PB 175 622

ON THE PROBLEMS OF MEASURING TRANSIENT TEMPERATURE IN CRYOGENIC FLUIDS

C. E. Miller, et al

National Bureau of Standards
Boulder, Colorado

April 1967

NASA ORDER R-45

FACILITY FORM 602

N68-16729
(ACCESSION NUMBER)

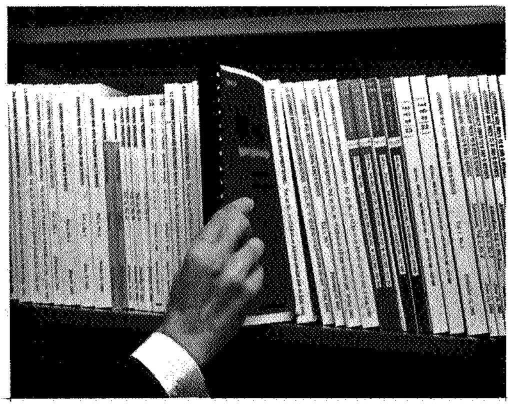
6
(PAGES)

CR#92741
(NASA CR OR TMX OR AD NUMBER)

(THRU)

1
(CODE)

23
(CATEGORY)



REPORT selection aids

Pinpointing R & D reports for industry

Clearinghouse, Springfield, Va. 22151

U.S. GOVERNMENT RESEARCH AND DEVELOPMENT REPORTS (USGRDR)—SEMI-MONTHLY JOURNAL ANNOUNCING R&D REPORTS. ANNUAL SUBSCRIPTION $30.00 ($37.50 FOREIGN MAILING). SINGLE COPY $3.00.

GOVERNMENT-WIDE INDEX—SEMI-MONTHLY INDEX TO U.S. GOVERNMENT RESEARCH AND DEVELOPMENT REPORTS. ANNUAL SUBSCRIPTION $22.00 ($27.50 FOREIGN MAILING). SINGLE COPY $3.00.

FAST ANNOUNCEMENT SERVICE—SUMMARIES OF SELECTED R&D REPORTS COMPILED AND MAILED BY SUBJECT CATEGORIES, $5.00 ANNUAL SUBSCRIPTION. WRITE FOR AN APPLICATION FORM.

DOCUMENT PRICES—ALMOST ALL OF THE DOCUMENTS IN THE CLEARINGHOUSE COLLECTION ARE PRICED AT $3.00 FOR PAPER COPIES AND 65 CENTS FOR COPIES IN MICROFICHE.

COUPONS—THE CLEARINGHOUSE PREPAID DOCUMENT COUPON SALES SYSTEM FOR PURCHASING PAPER COPIES AND MICROFICHE PROVIDES FASTER, MORE EFFICIENT SERVICE ON DOCUMENT REQUESTS. THE PREPAID COUPON IS A TABULATING CARD WITH A FACE VALUE OF THE PURCHASE PRICE OF A CLEARINGHOUSE DOCUMENT ($3.00 PAPER COPY OR 65 CENTS MICROFICHE). IT IS YOUR METHOD OF PAYMENT, ORDER FORM, SHIPPING LABEL, AND RECEIPT OF SALE.

THE USE OF THE CLEARINGHOUSE COUPON IS PREFERRED FOR ALL DOCUMENT REQUESTS. WHEN THE COUPON IS NOT USED, PREPAYMENT IS REQUIRED BY CHECK OR MONEY ORDER MADE PAYABLE TO THE CLEARINGHOUSE UNLESS PURCHASES ARE TO BE CHARGED TO CLEARINGHOUSE DEPOSIT ACCOUNTS.

COUPONS FOR PAPER COPY (HC) DOCUMENTS ARE AVAILABLE AT $3.00 EACH OR IN BOOKS OF 10 COUPONS FOR $30.00. COUPONS FOR MICROFICHE COPIES OF CLEARINGHOUSE DOCUMENTS ARE AVAILABLE IN BOOKS OF 50 COUPONS FOR $32.50. WRITE FOR A COUPON ORDER FORM.

ISA TRANSACTIONS: 6 (133-138) 1967

On the Problems of Measuring Transient Temperature in Cryogenic Fluids*

C. E. MILLER†
and
T. M. FLYNN‡
National Bureau of Standards
Boulder, Colorado

The complex and frequently unpredictable energy exchange mechanisms that govern the dynamic behavior of cryogenic sensors make the measurement of transient temperatures extremely difficult. Without suitable models by which to predict and evaluate sensor performance, considerable measurement errors can and do occur. The intent of this paper is simply to delineate in detail those factors which give rise to these errors. The validity of using notions based on the performance of the "ideal" thermometer for characterizing the cryogenic case is also discussed.

INTRODUCTION

The need to make precise temperature measurements in cryogenic systems has produced significant advances in cryogenic thermometry. Commercial cryogenic thermometers are available which are capable, under carefully controlled conditions, of precisions greater than ±0.05°K. It is common knowledge, however, that such precisions can only be realized under static or quasistatic conditions. When thermometers are forced to respond to rapid temperature fluctuations, such as occur in the cooldown of cryogenic transfer lines, the indicated temperature may depart significantly from the "true" temperature. Clearly, the loss in the validity of the measurement does not reflect a degradation in the accuracy of the temperature sensor, but rather indicates that the temperature of the sensor is not at all times the same as that of the surroundings.

An assessment of the validity of temperature measurements made under transient conditions can only be as good as our knowledge of the characteristics of the sensor and the manner in which energy is exchanged with the environment. It is well known that the transient behavior of thermometers is in general controlled by one or more complex energy exchange processes. Furthermore, the laws which govern these energy transfers are, in most cases, not well-defined. Accordingly, little success has been realized in attempts made at predicting what the performance of a particular thermometer will be to its environment.

Often the dynamic capability of cryogenic thermometers is specified in accordance with the classical notion of a "time constant." Simply stated, the time constant is defined as "the time required for the output of a transducer to reach 63.2% of its final value as a result of a step change in its measurand." Used properly, the definition is effective in characterizing the transient nature of many mechanical and electrical systems, including some thermometers. Unfortunately, the concept is consistently used to describe the dynamics of cryogenic temperature sensors without due consideration for the underlying assumptions stipulated in the development of the definition. Specifically, the definition applies *only* to systems which can be described by a linear, first-order,

---

*Received August 26, 1966; revised November 29, 1966.
†Project Leader.
‡Chief, Cryogenic Metrology Section; ISA Member, Unaffiliated.

differential equation. More often than not, cryogenic environments impose conditions which make these assumptions invalid.

Temperature measurements made in cryogenic environments are usually complicated by the existence of temperature-dependent heat transfer film coefficients, thermal resistance of the sensor, lead conduction, and radiation—to mention just a few. These influences, either individually or collectively, combine to cause a pronounced departure in the dynamics of the temperature sensor from the first-order system required for the time constant to possess any real significance. The purpose of this paper is to delineate those factors that contribute to the difficulty of measuring transient temperatures in cryogenic fluids.

GENERAL ANALYSIS

Attempts to formulate a generalized model that could be used to describe the dynamics of all cryogenic temperature sensors have been largely unsuccessful. This is not surprising considering the wide variety of existing cryogenic thermometers and the nonidealistic environments in which the sensor must function. In the absence of refined analytical models, users and suppliers of cryogenic thermometers have been forced to adopt concepts based entirely on the performance of "ideal" thermometers to specify and analyze the dynamic characteristics of cryogenic sensors. This observation is not unique to the cryogenic thermometer, but is equally applicable to many other types of sensors. For this reason, then, it is appropriate to begin this discussion with a definition and characterization of the ideal thermometer. A comparison can then be made between its performance and the performance typical of real cryogenic thermometers.

Consider the situation shown in Figure 1, in which it is intended that the thermometer measure only the temperature of the fluid. The thermometer and fluid are assumed initially to be in thermal equilibrium at a temperature, T_0. At time zero, the temperature of the fluid is increased in a stepwise fashion to the value T_m. The question now arises as to how long it will take the temperature sensor to reach thermal equilibrium again with the fluid. To answer this question it is necessary to establish certain facts regarding the sensor and its environment. If the response time of the thermometer can be described by knowing only its mass, specific heat, and surface area, we will consider it an ideal thermometer. The thermal conductivity of the ideal sensor is by definition infinite, which means that the sensor is at all times everywhere uniform in temperature. We will further stipulate an additional requirement, namely, that the physical properties of the thermometer be independent of temperature. To determine the response of our ideal thermometer requires that all modes of energy transfer be taken into account. Energy transferred to the sensor (1) by conduction along lead wires or some other supporting members and (2) by radiation from some body other than the fluid—while important in real cases—is for the ideal case extraneous and is therefore ignored. An energy balance of the system under these conditions need only consider the heat transferred by convection between the sensor and the fluid. Such an energy balance leads to the familiar relation

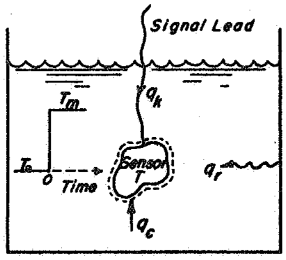


Figure 1. Thermometer model and environment.

$$MC_p\frac{dT}{d\theta} = -hA_s(T - T_m) \qquad (1)$$

where T is the temperature of the sensor at any time θ, T_m is the temperature of the fluid, and M, C_p, and A_s are the mass, specific heat, and surface area of the thermometer, respectively. The convective film coefficient is denoted by h. The above equation states that the rate at which energy is transferred to the sensor is equal to the rate of change of its internal energy. Note that the dynamics of the thermometer are controlled by a first-order ordinary differential equation. Whether the equation will be linear or nonlinear will obviously depend on the nature of its coefficients. Inasmuch as the time constant has significance only for the linear case, one additional requirement must be stipulated, namely, that the film coefficient h is independent of temperature. Environments in which the film coefficient is constant can be considered ideal from the standpoint of thermometer performance. If the coefficients in equation (1) are independent of temperature, the resulting linear differential equation can be readily integrated to yield

$$\frac{T - T_m}{T_0 - T_m} = \exp\left(-\frac{\theta}{\tau}\right) \qquad (2)$$

where τ ($\tau \equiv MC_p/A_sh$) is referred to as the time constant. Inspection of the above equation shows that the constant, τ can be determined by measuring the time θ required for the thermometer to reach 63.2% of its final value. It is clear that the time constant is not an intrinsic characteristic of the thermometer, but rather is unique only to the system (thermometer and environment). The usefulness of the time constant τ lies in the fact that it provides a means of obtaining an invariant time function β which is unique to the thermometer. If the film coefficient h is known, then the value of β can be determined from the following expression:

$$\beta = \left(\frac{MC_p}{A_sh}\right)h = h\tau \qquad (3)$$

The significance of this equality is that it gives to the thermometer a "transfer property": the dynamic behavior of the thermometer in one environment can be used to determine its behavior in a totally different environment. In developing the dynamic equation for the ideal case, several nontrivial assumptions involving both the temperature sensor and its environment are stipulated:

1. The film coefficient h is independent of temperature.
2. The thermal conductance k of the sensor is infinite.
3. Energy is transferred only between the sensor and the surrounding fluid.
4. Physical properties of the sensor, such as C_p, are independent of temperature.

It is important to weigh the validity of each of the above assumptions for the cryogenic situation in order to properly assess the applicability of the foregoing analysis for evaluating the dynamic performance of cryogenic thermometers. Of particular interest are the first two assumptions because of their known predominance in controlling the performance of cryogenic sensors. This is not to suggest that violating other assumptions will not directly influence the overall performance of the cryogenic thermometer. Effects of lead conduction and radiation, while important to the total response characteristic of a thermometer, can be made negligible by closely observing accepted installation techniques.(2,3) Furthermore, effects resulting from temperature-induced changes in the physical properties of the sensor can in most instances be neglected and become important only when the measurements are made over an extreme temperature range. All of these influences will vary in importance depending on the particular application and, hence, each should be weighed in any thorough analysis. We elaborate here only on the following effects: (1) variable h environment and (2) finite thermal conductance k, both of which are consistently troublesome and appear to present the greatest difficulties in predicting the response of cryogenic thermometers.

The Ideal Thermometer in a Variable *h* Environment

The mechanism by which energy is transferred to or from a temperature sensor in cryogenic fluids is generally complicated by the formation of a second phase. Figure 2 is a typical boiling heat transfer curve which shows the film coefficient as a function of the temperature difference existing between the sensor and the surrounding fluid. Investigations have shown that the unique behavior of the film coefficient is a result of variations in the boiling characteristic which occurs as a function of the temperature potential. At low potentials, a condition exists where heat is transferred through a film of superheated fluid. As the thermal potential increases, a point is reached, where, in certain places on the thermometer's surface, the energy level becomes so high that vapor bubbles begin to form. The turbulent action set up by the bubbles literally pumps the heated fluid away from the sensor thus accounting for the increase in the heat flux. The film coefficient will continue to rise with increasing potential until vapor begins to cover an appreciable portion of the surface area of the thermometer. The insulating effect caused by the vapor film begins to overshadow the beneficial effects of fluid agitation and the heat flux decreases with increasing potential. If the temperature difference is further increased, a stable vapor blanket will form over the surface, and the coefficient will be less dependent on the temperature. Although a qualitative explanation of the heat transfer mechanism exists, accurate data are not always available.(4) This is due in part to the fact that the main mechanism of heat flow is the formation of bubble nuclei which depends on various surface phenomena and to a lesser degree on other properties including density of liquid and vapor phases, heat of vaporization, velocity, gravity, and orientation of sensor—to mention just a few. Small variations in these factors exert a large influence on the boiling process and, therefore, on the heat transfer coefficient.

It is clear from equation (1) that the temperature-dependent behavior of the film coefficient will adversely affect the performance of a thermometer. This is possibly best shown in Figure 3 which presents the experimental response characteristic of a thermocouple in liquid nitrogen. The thermocouple was selected since it closely simulates the characteristic of the ideal thermometer. Of particular importance is the strong dependency of the time constant on the initial temperature potential. As seen, the time constant varies from approximately 5 to

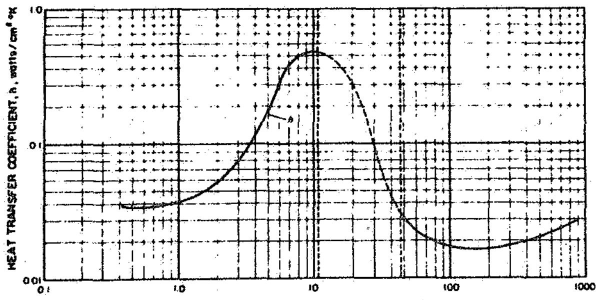


Figure 2. Experimentally determined heat transfer coefficient as a function of temperature difference.

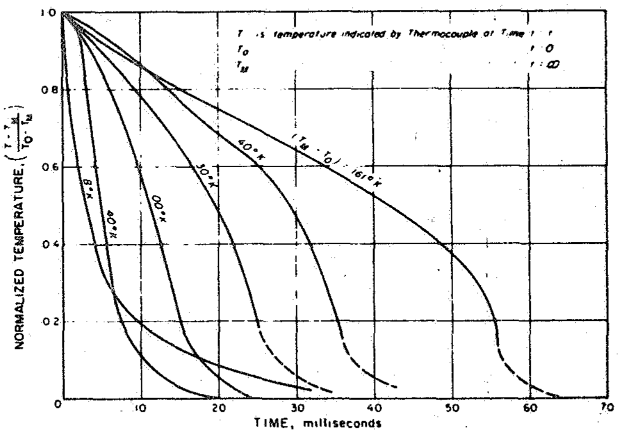


Figure 3. Response characteristics of a copper–constantan thermocouple at liquid-nitrogen temperatures.

50 msec depending on the initial conditions. Less apparent, but equally important, is the change in response characteristics with temperature. This can be clearly seen by comparing the 18 and 40°K curves. Note that while the 18°K curve has a smaller time constant, it nevertheless takes longer to come to thermal equilibrium than does the 40 or 100°K curve. This suggests, for this case, that the time constant is totally without practical significance and, furthermore, may lead to erroneous conclusions regarding the response time of the sensor. Clearly, it would be more meaningful to speak of total time of response (i.e., the time required for the sensor to reach a value close to its final value).

The unique behavior of the thermocouple is not surprising and can be predicted by taking into account the temperature dependence of the film coefficient. Figure 4 shows the results calculated from equation (1), in which the film coefficient is forced to assume the characteristic shape of the film boiling curve shown in Figure 1. Note the qualitative similarity between the experimental and calculated results. The response of the thermocouple results from the fact that its behavior is being controlled by a nonlinear differential equation, whereas the ideal case can be described by a linear differential equation.

Calculation of the transient behavior of any thermometer in a nonideal environment requires data on the film coefficient. There are several excellent references$^{(5,6)}$ which provide a thorough treatment of the subject of heat transfer coefficients in boiling cryogens. Reference to such information is requisite in order to make good, qualified judgments regarding the dynamic behavior of cryogenic thermometers. In many instances, only a rough qualitative analysis can be made; even so, such information is useful for analyzing and interpreting test results.

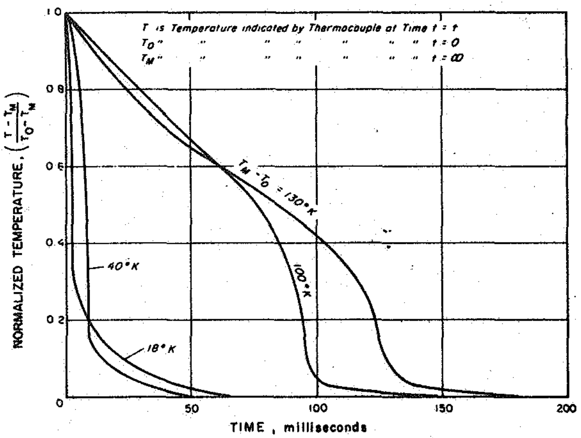


Figure 4. Calculated response characteristics of a copper–constantan thermocouple at liquid-nitrogen temperatures.

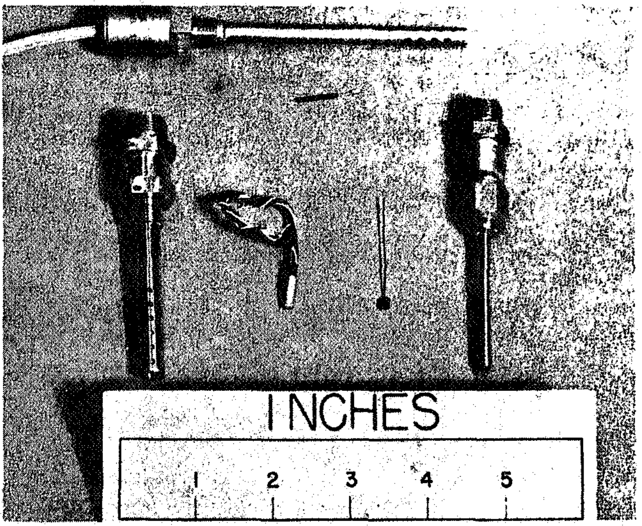


Figure 5. Typical commercially available cryogenic thermometers.

Thermometers Having Finite Thermal Conductivities

In treating the ideal thermometer, it was noted that by neglecting its internal thermal resistance, $1/k$, and considering its thermal capacitance as a lumped parameter, the mathematical description of the thermometer leads to an ordinary differential equation. In practice, for a sensor to be considered ideal, it is not required that it possess an infinite thermal conductivity, as was stipulated in the general analysis. Rather, it is important that the internal resistance, $1/k$, of the thermometer be small compared to the external resistance $1/h$. This criterion is satisfied for certain thermometers such as the bare thermocouple. As illustrated in Figure 5, there are many different types and sizes of cryogenic thermometers, each of which exhibits a different thermal response. For some thermometers, particularly the more massive types, internal resistance cannot be neglected. The response characteristic of a commercial thermometer of this type under a small temperature perturbation is presented in Figure 6. The curve was obtained by simply plunging the thermometer into a liquid-nitrogen bath from an initial temperature several degrees in excess of the bath temperature. By keeping the temperature perturbation small, the film coefficient h can be considered reasonably constant over the temperature range. Thus, any peculiarities in the response curve can be attributed to characteristics inherent in the sensor. The

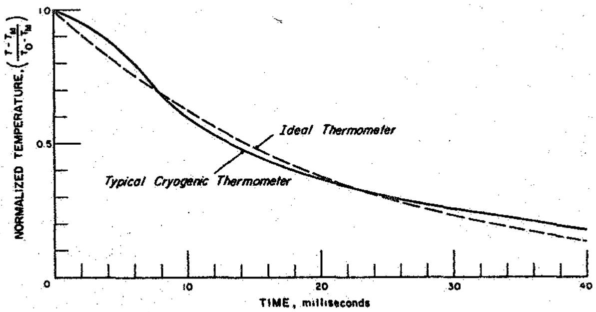


Figure 6. Response characteristics of a thermometer having a finite thermal conductivity.

effect of internal resistance is clearly shown by the second-order characteristic of the curve. Figure 7 shows a set of response curves obtained with the same thermometer for various temperature perturbations. Note the extreme dependency of the response time on the magnitude of the temperature perturbation. The response time is a much stronger function of the excess temperature in this case than it was for the thermocouple. This suggests that the internal resistance of a sensor weighs heavily in determining overall response characteristics of the thermometer.

Analysis of nonideal thermometers is greatly complicated as a result of their internal resistance. The fact that the thermometer possesses an internal resistance means that its temperature–time history can be described only by a partial-differential equation, since temperature is a function of time as well as location. Solutions to these partial-differential equations generally take the form

$$T(x, \theta) = X(x). \Theta(\theta) \tag{4}$$

where $\Theta(\theta)$ and $X(x)$ are independent functions of time and displacement, respectively. The nature of these functions is determined by geometric and thermal properties of the thermometer in addition to the heat transfer conditions existing at the surface. A detailed mathematical formulation of dynamic behavior of this type of thermometer is beyond the scope of this article. It will suffice to point out that exact mathematical solutions can be obtained only for objects which possess the simplest of geometric shapes. The consequence has been that there has been little success in modeling cryogenic sensors primarily because of their comparatively complicated geometries. For this reason, it has been necessary to adopt approximate models which may or may not be valid depending on the particular circumstances and the ingenuity of the individual performing the analysis.

SUMMARY

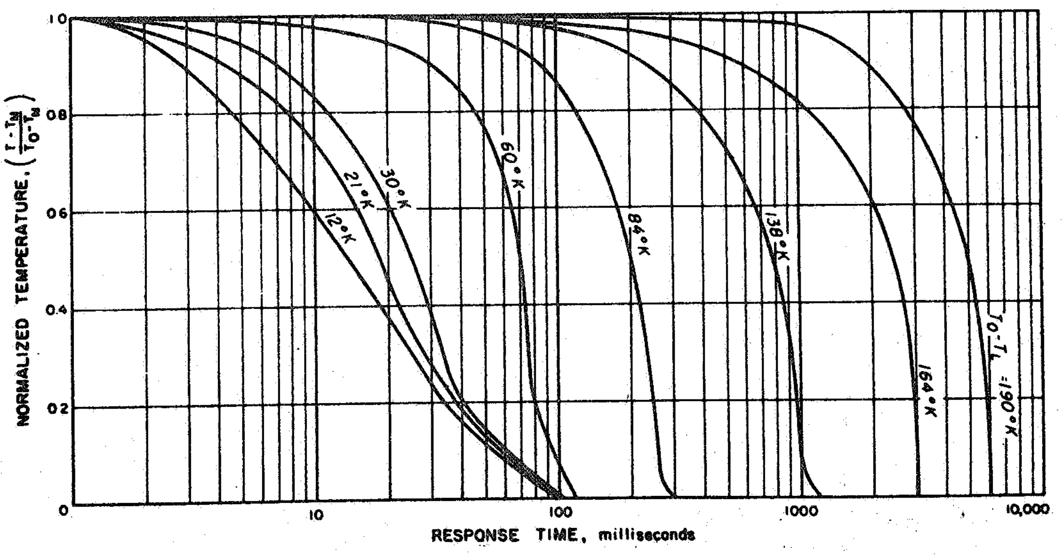
There are basically two factors which contribute to the difficulty encountered in predicting transient temperature measurements. The most troublesome one is that the response characteristics of thermometers are controlled by rather complex energy exchange processes which are strong functions of (1) the nature of the environment and (2) the geometrical and thermal properties of the thermometer. Furthermore, the laws which govern these energy interactions are generally not well-defined and, hence, predicting a thermometer's transient behavior, even under the best conditions, is difficult. Less apparent, but equally important, is that there do not exist meaningful, standardized definitions of terms which are commonly used by suppliers and users of cryogenic thermometers. Such a condition naturally frustrates any attempts made to evaluate the dynamic behavior of thermometers.

Literal use of the "63.2%" notion of a time constant has lead to numerous cases of misinterpretation of thermometer performance by both user and supplier. Specifications based on poorly defined terms inevitably result in misapplication of thermometers, but even more important, it is frequently responsible for invalid measurements.

An obvious first step forward in solving the difficulty is to develop and adopt terminology in order to provide guidelines for predicting and evaluating the performance of cryogenic thermometers. In the absence of suitable terminology, care should be taken to qualify all specifications affecting the dynamic capability of the particular thermometer.

Finally, we do not wish to leave the impression that performing a dynamic analysis on a thermometer is, in most cases, an exercise in futility. Analysis can frequently facilitate the selection and installation of thermometers and is an essential requirement for meaningful interpretation of test results. Rather, the intent of this article

Figure 7. Response characteristic of a commercial platinum resistance thermometer.



is simply to emphasize some of the more subtle factors which must be taken into consideration in order to effect a more meaningful analysis.

ACKNOWLEDGMENT

This work is supported by the National Aeronautics and Space Administration under Contract No. R-45.

NOTATION

A_s = Surface area of the thermometer
C_p = Specific heat
h = Film coefficient
k = Thermal conduction
M = Sensitive mass
q_c = Convection heat flux
q_k = Conduction heat flux
q_r = Radiation heat flux
T = Instantaneous thermometer temperature
T_m = Final steady-state fluid temperature
T_0 = Initial temperature of the thermometer
β = Time function
θ = Time
τ = Time constant

REFERENCES

1. Baker, H. D., E. A. Ryder, and N. H. Baker, *Temperature Measurement in Engineering, Volume I*, John Wiley and Sons, Inc., New York, 1953.
2. Scott, R. B., *Cryogenic Engineering*, D. Van Nostrand Company, Inc., New York, 1957, pp. 147–202.
3. Jakob, M., *Heat Transfer, Volume II*, John Wiley and Sons, Inc., New York, 1957.
4. Brentari, E. G., P. J. Giarratano, and R. V. Smith, "Boiling Heat Transfer for Oxygen, Nitrogen, Hydrogen, and Helium," *Natl. Bur. Std. Tech. Note* 317.
5. Kutatcladze, S. S., "Heat Transfer in Condensation and Boiling," in: *State Scientific and Technical Publication of Literature on Machinery*, second edition, Moscow, 1952.
6. McNelly, M. J., "A Correlation of Rates of Heat Transfer to Nucleate Boiling Liquids," *J. Imp. Coll. Chem. Eng. Soc.* 7, 18, 1953.