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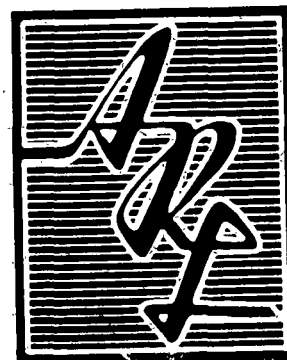
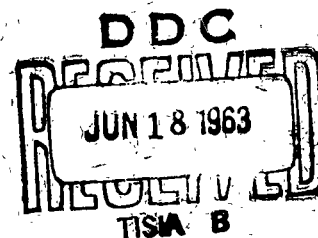
# EXPERIMENTAL EVALUATION OF A DUAL-ELEMENT TRANSDUCER FOR HIGH-TEMPERATURE-GAS MEASUREMENTS

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MOUNTAIN VIEW, CALIFORNIA

MARCH 1963

AERONAUTICAL RESEARCH LABORATORIES  
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CONTRACT AF 33(657)-8411  
PROJECT 7063  
TASK 7063-01

AERONAUTICAL RESEARCH LABORATORIES  
OFFICE OF AEROSPACE RESEARCH  
UNITED STATES AIR FORCE  
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

## FOREWORD

This final technical report was prepared by the Advanced Technology Laboratories, A Division of American Radiator and Standard Sanitary Corporation, Mountain View, California, on Contract AF 33(657)-8411 for the Aeronautical Research Laboratories, Office of Aerospace Research, United States Air Force. The work reported herein was accomplished on Task 7063-01, "Research in Heat Transfer Phenomena," of Project 7063, "Mechanics of Flight," under the technical cognizance of Capt. T. Andrada of the Thermo Mechanics Research Laboratory of ARL.

## ABSTRACT

An experimental evaluation was made of a dual-element transducer, in which gas-stream temperatures are inferred from simultaneous temperature-time measurements of two transducers of equal shape but unequal thermal capacity. The major effort was expended on measuring medium-temperature streams to prove the feasibility of the concept. The accuracy of the transducer was within  $\pm 6\%$  in measurements from 1950 to 2250°F, which was the best experimental accuracy predicted by an earlier analysis of the concept. A limited number of measurements were made with the transducer directly in an oxyacetylene flame. The indicated flame temperatures were 4700°F and 4789°F, which agree within 5% with measurements made by sodium-line-reversal techniques for equivalent combustion conditions in tests conducted at the University of California. In a third series of tests, the transducer was used to traverse a 2100°F gas stream, and from a single record the temperature profile in the stream was calculated within the accuracy to which the true profile could be established. It is concluded that the dual-element transducer is feasible for all the applications tested. Recommendations are made for continued improvement.

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# LIST OF SYMBOLS

| SYMBOL          | DEFINITION                                                                   |
|-----------------|------------------------------------------------------------------------------|
| A               | - surface area of thermocouple ( $\text{ft}^2$ )                             |
| B               | - constant in convection equation (dimensionless)                            |
| C               | - constant of integration                                                    |
| c               | - heat capacity of thermocouple ( $\text{Btu/lb-}^\circ\text{F}$ )           |
| d               | - diameter of thermocouple (ft; in.)                                         |
| F               | - combined geometric and emissivity factor (dimensionless)                   |
| F'              | - geometric factor (dimensionless)                                           |
| h               | - convection coefficient ( $\text{Btu/hr-ft}^2\text{-}^\circ\text{F}$ )      |
| K               | - time-constant ratio = $T_1/T_2$ (dimensionless)                            |
| k               | - thermal conductivity ( $\text{Btu/hr-ft-}^\circ\text{F}$ )                 |
| $N_{\text{Re}}$ | - Reynolds number (dimensionless)                                            |
| R               | - temperature-difference ratio = $(t - t_-)/(t_+ - t)$ (dimensionless)       |
| T               | - temperature ( $^\circ\text{R}$ ), or time constant (sec; hr)               |
| t               | - temperature ( $^\circ\text{F}$ )                                           |
| t'              | - temperature derivative = $dt/d\tau$ ( $^\circ\text{F/sec}$ )               |
| u               | - velocity (ft/hr)                                                           |
| V               | - velocity (ft/sec)                                                          |
| W               | - weight of thermocouple (lb)                                                |
| $\epsilon$      | - emissivity (dimensionless)                                                 |
| $\Theta$        | - temperature ratio = $(t_g - t)/(t_g - t_i)$ (dimensionless)                |
| $\nu$           | - kinematic viscosity ( $\text{ft}^2/\text{hr}$ )                            |
| $\sigma$        | - Stefan-Boltzmann constant ( $\text{Btu/hr-ft}^2\text{-}^\circ\text{R}^4$ ) |
| $\tau$          | - time (sec; hr)                                                             |

## Subscripts

|   |                                    |
|---|------------------------------------|
| 1 | - hollow thermocouple              |
| 2 | - solid thermocouple               |
| + | - at time ( $\tau + \Delta\tau$ )  |
| - | - at time ( $\tau - \Delta\tau$ )  |
| c | - convective heat transfer         |
| f | - gas film on thermocouple surface |
| g | - gas stream                       |
| i | - initial (at $\tau = 0$ )         |
| o | - reference thermocouple           |
| r | - radiant heat transfer            |
| s | - shield or surroundings           |

## I. INTRODUCTION

This program is the second phase of an effort to prove the feasibility of a novel concept for measuring temperatures in the range 5,000 to 10,000°F, which are presently being generated in rockets, arc-heated plasmas, and advanced propulsion systems. Although knowledge of these temperatures is essential for a complete evaluation of the characteristics and performance of the systems, such temperatures are extremely difficult to measure. Furthermore, the problem is usually magnified by the large variations found in a given stream.

In the dual-element approach, the instantaneous stream temperature is inferred from simultaneous temperature-time measurements of two transducers of equal shape but unequal thermal capacity. Analytical studies under the previous contract indicated that the dual-element transducer is feasible and that it should be possible to provide accurate measurements where previously no measurements, or at best only poor ones, could be obtained (ref. 8). Since laboratory confirmation in that program was meager, more detailed experimental work was undertaken in the present program to prove the reliability of the concept.

## II. DISCUSSION

### PRINCIPLE OF THE DUAL-ELEMENT TRANSDUCER

#### A Single Thermoelement in a Gas Stream

The output of a thermal transducer, such as a thermocouple or a resistance thermometer, placed in a hot stream will be a function of the stream temperature, the thermal capacity and geometry of the thermoelement, and the rates of convective and radiant heat exchange between the element and its surroundings. All of these quantities may change with time.

An instantaneous heat balance on such an element in a subsonic stream, as shown in Figure 1, yields

$$h_c A (t_g - t) + h_r A (t_s - t) = Wc \, dt/d\tau \quad (1)$$

Eq (1) can be simplified either 1) when the temperature of the surroundings follows the temperature of the thermoelement and  $(t_s - t) = 0$ ; or 2) when the temperature of the surroundings is equivalent to the gas temperature,  $t_g$ . Defining  $h = h_c + h_r$  in either case, Eq (1) becomes

$$hA (t_g - t) = Wc \, dt/d\tau \quad (2)$$

If  $h$  were known in Eq (2), it would be possible to calculate  $t_g$  from measured values of  $t$  and  $dt/d\tau$ . Unfortunately,  $h$  is a complex function of the flow on the surface of the thermoelement and its value can only be estimated.

The time constant of the thermoelement is defined (ref. 1) as  $T = Wc/hA$ .

#### The Dual-Element Concept

The necessity of knowing  $h$  is eliminated in the dual-element transducer, shown schematically in Figure 2. Two thermoelements of the same outside diameter and area,  $A$ , given the same orientation to the gas stream, have the same heat-transfer coefficient,  $h$ . Their thermal capacities, however, differ. The elements in Figure 2 are made of the same materials, their difference in capacity resulting from making one hollow and one solid. This difference could also be achieved by using different materials for the two thermoelements.

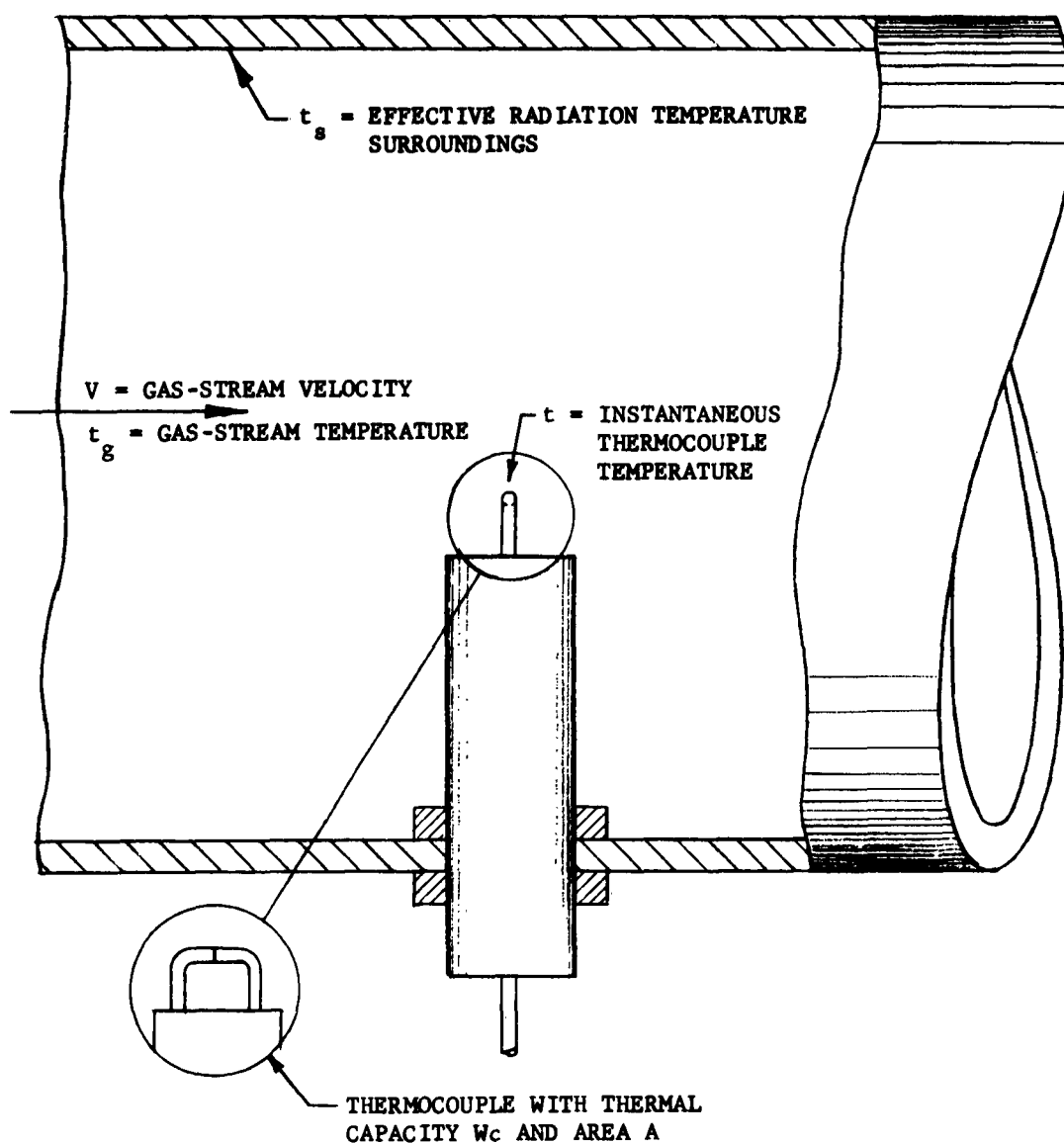
Writing Eq (2) for the two thermoelements:

$$hA (t_g - t_1) = (Wc)_1 \, dt_1/d\tau = (Wc)_1 t_1' \quad (4)$$

$$\text{and} \quad hA (t_g - t_2) = (Wc)_2 \, dt_2/d\tau = (Wc)_2 t_2' \quad (5)$$

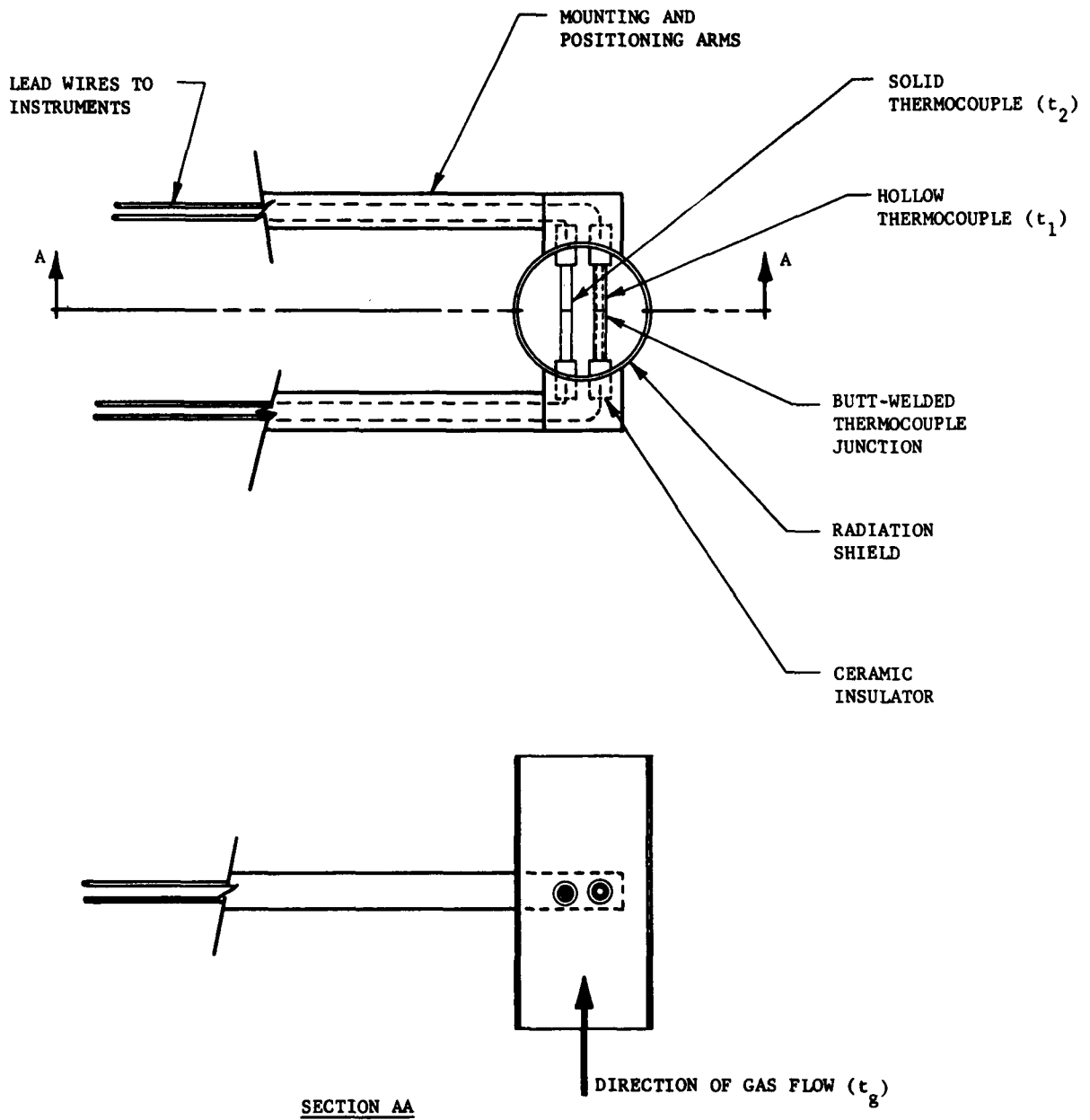
Eliminating  $hA$ , the common value,

$$t_g = \frac{t_1 - K \frac{t_1'}{t_2'} t_2}{1 - K \frac{t_1'}{t_2'}} \quad (6)$$



THERMOELEMENT IN A GAS STREAM

FIGURE 1



SCHEMATIC VIEW OF DUAL-ELEMENT TRANSDUCER

FIGURE 2

where  $K = (Wc)_1/(Wc)_2 = T_1/T_2$ . It is evident that instantaneous values of  $t_g$  can be computed from temperature records of the two thermoelements.

### Measurement of Temperature Distributions

Eq (4) and Eq (5) are instantaneous functions for the two thermoelements. The general result for the gas temperature, Eq (6), is thus equally applicable for computing a transient temperature or a steady temperature. The first case includes measuring the distribution of temperatures in a stream, where the ambient temperature of the transducer changes as a result of its travel across the stream.

It is interesting to note that, when the distribution of temperatures in the stream is steady, it is not necessary to pass the two elements through the stream simultaneously. It is necessary only that the response of each sensor as a function of position in the stream be known, and that the sensors traverse the same path through the stream at identical velocities.

### Additional Applications

When the stream velocity is greater than about Mach 0.5, the recovery temperature begins to deviate from the free-stream temperature,  $t_g$ , of the gas (ref. 1). In other applications, it may not be possible to make the simplification for radiant exchange leading to Eq (2). It should still be possible to measure stream temperatures under these conditions using equations similar to Eq (6), although these relationships will be more complex.

## ACCURACY OF THE DUAL-ELEMENT TRANSDUCER

It was concluded from an analytical study of the dual-element transducer (ref. 8) that an accuracy from  $\pm 6$  to  $\pm 20\%$  was probable in measuring subsonic gas temperatures in the vicinity of  $4900^\circ\text{F}$ . Attainment of the lower value ( $\pm 6\%$ ) was dependent primarily on achieving maximum accuracy in evaluating the derivatives,  $t_1'$  and  $t_2'$ , and the time constant ratio,  $K$ , in Eq (6).

The maximum accuracy resulted when the ratio,  $K$ , was not close to unity. In the approximate range  $0 < K < 0.5$ , the accuracy of the transducer was no longer affected by changes in the time-constant ratio.

The level of the gas temperature did not appear to have a strong effect on the transducer accuracy. In fact, decreased accuracy at lower temperatures seemed possible.

## EVALUATION OF THE CONCEPT

### Experimental Program

The purpose of the present contract was to confirm the reliability of the dual-element transducer as indicated by the studies of the preceding contract. The bulk of the laboratory investigation was performed over a range from  $1500$  to  $2200^\circ\text{F}$ , using an oxyacetylene apparatus available from the preceding contract. Additional testing was performed at about  $5000^\circ\text{F}$  in a second oxyacetylene apparatus available at ATL.



## Design of the Transducer

The general design of the transducer shown in Figure 2 was adopted for the present program. Hollow and solid Chromel/Alumel thermocouples, fabricated from butt-welded cylinders, were selected as thermoelements because of the availability, reliability, and convenience of the materials and configuration.

Three separate thermocouple pairs were tested, having the dimensions shown in Table I. Pairs A and B had equal convective coefficients at the surface but differing values of  $K$ , while the reverse was true for pairs A and C. The dimensions shown for pair C represented the minimum hole size and wall thickness readily machinable on the 3/4-inch-long thermocouple.

The thermocouple pairs were fitted with Chromel and Alumel leads, alumina insulators, and a stainless-steel radiation shield; this assembly was mounted in a supporting arm made from square, stainless-steel tubing (refer to Figures 3, 4, and 5). The radiation shield was fabricated with the dimensions 0.750-inch OD by 0.010-inch wall by 2 inches long. This length and thickness were chosen to give an estimated average time constant of 2.5 seconds for the shield, resulting in a thermal response midway between the two thermocouples in pairs A and B. In this way, the radiant condition of  $(t_g - t) = 0$  in the development of Eq (2) was approximated.

The thermocouple pairs were machined from butt-welded, 1/8-inch bar stock that was certified by the supplier to meet ISA special limits of accuracy ( $\pm 3/8\%$  maximum deviation from NBS tables over the range 530 to 2300°F). Because of the machining required, the thermoelements were recalibrated in the laboratory against laboratory standards after machining, but were found to be still within the above limits of accuracy.

## Additional Apparatus

The mounting arm for the dual-element transducer was connected to a solenoid-actuated pneumatic cylinder (Figure 6). The velocity of injection was regulated by adjusting the pressure acting on the cylinder. In this way it was possible to 1) inject the assembly rapidly to the centerline of the gas stream, approximating a step change in the ambient temperature of the transducer; or 2) move the assembly through the stream at a slower, approximately constant velocity, exposing the transducer to the temperature variations within the stream.

The standard, or "true" temperature of the gas stream was obtained with the reference thermocouple shown in Figure 7. Static measurements (usually at the centerline of the stream) were made after the reference thermocouple had reached steady state. This thermocouple was provided with triple shielding to minimize radiation losses to the surroundings. The gas-stream temperature was obtained from reference-thermocouple measurements as detailed in Appendix A.

The static output from the reference thermocouple was obtained from a Leeds & Northrup Model 8662 millivolt potentiometer. Temperature histories from the dual-element transducer were recorded on a Minneapolis-Honeywell Model 1108 "Visicorder," equipped with Kintel Model 112A wideband dc amplifiers. The Visicorder was calibrated against the L & N potentiometer before each test. The attenuation of the thermocouple outputs was adjusted to make

TABLE I  
THERMOCOUPLE PARAMETERS FOR DUAL-ELEMENT TRANSDUCER

| Thermo-<br>couple<br>Pair | Thermocouple 1 (Hollow Cylinder) |                             |                                   |                         | Thermocouple 2 (Solid Cylinder) |                                   |                         | Time-Constant<br>Ratio,<br>K |
|---------------------------|----------------------------------|-----------------------------|-----------------------------------|-------------------------|---------------------------------|-----------------------------------|-------------------------|------------------------------|
|                           | OD, d <sub>o</sub><br>(in.)      | ID, d <sub>i</sub><br>(in.) | h<br>(Btu/hr-ft <sup>2</sup> -°F) | T <sub>1</sub><br>(sec) | OD, d <sub>o</sub><br>(in.)     | h<br>(Btu/hr-ft <sup>2</sup> -°F) | T <sub>2</sub><br>(sec) |                              |
| A                         | 0.065                            | 0.055                       | 78.3 <sup>a</sup>                 | 1.04 <sup>b</sup>       | 0.065                           | 78.3 <sup>a</sup>                 | 3.65 <sup>c</sup>       | 0.285 <sup>d</sup>           |
| B                         | 0.065                            | 0.043                       | 78.3                              | 2.05                    | 0.065                           | 78.3                              | 3.65                    | 0.562                        |
| C                         | 0.051                            | 0.043                       | 82.1                              | 0.795                   | 0.051                           | 82.1                              | 2.74                    | 0.290                        |

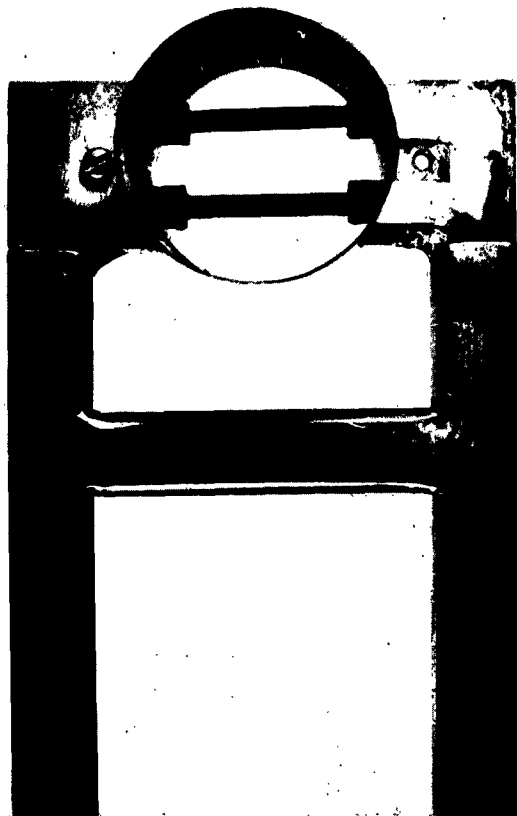
- a. Heat transfer coefficient on thermocouple surface estimated on basis of 1800°F air stream at velocity of 100 ft/sec.
- b. Time constant,  $T_1 = [Wc d_o / 4h] \left( 1 - \frac{d_i^2}{d_o^2} \right)$
- c. Time constant,  $T_2 = Wc d_o / 4h$ .
- d.  $K = T_1 / T_2 = \left( 1 - \frac{d_i^2}{d_o^2} \right)$  ; independent of heat transfer coefficient and properties of materials.



A cylindrical Chromel/Alumel thermocouple with lead wires attached, two insulators, and a radiation shield are shown before assembly.

#### TRANSDUCER COMPONENTS

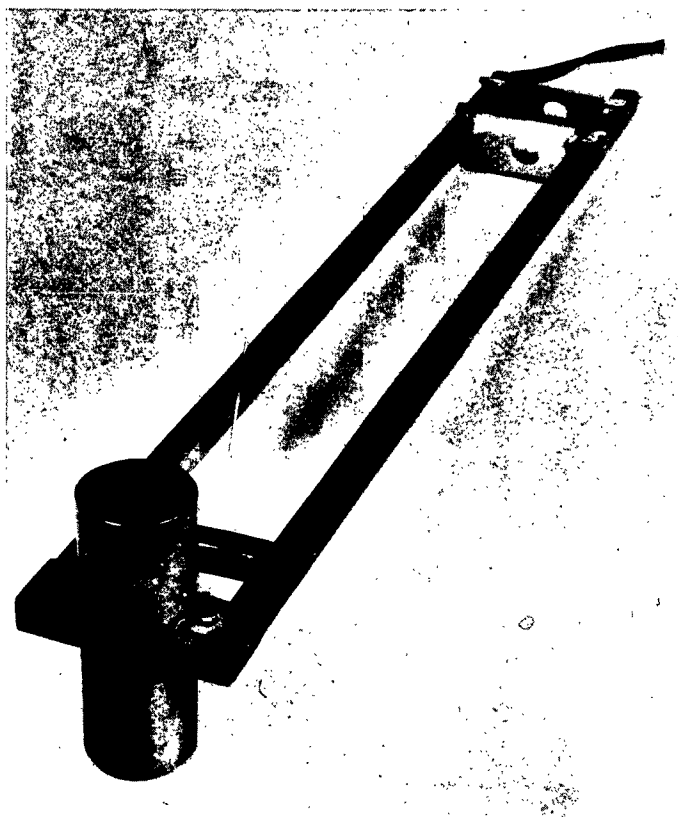
FIGURE 3



Chromel/Alumel thermocouple pair is shown installed with alumina insulators. Cover is removed from right side, exposing lead wires anchored with alumina cement.

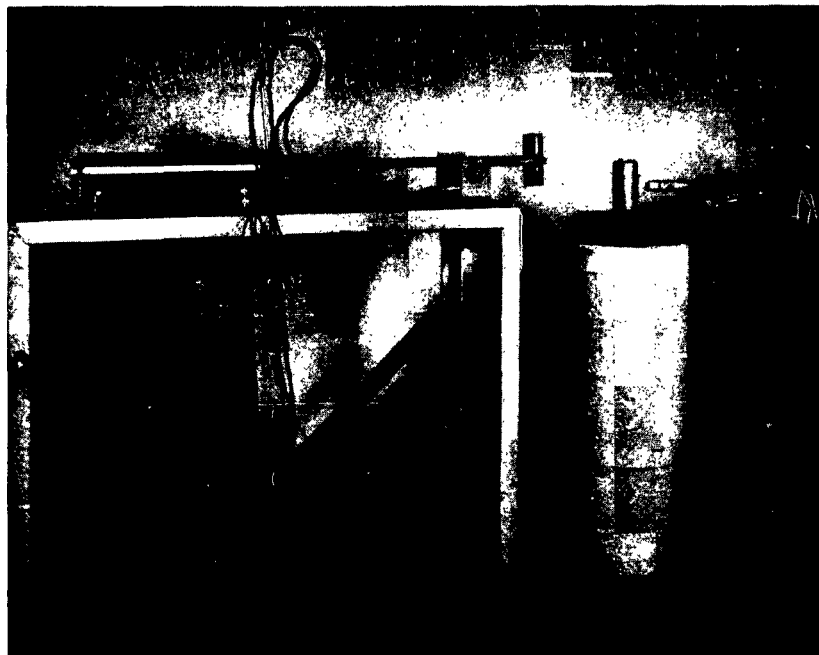
AXIAL VIEW OF DUAL-ELEMENT TRANSDUCER

FIGURE 4



OVER-ALL VIEW OF DUAL-ELEMENT TRANSDUCER

FIGURE 5



The dual-element transducer is shown attached to pneumatic cylinder for rapid injection over stream tube. The reference thermocouple is shown in position at the centerline of the stream tube. The stream tube is insulated with asbestos lagging, as used in testing thermocouple pairs A and C.

CLOSE-UP VIEW OF TEST STAND

FIGURE 6



OVER-ALL VIEW OF REFERENCE THERMOCOUPLE

FIGURE 7

maximum use of the 8-inch chart width on the Visicorder, giving the maximum accuracy in reducing the records to temperature data.

The assembled test stand is shown in Figure 8, with the heating apparatus used for testing in the range 1500 to 2200°F. A close-up view of the oxyacetylene apparatus used for testing at approximately 5000°F is shown in Figure 9.

## EXPERIMENTAL RESULTS

### Verification of Time-Constant Ratio

As mentioned earlier, analysis of the probable accuracy of the transducer (ref. 8) indicated that errors in the value of K have a strong effect on the accuracy with which  $t_g$  can be computed from Eq (6). It was therefore considered essential to determine actual values of K experimentally, for comparison with the predicted values in Table I.

When the transducer is injected into the stream rapidly, a step increase in the ambient temperature of the transducer results. This condition is discussed in Appendix B. Eq (B-2), which applies, can be rearranged to define the dimensionless parameter,  $\Theta$ , or

$$\Theta = \frac{t_g - t}{t_g - t_i} = 1 - \frac{t - t_i}{t_g - t_i} = e^{-\tau/T} \quad (7)$$

When the gas temperature,  $t_g$ , is known from the data, the experimental temperature data,  $t$ , can be expressed as  $\Theta$ , which, when plotted as a function of time on semi-log paper, should result in a straight line. The initial (negative) slope of this line is the inverse of the time constant.

Three preliminary runs were made at low temperatures with thermocouple pair C, and the data were reduced to plot  $\Theta$  as a function of time. The data from Run P-5 are given in Table II and plotted in Figure 10. The results of the three tests are shown in Table III; the average experimental value,  $K = 0.2905$ , is in agreement with the predicted value of 0.290 in Table I.

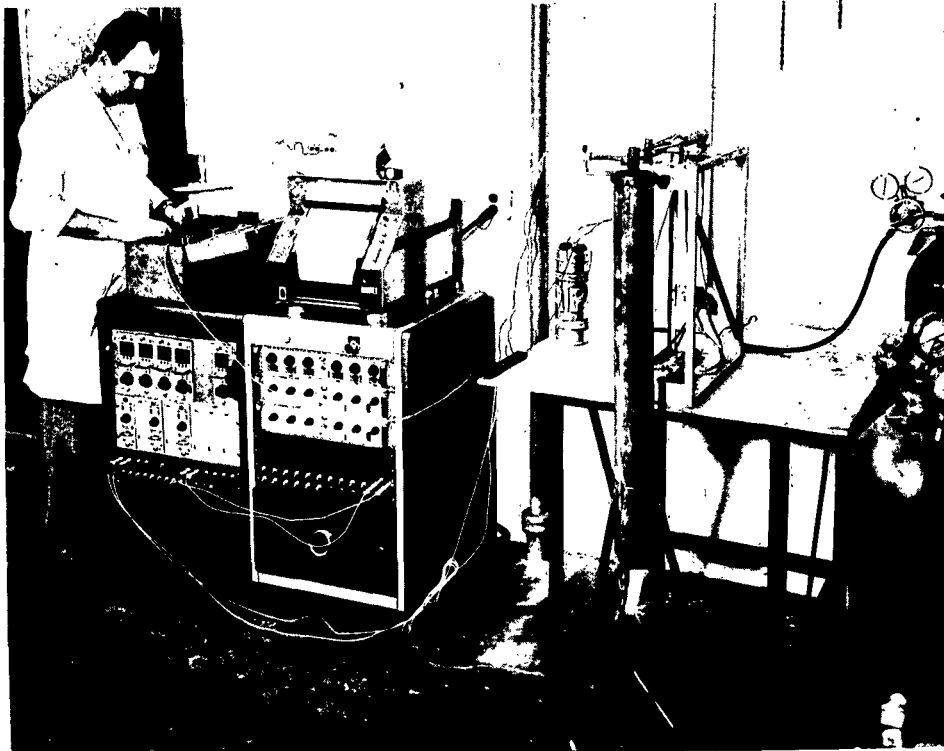
It was subsequently found that an experimental value of K could be obtained from tests in which  $t_g$  was not known, and that this value was also in agreement with Table I. Consequently, separate tests for the determination of the time-constant ratio were not made on thermocouple pairs A and B.

### Gas-Temperature Constant: 1500 to 2300°F

A number of tests were made with thermocouple pairs A, B, and C in which the dual-element transducer was rapidly injected into the centerline of the stream with the apparatus shown in Figure 6. The data from six representative tests were reduced and are presented in Tables IV through IX.

The first efforts to calculate derivatives from these data were based on tangents drawn to the temperature histories plotted on rectangular coordinates. A consistent value of the

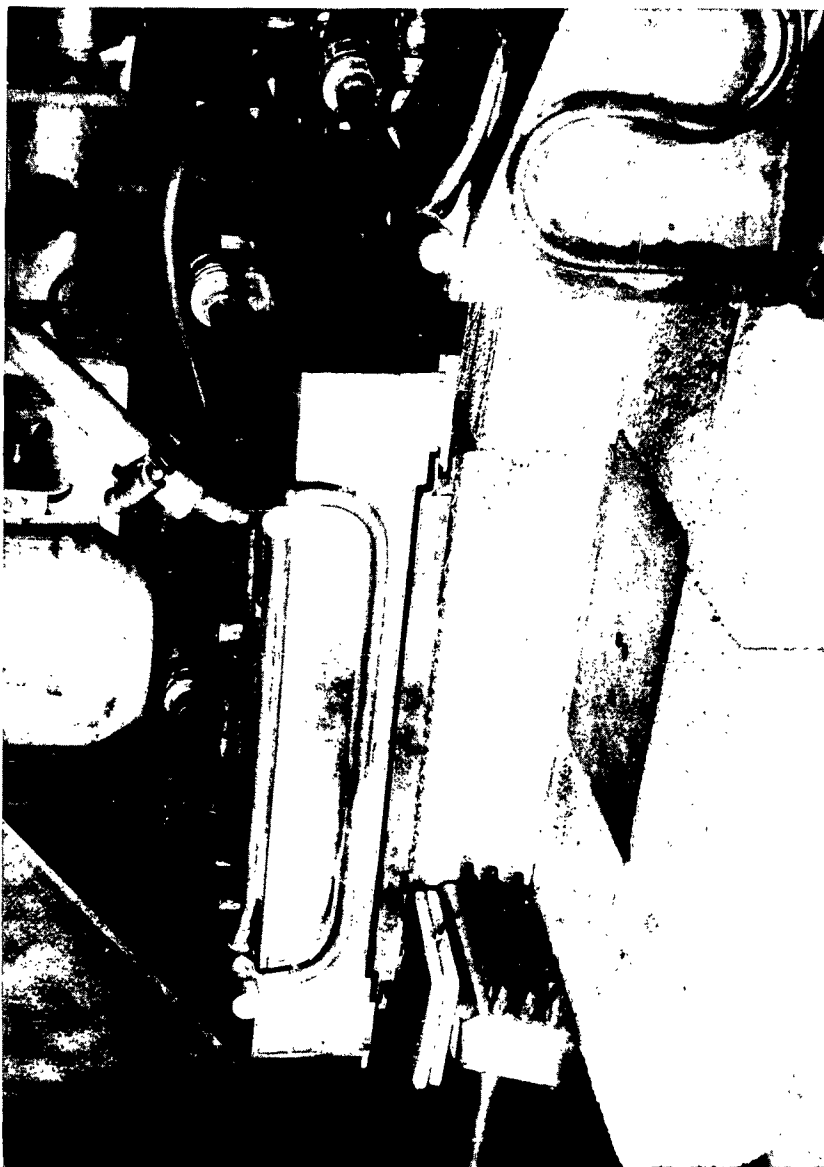




Dual-element transducer shown connected to Visicorder, with reference thermocouple connected to potentiometer. Insulation removed from stream tube, as used in Runs B-1 and B-9.

#### OVER-ALL VIEW OF TEST STAND

FIGURE 8



Apparatus used in Runs B-13 and B-15 includes a 30-tip oxyacetylene torch supplied through flowmeters for close control of fuel-to-oxygen ratio. On the right is a water-cooled exhaust duct; the graphite radiation source above the test section was not operated during the tests.

CLOSE-UP VIEW OF 5000°F TEST STAND

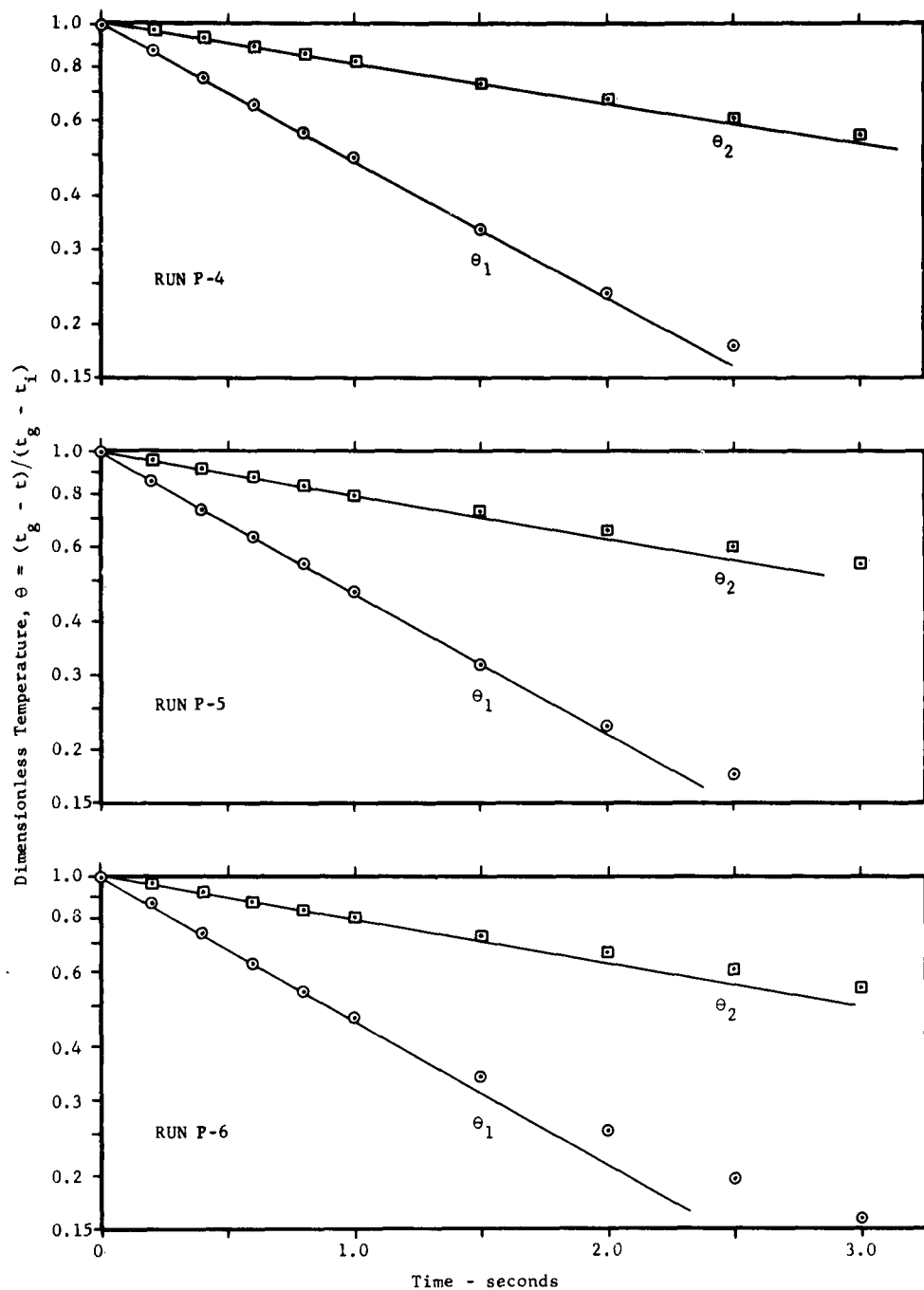
FIGURE 9

TABLE II  
EXPERIMENTAL VERIFICATION OF TIME-CONSTANT RATIO  
FOR THERMOCOUPLE PAIR C

| PRELIMINARY RUN P-5 |       |                               |            |       |                               |            |
|---------------------|-------|-------------------------------|------------|-------|-------------------------------|------------|
| Time                | $t_1$ | $\frac{t_1 - t_i}{t_f - t_i}$ | $\theta_1$ | $t_2$ | $\frac{t_2 - t_i}{t_f - t_i}$ | $\theta_2$ |
| (sec)               | (°F)  |                               |            | (°F)  |                               |            |
| 0                   | 104   | 0                             | 1.000      | 113   | 0                             | 1.000      |
| 0.2                 | 265   | 0.141                         | 0.859      | 165   | 0.047                         | 0.953      |
| 0.4                 | 409   | 0.267                         | 0.733      | 208   | 0.085                         | 0.915      |
| 0.6                 | 524   | 0.367                         | 0.633      | 251   | 0.124                         | 0.876      |
| 0.8                 | 624   | 0.454                         | 0.546      | 296   | 0.165                         | 0.835      |
| 1.0                 | 714   | 0.532                         | 0.468      | 337   | 0.202                         | 0.798      |
| 1.5                 | 888   | 0.685                         | 0.315      | 422   | 0.278                         | 0.722      |
| 2.0                 | 991   | 0.774                         | 0.226      | 493   | 0.342                         | 0.658      |
| 2.5                 | 1051  | 0.827                         | 0.173      | 563   | 0.405                         | 0.595      |
| 3.0                 | 1097  | 0.868                         | 0.132      | 619   | 0.455                         | 0.545      |
| 3.5                 | 1131  | 0.898                         | 0.102      | 675   | 0.506                         | 0.494      |
| 4.0                 | 1139  | 0.904                         | 0.096      | 722   | 0.548                         | 0.452      |
| $\infty$            | 1250  | 1.000                         | 0          | 1224  | 1.000                         | 0          |

TABLE III  
COMPUTATION OF TIME CONSTANTS  
FOR THERMOCOUPLE PAIR C

|      | $T_1$ | $T_2$ | $K = T_1/T_2$ |
|------|-------|-------|---------------|
|      | (sec) | (sec) |               |
| P-4  | 1.398 | 5.02  | 0.278         |
| P-5  | 1.321 | 4.46  | 0.296         |
| P-6  | 1.259 | 4.23  | 0.297         |
| Avg. |       |       | 0.2905        |



EXPERIMENTAL VERIFICATION OF  
TIME-CONSTANT RATIO FOR THERMOCOUPLE PAIR C

FIGURE 10



TABLE V  
EXPERIMENTAL DATA FROM RUN C-5

a. Dual-element Transducer Injected into Centerline of Gas Stream:

| Hollow Thermocouple, $t_1$ |        |             |               | Solid Thermocouple, $t_2$ |             |               |        |
|----------------------------|--------|-------------|---------------|---------------------------|-------------|---------------|--------|
| Time                       | $t$    | $(t - t_-)$ | $(t - t_-)^*$ | $t$                       | $(t - t_-)$ | $(t - t_-)^*$ | $t$    |
| (sec)                      | (°F)   | (°F)        | (°F)          | (°F)                      | (°F)        | (°F)          | (°F)   |
| 0                          | 130.0  |             |               | 130.0                     |             |               |        |
| 0.09                       | 211.0  |             |               | 154.7                     |             |               |        |
| 0.39                       | 442.0  | 231.0       | 234.0         | 232.0                     |             |               |        |
| 0.69                       | 624.3  | 182.3       | 180.0         | 300.0                     | 145.3       | 145.0         |        |
| 0.99                       | 769.0  | 144.7       | 138.5         | 363.5                     |             |               |        |
| 1.29                       | 868.0  | 99.0        | 107.0         | 415.5                     | 115.5       | 116.5         |        |
| 1.59                       | 949.0  | 81.0        | 82.0          | 464.0                     |             |               |        |
| 1.89                       | 1014.5 | 65.5        | 63.3          | 510.3                     | 94.8        | 94.3          |        |
| 2.19                       | 1063.0 | 48.5        | 48.7          | 549.7                     |             |               |        |
| 2.49                       | 1101.0 | 38.0        | 37.6          | 586.7                     | 76.4        | 76.0          |        |
| Avg.                       |        |             | 1.298         |                           |             |               | 1.2403 |

\* Adjusted to best straight line on semi-log graph.

\*\*  $t_1' = 2.92 (t_1 - t_-)$ ;  $t_2' = 1.492 (t_2 - t_-)$ .

+ Extrapolated from semi-log plot of derivatives.

††  $K = t_2'/t_1'$  at  $\tau = 0$ , or  $K = 0.288$ .

b. Reference Thermocouple at Centerline of Gas Stream:

|                                     |                                       |
|-------------------------------------|---------------------------------------|
| Thermocouple temperature:           | $t_o = 1520.5^\circ\text{F}$          |
| Shield temperature:                 | $t_s = 1396.0^\circ\text{F}$          |
| Gas velocity:                       | $V = 32.5 \text{ ft/sec}$             |
| Correction to thermocouple reading: | $(t_g - t_o) = 64.0^\circ\text{F}$    |
| Gas-stream temperature:             | $t_g = 1584.5^\circ\text{F}$          |
| Probable error in gas temperature:  | $\Delta t_g = \pm 21.2^\circ\text{F}$ |

TABLE VI  
EXPERIMENTAL DATA FROM RUN C-7

a. Dual-element Transducer Injected into Centerline of Gas Stream:

| Hollow Thermocouple, $t_1$ |        |             |               |        |             |               |       |             |               | Solid Thermocouple, $t_2$ |             |               |       |             |               |       |             |               |         |
|----------------------------|--------|-------------|---------------|--------|-------------|---------------|-------|-------------|---------------|---------------------------|-------------|---------------|-------|-------------|---------------|-------|-------------|---------------|---------|
| Time                       | $t$    | $(t - t_1)$ | $(t - t_1)^*$ | $t$    | $(t - t_1)$ | $(t - t_1)^*$ | $t$   | $(t - t_1)$ | $(t - t_1)^*$ | $t$                       | $(t - t_2)$ | $(t - t_2)^*$ | $t$   | $(t - t_2)$ | $(t - t_2)^*$ | $t$   | $(t - t_2)$ | $(t - t_2)^*$ | $t$     |
| (sec)                      | (°F)   | (°F)        | (°F)          | (°F)   | (°F)        | (°F)          | (°F)  | (°F)        | (°F)          | (°F)                      | (°F)        | (°F)          | (°F)  | (°F)        | (°F)          | (°F)  | (°F)        | (°F)          | (°F)    |
| 0                          | 110.0  |             |               | 110.0  |             |               | 110.0 |             |               | 110.0                     |             |               | 110.0 |             |               | 110.0 |             |               | 110.0   |
| 0.08                       | 213.3  |             |               | 212.0  | 127.5       |               | 1320  | 144.0       |               | 143.5                     | 39.7        |               | 406   | 143.5       |               | 3.25  | 1368        |               |         |
| 0.18                       | 339.5  | 126.2       | 127.5         | 339.5  | 115.8       | 1.101         | 1215  | 185.0       | 41.0          | 39.7                      | 183.2       | 38.1          | 390   | 183.2       | 38.1          | 3.12  | 2065        |               |         |
| 0.28                       | 455.3  | 115.8       | 115.8         | 455.3  | 106.0       | 1.092         | 1102  | 222.5       | 37.5          | 38.1                      | 221.3       | 36.7          | 374   | 221.3       | 36.7          | 2.95  | 1872        |               |         |
| 0.38                       | 553.5  | 98.2        | 106.0         | 561.3  | 96.2        | 1.101         | 1010  | 258.0       | 35.5          | 36.7                      | 258.0       | 35.3          | 360   | 258.0       | 35.3          | 2.80  | 1877        |               |         |
| 0.48                       | 651.5  | 98.0        | 96.2          | 657.5  | 97.6        | 1.099         | 917   | 293.3       | 35.3          | 35.3                      | 293.3       | 33.9          | 346   | 293.3       | 33.9          | 2.65  | 1883        |               |         |
| 0.58                       | 736.0  | 84.5        | 87.6          | 745.1  | 80.0        | 1.095         | 835   | 325.5       | 32.2          | 33.9                      | 327.2       | 32.6          | 333   | 327.2       | 32.6          | 2.51  | 1881        |               |         |
| 0.68                       | 816.0  | 80.0        | 80.0          | 825.1  | 72.7        | 1.100         | 763   | 357.3       | 31.8          | 32.6                      | 359.8       | 31.3          | 320   | 359.8       | 31.3          | 2.38  | 1870        |               |         |
| 0.78                       | 888.7  | 72.7        | 72.7          | 897.8  | 66.0        | 1.101         | 693   | 387.0       | 29.7          | 31.3                      | 391.1       | 30.0          | 307   | 391.1       | 30.0          | 2.26  | 1873        |               |         |
| 0.88                       | 959.7  | 71.0        | 66.0          | 963.8  | 60.1        | 1.098         | 629   | 418.3       | 31.3          | 30.0                      | 421.1       | 28.9          | 295   | 421.1       | 28.9          | 2.13  | 1850        |               |         |
| 0.98                       | 1025.0 | 65.3        | 60.1          | 1023.9 | 54.5        | 1.102         | 573   | 448.5       | 30.2          | 28.9                      | 450.0       | 27.8          | 284   | 450.0       | 27.8          | 2.02  | 1842        |               |         |
| 1.08                       | 1078.0 | 53          | 54.5          | 1078.4 |             |               |       | 475.0       | 26.5          | 27.8                      | 477.8       | 26.7          | 273   | 477.8       | 26.7          | 1.041 |             |               |         |
| 1.18                       | 1126   | 48          |               |        |             |               |       | 502.5       | 27.5          | 26.7                      | 504.5       | 25.6          | 262   | 504.5       | 25.6          | 1.042 |             |               |         |
| 1.28                       | 1171   | 45          |               |        |             |               |       | 528.3       | 25.8          | 25.6                      | 530.1       | 24.6          | 251.5 | 530.1       | 24.6          | 1.041 |             |               |         |
| 1.38                       | 1214   | 43          |               |        |             |               |       | 555.0       | 26.7          | 24.6                      | 554.7       | 23.7          | 241.5 | 554.7       | 23.7          | 1.039 |             |               |         |
| 1.48                       | 1248   | 34          |               |        |             |               |       | 577.5       | 22.5          | 23.7                      | 578.4       | 22.8          | 233   | 578.4       | 22.8          | 1.040 |             |               |         |
| 1.58                       | 1278   | 30          |               |        |             |               |       | 601.0       | 23.5          | 22.8                      | 601.2       |               |       | 601.2       |               |       |             |               |         |
| Avg.                       |        |             |               |        |             |               |       |             |               |                           |             |               |       |             |               |       |             |               | 1876    |
|                            |        |             |               |        |             |               |       |             |               |                           |             |               |       |             |               |       |             |               | 1.04043 |

\* Adjusted to best straight line on semi-log graph.

\*\* Adjusted to agree with  $(t - t_1)$ .

†  $t_1' = 9.53 (t_1 - t_2)$ ;  $t_2' = 9.82 (t_2 - t_1)$ .

††  $K = t_1'/t_2'$  at  $\tau = 0$ , or  $K = 0.2905$ .

b. Reference Thermocouple at Centerline of Gas Stream:

|                                     |                                       |
|-------------------------------------|---------------------------------------|
| Thermocouple temperature:           | $t_o = 1855.5^\circ\text{F}$          |
| Shield temperature:                 | $t_g = 1885.3^\circ\text{F}$          |
| Gas velocity:                       | $V = 58.0 \text{ ft/sec}$             |
| Correction to thermocouple reading: | $(t_g - t_o) = 103.5^\circ\text{F}$   |
| Gas-stream temperature:             | $t_g = 1959.0^\circ\text{F}$          |
| Probable error in gas temperature:  | $\Delta t_g = \pm 33.7^\circ\text{F}$ |

**TABLE VII**  
**EXPERIMENTAL DATA FROM RUN C-8**

a. Dual-element Transducer Injected into Centerline of Gas Stream:

| Time   | Hollow Thermocouple, $t_1$ |                                 |                                 |                                 |            | Solid Thermocouple, $t_2$ |                                 |                                 |                                 |            |
|--------|----------------------------|---------------------------------|---------------------------------|---------------------------------|------------|---------------------------|---------------------------------|---------------------------------|---------------------------------|------------|
|        | $t$                        | $(t - t_c)$<br>$\Delta t = 0.1$ | $(t - t_c)$<br>$\Delta t = 0.2$ | $(t - t_c)$<br>$\Delta t = 0.3$ | $t_c^{**}$ | $t$                       | $(t - t_c)$<br>$\Delta t = 0.1$ | $(t - t_c)$<br>$\Delta t = 0.2$ | $(t - t_c)$<br>$\Delta t = 0.3$ | $t_c^{**}$ |
| (sec.) | (°F)                       | (°F)                            | (°F)                            | (°F)                            | (°F/sec)   | (°F)                      | (°F)                            | (°F)                            | (°F)                            | (°F/sec)   |
| 0      | 124.3                      |                                 |                                 |                                 | 1720       | 123.0                     |                                 |                                 |                                 | 503        |
| 0.01   | 126.5                      |                                 |                                 |                                 | 1700       | 128.2                     |                                 |                                 |                                 | 501        |
| 0.11   | 282.0                      |                                 |                                 |                                 | 1550       | 179.3                     |                                 |                                 |                                 | 481        |
| 0.21   | 436.5                      |                                 |                                 | 309                             | 1409       | 224.5                     |                                 |                                 |                                 | 462        |
| 0.31   | 570.5                      | 134.0                           | 310.0                           |                                 | 1285       | 270.0                     | 96.3                            |                                 |                                 | 444        |
| 0.41   | 692.0                      | 121.5                           | 255.5                           | 267                             | 1172       | 315.3                     | 90.8                            | 141.6                           | 1.132                           | 425        |
| 0.51   | 807.5                      | 115.5                           |                                 |                                 | 1070       | 356.5                     | 41.0                            |                                 |                                 | 409        |
| 0.61   | 909.0                      | 101.5                           | 217.0                           | 214                             | 977        | 395.5                     | 80.2                            | 125.5                           | 1.131                           | 391.5      |
| 0.71   | 1004.0                     | 95.0                            |                                 |                                 | 890        | 435.0                     | 39.5                            |                                 |                                 | 374        |
| 0.81   | 1084.0                     | 80.0                            | 175.0                           | 178                             | 812        | 471.0                     | 75.5                            | 111.8                           | 1.136                           | 360        |
| 0.91   | 1158.0                     | 74.0                            |                                 |                                 |            | 507.3                     |                                 |                                 |                                 | 346        |
| 1.01   | 1218.0                     | 60.0                            | 134.0                           |                                 | 541.0      | 541.0                     | 70.0                            |                                 |                                 |            |
| 1.11   | 1271.0                     | 53.0                            |                                 |                                 | 572.3      | 572.3                     |                                 |                                 |                                 |            |
| 1.21   | 1322.5                     | 51.5                            | 104.5                           |                                 | 605.3      | 605.3                     | 64.3                            | 98.0                            | 1.131                           | 304.5      |
| 1.31   |                            |                                 |                                 |                                 |            | 634.0                     |                                 |                                 |                                 |            |
| 1.41   |                            |                                 |                                 |                                 |            | 662.0                     | 56.7                            |                                 |                                 |            |
| 1.51   |                            |                                 |                                 |                                 |            | 688.5                     |                                 |                                 |                                 |            |
| 1.61   |                            |                                 |                                 |                                 |            | 713.7                     | 51.7                            | 83.2                            | 1.131                           | 269        |
| 1.71   |                            |                                 |                                 |                                 |            | 739.3                     | 25.2                            |                                 |                                 |            |
| 1.81   |                            |                                 |                                 |                                 |            | 764.0                     | 24.7                            | 75.5                            |                                 |            |
| 1.91   |                            |                                 |                                 |                                 |            | 787.0                     | 23.0                            |                                 |                                 |            |
| 2.01   |                            |                                 |                                 |                                 |            | 811.0                     | 47.0                            |                                 |                                 |            |
| 2.21   |                            |                                 |                                 |                                 |            | 833.7                     | 22.7                            | 69.7                            |                                 |            |
| 2.31   |                            |                                 |                                 |                                 |            | 855.5                     | 44.5                            |                                 |                                 |            |
| 2.41   |                            |                                 |                                 |                                 |            | 878.0                     | 22.5                            |                                 |                                 |            |
| 2.51   |                            |                                 |                                 |                                 |            | 897.0                     | 41.5                            | 63.3                            | 1.1322                          | 2256       |

• Adjusted according to Figures C-1 and C-2.

.. 1 1 4560 -13.1 3130 -13

$$+ \frac{1}{2} (\epsilon_1 - \epsilon_2) \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right)$$
 $\epsilon_2/\epsilon_1$  at  $T = 0$ , of  $\approx 0.292$ .

#### b. Reference Thermocouple at Centerline of Gas Stream:

### The programme for managers

childhood temperature

Medical means

Gas velocity:

### Correction to the manuscript

Gas-stream temperature

### Probable error in gas temperature

2

1



TABLE VIII  
EXPERIMENTAL DATA FROM RUN A-5

a. Dual-element Transducer Injected into Centerline of Gas Stream:

| Time<br>(sec) | Hollow Thermocouple, $t_1$ |                  |                             |                         | Solid Thermocouple, $t_2$ |                  |                             |                         |
|---------------|----------------------------|------------------|-----------------------------|-------------------------|---------------------------|------------------|-----------------------------|-------------------------|
|               | $t$<br>(°F)                | $(t - t_-)$<br>* | $\frac{t - t_-}{t_+ - t_-}$ | $t_1$<br>**<br>(°F/sec) | $t$<br>(°F)               | $(t - t_-)$<br>* | $\frac{t - t_-}{t_+ - t_-}$ | $t_2$<br>**<br>(°F/sec) |
| 0             | 103.7                      |                  |                             | 1050 <sup>†</sup>       | 97.5                      |                  |                             | 303 <sup>†</sup>        |
| 0.08          | 193.0                      |                  |                             |                         | 124.0                     |                  |                             |                         |
| 0.28          | 386.0                      | 191.5            | 1.160                       | 889                     | 180.5                     | 59.2             | 1.058                       | 277.5                   |
| 0.48          | 559.0                      | 165.0            | 1.158                       | 766                     | 236.5                     | 56.0             | 1.072                       | 262.5                   |
| 0.68          | 701.7                      | 142.5            | 1.153                       | 661                     | 288.7                     | 52.2             | 1.059                       | 244.5                   |
| 0.88          | 825.0                      | 123.5            | 1.161                       | 573                     | 338.0                     | 49.3             | 1.069                       | 231                     |
| 1.08          | 932.0                      | 106.5            |                             | 494                     | 382.5                     | 46.1             | 1.051                       | 216                     |
| 1.28          | 1018.7                     |                  |                             |                         | 427.0                     | 43.9             | 1.058                       | 205.5                   |
| 1.48          | 1088.5                     |                  |                             |                         | 468.5                     | 41.5             |                             | 194.5                   |
| Avg.          |                            |                  | 1.1580                      |                         |                           |                  |                             |                         |

\* Adjusted to best straight line on semi-log plot.

\*\*  $t_1' = 4.64 (t_1 - t_-)$ ;  $t_2' = 4.69 (t_2 - t_-)$ .

† Extrapolated from semi-log plot of derivatives.

††  $K = t_2' / t_1'$  at  $\tau = 0$ , or  $K = 0.2875$ .

‡ Value at  $\tau = 0.28$  excluded.

b. Reference Thermocouple at Centerline of Gas Stream:

|                                     |                                       |
|-------------------------------------|---------------------------------------|
| Thermocouple temperature:           | $t_o = 1965.0^\circ\text{F}$          |
| Shield temperature:                 | $t_s = 1761.0^\circ\text{F}$          |
| Gas velocity:                       | $V = 82.5 \text{ ft/sec}$             |
| Correction to thermocouple reading: | $(t_g - t_o) = 135.9^\circ\text{F}$   |
| Gas-stream temperature:             | $t_g = 2100.9^\circ\text{F}$          |
| Probable error in gas temperature:  | $\Delta t_g = \pm 45.0^\circ\text{F}$ |

TABLE IX  
EXPERIMENTAL DATA FROM RUN B-1

Dual-element Transducer Injected into Centerline of Gas Stream:

| Hollow Thermocouple, $t_1$ |        |             |                             | Solid Thermocouple, $t_2$ |       |               |                             |                  |                     |       |
|----------------------------|--------|-------------|-----------------------------|---------------------------|-------|---------------|-----------------------------|------------------|---------------------|-------|
| Time                       | $t$    | $(t - t_-)$ | $\frac{t - t_-}{t_+ - t_-}$ | $t_1^{**}$                | $t$   | $(t - t_-)^*$ | $\frac{t - t_-}{t_+ - t_-}$ | $t_2^{**}$       | $\frac{t_1'}{t_2'}$ | $t_g$ |
| (sec)                      | (°F)   | (°F)        |                             | (°F/sec)                  | (°F)  | (°F)          |                             | (°F/sec)         |                     | (°F)  |
| 0                          | 236.0  |             |                             | 912 <sup>†</sup>          | 234.5 |               |                             | 531 <sup>†</sup> | 1.718 <sup>††</sup> | -     |
| 0.3                        | 489.3  | 253.3       | 1.176                       | 778                       | 387.5 | 152.0         | 1.105                       | 481              | 1.618               | 2135  |
| 0.6                        | 705.0  | 215.7       | 1.172                       | 662                       | 525.0 | 137.5         | 1.105                       | 435.5            | 1.520               | 2085  |
| 0.9                        | 888.7  | 183.7       | 1.182                       | 564                       | 648.5 | 123.5         | 1.111                       | 394              | 1.431               | 2100  |
| 1.2                        | 1044.0 | 155.3       |                             | 477                       | 759.0 | 110.5         | 1.103                       | 354.5            | 1.344               | 2175  |
| 1.5                        | 1185.7 |             |                             |                           | 859.3 | 100.3         | 1.105                       | 321.5            |                     |       |
| 1.8                        | 1309.7 |             |                             |                           | 951.0 | 91.7          |                             | 290.5            |                     |       |
| Avg.                       |        |             | 1.1767                      |                           |       |               | 1.1058                      |                  |                     | 2124  |

\* Adjusted to best straight line on semi-log plot.

\*\*  $t_1' = 3.070 (t_1 - t_-)$ ;  $t_2' = 3.165 (t_2 - t_-)$ .

† Extrapolated from semi-log plot of derivatives.

††  $K = t_2'/t_1'$  at  $\tau = 0$ , or  $K = 0.582$ .

Reference Thermocouple at Centerline of Gas Stream:

Thermocouple temperature:

Shield temperature:

Gas velocity:

Correction to thermocouple reading:

Gas-stream temperature:

Probable error in gas temperature:

$t_o = 2037.5^\circ\text{F}$   
 $t_s = 1811.5^\circ\text{F}$   
 $V = 95 \text{ ft/sec}$   
 $(t_g - t_o) = 155.1^\circ\text{F}$   
 $t_g = 2192.6^\circ\text{F}$   
 $\Delta t_g = \pm 49.7^\circ\text{F}$

stream temperature from Eq (6) could not be obtained by this method; in a preliminary run with pair C, random fluctuations in  $t_g$  of  $\pm 600^\circ\text{F}$  resulted from Eq (6), when the reference temperature of the gas stream was measured at  $1706^\circ\text{F}$ . It was apparent from these large variations that an improved method was needed for evaluating derivatives.

A more systematic method for computing derivatives from the temperature data is described in detail in Appendix B. This method involves evaluation of the temperature increase of each thermocouple over fixed intervals of time. It has two definite advantages:

- 1) The temperature increase is a direct exponential function of time, while the temperature itself is not. This makes it possible to plot the increase over each increment,  $\Delta\tau$ , as a function of time on semi-log paper and to select the best straight line for the data. The consistency of the temperature data is thereby increased.

- 2) The temperature derivative is the product of a constant and the temperature increase. The calculation of the derivatives is therefore very simple.

It must be noted, however, that this method of calculating derivatives is applicable only when the dual-element transducer is exposed to a step change in ambient temperature (i.e., when it is rapidly positioned at some location in the stream), since only this exposure results in a simple exponential response.

The evaluation of derivatives in Tables IV through IX was performed by the above method. The temperature of the gas stream was calculated from Eq (6), and the reference value of the stream temperature is given in each case. A sample calculation for Run C-8 is carried out in detail in Appendix C.

#### Gas-Temperature Constant: $5000^\circ\text{F}$

The dual-element transducer with its injection assembly was moved to the higher temperature oxyacetylene apparatus shown in Figure 9. The flowmeters on the supply lines were adjusted to supply  $310\text{ ft}^3/\text{hr}$  (STP) of both oxygen and acetylene to the torch, or a fuel-to-oxygen ratio of 1. Observation of the flame indicated that both mixing and combustion were completed about 2 inches downstream from the nozzle tips. Accordingly, the transducer was positioned with the thermocouples directly in the flame,  $3\frac{1}{2}$  inches downstream from the tips, and with the centerline of the shield on the centerline of the torch.

Several runs were made in which the transducer was rapidly injected and withdrawn from the flame. Runs B-13 and B-15 were selected for reduction because the settings for chart speed and signal attenuation on the Visicorder appeared the most satisfactory from the records. The data from these two runs are presented in Tables X and XI, and the temperature records from Run B-15 are shown in Figure 11. The calculation of the flame temperature was performed as described in Appendix C.

It is evident that the static, reference thermocouple could not be used for a comparative measurement near  $5000^\circ\text{F}$ , but comparable measurements have been made in oxyacetylene flames at the University of California (ref. 7). The torch at the University was identical to that used by ATL and the flow controls were similar. Their measurements of temperature,

TABLE X  
EXPERIMENTAL DATA FROM RUN B-13

Dual-element Transducer Injected into Centerline of Gas-Stream:

| Time<br>(sec) | Hollow Thermocouple, $t_1$ |                     |                             |                   |                     | Solid Thermocouple, $t_2$ |                     |                             |                   |                   |
|---------------|----------------------------|---------------------|-----------------------------|-------------------|---------------------|---------------------------|---------------------|-----------------------------|-------------------|-------------------|
|               | $t$                        | $(t - t_0)^*$       | $\frac{t - t_0}{t_0 - t_1}$ | $t_1^{**}$        | $\frac{t_1'}{t_2'}$ | $t$                       | $(t - t_0)^*$       | $\frac{t - t_0}{t_0 - t_1}$ | $t_2^{**}$        | $t_g$<br>(°F)     |
|               | (°F)                       | (°F)                |                             | (°F/sec)          |                     | (°F)                      | (°F)                |                             | (°F/sec)          |                   |
|               |                            | $\Delta\tau = 0.06$ |                             |                   |                     |                           | $\Delta\tau = 0.06$ |                             |                   |                   |
| 0             | 255.0                      | -                   |                             | 3730 <sup>†</sup> |                     | 208.7                     | -                   |                             | 2130 <sup>†</sup> |                   |
| 0.003         | 263.7                      | -                   |                             |                   |                     | 210.8                     | -                   |                             |                   |                   |
| 0.023         | 338.0                      | -                   |                             |                   |                     | 253.5                     | -                   |                             |                   |                   |
| 0.043         | 409.3                      | -                   |                             |                   |                     | 294.7                     | -                   |                             |                   |                   |
| 0.063         | 480.0                      | 217.0               | 1.080                       | 3480              |                     | 336.5                     | 125                 | 1.041                       | 2035              | 6700              |
| 0.083         | 550.0                      | 211.0               | 1.069                       | 3385              |                     | 377.0                     | 123.5               | 1.047                       | 2010              | 5160              |
| 0.103         | 617.0                      | 207.7               | 1.078                       | 3330              |                     | 417.5                     | 122                 | 1.048                       | 1985              | 5290              |
| 0.123         | 681.0                      | 201.0               | 1.070                       | 3225              |                     | 455.3                     | 120                 | 1.043                       | 1952              | 4500              |
| 0.143         | 742.7                      | 197.5               | 1.071                       | 3170              |                     | 495.0                     | 118                 | 1.043                       | 1920              | 4760              |
| 0.163         | 806.0                      | 192.5               | 1.070                       | 3085              |                     | 532.3                     | 116.5               | 1.040                       | 1898              | 4400              |
| 0.183         | 867.0                      | 188.0               | 1.074                       | 3015              |                     | 570.5                     | 115                 | 1.045                       | 1871              | 4340              |
| 0.203         | 930.0                      | 184.0               | 1.076                       | 2950              |                     | 607.0                     | 113                 | 1.042                       | 1840              | 4450              |
| 0.223         | 987.0                      | 180.0               |                             | 2885              |                     | 646.0                     | 112                 |                             |                   |                   |
| 0.243         | 1044.0                     | 175.0               |                             | 2805              |                     | 683.0                     | 110                 |                             |                   |                   |
| 0.263         | 1101.0                     | 171.0               |                             | 2740              |                     | 719.0                     | 108.5               |                             |                   |                   |
| Avg.          |                            |                     | 1.0735                      |                   |                     |                           |                     | 1.0436                      |                   | 4700 <sup>‡</sup> |

\* Adjusted to best straight line on semi-log plot.

\*\*  $t_1' = 16.03 (t_1 - t_0); t_2' = 16.28 (t_2 - t_0)$ .

† Extrapolated from semi-log plot of derivatives.

‡  $K = t_2'/t_1'$  at  $\tau = 0$ , or  $K = 0.571$ .

‡ Value at  $\tau = 0.063$  excluded.

TABLE XI  
EXPERIMENTAL DATA FROM RUN B-15

Dual-element Transducer Injected into Centerline of Gas-Stream:

| Time<br>(sec) | Hollow Thermocouple, $t_1$ |                                            |                             |                        | Solid Thermocouple, $t_2$ |                                            |                             |                        |
|---------------|----------------------------|--------------------------------------------|-----------------------------|------------------------|---------------------------|--------------------------------------------|-----------------------------|------------------------|
|               | $t$<br>(°F)                | $(t - t_-)$<br>$\Delta\tau = 0.06$<br>(°F) | $\frac{t - t_-}{t_+ - t_-}$ | $t_1^{**}$<br>(°F/sec) | $t$<br>(°F)               | $(t - t_-)$<br>$\Delta\tau = 0.06$<br>(°F) | $\frac{t - t_-}{t_+ - t_-}$ | $t_2^{**}$<br>(°F/sec) |
| 0             | 217.0                      | -                                          | -                           | 3570 <sup>†</sup>      | 185.2                     | -                                          | -                           | 2020 <sup>†</sup>      |
| 0.017         | 284.7                      | -                                          | -                           |                        | 220.7                     | -                                          | -                           |                        |
| 0.037         | 352.0                      | -                                          | -                           |                        | 260.0                     | -                                          | -                           |                        |
| 0.057         | 423.3                      | -                                          | -                           |                        | 299.2                     | -                                          | -                           |                        |
| 0.077         | 489.0                      | 207.5                                      | 1.052                       | 3370                   | 341.0                     | 119                                        | 1.026                       | 1958                   |
| 0.097         | 556.7                      | 204                                        | 1.051                       | 3315                   | 377.0                     | 118                                        | 1.027                       | 1941                   |
| 0.117         | 622.3                      | 200.5                                      | 1.055                       | 3260                   | 415.0                     | 117                                        | 1.021                       | 1925                   |
| 0.137         | 684.5                      | 197                                        | 1.052                       | 3200                   | 457.5                     | 116                                        | 1.019                       | 1908                   |
| 0.157         | 751.3                      | 194                                        | 1.054                       | 3150                   | 493.0                     | 115                                        | 1.019                       | 1891                   |
| 0.177         | 814.0                      | 190                                        | 1.050                       | 3090                   | 531.2                     | 114.5                                      | 1.022                       | 1882                   |
| 0.197         | 874.3                      | 187                                        | 1.050                       | 3040                   | 569.7                     | 114                                        | 1.028                       | 1876                   |
| 0.217         | 935.0                      | 184                                        |                             | 2990                   | 606.0                     | 113                                        |                             | 1859                   |
| 0.237         | 995.5                      | 181                                        |                             | 2940                   | 644.0                     | 112                                        |                             | 1842                   |
| 0.257         | 1052.5                     | 178                                        |                             | 2890                   | 680.0                     | 111                                        |                             | 1827                   |
| 0.357         | 1329.0                     |                                            |                             |                        | 859.3                     |                                            |                             |                        |
| 0.457         | 1520.5                     |                                            |                             |                        | 987.0                     |                                            |                             |                        |
| 0.557         | 1487.5                     |                                            |                             |                        | 974.5                     |                                            |                             |                        |
| 0.657         | 1448.0                     |                                            |                             |                        | 964.0                     |                                            |                             |                        |
| Avg.          |                            |                                            | 1.0520                      |                        |                           |                                            | 1.0231                      |                        |
|               |                            |                                            |                             |                        |                           |                                            |                             | 4789 <sup>‡</sup>      |

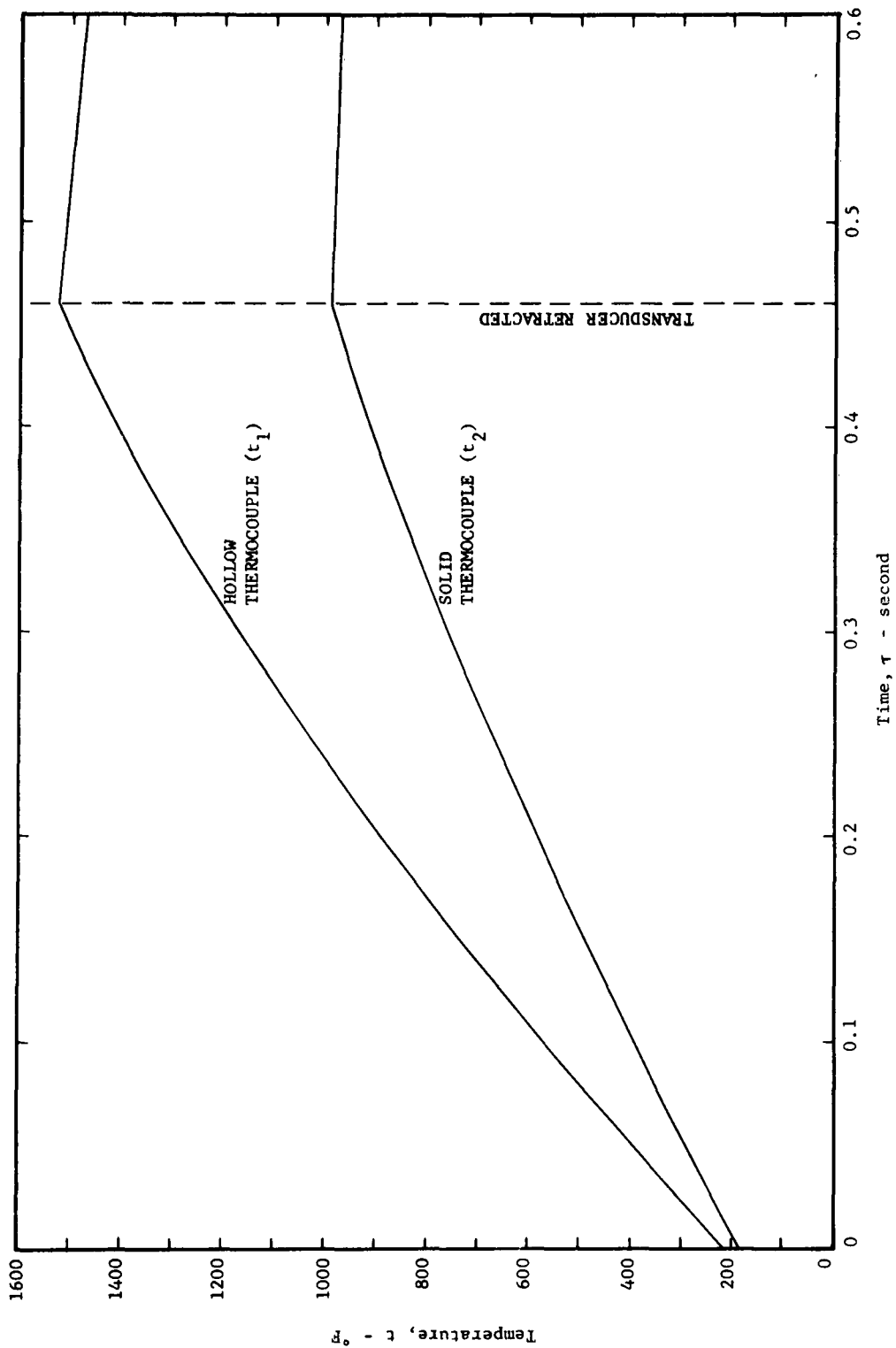
\* Adjusted to best straight line on semi-log paper.

\*\*  $t_1' = 16.26 (t_1 - t_-)$ ;  $t_2' = 16.45 (t_2 - t_-)$ .

† Extrapolated from semi-log plot of derivatives.

††  $K = t_2'/t_1'$  at  $\tau = 0$ , or  $K = 0.566$ .

‡ Value at  $\tau = 0.077$  excluded.



DUAL-ELEMENT TRANSDUCER RECORD IN 5000°F FLAME  
(DATA FROM TABLE XI, RUN B-15)

FIGURE 11

made by the sodium-line-reversal technique at locations downstream from the tip and at a fuel-to-oxygen ratio of 1.0, are shown in Figure 12, where they are compared to the results obtained in Tables X and XI.

#### Measurement of Temperature Distribution

The low-temperature apparatus shown in Figure 8 was used to demonstrate the application of the transducer to measurement of transient temperatures. A traverse of half the diameter of the gas stream was selected, with the transducer coming to rest at approximately the centerline. The pressure on the pneumatic cylinder was adjusted for a traverse velocity of approximately 1.8 in./sec, since this resulted in a maximum thermocouple temperature of about 1200°F at the centerline. Radiation losses were thus minimized throughout the traverse.

The motion of the transducer was found to be approximately linear over the region of primary interest, i.e., the region of maximum temperature change near the wall. To establish the relation of position and time to the temperature of the thermocouples, the shaft on a linear potentiometer was attached to the transducer arm. With a second resistor and a battery in series, the voltage drop across the potentiometer was statically calibrated as a function of transducer position. After calibration, the transient voltage drop was recorded simultaneously with the thermocouple outputs on the Visicorder.

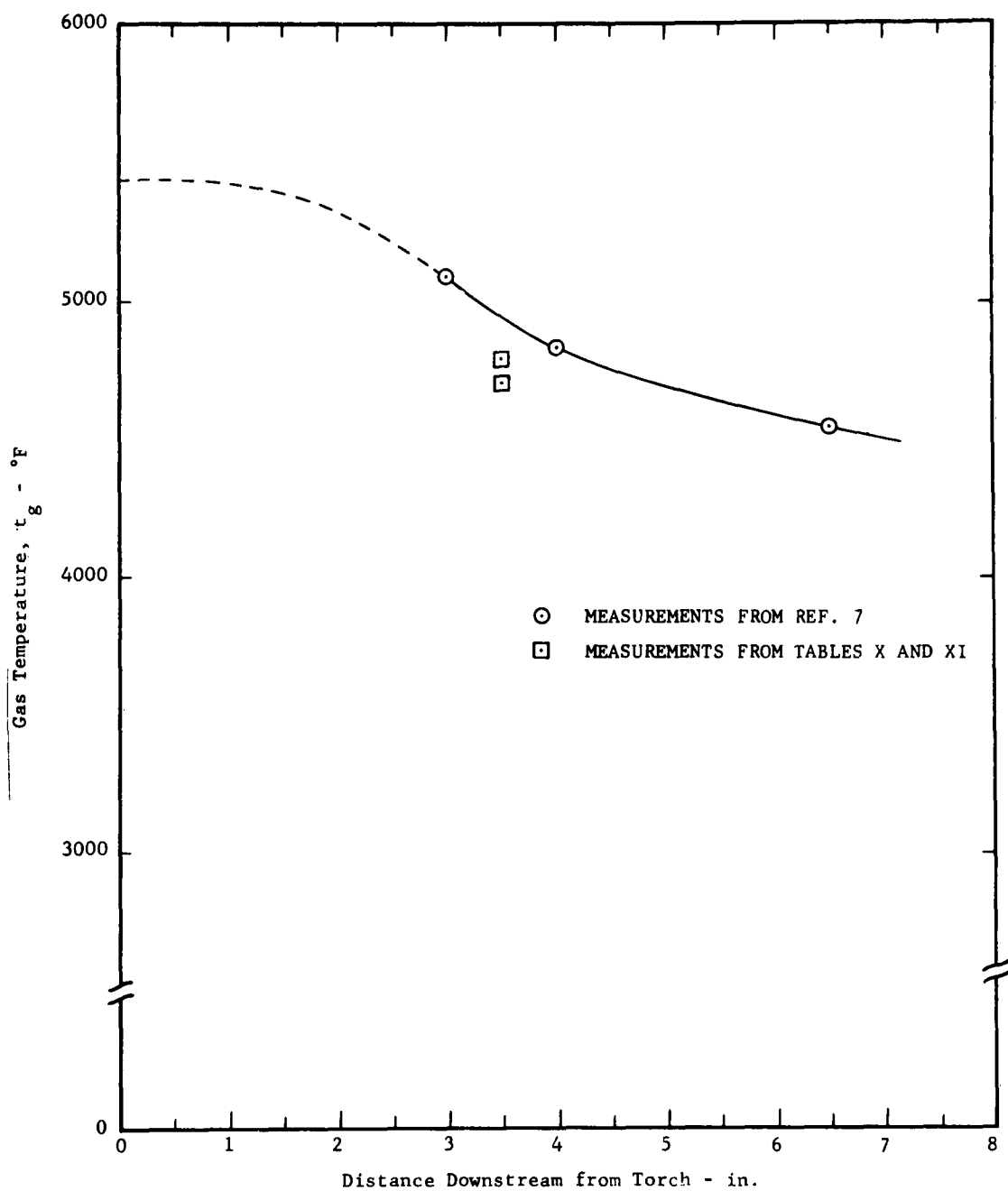
Table XIIa contains the data from Run B-9. The data from the two thermocouples were reduced as a function of true time indicated on the Visicorder record. By evaluating temperature increases over time increments of 0.2 second, it was found that the hollow and solid thermocouples entered a region of approximately constant gas temperature at about 1.3 and 1.7 seconds, respectively. This was indicated by a transition from nonlinearity to linearity when the temperature increases were plotted on semi-log paper. Beyond this time, derivatives were evaluated according to the constant-temperature method in Appendix C.

The derivatives during the earlier time of changing temperature were evaluated from tangents drawn to the temperature records plotted on rectangular coordinates. The slope method proved satisfactory in this case because the slopes changed rapidly in this region.

The centerlines of the two thermocouples (ref. Figure 4) are  $\frac{1}{4}$  inch apart. From the position record, it was determined that the hollow thermocouple preceded the solid thermocouple by 0.14 second in the region of changing temperature. Accordingly, the data from the solid thermocouple in Table XIIa were displaced to coincide with the position of the hollow thermocouple, and the gas temperatures were calculated from Eq (6). The results are shown in Figure 13.

Static measurements of the stream temperature were made with the reference thermocouple at a number of points across the radius before the transducer traverse was made. After the traverse, an additional reference measurement was made at the centerline. These results are shown in Table XIIb, and it is noted that the stream temperature apparently decreased 180°F between reference measurements.

A Chromel/Alumel thermocouple was peened to the inside wall at the upstream end of the pipe to further define the temperature distribution.



TEMPERATURE IN OXYACETYLENE FLAME  
DOWNSTREAM FROM 30-TIP TORCH

FIGURE 12



TABLE XII

## EXPERIMENTAL DATA FROM RUN B-9

a. Dual-element Transducer Traversing Gas Stream:

| Time<br>(sec) | Position of $t_1$<br>with Respect<br>to Pipe Wall<br>(in.) | Hollow Thermocouple, $t_1$ |                                         |                    | Solid Thermocouple, $t_2$ |                                         |                     | $t_2$ Adjusted to Correspond to<br>Position of $t_1$ |               |                     | $t_g$<br>(°F)      |
|---------------|------------------------------------------------------------|----------------------------|-----------------------------------------|--------------------|---------------------------|-----------------------------------------|---------------------|------------------------------------------------------|---------------|---------------------|--------------------|
|               |                                                            | $t_1$<br>(°F)              | $(t - t_1)$<br>$\Delta T = 0.2$<br>(°F) | $t_1'$<br>(°F/sec) | $t_2$<br>(°F)             | $(t - t_2)$<br>$\Delta T = 0.2$<br>(°F) | $t_2'$<br>(°F/sec)  | Time<br>(sec)                                        | $t_2$<br>(°F) | $(t - t_2)$<br>(°F) | $t_2'$<br>(°F/sec) |
| 0             | -1.54                                                      | 262.5                      |                                         | 0                  | 264.5                     |                                         | 0                   | 0.14                                                 | 264.5         | 0                   | -                  |
| 0.1           | -1.34                                                      | 262.5                      |                                         | 0                  | 264.5                     |                                         | 0                   | 0.24                                                 | 264.5         | 0                   | -                  |
| 0.2           | -1.16                                                      | 262.5                      |                                         | 0                  | 264.5                     |                                         | 0                   | 0.34                                                 | 264.5         | 0                   | -                  |
| 0.3           | -0.96                                                      | 264.0                      |                                         | 22.0 <sup>†</sup>  | 264.5                     |                                         | 0                   | 0.44                                                 | 264.5         | 0                   | -                  |
| 0.4           | -0.86                                                      | 267.3                      |                                         | 39.3               | 264.5                     |                                         | 0                   | 0.54                                                 | 264.5         | 0                   | -                  |
| 0.5           | -0.73                                                      | 272.0                      |                                         | 47.9               | 264.7                     |                                         | 0                   | 0.64                                                 | 269           | 97                  | 274                |
| 0.6           | -0.47                                                      | 282.5                      |                                         | 267                | 265.0                     |                                         | 53.7 <sup>†</sup>   | 0.74                                                 | 291           | 318                 | 273                |
| 0.7           | -0.26                                                      | 330.0                      |                                         | 540                | 281.5                     |                                         | 216.5               | 0.84                                                 | 332           | 408                 | 323                |
| 0.8           | -0.04                                                      | 394.5                      |                                         | 625                | 315.6                     |                                         | 405                 | 0.94                                                 | 373           | 408                 | 533                |
| 0.9           | +0.08                                                      | 459.0                      |                                         | 654                | 357.0                     |                                         | 410                 | 1.04                                                 | 414           | 402                 | 975                |
| 1.0           | +0.25                                                      | 522.5                      |                                         | 651                | 396.0                     |                                         | 409                 | 1.14                                                 | 454           | 397                 | 1384               |
| 1.1           | 0.42                                                       | 586.0                      |                                         | 639                | 438.0                     |                                         | 403                 | 1.24                                                 | 493           | 389                 | 1692               |
| 1.2           | 0.60                                                       | 649.3                      |                                         | 620                | 476.5                     |                                         | 399                 | 1.34                                                 | 531           | 381                 | 2002               |
| 1.3           | 0.89                                                       | 711.5                      | 125.5                                   | 596 <sup>*</sup>   | 517.3                     |                                         | 390                 | 1.44                                                 | 569           | 372                 | 2045               |
| 1.4           | 1.03                                                       | 768.3                      | 119                                     | 566                | 554.0                     |                                         | 382                 | 1.54                                                 | 607           | 362                 | 1965               |
| 1.5           | 1.10                                                       | 824.5                      | 113                                     | 537                | 592.6                     |                                         | 371                 | 1.64                                                 | 643           | 351                 | 1990               |
| 1.6           | 1.12                                                       | 875.3                      | 107                                     | 513                | 627.0                     |                                         | 359                 | 1.74                                                 | 677           | 341                 | 2000               |
| 1.7           | 1.13                                                       | 928.0                      | 102                                     | 485                | 664.5                     | 71.9                                    | 347.5 <sup>**</sup> | 1.84                                                 | 711           | 330                 | 1995               |
| 1.8           | 1.14                                                       | 974.5                      | 98.0                                    | 466                | 696.5                     | 69.2                                    | 334.5               | 1.94                                                 | 743           | 320                 | 2060               |
| 1.9           | 1.15                                                       | 1021.0                     | 93.0                                    | 442                | 731.3                     | 67.0                                    | 324                 | 2.04                                                 | 775           | 309                 | 2065               |
| 2.0           | 1.22                                                       | 1063.0                     | 88.0                                    | 418                | 762.0                     | 65.0                                    | 314                 | 2.14                                                 | 805           | 299                 | 2040               |
| 2.1           | 1.38                                                       | 1105.3                     | 83.5                                    | 397                | 793.6                     | 62.9                                    | 304                 | 2.24                                                 | 835           | 289                 | 2045               |
| 2.2           | 1.39                                                       | 1143.0                     | 80.0                                    | 380                | 822.3                     | 60.7                                    | 293.5               | 2.34                                                 | 863           | 279                 | 2080               |
| 2.3           | 1.41                                                       | 1181.5                     | 76.0                                    | 358                | 851.0                     | 58.7                                    | 284                 | 2.44                                                 | 890           | 271                 | 2050               |
| 2.4           | 1.42                                                       | 1215.0                     | 71.5                                    | 339                | 879.5                     | 56.9                                    | 275                 | 2.54                                                 | 917           | 262                 | 2030               |
| 2.5           | 1.57                                                       | 1249.0                     | 68.0                                    | 323                | 905.5                     | 55.0                                    | 266                 | 2.64                                                 | 942           | 253                 | 2045               |
| 2.6           | 1.70                                                       | 1279.3                     | 65.5                                    | 311                | 932.0                     | 53.2                                    | 257                 | 2.74                                                 | 967           | 247                 | 2055               |
| 2.7           | 1.78                                                       | 1310.5                     | 62.0                                    | 294                | 957.5                     | 51.6                                    | 249.5               | 2.84                                                 | 991           | 238                 | 2050               |
| 2.8           | 1.81                                                       | 1338.5                     |                                         |                    | 981.5                     | 49.8                                    | 240.5               |                                                      |               |                     |                    |
| 2.9           | 1.82                                                       | 1366.0                     |                                         |                    | 1006.0                    | 48.2                                    | 233                 |                                                      |               |                     |                    |
| 3.0           | 1.82                                                       | 1394.5                     |                                         |                    | 1028.0                    | 46.8                                    | 226                 |                                                      |               |                     |                    |

TABLE XII  
(concluded)

b. Reference Thermocouple Measurements:

| Position with<br>Respect to<br>Pipe Wall<br>(in.) | Thermocouple<br>Temperature,<br>$t_o$<br>(°F) | Shield<br>Temperature,<br>$t_s$<br>(°F) | Gas<br>Velocity,<br>$V$<br>(ft/sec) | Correction to<br>Thermocouple<br>Reading, ( $t_g - t_o$ )<br>(°F) | Gas-Stream<br>Temperature,<br>$t_g$<br>(°F) | Probable<br>Error,<br>$\Delta t_g$<br>(°F) |
|---------------------------------------------------|-----------------------------------------------|-----------------------------------------|-------------------------------------|-------------------------------------------------------------------|---------------------------------------------|--------------------------------------------|
|                                                   |                                               |                                         |                                     | Before Dual-Element Transducer Traverse                           |                                             |                                            |
| 0.03                                              | 1712.5                                        | 1562.5                                  | 48.5                                | 93.2                                                              | 1805.7                                      | ±30.4                                      |
| 0.28                                              | 1857.3                                        | 1649.5                                  | 66                                  | 133.0                                                             | 1990.3                                      | ±42.9                                      |
| 0.53                                              | 1940.7                                        | 1731.5                                  | 77.5                                | 140.2                                                             | 2080.9                                      | ±45.4                                      |
| 0.78                                              | 2009.0                                        | 1790.0                                  | 90                                  | 147.0                                                             | 2156.0                                      | ±47.3                                      |
| 1.03                                              | 2036.3                                        | 1812.0                                  | 95                                  | 151.1                                                             | 2187.4                                      | ±48.6                                      |
| 1.28                                              | 2040.0                                        | 1811.5                                  | 96                                  | 155.5                                                             | 2195.5                                      | ±50.3                                      |
| 1.53††                                            | 2020.0                                        | 1797.7                                  | 92                                  | 153.9                                                             | 2173.9                                      | ±49.7                                      |
|                                                   |                                               |                                         |                                     | After Dual-Element Transducer Traverse                            |                                             |                                            |
| 1.53††                                            | 1854.5                                        | 1667.0                                  | 66                                  | 140.2                                                             | 1994.7                                      | ±45.2                                      |
| 0                                                 | 756.0                                         |                                         |                                     | Thermocouple Attached to Pipe Wall                                |                                             |                                            |

Notes: \*  $(t - t_-)/(t_+ - t_-)$  avg. = 1.1059;  $t_1' = 4.75 (t_1 - t_-)$ .

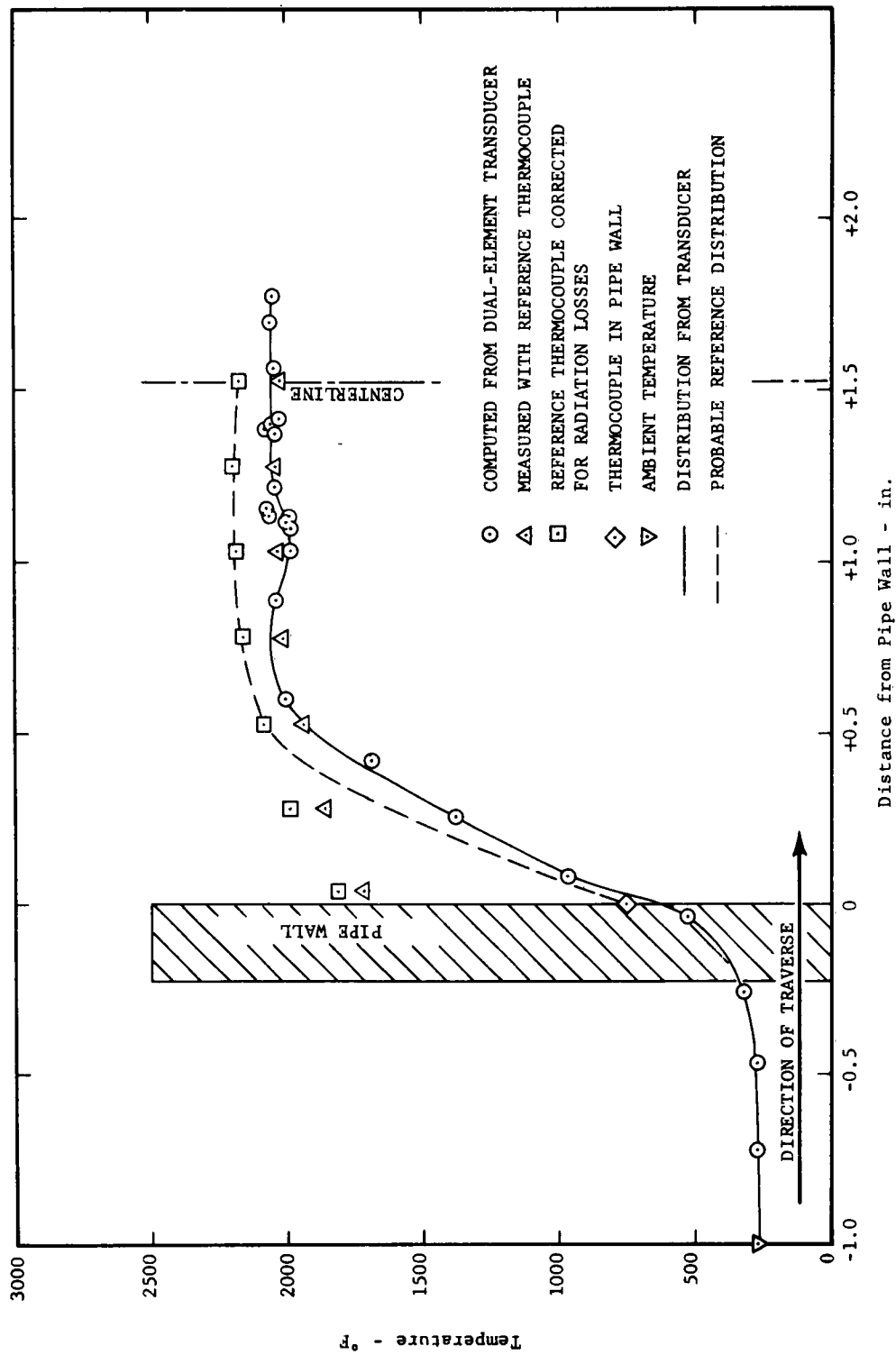
\*\*  $(t - t_-)/(t_+ - t_-)$  avg. = 1.0687;  $t_2' = 4.83 (t_2 - t_-)$ .

† Evaluated from tangents drawn to temperature history.

†† Evaluated by interpolation from preceding data.

‡ Evaluated using  $K = 0.565$ .

‡‡ At centerline.



TEMPERATURE DISTRIBUTION IN GAS STREAM  
MEASURED WITH DUAL-ELEMENT TRANSDUCER  
(DATA FROM TABLE XII, RUN B-9)

FIGURE 13

## DISCUSSION OF RESULTS

### Steady Measurements

A summary of the results obtained with the dual-element transducer in measuring steady gas temperatures is given in Table XIII. The accuracy was within  $\pm 6\%$  for measurements between 1950 and 2250°F. The error increased to  $\pm 15\%$  in measuring gas temperatures in the region of 1500°F.

These values agree closely with the experimental accuracy predicted in the preceding analytical study (ref. 8). It is believed that agreement within  $\pm 6\%$  of the standard temperature was made possible by the systematic method of calculating derivatives, a fact which was also predicted by the previous study.

The increasing error at 1500°F resulted primarily from the design of the transducer. The response of the thermocouples was slow, making the calculation of derivatives difficult even with the method outlined in Appendix C. It is believed that the accuracy could have been improved by using faster responding thermoelements; the region of 1500°F, however, was not of primary interest in this program.

It was noted in reducing the data that thermocouple pairs A and C produced more consistent results than did pair B. This, of course, results from the greater difference in time constants,  $T_1$  and  $T_2$ , in pairs A and C. The ratio of the derivatives,  $t_1'/t_2'$ , in Eq (6) is directly related to the ratio,  $K = T_1/T_2$ ; the calculation was improved when the derivative ratio was larger.

The results of the measurements at 4700°F are considered excellent, both in the consistency of the transducer measurements and in the agreement of the measurements with published values. It is noted that the transducer accuracy falls within the  $\pm 6\%$  that characterized the measurements from 1950 to 2250°F. The difference between the measurements at ATL and the published measurements by the sodium-line-reversal technique (ref. 7) are probably within the accuracy of the latter method.

It is especially important to note the fact illustrated in Figure 11. An excellent temperature measurement was made in a 4700°F flame from a record only 0.46 second long, in which the temperature of the thermoelements did not exceed 1500°F. This fact alone demonstrates the power of the dual-element concept.

Again the responses of the particular thermocouples created some difficulty. It is believed that better data in the region of 5000°F would result through the use of thermocouples with both higher individual time constants (i. e., slower response) and more widely separated time constants (i. e., a value for  $K$  of about 0.3).

An additional problem will be noted in the data in Tables X and XI. The calculated gas temperature appeared to decrease with time, although the consistency of the derivatives indicated that the measured gas temperature remained constant. This problem is believed to be related to the poor agreement in the initial temperatures of the two thermocouples, but

TABLE XIII  
SUMMARY OF RESULTS WITH DUAL-ELEMENT TRANSDUCER

| Run              | Reference <sup>*</sup><br>Temperature<br>(°F) | Probable Error<br>in Reference<br>Temperature<br>(%) | Temperature<br>from Dual-Element<br>Transducer<br>(°F) | Transducer <sup>**</sup><br>Accuracy<br>(%) |
|------------------|-----------------------------------------------|------------------------------------------------------|--------------------------------------------------------|---------------------------------------------|
| C-4              | 1522                                          | ± 1.05                                               | 1365                                                   | -10.3                                       |
| C-5              | 1585                                          | ± 1.34                                               | 1354                                                   | -14.5                                       |
| C-7              | 1959                                          | ± 1.72                                               | 1876                                                   | - 4.2                                       |
| C-8              | 2248                                          | ± 2.32                                               | 2258                                                   | + 0.45                                      |
| A-5              | 2101                                          | ± 2.14                                               | 2099                                                   | - 0.01                                      |
| B-1              | 2193                                          | ± 2.27                                               | 2124                                                   | - 3.1                                       |
| B-9 <sup>†</sup> | 2174                                          | ± 2.29                                               | 2050                                                   | - 5.7                                       |
| B-13             | 4940 <sup>††</sup>                            | ± 3.0 <sup>‡</sup>                                   | 4700                                                   | - 4.9                                       |
| B-15             | 4940 <sup>††</sup>                            | ± 3.0 <sup>‡</sup>                                   | 4789                                                   | - 3.1                                       |

\* From reference thermocouple, except Runs B-13 and B-15.

\*\* Based on reference temperature as standard.

† At centerline.

†† From ref. 7, as shown in Figure 12.

‡ As estimated in ref. 7.

sufficient time did not remain in the program to explore the matter fully. Again this problem was a matter of equipment design; the transducer could not be completely retracted from the region influenced by the flame.

### Transient Measurements

The transient measurement in Figure 13 shows encouraging agreement with the probable reference values. The agreement within 6% at the centerline agrees with the centerline accuracy in previous measurements.

The derivatives in the region of changing temperature could not be calculated by the method in Appendix C. The slope method proved satisfactory in this case, however, because the slopes changed rapidly in this region. Satisfactory accuracy was obtained to demonstrate the applicability of the dual-element transducer in measuring transient temperatures.

There was, however, considerable ambiguity in establishing the true distribution through the stream. It is believed that the rather massive reference thermocouple did not make an adequate measurement near the wall for two reasons: 1) the outside diameter of 1 inch makes a point measurement impossible in a region with a large temperature gradient, and 2) the system of shield tended to conduct heat from the hotter region and influence the primary thermocouple. The wall thermocouple has been given greater credence in Figure 13, although this value too may be dubious.

While the distribution calculated from the transducer appears reasonable, it is evident that more definitive work is needed in this area. Further effort is necessary in developing an accurate method of evaluating derivatives in regions of changing temperature. In this instance particularly, coupling the dual-element transducer with digital or analog computation of derivatives would be advantageous.

### III. CONCLUSIONS AND RECOMMENDATIONS

Experimental evaluation of the dual-element transducer has indicated accuracies well within  $\pm 6\%$  in measuring constant gas-stream temperatures in the range 1950 to 2250°F. This is the maximum accuracy predicted in an earlier study (ref. 8), and is made possible by an accurate method developed for determining temperature derivatives. It is concluded that the feasibility of the concept has been demonstrated.

Measurements with the transducer in an oxyacetylene flame near 5000°F have demonstrated the feasibility of that application also. This temperature was evaluated from records in which the temperature of the thermoelements did not exceed 1500°F. The accuracy of the measurement appeared to be within the accuracy of values published elsewhere (ref. 7).

Limited experimental work has demonstrated the probability of using the dual-element transducer to measure temperature variations within a gas stream at about 2000°F. Again, the profile measured by the transducer appeared to be within the accuracy to which the actual profile was established.

It is strongly recommended that the evaluation and development of the dual-element transducer be continued. The results indicate that, with minor design changes, the transducer in its present state of development can be applied to the measurement of steady temperatures of the order of 5000°F. Evaluation of this application should be continued.

Additional evaluation of the transducer in measuring transient temperatures is needed. Coupling the transducer with data handling by either digital or analog computation is particularly attractive in this application, to bring the results to their maximum accuracy.

Finally, based on the extremely encouraging results of this program, it is recommended that evaluation of the dual-element transducer in measuring the ultra-high temperatures of plasma states be undertaken.

#### IV. REFERENCES

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## V. APPENDIX A

### REFERENCE TEMPERATURE OF GAS STREAM

#### THE REFERENCE THERMOCOUPLE

The reference thermocouple was used for static measurements of the gas stream. The primary thermocouple was positioned at the center of three 2-inch-long stainless-steel shields with outside diameters by wall thicknesses of 1.000 by 0.049, 0.688 by 0.035, and 0.375 by 0.035 inch. Two additional thermocouples were spot-welded to the inner shield. All thermocouples were made from 10-mil Chromel/Alumel thermocouple wire certified by the supplier to meet ISA special limits of error ( $\pm 3/8\%$  maximum deviation from NBS tables over the range 530 to 2300°F).

The triple shielding was designed to minimize the radiation loss from the reference thermocouple, since this loss results in a depression of the thermocouple temperature below the true temperature of the gas stream. The depression was not completely eliminated, however, making it necessary to estimate the difference between the true gas temperature and the measured thermocouple temperature.

#### DETERMINATION OF THE GAS-STREAM TEMPERATURE

Assuming that the reference thermocouple radiates heat primarily to the inner shield, a heat balance on the thermocouple is:

$$t_g = t_o + \frac{\sigma F}{h} (T_o^4 - T_s^4). \quad (A-1)$$

The geometrical factor of the thermocouple with respect to the shield is  $F'_{os} = 0.93$  (calculated as that portion of the radiation emitted by the thermocouple that is intercepted by the shield). Again assuming the inner shield primarily influences the thermocouple, the combined geometrical and emissivity factor from the blackened thermocouple is (ref. 4):

$$F = \frac{1}{1/F'_{os} - (1 - 1/\epsilon_o)} = 0.888, \quad (A-2)$$

where the value  $\epsilon_o = 0.95$  is representative of oxidized Nichrome wire (ref. 5).

The thermocouple can be represented adequately for convection calculations as a small cylinder normal to the gas stream; therefore, for air with  $40 < N_{Re} < 4000$  (ref. 6),

$$h = B \frac{k_f}{d} \left( \frac{ud}{\nu_f} \right)^{0.466}, \quad (A-3)$$

with the constant (ref. 6)  $B = 0.615$ .

Data on the high-temperature properties of air can be correlated in the range  $1500 < T < 2700^\circ R$  by (ref. 3):

$$k_f = 4.46 \times 10^{-4} T_f^{0.59} \quad \text{and} \quad (A-4)$$

$$\nu_f = 0.798 T_f^{0.741}, \quad (A-5)$$

and these values also approximate those for  $O_2$ ,  $CO$ ,  $CO_2$ ,  $N_2$ , and water vapor (ref. 3).

Substituting the above values, and the relationship  $u = 3600V$ , the equation for the gas temperature becomes

$$t_g = t_o + 0.396 \frac{\sigma F T_f^{0.151} d^{0.534}}{B V^{0.466}} (T_o^4 - T_s^4). \quad (A-6)$$

Since the dependence of  $T_f$  on  $T_g$  implies a trial-and-error solution of Eq (A-6), the approximation is made that  $T_f = 1.03 T_o \pm 3\%$ .

The velocity of the hot stream was based on wind-gage measurements of the gas flowing from the unlighted torch, corrected for expansion due to heating.

#### ACCURACY OF THE GAS-STREAM TEMPERATURE

The probable deviation in computing the correction ( $t_g - t_o$ ) is defined by (ref. 2):

$$\Delta(t_g - t_o) = \pm \sqrt{\sum_i \left[ \frac{\partial (t_g - t_o)}{\partial x_i} \Delta x_i \right]^2}, \quad (A-7)$$

where  $x_i$  represents the seven "variables" in Eq (A-6). Evaluating the partial derivatives, the percentage deviation in the correction is defined by

$$\begin{aligned} \left[ \frac{\Delta(t_g - t_o)}{(t_g - t_o)} \right]^2 &= \left[ \frac{4}{1 - (T_s/T_o)^4} \frac{\Delta T_o}{T_o} \right]^2 + \left[ \frac{4}{(T_o/T_s)^4 - 1} \frac{\Delta T_s}{T_s} \right]^2 \\ &+ \left[ \frac{\Delta F}{F} \right]^2 + \left[ 0.151 \frac{\Delta T_f}{T_f} \right]^2 + \left[ 0.534 \frac{\Delta d}{d} \right]^2 \\ &+ \left[ \frac{\Delta B}{B} \right]^2 + \left[ 0.466 \frac{\Delta V}{V} \right]^2. \end{aligned} \quad (A-8)$$

The probable deviation in the computed gas-stream temperature is

$$\Delta t_g = \pm \sqrt{[\Delta t_o]^2 + [\Delta(t_g - t_o)]^2}. \quad (A-9)$$

The following deviations in the variables are representative:

- 1)  $\Delta T_o = \pm 0.00375 t_o$  and  $T_s = \pm 0.00375 t_s$ , representing the limits of accuracy of the thermocouple wire specified by the supplier.
- 2)  $\Delta F = \pm 0.05$ .
- 3)  $\Delta T_f = \pm 0.03 T_f = \pm 0.031 T_o$ .
- 4)  $\Delta d = \pm 0.001$  inch, when  $d = 0.020$  inch.
- 5)  $\Delta B = \pm 0.30 B$ , representing a deviation in the data from a number of investigators of approximately  $\pm 30\%$  from the mean convection relationship expressed by Eq (A-3) (ref. 6).
- 6)  $\Delta V = \pm 0.20 V$ .

Using typical data from Run C-8 ( $T_o = 2549^\circ R$ ,  $T_s = 2316^\circ R$ , and  $V = 110$  ft/sec):

$$\frac{\Delta(t_g - t_o)}{(t_g - t_o)} = \pm \sqrt{(14.7 + 6.57 + 25.0 + 0.21 + 7.11 + 900 + 86.8) \times 10^{-4}}$$

$$= \pm 0.323, \quad (A-10)$$

where the terms are given in the same order as in Eq (A-8). The error from the assumption for  $T_f$  is negligible. The uncertainty in the convection coefficient (represented by  $\Delta B$ ) obscures all other errors, indicating that further refinement in such measurements as  $V$  was unwarranted.

When the values  $B = 0.615$ ,  $d = 1.67 \times 10^{-3}$  ft,  $F = 0.888$ ,  $\sigma = 0.1713 \times 10^{-8}$  Btu/hr-ft<sup>2</sup>-°R<sup>4</sup>, and  $T_f = 1.03 T_o$  are substituted into Eq (A-6), the correction to the reference-thermocouple measurement can be estimated from

$$(t_g - t_o) = 32.3 \times 10^{-8} \frac{T_o^{0.131}}{V^{0.466}} (T_o^4 - T_s^4). \quad (A-11)$$

## VI. APPENDIX B

### CALCULATION OF DERIVATIVES FOR CONSTANT GAS TEMPERATURE

#### ANALYSIS

In most of the experimental work, the dual-element transducer was rapidly injected into the centerline of the gas stream. In other words, for  $\tau > 0$ , the gas-stream temperature was constant. Eq (1) or (2) can be integrated for this condition, yielding

$$\ln(t_g - t) = -\frac{\tau}{T} + C, \quad (B-1)$$

where  $T = Wc/ha$ . The constant,  $C$ , is determined by noting that  $t = t_i$  at  $\tau = 0$ , or

$$t = t_g - (t_g - t_i) e^{-\tau/T}. \quad (B-2)$$

The derivative is

$$t' = \frac{1}{T} (t_g - t_i) e^{-\tau/T}. \quad (B-3)$$

The derivatives were evaluated for this case of constant gas-stream temperature by a method represented in Figure B-1. The thermocouple temperature was evaluated from the experimental data at constant time increments,  $\Delta\tau$ . The time,  $\tau$ , represents the point at which the derivative is to be evaluated; the temperatures one increment back ( $t_-$ ) and one increment forward ( $t_+$ ) are also used.

From Eq (B-2),

$$t_- = t_g - (t_g - t_i) e^{-(\tau - \Delta\tau)/T}. \quad (B-4)$$

The differences  $(t - t_-)$  and  $(t_+ - t)$  are:

$$(t - t_-) = (t_g - t_i) e^{-\tau/T} (e^{\Delta\tau/T} - 1). \quad (B-5)$$

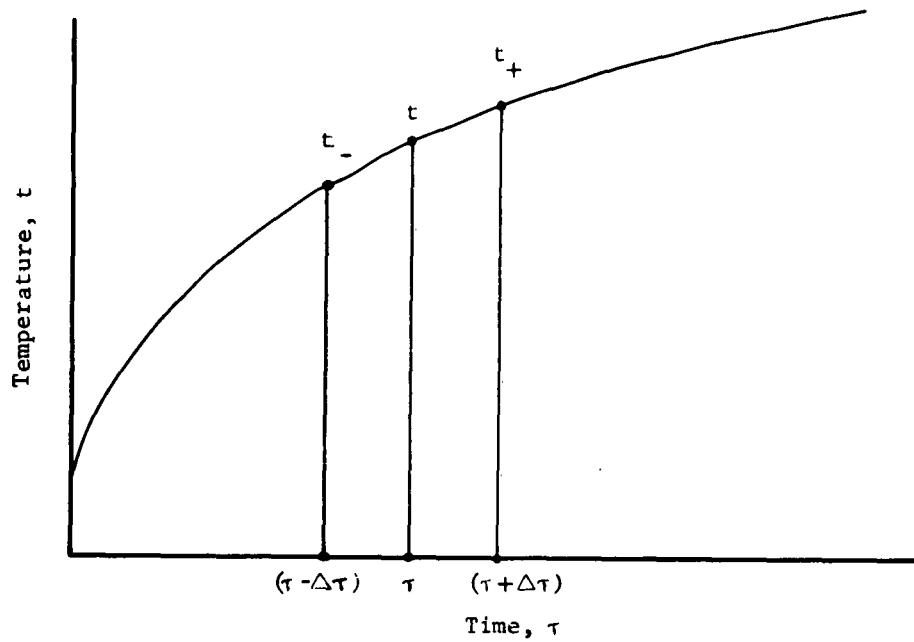
$$(t_+ - t) = (t_g - t_i) e^{-\tau/T} (1 - e^{-\Delta\tau/T}). \quad (B-6)$$

The ratio of these differences (defined as  $R$ ) is:

$$R = \frac{t - t_-}{t_+ - t} = \frac{e^{\Delta\tau/T} - 1}{1 - e^{-\Delta\tau/T}} = e^{\Delta\tau/T}. \quad (B-7)$$

Substituting Eq (B-5) and Eq (B-7) into Eq (B-3), the derivative is given by:

$$t' = \frac{\ln R}{\Delta\tau (R - 1)} (t - t_-). \quad (B-8)$$



EVALUATION OF TEMPERATURE DATA  
AT CONSTANT TIME INCREMENTS,  $\Delta\tau$

FIGURE B-1

## DATA-REDUCTION METHOD

The following points can be noted in the foregoing analysis:

- 1) The value of  $\Delta\tau/T$  is constant for any given thermocouple.
- 2) The difference  $(t - t_-)$  is an exponential function of time (since  $\Delta\tau/T$  is constant) during the interval in which Eq (B-2) applies. The differences  $(t - t_-)$  can therefore be plotted versus time on semi-log paper and faired to the best straight line.
- 3) The differences  $(t_+ - t)$  have the same numerical values as  $(t - t_-)$ , displaced one interval,  $\Delta\tau$ , since they are evaluated from the same data.
- 4) The ratio  $R = (t - t_-)/(t_+ - t)$  is a constant as long as Eq (B-2) applies.
- 5) The derivative  $(t')$  in Eq (B-8) is the product of a constant and the difference  $(t - t_-)$ .

This method has been followed in reducing the data included in this report. In computing the derivatives, the mean value of the constant,  $R$ , has been used in Eq (B-8).

## VII. APPENDIX C

### CALCULATION PROCEDURE FOR RUN C-8

#### DUAL-ELEMENT TRANSDUCER

The temperature histories for Run C-8 are shown in Table VII as obtained from Visi-corder records. The temperature differences,  $(t - t_-)$ , are computed from the experimental data and plotted in Figures C-1 and C-2. The interval of the subtraction,  $\Delta\tau$ , was varied in this set of data, and it was noted that the consistency of the temperature differences increases as the interval increases.

An interval of 0.3 second was selected for further calculation. The best straight line was drawn through the plotted points, and the temperature differences were adjusted accordingly in Table VII. When the constant ratio,  $R = (t - t_-)/(t_+ - t_-)$ , was evaluated and averaged for each thermocouple, the derivatives were computed from Eq (B-8) for  $\Delta\tau = 0.3$  second. The derivatives were also plotted in Figures C-1 and C-2 and were extrapolated to  $\tau = 0$ .

It will be noted from Eq (B-3) that the ratio of the temperature derivatives of the two thermocouples should equal the time-constant ratio initially, or

$$t_2'/t_1' = T_1/T_2 = K \text{ at } \tau = 0. \quad (C-1)$$

This ratio has a value of 0.292 for Run C-8, which agrees with the predicted value in Table I. The gas-stream temperature is calculated from Eq (6) in Table VII, using  $K = 0.292$ ; the average value is  $t_g = 2258^\circ\text{F}$ .

It will be noted that the data points for the hollow and solid thermocouples begin to deviate from the best straight lines at about 0.7 and 1.9 seconds, respectively. The deviations, however, occur in opposite directions because of the design of the transducer. Since the thickness of the radiation shield was chosen to make its thermal response midway between that of the two thermocouples, it can be assumed that the hollow, or faster responding thermocouple is losing heat to the radiation shield while the solid, slower responding thermocouple is gaining heat from the shield.

#### REFERENCE THERMOCOUPLE

The reference value of the gas temperature at the centerline of the stream was calculated, using the values  $T_o = 2549^\circ\text{R}$ ,  $T_g = 2316^\circ\text{R}$ , and  $V = 110$  ft/sec from Table VII, as follows:

$$(t_g - t_o) = 159.2^\circ\text{F} \quad (A-11)$$

$$t_g = 2248.2^\circ\text{F}$$

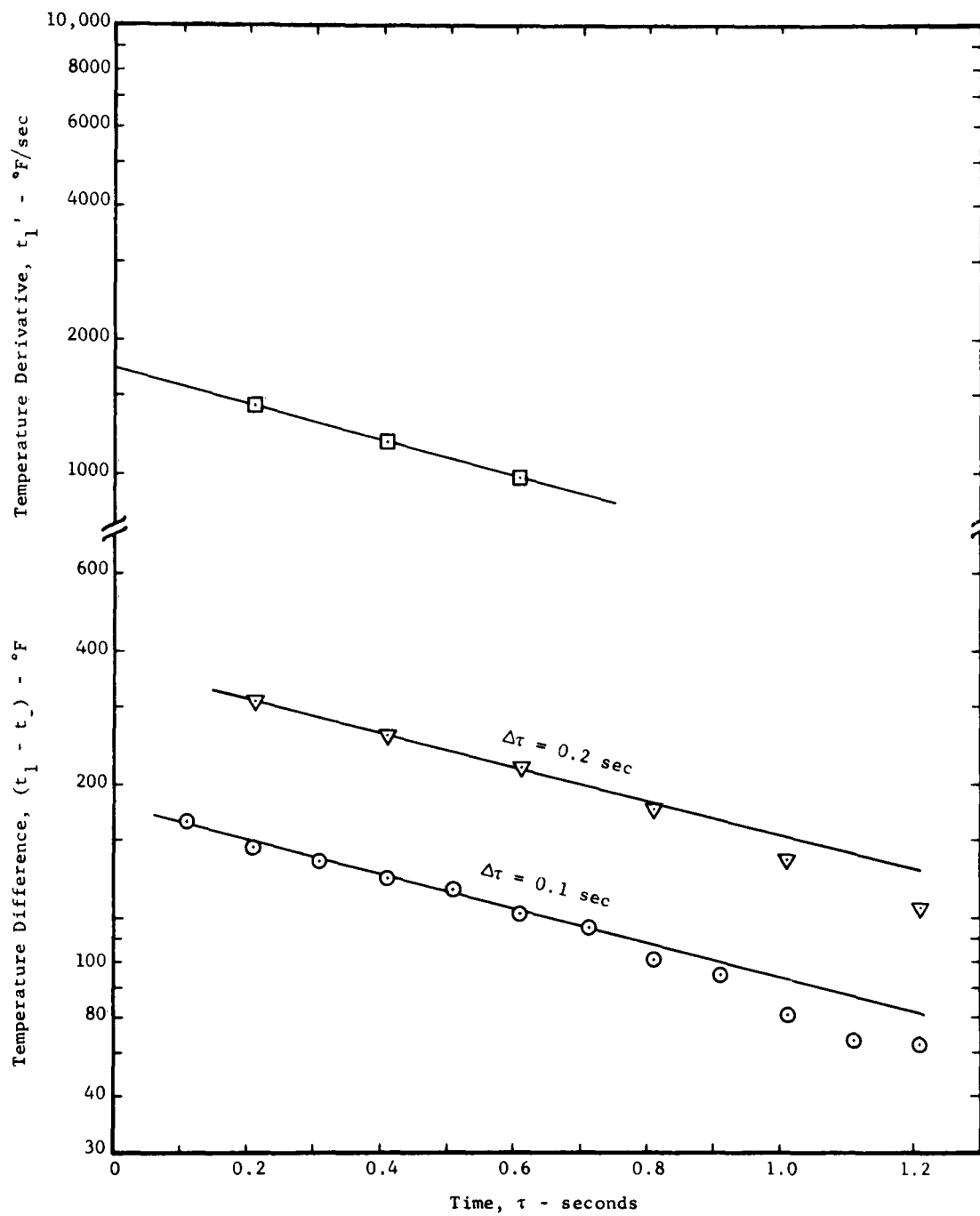
$$\Delta(t_g - t_o) = \pm 51.5^\circ\text{F} \quad (A-10)$$

$$\Delta t_g = \pm 52.1^\circ\text{F} \quad (\text{A-9})$$

$$\Delta t_g / t_g = \pm 2.31\%$$

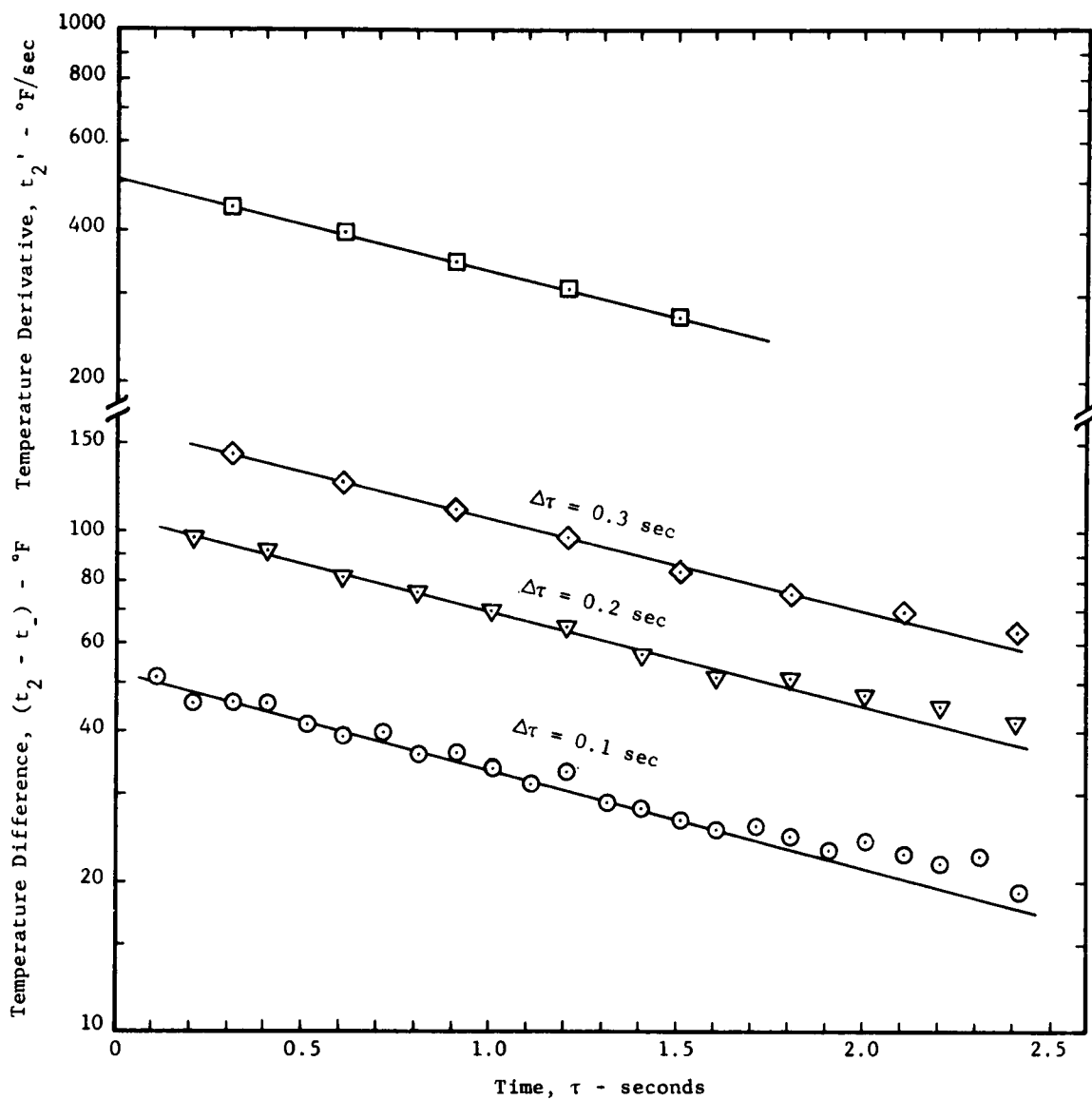
The average temperature evaluated from the dual-element transducer was 2258°F, representing a deviation of +10°F or +0.45% from the reference value of 2248.2°F; this deviation is less than the estimated error of the reference measurement itself.





CALCULATION OF TEMPERATURE DERIVATIVES,  $t_1'$ ,  
FOR RUN C-8

FIGURE C-1



CALCULATION OF TEMPERATURE DERIVATIVES,  $t_2'$ ,  
FOR RUN C-8

FIGURE C-2

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                     |                     |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|---------------------|
| <p>Aeronautical Research Laboratories, Wright-Patterson AFB, O. EXPERIMENTAL EVALUATION OF A DUAL-ELEMENT TRANSDUCER FOR HIGH TEMPERATURE-GAS MEASUREMENTS by J.T. Chambers, D. L. Rall, W.H. Giedt, Advanced Technology Labs., Mountain View, Calif. March 1963. 47 p. incl. illus. tables. (Project 7063; Task 7063-01) (Contract AF 33(657)-8411) Unclassified Report</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | <p>UNCLASSIFIED</p> | <p>UNCLASSIFIED</p> |
| <p>An experimental evaluation was made of a dual-element transducer, in which gas-stream temperatures are inferred from simultaneous temperature-time measurements of two transducers of equal shape but unequal thermal capacity. The major effort was expended on measuring medium temperature streams to prove the feasibility of the concept. The accuracy of the transducer was 2% with 1000°F, which was the best experimental accuracy predicted by an earlier analysis of the concept. A limited number of measurements were made with the transducer directly in an oxyacetylene flame. The indicated flame temperatures were 4700°F and 4780°F, which agree within 3% with measurements by sodium-line-reversal techniques for equivalent combustion conditions in tests conducted at the University of California. In a third series of tests, the transducer was used to traverse a 2100°F gas stream, and from a single record the temperature profile in the stream was calculated within the accuracy to which the true profile could be established.</p> | <p>UNCLASSIFIED</p> | <p>UNCLASSIFIED</p> |
| <p>capacity. The major effort was expended on measuring medium temperature streams to prove the feasibility of the concept. The accuracy of the transducer was 2% with 1000°F, which was the best experimental accuracy predicted by an earlier analysis of the concept. A limited number of measurements were made with the transducer directly in an oxyacetylene flame. The indicated flame temperatures were 4700°F and 4780°F, which agree within 3% with measurements by sodium-line-reversal techniques for equivalent combustion conditions in tests conducted at the University of California. In a third series of tests, the transducer was used to traverse a 2100°F gas stream, and from a single record the temperature profile in the stream was calculated within the accuracy to which the true profile could be established.</p>                                                                                                                                                                                                                       | <p>UNCLASSIFIED</p> | <p>UNCLASSIFIED</p> |