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Thermal Analysis of Balloon-Borne Instrument Packages

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PREFACE

After a flight of his scientific equipment to high altitude on a balloon from Palestine, Texas, Peter Fowler of the University of Bristol reported evidence of high temperature damage to his experiment. He diagnosed the difficulty and designed a modification to his equipment which he thought would maintain the temperature at an acceptable level. The National Center for Atmospheric Research agreed to carry out a test flight to test his modification.

Frank Kreith, a professor at the University of Colorado and consultant to NCAR, was asked to assist the NCAR Scientific Balloon Facility in the design of a test. It was to be specific enough to verify the efficacy of Fowler's temperature control system and yet general enough to be useful in the solution of other thermal design problems which might be encountered in scientific ballooning. The test flight was conducted by John C. Warren. Analysis of the results showed that Fowler's modification should satisfactorily control the temperature of his equipment, and on subsequent flights that prediction was verified.

This report shows how Fowler's problem was analyzed, describes the experimental flight, and compares the results of the analysis with the flight data.
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I. INTRODUCTION

When balloons carry sensitive scientific equipment to high altitudes it is usually necessary to control the temperature of the instrument package in order to insure proper functioning of temperature-sensitive components. Particular interest in the temperature control problem was generated recently by Peter Fowler, of the University of Bristol, who reported that during a series of three flights launched from the NCAR Balloon Flight Facility at Palestine, Texas, in May 1967, nuclear emulsion plates in the balloon-borne package deteriorated due to an excessive temperature rise.

The Bristol gondola (Fig. 1) was composed of nuclear emulsion plates sandwiched between two 1 in. layers of styrofoam plastic. The outer surfaces of the styrofoam layers were covered with household-type aluminum foil. Because of the low emissivity of the aluminum foil in the infrared and the low rate of convective heat transfer at float altitude (~3 mb), the rate of heat transfer from the package was not sufficient to achieve the desired package temperature.

The problems involved in the design of instrument packages for other applications may be more difficult than those encountered by Fowler, since the geometry of his package was simple and no internal heat sources were present. The analytical methods presented in this report, however, provide a means of evaluating pertinent thermal design parameters and of predicting package temperatures in the upper atmosphere for any type of package.
II. OBJECTIVES

The objectives of the project described in this report were:

1. To develop an analytical method for predicting the temperature of an instrument package at 70,000 ft altitude, and to compare the analytical results with test data obtained during a flight at that altitude with a specially designed and instrumented package.

2. To predict the package temperature at 130,000 ft, using the analytical procedure developed in the first phase and empirical constants adjusted to yield agreement between theory and experimental data obtained at 70,000 ft.

3. To compare the effectiveness of aluminum and Mylar-aluminum laminate as package covering at high altitudes.

The calculation procedures used in this report combine methods of approach outlined by Kreith (1962) for the thermal design of spacecraft instrumentation and by Lichfield and Carlson (1967) for the Nimbus D IRLS program.
III. THERMAL ANALYSIS

The system to be analyzed is the instrument package shown schematically in Fig. 2. During the day heat is transferred to the system by direct and reflected solar radiation and by infrared radiation from clouds and from the earth. At the same time heat is transferred from the system by free convection and infrared surface radiation. A heat balance for quasi-steady-state conditions, if we assume that the internal thermal resistance of the system is negligible, yields the following relation:

\[
A_u a_s G_{s,d} + A_{\varepsilon_s} a_s G_{s,r} + A_{\varepsilon_i} a_i G_{i} + A_u q_{c,u} + A_{\varepsilon} q_{c,l} + (A_u + A_{\varepsilon}) q_r = 0
\]  
(1)

where

- \(G_{s,d}\) = rate of direct solar irradiation
- \(a_s\) = effective absorptivity of the surface to radiation in the solar spectrum
- \(A_u\) = upper surface area
- \(G_{s,r}\) = rate of solar irradiation reflected from the earth and atmosphere
- \(A_{\varepsilon}\) = lower surface area
- \(G_{i}\) = rate of infrared irradiation from clouds and the earth
- \(a_i\) = effective absorptivity of the surface to infrared radiation
- \(q_{c,u}\) = rate of heat transfer per unit area by free convection from the upper surface
- \(q_{c,l}\) = rate of heat transfer per unit area by free convection from the lower surface
- \(q_r\) = rate of heat transfer per unit area by radiation from the surface of the package.
The area of the sides of the package is small compared to that of the top and bottom. The contribution of the heat transfer over the sides of the package is therefore relatively small and has not been included to avoid unnecessary complications in the analysis.

At night the first two terms of Eq. (1) are zero; after sundown the temperature of the package therefore decreases. The package temperature during transient conditions can be determined by including in Eq. (1) a term for the rate of change in internal energy of the instruments. For conditions after sundown, the relation is

\[
A_e a_1 G_i + A_u q_{c,u} + A_e q_{c,e} + (A_u + A_e) q_r = C_{th} \frac{dT}{dt} \tag{2}
\]

where

- \( C_{th} \) = effective heat capacity of the system
- \( T \) = temperature of the system
- \( t \) = time coordinate

In order to make quantitative estimates of the system's heat balance, each term in Eq. (1) must be calculated. In a steady-state design it is necessary first to estimate a system temperature, then calculate each term in Eq. (1) with this assumed temperature, and finally compare the heat transfer to the system with the heat transfer from the system. If more heat is received than lost, the assumed temperature was too low and the calculations must be repeated with a higher temperature. In our case the package temperature was known from flight data, and the experimental value corresponding to a sun angle of about 60° was used in the heat balance calculations wherever necessary (see Fig. 3).

A. DIRECT SOLAR IRRADIATION, \( G_{s,d} \)

At altitudes of 70,000 ft and above, the attenuation of radiation emanating from the sun is quite small and the radiation flux
incident upon a surface depends primarily on the angle between the
normal to the surface and the rays from the sun. If $\delta_n$ is this angle,
the unattenuated irradiation is

$$ G_{s,d} = G_o \cos \delta_n $$

where $G_o$ is the solar constant, taken as equal to 2.0 cal/min/cm$^2$
(442 Btu/hr/ft$^2$) (Kreith, 1962).

The effect of attenuation can be estimated using an analysis
presented by Germeles (1966). The attenuation is proportional to the
number of molecules in the path between the sun and the receiving
surface. Consequently, it depends not only on the altitude, but also
on the time of day, or sun angle. According to Germeles (1966), the
radiation flux on a horizontal surface at an altitude $h$ can be calcu-
lated from the semi-empirical relation

$$ G_{s,d,h} = G_o \left( e^{-0.65m} + e^{-0.095m} \right)/2 $$

where

$$ m = \left\{ \left[ 1229 + (614 \cos \delta)^2 \right]^{1/2} - 614 \cos \delta \right\} (p/p_o) $$

$p/p_o =$ ratio of pressure at altitude $h$ to standard atmospheric
pressure

$\delta =$ sun angle

At 70,000 ft $p/p_o = 0.045$, and at a sun angle of about 60° $G_{s,d,h}$
can be approximated by $G_o \cos \delta$ to within 1% accuracy.

B. REFLECTED SOLAR RADIATION, $G_{s,r}$

The heat transfer to the system by solar radiation reflected from
the earth and its atmosphere depends on the albedo of the earth-
atmosphere and on the geometric shape factor relating the surface
being irradiated, the position of the sun, and the reflecting surface. A detailed analysis of this problem has been made by Cunningham (1961) for satellites; but for the altitudes of balloon flights, the geometric shape factor can be approximated by considering the earth to be an infinite plane.

Assuming that the solar radiation is reflected isotropically, that the albedo is uniform, and that the entire horizon is both visible and illuminated, Camack and Edwards (1960) have shown that the reflected solar radiation incident on a surface whose normal toward the earth makes an angle \( \alpha \) with the normal from the earth surface can be approximated by the relation

\[
G_{s,r} = 2.0 \times \text{albedo} \times \cos \alpha \times \cos \delta \text{ cal/min/cm}^2
\]  

(5)

This relation is satisfactory for most of the day, but must be modified during the period just after sunrise and just before sunset. For the conditions of the flight being analyzed, where \( \delta \approx 60^\circ \), \( \alpha \approx 0^\circ \), and with an albedo taken at an average value of 0.3 (see AFCRL, 1960; Raschke, 1968),

\[
G_{s,r} = 2.0 \times 0.3 \times 0.866
\]

\[
= 0.520 \text{ cal/min/cm}^2 \text{ (114 Btu/hr/ft}^2) \]  

(5)

It would be desirable to know the magnitude of the albedo under prevailing weather conditions, but no satisfactory theory or reliable empirical correlation for the variation of the albedo with weather conditions has been found in the open literature. The assumed value agrees, however, with averaged values obtained recently from satellite observations of the earth's radiation budget (Vonder Haar and Suomi, 1969).

C. IRRADIATION FROM CLOUDS, \( G_i \)

Clouds contribute to the overall heat balance when the sky is overcast, and the rate of irradiation on the system from clouds depends
on the percentage of cloud cover and the altitude of the upper cloud layer (Kuhn, 1963; Kondrat'yev, 1965). With the sky overcast on the day of the test flight, the geometric shape factor for the lower surface of the package relative to the clouds, \( F_{\ell-c} \), was approximately unity. The upper layer of the clouds was probably in the stratosphere so that the effective temperature at which the cloud radiation emanated was about 218°K (or 392°R). If the top of the cloud layer had been in the troposphere, the effective radiation temperature could have been much higher.

The effective long wave emissivity of clouds can vary considerably (Kuhn, 1963). If we assume its value to be equal to unity in the infrared, the irradiation incident on the lower surface of the package is

\[
G_i = \varepsilon_i \sigma T^4_{\text{cloud}} F_{\ell-c}
\]

\[
= 1 \times 81.2 \times 10^{-12} \times 218^4 \times 1
\]

\[
= 0.183 \text{ cal/min/cm}^2 \ (40.3 \text{ Btu/hr/ft}^2)
\]

This agrees within 3% with the value calculated by Kondrat'yev for a latitude of 40°N (Kondrat'yev, 1965: Table 25, p. 208).

D. TOTAL HEAT LOAD

According to unpublished data released by W. Paul of the G. T. Schjeldahl Company, Mylar with aluminum foil coating has an absorptivity in the solar spectrum, \( a_s \), of about 0.15 and an emissivity in the infrared, \( \varepsilon_i (=a_i) \), of 0.58. Unpublished measurements from another source suggest that \( a_s = 0.19 \). If we take an average value for \( a_s \) of 0.17, the total heat load per unit cross-sectional area of the package is

\[
q_{in} = a_s (G_{s,d} + G_{s,r}) + a_i G_i
\]

\[
= 0.17 (1.73 + 0.52) + 0.58 \times 0.18
\]

\[
= 0.487 \text{ cal/min/cm}^2 \ (107.7 \text{ Btu/hr/ft}^2)
\]
E. EMITTED RADIATION, \( q_r \)

The radiation emitted per unit cross-sectional area from the upper and lower surfaces of the system at the measured average temperature of 258°K (or 465°R) is

\[
q_r = 2 \varepsilon_1 \sigma T^4
\]

\[
= 2 \times 0.58 \times 81.2 \times 10^{-12} \times 258^4
\]

\[
= 0.420 \text{ cal/min/cm}^2 (93 \text{ Btu/hr/ft}^2)
\]

F. EXPERIMENTAL CONVECTION HEAT TRANSFER COEFFICIENT

Subtracting the emitted radiation from the absorbed radiation leaves \( 0.487 - 0.420 = 0.067 \text{ cal/min/cm}^2 (14.7 \text{ Btu/hr/ft}^2) \) to be transferred by convection from the package. At the flight altitude, the ambient air temperature, \( T_0 \), is 218°K (392°R) and the average convection heat transfer coefficient for the upper and lower surfaces can be obtained from the relation

\[
\overline{h_c} = \frac{q}{A (T - T_0)} = \frac{0.067}{2 \times 40.6}
\]

\[
= 8.2 \times 10^{-4} \text{ cal/min/cm}^2/°C (0.1 \text{ Btu/hr/ft}^2/°F)
\]

If the solar absorptivity had been 0.18 rather than 0.17, the convection coefficient would have changed from \( 8.2 \times 10^{-4} \) to \( 1.18 \times 10^{-3} \text{ cal/min/cm}^2/°C \) (from 0.1 to 0.145 Btu/hr/ft\(^2\)/°F). These calculations establish the experimental order of magnitude of the free convection heat transfer coefficient in flight. The free coefficient will now be calculated from correlation equations used in engineering to predict convection heat transfer from laboratory tests.

G. EVALUATIONS OF CONVECTION HEAT TRANSFER COEFFICIENT AT 70,000 FT AND EXTRAPOLATION TO 130,000 FT

The empirical correlations of experimental data generally used to evaluate the average free convection heat transfer coefficient from
top and bottom surfaces of horizontal square or rectangular plates (Kreith, 1965) are:

\[
\bar{Nu} = 0.54 \left( Gr \times Pr \right)^{\frac{1}{4}} \quad \text{(top)} \tag{10}
\]

\[
\bar{Nu} = 0.27 \left( Gr \times Pr \right)^{\frac{1}{4}} \quad \text{(bottom)} \tag{11}
\]

where

\[
\bar{Nu} = \frac{h_{\text{top}} L}{k_{\text{air}}} \quad \text{(dimensionless)}
\]

\[
Gr = g \rho^2 \beta \left( T_{\text{surface}} - T_{\text{air}} \right) L^3 / \mu^2 \quad \text{(dimensionless)}
\]

\[
Pr = \frac{c_p}{\rho} \mu / k \quad \text{(dimensionless)}
\]

\[L = \text{length of plate}\]

\[k = \text{thermal conductivity of air}\]

\[g = \text{gravitational constant}\]

\[\rho = \text{density of air}\]

\[\beta = \text{coefficient of thermal expansion of air}\]

\[\mu = \text{viscosity of air}\]

\[c_p = \text{specific heat of air at constant pressure}\]

All physical properties in Eqs. (10) and (11) are evaluated at the mean temperature \(\left( T_{\text{surface}} + T_{\text{air at altitude}} \right)/2\).

The average value of the heat transfer coefficient for the top and bottom surfaces can be obtained by averaging the coefficients.
in Eqs. (10) and (11). Then

$$h_c = 0.405 \frac{k}{L} (Gr \times Pr)^{\frac{1}{4}}$$  \hspace{1cm} (12)$$

Under the experimental flight conditions, the average temperature at float altitude was $237^\circ K \ (427^\circ R)$. With a temperature difference of $40.6^\circ C \ (73^\circ F)$ and a length dimension of 1 ft

$$\frac{h_c}{c} = 0.405 \times \frac{0.012}{1} \times (1.4 \times 10^6 \times 0.70)^{\frac{1}{4}}$$

$$= 1.2 \times 10^{-3} \text{ cal/min/cm}^2/\circ C \ (0.15 \text{ Btu/hr/ft}^2/\circ F)$$  \hspace{1cm} (13)$$

The calculated value of the coefficient is somewhat larger than the measured value, but the difference between them is no larger than the uncertainties in the physical properties and the experimental measurements. The agreement is sufficient to lend support to the validity of applying conventional correlation of free convection heat transfer data to conditions in the upper atmosphere.

To estimate the free convection heat transfer coefficient at 130,000 ft we may either use Eq.(12) or scale the results obtained at 70,000 ft by means of the two similarity parameters $Gr$ and $Pr$. The atmospheric temperature at 130,000 ft is about $250^\circ K \ (450^\circ R)$ (Valley, Ed., 1965). The viscosity of air is only slightly dependent on pressure, and the ratio of density at 130,000 ft to that at sea level is $2.5 \times 10^{-3}$. For the same temperature difference between surface and atmosphere, the ratio of Grashof numbers at 70,000 and 130,000 ft is proportional to the square of the density ratio. The ratio of the heat transfer coefficients is, according to Eq.(12), proportional to the square root of the density ratio times the ratio of the thermal conductivities:

$$\frac{h_c, 130,000 \text{ ft}}{h_c, 70,000 \text{ ft}} = \frac{(k \rho^\frac{1}{3}) 130,000}{(k \rho^\frac{1}{3}) 70,000} = \frac{0.013}{0.012} \times \left(\frac{0.30}{0.67}\right)^{\frac{1}{2}} = 0.72$$  \hspace{1cm} (14)$$

Thus, at 130,000 ft the free convection heat transfer is small, but by no means negligible.
The temperature of the package at 130,000 ft can now be calculated from Eq. (1). If we assume that the sun angle at 130,000 ft remains between 50 and 60° and take the solar absorptivity as 0.17 and the albedo as 0.3, the heat load is 0.487 cal/min/cm² (107.2 Btu/hr/ft²).

The heat transfer rate from the package is

\[ q_{out} = 2[0.58 \times 81.2 \times 10^{-12} \times T_{surface}^4 + 5.7 \times 10^{-8} (T_{surface} - 250)] \]  

(15)

Setting \( q_{in} \) equal to \( q_{out} \) and solving for the surface temperature at 130,000 ft gives

\[ T_{surface} = 266°K (478°R) \]  

(16)

Under the same environmental conditions the temperature of the same instrument package, but covered with aluminum foil having a solar absorptivity, \( a_s \), of 0.15 and an infrared emissivity, \( \varepsilon_i \), of 0.04, will be considerably higher. The calculations are shown below:

\[ q_{in} = 0.15 (1.73 + 0.52) + 0.04 \times 0.18 \]
\[ = 0.345 \text{ cal/min/cm}^2 (76.5 \text{ Btu/hr/ft}^2) \]  

(17)

\[ q_{out} = 2 \times [0.04 \times 81.2 \times 10^{-12} \times T_{surface}^4 + 5.7 \times 10^{-8} (T_{surface} - 250)] \]  

(18)

Solving for \( T_{surface} \) gives

\[ T_{surface} = 401°K (725°R) \]  

(19)

It should be noted that for a package covered with aluminum foil, which has a low emissivity in the infrared, free convection transfers
as much heat as radiation. However, at an altitude of 130,000 ft, the convection coefficient is too low to cool the instrument package effectively, and the package temperature must increase to achieve equilibrium between the incoming and outgoing heat fluxes.
IV. EXPERIMENTAL PROCEDURE

In order to obtain experimental verification of the analytical temperature predictions under conditions resembling those encountered by the instrument package in flight, two simulated instrument packages were installed on one platform, as shown schematically in Fig. 4. The left package was covered by ordinary aluminum foil, while the right was covered with a Mylar-aluminum laminate. For each package the temperatures of the top and the bottom surfaces of the styrofoam body were measured by means of YSI-type thermistors, installed as shown in Fig. 5. The thickness of the styrofoam separating the upper from the lower thermistor was 1 in.

The output from the four thermistors was monitored by means of a telemetry system located in the center of the platform between the two simulated instrument packages (Fig. 4). The telemetry system had previously been developed for the Nimbus D IRLS program, which placed the system at our disposal for the test flight. Figures 6a and 6b show circuit diagrams of the telemetry unit; Fig. 7 shows the circuit diagram of the balloon-borne transmitter. The telemetry system had six channels, four of which were used to monitor the thermistors on the platform. The remaining two channels were to be used to record the battery temperatures and a reference, but this installation was not used in the flight.

A 39 ft surplus balloon, displacing a volume of 30,000 ft³, was selected as the test vehicle, and the platform was hung as shown in Fig. 8. The balloon was launched on 24 April 1968, when cloud conditions were estimated to be 70% cirrus. The recorded temperature data are shown in Fig. 3.
V. DISCUSSION AND CONCLUSIONS

The calculations shown in Sec. III provide a means of determining the temperature of instrument packages under various environmental conditions. The accuracy of the thermal analysis can be estimated by calculating analytically the upper surface temperature of the experimental instrument package covered with aluminum foil at an altitude of 70,000 ft and comparing this result with the measured value.

The rate of heat input by radiation is 0.36 cal/min/cm² (79 Btu/hr/ft²). Calculated as shown in Sec. III, the rate of heat loss by radiation and convection per unit cross-sectional area is

\[ q_{\text{out}} = 2[\varepsilon_i \, \sigma \, T^4 + h_c \, (T - T_o)] \]

\[ = (0.08 \times 81.2 \times 10^{-12} \, T^4) + (2.4 \times 10^{-3} \, T) - (2.4 \times 10^{-3} \times 237) \]

where \( T \) is in °K. Under equilibrium conditions (i.e., when \( q_{\text{in}} = q_{\text{out}} \)) the package temperature predicted from the thermal analysis is 326°K, whereas the values measured at top and bottom were 305 and 293°K, respectively. The difference may have resulted from the presence of a slight film over the surface of the aluminum foil, which could have increased the emissivity to a value larger than that reported in the literature; or the difference may have been due to neglecting in the analysis the heat transfer over the sides of the package, where the average heat transfer coefficient would be of the same order of magnitude as over the top and bottom surfaces.

The accuracy of all temperature predictions for instrument packages in flight depends largely on a precise knowledge of the radiation properties of the surfaces used. It also depends on the applicability of free convection heat transfer correlations calculated for regular geometrical shapes to the shapes used in practice. The degree of agreement between the temperatures calculated and the temperatures
measured in flight is encouraging. The analytical methods outlined in this report can serve as a basis for estimating equilibrium temperatures of other types of balloon-borne instrument packages. It would, however, be desirable to measure radiation properties pertinent to the design of balloon-borne instrument packages and to perform free convection experiments with shapes resembling those of instrument packages used in practice.
Fig. 2 Sketch illustrating heat balance on typical instrument package
Fig. 3 Temperature vs time record for experimental instrument package at 70,000 ft
Fig. 4 Schematic diagram of experimental instrument package
Fig. 5 Cross-sectional view of experimental instrument package and thermistors
Fig. 6a Circuit diagram of telemetry unit, logic card N-CC
Fig. 6b Circuit diagram of telemetry unit, six-channel commutator N-CM
Fig. 7 Circuit diagram of transmitter N-TX
Fig. 8 Sketch of balloon with instrument package
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