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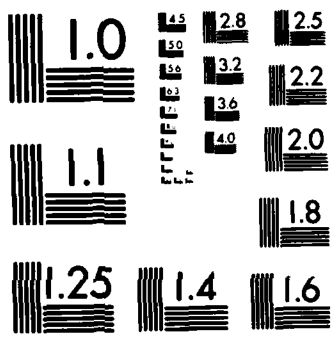

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User's Guide to Calibration of Analog Electronic Controllers in HVAC Systems

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DEFINITIONS

The calibration of analog electronic proportional controllers requires the knowledge of at least three characteristics of the controller: the action, the setpoint, and the throttling range.

Action. A controller is either direct acting or reverse acting. In a direct acting controller an increase in the input signal results in an increase in the output signal. In a reverse acting controller, an increase in the input to the controller results in a decrease in the output from the controller.

Setpoint. The value to which the control point setting mechanism is set. For example, a humidity controller might be set at 50% relative humidity. The actual measured value of humidity, or control point, may be different from the setpoint.

Throttling range. The change in the input variable required to produce a full scale change in the output variable. For example, if a 10% change in relative humidity results in the output of the controller varying from its minimum to maximum values, the throttling range is 10% rh. See Figure 1.

An additional specification, the ratio, is required to calibrate dual input controllers.

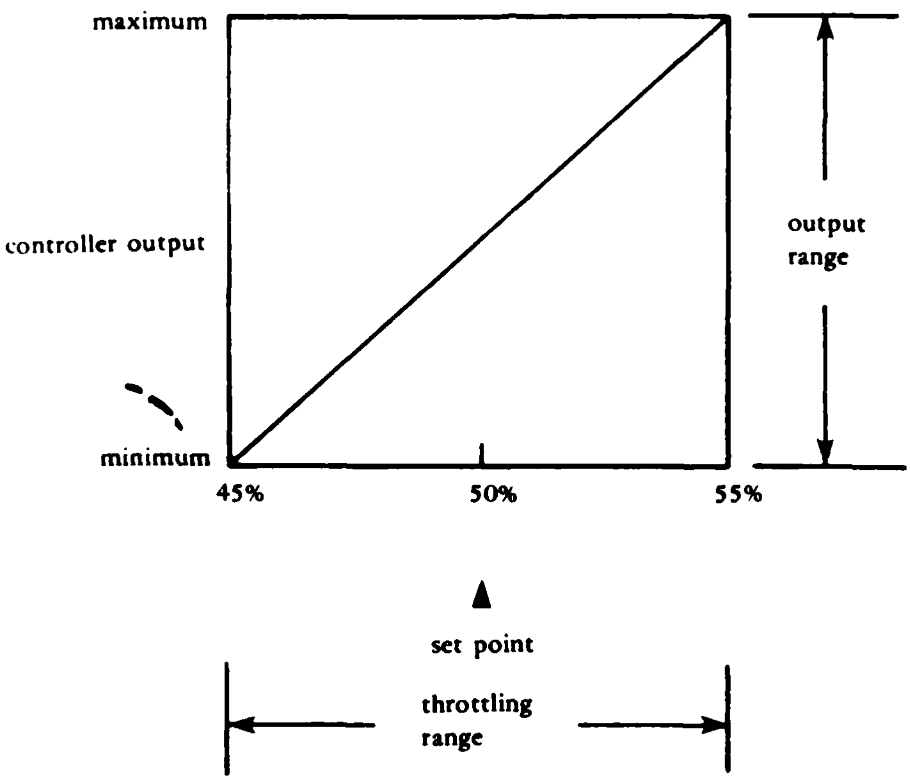


Figure 1. Illustration of control nomenclature.

Ratio. The amount of influence the second controller input has on the output as compared to the influence of the primary controller input.

$$\text{RATIO} = \frac{\text{Throttling Range of Second Sensor}}{\text{Throttling Range of Primary Sensor}} \qquad (1)$$

For example, if the ratio equals 1/2, a one unit change at the second sensor would have the same effect on the output as a 2 unit change at the primary sensor, if the ratio equals 1 both sensors have the same influence, and if the ratio equals 2, a 2 unit change at the second sensor would have the same effect on the output as a one unit change at the primary sensor. Electronic controllers usually permit adjustment of the ratio from a value of about 1/2 to a value of about 20.

Authority. The word AUTHORITY is used by some controller manufacturers to describe the relative influence of two controller inputs on the controller output.

$$\text{AUTHORITY} = \frac{\text{Throttling Range of Primary Sensor}}{\text{Throttling Range of Second Sensor}} \times 100$$

A picture of a two input controller is presented in Figure 2.

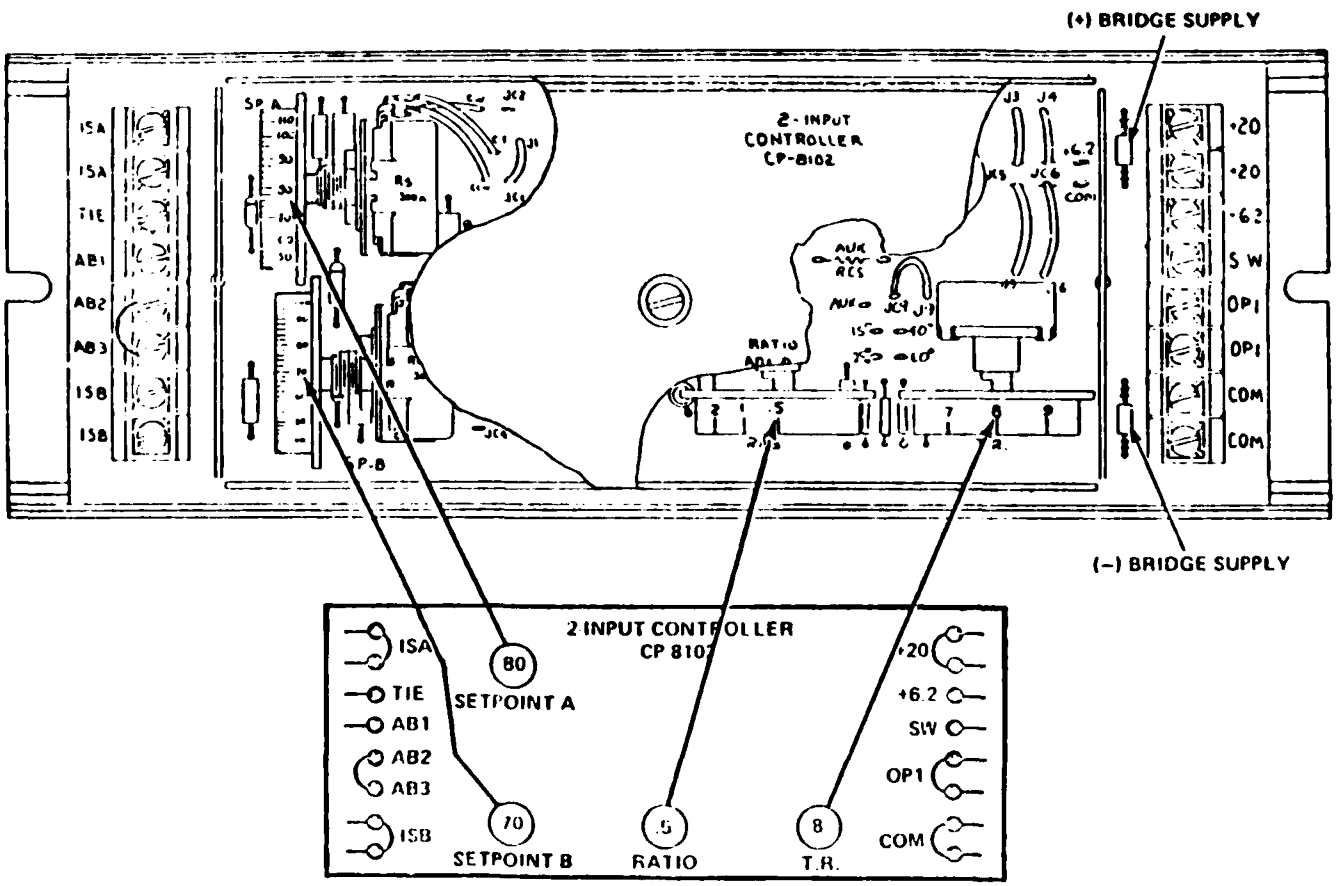


Figure 2. Typical 2-input temperature controller.

GENERAL PROCEDURE

The calibration procedure follows these steps:

(1) Measure the controller input(s)

(2) Calculate the predicted controller output

(3) Measure the actual controller output

(4) Adjust the controller as required.

Using this procedure, controller performance is evaluated at the control point, or actual condition, rather than the setpoint, which is the idealized, desirable condition. This means that only those controllers which are actually out of calibration need to be adjusted - controllers that are in calibration need not have any settings or adjustments changed. If a controller cannot be calibrated or will not remain calibrated for a responsble period of time, it is defective and should be repaired or replaced.

Single Input Controllers

First, determine the desired action, setpoint, and throttling range for the controller in question from the plans or specifications for the control system. Remove the cover from the controller and examine the settings on the controller chassis. Verify the action and throttling range setting. Most electronic controllers select action by jumper connections on the circuit board.

Next, measure the controlled variable-mixed air temperature for example. Use a calibrated, independent instrument for this measurement. Then apply these data to the following equation.

$$V_{OUT} = V_{Mid\text{-}Point} \pm \left(\frac{S - SP}{TR}\right) x \; VR \qquad (2)$$

where: V_{OUT} = predicted controller output, volts

$V_{mid\text{-}point}$ = controller output when sensor is at mid-point of throttling range, volts

S = value of measured variable, °F, % RH, psi

SP = setpoint, °F, % RH, psi

TR = throttling range, °F, % RH, psi

VR = Voltage range from (minimum to maximum) of controller output, volts

Voltage midpoint and range are usually adjustable. Commonly used values are 6 volts minimum to 9 volts maximum, for a midpoint value of 7.5 volts and a range of 3 volts. The positive sign is used for direct acting controllers; the negative sign for reverse acting controllers.

Next, measure the actual output voltage of the controller. Compare the measured voltage to the predicted output voltage. If the two values differ by more than about 5%, the controller needs to be calibrated.

Example. A direct acting analog electronic controller is used to control the mixed air temperature (see Figure 3). The controller setpoint is specified to be 55°F and the throttling range is 4°F. The measured mixed air temperature equals 56.5°F. The predicted controller output voltage (from equation 2) is therefore

$$V_{OUT} = 7.5 + \left(\frac{56.5 - 55}{4}\right) x\ 3 = 8.63V$$

The measured output voltage equals 8.2V, for a difference between predicted and measured values of about 5%. Therefore, the controller should be calibrated.

Calibration Procedure for Single Input Controllers

The calibration procedure for single input controllers is as follows:

Procedure A

(a) Loosen the set point scale.

(b) Turn the setpoint adjustment screw until the controller output voltage equals the predicted voltage (8.63 volts in the example)

(c) Turn the setpoint scale until the indicated value of setpoint equals the desired value (for example, the pointer points to 55°F).

(d) Tighten the set point scale.

(e) Wait for the HVAC system to come back into equilibrium and repeat steps (a) through (d) as a check. Since changing the controller output (Step b) will cause movement of the final control element (e.g., damper or valve), steps a through e may have to be repeated.

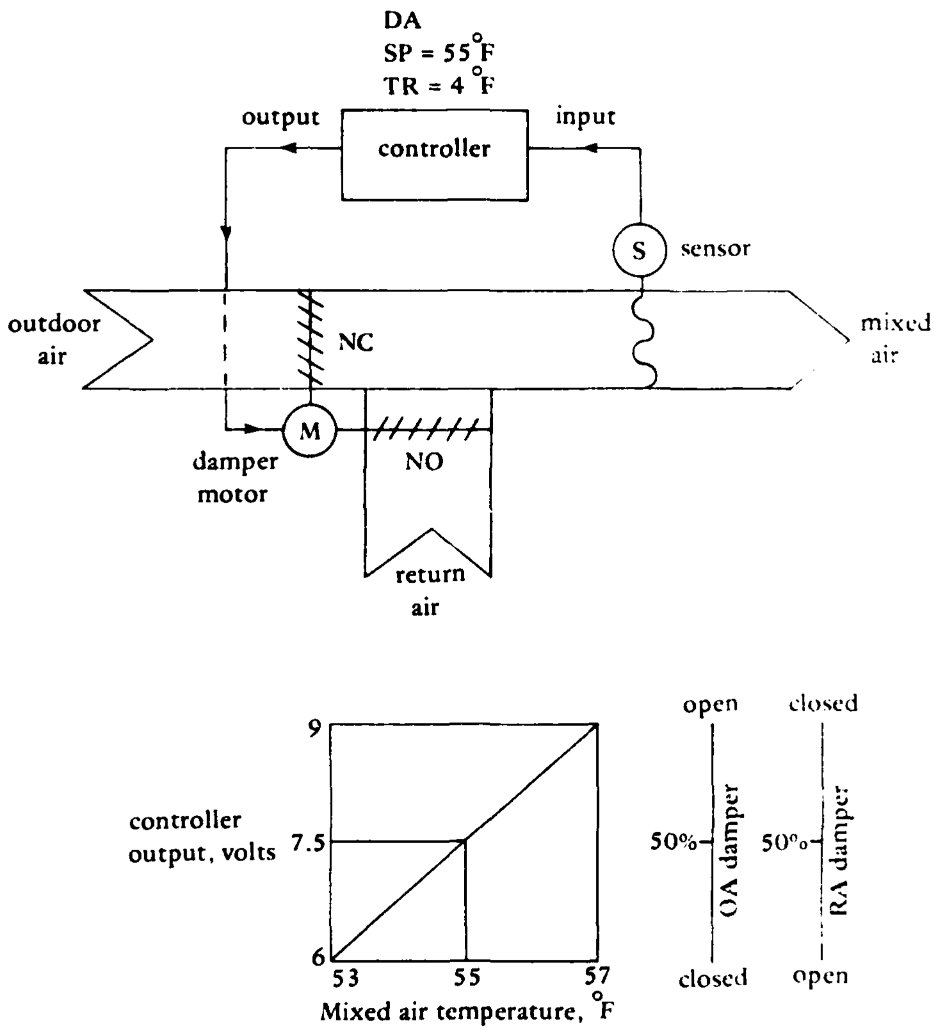


Figure 3. Control of mixed air temperature with single input controller.

A diagram illustrating the calibration procedure is presented in Figure 4.

A second calibration procedure may sometimes prove to be useful.

Procedure B

(a) Adjust a precision variable resistor or resistance decade box to the value of resistance of the sensor at the setpoint temperature. For example, 1,000 ohm BALCO™ wire sensing elements, which are frequently used as temperature sensors, have a resistance of 967.83 ohms at 55°F (see Appendix A) so the variable resistor would be set to 967.83 ohms as measured by volt-ohm meter.

(b) Disconnect the sensor from the controller and connect the variable resistor in its place.

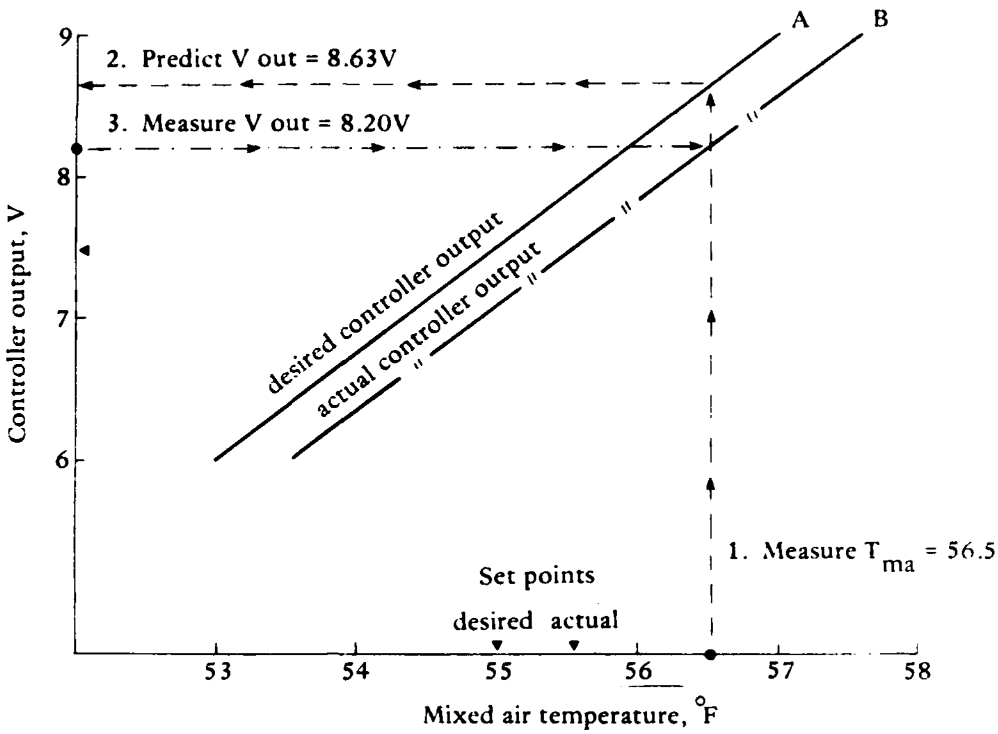
(c) Loosen the setpoint scale.

(d) Turn the setpoint adjustment screw until the controller output voltage equals the mid-point voltage (7.5 volts in the example).

(e) Turn the set point scale until the pointer is aligned with the desired value of setpoint.

(f) Tighten the setpoint scale hold down.

(g) Check calibration after system has returned to equilibrium conditions.



NOTES:

(1) Turning the set point adjustment screw shifts curve B upward and aligns it with curve A.

(2) Prior to calibration, the controller was controlling to a set point of about 55.6 °F, although the set point scale read 55 °F.

(3) Realigning the set point scale assures that the mid-range controller output occurs at the desired set point.

Figure 4. Diagram of calibration procedure A.

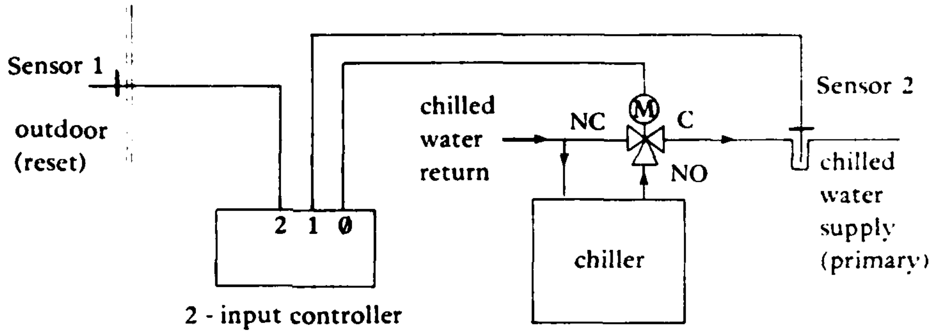
Dual Input Controllers

The calibration procedure for two input controllers is slightly more complicated because the setpoint of the controller is automatically changed, or "reset" by the second input to the controller. For example, a two input controller might be used to change the temperature of the water supplied to a chilled water cooling coil based on measurement of outdoor air temperature. This relationship between the variable measured by the first sensor (chilled water temperature) and the variable measured by the second sensor (outdoor air temperature) is called a "reset schedule". Knowledge of the specified reset schedule is required to calibrate a dual input controller. An example of the application of a two-input controller and reset schedule is presented in Figure 5.

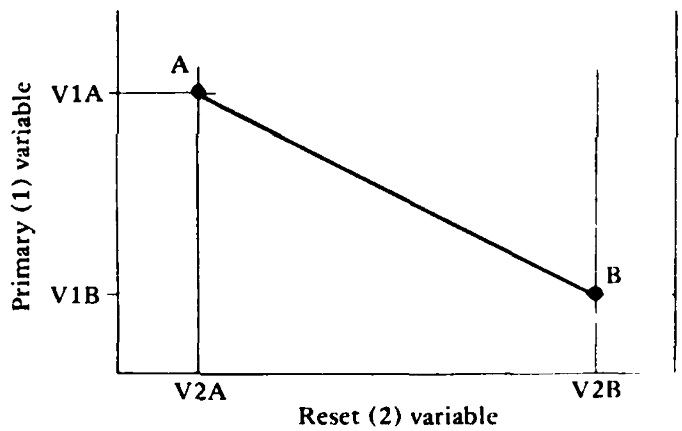
The applicable equation for predicting the output voltage of a dual input controller is

$$V_{OUT} = V_{Mid\text{-}Point} \pm \left(\frac{S_1 - SP_1}{TR_1}\right) \times VR \pm \left(\frac{S_2 - SP_2}{RATIO \times TR_1}\right) \times VR \qquad (3)$$

where the subscripts 1 and 2 refer to the primary and secondary (or reset) sensors respectively. Most dual input electronic controllers permit independent adjustment of SP_1, SP_2, TR_1 and RATIO.



Chilled water temperature reset



Reset schedule

Figure 5. Two input controller Nomenclature.

The values of SP_2 and RATIO are dependent on the characteristics of the reset schedule and should be noted in the schedule data. If the applicable values for SP_2 and RATIO are not available, or if it is desired to change the computed from the following relationships.

The value of RATIO can be calculated from the relationship:

$$\text{RATIO} = \frac{\pm\, T_{2B} - T_{2A}}{\frac{TR_1}{VR}\left(V_{OUT,B} - V_{OUT,A}\right) \pm \left(T_{1B} - T_{1A}\right)} \tag{4}$$

where the sign of the numerator is (+) if the reset sensor (sensor 2) has a <u>direct</u> action and (-) if the reset sensor has a reverse action. The sign of the second term in the denominator is (+) if the primary sensor (sensor 1) has <u>reverse</u> action and (-) if the primary sensor has <u>direct</u> action. The possible forms of equation 4 are presented in Appendix B.

Conditions "A" and "B" are any two points on the reset schedule.

With knowledge of the value of RATIO, the correct setpoint for the reset variable can be calculated from

$$\begin{aligned} SP_2 = T_{2A} \pm & \frac{\text{RATIO} \times TR_1}{VR} \\ & \times \left(V_{OUT,A} - V_{Mid\text{-}Point}\right) \\ & \pm \text{RATIO} \times \left(T_{1A} - SP_1\right) \end{aligned} \tag{5}$$

where the sign of the second term is (+) if the reset sensor has <u>reverse</u> action and (-) if the reset sensor has <u>direct</u> action. The algebraic sign of the third term is (+) if the action of the primary sensor is the same as that of the reset sensor and (-) if the action of the primary sensor is different from that of the reset sensor. The possible forms of equation 5 are presented in Appendix C.

With the knowledge of SP1, TR_1, RATIO, and SP2 in hand, the variables S1 and S2 can be measured and the output voltage of the controller can be predicted using equation 3. If the predicted value of the output voltage differs from the measured value of output voltage by more than 5%, then the controller should be recalibrated.

Example. A two input controller is used to change the setpoint of a controller regulating the temperature of the water supplied to cooling coils (Figure 5a). It is desired to change the chilled water temperature according to the relationship to outdoor temperature illustrated in Figure 6. Reset is used in this application to reduce energy consumption and preclude short cycling of equipment. This example illustrates a reverse action controller since an increase in the reset variable (outdoor air temperature) results in a decrease in the setpoint. Since SP_1, SP_2, TR_1 and RATIO are not specified, a few preliminary calculations are necessary. It is helpful to organize the data into tabular form as shown in Figure 6. Since reverse controller action is desired, both sensor inputs must have the same action. Set both inputs for direct action. Select one of the primary sensor values as the primary set point (SP_1). Choose SP_1 = 45°F. Select a reasonable value for the primary throttling range (TR_1). Choose TR_1 = 4°F. As in the previous example, the controller is assumed to be set for $V_{midpoint}$ = 7.5 V and Voltage range = 3V. From the information presented in Figures 4 and 5 and Appendix B,

$$\text{RATIO} = \frac{T_{2B}-T_{2A}}{\frac{TR_1}{VR}\left(V_{OUT,B}-V_{OUT,A}\right) - \left(T_{1B}-T_{1A}\right)}$$

$$= \frac{(60-80)}{\frac{4}{3}(9-6) - (55-45)}$$

$$= \frac{-20}{+4-10} = \frac{20}{6} = 3.33 \quad \ldots (6)$$

$$TR_2 = \text{RATIO} \times TR_1 = 13.33 \quad (7)$$

From equation (5)

$$SP_2 = T_{2A} - \frac{\text{RATIO} \times TR_1}{\text{Volt Range}}$$

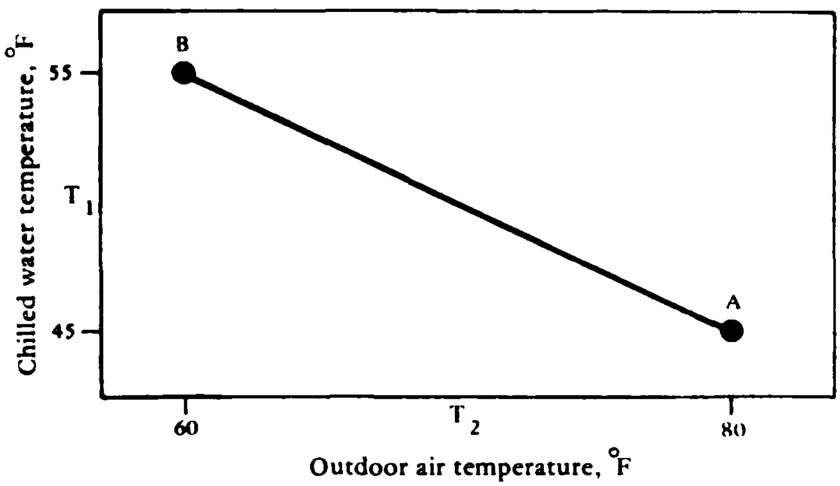
$$\times V_{OUT,A}-V_{Mid\text{-}Point}$$

$$+ \text{RATIO} \times \left(T_{1A}-SP_1\right)$$

$$= 80 - \frac{3.33 \times 4}{3} \times (6-7.5)$$

$$+ 3.33 \times (45-45) \quad (8)$$

$$= 80 + 6.66 + 0 = 86.6°F$$



Point	TCWS - "1"	TOA - "2"	Valve Position	Controller Output
A	45	80	open	6
B	55	60	closed	0

Table of reset schedule

Figure 6. Reset of chilled water temperature by outdoor air temperature.

Therefore, from equation 3,

$$V_{OUT} = 7.5 + \left(\frac{T_{cws} - 45}{4}\right) x\ 3 + \left(\frac{T_{OA} - 86.6}{13.33}\right)$$

$$x\ 3 + \left(\frac{T_{OA} - 86.6}{13.33}\right) x\ 3 \qquad (9)$$

Set the chilled water supply temperature controller for setpoint 1 = 45°F, setpoint 2 = 87°F, throttling range = 4°F and RATIO = 3.33.

After operating conditions have stabilized, measure the chilled water temperature (T_1) at a point near sensor 1 and measure the outdoor air temperature (T_2) at a location near the outdoor air sensor. Use independent, calibrated instruments for these measurements. Suppose the measured values of T_1 and T_2 are 49°F and 74°F respectively. Then the output voltage from the controller should be

$$V_{OUT} = 7.5 + \left(\frac{49 - 45}{4}\right) x\ 3 + \left(\frac{74 - 86.6}{13.3}\right)$$

$$x\ 3 = 7.65V$$

If the measured output voltage equaled 7.4 volts, the difference would be

$$\frac{7.65 - 7.3}{7.63} x\ 100 = 5\%$$

and the controller should be calibrated.

In the example presented above, the calculated values of both the RATIO and SP_2 were within the capabilities of existing hardware.

In some circumstances however, the calculated values of RATIO or SP_2 may not be compatible with the performance of the controller hardware, e.g., a value of RATIO = 0.1 or a value of SP_2 = -40°F. If the calculated values of the control parameters fall outside the capability of the controller being used, the values of the independent controller parameters can be changed and/or the reset schedule can be modified until a combination of values is found which falls within the capabilities of the hardware. For example, the value of TR_1 can be changed and the calculation of TR_2 and SP_2 repeated to see if they fall within acceptable limits (but do not make TR_1 so small as to affect control stability or so large as to affect control accuracy). Sometimes switching which sensor is designated to be the primary sensor and which is designated to be the reset sensor will resolve difficulties with controller capability limitations. Finally, the reset schedule may have to be modified (which usually means making the ranges of the primary and reset variables smaller) to make the desired performance conform to hardware.

Calibration Procedure for Dual Input Controllers

Because the output from a dual input controller is dependent upon two independent inputs, it is convenient to decouple the inputs and adjust each one independent of the other.

(a) Disable sensor 2 (also called sensor B on some controllers). This usually is done by disconnecting the sensor leads. Some controllers require removal of an additional jumper wire. See specific instructions for the type of controller being used.

(b) Calculate the predicted output voltage, measure the actual output voltage, and adjust the setpoint scale for the primary sensor using the procedures already presented for a single input controller.

(c) With the primary sensor now calibrated, reconnect the reset sensor. Measure the output voltage of the controller and compare the measured to the predicted value. Any difference now must be due to miscalibration of the reset sensor.

(d) Loosen the setpoint scale and adjust the setpoint dial for the reset sensor until the measured output equals the predicted output.

(e) Tighten the setpoint scale.

The preceding calibration procedure assumes that the throttling range and ratio adjustments are in calibration. If a precision variable resistor or resistance decade box is available, both TR and RATIO can also be checked for calibration. To check throttling range, disconnect the reset sensor and calibrate the primary sensor using procedure B for calibrating single input controllers. Use Equation 9 to calculate the temperatures that would have to be measured by the primary sensor to obtain the extreme values of output voltage. For example,

$$6V = 7.5V + \left(\frac{T_{1,min} - 45}{4}\right) x\ 3$$

and

$$9V = 7.5V + \left(\frac{T_{1,max} - 45}{4}\right) x\ 3$$

or

T_1,min = 43°F and T_1,max = 47°F

These values are, of course, equal to the setpoint plus and minus one half the throttling range. Set the variable resistor to simulate 43°F (942.64 Ω for the sensors in the examples) and connect the resistor in place of the primary sensor. The output voltage should be 6V. Repeat for 47°F; the output voltage should be 9V. Adjust the throttling range dial and scale as required to obtain the correct minimum and maximum output values.

After calibrating SP_1, TR, and SP_2, the RATIO adjustment can be checked for accuracy. First, it is necessary to eliminate the influence of the primary sensor. This can be done by setting the primary setpoint (SP_1) to the measured value of T_1 (49°F in this example). A better way is to use a variable resistor connected to the primary sensor input to exactly balance the primary sensor circuit. Again, calculate the temperatures that would have to be measured (this time by the reset sensor) to obtain the extreme values of output voltage. For this example

$$6V = 7.5V + \left(\frac{T_{2,min} - 86.7}{3.33 \times 4}\right) \times 3$$

and

$$9V = 7.5V + \left(\frac{T_{2,max} - 86.7}{3.33 \times 4}\right) \times 3$$

or

T_2,min = 80.0°F and T_2,max = 93.3°F

These values are equal to the reset setpoint plus and minus the value of RATIO times half the throttling range. Set the variable resistor to simulate 80.04°F and connect the resistor in place of the reset sensor. The output voltage should equal 6V. Repeat the procedure for 93.37°F; the output should equal 9V. Adjust the RATIO dial and scale as required to obtain the correct minimum and maximum values of output voltage.

Appendix A

TEMPERATURE VERSUS RESISTANCE DATA FOR BALCO™ SENSING ELEMENTS

BALCO WIRE SENSING ELEMENT
TEMPERATURE VS. RESISTANCE
(1000Ω ELEMENT CALIBRATED AT 70°F.)

TEMPERATURE DEGREES F.	RESISTANCE IN OHMS	OHMS/°F.	TEMPERATURE DEGREES F.	RESISTANCE IN OHMS	OHMS/°F
-50	763.510	0.000	-6	844.751	1.915
-49	765.288	1.778	-5	846.670	1.919
-48	767.069	1.781	-4	848.592	1.922
-47	768.853	1.784	-3	850.517	1.925
-46	770.641	1.788	-2	852.445	1.928
-45	772.432	1.791	-1	854.377	1.932
-44	774.225	1.794	0	856.312	1.935
-43	776.022	1.797	1	858.250	1.938
-42	777.823	1.800	2	860.192	1.942
-41	779.626	1.803	3	862.137	1.945
-40	781.432	1.806	4	864.085	1.948
-39	783.242	1.810	5	866.036	1.951
-38	785.055	1.813	6	867.991	1.955
-37	786.871	1.816	7	869.9[illegible]	[illegible]
-36	788.690	1.819	8	871.910	[illegible]
-35	790.512	1.822	9	873.[illegible]	1.964
-34	792.337	1.825	10	875.842	1.966
-33	794.166	1.829	11	877.813	[illegible]
-32	795.998	1.832	12	879.[illegible]	[illegible]
-31	797.833	1.835	13	881.7[illegible]	[illegible]
-30	799.671	1.838	14	883.[illegible]	[illegible]
-29	801.512	1.841	15	885.730	[illegible]
-28	803.357	1.845	16	887.71[illegible]	[illegible]
-27	805.205	1.848	17	889.709	[illegible]
-26	807.056	1.851	18	891.703	[illegible]
-25	808.910	1.854	19	893.700	[illegible]
-24	810.767	1.857	20	895.701	2.001
-23	812.628	1.861	21	897.70[illegible]	2.00[illegible]
-22	814.492	1.864	22	899.712	2.007
-21	816.359	1.867	23	901.723	2.011
-20	818.229	1.870	24	903.737	2.014
-19	820.102	1.873	25	905.754	2.017
-18	821.979	1.877	26	907.77[illegible]	2.021
-17	823.859	1.880	27	909.7[illegible]	2.024
-16	825.742	1.883	28	911.[illegible]	2.027
-15	827.628	1.886	29	913.[illegible]	2.031
-14	829.513	1.890	30	915.[illegible]	2.034
-13	831.411	1.893	31	917.92[illegible]	2.037
-12	833.307	1.896	32	919.[illegible]	2.04[illegible]
-11	835.205	1.899	33	92[illegible]	2.04[illegible]
-10	837.109	1.903	34	924.0[illegible]	2.047
-9	839.014	1.906	35	926.110	2.051
-8	840.923	1.909	36	928.[illegible]	2.054
-7	842.835	1.912	37	930.221	2.057

TEMPERATURE DEGREES F.	RESISTANCE IN OHMS	OHMS/°F.	TEMPERATURE DEGREES F.	RESISTANCE IN OHMS	OHMS/°F
38	932.282	2.061	89	1041.81	2.225
39	934.346	2.064	90	1044.04	2.227
40	936.413	2.067	91	1046.27	2.230
41	938.484	2.071	92	1048.50	2.233
42	940.558	2.074	93	1050.73	2.235
43	942.635	2.077	94	1052.97	2.238
44	944.716	2.081	95	1055.21	2.241
45	946.800	2.084	96	1057.46	2.243
46	948.888	2.087	97	1059.70	[illegible]
47	950.978	2.091	98	1061.95	[illegible]
48	953.073	2.094	99	1064.[illegible]	[illegible]
49	955.170	2.098	100	1066.[illegible]	[illegible]
50	957.271	2.101	101	1068.71	[illegible]
51	959.375	2.104	102	1070.97	[illegible]
52	961.483	2.108	103	1073.23	[illegible]
53	963.594	2.111	104	1075.50	2.265
54	965.709	2.114	105	1077.77	2.267
55	967.826	2.118	106	1080.04	2.270
56	969.948	2.121	107	1082.31	2.272
57	972.072	2.125	108	1084.[illegible]	2.275
58	974.200	2.128	109	1086.[illegible]	[illegible]
59	976.331	2.131	110	1089.14	[illegible]
60	978.466	2.135	111	1091.42	[illegible]
61	980.604	2.138	112	1093.71	[illegible]
62	982.746	2.142	113	1096.00	[illegible]
63	984.891	2.145	114	1098.[illegible]	[illegible]
64	987.039	2.148	115	1100.[illegible]	[illegible]
65	989.191	2.152	116	1102.[illegible]	[illegible]
66	991.345	2.155	117	1105.17	[illegible]
67	993.504	2.158	118	1107.48	2.301
68	995.666	2.162	119	1109.78	[illegible]
69	997.831	2.165	120	1112.[illegible]	[illegible]
70	1000.000	2.169	121	1114.[illegible]	[illegible]
71	1002.18	2.176	122	1116.71	2.311
72	1004.35	2.179	123	1119.[illegible]	[illegible]
73	1006.54	2.181	124	1121.[illegible]	[illegible]
74	1008.72	2.184	125	1123.[illegible]	[illegible]
75	1010.91	2.187	126	1125.[illegible]	[illegible]
76	1013.10	2.190	127	1128.[illegible]	[illegible]
77	1015.29	2.192	128	1130.[illegible]	[illegible]
78	1017.48	2.195	129	1132.[illegible]	[illegible]
79	1019.68	2.198	130	1135.[illegible]	[illegible]
80	1021.88	2.200	131	1137.[illegible]	[illegible]
81	1024.09	2.203	132	[illegible]	[illegible]
82	1026.29	2.206	133	[illegible]	[illegible]
83	1028.50	2.209	134	[illegible]	[illegible]
84	1030.71	2.211	135	[illegible]	[illegible]
85	1032.93	2.214	136	1149.[illegible]	[illegible]
86	1035.14	2.217	137	[illegible]	[illegible]
87	1037.36	2.219	138	1154.[illegible]	[illegible]
88	1039.58	2.222	139	[illegible]	[illegible]

TEMPERATURE DEGREES F.	RESISTANCE IN OHMS	OHMS/°F.	TEMPERATURE DEGREES F.	RESISTANCE IN OHMS	OHMS/°F.
140	1158.74	2.357	189	1277.17	2.473
141	1161.10	2.359	190	1279.65	2.475
142	1163.46	2.362	191	1282.13	2.477
143	1165.83	2.364	192	1284.61	2.480
144	1168.19	2.367	193	1287.09	2.482
145	1170.56	2.369	194	1289.57	2.484
146	1172.93	2.372	195	1292.06	2.486
147	1175.31	2.374	196	1294.55	2.489
148	1177.68	2.376	197	1297.04	2.491
149	1180.06	2.379	198	1299.53	2.493
150	1182.44	2.381	199	1302.03	2.495
151	1184.83	2.384	200	1304.52	2.497
152	1187.21	2.386	201	1307.02	2.499
153	1189.60	2.389	202	1309.52	2.502
154	1191.99	2.391	203	1312.03	2.504
155	1194.39	2.394	204	1314.53	2.506
156	1196.78	2.396	205	1317.04	2.508
157	1199.18	2.398	206	1319.55	2.510
158	1201.58	2.401	207	1322.06	2.513
159	1203.99	2.403	208	1324.58	2.515
160	1206.39	2.405	209	1327.10	2.517
161	1208.80	2.408	210	1329.62	2.519
162	1211.21	2.410	211	1332.14	2.521
163	1213.62	2.413	212	1334.66	2.523
164	1216.04	2.415	213	1337.18	2.525
165	1218.46	2.417	214	1339.71	2.527
166	1220.88	2.420	215	1342.24	2.529
167	1223.30	2.422	216	1344.77	2.531
168	1225.72	2.425	217	1347.31	2.534
169	1228.15	2.427	218	1349.84	2.536
170	1230.58	2.429	219	1352.38	2.538
171	1233.01	2.432	220	1354.92	2.540
172	1235.44	2.434	221	1357.46	2.542
173	1237.88	2.436	222	1360.00	2.544
174	1240.32	2.439	223	1362.55	2.546
175	1242.76	2.441	224	1365.10	2.548
176	1245.20	2.443	225	1367.65	2.550
177	1247.65	2.446	226	1370.20	2.552
178	1250.10	2.448	227	[illegible].75	2.554
179	1252.55	2.450	228	1375.31	2.556
180	1255.00	2.452	229	1377.87	2.558
181	1257.45	2.455	230	1380.43	2.560
182	1259.91	2.457	231	1382.99	2.562
183	1262.37	2.459	232	1385.56	2.564
184	1264.83	2.462	233	1388.12	2.566
185	1267.30	2.464	234	1390.69	2.568
186	1269.76	2.466	235	1393.26	2.570
187	1272.23	2.468	236	1395.83	2.572
188	1274.70	2.471	237	1398.41	2.574

Appendix B

EQUATIONS FOR RATIO

Case 1 - Controller action: Reverse, sensor actions (P/R): direct/direct

$$\text{RATIO} = \frac{\left(T_{2B}-T_{2A}\right)}{\frac{TR_1}{\text{Voltage Range}}\left(V_{OUT,B}-V_{OUT,A}\right) - \left(T_{1B}-T_{1A}\right)}$$

Case 2 - Controller action: Reverse, sensor actions: reverse/reverse

$$\text{RATIO} = \frac{-\left(T_{2B}-T_{2A}\right)}{\frac{TR_1}{\text{Voltage Range}}\left(V_{OUT,B}-V_{OUT,A}\right) + \left(T_{1B}-T_{1A}\right)}$$

Case 3 - Controller action: direct, sensor actions: direct/reverse

$$\text{RATIO} = \frac{-\left(T_{2B}-T_{2A}\right)}{\frac{TR_1}{\text{Voltage Range}}\left(V_{OUT,B}-V_{OUT,A}\right) - \left(T_{1B}-T_{1A}\right)}$$

Case 4 - Controller action: direct, sensor actions: reverse/direct

$$\text{RATIO} = \frac{\left(T_{2B}-T_{2A}\right)}{\frac{TR_1}{\text{Voltage Range}}\left(V_{OUT,B}-V_{OUT,A}\right) + \left(T_{1B}-T_{1A}\right)}$$

Appendix C

EQUATIONS FOR SP_2

Case 1 - Controller action: reverse, sensor actions (P/R): direct/direct

$$SP_2 = T_{2A} - \frac{\text{RANGE} \times TR_1}{\text{Voltage Range}} \times \left(V_{OUT,A} - V_{Mid\text{-}Range}\right) + \text{RATIO} \times \left(T_{1A} - SP_1\right)$$

Case 2 - Controller action: reverse, sensor actions: reverse/reverse

$$SP_2 = T_{2A} + \frac{\text{RATIO} \times TR_1}{\text{Voltage Range}} \times \left(V_{OUT,A} - V_{Mid\text{-}Point}\right) + \text{RATIO} \times \left(T_{1A} - SP_1\right)$$

Case 3 - Controller action: direct, sensor actions: direct/reverse

$$SP_2 = T_{2A} + \frac{\text{RATIO} \times TR}{\text{Voltage Range}} \times \left(V_{OUT,A} - V_{Mid\text{-}Point}\right) - \text{RATIO} \times \left(T_{1A} - SP_1\right)$$

Case 4 - Controller action: direct, sensor actions: reverse/direct

$$SP_2 = T_{2A} - \frac{RATIO \times TR_1}{Voltage\ Range} \times \left(V_{OUT,A} - V_{Mid\text{-}Point}\right) - RATIO \times \left(T_{1A} - SP_1\right)$$

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