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A THERMOCOUPLE TECHNIQUE FOR MEASURING
HOT-GAS-SIDE WALL TEMPERATURES
IN ROCKET ENGINES

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ABSTRACT

A technique is given for installing small-size, quartz-insulated, single-wire thermo-couples on thin-wall rocket cooling tubes to measure the hot-gas-side wall temperatures. The lead and junction are protected from the hot gases by electroplating metal on the wall, which buries the lead and junction. The plating is faired to the wall to prevent disruption of the boundary layer. The upper temperature limit, which is due to the breakdown of the quartz electrical insulation, is 2060° R (1144 K). Calibrations are given.

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SUMMARY

A technique is described for measuring the hot-gas-side wall temperature of thin-walled (0.010 in., 2.54×10^{-4} m) regeneratively cooled rocket engines. Small quartz-insulated platinel 7674 alloy thermocouple wire 0.0005 to 0.001 inch (0.1270×10^{-4} to 0.254×10^{-4} m) in outside diameter was spot welded to the stainless-steel wall. The junction and insulated wire are then covered by electroplating 0.005- to 0.011-inch (1.27×10^{-4}- to 2.79×10^{-4}-m) nickel or copper. This plating protects the wire from the hot gases flowing over the surface. Fairing the edges of the plated area prevents disruption of the hot-gas-side boundary layer.

The complete installation process is presented, along with thermocouple calibrations and test data. The reproducibility of the installation as determined from test samples and furnace calibrations was within ±3.1 percent of a standard temperature-measuring device used at 2155° R (1197 K). The practical upper temperature limit of the system is 2060° R (1144 K). This limit is imposed because the quartz electrical insulation properties decrease rapidly above this temperature.

INTRODUCTION

One of the major problems in obtaining better heat-transfer information in regeneratively cooled rocket engines has been measuring the hot-gas-side wall temperatures. This temperature determines, in large part, the burnout condition in a regeneratively cooled rocket engine, and its measurement is vital in correlating data used to design high-heat-flux engines. The use of thin-wall (0.010 in., 2.54×10^{-4} m) cooling tubes in rocket engines increases the difficulty of measuring the true gas-side wall temperature.

Krueger and Curren (ref. 1) and Curren, Price, Krueger, and Manning (ref. 2) used a 0.020-inch- (5.08×10^{-4}-m-) outside-diameter sheath Chromel-Alumel thermo-

couple embedded in a 0.020-inch (5.08×10^{-4}-m) slot milled in a 0.021-inch-
(5.334×10^{-4}-m-) thick stainless-steel wall. The thermocouple was covered by braze material. High heat flux requires thin (0.010 in., 2.54×10^{-4} m) walls for adequate cooling; thin walls are also desirable because of possible weight savings. The coolant pressures at which these tubes operate also impose limitations on tube thickness. Structural reasons limit the amount of milling that should be done on these walls.

Unpublished work by A. J. Bockstahler of Rocketdyne has resulted in the installation of 0.010-inch- (2.54×10^{-4}-m-) outside-diameter sheath-type platinel thermocouples on a rocket engine wall. A 1/4-inch (6.35×10^{-3}-m) length of sheath is flattened to 0.004 inch (1.016×10^{-4} m) at the thermocouple junction. Installation was accomplished by dimpling the 0.012-inch (3.048×10^{-4}-m) thick tubes to receive the thermocouple and then filling the dimple with braze material. This method disturbs the coolant side of the tube to some degree. The author has found that this type of thermocouple may have its junction mislocated as a result of wire shorting in the flattened section and/or braze penetration of the thin sheath material.

As part of a comprehensive rocket nozzle heat-transfer program conducted at the NASA Lewis Research Center a new thermocouple installation technique was developed to measure the hot-gas-side wall temperatures during hot firings of rocket engines (fig. 1). In this technique a quartz-insulated platinel 7674 thermocouple wire was spot welded to the hot-gas side of the 347 stainless-steel coolant tube (fig. 2). Together, the platinel and stainless steel form the thermocouple. The platinel wire was less than 0.001
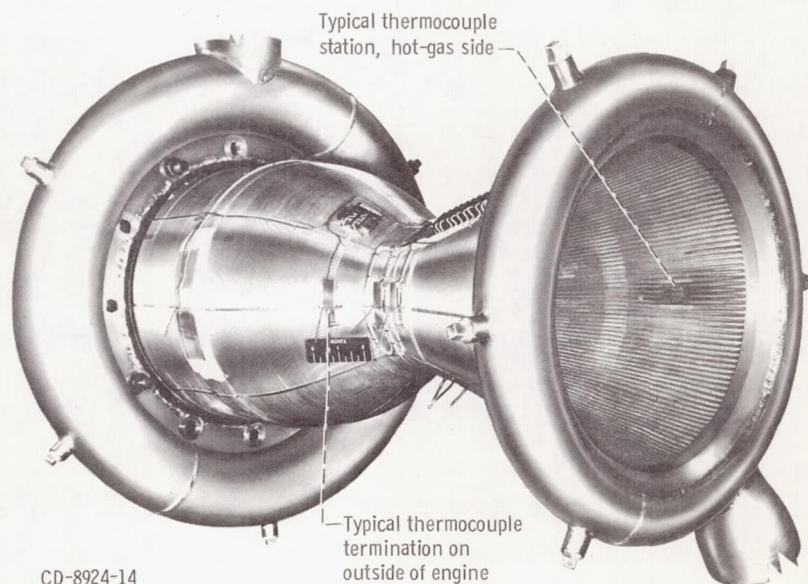

Typical thermocouple station, hot-gas side—

—Typical thermocouple termination on outside of engine

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Figure 1. - Regeneratively cooled rocket engine with thermocouples installed on hot-gas-side wall covered with copper.

Electroplated metal

High-temperature cement potted in access hole after electroplating

θ = 45°

Location of braze line

High-temperature cement potted in access hole before plating

Low-temperature cement

Engine-cooling-tube reinforcing strap

Quartz-insulated platinel thermocouple wire

Quartz access tube

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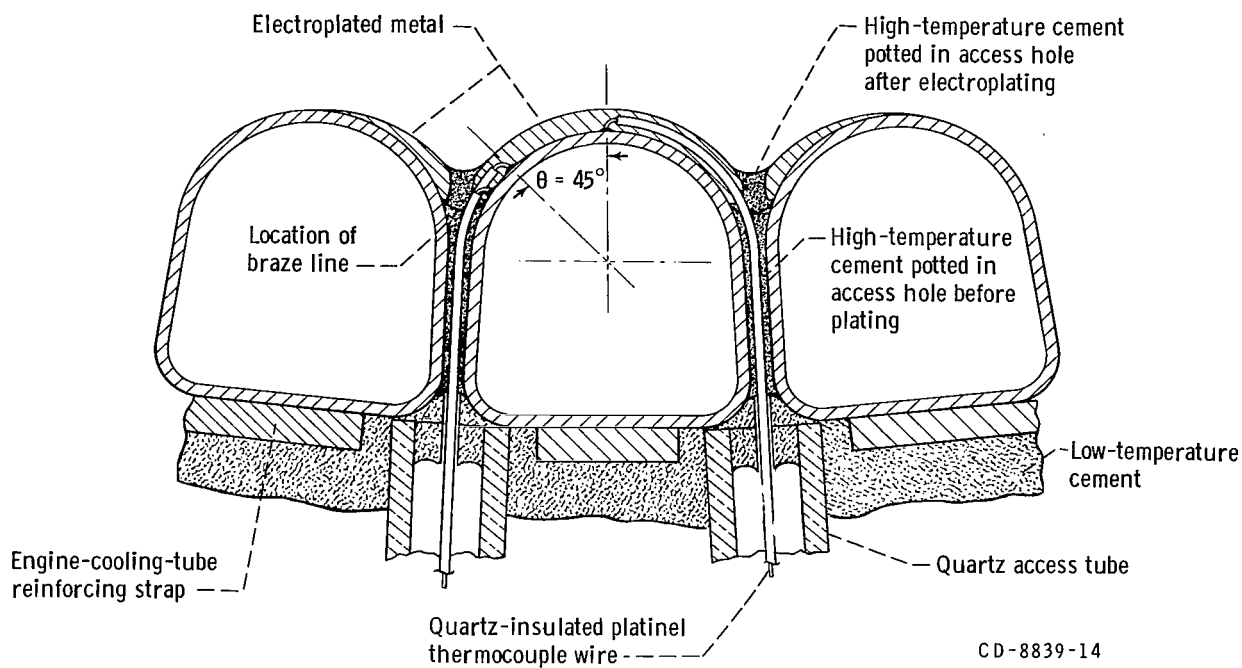
(a) Detail of thermocouple installation.

Thermocouple junction made by spot welding wire to cooling tube

Electroplated metal used to cover thermocouple

Quartz-insulated thermocouple wire

Hot-gas-side face of rocket engine

Coolant passage of rocket engine

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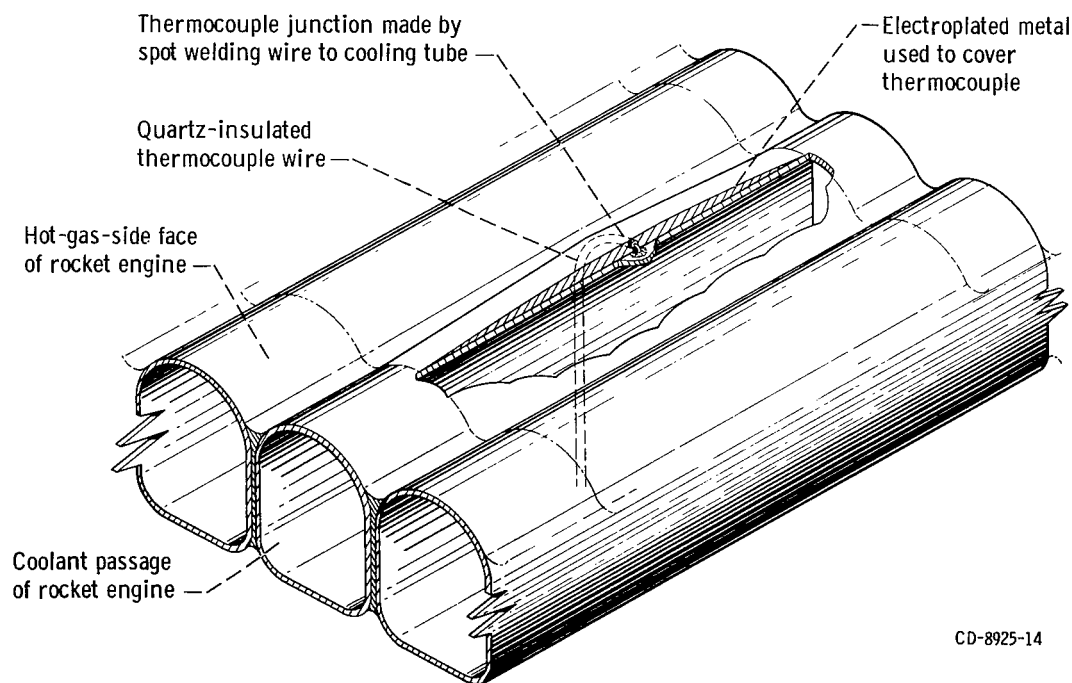
(b) Fairing of plated metal into tube surface.

Figure 2. - Installation of hot-gas-side thermocouples in regeneratively cooled rocket engine.

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inch (2.54×10^{-5} m) in outside diameter, and including insulation was less than 0.003 inch (7.62×10^{-5} m) in total outside diameter. The insulated wire and junction were then covered by electroplating with a suitable protective material (copper, nickel, etc.). The plating thickness was of the order of 0.005 to 0.011 inch (1.27×10^{-4} to 2.794×10^{-4} m). Pfahl and Dropkin (ref. 3) indicate a need for burying the sensor at least 2 sensor diameters below the surface in order to minimize the hot-side conduction error in the temperature measurement. This is easily accomplished with this technique. Access for the insulated thermocouple wire can be provided through a hole between adjacent coolant passages or by other special techniques provided for during fabrication of the rocket nozzle.

Details of the thermocouple fabrication process, calibration techniques, life, and tests performed to verify temperature readings obtained with these thermocouples are discussed herein.

DESCRIPTION OF THERMOCOUPLE INSTALLATION

The basic thermocouple installation is shown in figure 2(a). In this case three thermocouples are shown; one at the braze line, one at the crest of the tube, and the other at a point which is 45° from the crest ($\theta = 45^{\circ}$). The thermocouple is made by spot welding a single, quartz-insulated, platinel 7674 alloy wire to the point on the tube where the temperature is to be measured. Thus, the thermocouple consists of the platinel 7674 wire and the rocket cooling tube material, 347 stainless steel. This assembly is then covered by electroplating a metal such as nickel or copper on the surface of the cooling tube. The electroplated metal protects the assembly from the hot gases. Figure 2(b) shows a thermocouple installed in this manner. The edges of the electroplated metal are faired to the tube surface. This prevents disruption of the boundary layer which would change the heat-transfer characteristics at the measuring stations.

The platinel wire used in this work ranged in size from 0.0005 to 0.001 inch (0.127×10^{-4} to 0.254×10^{-4} m) in outside diameter. The quartz insulator which covered the wire ranged in size from 0.001 to 0.003 inch (0.254×10^{-4} to 0.762×10^{-4} m) in outside diameter.

Installation Procedure

The following information is presented in chronological order and gives the basic steps in the thermocouple installation.

(1) If a material which cannot be removed by ordinary cleaning processes covers the area on which the electroplating is to be done, special cleaning procedures must be used

or an adherent plate is impossible. This cleaning may be accomplished by grit blasting or, preferably, by filing. Filing will not embed material in the surface, while grit blasting will leave embedded in the surface small parts of grit that are hard to remove.

(2) The area to be electroplated is then masked off, as shown in figure 3, by painting the surrounding area with acid-resistant paint. The engine is now ready for the actual thermocouple installation.

(3) The preformed quartz-insulated thermocouple wire is then pushed through the access hole from the inside of the engine. The access hole is provided between the engine cooling tubes during the engine brazing process by placing stopoff material between the tubes and then removing the stopoff after the brazing has been completed. An alternate process is to insert small quartz tubing between the tubes before brazing and then after brazing to remove the quartz tubing by etching with hydrofluoric acid. After the quartz-insulated wire has been positioned by using the optical assembly shown in figures 3(a) and (b), the wire is spot welded to the cooling tube at the point where the temperature is to be measured. This is accomplished by means of the welding head shown in figure 3(b). A capacitive-discharge-type welder is used which has a range of 0 to 15 watt-seconds. Settings of the order of 2.5 to 3 watt-seconds are used with 0.001-inch- (0.254×10^{-4}-m-) outside-diameter platinel wire and 0.012-inch- (3.048×10^{-4}-m-) thick 347 stainless-steel walls.

(4) The exact location of the thermocouple is then determined by using the optical system shown in figure 3(a). By changing the objective lens to one having a high power and shallow depth of field (0.0002 in., 0.0508×10^{-4} m) and using dial indicators on the x, y, and z axes (fig. 3(a)) the location of the thermocouple is determined relative to the access holes. The thermocouple is considered to be located at the point where the wire emerges from the quartz insulator, which is somewhat offset from the spot weld (within 0.010 in., 2.54×10^{-4} m).

(5) If the thermocouple subassembly is not held close to the cooling tube surface during plating, two problems may be encountered. First, the quartz insulator may move away from the surface, which will result in an inability to cover the thermocouple assembly. Second, the quartz insulator may be covered at the crest and hence locked in place while the remainder of the quartz is allowed to move. This would result in breakage of the quartz and would allow the plated metal to short the thermocouple causing a secondary junction. To prevent this, weights are attached to the wire as shown in figure 4. The weights are cylindrical in shape having a hole drilled in one end to receive the thermocouple wire which is soldered in place. Care must be exercised during this operation to ensure that the wire and quartz are not pushed up into the access hole. This would cause kinking of the quartz and possible breakage, which would result in a shorted thermocouple and hence a mislocation of the junction. Screws in the bottom of the weight holder provide for individual height adjustment of each weight to adjust for the varying
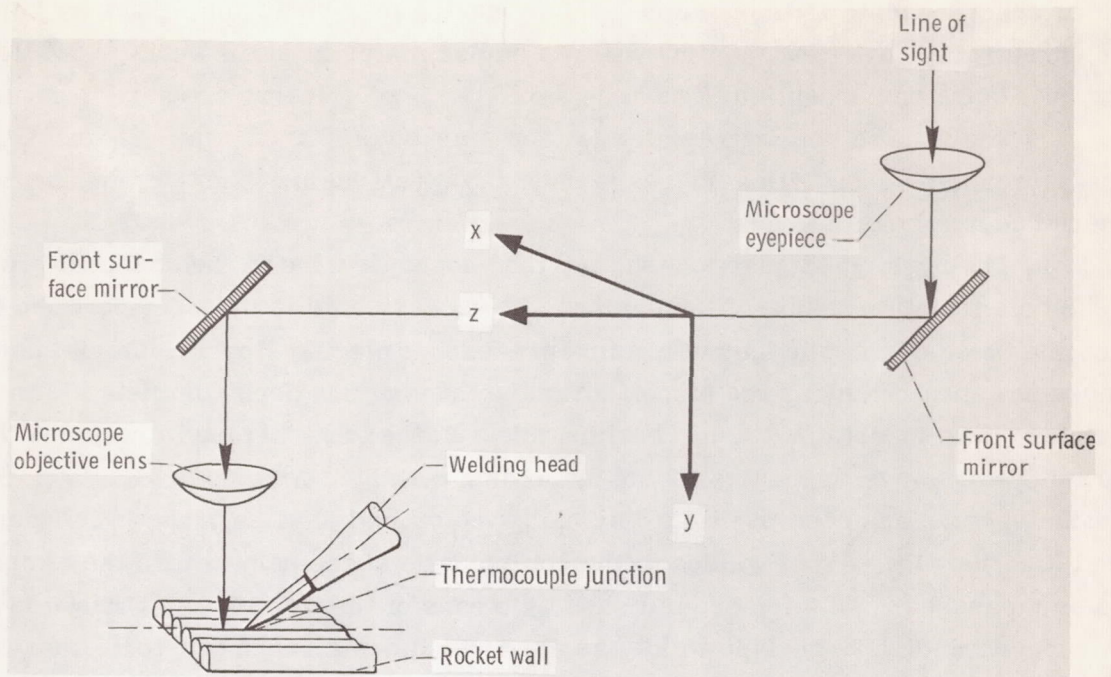
(Dial indicators are used to read x, y, and z position of object)

(a) Optical system used during thermocouple installation and for locating thermocouple junctions.
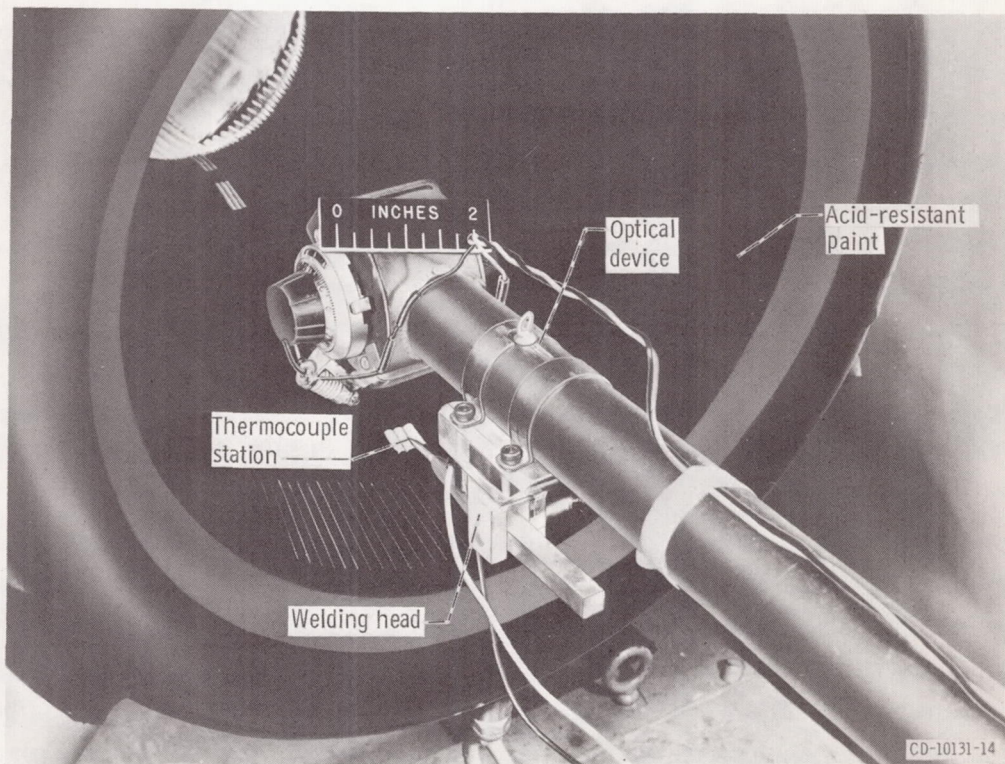
(b) A copper welding tip is used in conjunction with an optical device to locate and weld the thermocouple.

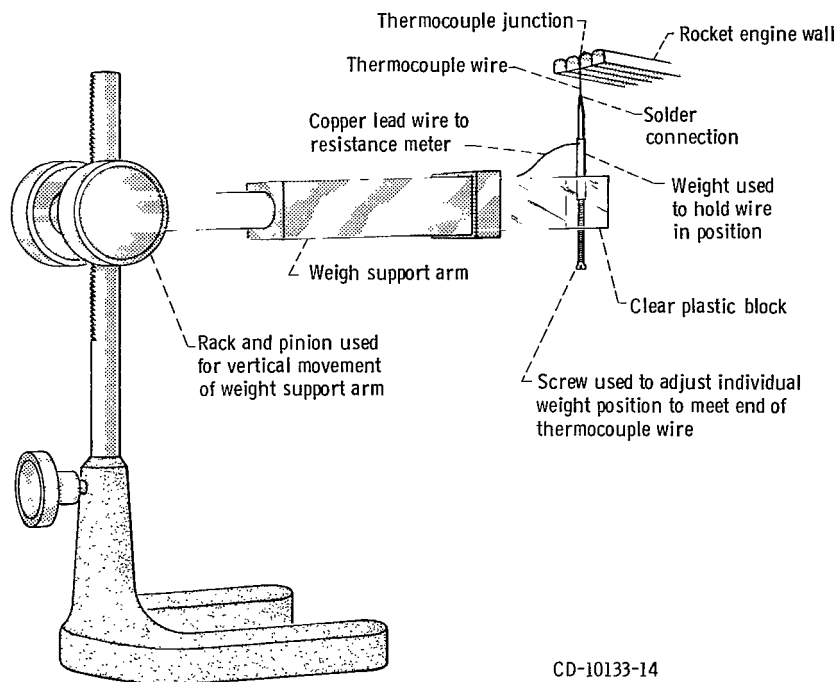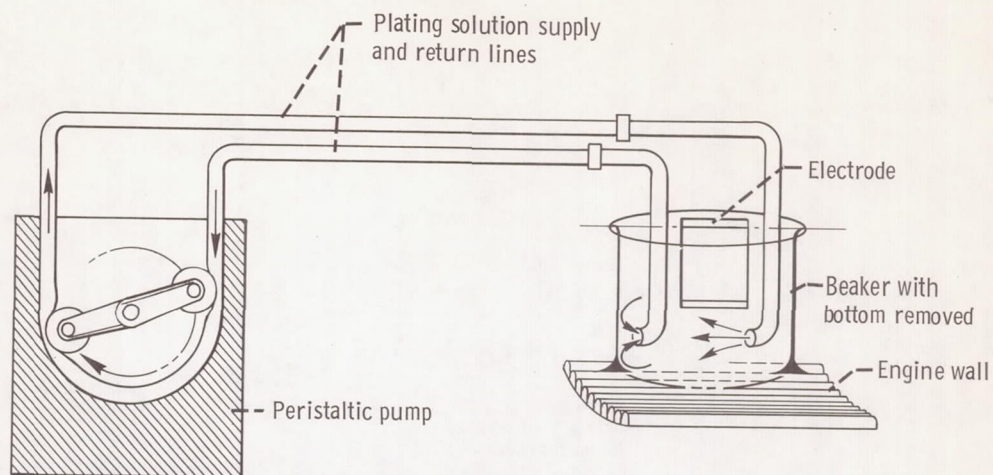Figure 3. – Thermocouple installation equipment.

Figure 4. - Method of applying force to thermocouple wire during electroplating.
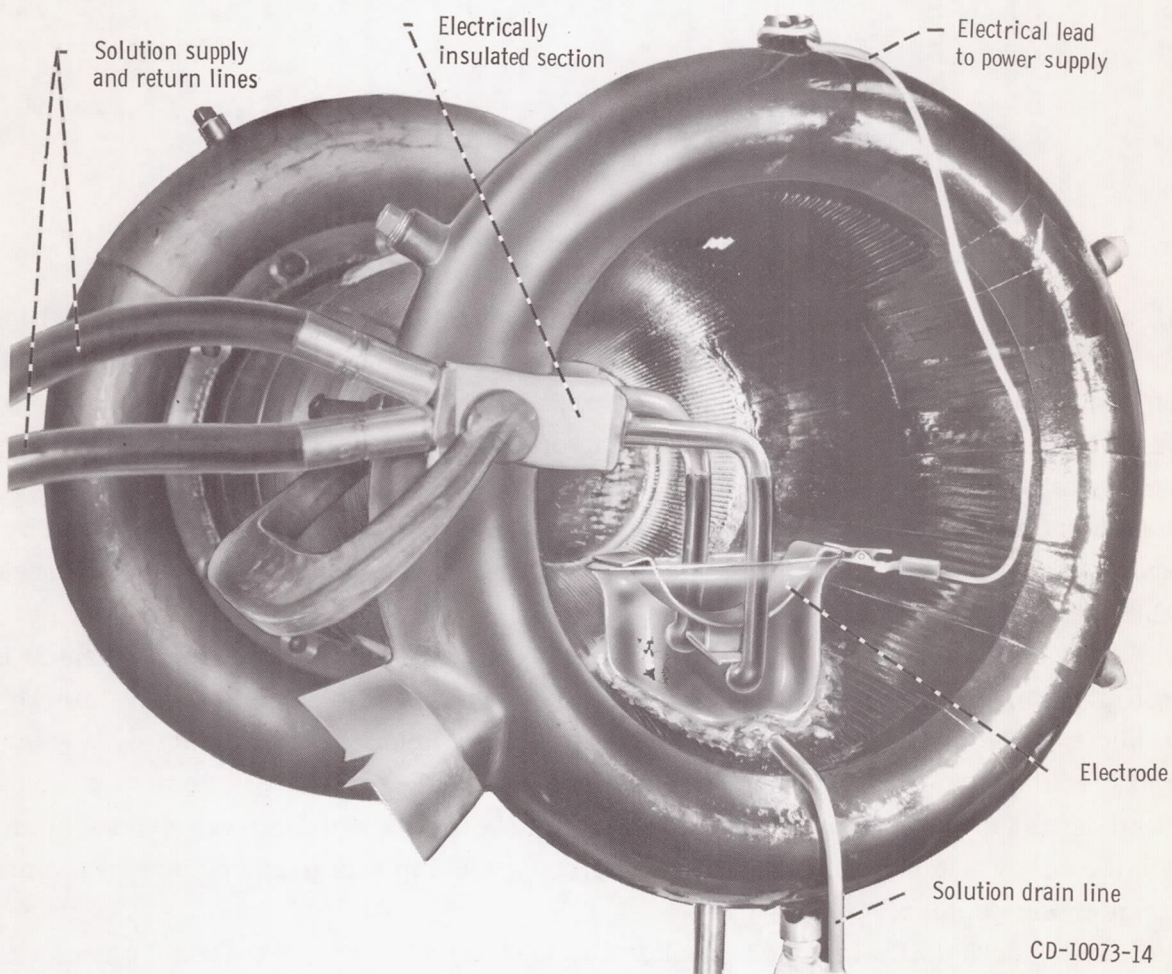
length of the thermocouple wire. After the weights are attached to each wire, the block supporting all the weights for a given station is ready for lowering by using the rack and pinion shown in figure 4. The weight is not applied at this point in the sequence to avoid undue stressing of the wire during succeeding operations. Fine copper lead wires (fig. 4) leading from the weights to an electrical-resistance-reading bridge circuit allow for the measurement of the thermocouple resistance during electroplating. The electrical resistance is monitored during plating as an aid in determining whether the quartz cracks and thus results in a shorted thermocouple.

(6) The area to be electroplated is surrounded by a bottomless beaker cemented in place (fig. 5(a)). A drain tube is included for removal of the plating solution. An electrode made of the metal to be electroplated is installed over the plating area. A pump is used to circulate the acidic plating solution (fig. 5(a)) to eliminate entrapment of gas bubbles and decrease plating time. The inlet and outlet for the solution-circulating pump are installed as shown in figure 5(b). A peristaltic-type pump was used because of the acidic solutions being pumped.

(7) After the installation of the beaker, electrode, and plating-solution-circulation system, the weight is then applied to the thermocouple wire by lowering the weight support block, as discussed in (5). Acid-resistant paint or cement is applied to the outside

Plating solution supply
and return lines

Electrode

Beaker with
bottom removed

Engine wall

Peristaltic pump

(a) Plating solution flow diagram.

Solution supply
and return lines

Electrically
insulated section

Electrical lead
to power supply

Electrode

Solution drain line

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(b) Plating setup in engine.

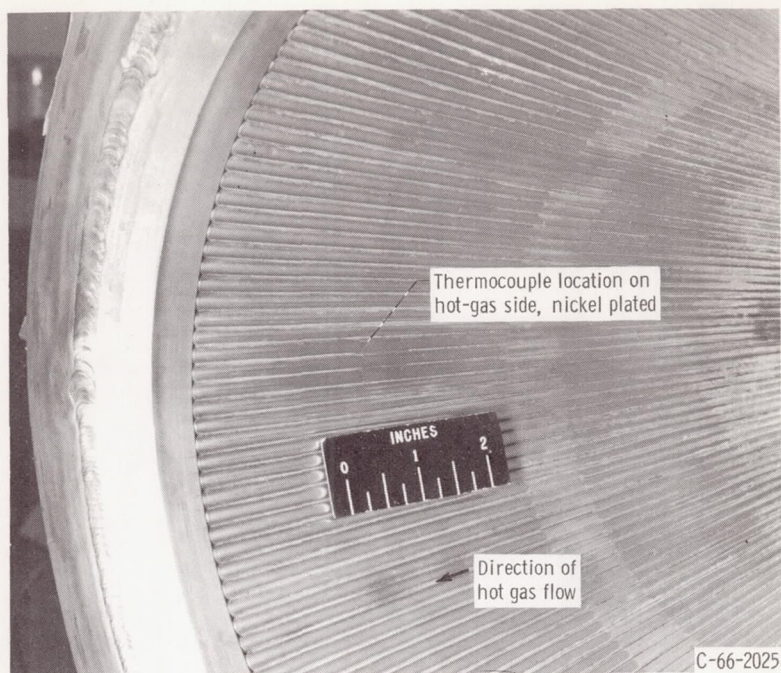Figure 5. – Electroplating system used in rocket engine.

Figure 6. – Finished installation, providing for smooth surface over which hot rocket gases flow with minimum of disturbance.

of the rocket engine around the thermocouple access holes to seal them against leakage of solution from inside the engine.

(8) Electroplating is now carried out, as described in appendix A. During the electroplating, the electrical resistance is recorded, as discussed in (5). An unusual decrease in electrical resistance may mean that the quartz has cracked and that a new thermocouple junction has been formed by the plated material.

(9) The plating is faired into the tube surface, as shown in figure 2(b), by filing its edges. This results in the installation shown in figure 6. The location of the thermocouple is practically impossible to find by observation after fairing. In fact, the only sure way of locating the thermocouple junction is by using a pointed soldering iron and reading the response of the thermocouple as the iron tip is moved from one point to another. It is this method which is used to check the location of the thermocouple against the locations found by means of the optical device. Disagreement of greater than 0.020 inch (5.08×10^{-4} m) indicates that the quartz insulator has cracked. The electroplated material completely surrounds the quartz insulator, as shown in the photomicrograph of figure 7. The elliptical shape of the wire and quartz is caused by the cross section not being exactly perpendicular to the quartz-insulated wire.

(10) The final step in the installation of the thermocouple is the termination of the
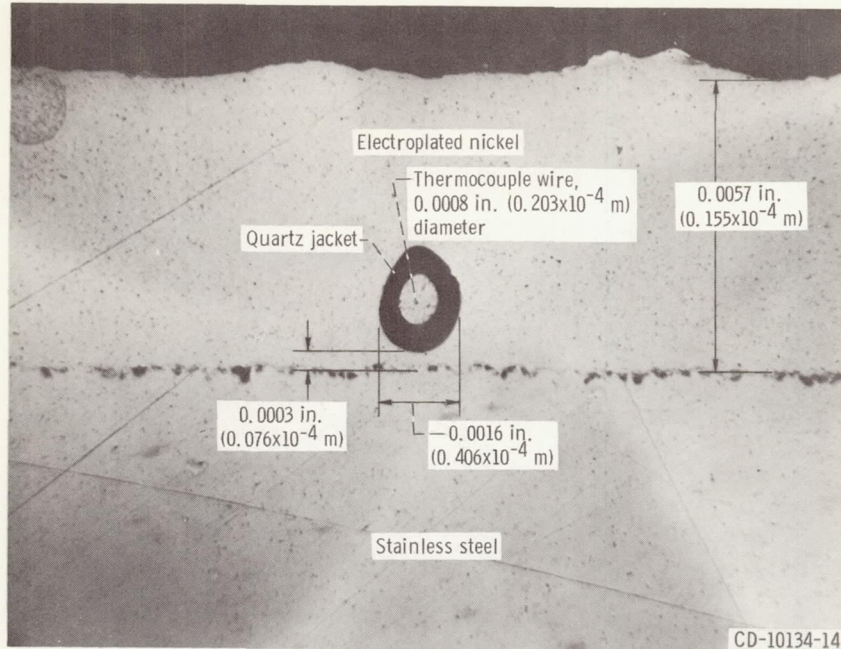
Figure 7. - Plated metal distribution around quartz-insulated thermocouple wire.

fine wire on the outside of the rocket engine. Figure 8 shows the fine platinel wire as it leaves the thermocouple passthrough and is attached to a heavier stainless-steel wire by spot welding. This spot weld forms the cold junction of the thermocouple. The plate to which the cold junction is attached is electrically insulated from the rocket engine. Another stainless-steel wire is attached by way of the strapping and mounting plate to the engine material. This stainless-steel lead is the positive side of the thermocouple indicator circuit, the stainless-steel lead from the cold junction being the negative side of the indicator circuit. Since the cold-junction temperature must be known in order to calculate the wall temperature, an additional chromel-constantan thermocouple is placed next to the cold junction. The cold junction along with the reference temperature measuring thermocouple are potted together using a cement which can withstand temperatures between 40° and 1060° R (22. 2 and 589 K). The cement minimizes the difference in temperature between the two junctions by insulating the junctions from the surrounding air. The cement also supports the spot weld at the reference junction; vibration could cause the spot weld to break if not supported.

As many as two thermocouples have been installed in one access hole (fig. 2(a)). This complicates the installation, however, and it is recommended that only one thermocouple be used in each access hole. This eliminates the possibility of the wires crossing one another and possible quartz cracking caused by bending around too small a radius.
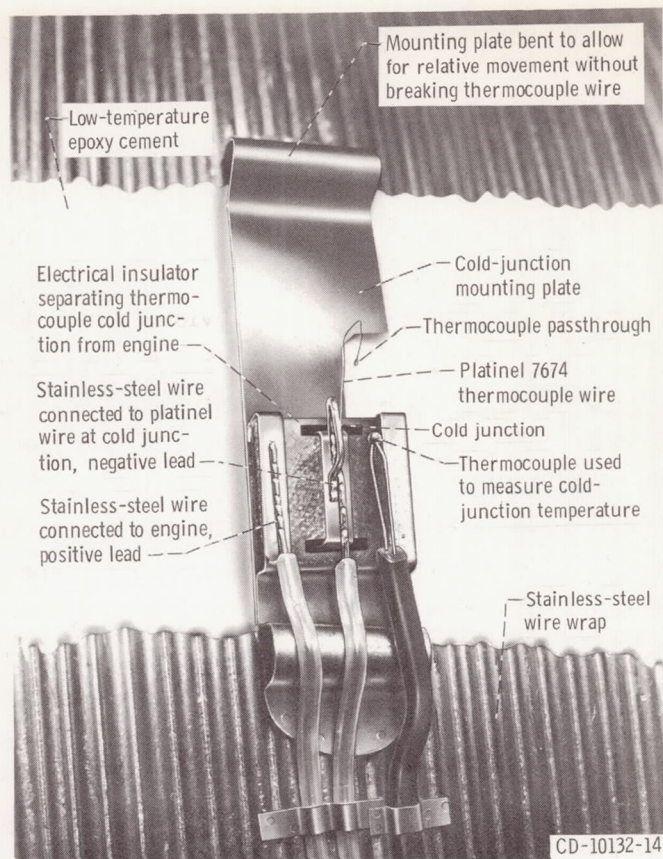
Figure 8. - Termination of fine thermocouple wire on outside of rocket engine.

As shown in figure 1, protective caps are placed over the installation on the outside of the engine. This is necessary to eliminate breakage during handling of the engine.

Thermocouple Material

Quartz-wire assembly. - The selection of platinel thermocouple wire was based on the testing of fine (0.001 in., 0.254×10^{-4} m) Chromel-Alumel and platinel (alloys 7674 and 5355) wire at temperatures up to 2260° R (1256 K). These tests indicated that the platinel alloy was more stable.

Two different methods were used to install the quartz insulation. The first is called the Taylor process, while the second involves small-bore quartz tubing through which the thermocouple wire is threaded.

The Taylor process consists of inserting a small amount of platinel 7674 alloy in a quartz tube, melting the platinel (3020° R, 1678 K), then drawing the quartz tube when it

reaches a plastic state (3260° R, 1811 K). As the quartz is drawn, the molten metal is forced to take the shape and size of the necked-down quartz tube, resulting in a quartz-insulated platinel thermocouple wire. Wire of the order of 0.0005 inch (0.127×10^{-4} m) in diameter with quartz insulation approximately 0.0015 inch (3.81×10^{-4} m) in outside diameter have been drawn (fig. 7) and are used in the rocket engine thermocouple installation. The major advantages of the Taylor-process wire are its small size and the minimum clearance between the wire and the quartz insulation. These minimize the disturbance of the isotherms in the wall.

An alternate to the Taylor-process wire, as previously mentioned, is the threading of 0.001-inch (0.254×10^{-4}-m) platinel 7674 alloy wire through preformed, small-bore quartz tubing (0.0025 to 0.003 in. (0.635×10^{-4} to 0.762×10^{-4} m) o.d. and 0.0015 to 0.002 in. (0.381×10^{-4} to 0.508×10^{-4} m) i.d.). The advantage of this method is that the wire is free to move in the quartz tube and, therefore, cannot be stressed as a result of differential expansion between the quartz tube and thermocouple wire. The disadvantages of this method compared to the Taylor-process wire are the increased size and the larger gap between the wire and quartz insulator, both of which will result in larger disturbances of the isotherms in the wall.

Electrical resistance of quartz-wire assembly. - The electrical resistance of the quartz insulator was determined by using the Taylor-process wire since this should give the lower limit because of the better electrical contact between the quartz and wire. Resistance calibrations were made on two samples: sample A, a stainless-steel flat plate on which a 0.5-inch (127×10^{-4}-m) length of quartz-insulated wire was covered by electroplated nickel; and sample B, a piece of stainless-steel rocket cooling tube on which a length of quartz-insulated wire, bent to the shape of the tube, was covered with electroplated nickel. In both samples, the wire was insulated from both the nickel and stainless-steel plate by the quartz, and no junction between the platinel wire and stainless-steel plate or tube was made. Stainless-steel wires were attached to the platinel wire and also to the stainless-steel plate or tube. These wires were connected to a vacuum tube voltmeter (with megohm range) which was used to read the resistance of the quartz. The sample was placed in an electrically heated furnace. The temperature was monitored using a Chromel-Alumel thermocouple which was spot welded to the test sample. The resistances of the two test samples as a function of temperature are shown in figure 9. The thickness of the quartz accounts for the difference in resistance between the two samples. At approximately 2060° R (1144 K), the resistance begins to decrease rapidly with temperature. The resistance above this temperature is considered marginal. Hence, 2060° R (1144 K) is considered the maximum safe temperature. A calculation using the Δ circuit shown in figure 10, details of which are given in appendix B, shows that 744 ohms will give an error of 2 percent for a thermocouple junction temperature of 2200° R (1222 K). This then is considered the maximum temperature at which the insu-

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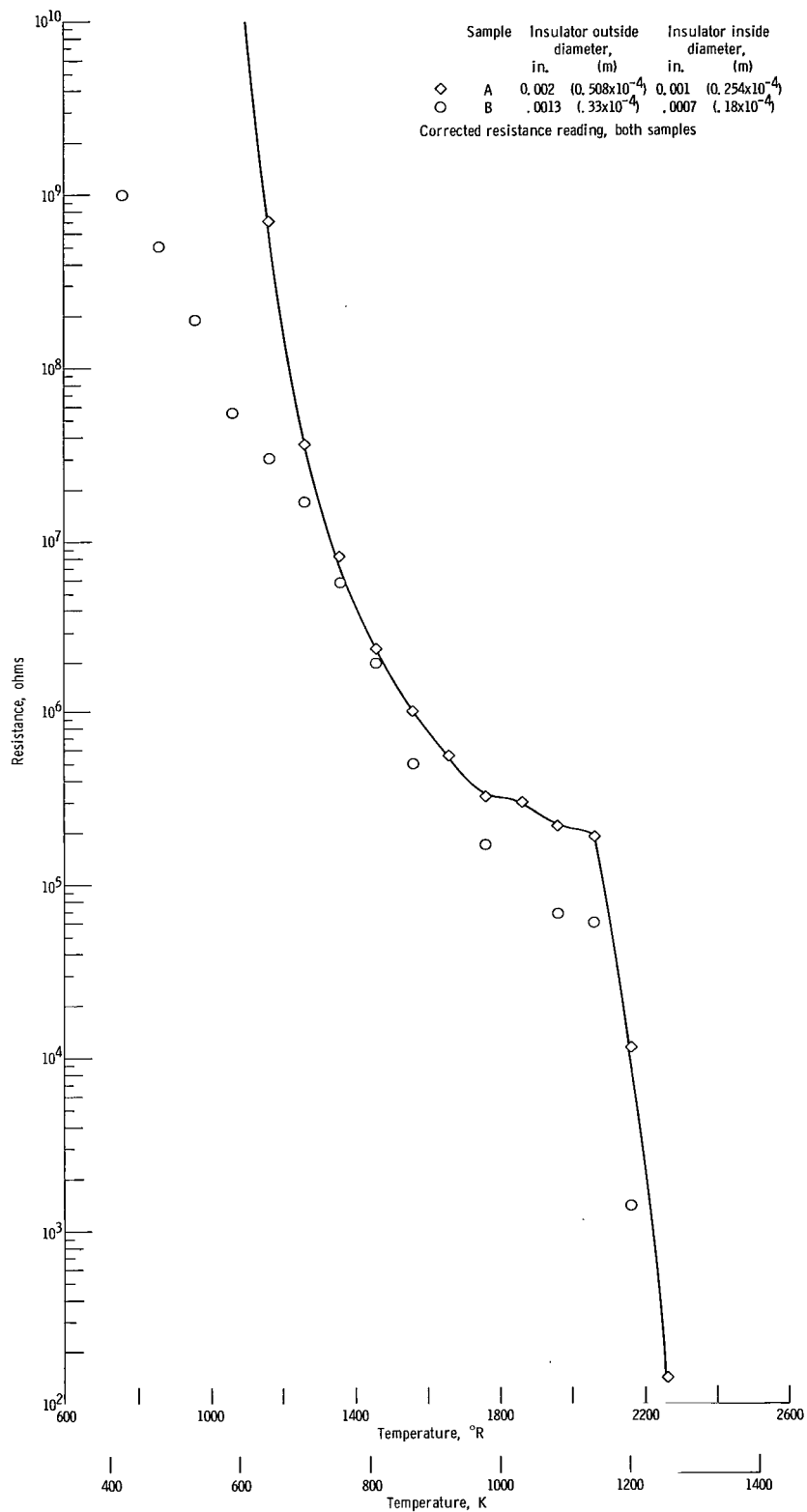
Figure 9. – Electrical resistance of thin-wall quartz as function of temperature.

The chart shows Resistance, ohms (vertical axis, 10^2 to 10^{10}) versus Temperature, °R (600 to 2600) and Temperature, K (400 to 1400).

Legend:

Sample	Insulator outside diameter,		Insulator inside diameter,	
	in.	(m)	in.	(m)
◇ A	0.002	(0.508×10^{-4})	0.001	(0.254×10^{-4})
○ B	.0013	$(.33 \times 10^{-4})$	.0007	$(.18 \times 10^{-4})$

Corrected resistance reading, both samples

(a) Thermocouple installation.

(b) Thermocouple electrical circuit (Δ circuit).
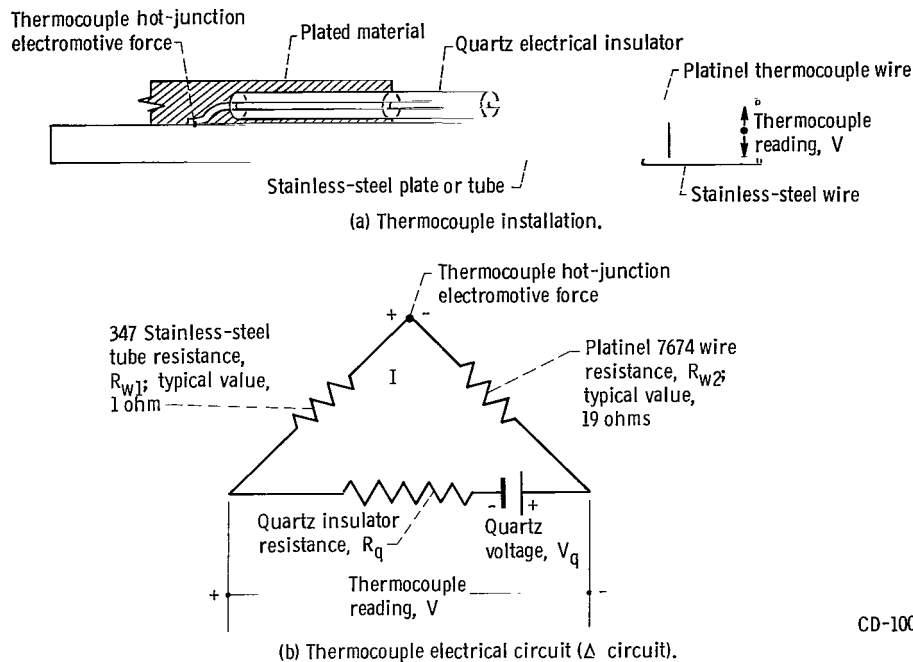
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Figure 10. - Basic thermocouple circuit.

lator can operate with an arbitrary chosen 2 percent error caused by shorting through the quartz insulator.

The resistance values shown in figure 9 have been corrected to account for a voltage which is developed in the quartz as installed for the quartz resistance tests described in step (5). This voltage does not affect the thermocouple calibration or readings. It is discussed further in appendix C.

Thermocouple calibration. - The 347 stainless-steel (plus leg) against platinel 7674 (minus leg) thermocouple was calibrated by spot welding the platinel wire to a 347 stainless-steel plate, placing the plate in an electric furnace, and monitoring the plate temperature with a 0.020-inch- (5.08×10^{-4}-m-) diameter Chromel-Alumel wire thermocouple spot welded next to the platinel junction. To determine the effect of the electroplated cover material copper was plated over the junction on one sample and nickel on another. The results of the calibrations are given in figure 11, in which the electromotive force (emf) of the thermocouple is plotted as a function of junction temperature. By extrapolating the calibration curve to zero temperature, a value of 0.2 millivolt was arrived at for the output of the stainless-steel - platinel thermocouple at liquid-hydrogen temperature. At 2000° R (1111 K), a 2.5-percent difference exists between the copper-covered sample and the bare thermocouple sample. A 0.5-percent difference exists between the nickel-covered thermocouple and the bare thermocouple at 2050° R (1139 K). The latter point was taken as a single checkpoint for the nickel-covered junction sample.
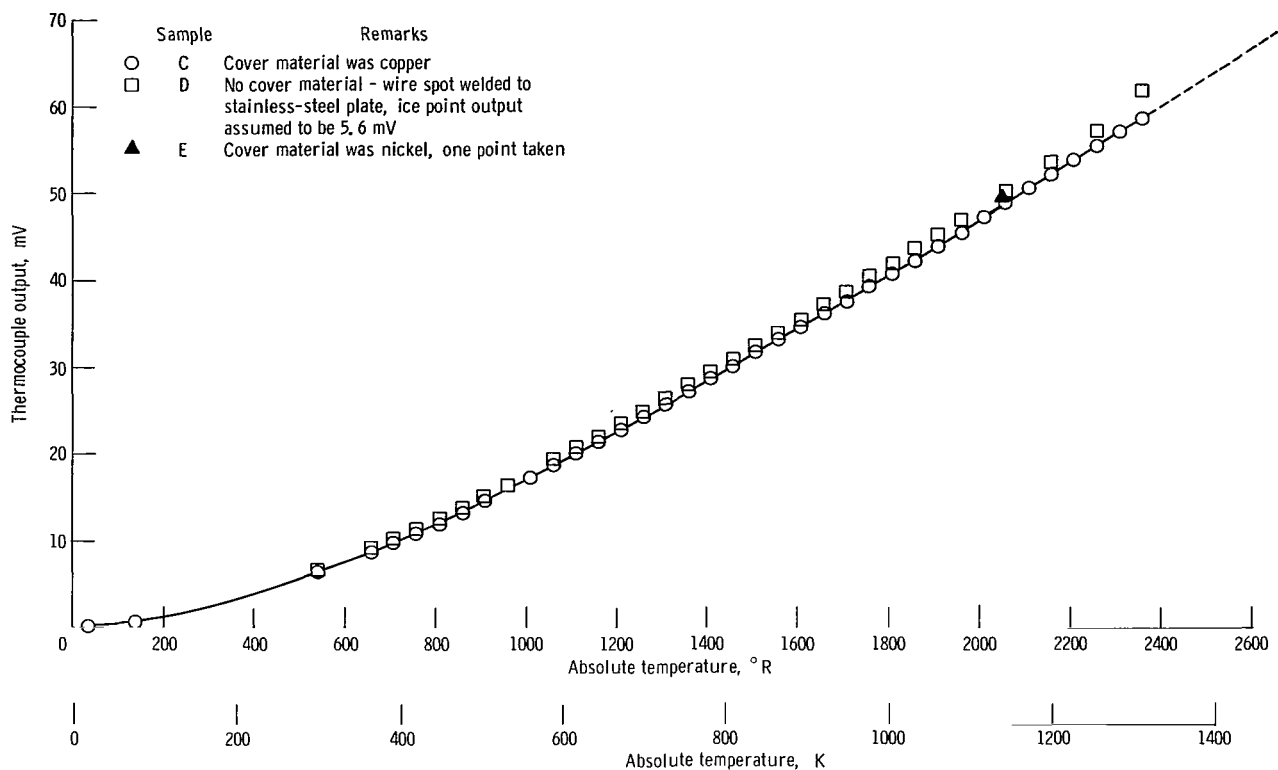
Figure 11. - Thermocouple calibration, 347 stainless steel against platinel 7674. Reference temperature, 0 °R. Output of thermocouple was assumed to be 0.20 millivolt at liquid hydrogen temperature to obtain this calibration.

These data show a maximum spread of 2.5 percent which is probably due to differences in thermocouple material and not due to the plated cover material.

The calibration of the stainless-steel - platinel thermocouple is nonlinear throughout the temperature range investigated (36.7° to 2360° R, 20.4 to 1311 K). The emf output of the thermocouple places it close to the Chromel-Alumel calibration; hence, the thermocouple is considered to be a high-output thermocouple.

Inhomogeneity tests. - Since inhomogeneity of thermocouple material can cause errors in the temperature being measured when large temperature gradients exist, a check was made to determine the magnitude of this error. A length of wire to be tested was connected to a microvoltmeter. A large temperature gradient was produced by immersing the wire in liquid nitrogen and then heating the wire at the surface of the nitrogen bath to a red glow, approximately 1860° R (1033 K). This was done along the length of both the platinel wire and the stainless-steel extension leads. Another test was done using a cross section cut from a rocket engine. Stainless-steel wires were spot welded to the crest of the rocket cooling tube, and another on the back of the wire wrap. These were, in turn, connected to a microvoltmeter. The tubes were then immersed in liquid nitrogen, and the wire wrap was heated to a red glow (approx. 1860° R (1033 K)). All tests showed less than 0.1 millivolt, indicating that inhomogeneity is not a problem.

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Preparation of Thermocouple, the Taylor-Process Quartz-Wire Assembly

Electrical insulation check. - Checks of the quartz insulation are required to locate cracks or flaws which may exist in the quartz material as it comes from the manufacturer or that develop during processing. The insulation checks are made with a Megger using 500 volts applied across the insulation. The checks consist of attaching the thermocouple wire to one terminal of the Megger, and then immersing the insulated section of wire into tap water into which an electrode from the other terminal of the Megger is immersed. The tap water may be made a better conductor by adding a small amount of hydrochloric acid. When the voltage is applied, gas bubbles will be generated if any crack exists in the insulator and in most cases are easily seen. In addition, any noticeable deflection of the Megger from infinity disqualifies the test sample.

This test was performed on the Taylor-process wire between each step in the preparation of the quartz-wire assembly. The first test was run on the assembly as received from the manufacturer.

These tests show that 65 percent of the wire tested (lot of 87 ft (26.5 m)) was usable (i.e., the insulated length is greater than $1\frac{1}{2}$ in. (3.8 cm), which was the minimum acceptable length allowed by the depth of the engine access hole).

Bending quartz-wire assembly. - The insulated, Taylor-process wire is bent to the desired diameter to fit onto the rocket cooling tube by using a hydrogen-oxygen, or similar, torch. The torch is directed into the end of a ceramic tube having the same diameter as the rocket cooling tube. The tube is heated to a bright red glow (2825° R, 1569 K). The quartz-jacketed wire is layed on the tube and gently but quickly bent to the desired shape. A Megger check is then run on the insulation. At least 57 percent of the bends are good at this point.

Removal of quartz jacket. - The quartz jacket is removed from the Taylor-process wire at the desired thermocouple location by etching with hydrofluoric acid. To ensure removal of the quartz at the correct location, the wires are layed in a slotted nickel block. Melted wax is poured into the slot to cover that portion of the quartz jacket which is required for insulating the thermocouple wire. The portion of the quartz-jacketed thermocouple wire which will be spot welded to the rocket engine sticks out from the slot. The block is then immersed in hydrofluoric acid, and the quartz jacket is etched away (40 min). The thermocouple wire is then removed from the block by melting the wax. The residue wax is cleaned from the quartz with a solvent. The quartz insulation is then checked by using the Megger test; 83 percent of the etched wires are good at this point. Of the Taylor-process material received from the manufacturer, 30 percent of the original 87 feet (26.5 m) is finally usable. The manufacturer states that his yield is 10 percent; therefore, the overall yield is 3 percent. It is clear that the Taylor process needs refining for use in this application.

Preparation of Thermocouple, the Wire-in-Quartz-Tube Assembly

In the case of the quartz-tube-insulated wire, the quartz tubing is bent as described for the Taylor-process wire, but in this case the wire is fed through the quartz tubing after the quartz is bent. The removal of the quartz, when necessary, is done by cracking the quartz tube and sliding the quartz off the wire.

Tests were made on the bent quartz tube to ensure that defective quartz would not be used. It was found that keeping the quartz at an elevated temperature 2860° R (1589 K) for prolonged periods (approx. 3 hr) caused it to shatter. Further investigation showed that, if the quartz tube was bent slowly (5 sec or more on the ceramic tube at 2860° R (1589 K)) or rebent, the number of flaws increased, while the number of flaws decreased if the quartz tube was bent as fast as possible and bent only once.

A test was devised to eliminate these inferior quartz insulators. It consisted of flexing several bent tubes (at room temperature) as shown in figure 12.
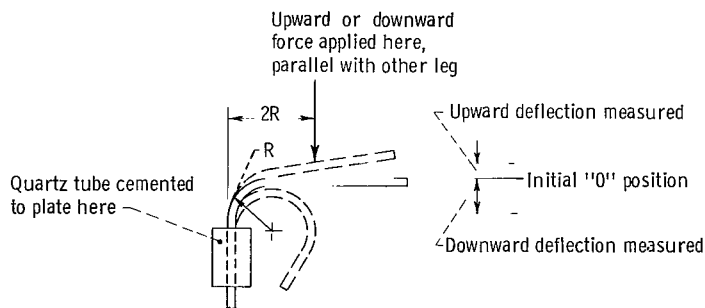

Figure 12. - Flexing test of tubular quartz insulator. Downward deflection results in quartz tube loop as shown. Deflection past a critical point results in quartz relieving itself.

The required deflection for a good tube was determined by running several tests and picking the deflection which clearly separated the good tubes from the bad. Both upward and downward deflections were caused, to stress the tube walls in both tension and compression. In the case of the 0.0025-inch- (0.635×10^{-4}-m-) outside-diameter quartz with an engine tube radius of 0.0625 inch (0.15875×10^{-2} m), the deflection in the downward direction was unlimited. After bending so far, the tube bowed past the point of application of the force, thereby relieving itself. The deflection in the upward direction was set at 0.150 inch (0.381×10^{-2} m). Installation of thermocouples using these quartz insulators showed a decrease in the number of faulty installations (i.e., cracked quartz defects).

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Plating Technique

Electroplating consists of both science and art. The weight of the material being plated can be calculated. The distribution of the plated material depends primarily on the electrode position and the geometry of the surface being plated. The distribution was determined experimentally and, in general, will vary from one setup to another. The ductility of the deposit is influenced by both the pH and the temperature of the plating bath. The bond depends on the plater's ability to clean and activate the surface of the base metal. The technique used for plating on stainless steel is basically that recommended in reference 4. The process used is described in appendix A. The plated material ranged in thickness from 0.005 to 0.011 inch (0.127×10^{-3} to 0.2794×10^{-3} m). Three tests were used on samples to determine the strength of the bond between the stainless steel and the nickel or copper plate. First, a dental tool was used to try to lift the plating from the surface. Second, the sample was heated to the melting point by using a hydrogen-oxygen torch. If blisters were found, the plating was considered to be bad. The last tests consisted of bending the plated surface through 180°. The first two tests are sufficient. The third test in all cases verified the results of the first two.

Without doubt, the most important step in electroplating is surface cleaning. The best surface for plating was that which existed on the stainless-steel sheet as received from the mill. This surface was degreased with acetone and plated by the procedure given in appendix A. If scale or other foreign material is present, it may be removed by filing the surface. During the course of this work, it was found that removing scale or dirt by sand or grit blasting yields a poor plating bond. Polishing the surface with emery cloth also causes a poor bond. The poor bond was apparently due to particles of sand or grit or emery particles which became embedded in the surface during the cleaning operation.

Selection of Plated Metal

When selecting the metal used to cover the thermocouple, the geometry of the installation must be considered. The error due to the circumferential conduction of heat toward the brazed junction of the adjacent tubes can be determined by calculating the temperature distribution in the tube and plated material, using numerical methods. A high-thermal-conductivity material may cause large errors in the thermocouple reading if heat is conducted away from the thermocouple junction and may create a cold spot on the surface. Low conductivity may create a hot spot on the tube surface, thus changing the heat-transfer coefficient. What is needed is a thermal conductivity which approaches that of stainless steel, so that the correction to the thermocouple reading is negligible

and the surface temperature on the plated surface is close to the stainless-steel surface temperature. Copper has 24 times the thermal conductivity of stainless steel at room temperature. The thermal conductivity of nickel is 5 times that of stainless steel.

A computer program using numerical methods was used to calculate the temperature distribution at the throat of the rocket engine shown in figure 1. Calculations were performed for a D-shaped tube (fig. 2) with a width of 0.105 inch (0.2667×10^{-2} m) and a wall thickness of 0.010 inch (0.254×10^{-3} m) with 0.005 inch (0.127×10^{-4} m) of plated material. The calculated temperature at the crest was decreased by 240$^{\mathrm{O}}$ R (133 K) when copper was used as the plating material, and 60$^{\mathrm{O}}$ R (33 K) when nickel was used. This temperature occurred at an input heat flux of 10.34 Btu per square inch per second (16.9 MW/m^2) with an assumed gas temperature of 6050$^{\mathrm{O}}$ R (3361 K). The coolant temperature was assumed to be 80$^{\mathrm{O}}$ R (44.4 K). Therefore, the choice of nickel for covering the thermocouple seems best from the standpoints of thermocouple installation error and uniformity of surface temperature.

TESTS OF THERMOCOUPLE INSTALLATION

Tests which tend to minimize the circumferential conduction errors caused by the plated material were made on samples with either copper or nickel plated over the thermocouples. The conduction error tends to be minimized because no coolant was used during the tests. These tests show that the system will reproduce temperature readings. Many samples were run to determine the as-installed calibration and the reliability of the thermocouple.

Accuracy and Reproducibility Tests

Three rocket cooling tubes were brazed together to represent the contour of the rocket engine wall. The thermocouple was installed in the usual way on the hot-gas side. On the back of the tube, the small wire was attached to a larger lead of the same alloy (usually 7674) which, in turn, was connected in a liquid-nitrogen bath to a stainless-steel lead, thus forming a reference temperature junction in boiling liquid nitrogen. This lead was then connected to the negative terminal of the voltmeter. A stainless-steel lead was welded to the sample tubes and connected to the positive terminal of the voltmeter.

Heating from the back is necessary because the optical pyrometer used to measure surface temperature is affected by the torch flame. Therefore, the back of the stainless-steel tube was ground away at the thermocouple location to allow the insertion of the hydrogen-oxygen torch which was used to heat the back of the tube.

TABLE I. - ACCURACY OF INSTALLED PLATINEL - STAINLESS-STEEL THERMOCOUPLE

Reading	Sample	Plated cover metal	Pyrometer reading		Chromel-Alumel thermocouple temperature		Platinel - stainless-steel thermocouple temperature		Maximum difference		
			°R	K	°R	K	°R	K	°R	K	Percent
1	F	Ni	----	----	1360	756	1350	750	-10	-5.56	-0.7
2			2120	1178	2135	1186	2110	1172	-25	-13.9	-1.2
3			2135	1186	2150	1194	2122	1179	-28	-15.55	-1.3
4			2384	1325	----	----	2370	1317	-14	-7.78	[a]-.6
5			2421	1345	----	----	2400	1333	-21	-11.67	[a]-.9
1	G	Ni	----	----	1360	756	1370	761	10	5.66	0.7
2			2050	1139	2050	1139	2100	1167	50	27.78	2.4
3			2100	1167	2090	1161	2155	1197	65	36.1	3.1
4			2068	1149	2060	1144	2100	1167	40	22.22	1.9
5			2045	1136	2040	1133	2065	1147	25	13.89	1.2
6			2063	1146	2060	1144	2100	1167	40	22.22	1.9
7			2316	1287	2335	1297	2370	1317	54	30.00	2.3
1	H	Cu	1950	1083	Open	Open	2105	1169	155	86.10	[a]8.0
2			1970	1094	Open	Open	2105	1169	135	75.00	[a]6.9
3			1979	1099	Open	Open	2115	1175	136	75.55	[a]6.9

[a]Standard changed to pyrometer because of failure of Chromel-Alumel thermocouple.

In addition, a Chromel-Alumel thermocouple was spot welded to the hot-gas-side surface as close to the embedded thermocouple as possible. Table I lists the temperature readings for the disappearing filament-type pyrometer, the Chromel-Alumel thermocouple, and the stainless-steel against platinel 7674 thermocouple along with the maximum differences between the test thermocouple and the test standard (pyrometer or Chromel-Alumel thermocouple). The pyrometer readings have not been correct for the emissivity of the plated metal.

Reading 3 from test sample G shows the maximum difference to be 3.1 percent of the absolute temperature using the Chromel-Alumel thermocouple as the standard and nickel as the cover material. The definite shift in percentage of error between samples F and G can be explained by the variation in calibrations between batches of wire (fig. 11). Sample H, which used copper as the cover material, showed a large error between the pyrometer and platinel thermocouple readings. This error may be explained by the fact that the emissivity for copper affects the pyrometer reading. Independent tests of a copper plate with a Chromel-Alumel thermocouple embedded in the surface show that an error in the pyrometer reading of 155° R (86 K) can be measured at 2310° F (1283 K). This difference is caused by an oxide film forming on the surface. Two samples were tested to verify this result.

TABLE II. - RESULTS OF CYCLING TESTS ON INSTALLATION

USING PLATINEL 7674 AGAINST 347 STAINLESS STEEL

[Cycling temperatures, 560° to 2090° R (311 to 1161 K).]

(a) Taylor-process type

Sample	Plated cover metal	Cycle on which thermocouple shows open circuit
I	Ni	9
J		32
K		30
L		[a]94
M	Cu	Past 50
N		12
O		101

(b) Quartz-tube type

Sample	Temperature		Plated cover metal	Cycle on which thermocouple shows open circuit or at which cycling temperature was changed
	$^{\circ}$R	K		
P	2100	1167	Ni	60
Q	2100	1167	Ni	64
R	1440	800	Ni	100
	1860	1033		150
	2100	1167		167 Crack in plating; thermocouple still good
S	1860	1033	Ni	85 Crack in plating; thermocouple open at cycle 86
T	1660	922	Ni	100 Crack in plating at cycle 70
	1860	1033		200 Crack in plating at cycle 70
	2080	1156		205 Crack in plating at cycle 70
	2190	1217		210 Crack in plating at cycle 70
	2250	1250		212 Open
U	1660	922	Ni	100 Crack in Ni plate at cycle 77
	1860	1033		177
Liquid-nitrogen-cooled cycle tests				
V	1860	1033	Ni	100
	2400	1333		101 Open

[a]Thermocouple was installed using 2.25 g wt to hold it on tube. All other samples used 0.5 g.

Reliability Tests

Further tests were run to determine the reliability of the thermocouple system. A series of cycling tests was run for which the thermocouple samples were made of three rocket cooling tubes but were heated from the hot-gas side of the engine tubes instead of the back side as in the accuracy tests. The reference temperature hookup was the same as that for the accuracy tests. The results of the cycling tests are given in table II. Samples I to O (table II(a)) were cycled from room temperature to 2090° R (1161 K). Samples P to V were cycled as shown in table II(b). The temperatures were monitored by the thermocouple being tested.

In running cycling tests it was observed that the nickel-plated samples started to crack after several thermal cycles. This cracking may then give rise to stresses in the thermocouple wire if the wire is locked to the quartz insulation as is the Taylor-process wire. This problem can be solved by using the wire-in-quartz-tube assembly which allows the wire to be free inside the quartz tubing. As shown in table II, the number of cycles obtainable before failure of the thermocouple is significantly greater for the quartz-tube type than for the Taylor-process type. Another solution to this problem is to deposit a more ductile material. This has been done by plating the nickel from a watts-type bath using a heated solution and maintaining a pH of 4.5. Tests at Lewis have shown that the nickel plated in this way will withstand thermocycling much better and give longer cycle life to the wire-in-quartz-tube installation.

Rocket Engine Installation

Reference temperature location tests. - Tests were made with the reference junction both on and off an actual engine installation. Two thermocouples were installed at the crest of the cooling tube. The leads were inserted from opposite sides of the tube. One lead was connected as usual, while the other was connected to a liquid-nitrogen reference bath away from the engine. The junction was heated while the engine tube was being cooled with air. The outputs of the two thermocouples after correcting for the different reference temperatures were within 0.8 percent of one another at 2185° R (1214 K). Placement of the reference junction has practically no effect on the temperature reading.

Thermocouple breakage on cooldown. - Both the Taylor-process and the wire-in-quartz-tube installations were made on rocket engines. Considerable breakage of the wire at the back of the cooling tube was encountered in both types of installation because of the close tolerance (0 to 0.005 in., 0 to 1.27×10^{-4} m) through the low-temperature epoxy cement used to support the back of the cooling tubes (fig. 2(a)). This close tolerance was caused by the flow of the cement into the quartz access tube between the engine

cooling tube and the bottom of the access tube. The breakage occurs because of the relative movement between the cement and the engine tube. Inspection showed that the cement was separated from the engine and indeed could be lifted out, exposing the thermocouple wire. When the wire was checked for electrical continuity, the break in the wire proved to be in the cemented area. One solution to this problem is to enlarge the inside diameter of the quartz access tube and prevent the flow of cement into this tube.

WALL TEMPERATURES MEASURED DURING ROCKET FIRING

Unpublished wall temperature data taken from an engine of the type shown in figure 1, which had been instrumented using the technique described in this report, is shown in figure 13. The data are taken from a playback of a digital recording system. The sampling rate for this test was 50 samples per second, and the system frequency response was from direct current to 500 hertz with 1/2 percent accuracy. The maximum temperature reached is 1010° R (561 K). The chamber pressure is also recorded for reference purposes. Total time of the run was approximately 15 seconds. The changes in chamber pressure coincide with the changes in wall temperature.
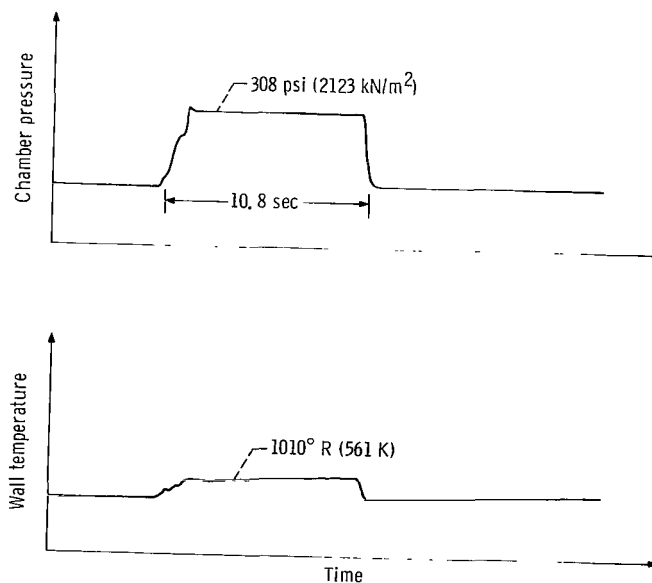
Figure 13. - Wall temperature and rocket chamber pressure as function of time.

CONCLUDING REMARKS

The measurement of a surface temperature involves a series of compromises between installation techniques and the accuracy of the temperature measurement. The

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thermocouple is a natural choice because of its ability to make nearly a point measurement. However, if the temperature gradient is large (40 000$^{\mathrm{O}}$ R/in., 875 000 K/m), the size of the thermocouple junction must be made as small as possible to minimize its disturbance to the heat flow path. Also, making the junction small will allow the location of the measured temperature to be more accurately determined. The technique which is the subject of this report has applied the thermocouple in a miniaturized state to the measurement of a surface temperature where a large temperature gradient exists. It is important to realize that the errors involved in using this system are of three basic types: first, the basic reproducibility of the voltage generated by the thermocouple junction; second, the change in temperature at the thermocouple junction caused by the addition of the electroplated metal; and third, the temperature gradient which exists across the thermocouple junction.

The first error is given by the thermocouple calibration. The second and third must be determined for each individual installation. The third error may be minimized by selecting a plated metal having a high thermal conductivity so that the temperature gradient in it is low. This, however, causes a larger change in the temperature at the junction as a result of circumferential conduction of heat through the plated metal. Therefore, a compromise is necessary. Nickel seems to be a good compromise for the cover metal.

In addition to the proper selection of cover metal, minimizing the thermocouple size will further reduce the third error. The smallest installation was obtained using the Taylor-process wire (wire diameter, 0.0005 in. (0.127×10^{-4} m); quartz outside diameter, 0.0015 in. (0.381×10^{-4} m)). However, the Taylor process for drawing wire inside quartz tubing needs further development. According to one manufacture only a 10 percent yield is obtained. Of this 10 percent about one-third is finally installed using the present thermocouple technique.

An alternate to the Taylor process is simply to thread wire through a quartz tube (0.003-in. (0.762×10^{-4}-m) o.d.). Although for practical reasons the final assembly is somewhat larger by this method.

The Taylor-process quartz-wire assembly has a number of advantages over the wire-in-quartz-tube assembly. First, its size is smaller, enabling the electroplated cover metal to be thinner. Second, the smaller-diameter quartz insulation can be bent around a smaller radius with less fear of breaking. Thus, irregularities in the cooling tube surface are less likely to break the quartz. Third, the gap between the wire and the quartz is the smallest possible; thus, the disturbance to the heat path through the wall is a minimum. Fourth, the wire comes from the manufacturer complete with the high-temperature electrical insulation installed.

The disadvantages of the Taylor-process wire compared to the wire-in-quartz-tube assembly are that the wire may be locked to the quartz as a result of irregularities in

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the quartz inside diameter, thus making it possible to strain the wire. The main disadvantage is the low yield of usable wire which results from the Taylor process itself.

In both systems reinstrumentation of a station may be accomplished after removal of the plated metal chemically. Copper is removed easily, while nickel requires more time but can be removed as well.

SUMMARY OF RESULTS

A thermocouple technique was developed to measure the hot-gas-side wall temperature in regeneratively cooled, thin-walled, rocket engines. The technique uses a small wire enclosed in a quartz insulator. This assembly is attached to the rocket engine cooling tube by electroplating a metal over the assembly and on to the cooling tube surface. The thermocouple junction is formed by the wire and the rocket cooling tube material.

The approximate upper temperature limit for this system is 2060° R (1144 K). This limit is imposed by the thin-wall (0.0003 to 0.001 in., 0.762×10^{-5} to 0.254×10^{-3} m) quartz, the electrical insulating property of which decreases rapidly above 2060° R (1144 K). However, the upper limit of the system may be extended as high as 2155° R (1197 K) if the poorer insulating properties of the quartz can be tolerated. At this temperature, the installation will be accurate to within 3.1 percent of the true temperature, providing two-dimensional conduction errors are not present.

Proper selection of thermocouple wire can be made, in this case platinel 7674 against 347 stainless steel, such that one wire in conjunction with the rocket engine material can be used to form a thermocouple.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, February 20, 1969,
            122-29-07-06-22.

APPENDIX A

ELECTROPLATING PROCESS

The electroplating process used in this study is described as follows:

(1) Degreasing of surface with acetone

(2) Cathodic alkaline cleaning

    (a) Composition of alkaline bath, 3 ounces per gallon (22.46 kg/m^3) of sodium hydroxide and 2 ounces per gallon (14.98 kg/m^3) of sodium carbonate

    (b) Temperature of bath, 600° R (333.3 K)

    (c) Current density, 30 amperes per square foot (323 A/m^2)

    (d) Time, 3 minutes

(3) Anodic alkaline cleaning

    (a) Composition and temperature of bath and current density, same as in step (2)

    (b) Time, 4 minutes

(4) Rinse with distilled water

(5) Activation treatment of surface by means of a 15-minute soak in a nickel strike solution

    (a) Composition of solution, 32 ounces per gallon (239.7 kg/m^3) of nickel chloride and 11 fluid ounces per gallon (0.08593 kg/m^3) of hydrochloric acid

    (b) Solution temperature, 530° R (294 K)

    (c) Current density, 30 amperes per square foot (323 A/m^2)

    (d) Electrodes, nickel

(6) Nickel strike: Using the same solution as used in step (5), a thin film (0.00025 in., 0.0635×10^{-4} m) of nickel is electroplated on the surface

(7) Heavy nickel plate: A high pH watts bath is used for the heavy nickel deposit. The solution is made up of distilled water to which are added, in ounces per gallon (kg/m^3), 32 (239.7) nickel sulfate, 6 (44.94) nickel chloride, and 4 (29.95) boric acid

(8) When copper plating was desired, the following bath was used: 3.95 ounces per liter (112 kg/m^3) of copper sulfate, 8.47 ounces per liter (24.02 kg/m^3) of sulfuric acid, and 0.10 ounce per gallon (0.749 kg/m^3) of molasses

APPENDIX B

DELTA Δ CIRCUIT CALCULATIONS

The circuit shown in figure 10(b) represents the thermocouple installation as shown in figure 10(a). To determine the effect of the quartz resistance R_q and the quartz-generated voltage V_q on the reading of the thermocouple V, the sum of the voltage drops is equated to zero. From this equation, the current flowing in the circuit is calculated. According to Ohm's law then the product of current and thermocouple wire resistance $R_{w1} + R_{w2}$ will be equal to the error in the thermocouple reading; that is, the difference between the electromotive force (emf) of the thermocouple and the thermocouple reading V. The equation for the thermocouple reading V is (using notation shown in fig. 10(b))

$$V = \text{emf} - \frac{V_q + \text{emf}}{1 + \dfrac{R_q}{R_{w1} + R_{w2}}} \qquad (1)$$

Solving this equation for R_q gives

$$R_q = (R_{w1} + R_{w2})\left(\frac{V_q + \text{emf}}{\Delta \text{emf}} - 1\right) \qquad (2)$$

where

$$\Delta \text{emf} = \text{emf} - V = \text{Error in measured thermocouple voltage}$$

and the remainder of the symbols appear in figure 10(b).

It is now required to find the minimum allowable quartz resistance which will give a 2 percent error in temperature measurement if the temperature is 2200° R (1222 K). The total wire resistance is assumed to be 20 ohms. It is assumed that for this calculation the quartz produces no voltage. The thermocouple voltage from figure 11 is emf = 53.5 millivolts. A 2 percent error in temperature is 44° R (24.4 K), which from the calibration is 1.4 millivolts. From equation (2)

$$R_q = 20\left(\frac{53.5}{1.4} - 1\right) = 744 \text{ ohms}$$

APPENDIX C

VOLTAGE GENERATED BY QUARTZ INSULATOR

During the electrical resistance checks made on the quartz-insulated Taylor-process thermocouple wire, it was noticed that a voltage V_q was being generated between the platinel wire and the stainless-steel plate by the quartz when at an elevated temperature. This voltage started at about 1460° R (811 K), peaked to approximately 300 millivolts at 1660° R (922 K), and had diminished to 100 millivolts at 2060° R (1144 K). This voltage affects the resistance readings of the vacuum tube voltmeter (VTVM) used to measure the quartz resistance. Two resistance readings were recorded, one with the leads connected normally and the other with them reversed. The resistance readings are corrected for this voltage by converting both of the recorded resistance readings to a voltage reading using a convenient scale of the VTVM. The resulting voltages obtained from the normal and reversed connected leads were then averaged. This cancels the impressed voltage V_q. This average was then set on the same VTVM voltage scale used to convert the resistance to voltage, and the resistance was then read from the resistance scale. These corrected resistance readings are recorded in figure 9.

The voltage generated by the quartz could be expected to cause an error in the thermocouple calibration. If this were true, the thermocouple calibration would show some irregularity. This is not the case. Examination of figure 11 shows only a small difference in calibration when comparing the metal-covered samples (C and E) to the bare thermocouple wire (sample D). With the magnitude of the quartz voltage V_q being as high as 300 millivolts compared to the thermocouple voltage of the order of 50 millivolts, any error introduced by V_q would be expected to have caused a much larger change in calibration than the 2.5 percent shown in figure 11. To explain this, equation (1) from appendix B is rewritten in terms of the percent error as

$$\frac{emf - V}{emf} = \left(\frac{\dfrac{V_q}{emf} + 1}{1 + \dfrac{R_q}{R_{w1} + R_{w2}}} \right) \times 100 \text{ percent} \qquad (4)$$

Assuming that the temperature is 1660° R (922 K), then from figure 11 the emf is 37.5 millivolts. Assume V_q to be 300 millivolts. From figure 9 (sample A), $R_q = 5.6 \times 10^5$ ohms. Assuming $R_{w1} + R_{w2} = 20$ ohms, from equation (4) the percentage of error is

$$\frac{emf - V}{emf} = \left(\frac{\dfrac{300}{37.5} + 1}{1 + \dfrac{5.6 \times 10^5}{20}} \right) \times 100$$

$$= 0.03 \text{ percent error}$$

This magnitude is much less than the 2.5 percent discussed previously. Examination of equation (4) shows that, as long as the quartz resistance remains high compared to the wire resistance and/or the emf of the thermocouple is large enough compared to the quartz-generated voltage V_q, the error in the thermocouple reading will remain small.

. This effect is similar to the effect of internal resistance in a battery in that, if the internal resistance of a battery is high, the voltage will drop off drastically when an external load is applied to the battery. A similar situation exists in the quartz since its resistance is high and a relatively low wire resistance is applied across the quartz by making the thermocouple junction. This requires that current flow through the high quartz resistance which, in turn, causes a large voltage drop, therefore nullifying the effect of V_q on the emf of the thermocouple.

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