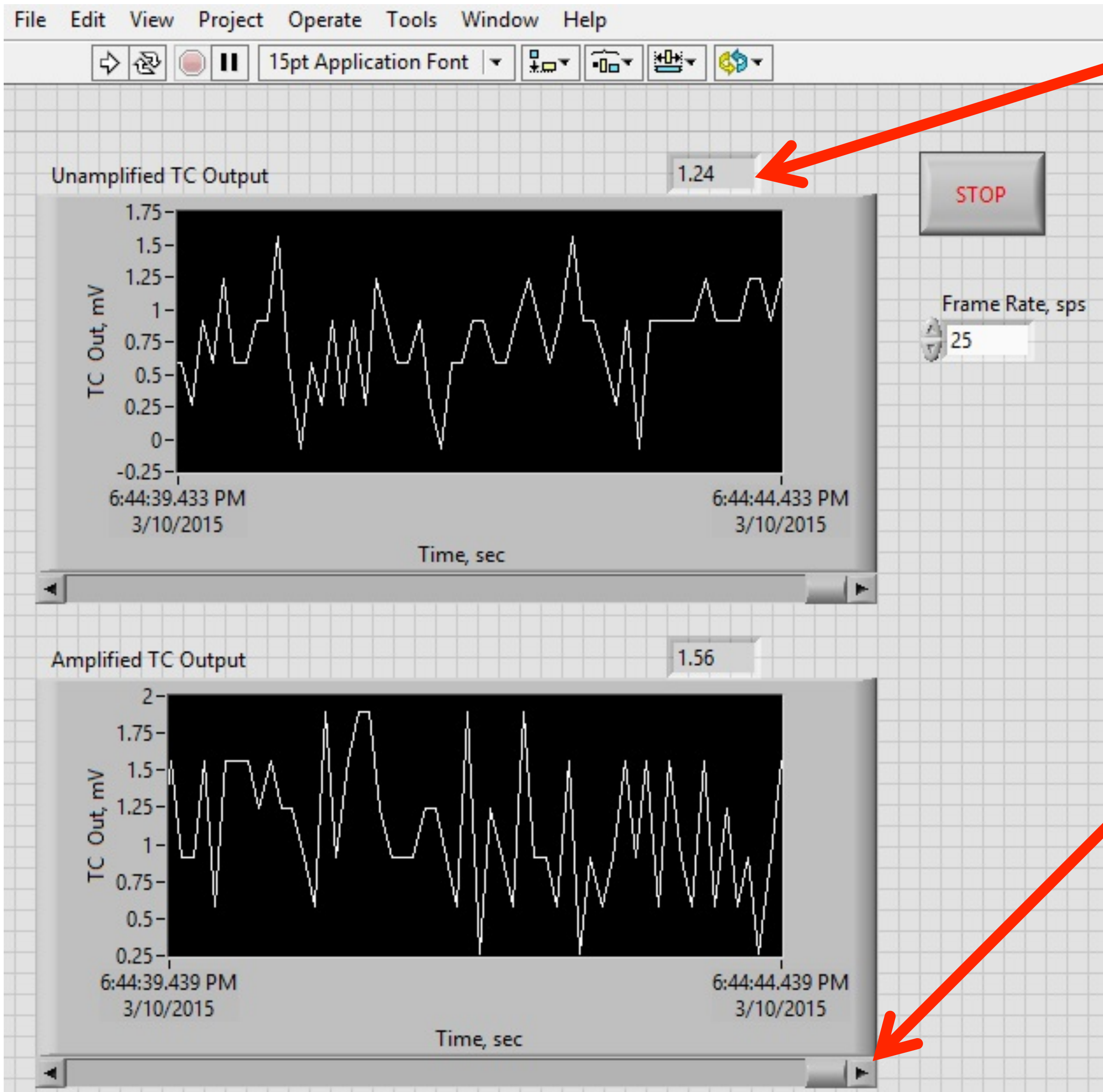
VI Programming Procedure (7)



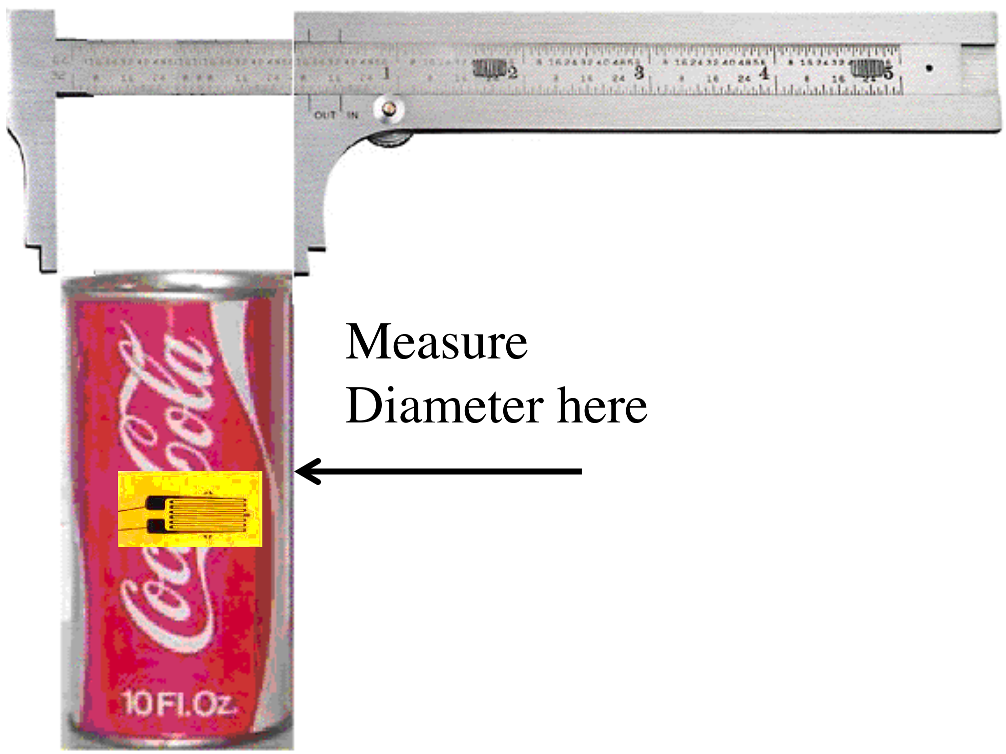
“Right click” for Digital Display

“Right click” for Time-Axis Scroll Bar, Drag to desired size.

Lab Test Procedure (1)

- 1) Each lab session will break into two groups …

- 2) Each Group will select two full soda cans …. Measure their diameters at mid length using Laboratory calipers … *write down data … see table at end of this lecture*



Lab Test Procedure (2)

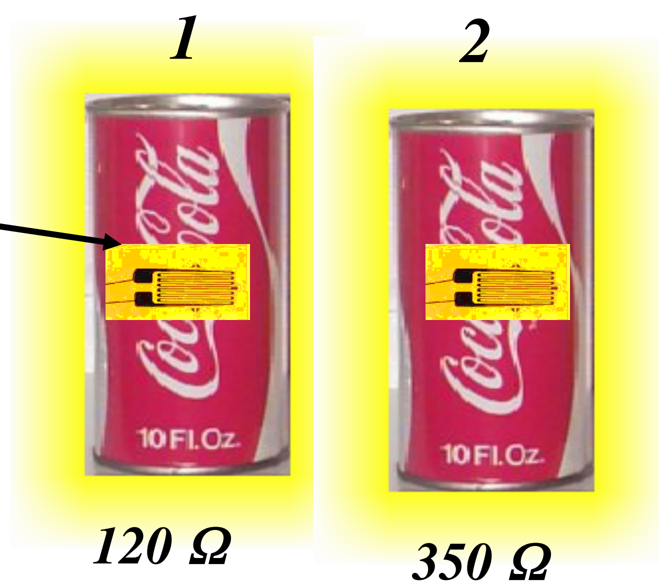
- 3) Install strain gauges per earlier instructions

- 4) Perform operations "serially" … so as to Give the bonding agent time to set up

- 5) Use the *120 Ω* strain gauges for can 1

- ~~5)~~ Use *350 Ω* gauges for can 2

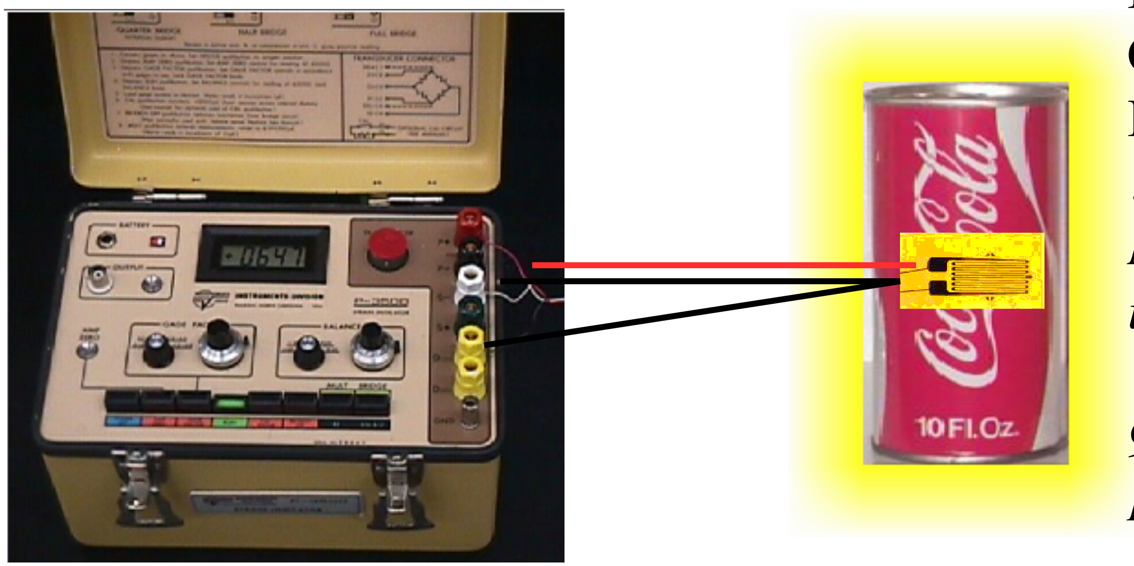
Install gauges
At mid length



Lab Test Procedure (~~4~~)(3)

• 6) Starting with ***"can 1"*** connect strain gauge to P-3500 per earlier Instructions, use ***Multiplication Factor as required***

• 7) Set gauge factor (written on strain gauge package) and balance bridge
record gauge factor settings in table

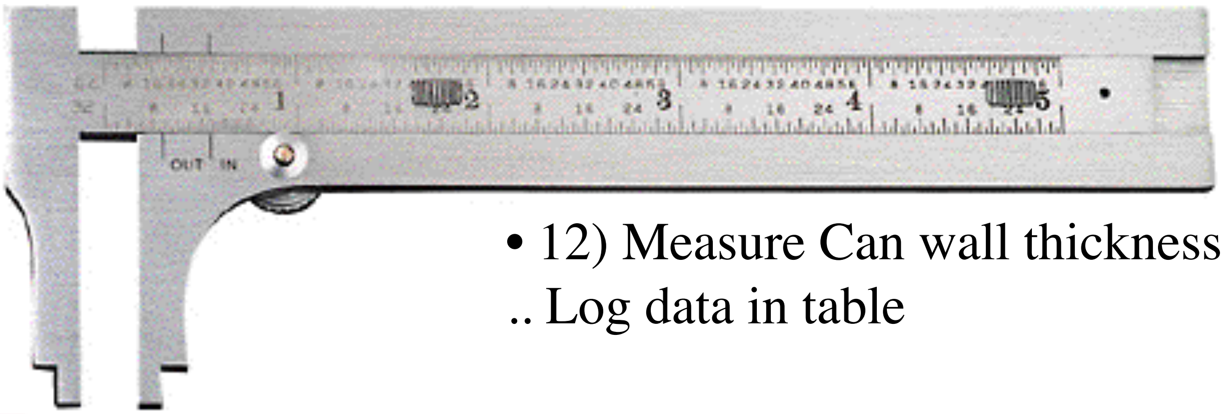


• 8) When bridge Is balanced ….open Can and read strain Indication from Vishay box … *record Microstrain level in table*

9) Simultaneously measure Reading using your voltmeter VI .. Be sure to Take "screen shot" and save

Lab Test Procedure (4)

- 10) Disconnect can from P-3500 … have volunteer consume soda …
- 11) Carefully cut open can at midpoint … just above gauge … using scissors



- 12) Measure Can wall thickness .. Log data in table

- 13) Repeat steps 3-10 for *Can 2*

As the data are acquired each group will populate the table shown (next page)***.. except the last two columns .. And the last two rows these calculations are to be performed individually***. In total … there should be 4 successful entries… one for each of the two cans for each of the 2 groups.

Data Analysis (1)

Individually, calculate internal pressure in can… and populate the last column of data table

Compute sample mean and standard deviation for Internal pressure in can based on populated measurement table. …then fill in the following blanks ….show work and attach to Lab REPORT

1) Sample Mean of the Pressure in the Can (kPa) ____________________________

2) Sample Standard Deviation Pressure in the Can (kPa) _____________________

3) Degrees of Freedom for the Measured Population__________________________

4) Using Student-T distribution for required degrees of freedom, calculate uncertainty range for sample mean of the pressure in can … use a 95% confidence interval ***(see following pages)*** __________________________________

5) Based on Manufacturer's specs for the various components of the measurement system ***(see following pages)*** … estimate uncertainty in Measured internal pressure in the soda can __________________________________

6) Compare estimated uncertainty with 95% confidence interval computed above ____

Data Analysis (2)

- ***Select one student from each lab to email me the raw test results for each soda can***
- ***I will distribute the results from all of the labs to the class for the post-lab analysis***

Repeat the procedure from part (1), except now use all of the collected data. Calculate the sample mean and standard deviation for Internal pressure in each can based all of the clected results (~ 60 data points) . …then fill in the following blanks below ….show work and attach to Lab REPORT

1) Sample Mean of the Pressure in the Can (kPa) (all measurements) ___________________________

2) Sample Standard Deviation Pressure in the Can (kPa) (all measurements) _____________________

3) Degrees of Freedom for the Measured Population (all measurements)_________________________

4) Using Gauss Distribution, calculate
uncertainty range for sample mean of the pressure in can … use a 95% confidence interval ***(see following pages)*** _________________________________

5) Based on Manufacturer's specs for the various components of the measurement system ***(see following pages)*** … estimate uncertainty in Measured internal pressure in the soda can _________________________________

6) Compare estimated uncertainty with 95% confidence interval computed above ____

Test Results Data Table

Can #	*Nom. Gauge Resistance, Ω*	G_F	*D, can, cm*	*t, wall, cm*	*ε, μ−strain (Vishay Display)*	*ε, μ−strain (VI Display)*	σ_{Hoop}, *kPa*	P_{gauge}, *kPa*
1	*120 Ω*							
2	*350 Ω*							
3	*120 Ω*							
4	*350 Ω*							
$\bar{x}$								
S_x								

Populate student – generated spreadsheet file

Error Analysis (1)

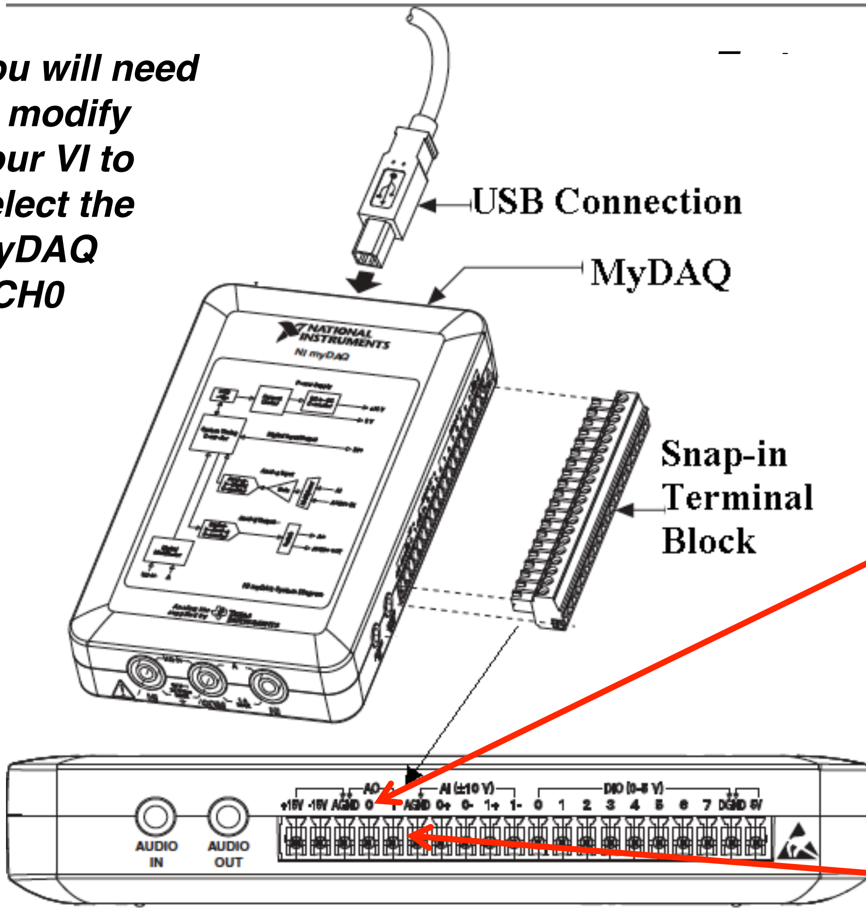
- Manufacturer's Accuracy Specifications for Strain gauges

Strain Gauge	$R_{g\ nom}$	$\delta R_{g\ (\Omega)}$	$\delta R_{g\ (\Omega)}$	Nominal G_F	$\delta G_{F\ (\%)}$
KFH-6-120-C1-11L3M3R	***120 Ω***	$\pm$0.42 Ω	$\pm$0.35%	2.0	$\pm$1%
KFH-6-350-C1-11L3M3R	***350 Ω***	$\pm$1.2255 Ω	$\pm$0.35%	2.0	$\pm$1%

Analog Output from the *Vishay Box (5)*

Signal Connections

You will need to modify your VI to select the MyDAQ ACH0



- **Be sure to use termination!**

- **Alligator clips and jumper wires might help here!**

Error Analysis (2)

- Manufacturer's Accuracy Specifications for Strain gauges

$$\varepsilon = \frac{1}{G_F}\frac{\Delta R}{R_g} \rightarrow \delta\varepsilon_{gauge} = \sqrt{\left\{\frac{\partial}{\partial G_F}\left[\frac{1}{G_F}\frac{\Delta R}{R_g}\right]\right\}^2 \delta G_F^{\ 2} + \left\{\frac{\partial}{\partial R_g}\left[\frac{1}{G_F}\frac{\Delta R}{R_g}\right]\right\}^2 \delta R_g^{\ 2}} =$$

$$\sqrt{\left\{\left[\frac{1}{G_F^{\ 2}}\frac{\Delta R}{R_g}\right]\right\}^2 \delta G_F^{\ 2} + \left\{\left[\frac{1}{G_F}\frac{\Delta R}{R_g^{\ 2}}\right]\right\}^2 \delta R_g^{\ 2}}$$

$$\rightarrow \frac{\delta\varepsilon_{gauge}}{\varepsilon_{mean}} \approx \sqrt{\frac{1}{\frac{1}{G_F}\frac{\Delta R}{R_g}}\left\{\left[\frac{1}{G_F^{\ 2}}\frac{\Delta R}{R_g}\right]\right\}^2 \delta G_F^{\ 2} + \left\{\left[\frac{1}{G_F}\frac{\Delta R}{R_g^{\ 2}}\right]\right\}^2 \delta R_g^{\ 2}} = \sqrt{\left(\frac{\delta G_F}{G_F}\right)^2 + \left(\frac{\delta R_g}{R_g}\right)^2}$$

$$\boxed{\frac{\delta\varepsilon_{gauge}}{\varepsilon_{mean}} \approx \sqrt{\left(\frac{\delta G_F}{G_F}\right)^2 + \left(\frac{\delta R_g}{R_g}\right)^2}}$$

Error Analysis (3)

- Resolution / Accuracy of P-3500 Bridge Completion Box

Resolution:	$1\mu\epsilon$ at MULT X1. $10\mu\epsilon$ at MULT X10.
Accuracy:	±0.05% rdg ±$3\mu\epsilon$ for Gage Factor ⩾1.000, MULT X1. ±0.05% rdg ±$10\mu\epsilon$ for Gage Factor ⩾1.000, MULT X10.

¶• Using Data from data Table calculations …

$$\delta\varepsilon_{p-3500} \approx \sqrt{\left(\frac{0.05_{\%}}{100}\cdot\varepsilon_{mean} + 3_{\mu strain}\right)^2 + \left(1_{\mu strain}\right)^2}$$

$$\rightarrow \frac{\delta\varepsilon_{p-3500}}{\varepsilon_{mean}} \approx \sqrt{\left(\frac{0.05_{\%}}{100} + \frac{3_{\mu strain}}{\varepsilon_{mean}}\right)^2 + \left(\frac{1_{\mu strain}}{\varepsilon_{mean}}\right)^2}$$

$$\left(\frac{\delta\varepsilon}{\varepsilon_{mean}}\right)_{total} \approx \sqrt{\left(\frac{\delta\varepsilon_{gauge}}{\varepsilon_{mean}}\right)^2 + \left(\frac{\delta\varepsilon_{p-3500}}{\varepsilon_{mean}}\right)^2} =$$

for multiplication factor of 1

for multiplication factor of 10 .. Use appropriate values

$$\left(\frac{\delta\varepsilon}{\varepsilon_{mean}}\right)_{total} \approx \sqrt{\left(\frac{\delta G_F}{G_F}\right)^2 + \left(\frac{\delta R_g}{R_g}\right)^2 + \left(\frac{0.05_{\%}}{100} + \frac{3_{\mu strain}}{\varepsilon_{mean}}\right)^2 + \left(\frac{1_{\mu strain}}{\varepsilon_{mean}}\right)^2}$$

Error Analysis (4)

- Resolution / Accuracy of Lab Calipers

Product Description: Electronic Calipers Maximum Measuring Range: 6, 150 mm Minimum Measuring Range: 0, 0 mm Resolution: 0.0005 In., 0.01 mm Accuracy: +or-.001 In.

$$\delta_{calipers} = \sqrt{\left(\delta_{resolution}\right)^2 + \left(\delta_{accuracy}\right)^2} = \sqrt{0.0005_{in}{}^2 + 0.001_{in}{}^2} = 0.00112_{in} \approx 0.00284_{cm}$$

- Since calipers are used for BOTH can diameter and thickness measurements

$$\left(\frac{\delta t}{t_{mean}}\right) = \left(\frac{0.00284_{cm}}{t_{mean\ cm}}\right) \qquad \left(\frac{\delta D}{D_{mean}}\right) = \left(\frac{0.00284_{cm}}{D_{mean\ cm}}\right)$$

Error Analysis (5)

- Total Error Estimate

$$p_{internal} = p_{ambient} + 2\frac{t}{D}\cdot E\cdot\varepsilon \rightarrow$$

$$\delta\left[p_{internal} - p_{ambient}\right]^2 = \left\{\frac{\partial}{\partial t}\left[2\frac{t}{D}\cdot E\cdot\varepsilon\right]\right\}^2 \delta t^2 + \left\{\frac{\partial}{\partial D}\left[2\frac{t}{D}\cdot E\cdot\varepsilon\right]\right\}^2 \delta D^2 + \left\{\frac{\partial}{\partial G_F}\left[2\frac{t}{D}\cdot E\cdot\varepsilon\right]\right\}^2 \delta\varepsilon^2 =$$

$$\left\{\left[2\frac{1}{D}\cdot E\cdot\varepsilon\right]\right\}^2 \delta t^2 + \left\{\left[2\frac{t}{D^2}\cdot E\cdot\varepsilon\right]\right\}^2 \delta D^2 + \left\{\left[2\frac{t}{D}\cdot E\right]\right\}^2 \delta\varepsilon^2$$

- Normalize Error

$$\left\{\frac{\delta\left[p_{internal} - p_{ambient}\right]}{\left[p_{internal} - p_{ambient}\right]}\right\}^2 = \left\{\left[\frac{2\frac{1}{D}\cdot E\cdot\varepsilon}{2\frac{t}{D}\cdot E\cdot\varepsilon}\right]\right\}^2 \delta t^2 + \left\{\left[\frac{2\frac{t}{D^2}\cdot E\cdot\varepsilon}{2\frac{t}{D}\cdot E\cdot\varepsilon}\right]\right\}^2 \delta D^2 + \left\{\left[\frac{2\frac{t}{D}\cdot E}{2\frac{t}{D}\cdot E\cdot\varepsilon}\right]\right\}^2 \delta\varepsilon^2 =$$

$$\left\{\frac{\delta\left[p_{internal} - p_{ambient}\right]}{\left[p_{internal} - p_{ambient}\right]}\right\}^2 = \left(\frac{\delta t}{t}\right)^2 + \left(\frac{\delta D}{D}\right)^2 + \left(\frac{\delta\varepsilon}{\varepsilon}\right)^2$$

$$p_{internal} - p_{ambient} = p_{"gauge"}$$

Error Analysis (6)

- Estimate variance (mean square error) …. Pressure measurement

$$\left(\sigma^2 p_{"gauge"}\right) = p^2_{gauge} \cdot \left[\left(\frac{\delta t}{t}\right)^2 + \left(\frac{\delta R_g}{R_g}\right)^2 + \left(\frac{\delta \varepsilon}{\varepsilon}\right)^2\right]$$

Where …

$$\left(\frac{\delta t}{t}\right) \approx \left(\frac{0.00284_{cm}}{t_{mean\ cm}}\right)$$

$$\left(\frac{\delta D}{D}\right) \approx \left(\frac{0.00284_{cm}}{D_{mean\ cm}}\right)$$

$$\frac{\delta\varepsilon}{\varepsilon} \approx \sqrt{\left(\frac{\delta G_F}{G_F}\right)^2 + \left(\frac{\delta R_g}{R_g}\right)^2 + \left(\frac{0.05_{\%}}{100} + \frac{3_{\mu strain}}{\varepsilon_{mean}}\right)^2 + \left(\frac{1_{\mu strain}}{\varepsilon_{mean}}\right)^2} \rightarrow \times 1 \ldots multiplier$$

$$\frac{\delta\varepsilon}{\varepsilon} \approx \sqrt{\left(\frac{\delta G_F}{G_F}\right)^2 + \left(\frac{\delta R_g}{R_g}\right)^2 + \left(\frac{0.05_{\%}}{100} + \frac{10_{\mu strain}}{\varepsilon_{mean}}\right)^2 + \left(\frac{10_{\mu strain}}{\varepsilon_{mean}}\right)^2} \rightarrow \times 10 \ldots multiplier$$

Appendix I: Industry Standard Procedure for Bonding the Strain Gauge to the Test Specimen

Bonding Strain Gauge to the Soda Can (2)

- ***M-Bond 200*** **…** M-Bond 200 is an excellent general purpose laboratory adhesive because of its fast room-temperature cure and ease of application.

- *M-Bond 200 is a modified methyl -2-cyanoacrylate compound.*

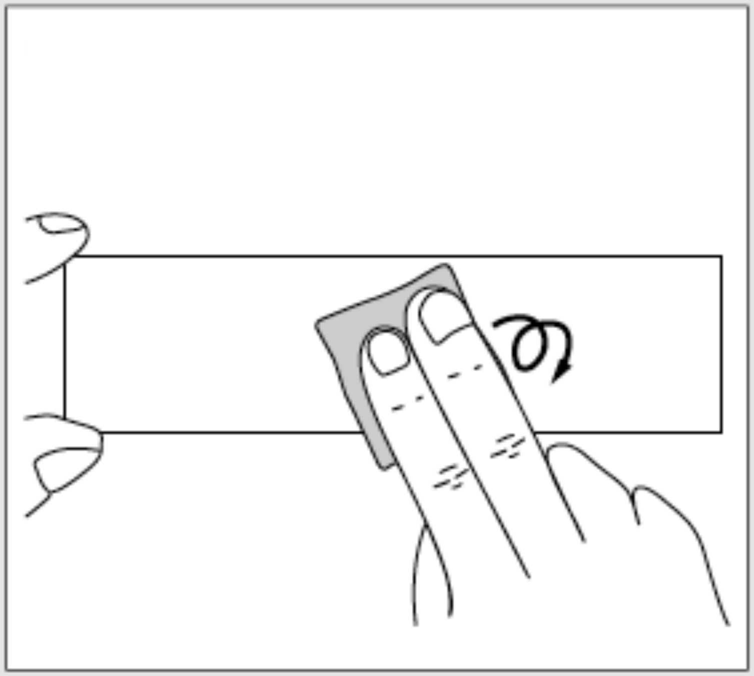
- The catalyst supplied with M-Bond 200 is specially formulated to control the reactivity rate. For best results, the catalyst should be used sparingly.

Bonding Strain Gauge to the Soda Can (3)

1) Degreasing

• DeGreasing is performed to remove oils, greases, organic i contamints, " and soluble chemical residues. Degreasing should *always* be the first operation.

Bonding Strain Gauge to the Soda Can (4)



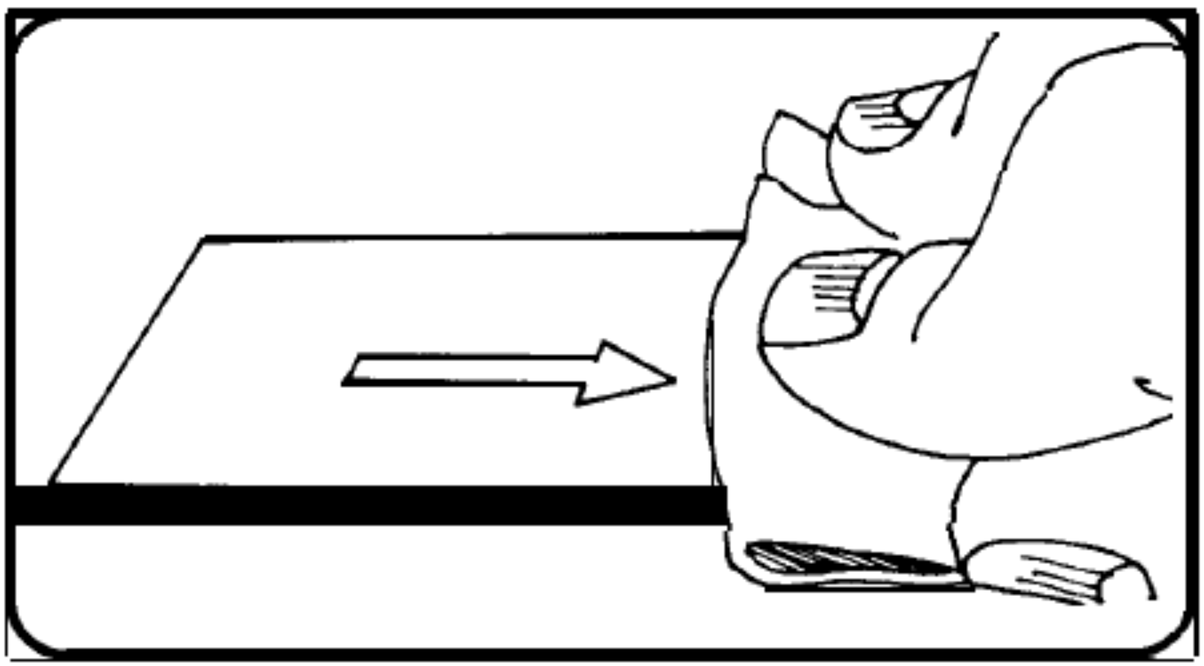
Like drawing a circle with sandpaper (#300 or so), polish the strain gage bonding site in a considerably wider area than the strain gage size.

(If the measuring object is a practical structure, wipe off paint, rust and plating with a grinder or sand blast. Then, polish with sandpaper.)

2) Surface Abrading

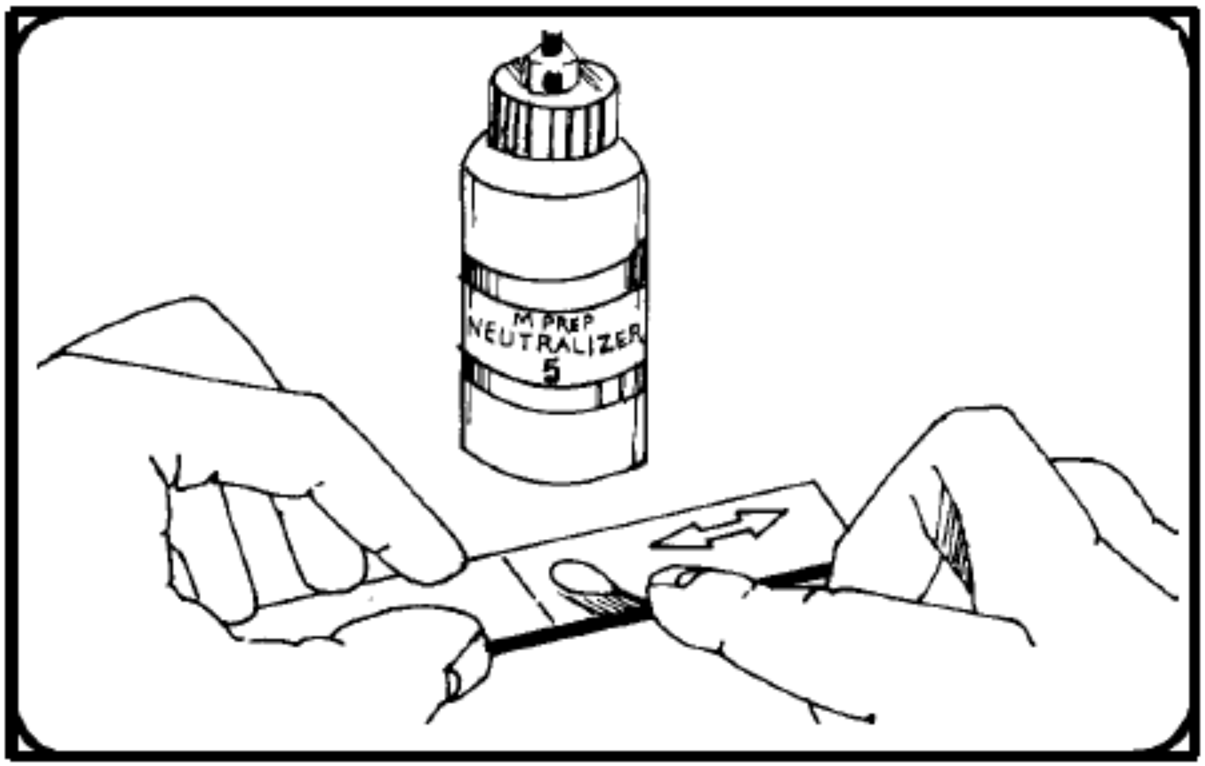
Bonding Strain Gauge to the Soda Can (5)

3) Surface Conditioning



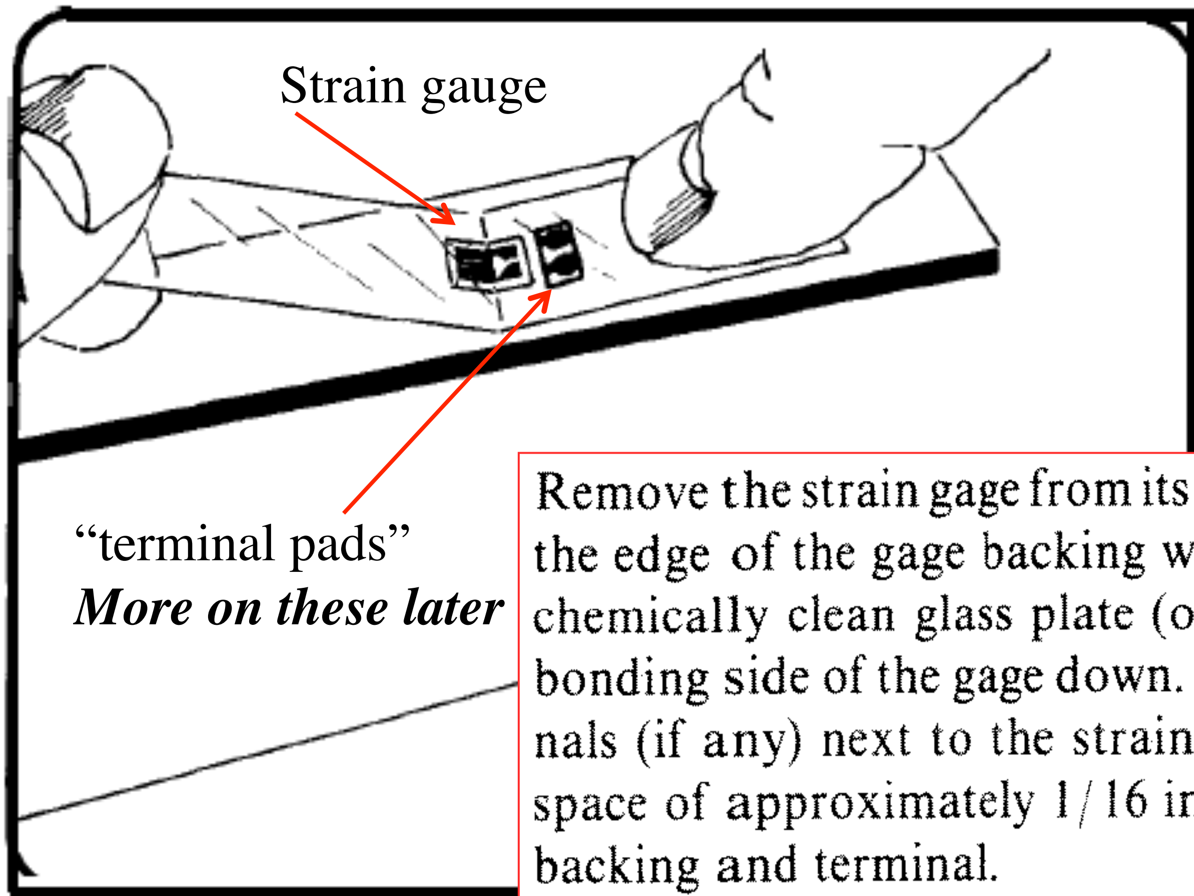
Bonding Strain Gauge to the Soda Can (6)

4) Neutralizing



Bonding Strain Gauge to the Soda Can (7)

5) Positioning on Test Article



Remove the strain gage from its acetate envelope by grasping the edge of the gage backing with tweezers, and place on a chemically clean glass plate (or empty gage box) with the bonding side of the gage down. Place the appropriate terminals (if any) next to the strain gage solder tabs, leaving a space of approximately 1/16 in *(1.5 mm)* between the gage backing and terminal.

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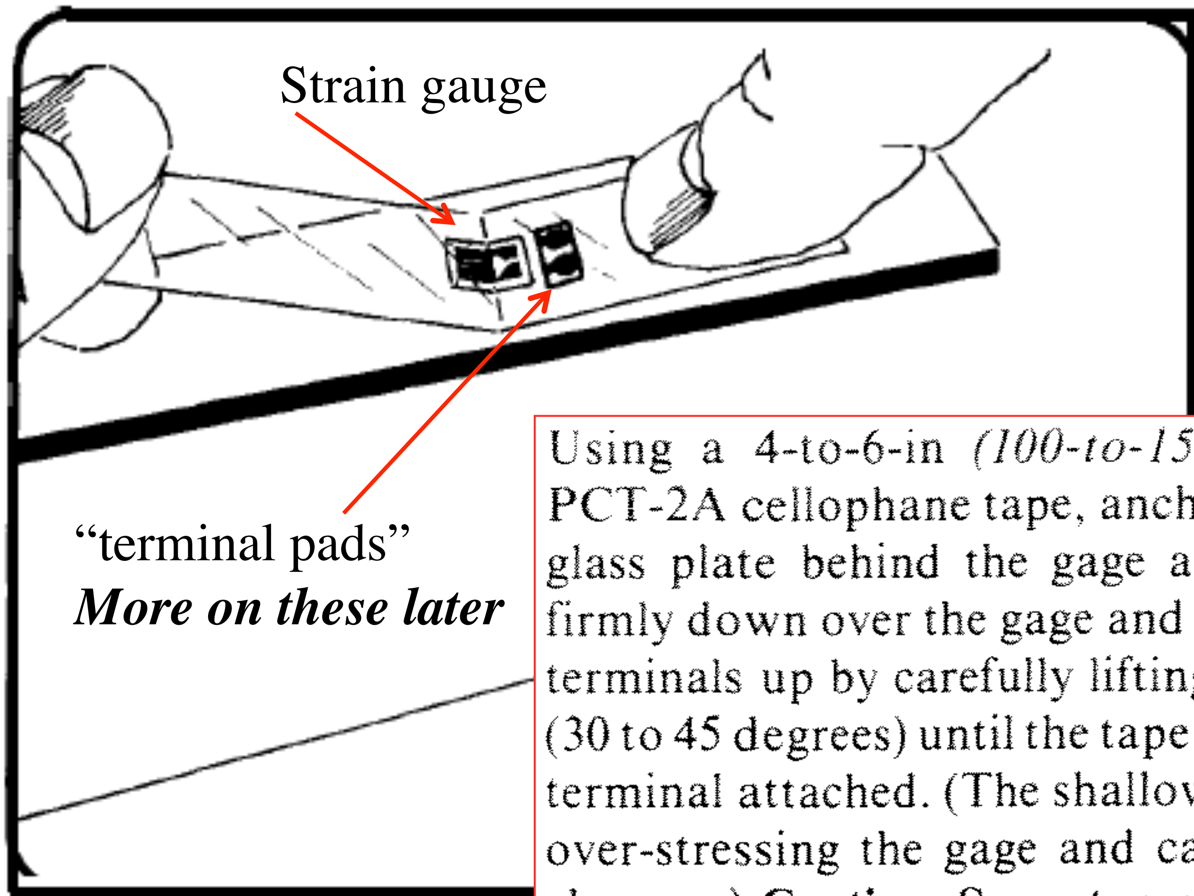
Bonding Strain Gauge to the Soda Can (8)

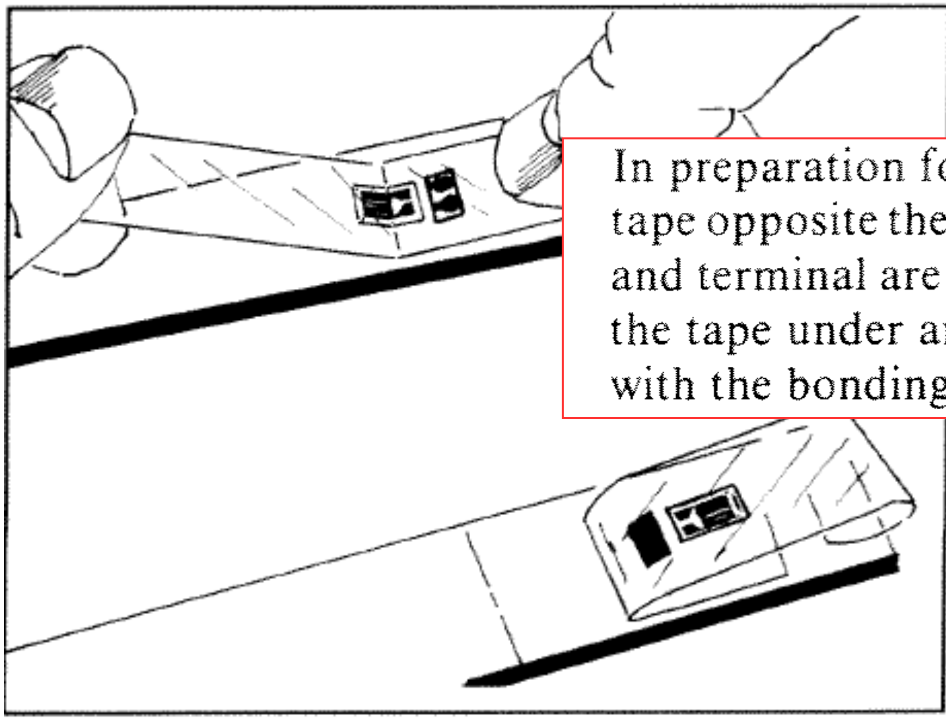
6) Secure gage To anchor tape



Using a 4-to-6-in *(100-to-150-mm)* length of *M-LINE* PCT-2A cellophane tape, anchor one end of the tape to the glass plate behind the gage and terminal. Wipe the tape firmly down over the gage and terminals. Pick the gage and terminals up by carefully lifting the tape at a shallow angle (30 to 45 degrees) until the tape comes free with the gage and terminal attached. (The shallow angle is important to avoid over-stressing the gage and causing permanent resistance changes.) **Caution: Some tapes may contaminate the bonding surface or react with the bonding adhesive. Use only tapes certified for strain gage installations.**

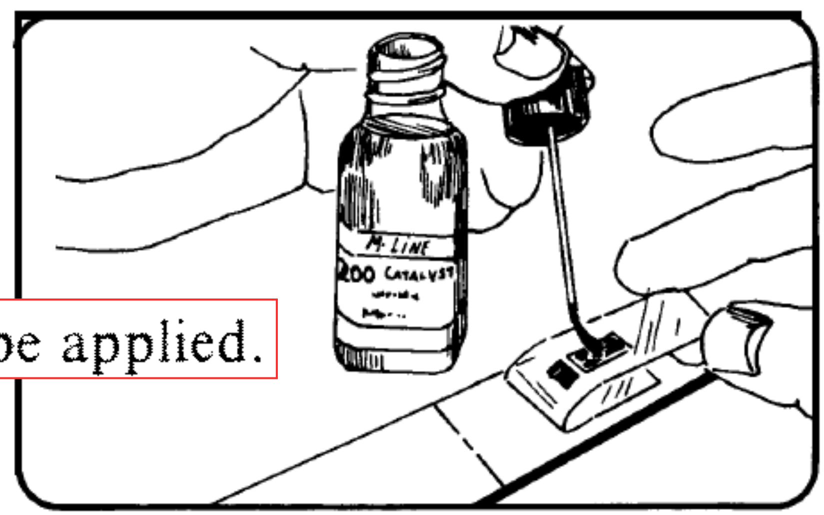
Bonding Strain Gauge to the Soda Can (9)

7) Bonding



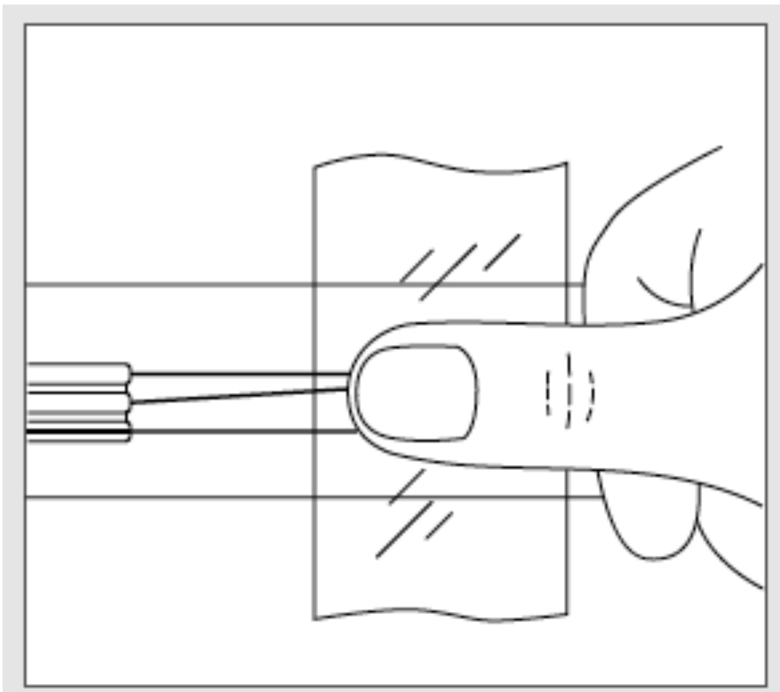
In preparation for applying the adhesive, lift the end of the tape opposite the solder tabs at a shallow angle until the gage and terminal are free of the specimen. Tack the loose end of the tape under and press to the surface so the gage lies flat with the bonding side exposed.

The appropriate adhesive may now be applied.



Bonding Strain Gauge to the Soda Can (10)

8) Securing



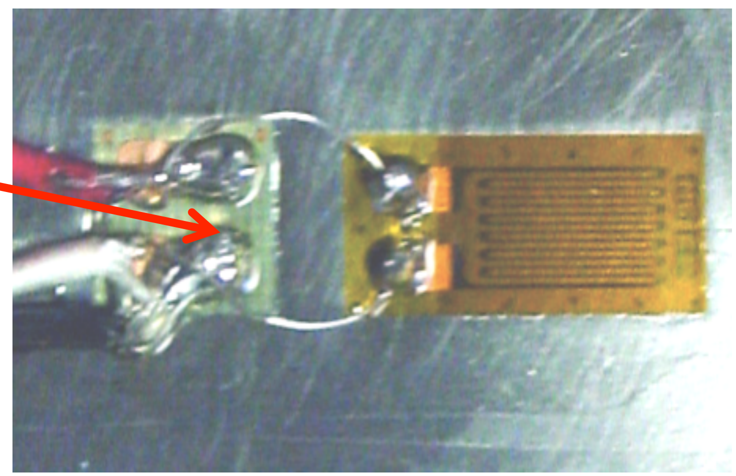
After glue has set appropriately
Gently but firmly pat the gauge into place

Electrical Connections to Gauge (1)

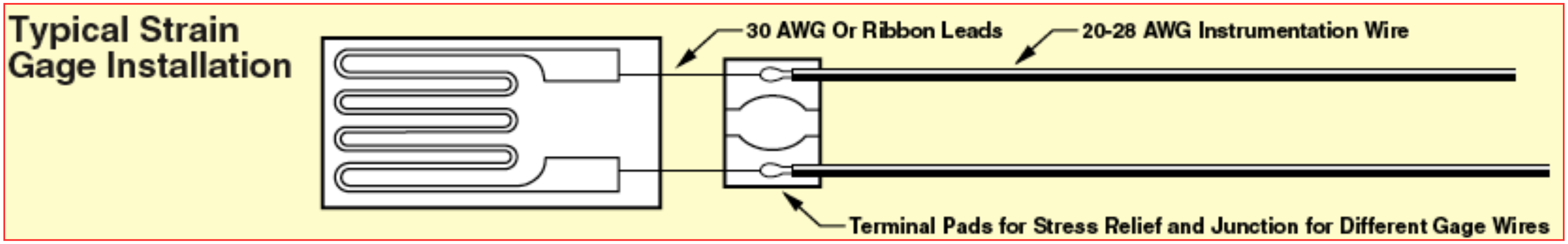
• Application of gages is easy; one cleans the metal surface, applies a catalyst for the adhesive, applies the adhesive, and then presses down the gage.

• The tricky part (sometimes) is soldering the lead wires to the gauges.

• Solder Tabs Eliminate potential Strain due to heavy Lead wires



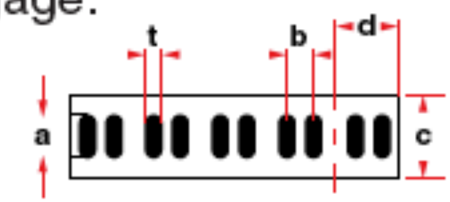
Electrical Connections to Gauge (2)



Terminal Pads

Terminal pads serve two main purposes. First, they act as intermediate points for attaching ribbon leads of thin gage wire to heavier instrumentation wires. Second, they provide stress relief to strain gage systems. When the heavy instrumentation wire moves, the terminal pad protects the strain gage.

Terminal Pads



TP-5 shown actual size