# Characteristics of Rhodium-Iron Resistance Thermometers and Interpolation Properties from 0.65 K To 24.5561 K

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**Abstract.** Resistance thermometers using wires of rhodium with 0.5 mol % of iron (Rh-Fe thermometers or RIRTs) were first made by H Tinsley & Co in 1969 for applications at low temperatures, below the range where standard platinum resistance thermometers can be used, and down to 0.5 K or lower. They were investigated at NPL and found to have good sensitivity and excellent stability. Subsequently RIRTs have been used as the standard thermometers which record and compare the results of experiments in thermometry particularly below 24.5561 K, the triple-point of neon. From 1969 until the early 2000s, when Tinsley ceased to manufacture them, several hundred RIRTs were made and many were calibrated at NPL, NIST and elsewhere. In order to document the resistance-temperature characteristics of the production, and indicate the variability from batch to batch, the present paper analyses representative data for the resistance at the triple-point of water and the low-temperature calibrations of a number of thermometers produced at various times. The opportunity has been taken to include data for three RIRTs which were made independently, two in Russia and one in China.

**Keywords:** Rhodium-iron, RIRT, resistance thermometer, low temperature.

## INTRODUCTION

The addition of a small concentration (up to ~1 mol %) of iron to rhodium was found in 1964 to give rise to an anomalous low-temperature resistivity with a significant positive temperature coefficient [1]. This is associated with the fluctuation of the localised magnetic moments on the iron atoms, which is slow compared with other scattering mechanisms at high temperatures but relatively fast at low temperatures. As a result the iron effectively loses its moment and the impurity resistivity gradually falls as the temperature passes through a characteristic spin fluctuation temperature of ~15 K [2].

Figure 1 shows that the resistivity, $\rho(T)$, of Rh-0.5 % Fe is dominated by the impurity effect at low temperatures, but that the resistivity of the host rhodium increasingly dominates above ~ 30 K. The cross-over point is marked by a minimum in the slope, below which the sensitivity, $d\rho(T)/dT$, increases to much larger values than are found in pure rhodium (or platinum) at these temperatures.

In the original publication Coles suggested that 'these materials could form very useful resistance thermometers down to very low temperatures'. To follow this up, wires of various iron concentrations were made by Engelhard Industries (UK) Ltd†, by depositing iron on rhodium powder, sintering, then hot-swaging and hot-drawing to the final diameter. The wires were then strand-annealed in hydrogen at >1100 °C to recrystallise the material without oxidising the iron. They were tested at NPL and a concentration of 0.5 mol % Fe was adopted for use in the thermometers, as a compromise between achieving a large enough resistivity and sensitivity, while avoiding excessive interaction between Fe atoms which tends to stabilise the moments and stifle the effect. Engelhard designated the product 'Alloy 1200'.

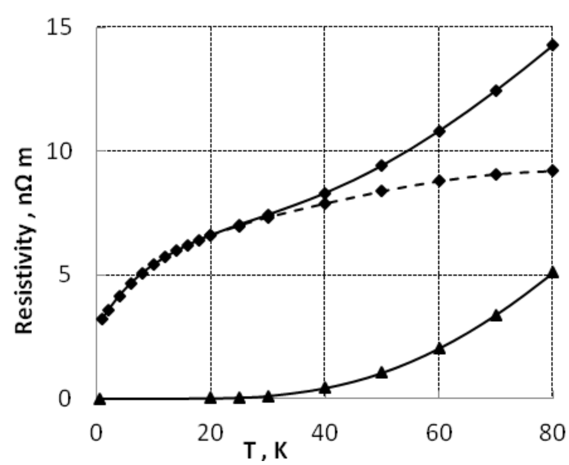


**FIGURE 1**. Resistivity of rhodium – 0.5 % iron [3], top, and rhodium [4], bottom, and the difference, being mainly due to the dissolved iron (dashed).

† *The identification of commercial products is not intended to imply recommendation or endorsement by the NIST or NPL, nor is it intended to imply that the products identified are necessarily the best available for the purpose.*

The first prototype thermometers were made by H. Tinsley and Co, in 1969, following their design of capsule-type Standard Platinum Resistance Thermometers (SPRTs). Before sealing in helium at ~ 30 kPa, the coil assembly was given a stress-relieving anneal at ~ 700 °C. Since the wires are not as soft as platinum wires used in SPRTs they are self-supporting in straight vertical tubes without any helical twist. As a result four tubes could be included in the capsule, rather than two as for SPRTs, and a shorter capsule was used which could more easily be accommodated in the confined space of a cryostat. The first results of measurements with these prototypes were presented at the 5th International Temperature Symposium in 1971 [5]. Later a thermometer of higher resistance was wanted for gas thermometry experiments [6], and full-sized capsules were used. This is the origin of the two types, designated by Tinsley 5187U and 5187W.

The main criteria for suitability of the wire are that the iron should be unoxidised and fully dissolved in the rhodium host, and that the annealing should lead to a resistance ratio $R_{4.2\ \mathrm{K}}$ / $R_{273\ \mathrm{K}}$ in the region of 0.07. However, good thermometers can be made with a wide range of characteristics and there was no requirement to match a particular reference specification or tolerance. The basic data for the Type 5187U and Type 5187W RIRTs are given in Table 1, with data for Type 5187L SPRTs for comparison.

**TABLE 1**. Parameters and approximate values for Tinsley RIRTs and SPRTs

| **Parameter** | **RIRT 5187U** | **RIRT 5187W** | **SPRT 5187L** |
|---|---|---|---|
| Capsule dia., mm | 5 | 5 | 5 |
| Capsule length, mm | 30 | 50 | 50 |
| Overall length, mm | 50 | 70 | 70 |
| Wire diameter, mm | 0.05 | 0.05 | 0.076 |
| Wire length, m | 2 − 2.5 | 4 | 1.2 |
| $R_{273\ \mathrm{K}}$ , Ω | 50 − 65 | 100 | 25 |
| $R_{24.5\ \mathrm{K}}$ , Ω | 6 − 8 | 12 | 0.21 |
| $R_{4.2\ \mathrm{K}}$ , Ω | 3.5 − 4.5 | 7 | 0.012 |
| $(dR/dT)_{24.5\ \mathrm{K}}$, $\Omega\cdot\mathrm{K}^{-1}$ | 0.08 − 0.10 | 0.15 | 0.03 |
| $(dR/dT)_{4.2\ \mathrm{K}}$, $\Omega\cdot\mathrm{K}^{-1}$ | 0.25 − 0.35 | 0.5 | 0.0004 |
| $(d\ln R/\mathrm{d}T)_{4.2\ \mathrm{K}}$, $\mathrm{K}^{-1}$ | 0.07 | 0.07 | 0.034 |

RIRTs can be measured using similar techniques and equipment as are commonly used for SPRTs, and precisions of 0.1 mK or better can be achieved throughout their range. Their first serious uses were in the gas thermometry of Berry in 1973-5 from 2.6 K to 27.1 K [6] and the helium vapour-pressure determinations of Rusby and Swenson, 1975-8, down to 0.5 K [7]. The long-term repeatability has been excellent [8], and they became the preferred sensor for working standards calibrated according to the ITS-90 (and the EPT-76 before it) from 0.65 K to 24.5561 K.

Over the years since 1970 several hundred Type U and W RIRTs were made but ultimately, as a result of saturation of the market and falling demand, making another new batch of wire could not be justified commercially and the production stopped. The purpose of this paper is to examine and document the characteristics of the thermometers which were made in that time and measured at NPL or NIST. It has not been practicable to include all the RIRTs, but over 40 examples have been taken covering almost the whole period of manufacture, with no other selection criteria and without discarding any cases examined. Some basic data for these RIRTs are given in Appendix 1.

Data for three thermometers sent to NPL from other sources have been included for comparison. One was from NIM, Beijing, made in China and received in 1978, and two were made at VNIIFTRI in Russia and submitted to the key comparison CCT-K1 [9] in 1989.

## RESISTANCE CHARACTERISTICS

To compare characteristics of RIRTs with widely varying resistances it is necessary to normalise the data. Figure 2 shows $W(T) = R(T)/R(273.16\ \mathrm{K})$, for the 14 RIRTs which took part in CCT-K1, including the two from VNIIFTRI, plus three others from NIST and one from NIM. As expected the ratios are similar, and mainly differ in vertical displacement. Above the main group are the three 1973 RIRTs and, at the top, an outlier from the early 1980s. The thermometer from NIM has a lower sensitivity, presumably because of a lower concentration of dissolved iron (nearer 0.4 % than 0.5 %), and as a result, $W(T)$ cuts across from the main group at 25 K to the 1973 group at 0.65 K.

The vertical shifts between $W(T)$ for different RIRTs strongly suggest that the concentration of dissolved iron was quite well controlled, but that the annealing treatments, which are intended to reduce the temperature-independent resistivity due to crystal defects, etc, were not. This has been tested by plotting $dW/dT$ and the relative sensitivity, $d\ln W/dT$, versus $W$, all at 4.22 K. If the concentration varied, $\mathrm{d}W/\mathrm{d}T$ would scale with $W$, but their ratio $d\ln W/dT$ should be constant. However, if the annealing were inadequate, $W$ would be increased while $dW/dT$ would be unchanged, so $d\ln W/dT$ would be decreased.

Figure 3 shows the correlations and confirms, on the above reasoning, that the annealing is the main cause of the variability in characteristic, though the scatter about the lines suggests that it is not the only factor. The NIM RIRT lies off the Tinsley lines, as a result of the lower concentration of dissolved iron. All but two of the Tinsley RIRTs made since 1974 are toward the left side of the figure, with $W(4.2\ \mathrm{K}) < 0.075$. It seems likely that the final stress anneal of the two exceptional thermometers was insufficient.

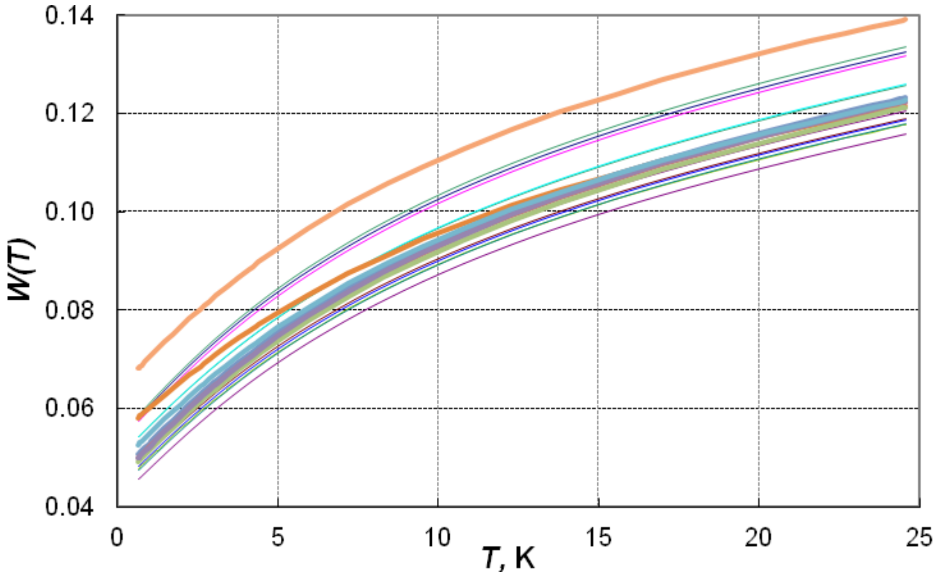


**FIGURE 2**. The normalized resistance $W(T)$ versus $T$ for 16 RIRTs

## Z-FUNCTION INTERPOLATION

The variations in $W(T)$ are too large to allow a successful reference function to be produced. Normalisation to a low temperature reference point, such as the triple point of neon, brings the characteristics together at the top end of the range, but the values at 0.65 K still differ by as much as 10 %. In these circumstances it is necessary to normalise the characteristic at two points using a $Z$-function [10],

$$Z(T) = \frac{R(T) - R(T_1)}{R(T_2) - R(T_1)}$$

which scales the resistance from 0 at $T_1$ = 4.2221 K to 1 at $T_2$ = 24.5561 K. The characteristics are now close enough that they are superimposed on each other in a graph of $Z(T)$ versus $T$. We can therefore plot the deviations $\Delta Z$ between RIRTs and consider the scope for defining a calibration using a reference Z-function.

An example is shown in Figure 4, where the reference is NIST RIRT 233180, and the deviations for 17 other RIRTs are converted to the temperature equivalents by dividing by $dZ/dT$. Except at the lowest temperatures twelve of the thermometers are grouped within 10 mK of the axis. Below them are the VNIIFTRI thermometers, and above them are the 1973 thermometers, and two later outliers at the top. These extrapolate to ~-70 mK at 0.65 K. The NIM thermometer oscillates centrally about the axis and extrapolates to +38 mK at 0.65 K.

The dispersion at low temperatures can be reduced by using a lower normalisation temperature. For example if the lambda temperature (2.1768 K) is used the maximum dispersion is reduced to 43 mK at 0.65 K, though the maximum deviations around 15 K are mostly about 50 % higher.

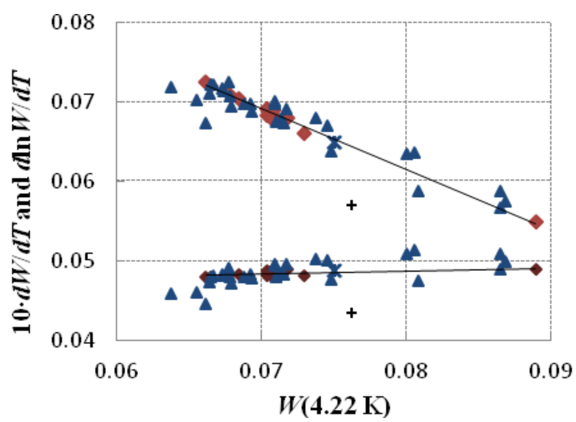


**FIGURE 3**. Relative sensitivity $d\ln W/dT$ (upper data) and $10 \cdot dW/dT$ (lower data) versus $W$, all at 4.22 K, for Tinsley RIRTs. Data are for 29 RIRTs from NPL (triangles), and 13 from NIST (diamonds). Data are also shown for the VNIIFTRI (X) and NIM (+) RIRTs.

Several RIRTs, notably the NIM thermometer, but also the VNIIFTRI and to a lesser extent some Tinsley thermometers, show two or three inversions in $\Delta Z$ with respect to the baseline RIRT, and it seems likely that this behaviour is related to concentration differences. In any case there is enough structure to suggest that several additional points would be needed to achieve a satisfactory interpolation over the range, say within 1 mK, even for the later (1974-) Tinsley RIRTs.

Conversely, much tighter control of the thermometer production would be needed if interpolation based on measurements at a few fixed-points, as has been proposed by Lin Peng [11], is to be reliable.

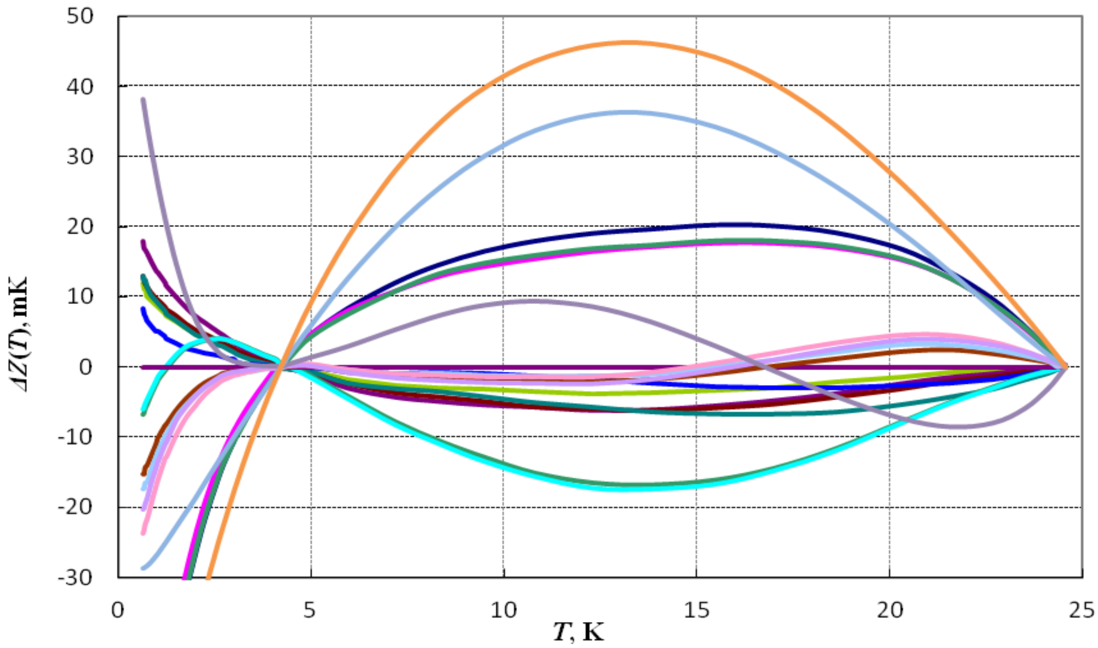


**FIGURE 4**. Deviations $\Delta Z$ from a reference $Z$-function, expressed in mK equivalents.

Finally, it should be noted that while Figure 4 relates to a small sample of RIRTs, those which happened to be compared together in CCT-K1 plus four others, they were not specially selected for their characteristics. In fact the 1973 RIRTs and two later outliers have been deliberately included, and the Tinsley production in general may bunch more closely as in the main group of 10. Moreover, they all function equally well as thermometers. It should also be clear that the $\Delta Z$ derived from resistance comparisons in CCT-K1 at a series of ~40 temperatures, make no reference to a particular temperature scale or realisation: $\Delta Z$ could just as well have been plotted against $Z$.

## SUMMARY

RIRTs have been found to be reliable secondary standards for thermometry at low temperatures, especially below the triple point of neon. They provide good sensitivity coupled with excellent stability and repeatability. The calibrations are generally obtained by comparison with standard thermometers at many points using a least-squares curve-fit for interpolation. Typically more than 30 points were used at NPL to achieve standard deviations < 0.2 mK over the range 0.65 K to 24.5561 K, though this could probably be achieved with 15-20 if the points are carefully spaced. Other possible economies have been considered in [8].

It must be expected that a reference function interpolation, as used for platinum thermometers in the ITS-90, would work less well for an alloy system such as this. The available fixed points may not be sufficient or suitably spaced, and making measurements at them is likely to prove more time-consuming and therefore more expensive than a comparison against standard RIRTs.

In contrast, reference functions have been successfully used for representing calibrations of the small rugged 'industrial' RIRT which has been made in large numbers (many 1000s) for general purposes, and with larger uncertainties, up to 300 K and even beyond [12].

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**APPENDIX 1.** Basic data for RIRTs plotted in Figure 3. Uncertainties, including small scale differences, are generally 0.5 mK equivalent or less.

| | **Serial number** | **Date made** | **Calibration date** | $R_{273.16\ K}$ **Ω** | $R_{4.2221\ K}$ **Ω** | $W_{4.2221\ K}$ | **d*R*/d*T*** **Ω / K** | **d*W*/d*T*** $K^{-1}$ | **dln*W*/dT** $K^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|
| NPL | | | | | | | | | |
| 5187U | 193880 | 1970 | 1977 | 40.96511 | 3.55594 | 0.086804 | 0.2037 | 0.00497 | 0.0573 |
| | 19387 | 1970 | 1977 | 40.04728 | 3.46452 | 0.086511 | 0.1970 | 0.00492 | 0.0569 |
| | 229822 | 1976 | 1976 | 63.61126 | 4.53995 | 0.071370 | 0.3102 | 0.00488 | 0.0683 |
| | 231966 | 1978 | 1978 | 58.37667 | 4.05072 | 0.069389 | 0.2807 | 0.00481 | 0.0693 |
| | 231969 | 1978 | 1978 | 56.28621 | 3.87396 | 0.068826 | 0.2705 | 0.00481 | 0.0698 |
| | A15 | 1980 | 1980 | 56.56185 | 3.77044 | 0.066660 | 0.2719 | 0.00481 | 0.0721 |
| | A22 | 1981 | 1981 | 52.39506 | 3.92199 | 0.074854 | 0.2508 | 0.00479 | 0.0639 |
| | A77 | 1986 | 1986 | 55.04115 | 3.60771 | 0.065546 | 0.2526 | 0.00459 | 0.0700 |
| | A88 | 1986 | 1986 | 55.39979 | 3.66519 | 0.066159 | 0.2469 | 0.00446 | 0.0674 |
| | A140 | ~1990 | 1998 | 67.92071 | 4.81642 | 0.070912 | 0.3372 | 0.00496 | 0.0700 |
| 5187W | 221481 | 1973 | 1974-76 | 102.9759 | 8.24444 | 0.080062 | 0.5236 | 0.00508 | 0.0635 |
| | 221484 | 1973 | 1974-76 | 93.71739 | 8.10550 | 0.086489 | 0.4769 | 0.00509 | 0.0588 |
| | 221485 | 1973 | 1974-76 | 90.18323 | 7.26337 | 0.080540 | 0.4625 | 0.00513 | 0.0637 |
| | 226242 | 1975 | 1977 | 99.20147 | 6.32886 | 0.063798 | 0.4545 | 0.00458 | 0.0718 |
| | 226950 | 1975 | 1977 | 105.516 | 7.55155 | 0.071568 | 0.5086 | 0.00482 | 0.0674 |
| | 229074 | 1976 | 1977 | 101.8174 | 6.90730 | 0.067840 | 0.4888 | 0.00480 | 0.0708 |
| | 229832 | 1977 | 1977 | 101.6394 | 7.03841 | 0.069249 | 0.4946 | 0.00487 | 0.0703 |
| | 232296 | 1978 | 1980 | 101.1755 | 7.18694 | 0.071034 | 0.4870 | 0.00481 | 0.0678 |
| | 234726 | 1981 | 1981 | 98.83987 | 6.71401 | 0.067928 | 0.4729 | 0.00478 | 0.0704 |
| | B34 | 1981 | 1981 | 98.40426 | 7.95684 | 0.080859 | 0.4707 | 0.00478 | 0.0592 |
| | B178 | ~1987 | 1990 | 94.87914 | 6.30722 | 0.066476 | 0.4484 | 0.00473 | 0.0711 |
| | B183 | ~1987 | 2000 | 91.48168 | 6.16820 | 0.067425 | 0.4399 | 0.00481 | 0.0713 |
| | B187 | ~1987 | 1990 | 93.79837 | 6.31742 | 0.067351 | 0.4525 | 0.00482 | 0.0716 |
| | B271 | ~1995 | 1998 | 100.4481 | 7.20369 | 0.071716 | 0.4977 | 0.00495 | 0.0691 |
| | B310 | ~1995 | 1998 | 99.392 | 7.04703 | 0.070901 | 0.4911 | 0.00494 | 0.0697 |
| | B366 | 1999 | 2000 | 98.00733 | 7.30898 | 0.074576 | 0.4900 | 0.00500 | 0.0670 |
| | B372 | 1999 | 2000 | 102.5726 | 7.56694 | 0.073772 | 0.5149 | 0.00502 | 0.0680 |
| NIST | | | | | | | | | |
| 5187U | 233180 | ~1979 | 2007 | 48.19572 | 3.39332 | 0.070407 | 0.2316 | 0.004806 | 0.0683 |
| | A38 | ~1983 | 2000 | 42.98 | 3.05084 | 0.07099 | 0.2076 | 0.004831 | 0.0681 |
| | A48 | ~1983 | 2001 | 58.05 | 4.24702 | 0.07316 | 0.2803 | 0.004827 | 0.0660 |
| | A128 | ~1989 | 1997 | 65.45653 | 4.43684 | 0.067783 | 0.3150 | 0.004812 | 0.0710 |
| | A129 | ~1989 | 1997 | 61.27166 | 4.19405 | 0.06845 | 0.2956 | 0.004824 | 0.0705 |
| 5187W | 229078 | 1976 | 2004 | 103.7902 | 6.90581 | 0.066536 | 0.4973 | 0.004791 | 0.0720 |
| | 229079 | 1976 | 2004 | 101.7166 | 6.73158 | 0.06618 | 0.4880 | 0.004798 | 0.0725 |
| | 229092 | 1976 | 2007 | 100.222 | 7.08499 | 0.070693 | 0.4820 | 0.004809 | 0.0680 |
| | B115 | ~1985 | 2007 | 99.71032 | 8.86793 | 0.088937 | 0.4871 | 0.004885 | 0.0549 |
| | B155 | ~1986 | 1992 | 97.49925 | 6.86914 | 0.070453 | 0.4753 | 0.004875 | 0.0692 |
| | B168 | ~1987 | 1997 | 102.347 | 7.20304 | 0.070379 | 0.4978 | 0.004864 | 0.0691 |
| | B174 | ~1988 | 1997 | 99.00589 | 7.01833 | 0.070888 | 0.4842 | 0.004891 | 0.0690 |
| | B211 | ~1989 | 1997 | 100.6794 | 7.23116 | 0.071824 | 0.4918 | 0.004885 | 0.0680 |
| NIM | 77111 | unknown | 1978 | 48.79969 | 3.72135 | 0.076258 | 0.2123 | 0.004350 | 0.0570 |
| VNIIFTRI | T79 | unknown | 2000 | 102.54041 | 7.68821 | 0.074977 | 0.4992 | 0.004869 | 0.0649 |
| | T89 | unknown | 2000 | 99.23446 | 7.44836 | 0.075058 | 0.4839 | 0.004876 | 0.0650 |