

A Network Manageable Advanced Gas Sensor

EPA Workshop on SF₆ Emission Reduction Strategies
Latest Advances in Leak Detection, Monitoring, and Repair
May 6–7, 2014

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Advanced?

Features and Benefits

Developed as an extension of a proven electromechanical design



Retain the benefits of a widely accepted density switch, easy installation, reliable operation

Accurate leak rate determination and tracking



Report instantaneous leak rate, time to alarm, time to lockout

Network interfaced



Remotely configure operation, access real time and stored data, **firmware updates**

Store years of data



Enable edge analytics, long term analysis, USB flash access, more

Embedded web server



Works with any PC, laptop, tablet, smart phone, with any web browser

Low pressure range operation (< 5 psig)



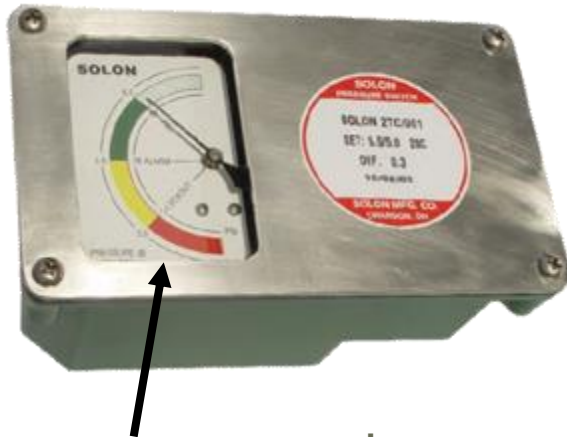
Know if the breaker operates under inadequate fill conditions

Advanced? Features and Benefits cont'd

- Simple 3-LED display → Operation signals status and density with 1 psi – even without gauge
- Acoustic monitoring → Capture breaker events: operation, compressor run, other activity
- Digital signal processing → Filter banks with each data path tuned to trend specific variables
- Virial equation computation → Accurately account for the non-ideal behavior of the target gas
- Thermal gradient estimation → Enhanced accuracy, detect self-heating, infer contact resistance
- Extensible data acquisition platform (DAQ) → Add sensors, digital and analog outputs, measure and integrate CT's

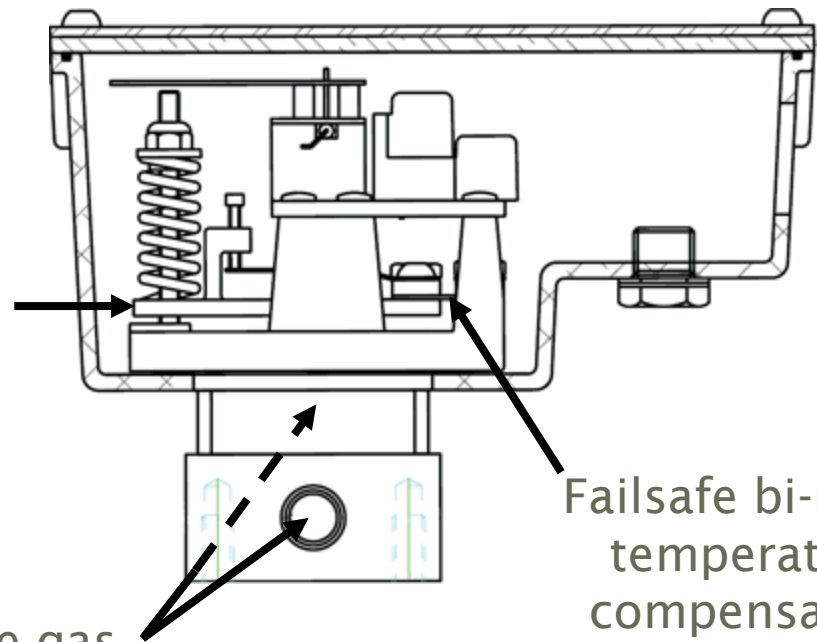
Platform

The advanced sensor is based upon a proven electro-mechanical density switch.



Integral density gauge

Lever actuates up to four SPDT switches adjusted for fill, alarm, and lockout density conditions



Reliable gas interface

Failsafe bi-metal temperature compensation

A typical intrinsic configuration is shown.
Bulb type and other styles available.

Electronics

Integrated electronics provide high resolution leak detection and network manageability. User acceptance and familiarity are preserved.



All electromechanical features are retained including integral density gauge

Foolproof circular connector or pluggable terminal



Redundant displacement measurement

SPDT sense interface

Flexible communications interface

Atmospheric pressure sensor

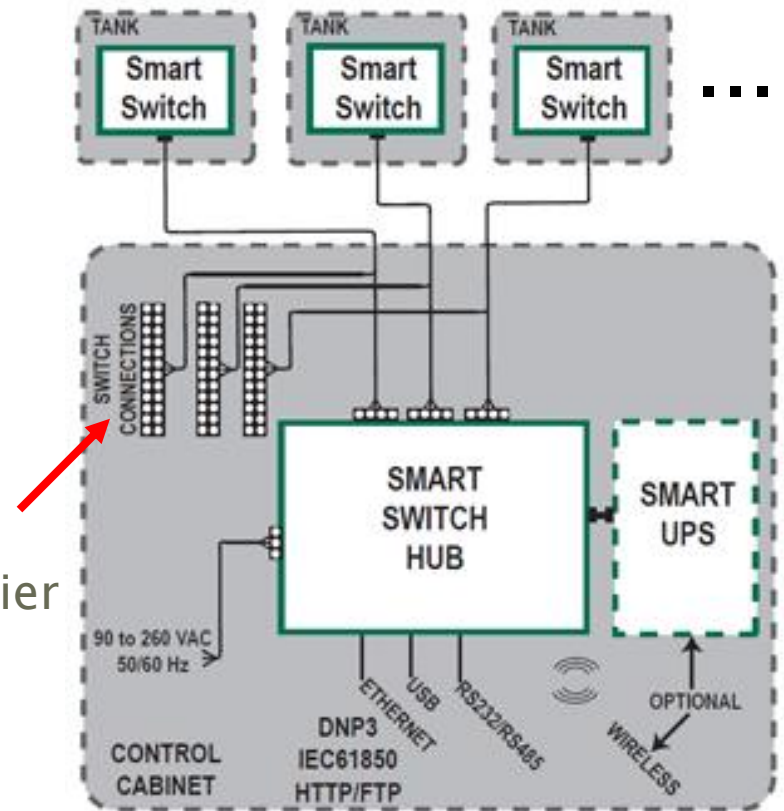
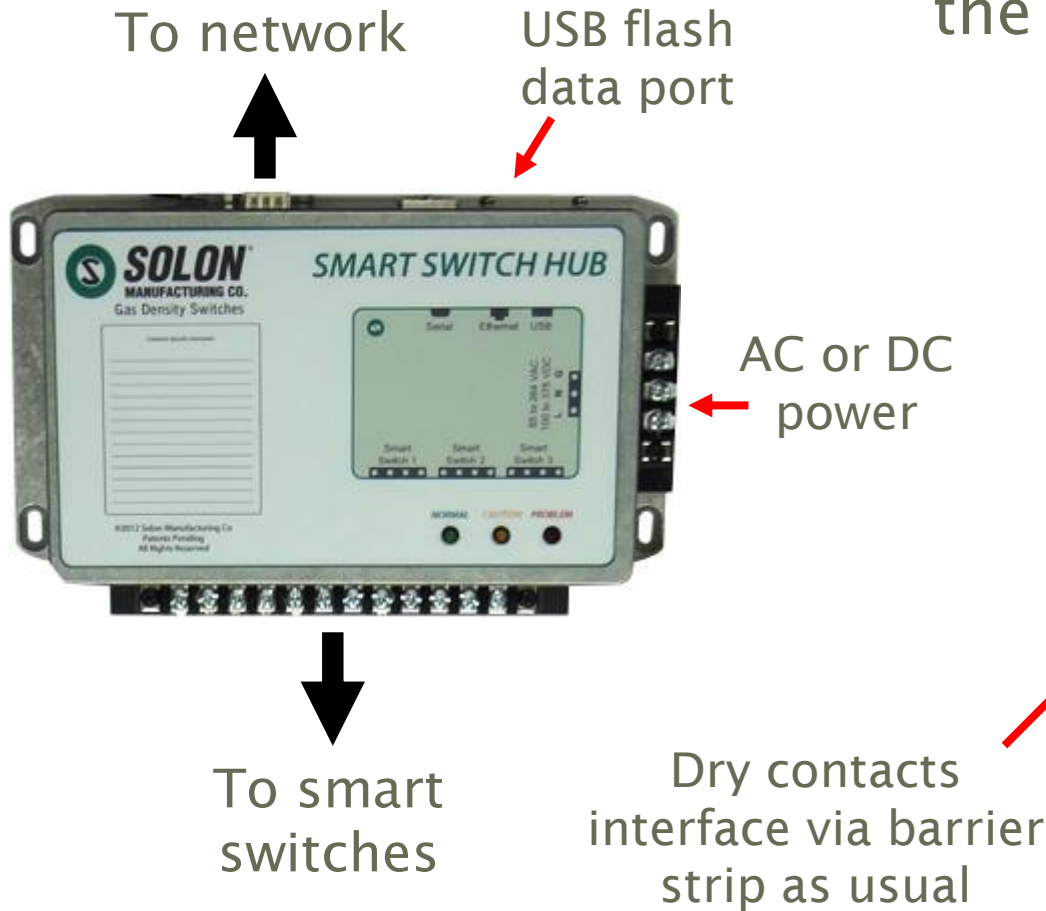
Micro-power microcontroller

Redundant temperature measurement

Robust printed circuit assembly

Hub included

Hub (RTU) interfaces multiple advanced gas sensors and the user's SCADA network.



Status



Butler, PA
38 kV, 1200 A
6.8 kg SF₆
~0.17 m³
75 psig at 21.1 °C

The advanced sensor has passed type tests, cold test, and is currently completing one-year field testing



Birmingham, AL
245 kV, 3000 A
53 kg SF₆
~1.4 m³
71 psig at 20 °C

Web browser view

SSH - Smart Switch Hub - Solon Manufacturing - Mozilla Firefox

File Edit View History Bookmarks Tools Help

SSH - Smart Switch Hub - Solon Manufacturing

The interface displays four pressure gauges and two temperature tables. The gauges show pressure levels with color-coded zones (green, yellow, red) and labels for '71 FILL', '64 ALARM', and '57 LOCKOUT'. The temperature tables show readings for various locations in degrees Celsius and Fahrenheit.

RTC	°C	°F
1	15	59
2	16.8	62.3
3	16.9	62.4
4	15.1	59.2
5	15	58.9
6	15.9	60.7

RTC	°C	°F
1	28.6	83.5
2	29.9	85.8
3	29.6	85.2
4	30.5	86.9
5	30.6	87.1
6	35.7	96.3

SW 1 2 3 4
HO NC 10 10 10

(modtech) Gauge #1

SW 1 2 3 4
HO NC 01 10 10

(butler) 2TC #1

SW 1 2 3 4
HO NC 01 10 10

(butler) DAO #1

SW 1 2 3 4
HO NC 10 10 10

(birmingham) 2TC #1

SW 1 2 3 4
HO NC 00 00 00

(birmingham) DAO #1

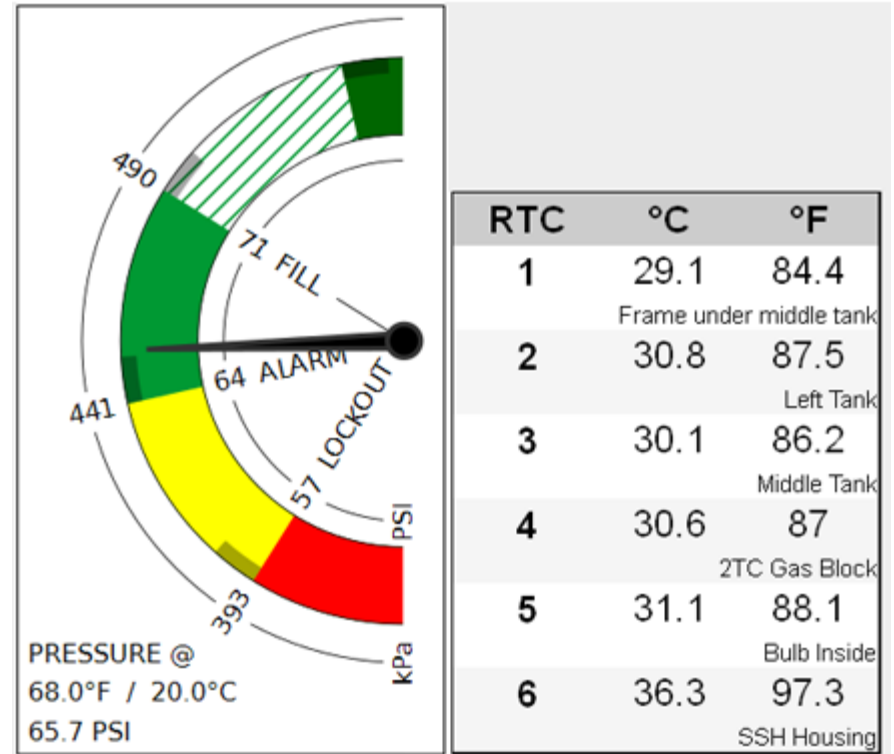
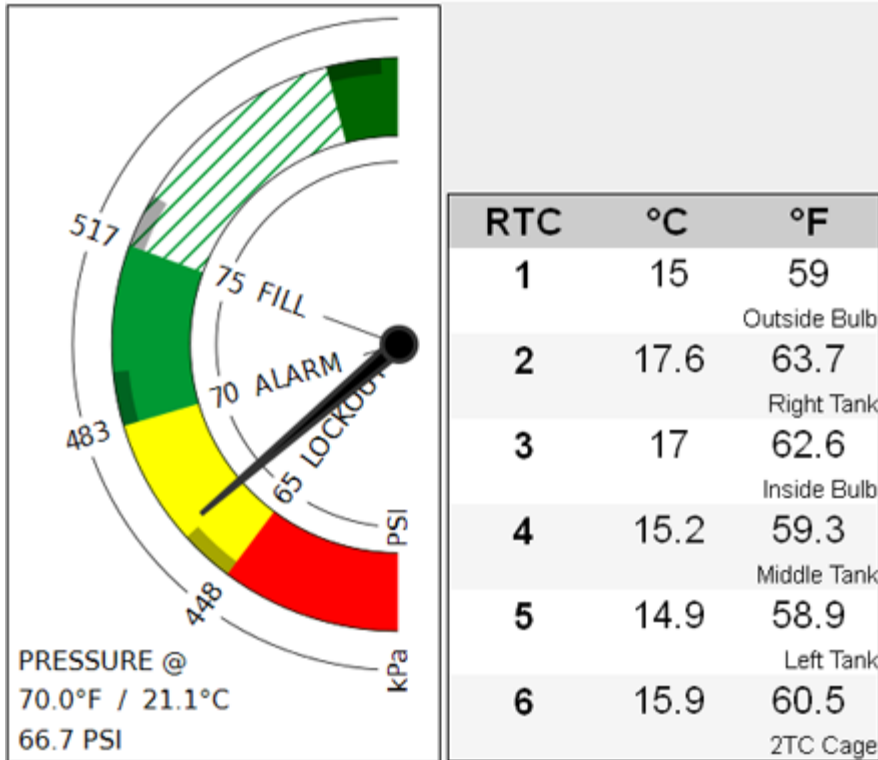
- + Device Summary
- + Leak Detection
- + Application Configuration
- + Profile Configuration
- + Device Configuration
- + Raw Data
- + Pressure
- + Displacement
- + Temperature Measurements
- + Contact Information
- + Sensor Information

Butler

Birmingham

Web

Real time contact states



SW	1	2	3	4
NO/NC	01	10	10	XX

(butler) 2TC #1

1

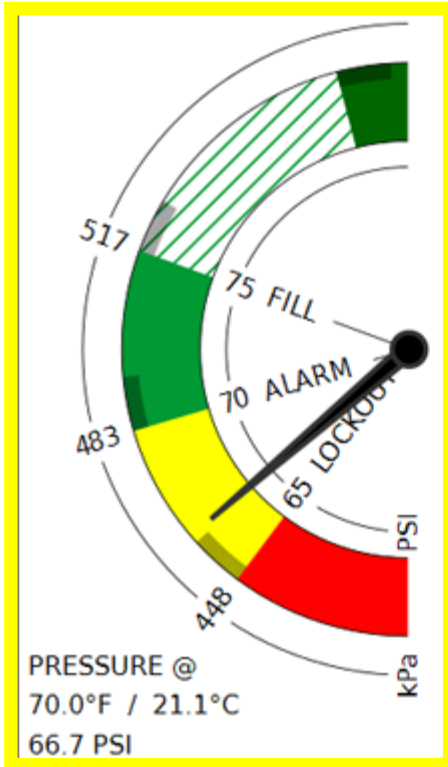
SW	1	2	3	4
NO/NC	10	10	10	XX

(birmingham) 2TC #1

2

Web

Temperature corrected pressure and alarm status



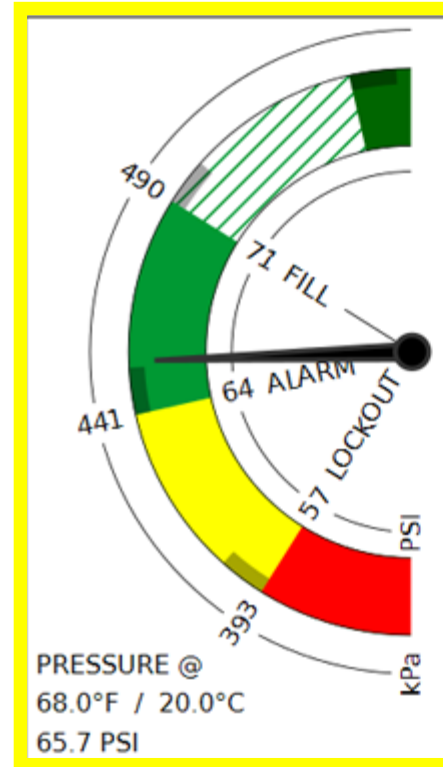
RTC	°C	°F
1	15	59
		Outside Bulb
2	17.6	63.7
		Right Tank
3	17	62.6
		Inside Bulb
4	15.2	59.3
		Middle Tank
5	14.9	58.9
		Left Tank
6	15.9	60.5
		2TC Cage

SW	1	2	3	4
NO/NC	01	10	10	XX

(butler) 2TC #1

SW	1	2	3	4
NO/NC	01	10	10	XX

(butler) DAQ #1



RTC	°C	°F
1	29.1	84.4
		Frame under middle tank
2	30.8	87.5
		Left Tank
3	30.1	86.2
		Middle Tank
4	30.6	87
		2TC Gas Block
5	31.1	88.1
		Bulb Inside
6	36.3	97.3
		SSH Housing

SW	1	2	3	4
NO/NC	10	10	10	XX

(birmingham) 2TC #1

SW	1	2	3	4
NO/NC	00	00	00	XX

(birmingham) DAQ #1

1

2

Web management

Device Summary

SSH - Smart Switch Hub - Solon Manufacturing - Mozilla Firefox

File Edit View History Bookmarks Tools Help

SSH - Smart Switch Hub - Solon Manufacturing +

Pressure Gauge: 490, 71 FILL, 64 ALARM, 441, 57 LOCKOUT, 393, PSI, kPa. PRESSURE @ 68.0°F / 20.0°C, 66.0 PSI

RTC	°C	°F
1	30.3	86.5
Frame under middle tank		
2	32	89.5
Left Tank		
3	31.1	88.1
Middle Tank		
4	30.4	86.7
2TC Gas Block		
5	32	89.6
Bulb Inside		
6	37.4	99.3
SSH Housing		

SW 1 2 3 4 SW 1 2 3 4
HO/IC 10 10 10 XX HO/IC 00 00 00 XX
2TC#1 DAQ#1

Device Summary

Power **On**

Temperature (C) 32.8

Gauge Pressure (psig) 70.1

Gas Mass (kg) 49.4

Alarm State Fill **LEAK**

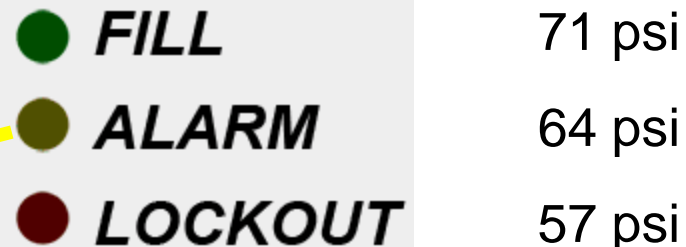
1 2 3 4 5

LED indication

Device Summary

Even without a gauge, a good indication of density can be noted by observing the LEDs on the smart switch

Four flashes of the yellow LED (3+1) indicate a temperature corrected pressure on the order of 3-4 psi below alarm level, i.e. 60 to 61 psi.

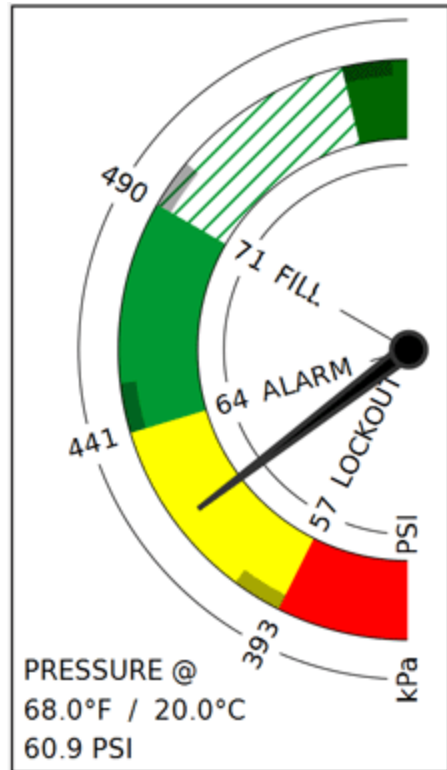


● FILL	71 psi
● ALARM	64 psi
● LOCKOUT	57 psi

A quick flash on the next lower LED indicates a leak condition has been detected.

LED indication

Device Summary



- FILL**
- ALARM**
- LOCKOUT**

71 psi

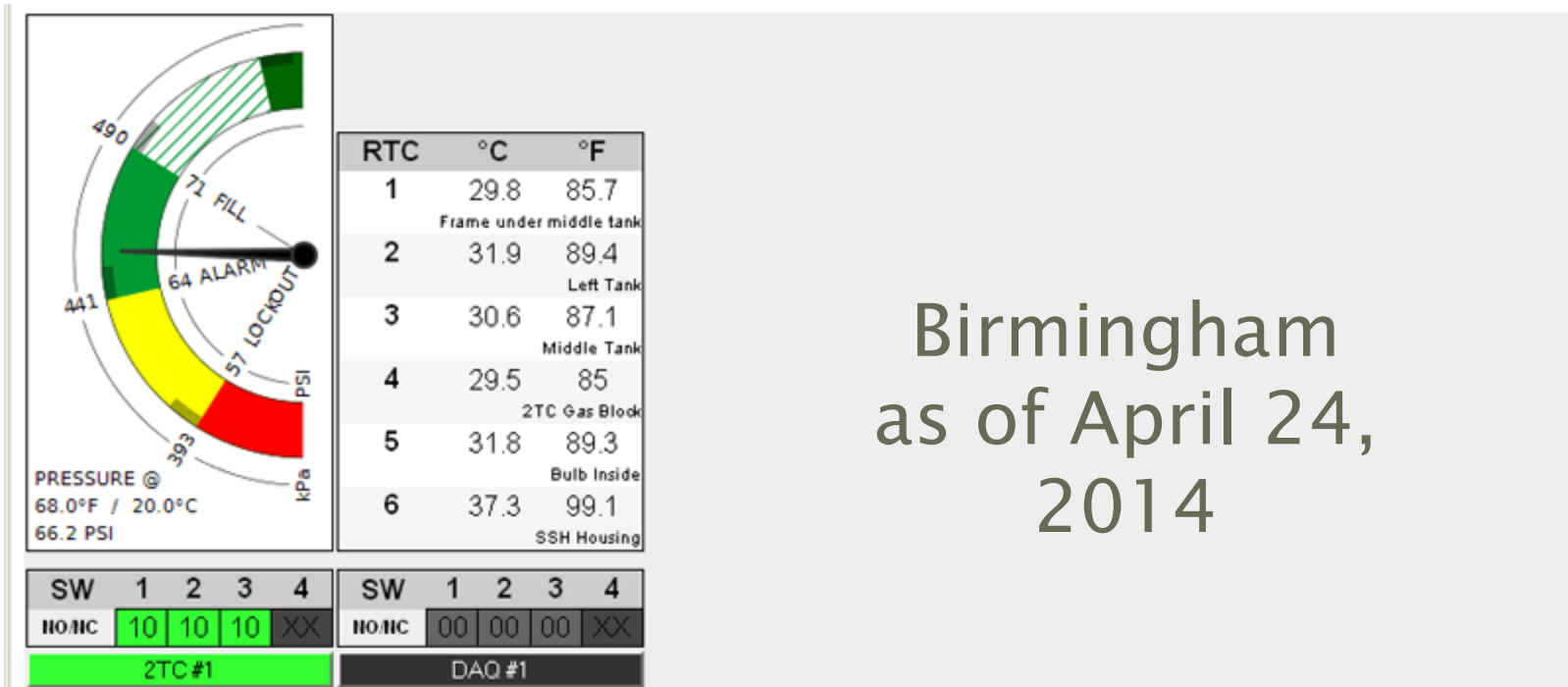
64 psi

57 psi

SW	1	2	3	4
NO/NC	10	10	01	XX
Gauge #1				

Web management

Leak Detection



Birmingham
as of April 24,
2014

+ Device Summary

Leak Detection

Current Leak Rate (g/d)

19

Time to alarm

58 Days
Sat Jun 21 2014

Time to lockout

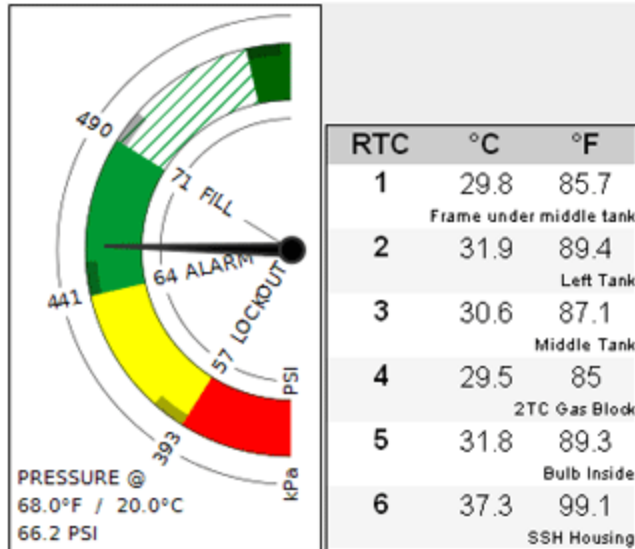
301 Days
Thu Feb 19 2015

1

2

3

Leak rate

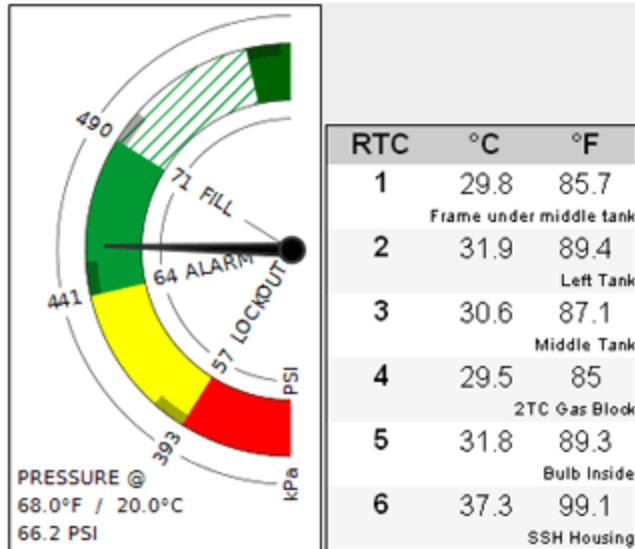


SW	1	2	3	4	SW	1	2	3	4
NO/NC	10	10	10	XX	NO/NC	00	00	00	XX
2TC #1					DAQ #1				

+ Device Summary

Leak Detection		
Current Leak Rate (g/d)	Time to alarm	Time to lockout
19	58 Days Sat Jun 21 2014	301 Days Thu Feb 19 2015

Time to alarm



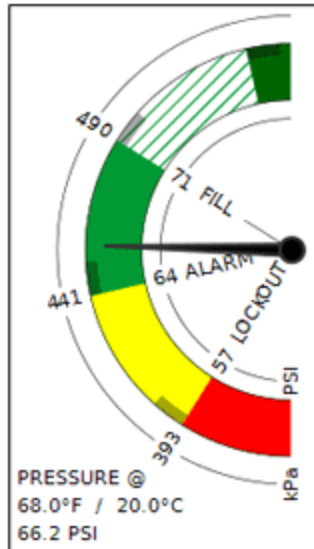
SW	1	2	3	4
NO/NC	10	10	10	XX
2TC #1				

SW	1	2	3	4
NO/NC	00	00	00	XX
DAQ #1				

+ Device Summary

Leak Detection		
Current Leak Rate (g/d)	Time to alarm	Time to lockout
19	58 Days Sat Jun 21 2014	301 Days Thu Feb 19 2015

Time to lockout



RTC	°C	°F
1	29.8	85.7
Frame under middle tank		
2	31.9	89.4
Left Tank		
3	30.6	87.1
Middle Tank		
4	29.5	85
2TC Gas Block		
5	31.8	89.3
Bulb Inside		
6	37.3	99.1
SSH Housing		

SW	1	2	3	4
NO/NC	10	10	10	XX
2TC #1				

SW	1	2	3	4
NO/NC	00	00	00	XX
DAQ #1				

+ Device Summary

Leak Detection

Current Leak Rate (g/d)

19

Time to alarm

58 Days
Sat Jun 21 2014

Time to lockout

301 Days
Thu Feb 19 2015

Web

Application Configuration

1

SW	1	2	3	4	1	2	3	4
NO/NC	10	10	10	XX	00	00	XX	
2TC #1				DAQ #1				

+ Device Summary
+ Leak Detection

Application Configuration

Gas Ref Temp (C)	Operate (psig)	Alarm (psig)	Lockout (psig)	Overpressure Relief (psig)	Breaker Nom V (kV)	Breaker Nom Inter I (kA)
20	71 52.8687 kg	64 48.1805 kg	57 43.5653 kg	78 57.6334 kg	245	3
Atmosphere (psi)	Operate Deadband (psig)	Alarm Deadband (psig)	Lockout Deadband (psig)	Overpressure Relief Deadband (psig)	Tank Volume (m^3)	Operate Gas Mass (kg)
14.4	1 53.5446 kg	1 48.8457 kg	1 44.2203 kg	1 58.3206 kg	1.3835	49.55
Leak Alarm (g/d)		SW Threshold (n)	Reading Averages	Gas Type	Cal Const 1	Cal Const 2
0.25		10	5	SF6	0.7	0

2

3

These parameters are set by the factory to match the switch setpoints

Web

Atmospheric Pressure Sensor

SW	1	2	3	4	SW	1	2	3	4
II01IC	10	10	10	XX	II01IC	00	00	00	XX
2TC #1					DAQ #1				

- + Device Summary
- + Leak Detection
- + Application Configuration
- + Profile Configuration
- + Device Configuration
- + Raw Data

Pressure

ROS Gauge Inc (psi)	ROS Gauge Dec (psi)	ROS Gauge Avg (psi)	ROS Absolute (psi)	TCor Avg (psi)
68.6	68.2	68.6	82.8	66.2
HES Gauge Inc (psi)	HES Gauge Dec (psi)	HES Gauge Avg (psi)	HES Absolute (psi)	Atmosphere Pres (psi)
71.6	71.3	71.6	85.8	14.25

1

Data log

Set log rates for each switch
Export data to spreadsheet

Profile Configuration

Label	Data Update Interval (s)	Data Commit Interval (s)
Gauge #1	1	10
Gauge #2	1	10
Gauge #3	1	10

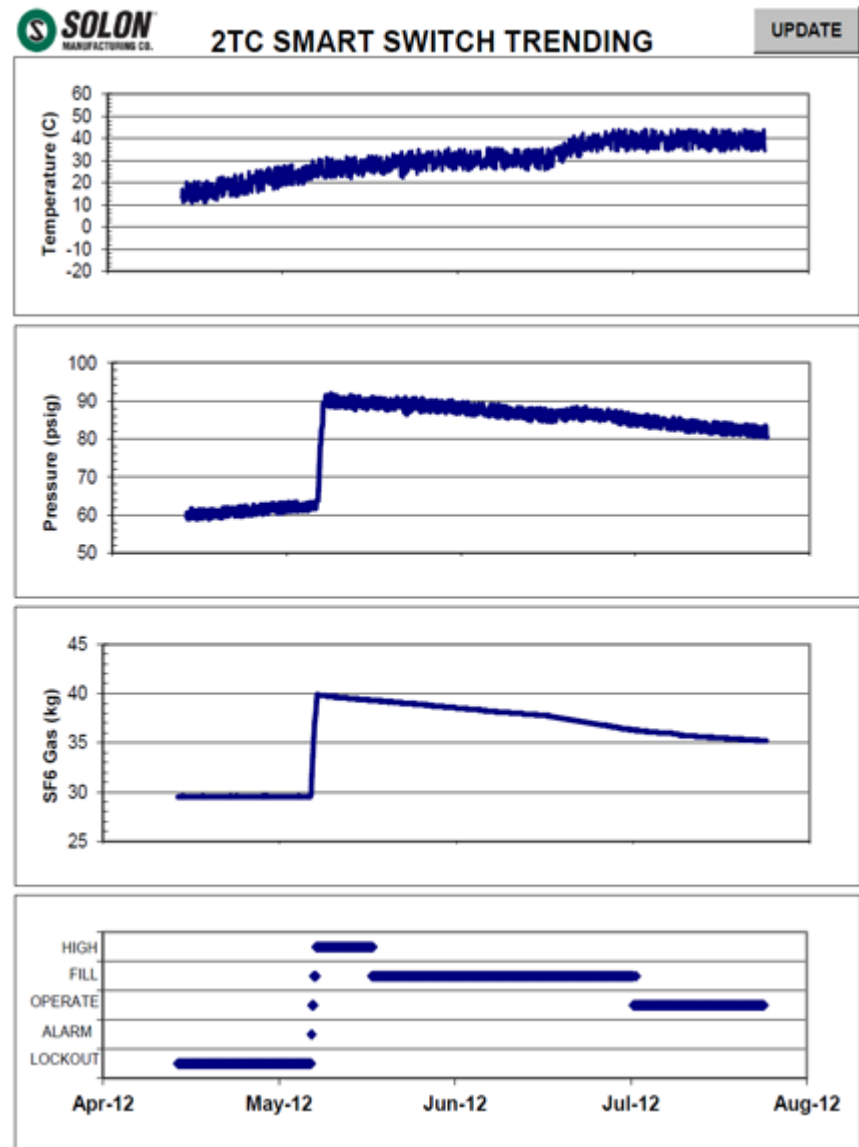
Data is logged for each switch, for years, ASCII format, spreadsheet compatible

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV	AW	AX	A	A	A	A
448	1371844166	0	64	1	10	4	1	1	1838	1842	1827	1827	93	201	1677	3113	0	1351	0	0	0	0	0	0	0	0	53	2100	2061	2112	157	2202	2070	2215	63	2111	2109	2114	135	2182	2089	2211	61	2021	1961	2115	151	2196	2068	2208	3	3	0	0
449	1371844167	0	64	1	10	4	1	1	1838	1842	1827	1827	92	201	1678	3112	0	1351	0	0	0	0	0	0	0	0	53	2100	2061	2112	157	2202	2070	2215	63	2111	2109	2114	135	2182	2089	2211	61	2021	1961	2115	151	2196	2068	2208	3	3	0	0
450	1371844168	0	64	1	10	4	1	1	1838	1842	1827	1827	92	200	1677	3112	0	1351	0	0	0	0	0	0	0	0	53	2100	2061	2112	157	2202	2070	2215	63	2111	2109	2114	135	2182	2089	2211	61	2021	1961	2115	151	2196	2068	2208	3	3	0	0
451	1371844169	0	64	1	10	4	1	1	1838	1842	1827	1827	92	200	1678	3112	0	1351	0	0	0	0	0	0	0	0	53	2100	2061	2112	157	2202	2070	2215	63	2111	2109	2114	135	2182	2089	2211	61	2021	1961	2115	151	2196	2068	2208	3	3	0	0
452	1371844170	0	64	1	10	4	1	1	1837	1842	1827	1827	2175	2415	1677	3112	0	1351	0	0	0	0	0	0	0	0	53	2100	2061	2112	157	2202	2070	2215	63	2111	2109	2114	135	2182	2089	2211	61	2021	1961	2115	151	2196	2068	2208	3	3	0	0
453	1371844171	0	64	1	10	4	1	1	1837	1842	1827	1827	2177	2415	1678	3112	0	1351	0	0	0	0	0	0	0	0	53	2100	2061	2112	157	2202	2070	2215	63	2111	2109	2114	135	2182	2089	2211	61	2021	1961	2115	151	2196	2068	2208	3	3	0	0
454	1371844172	0	64	1	10	4	1	1	1837	1842	1827	1827	2180	2417	1678	3112	0	1351	0	0	0	0	0	0	0	0	53	2100	2061	2112	157	2202	2070	2215	63	2111	2109	2114	135	2182	2089	2211	61	2021	1961	2115	151	2196	2068	2208	3	3	0	0
455	1371844173	0	64	1	10	4	1	1	1837	1842	1827	1827	2181	2417	1678	3112	0	1351	0	0	0	0	0	0	0	0	53	2100	2061	2112	157	2202	2070	2215	63	2111	2109	2114	135	2182	2089	2211	61	2021	1961	2115	151	2196	2068	2208	3	3	0	0
456	1371844174	0	64	1	10	4	1	1	1837	1842	1827	1826	2179	2420	1678	3113	0	1351	0	0	0	0	0	0	0	0	53	2100	2061	2112	157	2202	2070	2215	63	2111	2109	2114	135	2182	2089	2211	61	2021	1961	2115	151	2196	2068	2208	3	3	0	0
457	1371844175	0	64	1	10	4	1	1	1837	1842	1827	1826	2178	2421	1678	3112	0	1351	0	0	0	0	0	0	0	0	52	2097	1980	2106	154	2198	2069	2216	63	2111	2105	2113	136	2184	2164	2212	62	2024	1964	2113	157	2204	2115	2219	3	3	0	0
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460	1371844178	0	64	1	10	4	1	1	1837	1842	1827	1826	2180	2419	1678	3113	0	1351	0	0	0	0	0	0	0	0	52	2097	1980	2106	154	2198	2069	2216	63	2111	2105	2113	136	2184	2164	2212	62	2024	1964	2113	157	2204	2115	2219	3	3	0	0
461	1371844179	0	64	1	10	4	1	1	1837	1841	1827	1826	2180	2420	1678	3112	0	1351	0	0	0	0	0	0	0	0	52	2097	1980	2106	154	2198	2069	2216	63	2111	2105	2113	136	2184	2164	2212	62	2024	1964	2113	157	2204	2115	2219	3	3	0	0
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464	1371844182	0	64	1	10	4	1	1	1837	1841	1827	1826	2181	2420	1678	3113	0	1351	0	0	0	0	0	0	0	0	52	2097	1980	2106	154	2198	2069	2216	63	2111	2105	2113	136	2184	2164	2212	62	2024	1964	2113	157	2204	2115	2219	3	3	0	0
465	1371844183	0	64	1	10	4	1	1	1837	1841	1827	1826	2181	2417	1678	3113	0	1351	0	0	0	0	0	0	0	0	52	2097	1980	2106	154	2198	2069	2216	63	2111	2105	2113	136	2184	2164	2212	62	2024	1964	2113	157	2204	2115	2219	3	3	0	0
466	1371844184	0	64	1	10	4	1	1	1836	1841	1826	1826	2182	2420	1678	3113	0	1351	0	0	0	0	0	0	0	0	52	2097	1980	2106	154	2198	2069	2216	63	2111	2105	2113	136	2184	2164	2212	62	2024	1964	2113	157	2204	2115	2219	3	3	0	0
467	1371844185	0	64	1	10	4	1	1	1837	1841	1826	1826	2181	2419	1678	3112	0	1351	0	0	0	0	0	0	0	0	53	2098	1980	2114	155	2198	2071	2215	63	2111	2108	2116	134	2181	2089	2211	60	2024	1964	2113	156	2204	2118	2215	3	3	0	0
468	1371844186	0	64	1	10	4	1	1	1837	1841	1826	1826	2182	2421	1678	3113	0	1351	0	0	0	0	0	0	0	0	53	2098	1980	2114	155	2198	2071	2215	63	2111	2108	2116	134	2181	2089	2211	60	2024	1964	2113	156	2204	2118	2215	3	3	0	0
469	1371844187	0	64	1	10	4	1	1	1837	1841	1826	1826	2181	2421	1678	3113	0	1351	0	0	0	0	0	0	0	0	53	2098	1980	2114	155	2198	2071	2215	63	2111	2108	2116	134	2181	2089	2211	60	2024	1964	2113	156	2204	2118	2215	3	3	0	0

Data log

- Temperature
- Gas pressure (psig)
- Atmospheric pressure
- SF6 Gas density
- Alarm state
- Contact states
- Pressure (corrected)
- Leak rate
- Fill and fault events
- Contact bus voltage

Logged data includes:



Data log data

For each smart switch

	per record	per day	per month	per year
Data records	1	8.5E+04 *	2.6E+06	3.1E+07
Samples	70	5.9E+06	1.8E+08	2.2E+09
Bytes	292	2.5E+07	7.5E+08	9.0E+09
Compressed bytes	20	1.7E+06	5.1E+07	6.2E+08

*at 1 Hz standard sampling rate (other rates can be programmed)

64 Gb memory store accommodates 100 switch-years
(e.g. 33 years of data for 3 switches, or
1.7 years of data for 64 switches).

Data log data

For each smart switch

	per record	per day	per month	per year
Data records	1	8.5E+04*	2.6E+06	3.1E+07
Samples	70	5.9E+06	1.8E+08	2.2E+09
Bytes	292	2.5E+07	7.5E+08	9.0E+09
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*at 1 Hz standard sampling rate (other rates can be programmed)

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1.7 years of data for 64 switches).

Data log data

For each smart switch

	per record	per day	per month	per year
Data records	1	8.5E+04*	2.6E+06	3.1E+07
Samples	70	5.9E+06	1.8E+08	2.2E+09
Bytes	292	2.5E+07	7.5E+08	9.0E+09
Compressed bytes	20	1.7E+06	5.1E+07	6.2E+08

*at 1 Hz standard sampling rate (other rates can be programmed)

64 Gb memory store accommodates 100 switch-years
(e.g. 33 years of data for 3 switches, or
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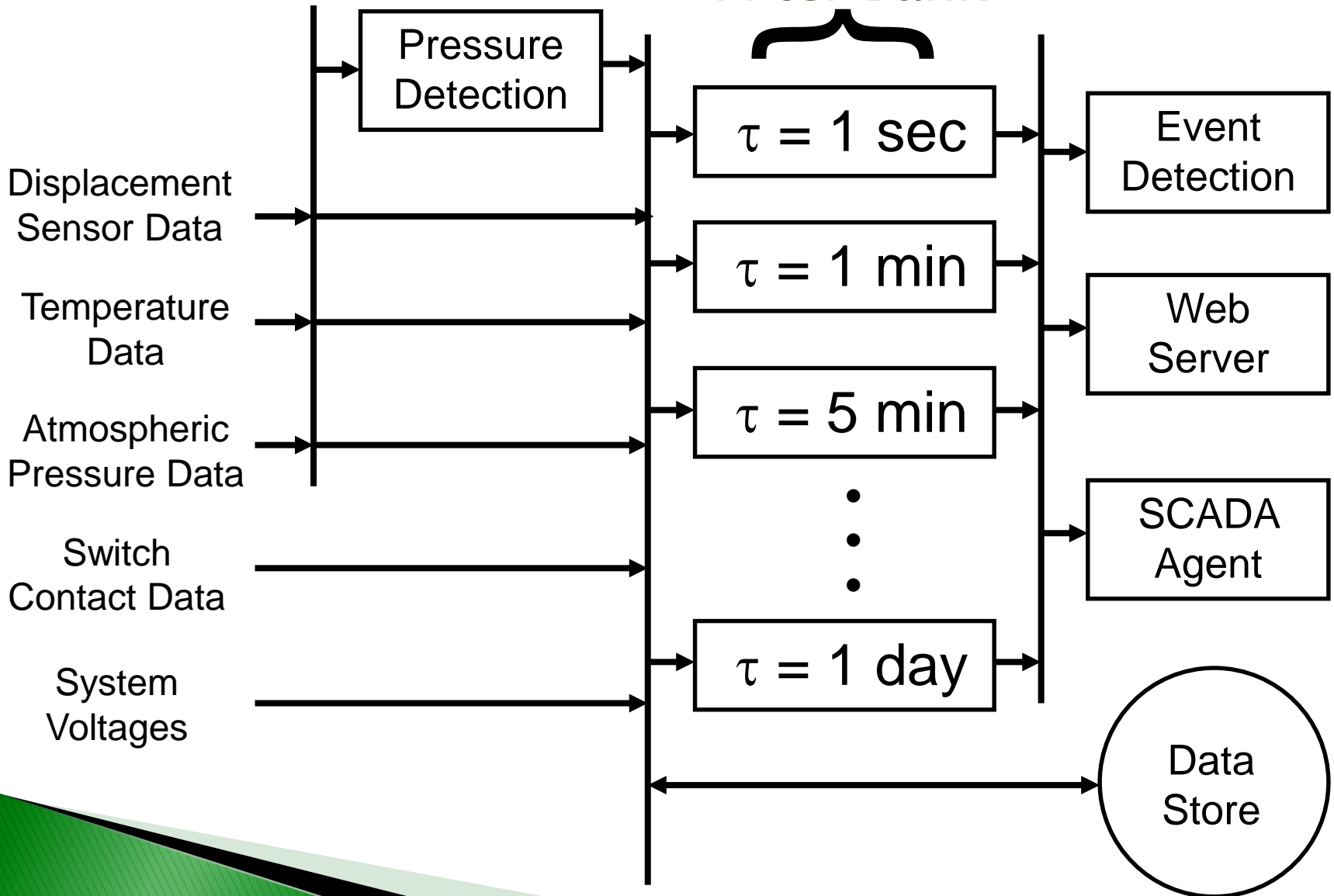
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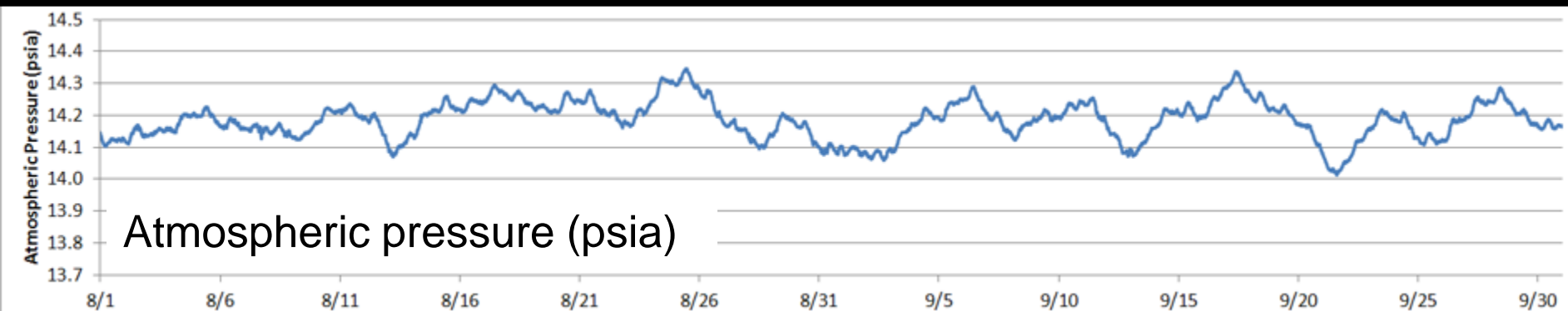
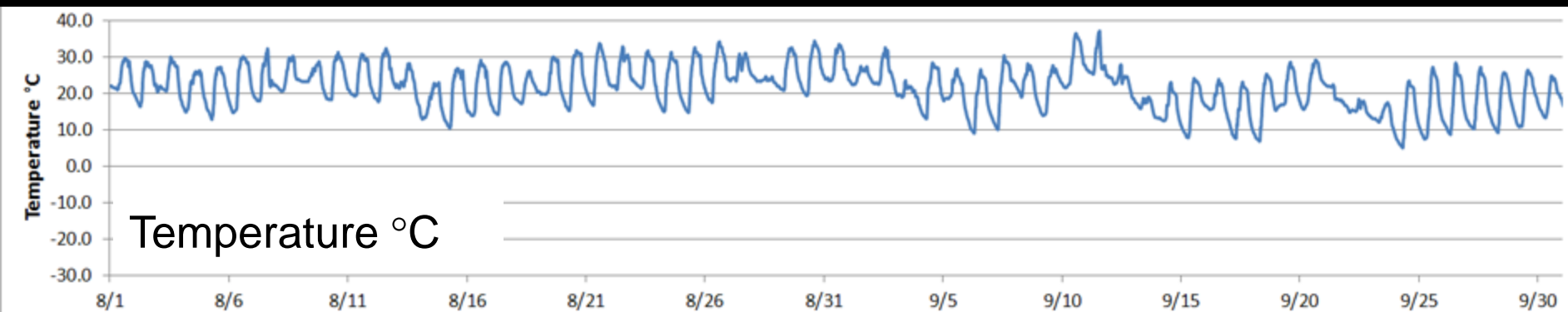
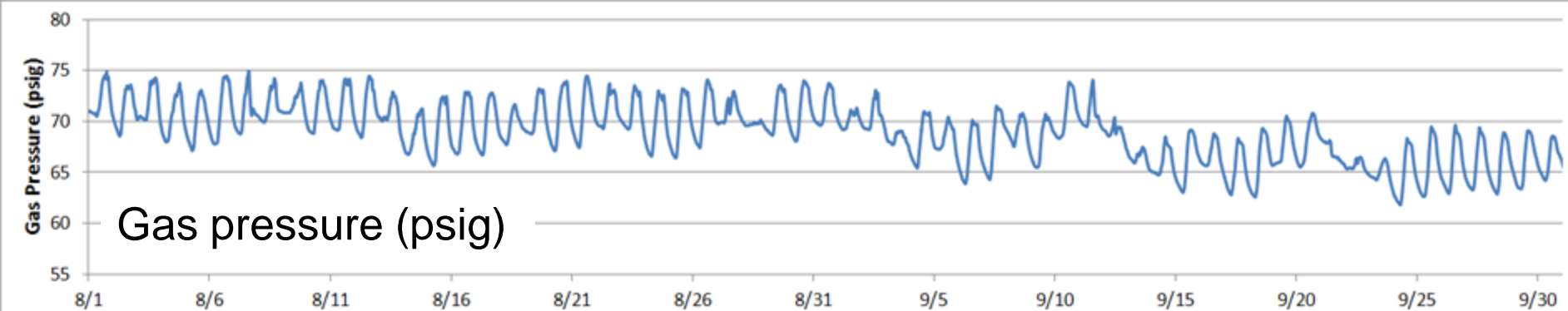
Data flow

Digital processing throughout
Filter Bank



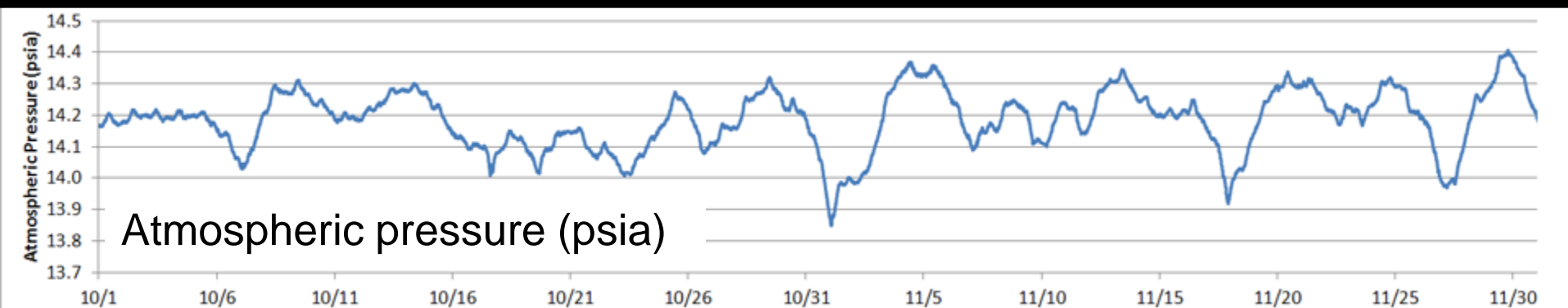
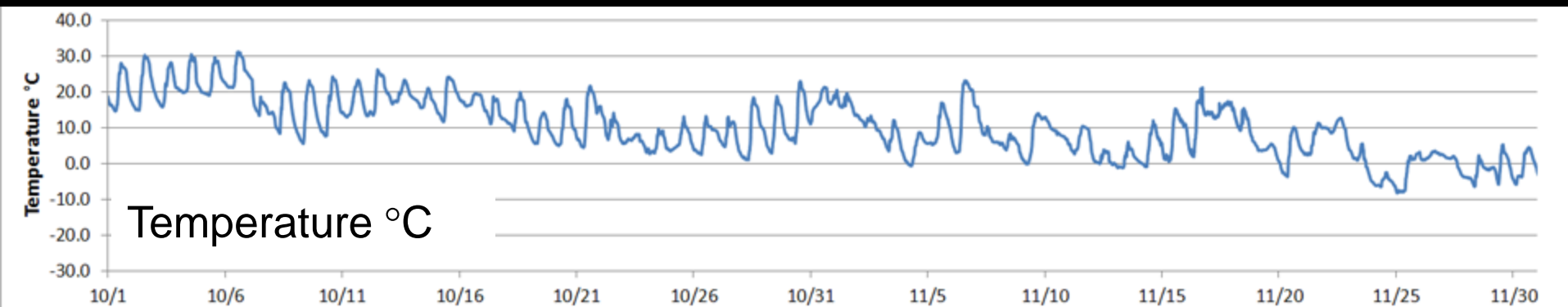
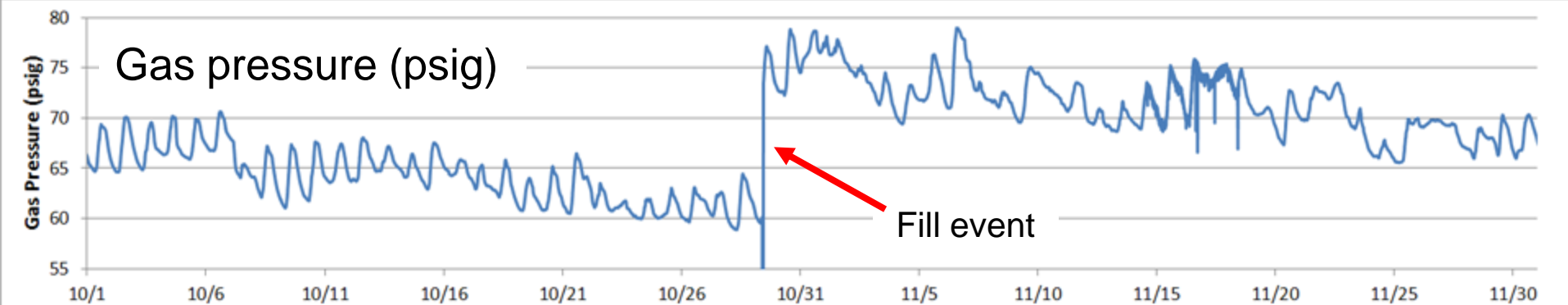
Basic data

Butler, PA Aug-Sep



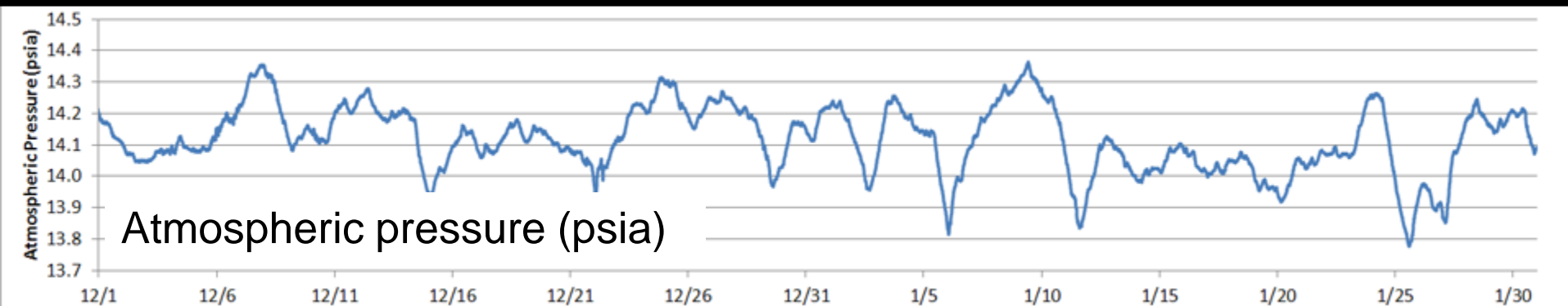
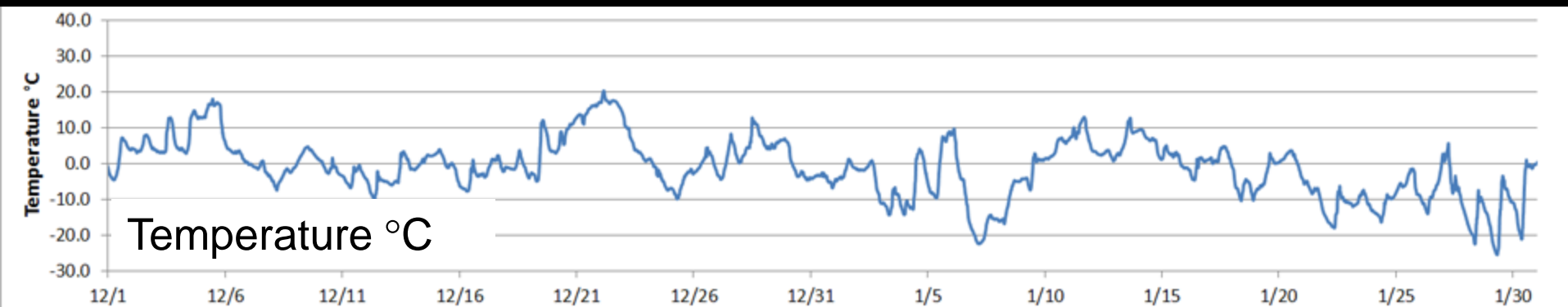
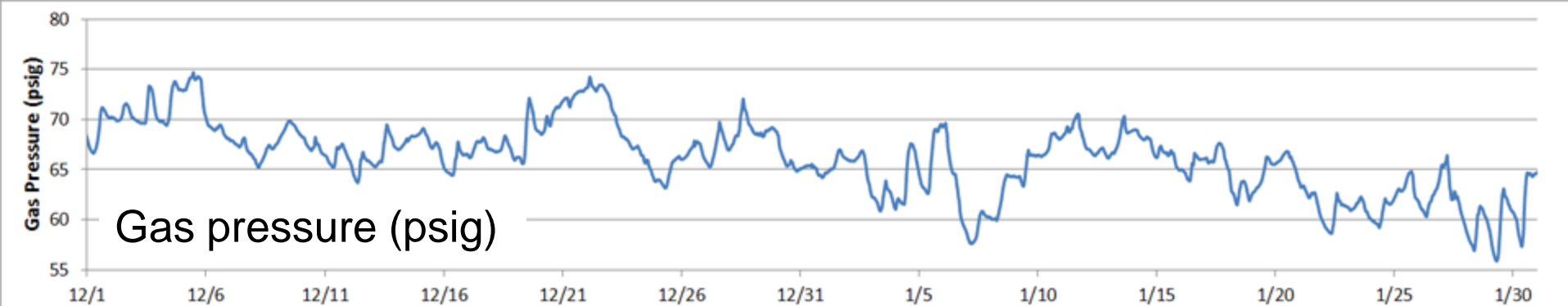
Basic data

Butler, PA Oct–Nov



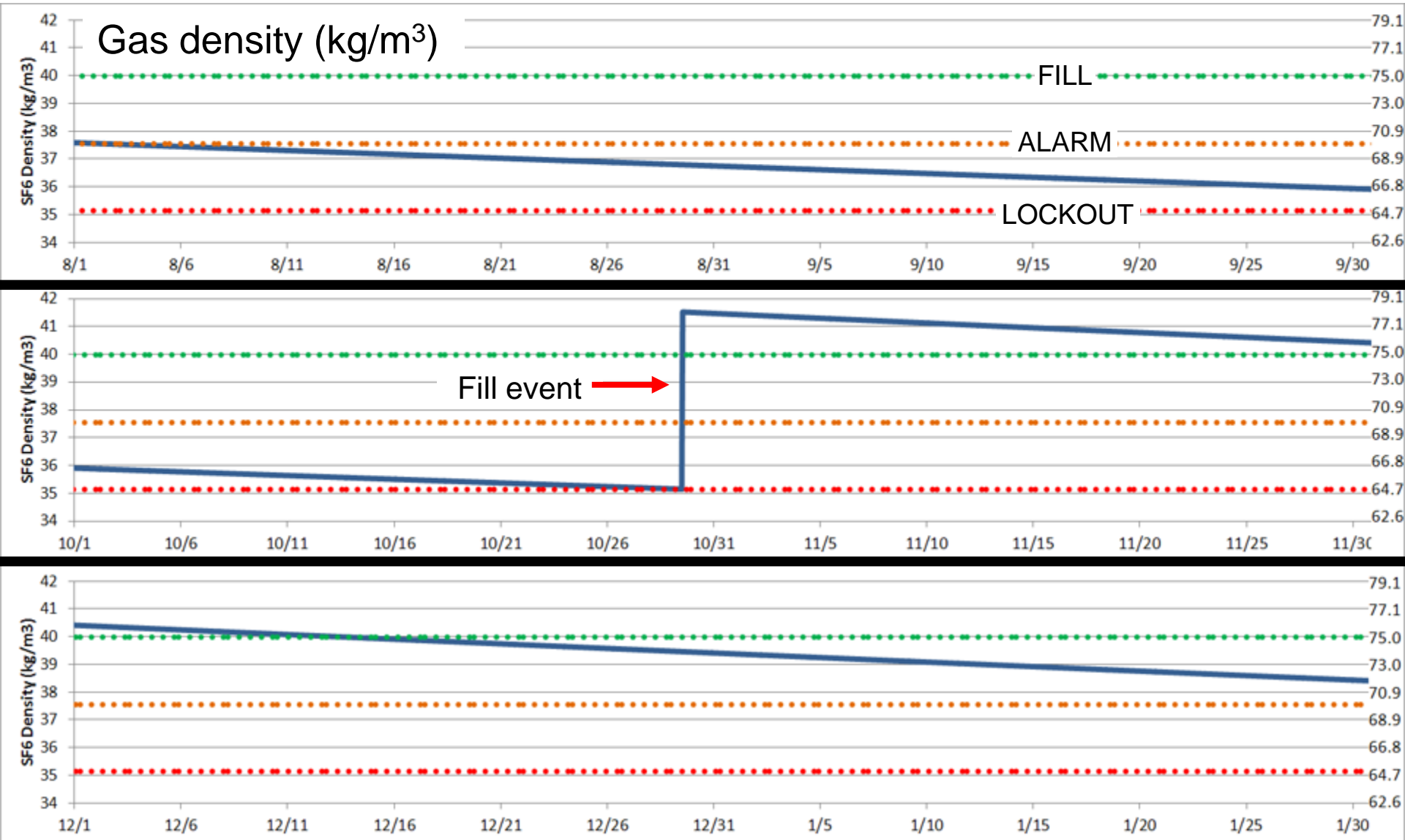
Basic data

Butler, PA Dec–Jan



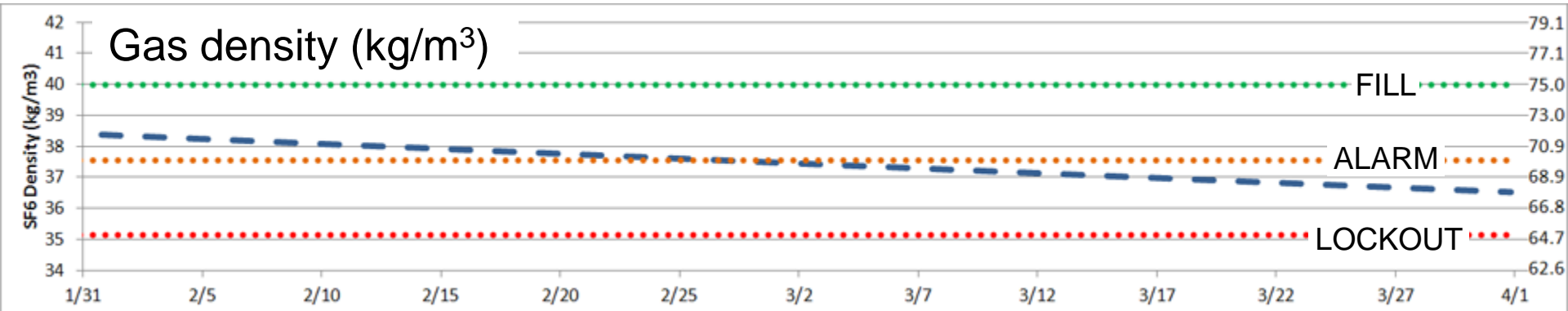
Leak estimation

Butler, PA Aug-Jan



Alarm prediction

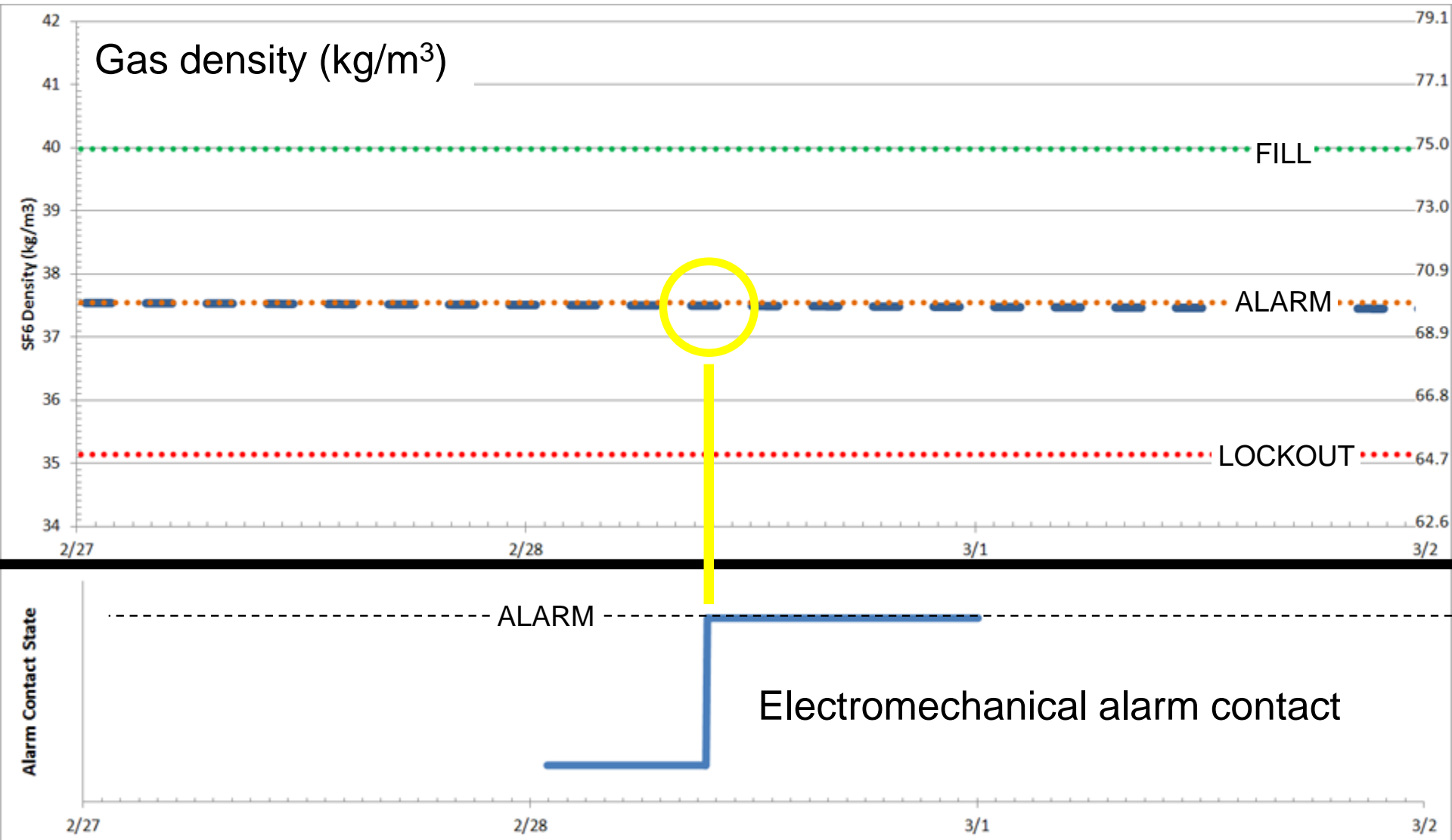
Butler



From January data, the smart switch predicts alarm threshold will be reached late February to early March

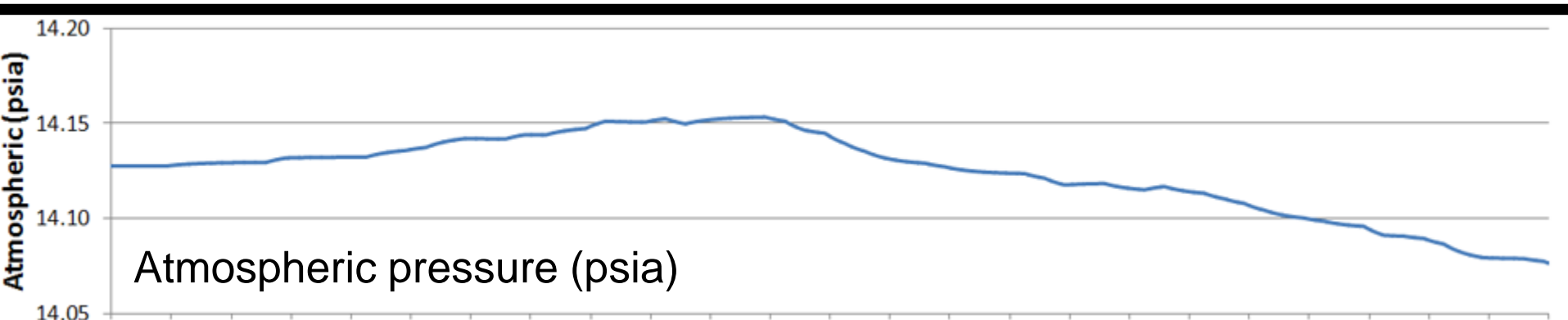
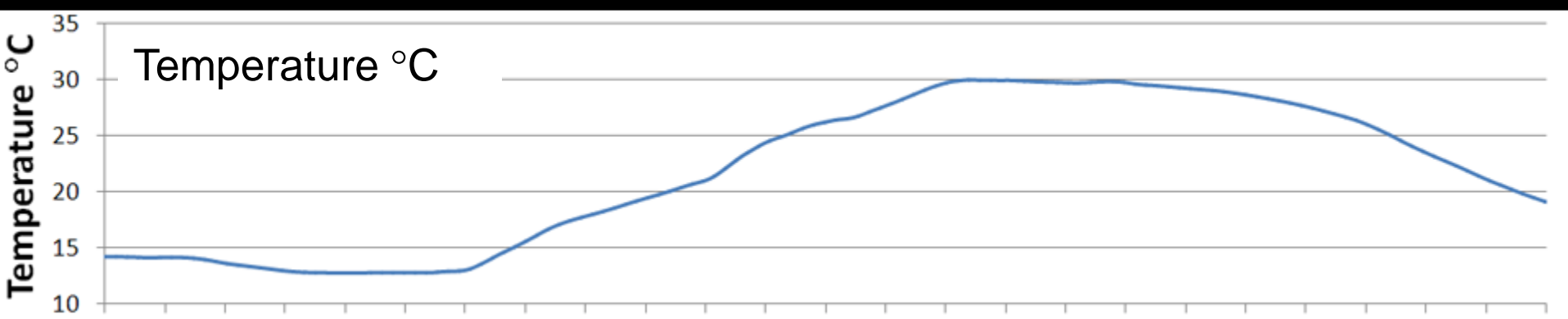
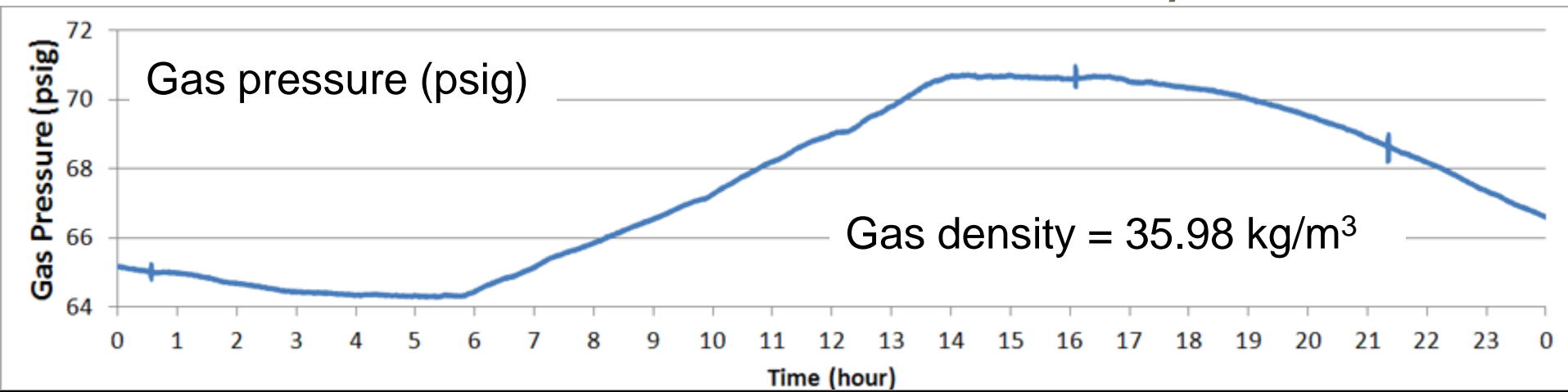
Good match!

Butler, 2/27 to 3/2/2014



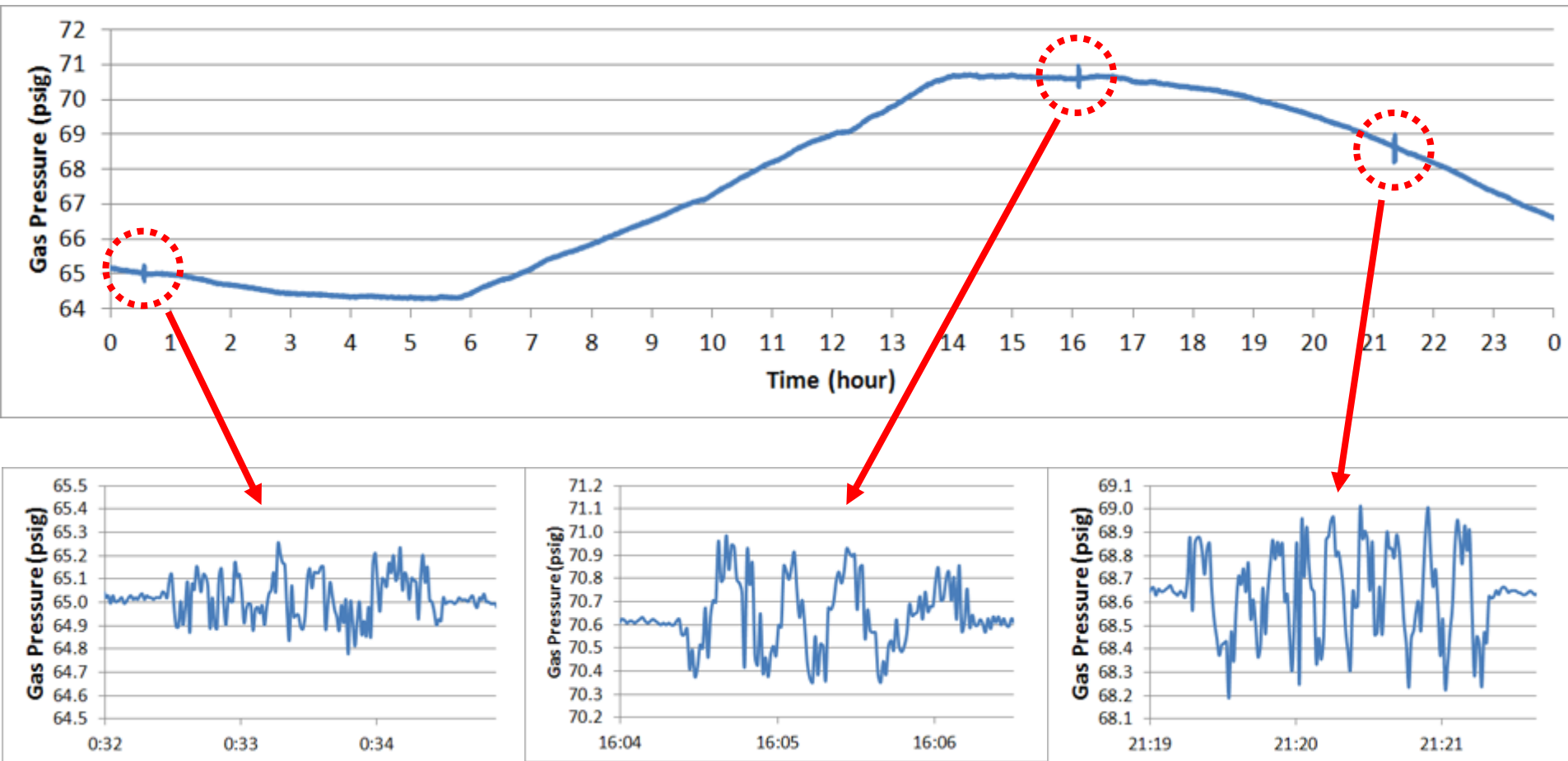
Hi-res data

Butler, Sunday, 4/13/14



Event capture

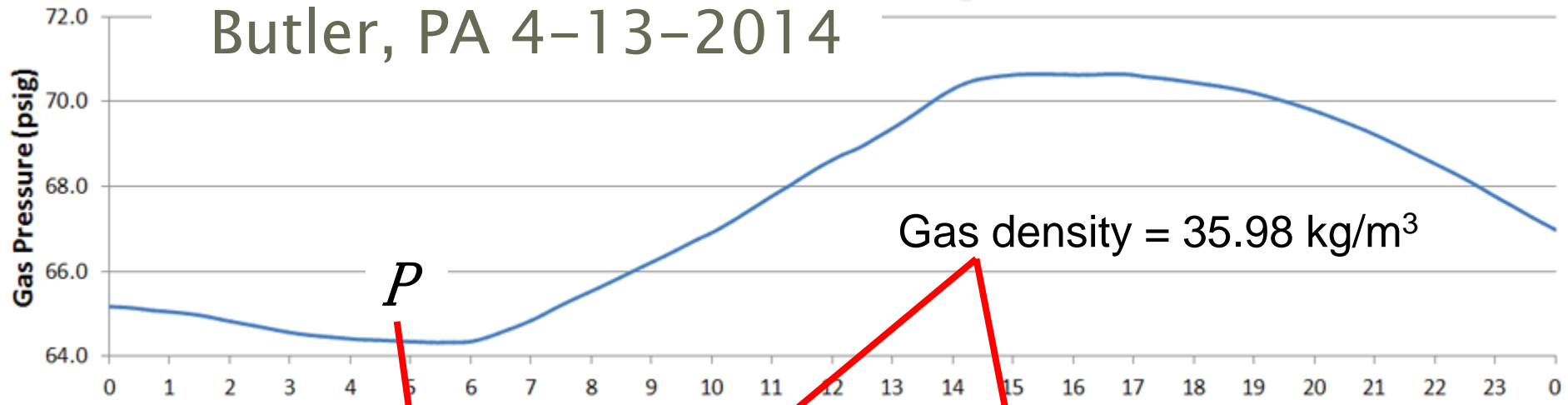
Butler, PA 4-13-2014



Air compressor operation: 2-minute runtime,
0.4 to 0.8 psi peak-to-peak vibration amplitude, operating
period varies from 5 to 15 hours

Data matches theory?

Butler, PA 4-13-2014

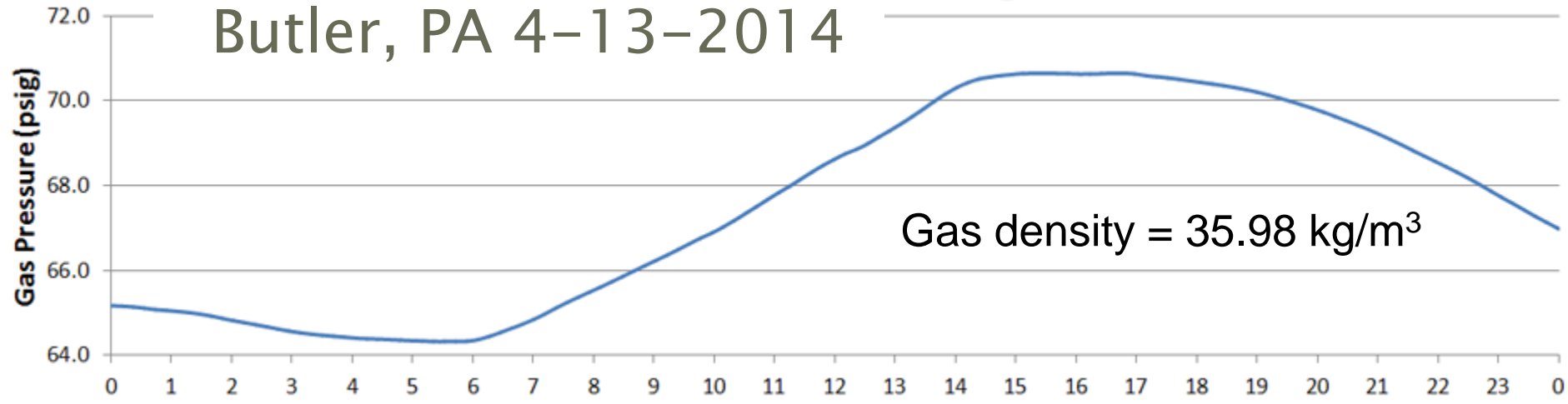


$$P = R \cdot T \cdot \left(\frac{n}{V} + B(T) \cdot \frac{n^2}{V^2} \right)$$

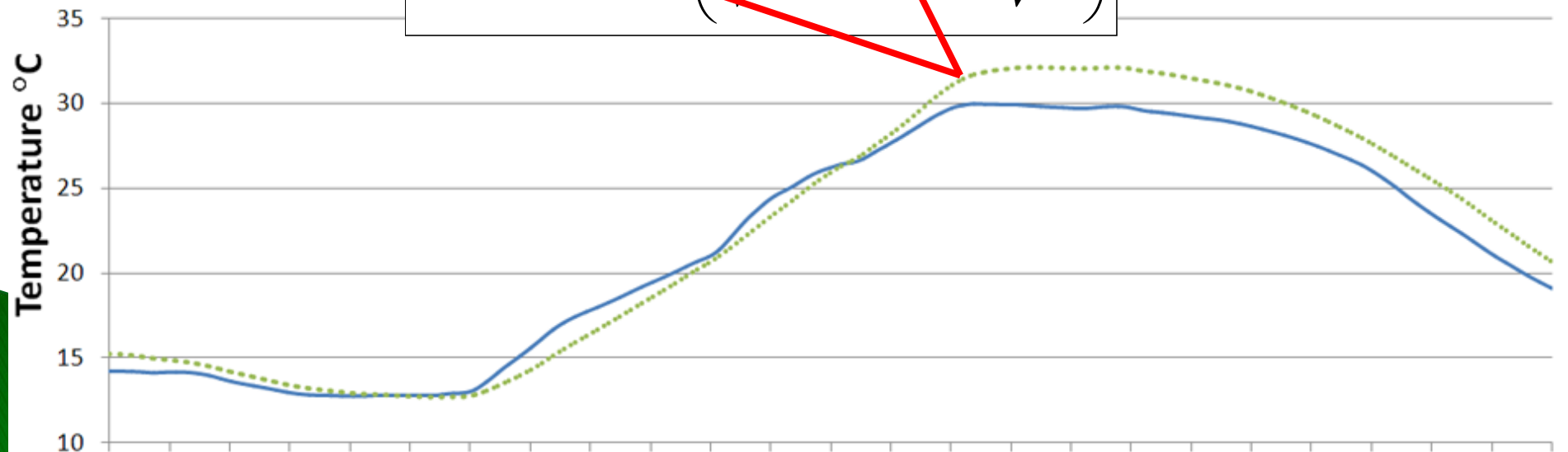


Density inferred temperature:

Butler, PA 4-13-2014



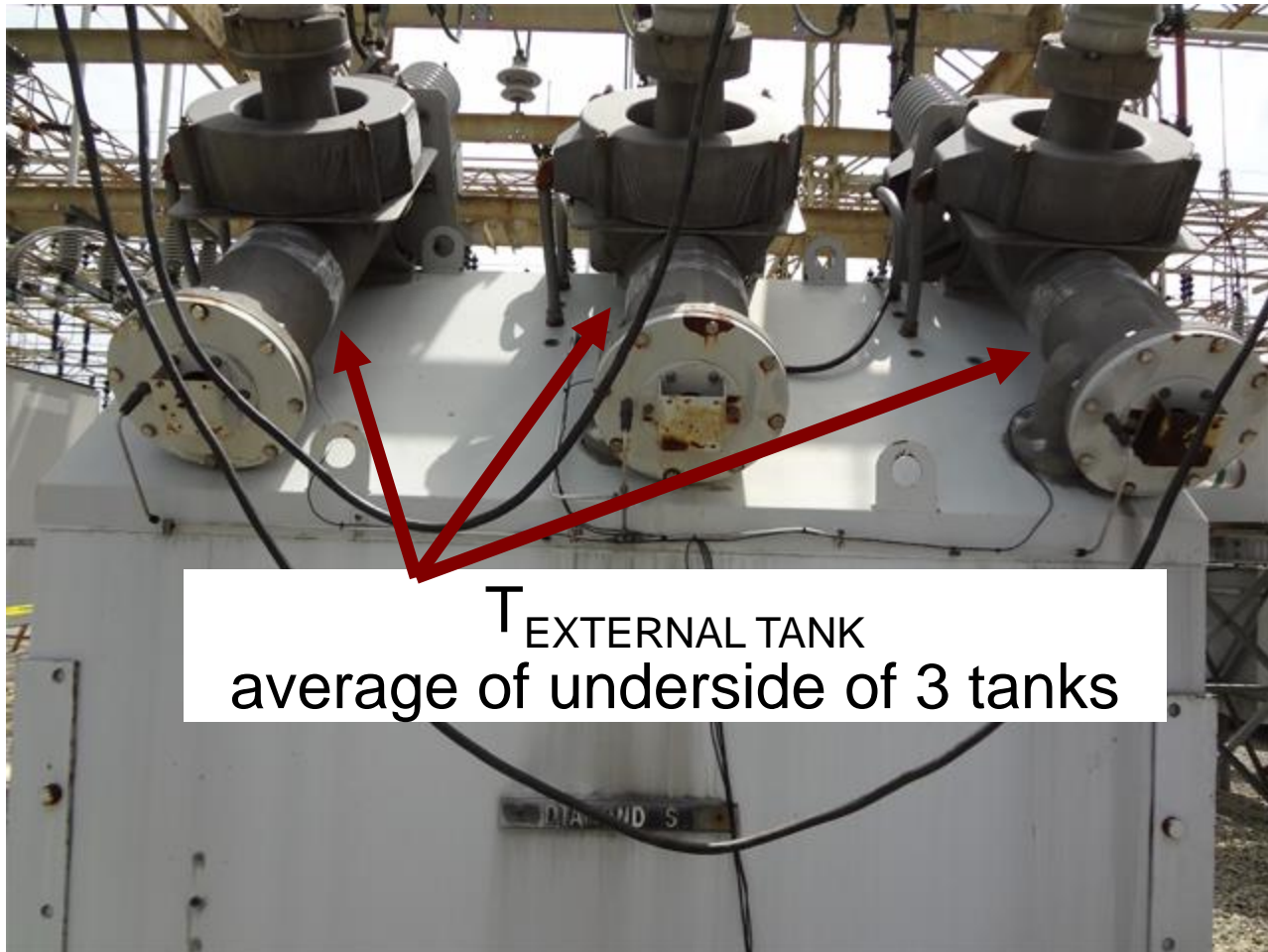
$$P = R \cdot T \cdot \left(\frac{n}{V} + B(T) \cdot \frac{n^2}{V^2} \right)$$



Configuration

Butler, 7/12/2013, 12:20

← N-NE



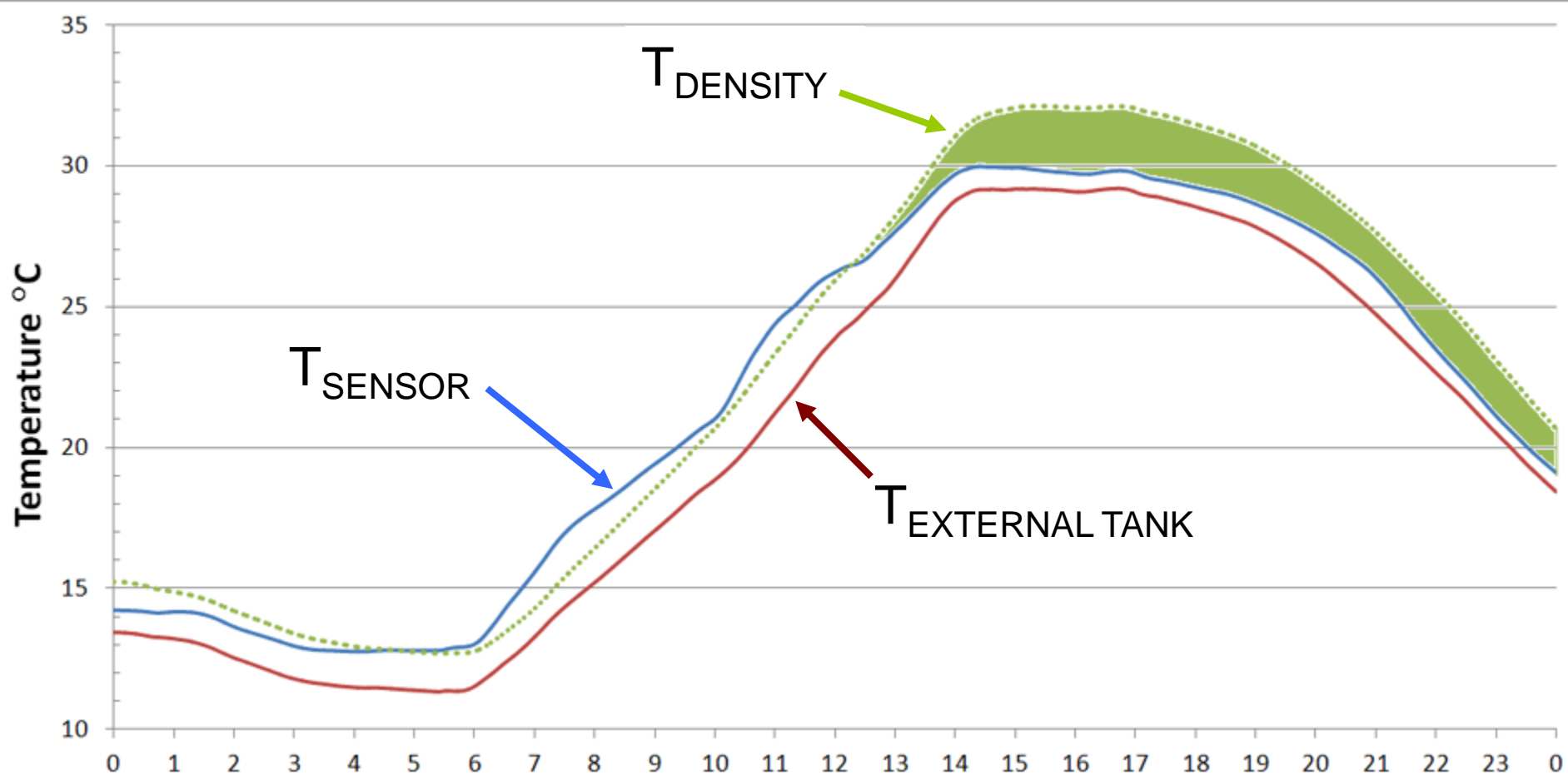
$T_{\text{EXTERNAL TANK}}$
average of underside of 3 tanks

T_{SENSOR} →
under cabinet



Double check

Butler, Sunday, 4-13-14

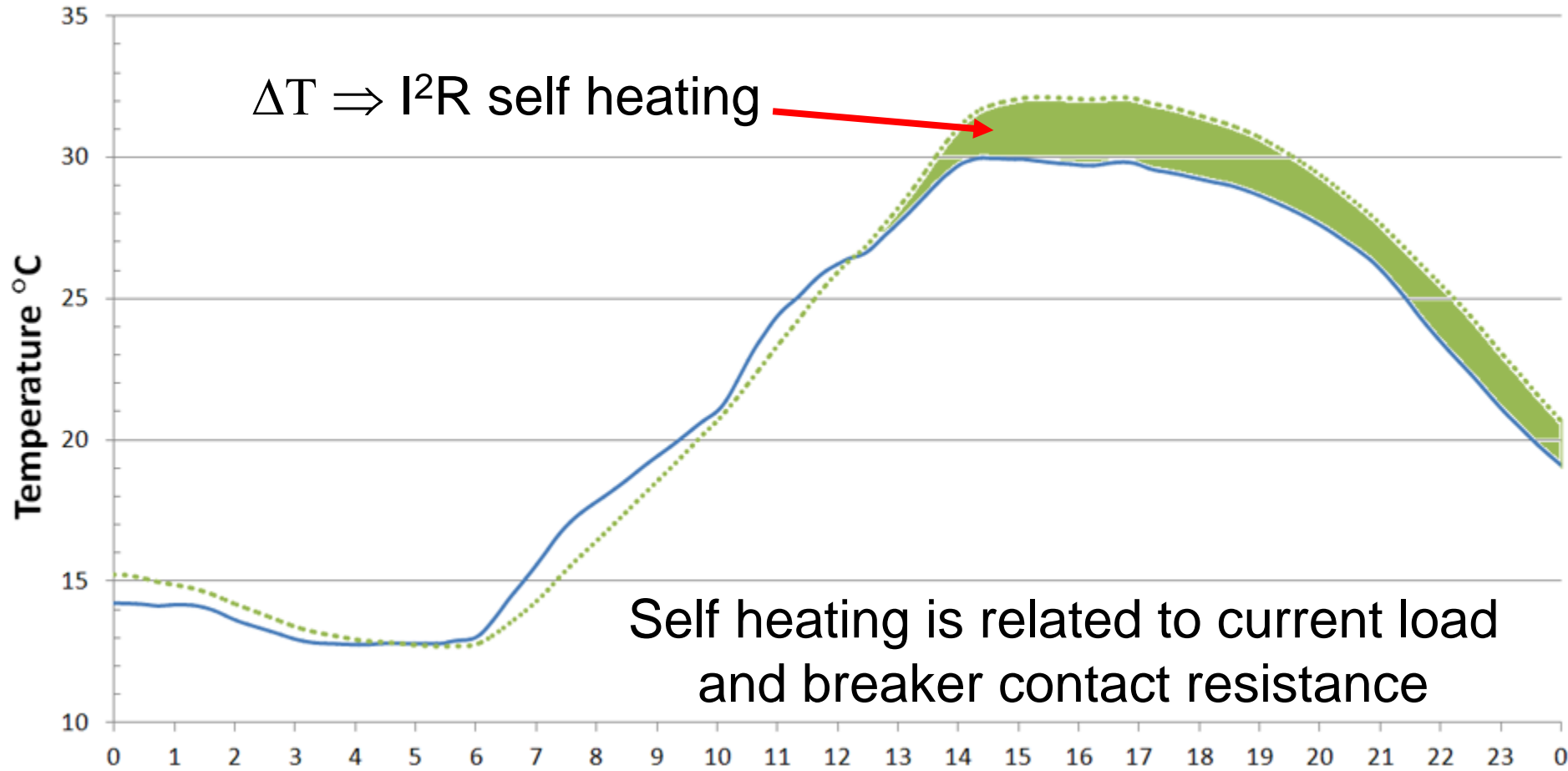


Temperature difference is not explained simply by tank vs. sensor differences

Interpretation

Butler, Sunday, 4-13-14

$\Delta T \Rightarrow I^2R$ self heating

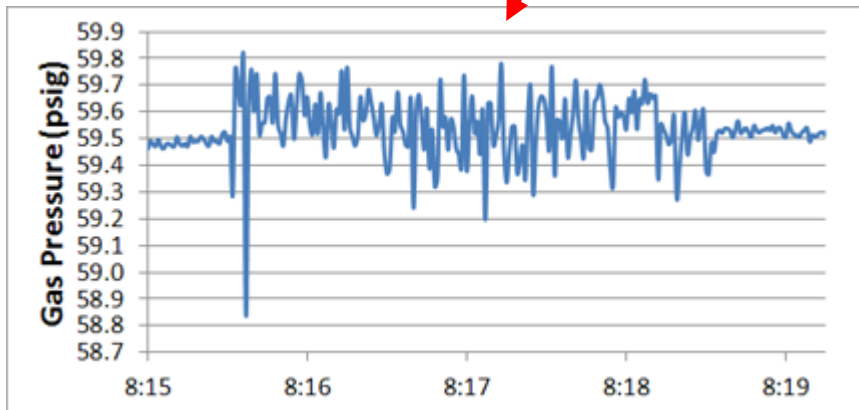
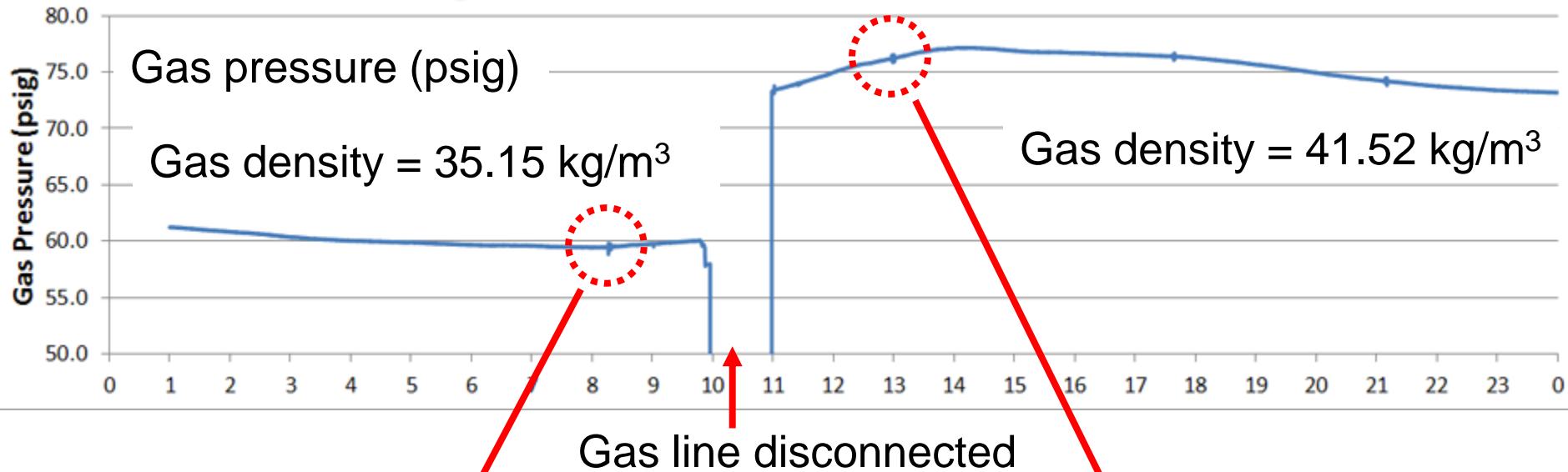


Self heating is related to current load and breaker contact resistance

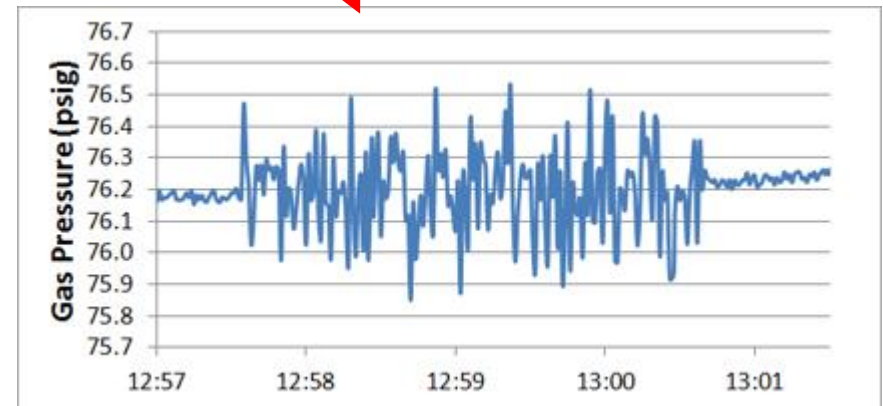
Trending changes in breaker contact resistance is valuable information

Event capture

Butler, Tuesday, 10/29/13



Breaker operates at 8:15

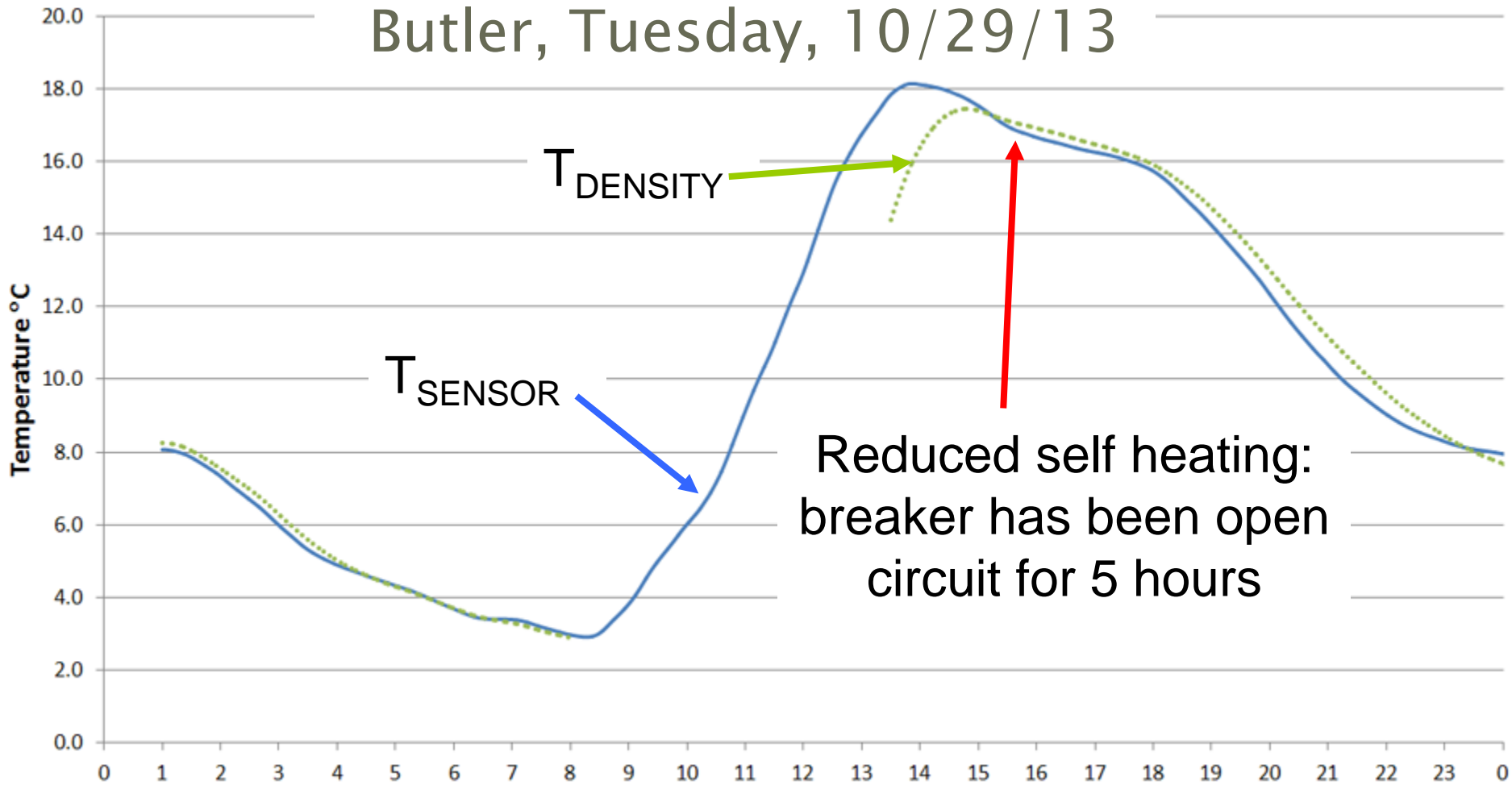


Restart at 12:58

Similar events captured to $< 5 \text{ psig}$

Density inferred temperature

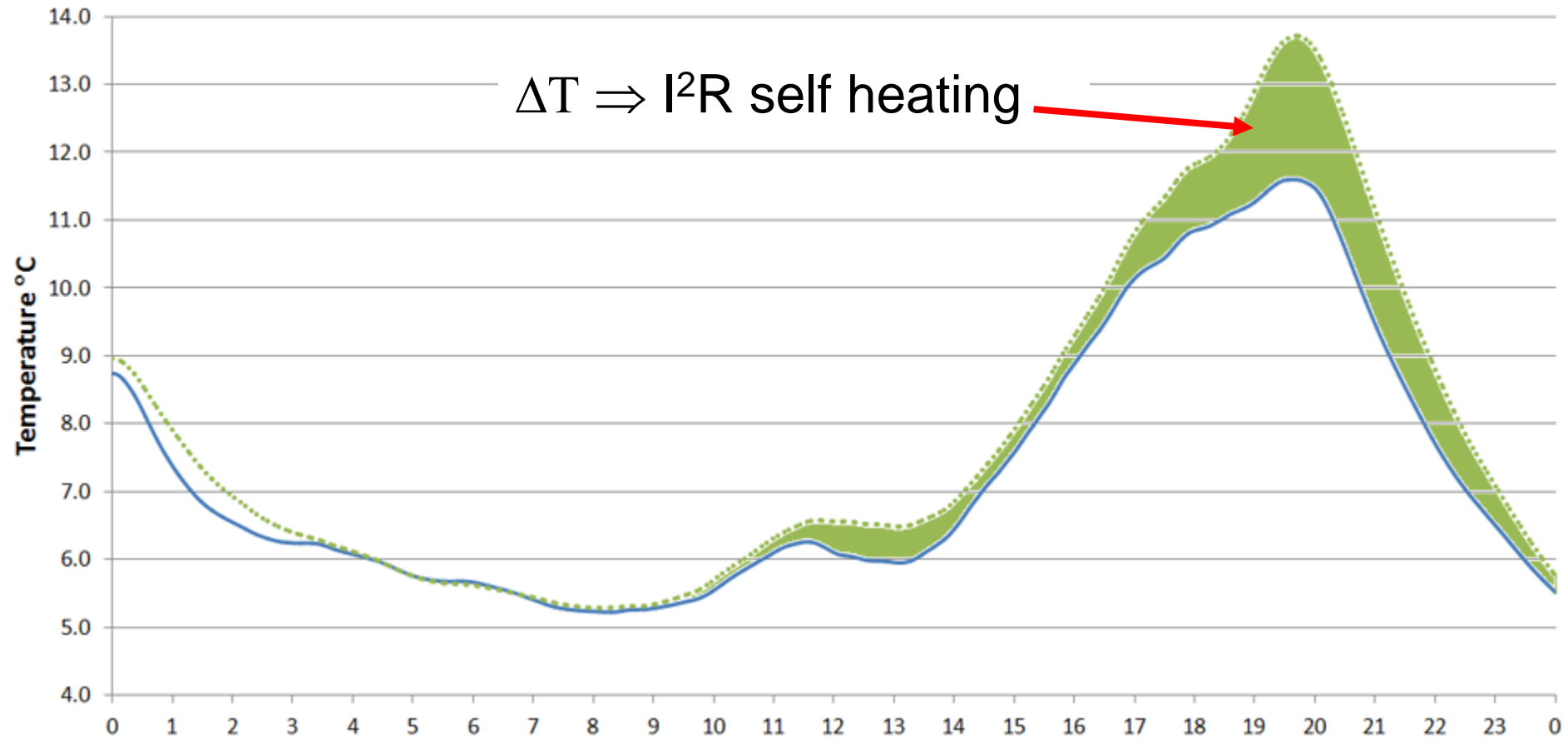
Butler, Tuesday, 10/29/13



Reduced self heating:
breaker has been open
circuit for 5 hours

Density inferred temperature

Butler, Wednesday, 4/23/14



Bulb failure

Instant detection

If this fails ...



The electronic adaptation is similar.

... electronics instantly detect and report lever over-deflection

The preceding examples have been intrinsic type devices. Bulb type and other styles are available. The electronic adaptation to all types is similarly effective.

Extensible

Data acquisition extension with temperature and switch tallies

Firefox
SSH - Smart Switch Hub - Solon Manufacturing

Monitor:

- Temperatures
- Integrate CTs
- Cabinet interlocks
- Compressors
- ...more...

Pressure Gauge:
PRESSURE @ 68F / 20C
75.1 PSI
Scale: 483, 517, 70 ALARM, 65 LOCKOUT, PSI, kPa

RTC	°C	°F
1	25	77
2	24.8	76.6
3	25.4	77.8
4	25.1	77.2
5	25.6	78.2
6	24.5	76.1

SW 1 2 3 4
10 10 10 00
Gauge #1

SW 1 2 3 4
01 01 01 11
DAQ #1

This DAQ monitors 6 external temperatures and 8 x form-C switch contacts

Extensible

Data acquisition extension with temperature and switch tallies

To Smart Switch



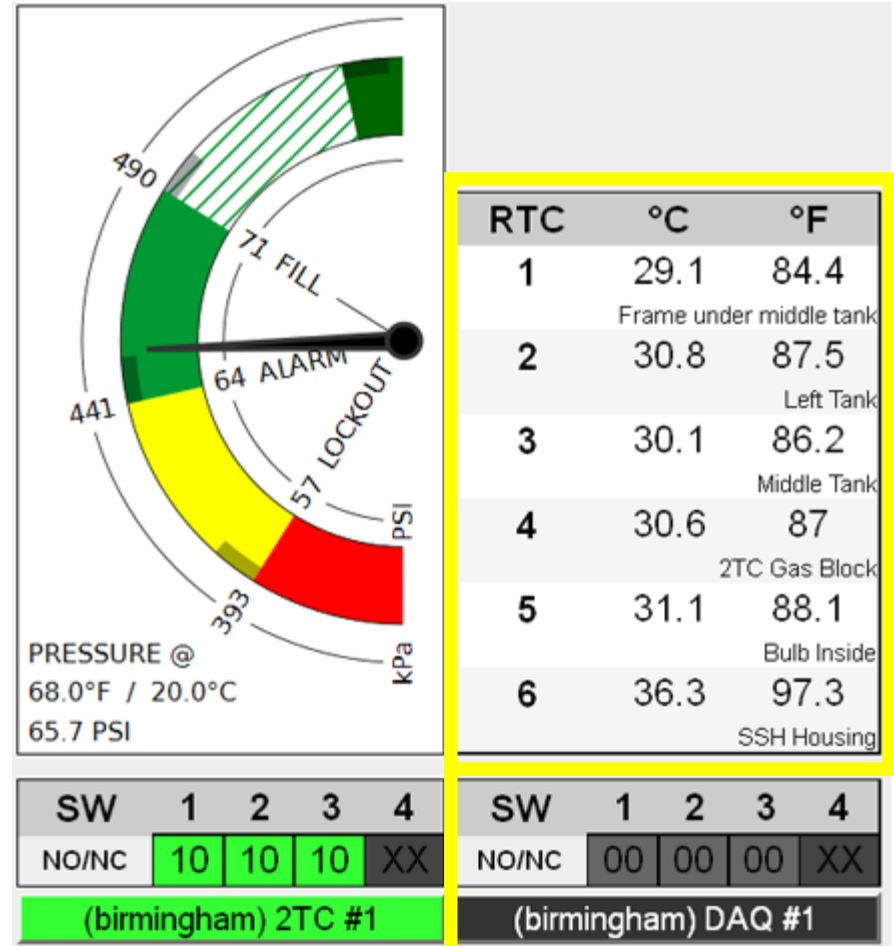
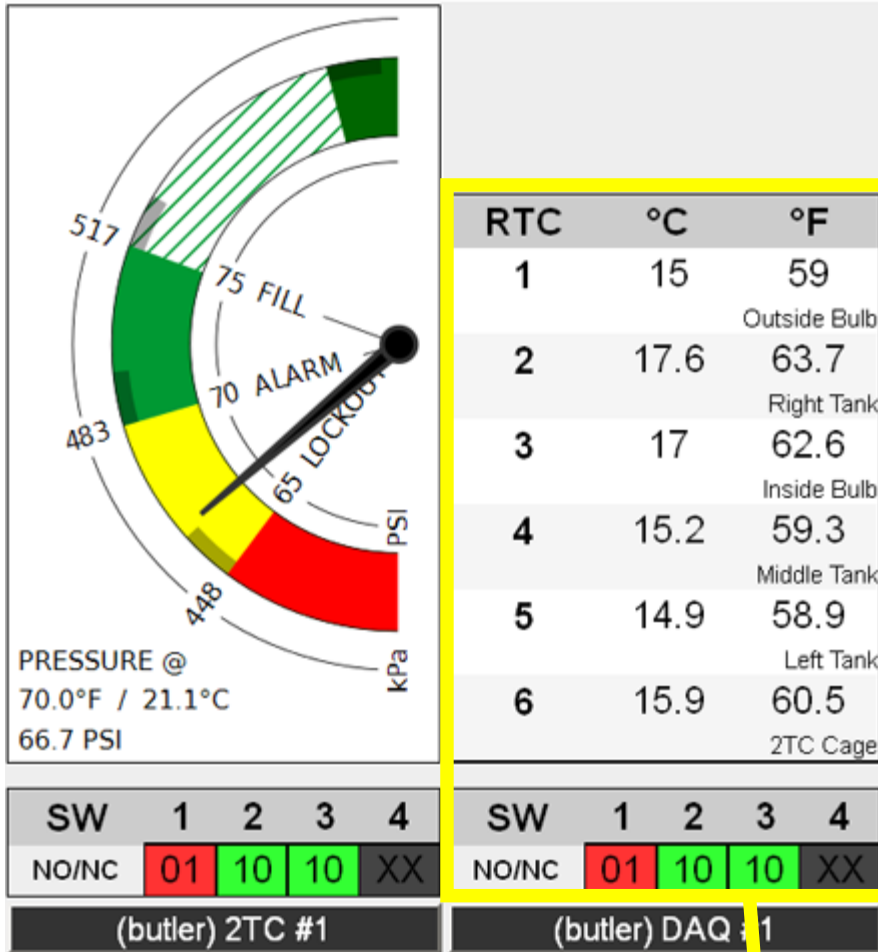
To 6 x External Temperature Probes

SPDT Contact Tallies

DAQ Type 1 interfaces to any hub switch port

Networked

Data acquisition extension with temperature and switch tallies

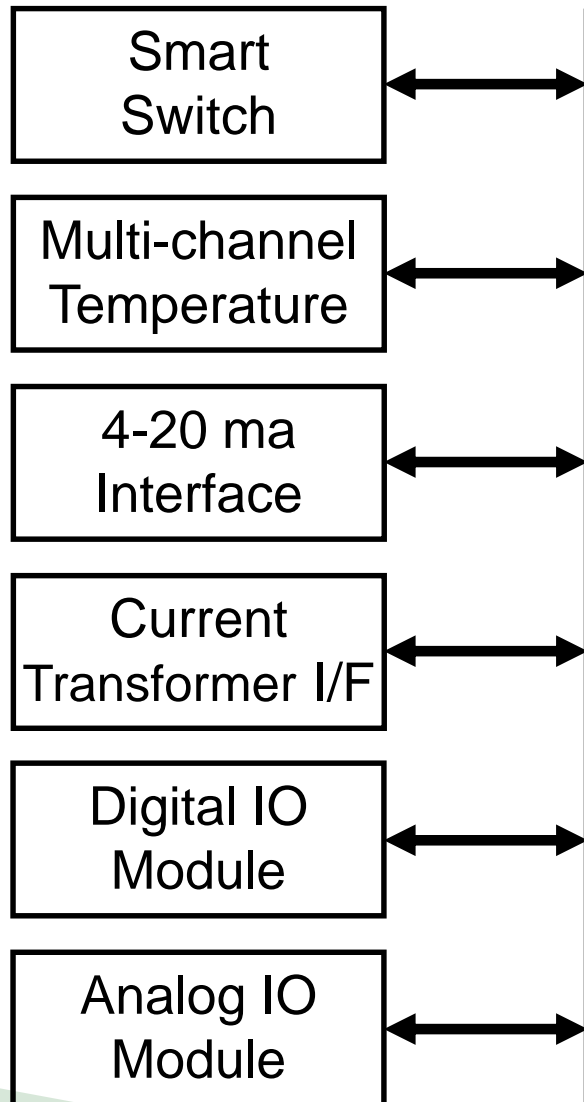


1

2

Extensible

Standard and custom DAQ modules



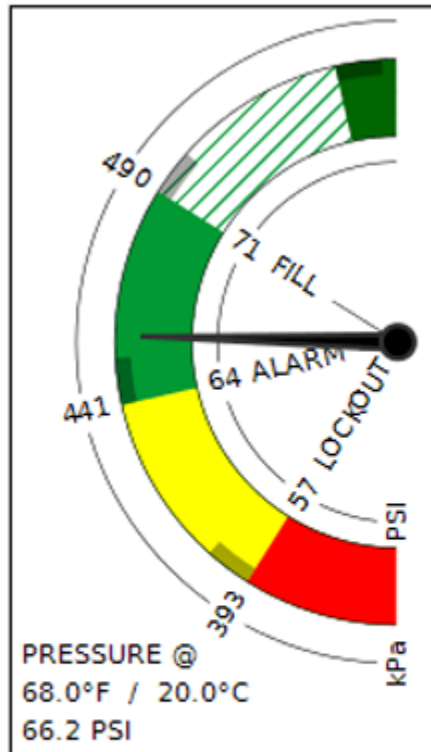
To network

USB flash
data port



Alarm prediction

Most important point



SW	1	2	3	4
HO/HC	10	10	10	XX
2TC#1				

Leak Detection

Current Leak Rate (g/d)
19

Time to alarm
58 Days
Sat Jun 21 2014

Time to lockout
301 Days
Thu Feb 19 2015

Current density	35.65 kg/m ³
Current mass	49.32 kg

Summary

Most important points

- Electromechanical density switch with up to four setpoints continues to operate independently (but electronics also serve to validate this operation)
- Advanced features bring many benefits including leak detection, time to alarm or lockout estimation, breaker event capture, valuable diagnostics, and more...
- Extensible data acquisition supports many maintenance and troubleshooting applications
- Flexible network interface, configuration, and data retrieval options allow data to be put to practical use, as well as remote firmware and algorithm updates



Belleville Springs and Pressure Switches

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Thank you!

Solon Manufacturing Co.
Pressure Switch Division



Advanced SF6 Gas
Monitoring Systems