

The Residual and Temperature-Dependent Resistance of Reference-Grade Platinum Wire Below 13.8 K

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Abstract. We report the Residual Resistance Ratio (RRR) and resistance ratio $W(\text{GaMP})$ (gallium melting point) values for well-annealed samples of the original NIST platinum thermoelectric standard (SRM 1967), for its contemporary substitute SRM 1967a, and for a collection of NIST capsule-type SPRTs. The RRR dependence on annealing temperature is investigated and our results are compared with calculations based on contemporary chemical impurity analyses. The data are corrected to remove temperature-dependent components to derive the RRR at 0 K using $W(T)$ data over the range $1\text{ K} < T < 14\text{ K}$ to fit coefficients of an intrinsic function. Finally, we analyze the correlations in our RRR and $W(\text{GaMP})$ data and compare our contemporary data with other archival data from the literature.

Keywords: reference grade platinum, Pt-67, Standard Reference Materials, Residual Resistance Ratio.

INTRODUCTION

High-purity or ‘reference-grade’ platinum wire is produced for use in both Standard Platinum Resistance Thermometers (SPRTs) and type S, type R, and Au-Pt thermocouples. The resistance ratio and thermoelectric characteristics of a given wire specimen are dependent on the chemical purity, physical strain and defects, which necessitated the development of high-purity platinum reference materials. The original platinum reference material was the Pt-27, later replaced by Pt-67, otherwise known as Standard Reference Material (SRM) 1967 [1]. While Pt-67 has served as the de facto standard thermoelectric reference material since 1972, the resistance ratio, $W(T) \equiv R(T)/R(273.16\text{ K})$, of this SRM is not well known on the International Temperature Scale (ITS-90) since the production of the original material pre-dated the advent of the scale.

The most common and readily observable metric for impurity and strain in metals is the so-called ‘residual resistance ratio’ (RRR) which is normally defined as $X(4.2\text{ K}) \equiv R(273.15\text{ K})/R(4.2\text{ K})$. The RRR as reported by measurements at the normal helium boiling point (i.e. $T_{\text{HeBP}} \sim 4.2\text{ K}$), however, will not yield accurate values for the actual residual resistance $R(0\text{ K})$ of high-purity platinum. These reported RRR values will underestimate $X(0)$ by as much as 15 % since high-purity platinum will exhibit a non-negligible temperature dependence even for $T \sim 4.2\text{ K}$.

Typically, we find $1600 < X < 3200$ for SPRTs but these specimens are normally produced in 25 μm to 75 μm diameter wires. In contrast, SRM 1967 was issued in 500 μm diameter lots, standard practice for thermocouples, and exhibits higher values for RRR.

The measurements by Powell *et.al.* [1] yielded a range of $3410 < X(4.0\text{ K}) < 3680$ for Pt-67, but until now, these results have never been replicated using the original SRM wire. The lower RRR values in SPRT elements are possibly a result of additional impurities or strain from the drawing down of the wire diameter. The annealing temperature may, in fact, be of equal or greater importance, but there are practically no archival data to confirm this.

Impurities and defects in platinum wire not only determine its suitability for SPRTs as defining interpolation instruments on the ITS-90, but also determine the degree of non-uniqueness exhibited under use [2]. While detailed comparison of $W(T_{90})$ values at $T_{90} \geq 13.8\text{ K}$ provides some insight into these matters, the comparison of X values is a more sensitive technique since it most readily yields an approximation of the actual residual resistivity ρ_0 that remains in the limit $T \rightarrow 0\text{ K}$. A common parameterization for the observed resistivity $\rho_s(T)$ of a sample ‘s’ of a high purity metal or dilute alloy is

$$\rho_s(T) = \rho_0(c_s, d_s) + \rho_{\text{pure}}(T) + \Delta\rho(T, c_s, d_s), \quad (1)$$

where the first two terms are the residual resistivity and pure-metal (e.g. phonon-scattering) resistivity $\rho_{\text{pure}}(T)$. The last term in Eqn. 1, $\Delta\rho$, is referred to here as the ‘incremental resistivity’, and represents the small deviation from the ideal characteristic known as ‘Matthiessen’s Rule’ [3,4]. The incremental resistivity is dependent on the aggregate impurity concentrations c_s , defect concentrations d_s , and temperature, which account for the common observation that the

temperature coefficient of resistance (TCR) $\alpha=dW/dT$, depends on the impurity concentrations [5].

At sufficiently low temperatures (i.e., $T \leq 14$ K), $\Delta\rho$ can usually be neglected. Furthermore, for even the highest purity samples, $\rho_{\text{pure}}(4.2 \text{ K}) \leq 15\%$ of ρ_0 , leading to the approximation,

$$X(T_{\text{HeBP}}) \cong X_0 \left(1 + \frac{\Delta\rho(T_{\text{IMP}}, c_i, d_j)}{\rho_{\text{pure}}(T_{\text{IMP}})} - \frac{\rho_{\text{pure}}(T_{\text{HeBP}})}{\rho_0(c_i, d_j)} \right), \quad (2)$$

where $T_{\text{IMP}} = 273.15$ K is the ice melting point (IMP) and $X_0 = X(0 \text{ K}) = \rho_{\text{pure}}(T_{\text{IMP}})/\rho_0$ is the RRR at 0 K. While the 1st correction term in Eqn. 2 is typically $< \sim 0.5\%$, the 2nd term, $\rho_{\text{pure}}(T_{\text{HeBP}})/\rho_0$, can be significant (e.g. $\approx 10\%$) in high-purity samples.

For $T < \sim 14$ K, high-purity Pt is known to approximately follow

$$W(T) \cong W_0 + aT^2 + bT^5, \quad (3)$$

where a and b are related to intrinsic constants associated with scattering processes for all platinum and $W_0 = W(0 \text{ K}) \cong 1/X_0$ (ignoring the $37 \mu\text{K/K}$ difference between T_{IMP} and T_{WTP}) [6]. The coefficients a and b may be: a.) fitted to data from SPRTs, b.) inferred from continuity to the ITS-90 reference function $W_r(T)$ at the equilibrium hydrogen triple point ($e\text{-H}_2\text{TP}$), or c.) taken from samples reported in the literature. Providing that the coefficients are sufficiently universal for all high purity platinum, they may be used to compute the correction term in Eqn. 2. and calculate X_0 from a single ratio measurement at T_{HeBP} .

We report on new measurements of $X(4.2 \text{ K})$ for annealed wire specimens from the original Pt-67 and from Pt-67a, its contemporary replacement SRM [7]. Additional $W(T)$ data are reported for Pt-67 specimens for $4.2 \text{ K} \leq T \leq 13.4 \text{ K}$. The use of bare wire samples (i.e., unencapsulated) from SRM lots allows annealing to be performed at high enough temperatures ($> \sim 600^\circ\text{C}$) to remove dislocations, point defects, and other common defects resulting from mechanical strain. The results are compared with values from capsule SPRTs and research specimens reported in the literature.

EXPERIMENTAL

Three samples of SRM Pt wire, 22 cm length \times 0.51 mm diameter, were prepared by the following method. The cut wire samples were electrically annealed in air for 10 min at 1200°C , cooled to 750°C and held at that temperature for 1 h. The heating current was then switched off and the samples

were allowed to cool slowly to room temperature.

A set of four-bore alumina insulators were prepared for use with the Pt wire samples. The insulators were cut to 5 cm in length, cleaned, dried, and baked at 900°C before use. Each wire sample was cut, threaded into the bores of the insulators, and re-welded forming a complete two-loop series-circuit conductor. At each of the two free ends, two additional small lengths of 0.25 mm diameter Pt wire were welded to serve as leads for the four-wire measurement. One such completed resistor assembly is shown in Figure 1. Each resistor assembly was placed in a quartz protection tube and annealed in air using a single-zone furnace. The annealing time and temperature schedule was variable between the samples, as shown in Table 1.



FIGURE 1. A completed resistor assembly from a 22 cm length of wire in a four-bore alumina tube.

For the RRR measurements, each resistor assembly was mounted in an aluminum heat sink inside of a 12.7 mm diameter sealed borosilicate glass tube. The glass tube was used for immersion within both the WTP cell and a liquid helium Dewar allowing the samples to remain mechanically unperturbed during the cycling between temperatures. Prior to use in liquid helium, the tube was evacuated and flushed with helium gas to 100 kPa pressure. The internal pressure at 4.2 K was ~ 1 kPa, which allowed a sufficient heat exchange to reduce self heating to negligible levels.

The annealed resistor assemblies exhibited stable resistances with $R(273.16 \text{ K}) \cong 0.1 \Omega$. Two separate series of resistance ratio measurements were performed on each of the three Pt samples. Measurements of R were performed using an AC resistance bridge operating at 30 Hz and 90 Hz using a 1Ω reference resistor. Excitation currents were 20 mA and 28.3 mA at 273.16 K, and 50 mA and 70.7 mA at 4.2 K. Given the low values of resistance at 4.2 K, a frequency dependence in the AC readings was evident from the active quadrature feedback circuit of the AC bridge. Consequently, a quadratic frequency correction

$R(0 \text{ Hz})=R(f)-a_2f^2$ with $a_2 \approx 1.2 \mu\Omega\cdot\text{Hz}^{-2}$ was applied for extrapolation to DC resistance values. The extrapolation was checked with a bipolar DC measurement and the total standard relative uncertainty in $X(4.2 \text{ K})$ was estimated to be approximately 0.1 %. It should be noted that variations in atmospheric pressure over freely-vented liquid helium produce variations in $X(4.2 \text{ K})$ of at most $\sim 0.1 \%$ for $X(4.2 \text{ K}) \sim 3500$.

A second series of low temperature measurements was later performed on the Pt-67 specimens by comparison of the $R(T)$ values with those from a calibrated Rhodium-Iron Resistance Thermometer over the range $4.2 \text{ K} \leq T \leq 13.4 \text{ K}$. This was accomplished via a small copper comparison block mounted within a 25 mm diameter perforated stainless-steel tube by immersion to variable depths into He vapor or liquid inside a helium storage dewar.

Measurements of $W(\text{GaMP})$ were accomplished using 7.5 mm diameter borosilicate tubes to facilitate immersion into NIST Ga triple point cells [8]. The resistance measurements were performed using an AC resistance bridge operating at 30 Hz with currents of 14.14 mA, 20 mA, and 28.3 mA. Corrections were applied for the observed self-heating, the static pressure head of the Ga cell, and the difference between triple point and melting point temperatures. The uncertainty in the resistance measurements was statistically limited at $\sim 1 \mu\Omega/\Omega$ corresponding to a thermometric uncertainty of 0.4 mK.

RESULTS

Results of the resistance ratio measurements for the three SRM samples are shown in Tables 1 and 2. Two of the samples, Pt-67-12 and Pt-67-13, are adjacent cuts of wire from a spool of the original SRM 1967, each with a single furnace anneal prior to the resistance measurements. For comparison, Table 1 also includes average ratio values from measurements by Powell, *et. al.* [1] made in 1973 of five samples, Pt-67(1-5), of the original SRM 1967 material. Powell's results have been corrected by 1 % to account for elevation/pressure differences. Also included are: two samples (1750-4490 and -4463) from the capsule SPRT SRM 1750 [9]; the SPRT that was used to define the ITS-90 reference function (ITS-90) [10]; a capsule SPRT with especially high RRR (1774096); and an exceptionally high RRR Pt research specimen (MR2-2) from Stewart and Huebener (S&H) [11].

The third sample, Pt-67a-33, is the trailing-end cut of the spool from SRM 1967a. In contrast, this sample was subjected to furnace anneals in four separate stages and the RRR measured after each stage. The results from each stage are shown in Table 2.

TABLE 1. Summary of contemporary results for RRR measurements, anneal temperature T_a , and time t_a , for two samples from Pt-67 together with historical values for Pt-67, some capsule SPRTs, and a research specimen (see text).

Sample	T_a t_a	$X(4.22 \text{ K})$	X_0
Pt-67(1-5)[1]	600 °C 1 hr.	3461 [†]	
MR2-2 [11]	900 °C 24 hr.	5690	6720
ITS-90 [10]	—	2872	3187
1750-4490 [9]	—	2156	
1750-4463 [9]	—	2324	
1774096	—	3245	3618
Pt-67-12	700 °C 0.5 hr.	3488	3711
Pt-67-13	700 °C 1.25 hr.	4320	5081

[†]Average $X(4.02 \text{ K})=3496$ of 5 specimens corrected to 4.22 K.

TABLE 2. Sample Pt-67a-33 RRR values after each of four separate annealing stages.

Stage	T_a t_a	$X(4.2 \text{ K})$	X_0
1	700 °C 1.25 h	2257	2431
2	700 °C 1.2 h	2614	2851
3	480 °C 45 h	2600	2834
4	800 °C 1.0 h	2755	3019

In order to correct these $X(4.2 \text{ K})$ values to X_0 , we use the expression $X_0=1/(W(4.2 \text{ K})-a(4.2)^2-b(4.2)^5)$ from combining Eqns. 2 and 3. We fit the a and b coefficients to data from a NIST capsule SPRT over the range 1 K to 13.8 K as shown in Fig. 2 [12]. This NIST capsule SPRT (s/n 1812279) exhibits small deviations from the ITS-90 reference function in the lowest temperature ranges. The deviations of the Eqn. 3 fit from the data are $< 0.25 \%$ in W over most of the range, which is sufficient for the purpose of making the correction to X_0 from $X(4.2 \text{ K})=2825$.

The $W(T)$ data from 4.2 K to 13.4 K for the two Pt-67 samples are also plotted in Fig. 2. Two other curves from research specimens found in the literature [13, 14] are included for comparison. The corresponding coefficients a and b are given for all these cases in Table 3.

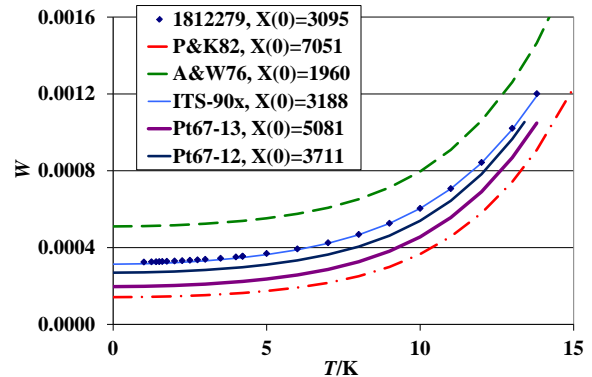


FIGURE 2. $W(T)$ data for SPRT 1812279 from 1 K to 13.8 K. Three curves derived from $W_0+aT^2+bT^5$: two literature samples, Azarbar & Williams [13] (A&W) and Poker and Klabunde [14] (P&K); and that extrapolated from the ITS-90 reference function ('ITS-90x' see text).

Another similar curve can be derived by assuming continuity in $W(T)$ and its first derivative from Eqn. 3 with that of $W_r(T)$ at 13.8033 K and $W(4.2 \text{ K})=1/2873$ [10]. This curve is identified as ‘ITS-90x’ in Fig. 2.

TABLE 3. Temperature coefficients for $W(T) < 14 \text{ K}$ of Pt samples from: the literature; a NIST SPRT; ITS-90x (see text); and two SRM Pt-67 specimens.

Pt Sample	a, K^{-2}	b, K^{-5}
A&W 1976	1.53E-06	1.33E-09
P&K 1982	1.15E-06	1.09E-09
SP 1812279	1.70E-06	1.11E-09
ITS-90x	1.85E-06	1.04E-09
Pt-67-12	1.51E-06	1.19E-09
Pt-67-13	1.43E-06	1.16E-09

The GaMP data for the Pt-67 and Pt-67a specimens are listed in Table 4. The data for Pt-67a were obtained after the final (stage 4) anneal.

TABLE 4. GaMP Data and calculated ratios.

Pt Sample	$\Delta W(\text{GaMP}) \times 10^5$	$W(100^\circ \text{C})^{\S}$
Pt-67-12	0.227	1.392780
Pt-67-13	1.463	1.392821
Pt-67a-33	-0.332	1.392762

^{\S} assuming ITS-90 deviation coefficients $a_{11}=a_{10}$

DISCUSSION

Due to the very small sampling of SRM specimens, general conclusions appropriate to all high purity platinum are not possible. Despite this fact, certain insights are gained when the data are compared to those obtained from SPRTs and from research specimens in the literature. Additional comparison of the SRM results for RRR under variable annealing conditions and impurity assays yield some inferences for the mechanism affecting the RRR values. Finally, we make some observations regarding correlations between X_0 and $\Delta W(\text{GaMP})$ that can be related to the work of Cochrane[5].

Impurities

The nominal purity of both Pt SRMs 1967 and 1967a is 99.999 % by weight. While Pt-67a is a contemporary commercial lot of Pt wire, Pt-67 was specially prepared for use as an SRM and extra efforts were made to reduce the impurities to the lowest practical levels [1]. A contemporary elemental analysis was performed on unannealed samples from each of the two wire lots by glow-discharge mass spectroscopy [15]. An abridged summary of the results is given in Table 5 which lists the most significant impurities. As expected, the original Pt-67 sample contains smaller amounts of impurities than the contemporary Pt-67a

sample, 9.5 $\mu\text{mol/mol}$ and 17 $\mu\text{mol/mol}$ respectively. The dominant impurities for Pt-67a are Fe, Rh and Au, while those for Pt-67 are Si and Fe. This contemporary elemental analysis of Pt-67 is reasonably consistent with the analysis given by Powell, *et. al.* [1].

TABLE 5. Partial list of impurities in Pt samples [15].

Impurity	Pt-67, $\mu\text{mol/mol}$	Pt-67a, $\mu\text{mol/mol}$
Si	3.27	1.11
Cr	0.11	0.24
Fe	2.13	5.59
Ni	0.56	0.18
Cu	0.55	1.54
Zn	0.21	0.36
Se	0.25	0.54
Ru	0.21	0.23
Rh	0.47	3.41
Pd	0.50	0.11
Ag	0.03	0.33
Ir	0.10	0.66
Au	0.99	2.97
Pb	0.17	0.03

In principle, it should be possible to use the results of the elemental analyses to predict values for both X_0 and α . Two difficulties, however, largely prevent a full quantitative treatment. First the required impurity coefficients for each element (E), $\beta_{0E} \equiv \partial \rho_0 / \partial c_E$ are poorly known. Second, even for those elements which may be reasonably known, and for which stable oxides of the impurity may be formed, the impurity may not be in substitutional solid solution with the Pt solvent [16] (i.e. not be ‘electrically effective’ [5]).

There are few reliable sources of data for impurity coefficients in the literature. Two known sources of data are: 1. Degussa [17], and 2. Savitskii [18]. In the case of the Degussa data, tables are given for $\beta_{AE} \equiv \partial \Delta \rho / \partial c_E$ at 273 K for 20 elemental impurities. The Savitskii data are in the form of nine binary alloy plots from measurements at ambient temperatures, so those impurity coefficients β_E have contributions from both ρ_0 and $\Delta \rho$, or $\beta_E \equiv \beta_{0E} + \beta_{AE} \equiv \partial \rho_0 / \partial c_E + \partial \Delta \rho / \partial c_E$. In addition, Cochrane has tabulated values for $\partial \alpha_{68} / \partial c_E$ for 13 elemental impurities [5]. Under the assumption that $\beta_{AE}(273 \text{ K}) \gg \beta_{AE}(373 \text{ K}) - \beta_{AE}(273 \text{ K})$ (i.e. the deviations saturate for $T > \sim 300 \text{ K}$), the Cochrane data can be recast to derive $\beta_{0E} + \beta_{AE}$. In addition, some data on both β_{0E} and β_{AE} for Au and Rh impurities are given in [11].

By combining the Cochrane and Degussa data for Fe, we estimate $\beta_{0Fe} \approx 5 \mu\Omega\text{-cm}/\%$ Fe (amount of substance). For Rh, we combine the Savitskii and Degussa data to yield $\beta_{0Rh} \approx 0.2 \mu\Omega\text{-cm}/\%$ Rh. For the most part, however, these impurity coefficient data are widely discrepant and most values for β_{0E} which may be inferred by combining the data are highly uncertain,

in some cases by factors of 2 to 3. Restricting consideration only to those impurities which are most abundant in Pt-67 and Pt-67a and known to be electrically effective [5] in well-annealed Pt, we further estimate $\beta_{0\text{Cu}} \approx 1 \mu\Omega\text{-cm}/\%$ Cu, $\beta_{0\text{Au}} \approx 0.5 \mu\Omega\text{-cm}/\%$ Au, and $\beta_{0\text{Pb}} \approx 20 \mu\Omega\text{-cm}/\%$ Pb.

Rough estimates of $X(0)$ may then be calculated from only these five impurities, assuming that a defect residual resistivity of $\rho_{0d} \approx 1 \times 10^{-4} \mu\Omega\text{-cm}$ exists in all samples, via the linear approximation

$$\rho_0(c_s) \approx \rho_{0d} + \sum_j \beta_{0j} c_j. \quad (4)$$

This approximation then yields $X_0(c_{\text{Pt-67}}) \approx 6100$ and $X_0(c_{\text{Pt-67a}}) \approx 3000$, which are within 20 % of the measured value for the Pt-67-13 sample and <1 % of the final anneal value for Pt-67a-33. Given the various assumptions being made, the highly uncertain estimates for the β_{0E} , and uncertain degree of oxidation or lattice substitution, this level of agreement should be considered largely fortuitous.

Temperature Dependence below 14 K

The low temperature $W(T)$ data for Pt-67-12 and -13 yield values for a and b which are in reasonable agreement, but somewhat different from those derived from data for other samples. At $T=4.2$ K the dominant correction term is aT^2 which varies from 5 % to 12.5 % of $W(4.2$ K) for the samples listed in Table 3. Uncertainties for research specimens from the literature are not known, and in the case of P&K all thermometry was derived from a type T thermocouple.

The available data for the two Pt-67 samples only extend to a lower limit of 4.2 K, while the data for SP 1812279 extend down to 1 K. The residuals to the Eqn. 3 fit are 1 to 2×10^{-6} in $W(T)$ for all three samples. Variable temperature data are not available for the Pt-67a-33 sample, in that case the corrections to X_0 as given in Table 2 were calculated using the a and b coefficients from SP 1812279.

While better fits to the data are possible with more parameters [19], we are not interested in pursuing empirical equations. In contrast, we wish to restrict the fits to the physically motivated T^2 and T^5 terms since they are more likely to be universal for high purity Pt. The aT^2 term originates from electron-electron scattering and is predicted for resistivity in most metals by the Fermi Liquid theory. Excluding the P&K [14] data, the a values of the remaining four Pt samples in Table 3 vary within ± 9 % of their average of $1.54 \times 10^{-6} \text{ K}^{-2}$. While that degree of variability is insufficient for the purposes of temperature interpolation, it would be sufficient for correcting

$X(4.2$ K) values of high-purity Pt specimens or thermometers within the range shown in Table 3 to an uncertainty of ~ 1 % in X_0 .

Dependence on Annealing

All of the SRM samples studied here were subjected to the same initial high-temperature electrical anneal, but then to variable furnace anneals after being formed. As shown in Table 1, Pt-67-12 was furnace annealed using a higher temperature (700 °C) but shorter time than used by Powell *et. al.* but yielded comparable RRR values. The adjacent cut, Pt-67-13, was also annealed at 700 °C but for 2.5 times the duration and yielded a considerably higher RRR than any of the samples measured by Powell. Since Powell observed differences of no more than $\Delta X=270$ over the entire length of his wire spool, it is unlikely that the difference of $\Delta X=830$ observed between our two samples is a consequence of inhomogeneity. Rather, the results suggest a diffusion-limited process which is removing defects or impurities from solid solution, rendering them ineffective in altering the transport properties of the Pt samples.

The results for the variable annealing with Pt-67a-33 are consistent with this mechanism. In this case, the first and second furnace anneals used the same schedule as used for Pt-67-13. The subsequent RRR measurement values were considerably lower than those observed for the Pt-67 samples as would be expected given the higher level of impurities found in the Pt-67a wire. A third anneal at 480 °C for 45 h yielded no further improvement in RRR, suggesting that an activation energy $E_a \gg k_B \cdot 653$ K is involved. The final anneal at 800 °C yielded a further incremental increase in the RRR, but less than that observed between the first and second anneals, suggesting that the diffusion process might be approaching saturation.

Correlations with $W(\text{GaMP})$

The $\Delta W(\text{GaMP})$ from Table 4 appear correlated with X_0 data, so a comparison with similar data from various capsule SPRTs is useful. The data are plotted in Fig. 3 for $\Delta W(\text{GaMP})$ versus $X(0)$.

The Pt-67/67a data appear correlated with a slope of 8.6×10^{-4} . In contrast, the lower RRR data from SPRTs appear to exhibit much steeper slopes $\approx 3 \times 10^{-3}$ or greater. Some SPRTs exhibit significant deviations from the bulk of the samples, presumably due to defects or specific impurities which are relatively unusual. As a whole, the data suggest an asymptotic behavior with an asymptote in $\Delta W(\text{GaMP})$ somewhere greater than $\sim +2 \times 10^{-5}$.

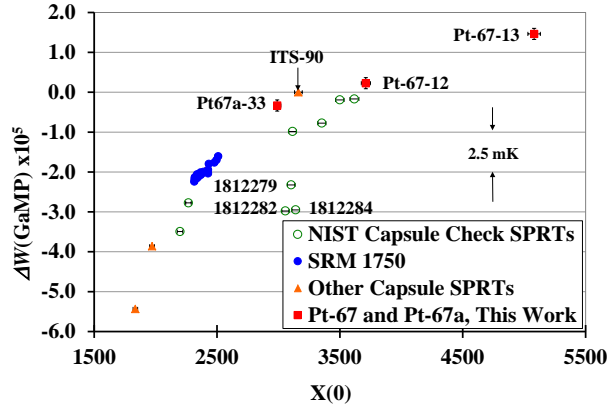


FIGURE 3. The Deviations at the Ga MP versus $X(0)$ values for SRM samples and SPRTs.

Comparison with Cochrane's Data

Cochrane [5] collected data on Pt samples with known impurities and determined the best fit impurity coefficients for electromotive force and α . His data for $\partial\alpha_{68}/\partial c_E$ can be used to predict the α_{68} values for the Pt-67/67a specimens. We first note the scale conversion from IPTS-68 which yields $\alpha_{90} = \alpha_{68} + 1 \times 10^{-6} = (W(100^\circ\text{C}) - 1)/100^\circ\text{C}$. We then calculate the ITS-90 deviation coefficient a_{10} from α_{90} and (assuming $a_{10} = a_{11}$) $\Delta W(\text{GaMP}) = a_{11}[W(\text{GaMP}) - 1]$, based on the Cochrane impurity coefficients. Cochrane found empirically that $\alpha_{68} = \alpha_{68-\text{max}} - \sum \beta_j c_j$ where $\alpha_{68-\text{max}} = 0.00392875$. For Pt-67 we calculate $\alpha_{90} = 0.0039282$ and $\Delta W(\text{GaMP}) = -2.7 \times 10^{-6}$ and for Pt-67a we obtain $\alpha_{90} = 0.0039266$ and $\Delta W(\text{GaMP}) = -5.0 \times 10^{-5}$. These values are considerably lower than our measured $\Delta W(\text{GaMP})$ values from Table 4. This suggests that either our actual chemical impurities are smaller than the assays indicated or that the Cochrane impurity coefficients are too large. Another possibility is that oxidation of Fe or other impurities during annealing has mitigated their influence in scattering. It should be noted that $\alpha_{90-\text{max}} = 0.00392975$ implies a maximum achievable value for $\Delta W(\text{GaMP})_{\text{max}} = +4.43 \times 10^{-5}$. While this is in qualitative agreement with our data, if the trend in Fig. 3 is asymptotic, it seems unlikely that any realistic values would be greater than $+3 \times 10^{-5}$.

Summary

Measurements of $X(4.2\text{ K})$ with 0.1 % uncertainty are possible using samples with $R(T_{\text{IMP}}) \approx 0.1\ \Omega$, but a correction should be made to derive $X(0)$ with $\sim 1\%$ uncertainty. We find some evidence for universal behavior in the observed temperature dependence below 14 K, but with noticeable deviations. The

original SRM 1967 wire can be prepared to yield RRR values in excess of 4000 when annealed in air at 700°C . It is also possible to obtain RRR values approaching 3000 using contemporary commercial Pt wire of $500\ \mu\text{m}$ diameter, but only after more extensive annealing. The results suggest that diffusive oxidation of elemental Fe impurities improves the RRR when samples are annealed in air for extended durations. Our results for RRR and $W(\text{GaMP})$ are qualitatively consistent with chemical assays, but quantitative agreement with predictions using literature data is lacking.

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