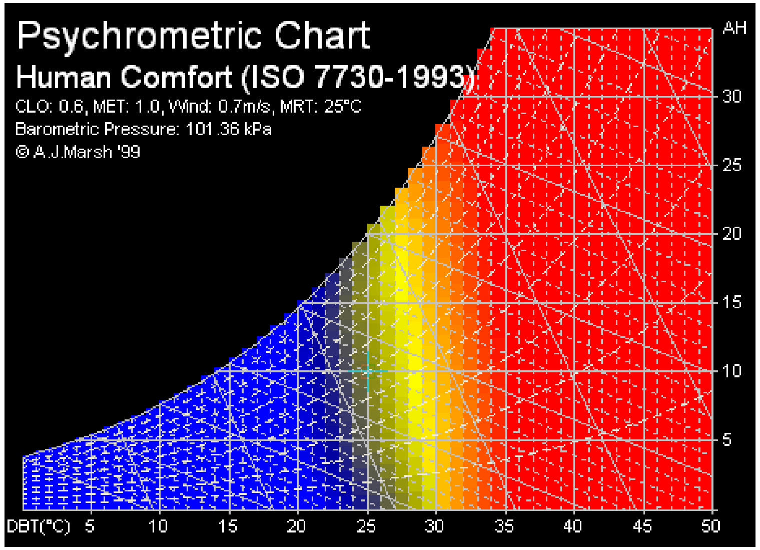
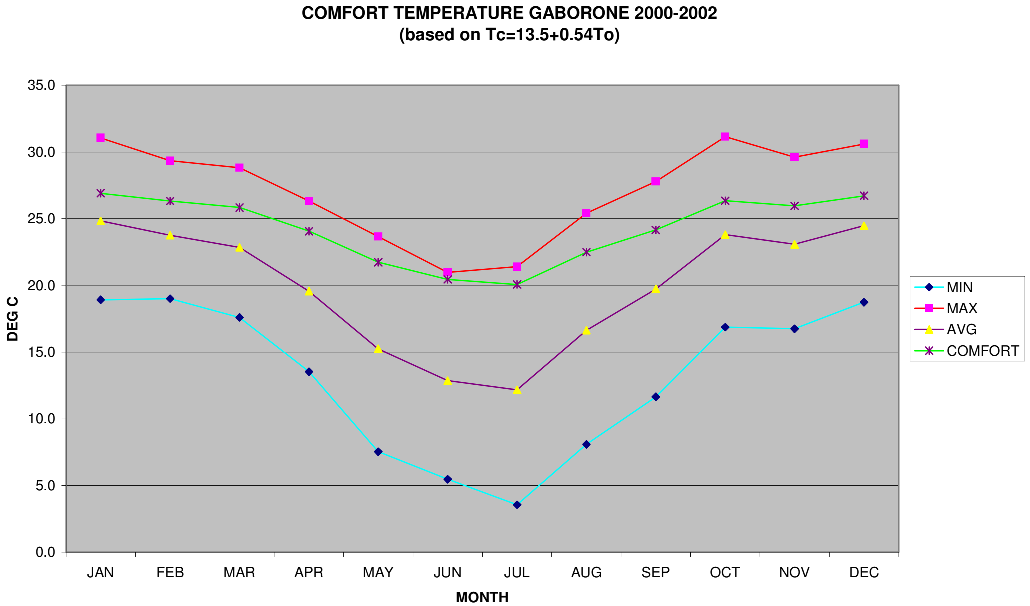
SECTION 4 INDOOR ENVIRONMENT





ENERGY EFFICIENCY BUILDING DESIGN GUIDELINES FOR BOTSWANA

Revision 1

September 2007

ENERGY EFFICIENCY BUILDING DESIGN GUIDELINES FOR BOTSWANA

Sections:

CONTENTS

4. INDOOR ENVIRONMENT

4.1. Overview

This Section addresses the subject of indoor environment and its impact on building energy performance in Botswana. The topics that will be covered are briefly outlined below.

A building may be defined as:

A structure that provides spaces having an environment that is amended from that of its surroundings to suit particular purposes.

The definition of the indoor environment that will be suitable for a particular purpose is therefore very important, as this is a key component of the specification for the building.

Indoor environment has a strong relation to energy performance in most buildings, since a large proportion of the building's energy consumption is used to amend the indoor environment particularly the climate and lighting.

The paper will consider the elements that make up the indoor environment, which include both climatic and non-climatic aspects.

Human comfort is often the main requirement of the indoor environment. The processes that the body uses to achieve climatic comfort will be discussed, as well as the factors that affect this.

Standards are available that attempt to define indoor conditions that will be experienced as 'comfortable'. These are briefly considered, as well as some recent developments in our understanding of how to define standards for comfort, particularly with regard to improving energy efficiency in buildings.

4.2. Elements of Indoor Environment.

The concept 'indoor environment' includes all aspects of the relationship between the occupants and contents of a building and their surroundings within the building. This may be considered in terms of climatic and non-climatic aspects, which are defined by the following principle parameters:

Climatic:

- Dry Bulb temperature.
- Relative Humidity.
- Mean radiant temperature.
- Air velocity.

Other parameters:

- Air quality.
- Aesthetic environment including
  - Spatial geometry
  - Colour.
  - Views.
- Lighting levels and daylighting.

- Acoustic environment.
- Vibration.
- Static electricity
- Ionizing radiation
- Occupancy density

These are discussed in more detail in the following sections, with emphasis on parameters relating to energy consumption.

4.3. Climatic aspects of the indoor environment.

4.3.1. Temperature and humidity.

Temperature and humidity are the most important aspects of the indoor climate. They largely determine human comfort; due to the impact they have on several of the body's heat transfer mechanisms (see below).

Storage of sensitive materials such as books, paper, food, medicines etc. and specifications for machines and equipment may dictate particular requirements for temperature and relative humidity other than for human comfort.

Relative humidity needs to be controlled both for comfort, but also to prevent algae, moulds, fungi etc from forming. Condensation at cold surfaces can also cause problems if humidity is too high. Part of the ventilation requirement comes from the fact that humans emit humidity into the air.

4.3.2. Mean radiant temperature.

The radiant environment may be as important a criterion for comfort as temperature and humidity. The extent of radiant heat transfer between the body and the environment is mainly dependant on the following:

Geometric arrangement of the radiating surfaces.
Surface characteristics of opaque surfaces (wall, ceiling, floor):

- Surface colour and texture (emissivity).
- Surface temperature.

Characteristics of translucent surfaces (window):

- Transmissivity
- Temperature / surface characteristics of bodies beyond the translucent surface (e.g. sun or night sky)

Human body:

- Surface area exposed
- Colour / texture of clothing.

Radiant heat transfer will be particularly significant in spaces in which people are exposed to large surfaces that are at a temperature that is different from the ambient temperature. This may be the case in buildings with large areas of glazing. If these are orientated to admit direct sun, this can be a source of heat gain. Thermal mass walls, floors and ceilings may be used for radiant cooling if the surface temperature is lower than ambient. However it is generally recommended (e.g. by the Danish Building Institute) not to have a $\Delta T > 5\text{-}10°$ C to avoid compromising human comfort in locations with stationary workplaces.

The radiant environment at any particular location is defined by the Mean Radiant Temperature, which is defined as:

"the uniform surface temperature of a black enclosure with which an individual exchanges the same heat by radiation as the actual environment considered".

The weighted average of the Mean Radiant Temperature and the Dry Bulb temperature is termed the 'Operative Temperature' and is the temperature that is generally used in standards for human comfort (e.g. the ASHRAE Standard 55-2004). Buildings with heavyweight ceilings and floors tend to have a lower Mean Radiant Temperature than those with lightweight partitioning elements due to the thermal capacity of these elements. As a result they have a lower Operative Temperature in the summer, even when the air temperature is the same resulting in a more comfortable indoor environment.

4.3.3. Air velocity.

Air movement affects both convection and evaporation, which are important methods of heat loss from the body. The comfort temperature is highly dependant on air velocity, particularly if light clothing is worn. Control of air movement with fans is an important opportunity to give individuals control over their climatic environment. Using air movement to control comfort is a delicate balance since too high an air velocity (or too large a temperature difference) will generally cause discomfort due to draught (typically at air velocities > 0.2 m/s – especially if the air temperature is significantly different from the comfort temperature (most people will have experienced discomfort from e.g. sitting in the cold air stream of an air conditioner, or the relief a fan can provide in an otherwise stifling heat).

4.4. Non-climatic aspects of the indoor environment.

4.4.1. Air quality.

Air quality is an important aspect of the indoor environment that is often neglected in naturally ventilated buildings. It may also conflict with other strategies for energy efficiency.

Reduction of infiltration is an important strategy to reduce energy consumption. This however has the effect of reducing natural ventilation, which allows the build up of indoor air contaminants.

Indoor air quality is determined by many factors, including:

- Equipment and appliances used in the building.
- Occupant activity (e.g. smoking).
- Building materials.
- Outdoor air quality.

Typical contaminants that affect air quality include gasses, particularly Carbon Dioxide, vapours and odours, fungi, moulds, dust particles that may be biological or mineral in origin.

Indoor air quality may be controlled by adopting standards for ventilation such as ASHRAE Standard 62-1989 or the proposed CEN standard "Ventilation for Buildings. Design Criteria for the indoor environment." CEN/CR 1752: 1998-12; CEN; Bruxelles 1998.

The ASHRAE standard is currently under revision, and sets requirements for outdoor air ventilation for different purposes (typically 2.5l/s per person for office spaces).

Danish guidelines recommend at least 7 l/s per person in offices (4 l/s per person is the minimum), where smoking is not permitted. If smoking is permitted 10 l/s pr person is the minimum and 20 l/s pr. person is recommended. Danish Building regulations require a minimum 0.5 ACH (air changes per hour).

Alternatively performance criteria may be adopted, specifying target concentrations of contaminants.

An example of such criteria is the National Ambient Air Quality Standards that are defined by the EPA as a requirement of the Clean Air Act (USA). Such standards are difficult to implement, due to the problem of measuring a large number of different potential contaminants.

4.4.2. The aesthetic environment.

The aesthetic environment is an important aspect of the indoor environment.

The geometry of the spaces in the building affects how people respond to the rooms. High ceilings create a feeling of spaciousness, but can also be intimidating, whereas low ceilings can make a room feel more intimate. Spatial geometry also affects the air temperature and air movement in a room. High ceilings can allow stratification of air, so that the warmer air rises above the inhabited zone, which will be cooler.

Colour is a very important aspect of the indoor environment. People respond to colours with their emotions and feelings, and colour can be used to change the perception of space, e.g. a dark colour on the ceiling makes it appear lower. Colours also impact on illumination contrasts which if too high may cause discomfort. Colour is an integral aspect of lighting design; light colours reflect light, and can reduce the number and power of light sources required to achieve a particular lighting level. White ceilings combined with light shelves can allow daylight to penetrate deeper into a building.

Views from windows change the way people respond to indoor environments. The opportunity to see outdoors can make people feel less enclosed, which can affect their work performance positively. Views to green areas, vegetation and water are generally considered to positively affect the perceived comfort of indoor environments. Excessive distraction can also reduce performance, especially in classrooms, where views may need to be limited to avoid this.

4.4.3. Lighting levels and daylighting.

The light characteristics of the indoor environment have a major impact on almost all activities that take place there, and also on the energy performance of the building.

The details of what these characteristics should be, and how they may be achieved in an energy efficient manner are discussed in detail in **Section 9, Lighting, Artificial and Daylighting**.

Specifications of lighting levels required for different tasks have been defined in various standards, codes and guidelines. Recent research has focussed on the impact of the quality of lighting as well as the quantity. For many years the importance of factors such as colour response of different light sources have been studied.

Many studies have been conducted on the impact of lighting levels on behaviour, including productivity, retail sales, absenteeism, etc. These have demonstrated a strong correlation between behaviour and lighting levels including for example, significant increases in retail sales with higher light levels.

4.4.4. Static electricity

Static electricity tends to be an important criterion for comfort in environments with low air humidity; frequently the case in Botswana. It is more serious where insulating floor finishes are used, and is a particular problem in environments in which sensitive electronic equipment is used, manufactured or repaired.

It is not especially relevant in relation to energy efficiency.

4.4.5. Ionising radiation

Increasing concern is being focussed on sources of ionising radiation, as for example from leakage of the gas Radon from the ground. This is a very localised phenomenon that appears not to have been sufficiently researched in Botswana to determine the extent to which it may be a problem.

4.5. Human comfort.

Human comfort is related to the individual's perception of the quality of the environment in which he or she is situated. People experience the environment differently, so that one person may feel uncomfortably hot and another too cold in the same place. Designing for human comfort is therefore always a compromise, the aim being to provide an indoor climate that is experienced as adequately comfortable by a large majority of people. A common unit for the measurement of human comfort is the PMV. This is the 'predicted mean vote', and indicates the percentage of people who are predicted to feel comfortable in any given set of conditions. In practice it is generally difficult to get acceptance ratings much over 80-90%, which are therefore generally used as normal design values.

The physiology of human beings as warm-blooded mammals requires the internal body temperature to be maintained within very close limits (between 36°C and 38°C, the normal temperature being 37°C). If it falls below 30°C or rises above 41°C, death is imminent. Considering that humans live in environments where the external temperature varies between -40°C to over 50°C, this is quite a demanding requirement. The body has a number of mechanisms that it uses to achieve this. Heat is released into the body by all metabolical processes, including eating, respiration, movement, etc. In order to maintain a balanced temperature, the body must therefore find ways to lose heat at the same rate at which it is being produced by these processes.

4.5.1. Mechanisms of heat exchange.

There are essentially four basic mechanisms by which the body exchanges heat with its environment.

- Evaporation.
- Convection.
- Radiation.
- Conduction.

Evaporation and convection are mechanisms of heat loss for the body. Radiation and conduction can result in either heat gain or heat loss depending on the temperature of body relative to its surroundings.

4.5.2. Evaporation.

Evaporation takes place during respiration, whereby fluid from the body enters the air that we breath in the lungs and the respiratory duct and is evaporated, absorbing the latent heat of evaporation from the surfaces of these organs.

Evaporation also takes place at the skin as a result of perspiration.

The rate of heat transfer by evaporation is determined by the rate at which moisture can be removed by the air. This in turn is dependant on both the capacity of the air to absorb moisture, and the rate of movement of the air. The capacity of the air to absorb moisture is dependant on its relative humidity, which is a function of temperature and absolute moisture content.

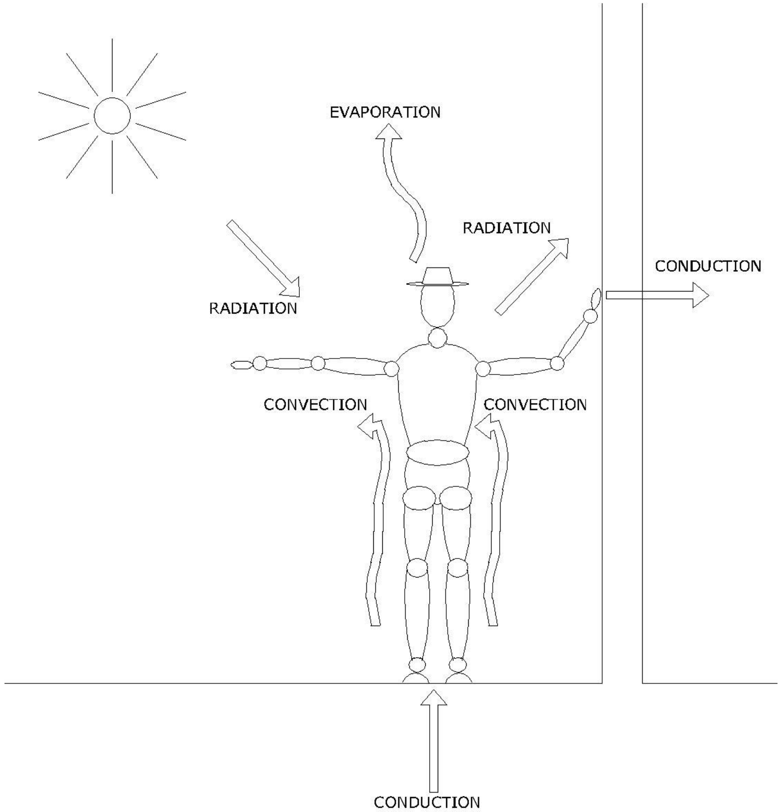


Fig 4.1 Heat exchange between the human body and its surroundings.

4.5.3. Convection.

Convective heat transfer occurs where the skin is in contact with a fluid at a different temperature, such as air.

The rate of heat transfer by convection is determined by the difference in temperature, and the flow rate of the fluid (air speed), as well as the geometry of the surface-flow interface (e.g. the exposed surface area).

4.5.4. Radiation.

Radiant heat transfer takes place between any two bodies that are in sight of each other and at different temperatures.

The rate of heat transfer by radiation is determined by the relative areas of the two surfaces, their surface temperatures and their emmittance / absorbtance properties at the respective wavelengths relating to these temperatures.

4.5.5. Conduction.

Heat transfer by conduction occurs where the skin is in direct contact with another surface, such as the floor, and there is a difference in temperature between the surfaces.

The rate of heat transfer by conduction is determined by the conductivity of the two surfaces, their heat capacity and the difference in temperatures.

4.6. Factors affecting human comfort.

4.6.1. Clothing.

All the four mechanisms of heat transfer are greatly influenced by clothing. This can provide insulation to reduce mainly convective and radiant heat transfer (but also conductive – e.g. wearing gloves and protective clothing when hot or very cold surfaces/objects are handled. Shoes reduce heat loss/gain from the floor). Clothing can prevent air movement at the skin, which almost eliminates convective and evaporative heat transfer from the skin. The effect of clothing on evaporative heat transfer is dependant on the type of material. Some materials, such as cotton and wool allow moisture to pass through, and therefore do not inhibit evaporative heat loss as much as non-porous materials. Clothing can also reduce radiant heat transfer, as the thermal resistance of the clothing will reduce the flow of heat from the body.

By selecting appropriate clothing for a particular climate and activity, the range of indoor climate that is experienced as comfortable can be considerably extended, both to lower temperatures, if insulating clothing is worn, or to higher temperatures with clothing that allows free flow of air to a larger area of the body.

Cultural aspects can have an important influence on what is acceptable attire for particular activities. Recently the Japanese government has introduced a policy called 'Cool Biz' to discourage the wearing of jackets and ties in the summer, as a way to reduce energy consumption in office buildings.

A measure of the thermal resistance of clothing has been developed, called the 'clo-value'. This is a measure of the ratio of thermal resistance of clothing to a standard value of $0.155m^2K/W$, which is typical of a business suit.

Typical clo values are as given in Table 4.1

Clo – value	**Example**
0	Naked, swimwear
0.5	Light trousers + shirt, light dress + blouse
1.0	Business suit, dress + jumper
2.0	Heavy suit, overcoat, gloves and hat

Table 4. 1.Typical clo-values. Source: www.esru.strath.ac.uk/Courseware/Class-16293/6-Comfort.pdf

4.6.2. Activity.

As stated earlier, the body is continuously producing heat as a result of metabolic processes. The rate of heat production varies greatly depending on the activity that one is engaged in. Typical rates of heat output are presented in Table 4.2.

Activity	Heat output (male): Watts	Heat output (female): Watts
Sleeping	70	60
Seated	115	98
Light work	150	128
Medium work	265	225
Heavy work	440	374

Table 4.2. Heat output for different activities.

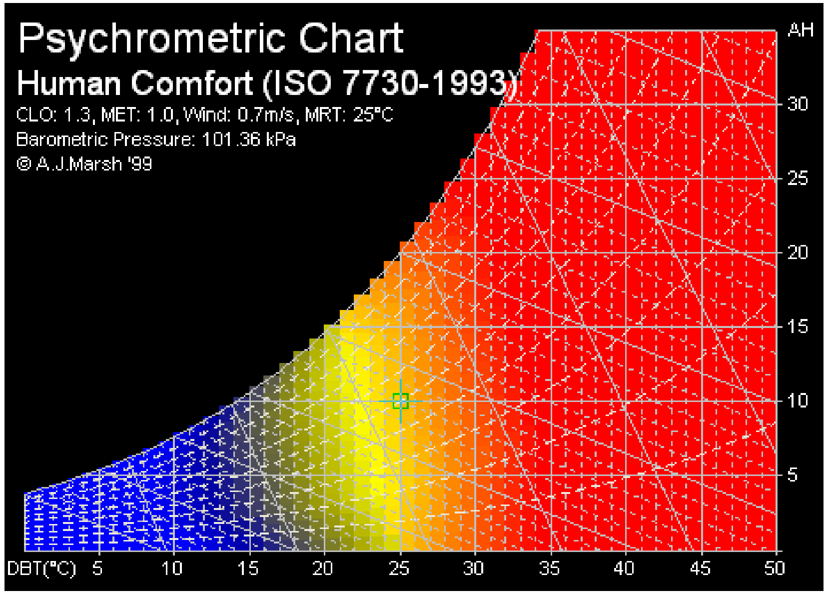


Fig 4.2 Psychometric chart (source: The Psych Tool, Square One Research Ltd.).

4.6.3. The comfort zone - the psychometric chart.

Human comfort in the indoor environment is related to the interaction of a large number of variables in addition to temperature.

These can be illustrated by means of a psychometric chart, which shows the interaction of temperature and humidity. The combination of these parameters that is experienced as comfortable can be shown for different levels of clothing and air speed. This is illustrated in Fig. 4.2.

4.7. Specification of the indoor thermal environment.

The specification of the indoor climate is an important component of an effective design brief for any building, particularly in relation to energy performance. The preceding discussion on the impact of climate on performance shows how comfort is influenced by factors such as activity and clothing. Other factors also influence comfort, including expectations based on recent weather. There is also considerable variation between individuals in their perception of comfort. As a result it is impossible to satisfy all the occupants of an indoor space.

Many studies have been conducted to determine the conditions for human comfort. These included surveys of large numbers of people who were asked to indicate their level of comfort on a scale from say, -3 (cold) to +3 (hot). This is known as the PMV scale (Predicted Mean Vote).

Tests were carried out on large groups of individuals by Fanger in Denmark and by others in many other countries. Fanger concluded that:

- there is no significant difference in comfort perceptions due to geographical location or season (including tropical regions);
- there is no significant difference due to age (e.g. because older people have lower metabolic rate counteracted by lower perspiration rates);
- there is no significant difference due to sex;
- there is no significant difference due to body build;
- there is no significant difference due to ethnic origin.

Based on these studies, empirical formulae have been prepared that predict the degree of comfort that will be reported by a certain proportion of occupants under particular conditions.

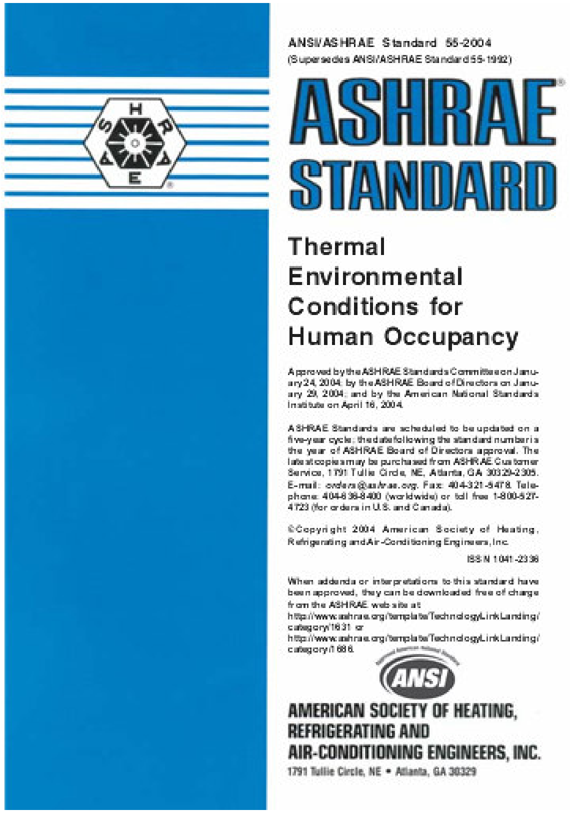
4.7.1. ASHRAE Standard 55-2004.

The most commonly accepted standard specifying the thermal indoor environment for comfort is the ASHRAE Standard 55-2004 - Thermal Environmental Conditions for Human Occupancy (ANSI Approved). This is similar to the CIBSE Standard 55-1992 - Thermal Environmental Conditions. This standard specifies the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants within a space. The environmental factors addressed are temperature, thermal radiation, humidity, and air speed; the personal factors are those of activity and clothing.

The ASHRAE standard has an upper limit for humidity ratio of 0.012. This translates approximately to a relative humidity of 75% at a dry bulb temperature of 21°C and 53% at 27°C. In Botswana RH is often above the minimum level, particularly in the mornings in summer.

There is some doubt as to whether this requirement is fully justified. The characteristic that is defined is humidity ratio, whereas it may be more appropriate to define relative humidity. It may also be that the boundary is lower than necessary in terms of people's perception of comfort.

The specification to be adopted for maximum humidity has a big impact in determining the conditions under which evaporative cooling is effective. An unnecessarily low ceiling for humidity would therefore restrict the use of evaporative cooling in situations where it may in fact be effective.


ANSI/ASHRAE Standard 55-2004
(Supersedes ANSI/ASHRAE Standard 55-1992)

ASHRAE STANDARD

Thermal Environmental Conditions for Human Occupancy

Approved by the ASHRAE Standards Committee on January 24, 2004; by the ASHRAE Board of Directors on January 29, 2004; and by the American National Standards Institute on April 16, 2004.

ASHRAE Standards are scheduled to be updated on a five-year cycle; the date following the standard number is the year of ASHRAE Board of Directors approval. The latest copies may be purchased from ASHRAE Customer Service, 1791 Tullie Circle, NE, Atlanta, GA 30329-2305. E-mail: orders@ashrae.org. Fax: 404-321-5478. Telephone: 404-636-8400 (worldwide) or toll free 1-800-527-4723 (for orders in U.S. and Canada).

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When addenda or interpretations to this standard have been approved, they can be downloaded free of charge from the ASHRAE web site at http://www.ashrae.org/template/TechnologyLinkLanding/category/1631 or http://www.ashrae.org/template/TechnologyLinkLanding/category/1686.

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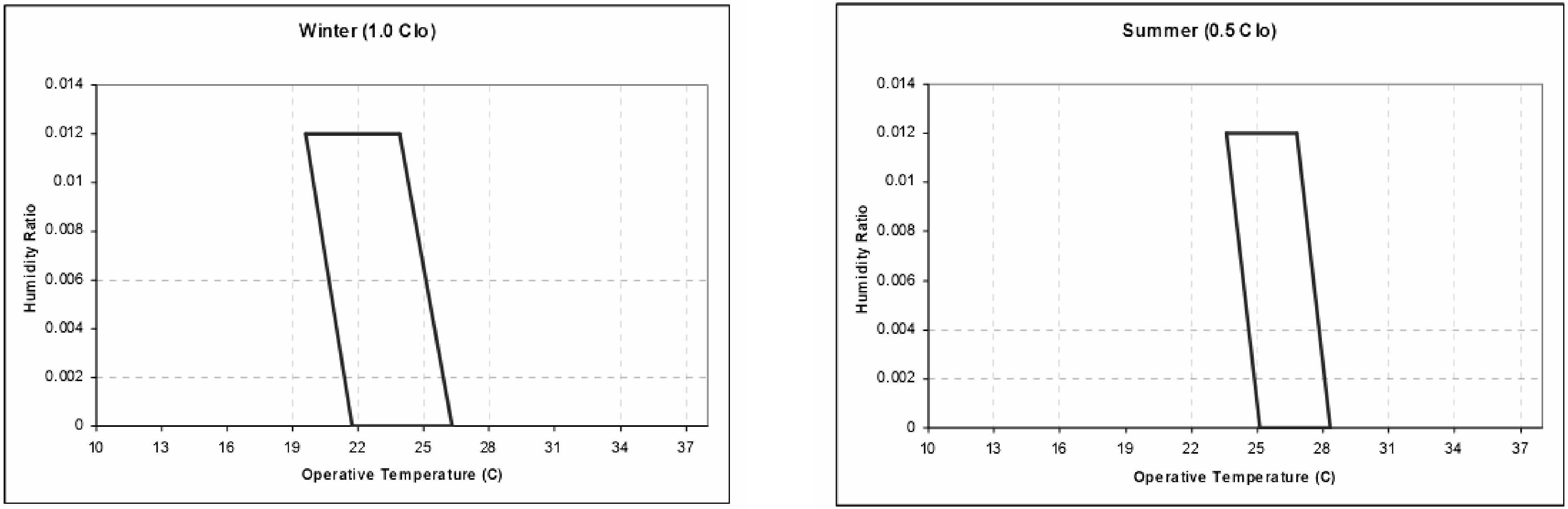

Fig 4.3 Simplified graphs indicating winter and summer comfort zones based on ASHREA 55-2004
(Source: Energy Plus Reference Manual)

4.7.2. Adaptive comfort.

The standard acknowledges the concept of adaptive comfort. It has been found that people experience thermal comfort quite differently in buildings that are naturally ventilated without mechanical cooling than in buildings that are mechanically cooled. The standard specifies a far more relaxed set of comfort conditions for such buildings, with the requirement that people should have the opportunity to open and close windows, and freedom to adapt their clothing to achieve comfort. The comfort zone is then related to mean outdoor air temperature, and for typical January conditions in Gaborone (To=25°C) would be between 22-29°C. The acceptable temperature range for air-conditioned buildings in the same situation is between 25-28°C for light clothing (0.5clo) or 19-25°C with more formal clothing (1.0clo).

The specification for air-conditioned buildings also requires that the variation in temperature during any 15min period is no more that 1.1°C. This typically determines the cycling band for the control system. No such requirement is made for the adaptive comfort specification, since it is assumed that people will respond to any variations within the comfort zone by making adjustments to their clothing, or ventilation.

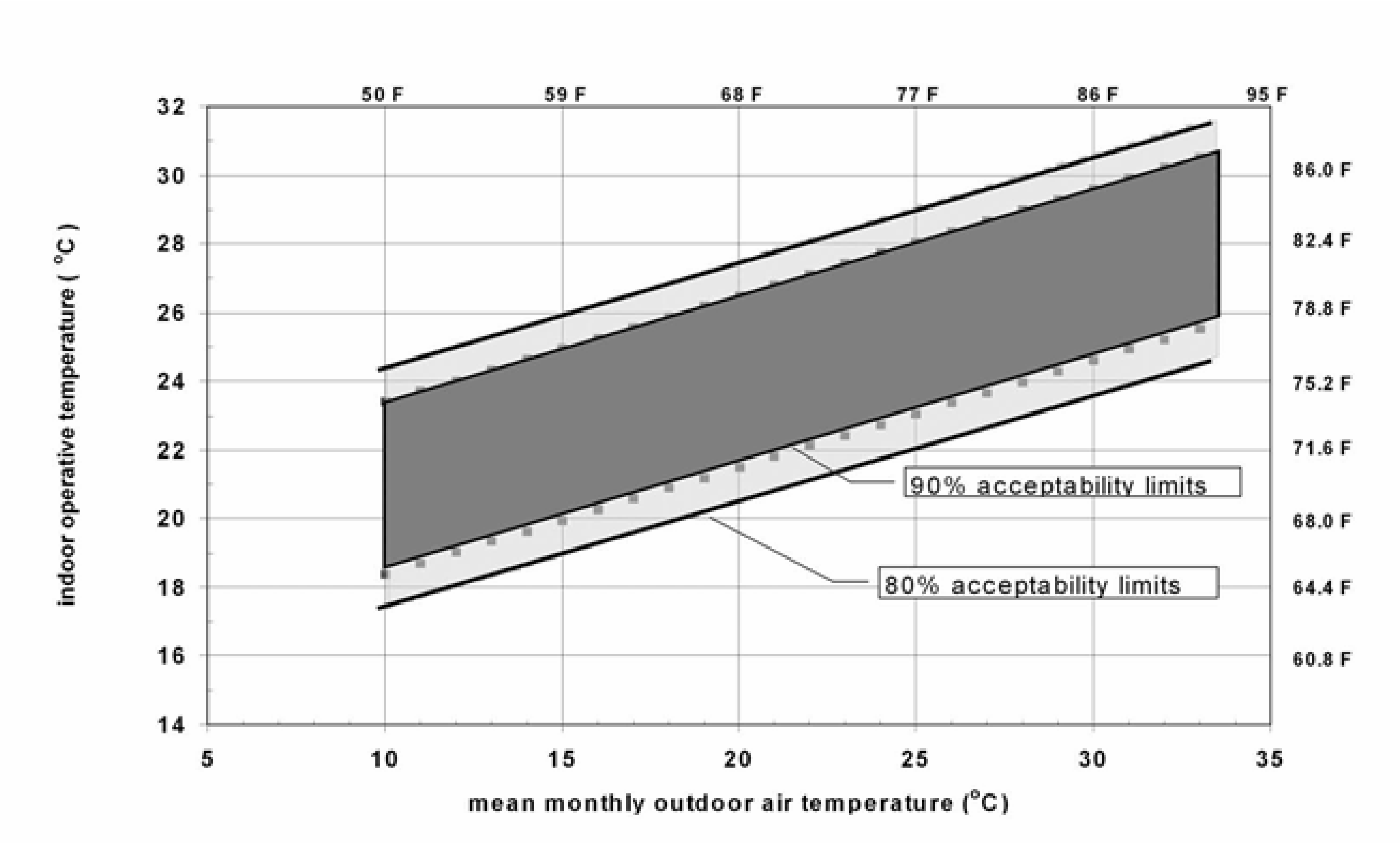

Fig. 4.4 Adaptive comfort temperatures (Source: ASHRAE Standard 55-2004)

4.7.3. Adaptive comfort in conditioned buildings.

It appears that there is considerable scope for energy savings if the concepts of adaptive comfort could also be applied to conditioned buildings. This would require an approach that allowed some user adaptation within the overall framework of a controlled mechanically conditioned building. A simple example of such an approach would be the use of individually controlled fans and radiant heaters to allow individuals more control of their immediate surroundings. Encouraging the use of thermally appropriate clothing would further relax the demands on the mechanical equipment.

Research summarised by Nicol, J.F. and Humphreys, M.A. in their paper "Adaptive thermal comfort and sustainable thermal standards for buildings." [3] suggests that the monthly mean temperature may not be the most appropriate for determining the comfort zone in an adaptive comfort model, and suggest that a method that accounts for the temperature variation of the previous few days would provide a more accurate model. An algorithm for determining this is proposed, which could also be used control temperature in conditioned buildings, resulting in substantial energy savings.

4.7.4. Adaptive comfort applied to Botswana climate.

The relationship between indoor comfort temperature and outdoor mean temperature has been consistently found to be close to:

$$\mathbf{Tc = 13.5 + 0.54To}$$

Where Tc = Thermal comfort temperature
To = Monthly mean outdoor temperature

When this is applied to the temperature data for Gaborone, the thermal comfort temperature is as shown in Fig.4.5.

This indicates that at all times of the year the comfort temperature is above the mean monthly temperature. This suggests that for buildings for which the envelope loads dominate, thermal comfort should be achievable with no mechanical equipment, although other aspects of indoor environment may still require this, e.g. mechanical ventilation to achieve air quality standards. Even buildings with more substantial internal loads could be comfortable with minimal energy use if this is acknowledged as an important design criterion, and the knowledge and tools to achieve it are available.

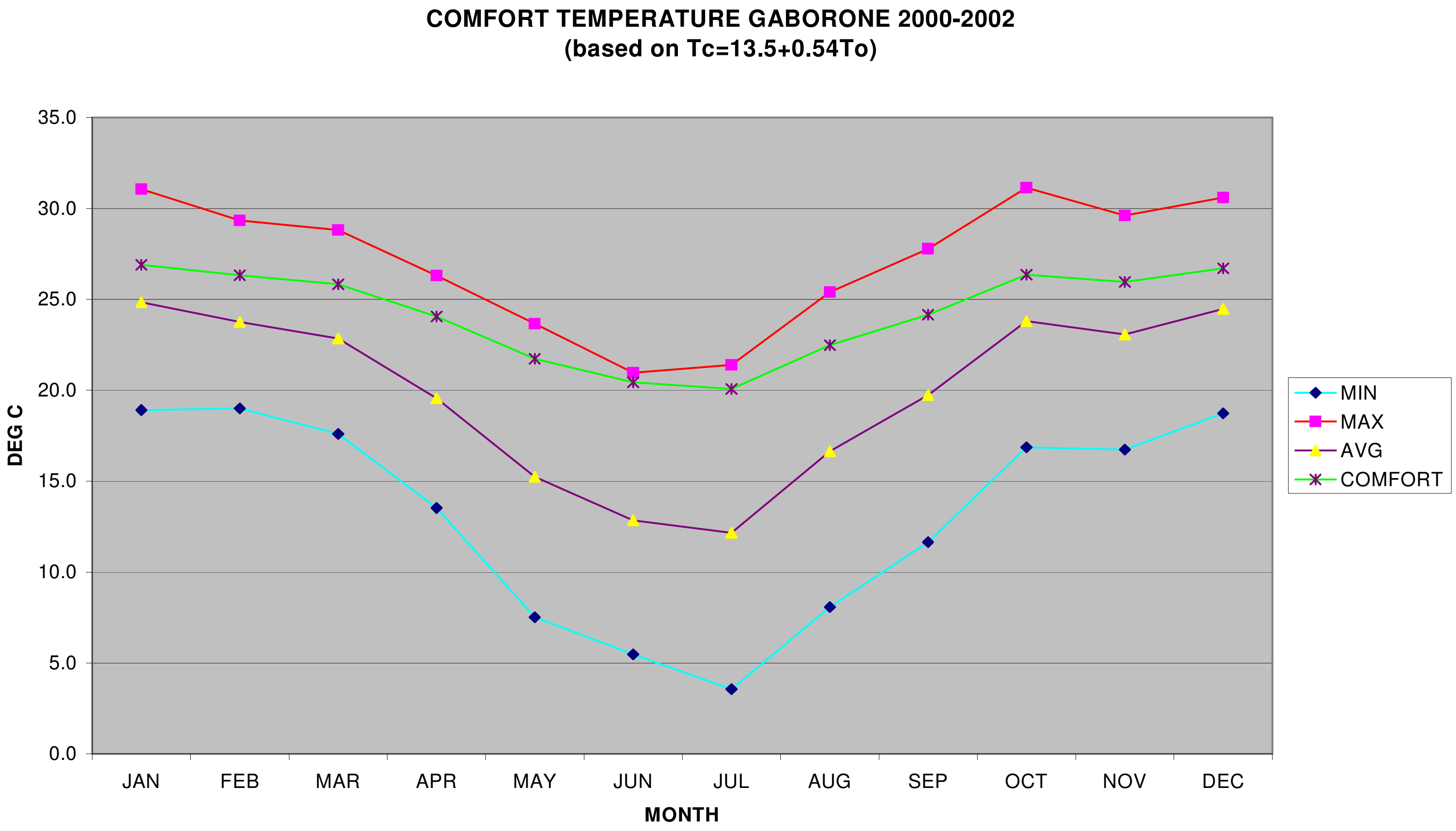

Fig. 4.5 Comfort temperature for Gaborone.

4.8. Resource material

4.8.1. Books and papers

Energy Plus. "Input Output Reference - The Encyclopedic Reference to EnergyPlus Input and Output" December 2005.

Green Building Guidelines: Meeting the Demand for Low-energy Resource-Efficient Homes, 2004. Sustainable Buildings Industry Council.

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Tutt, P. and Adler, D. (Ed.). 1979. New Metric Handbook – Planning and Design Data. Oxford: Butterworth-Heinemann Ltd.

University of Strathclyde. Unit 6 Thermal Comfort. Course 16293: "Environmental Engineering Science 1." Course material for Energy Systems Research Unit, (ESRU), University of Strathclyde.

4.8.2. Codes and Standards.

ASHRAE Standard 55-2004. Thermal Environmental Conditions for Human Occupancy

ASHRAE Standard 62.2-2004 – Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings (ANSI Approved)

CEN Standard: "Ventilation for Buildings. Design Criteria for the indoor environment. CEN/CR 1752: 1998-12; CEN; Bruxelles 1998

4.8.3. Websites.

ASHRAE American Society of Heating, Refrigerating and Air-conditioning Engineers. http://www.ashrae.org/

CIBSE Chartered Institute for Building Services Engineers http://cibse.org/

EERE Building Technologies Program Home Page
http://www.eere.energy.gov/buildings/

EDR. Energy Design Resources
http://www.energydesignresources.com/

SBIC. Sustainable Buildings Industry Council.
http://www.sbicouncil.org/

SQUARE ONE environmental design, software, architecture, sustainability.
http://www.squ1.com/site.html

WBDG - Whole Building Design Guide
http://www.wbdg.org/