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TEMPERATURE MEASUREMENTS ON HIGH SPEED MISSILES

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SUMMARY

The problem of making temperature measurements on missiles at velocities above Mach 5 imposes some rather severe demands on materials and techniques. An examination of the problem is made to determine the range in which temperature instrumentation is possible. An approach for extending the present range of temperature measurements is discussed.

INTRODUCTION

Because of the high temperatures encountered in high speed missile flights, the use of conventional materials and techniques for instrumentation may have to be abandoned. A study of the high temperatures expected and of the temperature characteristics of materials is necessary in any attempt to solve the high temperature measurement problem. Some idea of the difficulties expected may be obtained by examination of Fig. 1, which gives estimated stagnation temperatures as a function of altitude and Mach number, and Table I, which lists some materials with their temperature characteristics.

In order to start examining the practical problem of high temperature instrumentation, a preliminary design of a stagnation temperature gage is proposed as shown in Fig. 4.

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NATURE OF THE PROBLEM

Before any experimental checks can be made of temperatures on missiles, it is necessary to make some estimate of the expected temperatures. This is necessary to make sure the missile and instrumentation will "live" through the test period and to determine the settings of the gages and recording systems.

Considering first the aerodynamic data, an examination of the literature shows that basically five temperature measurements supply the information necessary for a reasonable understanding of the air-missile heating process. These five temperatures are the stagnation temperature, the insulated-skin temperature, the true skin temperature at the interface between the air and missile, the ambient temperature, and the temperature gradient at the outer surface of the missile skin. The last of these may be used as a check on the calculations made from the first four.

Of these five temperatures, the stagnation temperature is theoretically independent of the missile geometry and is probably as representative of the expected temperature ranges as any of the others. For this reason a plot is made of stagnation temperatures vs. altitude at several Mach numbers. This plot is shown in Fig. 1.

Below Mach 5, the stagnation temperature is computed from:

$$T_s = T_a(1 + .2M^2) \quad (1)$$

Where: T_s = the stagnation temperature ($^{\circ}\text{R}$)

T_a = the ambient temperature ($^{\circ}\text{R}$)

M = free stream Mach number

Above Mach 5, the stagnation temperature is computed from:

$$T_s = T_a + \frac{v^2}{2JG C_p} \quad (2)$$

Where: V = the missile velocity (ft./sec.)

J = mechanical equivalent of heat (ft./lbs./BTU)

G = local acceleration due to gravity (ft./sec.²)

C_p = specific heat at the temperature T_s (BTU/lb. -°R)

Since C_p varies with both pressure and temperature, the stagnation pressure at various altitudes below 100,000 ft. is calculated from tabulated values of $\frac{q}{M^2}$ listed in NACA TN 1428. Above this altitude the stagnation pressure was calculated from values of p listed in NACA TN 1200, and the expression:

$$q = 0.7 p M^2 \quad (3)$$

Where: p = ambient pressure

q = stagnation pressure

The values of C_p are taken from the data tabulated in Ref. 2 for temperatures up to 8640°R and extended by the enthalpy, h , vs. temperature, T , data in Ref. 1, and the relation:

$$C_p = \frac{dh}{dT} \quad (4)$$

The data represented by this plot take no account of radiation or pressure ionization but do take account of the dissociation effects in the air with the dissociation being considered instantaneous. As these results are very rough they are not intended to be used for calculations.

From such a plot as this, the rate of rise of temperatures can be estimated by combining it with the predicted Mach number vs. altitude and time data for a particular flight.

Besides the so-called aerodynamic data, engineering measurements are made to aid in designing away from dangerous conditions and these are usually more conservative in their demands on instrumentation. The temperatures encountered in these engineering measurements, for reasonably good designs, are held below the melting points of the construction materials. With the exception of motor exhausts and walls, the rates of temperature variation are lower than those encountered in the aerodynamic measurements.

METHODS OF MEASURING TEMPERATURES

Once the range and rate of change of temperature have been determined, the problem resolves itself into determining a method whereby the temperature may be sensed and recorded or transmitted.

The known methods of measuring temperature are the optical methods based on the Maxwell-Boltzmann law and Planks Radiation law, broadening of spectral lines with temperature, change of color of paints or dyes with temperature; electrical methods based on thermocouples, change of permeability of ferromagnetic materials with temperature and change of electrical resistance of certain metals or chemicals with temperature; and the change of shape with temperature. Recently it has been found that several semiconductors have an infrared transmission threshold that varies with temperature.

Before evaluating the relative merits or demerits of the various systems, it is necessary to establish a set of criteria against which they may be compared. The author and his associates have taken the following criteria as the basis of a developmental philosophy:

1. The transducer must be sensitive only to the desired function in the range in which it is to be used.

2. Any practical sensing device must be able to live in its environment throughout the period in which it is required to supply information. This implies a reasonable resistance to acceleration, vibration, pressure, temperature, corrosion and erosion.
3. The gage must produce negligible disturbances in the medium from which it collects information. Usually this means small size and mass.
4. Finally, any useful transducer must be compatible with a system for storing or transmitting its information. With the exception of a few photographic film recordings, nearly all present transmission and storage systems are electrical, thus requiring some sort of electrical output from the gage.

In the light of these criteria, it is concluded that the optical methods are the only methods available at present for measuring temperatures above the melting points of refractory materials. Optical systems offer rather serious disadvantages, particularly if the information is to be telemetered. The associated equipment such as photocells and power supplies is bulky and quite sensitive to environmental changes. For temperature measurements utilizing the radiation law, the emissivities of the observed materials must be known, but at present these have not been determined at the higher temperatures and they change radically with surface conditions. The optical methods do not lend themselves to temperature measurements in the interiors of materials and can be used only for surface measurements. The method employing color changes of paints and dyes is usually restricted to lower temperatures and the output information is not easily transmitted. They have some use in their temperature ranges as peak measuring devices

when they can be recovered.

Bimetal strips and other distortable units are not easily coupled to electrical systems. Additional disadvantages are that the units are usually large so that they disturb the observed media and are quite sensitive to acceleration.

The variation of the infrared transmission threshold for some semiconductors has been found to be a function of both temperature and pressure. Specific results have been obtained for silicon and germanium but since these materials have melting points below 1500°C their use in temperature gages is quite restricted. Whether some of the semiconducting refractories show this characteristic is not known.

The various electrical methods of temperature measurement seem to offer the most promise for the higher temperatures below the melting points of the materials used. Some chemicals have the ability to undergo sudden changes in electrical resistance upon reaching a certain temperature. This change is usually permanent. Since this phenomenon is compatible with electrical telemetering systems, this method can be used in step-by-step measurements of monotonic temperature changes. However, the transducers used in this method are usually of sufficient thermal mass to disturb the medium from which they obtain their information.

Variable resistance wires show some promise where the effects of the environment on lead resistance can be eliminated and where corrosion or erosion (which changes the geometry and the resistance) are not factors. These environmental effects generally eliminate their use in any hot or moving gas stream.

The highest Curie point known, 1140°C for cobalt, limits the range of magnetic temperature gages to temperatures below this point. Also these systems are inclined to be somewhat bulky.

Thermocouples appear to come nearer to meeting the requirements for measurement of the higher temperatures than do any of the other known methods. Thermocouples are not appreciably affected by corrosion and erosion, they can be made extremely small, they can be embedded in materials, they can be made to function up to the temperature of destruction of refractory materials from which they can be fabricated, and the output is compatible with telemetering systems.

The development of thermocouples for high temperature measurements on missiles presents two general problems. The first is the problem of fabrication of a thermocouple from materials that will withstand the high temperature and other environmental conditions to which the thermocouple will be subjected. This calls for the study of characteristics of existing materials and the development of new materials. It also calls for the development of techniques of working, grinding, depositing and forming of the high temperature metals and refractory materials. The second problem is one of analytical and experimental study of the behavior of the thermocouples under the conditions of their use. This will include such things as Peltier cooling, action under transient conditions, effect of the thermocouple and its mounting on the medium being measured, and the accuracy of measuring the output of the thermocouple. The present work represents an attack on these problems.

Inasmuch as it is desirable to develop stock items that can be used for both aerodynamic and engineering measurements, experience indicates that each flight or test requires a detailed study of the information desired and

the best method of acquiring the information. Much valuable information along this line has been collected in connection with tests made in the vicinity of exploding atomic bombs. In many respects the problems of high temperature instrumentation on missiles are similar to problems encountered with full scale nuclear tests, where time scales may be short and a controlled rate of the destruction of the instrumentation is necessary. Quite often the results are no better than "ball park" figures and give rise to the question of whether obtaining experimental data is possible beyond certain limits.

For some air measurements consideration has been given to the possibility of measuring the variables associated with statistical mechanics (density, momentum and energy distributions) in place of the variables associated with thermodynamics (pressure, temperature, density). Where sampling techniques and larger equipment are permissible, this approach to the problem may be possible.

EXPERIMENTAL MODELS

After considering the preceding requirements and methods, several projects were undertaken to construct gages in an attempt to determine the feasibility of using certain materials and designs. Because of the apparent advantages of thermocouples, some effort was given to building a silicon carbide-carbon probe with a boron nitride insulator as shown in Fig. 4. The silicon carbide-carbon thermocouple has one of the largest outputs known. Using either the boron nitride or silicon carbide as the external material, the rate of deterioration should be slow. The electrical resistivity of boron nitride at these higher temperatures is relatively good. Such a probe

may be useful up to 3000°C. Several alternate materials for thermocouples and insulators are contained in Table 1, from which it may be seen there is a very limited amount of data concerning the high temperature properties of these materials. This list does, however, represent a starting point for designing high temperature gages.

With the hopes of building a thermocouple .030" in diameter, an attempt was made to vapor deposit silicon carbide on porcelain tubes with the intention of later putting these deposits on thin fibers of insulated carbon. In the process of vapor depositing the silicon carbide, the porcelain tube is heated; and even though the silicon carbide was successfully deposited, on cooling the assembly, differences in expansion usually shattered the thin layer of silicon carbide. Very thin silicon carbide layers were successfully deposited on three porcelain tubes without shattering. These were joined to carbon and tested for voltage vs. temperature relations. Although only one of the thermocouples gave reasonable results, there is reason to believe that the process can be successful.

In the use of thermocouples, the question of the Peltier cooling appears when the thermocouple is used as a current source. According to the Peltier law, the rate at which a thermocouple junction is cooled or heated is:

$$\frac{\partial Q}{\partial t} = iT \frac{\partial E}{\partial T} \quad (5)$$

Where: $\frac{\partial Q}{\partial t}$ = rate at which heat is removed from the junction

i = current across the junction

T = absolute temperature

$\frac{\partial E}{\partial T}$ = slope of the voltage vs. temperature curve for the junction

A test procedure is devised which determines the errors introduced by passing currents through a thermocouple junction. Referring to Fig. 2, we see that the effects of the load and the thermocouple lead resistance can be eliminated by using an a.c.-d.c. measurement technique. This allows one to determine the effects of current on the thermocouple voltage. When the d.c. circuit is used, the thermocouple acts as a generator and the voltage developed across the load resistance, R_L , is determined by the voltage of the thermocouple and the resistance of the leads and R_L only, i.e.:

$$E_{dc} = i_{dc}(R_L + R) = e_{2dc} \frac{(R_L + R)}{R_L} \quad (6)$$

Where: R_L = Resistance of the load, both a.c. and d.c.

R = Resistance of the thermocouple loop, both a.c. and d.c.

E = The open circuit d.c. output of the thermocouple

e_{2dc} = d.c. voltage measured across the load resistance

A set of values for e_{2dc} vs. R_L is made at some particular set of thermal conditions surrounding the thermocouple junctions. The circuit is then opened at points A and B and an a.c. signal source which will not pass d.c. is connected in series with the thermocouple and R_L . From the d.c. data, the RMS values of a.c. voltages are set across R_L so that at a particular value of R_L :

$$e_{2dc} = e_{2ac} \quad (7)$$

Where: e_{2ac} = a.c. voltage measured across the load resistance. Since the a.c. current is now common to all parts of the circuit, we have:

$$E_{dc} = e_{2dc} \frac{R_L + R}{R_L} = e_{2dc} \frac{i_{ac} R_L + i_{ac} R}{i_{ac} R_L} = e_{1ac} + e_{2ac} \quad (8)$$

Where: e_{1ac} = a.c. voltage measured across the thermocouple loop resistance when e_{2ac} is across the load resistance

i_{ac} and i_{dc} are the currents present in the circuits when using the a.c. and d.c. circuits respectively.

This reduces the problem to one of measuring voltages only. It is necessary that the voltage measuring equipment read RMS values so that any $i^2 R$ heating in the a.c. and d.c. cases are identical.

By making a.c. measurements of sufficiently high frequency, the currents are reversed rapidly enough with each half-cycle so that the heating and cooling processes at the junctions produce essentially no change in the temperatures of the junctions. This phenomenon, when combined with the above technique, makes it possible to find the d.c. Peltier effect in a thermocouple loop.

A plot of $E_{d.c.}$ vs. $i_{d.c.}$ where $i_{d.c.} = \frac{e_{2dc}}{R_L}$ is given in Fig. 2 for a brass plate .122" thick and heated on one side in a molten lead bath. The thermocouple was .002" diameter chromel and alumel wires staked into the unheated surface of the brass plate. The upper current limit was determined by the lowest values of R_L across which the voltage could be read. The temperature of the lead bath was held as nearly constant as possible, being between 781°F and 783°F during the 1½ hours of the run. The cold junction was maintained between 75°F and 77°F during this same period. As can be seen by the plot of $E_{d.c.}$ vs. i , this cooling action is quite small for the test setup used here. A calculation of the a.c. resistance of chromel wire shows an increase of 1% at 180,000 cps. This certainly is not a source of appreciable error at the frequencies used in the experimental runs reported here.

In the case shown in Fig. 2, it appears that currents on the order of 10 ma can be drawn from the thermocouples used there without disturbing the accuracy of the measurement. This is important when these thermocouples are used in transistorized circuits as current generators.

Attempts were made to check the Peltier cooling on an air mass using .003" diameter butt-welded thermocouples, but convection currents were too great to allow any thermal stability in the air mass.

Because of the earlier uncertainties concerning the errors introduced by drawing current from thermocouples, a transistorized telemetering system was developed which could handle a full-scale range of 15 microamperes. However, this system required the thermocouple to be ungrounded. The aluminum inserts shown in Fig. 3 were designed to give the desired electrical insulation without disturbing the heat flow appreciably. The plugs were constructed by turning an aluminum rod to the diameter of the center section and then anodizing it. An outer aluminum tube was bored to a diameter .002" larger than the anodized rod and swaged onto it. In spite of the apparent mechanical weaknesses of the assembly, a plug of aluminum .050" thick, 3/8" O.D. with a center insulated portion $\frac{1}{4}$ " in diameter, withstood 275 psi for 30 minutes with an electrical resistance of 800 megohms on an anodized layer estimated to be .001" thick. Attempts at putting aluminum on other metals and then anodizing them have not been too promising.

In order to determine the thermal gradients at various points in missile members, a small thermocouple was insulated and embedded in a piece of metal. This assembly is shown in Fig. 4. If the silicon carbide-carbon thermocouple filament is successful, it will be incorporated in such an assembly.

CONCLUSION

From the estimated temperatures on missiles flying at high Mach numbers in the atmosphere, it appears that new materials and methods will be required to measure these temperatures. Since the known methods of sensing temperatures are not entirely satisfactory for these high temperature measurements, a search is necessary to find new approaches to the problem. Whether these new methods will lie in the fields of thermodynamics or metallurgy remains to be seen. The work discussed in this paper is an attempt to push these frontiers a bit further back.

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FIGURES AND TABLES

- Fig. 1 Temperature vs. Altitude and Mach No.
- Fig. 2 Circuits used to detect the Peltier cooling in a thermocouple and the results of one test
- Fig. 3 Insulated thermocouple mounting plug
- Fig. 4 Proposed and constructed thermocouple probes
- Table 1 A list of refractories with some of their thermal properties

STAGNATION TEMPERATURE vs ALTITUDE
AT VARIOUS MACH NUMBERS

FIGURE 1

INSULATED THERMOCOUPLE MOUNTING PLUG

FIGURE 3

THERMOCOUPLE CONNECTED BETWEEN
POINTS A & C

CIRCUITS USED TO DETECT THE Peltier
Cooling in a Thermocouple and the Results of
One Test

FIGURE 2

PROPOSED AND CONSTRUCTED THERMOCOUPLE
PROBES

FIGURE 4

TABLE I

A list of refractories with some of their thermal properties

<u>Material</u>	<u>Melting Point</u> (°C)	<u>Tensile Strength</u> (x10 ³ psi)	<u>Electrical Resistivity</u> (Ohm-cms)	<u>Corrosion Resistance</u>
303 SS	1400	80-90	70x10 ⁻⁶ RT	good to 760°C
Steatite	1440	10	10 ¹⁴ RT	excellent
			10 ⁶ 750(°C)	
Fused Silica	1710	up to 400 in fibers	10 ⁶ RT	good
			5x10 ⁵ 1200	
Platinum	1773	35-150	10x10 ⁻⁶ RT	good
			47 " 1000	
			63 " 1600	
Titanium	1820	100	56x10 ⁻⁶ RT	oxidizes above 120°C
Rhodium	1966	75-300	4.5x10 ⁻⁶ RT	good
			6.6 " 100	
Aluminum oxide	2050	25	10 ¹⁴ RT	good
			10 ⁶ 900	
Iridium	2454	50-80	6.1x10 ⁻⁶ RT	good but oxidizes at high temp.
			8.3 " 100	
Molybdenum	2620	150 (50-900°C)	5x10 ⁻⁶ 0	oxidizes over 500°C
			30 " 2000	
Osmium	2700		9.5x10 ⁻⁶ RT	poor
			9.9 " 100	
Magnesium oxide	2800	3	10 ¹⁴ RT	good
			10 ⁶ 900	
			2000 1500	
Silicon Carbide	2900		.08 RT	fair at high Temp.
			.14 1600	
Tantalum	2996	50-130	12.4x10 ⁻⁶ RT	oxidizes above 300°C
Boron Nitride	3000		1.7x10 ¹³ RT	excellent
			3.1x10 ⁴ 1000	
			1.9x10 ³ 2000	
Titanium Carbide	3250	8(1200°C)	4x10 ⁻⁶ RT	
			" 600	
Tungsten	3370	590	5.5x10 ⁻⁶ RT	oxidizes at high temperatures
			59 " 1700	
			118 " 3227	
Carbon	4700		35x10 ⁻⁴ RT	oxidizes rapidly at high temp.
			21 " 1000	
			9 " 2500	

(NOTE: RT refers to room temperature.)

TABLE I (Continued)

<u>Material</u>	<u>Thermal Conductivity</u> (cgs units)		<u>Thermal Expansion</u> (in/in/°C x 10 ⁻⁶)		<u>Thermal Shock Resistance</u>	<u>Total Emissivity</u>	
303 SS	.052	RT	19.8	RT			
Steatite	.006	RT	8.6	25-700(°C)	good		
Fused silica	.002-.003	100-1000(°C)	.5	over wide range	good	.80	1000(°C)
Platinum	.165	RT	8.9	RT		.04	RT
	.173	100				.10	500
						.15	1000
						.19	1500
Titanium			8.5	RT			
Rhodium	.21	RT	8.3	RT		.24	RT
Aluminum oxide	.06	RT	6.6	20-100	good	.30	RT
Iridium	.14	RT	6.8	RT		.30	RT
Molybdenum	.346	17	4.9	0-100		.13	1000
	.245	1000				.19	1500
	.225	2000				.24	2000
Osmium			4-6	RT			
Magnesium oxide	.00016-	RT	9	20-500	good	.20	RT
	.00045						
Silicon Carbide	.03 varies slowly with temperature		4.4	25-400	good	.8	RT
			.75	1700		.95	580
						.88	800
						.91	1100
						.8	1500
Tantalum	.13	RT	6.5	RT		.21	1500
						.26	2000
Boron Nitride	.036	300	3.3	25-1000	good	low	
	.032	700					
	.030	1000					
Titanium Carbide	-	-	-	-	-	-	-
Tungsten	.48	RT	4.5	RT		.50	227
						.47	1727
						.45	3227
Carbon	.01-.05	RT	.6-4.3	RT	good	.80-	RT
						.93	

TABLE I (Continued)

In addition to the above there exists several high temperature materials about which little is known. Some of these (together with their melting points in degrees Centigrade) are: Niobium (2500), Rhenium (3170), Hafnium Carbide (3890), Niobium Carbide (3500), Titanium Carbide (3250), Zirconium Carbide (3175), Vanadium Carbide (2830), Molybdenum Carbide (2695), Thorium Carbide (2655), Hafnium Nitride (3310), Tantalum Nitride (3090), Zirconium Nitride (2980), Titanium Nitride (2930), Thorium Oxide (3050), Zirconium Oxide (2690).