

Adiabatic Heating Effect on Bourdon Tube Gauges Encountered During Calibration

There are several methods and tools, which can be used to verify calibration of Bourdon Tube type pressure gauges. There are pros and cons to each which must be considered when selecting a calibration verification process. One of the most important considerations is the pressure media used to apply pressure to the gauge under test. When using a gas such as nitrogen or shop air, the adiabatic heating effect can cause mechanical gauges to appear to be out of tolerance.

How does adiabatic heating impact calibration processes?

In a closed system with gas as the pressure media, the temperature of the gas affects the volume of the gas, which has an impact on the pressure. When pressure increases quickly, the temperature of the gas will rise, and this higher temperature makes the gas expand, thus having a bigger volume and higher pressure. When the temperature starts to cool down, the volume of the gas becomes smaller, and this will cause the pressure to drop. This pressure drop may seem like a leak in the system, but it is caused by the adiabatic effect due to change in the gas temperature. The faster the pressure changes, the bigger is the effect is. The pressure change caused by this effect will gradually get smaller as the temperature stabilizes. So, if you change the pressure quickly, make sure you let it stabilize for a while before judging that there is a leak in the system.

What is the impact of adiabatic heating on a bourdon tube?

In simple terms, when gas is rapidly compressed, it gets warmer. When it decompresses, it becomes cooler. In a bourdon tube gauge, the heated compressed gas contained within the tube assembly transfers some of that heat energy to the tube. This transference can cause the tube to expand and change the tube's modulus of elasticity. The heated bourdon tube drives the gauge movement and can make it appear that the gauge is displaying pressure greater than what is being applied and appear to be out of tolerance.

A series of tests were run to quantify the adiabatic effect on two 0-3000 psi analog test gauges with $\pm 0.1\%$ of span accuracy. The test report demonstrates the effect that adiabatic heating has on these particular gauges, and the findings apply to any range gauge when using gas as the pressure media.

How to diminish the impact of adiabatic heating on calibration procedures?

There are a few different mitigation actions:

1. Using a pressure standard that uses liquid pressure media such as water or oil will eliminate this effect.
2. If gas pressure media is required, then controlling the rate by which the pressure increases and allowing time between readings to normalize the temperature will also yield favorable results.
3. Heat can be dissipated more quickly by increasing airflow around the tube assembly with a small fan.

Adiabatic Heating Effects on Heise Dial Gauge

Test Report by: Lucian Guadagnoli, Jeremy Payne



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ID: Adiabatic Heating Effects on Bourdon Tube Pressure gauge during the calibration process
8/1/2019

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1. Test Information

Date Requested: 4/10/2019

Requested by: Steve Andersen

Test Performed by: Lucian Guadagnoli

2. Product Tested

Table 1: Sample List

Sample #	Product Series	Product Code	Serial No.
Gauge 1	Heise Test	CCAUGV3000BCH-#XA6	CC-145321
Gauge 2	Gauge	CCAUGV3000BDP	CC-145510

3. Scope/Purpose

The purpose of this test is to determine the effects of heat generated by pressurizing Heise gauges on nitrogen gas.

4. Test Equipment

Table 2: Equipment Used in this Report

Lab I.D.	Model #	Description	Manufacturer
1294	34970A	Multiplexer	Keysight
1297	BTRC	Temperature Chamber	TPS
1445	CM2-17G	Pace 6000 Module (-15/+2000 PSIG)	GE Druck
N/A	SA1-K	K-Type Thermocouple	Omega
1056	ST-2H	Digital Indicator	Ashcroft
0016	HQS-2	Pressure Sensor (0-3000 PSIG, 0.025%)	Ashcroft
9517	938	Hydraulic Pump (Water)	Additel
0992	681	Digital Pressure Gauge	Additel

5. Test Procedure(s)

Adiabatic Heating Test

Reference: Custom Test

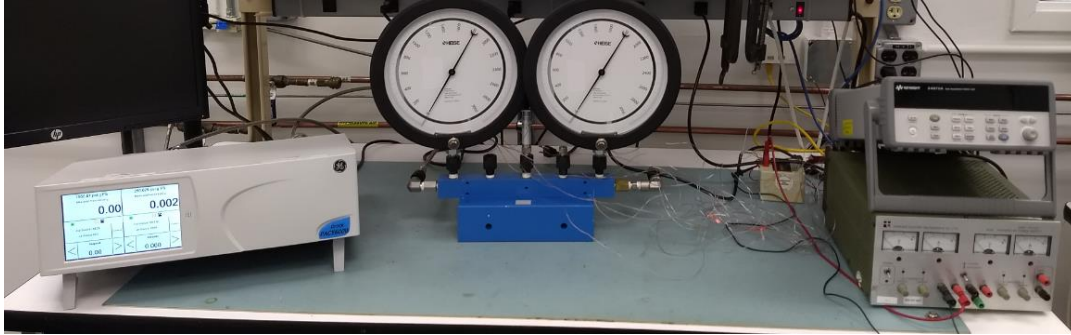


Figure 1: The adiabatic heating test setup with (from left to right) the pressure controller, the pressure manifold holding two gauges, and the multipler resting on a DC power supply.

Initial Setup

- The **pressure manifold** shall contain enough ports to allow connection to a pressure controller, a pressure transducer, and at least one port for test samples (two were used in this test).
- Attach at least four K-Type thermocouples to each bourdon tube in the configuration shown in Figure 2.

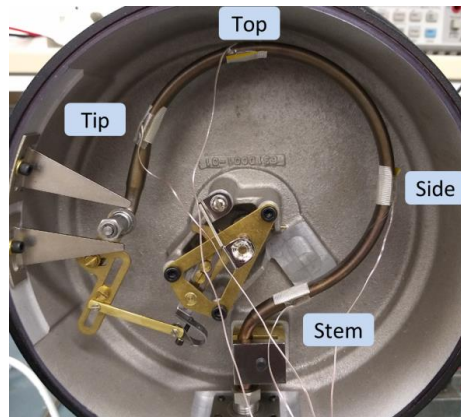


Figure 2: The thermocouple configuration on a test gauge. The four location labels shown in this image are used throughout this report.

- The **data acquisition system** (DAQ) consists of a model 34970A multipler (abbreviated to 'MUX') which measures the following instruments:
 - An RTD thermocouple to track the internal temperature of the multipler.
 - The K-type thermocouples, which are attached to the test gauge(s).
 - The reference pressure transducer (from the pressure manifold) and the means to energize it.

Procedure

1. Prepare the test system in accordance with the points outlined in the Initial Setup section.
2. Fixture the test gauge to the pressure manifold.
3. Zero the test gauge.
4. Review Table 3 to determine the condition of the gauge's back-cover.
5. Configure multiplexer profile to scan and record each thermocouple and transducer output every second for 20 minutes.
6. Run the multiplexer profile.
7. Pressurize the gauge in accordance with the 'Pressure Profile' in Table 3.
 - a. **No Cycle Profile:** Pressurize the gauge to span at the maximum slew rate.
 - b. **Triple Cycle Profile:** Pressurize the gauge to span at the maximum slew rate, then immediately depressurize to zero at the same rate. Repeat this cycle two more times, and then pressurize to span and hold.
8. Note the initial indication on each gauge, along with the indication drift as time elapses. Remain at the maximum pressure reached in step 7 until the multiplexer profile ends.
9. When the multiplexer profile ends, record the final location of the indicators, and depressurize the manifold to zero at the maximum slew rate.
10. The test run is complete.

Table 3: Adiabatic heating test run configurations

Test Run	Pressure Profile	Condition of Gauge
1	No Cycle	Back-Cover Installed
2	Triple Cycle	Back-Cover Installed
3	Triple Cycle	Back-Cover Removed
4	Triple Cycle	Back-Cover Removed, Fan-Cooled

6. Results

Adiabatic Heating Test

The charts presented in this section track the temperature of the bourdon tube(s) over a 20-minute scan duration. The reference pressure is presented to show how the temperature drifts after constant pressure is achieved. For all adiabatic heating charts in this section, the maximum pressure applied was 1950 PSI.

All charts presented in this section show outputs that are initially normalized against ambient temperature. This means that each thermocouple's output (before pressurizing) is compared to ambient temperature and offset so the readings now begin at ambient temperature. For example: if a thermocouple initially reports a temperature of 20°C, and ambient temperature is 19°C, then all readings for that thermocouple are shifted by -1°C. By normalizing temperature to ambient, the temperature drift can be compared between each thermocouple without considering different initial temperatures (see Figure 3).

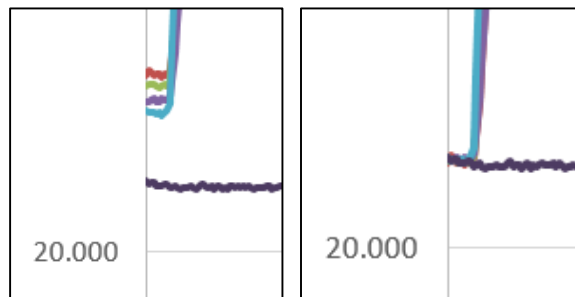


Figure 3: A comparison of the initial thermocouple temperature readings before normalizing (left) and after normalizing (right) against ambient temperature (the purple horizontal line).

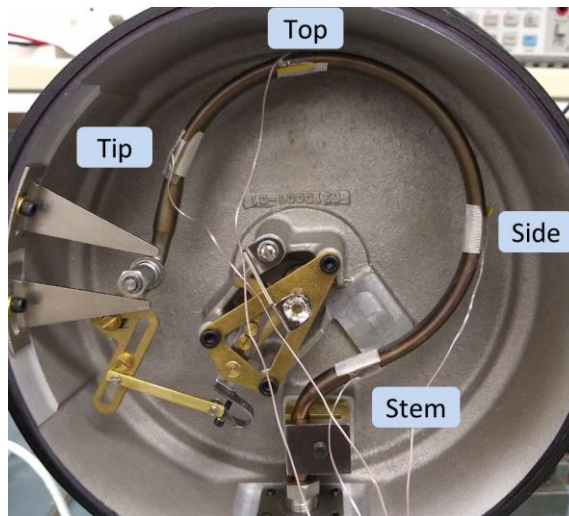


Figure 4: The thermocouple locations and labels, shown again for convenience.

Run 1: No Cycle, Cover On

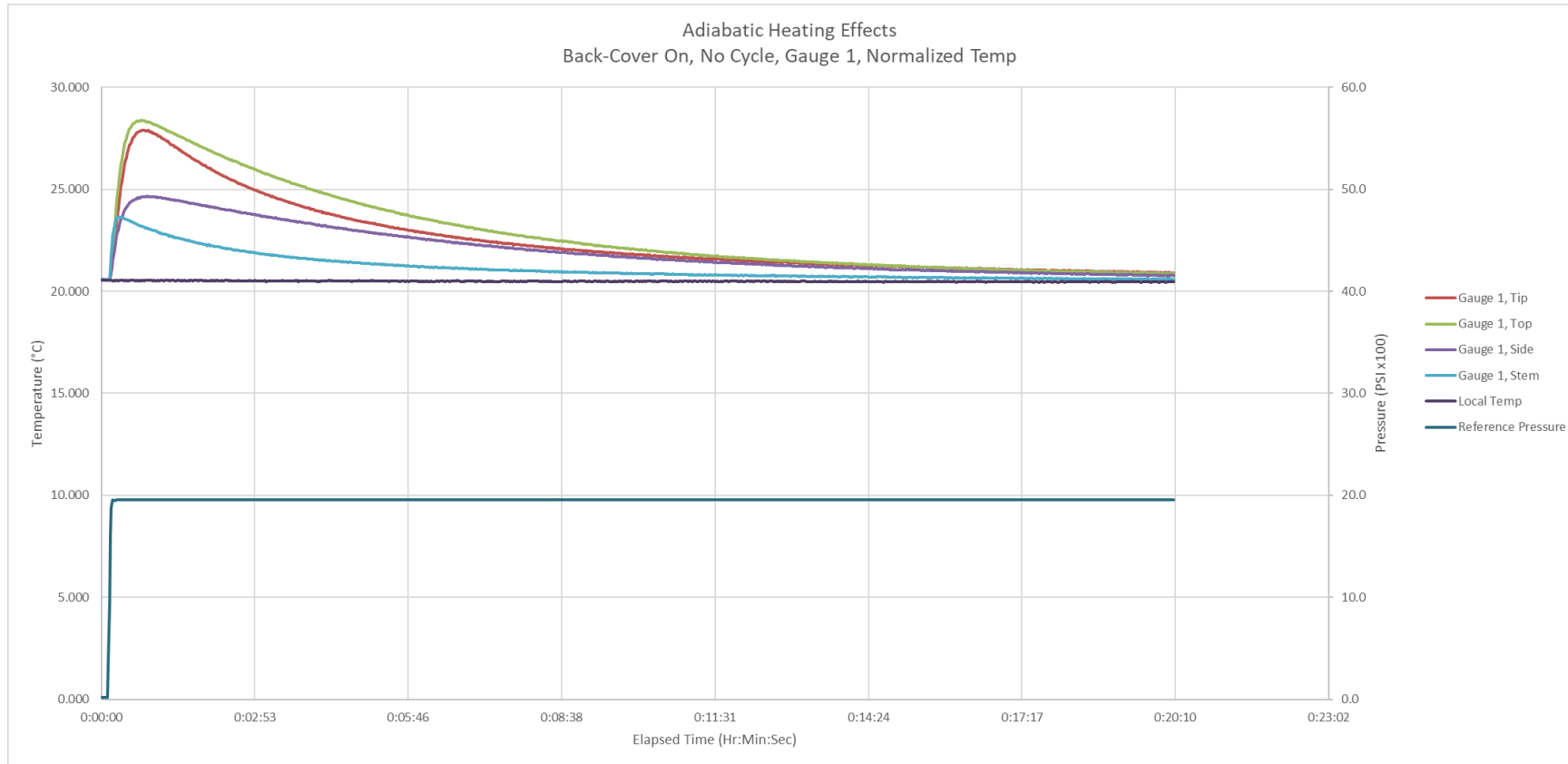


Figure 5: Gauge 1, Run 1

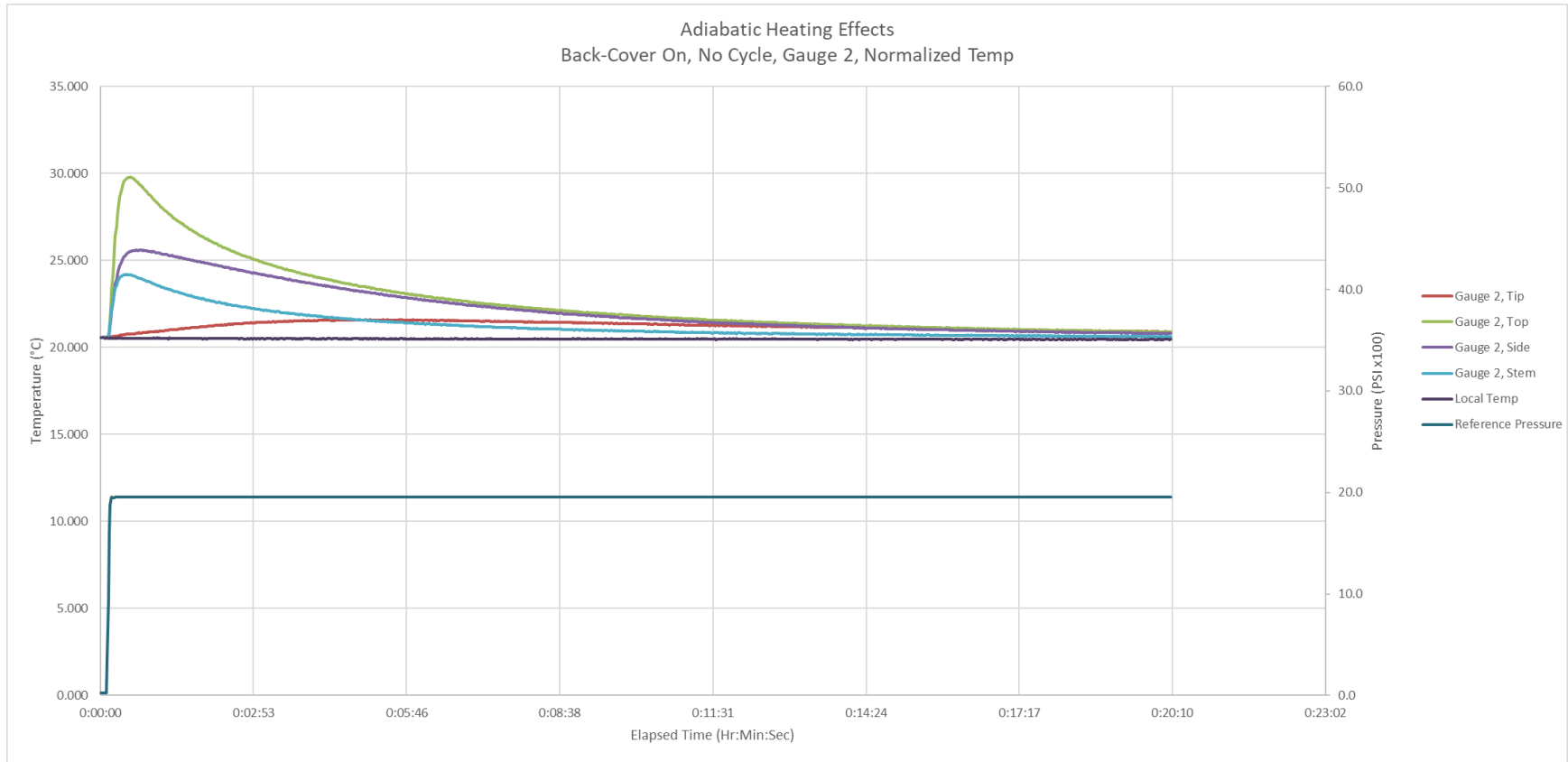


Figure 6: Gauge 2, Run 1

Run 2: Three Cycles, Cover On

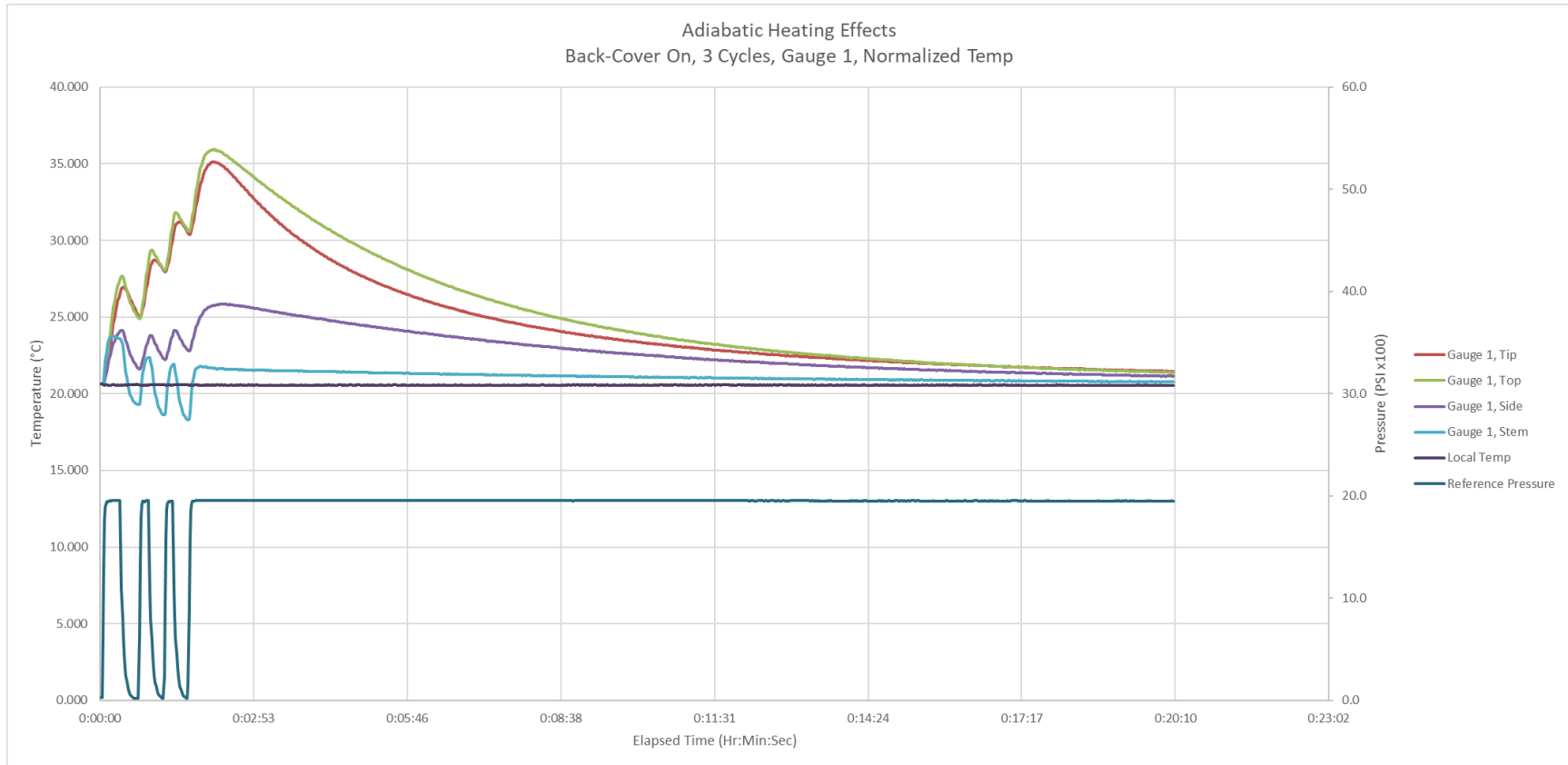


Figure 7: Gauge 1, Run 2

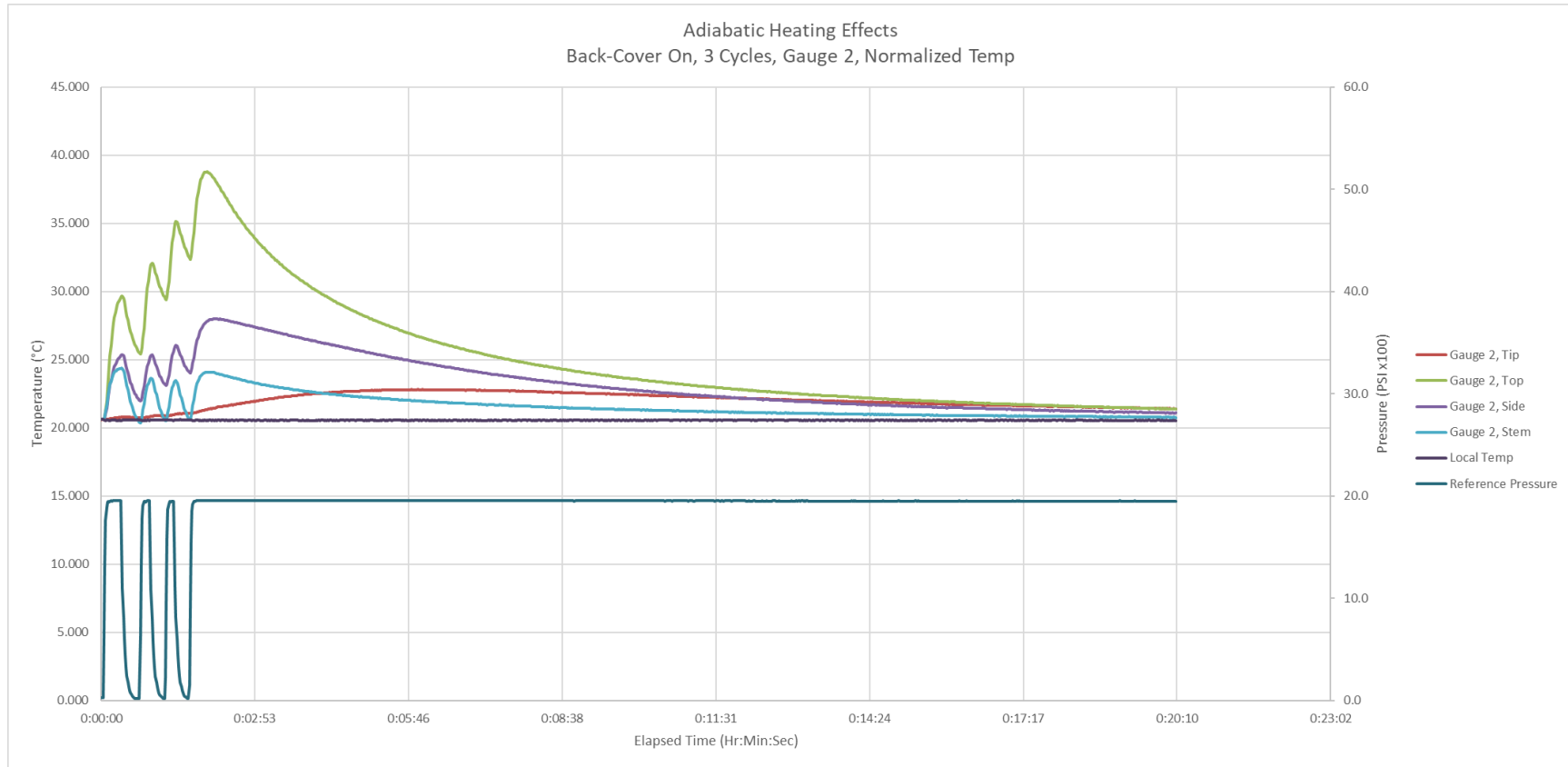


Figure 8: Gauge 2, Run 2

Run 3: Three Cycles, Cover Off

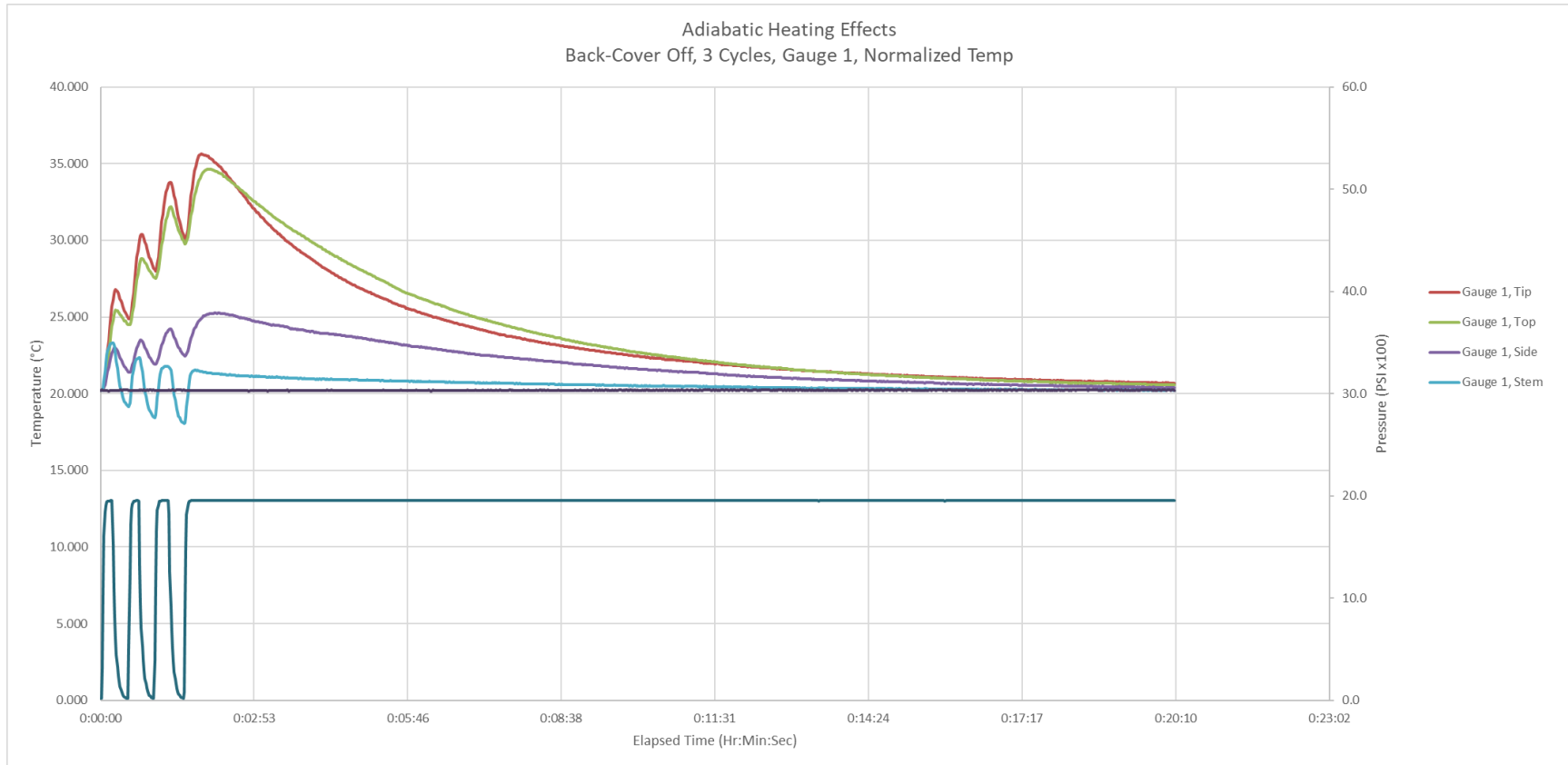


Figure 9: Gauge 1, Run 3

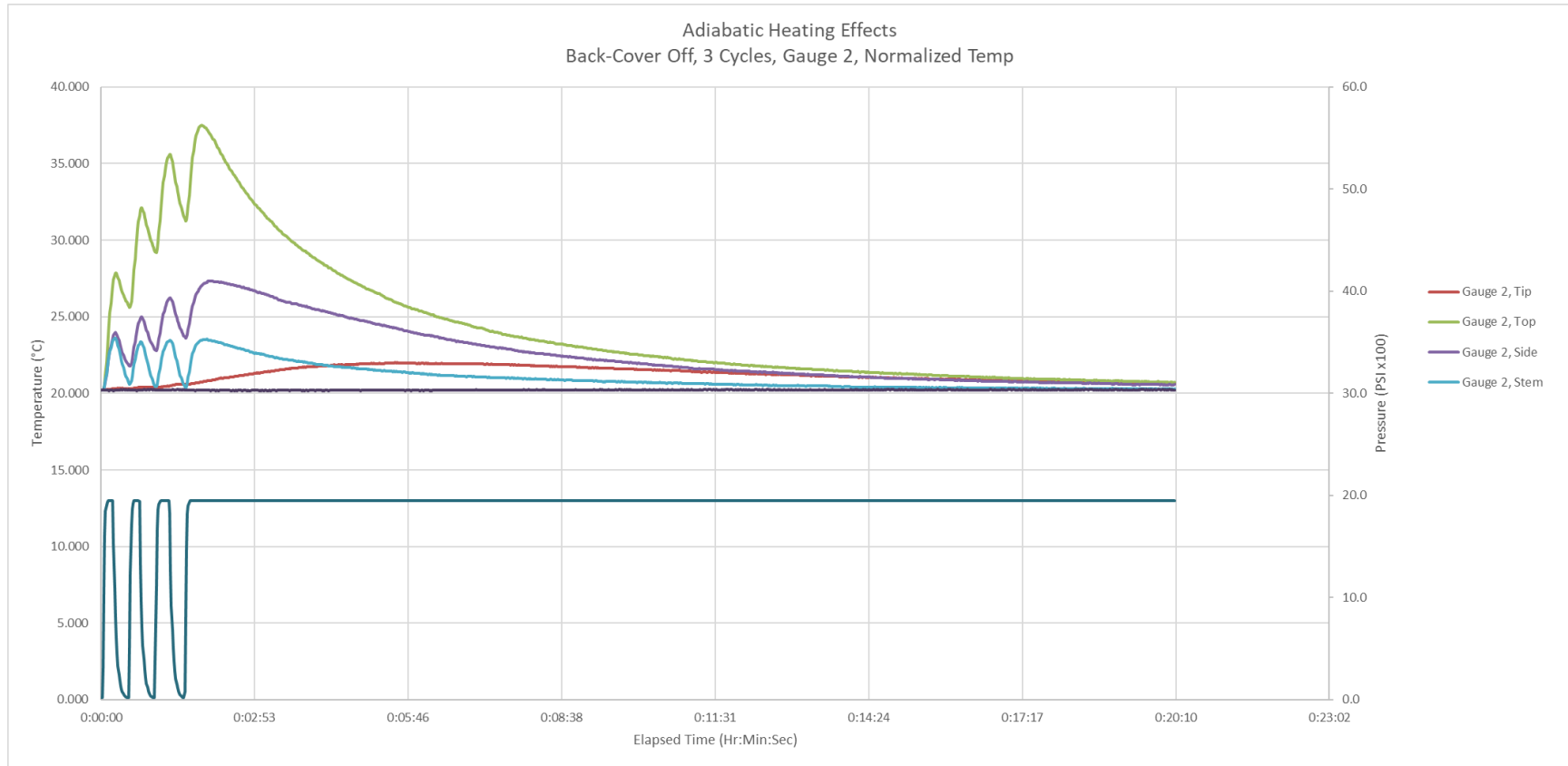


Figure 10: Gauge 2, Run 3

Run 4: Three Cycles, Cover Off, Fan Cooled

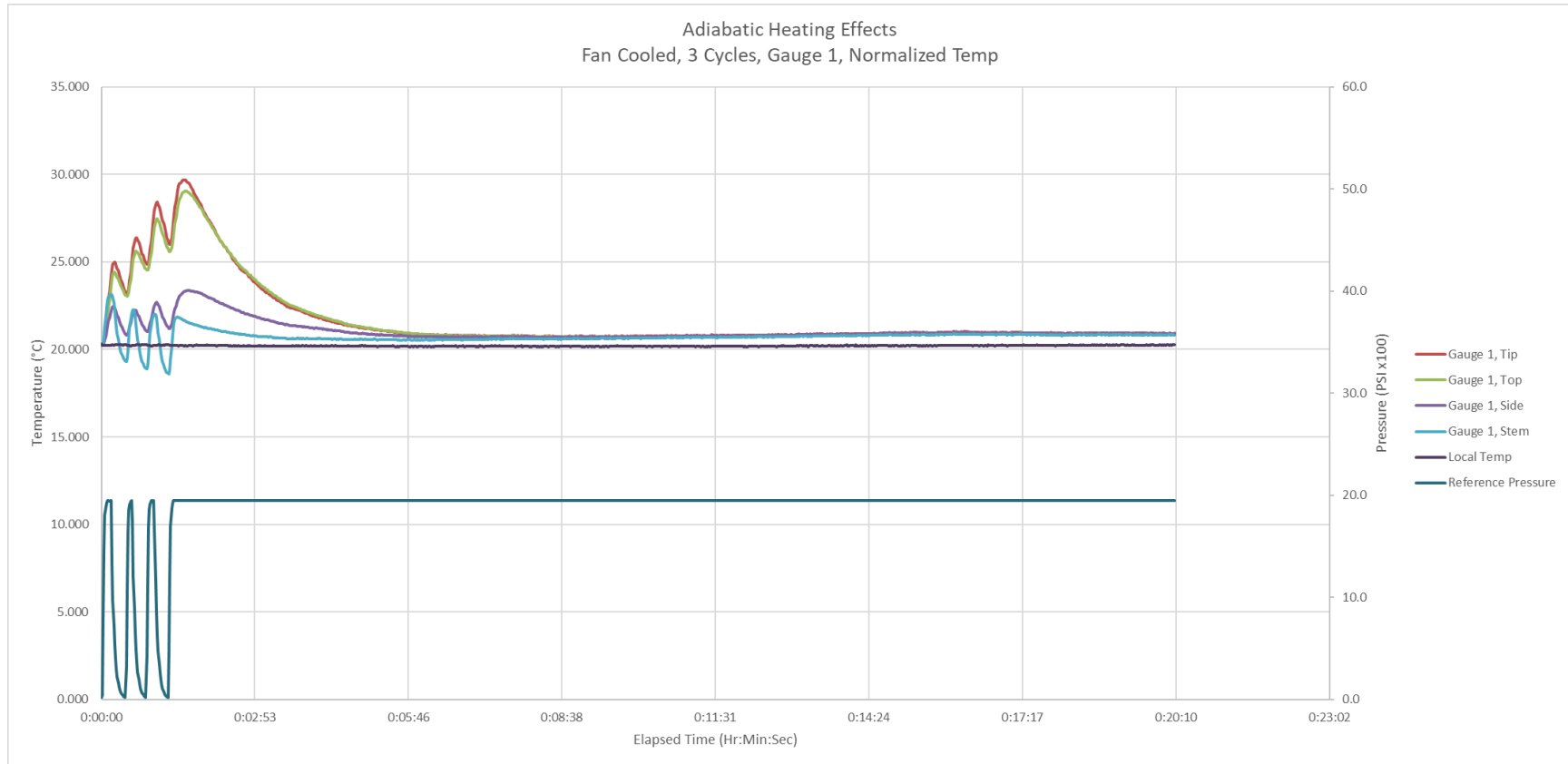


Figure 11: Gauge 1, Run 4

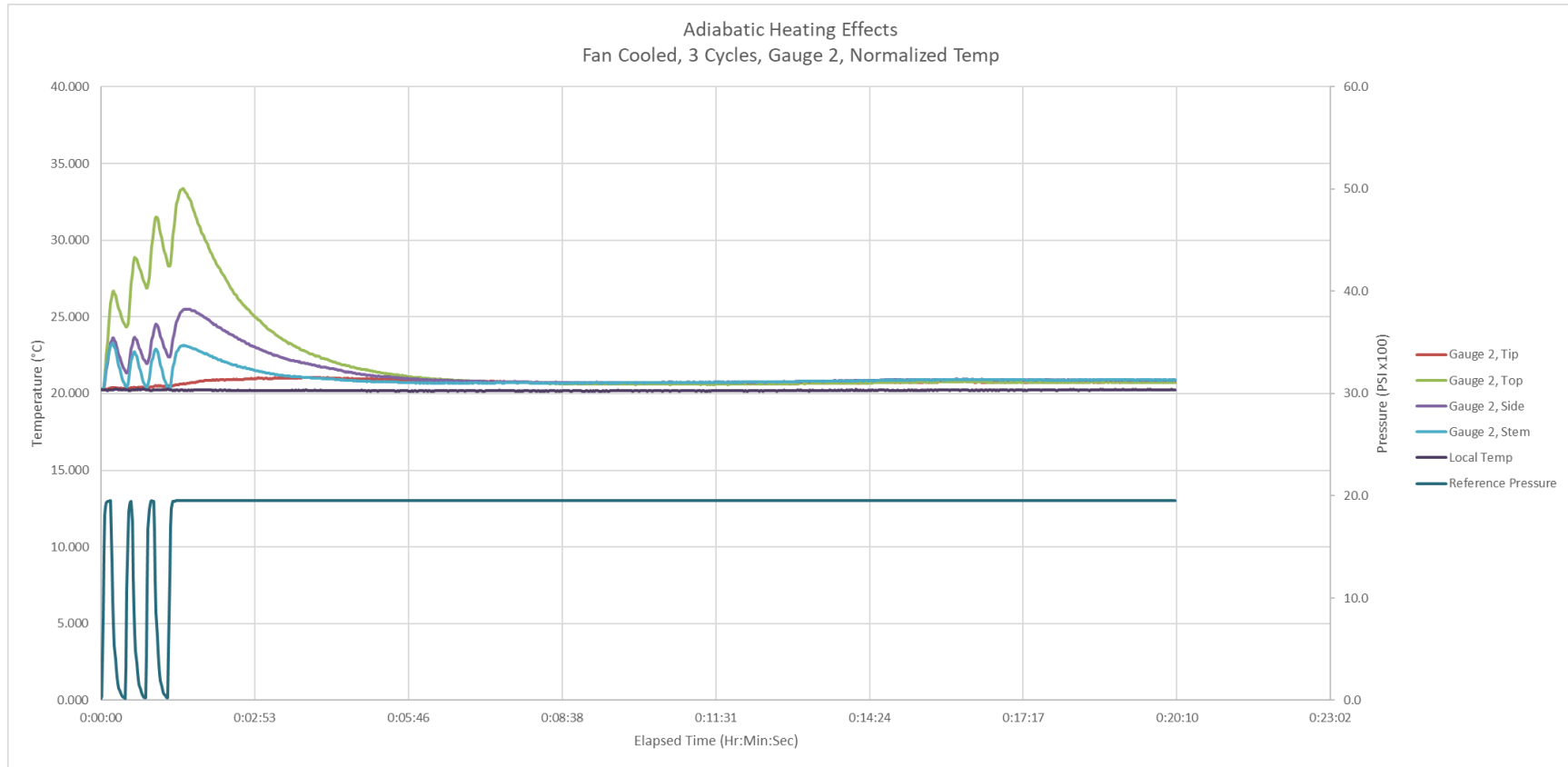


Figure 12: Gauge 2, Run 4

Additional Testing

Fan Cooled Gauge vs. Cover Installed Gauge

In this trial, one gauge had its back-cover installed, while the other gauge was left open and fan cooled. Both gauges were exercised three times and their thermal responses were recorded over 30 minutes. The maximum temperature observed was 36.603°C at the tip thermocouple of the Cover-On gauge (based off raw, non-normalized, data. Figure 13). This was an increase of about 16.174°C from the average local temperature for the duration of the test.

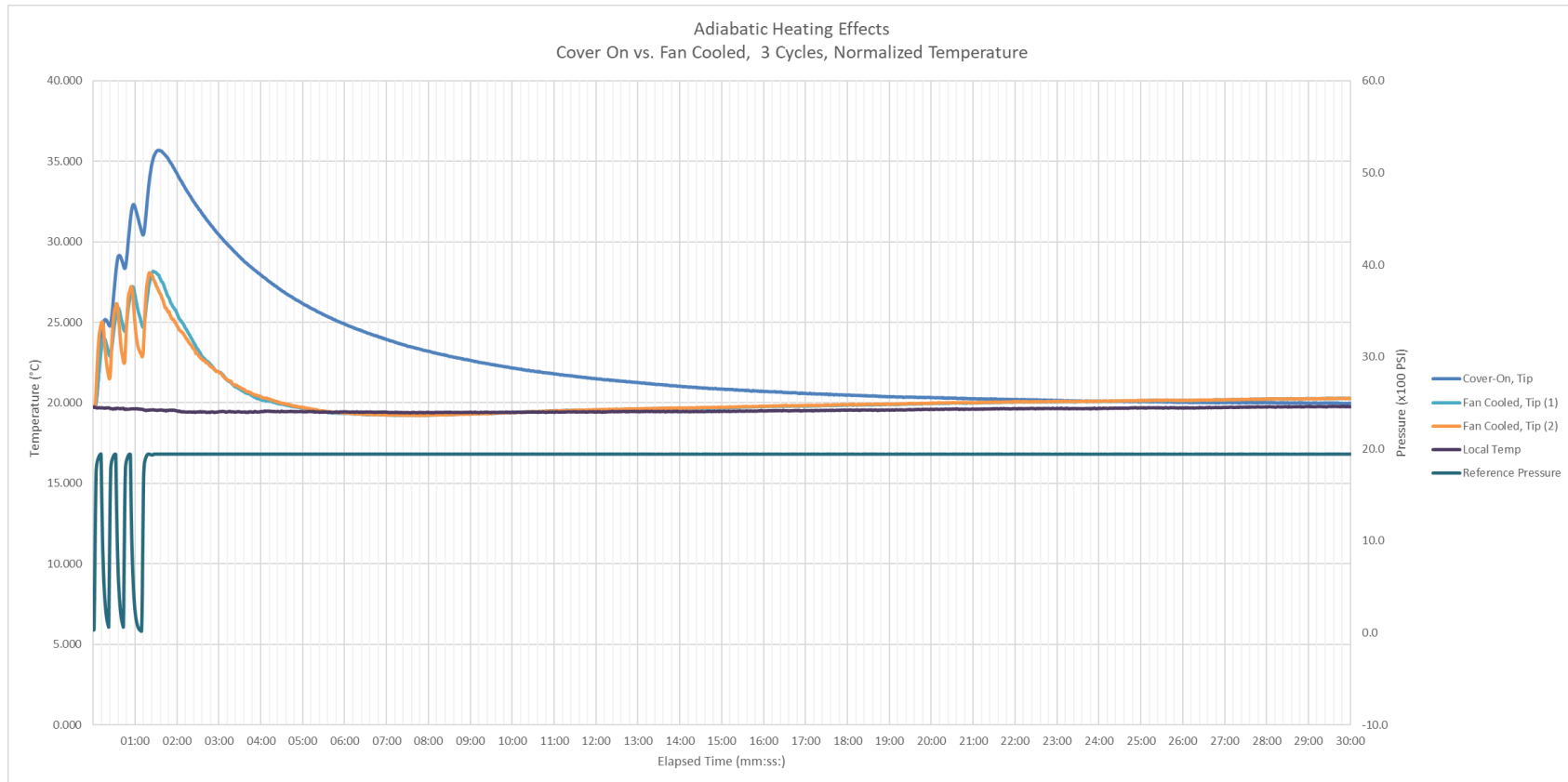


Figure 13: A chart comparing the thermal response of a fan cooled gauge to a cover-installed gauge. This chart shows the response at the tip of the gauge

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Water Trials

The purpose of the water trials are to demonstrate how a fluid-filled gauge does not experience the adiabatic heating effect seen on a gas-filled gauge. The test fluid was distilled water and a hand pump was used to bring the pressure up to span (3000 PSI).

In the No-Cycle trial (Figure 14), the maximum observed temperature across all thermocouples was 19.806 °C, which was 0.669 °C above the average local temperature at the time of testing. As for the Three-Cycle trial (Figure 15), the maximum temperature was 18.899 °C, about 0.729 °C over the average local temperature at the time of testing.

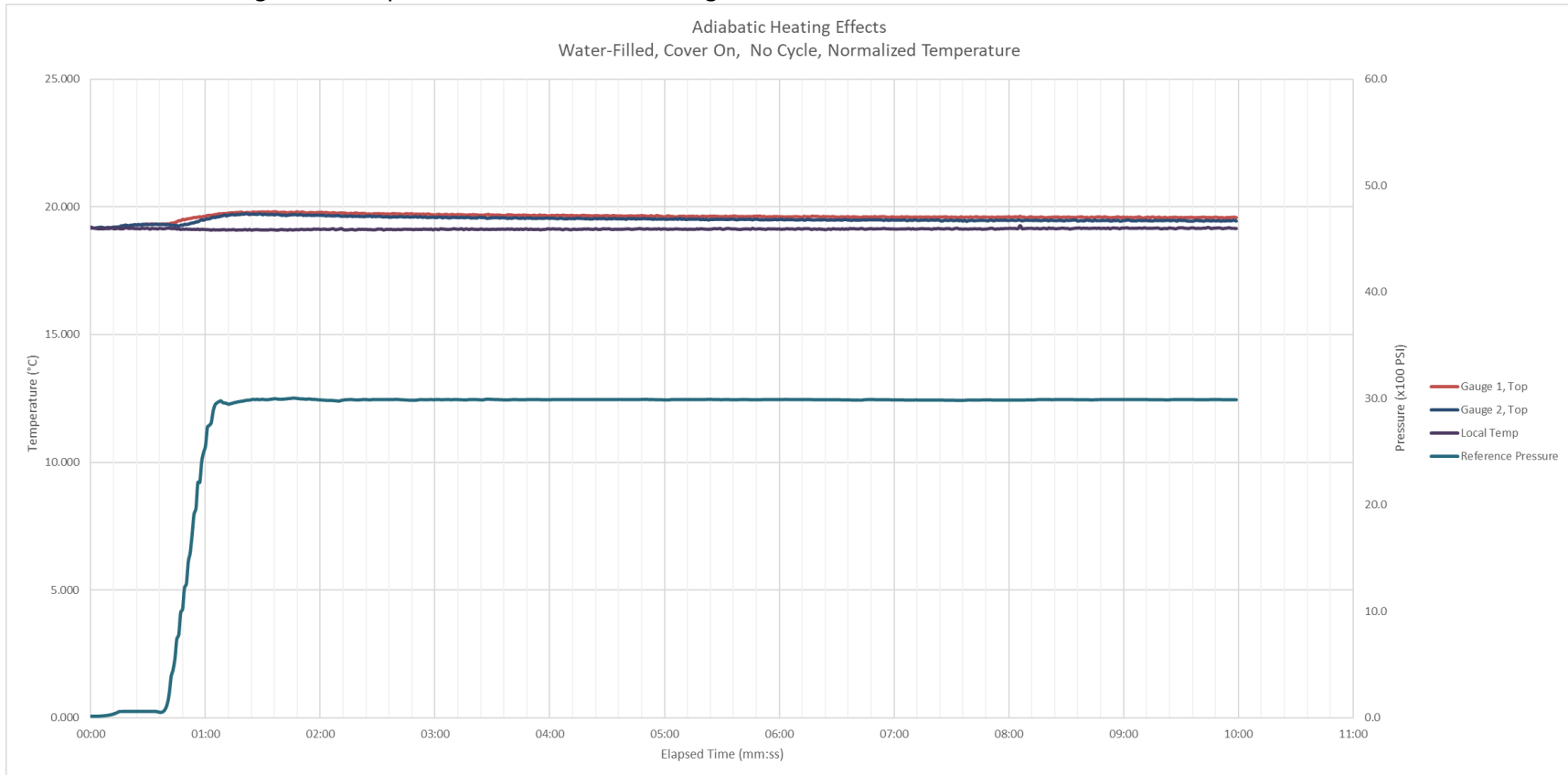


Figure 14: This chart shows the temperature change when pressurizing two water-filled gauges to span (3000 PSI). This chart shows the response at the top of the two gauge tubes.

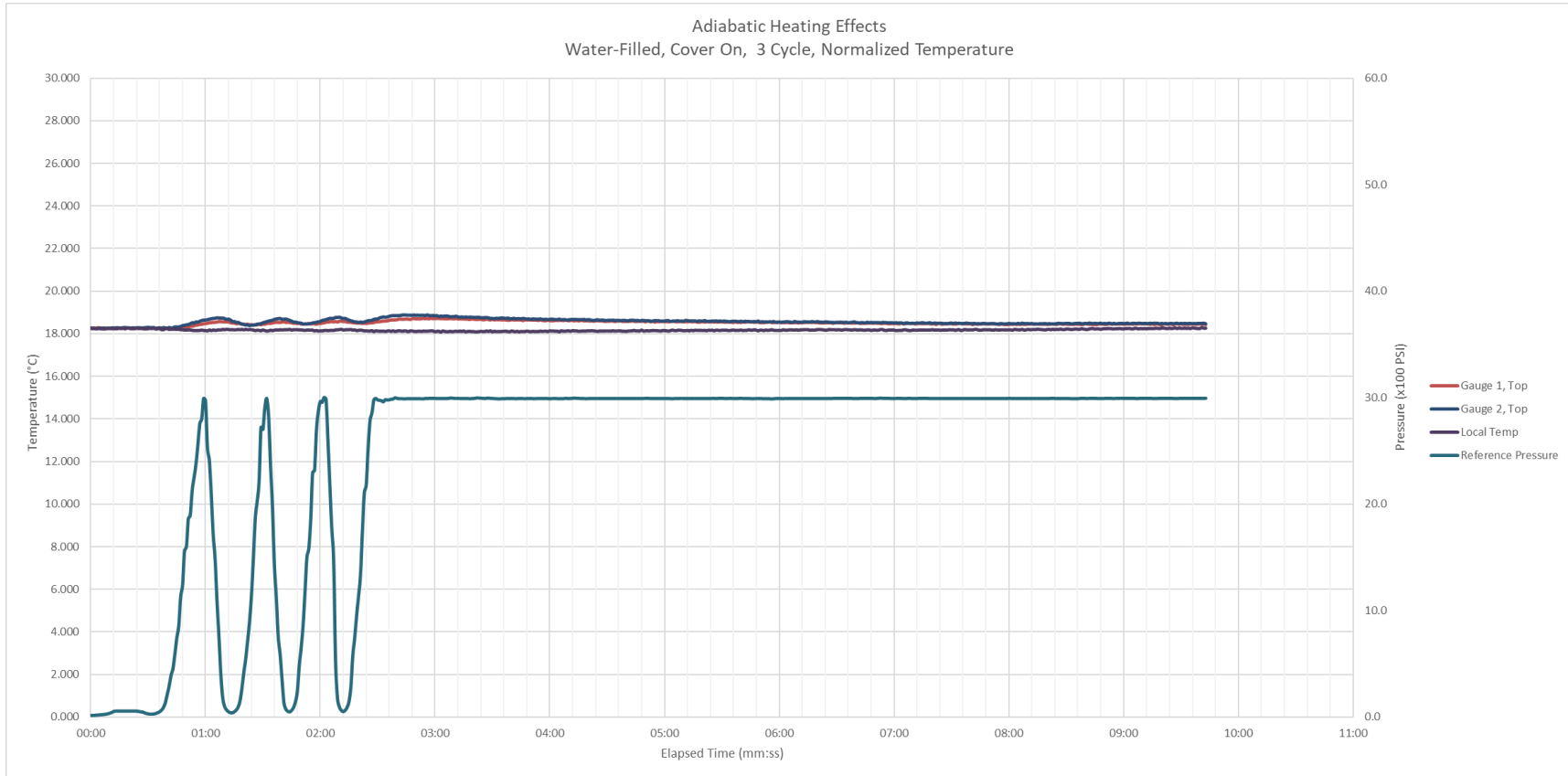


Figure 15: This chart shows the temperature change when first exercising two water-filled gauges three times, and then pressurizing to span (3000 PSI). This chart shows the response at the top of the two gauge tubes.

7. Analysis

Observed Phenomenon

The purpose of this test was to understand the thermal effects associated with using a gas on Heise test gauges. The underlying principle that governs this test is adiabatic heating. For reference: an adiabatic process is one in which heat does not enter or leave the system¹. This adiabatic heating can distort the indicated reading on the test gauge.

When a gas-filled gauge is rapidly pressurized, the pressure controller compresses the gas resting in the tube like a piston compressing a cylinder. The work done on the resting gas not only pressurizes the tube, but also increases the internal energy of the gas (based on the first law of thermodynamics)². This internal energy manifests itself as heat, and because the pressurization of the tube happens so fast, the heat loss through the walls of the bourdon tube is dwarfed by the increase in internal energy. This allows us to assume an adiabatic process while the tube is being pressurized.

An increase in the temperature of the tube leads to two relevant effects, thermal expansion and a change in the modulus of elasticity. When an isotropic metal heats up, it tends to enlarge linearly at a rate defined by its thermal coefficient of expansion. Its modulus of elasticity, or stiffness, lowers as well. A metal with a lower modulus of elasticity tends to stretch further under mechanical forces like pressure. Most of the heating occurred towards the tip of the tube, which is where the indicator linkages connect. Thus, any deformation by the tube near the tip would translate to an offset in the indication. Specially, the indicator should report higher readings than actual if the tube expands outwards.

Back Cover Configurations

As seen in the Results section of this report, the temperature response varies depending on the configuration of the back cover. This is because of the way the heat dissipates from the tube to the environment. If the back cover is on, then the gas inside the gauge (surrounding the tube) is trapped. This still gas will initially take heat from the tube via conduction, but cannot easily transfer this heat out of the gauge. As this trapped gas heats up, it becomes less efficient at removing heat from the tube. Even with the cover off (as seen in Figure 9 and Figure 10), the heat dissipation rate does not improve much. When a fan is added, however, both the maximum temperature and settling time (to room temperature) are significantly reduced (Figure 11 and Figure 12). This is because the fan carries the hot gas away from the tube and room temperature gas towards the tube.

Settling Time

The Fan Cooled Gauge vs. Cover Installed Gauge trial (in the 'Additional Testing' section) was used in determining the time it takes the gauge to return to local temperature. Table 4 shows these results. The settling time starts when steady maximum pressure was reached (about 01:17 into the test) and ends when the thermocouple temperature fell within 5% and 1% of the local temperature. Obviously, these times are not universal, since factors like maximum pressure, pressurization rate, local temperature and even fluid medium will affect the exact settling time. Rather, Table 4 seeks to illustrate that using a fan to cool the gauges is recommended to reduce the wait time between indicator readings.

¹ ("Adiabatic Heating." World of Earth Science. . *Encyclopedia.com*. 4 Jun. 2019 <www.encyclopedia.com>)

² *Adiabatic process*. (2019, April 4). Retrieved from Wikipedia: www.en.wikipedia.org/wiki/Adiabatic_process

Table 4: Settling time of a gauge in different configurations. Both gauges were pressurized to 1950 PSI.

Difference from Local Temp		Settling Time (mm:ss)	
		Cover On	Fan Cooled
1%	0.2°C	27:14	03:51
5%	1.0°C	16:09	02:41

Indicator Movement

One additional analysis performed on the Fan vs. Cover trial was a measurement of the total indicator movement as the test gauge returned to room temperature. Table 5 lists the indicator readings from the moment the system reached a steady pressure of 1950 PSI to after 30 minutes, when the gauges settle. The covered gauge reported a larger pressure reading than the fan-cooled gauge. This was expected, as the covered gauge experienced a larger maximum temperature. After 30 minutes of cooling, both gauges were within three psi of target, but the covered gauge's indicator travelled twice as far as the fan-cooled counterpart. Note that although both gauges settled on readings that were in spec, the initial indications on both gauges were more than 0.1% off from true pressure. This underpins the significance of adiabatic heating on accuracy.

Table 5: A table mapping indicator movement due to adiabatic heating.

Readings	Observed Pressure (PSI)			
	Cover On	Error (%F.S.)	Fan Cool	Error (%F.S.)
Initial	1959	0.30%	1956	0.20%
After 5 min	1952	0.07%	1952	0.07%
After 10 min	1950	0.00%	1951	0.03%
After 30 min	1947	-0.10%	1950	0.00%
Total Movement	12	-	6	-



Figure 16: The indication is offset from 1950 PSI after pressurizing to span.

Water-Filled Gauges

At Ashcroft, the test gauges are calibrated on water. Liquids feature larger heat capacities (i.e. it takes more energy to raise its temperature) than gas. Additionally, liquids are better conductors of heat, and can dissipate the heat to the tube much faster than gas. These properties become apparent in Figure 14 and Figure 15. In the three-cycle water trial, the highest temperature drift recorded was only 0.729°C, a stark contrast to the 16.174°C drift observed in the three-cycle gas trial (Figure 13) with the same back-cover conditions. Additionally, the water-filled gauges were pressurized to full span (3000 PSI), whereas the gas trial could only reach 66% of that. Therefore, one of the best methods to reduce the adiabatic heating effect is to switch to a liquid medium.

Gauge 2 Tip Thermocouple

In the Results section of this report, the tip thermocouple for gauge 2 reported surprisingly muted temperatures in all four trials. Observing the response of the gauge 1 tip thermocouple, and feeling the tip of the tube during a test suggested that the gauge 2 thermocouple was not behaving properly. To remedy this, the thermocouple was reattached to the tube, the electrical connections were checked, and a second thermocouple was placed adjacent to the tip (as seen in Figure 13). As expected, the thermocouple began to function correctly in the Fan Cooled Gauge vs. Cover Installed Gauge test. Therefore, the tip response should be disregarded in Figure 6, Figure 8, Figure 10, and Figure 12.

8. Conclusions

Based on the results obtained in this test:

- Rapidly pressurizing the test gauges using gas results in an increase in the temperature of the Bourdon tube.
- The increased tube temperature causes the gauge to indicate a higher pressure than actual.
- The adiabatic heating effect is significant enough such that the indication error, immediately after pressurizing, can exceed the accuracy rating of the gauge.
- Exercising (pressurizing, then depressurizing in rapid succession) the gauges before holding at a pressure generates more heat than pressurizing directly.
- Removing the back cover does not appear to cool the gauges much faster than if left on. Fan cooling the gauges with the back cover removed, however, cools the gauges significantly faster.
 - Fan cooling also reduces the maximum temperature reached during pressurization.
- Using distilled water almost eliminates the adiabatic heating effect.