Self-Heating Errors and Optimum AC Current Excitation with the Model 370

The following calculation of optimum ac current excitation facilitates the minimization of self-heating errors. In general, a user should use as large an excitation as possible to increase signal, and thus measurement resolution. For ultra-low temperature resistance measurements, there is an added constraint that too large an excitation will self-heat the sensor. The optimum excitation is a balance between minimizing self-heating errors (low excitation) and maximizing resolution (large excitation).

The self-heating is a function of the joule heating in the sensor and the thermal resistance, R_{TH}, between a sensor and its environment. R_{TH} can be determined empirically and is strongly temperature dependent: [1,2]

$$\Delta T = (I^2 R)R_{th}.$$

Rewriting in terms of percent change:

$$\frac{\Delta T}{T} = \frac{(I^2 R)R_{th}}{T}.$$

This can be rearranged to solve for current:

$$I = \left[\frac{\left(\frac{\Delta T}{T}\right)T}{RR_{th}} \right]^{\frac{1}{2}}.$$

This can be used to determine the optimum current to keep the self-heating less than a given percent error ($\Delta T/T$). To keep the self-heating error less than 1% of temperature, the excitation current needs to be equal to or less than the following:

$$I = \left[\frac{0.01T}{RR_{th}} \right]^{\frac{1}{2}}.$$

R_{TH} has been determined for select sensors in previous application papers.[1,2] It can also be determined empirically by the user.

Table 1 calculates the optimum current for a given temperature and resistance. The thermal resistance values are from the results in Reference 2 for the RX-202 sensor. It shows the optimum current for self-heating to be less than 1% of temperature.

There is one additional factor to consider. All ac resistance bridges have some level of dc current noise (leakage current), adding a dc bias current on top of the ac current. If the ac current is greater than the dc current, this will not be a noticeable effect. The problem results when the dc current is significantly greater than the ac current, causing self-heating in the sensor, especially at low temperatures.

		Various Resistance Values (Ω)						
T (mK)	RTH (K/W)	100,000	200,000	316,000	632,000	1,000,000	2,000,000	6,320,000
50	4.06×10^8	3.5 nA	2.5 nA	2.0 nA	1.4 nA	1.1 nA	780 pA	440 pA
20	6.35×10^9	560 pA	400 pA	320 pA	220 pA	180 pA	130 pA	71 pA
15	1.51×10^{10}	320 pA	220 pA	180 pA	130 pA	**100 pA**	**71 pA**	**40 pA**
10	5.08×10^{10}	140 pA	**99 pA**	**79 pA**	**5.6 pA**	**44 pA**	**31 pA**	**18 pA**
5	4.06×10^{11}	**35 pA**	**25 pA**	**20 pA**	**14 pA**	**11 pA**	**7.8 pA**	**4.4 pA**

TABLE 1 *The optimum excitation current for a given resistance and temperature based on the thermal resistance for a RX-202 (Reference 2).*
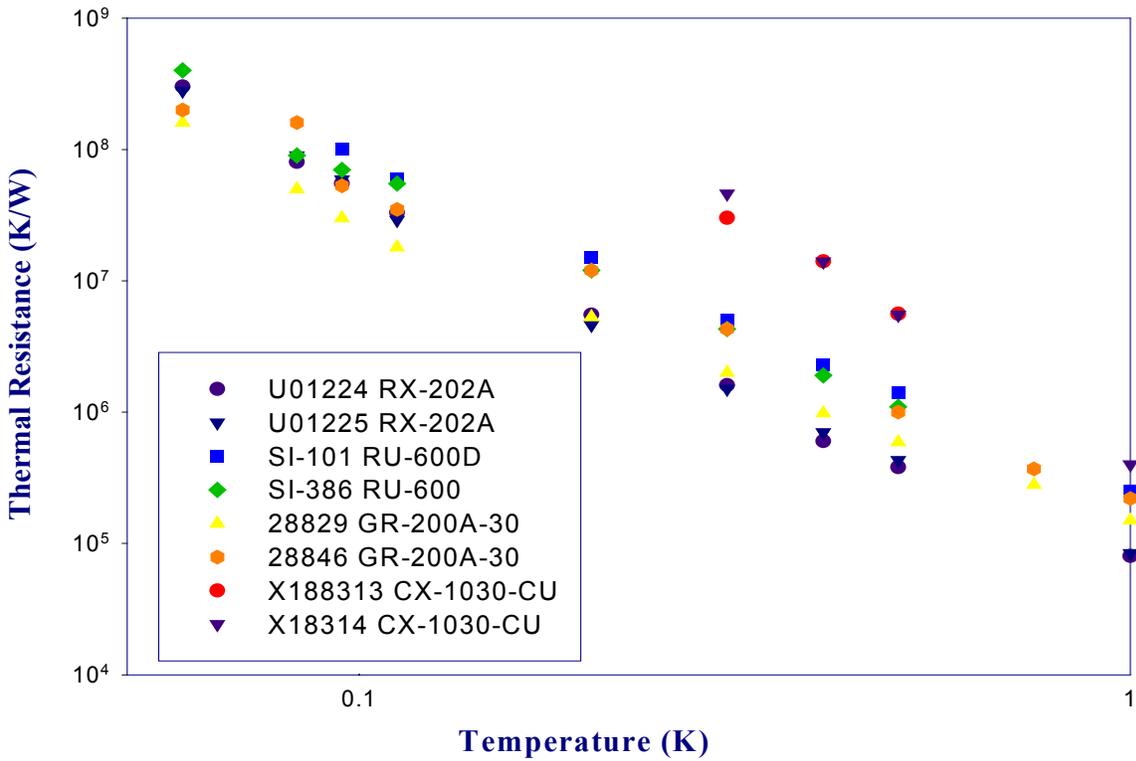
FIGURE 1 Plot *of thermal resistance vs. temperature for various temperatures. (from Reference 2)*

The Model 370S with the 3716 Pre-amp/Scanner has an exceptionally low dc leakage current of 3 pA. As seen in Table 1, the 3716 allows measurements to below 10 mK without self-heating due to leakage currents.

The 3716L, while having a larger leakage current, has a five times lower voltage noise. In general, the lowest noise pre-amp should be used as long as the ac excitation is greater than the dc leakage current. In Table 1, the bolded current values show where the 3716 is likely a better choice than the 3716L.

Environmental noise coupling into the instrument circuit—either through ground loops or capacitive coupling—can also contribute to the self-heating of the sensor. The Model 370 AC Resistance Bridge has a unique, patented, matched impedance current source that reduces or eliminates capacitive noise that couples to the leads. Additionally, the Model 370 optically isolates the analog front end from the digital circuitry and instrument chassis, which eliminates ground loops. By switching to the Lake Shore Model 370, users have actually experienced the benefit of eliminating environment noise coupling into their measurements.

Sensor Type	Serial Number	Temperature Range	Power Law Fit $R_{TH} = AT^N$ A (W/K)	N
RO-600D	101	50 mK to 1 K	244000	-2.5
RO-600	386	50 mK to 1 K	167000	-2.7
RX-202A-AA	U01224	50 mK to 1 K	50800	-3.0
RX-202A-AA	U01225	50 mK to 1 K	57700	-2.9
GR-200A-30	28829	50 mK to 1 K	114000	-2.5
GR-200A-30	28846	50 mK to 1 K	200000	-2.5
CX-1030-CU	X18313	300 mK to 1 K	628000	-3.3
CX-1030-CU	X18314	300 mK to 1 K	387000	-3.9

TABLE 2 *A summary of tested sensors and results to simple power law fit for the thermal resistance results (from Reference 2)*

References

1. Courts, S.S., Davenport, W.E., Holms, D.S., "Thermal Resistances of Cryogenic Temperature Sensors from 1 – 300 K," *Advances in Cryogenic Engineering* **45B**, edited by Q. Shu et al., Plenum, New York (2000), pp. 1699-1706.

2. Yeager, C.J., Courts, S.S., Davenport, W.E., "Thermal Resistance of Cryogenic Thermometers at Ultra-Low Temperatures," *Advances in Cryogenic Engineering* **47A**, edited by S. Breon et al., AIP, New York (2002), pp. 1644-1650.