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SURFACE TEMPERATURE MEASUREMENTS USING A THIN FILM THERMAL ARRAY

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SUMMARY

The device presented in this paper is a novel approach to performing multiple surface temperature measurements. This device--Thin Film Thermal Array (TFTA)--is composed of eight integrated circuit thermal sensors arranged in a 2 x 4 array on a 0.002" Kapton film. The sensors are monitored through an eight-channel integrated circuit multiplexer also mounted on the Kapton film. The TFTA was conceptualized, designed, and fabricated in-house.

The TFTA was mounted on a flat plate airfoil and wind-tunnel tested in the Instrument Research Division's velocity calibration facility. The test was conducted to study the performance of the device as compared to embedded thermocouples. The results of the tests indicated that the TFTA is a viable method of obtaining an array of surface temperature measurements.

Finally, recommendations for improvement of the TFTA are provided for future applications and configurations.

INTRODUCTION

The measurement of surface temperatures has been and is still an important thermal parameter for aerodynamic research, analysis, and design. Surface temperature measurements of turbine blades, nuclear reactor cores, electronic container surfaces, etc. are also important and required for effective design.

Knowledge of the surface temperature of airfoils provides fundamental information to the aerodynamicist in studying specific wind-tunnel model configurations. In obtaining this type of thermal data, care must be taken to prevent disturbance of the flow around the airfoil. Second, the measurement must be made with minimal impact on the structural integrity of the airfoil. Present techniques for instrumenting airfoil models fall into two basic categories [1]: (1) subsurface installations and (2) insertable plug installations (fig. 1). Subsurface installations require delicate machining techniques to insure consistent depth, diameter, and smoothness of the cavity. Once these factors are accomplished the sensor--thermocouple, diode, platinum resistance thermometer, etc.--must be inserted with the active sensing element flush to the bottom of the cavity to sense the surface temperature. Finally the sensor and lead wires must be secured with a potting material which is thermally and structually compatible with the model material. It should be noted that the temperature measured using this method can be corrected to obtain the actual surface temperature of the model through inverse heat transfer methods [2].

The insertable plug technique also requires delicate machining of the model to insure proper fit and ease of installation. A sensor is inserted inside the plug of material which has the same material characteristics as the model. In some cases the sensor is inserted flush to the surface of the plug and in other applications, it is just below the surface. The plug is then inserted into the model flush with the aerodynamic surface. From a heat transfer standpoint there is a thermal discontinuity between the plug, the model, and the bonding material. This difference must be addressed to obtain the most accurate surface temperature measurement.

The two techniques discussed require many of these sensors to be installed to obtain a thermal profile of a surface. The quantity of sensors required necessitates extensive modification of the model's surface and creates a large number of sensor lead wires exiting the model. Therefore the objective of this research was to develop a sensor that would: (1) accurately capture an array of surface temperature data without modification to the model surface and (2) reduce the number of sensor lead wires exiting the model.

SENSOR REQUIREMENTS

The task of developing a sensor that would accurately obtain an array of surface temperature measurements without substantially altering the surface being measured prompted an extensive literature search to determine if such a device existed. It was decided that the device would have the following characteristics:

- sensing elements would have to be very thin
- sensing elements would be mounted on a very thin substrate which would minimize disturbance of the boundary layer of airfoils
- the number of sensing elements would be flexible to accommodate any application
- the device would use time-division multiplexing to monitor the sensing elements on the substrate
- fabrication of the device would accommodate various configurations for different applications
- significant reduction in lead wires exiting the model.

No device or sensor technique to accomplish the task was found and it was decided to fabricate the device in-house. Figure 2 shows the original concept of the device for measuring temperature distributions. The concept features an array of six sensors attached to a thin substrate. The sensor selection process, the substrate determination, and the selection of other components was the next step in the design phase for the thermal sensor array.

THE DESIGN

An investigation was conducted to determine the substrate material, type of transducer, and other associated electronic components. The requirement for temperature measurements on contoured surfaces strongly influenced the selection of the substrate material. It was decided that the substrate should be flexible in order to conform to irregularly shaped surfaces. Kapton was selected as the material for the substrate because it can be made very thin and flexible, has a high temperature tolerance to accommodate the metal deposition process, and is electrically nonconductive. This was the first attempt by Langley's Microelectronics Development Laboratory to deposit printed wiring on a thin film of Kapton and was successful.

The temperature sensor selected for the array was the AD590 integrated circuit in chip form. This device is a two-terminal, monolithic IC transducer whose characteristics are described by Timko [3]. It was chosen because of ease of multiplexing, accuracy and repeatability, physical size, temperature range, and reliability. The AD590 produces an output current proportional to absolute temperature. In its working range, the device acts as a high impedance current source whose output has a temperature coefficient of 1μA/^{o}C. For this application, the AD590 has several advantages over more conventional sensors such as thermocouples, thermistors, PRTs, etc. Special linearization circuitry required by thermistors, precision voltage amplifiers, and cold junction compensation used with thermocouples, and resistance measuring circuits for PRT's are not necessary. Because of its high impedance current output, this device is insensitive to voltage drops over long lines making it particularly useful in remote sensing applications. The output characteristics also make the device easy to multiplex which is a definite advantage in the present application. The AD590 in chip form has the following minimum specifications for the absolute error over the operating temperature range of -55 ^{o}C to +1.50 ^{o}C [4]:

* Nonlinearity .... ± 1.5 ^{o}C max.
* Repeatability .... ± 0.1 ^{o}C max.
* Long Term Drift .... ± 0.1 ^{o}C max.

The sensor array will be calibrated and an output signal versus temperature relationship for each sensor will be obtained. This procedure will effectively eliminate inaccuracies associated with the errors in absolute temperature readings and nonlinearities. Thus, repeatability and long term drift become the most important parameters in determining overall accuracy. Even in the worst case combination of repeatability and long term drift, the maximum error in measurement is within 0.2 ^{o}C of calibrated values.

Figure 3 shows a simplified circuit of a single channel temperature sensor illustrating how the temperature dependent current is converted into a voltage at the end of a long, remote sensing line by multiplying the current by a 10 KΩ precision resistor. It should be noted that the resistance of the sensing lines has no effect on the temperature dependent current and, consequently, output voltage. It is also observed that the output voltage at 25 ^{o}C (298 K) is typically 2.98 volts and has a temperature variation of 10 mV/^{o}C. These relatively large values of voltage and temperature coefficient of voltage are easy to measure directly or to convert to digital data by an A/D converter for input to a computer.

Because of its costs, size, and electrical properties, the AD590 is an ideal device for use in a multiplexed array of temperature sensors. Figure 4 depicts such an array which uses a CD4051B CMOS multiplexer (MUX) chip to selectively switch between eight different AD590 chips. The CD4051B is capable of switching at speeds typically less than 10 nanoseconds per channel so that the sensors can be scanned at a very high rate. The maximum speed will be limited primarily by the speed of the data acquisition system. This circuit was fabricated on a 0.002 inch thick flexible Kapton substrate. Figure 5 is a photograph of the completed array showing the eight sensor chips and the multiplexer chip. Figure 6 is an enlargement of a portion of the array displaying details of the microfabrication techniques such as substrate construction and thermocompression bonding used to interconnect the chips.

TESTING

The thermal device in its final form was tested on a flat plate airfoil in the IRD calibration facility. The airfoil shown in figure 7 is made of stainless steel and is instrumented with subsurface 0.005" chromel-alumel thermocouples and a recessed surface mounted heater strip. The thermocouples are located along the centerline of the model and the heater is positioned laterally across the front of the airfoil. The purpose of the heater is to introduce a thermal gradient into the airfoil. This gradient is then sensed by the thin film array and the embedded thermocouples.

Test Set-up

The array was positioned on the airfoil as shown in figure 5 so that a comparative study could be conducted. Six of the eight AD590 sensor chips were operational for the tests, however, only four sensors--8, 7, 6, and 3--were in locations that corresponded to the three embedded thermocouples (fig. 8). The airfoil was then mounted in the IRD velocity calibration facility. This facility is a low-speed, open-circuit wind tunnel. This facility has a 30 cm x 40 cm test section and can attain flow speeds between 3.5 and 80 m/s. Speeds of 5, 10, and 15 m/s were used in this evaluation with input power to the airfoil heater of 0.1, 0.2, and 0.3 amperes for each speed. All thermocouple data were obtained and recorded with a Fluke data logger system which included a 2090A indicator, a 20300A 20-channel scanner, and a 2030A programmable printer. A free stream thermocouple was also monitored during the test. The data logging sequence began with the air flow speed at 5 m/s and the 200 ohm heater activated with a 0.1 ampere current. Once the free stream thermocouple and all embedded thermocouple temperatures stabilized, array sensor output data were collected. Subsequent tests were run using 0.2 and 0.3 amperes heater currents. The same procedure was used with flow speeds of 10 and 15 m/s.

Test Results

At the beginning of the test a baseline set of data was taken for thermocouples and AD590 sensors before flow or heater current was implemented (Table 1). It was discovered that attachment wires were broken at sensor #6 during installation of the test bed into the calibration facility and it could not be included in the data. The base line data in Table 1 shows that the TFTA values are higher by 0.05 °C than the thermocouple values because the calibration was not performed prior to testing. This behavior is consistent throughout testing except at 15 m/s for 0.1 amp heater current. The TFTA values are lower here because equilibrium was not established before data was taken, however this problem was corrected for later data. The average baseline temperature for all the sensors was 17.19 °C with a standard deviation of ± 0.05 °C. It was observed that once the heater current and air flow were activated, 10 to 15 minutes was required to let the temperatures of the embedded thermocouples stabalize before data could be taken. Figures 9 through 11 depict the general trend of how the temperatures of the AD590's and the thermocouples compare. The temperatures are in close agreement with respect to their location for all speeds and heater inputs. Table 2 shows the difference between the thermocouple and the AD590 for all test conditions. It can be seen that the maximum differential between the thin film sensors and the thermocouples was 0.55 °C and the minimum differential was 0.05 °C.

In summary, the agreement between the reference thermocouples and the thin film thermal sensor array was excellent.

Future Improvements

Consideration of alternate configurations for the measurement of surface temperature profiles dictates that alternative temperature sensors and substrate be investigated. Several candidate thermal sensors could be used to accomplish the measurements:

- Miniature silicon semiconductor temperature sensors, [5] which are much smaller than the AD590. The sensor is 0.08" x 0.0075" x 0.0006" thick and has a nominal output of approximately 0.5 volts.
- Thin film platinum resistance thermometers [6] which are smaller than the AD590. The dimensions of this sensor are 0.065" x 0.05" x 0.02" thick and has a nominal output of approximately 0.5 volts.
- Thin film thermocouples of pure metals could be vacuum deposited on the substrate to produce an ultra-thin sensor array. The output would be in the millivolt range. It is important to note that thermocouple materials that are not pure metals would not be suitable because they are not reproducible once vaporized and deposited on another surface.

Other sensors which provide low profiles and repeatable calibrations could be used in this device.

An alternative substrate material could be the model itself if the configuration would allow deposition of circuit paths. However, if the model is an electrically conductive material, a nonconductive coating must be deposited before the circuit is deposited.

Finally, the packaging of the TFTA's sensor should be protected from damage by coating their surfaces with a suitable covering.

CONCLUSION

A device designed to capture an array of surface temperatures on aerodynamic models has been developed. This device consisted of a matrix of eight integrated circuit chips--AD590, mounted on a 0.002" Kapton film. These chips were arranged in an array and are multiplexed using an integrated circuit multiplexing chip--CD4051B, to organize the data capturing task. The device's design reduces the number of sensor lead wires exiting from the model. The device was tested in the IRD Velocity Calibration Facility at 5, 10, 15 m/s using embedded thermocouples as references. The results of the test showed the device temperatures compared very well to the thermocouples with variation from 0.55 ^{o}C maximum and 0.05 ^{o}C minimum.

Future designs for this device can incorporate different sensors, other substrates, and substrate configurations suited to the application.

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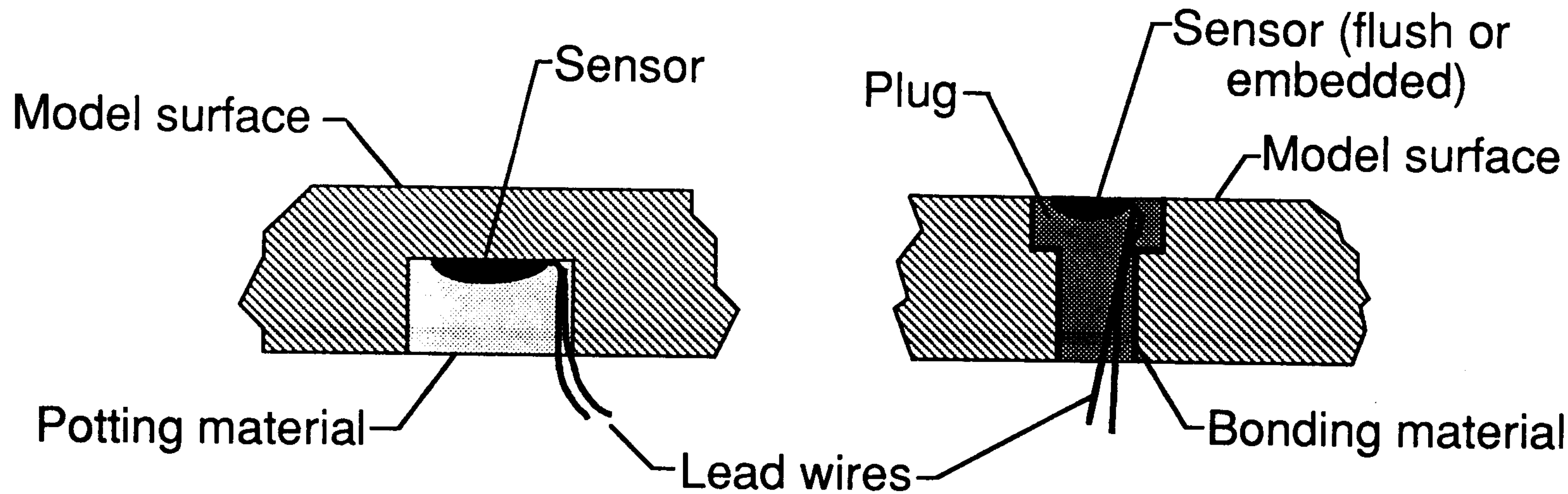
3. Timko, M. P.: A Two-Terminal IC Temperature Transducer. IEEE Journal of Solid-State Circuits, Vol. SC-11, No. 6, December 1976.

4. Analog Devices: Linear Products Data Book 1988. p. 10-7.

5. Senso-Metrics Incorporated; Simi Valley, CA, Data Sheets ST-080-050-10000N, May 1985.

6. HY-CAL Engineering; El Monte, CA, Data Sheet PD-315.1, 1987.



(a) Sub-surface

(b) Plug

Figure 1. Surface temperature sensor installation techniques

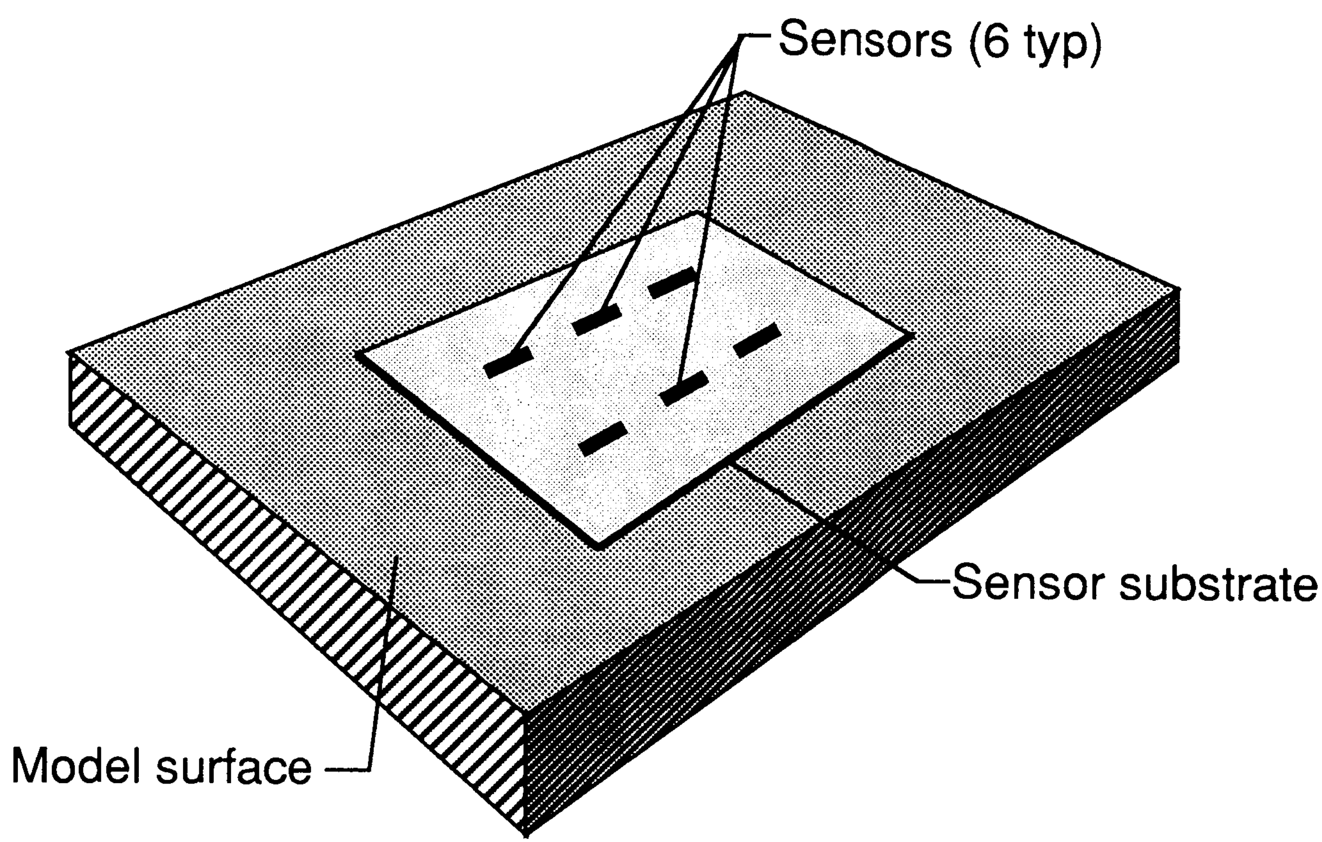
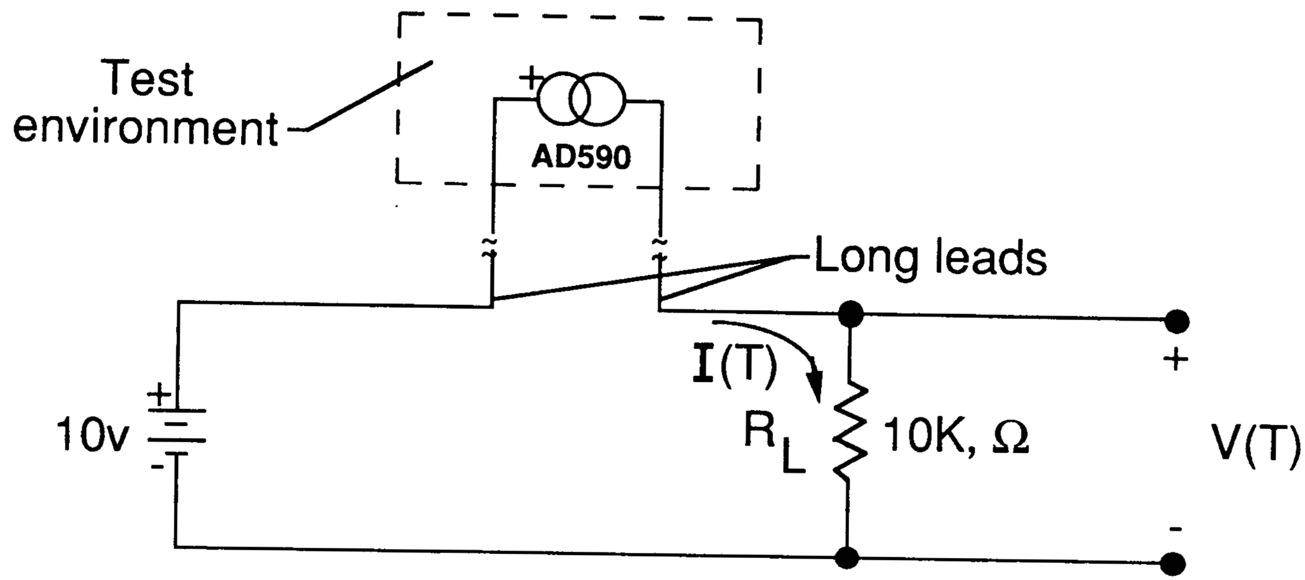


Figure 2. Thin film array sensor concept



$I(T) = 1\ uA/K$

$V(T) = 2.73V\ @\ 0℃\ + 10\ mV/℃$

Figure 3. Simplified circuit of single channel temperature sensor

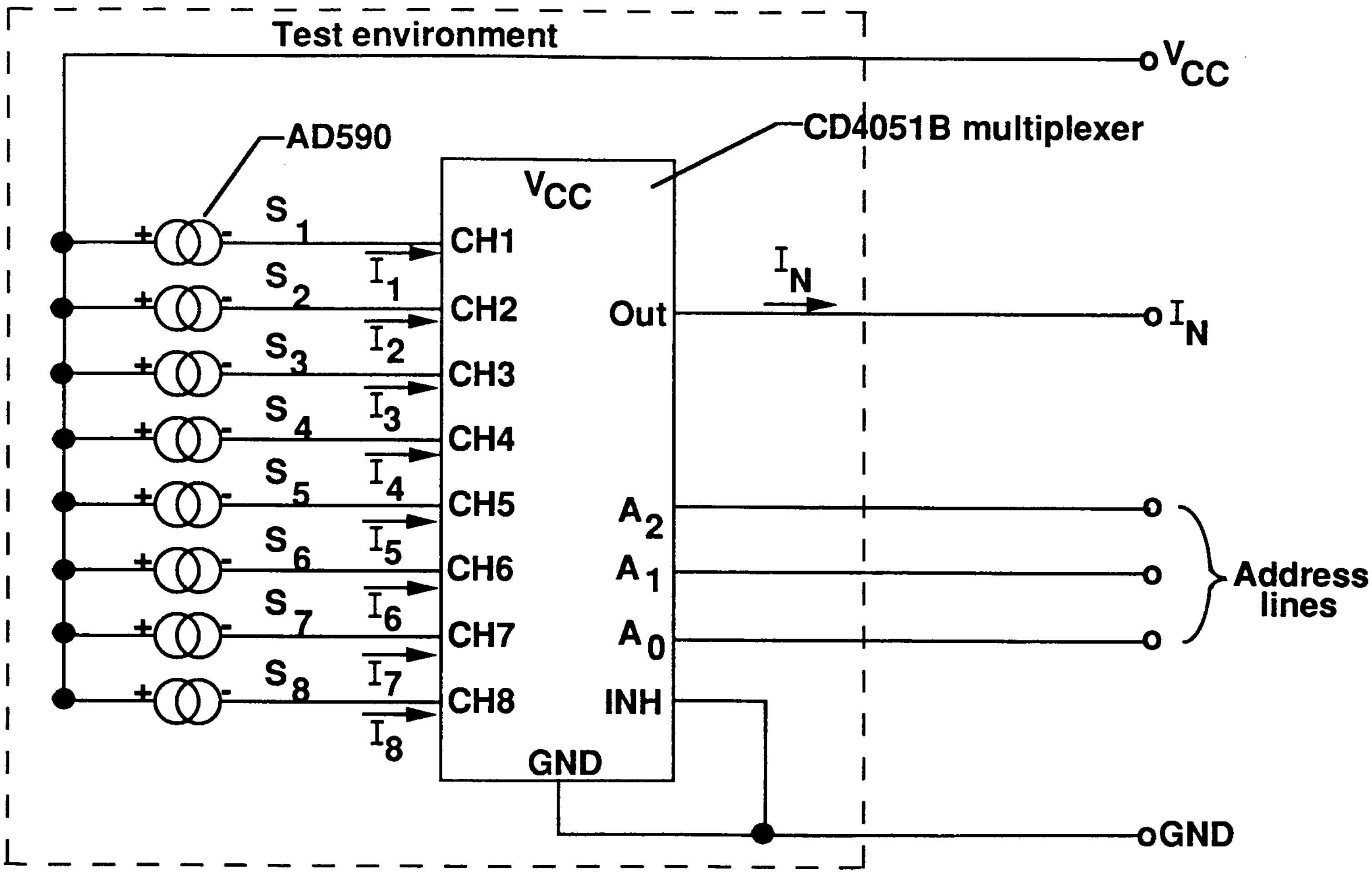


Figure 4. Circuit diagram of eight channel multiplexed temperature sensor array

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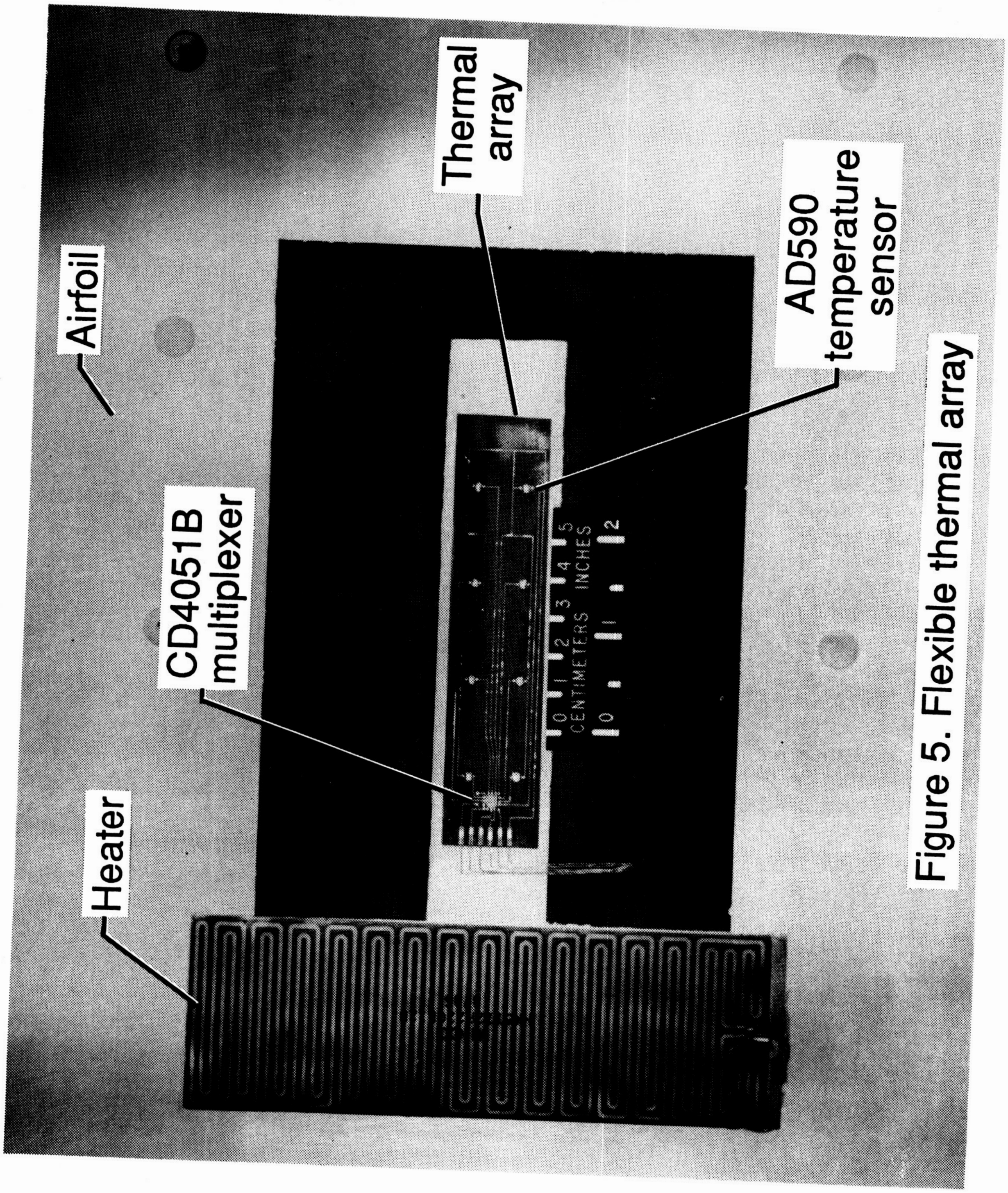

Figure 5. Flexible thermal array

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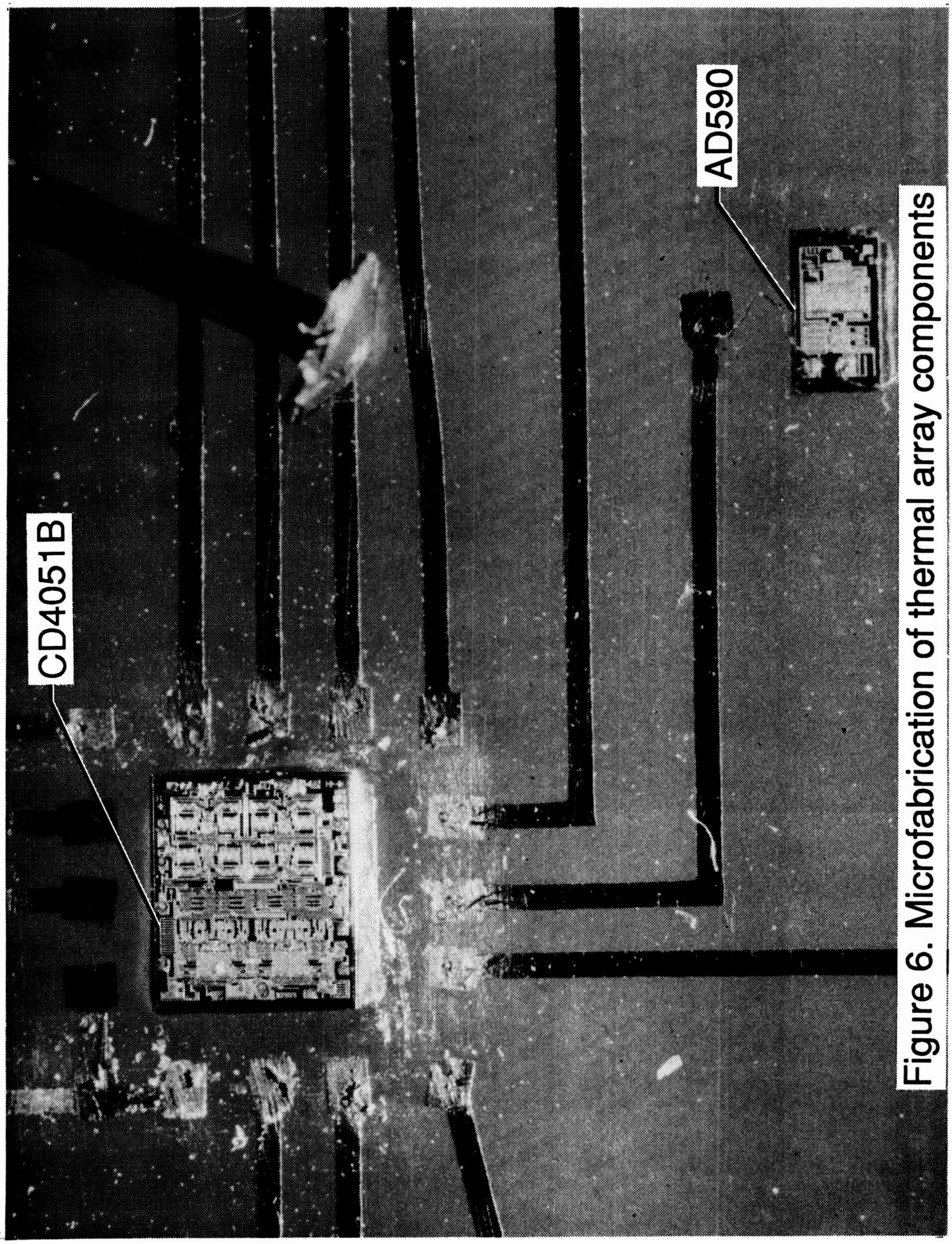

Figure 6. Microfabrication of thermal array components

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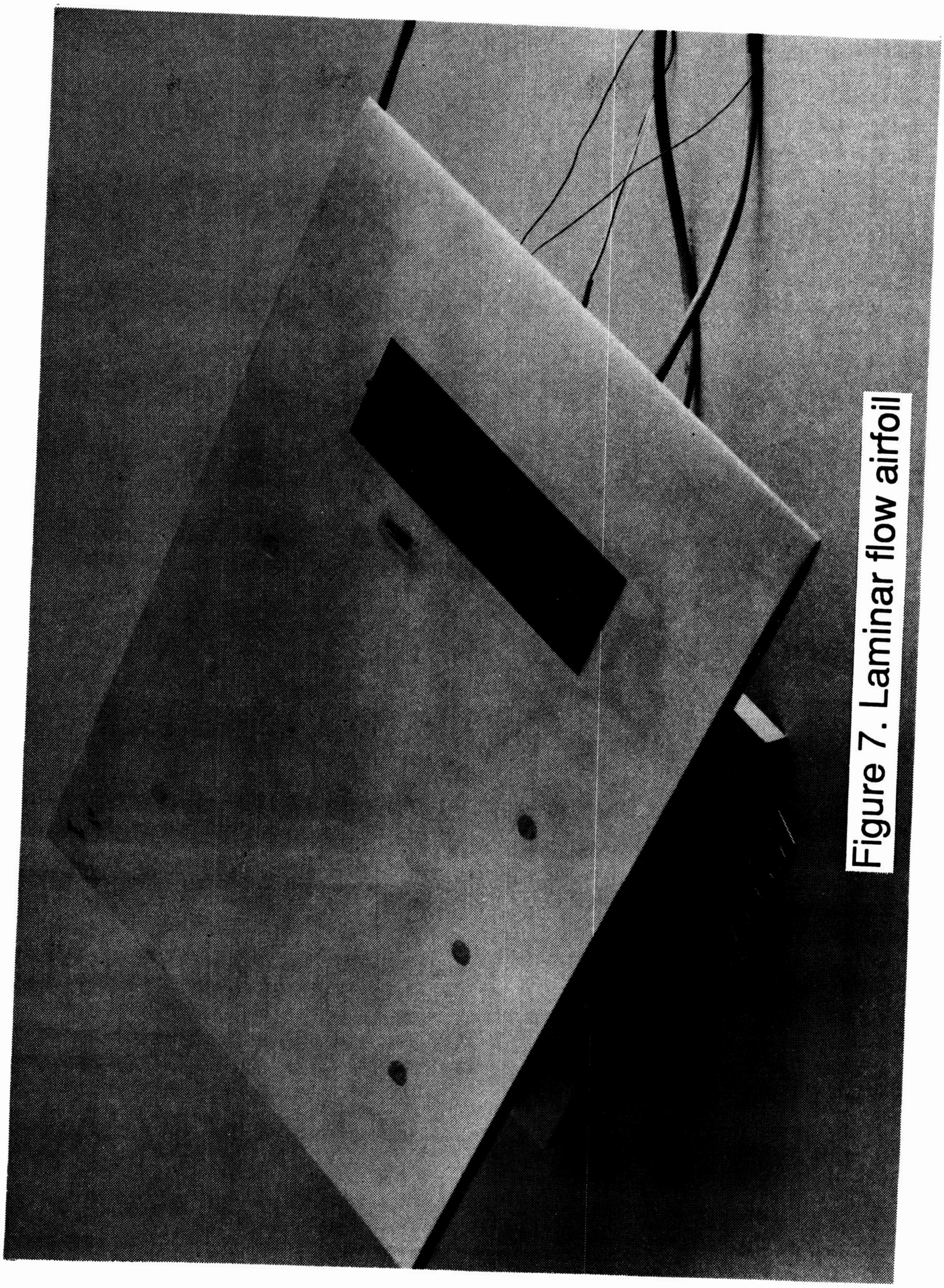
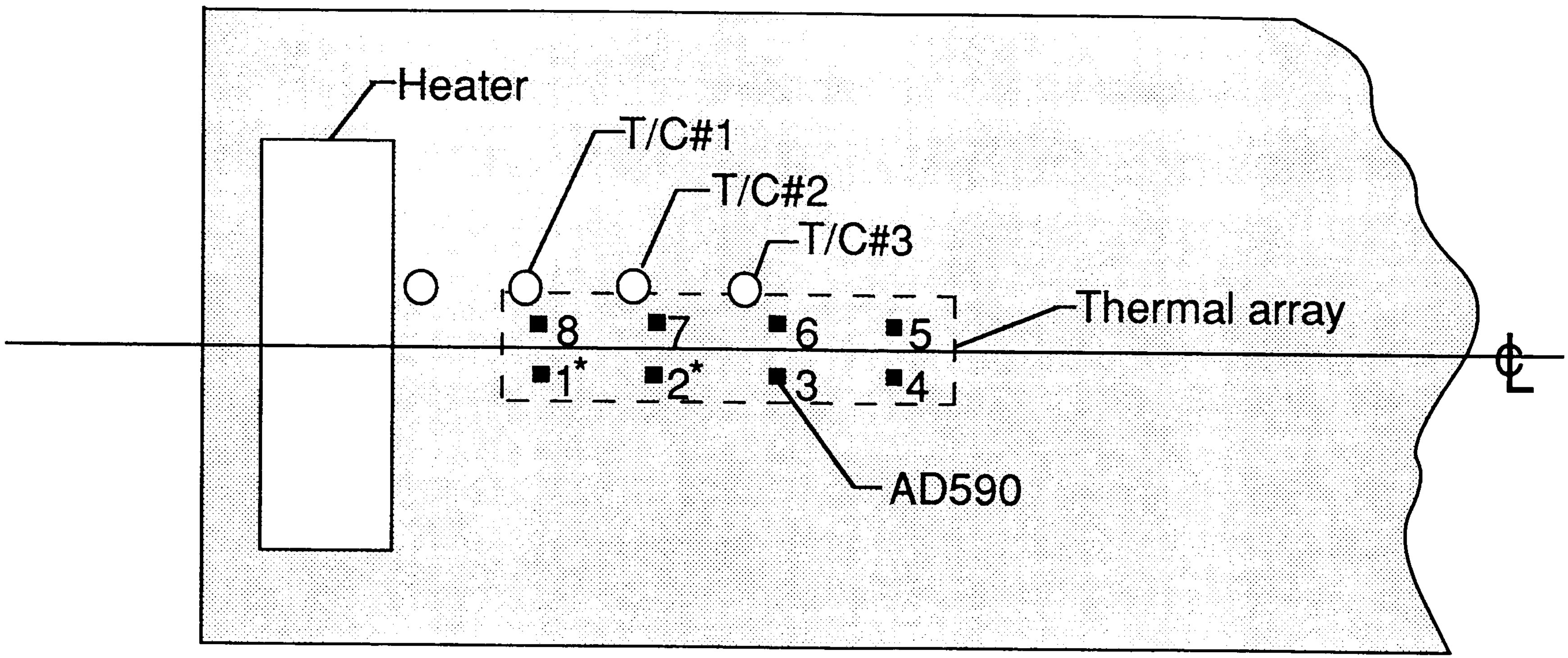


Figure 7. Laminar flow airfoil



*Sensors 1 and 2 not functional for this test

Figure 8. Thermal array test setup

THIN FILM MULTIPLEXED TEMPERATURE SENSOR TEST RESULTS @ 5 m/s

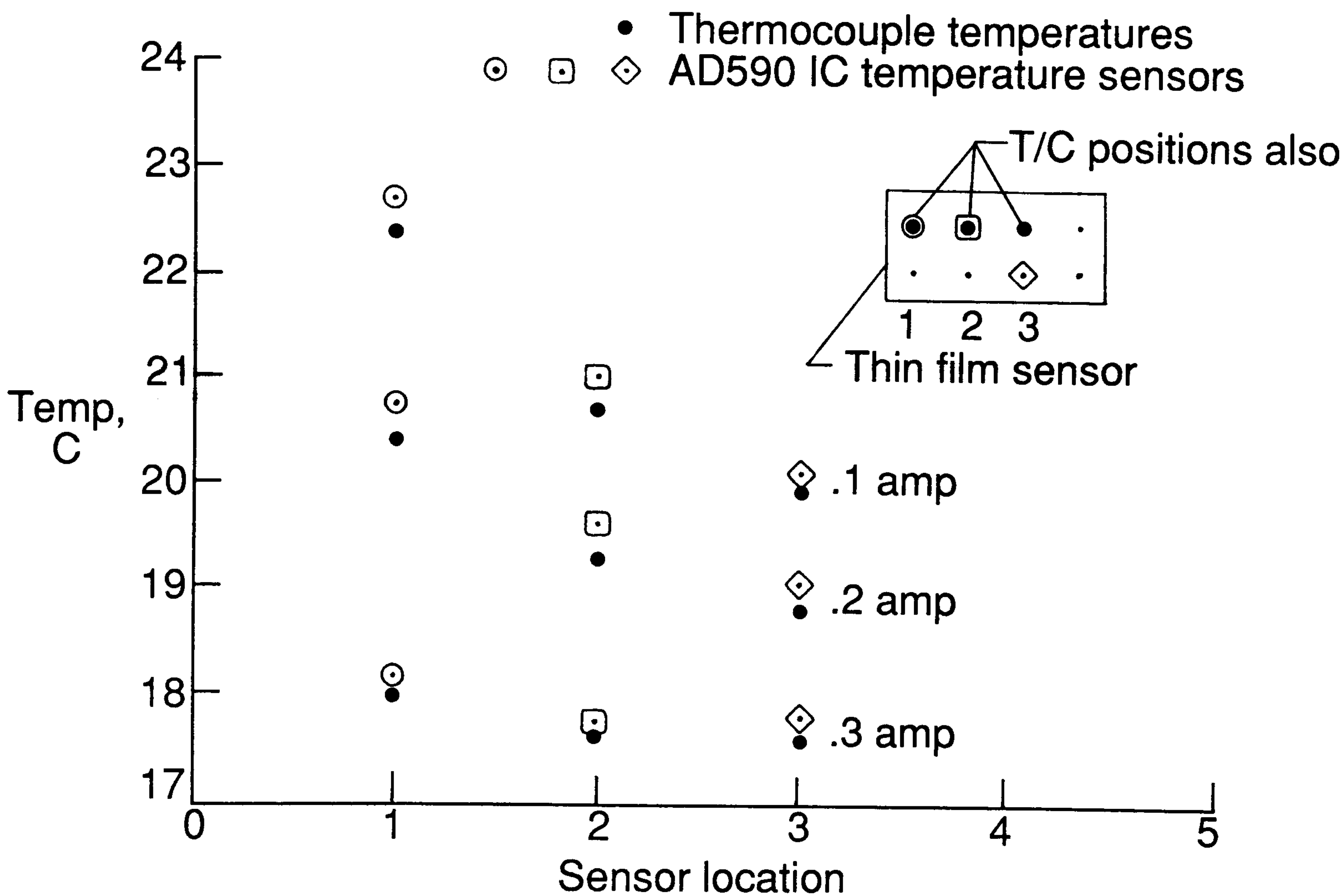


Figure 9.

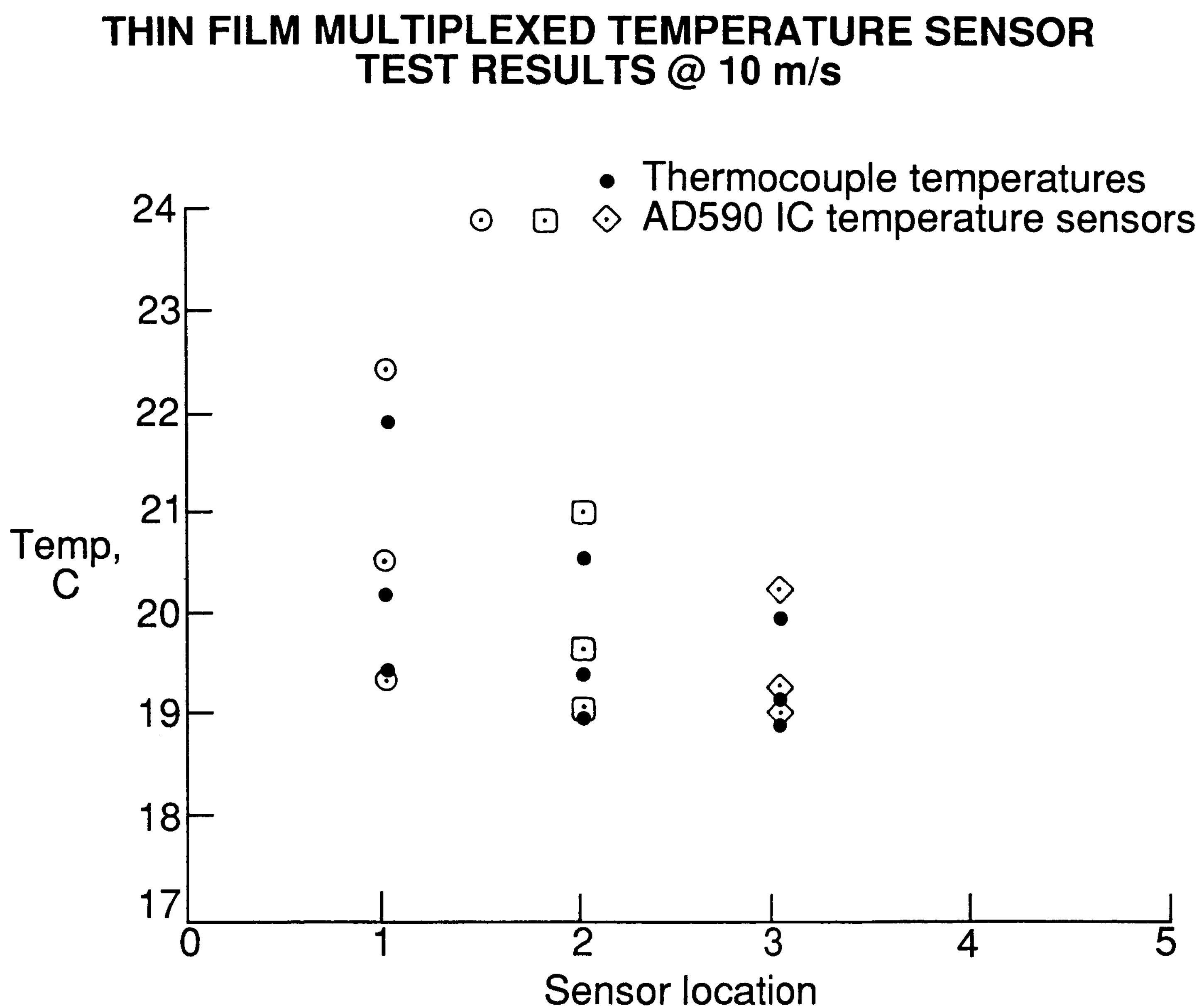

THIN FILM MULTIPLEXED TEMPERATURE SENSOR
TEST RESULTS @ 10 m/s
Thermocouple temperatures
AD590 IC temperature sensors
Temp, C
24
23
22
21
20
19
18
17
0
1
2
3
4
5
Sensor location

Figure 10.

THIN FILM MULTIPLEXED TEMPERATURE SENSOR TEST RESULTS @ 15 m/s

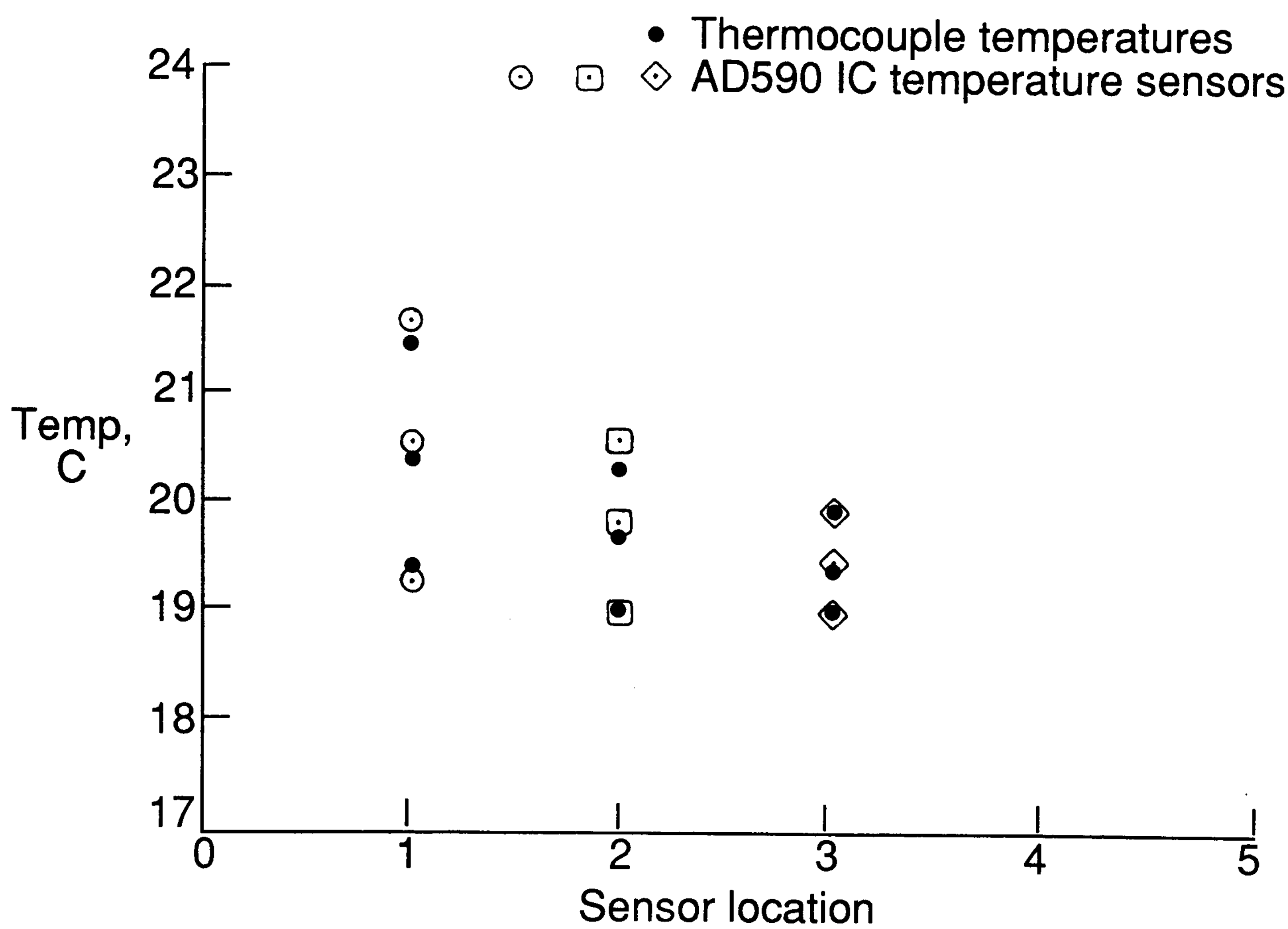


Figure 11.

TABLE 1

Indicated Temperature
of
Thermocouple (T/C) vs Thin Film Thermal Array (TFTA)

	T/C #1	TFTA #8	T/C #2	TFTA #7	T/C #3	TFTA #3	
Current (amp)	°C	°C	°C	°C	°C	°C	Air Speed
0	17.20	17.25	17.10	17.15	17.20	17.25	0 m/s (Baseline)
0.1	18.20	18.35	17.80	17.95	17.80	17.95	
0.2	20.80	21.15	19.60	19.95	19.10	19.35	5 m/s
0.3	22.90	23.25	21.10	21.45	20.30	20.45	
0.1	19.60	19.55	19.20	19.25	19.10	19.15	
0.2	20.40	20.75	19.60	19.85	19.30	19.35	10m/s
0.3	22.20	22.75	20.80	21.25	20.20	20.45	
0.1	19.70	19.55	19.30	19.25	19.3	19.25	
0.2	20.80	20.95	20.00	20.15	19.7	19.75	15m/s
0.3	21.90	22.15	20.70	20.95	20.2	20.25	

TABLE 2

Differential Temperature
of
Thermocouple (T/C) vs Thin Film Thermal Array (TFTA)

Current (amp)	(TFTA #8 - T/C #1) °C	(TFTA #7 - T/C #2) °C	(TFTA #3 - T/C #3) °C	Air Speed
0.1	0.15	0.15	0.15	
0.2	0.35	0.35	0.25	5 m/s
0.3	0.35	0.35	0.15	
0.1	0.05	0.05	0.05	
0.2	0.35	0.25	0.05	10 m/s
0.3	0.55	0.45	0.25	
0.1	0.15	0.05	0.05	
0.2	0.15	0.15	0.05	15 m/s
0.3	0.25	0.25	0.05	

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16. Abstract

A thin film device has been designed and fabricated to measure surface temperatures. An array of eight integrated thermal sensors are mounted on a 0.002" (0.05 mm) Kapton film and multiplexed to obtain an "area" thermal measurement. The device was tested on a flat plate airfoil and demonstrated a temperature variation of 0.55 ^{o}C maximum and 0.05 ^{o}C minimum compared to embedded thermocouples. Future improvements are also discussed.

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