7. THE MAJOR PARAMETERS AFFECTING TEMPERATURE INSIDE INHALATION CHAMBERS*

David M. Bernstein and Robert T. Drew

CONF-7810255--1

Control of the internal temperature of inhalation chambers is crucial to the proper performance of animal inhalation studies. Elevated temperatures can have detrimental effects on physiology and metabolism of foreign compounds as well as effects on chemical interaction of pollutant aerosols. Rats have been found to successfully acclimate to temperatures ranging from 5° to 32°C. While the metabolic rate of the rat is affected by factors such as diurnal and hormonal variations, it is also influenced by temperature variations, with a minimum metabolic rate achieved (thermal neutrality) at temperatures of approximately 28° to 32°C. (Laudenslager, 1978) The goal of inhalation toxicology studies is to compare in a reproducible manner any differences in effect between animals exposed to pollutants and statistically similar control animals not exposed to pollutants. It is therefore important to maintain the animals at a uniform temperature, both during exposure in the chamber and during housing outside the chamber, to reduce statistical variations in the results that may be related to temperature excursions. During exposure, chambers should be kept at 22° to 25°C which is the recommended temperature for housing of rats. (Melby and Altman, 1974) This report quantifies the different modes of heat transfer in a chamber and determines the most efficient methods of removing from the chamber the heat generated by the animals.

*This paper has recently been published in similar form (Bernstein and Drew, 1980).

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

7 - 1

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

METHODS

A 0.38-m³ stainless steel and glass chamber similar to that described by Hinners et al. (1968), except that the upper pyramid was at an angle of 67° with the horizontal, was used in these studies. Eight stainless steel wire cages (27 x 21 x 21 cm) were positioned symmetrically on two shelves (indicated by the dashed lines in Figures 7-1 and 7-2) in the chamber. The physical dimensions of the chamber are listed in Table 7-1, along with the airflow rates used. Intake air was used directly from the room or was first cooled by passing room air through copper tubes immersed in either icewater or dry ice - acetone mixtures. Forty thermocouples (copper constantan) were positioned throughout the chamber as shown schematically in Figure 7-1. (The x's mark the thermocouple locations with the closest distance to the wall being 5 cm.) Temperature measurements were made by a datalogger (Fluke Model 2240B) with a resolution of 0.1°C. In all cases the chamber was allowed to operate at the set conditions for 2 to 3 hours with subsequent temperature measurements used for calculation. Although the chamber was not in thermal equilibrium with its surroundings after two hours, this time period was sufficient to minimize rapid fluctuations. The temperature characteristics of the chamber were studied with and without rats in the chamber and with and without 5-cm fiber-glass insulation surrounding it (Table 7-2). The rats used in these studies were Fisher 344 males with a mean weight of 450 g. All experiments with rats were conducted without food or water in the chamber.

Thermocouple Error Analysis

The error introduced in the temperature measurements of the chamber air by thermal radiation from either the chamber steel or the rats was determined by

Table 7-1

Chamber Conditions

Cross section	0.69 x 0.69 m; 0.47 m ²	
Volume: with cones	0.38 m ³	
active volume	0.33 m ³	
Surface area	3.07 m ²	
Airflow rates	1) 0.0017 m ³ /sec (100 l/min)	2) 0.0028 m ³ /sec (170 l/min)
Velocity: at animal level	0.0036 m/sec	0.0061 m/sec
Mass flow	0.0022 kg/sec	0.0036 kg/sec

Table 7-2

Experimental Operating Conditions

Noninsulated		Insulated	
Without animals	Animals (8 cages)	Without animals	Animals (8 cages)
-----		-----	
Dry ice - acetone	One rat/cage	Dry ice - acetone	One rat/cage
100 l/min	Ice water	170 l/min	Ice water
(B)	100 l/min +	(M)	100 l/min +
	170 l/min		170 l/min
-----	(K)		(J)
Dry ice - acetone			
100 l/min			
(B)		-----	
-----	3 rats/cage	Air cond. exh. intake	
Ice water	Room air	170 l/min	3 rats/cage
100 l/min	100 l/min	(E)	Ice water
(A)	(C)		100 l/min +
			170 l/min
		-----	(H)
	5 rats/cage	Ice water	
	Ice water	100 l/min +	
	100 l/min +	170 l/min	
	170 l/min	(G)	5 rats/cage
	(L)		Ice water
			100 l/min +
		-----	170 l/min
		Dry ice - acetone	(I)
		100 l/min + 170 l/min	
		(F)	

placing identical thermocouples 3 cm apart in the chamber with a radiation shield over one of the thermocouples. The shield consisted of a cone of aluminum foil 5 cm long, painted black on the inside, and with holes punched around the top to permit convection. The chamber was operated in the various configurations of animals and cooled air intake described above. Without animals in the chamber no significant differences were found between the two measurements. With animals in the chamber the shielded and unshielded thermocouples produced significantly different ($p < 0.05$) measurements only when the intake air was cooled below 14°C (ice-water mixture). In this case an average difference of $(0.18 \pm 0.08)^\circ\text{C}$ was found. This error was of the same magnitude as that of the measuring system itself and was not considered to be a major bias in this system.

Heat Balance

The heat balance in a chamber can be visualized by referring to Figure 7-2. Air ($\dot{m}$) enters the chamber at temperature T_1 , is heated ($\dot{Q}_{\text{gen}}$) by the animals in the chamber, and leaves the chamber at temperature T_2 ($T_2 > T_1$). Heat is also lost to the surroundings across the chamber wall ($\dot{Q}_{\text{loss}}$). This heat balance is summarized by the following equations:

$$\dot{m}h_1 + \dot{Q}_{\text{gen}} - \dot{Q}_{\text{loss}} = \dot{m}h_2,$$

* * *

(1)

$$\dot{Q}_{\text{gen}} - \dot{Q}_{\text{loss}} = \dot{m} C_p (T_2 - T_1),$$

where

$\dot{m}$ = mass flow of air in the chamber (kg/sec),

h = enthalpy of air, $h = C_p T((J/kg \text{ } ^\circ K)\Delta \text{ } ^\circ K)$,

C_p = specific heat (J/kg $^\circ K$),

$\dot{Q}$ = rate of heat transfer with time (watts).

The heat liberated by a rat, $\dot{Q}_{gen}$, has been determined by gradient layer calorimetry. (Caldwell et al., 1966, Laudenslager et al., 1979) This method accounts for both dry heat loss and evaporative heat loss for the animals.

Caldwell et al. (1966) determined the average total heat produced by male rats of unspecified weight to be 6.5 ± 0.4 mW/g, while Laudenslager (1979) found for female rats with an average weight of 250 g an average heat production of 6.0 ± 0.2 mW/g. In general, dry heat loss was determined by these investigators to be approximately 80% of the total heat production.

Heat transfer through the stainless steel wall, $\dot{Q}_{loss}$, can be described in terms of resistances to heat flow as shown in Figure 7-3. The resistances to heat flow are those encountered in the convection (R_{ci}) and radiative transfer (R_{ri}) of heat to the inside surface of the wall, the conduction resistance through the stainless steel (No. 304, 0.198 cm thick) (R_k), convection of heat from the outside of the wall to the environment (R_{co}), and radiative heat transfer to the surroundings (R_{ro}). Heat loss through the wall to the environment can be described by

$$\dot{Q}_{loss} = \frac{T_i - T_e}{\frac{R_{ri} R_{ci}}{R_{ri} + R_{ci}} + R_k + \frac{R_{ro} R_{co}}{R_{ro} + R_{co}}}, \quad (2)$$

where

$$R_k = \frac{\Delta x}{k},$$

$$R_{ci} = \frac{1}{h_{ci}},$$

$$R_{co} = \frac{1}{h_{co}},$$

$$R_{ri} = \frac{1}{\sigma_e \bar{T}_{ri}^3 (\text{°K})}, \quad (3)$$

$$R_{ro} = \frac{1}{\sigma_e \bar{T}_{ro}^3 (\text{°K})},$$

and

T_i = Av temperature inside the chamber (°C),

T_e = Av temperature of the surrounding environment (°C)

Δx = Thickness of steel (cm),

k = Thermal conductivity of steel (W/cm °K),

h_{ci} = Coefficient of convective heat transfer from air to steel (W/cm² °K),

h_{co} = Coefficient of convective heat transfer from steel to air (W/cm² °K),

σ = Stefan-Boltzmann constant (5.67×10^{-12} W/cm² °K),

ϵ_s = Emissivity of steel,

ϵ_a = Emissivity of animal,

$\bar{T}_{ri}$ = (animal temperature plus chamber wall temperature)/2,

$\bar{T}_{ro}$ = (chamber wall temperature plus surrounding environment temperature)/2.

RESULTS

Temperature measurements indicated that with cooled intake air the chamber rapidly equilibrated with the temperature of the surroundings. Estimates from the literature of the coefficients in Eq. (2) and order of magnitude calculation of heat transfer through the chamber revealed that all the surface area of the chamber was not used to effect this heat transfer. This was probably due to the very high heat transfer of the steel and the difficulty in accounting for the effect of steel cages, shelves, and glass windows in the chamber. Therefore, the effective surface area of heat transfer for the chamber was not accurately known.

Since the chamber surface is fixed by the design of the chamber itself, it was decided to find an effective overall heat transfer coefficient for this chamber by looking at heat transfer into the non-insulated chamber (with no animals present). The chamber intake air was cooled to three different temperatures, (a) $(16.2 \pm 0.6)^{\circ}\text{C}$, (b) $(10.3 \pm 0.4)^{\circ}\text{C}$, (c) $(6.4 \pm 0.4)^{\circ}\text{C}$, and temperature profiles were recorded in the chamber with the room kept at a constant warmer temperature. Thus, heat was conducted from the warmer room through the chamber wall, heating the cooler air in the chamber ($\dot{Q}_w$). In this case:

$$\dot{Q}_w = h_{\text{eff}} A_{\text{total}} (\bar{T}_{\text{air}} - T_{\text{room}}),$$

where h_{eff} is the effective heat transfer coefficient through the wall, A_{total} is the total surface area of the chamber (3.07 m^2), and $\bar{T}_{\text{air}}$ = average temperature at loc 11 to 28 (Figure 7-1). In Eq. (1), $\dot{Q}_{\text{loss}} = \dot{Q}_w$, $\dot{Q}_{\text{gen}} = 0$ (no animals), and h_{eff} is determined by

$$h_{\text{eff}} = \frac{mC_p (T_2 - T_1)}{A_{\text{total}} (\bar{T}_{\text{air}} - T_{\text{room}})} \quad (4)$$

An average h_{eff} of $6.6 \pm 1.8 \text{ W/m}^2 \text{ }^\circ\text{C}$ was obtained. This value was in the same range as the radiant heat transfer coefficient ($h_{\text{ri}} = 1/R_{\text{ri}}$). Porter (1969) has shown that with high wall emissivity (#304 s.s., $\epsilon \approx 0.8$), and with the wall temperature equal to the air temperature, there would be a maximum energy loss from the animal to its surroundings by thermal radiation and a corresponding minimum energy loss by convection. Thus, most of the dry heat loss by the rat referred to above would be by thermal radiation, with the heat conductivity of the stainless steel walls not a limiting factor.

This empirically determined heat transfer coefficient could now be used in calculating the heat balance in the chamber with animals present. Two series of experiments were conducted, one using intake air at room temperature with 24 rats in the chamber, and the other using intake air cooled by an ice-water mixture surrounding the cooling tubes and with either 8 or 40 rats in the chamber. Temperature measurements were made at the locations shown in Figure 7-1 at 20-minute intervals. The results from these experiments (mean $\pm$ S.E.) are listed in Table 7-3.

Applying the heat balance equations (Equation (1)) and the empirically determined heat transfer coefficient, $\bar{h}_{\text{eff}}$, an average heat generation rate for the rats of $6.7 \pm 0.9 \text{ mW/g}$ was calculated (Table 7-4). The results compared very well with the measurements obtained by gradient layer calorimetry cited above (Caldwell et al., 1966; Laudenslager et al., 1979).

The variations in temperature as a function of time for these experiments at location 0 (intake air) and location 30 (exhaust air) are shown graphically in Figures 7-4 and 7-5. The fractions of heat removed from the chamber through the chamber wall as compared to the heat removed by the air stream are summarized in Table 7-4. When operated with intake air at room temperature (24 rats), 95% of the heat loss was through the chamber wall and 5% by the air stream. Cooling of the intake air allowed more heat to be removed by the airstream. With small animal loadings (8 rats), cooling the intake air was effective in removing between 40 and 80% of the animal heat by the air; with 40 animals, only 17 to 30% of the animal heat was removed by the air (depending upon flow rate) with the remainder transferred through the chamber wall. This situation could be changed, however, by increasing the airflow through the chamber to carry away the heat generated by the animals. Approximately 150 l/min/450-g rat would be required to remove all the heat liberated by the rats with a net increase in temperature of 1°C. With the chamber used in this study, animal loadings of 40 rats would require a flow rate of 6 m³/min with a corresponding linear velocity across the rats of 12.8 m/min. This high flow rate (equivalent to 15 air changes per minute) is not practical for three reasons. First, the linear velocity through the chamber may be excessive for the rats especially when they are not allowed food or water during exposure; second, much more test material would be required; and third, removal of that much material from the test atmosphere would pose many problems.

The difficulty of cooling a stainless steel chamber by cooling the intake air was exemplified by an experiment in which a fiber-glass-insulated chamber with no animals present was operated with an air intake temperature of 4°C. Under these conditions the chamber exhibited a cooling half time of over 12 hr

Table 7-3

Average Temperature
(mean $\pm$ S.E.: °C)

Experiments With Rats and No Insulation

Exp. No.	Total No. animals	Flow rate (ℓ /min)	Intake temp. loc. 0	Output temp. loc. 30	Chamber temp. loc. 11-28	Room temp. loc. 32-37
K ₁	8	100	14.1 $\pm$ 0.2	19.5 $\pm$ 0.1	19.9 $\pm$ 0.3	19.1 $\pm$ 0.1
K ₂	8	170	13.9 $\pm$ 0.5	19.7 $\pm$ 0.2	19.7 $\pm$ 0.3	19.5 $\pm$ 0.1
C*	24	100	23.0 $\pm$ 0.3	24.3 $\pm$ 0.7	25.9 $\pm$ 0.7	22.9 $\pm$ 0.2
L ₁	40	100	15.1 $\pm$ 0.1	24.3 $\pm$ 0.1	24.8 $\pm$ 0.8	19.8 $\pm$ 0.2
L ₂	40	170	12.9 $\pm$ 0.6	22.3 $\pm$ 0.2	23.4 $\pm$ 0.8	19.9 $\pm$ 0.2

*Exp. No. C was performed using room air as intake in contrast to exp. Nos. K and L for which the intake air was first cooled (see text).

Table 7-4
Heat Balance With Rats and No Insulation

Exp. No.	Total No. animals	Av intake temp., °C	Flow rate, l/min	Total heat produced by animals, W	Specific heat animals, W/g	Heat removal wall/airflow, W	Ratio wall total
K ₁	8	14.1 ± 0.2	100	29.2	8.0	17.2/11.0	0.60
K ₂	8	13.9 ± 0.5	170	25.2	7.0	4.5/20.7	0.20
C*	24	23.0 ± 0.3	100	63.8	5.9	60.8/3.0	0.95
L ₁	40	15.1 ± 0.1	100	121.0	6.7	100.7/20.3	0.83
L ₂	40	12.9 ± 0.6	170	103.6	5.8	69.5/34.1	0.67

Average heat produced:

$$(\dot{Q}_{\text{gen}}) = 6.7 \pm 0.9 \text{ mW/g}$$

*Exp. No. C was performed using room air as intake in contrast to exp. Nos. K and L which the intake air was first cooled (see text).

Table 7-5

Chamber Temperature

No Rats in Chamber -- With Insulation

(°C)

Exp. No.	$\dot{m}$, kg/sec	$\overline{T}_{in}^{air}$	$\overline{T}_{5cm, below}^{air intake}$	$\overline{T}_{out}^{air}$	$\overline{T}_{Room}^{env}$
1	0.0036	18.2 ± 0.2	19.2 ± 0.4	18.9 ± 0.2	19.5 ± 0.3
2	0.0036	14.1 ± 0.1	17.6 ± 0.1	17.1 ± 0.4	18.3 ± 0.1
3	0.0036	1.1 ± 0.2	15.2 ± 0.3	15.0 ± 0.1	17.1 ± 0.2

Table 7-6

Two Mechanisms of Heat Loss in the Chamber With Animals Present

$$\dot{Q}_{\text{loss (wall)}} = h_{\text{eff}} A (\bar{T}_{\text{cham}} - T_{\text{room}}) ,$$

$$\dot{Q}_{\text{airstream}} = \dot{m} C_p (T_2 - T_1) ,$$

With room air intake at 100 l/min:

$$\bar{T}_{\text{cham}} \sim T_2$$

$$h_{\text{eff}} A \sim 20$$

$$T_{\text{room}} \sim T_1$$

$$\dot{m} C_p \sim 2$$

From Eq. (3)

$$\dot{Q}_{\text{gen}} - \dot{Q}_{\text{loss (wall)}} = \dot{m} C_p \Delta T ,$$

$$\dot{Q}_{\text{loss (wall)}} \sim 0.9 \dot{Q}_{\text{gen}} .$$

(Figure 7-6). Insulating the chamber body with fiber glass did not isolate the chamber completely from the surroundings, presumably because much of the chamber support steel was not insulated. In spite of very cool intake air, the air mixing and the large steel surface caused rapid heating of the air, with the temperature 5 cm below the intake orifice being almost at thermal equilibrium with the surrounding environment (Table 7-5). This was also the case with animal experiments. In both types of experiments, the temperature at locations 11 to 28 (Figure 7-1) in the main body of the chamber varied by less than 3%.

SUMMARY

These studies showed that stainless steel chamber walls were very effective at removing heat from an (380 l) inhalation chamber. Cooling the incoming air was not as effective in cooling the stainless steel chamber, because most of the heat transfer from the animals in the chamber was by thermal radiation and the cooled intake air was rapidly heated through the chamber wall by the surrounding room environment. With the chamber air supply at room temperature, heat transfer through noninsulated stainless steel walls was effective in removing approximately 90% of the heat generated by the animals as compared to only 10% removed by the airstream at 100 l/min (Table 7-6).

It is important that design engineers be aware of the relatively large percentage of cooling that takes place as the result of heat transfer to and from the chamber surfaces. With low flow rates, the heat transfer to the surrounding environment can be increased when necessary by painting the chambers (independent of color), thereby maximizing the emissivity of the stainless steel, by attaching cooling fins or cooling coils to the chamber walls, or by directing the room air conditioning ducts directly onto the chamber. In situa-

tions where suitably higher amounts of toxin can be used, the airflow through the chamber can be increased to augment removal of the heat generated by the animals.

This study has also shown that by measuring an effective heat transfer coefficient for a chamber one can determine for specific flow rates the maximum room temperature permissible to maintain a reasonable chamber temperature with varying animal loadings.

ACKNOWLEDGMENTS

The authors wish to thank Mr. Robert Peck and Ms. Joanne Conte for much of the analytical work and Mr. Howard Pate for his assistance with the data handling and analysis. We would also like to thank Dr. Nesim Abuaf and Dr. Thomas Irvine, Jr. for their discussions and comments on heat transfer. This investigation was supported by the United States Department of Energy under Contract No. EY-76-C-02-0016.

Figure Captions

Figure 7-1 Schematic drawing of the 70-cm chamber showing thermocouple locations (x).

Figure 7-2 Schematic drawing of the 70-cm chamber showing heat sources and sinks.

Figure 7-3 Heat loss through the chamber wall depicted in terms of resistance to heat flow. R_{ci} and R_{co} are the resistances through heat conduction inside out outside the chamber, R_k is the resistance to heat transfer through the chamber wall, and R_{ri} and R_{ro} are the resistances through the radiative component of heat loss inside and outside the chamber.

Figure 7-4 Temperature of inlet air (0) and outlet air (30) for the three experiments with animals and no insulation on the chamber.

Figure 7-5 Ratio of the chamber temperature to the room temperature for the three experiments with animals and no insulation on the chamber. The flow rate was increased from 100 to 170 l/min during the time interval between 200 and 240 minutes.

Figure 7-6 Results from an experiment to determine the time required to cool down a semi-insulated chamber with no animals by the cooling of intake air through a dry ice - acetone mixture.

Figure 7-1

Figure 7-2

$$\dot{Q} = \frac{\Delta T}{R}$$

Figure 7-3

Figure 7-4

August 7-5

Figure 14