(NASA-CR-152102) SURVEY REPORT ON THE STATE-OF-THE-ART OF CRYOGENIC THERMOMETRY AND SIGNAL CONDITIONERS AND THEIR POTENTIAL FOR STANDARDIZED SPACE HARDWARE (Lake shore Cryotronics, Inc.) 86 p HC A05/MF A01 N78-22258

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# SURVEY REPORT

on

# THE STATE-OF-THE-ART OF CRYOGENIC THERMOMETRY AND SIGNAL CONDITIONERS AND THEIR POTENTIAL FOR STANDARDIZED SPACE HARDWARE

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## ABSTRACT

This survey report has investigated the possibility of standard low temperature detector(s) for use in upcoming cryogenically cooled satellite and Space Shuttle Payloads. These payloads operate from .3 kelvin to 300 kelvin. Standard detectors have been selected and matching signal conditioning equipment has been specified. This equipment will operate in a spacecraft environment and be compatible with the selected detector, typical spacecraft voltages, typical spacecraft telemetry systems, and the radiation encountered by a typical earth orbiting spacecraft. Work statements to better define and advance detector performance have been presented.

## FOREWORD

This survey report proposes standardized cryogenic thermometry and signal conditioning hardware for satellite and Space Shuttle Payloads. NASA's Technical Monitor was Mr. John Vorreiter. The detailed bibliography included in the survey report was prepared by Mr. L. G. Rubin, National Magnet Laboratory, Massachusetts Institute of Technology. Professor M. O. Thurston, Past-Chairman of the Department of Electrical Engineering, Ohio State University consulted on signal conditioning state-of-the-art.

## TABLE OF CONTENTS


| | | | Page |
|---|---|---|---|
| 1. | INTRODUCTION AND SUMMARY | | 1 |
| 2. | ADVANCES IN CRYOGENIC THERMOMETRY SINCE 1970 | | 5 |
| | 2.1 | Background | 5 |
| | 2.2 | Resistance Thermometry | 5 |
| | 2.3 | Diode Thermometry | 8 |
| | 2.4 | Capacitance Thermometry | 10 |
| | 2.5 | Comparison of Resistance and Diode Thermometry | 13 |
| 3. | RECOMMENDATIONS FOR STATE-OF-THE-ART STANDARD TEMPERATURE SENSING ELEMENTS | | 16 |
| | 3.1 | General | 16 |
| | 3.2 | Type 1 Temperature Sensing Element Recommendations | 16 |
| | 3.2.1 | Discussion | 16 |
| | 3.2.2 | Options Considered and Not Recommended | 18 |
| | 3.2.2.1 | Capacitance Temperature Sensing Element | 18 |
| | 3.2.2.2 | Carbon Glass Temperature Sensing Element | 18 |
| | 3.2.2.3 | Germanium and Platinum as Dual Units Sensing Element | 18 |
| | 3.2.3 | Unit Costs for Type 1 Sensing Elements | 21 |
| | 3.2.3.1 | Qualification Unit Cost Estimate Includes | 21 |
| | 3.2.3.2 | Unit Cost after Qualification | 21 |

Page

3.3 Type 2 and Type 3 Temperature Sensing Element Recommendations.................. 22

3.3.1 Discussion.............................. 22

3.4 Unit Costs for Type 2 and Type 3 Sensing Elements................................ 22

3.4.1 Qualification Unit Cost Estimate Includes.. 22

3.4.2 Unit Cost after Qualification............. 22

4. REQUIREMENTS FOR CRYOGENIC TEMPERATURE DETECTOR SIGNAL CONDITIONERS................................ 24

4.1 General.................................. 24

4.2 Signal Conditioner for Type 1 Temperature Detector Element.......................... 24

4.2.1 Discussion.............................. 24

4.2.2 Options to be Considered................. 26

4.2.2.1 Multiple Input Signal Conditioner......... 26

4.3 Signal Conditioner for Type 2 and Type 3 Temperature Detector Elements............. 26

4.3.1 Discussion.............................. 27

4.4 Development Required for Signal Conditioners............................. 27

4.4.1 Discussion.............................. 27

4.4.2 Basic Specifications for Signal Conditioners for Use with Type 1, Type 2, and Type 3 Detectors..................... 28

4.4.2.1 Comments on Listed Specifications......... 28

4.4.2.2 Specifications for Type 1 Signal Conditioner (For Use with Type 1 Detectors)............................... 28

Page

4.4.2.3 Type 2 Signal Conditioner (For Use with Type 2 and Type 3 Detectors).......... 29

4.5 Development and Unit Costs for Type 1 and Type 2 Signal Conditioners............. 30

4.5.1 Comment................................ 30

4.5.2 Development and Qualification Cost for Type 1 and Type 2 Signal Conditioners...... 31

4.5.3 Unit Cost after Qualification.............. 31

APPENDIX A.......................................... A-1

APPENDIX B.......................................... B-1

APPENDIX C.......................................... C-1

APPENDIX D.......................................... D-1

## INTRODUCTION AND SUMMARY

This survey report includes the following:

(1) Review the advances in cryogenic thermometry that have taken place since 1970.

(2) Review the status of cryogenic thermometry as it applies to space applications.

(3) Review the requirements for cryogenic temperature detector signal conditioners as they apply to space applications.

(4) Recommendation state-of-the-art standard temperature detector elements and compatible potential space qualified signal conditioners to cover the desired temperature ranges.

Estimate the qualification cost for the recommended state-of-the-art detector elements and signal conditioners identified.

Estimate the anticipated unit cost after qualification of the state-of-the-art detectors and signal conditioners identified.

Estimate the anticipated unit cost after development and qualification of the advanced detectors and signal conditioners identified.

(5) Identify and define any technical development required for either the temperature detector elements or the matching signal conditioning equipment, which would result in an advanced detector and signal conditioner.

Estimate the development and qualification cost of the advanced detector elements and signal conditioners identified.

Type 1, 2, and 3 detector requirements are defined graphically and mathematically in Figures 1, 2, and 3. Silicon Diode Temperature Sensing Elements are recommended for Type 1 requirements and Germanium Resistance Temperature Sensing Elements are recommended for Type 2 and Type 3 requirements. This selection required two basic signal conditioners; one for Type 1 and one for Type 2 and Type 3 applications. Internal set points on the signal conditioners allow the use of a "Universal" design which can be adjusted for the specific temperature range or application.

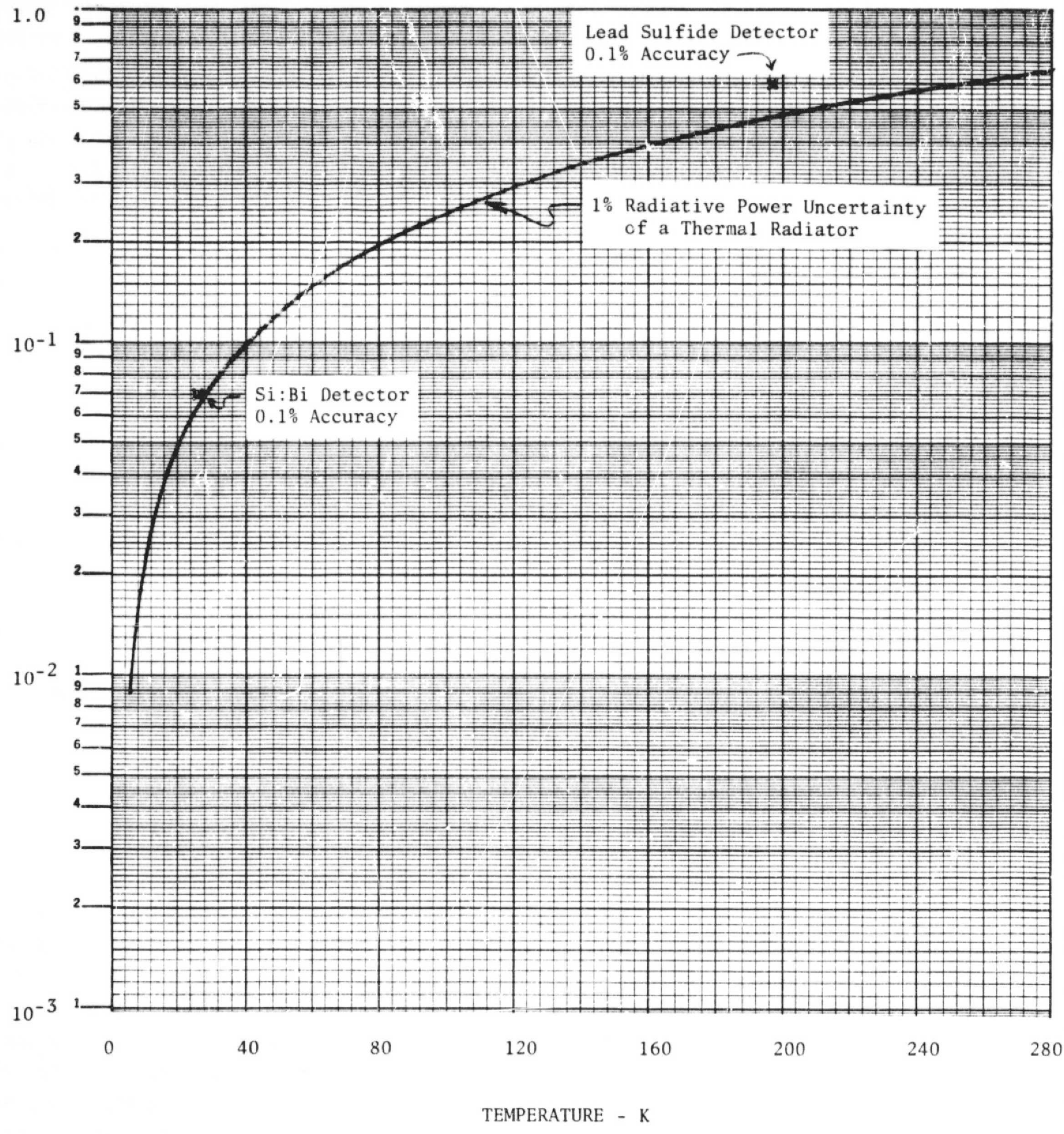


FIGURE 1: Type 1 Temperature Sensing Element Performance.
Temperature versus accuracy in kelvins.
Stated NASA Future Requirements.

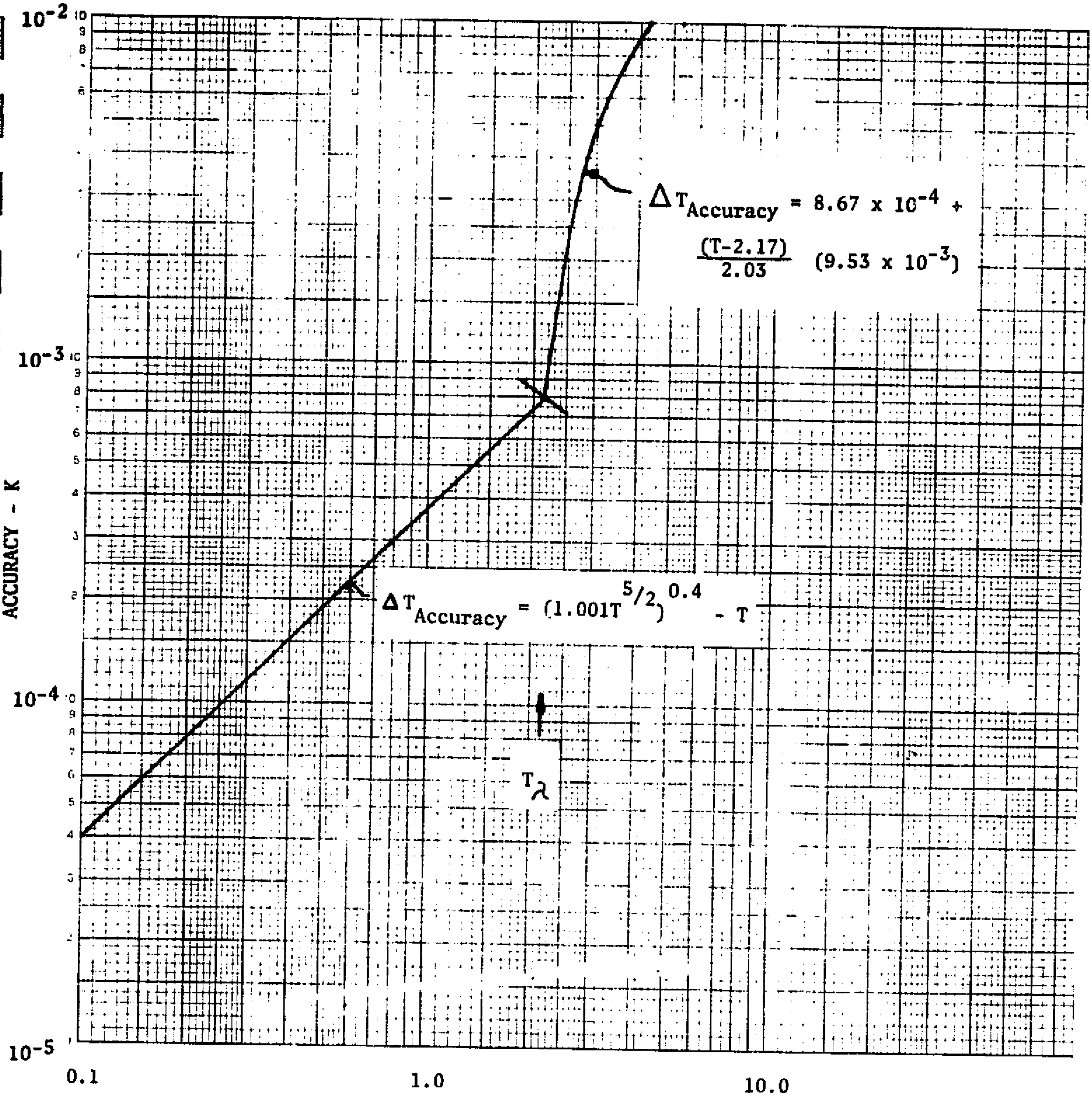


FIGURE 2: Type 2 Temperature Sensing Element Performance. Temperature versus accuracy in kelvins. Stated NASA Future Requirements.

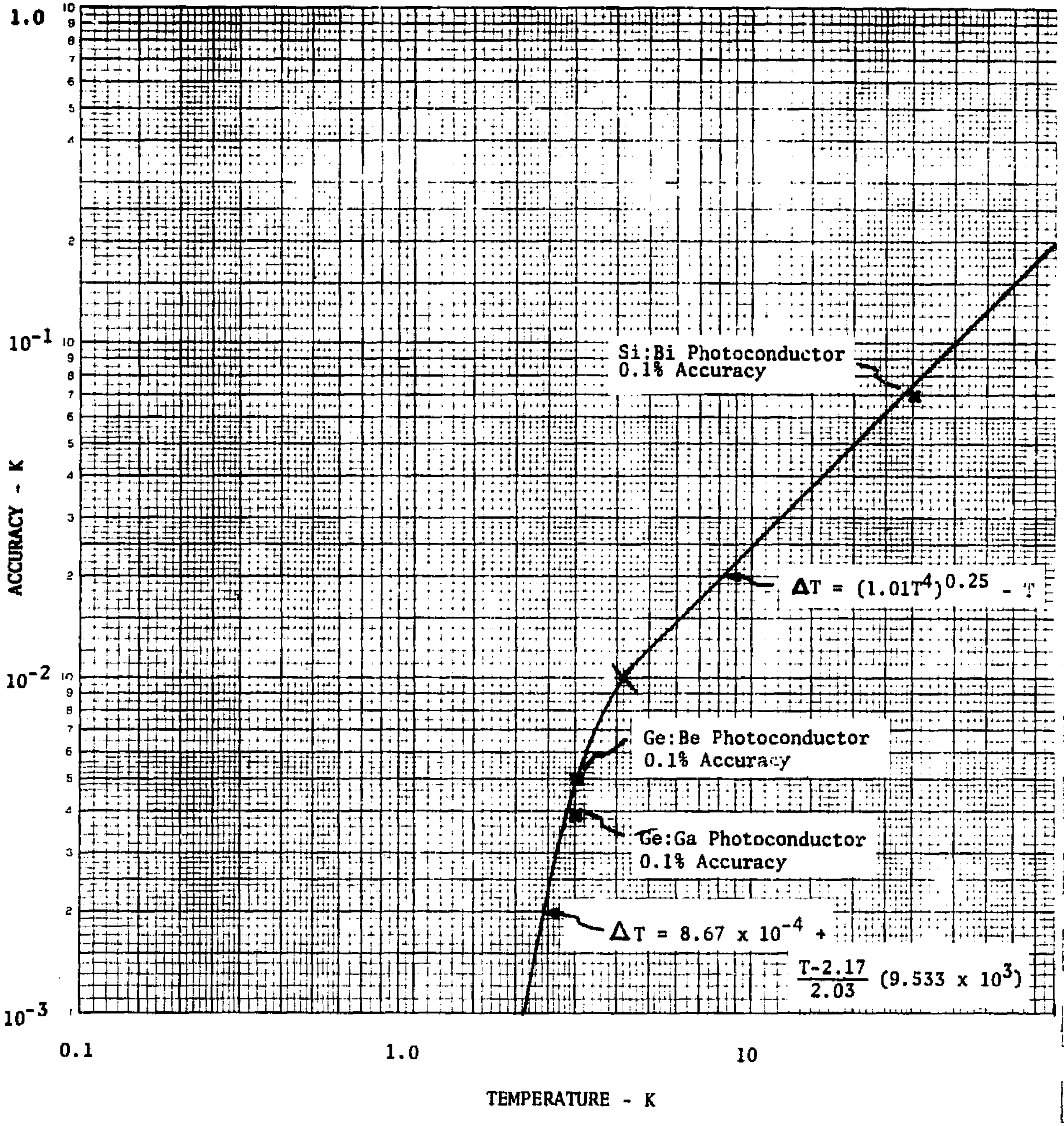


FIGURE 3: Type 3 Temperature Sensing Element Performance. Temperature versus accuracy in kelvins. Stated NASA Future Requirements.

## 2. ADVANCES IN CRYOGENIC THERMOMETRY SINCE 1970

### 2.1 Background

Cryogenic thermometry has significantly changed within the last decade, and in particular since 1970, due to the introduction of several new cryogenic temperature sensors. The result is that, perhaps for the first time, more than one type of thermometer can be considered for most applications. The purpose of this section is to discuss these recent advances in thermometry with regard to thermometer characteristics.

Cryogenic thermometry can be organized into approximately seven categories:

1. Resistance Thermometry
2. Diode Thermometry
3. Capacitance Thermometry
4. Thermocouples
5. Gas, Vapor-Pressure, and Acoustic Thermometry
6. Paramagnetic and Nuclear Magnetic Resonance Thermometry
7. Other Methods of Thermometry

This section concentrates on recent advances in the first three types of thermometers; resistance, diode and capacitance. These appear to cover the major interest for most cryogenic applications (actually all of these thermometers have usable sensitivity over most of the temperature range between 2 and 400 kelvin). Those readers interested in other thermometers, as well as the entire field of thermometry, are referred to "Temperature, Its Measurement and Control in Science and Industry", Volume 4 and for a detailed review of cryogenic thermometry, in particular to a review paper by Lawrence G. Rubin.

### 2.2 Resistance Thermometry

Perhaps the two best known low temperature thermometers in use today are the platinum and germanium resistance thermometers. Acceptance of platinum and germanium resistors as secondary standards over certain portions of the temperature scale by the United States National Bureau of Standards and other national standards laboratories has made them universally popular, resulting in an extensive amount of literature on their use as thermometers.

Because neither resistance thermometer can cover the temperature scale between 2 and 400 kelvin, both become necessary for full range (2 - 400 K) readout and control. An advantage of the platinum thermometer is its relatively linear response above 50 kelvin coupled with the straightforward calibration covering this temperature range utilizing 3 or 4 fixed temperature points. Germanium resistance thermometers, on the other hand, have rather complex resistance versus temperature curves resulting in the necessity of calibrating the thermometer over its entire range. Furthermore, interpolation is cumbersome because of the maxima and minima which occur in the first derivative of the resistance versus temperature curve.

An appreciable amount of work has been performed to determine the characteristics of commercial carbon resistors. These resistors are useful below 20 kelvin, but do suffer from the serious drawback of lack of reproducibility when compared to the germanium and platinum resistance thermometers. It is particularly important that they not be excessively heated after calibration. They are also adversely affected by the presence of water vapor, solvents, and thermal cycling but, because of their low cost, they are still in use today for low-accuracy thermometry and temperature control.

A new resistance thermometer was reported in December of 1972. This thermometer has a monotonic resistance-temperature characteristic between 1 and 400 kelvin with a large sensitivity at low temperatures (e.g., $R_{77}/R_{300}$ = 2 and $R_{4.2}/R_{300}$ = 100 to 200) and a relatively small resistivity of 0.7 ohm-cm at 300 kelvin.

The material is a carbon-impregnated glass (called carbon glass): The host glass is a phase-separable alkali-borosilicate glass which has been treated to form an alkali-and-boron-rich phase and a silica-rich phase. Acid-leaching of the phase-separated glass removes the alkali-and-boron-rich phase. Contacting the porous glass with acetophenone and sulfuric acid produces an acetophenone-and-sulfuric acid-impregnated glass. Heating the impregnated glass under nonoxidizing conditions causes the decomposition of the acetophenone to carbon and the consolidation of the glass. This results in carbon filaments being threaded throughout the porous glass. The material is then cut into a four lead structure which is presently encapsulated in a manner similar to the germanium resistance thermometer.

Figure 4 shows the resistance temperature characteristics of platinum, germanium, carbon, rhodium-iron, and carbon-glass resistors. The relative sensitivities of germanium, carbon, and carbon-glass are shown in Figure 5. The carbon-glass thermometer has very interesting possibilities of removing some of the drawbacks associated with germanium. First, since its curve is monotonic to 400 K, it has extended range. Second, its derivative, (dR/dT), is also monotonic and interpolation should be considerably easier than that associated with germanium. Third, the magnetic field dependence is not orientation dependent and the equivalent temperature error in magnetic fields is quite small (e.g., at 4.2 K, $\Delta T$ = -80 mK at 5 Tesla and $\Delta T$ = -0.14 K at 10 Tesla; at 77 K $\Delta T$ = 2.70 K at 10 Tesla). Fourth, the resistance temperature curves scale from unit to unit within a glass plate (.1 K appears to be possible) and possibly from one plate to another as improvements in manufacture of the carbon-impregnated porous glass plates occur. Indications are that $R_i = bR_j^m$ where b and m are temperature-independent constants, with m very close to unity. If $R_j$ (T) represents a calibrated thermometer, this calibration can in principle be transferred to a second unit $R_i$ by a two-point method to determine b and m. However, questions relating to the accuracy and reproducibility of such a procedure must be deferred.

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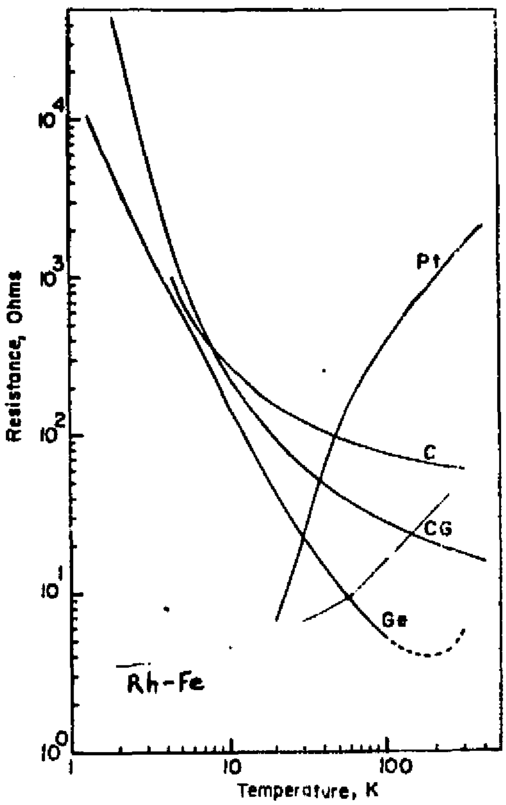


FIGURE 4:

Resistance-temperature characteristics of the germanium (Ge), platinum (Pt) ($R_0$=1380 ohms), rhodium-iron (Rh-Fe), and carbon glass (CG) resistors and an Allen Bradley carbon (C) resistor (56 ohms, ½ W.).

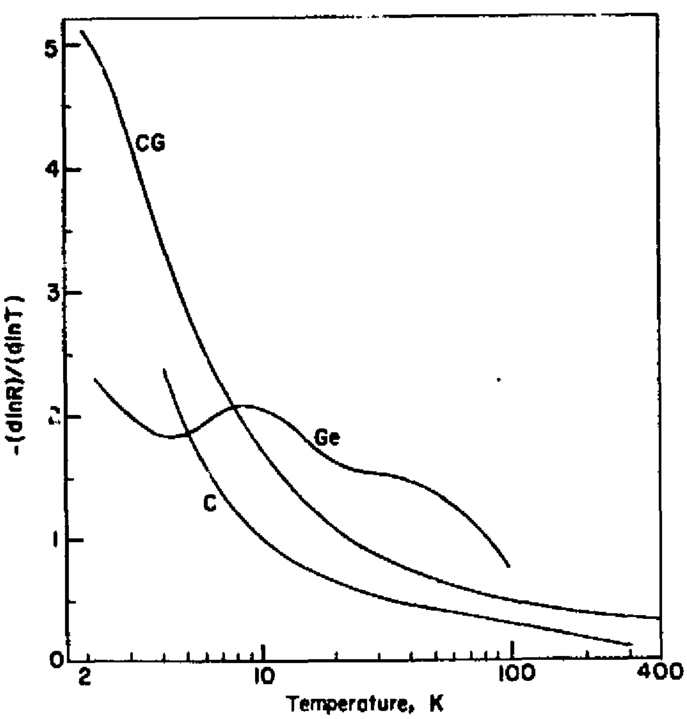


FIGURE 5:

Relative sensitivity data (d lnR)/(d lnT) versus the temperature for carbon (C), carbon glass (CG) and germanium (Ge) resistors.

The alloy of rhodium with 0.5 atomic percent iron has been investigated over the temperature range from 25 mK to 300 kelvin. An anomalous temperature dependence is dominant below 40 kelvin; at higher temperatures, the resistive behavior tends to that of the pure metal. For a 45 ohm nominal resistance at the ice point, as the temperature approaches zero kelvin, the resistance approaches a value between 2 and 3 ohms. The resistance rises approximately as $T^2$ between 0.040 and 0.1 K with a sensitivity of approximately 0.3 ohms per degree at 0.1 K. At temperatures above 0.5 K, the sensitivity slowly falls to a minimum value of 0.08 ohms per degree between 25 and 30 K with a resistance of approximately 7 ohms. Above this temperature the sensitivity first rises steadily to a maximum of 0.175 ohms per degree and then falls slowly to 0.165 ohms per degree at the ice point. From 100 K to 273 K the resistance temperature characteristic is linear to within ±1 K.

Preliminary long term stability data indicates that the rhodium-iron thermometers are reproducible to ±0.3 mK. Although the temperature resolution is not as good as that of a correctly doped germanium thermometer, reproducibility is as good, and interpolation between calibration points is easier.

## 2.3 Diode Thermometry

Interest in diode thermometry began in the early sixties when germanium, silicon, and gallium arsenide diodes were investigated and reported in the literature as possible cryogenic thermometers. An extensive amount of literature now exists on the use of diodes and transistors as thermometers for use at room temperature and down to cryogenic temperatures. The gallium arsenide diode thermometer was introduced commercially in 1966 with the silicon diode thermometer becoming available in late 1972. The diode thermometer makes use of the fact that, under conditions of constant forward current, the forward voltage drop of the diode junction increases with decreasing temperature. This forward voltage drop is somewhat current-sensitive and polarity of the voltage leads must be observed. The equipment needed to determine temperature using a diode thermometer consists of a constant-current source (normally 10 microamperes), a very high impedance voltmeter such as a digital or differential voltmeter, and a calibration curve or table for that particular diode.

The gallium arsenide (GaAs) diode has two principal advantages over resistance thermometry; first, its wide temperature range (1 to 400 K) and, second, its relative magnetic field insensitivity (when compared to germanium resistance thermometry). For example, in the temperature range from 2 to 40 K, the apparent temperature error for a GaAs thermometer is approximately 0.1 K in a magnetic field of 2 T (20 kilogauss). This error increases to between 0.6 and 1 K for magnetic fields of 4 T.

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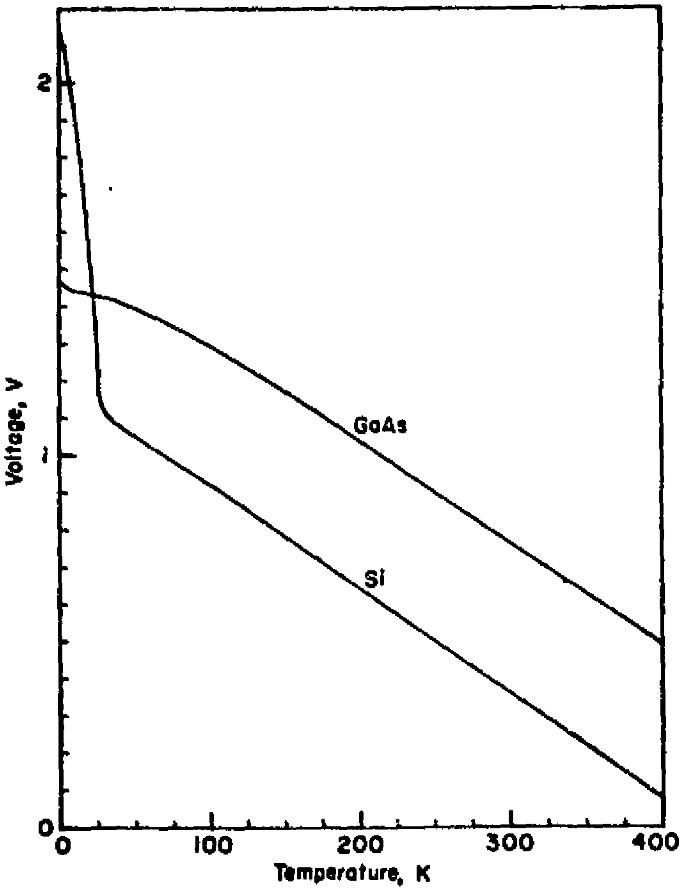



FIGURE 6:

Typical forward voltage versus temperature characteristics for the gallium arsenide (GaAs) and silicon (Si) diode thermometers.

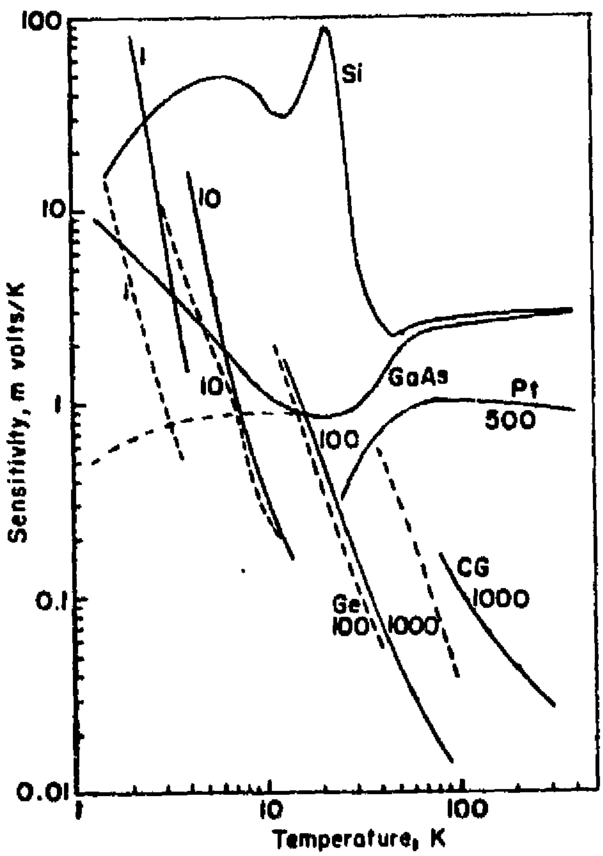



FIGURE 7:

Voltage sensitivity of temperature (dV/dT) as a function of temperature for silicon (Si) and gallium arsenide (GaAs) diode (solid and dotted line) thermometers and carbon glass (CG) (solid line), germanium (Ge) (dotted line), and platinum (Pt) ($R_0$=470 ohms) resistors. Numbers for resistors indicate current in microamperes. Diode thermometer data is at 10 microamperes.

Both of these advantages have been eliminated with the introduction of the carbon-glass resistance thermometer and the silicon diode thermometer. Typical response curves for the diode thermometers are shown in Figure 6 with their temperature voltage sensitivity shown in Figure 7. Note the minimum in sensitivity between 10 and 20 kelvin for the gallium arsenide diode. Also note the dotted curve at low temperatures in Figure 7 which shows the sensitivity of the first gallium arsenide diodes reported by Cohen, et al. The major difference in low temperature sensitivity of the two gallium arsenide types is due to the material parameters associated with the bulk starting crystal. This low sensitivity of the gallium arsenide diode below 30 kelvin compared with the extremely high sensitivity for the silicon diode over the same temperature range has substantially reduced the importance of the gallium arsenide diode as a low temperature thermometer. In addition, above approximately 30 K, the change in forward voltage is almost linear with the change in temperature to above 400 K. The silicon diode thermometers have another advantage over gallium arsenide diode thermometers in that it is possible to match the silicon diodes to better than 1 K within the range from 30 to 400 K and to 0.1 K at 4.2 K. The result is that the silicon diode is able to match or exceed the gallium arsenide diode in all but one characteristic, its magnetic field sensitivity. Typical sensitivity below 28 kelvin is 50 mV/K for the silicon diodes.

## 2.4 Capacitance Thermometry

An increasingly important application of thermometry is in the area of temperature measurement in magnetic fields. Detailed data of commercially available thermometers and the effect of magnetic fields on their characteristics has been carefully researched and reported. Until the introduction of the capacitance thermometer in 1971, electrical temperature sensors such as resistors, diodes, and thermo-electrics all exhibited magnetic field errors. The capacitance thermometer is unique in that it is presently the only electrical magnetic field independent thermometer. The capacitance thermometer developed by Corning Glass has been tested in fields to 18 Tesla with magnetic field induced errors no greater than 1 millikelvin being observed. This is to be expected since displacement current is not magnetic field dependent.

The capacitance thermometer is made by forming an aluminosilicate glass from a melt of the refractory oxides SrO and $TiO_2$ together with the solvent $SiO_2$ and the modifier $Al_2O_3$. Upon rapid quenching of the melt, a stable glass can be formed. If this glass is then reheated under controlled conditions, the perovskite $SrTiO_3$ is crystallized resulting in a glass-ceramic which has a large temperature-dependent dielectric permittivity at cryogenic temperatures, $\chi_r = 200$. The capacitor bare elements are 51-layer structures, 1 x 2 x 5 mm, with 0.025 mm-thick dielectric layers separated by Au-Pt plates. Silver leads are attached with a fired-on silver paste, the unit is glazed with a devitrifying glaze and then sealed into a platinum can with a low melting glass to complete the thermometer fabrication. A platinum can was chosen since its thermal expansion closely matches that of the glass-ceramic.

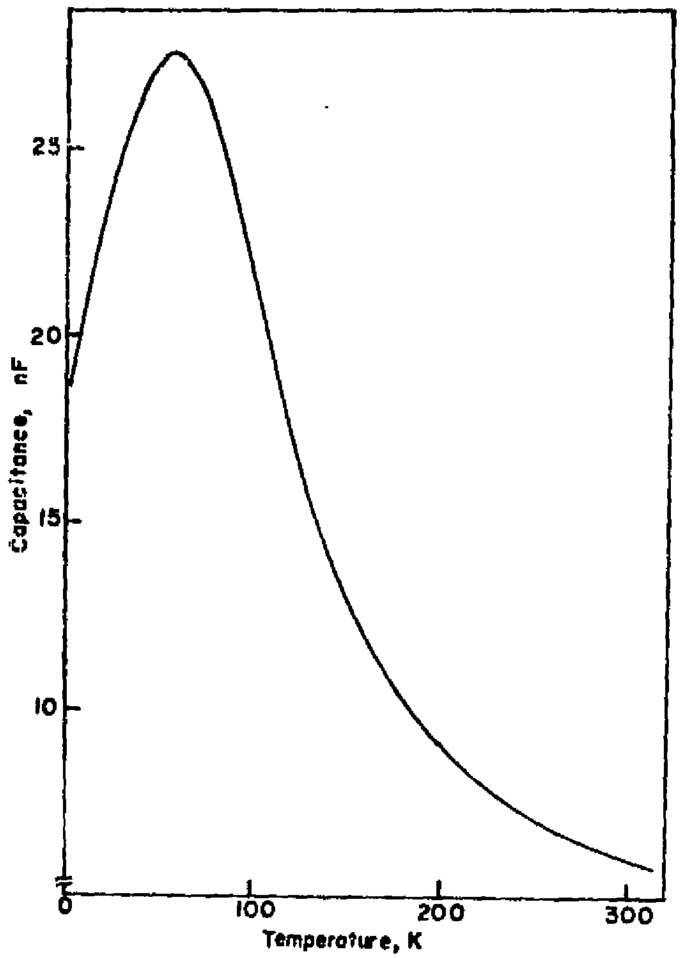



FIGURE 8: Typical capacitance temperature characteristics for $SrTiO_3$ capacitance thermometer.

The capacitance-temperature (C-T) curve for a typical unit is shown in Figure 8. The C-T curve displays a maximum near 65 kelvin which has been shifted from approximately 35 kelvin by appropriate doping of the glass-ceramic and glass-chemistry techniques. In addition to shifting the permittivity peak towards 77 kelvin, an anomalous 'knee' which occurs near 10 kelvin is reduced to the point where it is barely perceptable in the above C-T data. Above 100 kelvin the capacitance approximately follows a Curie-Weiss law $C \propto (T - T_0)^{-1}$, up to nearly 500 kelvin where the ac conductivity of the material begins to increase rapidly. Except for a small temperature region near 100 K, the maximum sensitivity for the capacitance thermometer occurs in the nearly linear temperature range from 1 to 5 kelvin (approximately 250 pF/K for the unit of Figure 8). Although the loss tangent is monotonic over the range where the capacitance maximum occurs, for most applications, the thermometer must be considered to be unusable near the peak in the C-T curve. The loss tangent of the thermometer is approximately 2% from 1 to 10 kHz and decreases with decreasing temperature below 50 kelvin. Therefore, self-heating is not only small, but decreases with decreasing temperature, which is the inverse of what occurs for most resistance and diode thermometers. For example, the self-heating of a capacitance thermometer at 5 kHz and 8 mV (rms) is approximately 100 picowatts at 20 kelvin and 50 picowatts at 2 kelvin.

Repeatability tests originally reported by Lawless indicated that there is a small "aging" of the capacitor with time under isothermal conditions. This small aging effect occurs whenever the glass matrix is spatially perturbed, either by thermal expansion, or by electrostrictive coupling to the micro-crystals, or by warming or cooling across the 65 kelvin transition temperature. The magnitude of the aging effect can vary from as much as .5 K to 15 mK at 1 kHz (from sensor to sensor) and decreases with increasing frequency to an extrapolated value below 1 mK at 500 kHz. The dielectric constant is also somewhat electric field strength dependent. Therefore, rms voltages less than 50 mV should be applied to the thermometer to avoid both a reduction in the apparent capacitance and to minimize aging effects.

For temperatures somewhat below the maximum in capacitance, curve fitting has indicated that a simple fourth order expansion in T(C) yields an excellent empirical fitting equation from 0.1 to 50 kelvin.

Below 1 kelvin, the 1100-type capacitor described above is monotonic in capacitance from 0.1 to 65 kelvin, and a 1200-type, monotonic from 50 mK to 10 kelvin. Both may be useful due to the small amount of self-heating and their reasonable sensitivity. The 1100 and 1200 designations refer to the crystallization temperature. Both thermometers display an unexpected increase in capacitance with decreasing temperature below their monotonically decreasing ranges, and in the case of the 1100-type, $C \propto T^{-1}$.

The capacitor's basic strength is as a temperature transfer standard or control element in the presence of strong magnetic fields.

## 2.5 Comparison of Resistance and Diode Thermometry

It is somewhat difficult to quantitatively compare the sensitivities of resistance thermometers to diode thermometers because of the very different characteristics of the two types of thermometers. Sinclair, et al. has attempted to compare them by considering the change in the static resistance of the diode thermometer with temperature as is done with resistance thermometry, i.e., (1/R) (dR/dT). This is of little use, however, since it is not the static resistance of the diode thermometer which is measured as a function of temperature.

Perhaps a better means of comparison, but certainly with its own drawbacks, is to consider the voltage sensitivity with changes in temperature at a constant current for each thermometer. For the case of diode thermometers, the current is usually chosen to be 10 microamperes. For resistance thermometry, the power input into the sensor is normally a limiting factor. Due to the poor thermal coupling of the strain-free mounting used for germanium resistance thermometers, the range would be $10^{-8}$ to $10^{-5}$ watts, depending on the temperature. For most platinum sensors this may be increased to $10^{-4}$ watts. Currents are chosen to be compatible with this criterion. Under these conditions, the sensitivity can be expressed as $dV/dT = I\ dR/dT$ (in mV/K).

The sensitivities of the germanium, platinum and carbon-glass resistance thermometers are plotted in Figure 7 for the constant currents indicated. To avoid confusion, the carbon resistance thermometer is not shown since its characteristics are quite similar to that of the carbon-glass resistance thermometer as can be seen from Figure 5.

If full range is understood to extend from 1 to 300 K (or 400 K) then the only full-range thermometers which qualify are the diode thermometers and possibly the carbon-glass resistance thermometers. As can be seen from Figure 7, carbon-glass has quite low sensitivity near room temperature.

A highly desirable property for a thermometer is constant sensitivity over the full temperature range, unless one is taking data which is dependent on reciprocal temperature, for which it might be more appropriate to have a thermometer with sensitivity proportional to 1/T. Obviously, none of the cryogenic thermometers shown in Figure 4 have this property although the diode thermometers and the platinum resistance thermometer are fairly linear from 100 to 400 K. Over this range, the silicon diode increases in sensitivity by about 10% while the platinum resistance thermometer decreases its sensitivity by about the same amount. Even though the sensitivities of the diode thermometers are approximately three times that of the platinum resistance thermometer, this could result in a somewhat misleading conclusion. For the platinum thermometers shown, the significant parameter 1/R dR/dT, i.e., the percent change in resistance per kelvin has a worst case change of 0.3% per kelvin. For the diode thermometers over the same 100 to 400 K range, the voltage change is approximately 3 millivolts per kelvin. For a voltage range of 0.8 to 0.1 for silicon (1.2 to 0.35 volts for gallium arsenide), this again results in a normalized worst case change of 0.3% per kelvin. Therefore, the choice of a thermometer for this temperature range must rest on other parameters; e.g., low temperature sensitivity, thermometer package size or configuration, requirement for a secondary standard, magnetic field sensitivity, ability to match more than one thermometer, cost, thermal response of the package, number of leads required, simplicity of instrumentation, etc.

Below 100 K all the thermometers considered in this paper are extremely non-linear so that linearity cannot be a consideration in the choice of a thermometer to a very large extent. It is obvious, of course, that resistance thermometers are considerably more non-linear than diode thermometers. However, the extreme sensitivity of the resistors is at the low temperatures where high sensitivity is most often desired. Therefore, once again, the choice of a thermometer is based on other considerations, such as those mentioned for the 100 to 400 K range.

Comparing the two diode thermometers in this temperature range is quite straightforward. If the thermometer is to be used in a magnetic field below 30 K, then gallium arsenide will continue to be the choice. If magnetic fields are not a consideration, however, then the silicon diode is preferable. It should be remembered, of course, that the obvious choice of a sensing element in a magnetic field, at least for control, is the capacitance thermometer.

Selecting a resistance thermometer is not quite as simple. If a secondary standard is desired, the choice must be the germanium and platinum resistance thermometers over their respective temperature ranges. If cost is the dominant factor or use in magnetic fields at low temperatures, then the carbon glass resistance thermometer has merit. The only wide range (1 to 400 K) resistance thermometers are carbon glass and rhodium-iron. However, due to the physical size of the rhodium-iron resistor, its use as a possible standard may be of most interest.

The sensitivity of the resistance thermometers and the silicon diodes are both quite high at the lower temperatures. This makes it possible to observe changes of less than 1 mK with both types of thermometers.

The silicon diode, however, retains its high sensitivity to nearly 30 K, which makes it attractive as a sensor for temperature control applications. Temperature controllers are also available for both resistance and capacitance thermometers.

Research on the temperature scale is continuing at a steady pace in several national laboratories. Currently, both rhodium-iron and carbon glass are under evaluation and it is possible that one or both may, sometime in the future, be accepted as secondary standards together with germanium and platinum over the cryogenic temperature range.

The increased demand for diode thermometry in laboratory and industrial environments was the basis for the introduction of the silicon diode with its improved sensitivity. It is now clear that this improved sensitivity below 30 K has caused the gallium arsenide diode to be replaced in almost all applications other than those involving magnetic fields. Even here the gallium arsenide diode may lose out since the carbon glass thermometer covers the same temperature range with an apparent temperature error (at 4.2 K and 5 Tesla) which is 10 times smaller than that of GaAs (= 80 mK for carbon-glass).

## 3. Recommendations for State-of-the-Art Standard Temperature Sensing Elements

### 3.1 General

The requirements for temperature sensing elements set forth in Figures 1, 2, and 3 give the desired accuracy for currently identified spacecraft requirements. Fortunately, it appears reasonable to expect that future unidentified requirements should not exceed these performance levels.

Unfortunately, no single sensing element can meet all the requirements. In fact, the defined requirements in Figure 2 below approximately 2 K are currently beyond state-of-the-art. Figure 3 requirements can marginally be met. Figure 1 requirements are state-of-the-art and can be met with a single detector. These observations assume that the temperature scale meets the requirements. This is not the case.

The currently defined temperature scale modified by the soon to be announced EPT-76 will give a certainty of the temperature scale for Type 2 and 3 requirements of 1 to 3 mK from .3 to 4.2 K.

Neither of the above constraints of sensing element sensitivity or temperature scale definitions consider the practical limitations of matching signal conditioners and their effect on the final temperature measuring and controlling sub-system accuracies.

These recommendations, therefore, are based on the considerations of the best choice for the requirements.

### 3.2 Type 1 Temperature Sensing Element Recommendations

The silicon diode temperature sensing element is recommended for Type 1 work.

#### 3.2.1 Discussion

Ample evidence exists that verifies properly designed and packaged silicon diode temperature sensing elements meet or exceed the Type 1 stability requirements. This sensing element, introduced in late 1972, currently is used in nearly 50% of the scientific and laboratory applications. This rapid market penetration has resulted in better understanding the use parameters of the sensing element than any other sensing element has enjoyed over the equivalent number of introductory years.

Advantages of the sensing element include:

a. Essentially immune to shock and vibration
b. Full range sensing detector element: 1 to 380 K
c. Sensitivity increases with decreasing temperature

d. Broad customer acceptance
e. Easily calibrated
f. Single excitation current
g. Output signal is several mV per K allowing use of state-of-the-art digital readout electronics
h. Proven stability
i. The most versatile in packaging of any sensing element.

Disadvantages include:

a. Relatively new - 6 years
b. Not a secondary standard - The response of a diode is not the result of an intrinsic material property such as capacitance or resistance
c. Must be curve fit in a manner similar to germanium
d. Radiation sensitivity is unknown.

#### 3.2.1.1 Silicon Diode Temperature Sensing Element Radiation Resistance

Radiation resistance for silicon diode temperature sensing elements is not known. Although extensive radiation damage literature exists on diodes, transistors, and integrated circuits, the criteria for failure is considerably different from temperature sensing elements. For this reason, consideration must be given to determining an appropriate upper limit of total dose on silicon diode temperature sensing elements.

#### 3.2.1.2 Stability Testing of Temperature Sensing Elements

With the possible exception of wire wound temperature sensing elements, every element described in this survey report must be subjected to intensive stability testing. Appendix B and Appendix C describe satisfactory performance and testing acceptance specifications for recommended Type 1, Type 2, and Type 3 sensing elements.

The literature is replete with reports on the requirements for dip stability testing of germanium sensing elements. It is now generally accepted that ten dip cycles from room temperature to liquid helium is sufficient to determine the stability characteristics with almost every temperature sensing element. Data and statistics taken at the factory of the authors of this report show the same is true for carbon glass and silicon diode temperature sensing elements. It is now clear that the yield will vary from 30 to 50% under optimum conditions when the test procedures in Appendixes B and C are followed. This was not recognized to be necessary in the case of the silicon diode sensing element until late 1976. Further, during the initial introduction of the silicon diode sensing element, certain not yet understood anomalies occasionally occurred which created instabilities at approximately 13 ±1 K. Again, specifications in Appendix B removes this chance for instability.

It has long been recognized that the majority of the heat leak into and out of the germanium temperature sensing element was through the leads. The realization that the effect was equal or even more important for some package configurations for the silicon diode temperature sensing element was not obvious until sufficient experience had developed in its use. The result was that for these packages, significant temperature errors resulted until enough history was accumulated on the various packages so that appropriate installation instructions could be determined.

In summary, when the requirements of Appendix B are met and the installation procedures regarding lead installation are proper, the silicon diode temperature sensing element can meet the requirements of the Type 1 temperature sensing element. It is important to note that this good installation practice is similarly required for all other temperature sensing elements.

### 3.2.2 Options Considered and Not Recommended

#### 3.2.2.1 Capacitance Temperature Sensing Element

This sensing element has two major flaws. First and most important, it is not stable from temperature cycle to cycle. Secondly, the temperature response curve has a reversal at 65 K making that temperature region useless.

#### 3.2.2.2 Carbon Glass Temperature Sensing Element

This sensing element is enjoying a rapidly increasing acceptance as a replacement for germanium, particularly in magnetic field applications. The stability at 4.2 K is as good as germanium, but the best that can be guaranteed at 77 K is 50 mK. This further degrades to approximately .1 K at room temperature.

This degraded stability at the higher temperatures has not affected the usefulness of the sensor in the prime use area noted above.

The selection of carbon glass temperature sensing elements would present circuit complications in signal conditioner design due to the need to switch excitation current. The remaining options are sufficiently better that these elements are not recommended.

#### 3.2.2.3 Germanium and Platinum as Dual Units Sensing Element

Two years ago this option would have been chosen. Data and operational experience available in 1975 and 1976 for silicon diode temperature sensing elements was not sufficient to offset the conservative approach that choosing platinum for temperatures above 40 K and germanium for temperatures below 40 K would require.

The 40 K crossover region for use is significant. A comparison of the relative sensitivity of germanium resistance temperature sensing elements and platinum resistance temperature sensing elements would suggest that 25 K is the better choice as the sensitivities are essentially equal at this temperature. The 40 K temperature is, however, a practical choice and is defined by the availability of reasonably sized platinum resistance temperature sensing elements. A review of the reasons for this observation are in order.

There are several types of platinum resistance temperature sensing elements available, but they fall roughly into two classifications. Industrial Grade platinum resistance temperature sensing elements are produced in the United States by the tens of thousands annually and can be used to maintain a calibration to about ±0.01 K at the best. Available from several manufacturers, their cost is on the order of $100.00. "Standard" platinum resistance temperature sensing elements are more carefully constructed and, with proper treatment, will hold a calibration to better than ±0.001 K below the triple point of water. Standard platinum resistance temperature sensing elements are, of course, more appropriate for laboratory maintenance of IPTS-68. They are produced by two companies in the United States, by one in England, and by one in Japan and cost about $1400.00 uncalibrated.

In order to adequately maintain a calibration of IPTS-68, a standard platinum resistance temperature sensing element must satisfy some general requirements: the resistor must be made from very pure, annealed platinum wire on a strain-free insulating support; to guarantee sufficient purity, the ratio of resistance at 100°C to that at 0°C must exceed 1.39250; upon thermal cycling over the usual range, the resistance at 0°C, R(0), must return to within 4 ppm of its original value; the resistor is to be constructed as a four lead element and is to be hermetically sealed in a protective sheath; and leakage conductances of the insulating support and the hermetic seal should be less than $4 \times 10^{-7}$ $R(0)^{-1}$. Within these general constraints, however, choice of insulating support material (mica, alumina, sapphire, fused silica), sheaths (platinum, stainless steel, borosilicate glass, or fused quartz), gas inside the hermetic seal ($He^4$ and $O_2$ or dry air), geometry of winding (coiled or "birdcage"), length and diameter of platinum wire is determined by the specific application.

The physical size of standard platinum resistance temperature sensing elements varies as well, but they generally fall into two classes, a "long stem" variety which is over 100 cm in length, and a much smaller "capsule" configuration 8 cm in length and 5.7 mm in diameter. Because of the much smaller size and other construction differences, the "capsule" type standard platinum resistance temperature sensing element is used in the cryogenic temperature region as defined in this article. A typical capsule standard platinum resistance temperature sensing element consists of a resistor with a value of 25 ohms at 0°C wound from 61 cm of 0.075 mm diameter wire contained in a platinum sheath with about 1/3 atmosphere of $He^4$ gas with trace amounts of $O_2$.

Industrial grade platinum resistance temperature sensing elements are normally manufactured from less pure platinum with the ratio of resistance at 100°C to that of 0°C of 1.385. The reduction in purity gives decreased sensitivity with decreasing temperature but, more importantly, the stability decreases by over an order of magnitude.

The most important consideration in considering platinum resistance temperature sensing elements is that the reputation enjoyed by standard platinum resistance temperature sensing elements is by inference tied to industrial grade platinum resistance temperature sensing elements. With the increase in use and improved instrumentation available in the last decade, this key point has become obvious. Degussa* literature suggests that $\pm\frac{1}{2}$°C is the one year stability. A recent intercomparison of the high quality miniature standard platinum resistance temperature sensing elements has shown shifts of .2 K at 20 K, 40 mK at 30 K, 55 mK at 80 K. The DIN standard allows a ½ K stability change in one year at 0°C (this is about 1.2 K at 40 K).

The evidence has become increasingly clear that regular calibrations of platinum resistance temperature sensing elements must be performed if they are to be used to the level of their reputations.

With these considerations, advantages and disadvantages of germanium and platinum resistance temperature sensing elements to cover Type 1 applications are listed:

Advantages include:

a. Accepted secondary standards
b. Germanium is required for Type 2 and Type 3 requirements

Disadvantages include:

a. Large size with incumbent in flexibility in applications
b. Require multiple excitation currents
c. Lower signal levels
d. Lower speed of response
e. No point sensing
f. Increased cost

*Degussa Corporation, Teterboro, New Jersey 07608 is the U.S.A. distributor for the major West German PRT manufacturer of the same name.

### 3.2.3 Unit Costs for Type 1 Sensing Elements

#### 3.2.3.1 Qualification Unit Cost Estimate Includes:

a. Engineering charge of $500.00 for each encapsulation configuration.

b. $125.00 for the silicon diode temperature sensing element to be encapsulated.

c. $50.00 for assembly.

d. Calibration from 4 to 300 K: $265.00

e. Documentation Costs: $100.00

#### 3.2.3.2 Unit Cost after Qualification

a. $175.00 for encapsulated silicon diode temperature sensing element

b. $265.00 for calibration

c. $100.00 for documentation

These unit costs can be expected to escalate at approximately 5% per year assuming a reasonable national economy inflation rate.

### 3.3 Type 2 and Type 3 Temperature Sensing Element Recommendations

The germanium temperature sensing element is recommended for Type 2 and Type 3 work.

#### 3.3.1 Discussion

The germanium temperature sensing element is internationally recognized as a secondary temperature standard. Recent testing has shown that stabilities of less than ½ mK can be expected over the life of the sensing element.

There is only one exception to this statement. Considerable evidence is in the literature reporting sudden shifts in calibration. These shifts are presumed to be a result of shock and vary from ½ to as much as 10 mK at 4.2 K. Fortunately, the largest shifts have been related to only one type of construction (shown as Type C in Figure A-1. This construction is not accepted for secondary standards.

The aforementioned stability does not meet Type 2 requirements and is marginal for Type 3 requirements. It is reasonably certain that the single crystal construction currently used will not allow improvement. In addition, no other sensing element equals germanium resistance temperature sensing elements in stability.

Acceptance test procedures for germanium resistance temperature sensing elements are included in the appendices of this survey report.

### 3.4 Unit Costs for Type 2 and Type 3 Sensing Elements

#### 3.4.1 Qualification Unit Cost Estimate Includes:

a. Engineering charge of $500.00 for each encapsulation configuration.

b. $125.00 for the germanium resistance temperature sensing element to be encapsulated.

c. $50.00 for assembly.

d. Calibration from .3 to 4.2: $400.00

e. Calibration from 1.3 to 40: $195.00

f. Documentation Costs: $100.00

#### 3.4.2 Unit Cost after Qualification

a. $175.00 for encapsulated germanium temperature sensing element

b. $400.00 for calibration from .3 to 40 K

c. $195.00 for calibration from 1.3 to 40 K

d. $100.00 for documentation

These unit costs can be expected to escalate at approximately 5% per year assuming a reasonable national economy inflation rate.

## 4. Requirements for Cryogenic Temperature Detector Signal Conditioners

### 4.1 General

From the requirements for temperature detector elements set forth in Figures 1, 2, and 3, and the output signal characteristics of recommended Type 1, 2, and 3 temperature detectors, we arrive at specific input specifications for the signal conditioners.

Beyond the input characteristics dictated by the recommended temperature detectors, consideration is given to the output characteristics desired and the requirement that the output signal be compatible with standard spacecraft telemetering systems. The desired output signal is the BCD equivalent of temperature in the form of one or two 8 bit words.

Other design criteria which must be considered in the development phase of the program shall include:

(1) Minimum size and weight

(2) Minimum power consumption

(3) Continuous long term operation (minimum lifetime approximately 5 years)

(4) Radiation resistance ($10^6$ Rads)

(5) Differential temperature measurement capability

### 4.2 Signal Conditioner for Type 1 Temperature Detector Element

The signal conditioner for use with Type 1 temperature detector elements must have an output accuracy versus temperature characteristic set forth in Figure 1 when interfacing with a Type 1 detector element.

#### 4.2.1 Discussion

Due to the dV/dT versus T characteristics of the Type 1 detector elements (silicon diodes) and the accuracy versus temperature requirements, two critical points exist which shall determine the minimum input voltage sensitivity and accuracy requirements for the Type 1 signal conditioner.

The two critical points are at 6 kelvin, where the diode sensitivity is approximately 55 mV/K, requiring a .009 K temperature accuracy; and at 40 kelvin, where diode sensitivity is approximately 2.45 mV/K, requiring a 0.1 K accuracy.

At 6 kelvin, a voltage resolution of 0.52 millivolts is required and at 40 kelvin, the resolution must be 0.25 millivolts. With the diode output levels of 2.35 volts at 4.2 kelvin and 1.07 volts at 40 kelvin, the signal conditioner must resolve 0.13 mV out of 2.36 volts and .06 mV out of 1.07 volts at 4.2 kelvin and 40 kelvin, respectively.

In determining the signal conditioner input resolution, a factor of four has been used to account for system induced errors.

Constant current excitation is required for Type 1 detectors with the optimum excitation level being 10 microamperes. Due to the true diode characteristics of Type 1 detectors, the accuracy and stability requirements for the current source are relaxed over that required for resistive type detectors. To achieve the required accuracy, current source stability of 0.05% is required.

To meet the above objectives, the signal conditioner must interface with the temperature detector element via a four lead connection. Constant current excitation of the detector will be supplied on one wire pair and the voltage output signal will be sensed on the second pair.

The input impedance of the signal conditioner must be high (1000 megohms or greater) and shall be accomplished by using an input amplifier stage with a gain of approximately 2. The input amplifier shall serve two additional purposes. First, it will provide input/output and power isolation of the detector from the rest of the system. Secondly, it will provide sufficient gain to input the signal to a state-of-the-art analog-to-digital converter of sufficient resolution and accuracy to maintain system goals.

The digitized signal can then be processed by a microprocessor to produce a BCD output equivalent to temperature. The RCA CMOS unit and Texas Instrument $I^2L$ unit, both MIL-SPEC versions, are currently being flight qualified and should be considered for this application.

To achieve the desired accuracy and resolution, it will be necessary to store calibration data for the specific detector in the signal conditioner. This will be done by programming a PROM from the actual detector calibration.

The output signal generated by the microprocessor will be stored as two 8 bit words unit addressed by the craft telemetering system.

The required accuracy and necessary data handling will limit the cycle time to between 10 and 20 readings per second using current state-of-the-art electronics.

Power requirements are estimated to be 50-100 milliamperes at 28 volts d.c.

It is expected that the signal conditioner can be designed so that the complete package will be approximately 1½ inches by 2½ inches by 4 inches and weigh approximately 12 ounces.

### 4.2.2 Options to be Considered

#### 4.2.2.1 Multiple Input Signal Conditioner

The signal conditioner described in Section 4.2.1 is ideally suited for experiments requiring only a single point measurement. However, it is not considered likely that many experiments will require only one temperature measurement point.

The incorporation of more than two or three single channel signal conditioners will in many cases be prohibitive in size, weight, and cost, particularly in satellite born experiments.

It is therefore important to consider signal conditioners capable of handling as many as ten separate Type 1 detector inputs.

In the multichanneled version of a Type 1 signal conditioner, much of the circuitry can be shared with all inputs. Required additions to the signal conditioner described in Section 4.2.1 will include:

(1) An input multiplexer circuit

(2) Additional PROM's to store individual detector calibration data

(3) Additional output signal storage

(4) Additional internal programming to properly sequence input selection, linearization and output storage.

With current state-of-the-art electronics, it should be possible to build a ten channel signal conditioner with only a very small sacrifice in package size, weight, and power consumption, while still maintaining high system accuracy.

Depending on how the multiple inputs are handled, it may be possible to vary the bandwidth of individual channels and thus allow one to achieve very high temperature resolution over a narrow temperature span.

The biggest disadvantage of a multichannel signal conditioner will be the necessary reduction in sample rate. This reduction in sample rate is due to the finite time necessary to perform the relatively complex calculations in the microprocessor required to linearize the detector output with high precision. For a ten channel signal conditioner, the sample rate will be one-tenth the rate for a single channel unit or one to two readings per second.

### 4.3 Signal Conditioner for Type 2 and Type 3 Temperature Detector Elements

The signal conditioner for use with Type 2 and Type 3 temperature detectors must have accuracy versus temperature characteristics as set forth in Figures 2 and 3, respectively.

### 4.3.1 Discussion

Signal conditioners for use with Type 2 and Type 3 detector elements will be quite similar to the signal conditioner required for Type 1 detectors with three significant differences. These differences are:

(1) Lower D.C. current source excitation level - one microampere as opposed to 10 microamperes for Type 1 detectors.

(2) Signal conditioners for Type 2 and Type 3 detectors will require higher current source stability, at least .025% stability.

(3) Input voltage sensitivity must be significantly higher. .1 microvolts in the worst case versus 60 microvolts worst case for Type 1 detectors.

The above differences apply primarily to signal conditioners for Type 2 detectors as the Type 2 detectors require considerably higher accuracy than Type 3 detectors. The Type 1 sensors will require a D.C. measurement and it is assumed that a D.C. measurement circuit will be used in the Type 2 signal conditioner.

Since a signal conditioner designed for Type 2 detectors more than meets the requirements for Type 3 detectors, further discussion shall be limited to signal conditioners for Type 2 detectors.

The lower current source excitation level (1 microampere) required for Type 2 detectors combined with the required current source stability (0.025%) is at best at the current state-of-the-art and considerable emphasis must be placed on this parameter in the development program. However, with semiconductor technology improving at a rapid pace, it is expected that the stringent specifications can be met in the time frame of the program.

To achieve the input voltage sensitivity required, the input amplifier gain must be approximately 200 or higher. Though an amplifier with a gain of 200 is not a problem, maintaining the necessary amplifier stability does represent an area which will require attention in the development of the signal conditioners.

As mentioned previously, the signal conditioners required for Type 2 and Type 3 detectors will be quite similar to signal conditioners for Type 1 detectors and this similarity will include the size, weight, and power requirements.

## 4.4 Development Required for Signal Conditioners

### 4.4.1 Discussion

Though no signal conditioners are currently known to exist which meet the requirements for the recommended detectors, no basic technological development work is expected to be required to meet the specifications outlined above.

It will be necessary, however, to develop a complete instrumentation package which will perform all of the necessary functions while operating in a satellite or space shuttle environment with the high degree of accuracy desired.

### 4.4.2 Basic Specifications for Signal Conditioners for Use with Type 1, Type 2, and Type 3 Detectors

#### 4.4.2.1 Comments on Listed Specifications

The specifications listed below are complete only to the extent that they specify the basic requirements for:

(1) Type of detector with which the signal conditioner must interface

(2) Output characteristics desired

(3) Realistic power requirements

(4) Realistic size and weight restrictions

Prior to initiating a full scale development program, complete specification goals or limits must be arrived at and will depend on such parameters as:

(1) Types of launch vehicles used

(2) Power supply characteristics

(3) Actual required lifetime

(4) Environmental conditions such as temperature, pressure/vacuum, radiation, etc.

(5) Compatibility with other system instrumentation

(6) Radiation resistance requirements

#### 4.4.2.2 Specifications for Type 1 Signal Conditioner (For Use with Type 1 Detectors)

Input Channels: 1 to 10

Input Voltage Range: 0.3 to 2.5 volts

Input Resolution: 0.06 millivolts

Input Impedance: 1000 megohms or greater

Detector Excitation: 10 microampere constant current

Current Source Stability: ±0.05%

Output: Serial BCD, two 8 bit words equivalent to absolute temperature in kelvin

Logical 0: -1.0 to +1.0 volts

Logical 1: +3.8 to +5.5 volts

Source Current at either logic state: -10 to +10 microamperes

Capacitive Drive Capability: 1500 picofarads

Sampling Rate: 8 bit bursts at 32.768 kbps ±1%

Data Capacity: 8 bits per read envelope, two 8 bit words per data set required

Supply Power: +28 ±2.8 volts d.c.

Supply Current: 50-100 milliamperes maximum

Size: 1½ inches by 2½ inches by 4 inches

Weight: 12 ounces

Lifetime: 5 years at rated performance

#### 4.4.2.3 Type 2 Signal Conditioner (For Use with Type 2 and Type 3 Detectors)

Input Channels: 1 to 10

Input Voltage Range: 1 to 10 millivolts

Input Resolution: 0.1 microvolts

Input Impedance: 1000 megohms or greater

Detector Excitation: 1 microampere constant current

Current Source Stability: ±0.025%

Output: Serial BCD, two 8 bit words equivalent to absolute temperature in kelvin

Logical 0: -1.0 to +1.0 volts

Logical 1: +3.8 to +6.0 volts

Source Current at either logic state: -10 to +10 microamperes

Capacitive Drive Capability: 1500 picofarads

Sampling Rate: 8 bit bursts at 32.768 kbps $\pm 1\%$

Data Capacity: 8 bits per read envelope, two 8 bit words per data set required

Supply Power: +28 $\pm 2.8$ volts d.c.

Supply Current: 50-100 milliamperes maximum

Size: $1\frac{1}{2}$ inches by $2\frac{1}{2}$ inches by 4 inches

Weight: 12 ounces

Lifetime: 5 years at rated performance

## 4.5 Development and Unit Costs for Type 1 and Type 2 Signal Conditioners

### 4.5.1 Comment

Since the Type 1 and Type 2 signal conditioners are essentially identical except for input characteristics, current source level, and current source stability, it is recommended that a single development program be undertaken. A single development program can produce both Type 1 and Type 2 signal conditioners without duplicating effort or incurring duplicate startup, testing and qualification costs. In addition, it appears likely that a single signal conditioner can be developed that satisfies both Type 1 and Type 2 requirements with possibly one to five discreet component changes to convert a dual purpose signal conditioner from Type 1 to Type 2 use or vice versa. The requirements for a Type 2 signal conditioner are more stringent than for a Type 1 signal conditioner. Therefore, a successful effort to develop and qualify a Type 2 signal conditioner essentially guarantees the development of the Type 1 unit.

The below estimated costs assume simultaneous development of Type 1 and Type 2 signal conditioners.

### 4.5.2 Development and Qualification Cost for Type 1 and Type 2 Signal Conditioners

The design and development of the dual purpose signal conditioner for use with Type 1, 2, and 3 detectors will include the delivery of:

(a) One complete single channel signal conditioner for a Type 1 detector

(b) One complete single channel signal conditioner for Type 2 and Type 3 detectors

(c) One complete ten channel signal conditioner for Type 2 and Type 3 detectors

Total estimated cost of the above: $89,000.00

### 4.5.3 Unit Cost after Qualification

(a) Single channel signal conditioner for Type 1, 2, or 3 detectors

(b) Single channel signal conditioner for Type 1, 2, or 3 detectors in 50 to 100 piece quantities: $2,800.00 per unit

(c) Ten channel signal conditioner for Type 1, 2, or 3 detectors in unit quantities: $6,900.00 per unit.

These unit costs can be expected to escalate at approximately 5% per year assuming a reasonable national economy inflation rate.

APPENDIX A

Recommended Technical Development Programs for Temperature Sensing Elements

Recommended temperature sensing elements for Type 2 and Type 3 requirements are the germanium resistance temperature sensing elements.

These elements are the most stable sensing elements available. However, it is not obvious from recent data taken at CSIRO and at other national laboratories that improvement in stability is probable utilizing current construction techniques. The methods described in Appendix C defining recommended testing will provide sensing elements with state-of-the-art stability.

Experience gained in production of germanium resistance temperature sensing elements has led to the conclusion that surface damage caused during element preparation, stress in the electrode to sensing element contact, and imperfect contacts all contribute to these instabilities.

The three principle construction methods for germanium resistance temperature sensing elements are shown in Figure A-1. These construction details are essentially identical to, or variations of, the original construction methods developed in the early 1960's. Configurations A and B are now accepted as the best available. Configuration C does not appear to be sufficiently stable because of the bar construction configuration and is not recommended.

The instabilities are of several types or apparent causes:

a. Failure to reproduce the same absolute resistance at a fixed temperature between temperature cycles in tests performed "in situ".

b. Failure to reproduce the same absolute resistance at a fixed temperature between temperature cycles when subjected to mechanical shock or vibration between temperature cycles.

c. Failure to reproduce the same absolute resistance at a fixed temperature between temperature cycles when subjected to excessive heating between temperature cycles.

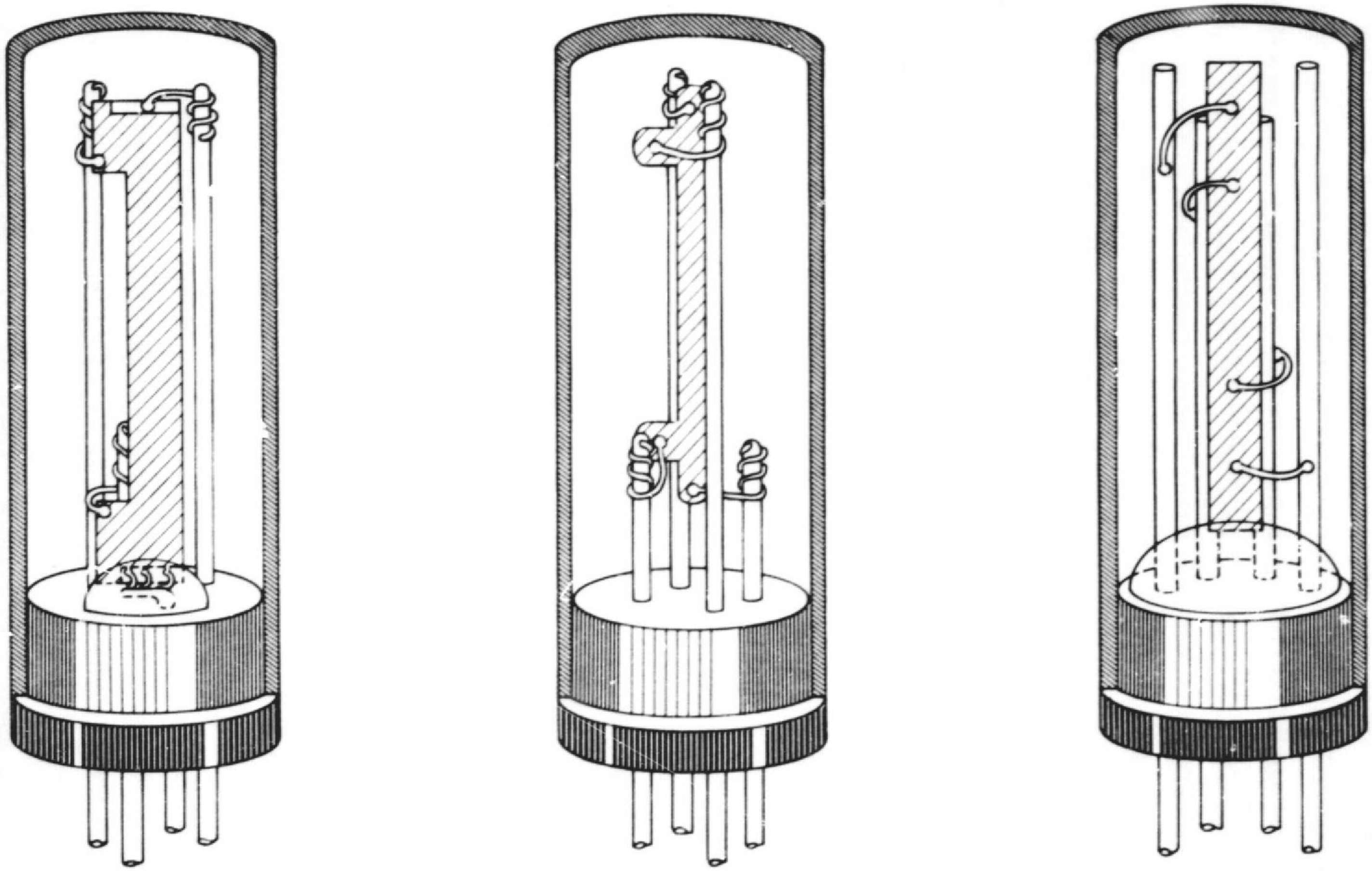
d. Failure to reproduce the same absolute resistance at a fixed temperature between temperature cycles when subjected to excessive excitation current between or during temperature cycles or during operation.

Other sources of sensing element error or failure include:

a. Complete failure of sensing element or loss of an internal contact due to shock and vibration.

b. Errors caused by nuclear radiation damage or electromagnetic radiation.

The literature does not quantify any of the above sources of instability. Efforts to improve stability by modifying size or general construction details similar to configurations A and B have failed.



Type A    Type B    Type C

FIGURE A-1: Construction details of three commercially available germanium temperature sensing elements.

Proposal Number 1

Present germanium resistance temperature sensing elements provide sufficient sensitivity and stability for the majority of space applications. This condition will continue to exist so long as the requirements of controlling a temperature with a typical precision of a millikelvin exist at temperatures below 2 kelvin and from 1 to 10 millikelvin from 2 to 4 kelvin. Absolute accuracies of less than .1% at 4 K scaling down to 1% at .1 K are also compatible with the current state-of-the-art.

Germanium resistance temperature sensing elements have been successfully utilized in prior space applications, but not to the precision and accuracies required in the future and as set forth in this study.

In order to accurately ascertain the exact operational parameters that can be expected for germanium resistance temperature sensing elements in the space environment (and after the shock and vibration received during launch), the following work statement is proposed.

(1) Select a group of at least 60 stable germanium resistance temperature sensing elements with known 4.2 K resistances and perform a launch profile of shock and vibration with 20 each mounted on the "x", "y", and "z" axis on vibration and shock machines.

The vibration and shock testing should proceed as follows:

A. Mount the 60 tested germanium resistance temperature sensing elements in a copper block designed with a liquid nitrogen cooling capability so that all vibration testing can be performed at liquid nitrogen temperatures.

B. Perform a brief functional and continuity checkout test to verify test procedures and equipment.

C. Perform selected launch vehicle profile on sensors.

D. Repeat stability testing on all sensors.

E. Perform additional vibration testing at selected critical frequency (ies) until an appropriate number fail.

F. Repeat stability testing on remaining sensors.

The stability testing outlined in this report is proposed for these measurements.

This will give the expected change in absolute resistance and can be expected to define the best accuracies that can be achieved for experiments from 1.2 K to 40 K.

(2) For experiments below 1.2 K, the above procedures should be followed for stability. However, this reduced sensitivity of the germanium resistance temperature sensing elements at 4.2 K requires that at least 50% be calibrated at the use range against a fixed primary standard SRM767, the NBS developed superconductive thermometric fixed point device.

This will define the best accuracies that can be expected between the .1 and 1.2 K use range.

Pages A-13, A-14, and A-15 are a report from Jet Propulsion Laboratory on testing performed on germanium resistance temperature sensing elements for a series of similar space applications where the requirements do not appear to have been as rigorous.

COST ESTIMATE - PROPOSAL 1

Part 1:

Item 1 - 60 each Tested germanium resistance temperature sensing elements in GR-200A-1500 and -2000 ohm configurations

$ 85.00 each = $ 5,100.00

Item 2 - Test block - design, machine, and install sensors. Fit to a NASA supplied $LN_2$ circulation system at flexible hose to block connection

2,500.00 = 2,500.00

Item 3 - Stability test after launch profile test

60 sensors at 40.00 each = 2,400.00

Item 4 - Stability test after critical frequency test

45 sensors at 40.00 each = 1,800.00

Item 5 - Estimated GFE/NASA testing = 5,000.00

Total for Part 1 = $16,800.00

Part 2:

Item 1 - 60 each Tested germanium resistance temperature sensing elements in GR-200A-100 and -250 ohm configurations

$ 106.25 each = $ 6,375.00

Item 2 - 12 Calibrations with 5 sensors each against a SRM767 at two temperatures:

Zinc at .844 K
Cadmium at .515 K

600.00 each = 7,200.00

Item 3 - Check calibrations as in Item 2 after launch profile test

12 calibrations at 600.00 each = 7,200.00

Item 4 - Estimated GFE/NASA testing = 3,000.00

Total for Part 2 = $23,775.00

Note (a) As physical construction is essentially identical, the critical frequency test is not recommended.

(b) The test block developed in Part 1 is to be used.

Optional Proposals:

1. In the construction of germanium resistance temperature sensing elements, acceptance and quality tests include stability; R at 4.2 K; R at 4.2 and 1.5 for germanium resistance temperature sensing elements with $R_{4.2}$ values of 100 ohms; and parasitic resistances (determined as the two lead resistance divided by the four lead resistance) at room temperature, 77.4 K and 4.2 K. 4.2 K parasitics over 1.5 are rejected for standard product.

   Use of germanium resistance temperature sensing elements that meet all requirements except that the parasitic resistance ratio is extended from 1.5 to 1.8 would save $25.00 per germanium resistance temperature sensing element. It is recommended that no more than 50% of the germanium resistance temperature sensing elements tested be relieved in this manner. Savings would be $25.00 each at 60 units = $1,500.00.

Proposal Number 2

Although the germanium resistance temperature sensing element has been commercially available since the early 1960's and has been accepted as a secondary standard for the .5 to 30 K temperature range, every effort to improve stability, uniformity, and reduce size have been unsuccessful.

The work in Proposal Number 1 is expected to determine, for the first time, the absolute accuracy that can be expected in the space environment. However, it is apparent that this data will not meet the requirements of the future, particularly below 4.2 K.

In the early 1960's, a series of investigations were started to develop diffused germanium resistors. The experiments were not successful at that time and the work was stopped.

Subsequent to this time, the state-of-the-art of semiconductor technology has dramatically advanced. Recent efforts toward the use of microcircuit techniques for thermometers have shown real promise. It is now believed that with state-of-the-art techniques, this approach will generate a successful, improved germanium resistance temperature sensing element. Diffused germanium resistance temperature sensing elements should allow better control over the R versus T characteristic as well as better uniformity and stability.

Preliminary investigations performed by Lake Shore Cryotronics in 1977 made considerable progress. A well organized and thought out program should lead to success in meeting the goals of small size, potentially greater uniformity, and increased stability.

It would appear at first glance that a resistor made by a sheet diffusion would have to have an unmanageable geometry to have the same resistance at 4.2 K as that of a bulk device with the same doping. However, a diffused device consists of an infinite number of resistors with different degrees of compensation in parallel. Therefore, it is possible to make a diffused resistor with a favorable geometry in which the different layers compliment each other to yield the proper resistance versus temperature curve. Blakemore, Herder, and Olson demonstrated this fact experimentally in the mid 1960's by producing diffused Ge resistors which reproduced the resistivity-temperature characteristic of the uniformly doped material very closely, as shown in Figure A-2.

There were problems, however, with the reproducibility of both the resistivity from diffusion to diffusion (10 to 100 ohms per square) and of device resistance with repeated temperature cycling (±0.005 K). A hydrogen stream flowing over a metallic arsenic source was used in these diffusions, a process with an inherently low degree of control. They also used a straight bar geometry with four doped gold wires bonded to the bar along the long axis without any other processing.

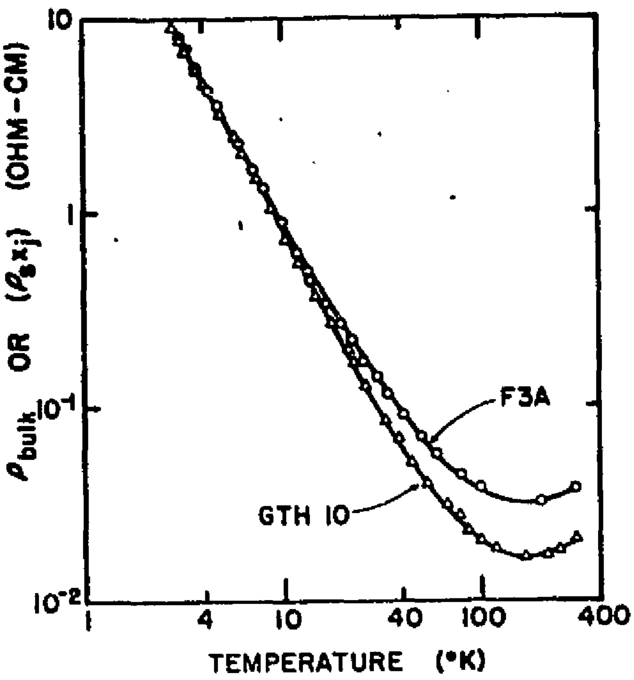



FIGURE A-2: Temperature Dependence of Resistivity for Arsenic-Doped Germanium. F3A is a diffused resistor and GTH 10 is a uniformly diffused bulk device.

We now know that, even with uniformly doped bulk resistors, this method of contacting does not produce stable thermometers. Another problem was that the critical concentrations of impurities occurred right at the surface in these devices, with a high probability of surface related problems. Finally, the technology current at the time could not prevent the appearance of better than $10^{15}$ $cm^{-3}$ of copper atoms in the resistors, with unknown effects on the resistivity and noise characteristics.

We believe that planar technology for non-silicon semiconductors has reached the stage that significant improvements can be obtained over the diffused thermometers made by Blakemore, et al. We have made some test diffusions of arsenic into germanium wafers using new commercially available solid sources. These sources give uniformity of resistivity of better than $\pm5\%$ across a wafer surface and from diffusion to diffusion. The resistivities obtained have been in the range desired for good thermometry. We have progressed to the point of overcoming the tendency of the arsenic from these sources to aglomerate, causing surface pits during diffusion and subsequent etching steps. This is demonstrated in Figure A-3. Figure A-3(a) shows a mesa resistor almost obliterated by etch pits. In Figure A-3(b), it is obvious that the resistor itself is undamaged, with the etch pits confined to the background, from which the resistor is junction-isolated. These etch pits are probably due to dislocations present in the crystal before diffusion.

The resistors from the diffusion shown in Figure A-3(b) were contacted by the techniques used for bulk resistors and had the typical resistances listed in Table I. This data indicates that the planar resistors have more sensitivity at higher temperatures than presently available sensors, a very favorable result. It is expected that when planar technology is extended to the contacts also, the stability of the final planar devices will greatly exceed the $\pm0.01$ K (at 4.2 K) obtained using bulk contact technology.

Table I: Comparison of Typical Resistances of Planar and Bulk Resistors

| | Bulk | Planar Diffused |
|---|---|---|
| 300 K | 3 ohms | 20 ohms |
| 77 K | 5 ohms | 70 ohms |
| 4.2 K | 1000 ohms | 1000 ohms |

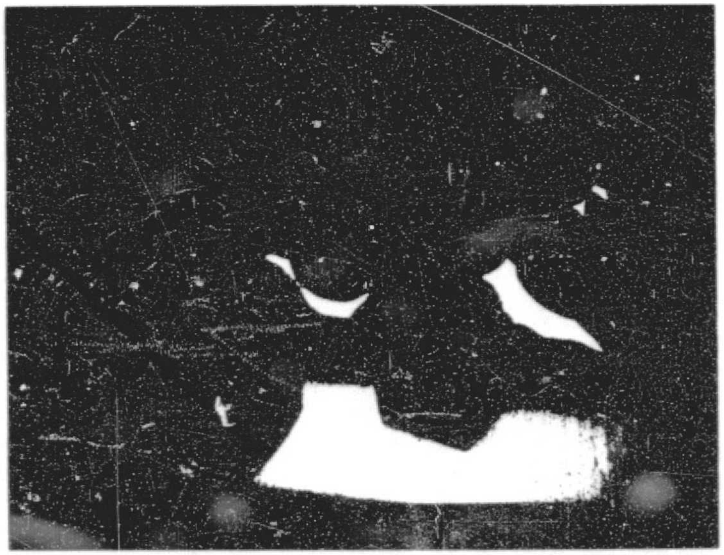


FIGURE A-3(a): A mesa resistor destroyed by etch pits.

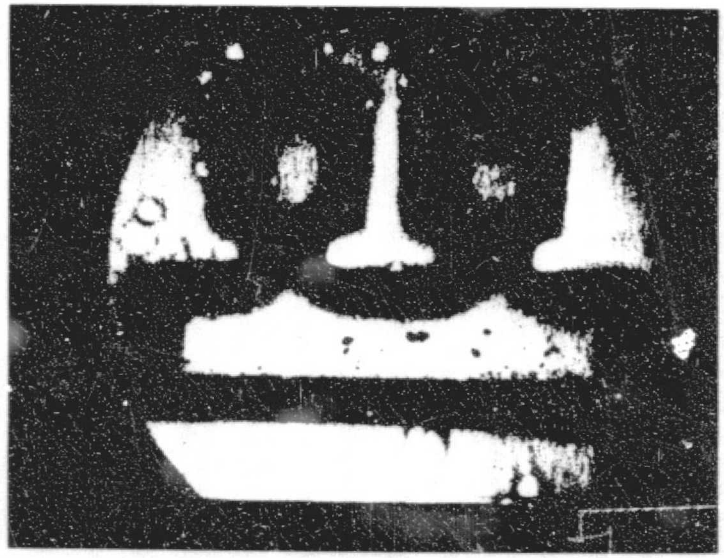


FIGURE A-3(b): A later resistor free of major defects. The long dimension is about 0.035 inches. The current contacts will be at either end of the bar with the voltage contacts on the side-arms. The equivalent length of a bulk device would be about 0.170 inches.

We propose to continue this work with the following objectives:

1. Develop low resistance, ohmic contacts to the diffused arsenic layer to obtain parasitic resistances of less than 50% of the four lead resistance.

2. Bury the arsenic layer by a second diffusion of the acceptor impurity. This should enhance stability, as will step 1 above.

3. Develop packaging and mounting techniques to enhance stability and reliability.

4. Increase control of the doping processes in order to provide thermometers with specific sensitivities at given temperatures to satisfy a wide range of systems and applications.

5. Carry out testing procedures as detailed in the cost statement.

COST ESTIMATE - PROPOSAL 2

Part 1:

Demonstrate pertinent functions and characteristics. Perform bread-board testing in relevant laboratory environment.

| | | |
|---|---|---|
| (a) | Sensing element manufacture | $30,000.00 |
| (b) | Encapsulation and testing | 8,000.00 |

Part 2:

Model test in an aircraft/spacecraft environment.

| | | |
|---|---|---|
| (a) | Provide 60 packaged sensing elements | 5,000.00 |
| (b) | Estimated GFE/NASA testing | 5,000.00 |
| (c) | Stability test after GFE/NASA testing | 2,400.00 |

# Germanium Resistor Thermometers Used in Space Environment (Rocket, Zero-G Aircraft)

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Encapsulated germanium resistor thermometers (GRT) were used by JPL in an aerospace environment in an experimental superfluid cryostat aboard a ten minute sounding rocket flight launched in May 1976 (JPL, LASL, GSFC, Sandia Lab). The same package was flown on zero-G aircraft flights in March 1976, providing 45 periods of zero gravity lasting about 20 seconds each. In addition, we utilized unencapsulated GRT's in the zero-G aircraft facility in 1977 and 1978 in a small superfluid cryostat in supporting studies for IRAS (Infrared Astronomy Satellite).

## 1. Description of GRT

The GRT's were manufactured by CryoCal, Inc. In the rocket test we used the types CR 1000. The single crystal bar of balanced-dopant germanium is supported by four gold leads connected in a strain-free manner to a platinum-glass hermetic seal. The sensing element is encapsulated within a gold-plated can with helium gas for heat transfer. The diameter of the assembly is 0.124", length 0.435". Outside electrical leads are 32 gauge copper leads with colored teflon for lead identification. Four wire potentiometric measurements give resistance of the order of 8 ohms at room temperature and ~1000 ohms at 4.2 K (liquid helium). The calibration reference is based on helium vapor pressure scale with an accuracy of 3 mK. The accuracy of the resistance measurement is within 0.1%.

Exposed germanium elements, Type CR-1000, were also used with various stress free mountings.

## 2. Description of the Rocket Cryostat

The Rocket payload included a ruggedly-built superfluid cryostat (built by LASL) with guarded shields cooled by vessels of helium at 4.2 K and liquid nitrogen (77 K). The superfluid vessel has a volume of about eight liters with an insert (provided by JPL) carrying three smaller experimental volumes. Two encapsulated GRT's were potted in the grooves at two different parts of this insert. In addition to GRT there were other types of thermometers and sensors aboard (liquid-vapor sensors, carbon film thermometers, thermistors).

### 3. Description of Vibration Test Environment

Vibrational test environment consisted of sinusoidal and random vibrations. Z-axis was along the GRT sensors. The details of these tests are presented in the Appendix. The g levels measured during the launch of the rocket fall within the tested values. The GRT performance was within calibration precision after about 30 thermal cycles between room temperature and liquid helium.

### 4. Description of Performance of Temperature Sensors During End of Shake

The vibrational testing of the sensors and accompanying electronics was done separately. The electronics package included resistors which simulated the GRT values. We were interested in the calibration before and after the tests and, in particular, the mechanical integrity of the experimental units in which GRT were built. We have not detected calibration changes of the GRT thermometers.

In a small stainless steel cryostat with windows for visual access for experiments in zero-G aircraft, we used exposed germanium elements which were mounted stress-free on the gold leads 0.002" diameter. The calibration was performed in-house and the sensors were found to be very rugged once installed.

### 5. Readout Instrumentation During the Rocket Flight

The GRT were fed with constant current. The voltage difference in mV range was amplified to the voltage levels required for the multichannel telemetry. Additional voltage offset capability brought the amplified response of the thermometers between 2.2 K and 1.5 K within the range of the telemetry, which was between 0.5 volts to 5 volts. The average readout sensitivity dV/dT for the desired temperature interval between 1.7 K and 2.2 K was 5mV/mK. This sensitivity gives 5 to 10 mK accuracy.

### Conclusions:

GRT sensors appear suitable for the aerospace environment. Specific applications of the bare exposed elements do require testing of the sensor mounting and extreme care in appropriate calibration procedures in transfer to the specific environmental conditions. Stability and sensitivity of the processing electronics must be appropriate in each specific case to satisfy the accuracy requirement.

## Environmental Vibrational Tests Performed at JPL

TABLE I

Sinusoidal Vibration

| | QUAL | | FA |
|---|---|---|---|
| Sweep Rate | 2 octaves/minute | | 4 octaves/minute |
| Z Axis levels | 4.5 in/second | 10 - 144 Hz | 3.0 in/second |
| | 10.5 gpk | 144 - 2000 Hz | 7.0 gpk |
| X Axis levels | 4.5 in/second | 10 - 35 Hz | 3.0 in/second |
| | 10.5 gpk | 35 - 105 Hz | 7.0 gpk |
| | 7.5 gpk | 105 - 2000 Hz | 5.0 gpk |

TABLE II

Random Vibration

| | QUAL | | FA |
|---|---|---|---|
| Duration | 40 seconds/axis | | 20 seconds/axis |
| Z Axis levels | .113 $g^2$/Hz | 25 - 2000 Hz | 0.05 $g^2$/Hz |
| X Axis levels | | 25 - 2000 Hz | 0.03 $g^2$/Hz |
| Wideband level | | | |
| Z Axis | 15.0 GRMS | | 10.0 GRMS |
| X Axis | | | 7.6 GRMS |

The final run was performed with Qual random excitation. For this case, the unit was chilled with $LN_2$ just prior to actual shake.

Z-axes is

along the axes of the germanium thermometer

Environmental Test Equipment
60 KVA System/C126 and L335 Exciters

APPENDIX B

Performance and Testing Acceptance Specification: Silicon Diode Temperature Sensing Element

1. Ratings:
   A. Recommended Operating Current: 10 uA dc
   B. Operating Temperature Range: 1 to 400 K
   C. Storage Temperature Range: 1 to 400 K

2. Weight: Determined and specified by configuration.

3. Encapsulation Material:
   A. Determined and specified by configuration
   B. Thermowells will be mass-spectrometer leak tested when required.

4. Inspection Lot: An inspection lot is a collection of units of the product from which a sample is drawn and inspected to determine compliance with the specified acceptance criteria.

   A. Lot Characteristics: Each inspection lot shall consist of devices whose diode chips are from the same wafer.

   B. Lot Identification: Lot identification shall be maintained from the time the lot is assembled to the time it is accepted.

   C. Wafer Selection: The following evaluation will be conducted on each wafer candidate (The supplier shall not be limited to this evaluation and may conduct any other evaluation deemed necessary or beneficial in selection of wafers for use in high reliability applications).

      Twenty chips from the wafer candidate shall be assembled into a standard TO-46 package. The packaged devices shall then be subjected to the supplier's standard calibration procedure including approximately 100 calibration points between 1.5 K and 380 K. The minimum, maximum, and mean value of $V_f$ at each calibration temperature shall be summarized and compared to the forward voltage versus temperature characteristic curve shown in Figure 2 herein. The supplier shall select wafers which exhibit compliance to this characteristic curve.

5. Forward Voltage ($V_f$) versus Temperature Characteristic: Sensing element supplied shall meet the requirements specified in Figure B-1 (at $I_f$ = 10 uA) within the following limits of accuracy.

| Temperature (K) | $V_f$ Range (VDC) |
|---|---|
| 4.2 | 2.1 to 2.5 |
| 77 | 0.979 to 0.989 |
| 296 | 0.365 to 0.385 |

6. Calibration Measurements: Calibration measurements shall be made in accordance with the following requirements:

   A. The parameter used for calibration shall be the forward voltage, $V_f$, at a forward current, $I_f$, of 10 uA.

   B. Calibration measurements shall be made employing good measurement and instrumentation techniques including:

      (1) A four-wire potentiometric circuit.

      (2) Stabilization at calibration temperature.

      (3) Stabilization at calibration current and using a regulated current supply.

      (4) The use of secondary standards.

   C. All calibration measurements shall be made to a precision of $\pm 0.01$ K with respect to standards traceable to the National Bureau of Standards or the National Physical Laboratory. The accuracy of calibration measurements shall be $\pm 0.005$ K at 4.2 K and $\pm 0.02$ K at 77 K at the fixed points of LHe and $LN_2$, respectively.

   D. Specific temperature points for calibration measurements shall be selected by the manufacturer. The calibration measurement data printouts supplied by the manufacturer may show temperatures above 5 K in whole degrees and in tenths of a degree for temperatures below 5 K rather than the actual temperatures obtained at each point during calibration measurements, as long as the required specified accuracy is obtained.

7. Marking: Sensing elements shall be individually packaged and each package marked with the following information:

   A. Procurement Reference Number
   B. Date/Code Traceable to the Wafer
   C. Manufacturer's Code Identification Number followed by a dash and the Manufacturer's Part Number
   D. Serial Number

8. Data Submittal: The following data shall be supplied with each device:

   A. The data obtained during wafer selection (See Note 4C).

   B. The calibration measurement data obtained during calibration measurements (See Note 6D).

   C. Calibration data of individual devices (See Note 9D).

   All data shall contain the serial number of the device when applicable.

9. Quality Conformance Inspection: The manufacturer shall perform the following examinations and tests prior to shipment of the devices. Failed devices shall not be shipped.

A. Dimensions: Each device shall be examined to verify conformance to specified configuration.

B. Hermeticity: Each device shall be stabilized in air at room ambient temperature and then immersed in liquid nitrogen for 30 seconds minimum. The devices shall then be removed from the liquid nitrogen and immediately immersed in alcohol maintained at room ambient temperature. Devices that emit bubbles shall be rejected.

C. Thermal Shock: Each device shall be stabilized in air at room ambient temperature and then subjected to ten cycles of thermal shock, with a cycle being conducted as follows: Immerse the device in liquid nitrogen for 10 seconds minimum. Remove the device and immediately immerse it in liquid helium for 30 seconds minimum. Remove the device and place it under room ambient conditions for 10 minutes minimum. Supplementary heat may be used to bring sensing element to room temperature and reduce 10 minute warmup time. This completes one cycle. During each cycle, measure $V_f$ at $I_f$ = 10 uA while the device is immersed in liquid helium. Devices exhibiting excessive drift shall be rejected.

D. Calibration of Individual Sensing Elements: All sensing elements shall have been calibrated as follows:

Two devices from the line item quantity shall be calibrated over the temperature range with at least the minimum number of calibration points specified below:

| Temperature Range (K) | Minimum Number of Calibration Points | Accuracy (K) |
|---|---|---|
| 4 to 350 | 100 | ±.01 |
| 4 to 77 | 50 | ±.01 |
| 77 to 350 | 35 | ±.1 |
| 77 to 350 | 4 (Suggested temperatures are 77, 200, 273, 350 K) | ±1.0 |

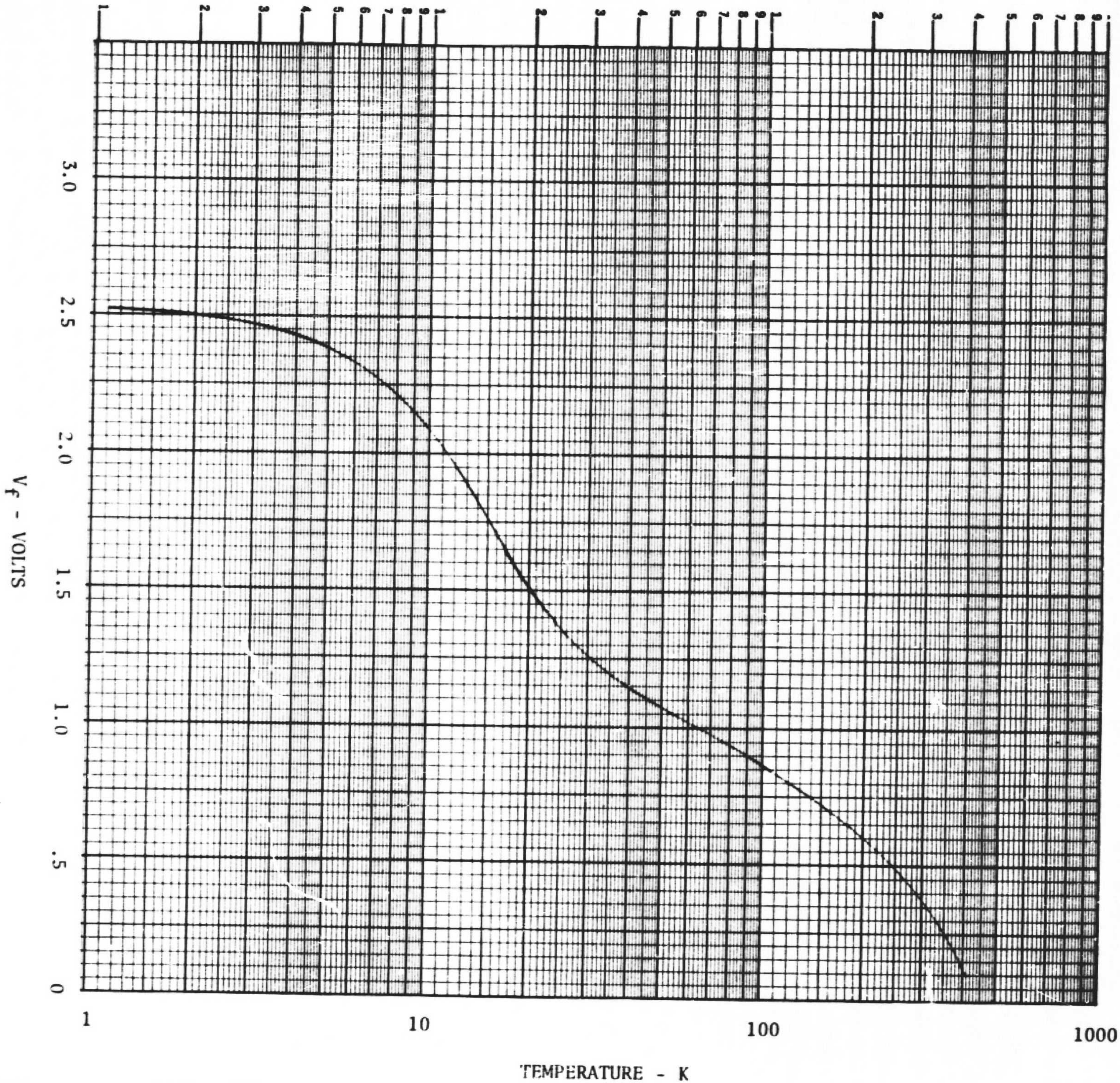


FIGURE B-1

APPENDIX C

Performance and Testing Acceptance Specification: Germanium Resistor Temperature Sensing Element

1. Ratings:
   A. Recommended Signal Voltage: 1 to 10 mV dc
   B. Operating Temperature Range: .1 to 35 K
   C. Storage Temperature Range: .1 to 400 K

2. Weight: Determined and specified by configuration.

3. Encapsulation Material:
   A. Determined and specified by configuration
   B. Thermowells will be mass-spectrometer leak tested when required.

4. Inspection Lot: An inspection lot is a collection of units of the product from which a sample is drawn and inspected to determine compliance with the specified acceptance criteria.

   A. Lot Characteristics: Each inspection lot shall consist of devices whose sensing elements are from the same crystal.

   B. Lot Identification: Lot identification shall be maintained from the time the lot is assembled to the time it is accepted.

   C. Crystal Selection: The following evaluation will be conducted on each crystal candidate (The supplier shall not be limited to this evaluation and may conduct any other evaluation deemed necessary or beneficial in selection of crystals for use in high reliability applications).

      Twenty sensing elements from the crystal candidate shall be assembled into a standard package. The packaged devices shall then be subjected to the supplier's standard calibration procedure including approximately 50 calibration points between 1.5 K and 100 K. The minimum, maximum, and mean value of R at each calibration temperature shall be summarized and compared to the resistance versus temperature characteristic curve shown in Figure C-1 herein. The supplier shall select crystals which exhibit compliance to this characteristic curve.

5. Resistance (R) versus Temperature Characteristic: Sensing element supplied shall meet the requirements specified in Figure C-1 within the limits of accuracy of $\pm 20\%$. Germanium resistance temperature sensing element's maximum R at low end of use range should not exceed 25,000 ohms below 1.2 K and 15,000 ohms above 1.2 K.

6. Parasitic Resistance: Sensing element will have a two lead resistance (measured through the current leads) which will be less than 1.5 times the four lead resistance. This insures minimum heating of the thermometer.

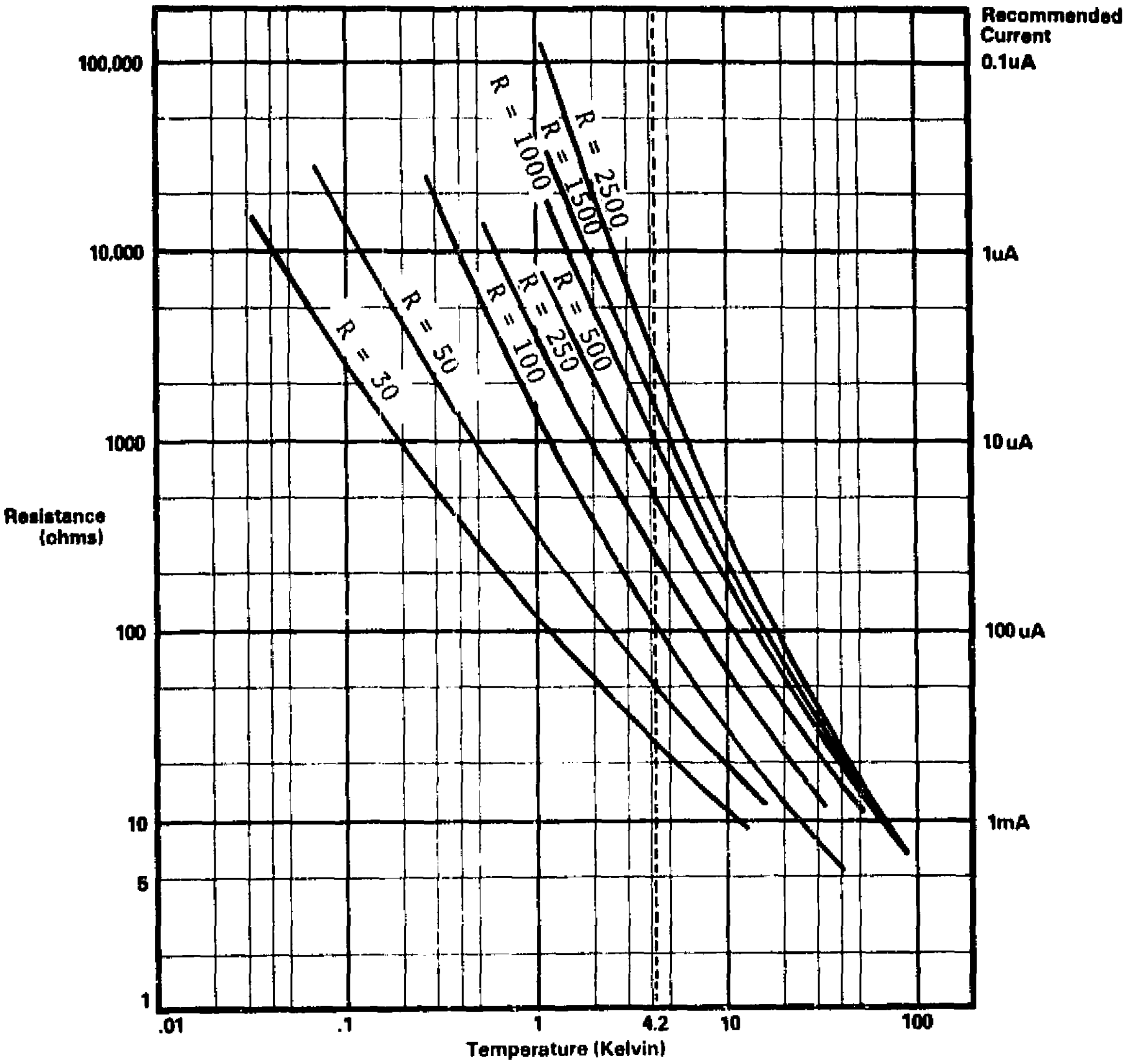


FIGURE C-1: Typical R versus T for Germanium Resistance Temperature Sensing Element

7. Calibration Measurements: Calibration measurements shall be made in accordance with the following requirements:

   A. The parameter used for calibration shall be the resistance, R, at a current, I, that will give a signal voltage of 1 to 10 mV.

   B. Calibration measurements shall be made employing good measurement and instrumentation techniques including:

      (1) A four-wire potentiometric circuit.

      (2) Stabilization at calibration temperature.

      (3) Stabilization at calibration current and using a regulated current supply.

      (4) The use of secondary standards.

   C. All calibration measurements shall be made to a precision of $\pm 0.005$ K with respect to standards traceable to the National Bureau of Standards or the National Physical Laboratory. The accuracy of calibration measurements shall be $\pm 0.005$ K at 4.2 K and $\pm 0.01$ K at 77 K at the fixed points of LHe and $LN_2$, respectively. Accuracy of calibration shall be 1% between .1 and .5 K.

   D. Specific temperature points for calibration measurements shall be selected by the manufacturer. The calibration measurement data printouts supplied by the manufacturer may show temperatures above 5 K in whole degrees and in tenths of a degree for temperatures below 5 K rather than the actual temperatures obtained at each point during calibration measurements, as long as the required specified accuracy is obtained.

8. Marking: Sensing elements shall be individually packaged and each package marked with the following information:

   A. Procurement Reference Number
   B. Date/Code Traceable to the Crystal
   C. Manufacturer's Code Identification Number followed by a dash and the Manufacturer's Part Number
   D. Serial Number

9. Data Submittal: The following data shall be supplied with each device.

   A. The data obtained during crystal selection (See Note 4C).

   B. The calibration measurement data obtained during calibration measurements (See Note 6D).

   C. Calibration data of individual devices (See Note 9D).

   All data shall contain the serial number of the device when applicable.

10. Quality Conformance Inspection: The manufacturer shall perform the following examinations and tests prior to shipment of the devices. Failed devices shall not be shipped.

A. Dimensions: Each device shall be examined to verify conformance to specified configuration.

B. Hermeticity: Each device shall be stabilized in air at room ambient temperature and then immersed in liquid nitrogen for 30 seconds minimum. The devices shall then be removed from the liquid nitrogen and immediately immersed in alcohol maintained at room ambient temperature. Devices that emit bubbles shall be rejected.

C. Thermal Shock: Each device shall be stabilized in air at room ambient temperature and then subjected to ten cycles of thermal shock, with a cycle being conducted as follows: Immerse it in liquid helium for 30 seconds minimum. Remove the device and place it under room ambient conditions for 10 minutes minimum. Supplementary heat may be used to bring sensing element to room temperature and reduce 10 minute warmup time. This completes one cycle. During each cycle, measure R at I as specified in 6C while the device is immersed in liquid helium. Devices exhibiting drift in excess of $\pm\frac{1}{2}$ mK shall be rejected.

D. Calibration of Individual Sensing Elements: All sensing elements shall have been calibrated as follows:

Two devices from the line item quantity shall be calibrated over the temperature ranges with at least the minimum number of calibration points specified below:

| Temperature Range (K) | Minimum Number of Calibration Points | Precision (K) |
|---|---|---|
| 4 to 77 | 50 | $\pm.05$ |
| 1.2 to 4.2 | 16 | $\pm.05$ |
| .3 to 1.2 | 10 | See 6C |
| .1 to .3 | 4 | See 6C |

APPENDIX D

## Bibliography

The bibliography includes most of the more important cryogenic instrumentation references published over the last two decades.

The first approximately 200 references were predominately published after 1969 and references #200 and after prior to 1970.

To facilitate ready reference to the many categories of cryogenic instrumentation, a table of specific (and arbitrary) categories by reference numbers follows these paragraphs. Because subject overlapping occurs in almost every reference, only the principle category is listed. To facilitate cross referencing, the titles of the first section have been included.

Very few references are listed for temperatures below 1 K. This rather sharp line of temperature demarcation was chosen as a result of the availability through recent and very complete reviews on this category.

Germanium: 1-14, 229-245

Metallic Resistance Thermometers including Platinum: 34-42, 82-91, 204-228

Junction Devices including Silicon, GaAs, Germanium: 43-52, 178-181, 273-281

Other Semiconductors including Carbon Glass, Silicon, GaSb, and GaAs: 64-67, 271, 272

Carbon and Carbon Film: 15-33, 246-270

Electronic including Capacitance: 53-63

Thermocouples: 69-81, 287-307

Vapor Pressure, Gas Thermometry, and Fixed Points: 96-121, 232, 308-327

Thermometry below 1 K: 93-95, 186, 188, 235-237

Measurement in Magnetic Fields: 34, 49, 54, 59, 66, 72, 75, 78, 81, 82, 85, 167, 186, 187

Instrumentation and Techniques: 68, 122-130, 142-177, 183, 189, 386-438

Interpolation Techniques: 1-5, 9-13, 16, 27-28, 30, 33, See Platinum References, 97, 186, 219, 233, 240-243

Temperature Scales and Reviews: 92, 131-141, 184, 185, 201-203, 334, 345

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