GOODRICH

SENSOR SYSTEMS

Total Temperature Sensors
Technical Report 5755

GOODRICH TOTAL TEMPERATURE SENSORS

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1. INTRODUCTION

Modern jet power aircraft require very accurate measurements of Outside Air Temperature (OAT) for inputs to the air data computer and other airborne systems. What does OAT mean? There are actually four temperatures of concern. These are defined as follows:

Static Air Temperature (SAT or T_s)
The temperature of the undisturbed air through which the aircraft is about to fly;

Total Air Temperature (TAT or T_t)
The maximum air temperature which can be attained by 100% conversion of the kinetic energy of the flight;

Recovery Temperature (T_r)
The adiabatic value of local air temperature on each portion of the aircraft surface due to incomplete recovery of the kinetic energy; and

Measured Temperature (T_m)
The actual temperature as measured, which differs from T_r, because of heat transfer effects due to imposed environments.

For flight conditions in clear air at low altitudes and low airspeeds the four temperatures are practically the same and OAT can apply to any of these four temperatures. As the airspeed and altitude increase the four temperatures will differ, and the term OAT becomes meaningless.

Figure 1 illustrates the general relationship between the four temperatures. The first three can be related by equations to flight speed, as will be discussed in the next section. The measured temperature, on the other hand, must be defined at a particular flight condition. Its value may be higher or lower than TAT or T_r, due to sensor design, location or imposed heat transfer environment. If a severe environment is imposed, the value of T_m can fall below that of SAT (e.g., vortex-producing designs or for severe weather).

The static air temperature is difficult to measure accurately, and total air temperature, by definition, can never be measured exactly (100% energy conversion). We are then left with a design objective for total air temperature sensors to impose an environment which will make T_m approximately equal to the ideal TAT value for all flight conditions.

As will be shown later, the ratio of TAT to SAT (T_t/T_s) is known for each flight condition. Thus, if T_m is close enough to TAT, SAT can be calculated with greater accuracy than it can be measured. In general, our total air temperature sensors exhibit a $T_m \geq 0.995\ T_t$.

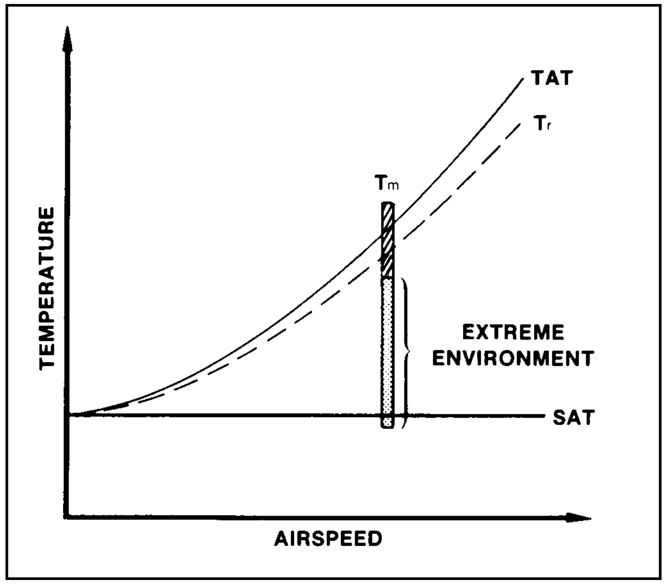


Figure 1: Temperature Relationships in Flight

2. PERFORMANCE PARAMETERS

A thorough understanding of the application of total air temperature sensors involves an acquaintance with a number of performance parameters. Many of the parameters depend on Reynolds number and Mach number as described in the referenced literature. In turn, these two parameters are dependent upon the flight condition; that is, the speed and altitude of the aircraft.

In the past, our technical literature introduced the usage of total pressure behind the normal shock, which was valid but somewhat difficult to work with. This bulletin utilizes terminology familiar to all who work with aircraft: Mach number and air density. To maintain the non-dimensional concept, density ratio (ρ/ρ_0) will be used. The density ratio variation with altitude for the 1962 U.S. Standard Atmosphere is given in **Table 1**.

Total air temperature sensor performance, given the aircraft's flight envelope in terms of Mach number and altitude (converted to ρ/ρ_0 from **Table 1**), now is directly obtainable. **Figure 2** shows how the parameters relate in subsonic flight. The free stream values of M and (ρ/ρ_0) apply in subsonic flight for a properly located total air temperature sensor; the product being a parameter upon which the correction of measured temperature to recovery temperature depends.

ALT. FT	ρ/ρ_0	ALT. FT.	ρ/ρ_0	ALT. FT.	ρ/ρ_0	ALT. FT.	ρ/ρ_0
0	1.000	26000	.433	52000	.138	78000	.0392
1000	.971	27000	.417	53000	.132	79000	.0373
2000	.943	28000	.402	54000	.126	80000	.0355
3000	.915	29000	.388	55000	.120	81000	.0338
4000	.888	30000	.374	56000	.114	82000	.0323
5000	.862	31000	.361	57000	.109	83000	.0307
6000	.836	32000	.347	58000	.104	84000	.0293
7000	.811	33000	.334	59000	.0988	85000	.0279
8000	.786	34000	.322	60000	.0941	86000	.0266
9000	.762	35000	.310	61000	.0897	87000	.0253
10000	.738	36000	.297	62000	.0855	88000	.0242
11000	.716	37000	.284	63000	.0815	89000	.0230
12000	.693	38000	.271	64000	.0777	90000	.0220
13000	.671	39000	.258	65000	.0740	91000	.0209
14000	.650	40000	.246	66000	.0705	92000	.0200
15000	.629	41000	.235	67000	.0671	93000	.0190
16000	.609	42000	.224	68000	.0639	94000	.0181
17000	.589	43000	.213	69000	.0608	95000	.0173
18000	.570	44000	.203	70000	.0579	96000	.0165
19000	.551	45000	.194	71000	.0551	97000	.0157
20000	.533	46000	.185	72000	.0525	98000	.0150
21000	.515	47000	.176	73000	.0500	99000	.0143
22000	.498	48000	.168	74000	.0476	100000	.0136
23000	.481	49000	.160	75000	.0453	150000	.00139
24000	.464	50000	.152	76000	.0432	200000	.00021
25000	.448	51000	.145	77000	.0411	250000	.000026

Table 1: U.S. Standard Atmosphere: ρ/ρ_0 Density Ratio Versus Geopotential Altitude, 1962 Values

Free Stream Mach Number	Multiplier
1.0	1.0000
1.1	.9690
1.2	.9419
1.3	.9166
1.4	.8929
1.5	.8703
1.6	.8489
1.7	.8281
1.8	.8080
1.9	.7887
2.0	.7700
2.1	.7516
2.2	.7339
2.3	.7168
2.4	.7001
2.5	.6840
2.6	.6684
2.7	.6533
2.8	.6388
2.9	.6247
3.0	.6109
3.5	.5493

Table 2: Multiplier Values for Correcting M (ρ/ρ_0) to M_1 (ρ_1/ρ_0) = Z (Normal Shock Theory)

In supersonic flow, a correction must be made for the normal shock wave which forms just upstream of the sensor inlet. The shock wave causes the Mach number to drop to a subsonic value at the inlet, but the local air density behind the shock wave increases. **Table 2** lists values of the correction factor for twenty-two values of flight Mach number. Using a subscript to denote conditions downstream of a normal shock, the correction factor is the product of M_1/M and ρ_1/ρ. To determine the performance of a total air temperature sensor for a supersonic flight application select specific values of Mach number M and multiply these by the ρ/ρ_0 values from **Table 1** for the altitude appropriate application. Then correct the M (ρ/ρ_0) product to M_1 (ρ_1/ρ_0) using **Table 2**. Parameter Z (zeta) will be used for brevity: $Z=M_1(\rho_1/\rho_0)$.

For a particular flight condition or set of M and (ρ/ρ_0) values, sensor design variations (even seemingly insignificant variations in the sensor geometry) yield detectable variations in sensor performance. These design-dependent variations are categorized by a number of performance parameters which have been used extensively in various technical reports and design specifications. The important parameters are defined and discussed in the following paragraphs.

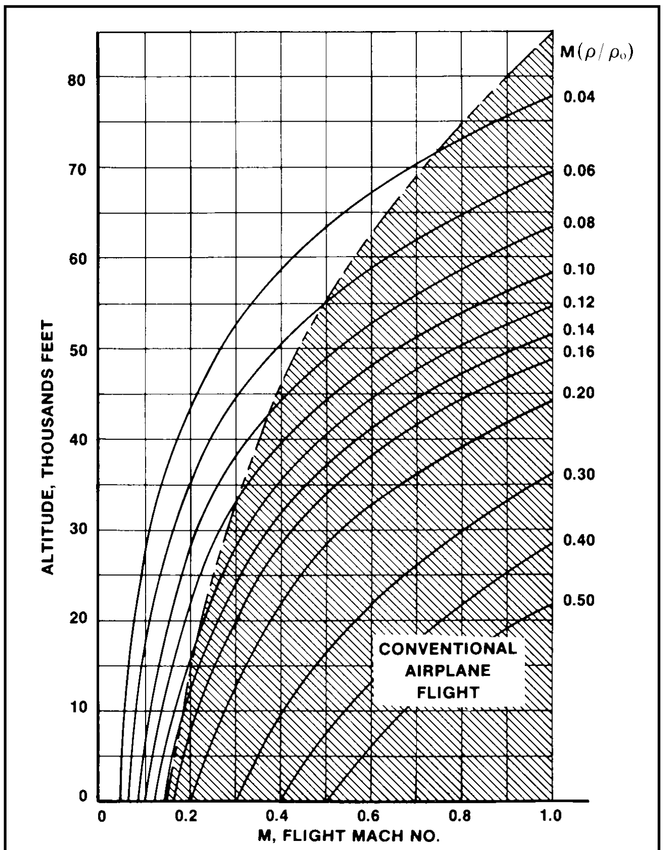


Figure 2: Subsonic Flight in U.S. Standard Atmosphere

2.1 THERMAL RECOVERY

The relationship between total and static temperature, absolute units (°K or °R), is:

$$\frac{T_t}{T_s} = 1 + \frac{\gamma - 1}{2} M^2$$

Equation 1

Where the γ is the ratio of specific heats.

This is the equation programmed into air data computers to calculate SAT from T_m values which are very close to TAT.

If the total temperature sensor is designed such that there are no significant heat sources or thermal paths to heat sinks and such that flow over the sensing element is uniform and continuous, the sensor will indicate the adiabatic value T_r very closely.

One parameter which relates T_r to TAT and SAT is called the recovery factor, defined as follows:

$$r = \frac{T_r - T_s}{T_t - T_s}$$

Equation 2

Some geometric shapes have constant recovery factors (e.g., the classic flat plate with airflow parallel to its surface). For sensors with a constant adiabatic recovery factor, **Equation 1** and **2** can be combined.

$$\frac{T_r}{T_s} = 1 + r\left(\frac{\gamma - 1}{2}\right) M^2$$

Equation 3

However, most sensors exhibit a variable recovery factor, and it is more convenient to use a recovery correction defined as:

$$\eta = \frac{T_t - T_r}{T_t}$$

Equation 4

Our total temperature sensors exhibit a variable η for M values below 1.0 but constant η for M values above 1.0. Once T_r and η are known, T_t is calculated by:

$$T_t = \frac{T_r}{1 - \eta}$$

Equation 5

The relationships between η and r are given by:

$$r = 1 - \eta \left[1 + \frac{2}{(\gamma - 1) M^2} \right]$$

Equation 6

$$\eta = \frac{(1 - r)\left(\frac{\gamma - 1}{2}\right) M^2}{1 + \left(\frac{\gamma - 1}{2}\right) M^2}$$

Equation 7

For non-adiabatic conditions, additional parameters are involved in calculating TAT and SAT.

2.2 THERMAL CONDUCTION

A condition error may occur when the fuselage of the aircraft is at a different temperature than the sensor. This usually occurs on the ground during taxi conditions on hot summer days or in the winter. Our total air temperature sensor is designed to have its air inlet located in the free stream beyond the aircraft boundary layer. Thus, during flight, this design provides sufficient internal airflow over the sensing element to negate the conduction mode of heat transfer, when the Mach number is below 2, the altitude is below 50,000 feet and Z (zeta) is above 0.15.

2.3 THERMAL RADIATION

When the total temperature being measured is relatively high, heat is radiated from the sensing element, resulting in a reduced indication of temperature. This effect is increased at very high altitude for a sensor of simple design, where the low air density decreases the ability of the internal air flow to make up for this radiation heat loss. Radiation error is negligible for our multiple shielded total air temperature sensors when the Mach number is below 2, the altitude is below 50,000 feet, and Z (zeta) is above 0.15.

2.4 TIME CONSTANT

An instantaneous response by a sensor to a temperature change is impossible due to the heat capacity of the sensor parts and surrounding structure. This results in an indicated temperature/time transient. The time constant is a performance parameter typically used to describe this temperature/time transient.

The time constant is classically defined as the time required for the sensor to respond to 63.2% of an instantaneous (step) change in temperature, **Figure 3-A**. Thus time constant is an index of how rapidly the temperature sensing element can follow a changing temperature. Something close to a step change in temperature may occur as the aircraft emerges from a cloud bank into clear air.

A more common type of temperature change in flight is the gradual change or ramp change, reference **Figure 3-B**. This type of change occurs when the aircraft changes altitude or speed. In this case the sensor begins its response to the temperature change slowly and approaches a straight line parallel to the ramp change in temperature. The transient is displaced by one time constant as in **Figure 3-B** after a time period equal to approximately 4 time constants.

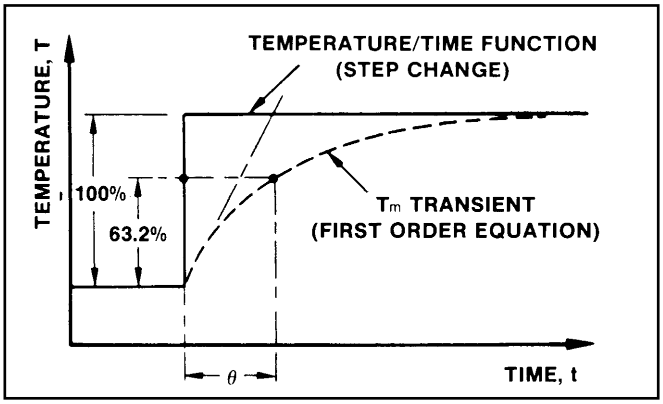


Figure 3-A: Temperature/Time Function (Step Change)

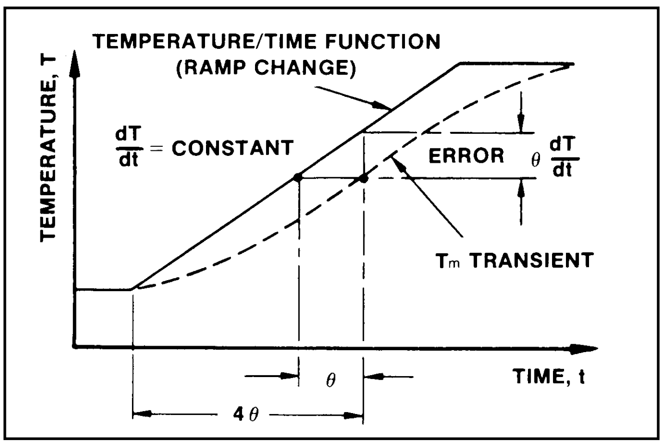


Figure 3-B: Temperature/Time Function (Ramp Change)

When the temperature is not changing or changing very slowly, the error due to the time constant is insignificant. When the rate of change of temperature with time becomes greater, the error caused by a sensor time lag can be approximated by the product of the time constant times the rate of change of temperature with time. This method of computing the time response error is only an approximation because most temperature changes are not characteristic of a true ramp change as in **Figure 3-B** and all temperature sensors have some small second-order effects.

2.5 AIRFLOW DIRECTION

When the airstream approaches the inlet of a total air temperature sensor from a direction other than directly forward, errors may be introduced. Our total temperature sensors are designed to be insensitive to a wide range of angle of attack in powered flights.

2.6 SELF-HEATING

Total air temperature sensors which use resistance elements require that a small electrical current pass through the sensing element. This current causes a self-heating effect (I^2R - Joule heating) which results in a small increase in the measured temperature. The magnitude of the temperature increase can be kept below 0.10°C if care is taken to keep the power low. The self-heating effect is controlled by convective cooling in flight and is minimized by keeping the applied electrical current to a practical minimum.

2.7 DEICING HEAT ERROR

For total temperature sensors with deicing heaters, application of the deicing heat can cause T_m to increase at low airspeeds. Basically, this effect is a conduction error, internal to the sensor, caused by the close proximity of heated portions of the sensor housing to the sensing element. Our deiced total air temperature sensors are designed to provide maximum thermal resistance between the heated housing and the element, thus minimizing the deicing heater effect.

2.8 AERODYNAMIC DRAG

Although the drag is not involved with the accuracy of total air temperature sensors, it can be important in trade-offs with other performance parameters. For example, deiced total air temperature sensors usually exhibit a higher drag than non-deiced sensors. The drag is influenced by the shape and size of the sensor and varies with the aircraft speed and altitude.

3. TOTAL TEMPERATURE SENSOR APPLICATIONS

3.1 TRUE AIRSPEED COMPUTATION

True airspeed is the actual airspeed of the vehicle through the air. If the air mass at the flight altitude is relatively stationary, it represents a ground speed as well. True airspeed is by far a more useful measurement for navigation than indicated airspeed; which is merely a reference to pitot minus static pressure. True airspeed is a necessary input to any airborne system relating to ground co-ordinates.

True airspeed is Mach number times the speed of sound. As the speed of sound is a function of static temperature,

$$a = (\gamma R)^{1/2} (T_s)^{1/2}$$

Equation 8

and from **Equation 1** SAT is itself a function of T_t, γ and M, true airspeed (TAS) can be expressed as:

$$TAS = M (a) + M (T_t)^{1/2} \left[\frac{\gamma R}{1 + (\frac{\gamma - 1}{2}) M^2} \right]^{1/2}$$

Equation 9

Modern airborne air data computers can calculate TAS in real time for accurate navigation.

3.2 JET ENGINE CONTROL

Engine control can be scheduled in terms of an operating line on a “compressor map”. The compressor map involves total pressure and total temperature ratios across the compressor referenced to engine performance at sea level standard conditions. A total temperature sensor can be used to supply the compressor inlet temperature inputs to the engine control system.

Of special interest is the use of the total temperature sensor in the *selection of engine pressure ratio (EPR) prior to takeoff*. EPR is a function of the engine inlet temperature. Often the pilot obtains the tower temperature measurement. Unfortunately the tower measurement is not always current nor does it reflect the actual runway conditions at the engine inlet. Many aircraft have an automatic EPR computer requiring a continuous and accurate reading of total temperature.

A more accurate temperature reading will be accomplished on the aircraft by a total temperature sensor in the engine inlet (contact our product engineer for more information on Series 154 engine inlet total temperature sensors) or on the fuselage. The fuselage-mounted sensors discussed in this technical report can supply the needed engine inlet temperature if internal airflow is induced over the sensing element. This can be accomplished by taxing the aircraft or by use of a special sensor which incorporates an ejector using 7-40 psig air provided by engine bleed or other on-board sources (see Section 7.1).

3.3 METEOROLOGICAL STUDIES

In-flight temperature measurements are very important to ecological studies and advanced weather prediction. Accurate determination of the static air temperature by measuring total air temperature and using **Equation 1** are important inputs to the studies.

Temperature variations are becoming increasingly important to clear air turbulence prediction and the improvement of airline passenger comfort and safety. Closely aligned with this activity is the study of jet streams. The total air temperature sensor can be used to determine the unusual gradients that are present in the vicinity of jet streams.

3.4 FLIGHT TESTING

Verification of a new aircraft’s performance is dependent on static air temperature and true airspeed measurements. Modern airborne electronic computers provide the capability during flight test programs of obtaining static air temperature and true airspeed from total air temperature readings more accurately than by radiosonde techniques. Our non-deiced, open-wire sensing element provides very accurate total temperature measurement since it minimizes time lag as an error source.

3.5 GROUND TEST FACILITIES

Total temperature sensors are used as reference temperature sensors in wind tunnels and icing test facilities. In cases where the test airflow velocity is less than 100 feet per second, special models with air ejectors to induce airflow over the sensing element are recommended (see Section 7).

3.6 SAFETY OF FLIGHT

The output from a total air temperature sensor applies directly to safety of flight at high airspeeds. The application is normally restricted to supersonic aircraft which require an automatic indication of excessive aerodynamic heating.

3.7 GLOSSARY

Nomenclature	Definition
a	speed of sound
M	Mach number
M_1	Mach number at sensor inlet
R	gas constant = 1716 ft^2/sec^{2}°R
r	recovery factor
SAT, T_s	static air temperature*
TAS	true airspeed
TAT, T_t	total air temperature*
T_m	measured temperature*
T_r	recovery temperature (adiabatic)*
γ	ratio of specific heats
ρ	air density
ρ_1	air density at sensor inlet
ρ_0	sea level standard air density
η	recovery correction
θ	time constant
Z	internal flow = $M_1\ (\rho_1/\rho_0)$

* Absolute units, °K or °R

3.8 REFERENCES

1. P.D. Freeze, *Bibliography on the Measurement of Gas Temperature*, National Bureau of Standards Circular 513, Washington, D.C., 1951.
2. R.V. DeLeo and F.D. Werner, *Temperature Sensing from Aircraft with Immersion Sensors*, ISA Proceedings, 1960 Conference, Vol. 15, Part II, p. 91, NY 60-91, 1960.

3. T.M. Stickney and M. Dutt, *Thermal Recovery and the Accuracy of Air Total Temperature Sensors*, ISA, Instrumentation in the Aerospace Industry, Vol. 16, p. 66, 1970.

4. F. Trenkle and M. Reinhardt, *In-Flight Temperature Measurements*, AGARDograph No. 160, NATO, 1973.

4. INSTALLATION OF TOTAL TEMPERATURE SENSORS

4.1 ADVANTAGES OF FORWARD LOCATIONS

The principle requirements for the proper installation of a total temperature sensor are that it points upstream; that the scoop inlet (intake) of the sensor is located entirely outside of any boundary layer at all flight conditions; and that the intake is not in the wake of another sensor, antenna, or upstream structure on the aircraft or vehicle. (Similar restrictions apply to pitot-static tubes.)

A good location is a reasonably flat portion of the fuselage nose or under a wing or horizontal pylon near the leading edge. For supersonic aircraft the location should also be chosen to assure that a detached bow shock always exists upstream of the sensor intake, and that the Mach number and air density just upstream of this shock can be determined. When these precautions are taken, flight tests will normally confirm that position or location errors can be neglected. For ultimate accuracy the location should be chosen such that the boundary layer on the mounting surface at maximum altitude (and red line minimum airspeed at that altitude) remains thin enough to allow the sensor internal airflow to exit into the free stream.

4.2 LOCATION RELATIVE TO WATER LINE

Assuming that the previous installation precautions have been observed and adhered to, selection of the water line location should be based on the following:

a. Proper separation from water line locations of the other sensors or projections.

b. Minimum ingestion of airborne contaminants including insects and sand.

c. Minimum exposure to splashed-up contaminants from the ground.

d. Maximum drainage of ingested contaminants, and,

e. Flight line human engineering (e.g., no step, no handle, etc.).

5. NON-DEICED MODEL 101 SERIES

5.1 GENERAL DESCRIPTION

Figure 4 shows the internal construction of the Model 101 total air temperature sensor. It uses a platinum resistance sensing element which is fully encased and hermetically sealed in the wall of a platinum shell. The hermetically sealed element is surrounded by a gold-platinum alloy radiation shield which, in turn, is surrounded by a stainless steel shield. Airflow inside the element and in the annular passages between the shields is controlled by “sonic throats” which act like orifice plates to restrict the range of internal Mach numbers in flight. Model 101 total air temperature sensors are flight qualified; meeting applicable requirements of MIL-P-25726B (ASG), Amendment 3. The standard configuration is shown in **Figure 5**. The element and shields are mounted to a tapered stainless steel airfoil strut, which is integrally cast with the mounting base. This construction provides maximum strength and minimum aerodynamic drag for flight applications to Mach 3.0.

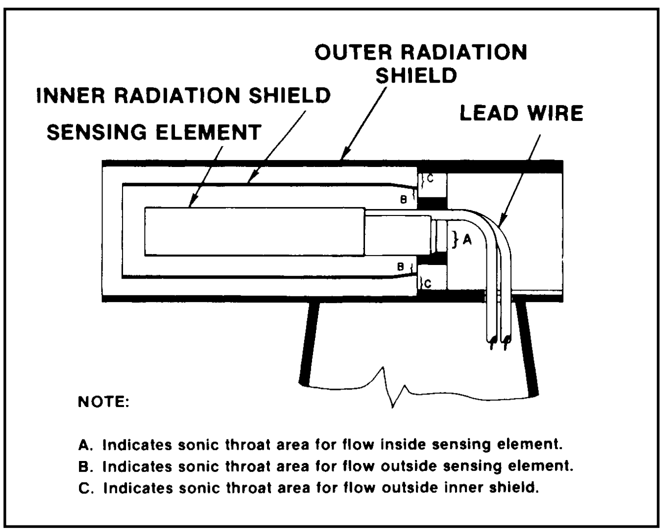


Figure 4: Cross Section of Model 101 Sensor Head

5.2 APPLICATIONS

Model 101 total air temperature sensors are ideally suited to high altitude applications above the weather or in clear air at any altitude. They are not recommended for long-term severe weather applications where the sensing element is exposed to rain, snow, hail, and icing. When thus exposed, the accuracy is compromised by change-of-state effects (freezing, evaporation, etc.) and some damage to the sensing element may occur. Thousands of these total air temperature sensors are currently used on a variety of military and commercial aircraft.

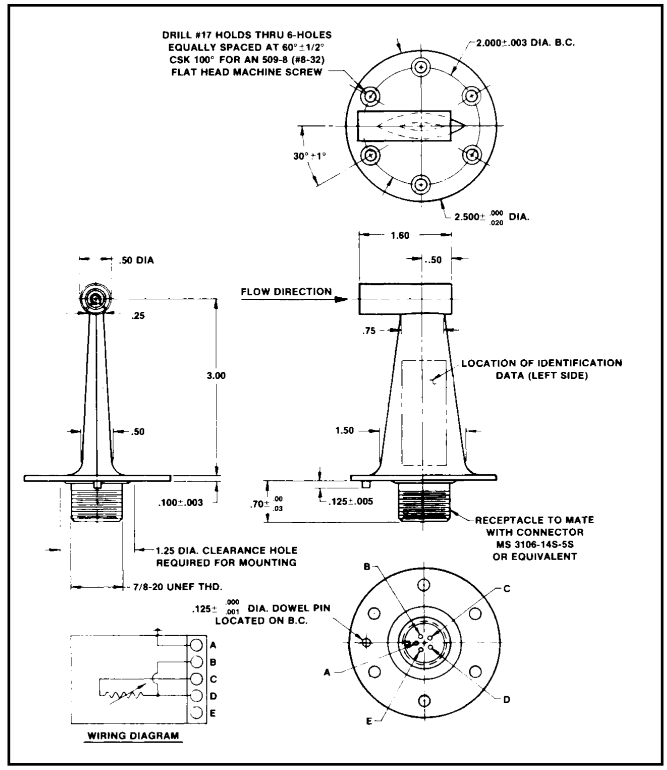


Figure 5: Model 101F Configuration

Model 101 can also be useful in the more rugged phases of flight testing, such as weapons system testing, where more delicate sensors might be damaged. The Model 101 is used as the total temperature reference sensor for Goodrich wind tunnel testing.

5.3 PERFORMANCE DATA

RESISTANCE VS. TEMPERATURE, as determined in agitated fluid baths, may be defined by the Callendar-VanDusen equation:

$$\frac{R_r}{R_0} = 1+\alpha \left[T-\delta \left(\frac{T}{100} -1\right) \left(\frac{T}{100}\right) - \beta \left(\frac{T}{100} -1\right) \left(\frac{T}{100}\right)^3 \right]$$

Equation 10

Where:
T = Temperature, Degrees Celsius (C°)
R_T= Resistance at T
R_0= 50.000 ohms
α = 0.003925
δ = 1.45 (IPTS-48), or 1.46 (IPTS-68)
β = 0.1 for negative T, and
β = 0 for positive T

T	R_T	T	R_T	T	R_T	T	R_T	T	R_T	T	R_T	T	R_T	T	R_T	T	R_T	T	R_T
−150	19.33	−100	29.77	−50	39.97	0	50.00	+50	59.88	+100	69.62	+150	79.22	+200	88.68	+250	97.98	+300	107.15
149	19.54	99	29.97	49	40.17	+1	50.20	51	60.08	101	69.82	151	79.41	201	88.86	251	98.17	301	107.33
148	19.75	98	30.18	48	40.37	2	50.40	52	60.28	102	70.01	152	79.60	202	89.05	252	98.35	302	107.51
147	19.96	97	30.38	47	40.58	3	50.60	53	60.47	103	70.20	153	79.79	203	89.24	253	98.54	303	107.70
146	20.17	96	30.59	46	40.78	4	50.80	54	60.67	104	70.40	154	79.98	204	89.43	254	98.72	304	107.88
145	20.39	95	30.80	45	40.98	5	50.99	55	60.86	105	70.59	155	80.18	205	89.61	255	98.91	305	108.06
144	20.60	94	31.00	44	41.18	6	51.19	56	61.06	106	70.78	156	80.37	206	89.80	256	99.09	306	108.24
143	20.81	93	31.21	43	41.38	7	51.39	57	61.25	107	70.98	157	80.56	207	89.99	257	99.28	307	108.42
142	21.02	92	31.41	42	41.58	8	51.59	58	61.45	108	71.17	158	80.75	208	90.17	258	99.46	308	108.60
141	21.23	91	31.62	41	41.79	9	51.79	59	61.65	109	71.36	159	80.94	209	90.36	259	99.65	309	108.79
140	21.44	90	31.82	40	41.99	10	51.99	60	61.84	110	71.56	160	81.13	210	90.55	260	99.83	310	108.97
139	21.65	89	32.03	39	42.19	11	52.19	61	62.04	111	71.75	161	81.32	211	90.74	261	100.01	311	109.15
138	21.86	88	32.23	38	42.39	12	52.38	62	62.23	112	71.94	162	81.51	212	90.92	262	100.20	312	109.33
137	22.07	87	32.44	37	42.59	13	52.58	63	62.43	113	72.13	163	81.70	213	91.11	263	100.38	313	109.51
136	22.28	86	32.64	36	42.79	14	52.78	64	62.62	114	72.33	164	81.89	214	91.30	264	100.57	314	109.69
135	22.49	85	32.85	35	42.99	15	52.98	65	62.82	115	72.52	165	82.08	215	91.48	265	100.75	315	109.87
134	22.70	84	33.05	34	43.20	16	53.18	66	63.02	116	72.71	166	82.26	216	91.67	266	100.93	316	110.05
133	22.91	83	33.26	33	43.40	17	53.38	67	63.21	117	72.90	167	82.45	217	91.86	267	101.12	317	110.23
132	23.12	82	33.46	32	43.60	18	53.57	68	63.41	118	73.10	168	82.64	218	92.04	268	101.30	318	110.42
131	23.33	81	33.67	31	43.80	19	53.77	69	63.60	119	73.29	169	82.83	219	92.23	269	101.48	319	110.60
130	23.54	80	33.87	30	44.00	20	53.97	70	63.80	120	73.48	170	83.02	220	92.42	270	101.67	320	110.78
129	23.75	79	34.08	29	44.20	21	54.17	71	63.99	121	73.67	171	83.21	221	92.60	271	101.85	321	110.96
128	23.95	78	34.28	28	44.40	22	54.37	72	64.19	122	73.87	172	83.40	222	92.79	272	102.04	322	111.14
127	24.16	77	34.48	27	44.60	23	54.56	73	64.38	123	74.06	173	83.59	223	92.98	273	102.22	323	111.32
126	24.37	76	34.69	26	44.80	24	54.76	74	64.58	124	74.25	174	83.78	224	93.16	274	102.40	324	111.50
125	24.58	75	34.89	25	45.00	25	54.96	75	64.77	125	74.44	175	83.97	225	93.35	275	102.59	325	111.68
124	24.79	74	35.10	24	45.20	26	55.16	76	64.97	126	74.63	176	84.16	226	93.53	276	102.77	326	111.86
123	25.00	73	35.30	23	45.40	27	55.35	77	65.16	127	74.83	177	84.35	227	93.72	277	102.95	327	112.04
122	25.21	72	35.50	22	45.60	28	55.55	78	65.36	128	75.02	178	84.54	228	93.91	278	103.14	328	112.22
121	25.41	71	35.71	21	45.81	29	55.75	79	65.55	129	75.21	179	84.73	229	94.09	279	103.32	329	112.40
120	25.62	70	35.91	20	46.01	30	55.94	80	65.74	130	75.40	180	84.91	230	94.28	280	103.50	330	112.58
119	25.83	69	36.12	19	46.21	31	56.14	81	65.94	131	75.59	181	85.10	231	94.46	281	103.68	331	112.76
118	26.04	68	36.32	18	46.41	32	56.34	82	66.13	132	75.78	182	85.29	232	94.65	282	103.87	332	112.94
117	26.25	67	36.52	17	46.61	33	56.54	83	66.33	133	75.97	183	85.48	233	94.84	283	104.05	333	113.12
116	26.45	66	36.73	16	46.81	34	56.74	84	66.52	134	76.17	184	85.67	234	95.02	284	104.23	334	113.30
115	26.66	65	36.93	15	47.01	35	56.93	85	66.72	135	76.36	185	85.86	235	95.21	285	104.42	335	113.48
114	26.87	64	37.13	14	47.21	36	57.13	86	66.91	136	76.55	186	86.05	236	95.39	286	104.60	336	113.66
113	27.08	63	37.34	13	47.41	37	57.33	87	67.10	137	76.74	187	86.23	237	95.58	287	104.78	337	113.84
112	27.28	62	37.54	12	47.61	38	57.52	88	67.30	138	76.93	188	86.42	238	95.76	288	104.96	338	114.02
111	27.49	61	37.74	11	47.81	39	57.72	89	67.49	139	77.12	189	86.61	239	95.95	289	105.15	339	114.20
110	27.70	60	37.94	10	48.01	40	57.92	90	67.69	140	77.31	190	86.80	240	96.13	290	105.33	340	114.38
109	27.91	59	38.15	9	48.20	41	58.11	91	67.88	141	77.51	191	86.99	241	96.32	291	105.51	341	114.56
108	28.11	58	38.35	8	48.40	42	58.31	92	68.07	142	77.70	192	87.18	242	96.50	292	105.69	342	114.74
107	28.32	57	38.55	7	48.60	43	58.51	93	68.27	143	77.89	193	87.36	243	96.69	293	105.88	343	114.92
106	28.53	56	38.76	6	48.80	44	58.70	94	68.46	144	78.08	194	87.55	244	96.88	294	106.06	344	115.10
105	28.73	55	38.96	5	49.00	45	58.90	95	68.66	145	78.27	195	87.74	245	97.06	295	106.24	345	115.28
104	28.94	54	39.16	4	49.20	46	59.10	96	68.85	146	78.46	196	87.93	246	97.25	296	106.42	346	115.46
103	29.15	53	39.36	3	49.40	47	59.29	97	69.04	147	78.65	197	88.12	247	97.43	297	106.60	347	115.64
102	29.35	52	39.56	2	49.60	48	59.49	98	69.24	148	78.84	198	88.30	248	97.62	298	106.79	348	115.81
101	29.56	51	39.77	1	49.80	49	59.69	99	69.43	149	79.03	199	88.49	249	97.80	299	106.97	349	115.99
																		350	116.17

Table 3: Resistance (Ω) Versus Temperature (°C) for 50-Ohm Elements (MIL-P-25726B and MIL-P-27723E)

Table 3 contains values of R_T computed from the above equation with the appropriate constants at 1°C intervals of T defined per IPTS-68. The allowable tolerance is ±0.25°C plus 0.5 percent of the magnitude of the temperature in degrees Celsius (C°). Interpolating equations are optional. For temperatures normally encountered in the flight on conventional aircraft the difference between **Equation 10** and the new set of ITS-1990 interpolating equations is negligible compared to other errors.

TIME CONSTANT data from tests in our altitude wind tunnel are summarized in **Figure 6**. Nominal values are listed in **Table 4**. Time response is a function of internal mass flow over the element and supporting structure, and is thus dependent upon both Mach number and air density at the sensor inlet. The band in **Figure 6** and the ± values in **Table 4** encompass both the variation of performance of different units of the same design and variations between different designs in the Model 101 series. The repeatability of the wind tunnel test is also included within the band. A shock wave forms just upstream of the sensor inlet in supersonic flight. This is a bow-shaped wave, but has the characteristics of a normal shock wave at the sensor inlet of the Model 101. The flow is subsonic downstream of the

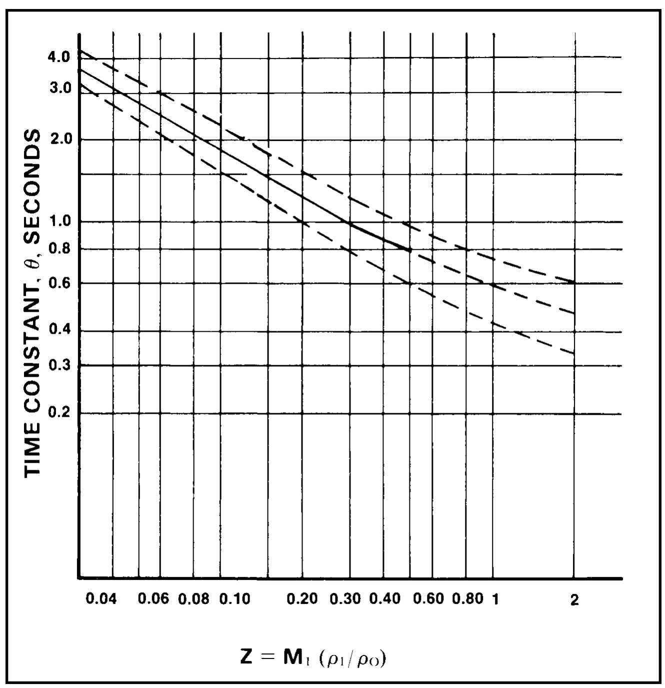


Figure 6: Wind Tunnel Data; Time Constants for Model 101 Series

shock as discussed previously, and the data of **Figure 6** applies for the parameter $Z=M_1\ (\rho_1/\rho_0)$ at the inlet.

$Z=M_1\ (\rho_1/\rho_0)$	θ, Seconds	SHE, °C/mw
.04	3.2 ± 0.5	.026 ± .004
.06	2.5 ± 0.4	.021 ± .003
.08	2.1 ± 0.3	.019 ± .003
.10	1.9 ± 0.3	.017 ± .003
.12	1.7 ± 0.3	.015 ± .003
.14	1.5 ± 0.3	.014 ± .003
.16	1.4 ± 0.3	.013 ± .003
.20	1.3 ± 0.3	.012 ± .002
.30	1.0 ± 0.2	.010 ± .002
.40	0.9 ± 0.2	.009 ± .002
.50	0.8 ± 0.2	.008 ± .002
1.00	0.6 (est.)	.006 (est.)
2.00	0.5 (est.)	.005 (est.)

Table 4: Model 101 Time Constant and Self-heating Error Values; Subsonic and Supersonic Flight

RECOVERY CORRECTION, η, shown in **Figure 7** is applicable to the recovery temperature value as discussed in Section 2.1. Therefore, it should not be applied until the indicated temperature value in flight is corrected for self-heating and other systematic errors. The data in **Figure 7** was obtained under conditions of negligible self-heating. This data is a composite of many tests in a variety of wind tunnels. Note that the nominal value for Model 101 sensors is a constant 0.5 percent in supersonic flight.

SELF-HEATING as can be seen in **Table 4** for the Model 101 total air temperature sensor, is essentially directly proportional to the time constant over a wide range of flight conditions. For convenience, the dimensional units are chosen as degrees Celsius per milliwatt of excitation power.

RADIATION ERROR is small for Model 101 sensors due to the low emissivity of the sensing element surfaces and the effectiveness of the shielding. A very large temperature difference is required to yield a significant drop in indicated temperature due to radiative heat losses to the atmosphere and cooler surfaces on the aircraft. The radiation error is negligible for Mach numbers below 2.0 if Z is above 0.15 and the measured total temperature is below 200°C. Limited data suggests that the error is less than 0.3 percent for all flight conditions to Mach 3.0 and 100,000 feet.
AIRFLOW DIRECTION SENSITIVITY for Model 101 sensors, shown in **Figure 8**, was determined from tests in a supersonic wind tunnel. Angle of attack errors can be ignored for aircraft attitudes in normal flight.

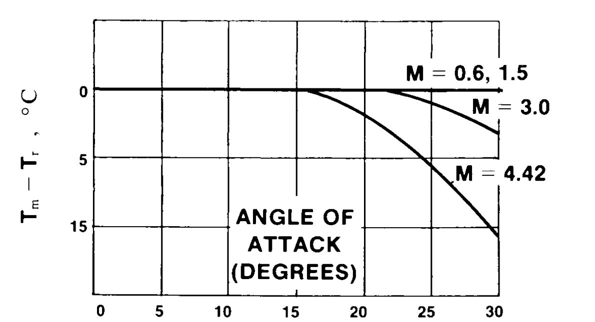


Figure 8: Airflow Direction Sensitivity

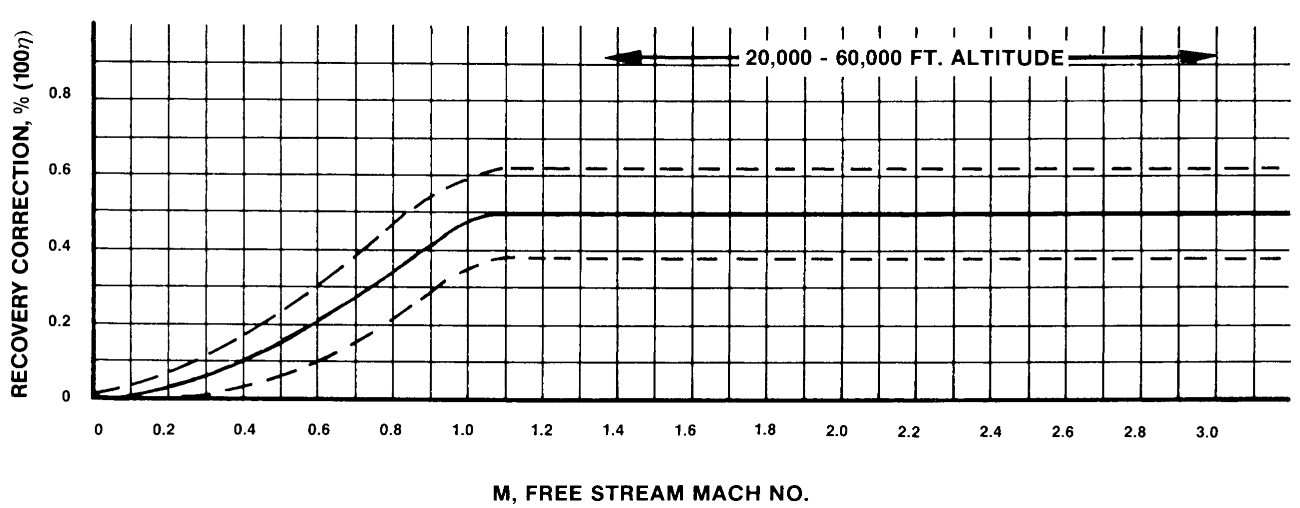


Figure 7: Wind Tunnel Data; Model 101 Recovery Corrections

AERODYNAMIC DRAG is given in **Figure 9**. Data obtained in our transonic wind tunnel provides definition of the subsonic drag characteristics. Although supersonic data is limited, the dashed curve shows the typical variation for aerodynamic shapes of this type. Note that the drag is influenced by Mach number in two ways, namely: 1) the variation of D/q shown in **Figure 9**; and 2) the variation of q with M. Model 101 has a lower drag than Model Series 102.

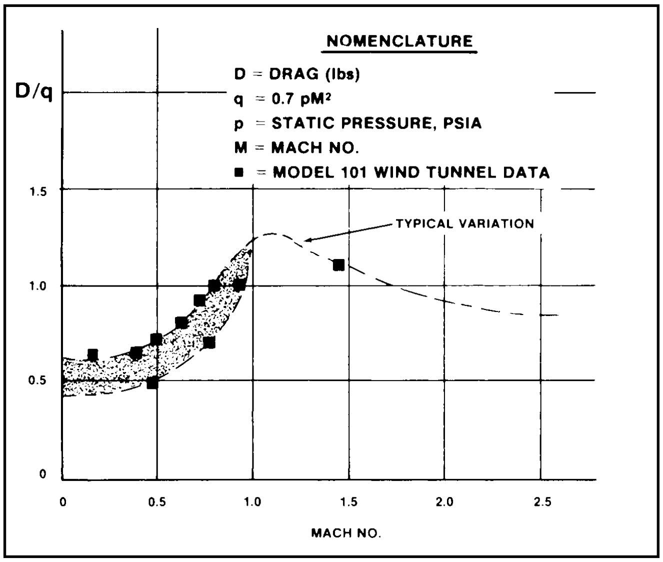


Figure 9: Wind Tunnel Data; Aerodynamic Drag of Model 101 Sensors

6. DEICED MODEL 102 SERIES

6.1 DESCRIPTION

The deiced Model 102 series is available in two housing configurations as shown in **Figures 10-A** and **10-B**. Both configurations permit use of platinum resistance elements of the type described in the previous section for Model 101 sensors. These two configurations make use of unique boundary layer control techniques to minimize adverse thickening of the internal boundary layer. As shown in **Figure 10** the internal boundary layer air is drawn off via the holes indicated. Furthermore, the sampled airflow is caused to turn a rather abrupt right angle before it contacts the sensing element. This protects the element from damage by dirt, sand, insects and bird strikes and negates errors due to liquid droplet impingement. Flow separation at the turn is effectively prevented using the previously discussed boundary layer control techniques. These techniques also allow the application of anti-icing heat to the housing with minimal effect on accuracy.

A hermetically sealed deicing heater is brazed integrally into the housing of the Model 102 total air temperature sensor. The heater is in the form of a tube containing an axial heating element. This tubular heater is brazed into the thermally conductive metal housing and keeps all surfaces effectively free of ice under severe icing conditions.

The two standard configurations are shown in **Figures 11-A** and **11-B**. Configuration "a" is the newer of the two and is qualified to MIL-P-27723E (ASG).

The housing below the flange of the sensor in each case serves as a "junction box" for mounting an electrical receptacle. This construction results in entirely hermetically sealed wiring for both the heater and the sensing element.

6.2 APPLICATIONS

Deiced Model 102 total air temperature sensors have been specifically designed for all-weather service. Both configurations have been used extensively on both commercial and military aircraft. These sensors have been qualified to stringent deicing and anti-icing specification requirements. Model 102 sensors have been used as reference sensors in icing test facilities. First extensive use of the configuration "b" sensors was on the B707 commercial airliners. Both configurations have been successfully applied to nearly every type of high performance aircraft since that time. It has been amply demonstrated that the Model 102 sensors have maintained a high level of accuracy and reliability over many years of continuous flight service in all parts of the world.

6.3 PERFORMANCE DATA

The following information is directly applicable to configuration “a” sensor; MIL-P-27723E (ASG) Type I or Type II. Configuration “b” sensors have comparable performance. Where a single band is used in the figures to show the range of wind tunnel data configuration “b” data falls within the band with slightly higher nominal values than shown.

RESISTANCE VS. TEMPERATURE for the 50-ohm MIL-SPEC elements is defined by **Equation 10** (See 5.3) and **Table 3**. Commercial airliners generally utilize 500-ohm elements having different α and δ constants as will be described later

TIME CONSTANT data from tests in our wind tunnels are summarized in **Figure 12**. The band indicates the range of recorded data. Due to wind tunnel size and the drag of the time response apparatus, values of Z above 0.6 could not be obtained. It is evident, however, that most Model 102 sensors will have time constants below 1.0 second at Z values above 1.0. As previously discussed, this flow parameter is utilized to cover both subsonic and supersonic flight situations. Nominal values and limits of the data band are listed in **Table 5**. As before, the band includes the effects of design variations within the Model 102 series and the repeatability of the wind tunnel tests.

$Z=M_1\ (\rho_1/\rho_0)$	θ, Seconds
.04	5.7 ± 1.7
.06	4.3 ± 1.3
.08	3.5 ± 1.0
.10	3.0 ± 0.9
.12	2.7 ± 0.8
.14	2.4 ± 0.7
.16	2.2 ± 0.7
.20	1.9 ± 0.6
.30	1.5 ± 0.5
.40	1.2 ± 0.4
.50	1.1 ± 0.4
.60	1.0 ± 0.4

Table 5: Deiced Model 102 Time Constants; Subsonic and Supersonic Flight

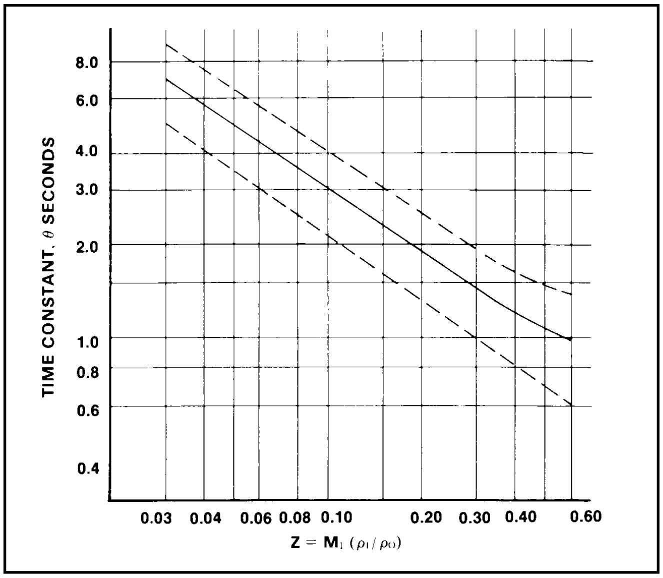


Figure 12: Wind Tunnel Data; Time Constants for Model 102 Sensors

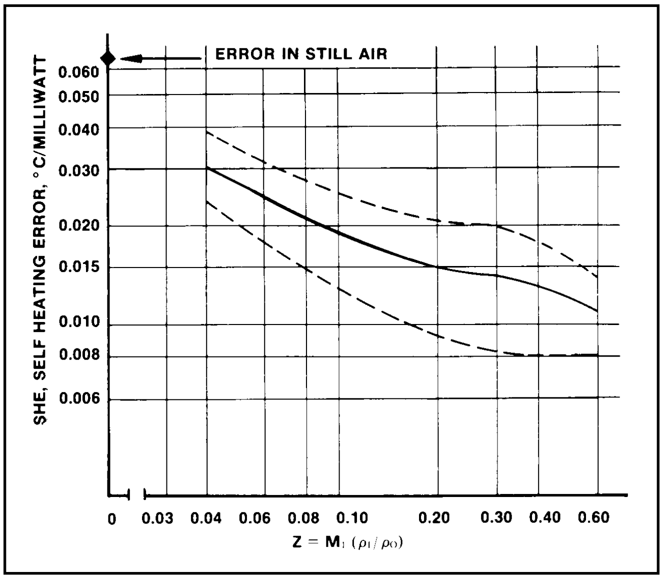
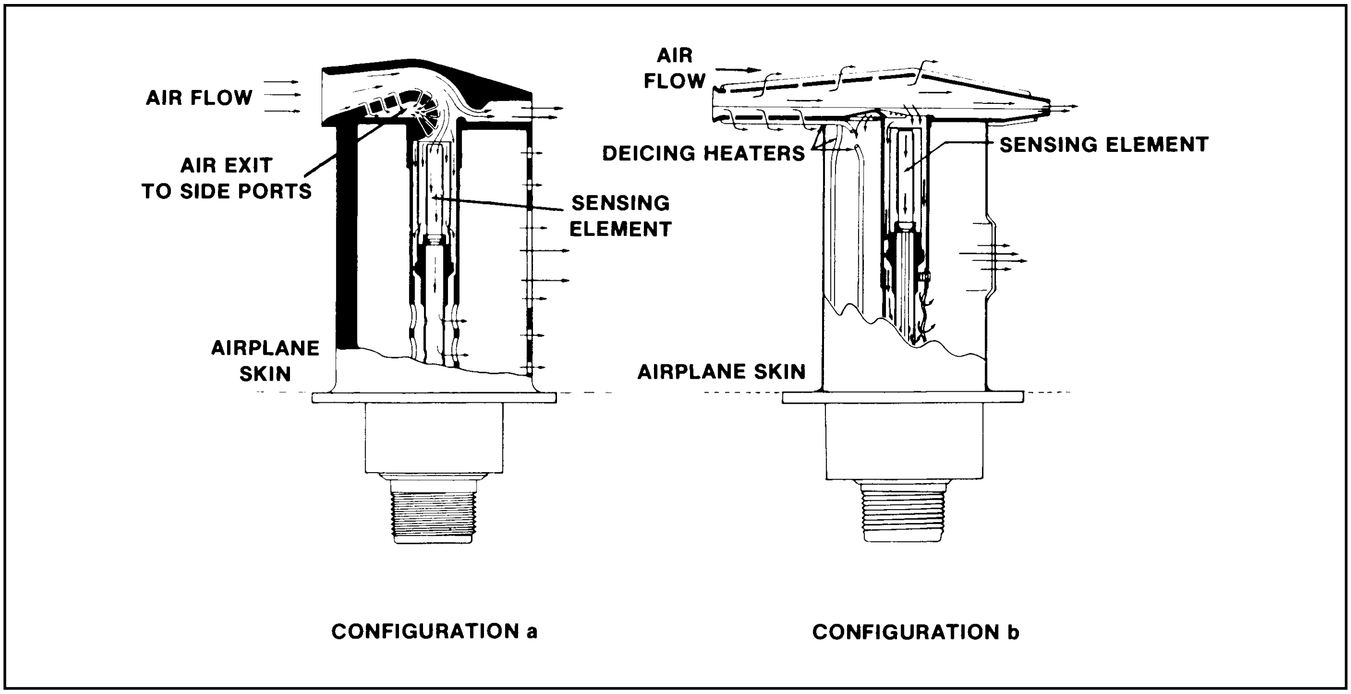
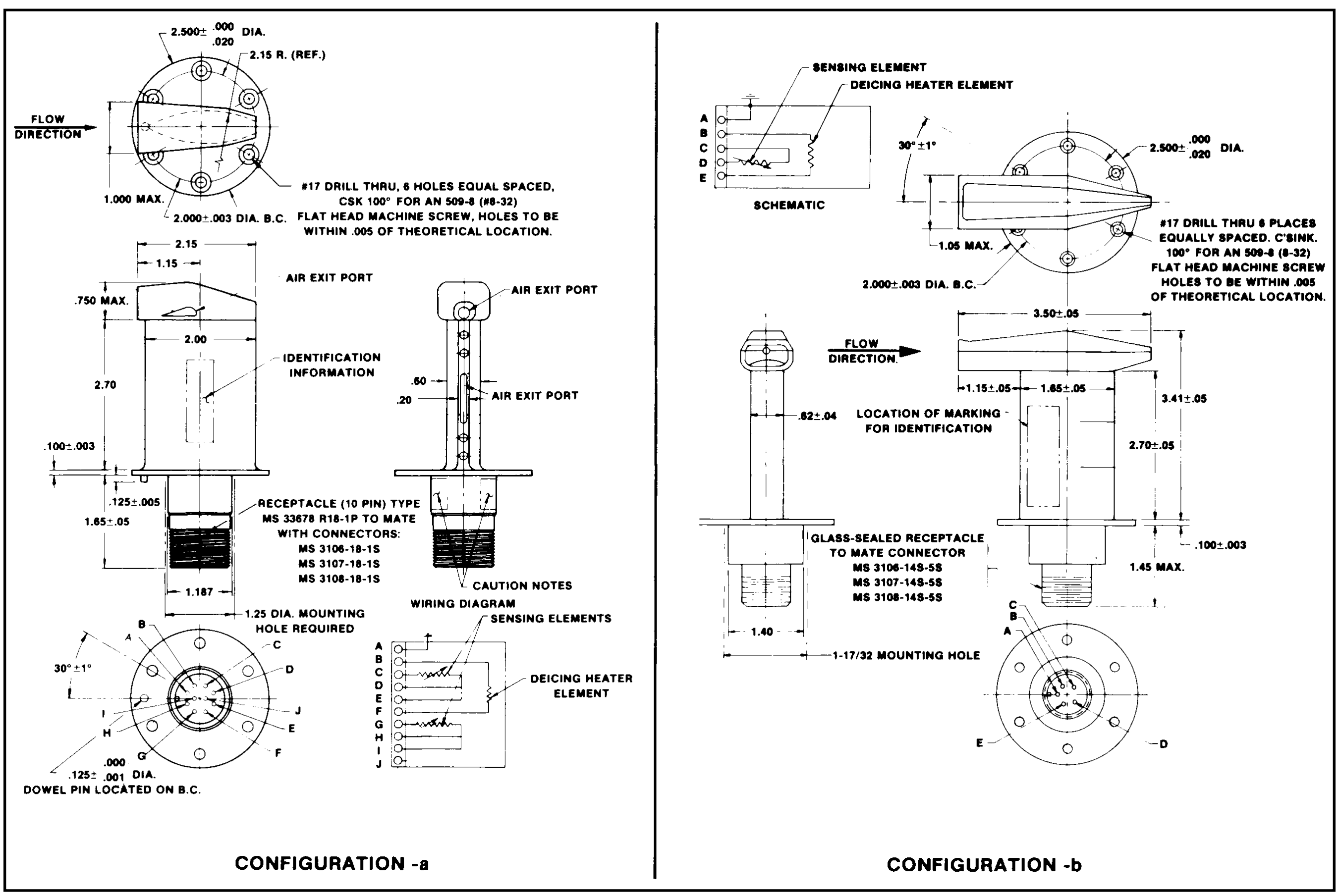


Figure 13: Wind Tunnel Data; Model 102 Self-heating Errors

RECOVERY CORRECTION η, as determined in subsonic, transonic, and supersonic wind tunnels, is given as a function of free stream Mach number in **Figure 14**. Again, the band represents the spread of data points obtained in the various wind tunnels. This data presents the difference between T_r and TAT very closely since the heater is off and the excitation current is adjusted for negligible self-heating. Another testing precaution is to stabilize the wind tunnel air temperature at a value as close as possible to test section wall temperature to avoid thermal conduction errors.



Figures 10-A, -B: Internal Configurations of the Model 102 Deiced Sensors Showing Boundary Layer Control, Particle Separation Path, and the Hermetically Sealed Sensing Element



Figures 11-A, -B: Deiced Model 102 Standard Configurations

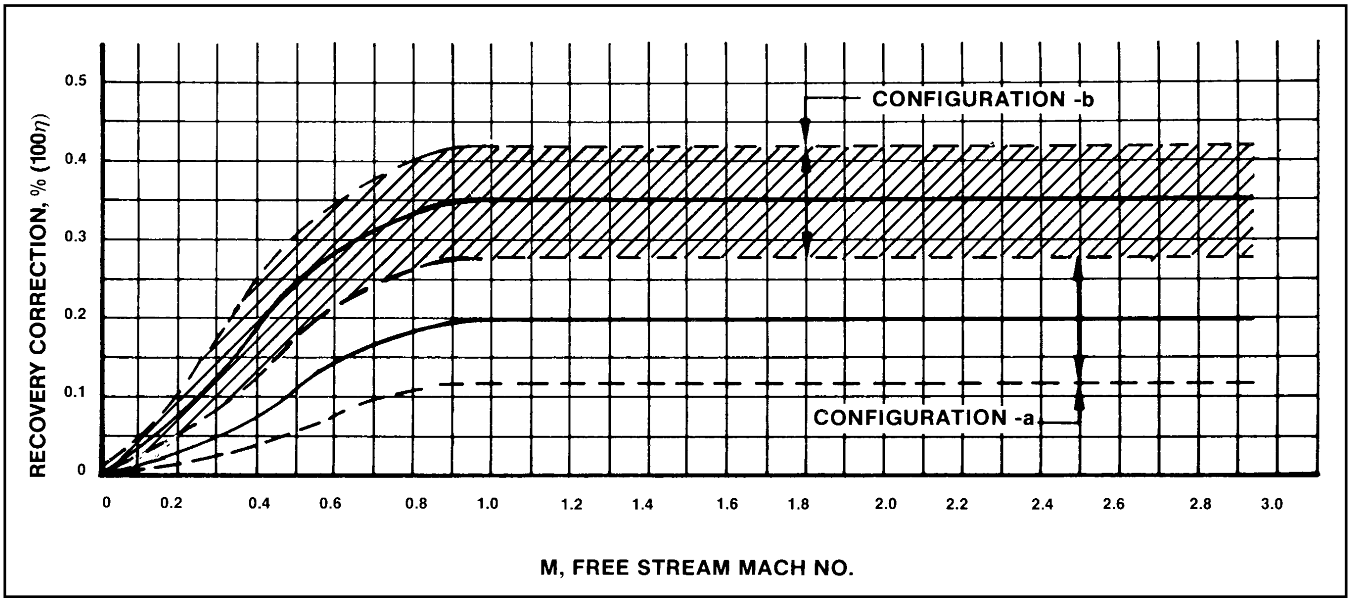


Figure 14: Wind Tunnel Data; Model 102 Recovery Corrections

Note that the recovery correction for configuration “b” sensors is slightly higher than that for “a” sensors. This is a direct result of the design differences shown in **Figure 10**. The data bands in **Figure 14** include tests at simulated altitudes between 2,000 and 89,000 feet. There does not appear to be a systematic altitude effect on the recovery correction under conditions of negligible self-heating and thermal conduction. In supersonic flight, the nominal recovery corrections for configuration -a and configuration -b sensors are 0.2 percent and 0.35 percent respectively.

SELF-HEATING errors for the Model 102 total air temperature sensors are relatively insensitive to variable flight conditions. **Figure 13** summarizes wind tunnel data for both housing configurations and for a variety of sensing elements, both single and dual construction. Note that the error is still fairly low at the zero flow rate condition corresponding to an aircraft in the hangar. In this case, the indicated temperature is a rather unstable equilibrium value dependent upon conductive and radiative heat losses to the aircraft structure. In flight the internal mass flow increases, yielding a lower indicated temperature through convective cooling which counteracts the Joule heating of the element. Nominal and limit values of self-heating error are listed in **Table 6** and are plotted in **Figure 13**. Since the band includes variations of both element and housing design, the corresponding band for a particular Model 102 sensor (e.g., single element standard configuration-a) would be much narrower.

$Z=M_1\ (\rho_1/\rho_0)$	SHE, °C/Milliwatt
.04	.030 ± .007
.06	.024 ± .007
.08	.021 ± .007
.10	.019 ± .006
.12	.018 ± .006
.14	.017 ± .006
.16	.016 ± .006
.20	.015 ± .006
.30	.014 ± .006
.40	.013 ± .005
.50	.012 ± .004
.60	.011 ± .003

Table 6: Deiced Model 102 Self-heating Error; Subsonic and Supersonic Flight

RADIATION ERROR is small for Model 102 sensors as for Model 101 sensors. Again, it is considered to be negligible for Mach numbers below 2.0 if Z is above 0.15 and T_m is less than 200°C. The maximum combined radiation and conduction error for Mach 3.0 at 100,00 feet is specified at 0.5 percent in MIL-P-27723E (ASG).

ERROR DUE TO DEICING HEAT is sensitive to variable flight conditions, especially at high altitudes. Icing encounters are rare occurrences above 30,000 feet. Turning the heater off at high altitudes should be considered, as will be discussed later.

The error due to deicing heat remains very low (less than 0.7°C) at high flight speeds typical of turbine powered aircraft. Significant errors occur only at conditions which yield a low internal mass flow. These conditions cause the boundary layer on the interior surfaces of the heated housing to thicken enough to contact portions of the sensing element. As can be seen in **Figure 15**, Model 102 total air temperature sensors are sensitive to variable flight conditions at $Z=M_1\ (\rho_1/\rho_0)$ values below 0.3. We use two general forms of element construction in Model 102 sensors. The preferred construction utilizes a single mandrel containing either one or two separate element windings (outputs). Thus, most sensors have a deicing-heat-error characteristic per **Figure 15-A**. Other Model 102 sensors utilize a dual element construction involving side-by-side mandrels. This design has a larger deicing-heat error because the increased element surface contacts a greater portion of the heated boundary layer. Error values are listed in **Table 7**.

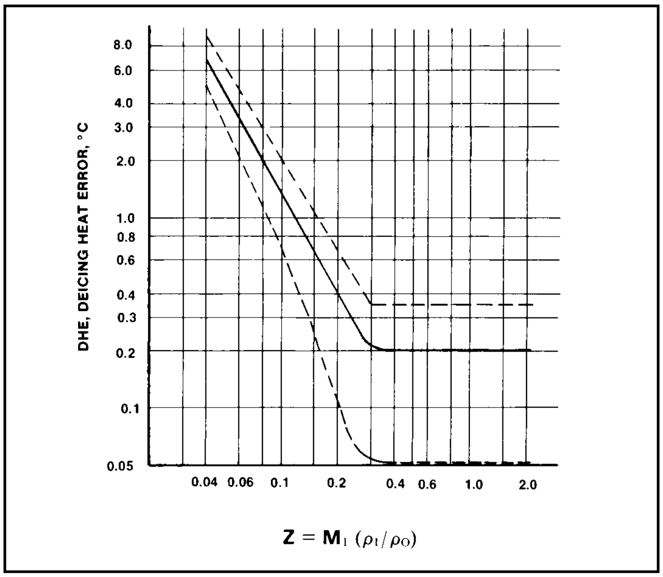


Figure 15-A: Wind Tunnel Data; Deicing Heat Errors for Model 102 Sensors, Single Mandrel Construction (1 or 2 Elements)

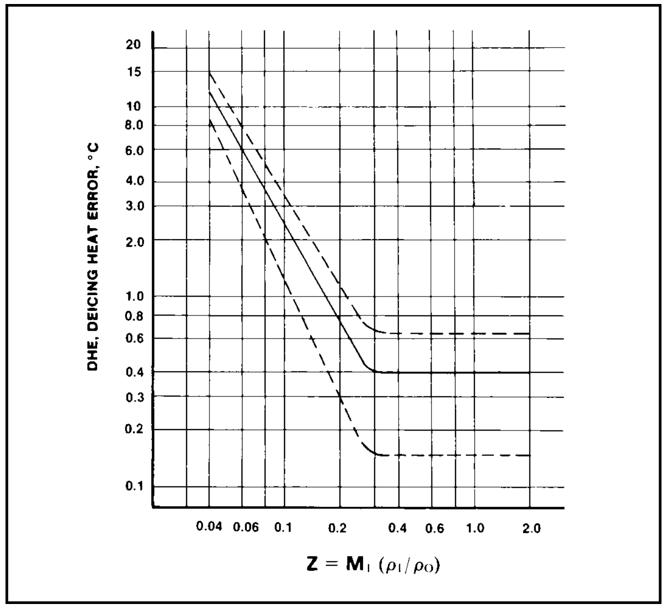


Figure 15-B: Wind Tunnel Data; Deicing Heat Errors for Model 102 Sensors, Dual Mandrel Construction (Multiple Elements)

AIRFLOW DIRECTION SENSITIVITY for Model 102 sensors is somewhat greater than for Model 101 sensors. However, with the heater turned off, Model 102 sensors have negligible sensitivity to ±15 degrees angle (e.g., **Figure 22**). Flow direction is measured in a plane parallel to the surface on which the sensor is mounted. The angle may represent either angle of attack or angle of yaw (sideslip) depending on the location of the sensor on the aircraft. The sensitivity to flow direction in a plane perpendicular to the surface on which the sensor is mounted is relatively unimportant since the proximity of the surface, (and normally its low degree of curvature), tends to straighten the flow. Sensitivity increases when the heater is turned on, and is more configuration dependent. Some military aircraft have a high angle of attack capability at very low airspeed. The Model 102 heater should be off at this condition to prevent high errors. Configuration -b is somewhat less sensitive than configuration -a for the same range of flow angles. Both configurations, however, exhibit less than ±0.5°C variation of indicated temperature with heater on for ±10 degrees change of angle at Z≥0.25.

AERODYNAMIC DRAG for Model 102 total air temperature sensors is approximately twice that for Model 101 sensors (see **Figures 9** and **24**). This is due to the greater projected area of the sensor strut, the thicker housing walls, and increased design complexity.

$Z=M_1 (\rho_1/\rho_0)$	Single Mandrel °C	Dual Mandrel °C
.04	7 ± 2	12 ± 3
.06	3.4 ± 1.3	6.0 ± 2.2
.08	2.0 ± 0.9	3.5 ± 1.6
.10	1.3 ± 0.7	2.4 ± 1.1
.12	1.00 ± 0.60	1.8 ± 0.9
.14	0.75 ± 0.45	1.3 ± .07
.16	0.60 ± 0.40	1.1 ± 0.6
.20	0.40 ± 0.30	0.70 ± 0.40
.30	0.20 ± 0.15	0.40 ± 0.25
.40	0.20 ± 0.15	0.40 ± 0.25
.50	0.20 ± 0.15	0.40 ± 0.25
.60	0.20 ± 0.15	0.40 ± 0.25
.80	0.20 ± 0.15	0.40 ± 0.25
1.000	.20 ± 0.15	0.40 ± 0.25
2.00	0.20 ± 0.15	0.40 ± 0.25

Table 7: Model 102 Deicing Heat Error; Subsonic and Supersonic Flight

7. DEICED MODEL 102 SERIES WITH EJECTORS

7.1 GENERAL DESCRIPTION

The Model 102LA-series total temperature sensors utilize a configuration "a" housing with the addition of an ejector tube as shown in **Figure 16**. When the ejector tube is supplied with compressed air at 7 to 40 psig pressure and 0 to 100°C (32 to 212°F) temperature, self-heating error and the errors due to solar radiation at zero airspeed are no greater than MIL-P-27723E allowable errors in flight. This also applies for any aircraft taxi speed or any vector value of the relative wind in ground operation. It does not apply for ground operation with the heater turned on. Model 102 heaters may be cycled on and off during ground operations if ground icing conditions inhibit flow through the sensor, but normal procedures should require that the heater be off until the aircraft is airborne.

The ejector action pulls ambient air by and through the sensing element (see the sectional view in **Figure 16**).

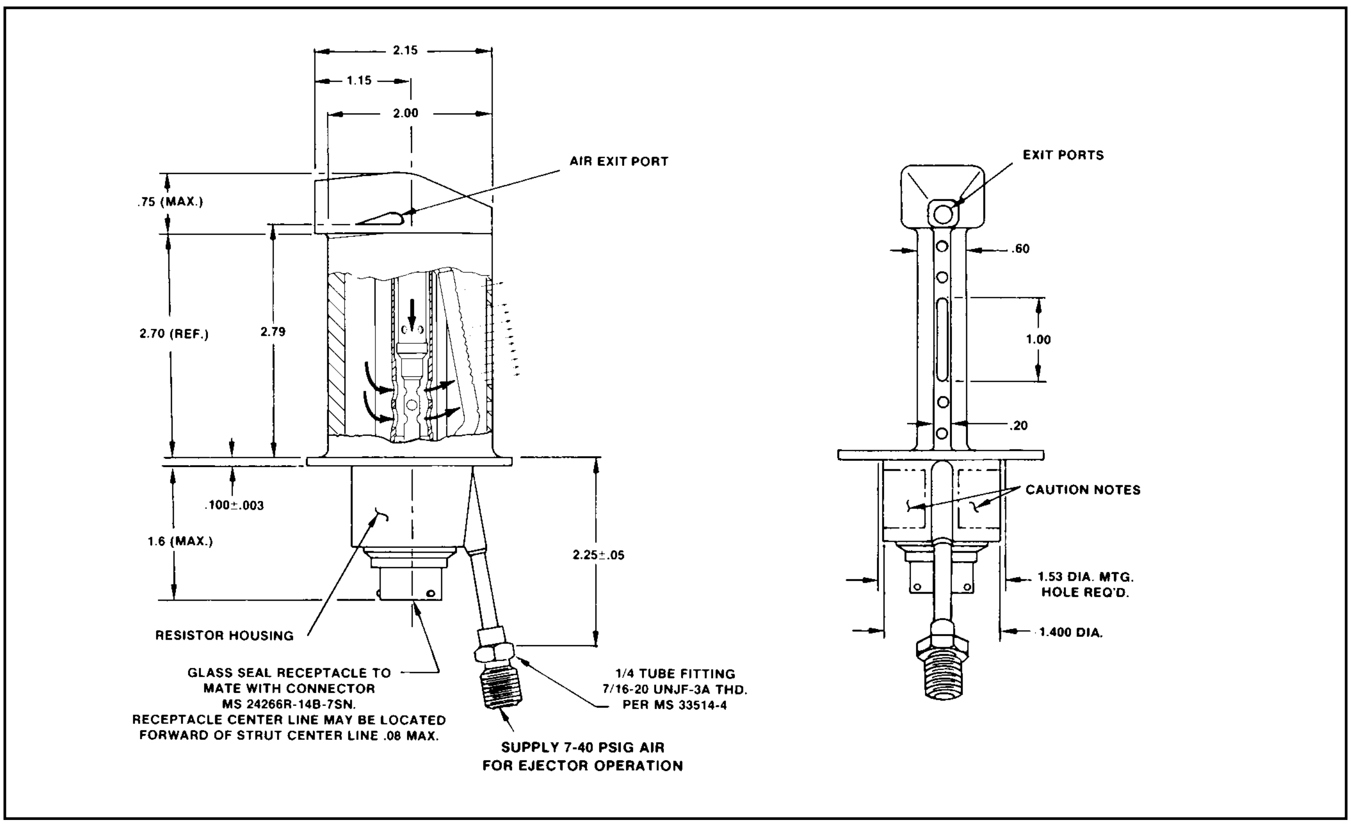


Figure 16: Ejector Model 102 Configuration

7.2 APPLICATIONS

Ejector models are used extensively on the newer jet aircraft which feature "auto-throttle" systems. These systems set engine pressure ratio automatically, and thus require an accurate measurement of ambient temperature at zero or low taxi speeds. Model 102LA series sensors provide accurate OAT on the ground when the ejector is operating and the heater is de-energized. Two minutes should be allowed for the ejector action to overcome solar heating error.

Short-term application of ejector air (overtest) up to 200 psig pressure and up to 200°C temperature will not cause damage to the sensor. An arrangement of ejector orifices yield volume flow rates ranging from 2.0 cubic feet per minute at 7 psig with 180°F ejector air temperature to 4.0 cubic feet per minute at 40 psig with 60°F air temperature. The ejector may be turned off as soon as the aircraft is off the ground. Turning the ejector off and on in flight at Z (zeta) values above 0.15 will not produce systematic shifts in sensor output according to wind tunnel test results (dry air).

Aircraft which must operate from airfields not equipped to provide "tower" or outside air temperature may require ejector models, especially in polar or desert region operations in bright sunshine.

7.3 PERFORMANCE DATA

Systematic errors in normal flight are unaffected by the addition of an ejector, as discussed in the preceding paragraph. Therefore, the performance of the ejector models is defined by **Figures 12** through **15**, **Table 5** and **Table 7**. However, if Z is less than 0.15 with the deicing heater off, sensor accuracy is improved by ejector operation. This is shown in **Figure 17**, and explicit values are listed in **Table 8**.

Figure 18 shows ejector model data representing ground operation characteristics with the deicing heater on. The variation of error with ground speed is given in **Figure 18-A**. Note that high errors occur below 30 knots, and that the ejector intensifies the error between ground speeds of 7 and 50 knots. **Figure 18-B** shows the time variation of error for two conditions. **Figure 18** emphasizes that the ejector is of little benefit in ground operation with the heater energized.

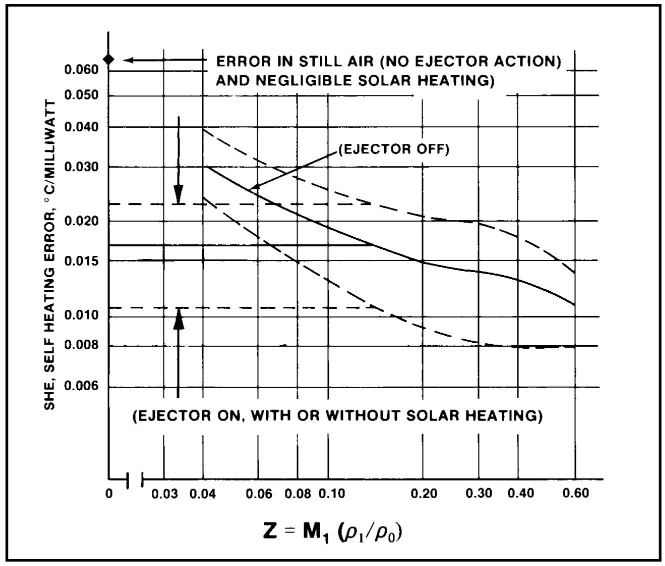


Figure 17: Wind Tunnel Data; Ejector Model Self-heating Errors

$Z=M_1\ (\rho_1/\rho_0)$	SHE, °C/Milliwatt
.04	.017 ± .006
.14	.017 ± .006
.16	.016 ± .006
.20	.015 ± .006
.30	.014 ± .006
.40	.013 ± .005
.50	.012 ± .004
.60	.011 ± .003

Table 8: Ejector Model 102 Self-heating Error; Subsonic and Supersonic with Ejector On

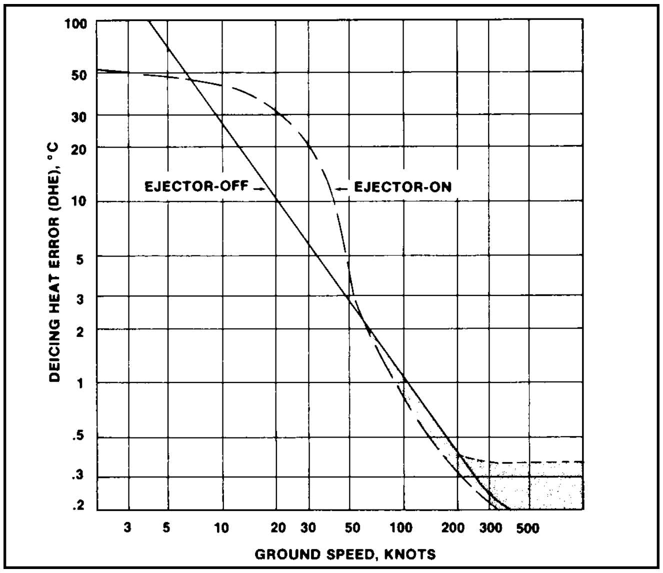


Figure 18-A: DHE Versus Constant Values of Ground Speed

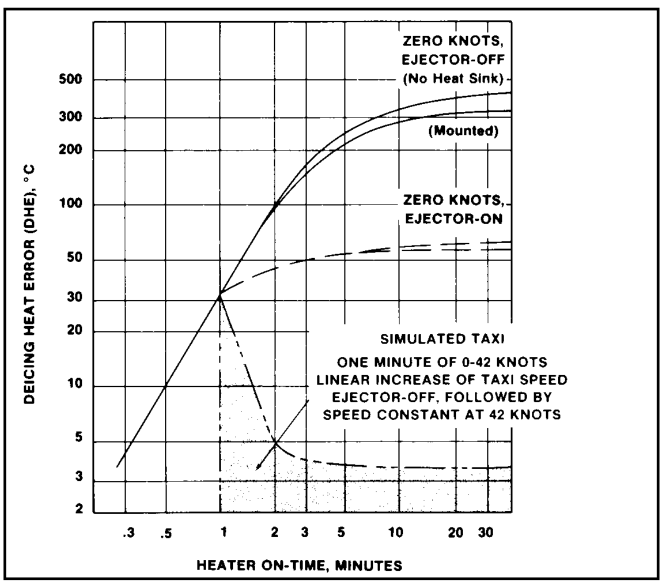


Figure 18-B: Time Variation of DHE

8. MODEL 102 NON-DEICED SERIES

8.1 GENERAL DESCRIPTION

The housing for the Model 102 non-deiced total air temperature sensor is quite similar to the configuration -b deiced housing. The elimination of the heater element allows much thinner walls and welded stainless steel construction. Another difference is a reduced frontal area at the inlet of the non-deiced air scoop. As in the deiced series these total air temperature sensors make use of boundary layer control techniques. The flow is caused to turn a rather abrupt right angle before it contacts the sensing element. This protects the element from damage by air-entrained solids and negates errors due to liquid droplet impingement. A major advantage of this design is that it allows the use of an "open wire" sensing element yielding fast response and improved accuracy. The element is removable from the housing for replacement purposes. The dimensions of the standard configuration are given in **Figure 19**.

8.2 APPLICATIONS

The Model 102 non-deiced series sensor is particularly intended for flight test applications. Its successful use on a wide variety of aircraft over a period of many years has established certain models in this series in the "reference standard" category. Flight tests with sensors of standardized design have the advantage of allowing intercomparisons between flight data for aircraft of various designs during a particular maneuver. Pilots normally avoid clouds during flight tests. Nevertheless a non-deiced Model 102 sensor will maintain its accuracy and fast response in ice crystal clouds where temperatures are below –40°C. This would generally apply to straitform clouds at altitudes above 30,000 feet.

8.3 PERFORMANCE DATA

The following information is directly applicable to the classic open wire construction for the element and a housing configuration per **Figure 19**. The same type of element in a deiced configuration -a or configuration -b housing will yield comparable performance. Test data is also presented for a ruggedized open-wire element in a **Figure 19** housing.

RESISTANCE VS. TEMPERATURE conforms to MIL-P-25726B (ASG) and MIL-P-27723E (ASG) as defined by **Equation 10** and as listed in **Table 3**.

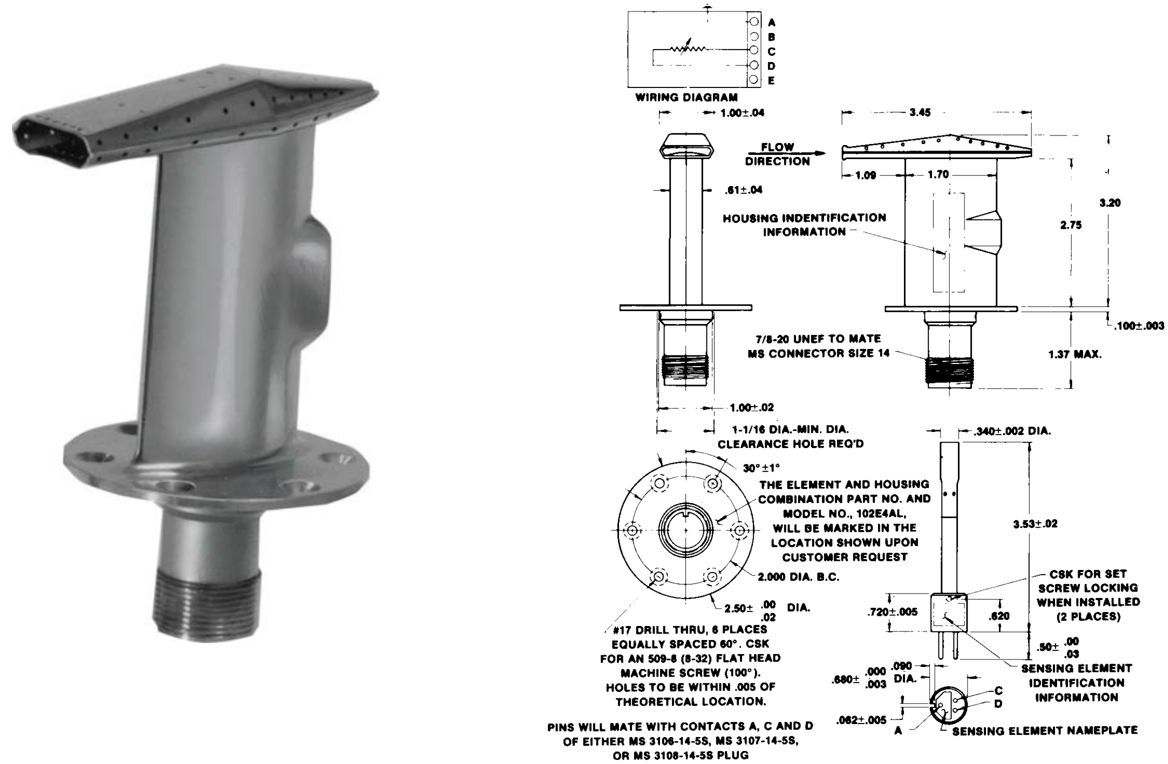


Figure 19: Standard Configuration, Non-deiced Model 102E4AL

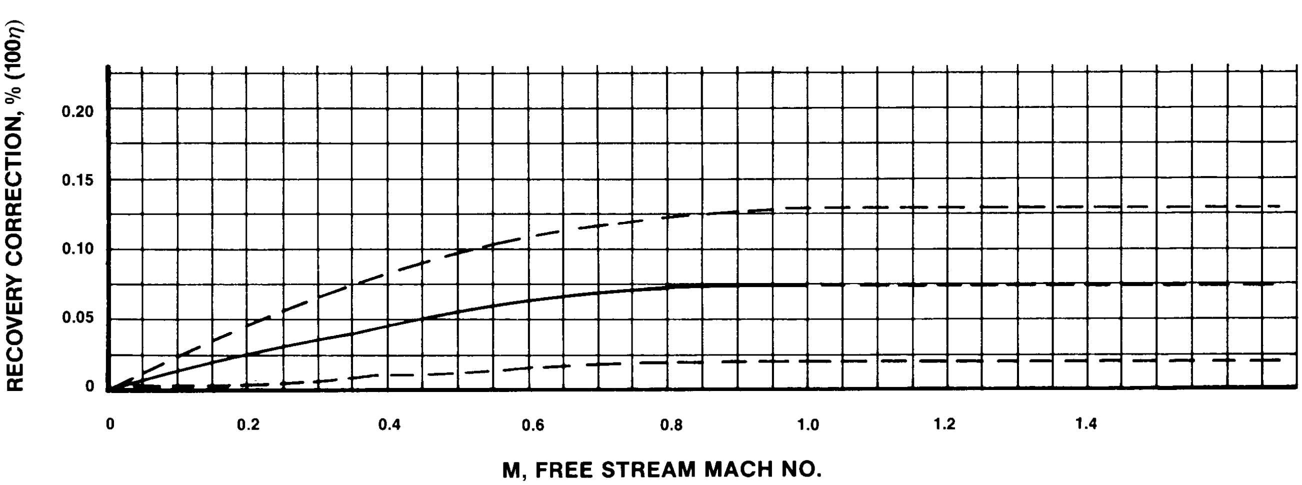


Figure 20: Wind Tunnel Data; Non-deiced Model 102 Recovery Corrections

TIME CONSTANT data for open wire elements is complicated to some extent by the fact that two time constants are involved in a precise definition of the transient shape. Prior literature presented two time constant values and the approximate equation of the transient for a step change of temperature. Flight test personnel usually deal with ramp changes in temperature rather than step changes. Predictions of transient shapes for other than pure step or pure ramp (constant rate of change of temperature) changes require elaborate mathematical analysis. As discussed in 2.4 the time constant is simply an index of how rapidly the temperature sensor can follow a sudden change in temperature. The error due to time lag when more than one time constant is involved must be determined for each sensor design at a number of simulated flight conditions in a wind tunnel.

Model 102 time constant data is summarized in **Figure 23**. The lower band indicates the range of data for classic (cross card) elements as determined in our wind tunnels. The extrapolated portion above unity M_1 (ρ_1/ρ_0) is considered conservative. No wind tunnel data is available for this flow range due to facility mass flow restrictions. These are the values associated with the initial slope of the transient produced from a step change in temperature at constant altitude and flight speed. Essentially, we present the response of the element alone, neglecting supporting structure and sensing housing. The sensor housing can retard the total sensor response to ramp changes by as much as a factor of 20.

Also shown in **Figure 23** are the time constant characteristics for a ruggedized open-wire element, a MIL-P-25726B and a MIL-P-27723E element. The transient of this ruggedized element is closer to a standard first-order transient defined by a single time constant. A faster initial time constant exists, as for the classic element, but is effective for less than half of the amplitude of the step change. The response is about four times faster than the MIL-P-27723E sensor and between two and three times faster than the Model 101 or MIL-P-25726B sensor. The user is reminded that a more precise definition of the transient shape is required for determination of errors due to thermal response lag. In general, the initial response value is applicable only for the time period within one-half second of the start of the temperature change, (4θ in **Figure 3-B**). Then the housing effects begin to dominate.

RECOVERY CORRECTION η, is very small for the non-deiced series as shown in **Figure 20**. This is a direct result of the fact that the internal Mach number is less than half as great as the internal Mach number for deiced sensors. Use of an open-wire element and the absence of deicing heat permit the use of a lower flow rate and internal Mach number, yielding a much lower recovery error.
Error cancellation can be utilized in special cases. Whereas it is always better to make the systematic corrections, it is true for some flight profiles using non-deiced Model 102 total air temperature sensors that the recovery correction opposes the self-heating correction and the indicated reading may be assumed to equal total air temperature with negligible overall error.

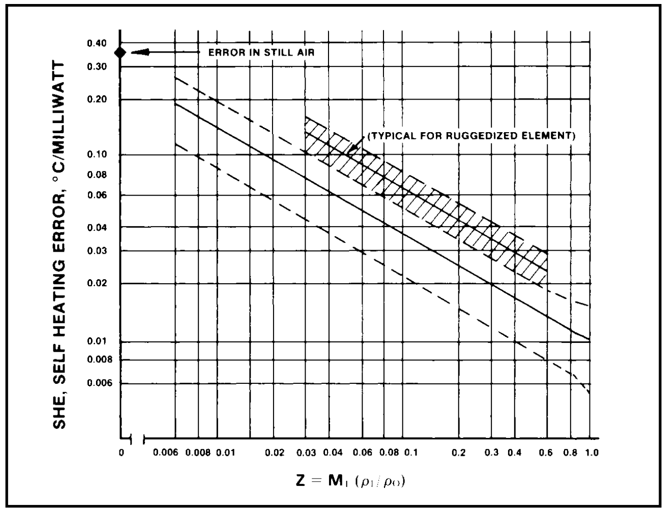


Figure 21: Wind Tunnel Data; Non-deiced Model 102 (0pen-wire Element) Self-heating Errors

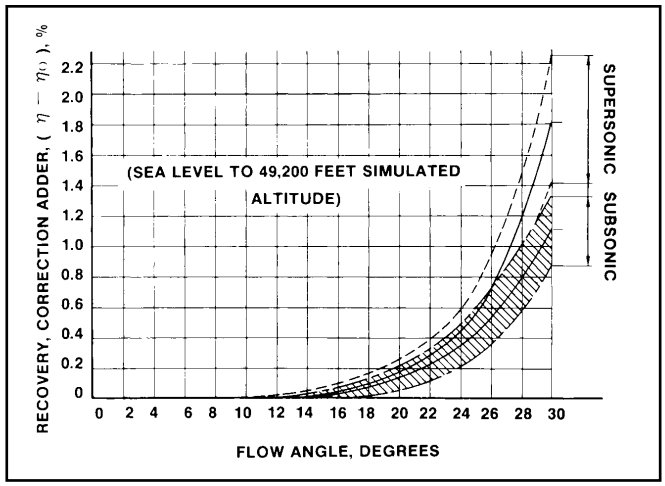


Figure 22: Wind Tunnel Data; Non-deiced Model 102 Flow Angle Sensitivity in Subsonic and Supersonic Flow

SELF-HEATING errors for non-deiced Model 102 total air temperature sensors are summarized in **Figure 21**. Nominal and limit values of self-heating errors for open-wire elements are listed in **Table 9**.

$Z=M_1\ (\rho_1/\rho_0)$	Self-Heating Error, SHE, °C/mw Standard Element	Ruggedized (TYP)
.01	.136 ± .053	.241
.02	.092 ± .036	.163
.03	.073 ± .029	.130
.04	.062 ± .025	.111
.06	.049 ± .020	.088
.08	.041 ± .016	.073
.10	.036 ± .014	.064
.12	.033 ± .013	.059
.14	.030 ± .012	.053
.16	.028 ± .011	.050
.20	.024 ± .010	.043
.30	.019 ± .008	.034
.40	.016 ± .006	.028
.50	.014 ± .006	.025
.60	.013 ± .005	.023
.80	.011 ± .005	.020
1.00	.010 ± .005	.019

Table 9: Open-wire Element Self-heating Error; Model 102 Non-deiced Housing in Subsonic or Supersonic Flight

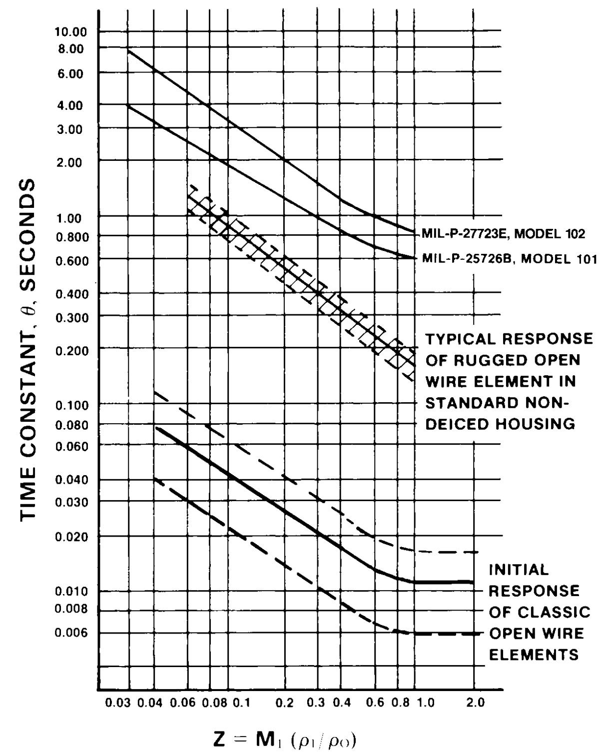


Figure 23: Wind Tunnel Data; Time Constant of Open Wire Elements and MIL-SPEC Elements

Care must be exercised regarding the previously mentioned cancellation of recovery and self-heating corrections. Recovery correction is Mach number dependent, whereas self-heating depends on both altitude and Mach number. For best accuracy the indicated temperature should be corrected to recovery temperature using **Table 9** SHE values multiplied by the excitation power in milliwatts. Then recovery temperature can be converted to total air temperature using **Figure 20**.

RADIATION ERROR for the non-deiced Model 102 total air temperature sensor is negligible for Mach numbers below 2.0 and altitudes below 50,000 feet. Based on flight experience the radiation error is expected to be less than 0.3 percent of absolute temperature in supersonic flight to Mach 3.0 and 100,000 feet altitude.

FLOW DIRECTION SENSITIVITY for non-deiced Model 102 sensors is negligible to ±15 degrees with flow direction measured in a plane parallel to the mounting surface. **Figure 22** shows characteristics plotted from subsonic and supersonic wind tunnel data. The item tested was the **Figure 19** configuration, but generally represents any Model 102 configuration with no deicing heat applied (see Section 6.3).

AERODYNAMIC DRAG for both deiced and non-deiced Model 102 total air temperature sensors is described in **Figure 24**. The curve shape above M=0.9 is hypothetical to the extent that it reflects the characteristics of a less complex configuration without internal airflow.

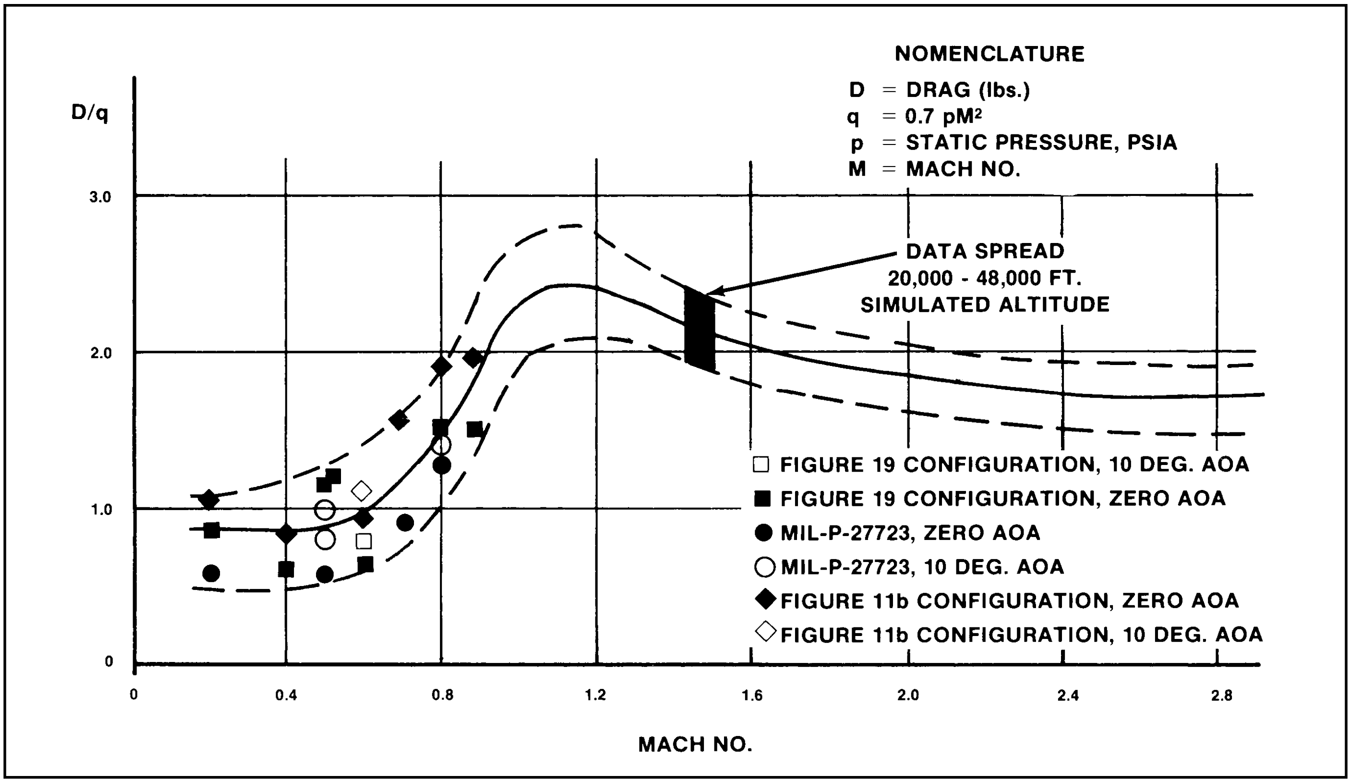


Figure 24: Wind Tunnel Data; Drag of Deiced and Non-deiced Model 102 Sensors

9. SYSTEMATIC ERRORS IN FLIGHT

9.1 FLIGHT ENVELOPE CHARACTERISTICS

In the preceding pages it was shown that many of the systematic corrections are direct functions of the Z parameter. For example, choosing Z equal to 0.200 defines a nominal time constant of 1.9 seconds in **Figure 12**, a self-heating error of 0.015°C/milliwatt in **Figure 13**, and a deicing-heat error of 0.4°C in **Figure 15-A**. Flight at a cruise condition of 0.775 Mach number at 39,000 feet can be defined by a product of M and (ρ/ρ_0) using **Table 1** as follows:

$$M(\rho/\rho_0) = 0.775 \times 0.258 = 0.200$$

Equation 11

Since this is a subsonic flight, $Z = M(\rho/\rho_0) = 0.200$ and the above parameters apply. From **Figure 2** it is seen that a time constant of 1.9 seconds, a self-heating error of 0.015°C/milliwatts, and a deicing-heat error of 0.4°C apply to a single element deiced Model 102 sensor mounted to an aircraft which takes off at 0.2 Mach number and follows the 0.20 Zeta value to 44,000 feet.

A value of 0.200 for Z also defines a supersonic flight condition of Mach 1.4 at 49,000 feet. This can be proved using values from both **Table 1** and **Table 2**.

$$Z = 1.4 \times 0.160 \times 0.8929 = 0.200$$

Equation 12

Again the time constant will be 1.9 seconds, the self-heating error 0.015°C/milliwatts, and the DHE 0.4°C for this case.

From the foregoing it is seen that time constants and systematic corrections have been related to a wide range of airborne conditions typical of powered flight. In many cases the sensor performance allows the aircraft performance, and high errors occur only outside the normal flight envelope for the aircraft.

9.2 SAMPLE CALCULATIONS

Initially, at least, an accuracy requirement is associated with a particular Mach number at a given altitude. Two examples, one subsonic and one supersonic, will be worked out to show how the corrections are found.

9.2.1 DUAL MANDREL MODEL 102 (Figure 11B)

The time constant and systematic corrections are to be determined for 0.802 Mach number at 30,000 feet with 10 milliwatts excitation.

Table 1: $\rho/\rho_0 = 0.374$
Compute $Z = M\ (\rho/\rho_0) = (0.802)\ (0.374) = 0.30$
Table 5: $\theta = 1.0$ to 2.0 seconds
Figure 14: $\eta = 0.26$ to 0.40%
Table 6: SHE = 0.008 to 0.020°C/milliwatt
Table 7: DHE = 0.15 to 0.65°C
Compute $(T_m - T_r) = 10\ (0.008) + 0.15 = 0.23$°C min.
Compute $(T_m - T_r) = 10\ (0.020) + 0.65 = 0.85$°C max.

If the measured temperature is –13°C or 260°K, the true total temperature is calculated as follows:

$$\text{Min. TAT} = \frac{260.00 - 0.85}{1 - 0.0026} = \frac{259.15}{0.9974} = 259.8°\text{K}$$

Equation 13

$$\text{Max. TAT} = \frac{260.00 - 0.23}{1 - 0.004} = \frac{259.77}{0.996} = 260.8°\text{K}$$

Equation 14

The time constant, θ, does not enter into these computations since it was assumed that both T_m and M were constant.

9.2.2 SUPERSONIC FLIGHT, SINGLE MANDREL CONFIGURATION-a SENSOR (MIL-P-27723D)

The nominal time constant and systematic corrections are to be determined for a **Figure 11-A** Model 102 sensor starting with a cruise condition of Mach 2.2 at 62,000 feet with 10 milliwatts of electric power used for element excitation. Even though the deicing heater should be turned off at this flight condition, it will be assumed to be on.

Table 1: $\rho/\rho_0 = 0.0855$
Table 2: Multiplier = 0.7339
Compute $Z = 2.2\ (0.0855)\ (0.7339) = 0.138$
Figure 12: $\theta = 2.45$ seconds nominal
Figure 13: SHE = 0.017°C/milliwatt
Figure 14: $\eta = 0.2\%$ or 0.002
Figure 15: DHE = 0.78°C nominal
Compute $(T_m - T_r) = 10\ (0.017) + 0.78 = 0.95$°C

If the measured temperature is 420.38°K, the true value of total air temperature at this steady supersonic flight condition is calculated as follows:

$$\text{Nom. TAT} = \frac{420.38 - 0.95}{1 - 0.002} = \frac{419.43}{0.998} = 420.27°\text{K}$$

Equation 15

Note that the indicated temperature is very close to the true total air temperature at this particular set of conditions. Now let us suppose that the cruise portion of the flight is over and the pilot throttles back for a descent to lower altitude. The static temperature remains constant between 37,000 and 65,000 feet altitude.

For convenience, we may assume that the initial descent involves a drop to 1.4 Mach number. Let us also assume that this is done such that there is a linear ramp change drop in the total air temperature from 420.27°K to 297.19°K or about 123°K in 300 seconds.

To simplify matters let us also assume that zeta during descent remains fixed at the cruise value of 0.138 (leaving SHE and DHE constant). The time constant from **Figure 12** is 2.45 seconds so the time lag from the true ramp change is 2.45 seconds during most of the descent. The error due to time lag at this idealized condition is the product of the time constant and the rate of change of temperature, or:

$$\text{Lag Error} = 2.45\ \left(\frac{123}{300}\right) = 1.00°\text{K}$$

Equation 16

The sensor will indicate 1.0°K higher than TAT during this descent. At Mach 1.4:

$$T_m = 297.19\ (0.998) + 1.00 = 298.55°\text{K}$$

Equation 17

From the foregoing examples it is evident that with proper care, and for simplified flight conditions, correction parameters obtained from wind tunnel tests may be programmed for on-board computation of TAT in flight. The degree of uncertainty involved in making these systematic corrections of the indicated temperatures to obtain true TAT values will be discussed next.

10. ACCURACY IN FLIGHT

10.1 DYNAMICS

Systematic errors were dealt with in the preceding section. These are uni-directional, and therefore correctable. Using the nominal corrections from the performance data tables, it is possible to approach the true value of total air temperature quite closely. However, there is an element of uncertainty in every temperature indication as well as in every correction of a systematic error. For example, wind tunnel test results always involve data scatter. The uncertainty is bi-directional; the true value could be higher or lower than indicated. Such errors are called random errors. They apply to accuracy in flight through stability, contamination, manufacturing tolerances, gradients, environmental variations and test repeatability.

10.1.1 STABILITY

If the temperature of a resistance element is raised slowly to the maximum rated value and held there for thousands of hours, a very small and very gradual resistance change (drift) will occur. This is normally due to metal evaporation or oxidation. Other effects occur in actual service due to alternate heating and cooling of the resistance element. However, for indicated temperatures in the range –70°C to +300°C these effects are generally less than the equivalent of ±0.05°C for a period of two years of flight service.

10.1.2 CONTAMINATION

Open-wire elements may be subject to contamination errors. Normally, element wire contamination causes a resistance increase, whereas insulation contamination drops the resistance through shunting. These effects are negligible for our hermetically sealed platinum elements.

10.1.3 MANUFACTURING TOLERANCES

It is impossible to physically reproduce exactly a nominal element design or a nominal housing design. Thus the subject of interchangeability enters into the definition of resistance versus temperature as well as into the various corrections determined in the wind tunnel.

Our calibration data shows that Model 101 and Model 102 sensing elements are interchangeable well within the MIL-SPEC requirements of ±0.25°C plus 0.5 percent of temperature. Special PCI circuits yield ±0.10°C interchangeability; these will be described later. The interchangeability of corrections for recovery, self-heating, and errors due to deicing heat involve the repeatability of wind tunnel tests as discussed later.

10.1.4 GRADIENTS

Unusual flight conditions and ground operation can yield temperature gradients which may produce random errors from thermal conduction and radiation effects. Under controlled conditions, such errors could be systematic and correctable. However, weather variations combined with unpredictable exposure times and other variables may cause gradient slope reversals. These random effects are further complicated by mass flow gradients (thick boundary layers). For normal flight conditions, gradient errors are less than ±0.05°C for Goodrich sensor designs. Proper wind tunnel test procedures will also eliminate gradient problems at normal mass flows during wind tunnel testing. Repeatability of test data at low Mach numbers and high simulated altitudes, on the other hand, can account for a large percentage of the apparent interchangeability between several sensors of the same design. This will be discussed later under the heading of “test repeatability”.

10.1.5 ENVIRONMENTAL VARIATIONS

Sudden variations of combined stresses occur in the actual flight environment. These stresses are caused by thermal shocks from rain or sleet encounters, impact of hailstones, lightning strikes, and random vibrations. A strained element generally will exhibit in increased R_0 and a reduced R versus T slope. Severe stresses have been absorbed successfully by Model 101 and Model 102 sensors during formal qualification test programs. Calibrations repeat after testing to within ±0.1°C of initial readings. Model 102 sensors have also repeated within ±0.1°C after several years of scheduled airline service. Open-wire elements should be calibrated periodically if exposed to severe environments.

10.1.6 TEST REPEATABILITY

The data bands shown in the various figures referred to earlier include the aforementioned random errors, the effects of minor geometric variations between various designs in the same model series (e.g., configuration -a and configuration -b in **Figure 14**), and the repeatability of several wind tunnel tests on the same sensor. Some tests exhibit a high degree of repeatability. The absolute accuracy of calibrations in agitated fluid baths is better than ±0.04°C at 0°C. The repeatability is much better for a series of tests on a particular sensor using the same test setup. Indicated temperatures and the readings of flow metering instruments during wind tunnel tests are less stable with time, and are therefore less repeatable. Depending on the value of Z, the true performance interchangeability is less than the 3-sigma variation of wind tunnel data (data scatter) indicated by the bands in the figures. **Figure 25** gives a repeatability factor which may be applied except for near-stall flight conditions and slow taxi speeds on the ground.

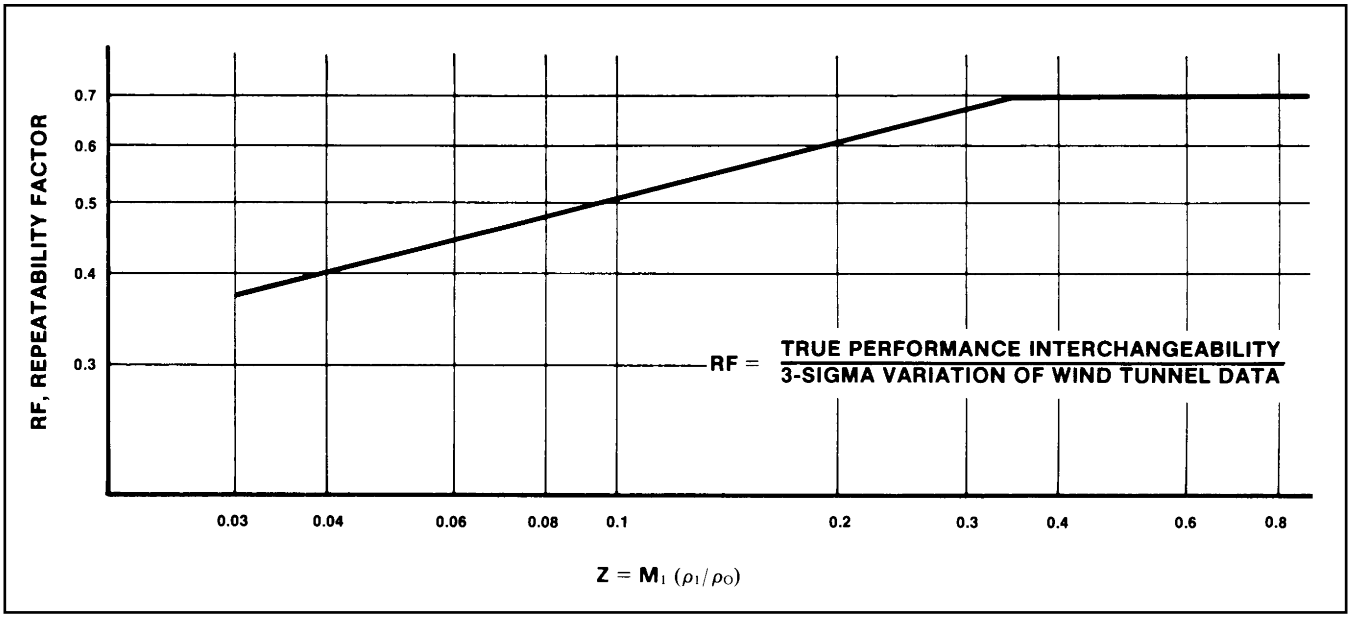


Figure 25: Repeatability Factor for Wind Tunnel Data

10.1.7 SUMMATION OF RANDOM ERRORS

Although a summation of systematic errors is done algebraically, random errors must be combined on a statistical basis. It is never reasonable to add the magnitudes of the random errors, since they are equally likely to add or to cancel. For most applications the random errors are independent and may be root sum squared to give the overall uncertainty of the corrected total air temperature indication. This is more easily understood by returning to the sample calculation in Section 9.2.2. If this sensor has a standard element, the element interchangeability will be:

±0.25°C + / (0.005) (147°C) / = ±0.99°C

Equation 18

This includes the accuracy of fluid bath calibrations and represents the limits of error rather than the probable error. It would be reasonable to assume a probable error of ±0.6°C, but a conservative approach will be used in this example. The assignable random errors are root-sum-squared totaled in **Figure 26**. On the absolute temperature scale this is an accuracy of ±(1.0466 / 420.27) or ±0.249 percent. Note that the element interchangeability is the dominant source of random error. Use of a PCI network can reduce the overall random error in the above example to ±0.3°C. Random errors by nature can be treated as in **Figure 26** using °C values. However, the accuracy of the system which includes the TAT output should be calculated in absolute units (°K). This is imperative for percent error determinations.

Error Source	± Error, °C	$(Error)^2$
Element Calibration Interchangeability	.99	.9801
Recovery Correction Interchangeability*	.19	.0361
Self-heating Correction Interchangeability*	.04	.0016
Deicing Heat Correction Interchangeability*	.25	.0625
Environmental Variations	.10	.0100
Stability	.05	.0025
Gradients	.05	.0025
	1.0466 ←	1.0953

*(For Z = 0.138, RF = 0.55 from Figure 25)

Figure 26: Root Sum Squaring Random Errors (Sample Calculation)

10.2 TECHNIQUES FOR IMPROVED ACCURACY

10.2.1 PCI Networks; ARINC Characteristic

Element interchangeability is reduced to ±0.°1C in the –50°C to +150°C range using a network of precision resistors. These resistors are very stable, contributing less than ±0.01°C error over the stated temperature range. The technique is identified by the term "Precision Calibration Interchangeability" (PCI), and trims each individual sensing element to a modified R vs. T characteristic.

The R vs. T characteristic for sensors using PCI can also be approximated very closely using the Callendar-VanDusen equation. The ARINC characteristic is described by the equation and constants of Section 5.3 except that:

R_0 = 500 ohms
α = 0.003832
δ = 1.82 (IPTS-68)
δ = 1.81 (IPTS-48)

Resistance at selected temperatures for 500-ohm elements with and without PCI are compared in **Table 10**. Differences between resistance values due to redefinition of the International Practical Temperature Scale (IPTS) are seen to be minimal. The IPTS-48 table used by ARINC and most airlines appears in **Table 11**.

	Without PCI		**With PCI**	
Temp., °C	**IPTS-48**	**IPTS-68**	**IPTS-48**	**IPTS-68**
–50	399.70	399.69	401.56	401.55
–25	450.04	450.04	451.01	451.01
0	500.00	500.00	500.00	500.00
25	549.60	549.60	548.55	548.55
50	598.84	598.84	596.67	596.67
75	647.72	647.72	644.35	644.35
100	696.25	696.25	691.60	691.60
125	744.42	744.42	738.42	738.41
150	792.24	792.23	784.80	784.78
CVD Parameters			**(ARINC 706)**	
R_0, OHMS	500.00	500.00	500.00	500.00
Alpha	.003925	.003925	.003832	.003832
Delta	1.450	1.456	1.810	1.820
Beta	0.10	0.11	0.10	0.11

Table 10: Effect of PCI Network on Resistance Output

10.2.2 Inducing Airflow

Significant errors can occur during ground operations due to inadequate airflow through the sensor. When the aircraft is at rest on a hot sunny day with no wind, the indicated reading may be 5°C or more higher than true air temperature. If the deicing heater is energized the error can exceed 100°C. The heater should be left off until the aircraft is in flight (rotation) for accurate measurements. Accurate air temperatures on the ground can be obtained with heater off at 40 feet per second taxi speeds. Where such a technique is not practical, a Model 102 sensor which utilizes and ejector is recommended. The ejector blows air from the exit slot to induce internal airflow even when the aircraft is not moving. The accuracy and performance of ejector models are comparable to corresponding models without ejectors in flight. On the ground, errors are reduced significantly (see Section 7).

10.2.3 Heater Cycling

From **Figure 15** and **Table 7** it is apparent that the accuracy of deiced total air temperature sensors at Z values below 0.2 is significantly reduced. Additionally, the steep slope (of error versus Z) introduces the random error of uncertainty regarding the value of Z in flight. A review of Section 2 and **Figure 2** shows that values of Z below 0.2 occur only above 30,000 feet altitude at normal flight Mach numbers for jet powered aircraft. Icing encounters are few above 30,000 feet. Deicing heat *may produce icing* when flying through ice crystal clouds. Accuracy is much improved with the heater off at high altitudes.

10.2.4 Circuitry

Significant errors can be introduced by a poor choice in circuitry. The cables connecting sensors to bridge completion networks or air data computers and connections thereto contain electrical resistances which may be sizeable on large aircraft. For example, a temperature change in a cable may produce a false indication of air temperature variation.

A long two-wire cable should not be used to connect a 50 ohm element sensor but may be quite suitable for connection to a 500 ohm element. Three-wire or four-wire connections to special bridge circuits provide good accuracy using 50 ohm standard elements. Further discussion of accuracy improvement through choice of circuitry may be found in the referenced literature or in our bulletins.

10.2.5 On-board Computation OF Z

Systematic corrections require an accurate knowledge of the value of Z. Random errors increase if Z is uncertain and if there is a significant variation with Z (e.g., **Figure 15**). If Z can be accurately computed on-board from in-flight measurements of Mach number, static pressure (or pressure altitude), and indicated air temperature, the overall random error will be as stated previously. This technique is used to advantage on weather reconnaissance aircraft.

T	R_t	T	R_t	T	R_t	T	R_t	T	R_t	T	R_t
−100.00	301.08	−58.00	385.63	−16.00	468.70	26.00	550.48	68.00	631.04	110.00	710.38
−99.00	303.11	−57.00	387.63	−15.00	470.66	27.00	552.42	69.00	632.95	111.00	712.25
−98.00	305.15	−56.00	389.62	−14.00	472.62	28.00	554.35	70.00	634.85	112.00	714.13
−97.00	307.18	−55.00	391.61	−13.00	474.58	29.00	556.28	71.00	636.75	113.00	716.00
−96.00	309.21	−54.00	393.61	−12.00	476.54	30.00	558.21	72.00	638.65	114.00	717.87
−95.00	311.24	−53.00	395.60	−11.00	478.50	31.00	560.14	73.00	640.55	115.00	719.74
−94.00	313.26	−52.00	397.59	−10.00	480.46	32.00	562.07	74.00	642.45	116.00	721.61
−93.00	315.29	−51.00	399.57	−9.00	482.42	33.00	563.99	75.00	644.35	117.00	723.48
−92.00	317.32	−50.00	401.56	−8.00	484.37	34.00	565.92	76.00	646.25	118.00	725.35
−91.00	319.34	−49.00	403.55	−7.00	486.33	35.00	567.85	77.00	648.15	119.00	727.22
−90.00	321.36	−48.00	405.54	−6.00	488.28	36.00	569.77	78.00	650.04	120.00	729.09
−89.00	323.39	−47.00	407.52	−5.00	490.24	37.00	571.70	79.00	651.94	121.00	730.95
−88.00	325.41	−46.00	409.51	−4.00	492.19	38.00	573.63	80.00	653.83	122.00	732.82
−87.00	327.43	−45.00	411.49	−3.00	494.14	39.00	575.55	81.00	655.73	123.00	734.69
−86.00	329.45	−44.00	413.48	−2.00	496.10	40.00	577.47	82.00	657.62	124.00	736.55
−85.00	331.47	−43.00	415.46	−1.00	498.05	41.00	579.39	83.00	659.52	125.00	738.42
−84.00	333.49	−42.00	417.44	0.00	500.00	42.00	581.32	84.00	661.41	126.00	740.28
−83.00	335.50	−41.00	419.42	1.00	501.95	43.00	583.24	85.00	663.30	127.00	742.14
−82.00	337.52	−40.00	421.40	2.00	503.90	44.00	585.16	86.00	665.19	128.00	744.01
−81.00	339.54	−39.00	423.38	3.00	505.85	45.00	587.08	87.00	667.08	129.00	745.87
−80.00	341.55	−38.00	425.36	4.00	507.80	46.00	589.00	88.00	668.97	130.00	747.73
−79.00	343.56	−37.00	427.34	5.00	509.74	47.00	590.92	89.00	670.86	131.00	749.59
−78.00	345.58	−36.00	429.31	6.00	511.69	48.00	592.83	90.00	672.75	132.00	751.45
−77.00	347.59	−35.00	431.29	7.00	513.64	49.00	594.75	91.00	674.64	133.00	753.31
−76.00	349.60	−34.00	433.27	8.00	515.58	50.00	596.67	92.00	676.53	134.00	755.16
−75.00	351.61	−33.00	435.24	9.00	517.53	51.00	598.58	93.00	678.41	135.00	757.02
−74.00	353.62	−32.00	437.21	10.00	519.47	52.00	600.50	94.00	680.30	136.00	758.88
−73.00	355.62	−31.00	439.19	11.00	521.42	53.00	602.41	95.00	682.18	137.00	760.73
−72.00	357.63	−30.00	441.16	12.00	523.36	54.00	604.33	96.00	684.07	138.00	762.59
−71.00	359.64	−29.00	443.13	13.00	525.30	55.00	606.24	97.00	685.95	139.00	764.44
−70.00	361.64	−28.00	445.10	14.00	527.24	56.00	608.15	98.00	687.84	140.00	766.30
−69.00	363.65	−27.00	447.07	15.00	529.18	57.00	610.06	99.00	689.72	141.00	768.15
−68.00	365.65	−26.00	449.04	16.00	531.12	58.00	611.97	100.00	691.60	142.00	770.00
−67.00	367.65	−25.00	451.01	17.00	533.06	59.00	613.88	101.00	693.48	143.00	771.86
−66.00	369.65	−24.00	452.98	18.00	535.00	60.00	615.79	102.00	695.36	144.00	773.71
−65.00	371.65	−23.00	454.95	19.00	536.94	61.00	617.70	103.00	697.24	145.00	775.56
−64.00	373.65	−22.00	456.91	20.00	538.87	62.00	619.61	104.00	699.12	146.00	777.41
−63.00	375.65	−21.00	458.88	21.00	540.81	63.00	621.52	105.00	701.00	147.00	779.26
−62.00	377.65	−20.00	460.85	22.00	542.75	64.00	623.42	106.00	702.88	148.00	781.10
−61.00	379.65	−19.00	462.81	23.00	544.68	65.00	625.33	107.00	704.75	149.00	782.95
−60.00	381.64	−18.00	464.77	24.00	546.62	66.00	627.23	108.00	706.63	150.00	784.80
−59.00	383.64	−17.00	466.74	25.00	548.55	67.00	629.14	109.00	708.50		

Table 11: Resistance (Ω) Versus Temperature (°C) for 500 Ohm PCI Platinum Elements

11. ENVIRONMENTAL DATA

This section summarizes the results of environmental testing conducted in our laboratory facilities and discusses the qualification status and service experience on Model 101 and Model 102 sensors.

11.1 DEICING AND ANTI-ICING

As for most environmental test specifications, the requirements for clearing ice from the Model 102 sensors calls for a simulation of extreme icing conditions rather than a typical or average encounter. The MIL-P-27723E (ASG) requirement is 325±25 knots true airspeed, –30°C±5°C static air temperature, and with a liquid water content of 1.25±0.25 grams of water per cubic meter of air. NASA data for 3,200 actual icing encounters in North and Central America indicates that –16°C is the typical static air temperature. Also, 70 percent of the actual flight data registered values of water content at less than 0.5 grams per cubic meter. Nevertheless, Model 102 sensors have been successfully tested many times in our icing wind tunnel facility at the MIL-P-27723E conditions. The deicing portion of this test demonstrates the capabilities of the 102 sensor heater construction. Following a buildup of approximately one-half inch of ice up-stream of the sensor scoop inlet, application of rated heater power eliminates the heavy ice accumulations within one minute, and airflow through the sensor is restored within two minutes.

11.2 HEATER POWER

The heating elements for deiced Model 102 sensors have a high temperature coefficient of resistance, which results in a considerable reduction of power when the sensor becomes warm. Conversely, the power increases as the sensor is chilled during an icing encounter. When the sensor is immersed in a stirred ice bath, the power dissipation is approximately the same as for flight during an icing encounter (e.g., 0.5 Mach number at 10,000 feet). In still air the sensor runs quite hot and the power is reduced by more than 25 percent. Because of the high temperature coefficient of the heating element, there is an inrush of current when the heater is first energized. Peak power may exceed 700 watts during the first one-tenth second but reaches an equilibrium or steady value in less than 10 seconds. The MIL-P-27723E requirement is for an equilibrium power level of less than 350 watts in the stirred ice bath and less than 170 watts in still air.

11.3 DIELECTRIC PROPERTIES

Refractory insulants are employed in the element and heater circuits of our total air temperature sensors. This allows safe operation at total temperatures above 350°C assuming that the insulant is clean and dry. When the circuits are hermetically sealed, the insulant will remain clean and dry for many years in world-wide service. The dielectric strength of these hermetically sealed circuits do not degrade with increase of altitude. Dielectric strength can be demonstrated at 500 volts AC or DC for heater circuits and 100 VDC for element circuits.

The MIL-P-27723E dielectric requirements for total air temperature sensors are 10 megohms at 100 VDC for the element circuit and one megohm at 500 VAC for the heater circuit. These tests are preceded by an eight hour water soak to assure that the circuits will not become contaminated in service. All Model 102 sensors contain caution notes warning the user to not exceed 100 VDC applied voltage when testing the sensing element circuit and to not exceed 500 VAC when testing the heater circuit.

11.4 EMI CHARACTERISTICS

Model 101 and 102 total air temperature sensors are essentially pure resistive loads. The impedance increase of a standard 50-ohm element between D.C and 2,000 Hz is less than 0.04 ohms, or less than 0.8 percent. Considering this and the fact that all circuits are completely shielded by metal, electromagnetic interference (EMI) effects are normally found to be external to the sensor.

11.5 CORROSION

The Model 101 series and the non-deiced Model 102's are of stainless steel and precious metal construction and seldom corrode even in near-ocean service. Corrosion protection of the copper alloy portions of deiced Model 102 sensors is afforded by MIL-C-26074A nickel plating. This turns dark in service but offers good corrosion protection until worn through by the erosion of sand particles and contact with other foreign objects during landing and takeoff. *Under no circumstances should coarse abrasives be used* in polishing the plated surfaces. Phosphoric acid base solutions must also be avoided unless a thorough flushing with water follows. Once the plating has been removed, an erosion/corrosion process can severely attack the leading edges of the sensor housing, resulting in reduced service life.

11.6 MECHANICAL STRENGTH

Model 101 and 102 total air temperature sensors are designed to withstand much greater stresses than they will normally experience in flight service. For example, static load tests representative of Mach 2.0 flight at sea level are passed routinely. Whereas applied vibration levels seldom exceed 5 g's on forward positions of the aircraft fuselage where the sensors are normally mounted, 10 g's are survived for many hours at frequencies up to 400 Hz. The housing of deiced Model 102 sensors exhibits a very pronounced prime resonance in the axis of minimum structure thickness (normally defined as the horizontal axis). A typical amplitude/frequency plot for a configuration -a sensor is shown in **Figure 27**. Obviously a continued vibration at the precise resonant frequency could cause damage to the sensor. Consult the individual specifications covering the vibration capability of your particular model.

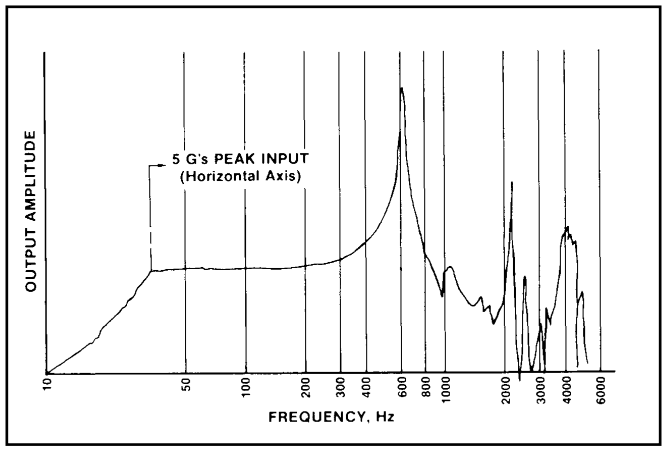


Figure 27: Typical Vibration Plot; Model 102, Configuration -a

11.7 MODEL 102 SERVICE EXPERIENCE

As a complement to the accumulated test data, over twenty years of successful world-wide service on a great variety of aircraft have conclusively proved the high reliability of our deiced Model 102 total air temperature sensors. Service experience has been so good that most users find little need to keep service life data on file. After 3-5 years of service, refurbished or replaced housings can be combined with a reused or original sensing element. Often, it is determined that these elements repeat their original calibrations at 0 and 100°C within ±0.1°C. It is difficult to establish maximum service life in terms of flight hours because of the lack of field data, especially data which includes the frequency of occurrence of foreign object damage (FOD) and lightning strikes. Some returned housings, notably configuration -b type, have pits at the corners evidencing high amperage electrical arcing.

Mechanical damage is negligible and the element is usually still good, but high current from lightning strikes damages the heater and plating which can in time result in a premature housing failure. Premature failure can also occur from the impact of foreign objects such as hail, sand, and birds. Mechanical damage may result from large hailstone (greater than one inch diameter) and large bird impacts at airspeeds above 250 knots. Other foreign object impacts are more likely to compromise the integrity of the plating as discussed previously. The best guide to expected service life is the experience of other users with similar aircraft and comparable service environments.

Neglecting the unpredictable encounters with foreign objects and lightning, a long service life (MTBF greater than 20,000 hours) is assured using the following precautions during servicing of aircraft prior to or at the conclusion of a flight.

a) Keep deicing heater off except for one-minute checkout.
b) Remove cover (if any) before turning on deicing heat.
c) Do not use coarse abrasives to clean.
d) Remove foreign objects from scoop inlet.
e) Flush with water following cleaning.

Using these precautions, Model 102 total air temperature sensors will remain operational for all extreme climatic conditions specified in MIL-STD-210A.

11.8 ACCEPTANCE TESTS

Prior to shipment, each total temperature sensor must pass certain electrical tests and mechanical inspections which prove conformance to the appropriate specifications. These tests include, but are not limited to, dielectric tests, heater power measurements (as applicable), and calibrations at two or more temperatures in agitated fluid baths. Additional tests are conducted periodically to monitor the effects of procedural changes such as process sequence, change of vendor, and such other variations not classified as either Class 2 or Class 1 design changes. The purpose of acceptance testing is to establish that the sensors which are shipped are the same as the original qualification test units.

11.9 QUALIFICATION STATUS

We are rated by Government agencies as a qualified source for MIL-P-25726B (ASG), Amendment 3 (Model 101) sensors, and for MIL-P-27723E, Type I and II (Model 102, configuration -a) sensors. Other agencies and airframe manufacturers consider us as the prime source for all sensors which relate to the above by design similarity. The Federal Aviation Agency (FAA) utilizes similarity to MIL-P-27723E (ASG) as the basis for their acceptance of deiced total air temperature sensors destined for commercial airline service. Each of our Models has a specification drawing that details the design variations from the qualified military unit.

12. DESIGN VARIATIONS

12.1 STRUT LENGTH

Standard Model 101 and 102 sensors are designed to measure the temperature of the air 3.0 inches from the mounting surface. The structural mathematical model is a 3.0 inch long cantilevered tubular beam. The thermal mathematical model is a 3.0 inch long classic fin with internal cooling airflow passages. Any change of strut length alters both the mechanical and thermodynamic performance characteristics.

The standard length is ideal for mounting to forward areas of the fuselage where boundary layer thickness remains less than 1.5 inch (approximately within 150 inches of the nose). Mounting in areas of thicker boundary layers requires a non-standard longer strut with less vibration capability. We strongly recommend that a forward mounting location be chosen allowing use of standard configurations.

12.2 MOUNTING OPTIONS

Curved baseplate models are available for mounting on surfaces with large radii of curvature. A flat location or the use of a boss is preferred to allow use of a standard design.

A dowel pin as shown in **Figure 5** and in **Figure 11-A** is available to assure that the unit is aligned with the flow direction when mounted. Unless such precautions are utilized a sensor could be subjected to large flow angles thus negating all statements regarding accuracy in flight. Use of a dowel pin is the most effective means of avoiding mounting errors.

12.3 SENSING ELEMENT OPTIONS

Selections of sensing elements are based upon nominal resistance values at 0°C (ice point) and sensitivity in ohms per degree (C°). **Table 12** lists standard available sensing elements. Dual outputs of the same type or different types are available in a single Model 102 housing.

12.4 INTERCHANGEABILITY

Standard resistance versus temperature interchangeability of platinum element sensors is ±0.25°C + 0.005 /T/. Element interchangeability is improved to ±0.1°C over the range –50°C to +150°C by the use of a PCI network. Section 10.2.1 defines PCI in more detail. **Table 10** indicates the dictates the difference between standard and PCI element characteristics.

12.5 HEATER VOLTAGE OPTIONS

Deiced Model 102 total air temperature sensors are available in one of three heater voltages: 28, 115 and 230 volts. The model number (102XX XX) designation identifies the heater voltage as follows:

Number	Heater Voltage
102XX1XX	28 VAC or VDC
102XX2XX	115 VAC, 60 or 400 Hz
102XX3XX	230 VAC, 60 or 400 Hz
102XX4XX	No Heater

12.6 COMBINATION SENSORS

There are specialized applications where a pitot probe is added to the strut of Configuration -a deiced Model 102 sensors. The pitot opening is deiced without affecting the accuracy of total temperature measurements. The consequence of combining sensing functions is reduced strength under dynamic loading. Locating the sensor in zones of minimal vibration is required.

Aerodynamic analysis and performance testing can be accomplished with our transonic wind tunnel facilities. Your local Goodrich office will assist you in your sensor selection

Specification	Winding	R_0, Ohms	R_{100}-R_0, Ohms	Max. Temp., T_m °C*
MIL-P-25726B } MIL-P-27723E	Platinum	50.00	19.62	350
(PCI)	Platinum	50.00	19.16	250
	Platinum	500.00	196.20	350
ARINC (PCI)	Platinum	500.00	191.60	250
	Platinum	200.00	78.48	350
	Platinum	100.00	39.24	350
MIL-B-7258	Nickel	1200.00	660 (approx.)	70
MIL-T-7990B	Nickel	90.38	38.47	300

*Much higher temperatures can be survived, but at reduced accuracy and/or stability.
(The sensor receptacle pins should not exceed 200°C.)

Table 12: Element Options

Goodrich Total Temperature Model Description Chart

Model	Housing Config.	Deicing Heater Voltage	Connector Type	No. of Elements	PCI	Resistance at 0°C (ohms)	Aircraft Application
102CP2AF	a	115VAC	Bayonet	1	Yes	500	S-3A, Canadair Challenger
102CP2AG	a	115VAC	Bayonet	2	Yes	500	L1011, B-747
102CT2CB	a	115VAC	Bayonet	2	Yes No	50 500	DC-9
102CU2Y	a	115VAC	Bayonet	1	Yes	50	DC-9
102LA2AG	a	115VAC	Bayonet	2	Yes	500	B-747, B-757, B-767
102CA2W	a	115VAC	Threaded	2	No	50	A-10, C-5, C-141, F-14, F-15, F-16, F-18, F-111
102DB1CB	a	28VDC	Threaded	2	Yes No	50 500	Gulfstream II
102DB1CK	a	28VDC	Threaded	2	No	500	Gulfstream III
102AH2AF	b	115VAC	Bayonet	1	Yes	500	B-707, B-720, B-727
102AH2AG	b	115VAC	Bayonet	2	Yes	500	B-727, B-737, DC-8, DC-10
102AR2U	b	115VAC	Bayonet	1	No	50	F-4
102JD2FE	b	115VAC	Bayonet	3	Yes Yes Yes	50 500 500	DC-9-80
102JE2FG	b	115VAC	Bayonet	3	Yes	500	B-727, B-737
102AU1AF	b	28VDC	Bayonet	1	Yes	500	Jet Star, Citation, King Air, Learjet, Westwind, Diamond I
102AU1AG	b	28VDC	Bayonet	2	Yes	500	BAC 125-700
102AU1AP	b	28 VDC	Bayonet	1	No	500	Falcon 20/50

This list represents major Goodrich Total Temperature models. The list is by no means inclusive. Variations of the above options exist or can be produced upon request.

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