

Calibration of the Temperature Gauge

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June 18, 2007*

Background

Whenever the XJ-S driver sees the dash temperature gauge creeping up higher than he/she is comfortable with the first question is generally “Is the gauge right?” One way to answer this is to make some kind of independent measurement. Some have gone so far as to fit additional sensors to the engine and mount a separate gauge or gauges in the car. More commonly, an infrared radiation (IR) “gun” is used to measure temperature of various surfaces on the engine, e.g., the top radiator hoses or thermostat housings. Presented here is another method that’s not very difficult or expensive.

Note that the gauge discussed here is the “barrel style” gauge used in the XJ-S from 1975 through 1990.

The Approach

The approach taken here employs a two stage calibration process. First, the sender for the gauge (part number DAC 2583) is removed from the car and tested on the stove top, producing a curve of resistance vs. coolant temperature. Then the gauge itself is calibrated in the car by substituting an adjustable resistor (a potentiometer, or pot for short) for the sender, producing a table of gauge position vs. resistance. These two calibrations can be used together to give a table of coolant temperature vs. gauge position, or the reverse.

I carried out these calibrations for two different senders and two different gauges and used the results to get curve fits of the components individually and for the sender and gauge working together. If your sender and gauge are in good working order the results can be used directly since the differences between the components I tested were relatively small. Or, you can use the methods I describe to test and calibrate your components specifically. If you do some tests of your own, carefully following the procedures I describe here, I would be grateful if you would send them to me.

Results

The final results are presented in Figure 1. Temperature is in Fahrenheit and gauge position is in “needle widths,” or NW. The center of the gauge was defined to be 0, and the top and bottom “tick marks” on the barrel are +11 and -11 NW respectively. This puts the C, N and H marks on the instrument cluster at -10, 0, and +10 NW respectively.

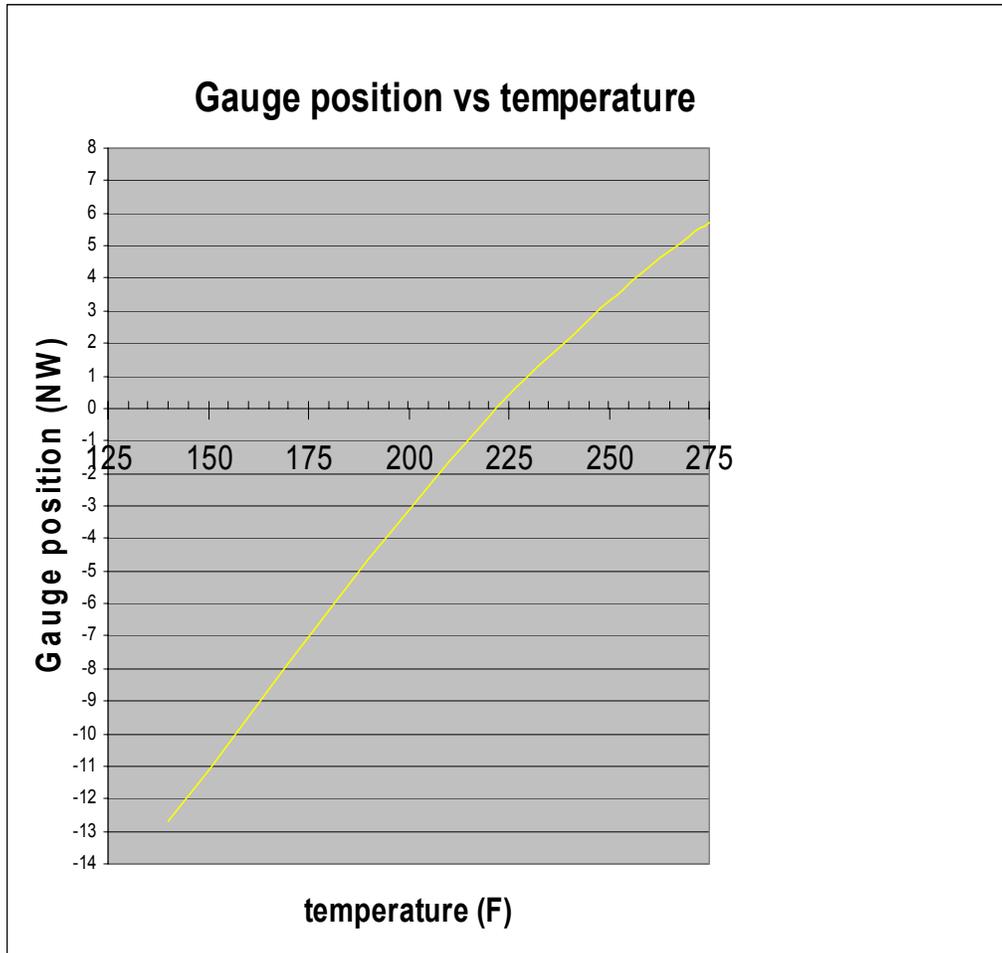


Figure 1 Gauge position vs. Coolant temperature

Figure 1 supports the common wisdom among XJ-S owners, i.e., N is really pretty hot and the area above N is reached only under stress, e.g., heavy engine load, high outside temperature, and/or faults in the cooling system. In other words, for our cars the N should be thought of as the *top of the normal range*, rather than the normal operating point. That is not to say the needle should never be above N, but simply that if it is, the coolant is above 225 F. See Discussion of Results below.

The data is presented in tabular form in Table 1. The right column of the table shows gauge sensitivity, i.e., the degree F change per NW of needle movement. In the lower half it is about 6 DegF/NW, while it's about 8 DegF/NW around the N mark and on into the more tolerable portion of the above-N scale.

Table 1 Coolant temperature vs. Gauge Reading

Gauge (NW)	Temperature (F)	Sensitivity (Deg/NW)
-11	151	
-10	157	6
-9	163	6
-8	169	6
-7	175	6
-6	181	6
-5	188	6
-4	194	6
-3	201	7
-2	207	6
-1	214	7
0	222	8
1	230	8
2	238	8
3	247	9
4	256	9
5	267	11
6	278	11
7	291	13

Discussion of Results

If you are really paranoid, you might print it out the above table and tape it to the back side of your visor or something. Most will be happy with some simple rules of thumb. Here are some points on the scale that are easy to remember:

- Halfway between N and H is about 267 F (130 C). Post-shutdown coolant boil-off is likely.
- 2 NW above N is about 238 F(114 C)
- Overlining N (bottom of needle at top of N) about 234 F (112 C)
- N is about 220F (104 C)
- Underlining N(top of needle at bottom of N) about 210 F (99 C)
- 2 NW below N is about 207 F(97 C). 88C thermostats probably fully open.¹
- 4 NW below N is about 194 F (90 C), 82 C thermostats almost fully open.
- Halfway between C and N is about 188 F (87 C).

To put these temperatures in perspective, though, you need to keep a couple facts in mind. One is that you have (or should have) a 15-16 PSI pressure cap on the remote header filler neck, meaning that the cooling system operates at about 30 PSI absolute (about 2 atmospheres). The

¹ I'm assuming the thermostats go from closed to open over a 10 degree F range, beginning at the rating point.

other fact is that pure water at 30 PSI absolute doesn't boil until it gets to 250 degrees F (121 C). Thus if your gauge reading 3-4 NW above N and you have pure water in the system (which you shouldn't) you will be at the boiling. But, since you probably have a 50/50 mix of water and coolant, the boiling point is somewhat higher. A UK Jaguar fan, Bob Egerton, has spoken with coolant manufactures in the UK and was told that "...a 50:50 solution of their product with H₂O at atmospheric pressure would boil at 108 C and at 2 atmospheres at 135.8 C (281 F)". (See <http://www.far-out.demon.co.uk/cardiy/moreinfo.htm>). Putting all this together, if your gauge and sender are good, you have a good pressure cap, and have a fresh 50/50 coolant mix, you are probably not going to be boiling until you get about 6-7 NW above N.

I say "probably not" because there were a lot of "ifs" in that sentence. Here are some other things to think about:

- Post-shutdown heat soak-back. I have no specific data to offer, but I can say that at times when my cooling system was not up to snuff I have had "total loss of coolant events" in the garage when there was no sign of boiling at shutdown.
- Yet another reason for not treating the +3 to +7 NW area as free headroom is the possibility of hotspots in the engine. That is, places where the circulation perhaps isn't as good as it should be and/or near the combustion chamber can be significantly hotter than what the sender sees.
- Even an 88 C (190 F) thermostat is fully open when the needle is about 2 NW below N. What this means is that when the needle is on N or above the engine is well into the "free float" range, with respect to temperature. Any increase in outside temperature will result in a degree-for-degree increase in engine temperature, and any increase in engine load will result in further coolant temperature increases.
- And, finally, as Kirby Palm frequently points out, the left bank may be hotter than the right where the gauge sender is. So, it would be prudent to follow the conventional wisdom and get a bit worried when you get more than a couple NW above N.

A Simple Test

A simple test of the gauge as installed requires only a 50 Ohm resistor and a pair of jumper wires. First, disconnect the sender. Use one jumper to connect one end of the resistor to ground. Using the second jumper, connect the other end of the resistor to the disconnected sender wire. Turn on the ignition and look at the gauge. If the needle goes to the center of N your gauge is working fine. If it doesn't, take out the instrument cluster and clean up the connectors. This will probably correct the problem because the gauge and sender units seem to be fairly robust.

Effect of Poor Ground

Numerous XJ-S owners have reported erratic instruments having been traced to poor grounding of the instrument cluster or the ground connection to the gauge in question. I can show that there is a theoretical effect of resistance (such as would be caused poor grounding) between the temperature gauge terminal that is supposed to be grounded and engine ground (where the sender is solidly grounded since its screwed into the engine). However, since any such resistance would be in series with one of the windings in the gauge that happens to be about 64 ohms it would have to be quite a bad connection before a significant effect would be seen at the gauge.

I have bench tested this theory on my spare gauge. I put a 47 Ohm resistor (that I happened to have handy) in place of the sender and this brought the gauge to about 1 NW above the N when the ground terminal was connected to battery ground. I then placed 2 Ohm resistor between the ground terminal and battery ground, which raised the needle a tiny bit. I then put a 10 Ohm resistor in the ground path, raising the needle by about 1 NW. I conclude that a bad ground will indeed increase gauge readings, but it has to be a really bad ground to affect it significantly.

Voltage Effects

The question of battery voltage effect on temperature gauge readings occasionally comes up. As shown in the Appendix, there is a theoretical linear relationship between the gauge position (or at least the currents upon which it depends) and the voltage difference between the gauge 12 volt (nominal) supply and ground. Joe Bialy (Jaguar Joe on the Jag Lovers list) has done some bench tests on his spare instrument cluster using a variable voltage source. Here are his findings:

“Attaching a 49.8 ohm resistor to the temperature gauge input and varying the gauge's supply voltage produced the following results:

9.00 volts supply = needle at bottom of the N

13.2 volts supply = needle at center of the N

17.0 volts supply = needle at the top of the N

Further, Joes says

“Voltage between 12 and 14, which is pretty much where these cars run at, provided almost imperceptible changes in needle movement. “

So, there you have it. Not to worry, because if the engine will start the gauge will be pretty good over the expected voltage swings, provided the gauge is well grounded and doesn't have too much resistance in the supply voltage.

Also, you might note that Joe has confirmed that a 50 Ohm resistor in place of the sender should give a gauge reading of N. This is the 3rd confirmation of this I've had from Jag Lovers list members.

Method Used and Basis of the Results

You don't need to read this rest of this unless you want to know more about how I came to the above results, or you want to do the tests on your own components.

Sender Tests

I had three senders on hand, Figure 2. The one at the left is the one that came with the car, part number GTR108. The parts book shows an inline resistor in to go with it, but I don't recall ever having seen one on my car. (This sender is no longer available so I shouldn't even bother you with it.) The other two are both the current part (DAC2583) listed for my car as well as later models, probably up until the 6.0 L engine. The rightmost one is brand new, and the one in the middle is the one I put in several years ago. I was going to replace it but decided not to for two reasons. For one thing, the test showed no difference significant between the new and old parts. Second, the new one would not easily screw into the hole, while the old one does. Rather than

investigating, I decided to reinstall the old one after the tests. Note that the probe is longer on the new one. That could be to ensure it projects well into the coolant stream.



Figure 2 Senders tested

The test setup is shown in Figure 3 and Figure 4. I formed a jig out of #6 ground wire (any hardware store has it) to hold two senders in the pot at once because I wanted to compare them under identical conditions. (That turned out not to be much of an issue because the data is very repeatable.) The jig has to grip tightly around threads of the senders so it can serve as a ground path for resistance measurements.

I used two DMMs, one fitted with a thermocouple temperature probe adapter (www.tequipment.net, TPI A301) and the other to measure resistance. The negative probe of the resistance DMM is clipped to the mount jig, and the positive probe is shifted between the two senders at each measurement point.

I also tried using my digital kitchen thermometer, partially seen in the lower left of the photo. The readings agreed pretty well, so it would be a less expensive alternative compared to the thermocouple adapter. The advantage of the thermocouple is it can be wound around the mounting jig to reliably hold it in the water near the senders, whereas the kitchen thermometer has to be held in the water for a few minutes to get an accurate reading. That plus switching the resistance measuring DMM between the two senders under test makes it difficult to record data for each sender at exactly the same temperature.

The technique I developed starts with the water cold, straight from the tap, and the burner set to the lowest possible level. A higher flame results in water temperature changing so fast that it's difficult to accurately read and record the data. As the water warms up the flame has to be turned up a bit, but not too high. It will take the better part of an hour to complete the test.

Since I used water the highest temperature I could get was about 212 F. At some future time I may do a test using cooking oil so I can get some higher data points. However, as you will see below the trend line is well behaved so extrapolation beyond 212 F shouldn't be a problem.



Figure 3 Test setup



Figure 4 Close-up of sender test.

Correlation of the Sender Data

With the setup and procedures described above I recorded many data points, i.e., pairs of water temperature and corresponding sender resistance. In addition, I had some data published by Bob Egerton mentioned previously. I put all of this data into a program called CurveExpert (<http://curveexpert.webhop.biz/>). After trying various forms from the CurveExpert menu I found a very good fit to a formula of the form

$$R_s = \exp(a + b/T + c \ln(T)) \quad \text{Eq. 1}$$

where R_s is sender resistance and T is temperature in degrees F. The values of the coefficients found by CurveExpert are

$$a = 26.61777 \quad b = -185.966 \quad c = -4.04296$$

I realize this is more mathematical than many readers will appreciate, the important thing is the fit is very, good. That is, all of my data plus Bob Egerton's fall very close to the fitted curve, as can be seen in Figure 1.²

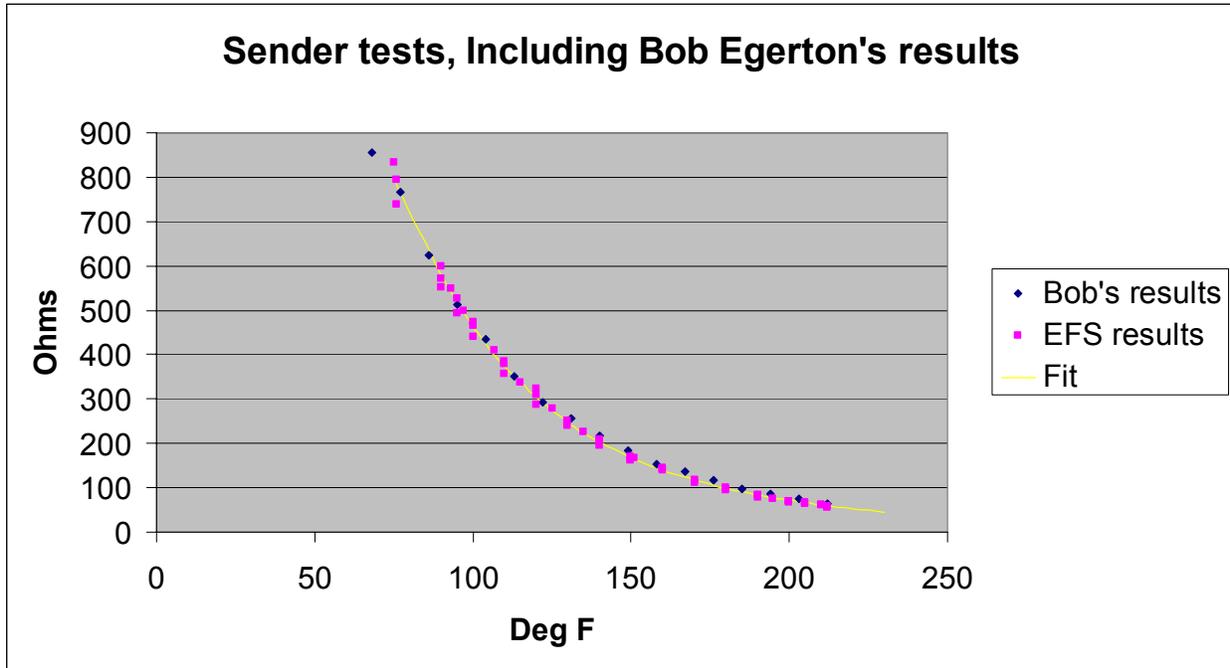


Figure 5 Correlation of Sender Test Results

So, it appears that these senders are quite predictable across time and geographic distance. I also believe these senders are reliable since even the old GTR8 part (which was in service for 25 years) was still giving a signal that, while a little different from the DAC2583, was not wildly out of the ballpark. I am moved to say that unless your sender has suffered a fire incident or some other catastrophe, you may well assume it's OK and performs as indicated by the formula. Nonetheless, if you want to be absolutely sure yours is OK, just make three careful measurements: It should read close to 240-250 ohms at 125 F, about 70 ohms at 200 F, and 59 or so at 212 F. If it passes that test, it's alright. Change your focus to the gauge.

Calibrating the Gauge

Since the gauge has no scale other than C-N-H we need to make one up. Following the custom among many XJ-S drivers, I chose the "needle width" (NW) as the units. I happened to have a spare gauge so I did some measurements on it to determine that there are about 22 NWs between the centers of the large "tick marks" at the two ends of the barrel itself, Figure 6.. If we arbitrarily set the 0 of our scale at the center of the barrel, there are 11 NWs above and below. However, the C, N, and H are on instrument cluster aperture through which the gauge is seen. Sitting in the driver's seat, the C appears to be about 1 NW above the lower barrel tick mark, and

² I also have some data from Sean Straw that doesn't fit the above curve very well. Don't know why.

the H is about 1 NW below the upper tick mark.³ Therefore the C is at -10 NW, the N is at 0, and the H is at +10.

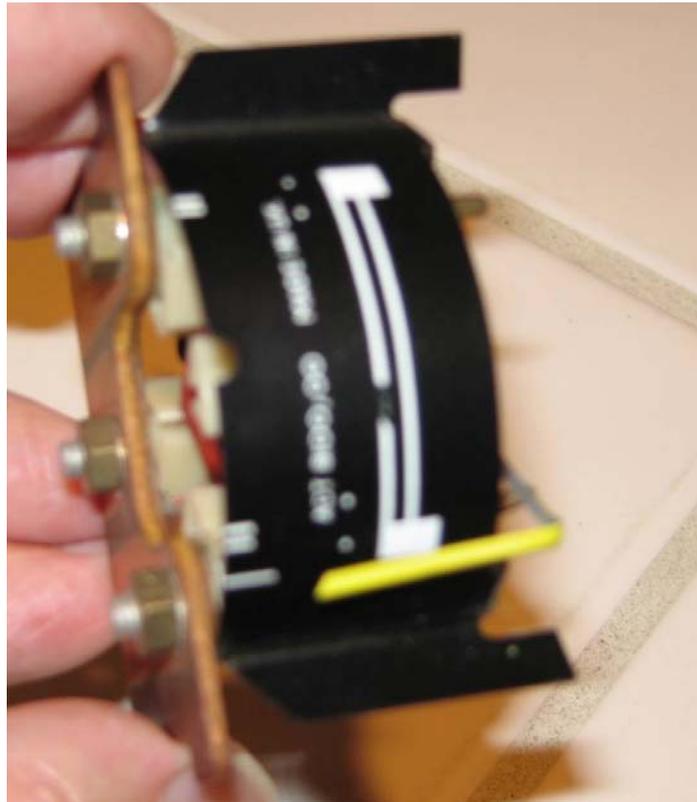


Figure 6 Temperature Gauge, Front

With this scale defined the calibration tests can begin. As mentioned earlier, to do the tests we need to adjust the resistance to ground seen by the gauge until the needle rests at a particular position on the gage, e.g., C, N, or H. I wanted to do this with the gauge installed on the car, so I built the test rig shown in Figure 7. I used a 12 foot length of lamp cord, an alligator clip, a male spade connector, a 500 Ohm trim pot, and single throw double pole switch. The purpose of the switch is to disconnect the pot from the gauge while measuring its resistance. The alligator clip and spade connector are attached at one end of the cord, to be connected to engine ground and the (disconnected) sender wire on the engine. The switch and pot are connected at the other, Figure 8. The pigtails are for easy connection of the DMM. One of the pigtails is the ground, and is so marked.

To carry out the test, you will need a clipboard and paper to record gauge position and resistance. When this has been prepared, connect the test rig to ground and the (disconnected) sender lead in the engine compartment. Then get into the drivers seat so you have a good view of the gauge. Connect the DMM to the pigtails on the test rig, being sure the black lead goes to the ground wire. Now turn on the ignition. Set the switch to the position that puts the pot in the gauge circuit and turn the pot so as to set the needle to the middle of C. Flip the (if it's a trim pot you will need a small flat blade screwdriver). Flip the switch the other way and take a reading from the DMM and record it along with the gauge position in NWs. Remember, C is -10, N is 0, and

³ Unless otherwise noted, when I refer to C, N, H, or the needle itself I am referring to their centers.

H is +10. Repeat the process for other positions on the gauge. C, N, and H are important because your ability to discern the needle position is better at these points. But, you can also estimate the mid-way marks between C and N (-5) and N and H (+5).



Figure 7 Gauge test rig.

One thing you will notice in doing these tests is the gauge is kind of lazy when going down. That is, it responds fairly quickly when you are moving the needle up (reducing the resistance), but when you increase the resistance the needle takes a long time to drop. This can be a big source of error if you don't wait long enough for the needle to stabilize after adjusting the pot. To avoid this problem I made it a practice to take readings in an *increasing direction*, i.e., starting from C and moving point by point to H. If in the process you accidentally overshoot, try this trick. Turn the pot so as to drop the needle (i.e., increase the resistance) a little, then flip the switch. This opens the gauge circuit, causing fairly rapid needle fall. Then flip it back and let it rise to its new position.



Figure 8 Close-up, gauge test rig.

Results of Gauge Tests

The results obtained for both of the gauges tested are presented in Figure 9. Only three points were measured for the spare gauge since when removed from the instrument cluster the only reference points are the end tick marks on the barrel. I took readings at these two points and at the middle of the range.

This data shows a lot more scatter than the sender results. One reason for this scatter is the difficulty in estimating needle position. Another is the “laziness” of the gauge mentioned earlier. These factors result in a difference of perhaps 5 ohms when repeating a particular needle position in the upper range of the scale, and sometimes as much as 25-30 ohms in the lower portion. Nonetheless, it is striking how closely the two different gauges perform.

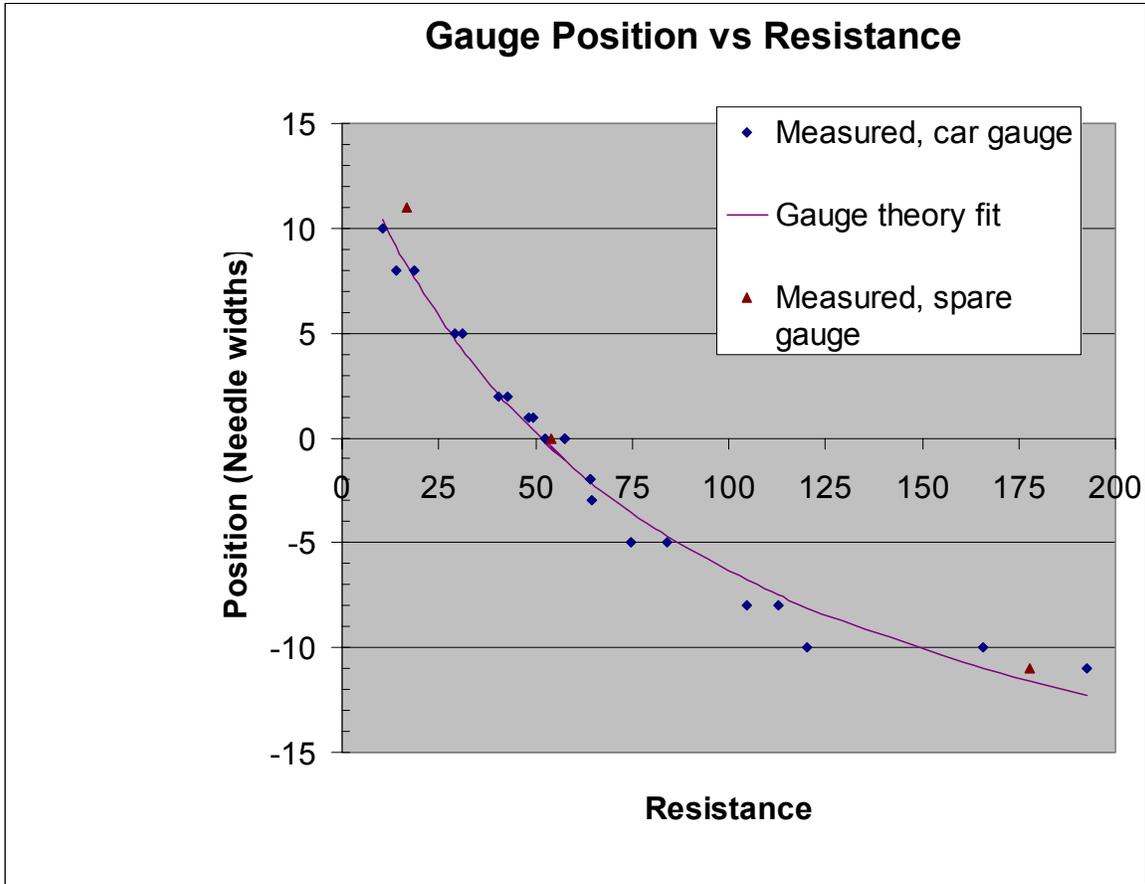


Figure 9 Gauge test results

As with the sender data I did a curve fit of this data. In this case, however, none of the built-in equation forms in the CurveExpert program did a very good job. To get a better fit I did a circuit analysis of the gauge (See Appendix) to find theoretical characteristics. This leads to the formula

$$G_p = 12 \cdot (a \cdot R_s + b) / (R_s + c) \quad \text{Eq. 2}$$

Where

G_p = Gauge position (NW)

R_s = Sender resistance (Ohms)

Coefficients: $a = -2.0107707$ $b = 103.26638$ $c = 84.416784$

The trend line in Figure 9, labeled Gauge theory fit, shows that the data is represented very well by this formula.

Combining the Sender and the Gauge Results

The results shown in Figure 1 were calculated using Eq. 1 and Eq 2 in a Microsoft Excel worksheet. That is, Eq. 1 was used to calculate sender resistance for a range of values of coolant temperature, then that resistance was used in Eq. 2 to calculate gauge position.

The results shown in Table 1 were calculated by reversing this process. That is, sender resistance was calculated for a range of gauge positions using Eq. 2, then the corresponding coolant temperatures were calculated using Eq. 1.⁴

Appendix Gauge Circuit Analysis

By careful examination of the temperature gauge the circuit shown in Figure A1 can be drawn.

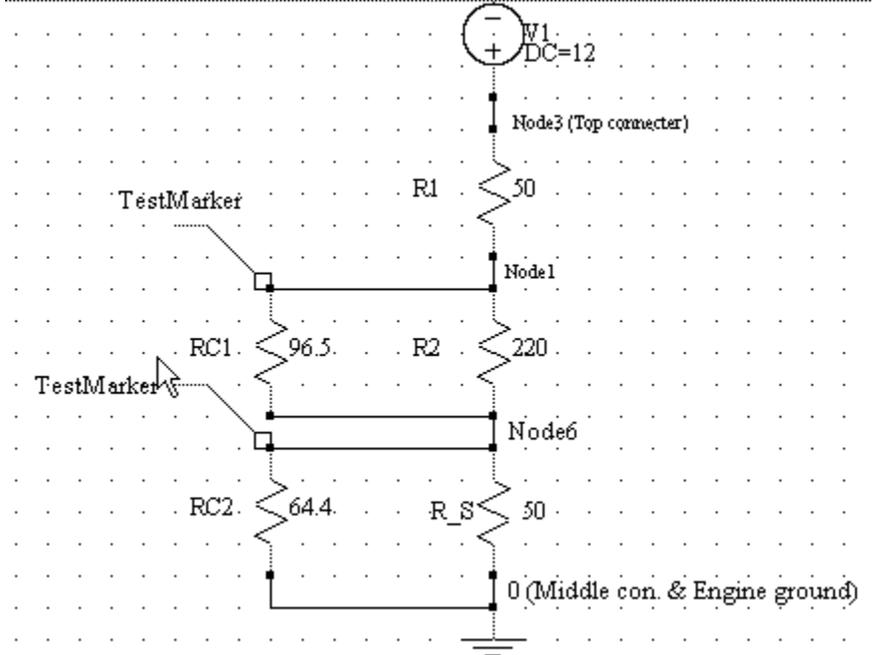


Figure A 1 Gauge circuit

Relative to the physical gauge, Node 3 corresponds to the uppermost connection point, which is connected to switched battery power in the instrument cluster. The node marked 0 represents both the engine ground of the sender and the middle connector, which is grounded in the instrument cluster. Node 6 is the bottom connector. Also,

R_s = Sender resistance

R_1 = 50 ohm resistor on the gauge

R_2 = 220 ohm resistor on the gauge

RC_1 = resistance of inner coil on the gauge, 96.5 ohms.

RC_2 = resistance of outer coil on the gauge, 64.4 ohms.

The values of the resistances RC_1 and RC_2 were measured. The values of the discrete resistors R_1 & R_2 were 53 and 220 as read from the color codes, but R_1 measured closer to 50 ohms.

Since I did not want to take the instrument cluster out of the car I did these measurements on my spare gauge. Note that the R_2 resistor had to be clipped out of the circuit to get a good measurement of it and RC_1 . (I don't recommend doing this on your good and only gauge because it's hard to solder a new resistor in due to the plating on the posts. It doesn't want to stick.) Also, I determined the connection points by experimentation. That is, I the six possible

⁴ Since Eq. 1 cannot be inverted algebraically it had to be done numerically using the Excel Solver add-in.

ways it could be connected and eliminated those that were obviously not correct. The connections I arrived at, described above, were the only set that worked on the bench.

I am not familiar enough with instruments of this kind to know exactly how it works, but I'm told that the position of the needle is set by the direction of the resultant magnetic field due to the combined effect of the fields of the two coils. (Get ready, because we are going to get technical here... sorry!)

Since the coils are at 90° apart in the gauge the combined field will point in a direction between the two coils, specifically at an angle relative to one of the coils whose *tangent is the ratio of the two field strengths*. And since the field strengths are proportional to coil currents, this means that the needle pointing angle is determined by the ratio of the currents in RC1 and RC2. Analysis of the circuit and a little algebra leads to

$$i_1/i_2 = (R_2/R_s)(R_s + R_{C2})/(R_2 + R_{C1}) \quad \text{Eq A1}$$

Now, this could be taken further to find a theoretical formula for needle position itself (by taking the arctangent of the above formula), but this is pointless. It's easier to simply take guidance from this current ratio in guessing a form of a formula to curve-fit to the data. That is the basis of trying a ratio of polynomials in R_s , as mentioned in Results of Gauge Tests. As we have seen there, the fit works pretty well.