THERMAL MODELLING OF SMALL BIRDS EXPOSED TO MICROWAVE RADIATION (2.45 GHz CW)

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SUMMARY

(1) An analytical steady-state heat transfer model of a bird subjected to continuous wave (CW) microwave radiation (2.45 GHz) was developed.
(2) The model was created from physiological and biophysical energy exchange data from the published literature and was calibrated with the body temperature responses of restrained birds exposed to microwave irradiances of 250 and 500 W m\(^{-2}\).
(3) The model predicts that tolerance to microwave radiation for a bird should be positively correlated with its mass and that ambient temperature is the environmental variable that has most influence on the level of tolerance for microwave radiation.
(4) Other predictions are that tolerance to microwave radiation should be dependent on ambient relative humidity at high ambient temperatures, that 2.45 GHz CW radiation is absorbed by a small bird with an average solar absorptance at approximately twice the rate that solar radiation is absorbed, and that a small change in wind speed will have considerable effect on tolerance when wind speeds are low (<10 km h\(^{-1}\)).

INTRODUCTION

It has been proposed that a satellite power system (SPS) be used to collect solar energy, and transmit microwave energy to receiving antennas (rectennas) on the earth’s surface. Electricity would be produced at the rectennas and transmitted by conventional high voltage lines to population centres (Glaser 1968, 1980). Each rectenna would have a diameter of c. 10 km and the proposed microwave irradiances would range from c. 230 W m\(^{-2}\) to 10 W m\(^{-2}\) at the rectenna edge. Birds would be irradiated because no practical method exists to prevent their access to the rectenna, either during migratory flights across the area or when landing to rest or nest.

The maximum combined direct solar and diffuse sky radiation incident on a horizontal surface at noon at latitude 40°N is 865 W m\(^{-2}\) on 22 June and 311 W m\(^{-2}\) on 22 December (Gates 1980). A bird or any other three-dimensional object absorbs solar radiation in relation to its area normal to the solar beam and in relation to the solar irradiance normal to the solar beam. If the above combined solar and diffuse radiation values are corrected by dividing them by the cosine of the solar zenith angle, they become 910 W m\(^{-2}\) for 22 June and 662 W m\(^{-2}\) for 22 December. The microwave irradiance would be a substantial fraction of the total environmental electromagnetic energy irradiating the central area of the rectenna and the SPS could, therefore, have a serious negative impact on airborne biota (Westerdahl & Gary 1981).

The total heat load on a free-living bird irradiated by microwaves, and the resulting thermoregulatory behaviour, would be affected by a number of environmental factors

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including ambient temperature and humidity, solar radiation and wind speed (Porter &
Gates 1969). The additional effects of microwave irradiation on a bird’s heat load and
resultant thermoregulatory behaviour are unknown. In order to predict the effect of these
environmental factors on a bird’s ability to tolerate microwave irradiation by the SPS, we
developed an analytical heat transfer model of a bird subjected to microwave radiation.

The heat transfer model assumes steady-state conditions in order to provide conservative
estimates of response to a range of microwave dosages. The model was calibrated using
biophysical energy-exchange data from the published literature and the responses of birds
to microwave irradiation (Wasserman et al. 1985). The calibrated model was then applied
to several species of birds to predict maximum tolerable levels for ranges of
micrometeorological variables typical of the field.

THE MODEL

Under steady-state conditions, a bird irradiated by microwaves is in thermal balance,
dissipating heat at a rate equal to the sum of the rates of heat absorption and internal
metabolic heat production. This energy budget can be expressed by the following equation:

\[ Q_c + Q_R + E = (A_c/A_b) a_s \phi_s + (SAR \ m_b/A_b) \phi_M + M \]  

(1)

where \( Q_c \) is the rate of heat loss per unit surface area by convection (W m\(^{-2}\)), \( Q_R \) is the rate
of heat loss per unit surface area by radiation (W m\(^{-2}\)), \( E \) is the rate of heat loss per unit
surface area by evaporation (W m\(^{-2}\)), \( \phi_s \) is the incident solar irradiance (W m\(^{-2}\)), \( \phi_M \) is the
incident microwave radiation flux (W m\(^{-2}\)), \( M \) is the rate of metabolic heat production per
unit of feathered surface area (W m\(^{-2}\)), \( A_c \) is the cross-sectional area of the bird normal to
the solar radiation (m\(^2\)), \( A_b \) is the surface area of the bird with plumage (m\(^2\)), \( m_b \) is the
mass of the bird (kg), \( SAR \) is the specific absorption rate for microwave radiation
(W kg\(^{-1}\) W\(^{-1}\) m\(^{-2}\)) and \( a_s \) is the solar absorptance of the bird.

Equation (1) can be rearranged to obtain the expression for \( \phi_M \):

\[ \phi_M = [(A_b/m_b)/SAR] [(Q_c + (E - M)) \]  

(2)

where

\[ Q_c = Q_c + Q_R - (A_c/A_b) a_s \phi_s \]  

(3)

For treatment of the convective and radiative components, \( Q_c \) is expressed as:

\[ Q_c = (C_s/r_\tau)(T_b - T_e) \]  

(4)

where \( r_\tau \) is the total thermal resistance, \( T_b \) is the internal body temperature of the bird, \( T_e \) is the ‘blackbody equivalent’ or operative temperature of the environment, and \( C_s \) is the
volumetric heat capacity of air at standard conditions (Bakken 1976; Robinson,
Campbell & King 1976).

The total resistance to heat transfer is the sum of two resistances in series:

\[ r_T = r_b + r_e \]  

(5)

where \( r_b \) is the internal body resistance of the bird associated with subcutaneous tissue and
feathers. The term \( r_e \) is the external resistance, which is a function of environmental
conditions. This is the sum of two parallel resistances:

\[ (1/r_e) = (1/r_\tau) + (1/r_s) \]  

(6)

In this expression, \( r_\tau \) is a fictitious ‘radiative’ resistance resulting from the manner in which
the radiation heat-transfer term is treated numerically. This resistance is defined as:
where \(\varepsilon\) is the emissivity of the bird’s outer surface, \(\sigma\) is the Stefan-Boltzmann constant, and \(T_\ast\) is the ambient air temperature.

The resistance \(r_\ast\) is that associated with the air boundary layer. Empirical expressions from the literature (Robinson, Campbell & King 1976) were used in evaluating \(r_\ast\) for different conditions. In the case where there is no wind, \(r_\ast\) is the free convection resistance and can be estimated as:

\[
r_\ast = 820[d/(T_\ast - T_\text{w})]^{1/4} \text{ s m}^{-1}
\]  

(8)

where \(d\) is the characteristic dimension (torso diameter) of the bird in metres and \(T_\ast\) is the surface temperature in kelvin. For the case where a wind is blowing at \(U\) m s\(^{-1}\), \(r_\ast\) is given by the following correlation for forced convection:

\[
r_\ast = 310(d/U)^{1/2} \text{ s m}^{-1} \quad (\text{Monteith 1973})
\]  

(9)

The blackbody equivalent temperature (operative temperature) \(T_\text{e}\) is defined as the equilibrium value which a model animal with no internal heat production would reach when exposed to the environment of the actual bird. The expression defining \(T_\text{e}\) is obtained from an energy balance as follows:

\[
T_\text{e} = T_\ast + S_\lambda/(C_\lambda/r_\ast) \quad (\text{Gagge & Hardy 1967; Bakken 1976})
\]  

(10)

where the term \(S_\lambda\) is the rate of absorption per unit surface area of the incident solar radiation:

\[
S_\lambda = (A_\lambda/A_\text{b}) a_\lambda \phi_\lambda
\]  

(11)

### SOLUTION PROCEDURE

The value of \(\phi_\lambda\) given by eqn (2) can be evaluated to give the maximum level of microwave radiation at which a bird can maintain thermal equilibrium with the environment at a given metabolic state. This value is dependent on the environmental conditions (such as ambient temperature, wind velocity, etc.) through their effect on \(Q_\lambda\). In addition, \(\phi_\lambda\) is a function of the biothermal parameters, \(E\), \(M\), \(T_\text{b}\) and \(r_\text{b}\). These parameters vary not only with bird species, but also with thermoregulatory behaviour. Different values would correspond to the onset of different responses to thermal stress, such as the elevation of body temperature, gaping, panting and eventually death. Since these parameters cannot be predicted analytically, it is necessary to rely on empirical data in order to implement the model for any given species.

Measurements of the physiological responses of birds to changes in environmental temperature have typically consisted of placing individual birds in metabolic chambers maintained at constant temperature and ventilated with a low flow of dry CO\(_2\)-free air (e.g., Hinds & Calder 1973; Weathers & Caccamise 1975). Rates of oxygen consumption, carbon dioxide production and evaporative water loss are determined by continuously measuring the concentrations of oxygen, carbon dioxide and water vapour entering and leaving the chamber. Cloacal temperatures are measured at the start and conclusion of each test period. The results of such tests provide data on the variations of biothermal parameters with the environmental conditions imposed on the bird.
Results typical of such studies obtained from the monk parakeet, *Myiopsitta monachus* (Boddart) (Weathers & Caccamise 1975), are illustrated by Fig. 1. The indicated variations of $M$, $E$, and $T_b$ with ambient temperature represent smoothed curves which provide the best fit to the experimental data. The heat loss to the environment by convection and radiation ($Q_c$) can be calculated from the corresponding curves for $M$ and $E$. We can consider the heat loss mechanisms of a bird to differ in each of four different $T_a$ ranges. Below the lower critical temperature ($T_a < 25 \, ^\circ C$), a bird must raise its metabolic rate to combat cold stress. In this condition, an increasing heat load would allow a reduction of metabolic rate. The thermal neutral zone of the monk parakeet is approximately 25–35 $^\circ C$, a temperature range within which $M$ is at the minimum value and the bird resorts to decreasing $r_b$ to dissipate the increased heat load. In the range between 35 and 40 $^\circ C$, $M$ and $r_b$ are at their minimum values and the bird increases its evaporative heat loss. This is only partially successful, as indicated by the rise in body temperature. At $T_a > 40 \, ^\circ C$, the increased metabolic rate associated with the panting necessary to increase $E$ results in an increasing $T_b$, which is imminently lethal. Because the experiments on monk parakeets were terminated at conditions which appeared to be close to lethal, we assumed that the extremes of $E$, $M$ and $T_b$ corresponded to the maximum tolerable values that this species could maintain without succumbing to heat prostration.

The data summarized in Fig. 1 were used to compute the thermal body resistance ($r_b$) of monk parakeets as it varied with ambient temperature (Fig. 2). The resistance remained fairly constant over a wide range of ambient temperatures. As the ambient temperature rose within the thermal neutral zone, $r_b$ dropped dramatically, exhibiting a sharp minimum at $T_a = 37 \, ^\circ C$, and then increased slightly. The dependence of $M$, $E$, $T_b$ and $r_b$ on ambient temperature as described above is similar to the results obtained for other birds, but the absolute values of these parameters are dependent on the physical characteristics of the species.

Published physiological data for three bird species may be summarized (Hinds & Calder 1973; Weathers & Caccamise 1975; Fig. 3). The higher values of $r_b$ correspond to the body resistance under normal conditions (i.e., no heat stress). The broken curve drawn through

![Fig. 1. Effect of ambient temperature ($T_a$) on energy budget for monk parakeets (Weathers & Caccamise 1975). See text for explanation of symbols.](image-url)
Fig. 2. Variation of body resistance of monk parakeets with difference between body temperature and ambient temperature.

Fig. 3. Variation of heat rejection ability of three bird species in relation to body mass: (■) Pyrrhuloxia (Hinds & Calder 1973); (▲) Arizona cardinal (Hinds & Calder 1973); (■) the monk parakeet (Weathers & Caccamise 1975). (---) Empirical correlation of Herreid & Kessel (1967).

These points represent an empirical correlation (Herreid & Kessel 1967) and fits the data closely. The lower values for $r_b$ are the minimum values calculated from available data in the literature. These appear to be independent of size for the three species shown in Fig. 3. Data on body temperature elevation above normal represent the maximum values measured by each investigator. Although the results indicate a slight increase with decreasing body weight, it was assumed that the maximum tolerable temperature elevation is roughly the same for all species, nominally around 4 °C.
In order to correct for differences in the humidity of the air inhaled by the three species, the values of \( E \) in Fig. 3 have been adjusted:

\[
E = \left[ \frac{V_{\text{air}} L (W_{b, \text{sat}} - W_s)}{A} \right]
\]

where \( V_{\text{air}} \) is the flow rate of air, \( L \) is the latent heat of vaporization, \( W_{b, \text{sat}} \) is the absolute humidity corresponding to saturated conditions, \( W_s \) is the absolute humidity of the air in the test chamber, and \( A \) is the surface area of the bird. The same procedure can be used to estimate the value of \( E \) for any set of conditions.

The data for \( E_{\text{min}} \) and \( M_{\text{min}} \) in Fig. 3 correspond to the lower critical temperature, the point where the metabolic rate had been reduced to a minimum (Fig. 1). The results indicate that for these three species, minimum evaporative heat loss and metabolic heat production were relatively independent of body size when calculated with respect to body surface area. The curves labelled \( E_{\text{max}} \) and \( M_{\text{max}} \) show the corresponding values measured at the highest ambient temperature tested by each investigator. As noted previously, we assumed that these provide an indication of the upper lethal conditions for these species. From Fig. 3, it is apparent that the relevant biothermal parameters correlate fairly well with body mass. Consequently, in considering any particular species, its characteristic body mass was used in conjunction with the data from the literature to estimate the appropriate values of the required biothermal parameters in the present study.

**MODEL CALIBRATION**

Specific absorption rates (SAR) for microwave radiation were obtained from a series of tests with six bird species. Each test consisted of placing a dead bird in an insulated box, exposing it to a constant known flux of microwave radiation, and monitoring its internal temperature rise. These test data were used in conjunction with measured values of the specific heat of bird carcasses to compute SAR for each sample. Microwave absorptivity appears to be primarily a function of body size, as indicated by the observed variation with body mass (Fig. 4). Orientation of the body axis parallel to the E vector results in the

![Fig. 4. Experimentally determined variation of microwave absorptivity of birds in relation to body mass, E vector orientation and wing position.](image)
highest values of SAR, particularly for the smallest birds. Wing position seems to have little
effect except for small birds, i.e., < 30 g when oriented perpendicular to the E vector.

The internal thermal body resistance can vary dramatically in response to varying heat
load imposed on the bird. The appropriate minimum achievable resistance value can be
inferred from results obtained from a series of tests involving irradiation of live house
finches (Carpodacus mexicanus (Müller)) and blue jays (Cyanocitta cristata (Linnaeus)) in
which the \( T_b \) values of restrained birds were monitored during exposure to different flux
levels (Wasserman et al. 1985). Figure 5 summarizes the results obtained by applying our
thermal model to the house finch. This model allows predictions of the relationship between
maximum tolerable flux level and internal body resistance. At 500 W m\(^{-2}\), the average rise
in \( T_b \) was 4-4 °C within 10 min, by which time two of the five irradiated birds had
died. A comparison of these results with the predicted curve indicates that the apparent
body resistance of the irradiated birds, under the condition of extreme thermal stress, was
approximately 50 s m\(^{-1}\), which corresponds to the minimum value reported in the literature
for at least three different species (Hinds & Calder 1973; Weathers & Caccamise 1975).
Comparable studies at 500 W m\(^{-2}\) with a parallel orientation were not conducted for blue
jays. Based on the available information, however, we estimate that the minimum 50 s m\(^{-1}\)
value of body resistance is an appropriate value to be used in evaluating the maximum
tolerable microwave flux. The minimal achievable \( T_b \) is most likely independent of the
source of thermal stress; i.e., the minimum value is the same whether the bird is heated by
high ambient temperature, solar radiation or microwave radiation.

ESTIMATED THERMAL RESPONSES FOR BIRDS IN THE FIELD

The thermal model developed here was used to calculate a series of parametric estimates of
the threshold values of microwave flux corresponding to the two following conditions:

(i) The onset of thermoregulatory behaviour is assumed to begin at the point where the
metabolic rate has been reduced to the minimum value.
**Table 1.** Range of environmental variables used to predict thermal responses for birds in the field

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature, $T_a$ (°C)</td>
<td>20</td>
<td>0–50</td>
</tr>
<tr>
<td>Ambient relative humidity, $W_a$ (%)</td>
<td>50</td>
<td>0–100</td>
</tr>
<tr>
<td>Absorption of solar radiation, $S_a$ (W m$^{-2}$)</td>
<td>150</td>
<td>0–300*</td>
</tr>
<tr>
<td>Apparent wind speed, $U$ (km h$^{-1}$)†</td>
<td>16‡</td>
<td>4–0.6–48</td>
</tr>
</tbody>
</table>

* The maximum value of $S_a$ was calculated using the method described by Campbell (1977) for the case of dark plumage, clear air and direct sunlight.
† Apparent wind speed is the speed of the wind relative to the bird.
‡ The annual mean values of wind speed for the United States are in the range of 8–26 km h$^{-1}$ (Ruffner & Bair 1981).
§ Except for controlled laboratory conditions, wind speed is never zero and rarely falls below half the annual mean value (Anon. 1978).

![Graphs of predicted effects of ambient temperature and relative humidity on the threshold microwave irradiance levels for two bird species.](Fig. 6)

**Fig. 6.** Predicted effects of ambient temperature and relative humidity on the threshold microwave irradiance levels for two bird species when the ambient wind speed is 16 km h$^{-1}$ and solar radiation is 150 W m$^{-2}$ (a), and the predicted effects of ambient temperature and solar radiation ($S_a$) on the threshold microwave irradiance levels when ambient wind speed is 16 km h$^{-1}$ and the ambient relative humidity is 50% (b). The SAR of the house finch is 0–13 W kg$^{-1}$ W$^{-1}$ m$^{-2}$, and that of the blue jay is 0–06. Solid lines represent the threshold for imminent death, and the dashed line the threshold for the onset of thermoregulatory behaviour.

(ii) Imminent death from hyperthermia is assumed to occur when $T_b$ and panting rate have reached maximum values.

The calculations were performed for house finches and blue jays over the ranges of ambient temperature, humidity, solar radiation and wind speed listed in Table 1. The values are representative of those that might be encountered in the natural environment.

The results of the analysis in which one variable was changed at a time are plotted in Figs 6 and 7 and show the predicted effects of ambient temperature for different values of humidity, solar radiation and wind speed. On the basis of these results, it was concluded that:
Fig. 7. Predicted effects of ambient temperature and wind speed on threshold microwave irradiance levels for two bird species when the ambient relative humidity is 50% and the solar radiation is 150 W. The SAR of the house finch is 0.13 W kg$^{-1}$ W$^{-1}$ m$^{-2}$, and that of the blue jay is 0.06. Solid lines represent the threshold for imminent death, and the dashed line the threshold for the onset of thermoregulatory behaviour.

(i) Blue jays (approximate mass = 75 g) should be more tolerant to microwave radiation than house finches (approximate mass = 16 g) due to differences in the SAR.

(ii) Ambient temperature has the greatest effect on the threshold to microwave flux levels. For most ambient conditions, this effect is essentially linear.

(iii) The threshold values are relatively independent of air humidity except at elevated ambient temperatures, e.g., those approaching $T_b$.

(iv) Solar radiation exhibits a linear effect on thermal burden. The absorption by small birds of microwave energy is stronger and more complex because the bird dimensions approximate to the wavelength of the 2.45 GHz microwave irradiance, causing the bird to respond as a badly tuned dipole antenna and creating a strong dependence of SAR on body size. It is clear that absorbance of 2.45 GHz microwaves by the dorsal surface of small birds is higher than that for visible light radiation, which typically ranges between 0.65 and 0.90 (Gates 1980).

(v) Apparent wind speed has a non-linear effect on threshold microwave flux values. The threshold increases with increasing speed. Beyond c. 48 km h$^{-1}$, increasing wind speed has relatively little influence on threshold. A wind speed of 4 km h$^{-1}$ is a conservative estimate for the wind likely to be experienced by birds perched on the rectenna 2.6 m above the ground. At that wind speed and at air temperatures above 10 °C, a power density of 250 W m$^{-2}$ should produce significant effects on avian behaviour. Behaviour should be adversely affected when air temperatures are >20 °C, $S_A$ is above 300 W m$^{-2}$ and winds speeds <5 km h$^{-1}$.

The results discussed above are for the case where a bird is at rest. The maximum tolerated threshold to microwave radiation should decrease with increasing physical activity, as would occur during flight. Unfortunately, there are few published data on the variation of the relevant biothermal parameters during different levels of activity for birds. A 'rule of thumb' estimate as to effect of activity on metabolic rate indicates that at maximum sustainable activity, $M$ is increased over the basal level by a factor of ten (Campbell 1977). This 'rule of thumb' was used to estimate the effect of flight on the lethal threshold levels of microwave radiation (Fig. 8). If the solar radiation is 150 W m$^{-2}$ and the
wind speed is 48 km h\(^{-1}\), microwave power densities of 250 and 500 W m\(^{-2}\) should prevent birds from flying (maximum exertion) at air temperatures > 15 and 12 °C respectively.

Budgerigars (Melopsittacus undulatus (Shaw)) cannot fly at 37 km h\(^{-1}\) normal to the E vector (SAR = 0.81) of a 500-W m\(^{-2}\) field for more than 600 s if the ambient temperature is > 32 °C (Byman et al. 1985). The flying budgerigars were not exposed to solar radiation and a flight speed of 37 km h\(^{-1}\) should not have required maximum exertion (Tucker 1968). If a budgerigar is flying in the field, exposed to 250 W m\(^{-2}\) of solar radiation as well as 500 W m\(^{-2}\) of microwave radiation, the tolerable ambient temperature should approximate to 30 °C. These results suggest that the thermal model slightly overestimates the thermal load induced by flight, as it predicts that flight (50% maximum exertion) should not be possible at ambient temperatures > 25 °C if the microwave power density is 50 W m\(^{-2}\) (Fig. 8). The model and budgerigar experiments together indicate that birds would not be able to fly across the centre of the SPS rectenna if \(T_e\) is > 30 °C.

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