

NASA Technical Memorandum 100491

EVALUATION OF INDUSTRIAL PLATINUM RESISTANCE
THERMOMETERS

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JULY 1987

(NASA-TM-100491) EVALUATION OF INDUSTRIAL
PLATINUM RESISTANCE THERMOMETERS (NASA) 28
P Avail: NTIS EC A03/MF AC1 CSCL 14B

N87-26885

Unclas
G3/35 0099844

NASA

National Aeronautics and
Space Administration

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SUMMARY

An evaluation procedure for characterization of industrial platinum resistance thermometers (IPRT's) for use in the temperature range -120°C to 160°C was investigated. This evaluation procedure consisted of calibration, thermal stability and hysteresis testing of four surface measuring IPRT's. Five different calibration schemes were investigated for these sensors: IPTS-68, Callendar-Van Dusen, two Z function calibrations, and a second degree polynomial with a deviation function. The IPTS-68 formulation produced the most accurate results, yielding average sensor systematic error of 0.02 and random error (one standard deviation) of $\pm 0.1^{\circ}\text{C}$. The sensors were checked for thermal stability by successive thermal cycling between room temperature, and either 160°C or boiling point of nitrogen (-195.8°C). The sensors were also checked for thermal hysteresis by successive thermal cycling between room temperature, 160°C , and boiling point of nitrogen. All the IPRT's suffered from instability and hysteresis.

INTRODUCTION

The calibration and stability of four industrial platinum resistance thermometers has been investigated. This work was motivated by the need for an overall evaluation procedure for resistance thermometers. Such data could be used for assessing the performance of thermometers for specific applications.

An overall evaluation of a resistance thermometer would include calibrating the sensor, checking its static and dynamic thermal stability, checking the insulation resistance, and determining its thermoelectric effect, self heating, and time constant (ref. 1). Calibration and thermal stability were considered sufficient for characterizing the thermometers used in this study.

The known, accurate, and reproducible temperature dependence of the resistance of platinum has long been utilized for thermometry. Two different classifications of platinum resistance thermometers (PRT's) exist. The standard version--SPRT--is used to define the International Practical Temperature Scale (IPTS) over the range from 13.81 K to 903.89 K (ref. 2), because of its high reproducibility and precision. A SPRT uses very pure platinum wire mounted in such a way that it is free to expand and contract relative to its insulating supports. This implies that the platinum wire remains as strain free as possible over its operating temperature range. Because of this delicate construction, SPRT's are very susceptible to vibration and mechanical shock, thus only suitable for laboratory environments. The industrial version of platinum resistance thermometers--IPRT's--are utilized for rugged mechanical environments. These employ doped platinum wire which is fixed to the supporting structure by direct bonding or close-packed insulating powder. These fully supported element windings may lead to wire contamination, and will inevitably result in some strain on the platinum wire over the operating temperature range.

These strains are caused by the difference in the thermal expansion rates of platinum and the supporting material on which it is mounted. These strains cause irregularities and instabilities in the resistance-temperature relationship, which limit the precision and reproducibility of temperature measurement. Thin and thick film resistance thermometers also suffer from similar strain effects.

The purpose of this study was to investigate the calibration of IPRT's as well as their susceptibility to changes in resistance-temperature relationship caused by strain effects during thermal transients. IPRT's are generally usable over a wide temperature range, are available in a variety of sizes and shapes, and are fairly rugged. A brief summary of the available literature on the calibration and stability of IPRT's in the temperature range of -120°C to 160°C is presented here. Knobler et al. (ref. 3) have studied the stability and calibration of several wire wound IPRT's in the range from 77 K to 300 K. Thulin (ref. 4) has also investigated the stability and calibration of wire wound IPRT's in the range from -50°C to 100°C . Carr (ref. 1) has presented an overall evaluation procedure of IPRT's in the range from 0°C to 650°C . Sinclair, et al. (ref. 5) have studied the calibration of wire wound and film type IPRT's in the range from 4 K to 273 K. Chattle has considered the stability and calibration of wire wound and thick film IPRT's (refs. 6 and 7, respectively). The stability and different calibration techniques for wire wound IPRT's in the range from -200°C to 420°C have been investigated by Actis and Crovini (ref. 8). Connolly (ref. 9) has studied the stability and calibration of wire wound IPRT's over the temperature range 0°C to 250°C . The thermal hysteresis of IPRT's has been addressed by Curtis (ref. 10) in the range -196°C to 196°C . Besley and Kemp (ref. 11) have investigated the stability and calibration of IPRT's in the range from 77 K to 273 K. Verpek (ref. 12) and Mangum (ref. 13) have studied the stability of IPRT's in the ranges 77 K to 273 K and 273 K to 533 K, respectively. Despite the available literature, there is still some confusion about evaluation of IPRT's, especially their calibration. Therefore, it was decided to perform this investigation to compare different calibration procedures, and study the effects of stability and hysteresis for the specific sensors used in this study.

SYMBOLS

a	constant
A, B, C	calibration constants
b_4, e_4	calibration constants for IPTS-68
$^{\circ}\text{C}$	degrees Celsius
K	Kelvin
R	resistance
R_0	ice point resistance
T	temperature, in Kelvin
t	temperature, in degrees Celsius
W	resistance ratio

W* reference resistance ratio
 Z ratio of resistance differences
 α, β, δ, γ calibration constants

THERMOMETER DESCRIPTION

Four industrial platinum resistance thermometers were investigated. These IPRT's were surface temperature thermometers. The listing of these IPRT's and some general information about them is contained in table 1*. These IPRT's were chosen only because of their availability at the time of the experiments and they do not necessarily represent the best available selection for this purpose. All PRT's had nominal ice point resistance (R_0 , resistance at the freezing point of water) of 100 ohms. Three of the thermometers were wire wound, while one was of thin film construction. Their nominal specified operating range was from -200°C to 400°C . The two lead-wire thermometers were modified into four lead-wire configuration by soldering two copper leads to each of the existing leads as close to the sensor as possible.

CALIBRATION

The use of a platinum resistance thermometer involves relating the resistance of the thermometer to temperature using interpolation equation(s). The interpolation equation is thoroughly defined by calibration of the PRT at a sufficient number of points in order to evaluate the constants in the interpolation equation. The calibration consists of measuring the resistance of the PRT at a number of reproducible equilibrium states whose temperatures are well defined. A few of the present calibration procedures for PRT's are summarized here.

IPTS-68 calibration.- This calibration procedure is the most recent procedure utilized for the International Practical Temperature Scale (ref. 2). It consists of precise realization of four equilibrium states for the temperature range from 90.188 K to 903.89 K. These calibration points are listed in table 2. The values of the International Practical Temperature assigned to the equilibrium states used as calibration points are presented in table 3. The interpolation equation for the temperature range $90.188 \text{ K} < T < 273.15 \text{ K}$ is:

$$W(T) = W^*(T) + \Delta W(T) \quad (1)$$

where $W(T)$ is the ratio of the resistance of the PRT to its ice point resistance, $W(T) = R(T)/R_0$. $W^*(T)$ is a resistance ratio given by the reference function:

*The commercial equipments, instruments, or materials identified in this report do not either imply recommendation by the authors, or that they are the best available for the purpose. These identifications are only for adequate specification of the experimental procedure.

$$T = \sum_{i=1}^{20} a_i \left[\frac{\ln W^*(T) + 3.28}{3.28} \right]^i \quad (2)$$

$\Delta W(T)$ represents the deviation between the actual and reference function resistance ratios. The deviation function for the specified temperature interval is:

$$\Delta W(T) = b_4 (T - 273.15) + e_4 (T - 273.15)^3 (T - 373.15) \quad (3)$$

where the constants b_4 and e_4 are determined by the measured deviations at the boiling point of oxygen (or triple point of argon) and the boiling point of water (or freezing point of tin). For the temperature interval $273.15 \text{ K} < T < 903.89 \text{ K}$, the interpolation equation is:

$$t = t' + 0.045 \left(\frac{t'}{100} \right) \left(\frac{t'}{100} - 1 \right) \left(\frac{t'}{419.58} - 1 \right) \left(\frac{t'}{630.74} - 1 \right) \quad (4)$$

where t' is an apparent temperature defined by the equation:

$$t' = \frac{1}{\alpha} [W(t') - 1] + \delta \left(\frac{t'}{100} \right) \left(\frac{t'}{100} - 1 \right) \quad (5)$$

where α and δ are determined from measurements at the boiling point of water (or freezing point of tin) and the freezing point of zinc. Equation 5 could also be presented in the following simpler form:

$$W(t') = 1 + At' + Bt'^2 \quad (6)$$

The IPTS-68 calibration procedure is rather complicated, but when applied to SPRT's is capable of producing 1 mK precision in comparison with the Thermodynamic Temperature Scale (ref. 2). Thermodynamic scale is based on functions that are derived from the first and second laws of thermodynamics, and gives values of temperature consistent with the entire system of logic (thermodynamics) (ref. 14). Actual measurements of temperature on this scale are very difficult experimentally. Therefore, Practical Scales have been developed to provide more easily producible temperatures as close to the Thermodynamic Scale as possible.

Callendar-Van Dusen Calibration.— This calibration procedure was utilized for the International Practical Temperature Scale until 1968 (ref. 15). It consisted of precise realization of four equilibrium states for the temperature range from 90.18 K to 903.65 K. These calibration points are listed in table 2. The interpolation equation for the whole temperature range is:

$$\frac{R(t)}{R_0} = 1 + \alpha \left\{ t - \delta \left(\frac{t}{100} - 1 \right) \left(\frac{t}{100} \right) - \beta \left(\frac{t}{100} - 1 \right) \left(\frac{t}{100} \right)^3 \right\} \quad (7)$$

with $\beta = 0$ for $t > 0^\circ\text{C}$

where α , δ , and β are determined by calibrations at boiling point of water, freezing point of zinc, and boiling point of oxygen, respectively. This equation could also be presented in the following simpler form:

$$W(t) = 1 + At + Bt^2 + Ct^3 \left(\frac{t}{100} - 1 \right) \quad (8)$$

While IPTS-68 formulation is the most accurate calibration procedure for SPRT's, the maximum temperature difference between the Callendar-Van Dusen and IPTS-68 formulations is 0.034 K in the range from 90.188 K to 273.15 K, and 0.182 in the range from 273.15 K to 903.89 K (ref. 2).

Second degree polynomial with deviation function.- This calibration procedure has been proposed by Actis and Crovini (ref. 8), and resembles that of IPTS-68. It consists of calibration at four equilibrium points which are listed in table 2. The interpolation equation for the range from -100°C to 420°C is:

$$t = t' + \gamma \left(\frac{t}{100} \right) \left(\frac{t}{t_1} - 1 \right) \left(\frac{t}{t_2} - 1 \right) \left(\frac{t}{630.74} - 1 \right) \quad (8)$$

where t' is an apparent temperature defined by

$$W(t') = 1 + At' + Bt'^2 \quad (9)$$

t_1 and t_2 are the calibration temperatures for determining A and B. Actis and Crovini have proposed using the boiling point of water and freezing point of zinc for t_1 and t_2 , and determining γ by calibration at the freezing point of tin. This calibration procedure is reported to provide accuracies of $\pm 0.015^\circ\text{C}$. This calibration method will be referred to as the Actis and Crovini method.

Z functions.- Substantial effort has been devoted to investigating two-point calibration of PRT's over a wide temperature range. These procedures involve using ratios of resistance differences called Cragoe's Z functions. The Z function normalizes the resistance versus temperature relationship for the PRT, and is claimed to cancel residual resistances which are not temperature dependent (ref. 5), thus enabling generation of universal Z functions for all PRT's. The interpolation equation is:

$$Z(T) = \frac{R(T) - R(T_1)}{R(T_2) - R(T_1)} \quad (10)$$

with $T_1 < T < T_2$

where $R(T_1)$ and $R(T_2)$ are resistance values at calibration temperatures T_1 and T_2 , respectively.

Two types of Z functions were considered in this study. One is by Sinclair, et al. (ref. 5) who have produced a table of universal Z functions using data from a few PRT's. This calibration procedure requires calibration at the boiling point of nitrogen and freezing point of water for covering the temperature range between the two calibration temperatures. This calibration method will be referred to as Sinclair's Z function method.

The second Z function used is that proposed by Besley and Kemp (ref. 11). They have provided a functional relationship between Z and temperature based on their study of 27 IPRT's for the temperature range from 90.188 K to 273.15 K:

$$Z(T) = \sum_{i=1}^9 a_i T^{(i-1)} \quad (11)$$

This requires calibration at the boiling point of oxygen and the freezing point of water. It has been reported that a measurement accuracy of 35 mK can be obtained using this technique (ref. 11). It has also been suggested that the use of the boiling point of nitrogen instead of the boiling point of oxygen will not introduce errors greater than 30 mK when this method is used.

Calibration Procedure

Exact realization of some of the calibration points listed in table 2 such as the freezing points of zinc and tin, and triple point of water is expensive and time consuming, and most laboratories lack such calibration facilities. Calibration at the boiling point of oxygen is usually avoided due to the safety hazards involved. Therefore, it is usually common practice to comparison calibrate IPRT's with a SPRT in a temperature controlled bath at temperatures close to the specified calibration points. The IPRT's used in this study were comparison calibrated with a SPRT (calibrated by the National Bureau of Standards) at the following temperatures: boiling point of nitrogen, -120°C , -90°C , -60°C , -30°C , 0°C , 40°C , 80°C , 100°C , 120°C , and 160°C . Calibration at the boiling point of oxygen was replaced with the more convenient calibration at the boiling point of nitrogen (IPTS-68 has recommended using the triple point of argon for this purpose). The calibration at the boiling point of nitrogen was performed in a liquid nitrogen bath exposed to atmospheric conditions. All the other calibrations were conducted in a well stirred, temperature controlled Rosemount 913AB oil bath. Isopentane oil was used for the temperature range from -150°C to -40°C , and Dow Corning 200 oil was used for the remaining temperatures. The uniformity of temperature in the bath was estimated to be around 5 mK. The oil bath temperatures were measured with the SPRT. The resistance readings of the SPRT and IPRT's were measured with a Neil Brown ATB-120 automatic a. c. bridge.

Comparison of Calibration Methods

The IPRT's were calibrated using the five specified calibration procedures. The interpolation equations specified in each calibration procedure were used, but the constants of the interpolation equations were evaluated at the modified calibration points listed in table 4, since it was neither desirable nor possible to reproduce the exact calibration points specified in these calibration procedures. It should be noted that the calibration at the tin point for the Actis and Crovini method was dropped, and consequently, two values of γ were used: $\gamma = 0.056$ which is representative of the IPRT's used by Actis and Crovini, and $\gamma = 0.045$ which is the value specified in IPTS-68 formulation.

In order to check the precision of the calibration procedures, the temperature of each IPRT was calculated using its interpolation equation at the calibration points that were not used in evaluating its interpolation constants, and then compared with SPRT temperature indications at these points. These deviations for each PRT for the five different calibration schemes are shown in figures 1a-d, and summarized in table 5. It should be noted that all these deviations were with respect to the SPRT temperature indications. It was found that Actis and Crovini

methods using the two specified values of γ resulted in comparable results. Therefore, only the results pertaining to $\gamma = 0.056$ are presented here.

From the results, it can be seen that IPTS-68 formulation produced the best calibration for three of the thermometers, IPRT's designated as 1, 2, and 4. The other thermometer, which was the only thin film thermometer, was best suited with Callendar-Van Dusen equation. The Actis and Crovini formulation and Sinclair's Z function produced comparable accurate results. The Z function proposed by Besley and Kemp was unsatisfactory leading to deviations on the order of 5°C , and therefore these deviations are not shown in figure 1 and are only presented in table 5. From the results of this experiment, it appears that both IPTS-68 and Callendar-Van Dusen formulations provide the best calibrations. Even though the calibrations were not performed at the exact points defined by these two procedures, they still yielded the most accurate results.

Furthermore, the wide temperature range covered by both formulations (90.188 K to 903.65 K) is a very desirable feature. Both formulations require implementation of computers for converting resistance readings to temperature, especially below 0°C . It was not possible to check the accuracy of these calibration procedures on the tested IPRT's at temperatures below -150°C due to unavailability of mediums for producing stable temperatures in that range. However, it is believed that the inaccuracy of PRT's will increase with decreasing temperatures if PRT's are calibrated at the boiling point of nitrogen instead of the boiling point of oxygen. Actis and Crovini (ref. 8) have shown that calibration at these two points can not be interchanged without incurring systematic differences at amounts up to $\pm 0.1^{\circ}\text{C}$. The other three calibration procedures did not seem desirable. The Z function proposed by Besley and Kemp was very inaccurate for the sensors used in this study. Sinclair's Z function is intended for temperatures below 0°C , and its extrapolation to temperatures above 100°C sometimes resulted in large errors ($\sim 1^{\circ}\text{C}$ at 160°C). The other problem with this method is that it requires use of "look-up" tables for the Z values. Actis and Crovini method is limited to temperatures above -100°C , and therefore not desirable for cryogenic applications.

STABILITY AND HYSTERESIS

The stability of a standard resistance thermometer is such that its ice point resistance (R_0) does not change by more than $4.E-6 * R_0$ when subjected to thermal cycling (ref. 14). This requirement is not usually met by the less expensive and more robust industrial platinum resistance thermometers. IPRT's employ platinum wires which are fixed to a supporting structure by direct bonding or close-packed insulating powder. This type of construction might lead to some strain on the platinum wire over the operating temperature range, caused by the difference in the thermal expansion rates of platinum and the substrate. These thermally induced stresses will possibly cause irregularities in the resistance-temperature relationship of the element. This will manifest itself as a change in the calibration of the IPRT. These irregularities may even lead to thermal hysteresis. That is, the IPRT may have a different but reproducible resistance-temperature relationship depending on the thermal history of the element, and whether it is being cooled or heated. IPRT's are also susceptible to changes in resistance temperature relationship after long periods of storage under constant environmental conditions (static stability).

Mangum (ref. 13) has investigated the stability of small wire wound IPRT's after heat treatment at 235°C. He has reported three distinct types of behavior due to this heat treatment (the sensors resistances were measured at 0°C, 20°C, 40°C, 60°C, 80°C, and 100°C after each heat treatment):

1. Decreasing resistances by amounts equivalent to 2 mK - 900 mK. It has been suggested that these resistance decreases were due to shunting as a result of wetness.

2. Increasing resistances by amounts equivalent to 1 mK - 120 mK.

3. Scatter but no discernible drift.

These distinct patterns have been generally consistent for each PRT at all of the measurement temperatures. Large changes in the resistance-temperature relationship of IPRT's upon either heat or cold treatment will lead to erroneous temperature measurements if these changes in calibration are not accounted for.

Curtis (ref. 8) has studied the thermal hysteresis of some wire wound and film type IPRT's. He has reported that the thermal hysteresis of PRT's is very reproducible; and that the magnitude of the hysteresis is proportional to the temperature span, with the largest difference occurring at midspan. He has studied the thermal hysteresis of IPRT's at the ice point upon successive exposures to -196°C and 196°C, and has found varying degrees of hysteresis among different IPRT's.

Test Procedure

The thermometers were checked for static stability by measuring their ice point resistances after storing them for 120 days at room temperature. Then the stability of the IPRT's upon nine thermal cyclings between liquid nitrogen temperature and room temperature were checked. Each cycle consisted of the following steps: cooling IPRT's to liquid nitrogen temperature by immersing them in a liquid nitrogen bath for three minutes; removing them from liquid nitrogen, exposing them to the room temperature environment for 15 minutes, and blowing room temperature air over them to warm them to room temperature and remove any moisture present; placing them in an ice bath to measure their ice point resistances; removing them from ice bath, and blowing room temperature air over them to remove any moisture present. Afterwards, the stability of the IPRT's upon eight thermal cyclings between 160°C and room temperature was analyzed. Each cycle consisted of heating the IPRT's to 160°C by placing them in an oven maintained at 160°C for 10 minutes; removing them from the oven, and exposing them to the room temperature environment to cool them to room temperature; placing them in an ice bath to measure their ice point resistances; removing them from the ice bath, and blowing room temperature air over them to remove any possible moisture present. Each of the specified cycles would take about two hours, with most of this time spent on achieving thermal equilibrium for the sensors in the ice bath. Finally, the IPRT's were checked for thermal hysteresis upon eight thermal cyclings between liquid nitrogen temperature, room temperature, and 160°C. Each cycle consisted of performing the two cycles specified above--thermal cycling between liquid nitrogen and room temperature and between 160°C and room temperature.

The oven used was a Delta Design Type III oven. The ice point measurements were performed in a dewar filled with a tap water and ice slush mixture. The temperature of the ice bath was monitored by a capsule type standard platinum resistance thermometer calibrated by the National Bureau of Standards. The IPRT's were all placed in tightly sealed plastic bags purged of air, and then placed in the ice bath. This was done to avoid moisture absorption by the IPRT's, but would also result in lengthening the time required for the sensors to achieve thermal equilibrium in the ice bath. The resistances of the sensors were determined using the potentiometric method (ref. 14). A Fluke voltage/current calibrator, Model 382A, was used to supply the one milliamp current required by the PRT's. The voltage drops across the thermometers were measured with a Fluke digital multimeter, Model 8840A. A scanner, Racal-Dana, Series 1200, was used for switching the appropriate potential leads for the PRT's to the digital multimeter. The current that passed through the PRT's was monitored by measuring the voltage drop across a 100 ohm Honeywell standard resistor that was connected in series with the PRT's. The measurements were automated by incorporating a Hewlett Packard Model 216 personal computer.

Presentation of Results

The results of the static stability tests are presented in table 6. The shift in the ice point resistances of the PRT's after 120 days of storage, along with the corresponding temperature errors are listed in this table. Some of these differences might be related to: using different instruments and possible different heat generation effects from the original calibration, as well as general experimental uncertainty. It can be seen that all the thermometers suffer more or less from static instability, with IPRT #3 experiencing the least change.

The results of the dynamic stability tests are presented in table 7 and figure 2. Table 7 consists of the resistance shifts after each cycle in comparison with the ice point measurement after the 120 day storage period, while figure 2 depicts the corresponding temperature errors. The cycles designated as one through nine correspond to the nine thermal cyclings between liquid nitrogen and room temperatures, while cycles designated as 10 through 17 correspond to the eight thermal cyclings between 160°C and room temperature. It should be mentioned that the ice bath temperature was maintained at $-0.01 \pm 0.01^\circ\text{C}$ throughout all the stability tests. It can be seen that all the thermometers suffered from instability due to liquid nitrogen cycling. IPRT #3 had the least amount of instability. IPRT #2 experienced a permanent ice point resistance shift of about 180 milliohms (0.45°C) upon first exposure to liquid nitrogen, which was not recoverable with heat treatments at 160°C. The other three IPRT's had almost complete recovery from their ice point resistance shifts upon exposure to 160°C. Even though these three still showed signs of instability after 160°C cyclings, the magnitude of their instability was much less in comparison with the instability caused by liquid nitrogen cyclings. It is evident that IPRT #3 showed more stability upon 160°C cyclings compared to the other thermometers. It should be noted that when a thermometer is heated or cooled rapidly (as was the case with the IPRT's used in this study), it exhibits shifts in the ice point resistance which are much larger in magnitude than would be predicted for the long term drift rates. It should also be noted that erratic behavior in stability tests of PRT's might be related to badly soldered or heavily oxidized lead junctions (refs. 1 and 3). Some of the changes in the ice point resistances may have been due to the experimental technique or small mechanical deformation of the platinum wires caused by handling (ref. 13).

The results of the thermal hysteresis tests are presented in table 8 and figure 3. Table 8 includes the ice point resistance shifts after each cycle in comparison with the ice point measurement after the 120 day storage period, while figure 3 shows the corresponding temperature errors. The cycle designated as "0" in this figure was the same as the cycle designated as "17" in figure 2. It can be seen that all three IPRT's (#1, 3, and 4) suffered from thermal hysteresis. The magnitude of the hysteresis for IPRT #3 was the least in comparison with the other thermometers. IPRT #2 did not recover from its permanent resistance shift after exposure to hysteresis testing. At the end of the hysteresis testings, the thermometers were subjected to two additional 160°C cycles (cycles designated as 17 and 18 in table 8 and figure 3) to see whether they could recover from the resistance shifts caused by the hysteresis testings. IPRT's #1 and #4 managed to recover, while IPRT #3 did not fully recover. It seemed that IPRT #3 needed heat treatment at higher temperatures for recovery.

It appeared that the stability and hysteresis tests used in this study were sufficient to characterize the behavior of the thermometers in applications with rapidly changing environments. Even though most applications would not require such harsh and rapid environmental changes, it is preferable to have an indication of the maximum temperature error that may be experienced when IPRT's are exposed to such environments.

CONCLUSION

An evaluation procedure for IPRT's in the temperature range -120°C to 160°C was investigated, and proved to be sufficient for characterizing the IPRT's. This evaluation procedure consisted of calibrating, and evaluating the thermal stability and hysteresis of IPRT's. The IPTS-68 formulation was found to provide the most accurate calibration scheme for the IPRT's used in this study, yielding average sensor systematic error of 0.02 and random error (one standard deviation) of $\pm 0.1^\circ\text{C}$. The Callendar-Van Dusen formulation also proved to be suitable, yielding average sensor systematic error of -0.01 and random error (one standard deviation) of $\pm 0.25^\circ\text{C}$. It was found that by thermally cycling the IPRT's between room temperature, and either 160°C or liquid nitrogen, the thermal stability of sensors could be fully characterized. It was found that IPRT's suffer from varying degrees of instability and hysteresis upon thermal cycling. Thermal cycling between room temperature, 160°C, and liquid nitrogen proved to be sufficient for characterizing sensor hysteresis.

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TABLE I.- DESCRIPTION OF THERMOMETERS

IPRT No.	Manufacturer	Model No.	Sensor Type	Operating Temperature Range
1	Rosemount	118 MF	Wire	-260°C to 400°C
2	Rosemount	118 MG	Wire	-260°C to 600°C
3	Omega	TDF-M	Thin Film	-200°C to 500°C
4	Minco	S201	wire	-200°C to 550°C

TABLE II.- LISTING OF CALIBRATION POINTS REQUIRED BY DIFFERENT
CALIBRATION SCHEMES

Calibration Scheme	Calibration Points
IPTS-68 (ref. 2)	boiling point of oxygen (or triple point of argon), triple point of water, boiling point of water (or freezing point of tin), freezing point of zinc
Callendar- Van Dusen (ref. 15)	boiling point of oxygen, triple point of water, boiling point of water, freezing point of zinc
Actis & Crovini (ref. 8)	boiling point of water, freezing point of tin, freezing point of zinc
Z function (Sinclair, et al.) (ref. 5)	boiling point of nitrogen, freezing point of water
Z function (Besley & Kemp) (ref. 11)	boiling point of oxygen, freezing point of water

TABLE III.- TEMPERATURE VALUES ASSIGNED TO
CALIBRATION POINTS

Equilibrium States	Value of International Practical Temperature	
	T(K)	t(°C)
Boiling point of nitrogen	77.344 ^(a)	-195.806
Triple point of argon	83.798	-189.352
Boiling point of oxygen	90.188	-182.962
Triple point of water	273.16	0.01
Boiling point of water	373.15	100.
Freezing point of tin	505.1181	231.9681
Freezing point of zinc	692.73	419.58

(a) Except for the triple points, the assigned values of temperature are for equilibrium states at standard atmospheric pressure (101325 Pascal)

TABLE IV.- LISTING OF CALIBRATION POINTS USED IN THIS STUDY
FOR DIFFERENT CALIBRATION SCHEMES

Calibration Scheme	Calibration Points
IPTS-68	boiling point of nitrogen, 0°C, 100°C, 160°C
Callendar-Van Dusen	boiling point of nitrogen, 0°C, 100°C, 160°C
Actis & Crovini	0°C, 100°C
Z function (Sinclair, et al.)	boiling point of nitrogen, 0°C
Z function (Besley & Kemp)	boiling point of nitrogen, 0°C

TABLE V.- PRECISION OF THERMOMETERS BASED ON DIFFERENT CALIBRATION SCHEMES

Calibration Schemes	Average Deviation Between Respective Thermometers and a SPRT ($^{\circ}\text{C}$)				Temperature Range
	IPRT #1	IPRT #2	IPRT #3	IPRT #4	
IPTS-68	+0.01 \pm 0.01	+0.06 \pm 0.11	-0.07 \pm 0.08	+0.08 \pm 0.09	-120 to 160 $^{\circ}\text{C}$
Callendar-Van Dusen	-0.01 \pm 0.02	-0.21 \pm 0.38	-0.02 \pm 0.02	-0.15 \pm 0.32	-120 to 160 $^{\circ}\text{C}$
Actis & Crovini	-0.01 \pm 0.03	+0.06 \pm 0.42	-0.01 \pm 0.02	-0.10 \pm 0.33	-90 to 160 $^{\circ}\text{C}$
Z function (Sinclair, et al.)	-0.08 \pm 0.25	+0.09 \pm 0.19	-0.28 \pm 0.57	+0.01 \pm 0.16	-120 to 160 $^{\circ}\text{C}$
Z function (Besley & Kemp)	+5.18 \pm 2.62	+5.01 \pm 2.56	+5.26 \pm 2.63	5.17 \pm 2.63	-120 to 0 $^{\circ}\text{C}$

TABLE VI.- RESULTS OF THE STATIC THERMAL STABILITY TESTS

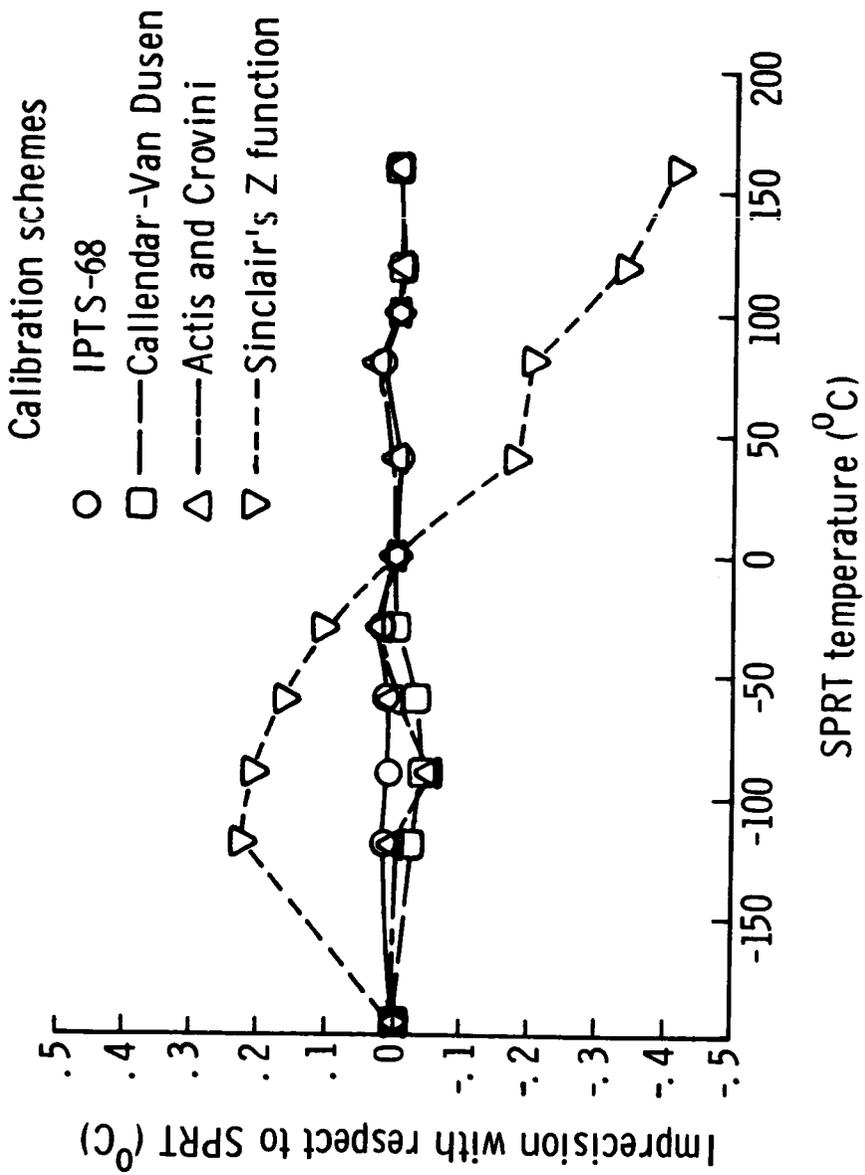
	IPRT #1	IPRT #2	IPRT #3	IPRT # 4
Original ice point resistance (Ω)	100.030	101.566	99.847	100.533
Ice point resistance after 120 days of storage (Ω)	100.146	100.596	99.872	99.695
Shift in ice point resistance (Ω)	+0.116	-0.97	+0.025	-0.838
Corresponding temperature error ($^{\circ}\text{C}$)	+0.29	-2.41	+0.06	-2.12

TABLE VII.- RESULTS OF THE DYNAMIC THERMAL STABILITY TESTS

Cycle No.	Description of Cycles	Shifts in Ice Point Resistance (Ω)			
		IPRT #1	IPRT #2	IPRT #3	IPRT #4
1	Liquid Nitrogen cycling #1	-0.064	-0.174	-0.020	-0.099
2	Liquid Nitrogen cycling #2	-0.058	-0.174	-0.035	-0.113
3	Liquid Nitrogen cycling #3	-0.044	-0.167	-0.012	-0.099
4	Liquid Nitrogen cycling #4	-0.080	-0.175	-0.028	-0.115
5	Liquid Nitrogen cycling #5	-0.091	-0.185	-0.033	-0.116
6	Liquid Nitrogen cycling #6	-0.103	-0.183	-0.046	-0.130
7	Liquid Nitrogen cycling #7	-0.082	-0.177	-0.044	-0.114
8	Liquid Nitrogen cycling #8	-0.053	-0.176	-0.027	-0.117
9	Liquid Nitrogen cycling #9	-0.092	-0.176	-0.042	-0.111
	Mean	-0.074	-0.176	-0.032	-0.113
	Standard Deviation	± 0.020	± 0.005	± 0.011	± 0.009
10	160°C cycling #1	-0.001	-0.183	0.018	-0.023
11	160°C cycling #2	0.003	-0.185	-0.019	0.004
12	160°C cycling #3	-0.009	-0.196	-0.032	-0.008
13	160°C cycling #4	0.012	-0.185	-0.020	0.004
14	160°C cycling #5	0.008	-0.180	-0.017	0.025
15	160°C cycling #6	0.016	-0.180	-0.019	0.029
16	160°C cycling #7	0.015	-0.187	-0.016	0.059
17	160°C cycling #8	0.018	-0.185	-0.017	0.020
	Mean	0.008	-0.185	-0.015	0.014
	Standard Deviation	± 0.009	± 0.005	± 0.014	± 0.025

TABLE VIII.- RESULTS OF THE THERMAL HYSTERESIS TESTS

Cycle No.	Description of Cycles	Shifts in Ice Point Resistance (Ω)			
		IPRT #1	IPRT #2	IPRT #3	IPRT #4
1	Liquid Nitrogen cycling #1	-0.088	-0.189	-0.053	-0.101
2	160°C cycling #1	0.021	-0.181	0.009	0.043
3	Liquid Nitrogen cycling #2	-0.074	-0.167	-0.040	-0.069
4	160°C cycling #2	-0.002	-0.180	-0.032	-0.020
5	Liquid Nitrogen cycling #3	-0.084	-0.171	-0.051	-0.123
6	160°C cycling #3	0.002	-0.174	-0.030	0.020
7	Liquid Nitrogen cycling #4	-0.078	-0.178	-0.050	-0.094
8	160°C cycling #4	0.003	-0.179	-0.031	0.007
9	Liquid Nitrogen cycling #5	-0.070	-0.169	-0.052	-0.105
10	160°C cycling #5	0.004	-0.170	-0.033	-0.004
11	Liquid Nitrogen cycling #6	-0.076	-0.172	-0.052	-0.098
12	160°C cycling #6	-0.006	-0.184	-0.040	-0.034
13	Liquid Nitrogen cycling #7	-0.086	-0.178	-0.047	-0.106
14	160°C cycling #7	0.014	-0.171	-0.028	-0.005
15	Liquid Nitrogen cycling #8	-0.074	-0.165	-0.046	-0.123
16	160°C cycling #8	0.006	-0.158	-0.019	-0.016
17	160°C cycling #9	0.009	-0.180	-0.026	0.001
18	160°C cycling #10	0.012	-0.182	-0.029	0.005



(a)

Figure 1.- Precision of Different Thermometers Based on Different Calibration Schemes
 a. IPRT #1 b. IPRT #2 c. IPRT #3 d. IPRT #4

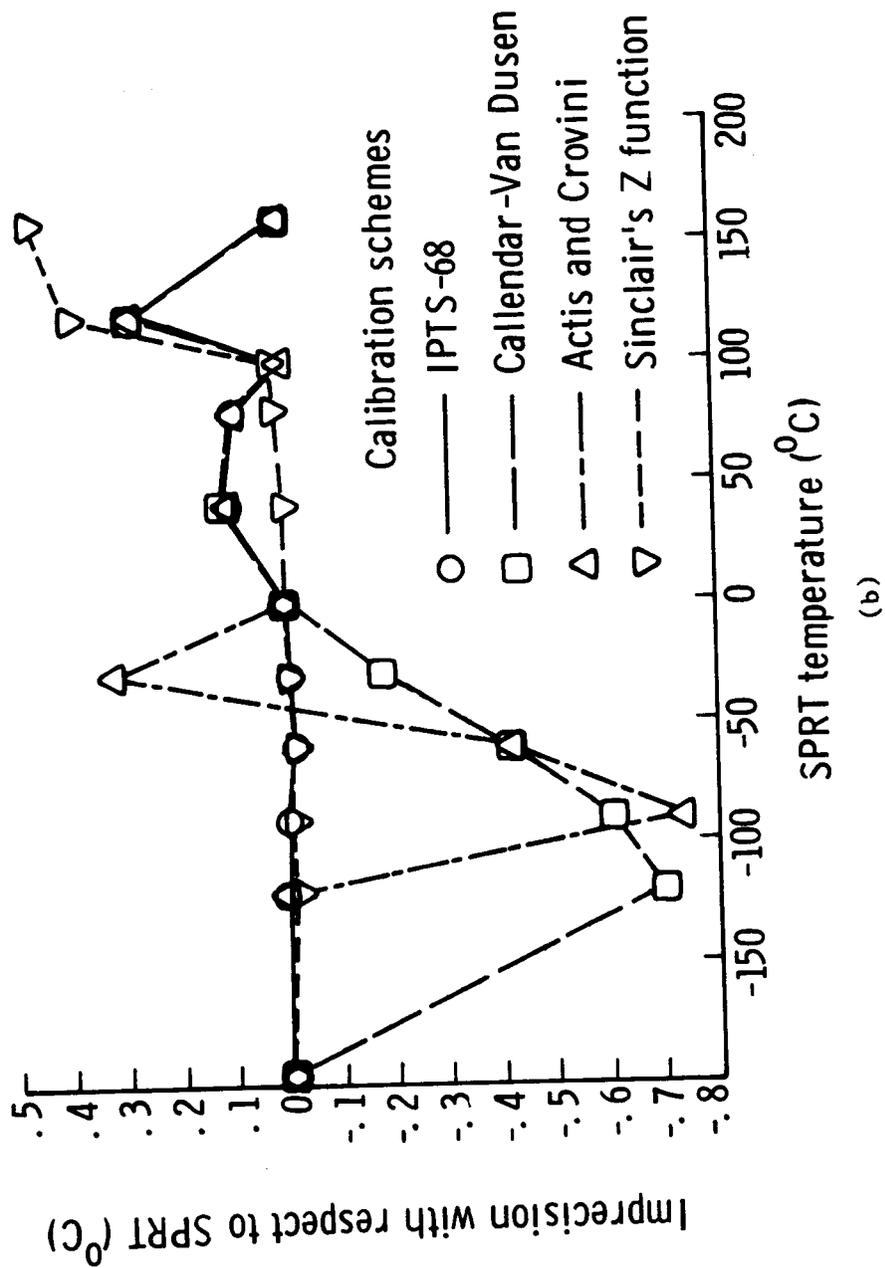


Figure 1.- (continued)

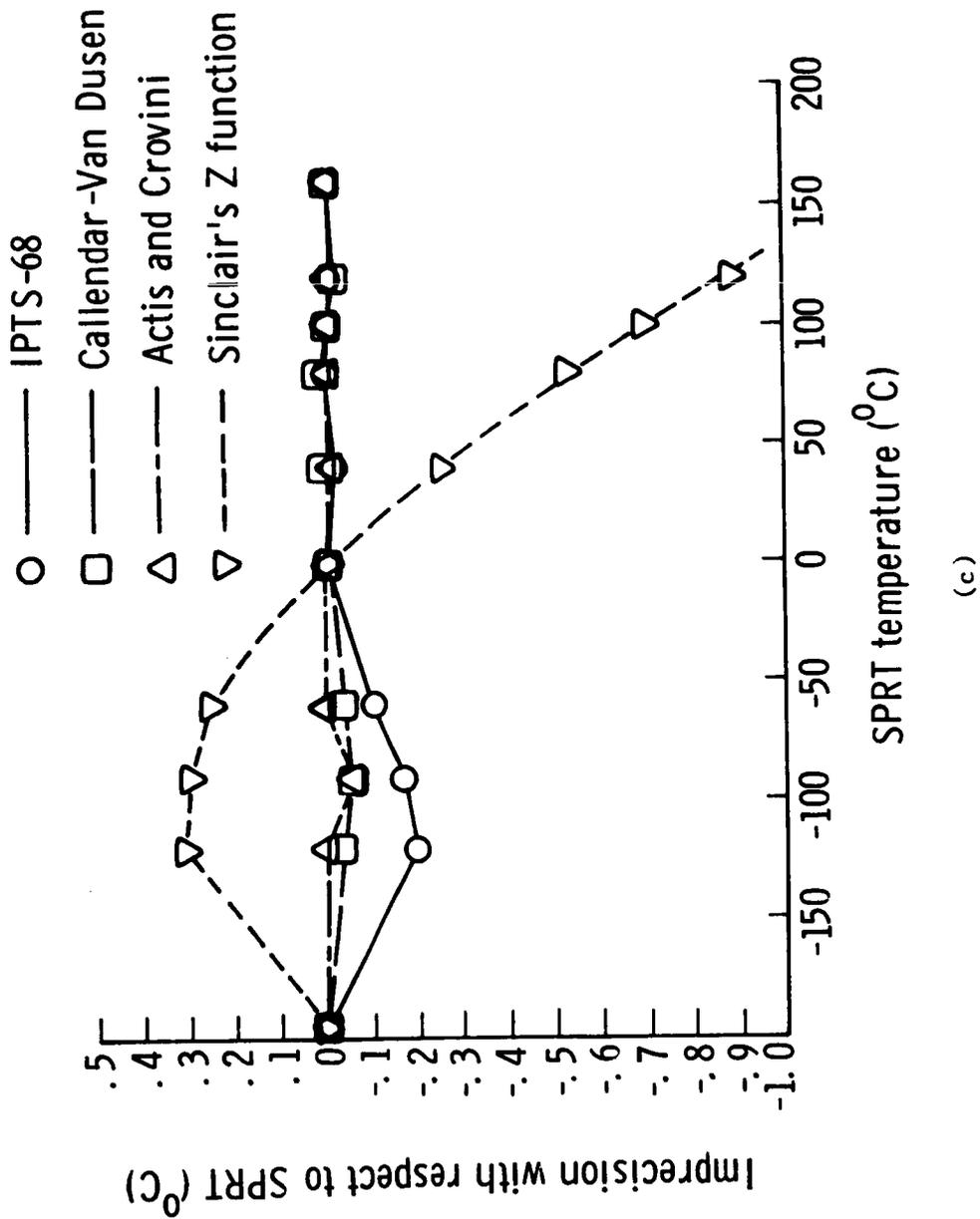


Figure I.- (continued)

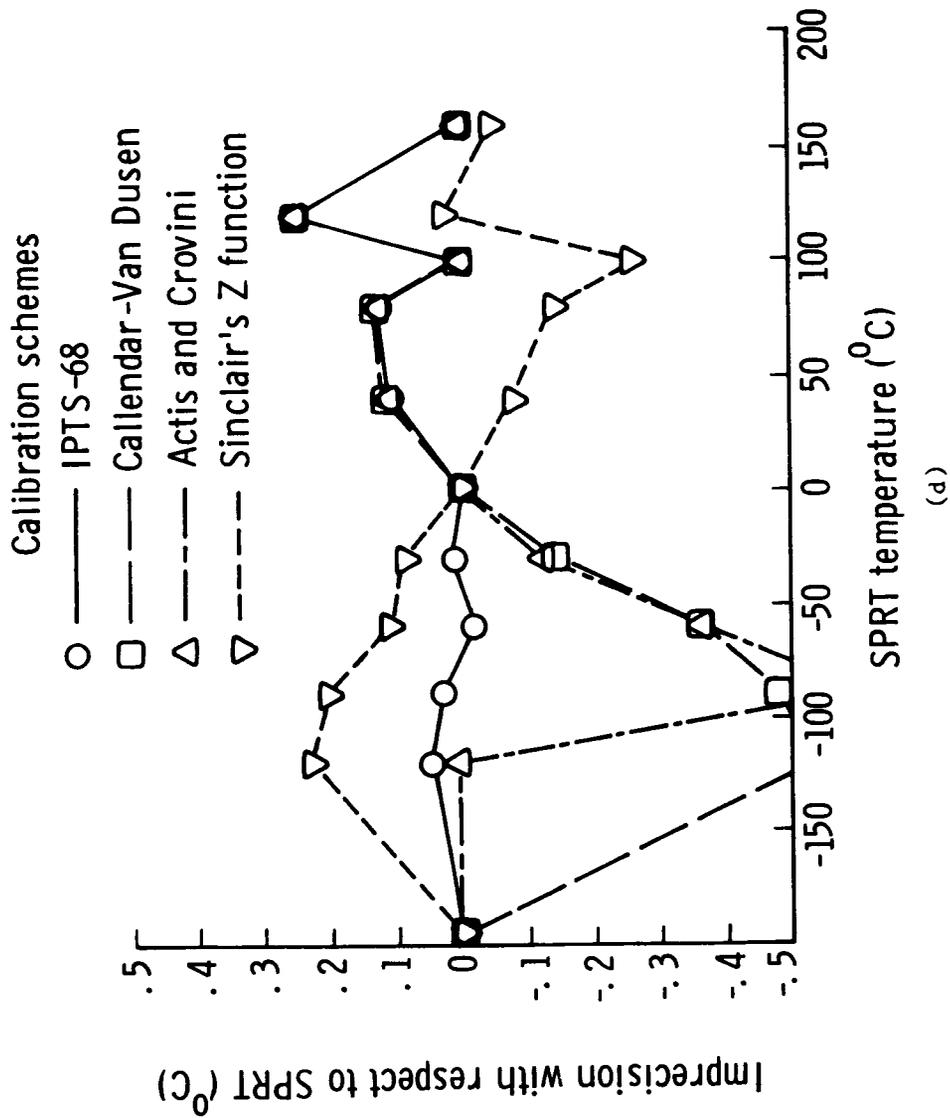


Figure I. (concluded)

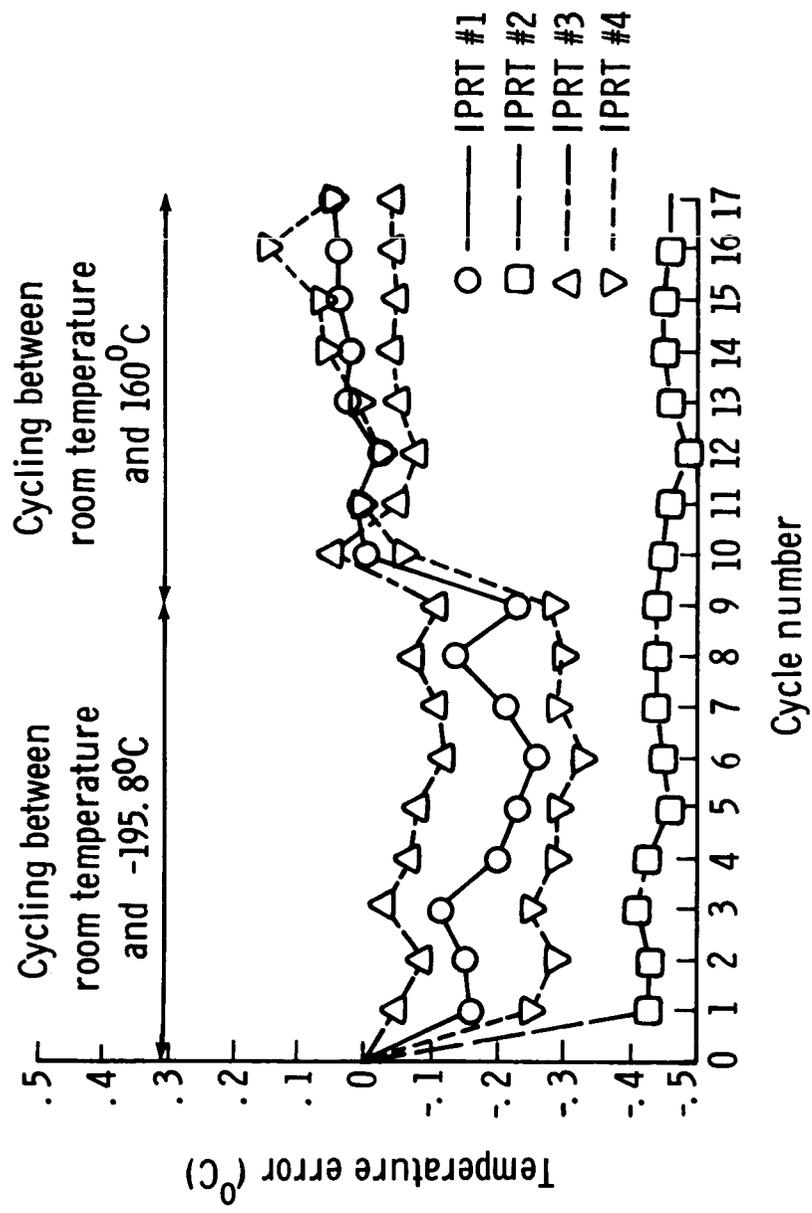


Figure II.- Variation of the Temperature Error Corresponding to the Shift in Ice Point Resistance of Thermometers with Thermal Cycling

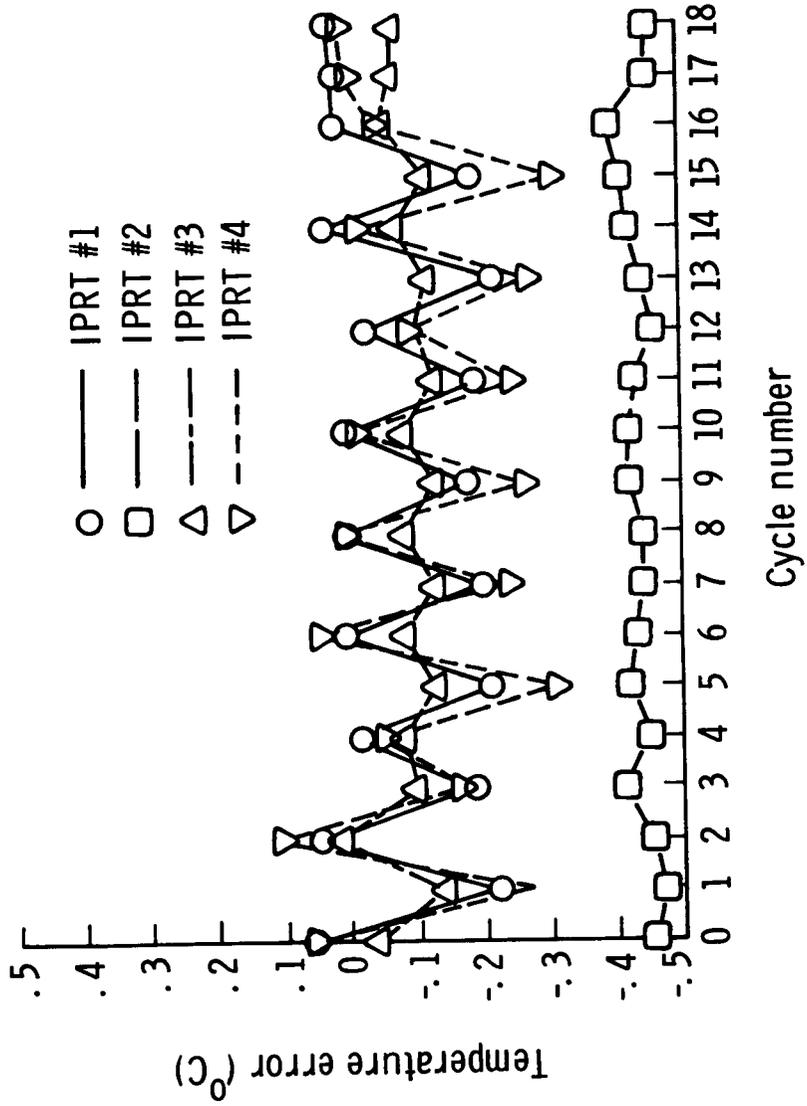


Figure III.- Variation of the Temperature Error Corresponding to the Shift in Ice Point Resistance of Thermometers with Thermal Hysteresis

Standard Bibliographic Page

1. Report No. NASA TM-100491		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Evaluation of Industrial Platinum Resistance Thermometers				5. Report Date July 1987	
				6. Performing Organization Code	
7. Author(s) Kamran Daryabeigi, Lawrence A. Dillon-Townes, and David W. Alderfer				8. Performing Organization Report No.	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Virginia 23665-5225				10. Work Unit No. 505-61-01-05	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001				13. Type of Report and Period Covered Technical Memorandum	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract The calibration and stability of four surface temperature measuring industrial platinum resistance thermometers for use in the temperature range -120°C to 160°C was investigated. It was found that the calibration formulation of the International Practical Temperature Scale of 1968 provided the most accurate calibration. It was also found that all the resistance thermometers suffered from varying degrees of instability and hysteresis.					
17. Key Words (Suggested by Authors(s)) Platinum Resistance Thermometer Calibration Stability Hysteresis				18. Distribution Statement Unclassified - Unlimited Subject Category 35	
19. Security Classif.(of this report) Unclassified		20. Security Classif.(of this page) Unclassified		21. No. of Pages 27	22. Price A03

For sale by the National Technical Information Service, Springfield, Virginia 22161