PROBE DIAGNOSTICS OF HIGH - TEMPERATURE GASES

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INTRODUCTION

Cooled probes have been developed as a direct result of the need to measure gas properties at high temperatures or in corrosive environments. Originally developed for "exotic" gas environments at temperatures so high as to entirely preclude the use of more conventional methods, (e.g., arcjets, rocket engines, hyperthermal wind tunnels), cooled probe techniques have only recently been applied to the more moderate temperatures encountered in industrial furnaces, thermal cracking columns, incinerators, nuclear power reactors, metal smelting and refining furnaces, etc.

The most frequently used cooled-probe method is the calorimetric principle, for the measurement of gas enthalpy (and thereby the gas temperature, in most industrial applications). Specific benefits of this method are as follows:

(a) Maximum probe material temperature may be maintained only a few degrees higher than that of the coolant, thereby providing long life in high-temperature or corrosive gas environments. This feature can be contrasted with thermocouples, resistance thermometers, or even fluidic oscillators, which by their very nature must operate at the temperature of the gas to be measured.

(b) The cooled calorimetric probe functions solely as a mechanical structure; that is, it can be fabricated from materials which are fully compatible with the environment, since it requires no special electrical properties as do thermocouples or resistance thermometers. Further, even if some material deterioration does occur, the probe's operation is totally unaffected, as compared with the other devices, which immediately begin to suffer variations in electrical output.

(c) Effects on probe output signal due to contamination by particulate matter, condensibles, etc., which may erode or coat the probe, are generally negligible or can be eliminated by either relatively simple coolant flow management or periodic cleaning of the probe's internal passage in situ, with access from the outside.

(d) Since the output sensors are located remotely from the probe tip, they can be serviced or replaced without removing the probe itself from the measurement region. This feature is particularly important in nuclear reactor core measurements or in any other application where instrumentation replacement would otherwise require a plant shutdown.

(e) For environments which are so severe as to have been formerly inaccessible to all but remote temperature measurement (e.g., optical pyrometers), the cooled immersion probe provides a degree of accuracy and multiplicity of measurement far beyond that attainable with non-local viewing devices of comparable cost and complexity.

(f) In many applications, the direct probe output signal can be made proportional to either gas enthalpy (temperature) or total power (product of enthalpy or temperature and mass flow rate).

Disadvantages of the cooled calorimetric probe as compared with more conventional immersion devices (e.g.,thermocouples or resistance thermometers) are high first cost and the requirement for a coolant supply. It can, however, be argued that the higher first cost of a cooled probe installation is more than compensated by its greater lifetime and higher reliability, both of which sharply reduce plant shutdown time or failures due to deterioration or loss of control function. Also, in most industrial applications, readily-available shop air supplies or city water provide adequate probe coolant capability.

The present paper provides a review of cooled calorimetric probe principles and applications, and mentions several other cooled-probe diagnostic techniques applicable to industrial environments.

THE COOLED CALORIMETRIC PROBE

The basic principle of the calorimetric probe is as follows: a small sample of the gas to be measured is allowed to flow continuously through a hollow-walled tube. The tube walls are cooled by either a gas (e.g., air, nitrogen, hydrogen, helium, etc.) or a liquid (e.g., water, hydraulic fluid, ethylene glycol, etc.). By measuring the heat given up to the coolant by the hot gas sample, therefore, one can determine directly what its enthalpy was before it was cooled.

The simplest form of this device (Ref. 1) is the so-called "tare-measurement" probe (Figure 1), in which the coolant serves not only as the calorimetric fluid, but also to cool the probe exterior. In this case two measurements are required: first the total coolant energy is measured (coolant flow multiplied by its temperature rise); then the gas sample flow is shut off by a valve and the coolant energy is measured again (the "tare" measurement). The difference between the two coolant energy measurements is then the enthalpy given up by the gas sample:

$$h_{ig} = \frac{(w_c\, c_{pc}\, \Delta T_c)_f - (w_c\, c_{pc}\, \Delta T_c)_{nf}}{w_g} + c_{p2g}\, T_{2g}$$

where

w_c = coolant flow rate (lb/sec)

c_{pc} = coolant specific heat, (Btu/lb-°F)

ΔT_c = coolant temperature rise, (°F)

w_g = gas sample flow rate, (lb/sec)

c_{p2g} = cooled gas sample constant-pressure specific heat at probe exit, (Btu/lb-°F)

T_{2g} = cooled gas sample temperature at probe exit, (°F)

$()_f$ indicates gas sample flowing

$()_{nf}$ indicates gas sample flow shut off

The principal purpose in utilizing this type of probe is that its simplicity of design permits the use of very small overall diameters (as small as 1/32"), and also provides effective cooling in extremely high heat-flux environments. It is particularly useful where the operating conditions are such that the tare or calibration measurement need only be made periodically (e.g., once per hour or per day), i.e., wherever temperature, flow, and pressure conditions do not vary over wide ranges. Under these conditions, the tare-measurement probe becomes a useful, practical, continuous-output instrument.

Note that in order to provide proper duplication of heat

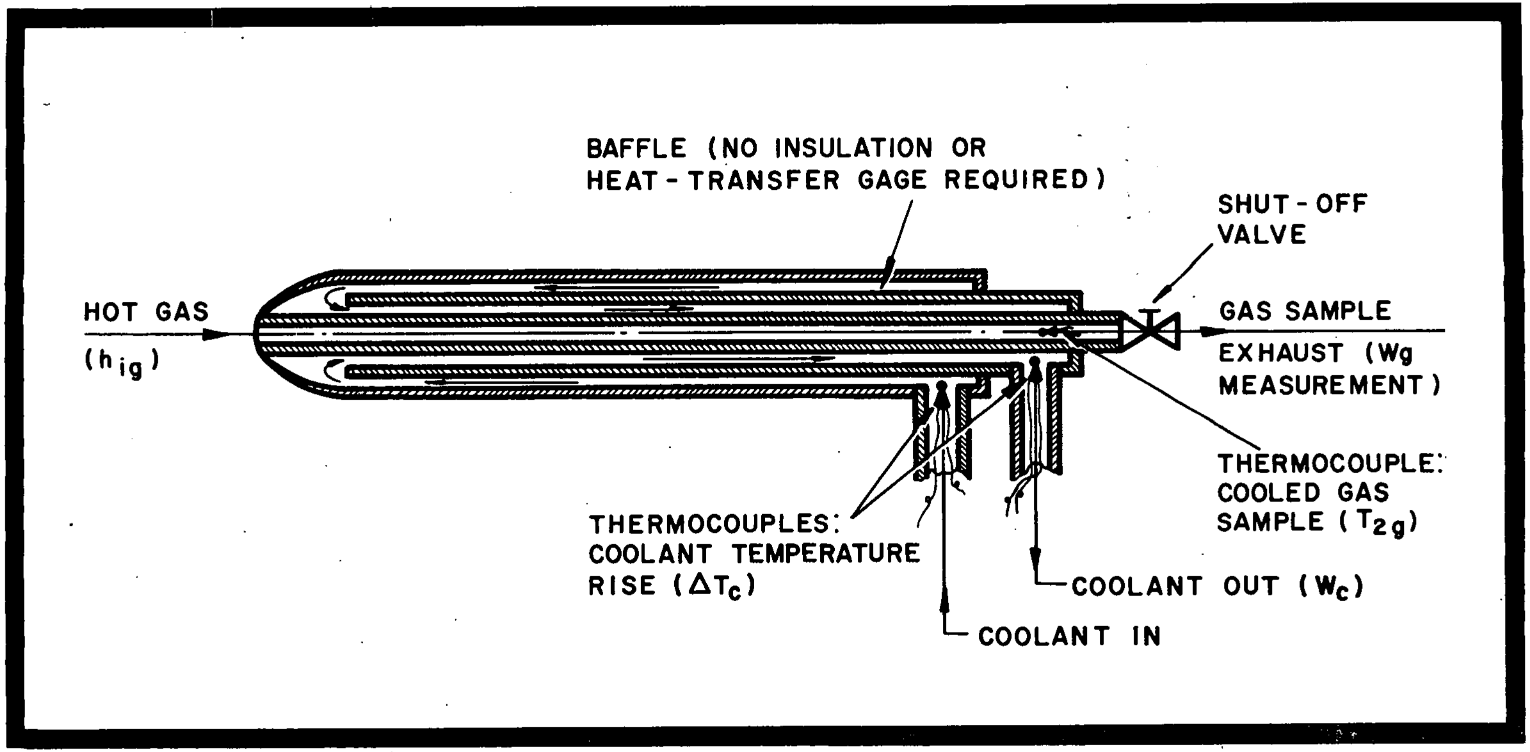


FIGURE 1

SIMPLE TARE-MEASUREMENT PROBE FOR MEASUREMENT OF ENTHALPY, IMPACT PRESSURE, AND GAS COMPOSITION.

flux to the exterior of the probe between the "tare" and "non-tare" measurements, it is necessary that the gas sample flow rate be sufficiently small so as not to disturb the general flow pattern at the probe tip. When the product of gas pressure and enthalpy drops so low that this requirement conflicts with the requirement for adequate sensitivity (i.e., difference in coolant temperature rise between the tare and non-tare measurements), this class of probe has reached its limit of usefulness.

In this event, and for lower heat-flux conditions in general, the fully-isolated non-tare-measurement probe of Figure 2 is recommended (Ref. 2). Here the calorimetric portion of the probe is isolated from the cooling jacket by an air gap (this may, obviously, also be vacuum or another gas). The enthalpy measurement is then obtained directly, without the necessity for a tare measurement, as follows:

$$h_{ig} = \frac{(\dot{w}_c \, c_{pc} \, \Delta T_c)_i}{w_g} + c_{p2g} \, T_{2g}$$

where now subscript $()_i$ indicates the inner calorimetric jacket, and all other notation is indicated below the previous equation.

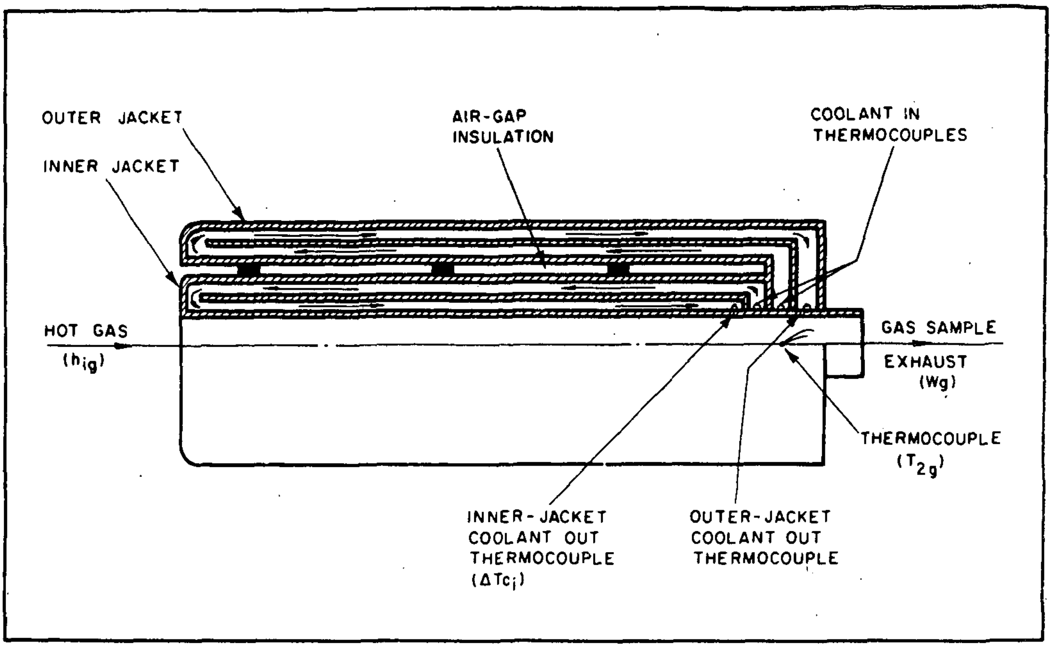
The only conditions on the use of the non-tare-measurement probe are

(a) No heat transfer occurs between the inner and outer jackets of Figure 2.

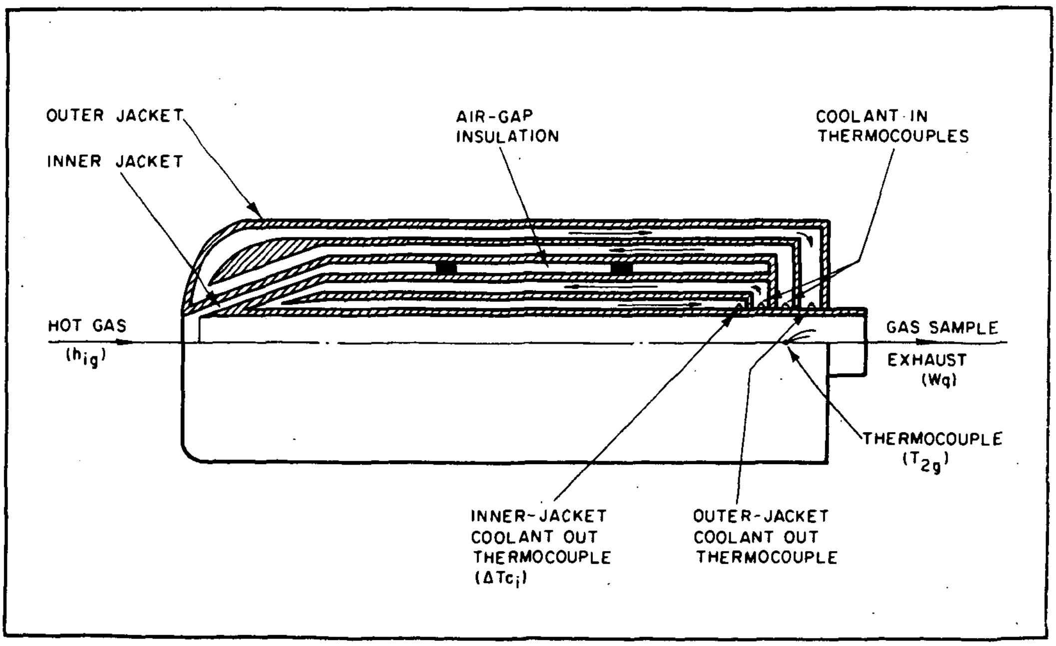
(b) All of the gas which is aspirated is cooled by the inner jacket, and none of it is cooled by the outer jacket.

The first of these conditions is accomplished by designing the probe geometries and relative coolant flow rates through the two jackets so that wall temperatures at opposing points all along the air gap will be as nearly equal as possible, thus minimizing interjacket heat transfer. The second condition is achieved either by proper adjustment of the aspirated gas sample flow rate (i.e., locating the flow stagnation point at the insulation-gap entrance), or, in Configuration A of Figure 2, by correcting for the small amount of heat transfer to the exposed portion of the calorimeter.

In either of these probe designs, if the cooled gas sample temperature T_{2g} is either (a) very nearly equal to the calorimetric coolant exit temperature; (i.e., the probe length/diameter ratio is sufficiently large), or (b) very nearly constant, or



CONFIGURATION "A"



CONFIGURATION "B"

FIGURE 2

CONTINUOUS-FLOW JACKETED CALORIMETRIC PROBE

(c) very low compared with the "unknown" hot gas temperature, the measurement of T_{2g} can be eliminated. Also, for long-term monitoring purposes, the coolant flow rate can be controlled to a preset value, so it need not be measured, and the cooled gas sample flow can be extracted through a choked orifice so that its flow rate will be directly proportional to the gas pressure at the orifice inlet (its temperature is already known). The only auxiliary requirements under these conditions, therefore, are a constant-mass-flow source of coolant and recorders for one pressure and either the coolant temperature rise or the inlet and outlet coolant temperatures (measured by thermocouples, resistance thermometers, or thermistors).

Note also that both probe designs permit measurement of impact pressure (intermittently in the tare probe; continuously in the jacketed probe, via the insulating gap) and extraction of gas samples for composition measurement or monitoring. Either probe can be bent at angles up to 90°, and all instruments, fittings for coolant flow, etc. are mounted in a series of modular terminator blocks at the probe base (see Fig. 3).

It is of particular interest to note that if the probe L/D is sufficient, there will be virtually no effect on probe output due to even extensive contamination by combustion or corrosion products. In fact, if T_{2g} is monitored, no amount of contamination or corrosion can affect the probe output, up to the point of physical failure of the probe structure. (The gas sample passage can be cleaned periodically from the outside, if necessary, without removing the probe, by simply removing the discharge orifice fitting and inserting a pipe cleaner or scraper through the gas sample tube -- see Fig. 3.)

This type of probe has been employed extensively for enthalpy and temperature measurements in arcjet environments (e.g., see Refs. 3,4,5,6,etc.). An indication of the calorimetric probe's repeatability is shown in the turbulent-flow profile measurements of Figure 4 (from Ref. 7); Figure 5 shows the accuracy obtained with even the relatively crude tare-measurement probe (Ref. 3).

One particularly useful application of the calorimetric probe principle is in the control of a Brayton power cycle; e.g., the gas turbine engine. It can be shown (Ref. 8) that if the probe is located at the inlet to the turbine (the combustion chamber exit) and is cooled by compressor discharge gas, the calorimetric jacket temperature rise is almost directly proportional to the turbine inlet temperature; i.e., no flow measurements are required:

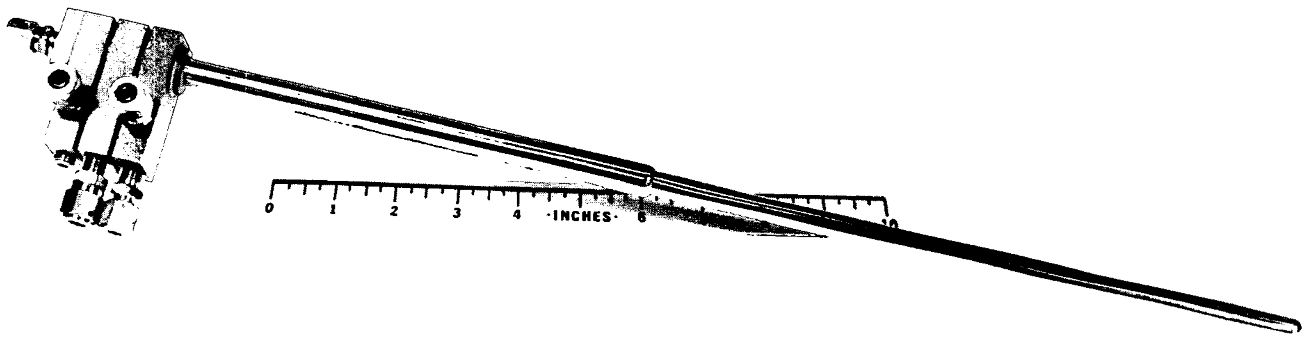


FIGURE 3

TYPICAL COOLED CALORIMETRIC
PROBE CONFIGURATION FOR
INDUSTRIAL APPLICATIONS

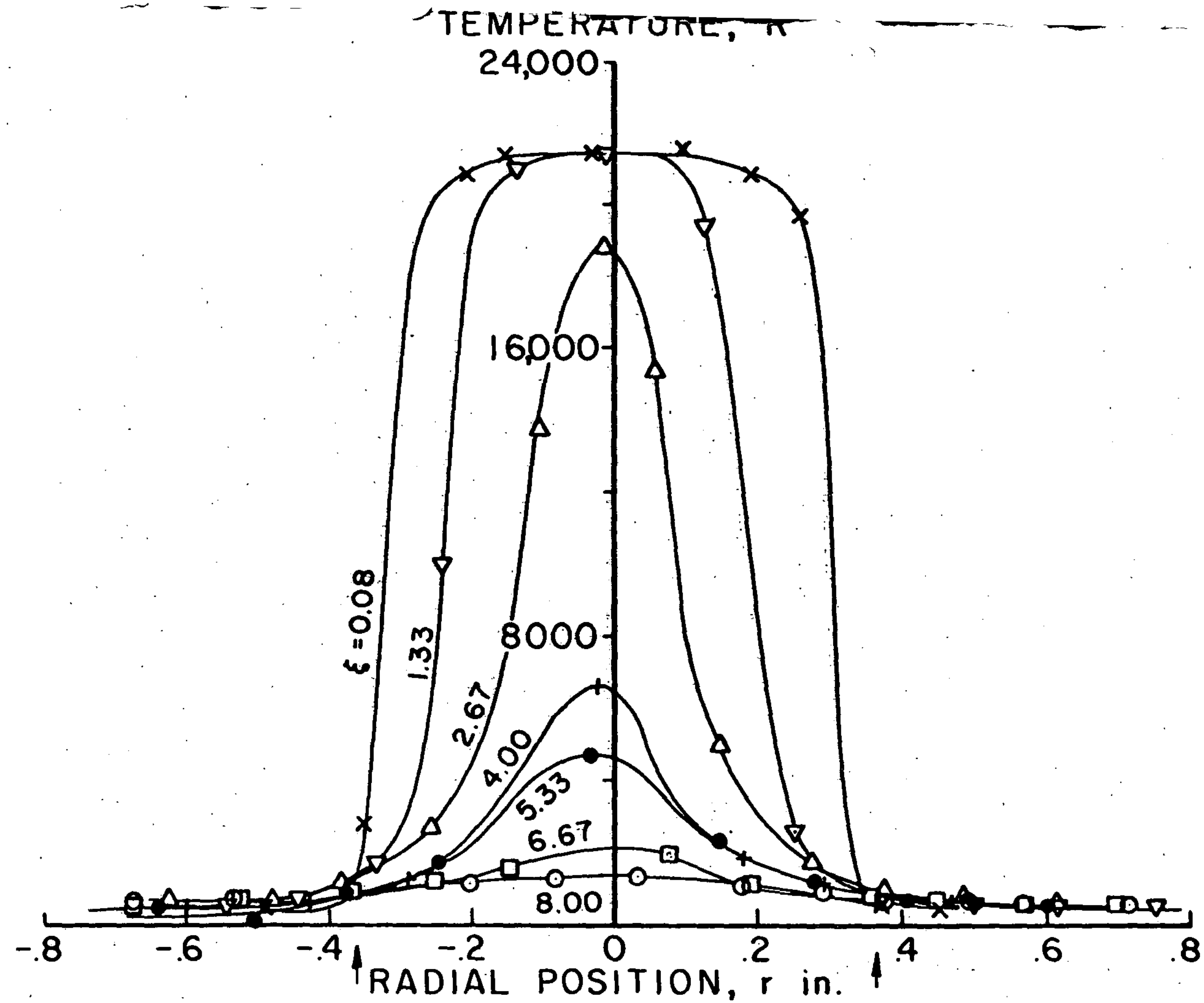


FIGURE 4

TYPICAL COOLED-PROBE TURBULENT-FLOW PROFILE MEASUREMENTS

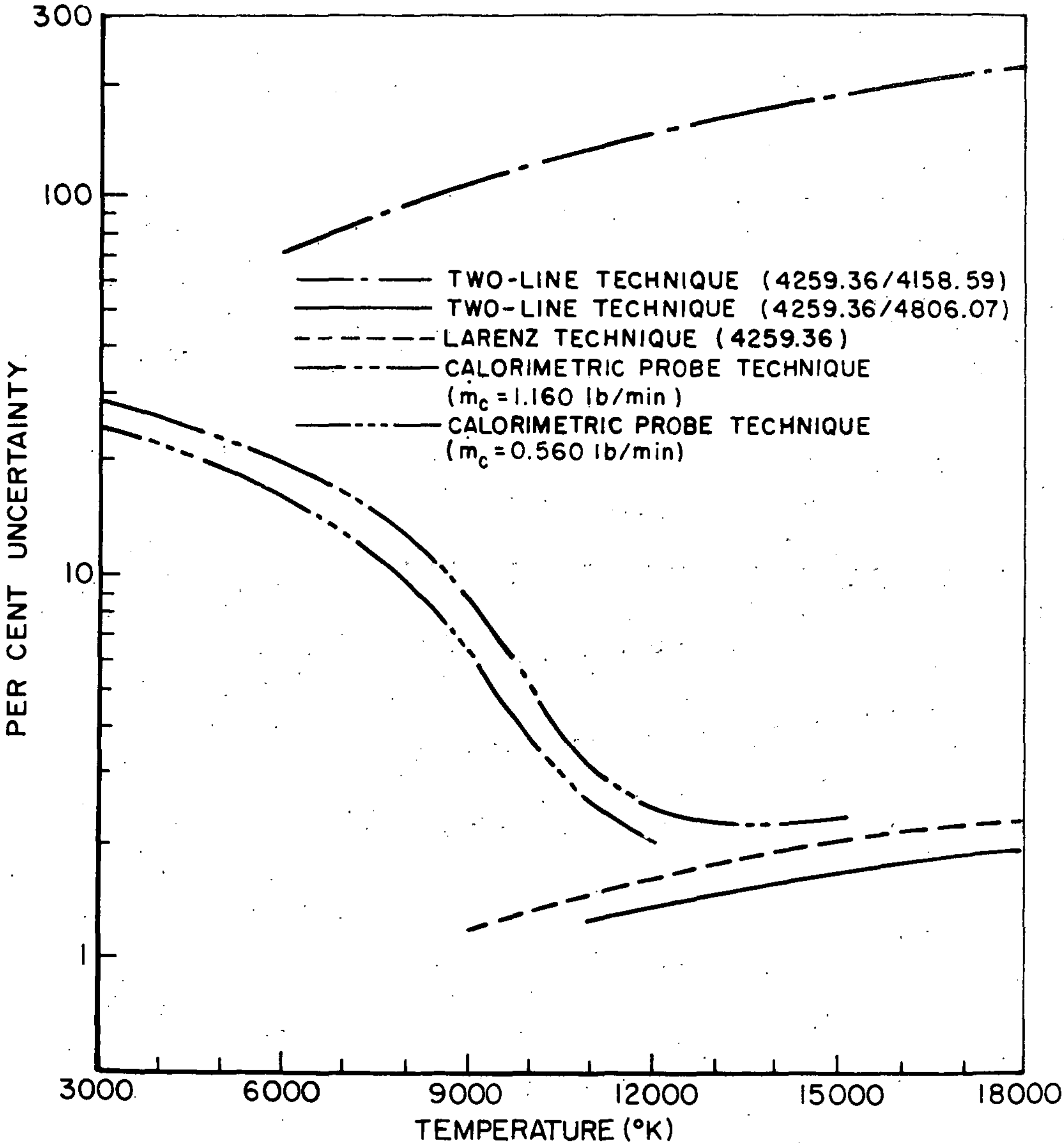


FIGURE 5

CRUDE TARE-MEASUREMENT CALORIMETRIC
PROBE ACCURACY COMPARED WITH
SPECTROMETRIC METHODS

$$T_{t_4} \approx k_1 + k_2 (\Delta T_i)$$

where T_{t_4} = total temperature at turbine inlet, °R

k_1, k_2 are approximately constant

ΔT_i = temperature rise of the coolant in the calorimetric jacket, °F

On the other hand, if the probe is cooled by a constant-flow, constant-temperature coolant source (e.g., hydraulic fluid, fuel, compressed air, water, etc.), it can be shown (Ref. 8) that the calorimetric coolant temperature rise is directly proportional to the product of engine mass flow rate and turbine inlet temperature; i.e., to total engine power:

$$W_a T_{t_4} \approx k_3 + k_4 (\Delta T_i)$$

where W_a = engine air mass flow rate

k_3, k_4 are approximately constant

OTHER COOLED-PROBE MEASUREMENTS

The concept of utilizing cooled immersion surfaces has been applied to such diverse hot-gas property measurements as electron temperature and density in plasmas (Ref. 9), scale of turbulence (Ref. 10), degree of nonequilibrium (Ref. 11), radiation intensity (Ref. 12), transient pressure oscillations (Ref. 13), heat flux (Refs. 14, 15), velocity (Ref. 16), temperature (Ref. 17), and, of course, the pressure and gas sampling functions already discussed. In fact, single probes with multiple functions can often minimize the total instrumentation requirement. Figure 6, for example, shows a multipurpose probe used for diagnostics of a sonic-velocity RF-generated plasma, with simultaneous measurement capability for enthalpy, electron temperature and density, impact pressure, static pressure, and gas-sample extraction. In many industrial applications where multiple measurements are required, but where either access is difficult or lifetime is a problem, the use of a single cooled probe to perform many functions can often be highly effective.

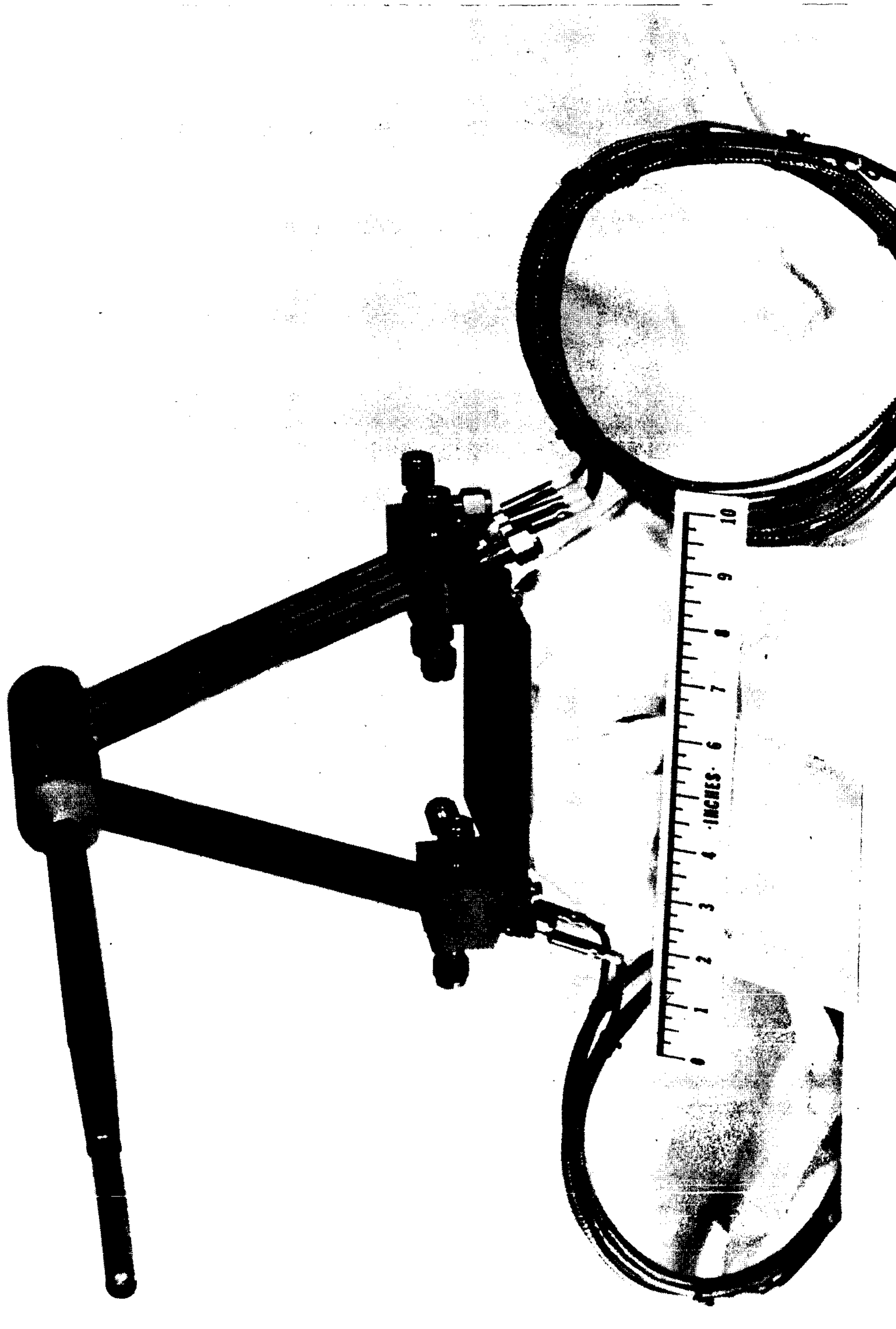


FIGURE 6

TYPICAL MULTIPURPOSE COOLED PROBE FOR PLASMA DIAGNOSTICS

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