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A Water Bath Blackbody for the 5 to 60°C Temperature Range: Performance Goal, Design Concept, and Test Results

Jon Geist and Joel B. Fowler

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Abstract

A water bath blackbody has been built under contract for the Electromagnetic Metrology Engineering Branch at Newark Air Force Station. The performance goal was a large-area, self-calibrating, high-accuracy blackbody covering the majority of the liquid water temperature range. With the exception of self-calibration, these goals were met. This report describes both the conceptual design of the water bath blackbody and the results of the tests that were carried out to characterize the performance of the actual water bath blackbody that was built for Newark Air Force Station. The details of the construction and operation of that water bath blackbody are described in a companion report.

Key words: blackbody; blackbody standard; high-accuracy blackbody; large-area blackbody; room-temperature blackbody; water bath blackbody.

1. Introduction

Since the early 1970s, there has been a need within DOD for a low-temperature blackbody calibration source accurate to within a few tens of mK in the ambient temperature range. As a first step in this direction, NBS designed and built a low-temperature reference blackbody standard and infrared broad band radiometer with an effective wavelength of about 10 μm for near ambient radiation. The original design goal required a temperature range from −40°C to 300°C at whatever accuracy could be achieved by applying the existing NBS high-temperature blackbody technology to this lower temperature range. The original approach consisted of a thin walled graphite cavity in intimate contact with a massive copper cylinder that surrounded the cavity to minimize temperature gradients over the cavity interior. The cylinder was provided with a number of thermocouples measuring its temperature at different locations, and was mounted in a multiple winding furnace to allow better control of any gradients that might be detected.

The first blackbody was constructed in 1975, and estimated to be accurate to ±500 mK on the basis of the characterization studies performed at that time. In 1982, construction of a duplicate was initiated, but problems with assuring the intimate contact between the graphite crucible and the surrounding copper cylinder were encountered, and it was not completed until 1984. The second blackbody was compared with the first blackbody over the temperature range from 0°C to 40°C. At room temperature, the two blackbodies produced the same radiance at a wavelength of 10 μm when set to the same temperature, but at 40°C, they had to be set at temperatures that differed by 200 mK in order to produce the same radiance. While this result is much better than the initial accuracy estimate, it is much worse than the few tens of mK required by some DOD programs.

In attempting to find a solution to this problem, it was noted that neither of these blackbodies was ever calibrated by NBS outside the range from 0°C to 40°C. Therefore, it was proposed that NBS develop a new high-accuracy standard for this limited range based upon a temperature-controlled water bath.

Such a device promised other advantages besides improved temperature accuracy. A large-area aperture (for example, a few inches) would not significantly degrade the accuracy of such a device, provided that the interior of the cavity was coated with a specular black paint. The latter appeared to be feasible with a cavity that would never be used above 100°C. So the water bath blackbody could have a much larger aperture than the copper blackbodies.

The advantage of a large aperture is that it allows direct measurement and correction of size of source errors affecting the radiometer, if such exist. Once these are determined or found to be negligible, then the large aperture allows self-calibration of the radiometric errors affecting the blackbody itself.

Also, measurements of the variation in radiance as a function of position over the interior of the blackbody cavity would provide the data needed to determine corrections and limits of error associated with temperature gradients in the cavity. Similarly, measurements of the variation in radiance with aperture size for a set of infrared reflecting cavity covers with various size apertures would provide the data needed to determine corrections and limits of error associated with the reflectance of the cavity walls.

It was also proposed to enhance the self-calibration capability of the water bath blackbody by adding temperature self-calibration based on the ice, the gallium, and the succinonitrile freezing points, since calibration cells containing the latter materials in very pure form are available from NBS as Standard Reference Materials. The use of these freezing point standards was found to be more complicated than originally anticipated, and implementation of this aspect of self-calibration was postponed as a possible future project.

The water bath blackbody constructed on this project has an aperture of about 4 in. in diameter. Nonradiometric measurements indicate that it is uniform in temperature to better than ± 15 mK over at least the bottom half of its aperture. The thermistor used to measure the water bath temperature is accurate to within a few mK provided that it is recalibrated periodically. The measurement instrumentation and software for calculating the temperature as a function of resistance that are provided with the blackbody are accurate to within 10 mK. Radiometric testing will most likely show that the cavity is uniform in temperature over all of its aperture to a much tighter tolerance than listed above.

The remainder of this report describes the design principles for converting a water bath into a blackbody, the results of tests and analyses that verify the radiometric quality of the blackbody, and the nature of the modifications made to the water bath to use it as a high-accuracy blackbody near ambient temperature.

2. Design Concept

2.1 Mechanical design

The design concept for the water bath blackbody is illustrated in figure 1, which shows a cut-away view of a temperature-controlled water bath with a blackbody cavity mounted in its front wall.

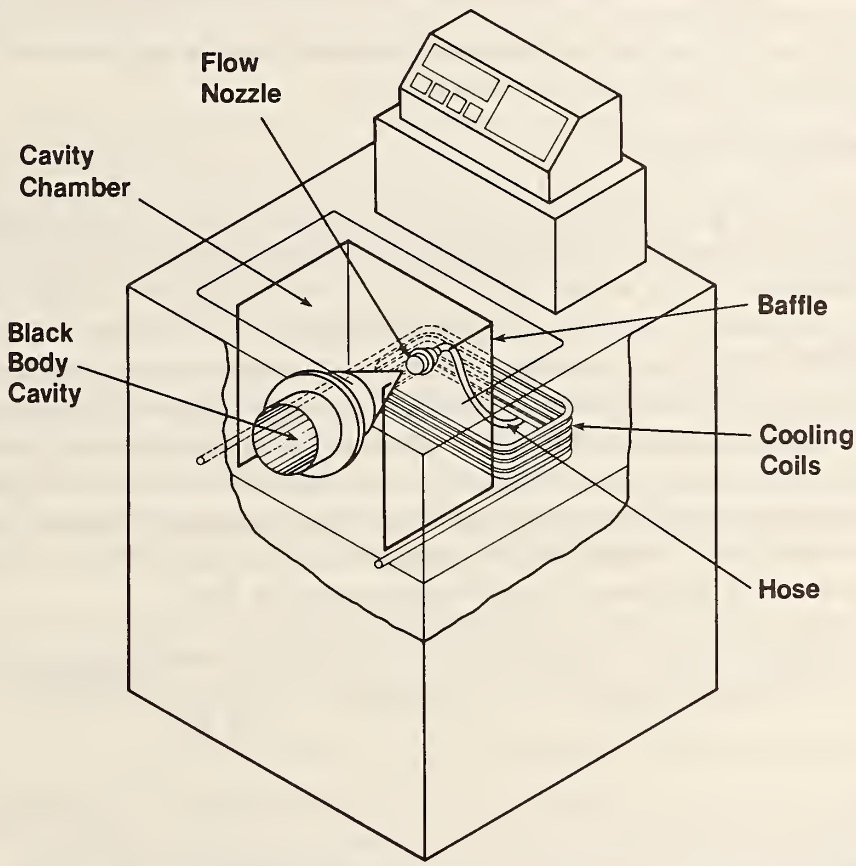

Figure 1. Cut-away view of water bath emphasizing changes made to use it as a near ambient blackbody standard.

Note the baffle that divides the water bath into a rear chamber and a cavity chamber. The rear chamber houses the heating and cooling coils. Only the cooling coils are shown in the figure. The front chamber houses the cavity and isolates it from the heat sources and sinks within the heating/cooling chamber. Also note that the pump outlet is directed into the chamber that houses the cavity.

Ideally, heating and cooling would occur at the same coils, and the flow rate of the pump would be infinite. In this case, separate chambers would not be needed. However, in a real system, the chamber walls isolate the cavity from any flow vortices that might carry water from the heating or cooling coils directly to the cavity wall without sufficient mixing. Under unfavorable conditions, such vortices can cause temperature nonuniformities as large as a few 100 mK.

The pump outlet is directed through the flow nozzle into the cavity chamber to reduce the time lag between the temperature in that chamber and the temperature in the heating/cooling chamber to the minimum value consistent with good mixing. The location of the flow nozzle in the cavity chamber wall is chosen to direct the well-mixed water from the pump to flow over the cavity surface as a final attempt to assure an isothermal cavity.

The nature of the modifications to a commercial water bath in order to realize this design concept is described in more detail in reference [1].

2.2 Control and measurement

Figure 2 is a block diagram of the temperature control aspects of the system. The current source drives a constant current through the four-wire thermistor R1 that is located in the cavity chamber of the water. The temperature-dependent voltage drop across R1 is measured by the computer using the digital voltmeter (DVM), which it is controlling through the IEEE BUS. The computer calculates the water temperature that corresponds to R1, and compares this with the operating point temperature input by the operator. If the water temperature differs from the operating point temperature by more than a (programmable) tolerance, then the computer uses an internally mounted Digital-to-Analog (DAC) converter to change the set point of the time proportional, analog controller that is built into the water bath. This controller regulates the current flowing in heater R3 based on the resistance of the platinum resistance thermometer R2.

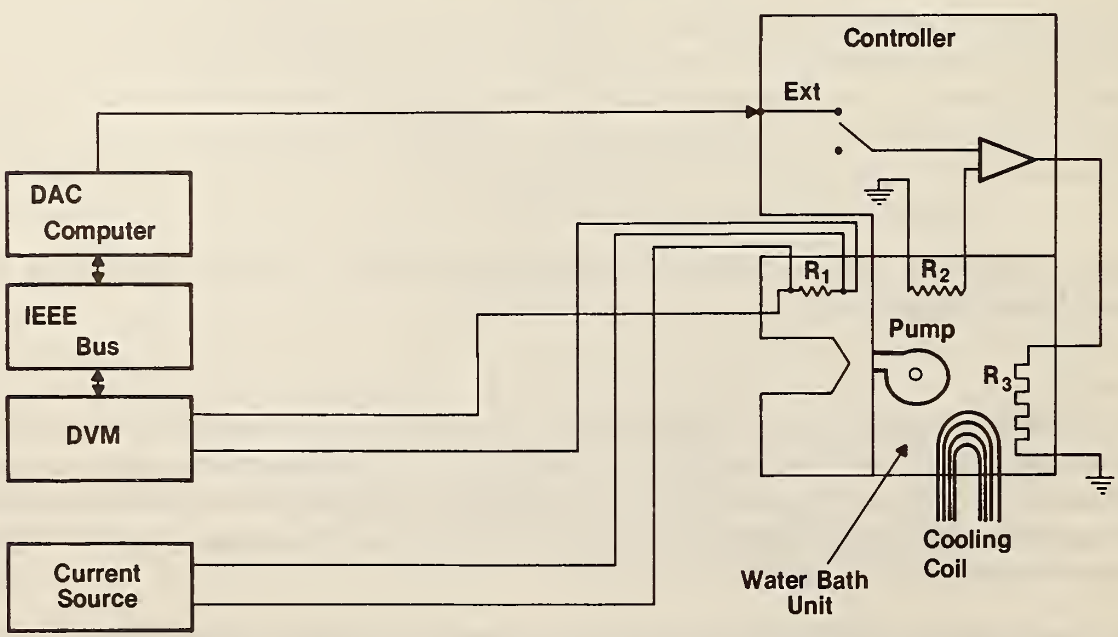

Figure 2. Block diagram of control and measurement subsystems of water bath blackbody.

This control scheme is necessary because the bath's set point circuitry has a large temperature coefficient, and as a result, is not capable of holding the bath at a constant temperature until the circuitry has warmed up for quite a few hours.

2.3 Temperature measurement uncertainties

The sources of error that have a bearing on the quality of the blackbody can be divided into two types. The first type consists of the sources of errors associated with the measurement of the temperature of the water surrounding the blackbody cavity, and the second consists of the sources of error associated with the radiative transfer in the blackbody cavity. Errors of the first type are briefly described in the following paragraphs, while errors of the second type are discussed in more detail in the next section.

The constant current source that drives the four-wire thermistor that is used to measure the temperature in the cavity chamber delivers 10 μA with an uncertainty of considerably less than $\pm$100 parts per million and a precision of better than $\pm$10 parts per million. This uncertainty corresponds to $\pm$2.4 mK at 0°C and $\pm$3.2 mK at 60°C. The constant current source was designed and built at NBS, and is described in more detail in reference [1].

The resistance of the thermistor decreases from about 10000 Ω at 5°C to about 1000 Ω at 60°C. The uncertainty in the calibration of the thermistor is less than $\pm$1.5 mK over the 0 to 60°C temperature range, while its temperature as a function of resistance is accurate to within 1.2 mK over the same range when calculated from a three-parameter equation whose parameters have been adjusted to agree with measured values at three points spaced approximately uniformly over this range. More information on the thermistor can be found in reference [1].

The DVM reads the voltage drop across the thermistor caused by the 10-μA current with an uncertainty of $\pm$(0.0039 mV plus 0.0025% of reading). This corresponds to $\pm$2.6 mK at 5°C and 11.6 mK at 60°C. More information on the digital voltmeter can be found in reference [1].

The DAC is based upon a commercial device that mounts in one of the expansion slots on an IBM PC [2] or compatible computer. It has been modified to provide an output from 0 to 1 V with a resolution of 15 μV. This corresponds to a temperature resolution of 1.5 mK in setting the water bath operating temperature, which is better than the actual temperature accuracy and stability limits that are imposed by other components of the overall system. A little more information on the DAC can be found in reference [1].

The computer used to control the system is an IBM PC-compatible that is better suited to laboratory automation applications than the IBM PC itself. This computer is no longer manufactured commercially, but a company with a nationwide network of service facilities continues to support these machines. A little more information on the computer can be found in reference [1].

The uncertainties associated with the measurement of the water bath temperature are summarized in Table 1.

TABLE 1. Uncertainty in the measured temperature of the water in the water bath as a function of temperature over the operating range of the water bath blackbody.

Measured temperature	Uncertainty in temperature
0°C	3.4 mK
10°C	4.9 mK
20°C	5.2 mK
30°C	5.5 mK
40°C	6.5 mK
50°C	8.6 mK
60°C	12.2 mK

In order to maintain the uncertainties listed in Table 1, the constant current source, the thermistor, and the digital voltmeter all require periodic recalibration. For applications requiring the highest accuracy, recalibration of these subsystems before use of the blackbody is recommended.

3. Blackbody Quality

The quality of the water-bath-mounted cavity as a blackbody when a particular portion of its cavity walls is viewed during a measurement or calibration is given by

$$\begin{aligned} Q &= \epsilon \cdot [\exp(c_2/\lambda \cdot T_0) - 1]/[\exp(c_2/\lambda \cdot T) - 1] \\ &\approx \epsilon \cdot [1 + (\Delta T/T_0) \cdot (c_2/\lambda T_0)/(1 - \exp(-c_2/\lambda \cdot T_0)], \end{aligned} \tag{1}$$

where ϵ is the cavity emissivity for the viewing geometry, $c_2 = 1.43879 \cdot 10^4 \mu m \cdot K$, λ is the wavelength of interest, T_0 is a convenient (that is, subject to measurement) reference temperature, and T is the suitably averaged effective temperature of the portion of the cavity walls that is actually viewed by the radiometer. The approximation shown on the second line, where $\Delta T = T - T_0$, can be used whenever the second term in the square brackets is small compared to unity.

A truly rigorous, general analysis of the quality of a blackbody cavity is surprisingly complicated, and not particularly useful. The problem is that the thermal radiation transfer properties of the interior surface of the cavity wall are never known with sufficient accuracy to allow an uncertainty to be applied to the result of the calculation.

The solution to this problem is to overdesign the cavity so that a relatively simple worst case estimate can be used to determine the maximum deviation from ideal blackbody behavior. This is the approach that was taken for the water bath blackbody under discussion here. Thus, one half of the worst case estimate will be used both as the correction factor and as the uncertainty.

The details of the cavity that are needed for a worst case analysis of its use as a ±20-mK blackbody near ambient are shown in figure 3. Region 3 is the opening of the cavity.

Region 2 is the portion of the cavity wall that is not in direct contact with the water in the bath. Region 1 is the interior surface of the portion of the cavity wall that is in direct contact with the water. And Region 0 is the exterior surface of the portion of the cavity wall that is in direct contact with the water. The worst case analysis will apply only to measurements in which the viewed portion of the cavity is restricted to Region 1.

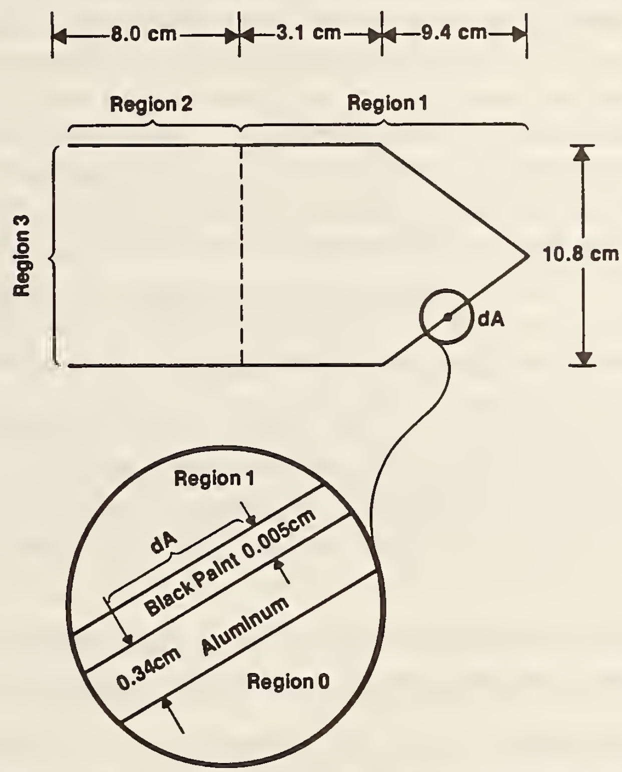

Figure 3. Details of cavity design affecting blackbody quality.

3.1 Cavity emissivity

Because the walls of the cavity are in local thermodynamic equilibrium, the emissivity ϵ of the cavity is given by one minus the cavity reflectance. This fact can be used to calculate a very simple approximation for ϵ based upon the assumption that the reflectance of the interior wall of the cavity is the sum of a perfectly specular contribution ρ_s and a perfectly diffuse contribution ρ_d, where ρ_s and ρ_d are assumed to be independent of the incidence angle of the incident radiation. A simple ray trace using the geometry of figure 3 shows that for radiation entering the cavity at near normal incidence

$$\epsilon = 1 - \rho_s^3 - dF_{13} \cdot \rho_d, \tag{2}$$

where dF_{13} is the differential configuration factor from the point of interest in Region 1 to all of Region 3. (A configuration factor from one region to another is the fraction of the diffusely emitted or reflected flux that originates in the first region and is incident on the second.) Equation (2) is not a worst case approximation, but conservative choices for ρ_s, ρ_d, and dF_{13} allow eq (2) to be used as the basis for a worst case analysis.

Measurements were carried out to characterize the reflectance of the gloss enamel paint used to coat the interior of the cavity. These showed that the specular component of reflectance for near normal incidence is less than 5% from 1 μm to 19 μm, and that the nonspecular component of reflectance for near normal incidence is less than 0.2% from 800 nm to 2.5 μm. No data are available for the diffuse reflectance of the glossy enamel beyond 2.5 μm, but the general trend is well established. The enamel will become more specular and less diffuse with increasing wavelength. Similarly, no data are available on the specular reflectance at other than normal incidence. Again, the general trend is well established. The average reflectance for both polarizations of the incident radiation is approximately constant with angle of incidence below Brewster's angle, but increases rapidly with angle above Brewster's angle, reaching a maximum value of 1 at 90 deg. Thus, 10% and 0.2% were chosen as conservative upper bounds for ρ_s and ρ_d, respectively.

The value of F_{13} was calculated from the nominal cavity dimensions. It varied from 0.03 near the tip of the cavity to 0.07 on the conical portion of the cavity near the intersection with the cylindrical portion, the maximum occurring for points on the conical portion of the cavity where it intersects the cylindrical section. Thus, 0.07 was chosen as a conservative estimate for dF_{13}.

With the above values for ρ_s, ρ_d, and dF_{13}, eq (2) gives 0.9988 as a lower bound for ϵ, and $\epsilon = 0.9994 \pm 0.0006$ as a conservative estimate for the emissivity of the cavity.

If a baffle with a 2-in. aperture and a high infrared reflectance were mounted on the front of the cavity, then the conservative estimate of ϵ for off-axis viewing of Region 1 would be increased to 0.99993 $\pm$ 0.00007. It is, however, important to note that the increase in ϵ applies only to off-axis viewing. Little improvement in ϵ is predicted for on-axis viewing. So careful alignment of the measurement geometry based on ray tracing is necessary before this sort of improvement in cavity emissivity can be obtained.

3.2 Temperature distribution over interior of cavity

The following worst case approximations can be used to obtain a simple equation for the temperature drop across the wall between Regions 0 and 1 in the cavity:

1) Region 3 is at a uniform temperature represented by T_3.

2) Region 2 is at a uniform temperature represented by T_2.

3) The worst case value for T_2, which is the temperature at the lip of the cavity, will be used.

4) Region 0 is at a uniform temperature represented by T_0.

5) T_0 is the temperature of the water in the bath as measured by the thermistor.

6) The worst case emissivity for the interior cavity wall, which is unity, will be used.

For high accuracy, these approximations require that the temperature of Region 0 be accurately known. This is the role of the water bath and the high-accuracy thermistor. However, worst case approximations based on measurements of very modest accuracy are sufficient for the remainder of the cavity wall. This is similar to the way that this particular choice of cavity geometry in conjunction with a specular black paint permits the use of crude estimates of the reflectance of the cavity wall.

Two sets of measurements were carried out in order to characterize the temperature gradients existing in the blackbody cavity. The uniformity of the water in the chamber surrounding the cavity was carefully measured with the highest accuracy possible, while the temperature of the outer lip of the cavity was measured to no better than ±50 mK.

3.2.1 Temperature uniformity in water surrounding cavity

In order to measure the variation in the temperature of the water surrounding the cavity to the highest accuracy possible, it was necessary to monitor the temperature in the cavity chamber during the time that a test thermistor was moved to different locations in the chamber. The only test thermistor readily available for these measurements was out of calibration. A special Plexiglas jig was constructed to hold the test and reference thermistors in close proximity while they were immersed in the cavity chamber, and the bath was run first at 5°C, then 30°C, and finally at 60°C, while 20 simultaneous readings from the two thermistors were recorded. The results are listed in Table 2.

TABLE 2. Test thermistor corrections at 5, 30, and 60°C.

Nominal Temperature	(Test Temperature) – (Standard Temperature)
5°C	–20.1 ±1.2 mK
30°C	–15.0 ±0.7 mK
60°C	+ 2.5 ±0.8 mK

The uncertainties listed in Table 2 are single standard deviations of the means of the 20 differences. These corrections were applied in the measurements to be described next.

A special Plexiglas cover for the water bath was made to support the two thermistors during the measurement of the temperature variations in the cavity chamber. It had a continuous slot connecting eleven short slots used to locate the test thermistor, and a separate hole for the reference thermistor as shown in figure 4. The location of the cavity relative to the test slots with the cover in place on the water bath is also indicated with a dotted line in that figure.

For these measurements, the water bath was allowed to stabilize at one of the temperatures, 5, 30, or 60°C. The reference thermistor was located in the reference hole, and the test thermistor was moved from short slot to short slot without changing its immersion depth in the water, pausing in each slot long enough to allow 20 simultaneous readings of both

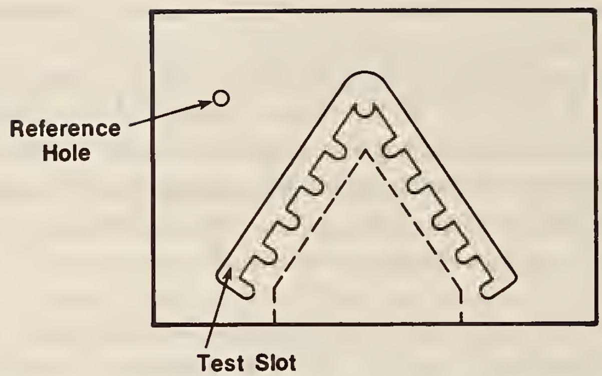

Figure 4. Configuration of water bath cover specially made for measuring the variation in temperature in the water surrounding the cavity.

thermistor voltages. This procedure was repeated at each of the three temperatures with two, one, or no styrofoam spacers controlling the immersion depth of the test thermistor. The immersion depth with the two spacers supporting the test thermistor was less than an inch, and the data at this depth were subject to a very noisy immersion error of the order of 1°C. The data obtained at the two lower depths are shown in figure 5.

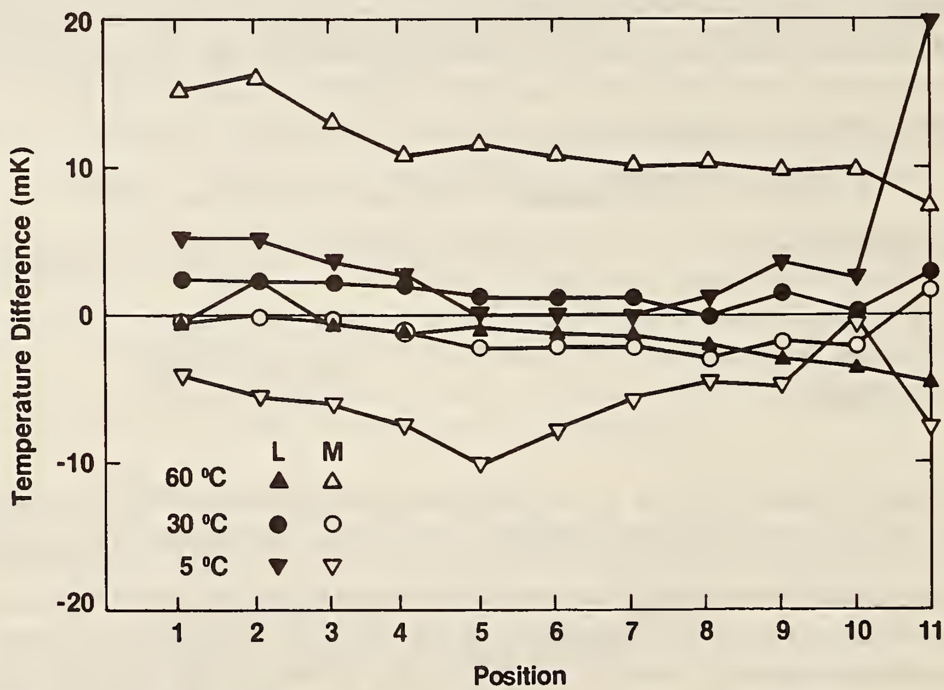

Figure 5. Temperature differences measured at different locations in cavity chamber in water bath blackbody.

Notice that the deep immersion values all fall within a range of ±5 mK. Also notice that the test thermistor measures closer to ambient at the medium immersion depth than at the low immersion depth. This is probably caused by an immersion error associated with the test thermistor rather than an indication of a true vertical temperature gradient in the cavity chamber. Radiometric data will be necessary to decide between these two alternate interpretations of the data in figure 5.

Even without knowing the correct interpretations of the data in figure 5, it is possible to make some fairly strong statements about the temperature uniformity in the cavity chamber, namely: The bottom half of the outside walls of the cavity that are actually in contact with the water are uniform in temperature to well within ±15 mK. Since the bottom half contains 2 in. of vertical distance, this region is accessible for most calibration applications.

3.2.2 Temperature drop at lip of cavity

A differential thermocouple was made from a commercially available, glass-insulated, Chromel/Alumel duplex thermocouple wire, and each junction was insulated with enamel insulating paint. The reference junction was immersed in the cavity chamber of the water bath. The test junction was pressed flat between the outside surface of the cavity and the foam surrounding the cavity for one turn around the cavity lip. The free ends were connected across the input to a DVM, and the voltage recorded when the bath was running at 60°C. The test junction was then immersed in a dewar containing 11°C tap water, and the output voltage was again recorded. The general configuration for these measurements is shown in figure 6.

The voltage difference between the test and reference junctions with the test junction at the lip of the cavity was 0.17 mV ± 0.01 mV. The voltage difference with the test junction in the 11°C water was 2.02 mV. The uncertainties in the temperatures of the 11°C tap water and the 60°C cavity chamber water were both well within ±1°C. Thus, when the water bath temperature is about 60°C, the temperature of the lip of the cavity is 4.12°C ± 0.12°C lower than the temperature of the water in the cavity chamber. This is a worst case, because 60°C is as far as the water bath will ever get from ambient according to the performance specification for the entire system.

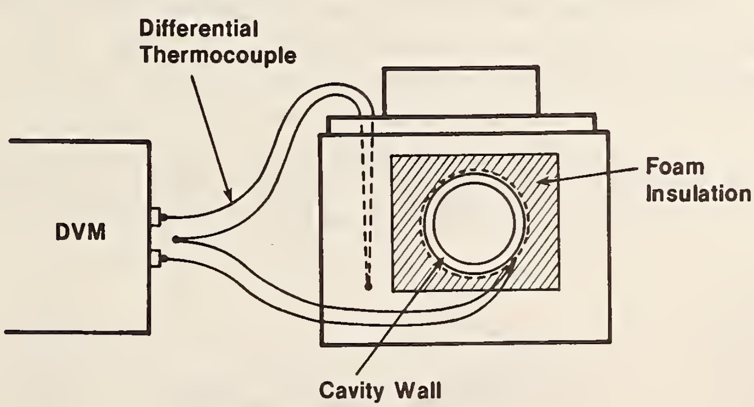

Figure 6. Configuration of water bath blackbody for measurement of temperature drop at lip of cavity.

For the analysis in the next section, the temperature drop at the cavity lip is assumed to scale with the temperature difference between the water bath and ambient temperatures.

3.2.3 Temperature drop across cavity wall and paint

Subject to the worst case assumptions described at the beginning of this section (3.2), the equilibrium between the heat radiated out the cavity opening and the heat conducted across the cavity walls satisfies the following equations:

The differential power conducted through the wall and black paint per unit area at any point in Region 1 is given by

$$dP = (T_0 - T_1)/(d_{al} \cdot K_{al} + d_{ac} \cdot K_{ac}), \tag{3}$$

where d_{al} and K_{al} are the respective thickness and conductivity of the aluminum cavity wall, and d_{ac} and K_{ac} are the same quantities for the acrylic black paint on the interior of the cavity wall. The above quantity must be balanced by the net differential radiant power leaving the surface of the paint at the same point in Region 1. Thus,

$$dP = dF_{13} \cdot \sigma \cdot (T_1^4 - T_3^4) + (dF_{12} - dF_{13}) \cdot \sigma \cdot (T_1^4 - T_2^4), \tag{4}$$

where σ is the Stefan-Boltzmann constant, and dF_{ij} is the differential configuration factor from the point in question in Region i to all of Region j.

Because the temperature difference between T_1 and T_0 will be quite small, negligible error is introduced by approximating T_1^4 by

$$T_1^4 = T_0^4 + 4 \cdot T_0^3 \cdot \Delta T, \tag{5}$$

where $\Delta T = T_1 - T_0$ is the temperature drop across the wall and black paint. With this approximation, eqs (3) and (4) can be solved simultaneously for ΔT in closed form. The result is

$$\Delta T = \frac{\beta \cdot T_0 \cdot (dF_{13} \cdot [1 - (T_3/T_0)^4] + [dF_{12} - dF_{13}] \cdot [1 - (T_2/T_0)^4])}{1 + 4 \cdot dF_{12} \cdot \beta} \tag{6}$$

where

$$\beta = \sigma \cdot T_0^3 (d_{al} \cdot K_{al} + d_{ac} \cdot K_{ac}). \tag{7}$$

Table 3 lists the nominal values of the cavity parameters that were used to evaluate ΔT. The temperature of Region 3 was chosen to be 293.16 K = 20°C.

TABLE 3. Values of parameters used to calculate ΔT from eq (6).

Parameter	Value
inside diameter of cavity	10.8 cm
length of cylindrical portion of cavity	11.1 cm
full angle at tip of cone	60 deg
thickness of cavity wall in Region 1	0.340 cm
thickness of black paint on cavity wall	0.005 cm
thermal conductivity of cavity wall	1.4538 W/cm· K
thermal conductivity of black paint	0.0018 W/cm· K

The effect of the uncertainty in the thickness of the black paint on ΔT is much larger than the effect of the uncertainty in all of the other parameters in Table 3 combined. Therefore, the uncertainties are not listed in the table. The black paint was applied to the cavity by introducing a few drops into the cavity tip with a medicine dropper, and inverting the cavity so that the paint could run down the cone. A sample of the paint on a first surface aluminum mirror was prepared in the same way for the reflectance measurements described in Section 3.1 of this report. After drying, the paint was removed from a corner of the mirror, and the thickness of the mirror was measured in this corner, and in the adjacent painted area. The difference in thickness was 0.0010 $\pm$ 0.0002 in. This number is not necessarily a good value for the thickness of the coating on the interior of the cavity. The mirror is smoother than the interior of the cavity, and the geometry of the surfaces is different. Therefore, $d_{ac} = 0.005$ cm $\pm$ 0.005 cm (0.0020 $\pm$ 0.0020 in.) was chosen as a conservative estimate of the paint thickness.

For the values shown in Table 3, dF_{12} and dF_{13} varied from 0.079 and 0.032, respectively, at the tip of the cone, to 0.180 and 0.070, respectively, on the conical portion of the cavity wall where it intersects the cylindrical portion of the cavity wall. Table 4 shows the calculated variation of ΔT with the water temperature T_0 for points at the latter location on the conical portion of the cavity wall. The stated uncertainty is less than 10% larger than that associated with the uncertainty in the thickness of the paint.

TABLE 4. The calculated variation in the temperature drop ΔT across the wall of the cavity and the black paint on the conical section of the cavity where it intersects the cylindrical section, as a function of water bath temperature T_0.

Operating temperature	Temperature drop	Uncertainty
0°C	−2.5 mK	±2.5 mK
10°C	−1.4 mK	±1.4 mK
20°C	0.0 mK	±0.0 mK
30°C	1.5 mK	±1.5 mK
40°C	3.2 mK	±3.2 mK
50°C	5.0 mK	±5.0 mK
60°C	7.1 mK	±7.1 mK

If a baffle with a 2-in. aperture, a high infrared reflectance, and thermal insulation on its exterior surface, were mounted on the front of the cavity, then the calculated values of ΔT would be reduced by a factor of 4. A carefully conducted experiment comparing the cavity radiance with and without a baffle of this nature in place could be used as a self-calibration procedure to determine ΔT directly. However, because ϵ might also vary in this experiment, measurements at two widely separated wavelengths would be necessary to assign independent values to ϵ and ΔT.

3.3 Overall estimate of blackbody quality

We now have all of the information needed to use eq (1) to calculate the quality of the water bath blackbody at any wavelength. The values of the parameters needed to evaluate eq (1) are summarized in Table 5. The uncertainty for ΔT consists of the sum in quadrature of the uncertainty associated with the calculation of ΔT, the variation in water temperature around the cavity, and the uncertainty in the measurement of the water temperature. The values only apply when viewing is restricted to the bottom half of the cavity.

TABLE 5. Parameters for use in calculating the quality and the uncertainty in the quality of the water bath blackbody from eq (1).

Parameter	Value	Uncertainty	Restriction
ΔT	−2.5 mK	±15.6 mK	$T_0 =$ 0°C
ΔT	−1.4 mK	±15.8 mK	$T_0 =$ 10°C
ΔT	−0.0 mK	±15.9 mK	$T_0 =$ 20°C
ΔT	+1.5 mK	±16.0 mK	$T_0 =$ 30°C
ΔT	+3.2 mK	±16.7 mK	$T_0 =$ 40°C
ΔT	+5.0 mK	±18.0 mK	$T_0 =$ 50°C
ΔT	+7.1 mK	±20.6 mK	$T_0 =$ 60°C
ϵ	0.9994	±0.0006	full aperture
ϵ	0.9999	±0.0001	half aperture

A simple equation for the uncertainty in the quality of the blackbody can be derived from eq (1). It states that

$$dQ = Q * ([d\epsilon/\epsilon]^2 + [F(c_2/\lambda T_0) \cdot (dT/T_0)]^2)^{1/2}, \tag{8}$$

where

$$F(u) = u/(1 - exp(-u)). \tag{9}$$

The uncertainty dQ in the quality of the water bath blackbody is plotted as the upper curve in figure 7 for an unbaffled cavity operated at 0°C. This curve is based on the conservative estimates of the thermometric properties of the water bath, and the radiometric properties of the cavity that were derived earlier in this report. The curves at the other temperatures between 0°C and 60°C fall a little below this curve, the minimum occurring at 40°C. The differences are so small that the 0°C curve is applicable at all temperatures. At the long wavelengths, the uncertainty is dominated by the ±0.0006 uncertainty in the cavity emissivity. At the shortest wavelengths, the uncertainty is dominated by the uncertainty in the cavity wall temperature, due primarily to the uncertainty in the uniformity of the water temperature surrounding the cavity.

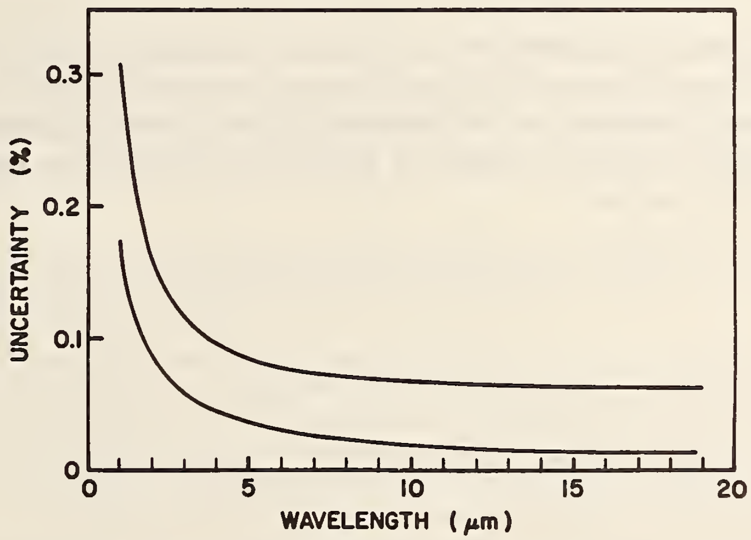

Figure 7. The uncertainty in the quality of the water bath blackbody. Case 1, upper curve: Full aperture, viewing confined to bottom half of cavity, uncertainties as determined in this report. Case 2, lower curve: Aperture limited by insulated, reflective baffle with 2-in. diameter aperture, and uniformity of cavity walls no worse than ±5 mK.

If the level of accuracy shown by the upper curve in figure 7 is not satisfactory for some applications, then careful measurements of the relative radiance over the conical portion of the cavity should be made. Most likely, these will show that the cavity bottom is uniform in temperature to ±5 mK. If this is the case, then there would be a considerable improvement in accuracy at the long wavelengths if the cavity were equipped with an insulated, reflective baffle having a 2-in. diameter aperture. The lower curve in figure 7 shows the uncertainty that would apply in this hypothetical case. Obviously, considerable improvement would be achieved to the extent that the relative radiance measurements showed considerably less than ±15-mK variation over the cavity bottom.

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References

1. J. B. Fowler and B.J. Belzer, *Water Bath Blackbody Operating Instructions*, to be published as an NBS Tech. Note.

2. Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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A water bath blackbody has been built under contract for the Electromagnetic Metrology Engineering Branch at Newark Air Force Station. The performance goal was a large-area, self-calibrating, high-accuracy blackbody covering the majority of the liquid water temperature range. With the exception of self-calibration, these goals were met. This report describes both the conceptual design of the water bath blackbody and the results of the tests that were carried out to characterize the performance of the actual water bath blackbody that was built for Newark Air Force Station. The details of the construction and operation of that water bath blackbody are described in a companion report.

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blackbody; blackbody standard; high-accuracy blackbody; large-area blackbody; room-temperature blackbody; water bath blackbody

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$$dP = (T_0 - T_1)/(d_{al}/K_{al} + d_{ac}/K_{ac}), \tag{3}$$

where d_{al} and K_{al} are the respective thickness and conductivity of the aluminum cavity wall, and d_{ac} and K_{ac} are the same quantities for the acrylic black paint on the interior of the cavity wall. The above quantity must be balanced by the net differential radiant power leaving the surface of the paint at the same point in Region 1. Thus,

$$dP = dF_{13} \cdot \sigma \cdot (T_1^4 - T_3^4) + (dF_{12} - dF_{13}) \cdot \sigma \cdot (T_1^4 - T_2^4), \tag{4}$$

where σ is the Stefan-Boltzmann constant, and dF_{ij} is the differential configuration factor from the point in question in Region i to all of Region j.

Because the temperature difference between T_1 and T_0 will be quite small, negligible error is introduced by approximating T_1^4 by

$$T_1^4 = T_0^4 - 4 \cdot T_0^3 \cdot \Delta T, \tag{5}$$

where $\Delta T = T_0 - T_1$ is the temperature drop across the wall and black paint. With this approximation, eqs (3) and (4) can be solved simultaneously for ΔT in closed form. The result is

$$\Delta T = \frac{\beta \cdot T_0 \cdot (dF_{13} \cdot [1 - (T_3/T_0)^4] + [dF_{12} - dF_{13}] \cdot [1 - (T_2/T_0)^4])}{1 + 4 \cdot dF_{12} \cdot \beta} \tag{6}$$

where

$$\beta = \sigma \cdot T_0^3 (d_{al}/K_{al} + d_{ac}/K_{ac}). \tag{7}$$

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