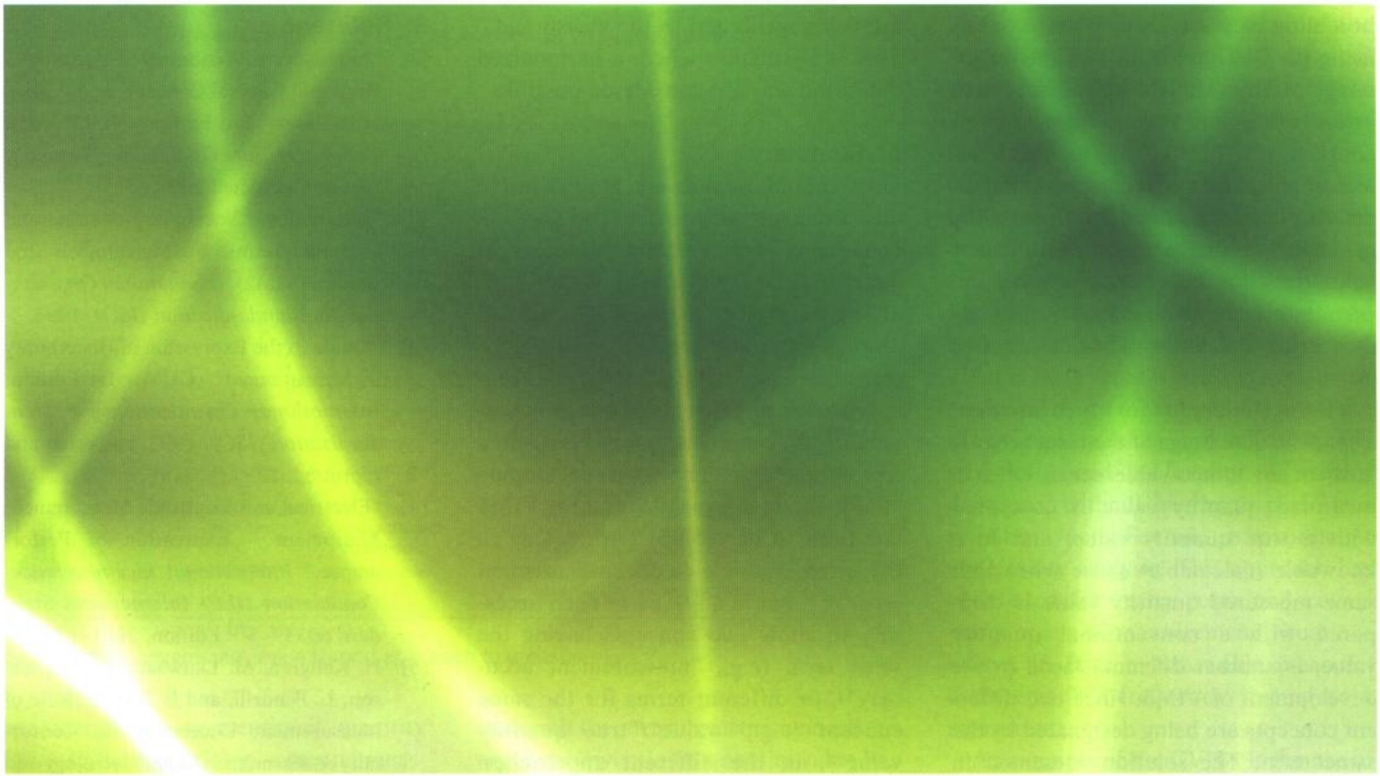

Measurement Techniques of Low-Value High-Current Single-Range Current Shunts from 15 Amps to 3000 Amps

Marlin Kraft

Abstract: Standard resistors that are used to measure current and are designed to dissipate relatively high levels of power are known as current shunts. This paper will discuss some of the many different types of single-range current shunts in use today, and describe self-heating effects and errors associated with specific current shunt designs. The importance of the length of time it takes for some shunts to reach both temperature equilibrium and resistance equilibrium will be discussed. Because the effects of temperature are non-uniform, these lengths of time differ for some shunts and may depend on the location of the temperature sensor. The paper also discusses how errors in measuring current shunts can be reduced by making symmetric, low-resistance connections, and considers how the current distribution and the placement of the potential terminals affect the measurement.

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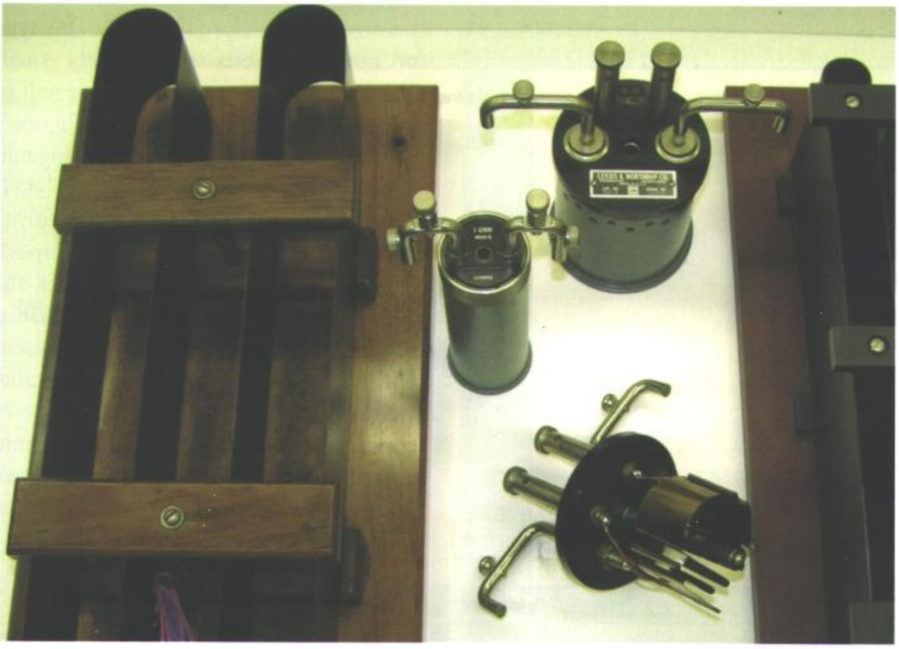

Figure 1. Example of 10 mΩ 100 amp ribbon shunts and 10 mΩ Reichsanstalt resistor element.

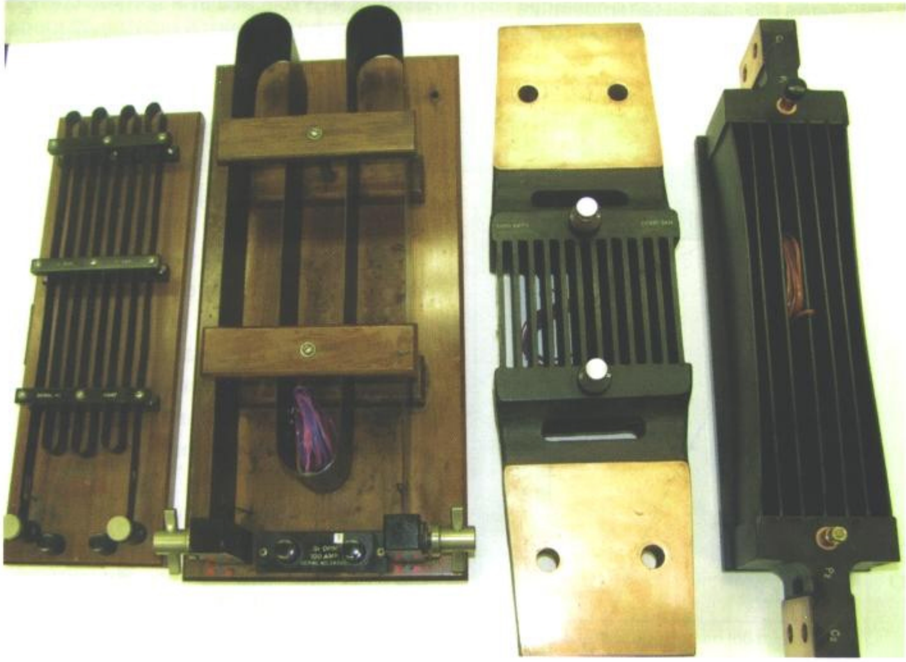

Figure 2. Shown from left to right are a 0.1 Ω / 15 A ribbon shunt, a 0.01 Ω /100 A ribbon shunt, a 10 µΩ /3000 A parallel element shunt, and a 100 µΩ /1000 A parallel element shunt.

1. What is a Current Shunt?

In general, standard resistors are measured at 10 mW or less to reduce self-heating and for quick stabilization of the measurements. The drift characteristics of the resistor are more predictable at low power and the level of uncertainties is reduced significantly. These resistors are generally sealed and if used at 1 W or above, a change in the value and drift characteristics will occur.

Resistors used for higher currents are not sealed, and have their resistive element exposed. This Reichsanstalt design [1, 2] was commercialized by the Otto Wolff Company[2] in Berlin and is preferred for low value (less than 1 Ω) high power (greater than 0.1 W) resistors. It is generally known that these resistors should be used in stirred oil to aid in cooling and to prevent a permanent change in value, which will occur if used in air at the rated current.

A current shunt is a resistor that is designed to dissipate high levels of power in air. The majority of standard precision shunts were designed to dissipate 90 W to 100 W at full current with a typical 400 µΩ/Ω total change from minimum to maximum current. Figure 1 shows the difference in size and construction of a Reichsanstalt standard resistor rated at 1 W and two ribbon current shunts rated at 100 W, all of which are a nominal value of 10 mΩ. The smaller resistor at center is of the NBS-Type design [1, 2] shown for size comparison only.

2. Construction and Characteristics of Current Shunts

There are basically two different type of construction for precision current shunts as shown in Fig. 2. The ribbon shunt is constructed with a continuous strip of resistive material with one or more folds. The other type is the parallel element shunt, which has several bars of resistive material attached to large copper or brass blocks on each end with the potential terminals closest to the parallel elements.

The resistance/temperature curve is found by measuring the shunt at several different current levels and plotting the equilibrium points. This type of curve determines the characteristics of the shunt when heat is dissipated by the shunt elements and is modeled by a 2nd order polynomial. Equilibrium is obtained when the temperature and resistance of the shunt reach a steady state at the current level being measured. Once the resistance/temperature equilibrium curve has been established the shape does not change, but the resistance will drift as does a typical resistance standard.

The precision resistance material Manganin [1], an alloy of Copper, Manganese, and Nickel, is the material that is used in most high current shunts. Figure 3 shows the typical Manganin resistance/temperature curve as measured for a 1500 A parallel element shunt. The resistance change at low temperature is about 16 (µΩ/Ω) / °C then decreases

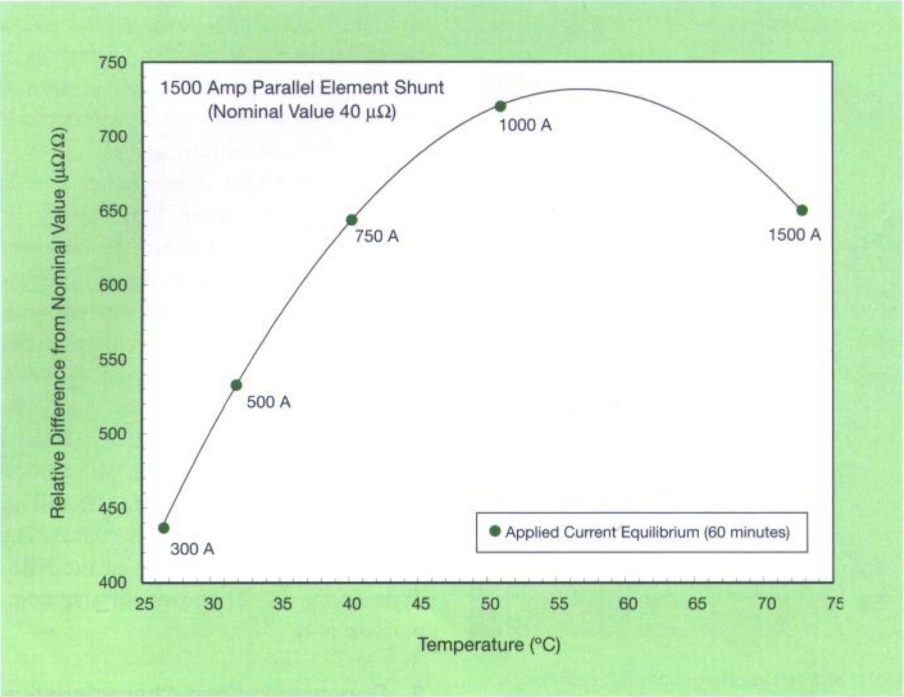

Figure 3. Equilibrium curve for the parallel element Manganin 1500 A shunt (similar in design to the shunt shown in Fig. 2 third from the left) shows the resistance/temperature curve peaking around 55 °C. The resistance change is about 16 (µΩ/Ω) / °C at low temperature. Typical uncertainties are 50 µΩ/Ω.

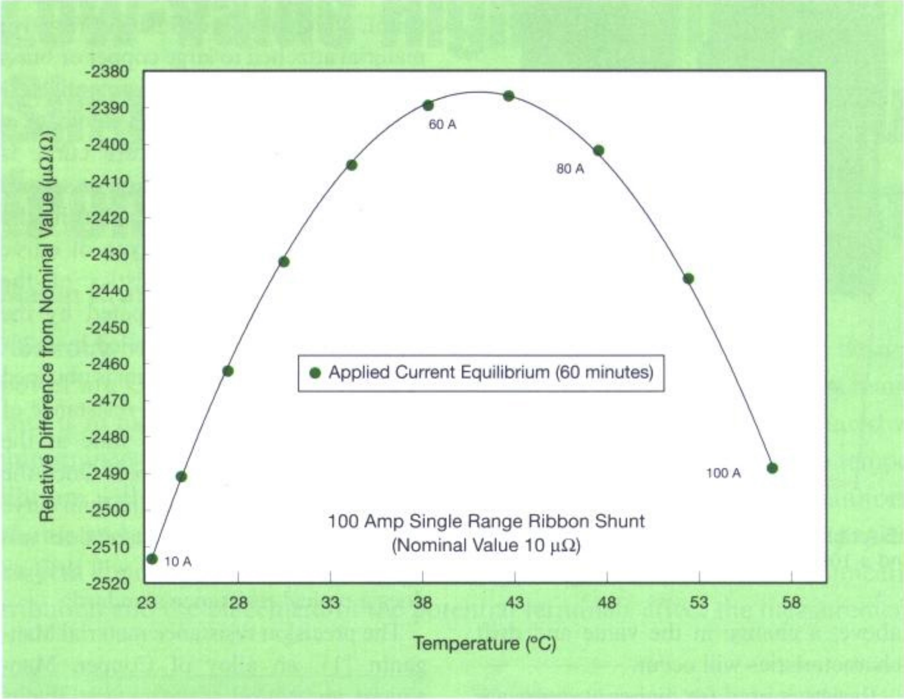

Figure 4. Equilibrium curve for the ribbon type Manganin 100 A shunt shown in Fig. 2 (second from the left) shows the resistance/temperature curve peaking around 41 °C. The resistance change is about 11 (µΩ/Ω) / °C at low temperature.

before peaking close to 55 °C. This type of curve exhibits a relatively small change in resistance in the upper half of its current range. Figure 4 and Figure 5 show different behaviors of Manganin current shunts as measured at NIST. These figures show how manufacturing processes, including material composition and or annealing, can affect the curve. Similar behaviors were described in Ref. [3]. Figure 6 shows the resistance/temperature curve of a parallel element shunt of an unknown type of copper alloy. Equilibrium at maximum current occurs at a temperature above 70 °C, higher than would be expected of Manganin.

3. Temperature Sensors

In the past, shunts were calibrated at specific currents, and temperature was not measured. In our precision shunt measurements at NIST, resistance equilibrium was reached at a specific current level and then the resistance reported for that current. Because the temperature was not determined it was impossible to know when the shunt had reached thermal equilibrium, and the change of the shunt resistance due to environmental temperature conditions was unknown. For most shunts, resistance values approach the equilibrium curve within 30 minutes after current is applied. The resistance/temperature equilibrium curve gives the end user the ability to determine more accurate resistance values before the shunt reaches complete equilibrium.

The most cost effective way to accomplish this task is to attach a thermocouple [4] to the shunt element. A thermocouple is a thermoelectric sensor consisting of two dissimilar metals joined together at one end, preferably welded. When the junction of the two metals is heated or cooled a thermoelectric voltage is produced that can be correlated to temperature. There are EMF-temperature tables for the different types of thermocouples when used with a second, reference junction, or there are electronic thermocouple readouts that have internal references. NIST prefers to attach thermocouples to all high current shunts that are calibrated, so that a resistance/temperature curve can be gen-

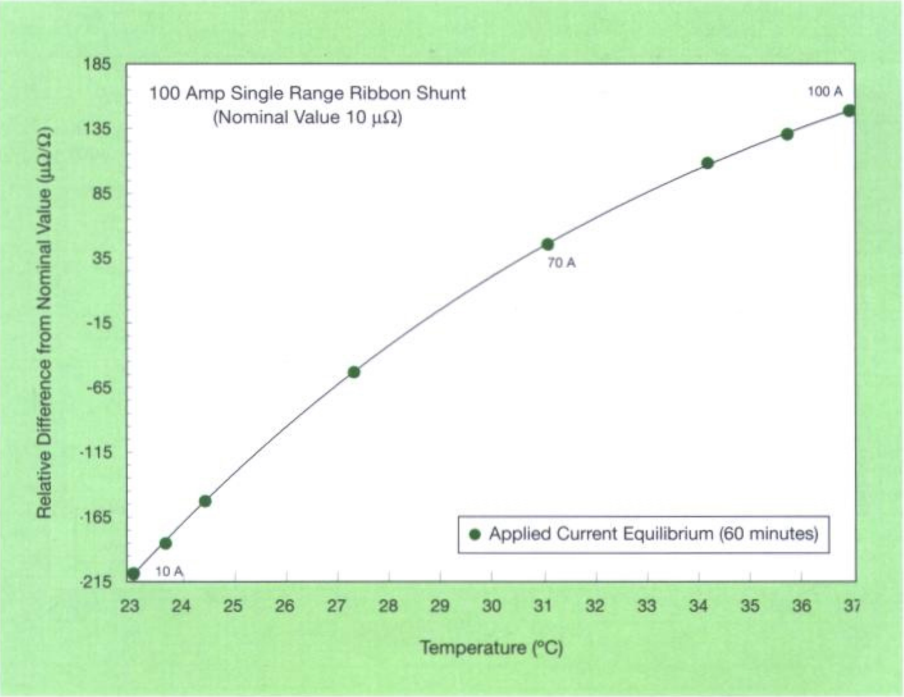

Figure 5. Equilibrium curve for the ribbon type Manganin 100 A shunt shown in Fig. 1 (far right) shows the resistance/temperature curve does not reach a maximum. This shunt has about 25 (μΩ/Ω) / °C slope in first portion of the equilibrium curve.

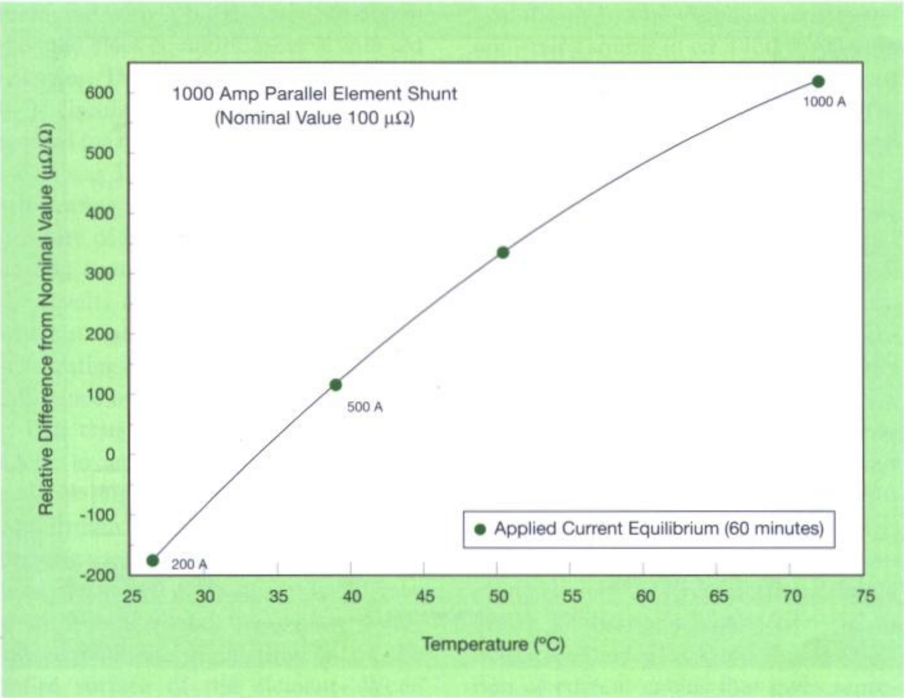

Figure 6. Equilibrium curve for the parallel element 1000 A shunt shown in Fig. 2 (far right) of an unknown copper alloy. This shows the resistance/temperature curve does not reach a maximum at the rated current. This shunt has about 24 (μΩ/Ω) / °C slope in first portion of the equilibrium curve.

erated. NIST will attach a Type T (Copper-Constantan) thermocouple free of charge. The thermocouple is attached with an epoxy to the center of the ribbon or the center element of the shunt.

4. Current Cable Connections

The connection of current leads is critical for shunt accuracy [5, 6]. Generally ribbon shunts can only be connected in one way, and their potential terminals are located in the body of the ribbon material some distance from the current connections. The placement of the potential terminals greatly reduces the errors due to current flow. Great care must be taken to ensure that current flows uniformly and evenly through all the parallel elements in parallel element shunts. Figure 7 shows incorrect current connections. The current distribution is greater for the elements on one side of the shunt. As shown in Fig. 2, the potential terminals on parallel element shunts are located in the terminal block near the current connections. Thus, the non-uniform current flow past the potential terminals can also contribute to the error. Some current terminal designs do not allow for uniform and even current distribution through all the parallel elements.

In Fig. 8, the green circular dots illustrate the error in resistance that was measured at 350 A after reaching resistance/temperature equilibrium for the current connections shown in Fig. 7. Red triangle points with the solid regression line are the equilibrium curve using current cable connections that give a more reproducible curve are shown in Fig. 9.

5. Applied Current Self-Heating Versus External Heating

Some shunts require several thousand amperes for proper calibration. Presently there is only one commercial 2000 A system available to calibrate shunts. Some laboratories have developed an alternative method of using an external source to heat the shunt. Is it possible to retain the same uncertainties for the resistance/temperature curve with artificial heating?

In Fig. 10, a 15 A ribbon shunt was measured with applied current after

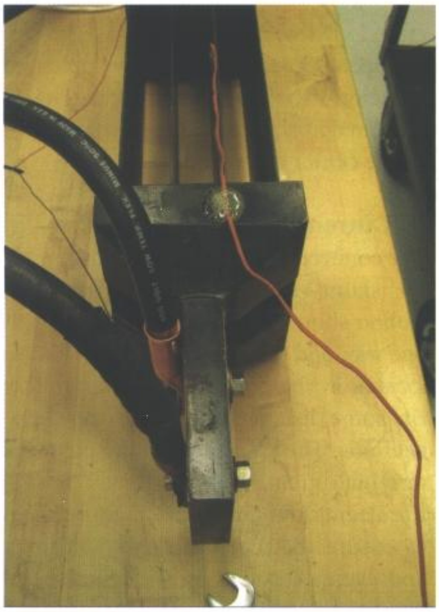

Figure 7. Incorrect connections of heavy current cables for this parallel element shunt.

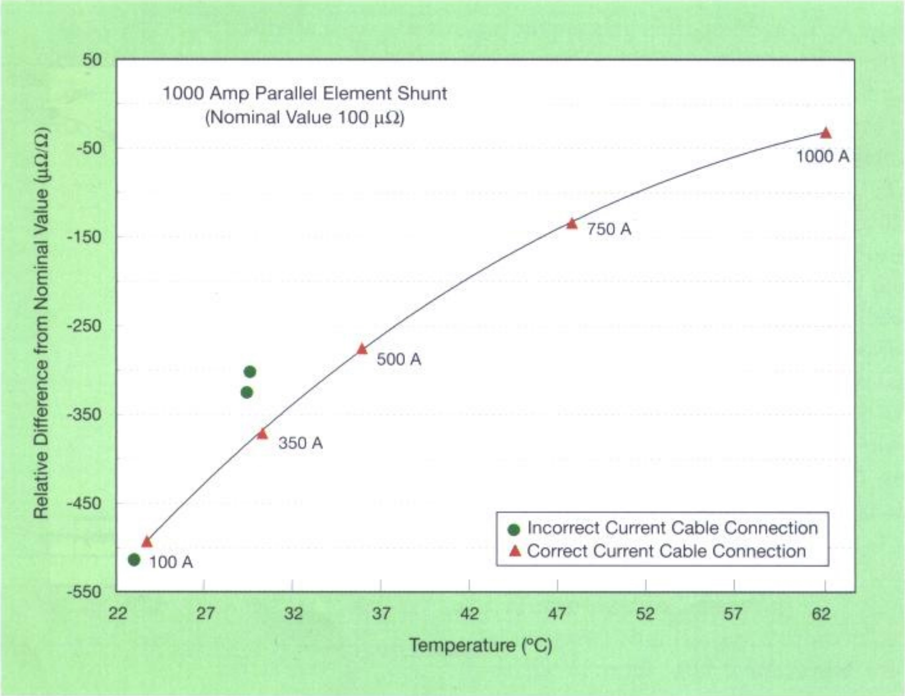

Figure 8. Reproducible current cable connection equilibrium curve and results with incorrect connection. Typical uncertainties are 50 μΩ/Ω.

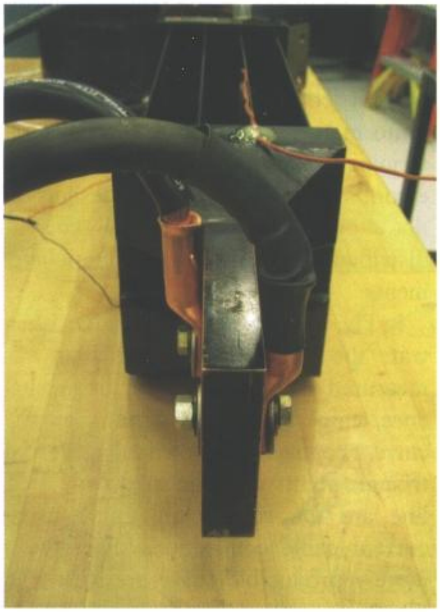

Figure 9. Correct current cable connections for this type of parallel element shunt.

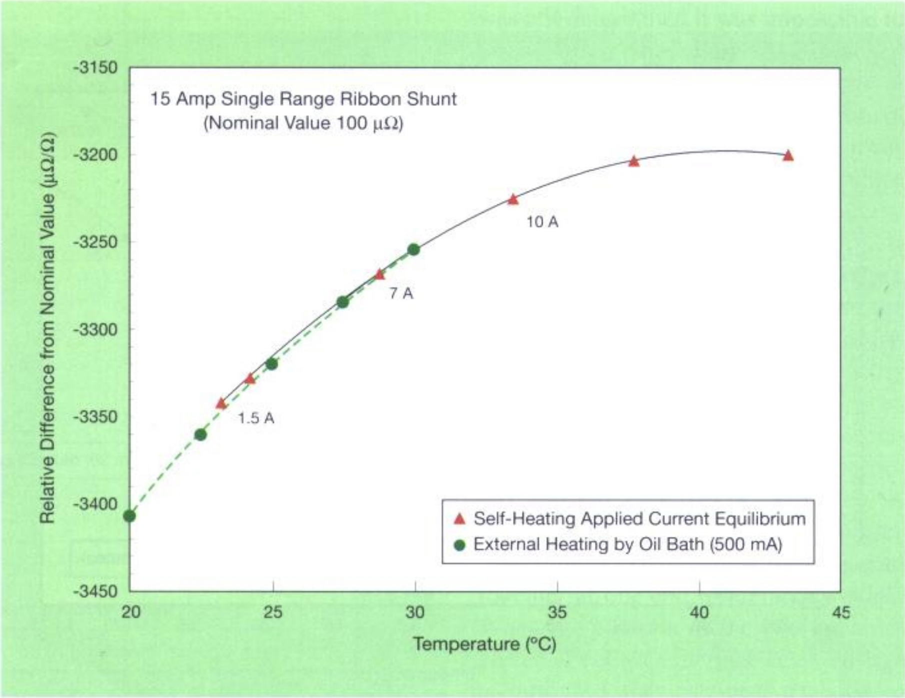

Figure 10. 15 A ribbon shunt self-heating equilibrium curve vs. external heating curve.

reaching equilibrium to obtain the solid line with red triangles equilibrium curve. The shunt was then immersed in a circulating oil bath. The current applied for the oil bath measurements was 500 mA so that minimal self heating was introduced, and the temperature of the oil bath was varied. The green circles with the dashed curve are the result of the heating of the shunt with circulating oil, and this tracks the self-heating curve.

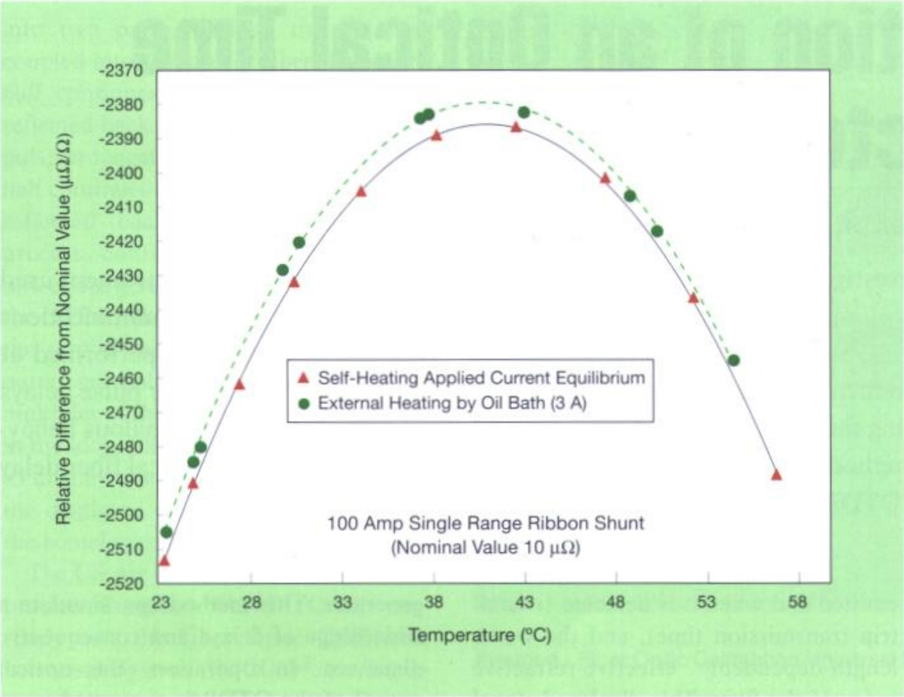

Figure 11. 100 A ribbon shunt self-heating equilibrium curve vs. external heating curve. Typical uncertainties are 25 μΩ/Ω.

In Fig. 11, a 100 A ribbon shunt was measured with applied current to obtain the solid black equilibrium curve with red triangles. The shunt was then immersed in a circulating oil bath. The current applied for the external heating measurements was 3 A (100 mW) so that minimal self-heating was introduced and the temperature of the oil bath was varied. The dashed curve with green circles shows the results of the heating of the shunt with circulating oil. This again tracks the self-heating curve but with the maximum difference of 8 μΩ/Ω.

The tests of external heating conducted to date indicate that indirect heat in a circulating oil bath can reproduce the equilibrium curve using applied current because the curves are similar. The error seen in the 100 A shunt in Fig. 11 may result from the shunt being more evenly heated with the circulating oil on the entire surface of the element. When heated only with applied current, air currents are flowing continuously over the shunt element. The different parts of the resistive element will have different temperatures in air. The temperature differences or gradient may cause a change in the measured resistance.

It would be much more practical to heat the air around the shunt rather than immersing shunts in oil if this resulted in the same equilibrium curve. Oil cannot be removed from all surfaces of the shunt and the heated oil residue could be a hazard when full current is applied.

6. Conclusion

To achieve better uncertainties for high current shunts, a resistance/temperature curve should be generated. Accomplishing this requires permanently attaching a thermocouple to the resistive element. This allows the end user to measure current more accurately without waiting for the shunt to reach resistance and temperature equilibrium.

For proper current distribution, appropriate current cable connections should utilize all bolt-type connection points that are provided. A symmetric connection of current cables that gives reproducible results is crucial in preventing errors in the measured resistance values of some high-current shunts. This connection scheme should be communicated to the end user.

7. References

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