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PRECISION TEMPERATURE GRADIENT MEASUREMENTS ON WINDOW GLASS

George Mikk and Ward Petrie, *Senior Engineers at The Perkin-Elmer Corporation, Optical Technology Division, 100 Wooster Heights Road, Danbury, Connecticut 06810*

ABSTRACT

Surface temperature gradients were measured with miniature thermocouples installed in a 58.5 cm (23-inch) square window. Test measurements at 25 locations were made under vacuum and with the window operating in radiant heat transfer mode. The analysis of thermocouple design and installation is presented along with a lead wire routing scheme to allow for both differential and absolute temperature measurements while using a minimum number of signal feedthru paths through the test chamber wall. Typical test data and operational precautions are presented along with the accuracy analysis for installation effects and measurement effects to support differential temperature measurement precision values of $\pm 0.06^{\circ}$C RMS ($\pm 0.1^{\circ}$F RMS).

INTRODUCTION

Typically in design activity, a mathematical model is created of the proposed system, followed by a physical test model, the operation of which, under simulated conditions, is used to verify the accuracy of the mathematical model. The confirmed mathematical model is then used for further detailed design analysis and development.

The subject of this paper is the measurement of surface temperature gradients on a glass window in order to confirm the accuracy of a system mathematical model using such a window. The window, a 25.4 mm thick glass plate, 58.5 cm square, was required to operate in a vacuum environment in a radiative heat transfer mode. The relationship of the plate to this heat flux environment is shown schematically in Figure 1.

The requirements of the test were to instrument a representative plate with temperature sensors, expose the plate to the simulated heat flux environment, and measure the resulting surface temperature differences to a precision of $\pm 0.06^{\circ}$C or better with the plate operating at a predicted mean temperature level of approximately 21°C.

Various measurement approaches were evaluated with the choice made to use copper-constantan thermocouples made from small diameter wire and operated in a differential mode in order to provide the required precision.

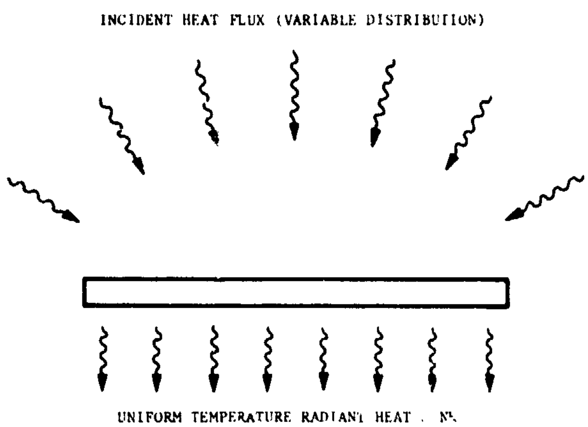


Fig. 1-Heat flux environment relationship

Sensor Analysis

Two installation approaches were considered for this application. The first, and simplest, used a miniature thermocouple attached on the front surface of the window with a patch of adhesive tape; the second employed a miniature thermocouple element inserted into a hole drilled from the back of the glass plate to a point 2.54 mm below the front surface.

Evaluation of these proposed installations was carried out using a steady state thermal analysis computer program available at our facility computer library. This program calculates node temperatures to yield the steady state temperature distribution and also calculates the steady state heat flow between the nodes.

Figure 2 shows the node arrangement used for calculating the patch thermocouple case, and Figure 3 shows the node arrangement for the case with imbedded thermocouples. In all cases of thermocouple installation evaluation, a uniform incident heat flux from a 26.6 $^{\circ}$C (80 $^{\circ}$F) blackbody irradiated the front surface of the plate and the rear surface radiated to a blackbody radiant sink at 18.6 $^{\circ}$C (65 $^{\circ}$F).

Results of calculations showing surface temperature depression for the case utilizing an adhesive patch to fasten the thermocouple onto the front surface are shown in Figure 4 with the associated nodal temperature map shown in Figure 5, where the temperatures are expressed as amount of temperature depression in $^{\circ}$C. Patch size was varied from 12.7 mm diameter to 25.4 mm diameter to evaluate the radiant energy blockage effects caused by the patch. The surface temperature perturbations range from 0.08 $^{\circ}$C to 0.12 $^{\circ}$C, which is in excess of the requirement 0.06 $^{\circ}$C. These values by themselves could be acceptable if it could be guaranteed that the temperature measurement perturbation at each location would be the same, but questions such as thermal contact between the thermocouple and glass, a variation of which would cause a variation in indicated temperature cannot be fully assessed. These effects are indeterminate depending on thermal contact, lead conduction, and tape patch temperature. For this reason, this approach was discarded, even though it would have been the simplest to implement.

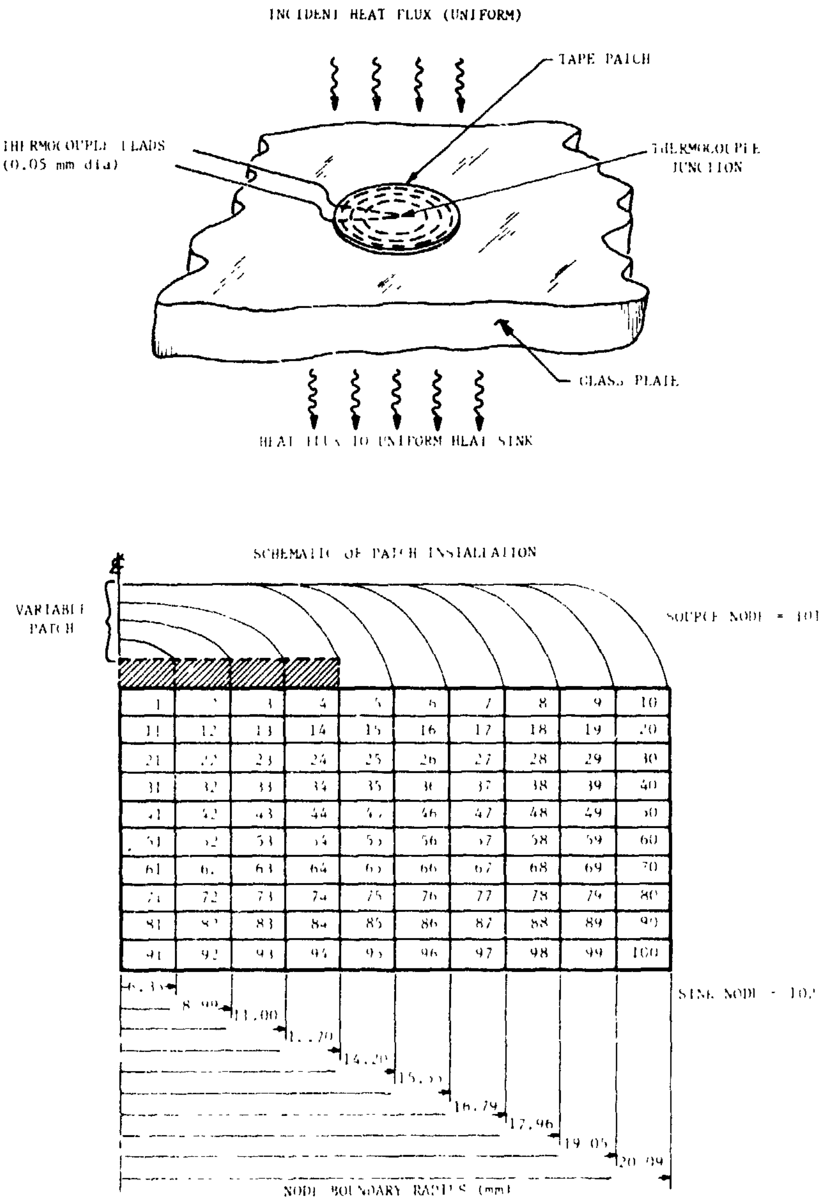
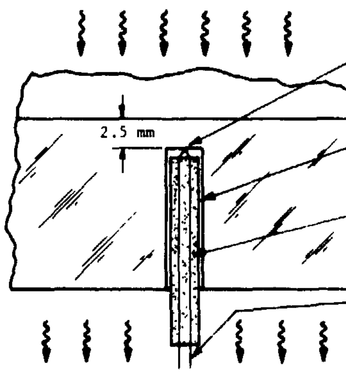
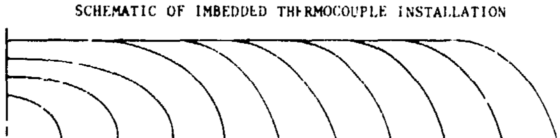


Fig. 2-Node arrangen.ent for computation (Equal area nodes)



SCHEMATIC OF IMBEDDED THERMOCOUPLE INSTALLATION



1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100

NODE RADII ARE THE SAME AS FIG. 2

NOTE:
The installation of the imbedded thermocouple is handled by modifying the thermal properties of nodes 11, 21, 31, 41, 51, 61, 71, 81, and 91 to account for the presence of the wire, ceramic and plastic filler.

Fig. 3-Node arrangement for case with imbedded thermocouples

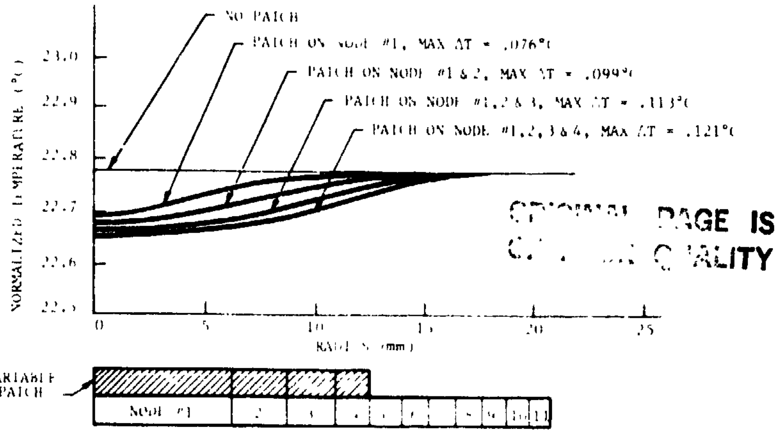


Fig. 4-Surface temperature suppression due to patch

.121	.095	.077	[illegible]	.032	.018	.009	.004	.002	.000
[illegible]	.107	.093	.081	.069	.061	.056	.052	.049	.049
[illegible]	.127	.119	.111	.104	.099	.096	.094	.092	.092
.166	[illegible]	.148	.143	.139	.136	.134	.132	.132	.131
.191	.182	.178	.176	.173	.171	.170	.169	.168	.168
.219	.213	.211	.208	.207	.206	.205	.204	.204	.204
[illegible]	[illegible]	.243	.242	.241	.240	.239	.239	.239	.239
[illegible]	.277	.276	.275	.274	.274	.273	.273	.273	.273
[illegible]	.309	.309	.308	.308	.307	.307	.307	.307	.307
[illegible]	.343	.342	.342	.341	.341	.341	.341	.341	.341

Fig. 5-Nodal temperature map for patch on nodes #1,2,3 & 4
Temperature depression (°C)

The alternate method considered a thermocouple element inserted to just beneath the front surface by means of a hole drilled from the rear surface. This proposed configuration was also analyzed using the computer model to assess its effect on the glass.

The thermocouple set in the bored hole, using a ceramic rod, results in a temperature distribution which is only slightly perturbed. The distribution is somewhat different in that there is a slight depression in temperature at the central nodes near the top of the glass. (See Figure 6.) This condition reverses itself near the bottom of the glass, giving a slight rise in temperature at the bottom. This unusual temperature distribution results from the greater conductance of the ceramic rod/thermocouple wire combination compared to that of the glass itself. The greater conductance path transfers heat away from the top surface more rapidly at the central node depressing its temperature. This greater conductance path also will conduct greater amounts of heat to the central node at the bottom surface, causing its temperature to rise slightly. In both areas, these effects are negligibly small in a practical sense and the temperature distribution closely approximates the temperature distribution of the undisturbed window.

TEMPERATURE DEPRESSION IN °C

0.006	0.004	0.002	0.001	0.001	0.000	0.000	0.000	0.000	0.000
0.054	0.049	0.047	0.045	0.045	0.045	0.044	0.044	0.044	0.044
0.093	0.092	0.091	0.089	0.089	0.088	0.088	0.088	0.088	0.088
0.134	0.134	0.133	0.133	0.132	0.132	0.132	0.132	0.132	0.132
0.177	0.177	0.177	0.176	0.176	0.176	0.176	0.176	0.176	0.176
0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203	0.203
0.246	0.246	0.246	0.247	0.247	0.247	0.247	0.247	0.247	0.247
0.306	0.306	0.306	0.307	0.307	0.307	0.307	0.307	0.307	0.307
0.348	0.349	0.349	0.350	0.351	0.351	0.351	0.351	0.351	0.351
0.389	0.391	0.392	0.394	0.394	0.394	0.394	0.395	0.395	0.395

Fig. 6-Nodal temperature map for inserted thermocouple

It is important to note that the thermocouple itself is located at a point approximately 2.54 mm below the surface. Thus, its temperature will be the temperature of the glass 2.54 mm below the surface. For this model, it will differ from the undisturbed temperature by no more than 0.06°C. This may be important for absolute temperature measurements, but should be of little importance to differential measurements where all the sensors will be similarly affected.

On the basis of this analysis, it was determined that a sensor of this type would be the optimum design approach.

Instrumentation Implementation

A sample window was used as the test article. The 2.16 mm diameter thermocouple holes were drilled by an ultrasonic technique using a diamond impregnated core drill, followed by a solid drill to provide a flat bottomed hole.

The sensor design was fabricated using bare 0.05 mm (0.002-inch) diameter copper-constantan thermocouple wire to insure minimum lead conduction effects. A ceramic rod with four axial holes was used to hold the junction in place in the drilled hole. Lead wires from the junction were run through the axial holes. The thermocouple assembly was potted in the hole with Laminar X-500 conformal coating. This technique provided an added benefit because the junction could be easily removed from the hole with a drill bit in a tap handle in the event of sensor failure. A typical installation is shown in Figure 7. A line of nine such sensors was installed in the plate as shown in Figure 8. An additional 16 sensors, not shown in Figure 8, were installed to provide confirmation of temperature stability.

Lead wire hook-up was accomplished in a special manner. It was desired to provide an absolute reading for at least one of the sensor locations. All locations were to be read differentially, either as selected pairs or all referenced to one selected location. To meet both of these aims, a common constantan lead was provided. All junctions were connected to this common run. This common constantan run was then brought out and combined with a reference junction. The copper side of each junction was brought out separately. The scheme is shown in Figure 9. To differentially read any pair of junctions, it is only necessary to read across the copper leads for each junction of the pair. By reading across the copper lead of any junction and the copper lead of the reference junction, an absolute reading of the junction can be made. Thus, a highly flexible readout capability resulted which enabled the readout of any differential pair desired, and still enabled the absolute temperature of each location to be read.

Fig. 7-Thermocouple installation

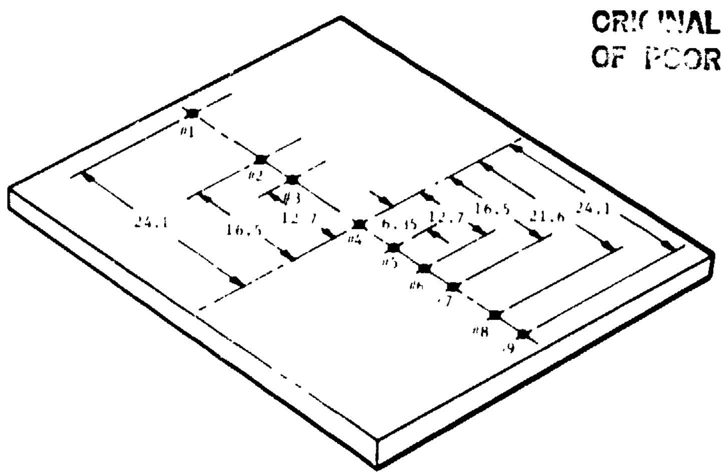


Fig. 8-Thermocouple locations (cm)

The copper leads on the window were routed to an edge area where 14 pin IC chip connectors were mounted. The connectors had been modified by breaking off the pins on one side of the connector. The connectors could now be bonded to the side of the window with the remaining pins extending over the surface, facilitating hook-up of the copper leads. The constantan lead was hooked up to the constantan side of a miniature thermocouple connector which was also bonded to the side of the window.

The copper leg of each junction was routed from the connector interface on the window by way of the copper leg of a copper-constantan harness. DIP component headers were attached to the harness to enable it to interface with IC chip connectors. The mating plug for the constantan lead connector was used to complete the harness interface.

The harnessing was routed to its own penetration through the test chamber where compensated copper-constantan feedthrus were used. From the penetration, the harness was routed to a switch box. Here the switch was wired to provide two readouts, a differential reading of each junction to one of the junctions which serves as a reference, and an absolute reading for each junction including the one used as a reference. The wiring arrangement is shown in Figure 9. At the switch, the constantan leg was wired to a 0°C reference junction, providing the absolute readout. The absolute readings were made using a Doric DS 350 digital temperature indicator (DTI). The switching provides readout of the thermocouple junctions as differential pairs with TC #1 as the common or reference junction of the pair for each junction. In this way, differential temperatures could be deduced for any combination of the sensors. Differential readings were made using a Hewlett-Packard 419 DC null volt-ammeter. The switch is wired in such a way that a short across the switch and a short across the connectors on the window can be read. This was done to identify any effects on the readings due to the lead wires or the switches. With the polarity switch in position #1, the absolute temperature of the individual junctions is read. In position #2, the absolute temperature of the common or reference junction is read.

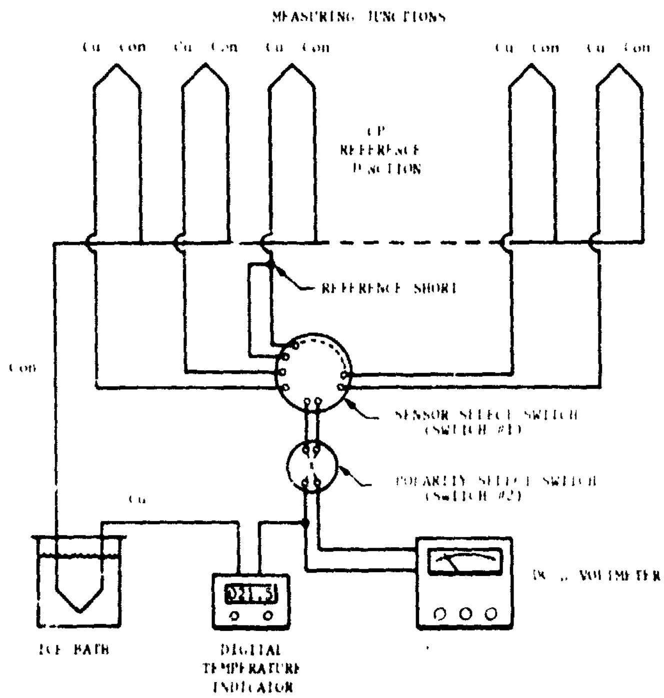


Fig. 9-Wiring arrangement

The accuracy of the absolute temperature data from the window thermocouples is $\pm 0.64^{\circ}C$ ($\pm 0.46^{\circ}C$ RMS). Differential measurements are accurate to $\pm 0.06^{\circ}C$ in magnitude. For values less than $0.56^{\circ}C$ in magnitude, accuracy is better than $\pm 0.03^{\circ}C$.

Wire error of $\pm 0.42^{o}C$ is included in absolute temperature. The readout error for the Doric DTI is $\pm 0.19^{o}C$. Reference junction error is $\pm 0.025^{o}C$. The sum of these errors gives $\pm 0.64^{o}C$ ($\pm 0.46^{o}C$ RMS) for absolute temperature measurements. Wire error is not considered in the differential measurements since the junctions were all made from the same batch. The readout error is the accuracy of the Hewlett-Packard voltammeter. The meter's accuracy is $\pm$(2% of range $\pm 0.1\mu v$). For these measurements, the $30\mu v$ and $100\mu v$ ranges were used. The corresponding accuracies are $\pm 0.7\mu v$ and $\pm 2.1\mu v$, respectively. Temperatures are derived by dividing these values by the conversion value of $39.6\mu v/^{o}C$. This gives temperature accuracies of $\pm 0.02^{o}C$ on the $30\mu v$ range and $\pm 0.06^{o}C$ on the $100\mu v$ range.

Test Program

The testing was carried out in a vacuum chamber at vacuum levels better than 10^{-5} torr. Incident radiant energy was provided by a zoned array of quartz IR lamps, which irradiated an intermediate, thin metal shroud which was then the primary test energy source. The test chamber containing the lamp array also incorporates a LN_2 temperature background shroud used as a reference heat sink for the lamp array system.

During temperature measurement system checkout prior to start of the test program, considerable data scatter and absolute temperature level errors were noted. Data and test log review indicated that the problem was related to the LN_2 background shroud cool-down.

A detailed investigation isolated the problem to the chamber penetration consisting of a standard "copper-copper" feedthru which was used in bringing out the lead wires from the window thermocouples, both legs of which were now copper due to the wiring arrangement on the plate for the differential measurements. Investigation revealed that the pins in the feedthru were a nickel alloy similar to constantan and that since the back of the feedthru had a good view of the LN_2 shroud, as the shroud was cooled a temperature differential became established across and through the feedthru. Since copper wires were attached to both sides of the feedthru, different differential thermocouple elements were created at this point in each circuit leg which introduced the scatter noted. Since the constantan leg, which was used for absolute temperature measurement, was routed through a normal constantan pin, the differential in the copper leg caused errors to up to $6^{o}C$ ($10^{o}F$). The solution in this instance was to use a thermocouple grade copper-constantan feedthru, using only the copper pins for the differential thermocouple wires. When this was done, the scatter was eliminated and the absolute temperature level returned to normal.

A vendor search for feedthrus with all pure copper pins has thus far proved negative. Therefore, this problem should be considered any time low level voltage measurements are to be made in a situation where temperature gradients are possible on the feedthrus.

With the resolution of the temperature measurement anomalies, the test program was carried out without further incident and good quality, consistent data was obtained over an extensive program encompassing a range of incident heat flux levels.

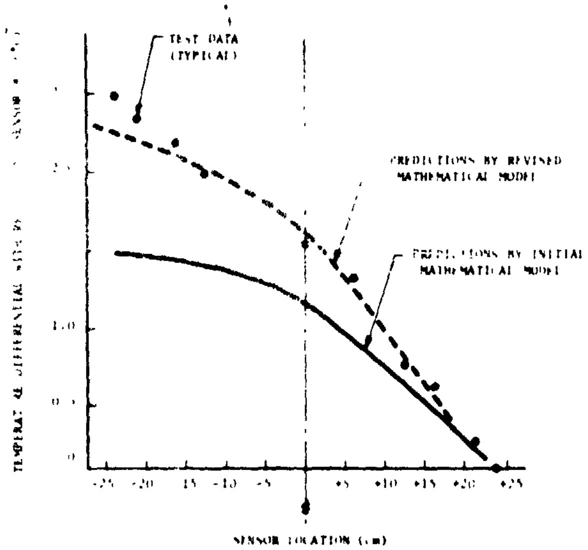


Fig. 11 Summary of test data

The initial predicted temperature response for the window under typical heat flux inputs is shown in Figure 10. When compared to test data, a discrepancy was present. A reevaluation of the mathematical model of the window in its test environment yielded several refinements and modifications in the model, which then provided the expected correlation to verify the model.

Conclusions and Recommendations

Detailed sensor installation analysis, using mathematical modeling, provides effective information on sensor choice, installation effects, test use, and data validity.

Assessment of thermal sensitivity of the total measurement circuit is a must when low level signals in the μv range are being measured. Special care must be given to material compatibility in the case of vacuum chamber feedthrus and associated wiring.

This paper has described a successful test setup using thermocouples to measure temperature gradients in glass with a precision level of $\pm 0.06^{\circ}$C and has highlighted the use of mathematical modeling in the design of sensor installation.

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