ORNL/TM-4573

Measurement of the Transient Response of Thermocouples and Resistance Thermometers Using an In Situ Method

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OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy $4,50; Microfiche $3.00

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ORNL/TM-4573
Dist. Category
UC-79, -79m

Contract No. W-7405-eng-26

INSTRUMENTATION AND CONTROLS DIVISION

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Date Published: June 1977

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ABSTRACT

A loop-current step-response (LCSR) method was developed to measure, in situ, the transient response of temperature sensors, such as thermocouples and resistance thermometers. In this method, a sensor is heated with an electric current, and the time dependence of cooling is analyzed when the current is turned off. The cooling analysis is mathematically transformed into an equation to predict the transient response of the sensor to a change of external temperature. The method was verified for a limited class of sensors by comparing the predicted transient response with that measured after plunging the sensors into hot water.

The transient responses of sheathed, insulated junction, Chromel/Alumel thermocouples of various diameters were measured with the sensing junction in flowing sodium at temperatures from 180 to 600°C. The results showed that the transient response was slower as the temperature increased, it depended on the compaction of the MgO insulation around the junction, and it varied with the square of the sheath diameter. The transient response was faster when the sheaths of the thermocouples were swaged so that the insulation compacted around the junction.

The transient response of thermocouples in thermal wells was dominated by the thermal coupling between the well and the thermocouple. Liquid metal in the annulus between the well and the thermocouple quickened the transient response an order of magnitude.

The transient response of grounded junction thermocouples was about 50% faster than that of insulated junction thermocouples; however, when the sheaths of the insulated junction thermocouples were swaged, the transient response was about the same as a grounded junction thermocouple. The transient response of a grounded junction thermocouple did not change when the mass of metal at the hot junction was reduced.

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1. INTRODUCTION

Thermocouples and resistance thermometers are used extensively to measure the temperatures of flowing fluids. Both process control and safety analysis require knowing the time lapse before a temperature sensor will register a sudden change of the temperature of the fluid. The time dependence of temperature indication following a temperature change (hereafter called the transient response) of a sensor depends strongly on its operating conditions, which often cannot be duplicated in bench tests. Moreover, the transient response may change during the service life of the sensor. Thus, an in situ measurement of the response rate is necessary.

The Loop-Current Step Response (LCSR) method was developed to measure the transient response of a sensor either before or during operation.[1] An electric current is passed through the sensor[2] circuit until the sensor attains a steady state temperature a few degrees higher than the operating temperature. The current is turned off, and the time dependence of the cooling is analyzed to predict the transient response if the fluid temperature should change.

The mathematical transform used in this report was derived for the case of one-dimensional heat flow in a homogeneous body. Moreover, the variation of the transform used in this report will apply only to LCSR tests where the sensors have a much higher internal heat resistivity than the resistivity at the sensor surface. We have found that the model is adequate for LCSR tests on insulated junction thermocouples and for the one resistance thermometer we tested. LCSR tests could not be made on grounded junction thermocouples because of the problems in heating the junction, but the transient response to plunge tests on both insulated and grounded junction thermocouples was described by the model.

This report compares the transient responses predicted by the LCSR method to those measured by plunging the sensor into hot water. Sources of error in both methods are reported. The construction features affecting the transient response of thermocouples were investigated. The transient responses are given for thermocouples of various diameters as

a function of temperature, using a sodium loop with temperatures ranging from 180 to 600°C. Ways were explored to make the transient response faster for insulated junction thermocouples, grounded junction thermocouples, and thermocouples in thermal wells.

2. THEORY OF LCSR METHOD

In this report the word "thermometer" means a sheathed assembly containing an internal temperature-sensitive sensor. For transient response studies, the sheath of the thermometer is the part in contact with the coolant fluid; that is, a sheathed thermocouple in a well comprises a thermometer, but the outside of the well is the sheath of the thermometer.

The model that describes the transient response is given in detail elsewhere.[3] Briefly, in this model the heat transfer within the thermometer is represented by a lumped-parameter model with nodes coupled by appropriate node-to-node heat transfer resistances to form a series network. One conclusion of this model is that if a step change of temperature occurs in the fluid surrounding the thermometer, the thermometer will indicate a temperature (T) at a time (t) expressed by the transient response:

$$T(t) = K\left[\frac{1}{(-p_1)(-p_2)\cdots(-p_N)} + \frac{1}{p_1(p_1 - p_2)(p_1 - p_3)\cdots(p_1 - p_N)}\, e^{p_1 t} + \frac{1}{p_2(p_2 - p_1)(p_2 - p_3)\cdots(p_2 - p_N)}\, e^{p_2 t} + \cdots\right], \qquad (1)$$

where K is a constant, and the p_i are always negative numbers.

Measurements by the LCSR method begin just as the current is turned off and temperature gradients across the thermometer are at maximum. From the model, the transient response of the thermometer is expressed as

$$T(t) = \frac{(p_1 - z_1)(p_1 - z_2) \ldots (p_1 - z_{N-1})}{(p_1 - p_2)(p_1 - p_3) \ldots (p_1 - p_N)} e^{p_1 t}$$

$$+ \frac{(p_2 - z_1)(p_2 - z_2) \ldots (p_2 - z_{N-1})}{(p_2 - p_1)(p_2 - p_3) \ldots (p_2 - p_N)} e^{p_2 t} + \ldots \quad . \qquad (2)$$

The exponential terms are the same for both the LCSR test [Eq. (2)] and the step change of fluid temperature [represented by a plunge test, Eq. (1)], although the coefficients are different for the two equations. Equations (1) and (2) can be expressed generally as

$$T(t) = A_1 \exp(p_1 t) + A_2 \exp(p_2 t) + A_3 \exp(p_3 t) + \ldots \qquad (3)$$

with A_i different for each equation.

Only a limited number of terms in Eq. (3) have practical significance because experimental data contain noise and the computer fitting program cannot resolve the very small influence of the higher terms of Eq. (3) in the presence of the noise. We found that only the first three terms of Eq. (3) were useful to describe a plunge test and only the first two terms were useful for an LCSR test. More terms are used in the plunge test because the plunge test (external step) has a "dead time" at the start of a transient (Fig. 1), and the LCSR test (internal step) does not have a "dead time" (Fig. 2). Thus, the magnitudes of the terms of Eq. (3) decrease more rapidly for an LCSR test than for a plunge test (i.e., the third term is insignificant for an LCSR test but not for a plunge test).

Kerlin's analysis,[3] based on a homogeneous model, shows that if the surface of the thermometer is at the same temperature as the surrounding fluid, the values of A_i in Eq. (3) depend on the initial temperature distribution in the thermometer, and the relative values of p_i are determined by the geometric shape of the thermometer. The effect of shape on the response rate is shown in Fig. 1. For a homogeneous body, with its surface

at the same temperature as the surrounding fluid, we have discovered that the p_i have the emperical relation

$$p_i = p_1[1 + (i - 1)R]^2 , \tag{4}$$

where R is a constant for a given geometry (Fig. 1).

Equation (4) provides exact values of p_i for the shapes of a sphere and a slab.[3] For a given homogeneous mass suddenly immersed in the same fluid, the temperature change at the center of the mass will be the slowest if the mass is in the shape of a sphere (R is 1), and the temperature change will be the fastest if the mass is fabricated into a thin slab (R is 2). The value of R is approximately correct for the shape of a cylinder (R is about 1.296). Thus, for heat transfer from any shape, we expect the value of R to be between 1 and 2 and related to p_i approximately by Eq. (4).

Equation (4) applies to the condition where the surface temperature of the body and the temperature of the surrounding fluid are the same. During temperature transients, however, there is always a temperature differential between the body and the fluid. In ref. 3 Kerlin shows that the ratio p_i/p_1 is affected by the relative values of the surface and internal resistances to heat flow, and he calculates that Eq. (4) predicts the first three values of p_i for a slab to within 4.4% if the quantity (hL/K) is $\geqslant 10$, where h is the film heat transfer coefficient, L is the body thickness, and K is the thermal conductivity of the body.

The significance of Eq. (4) is that if p_1 and R are known, the first three terms of Eq. (1) can be constructed. Equation (1) gives the transient response of a thermometer to a step change of external temperature, which is what we wish to determine. The components of Eq. (1) must be obtained from an analysis of the rate of cooling after a step change of internal power. If the analysis of the internal power step (LCSR) yields the ratio p_1/p_2 in Eq. (2), the value of R can be calculated. The time dependence of the response of a thermometer to a change of fluid temperature is thus calculated from the analysis of the LCSR test.

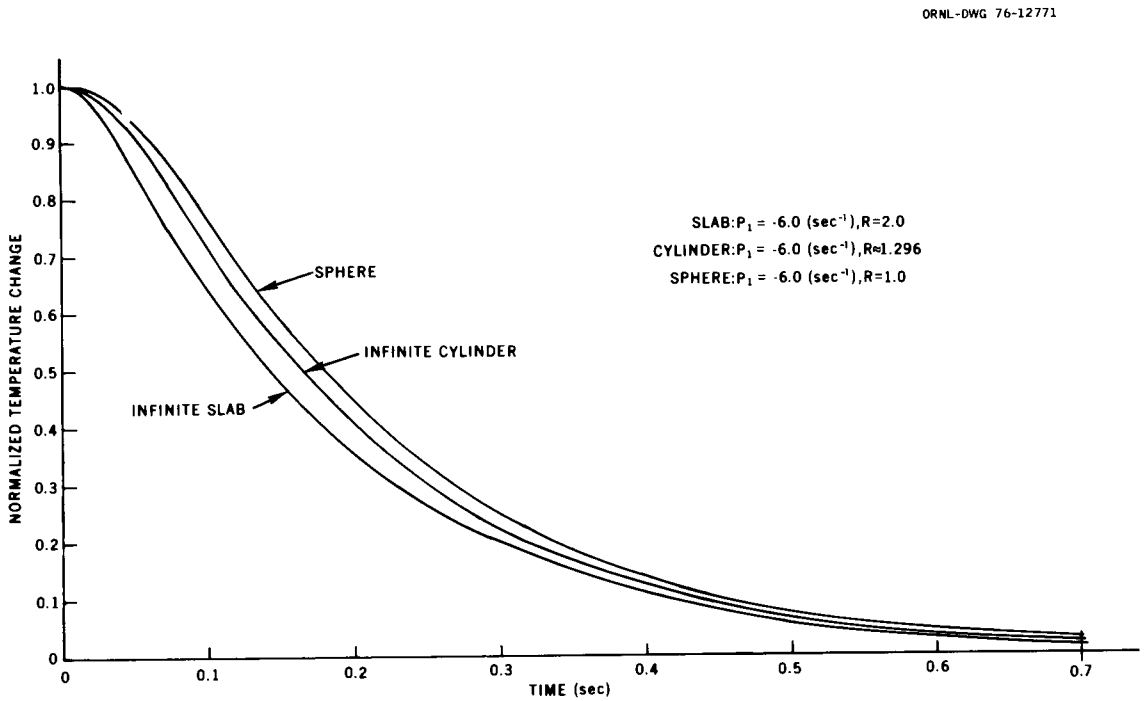

Fig. 1. Transient response of a homogeneous body as a function of shape after a step change of coolant temperature.

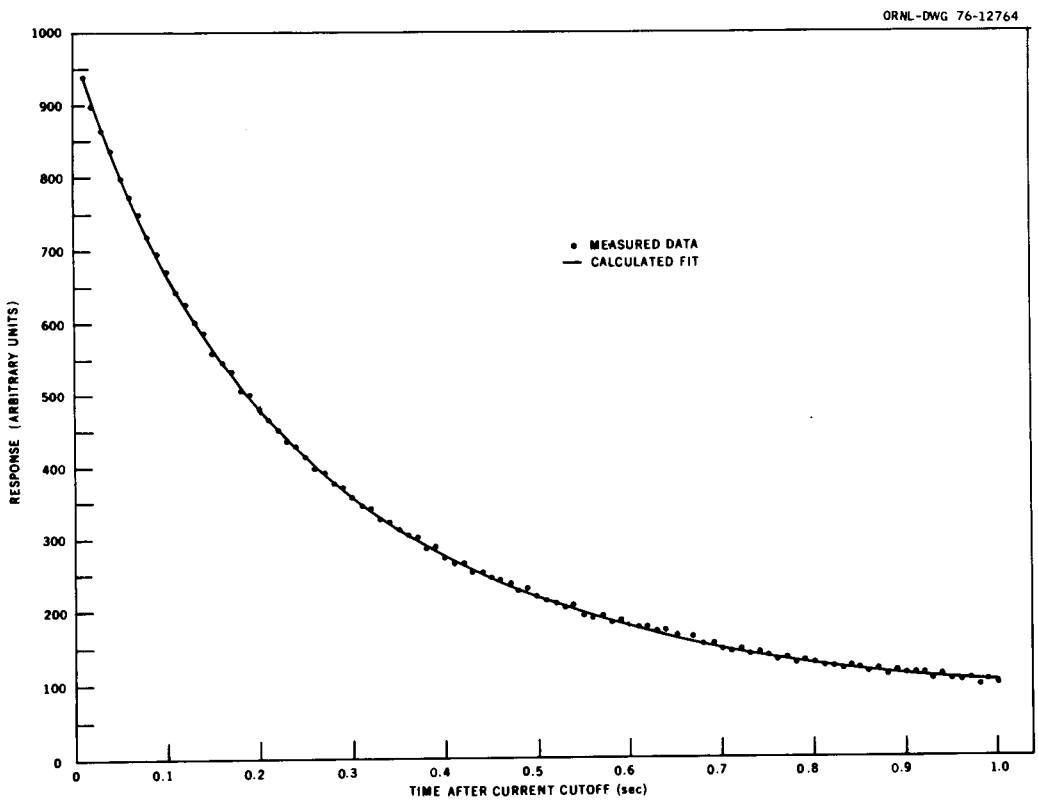

Fig. 2. Comparison of measured and calculated responses for a loop-current step-response (LCSR) test. The specimen was a 0.16-cm-OD, stainless steel sheathed, insulated junction, Chromel/Alumel thermocouple.

2.1 Application of LCSR Method

The model is applied by first recording the cooling curve after the current is turned off (Fig. 2). The first two terms of Eq. (2) are used to fit the measured LCSR data; so the time dependence of the temperature is expressed as

$$T(t) = (T_0 - T_F)\left(\frac{z - p_1}{p_2 - p_1} e^{p_1 t} + \frac{z - p_2}{p_1 - p_2} e^{p_2 t}\right) + T_F , \qquad (5)$$

where T_0 is the temperature at $t = 0$ and T_F is the temperature at $t = \infty$. By letting $A = (z - p_1)/(p_2 - p_1)$ and using Eq. (4), we can write

$$T(t) = (T_0 - T_F)\left[Ae^{p_1 t} + (1 - A)e^{(1+R)^2 p_1 t}\right] + T_F . \qquad (6)$$

The numerical values of p_i, R, A, T_0, and T_F of Eq. (6) are obtained from a computer program to give the best fit to the data.* As shown in Fig. 2, the fit is good over the entire cooling span of the thermometer. From the values of R and p_1, the transient response for a sudden change of external temperature can be calculated using Eq. (4) and the first three terms of Eq. (1).

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*For some thermometer tests the cooling rate can be described with a single exponential equation. Computer fitting of such data by Eq. (6) produces a value of A that is ≈ 1; the value of R is then indeterminate since the coefficient $(1 - A) \approx 0$. The program solution will not usually (depends on noise level) converge for values of A more than 0.97. Only a few thermometers had a cooling curve that could not be fitted by Eq. (6). We could not establish what internal thermal coupling processes were involved in those thermometers (that were not involved in the thermometers of the same class, apparently constructed in the same manner). Those cases that could not be fitted with Eq. (6) were fitted with the equation

$$T(t) = (T_0 - T_F)\, e^{p_1 t} + T_F .$$

For prediction purposes, the R value found for other thermometers of that class was used.

2.2 Plunge Test Calculations

Since it is difficult to produce a step change of temperature in a flowing liquid, a step change was approximated by plunging the thermometers being tested into a flowing or stirred bath. The first three terms of Eq. (1) with Eq. (4) describe the transient response of the sensor. Equation (1) becomes

$$T(t) = (T_0 - T_F) \left\{ \left[(2 + 15R + 44R^2 + 63R^3 + 44R^4 + 12R^5) e^{p_1 t} - 4(1 + 5R + 8R^2 + 4R^3) e^{(1+R)^2 p_1 t} + (2 + 5R + 4R^2 + R^3) e^{(1+2R)^2 p_1 t} \right] \Big/ 4R^2(4 + 12R + 11R^2 + 3R^3) \right\} + T_F \ . \tag{7}$$

The values of T_0, T_F, p_1, and R are obtained from a computer fit of the data, and these are used in Eq. (7) to calculate the response (Fig. 3). From Fig. 3 one can conclude that the first three terms of Eq. (1) are sufficient to describe the entire response of the sensor to a plunge test, including the so called "dead time" at the start of the transient.

Equation (7) is fitted directly to data obtained from a plunge test to obtain numerical values for the T_0, T_F, p_1, and R. It should be noted that the parts of Eqs. (6) and (7) enclosed in {} have a value of 1 at $t = 0$ and a value of 0 at $t = \infty$. Thus, often the thermometer response will be given as the normalized temperature change (see Fig. 1), which is the value of the portion of the equation enclosed in {}. The values of T_0 and T_F serve only to scale the value of T(t).

After the LCSR data are fitted to Eq. (6) to obtain values of p_1 and R, these are used in the {} section of Eq. (7) to calculate the transient response of the thermometer to a sudden change of fluid temperature.

3. EXPERIMENTAL METHOD

The procedure for the LCSR method was to pass an electric current from a variable voltage, 1-kHz power supply through the thermocouple loop and through a timer with the heating time preset (Fig. 4). A variable-phase cut-off system (Sect. 3.1) turned off the current. The relay switch then disconnected the thermocouple from the power supply and connected the thermocouple to the measuring system. The relay switch system contained an adjustable, dc bucking voltage so that the emf from the thermocouple at steady-state conditions could be adjusted to zero.

The emf from the cooling thermocouple was amplified, and its time dependence was recorded on a transient recorder having a 1024-word, 10-bit per word memory. The data in the memory were displayed on a scope monitor and later transferred to a magnetic tape via an electronic data terminal. At some convenient time, the data were transferred by telephone to a computer, and a nonlinear least-squares data-fitting program computed the numerical values for the components of Eq. (6).[4]

3.1 Power Cut-Off Systems

When the LCSR method is used for Chromel/Alumel thermocouples, a secondary emf is generated by the activating current. The secondary emf is time dependent, of variable magnitude, and a source of errors in the analysis. Thus, it was necessary to find the cause of the secondary emf and to eliminate it so that the LCSR method could be applied to Chromel/Alumel thermocouples.

We found that the Alumel leg of the Chromel/Alumel thermocouple was responsible for the secondary emf. A length of Alumel wire would produce the emf after passage of the current in the usual LCSR test. The same current would not produce an emf in wires of Chromel, iron, constantan, copper, nickel, or Nicrosil II.

We believe the electric current magnetized the Alumel wire and, as soon as the current was turned off, the magnetic state began to decay, creating an emf because of the changing magnetic field. This belief was confirmed by three observations:

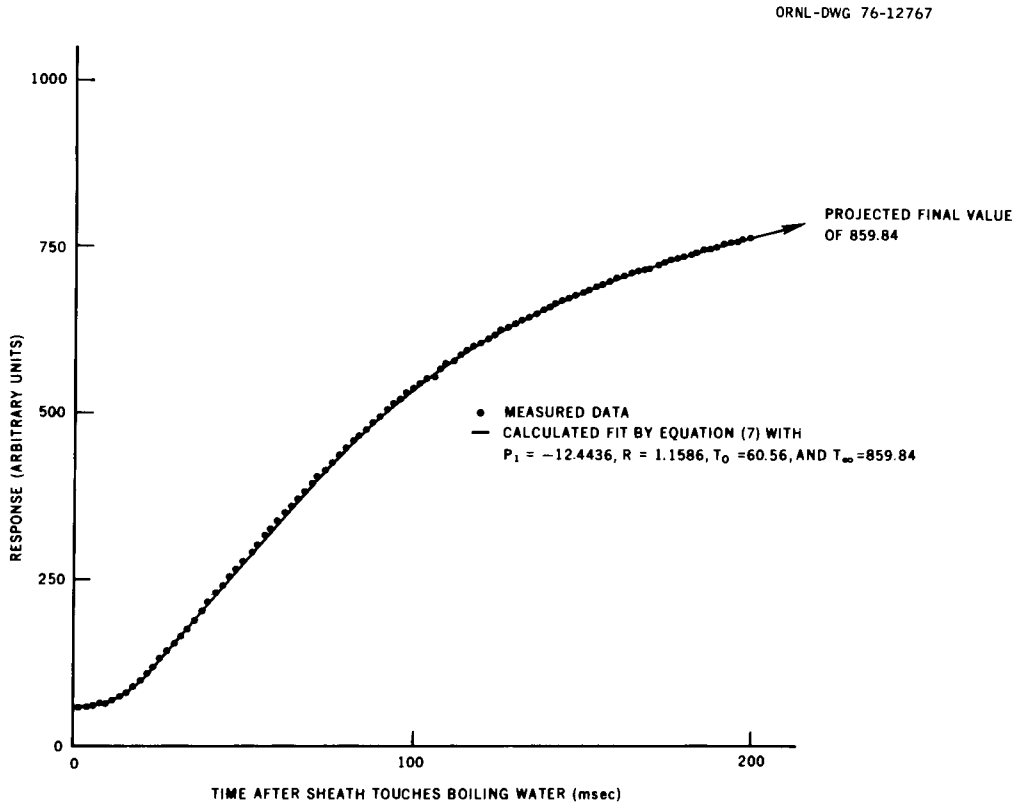

Fig. 3. Measured and calculated emf's from a plunge test. The specimen was a 0.16-cm-OD, stainless steel sheathed, grounded junction, Chromel/Alumel thermocouple.

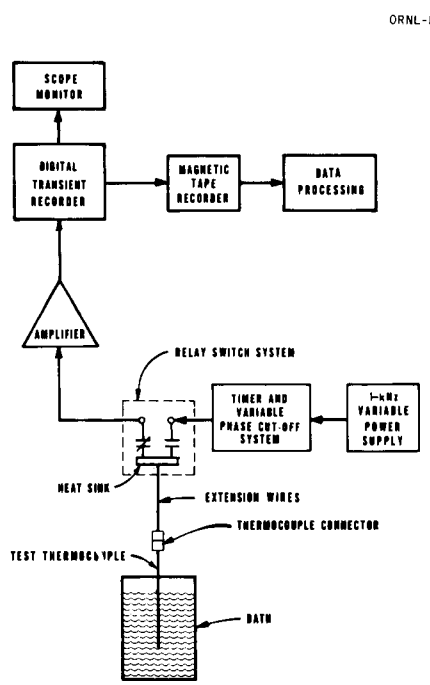

Fig. 4. Loop-current step-response method of predicting the transient response of a thermocouple.

1. The emf would not be generated if the Alumel wire was above about 170°C (the Curie temperature).
2. Nisil, a nickel base alloy like Alumel, has a Curie point below room temperature. At room temperature the emf could not be produced, but when the Nisil wire was cooled below 0°C, the emf could be generated.
3. When a coil of Alumel wire was placed in a static magnetic field of about 1 tesla (10,000 gauss), the emf was not produced. We think the imposed external magnetic field either prevented the alignment of magnetic domains by the current or else prevented the relaxation of the magnetic alignment after the current was turned off.

The secondary emf from Alumel had a polarity opposite to the direction of the loop current. The magnitude of the emf was proportional to the resistance of the Alumel wire and the square of the current. The emf decayed with a time constant of about 0.4 sec. If alternating current was used, the polarity of the secondary emf depended on the direction of the current when it was turned off. If the frequency of the alternating current was raised, there was a decrease of the secondary emf; a direct current produced about twice the secondary emf as a 1 kHz current of the same rms amperage.

We minimize the effect of the secondary emf by using a 1-kHz activating current, large extension wires (to reduce the resistance), and a current just large enough to produce an acceptable signal from the sensor. The main control of the secondary emf, however, is achieved by the manner of cutting off the activating current.

Two types of cut-off systems* were used to prevent generation of the secondary emf in the Alumel. One type, a variable phase system (Fig. 4), used the principle that the magnetic state reversed with each cycle of the alternating current. By adjusting the time of current turn-off so that it occurred at the voltage phase when the internal magnetic field was zero, the secondary emf was eliminated. In practice, considerable adjustment was needed to achieve a negligible secondary emf. In the second type of cut-off system, called a damped phase system, the current

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*Both systems were designed by W. R. Miller, ORNL.

was ramped to zero in 0.01 sec. Since ten cycles occurred in this time, the magnetic state was reduced a factor of ten, making it negligible.

3.2 Plunge Test

The purpose of the plunge test was to subject the thermometers to an external step change of temperature. The same measurement equipment (Fig. 4) used for the LCSR test was used for the plunge test, but the power supply system was disconnected. The thermometer to be tested was plunged into an agitated water bath; a voltage difference between the thermometer sheath and the bath started the transient recorder when the sheath touched the water. The emf was recorded and processed as described in Sect. 2.2.

3.3 Platinum Resistance Thermometers

Platinum resistance thermometers (PRTs) measure the voltage drop across a platinum resistance element when a constant sensing current is passed through the circuit. To test a platinum resistance thermometer by the LCSR method, the equipment shown in Fig. 4 was used except that the ac power supply was replaced with a dc supply. The platinum resistance thermometer was self-heated by increasing the sensing current from 3 to 70 mA for about 60 sec. The PRT attained a steady-state temperature 8°C higher than that of the water bath within 30 sec of heating. The current was then reduced abruptly to the usual sensing current of 3 mA, the transient recorder was started and the emf was recorded as the resistance element cooled. The data were analyzed as described for the LCSR tests (Sect. 2.1).

3.4 Sodium Loop Test

A sodium loop* was used as a high temperature bath for thermocouples (Fig. 5). The test thermometers were inserted through the thermocouple

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*The authors are grateful to R. E. MacPherson, Jr., and R. E. Dial, of the Reactor Division, ORNL, for permission to use the loop and for their advice and assistance.

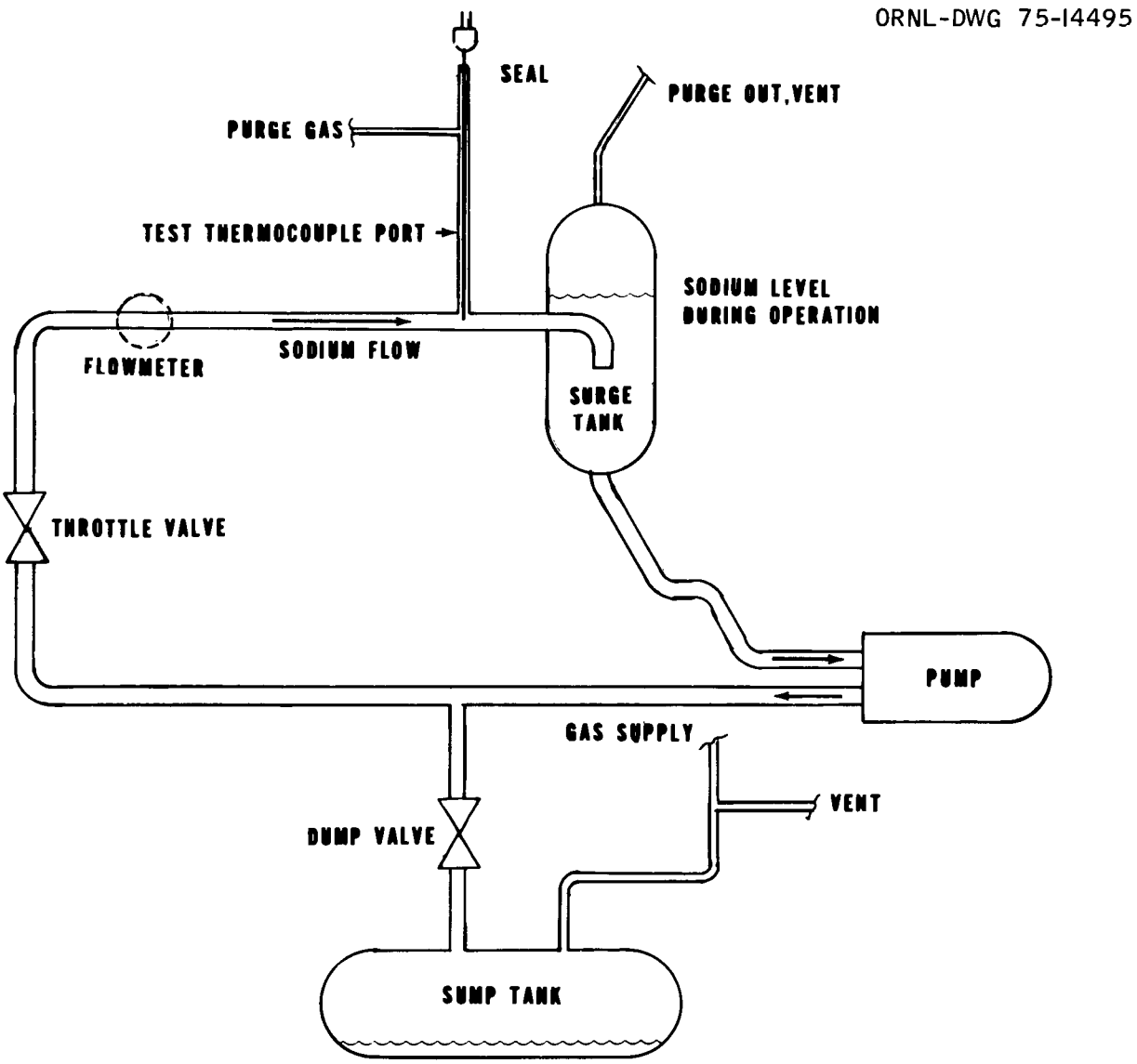

Fig. 5. Sodium loop thermocouple test facility.

port standpipe so that the lower 19 mm of the sensor was in flowing sodium. The sodium loop temperature was variable from 150 to 600°C, and the sodium flow rate was continuously variable up to about 150 cm/sec. LCSR tests were performed in the sodium loop, and the procedure for these tests was as described in Sect. 3.

4. RESULTS

The response of a thermometer to a sudden change of temperature of the surrounding fluid is shown in Fig. 3. The data (every tenth point is shown) are fitted very well by Eq. (7) using four variables, two of which (T_0 and T_∞) are only scale factors. The numerical evaluation of Eq. (7) for the calculated best fit to the data in Fig. 3 is

$$T(t) = (60.56 - 859.84)\left\{1.4005e^{-12.44t} - 0.474e^{-57.98t} + 0.0734e^{-136.9t}\right\} + 859.84 \ . \tag{8}$$

Equation (8) is bulky, and the curve shape is hard to visualize from either the equations or the four variables listed in Fig. 3. Thus, we calculate, by Eq. (7), the time required to achieve 20 and 63.2% of the total response. The 20% response time indicates the amount of "dead time," and the 63.2% response time is often called "the" time constant.

The use of the terms "20% response time" and "63.2% response time" should not obscure the fact that the transient response, T(t), is expressed as an equation. The 20% response time is the time required for T(t) to change by 20% of the range between T_0 and T_∞. The 63.2% response time is the time required for T(t) to change by 63.2% of the range between T_0 and T_∞. The use of these two response times is only a device to allow a simple, but not a precise, comparison of the transient response for different thermometers.

4.1 Confirmation of the LCSR Method

The LCSR method is intended to predict the transient response of a thermometer if the temperature of the surrounding fluid should suddenly

change. A plunge test was used to confirm the predicted response rate. Figure 6 shows a predicted transient response and a measured transient response for a 0.16-cm-OD, insulated junction thermocouple plunged into stirred hot water. The widths of the curves give the standard deviations for repeated measurements. The transient response measured by the plunge test was about 18% faster than that calculated by the LCSR test. In a plunge test, however, the fluid film at the sheath is disturbed by the motion of the thermometer. A sudden change of coolant temperature would not disturb the fluid film. The heat transfer conditions are thus not the same and the plunge test only approximates a step change of fluid temperature.

4.1.1 Effect of Vibration on Transient Response

The 18% difference shown in Fig. 6 can be explained by the heat transfer rates across the fluid film at the thermocouple sheath surface: the thermocouple is stationary in the flowing water during an LCSR test, and the fluid film is stable during the test; but a plunge test causes a small-diameter thermocouple to vibrate like a plucked string. The vibration creates faster heat transfer by effectively increasing the velocity of the water relative to the sheath.

When the thermocouple plunge test was arranged so that vibration was minimized, the measured transient response was 20% slower. To compensate for the different heat transfer rates, we increased the velocity of the flowing water during the LCSR test; the transient response was then faster than that determined by a plunge test into more slowly moving water.

Because it seemed impossible to compensate for the fluid film differences between the LCSR and plunge tests, the two tests were performed in a bath agitated at the same rate. The results (Fig. 6) show that although the LCSR predictions are about 18% different than the plunge test, they are within the more than 20% uncertainty of the confirming plunge test. It will be shown later (Sect. 4.8.4) that vibration during the plunge test is not as important for larger, more slowly responding thermometers.

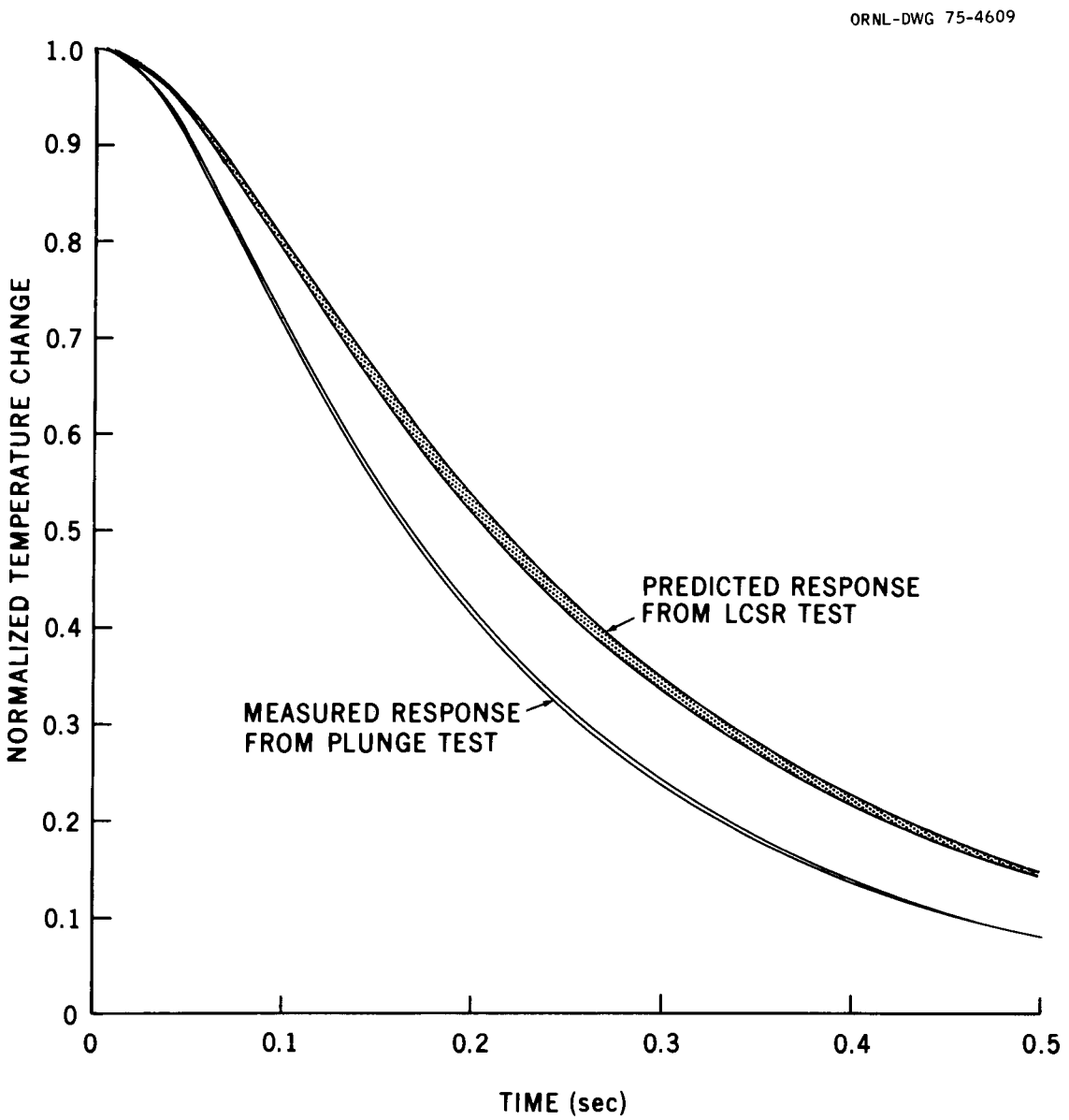

Fig. 6. Transient response of a 0.16-cm-OD, Chromel/Alumel thermocouple measured by a plunge test and predicted by a loop-current step-response test.

4.1.2 Platinum Resistance Thermometer

The response of a platinum resistance thermometer plunged into water at near-room-temperature and flowing at 90 cm/sec is compared in Fig. 7 to a response calculated from LCSR data for the same conditions. The predicted plunge test response was calculated from the measured data of the LCSR cooling curve as described in Sect. 2.1.

Compared to the measured response, the transient response predicted by the LCSR test is slower at the start of the test (a plunge stirring difference ?) and is the same during the midportion and the final portion. However the differences between the predicted and measured transient responses (Fig. 7) are always less than 10%.

Only one platinum resistance thermometer was tested to verify that the LCSR method could be used to predict its transient response.

4.1.3 Thermocouple in Thermal Well

The transient response of a thermocouple-well thermometer system was predicted by the LCSR method, with the well in flowing sodium at 188°C (Fig. 8). The response rate of the same thermocouple-well system was measured by plunging the well into boiling water. Figure 8 shows the mean value of the transient response to the plunge test as a line surrounded by a standard deviation band. The standard deviation of the LCSR prediction is within the width of the line. The transient response from the plunge test is about 5% faster than the LCSR predicted transient response. However, because the LCSR test was performed at higher temperatures, the 5% difference is not significant since temperature also affects the transient response, as discussed in the next section.

4.2 Effect of Temperature and Sodium Flow on Transient Response

In this work, we found that the transient response in water was greatly influenced by the water velocity. In the sodium loop the higher thermal conduction of sodium made negligible the effect of flow rate at rates of more than 35 cm/sec (Reynolds number $\sim$10,000). The operating temperature of the sodium, however, had a large effect on the transient response. The calculated transient response of a thermocouple is shown

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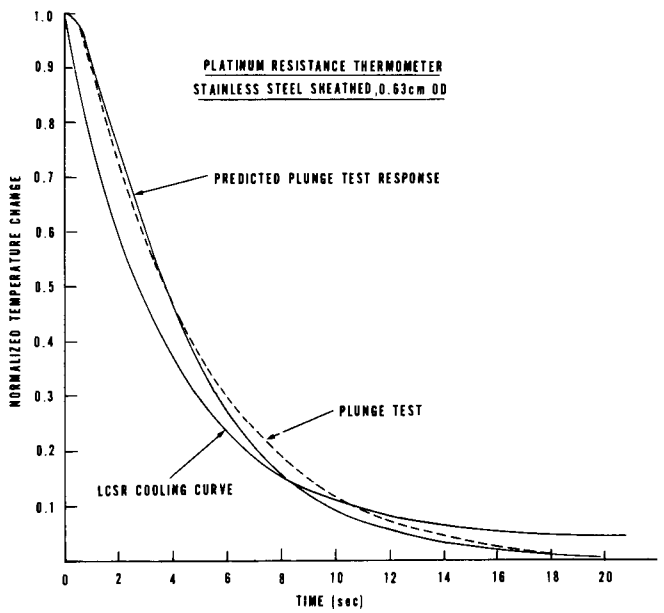

Fig. 7. Transient response of a 0.63-cm-OD platinum resistance thermometer measured by a plunge test and predicted by a loop-current step-response test.

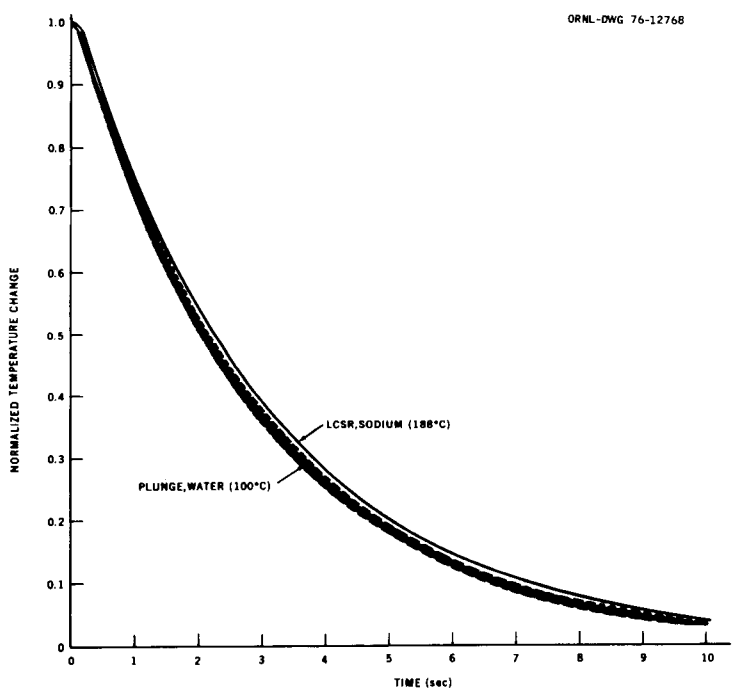

Fig. 8. Transient response of a 0.16-cm-OD, stainless steel sheathed, Chromel/Alumel thermocouple spring loaded in a 0.18-cm-OD, 0.25-cm-OD stainless steel well. The transient responses were measured by a plunge test and predicted by a loop-current step-response test.

in Fig. 9 for three temperatures in the sodium loop; a transient response for the same thermocouple in stirred water at room temperature is shown for comparison.

The 63.2% response time at different temperatures is shown in Fig. 10. These data were obtained over several days, with random temperature variation. All the data show the 63.2% response time to be longer when the thermocouple operated at a higher temperature. Fourteen more thermocouples of the same type were tested, and all showed longer response times at higher operating temperatures. Each of the other thermocouples, however, had a somewhat different temperature dependence than that shown in Fig. 10. Thus, we conclude that insulated junction thermocouples of the same nominal size may have different transient responses at higher temperatures because each thermocouple has its own temperature dependence. It is likely that differential expansion of the sheath in relation to the MgO insulation (Fig. 11) lowers the compaction pressure in the MgO powder and, consequently, lowers the thermal conductivity of the MgO.

4.3 Effect of Construction on the Transient Response of Insulated Junction Thermocouples

Twelve thermocouples were constructed to study the effect of physical parameters on the response time. All were 0.16-cm-OD, insulated junction, 304 stainless steel sheath, Chromel/Alumel thermocouples made from the same stock. Six of the thermocouples were fabricated to a standard specification,[5] and six were fabricated with significant deviations from the specification. (The deviations are described in Table 1. Also, see Fig. 11.)

Each thermocouple was x-rayed from four different orientations, and enlargements of the images were measured to calculate the mass of the thermocouple junction and of the closure weld. The distances of the junction from the sheath and from the end closure welds were measured from the images. Since the density of the hand-packed MgO could not be measured from x rays, it remained unknown.

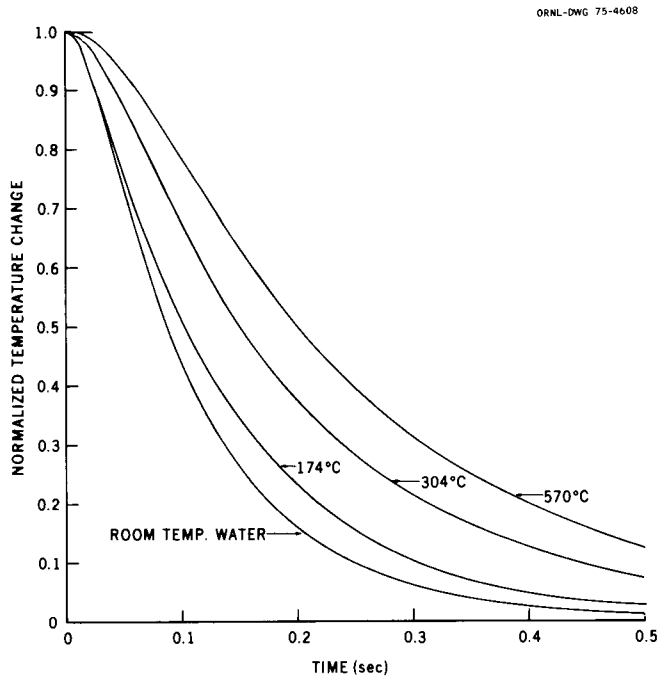

Fig. 9. Transient response of a 0.16-cm-OD, Chromel/Alumel thermocouple in flowing sodium (fluid velocity = 61 cm/sec) at three temperatures. The transient response of the same thermocouple in stirred water at room temperature is shown for comparison.

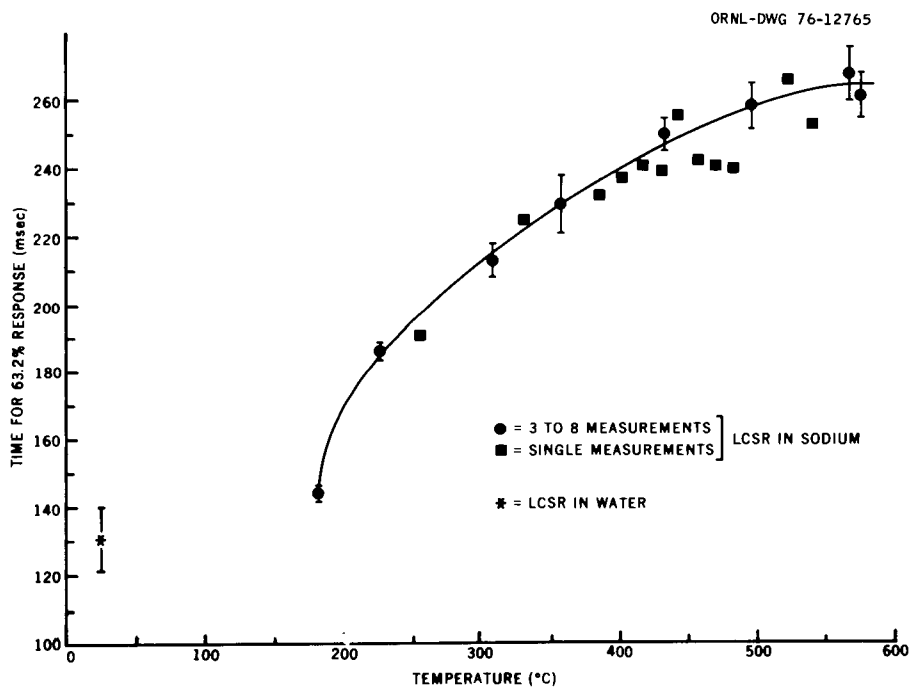

Fig. 10. Response time of a thermocouple as a function of temperature. The specimen was a 0.16-cm-OD, type 304 stainless steel sheathed, insulated junction, Chromel/Alumel thermocouple.

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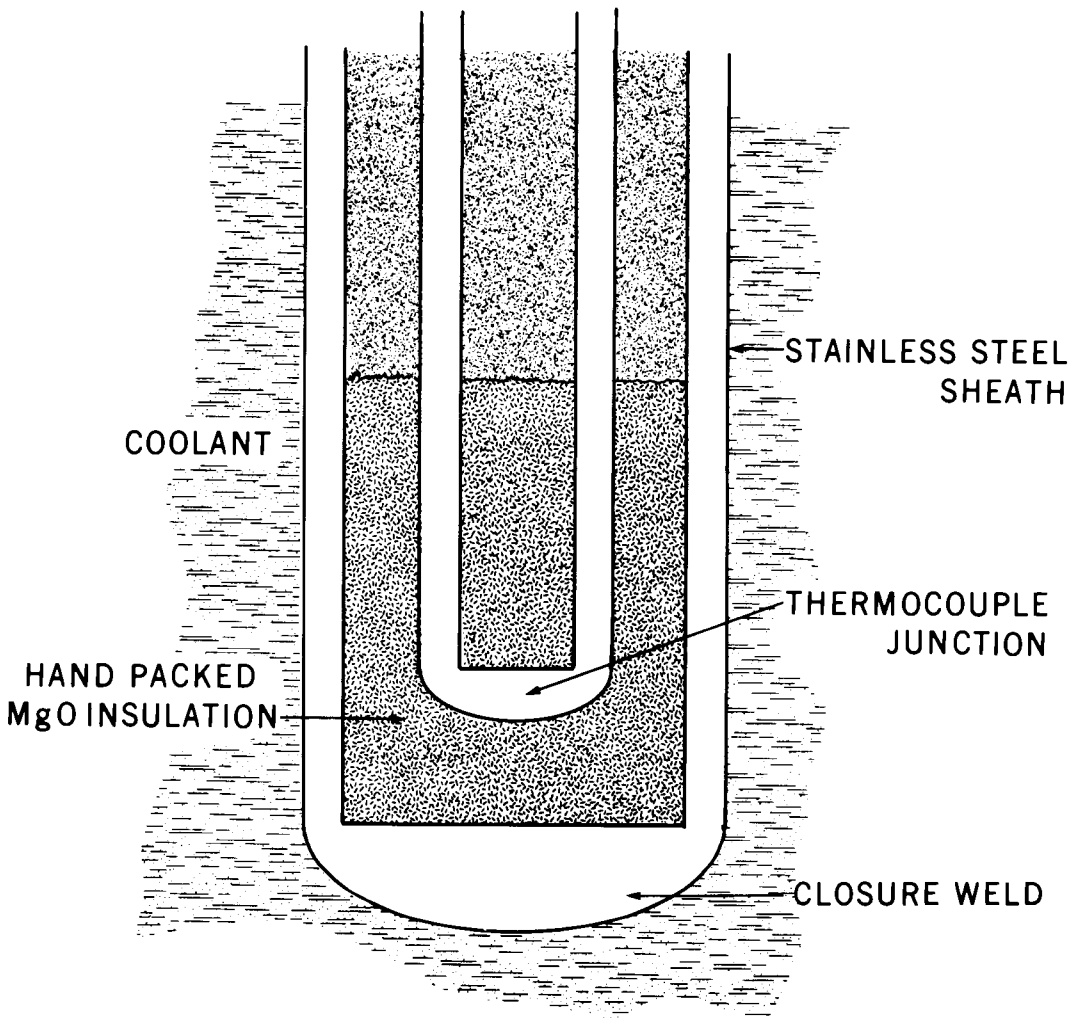

Fig. 11. Insulated junction thermocouple.

The times required for 20% and 63.2% of the total response are given in Table 1 for the thermocouples. There appears to be no correlation between the response time and any of the construction parameters, except possibly the MgO packing. Perhaps, variations of MgO packing around the junction (the one factor that could not be measured) had the greatest effect on the response time.

Table 1. Average time for thermocouples[a] to respond 20% and 63.2% of total response as predicted by the LCSR method

Thermocouple No.	Response Time (msec) for				Characteristics
	20%[b]	Std. Dev.	63.2%[b]	Std. Dev.	
1	46	2	145	2	Construction specification[c]
2	52	1	158	1	Construction specification
3	48	1	158	1	Construction specification
4	71	4	193	10	Construction specification
5	65	10	176	21	Construction specification
6	68	11	181	26	Construction specification
7	62	6	195	10	Large closure weld
8	42	1	138	2	Large junction bead
9	37	2	108	2	Tight MgO (packed tightly)
10	77	1	207	2	Loose MgO (packed loosely)
11	51	3	155	6	No MgO at junction
12	58	19	156	39	Large space between junction and closure weld

[a] 1.6-mm-OD thermocouples in flowing sodium at ∿190°C.

[b] Percentage of total response.

[c] Constructed to RDT Standard C7-6T.

4.4 Effect of Sheath Swaging on Transient Response

Since compaction of the MgO between the junction and the sheath (Fig. 11) was an uncontrolled variable, we examined its effect by further compacting the MgO after the thermocouple was constructed by swaging the sheath to reduce its outside diameter about 8% (Fig. 12). Three results were achieved by the swaging: (1) the transient response was much faster, (2) the transient responses were more consistent among different thermocouples of the same type, and (3) the temperature dependence of the transient response was reduced (Fig. 13).

Table 2 gives the response times of thermocouples before and after being swaged. In all cases, the transient response was faster after swaging, but the amount of change caused by swaging varied widely. This is likely because the initial amount of compaction and thermal conductivity of the hand packed MgO insulation varied. Swaging compacted the MgO to about the same degree, and, consequently, the variation of the response rate among the thermocouples was not as great after swaging.

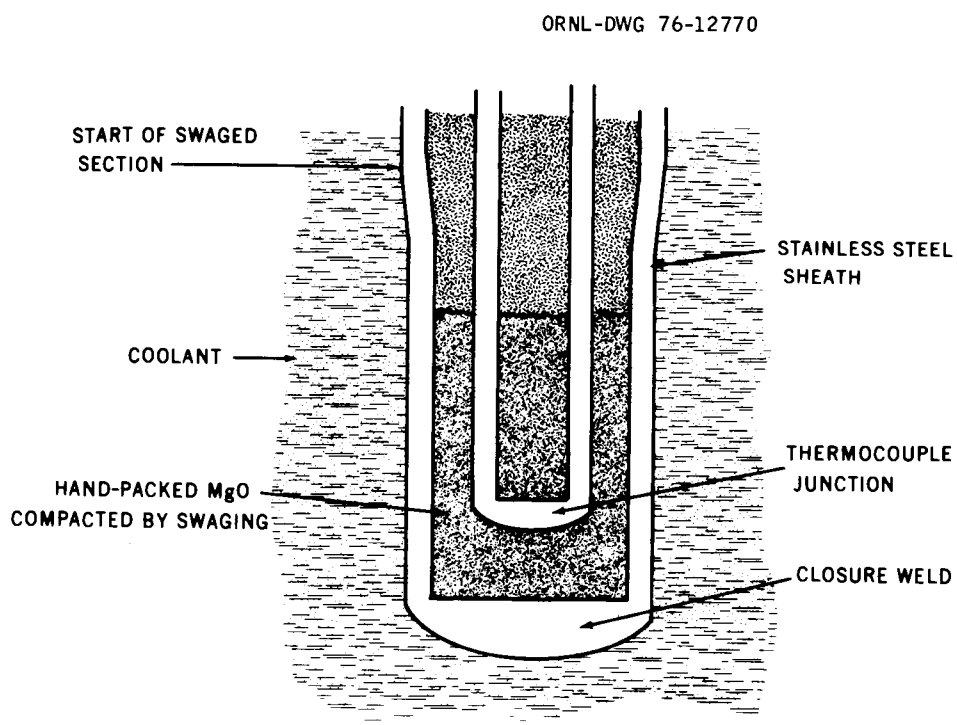

Fig. 12. Insulated junction thermocouple swaged to compact the insulation.

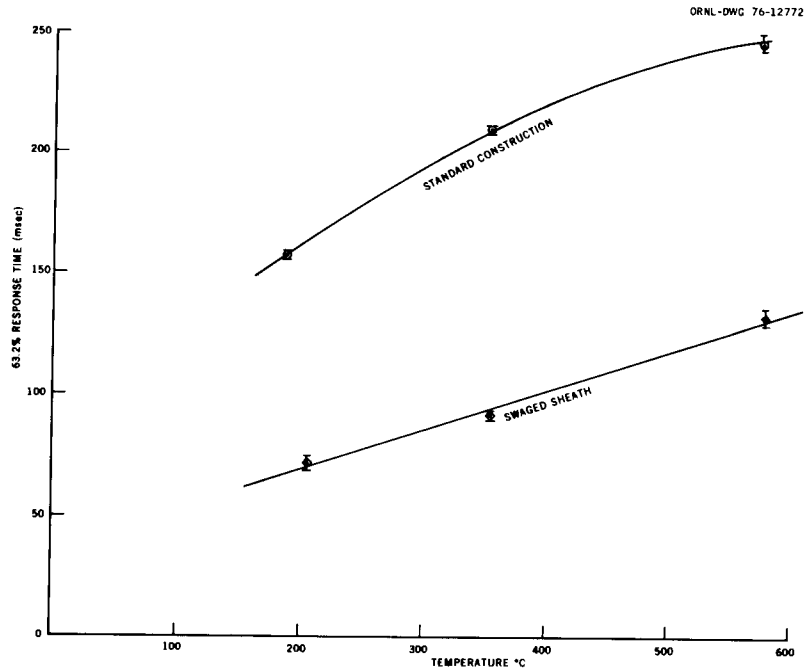

Fig. 13. Response times of a stainless steel sheathed, MgO insulated, Chromel/Alumel thermocouple before and after the sheath was swaged from 0.16 to 0.148 cm OD.

Table 2. Effect of swaging on the average time for insulated junction thermocouples[a] to respond 20% and 63.2% of the total response predicted by the LCSR method

Swaging Step	Sheath OD (mm)	Response Time (msec) for			
		20%[b]	Std. Dev.	63.2%[b]	Std. Dev.
Before	1.59	52	1	158	1
After	1.48	21	3	72	5
Before	1.59	71	4	193	10
After	1.48	31	2	88	6
Before	1.59	68	11	181	26
After	1.48	45	5	118	9
Before	3.18	324	18	918	51
After	2.79	285	40	754	76
Before	3.18	192	61	568	1
After	2.78	189	7	535	21
Before	3.18	598	102	1505	236
After	2.81	226	34	655	13

[a]In flowing sodium at ∿195°C.

[b]Percentage of total response.

4.5 Transient Response Dependence on Sheath Diameter

It has been noted in the literature that the time for 63.2% response of a thermocouple increases roughly as the square of the sheath diameter.[6,7] Plunge tests were used to determine the 63.2% response time for thermocouples made in accordance with RDT Standard C7-6T,[5] some swaged, some insulated junction and some grounded junction, and some thermocouple--thermal-well combinations. The results of the tests shown in Fig. 14 are averages of the response rates of all thermometers of an indicated class. The error bars show the standard deviation of the thermocouples within the class rather than the precision of the test.

These results show that the 63.2% response times of swaged thermocouples and wet wells (thermocouples in a well with a liquid-metal thermal coupling) agree with the values of response times from ref. 7. The RDT Standard[5] C7-6T thermocouples had longer and more scattered response times. The response times of grounded junction thermocouples were not much faster than the response times of thermocouples that were swaged after construction.

The transient response for thermometers immersed in flowing sodium at about 190°C was calculated using the LCSR method. The results plotted in Fig. 15 show that the calculated response is somewhat faster than that measured by the plunge test (Fig. 14), but the relative positions of the data points are retained when Figs. 14 and 15 are compared. The uniform response of the swaged thermocouples versus diameter is in contrast to the scattered response of the standard thermocouples.

4.6 Transient Response of Thermocouples in Wells

Two sizes of wells were used with the same thermocouple to determine the effect of well size on the transient response (Fig. 16). The inside diameter of both wells was 1.8 mm; the outside diameter of one well was 2.26 mm (0.23 mm wall), and of the other was 2.52 mm (0.36 mm wall). The 63.2% response times are listed in Table 3. For plunge tests, the well-thermocouple assembly was plunged into boiling water.

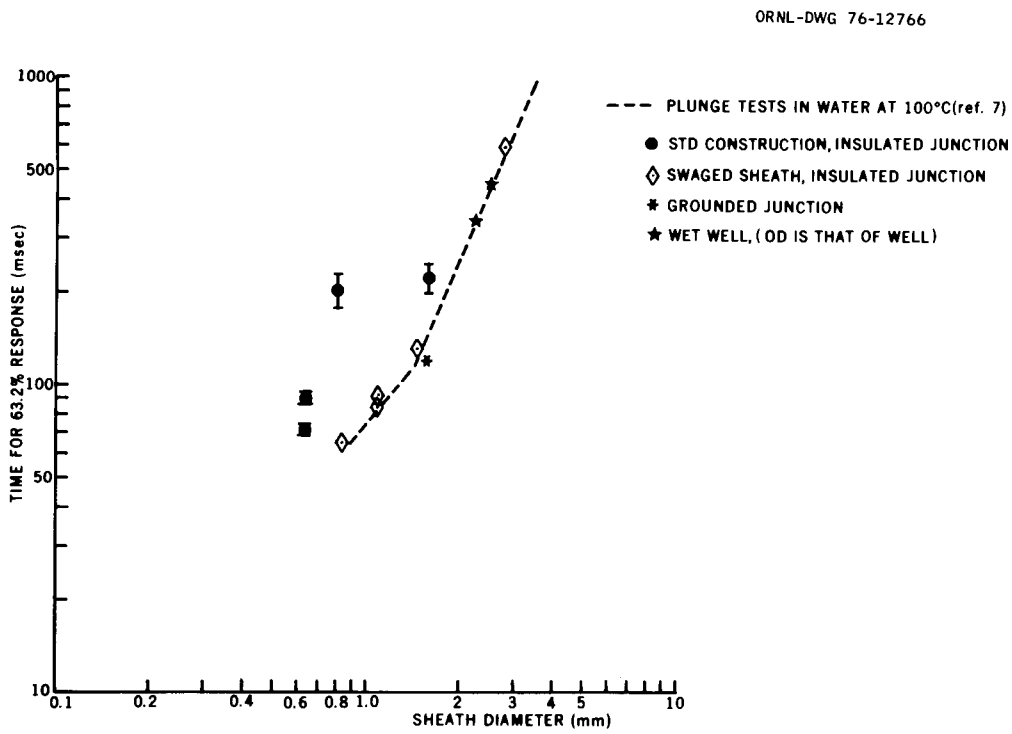

Fig. 14. Response time vs sheath diameter for thermocouples plunged into boiling water.

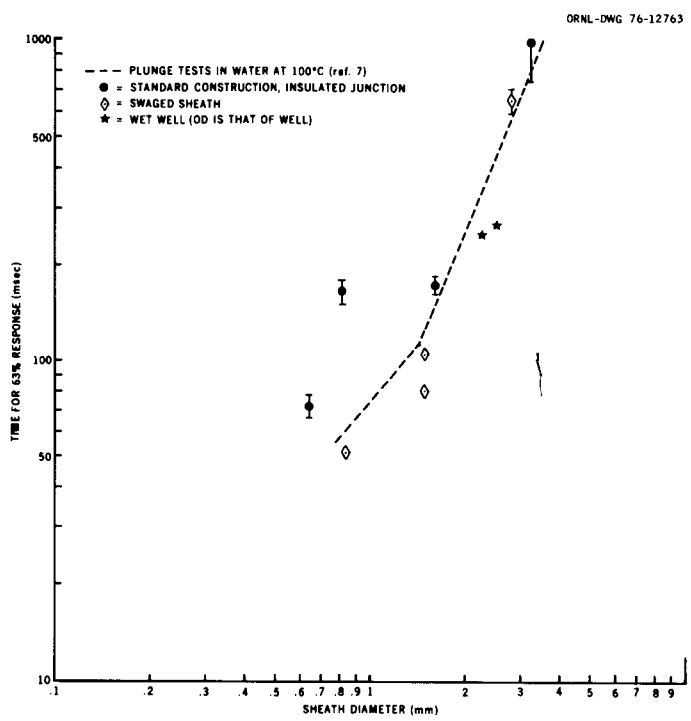

Fig. 15. Response times as calculated by the loop-current step-response method for various thermocouples at 190°C in flowing sodium compared with response time measured by a plunge test at 100°C.

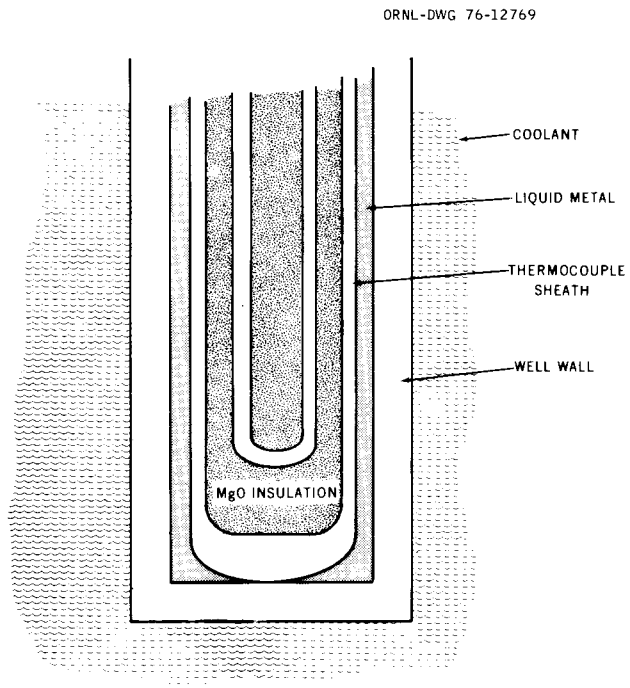

Fig. 16. Insulated junction thermocouple in a thermal well with a heat exchange liquid added.

Table 3. Time for 63.2% response of a 1.6 mm-OD thermocouple in 1.8-mm-ID wells

Type Test	Walls Thickness (mm)	Type Well	Fluid Temp (°C)	Average Time for Response (msec)	Standard Deviation (msec)
Plunge[a]	0.23	Dry[b]	100	2829	54
Plunge	0.36	Dry	100	2861	213
LCSR[c]	0.23	Dry	190	2719	36
LCSR	0.36	Dry	190	3160	16
LCSR	0.23	Wet[d]	190	250	12
LCSR	0.36	Wet	190	267	13
Plunge	0.23	Wet	100	355	10
Plunge	0.36	Wet	100	428	18

[a]Plunge test in water.

[b]Dry well; thermocouple was spring loaded for good contact.

[c]LCSR test in flowing sodium.

[d]Wet well; gallium alloy, a liquid at room temperature, was used as a heat exchange medium.

The results show that poor thermal coupling between the thermocouple sheath and the well wall is the major factor that affects the transient response of the dry-well system. For the thermocouple in the dry well, the LCSR method predicts the same transient response as determined by the plunge test because the actual heat transfer conditions (large ΔT across the thermometer compared to the ΔT at the sheath-fluid interface) match the LCSR model (see Fig. 8 and Table 3).

4.7 Influence of Sheath Closure Thickness on Transient Response

The thickness of the sheath closure was measured from x rays for all insulated junction thermocouples listed in Table 1. Analysis of closure thickness versus response time showed no correlation of these two variables.

Twelve, grounded junction thermocouples (constructed from the same stock as the insulated junction thermocouples) were fabricated. The sheath closure thickness of six thermocouples met RDT Standard C7-6T,[5] (Fig. 17), but the closure of the other six was much thicker. The transient responses of all thermocouples were measured by plunge tests. The average 20% response time was 44.4 msec (3.3 msec standard deviation) for the acceptable closures and 49.3 msec (4.7 msec standard deviation) for the thick sheath closures, a negligible difference.

One of the grounded junction thermocouples with an acceptable sheath closure was thinned by grinding about 0.03 mm from the closure, and then the transient response was measured by a plunge test. This thinning process was repeated; the thickness of the closure was measured for each test from an x ray enlargement such as Fig. 17. The results of these tests are shown in Table 4.

If the first three 63% response times are averaged and compared to the average of the last three measurements of Table 4, the difference is only 6 msec. Thus, although the sheath closure was thinned to 0.12 mm (the wires were 0.263 mm OD), the transient response was not changed significantly by thinning the sheath closure. See Sect. 5.5 for an explanation of this unexpected result.

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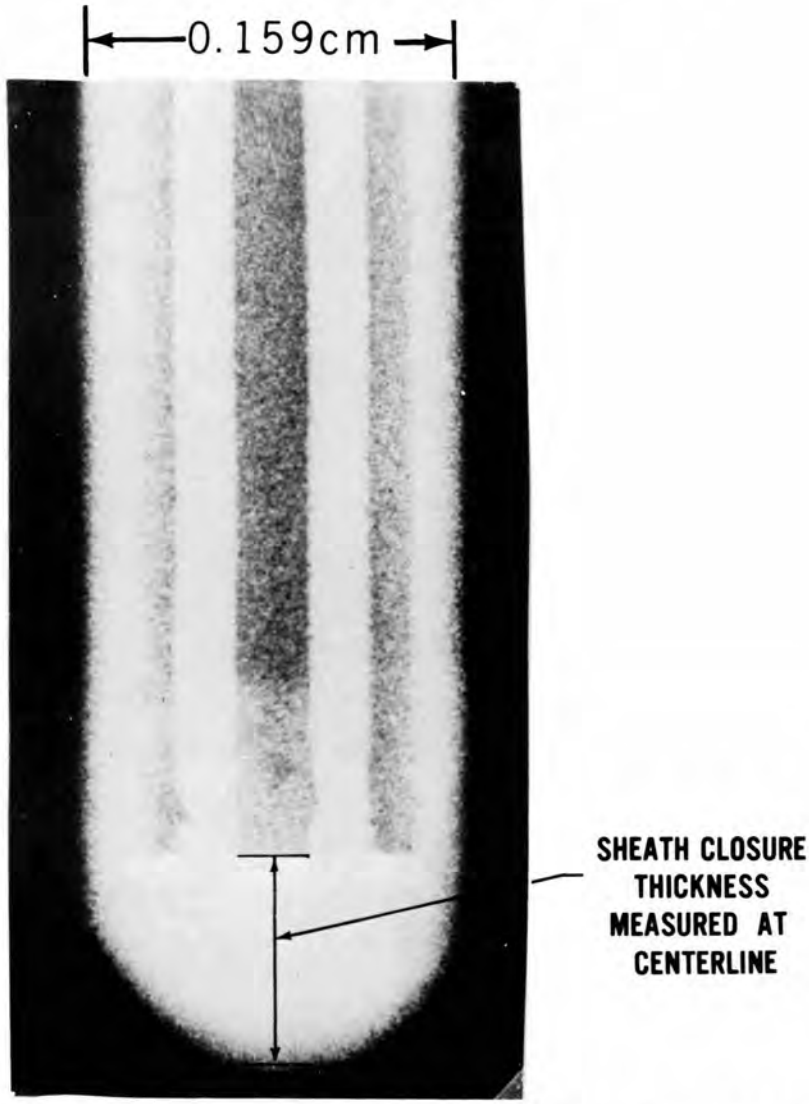

Fig. 17. X ray of type 304 stainless steel sheathed, grounded junction, Chromel/Alumel thermocouple.

Table 4. Mean response time ($\bar{X}$, msec) and standard deviations for various end-closure thicknesses of a 1.59-mm-OD grounded junction thermocouple

End Closure Thickness[a] (mm)	No. of Tests (n)	20% Response[b]		63.2% Response[b]	
		$\bar{X}$	s	$\bar{X}$	s
0.96	4	45	5.0	122	10.
0.91	4	45	2.8	117	3.6
0.87	4	46	3.8	120	8.2
0.80	4	43	1.6	116	4.4
0.75	4	44	3.2	118	6.6
0.71	3	42	2.1	113	4.3
0.64	4	42	1.6	112	1.6
0.58	3	47	5.0	119	8.1
0.51	4	44	1.8	116	3.6
0.45	6	40	3.6	106	4.6
0.42	6	41	1.7	110	4.6
0.37	6	43	2.7	111	7.5
0.35	6	44	2.4	116	4.2
0.34	6	45	2.9	119	7.6
0.29	6	42	2.0	113	4.4
0.22	8	42	2.3	115	5.1
0.18	8	41	2.0	115	8.2
0.12	8	33	2.5	111	7.9

[a]End closure thickness from x-ray measurements.

[b]Response measured by plunge tests into boiling water.

4.8 Error Analysis for LCSR and Plunge Tests

Whether the transient response is measured by plunge tests or calculated from LCSR measurements, there will be an uncertainty in the time required for a given fractional response. The uncertainty has two main sources: (1) from a measured emf not related to the sensor temperature, and (2) from calculations based on an idealized heat flow model. Minor errors are introduced by the process of recording data.

4.8.1 Data Processing Errors

The digital transient recorder used in the experiments (Fig. 4) records 1000 words with a selected constant time interval between words. Each word stores an integer number ranging from 0 to 1023 so that the number is proportional to the emf measured when the word was recorded. This recording process transforms a continuous voltage into a set of numbers.

The effects of digitizing the data were found by using a computer program to generate a continuous known function, using Eqs. (6) and (7). The program was arranged so that the equation parameters could be varied and selected levels of random noise and 60 Hz noise could be imposed on the generated function. The function was then digitized into integer data sets of the same type used in the experiments, and the usual computer fitting routine was used to obtain the (already known) parameters of the model.

The computer fitting routine gives an evaluation of how well the model fits the data. The measure of goodness of fit, E, is

$$E = \sum_{i=0}^{i=1000} (M_i - C_i)^2 , \tag{9}$$

where M_i is the measured integer for word i, and C_i is the calculated real number for word i. Digitizing the function gave an E of about 600 for both the LCSR and the plunge tests. For the plunge test, the 63.2% of response time was calculated as 0.2068 sec, the true value. For the

LCSR test the 63.2% response time was calculated as 0.2055 sec, a 0.6% error (see Table 5).

It will be noted that the LCSR model will have a larger error than the plunge test model for a given data fitting error E. The reason is that the LCSR fitting routine has one more variable, A, (see Eq. 6) than the plunge test.

4.8.2 Errors from Random and 60 Hz Noise

The term "electrical noise" designates small, fluctuating signals imposed on measurements of the emf. The computer simulation of noise used a random addition (fixed maxima) to the data set; however, the real electrical noise may not be random or constant. For example, one source of electrical noise is the emf generated by changing stresses in the thermocouple wire. A thermocouple in a flowing liquid may vibrate, which can generate a noise that corresponds to the vibrational frequency and amplitude. A thermocouple plunged into a flow liquid will produce noise that reflects the stress of impact and momentary vibration. In some cases, the change of temperature will cause stresses from differential expansion; as a result, a burst of noise occurs at a specific zone in the temperature-time relation.

Electrical pickup of 60 Hz is the most common source of fixed frequency emf imposed on the temperature signal. The magnitude of the 60 Hz pickup may vary during the time of the measurements, depending on electrical activity in the vicinity.

The effects of random noise and 60 Hz noise were studied by the use of the program described in Sect. 4.8.1, and the results are given in Table 5. In Table 5, the percentage error is the difference between the known response time and that calculated using digitized data which contains the stated amount of noise and 60 Hz pickup. The fit, E, does not have a one-to-one relation with the percentage error in the data of Table 5; the fit indicates the scatter of the data points about the calculated value, but the percentage error is the deviation of the calculated value from the true value. Also, the difference of the fitting equations produce a larger percentage error in the LCSR calculations for a given value of E than produced in the plunge calculations.

Table 5. Effect of random and 60 Hz noise on measured transient response when [in Eqs. (6) and (7)] $T_0 = 1000$, $T_F = 100$, $R = 1.5$ and $P_1 = -6$, measured over a time, t, from 0 to 2.0 sec

Maximum Amplitude[a]			From Eq. (9)	63.2% Response Time (msec)[b]		
Noise	60 Hz	Type Test	$E \times 10^{-5}$	Calculated	% Error	A, Eq. (6)
0	0	Plunge[c]	0.0006	206.8	0	--
0	0	LCSR[d]	0.0006	205.5	-0.6	0.95
0	10	Plunge	0.501	206.8	0	--
10	0	Plunge	0.350	206.8	0	--
10	10	Plunge	0.918	206.9	+0.05	--
10	10	LCSR	0.918	206.9	+1.5	0.95
10	10	LCSR	0.917	208.4	+0.77	0.80
0	20	Plunge	2.00	206.9	+0.05	--
20	0	Plunge	1.40	207.7	+0.44	--
20	20	Plunge	3.67	207.9	+0.53	--
20[e]	20	LCSR	3.67	213.9	+3.43	0.95
0	40	Plunge	8.01	207.0	+0.10	--
40	0	Plunge	5.59	208.7	+0.92	--
40[e]	0	LCSR	5.60	216.6	+4.74	0.95
40	40	Plunge	14.70	209.0	+1.06	--
40	40	LCSR	14.70	217.9	+5.37	0.95

[a]Maximum amplitude is defined as the maximum value of a fluctuating signal added to T(t) [see Eqs. (6) and (7)] while T(t) changes from 1000 to 100.

[b]Actual 63.2% response time is 206.8 msec.

[c]Equation (6).

[d]Equation (7).

[e]Repeated measurements yielded the same values.

Variations of the values of R, p_i, and the time span have only small effects on the fit of Eqs. (6) and (7) to the data sets of Table 5. The value of A = 0.95 selected for Eq. (6), LCSR test, represents the case where the higher-order terms are very small; a smaller percentage error is obtained for the same fit, E, if A = 0.8 (see Table 5).

4.8.3 Extraneous emf in LCSR Measurements

In LCSR tests, the electric current passed through the thermocouple circuit may excite voltages at different parts of the circuit for the following reasons:

a. The Peltier effect will cause temperature changes at a thermoelectric inhomogeneity. The temperature will increase or decrease depending on the direction of the current and the relative effect of resistive heating. A temperature gradient at a thermoelectric inhomogeneity will create a voltage, which will change as the system returns to ambient temperature. We eliminate the Peltier effect by using a 1-kHz power supply (Fig. 4) for the loop current. Thus, the driving frequency is too high for the temperature fluctuations to respond, and only resistive heating has an effect.

b. The voltage caused by a temperature gradient at a thermoelectric inhomogeneity can be a large fraction of the total measured emf. However such a situation is obvious from an examination of the scope monitor (Fig. 4) because the emf versus time trace is distorted, in comparison to the usual trace (Fig. 2).

Sometimes the inhomogeneity can be eliminated. In sheathed thermocouples, the clamp connecting the thermocouple wire to the plug will produce cold work in the wire. Since the wire is heated more than the plug by the current, a temperature gradient will exist at the inhomogeneity caused by the cold work. If the wire is doubled at the connecting clamp, the temperature gradient is reduced.

If extension wires are cross connected, extraneous emf's will be observed in the LCSR test. We once discovered a mislabeled thermocouple plug by use of an LCSR test that gave a distorted response.

c. Magnetic relaxation in Alumel can cause extraneous emf (see Sect. 3.1).

4.8.4 Factors Affecting Reproducibility of Measurements

Table 4 shows that if the value of E is less than 1×10^5, an individual measurement of the 63.2% response time is accurate to within 1.5% of the true value. This, however, does not indicate that repeated measurements will agree with each other. There are two types of tests used to find if repeated measurements will agree: (1) the test is repeated as rapidly as possible; and (2) an attempt is made to repeat an earlier test by duplicating the test conditions.

The transient response is affected very strongly by the fluid film at the thermometer sheath. Thomson[6] has used plunge tests to show that the 63.2% response time of a 1.59-mm-OD sheathed thermocouple changed from 200 msec to 100 msec when the Reynolds number of the flowing bath increased from 2,000 to 10,000. When a thermocouple is plunged into a flowing bath, the plunging motion and the vibration effectively increase the velocity of the bath relative to the sheath. The motions will be somewhat different for each test.

Plunge tests of type (1) on 1.59-mm-OD sheathed thermocouples show that the 63.2% response time has a standard deviation of 5% of the response time. The same tests on 3.18-mm-OD sheathed thermocouples show a standard deviation of 3% of the response time, presumably because the larger thermocouples vibrated less during the plunge. Thermocouples with sheaths 0.813 mm OD and 0.635 mm OD were stiffened by inserting them through a 3.18-mm-OD tube so that only the junction end of the smaller sheath protruded. These stiffened thermocouples also had a standard deviation of 3% of the 63.2% response time.

LCSR tests of type (1) on 1.59-mm-OD sheathed thermocouples show that the 63.2% response time has a standard deviation equal to 3% of the response time. In Sect. 4.8.1 we pointed out that LCSR tests have greater error than plunge tests for a given amount of noise because of the model used in the fitting. In repeated tests, however, the 1.59-mm-OD sheathed thermocouples had a standard deviation of 5% for plunge tests and 3% for LCSR tests; this is because the thermocouple movement is different for each plunge test and the thermocouple is not moved during the LCSR tests. LCSR tests on thermocouples of other diameters showed no effects of

diameter on the ratio (standard deviation/63.2% response time); the ratio ranged from 7% to 3.9%. Thus, we can expect repeated LCSR tests to agree with a standard deviation of about 4.5% of the 63.2% response time.

We have not made enough tests of type (2) to obtain a meaningful error analysis for either the LCSR or plunge tests. We judge that the result would depend almost entirely on how well the experimental conditions were duplicated.

4.8.5 Errors from Model Failure

The models used for computer fitting of the data for both plunge and LCSR tests are based on the assumption that the thermometer is homogeneous and the heat flow is one-dimensional (radial) in the thermometer. Obviously, there will be some axial heat flow in the thermometer, and there is no way of knowing in advance how well the model will agree with the actual heat flow. The plunge tests show that the model, Eq. (7), fits the actual data (see Fig. 3) to within the noise of the data; thus, model errors in the plunge test are negligible.

In LCSR tests, the main proof that the heat flow is sufficiently radial so that the model will apply is that the LCSR measurements of transient response agree with the plunge test measurements when allowance is made for differences in the tests--mainly vibration stirring during the plunge test. If the assumptions of the model are not correct, the values of R and A in Eq. (6) will be outside the range postulated for the model. The value of R should be between 1 and 2 for radial heat flow in a homogeneous body. The value of A should be positive and less than 1 (see footnote, Section 2.1).

To obtain the data for this report, 42 different, insulated junction, stainless steel sheathed, Chromel/Alumel thermocouples were tested by the LCSR method. Multiple tests were made on the thermocouples, some after they were swaged to smaller sizes. There were 27 thermocouples with a sheath diameter of 1.59 mm, and only two were not fitted well by the model, both having been swaged to the extent that damage to the wires and junction was suspected.

Of six thermocouples with a 3.18-mm-OD sheath, two would not fit the LCSR model because the value of A was almost 1.

Three of five thermocouples with a 0.813-mm-OD sheath did not fit the LCSR model. Three of four thermocouples with a 0.635-mm-OD sheath did not fit the model. We suspect that these small-sheath-diameter thermocouples did not have MgO packed around the junction. This suspicion is confirmed by the much longer than expected time for 63.2% response in plunge tests (Fig. 14) and by the small temperature dependence of the transient response (Sects. 4.2 and 5.4). A poor thermal conductivity at the junction would force a higher proportion of axial heat flow along the wires as the junction cooled, and the model would fail.

4.8.6 Total Errors in LCSR and Plunge Tests

We have shown the errors that can be caused by an improper heat flow model, extraneous voltages, noise, 60 Hz pickup, and digitizing the data. All these effects will influence the fit, E, of the data to the model. Thus, E [Eq. (9)] reflects the summation of all the errors. Table 5 shows only the effects of random noise and 60-Hz pickup. However, it is possible to examine E of the experimental data and to obtain an estimate of the total error. Table 4 shows that when E is less than 1×10^5, the maximum error in finding the 63.2% response time is 1.5% for LCSR tests and negligible for plunge tests.

For this report, we made 572 LCSR tests on insulated junction, Chromel/Alumel thermocouples, and E for only 19 of these was larger than 1×10^5. We made 292 plunge tests, and E for only five was larger than 1×10^5. In none of the tests was E larger than 2×10^5.

The reason that few tests showed a large E is that noisy tests or those with extraneous voltages were observed on the scope monitor (Fig. 4), and steps were taken to eliminate the problem. For example, the heating current was increased to raise the sensor temperature, thus increasing the signal-to-noise ratio.

For individual LCSR tests, the analysis error is about 1.5% of the time for 63.2% response. Individual plunge tests have negligible analysis errors. Tests repeated on thermocouples with 1.59-mm-OD sheaths,

without changing the test conditions, will agree within a standard deviation of about 3% of the 63.2% response time for LCSR tests and about 5% for plunge tests (see Sect. 4.8.4 for variation of repeated tests as a function of sheath diameter).

The problems in obtaining the same response times when repeating or comparing different types of tests on a thermocouple are mainly those of having the same heat transfer conditions at the thermocouple sheath for each test. We used turbulent water for all the plunge tests to minimize the heat transfer problems. Nonetheless, we found the response time to be 20% longer if a plunge test with a 1.59-mm-OD thermocouple was arranged so as to dampen the vibration during a plunge test. For this reason, we state that the differences of transient response shown in Fig. 6 are entirely caused by the different heat transfer conditions between plunge and LCSR test.

5. DISCUSSION OF RESULTS

The LCSR method provides a means of measuring the transient response of a thermometer after it is installed and at operating conditions. The LCSR method can be used for many thermometers which can be heated by an electric current so that an emf with a signal-to-noise ratio of about 20 can be measured. The results imply that for insulated junction thermocouples, and for any other thermometer that will meet the conditions for LCSR testing given in the introduction, the LCSR method will describe the transient response characteristics as accurately as plunge tests.

A common error is to refer to <u>the</u> time constant of a thermometer. An operating thermometer has a time dependence of temperature response which is influenced by its construction and operating conditions. This time dependence can, however, be described accurately only by the use of an equation such as Eq. (8). Our use of the time required for 20% and 63.2% response was for convenience in comparing thermocouples and operating conditions.

The time dependence of the response of a thermometer depends on its temperature and the heat transfer rate at the surface. Thus, it is essential to measure the time-response character of the thermometer at the operating conditions; this can be done only with an in situ test.

5.1 Extraneous emf's

If extraneous emf's, activated by the current passage through the thermometer circuit, are present, they may reduce the precision of the predicted response. Often, useful information can be obtained from extraneous emf's; i.e., bad connections or cross-connected compensating extension wires can be detected from their extraneous emf's (Sect. 4.8.3).

5.2 Poor Heat Transfer at the Sheath Surface

A layer of stagnant fluid or low-conduction deposits on the thermometer surface will change the relative values of the surface-to-internal resistance to heat flow. If the surface resistance to heat flow becomes large (see section 2), the LCSR method will not accurately predict the plunge transient response. The predicted transient response will, however, be slow compared to the transient response before the fluid became stagnant or the encrustration was deposited. Thus, fluid stagnation or deposit buildup could be detected by comparing the LCSR predicted transient responses with those measured earlier on the thermometer.

5.3 Thermal Conductivity Inside the Sheath

The transient response of thermocouples varies approximately as the inverse square of the sheath diameter. Insulated junction thermocouples of the same size and stock will have transient responses that are not uniform, because the MgO insulation hand packed around the junction will vary in compaction from thermocouple to thermocouple (Fig. 11). If the diameter of the thermocouple sheath is reduced in the vicinity of the junction by swaging, the MgO will be compacted to a uniform high density between the junction and the sheath (Fig. 12). The transient response of the swaged, insulated junction thermocouples will then be more uniform, more predictable, and faster.

5.4 Effect of Temperature on Transient Response

The transient response of an insulated junction thermocouple is a function of temperature. The transient response is usually slower as the temperature increases, probably because the sheath expands more than the MgO insulation with the result that the thermal conductivity of the MgO powder (strongly influenced by pressure) is lowered. The temperature dependence of the transient response for the swaged thermocouple is more nearly linear and somewhat lower (Fig. 13). It is speculated that when the sheath is swaged the pressure on the MgO is increased, and the sheath will be in a prestressed condition; some pressure on the MgO will remain as the temperature increases.

The smallest thermocouples (0.813 mm and 0.635 mm OD) we tested showed a slower transient response than expected from the response-size dependence (Figs. 14 and 15) and an essentially zero temperature dependence. This is likely because little or no MgO was packed around the junction.

The conclusion is that neither the time dependence of the temperature response nor the influence of temperature on the time dependence can be predicted in advance for an insulated junction thermocouple. If the sheath is swaged around the junction after the closure weld is made, the time dependence and temperature dependence are much more predictable.

5.5 Fast Response Thermocouples

The average transient response for six grounded junction thermocouples (measured by plunge tests) is shown in Fig. 14 to be about 45% faster than the same size insulated junction thermocouples. Swaging the sheaths of the insulated junction thermocouples made the transient response faster; to within 14% of that of the grounded junction thermocouples.

There was no significant change in the response rate of grounded junction thermocouples as a function of the thickness of the sheath closure weld (Table 4, Fig. 17). This result was contrary to our expectations; it implies that the radial conduction of heat through the sheath is the controlling process rather than the axial conduction of

heat through the closure weld. In retrospect, we should have expected this result since the plunge test data were fitted very well by Eq. (7) which is based on a radial heat flow model (see Fig. 3).

We believe the reason that radial heat flow is the dominant process for the grounded junction thermocouple is that when the sheath closure was welded the thermocouple wires were melted and alloyed with stainless steel from the sheath. This damage zone can sometimes be observed as a neckdown of the wires, see Fig. 17. Thus, the emf generated at the junction of the stainless steel sheath with the alloyed wires would be small; most of the emf would be generated in the wires above the alloyed zone. The radial transfer of heat into the undamaged zone would thus be the major mechanism of heat transfer rather than the axial conduction of heat along the wires.

If our conjecture is correct, the emf from a grounded junction thermocouple is mostly a function of the temperature of the undamaged part of the thermocouple wires, some distance from the welded junction. The results given in Table 4 cast doubt on the belief that the transient response of a grounded junction thermocouple will become faster if the sheath closure is made thinner, unless means are taken to reduce the alloying of the wires at the junction closure.

5.6 Thermocouples in Thermal Wells

The transient response of a thermocouple in a thermal well is dominated by the characteristics of the well. If the well contains no liquid (dry well) to transfer heat from the well's wall to the thermocouple sheath, the dominant factor is the heat transfer in the annulus (Table 3). If a liquid metal that will wet the surfaces is poured in the annulus (Fig. 16), the thermometer can be considered as a thick-walled thermocouple (Fig. 14). The transient response of the wet-well thermocouple assembly is controlled mainly by the diameter of the well; the transient response of the assembly does not change much whether an insulated junction or a grounded junction thermocouple is used in the well.

6. CONCLUSIONS

The transient response of a thermometer cannot be calculated from present knowledge of the thermal properties of the constituents of the thermometer or knowledge of the effects of external heat transfer conditions. Therefore, we conclude that the transient response of a sensor must be measured at its operating condition by use of an in situ method. The major conclusions from this work are listed below.

1. We have developed a loop-current step-response (LCSR) method to calculate the transient response of insulated junction thermocouples and Platinum Resistance Thermometers (PRT). The transient response calculated by the in situ LCSR method was verified by plunge tests. The test specimens were one PRT and 42 insulated junction, Chromel/Alumel thermocouples with sheath diameters ranging from 0.365 mm to 3.18 mm.

2. The use of an equation containing 3 exponential terms, rather than only one term, improves the description of the transient response, including the "dead band" at the start of the transient response.

3. The transient response of sheathed Chromel/Alumel thermocouples became slower as the sheath diameter increased; the change was approximately proportional to the square of the sheath diameter.

4. Grounded junction, sheathed thermocouples had 50% faster transient response than insulated junction thermocouples of the same sheath diameter.

5. The transient response of the insulated junction thermocouples was faster when the insulation was compacted around the junction. The transient response of insulated junction thermocouples was about 50% faster after the sheath diameter was reduced about 8% by swaging at the junction after the closure weld was made. The transient response of the swaged thermocouples was almost as fast as that of grounded junction thermocouples.

6. The transient response was slower when the temperature became higher for insulated junction thermocouples with a sheath diameter larger than 1.5 mm.

7. The transient response of the sheathed thermocouples we tested were not affected significantly by the sheath closure thickness.

8. The transient response of a thermocouple in a thermal well was influenced more by the thermal coupling to the well than by the junction type. Filling the well with liquid metal made the transient response an order of magnitude faster.

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