A New Approach to Radiant Cooling for Human Comfort

By

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Summary.—Radiant cooling panels are described in which the temperature of the heat sink is considerably lower than the dewpoint of the surrounding air. The cold plate is covered by several layers of polythene which is transparent to the long wavelength radiation from the human body, but effectively insulates the plate as regards convection and condensation.

Tests with an artificial body show that a cooling rate of 200 to 300 B.Th.U. per hour is possible by radiation alone, which should be adequate for the comfort cooling of subjects at rest. No systematic observations have yet been made on the comfort of human subjects.

Radiant cooling appears to have useful applications in the Tropics, since it is not affected by natural ventilation or high humidities.

1.—Introduction.

The principles which govern the heat balance between the human body and its surroundings have been well understood for some time. The importance of radiation in this heat balance is also known. For example, when the surrounding walls and air are at 70°F., radiation from a clothed subject at rest accounts for about 50 per cent and convection about 25 per cent of the total heat loss (Refs. 1, 2, 3). Heating systems are frequently designed using radiant panels to provide comfort conditions. The reverse process of providing cool panels to which the body can radiate when the air temperature is unacceptably high has also been used, although it is not at all common.

The problem associated with this type of cooling has been that the wall temperature must be kept above dewpoint to prevent condensation, and therefore the radiation intensity at the wall surface is very low since there can be only a small temperature difference between the wall and body temperature. Accordingly it is very difficult in such installations to arrange sufficient area of cooling panels to provide comfort conditions by radiant cooling alone. Furthermore, such systems are completely impracticable under tropical conditions where high humidities are common.

The equipment described in this paper has been developed to overcome this problem and aims to provide a heat sink to which the body can radiate, especially when the environment is such that the only other way it can lose heat is by extensive sweating, as is frequently the case in the Tropics. The work is part of a programme of research concerned with the reduction of human environmental stress under tropical conditions.

The basic heat balance relationship is :—

$$M = \pm R \pm C + E \pm S$$

where

- M = the heat production of the human body due to metabolism.
- R = the radiation exchange with the surroundings.
- C = the heat transfer by convection.
- E = the heat lost by evaporation.
- S = the heat stored in the body due to change in deep body temperature.

For equilibrium conditions over long periods $S = 0$, and the value of M depends on the work output of the subject. Normal metabolism for a clothed subject at rest is usually taken to be 400 B.Th.U. per hour. If such a subject is exposed to conditions where the wall and air temperatures are steadily increased, the value of R decreases until it becomes zero at about 100°F. (Fig. 1). The body then is solely dependent on evaporation of sweat E to offset its heat production. It is this large increase in E which causes the discomfort associated with a hot environment. If, however, means could be found of increasing R under these conditions, the body's automatic regulating mechanisms would reduce E and the subject would once again feel comfortable. A certain amount of sweating does not appear to affect comfort : in fact it would seem that this could be 100 to 150 B.Th.U. per hour. It is not known to what extent this evaporation loss could be increased in the presence of a heat sink without the subject becoming uncomfortable.

The object of the present work, therefore, has been to devise a radiation sink capable of removing 200 to 300 B.Th.U. per hour from a clothed subject in a tropical environment. The method, nevertheless, can be applied equally in temperate zones and may be used for heating as well as cooling.

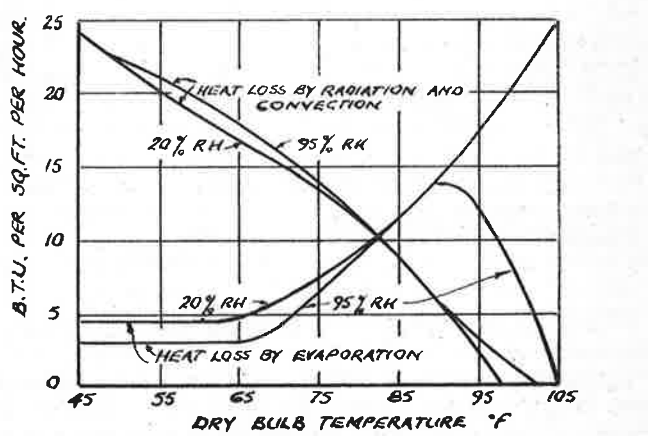

Fig. 1.—Normal Heat Loss by Evaporation and by Radiation and Convection Combined, in relation to Environmental Temperature and Humidity. Yaglou (Ref. 2).

The heat sink is a radiant cooling panel which is constructed on the principle that a flat plate absorber, if covered with one or more sheets of a transparent vapour-proof material, will prevent condensation on the cool plate and at the same time reduce losses due to convection to a very small value. The construction must be such that the outer transparent layer is above the dewpoint of the air in the room. Moreover, it is necessary that the materials selected be transparent to the long wavelength radiation from a body at 85°F. One such substance is polythene, which as a 0.004 in. thick sheet has a transmittance of about 85 per cent for wavelengths between 4 and 35μ.

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When such a panel or system of panels is placed in a room the heat exchange between them and any human subjects is by radiation alone. It is therefore necessary to take into consideration not only the temperature of the various surfaces but also their emissivities and shape factors with respect to one another. The development of a rational equation which takes these factors into consideration has been undertaken by Raber and Hutchinson (Ref. 4), who also have published a series of curves from which the shape factors of plane surfaces and the human body in various attitudes may be evaluated. It will be appreciated that the shape factor and therefore the heat exchange will vary as the subject moves around the room. This is only one of the many factors which would have to be taken into consideration by designers before such a system could be properly evaluated. The work, however, is presented at its present stage of development in order to report what is believed to be a new approach to the problem of human comfort cooling, and no claim is made that it is fully developed.

2.—Description of Equipment.

The experiments were carried out in a specially constructed room capable of being maintained at high temperatures and high humidity. The initial work was done with the room at 85°F. D.B., 81°F. W.B., (85 per cent R.H.), which is an effective temperature of 83°F. More severe conditions will be considered in later experiments. In this connexion it should be noted that Jones and MacVicar (Ref. 5) quote 90° D.B., 86° W.B. as the outside conditions for which passenger vessels should be designed when passing through the Red Sea.

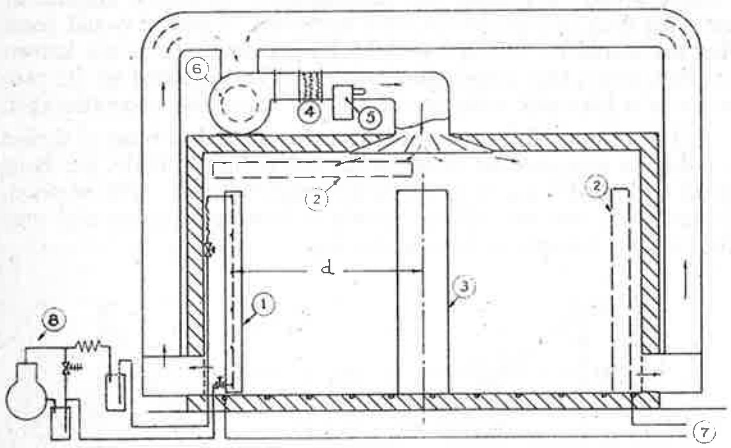

Fig. 2.—Test Room for Radiant Cooling Measurements.

1. Radiant cooling panel.
2. Alternative cooling panel positions.
3. Artificial body.
4. Air heater.
5. Electrode humidifier.
6. Fan.
7. Floor heater.
8. Refrigeration system for panels.

The test room (Fig. 2) is insulated and vapour-sealed, and temperature gradients within it are reduced by means of wall panels of light gauge sheet-metal behind which room air can circulate, the floor being electrically heated by M.I. cable. In this way air velocity in the vicinity of the subject can be kept to a low value of less than 30 ft./min., and temperature gradients within the room can be kept below 2°F. The accuracy of control at the control point is $\pm\frac{1}{2}$°F., and no point departs from this by more than ± 1°F. This order of accuracy is necessary since a change in wall temperature of even a few degrees could introduce a serious error into the radiant heat exchange observations. Humidity control is by means of an electrode humidifier (Ref. 6) and hair humidistat which gives short term control to ± 2 per cent R.H.

The radiant cooling panels may be moved around inside the room to provide a variety of experimental set-ups. The panels are cooled by direct expansion through capillary tubes supplied by flexible connexions from a Freon-12 refrigeration compressor outside the room. The suction pressure, and therefore the plate temperature, is controlled by the bypass system described by Kowalczewski (Ref. 7), modified for use with capillary expansion control. The capillary is chosen so that the refrigerant returning to the low pressure receiver is always saturated, thus avoiding the necessity of any liquid injection into the bypass hot gas. In this way the mean temperature of the plate can be kept constant. With this arrangement observations can be made on the radiation exchange from human subjects or, alternatively, from an artificial body of the same surface area as the human body. For measuring radiation exchange a net radiometer was employed.

2.1 *Radiation Absorbing Panel*:

The radiation absorbing panel (Fig. 3) consists of a blackened absorbing plate to which tubes are thermally bonded, forming the refrigeration evaporator. In the experimental model, this plate (1) is nominally 6 ft. by 4 ft. and is used in a box frame (3) with insulation (2) to prevent excessive heat leakage from the rear. In front of this are three frames (4), (5), and (6), over which 0.004-in. polythene is stretched and sealed at the edges to prevent moisture ingress. Whilst the polythene has a transmittance of over 85 per cent, even a thin film of water would be almost opaque, so it is important that no condensation on any of these films is permitted to take place.

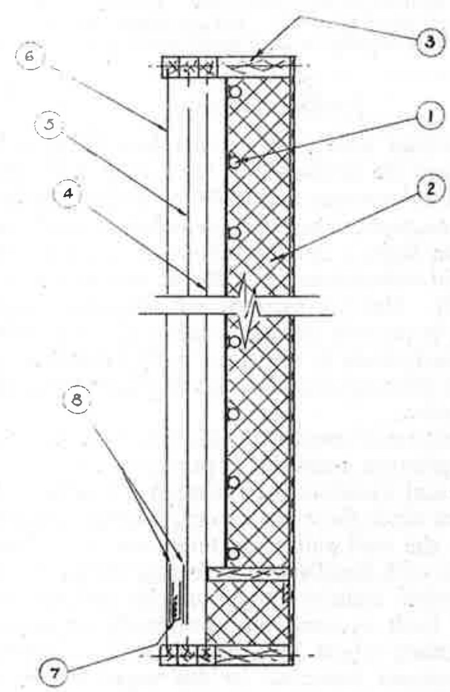

Fig. 3.—Radiation Absorbing Panel.

Condensation on the outside is prevented by maintaining the temperature of film (6) as near as possible to the dry bulb temperature in the room, by means of a small electric heater (7). This causes a current of warm air to pass up between films (5) and (6), and down between films (4) and (5) through holes in the top and bottom of film (5). Condensation on the inside is controlled by means of small connecting holes in film (4), equalizing the water vapour pressure inside and maintaining it at the saturation vapour pressure corresponding to the temperature of the cold plate. Thus, any water vapour which diffuses, either through the polythene or any imperfectly made joints, will condense and freeze on cold plate (1) where, as a black body, it does no harm. Periodically, of course, it would have to be defrosted. In order to prevent excessive radiation exchange between the heater (7) and the surroundings, two radiation shields (8) are provided on either side of it. The plate temperature is measured by nine copper-constantan thermocouples soldered to it.

2.2 *The Artificial Body*:

The artificial body for physical radiation exchange measurements comprises an elliptical cylinder 5 ft. 10 in. by 1 ft. 6 in. by 9 in., having a total surface area including the top end of 22.5 sq. ft.

The surface temperature of the artificial body used in the present experiments is controlled by M.I. cable soldered to the inside surface and measured by means of ten thermocouples, five on the front and five on the rear face. The power input could be varied from a few watts to several hundred watts.

2.3 *Radiation Measurements* :

For radiation measurements the net radiometer used is based on the principle proposed by Gier and Dunkle (Ref. 8), and subsequently developed by Funk (Ref. 9) of the C.S.I.R.O. Division of Meteorological Physics and now manufactured commercially in Australia. It consists of a thermopile with 250 junctions, which detects the temperature difference between two parallel plates close together which are exposed to radiation, but protected from convection by means of two small polythene hemispheres. It measures the net radiation intensity normal to the plane of the instrument and will detect a radiation intensity of 0.5 B.Th.U. per hour per sq. ft.

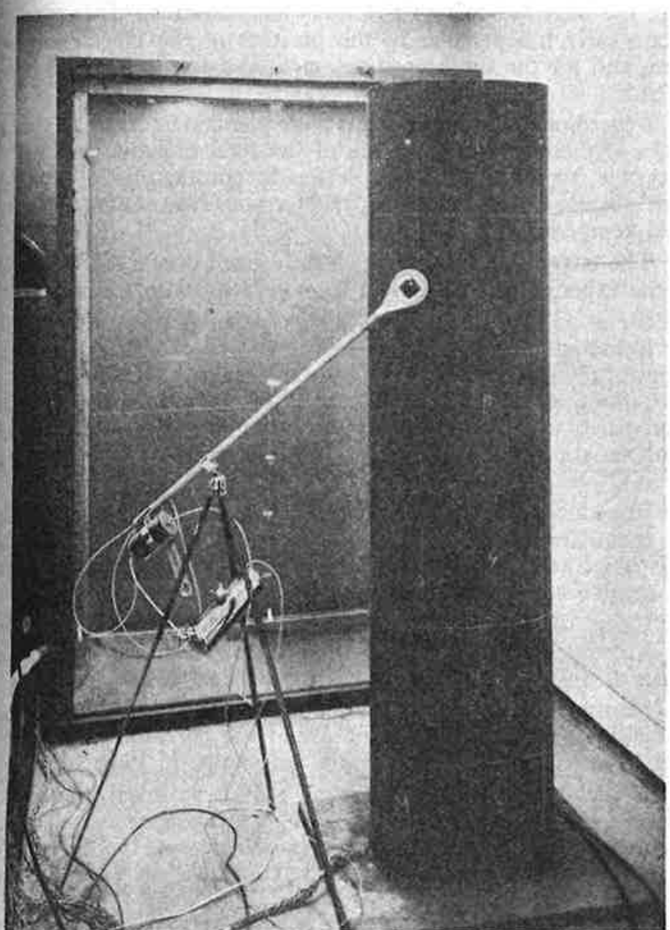

Fig. 4 (*a*).—*Experimental Arrangement showing Radiant Cooling Panel, Net Radiometer and Artificial Body.*

The radiant cooling panel, the artificial body, and radiometer can be seen in Fig. 4(*a*), while Fig. 4(*b*) shows an external view of the air conditioned room with some of the instrumentation.

Integrating the net radiation over the surface of the artificial body with this instrument is very time consuming. Accordingly a "zero convection" method was developed enabling the total radiation from the artificial body to be obtained by a single reading from outside the test room.

Twelve copper constantan thermocouples distributed over the surface of the body and thermally bonded to it were connected in series with 12 others supported about 1 in. from the surface. The first group represented the mean surface temperature of the body, and the second group, the mean temperature of the surrounding air. When the e.m.f. from the 24 thermocouples is zero the convection heat exchange is also zero, and the power input to the body is a measure of the radiation from the body to the surroundings.

The e.m.f. was measured on a 0 to 1 mV potentiometer recorder and the method gave good agreement with the net radiometer values.

3.—Experimental Results.

The development and testing of the radiation absorbers was planned in three stages :

(1) A pilot experiment to check the overall effectiveness of the construction proposed for the radiant cooling panel.

(2) Measurement of the radiation exchange between an artificial human body and various panel arrangements to determine the most promising arrangement to be used in further tests with human subjects.

(3) Using these panel arrangements to determine their influence on the comfort of human subjects.

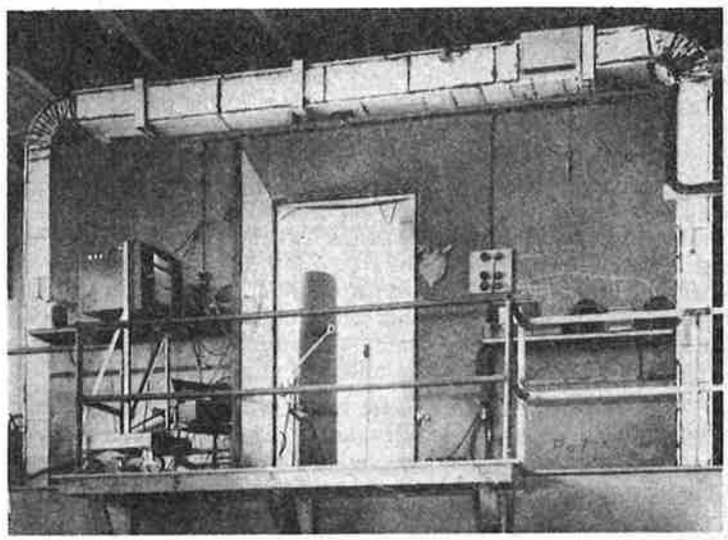

Fig. 4 (*b*).—*General View of Test Room.*

Since this third stage will be difficult to arrange, it was considered essential to carry out as much as possible of the development of the equipment during stage (2), when the effect of alterations could be measured in terms of actual values of radiation exchange. Stage (3) of this work has not yet been started.

The initial work has been performed with the object of confirming that a radiation exchange of 200 to 300 B.Th.U. per hour from the human body is possible, and for this purpose an object approximately the same size and shape as a typical human is adequate. Subsequently, physiological observations will be conducted in collaboration with the School of Public Health and Tropical Hygiene to determine on a statistical basis the effect on human comfort.

Methods of conducting such experiments have now been established, and in particular it has been shown by Adam et al (Ref. 10) that simple acclimatization precautions will enable subjects living in cold climates to be used to give reliable indications of the behaviour of subjects accustomed to hot climates. This phase of the work, however, is not yet commenced.

3.1 *Pilot Experiments* :

Since the transmittance of polythene for wavelengths between 4 and 35μ would have a critical effect on the success of the project, it was decided to determine experimentally the radiation exchange between a heated surface and a radiant cooling panel constructed along the lines proposed. The available information on the transmittance of polythene is shown in Fig. 5, from which it may be seen that its behaviour between 15 and 25μ could not be predicted with confidence.

In the experimental arrangement the plates which were about 3 ft. square were mounted horizontally, the hot plate uppermost,

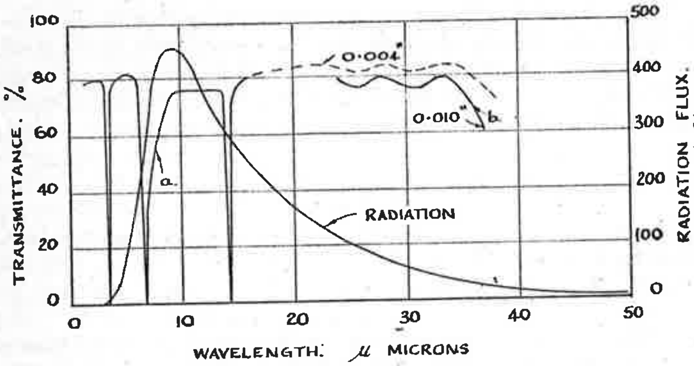

Fig. 5.—Transmittance of Polythene and Radiation from Black Body at 85°F.

(*a*) C.S.I.R.O. Chemical Research Laboratories.

(*b*) E. K. Plyler—J. Res. Nat. Bur. Stds., Vol. 41 : 125 (1948).

to reduce convection effects, and each was covered with two polythene films spaced about 1 in. apart. The hot plate was electrically heated by means of M.I. cable and maintained at 85°F., the other being cooled by refrigeration. At this stage of the project no suitable radiometer was available, and the radiation exchange was measured by observing the difference between the electrical input to the hot plate when shielded by a polished aluminium screen, compared with the value when exposed to the heat sink. The measured value of radiation exchange was then compared with the calculated values for spacings of 1 ft., 2 ft., 3 ft., and 4 ft. between plates and cold plate temperatures of 20°F. and 5°F., using the shape factors computed by Raber and Hutchinson (Ref. 4). Good agreement was obtained assuming the emissivity of the radiating surfaces to be 0.9 and the transmittance of polythene 0.87.

These results, therefore, were better than had been expected after allowing for the relatively crude experimental technique. They were sufficiently encouraging to justify the fairly elaborate equipment necessary for the second and third stages.

3.2 *Performance of Radiant Cooling Panel with Artificial Body* :

The radiation loss from the artificial body was measured for various values of panel temperature T_P for distances d (Fig. 2) from the cooling panel of 3 ft., 4 ft., and 5 ft. All readings were taken at a nominal air temperature of 85°F. and the temperature of the front face of the body which could see the cooling panel was adjusted until it was within 0.5°F. of the air temperature by varying the electrical power input to it. The total radiation flux was obtained by summing 30 readings, six on the front face, six on the rear face, and nine on each side of the artificial body.

The total radiation exchange Q_T between the body and the cooling panel can be considered as being made up of two components :

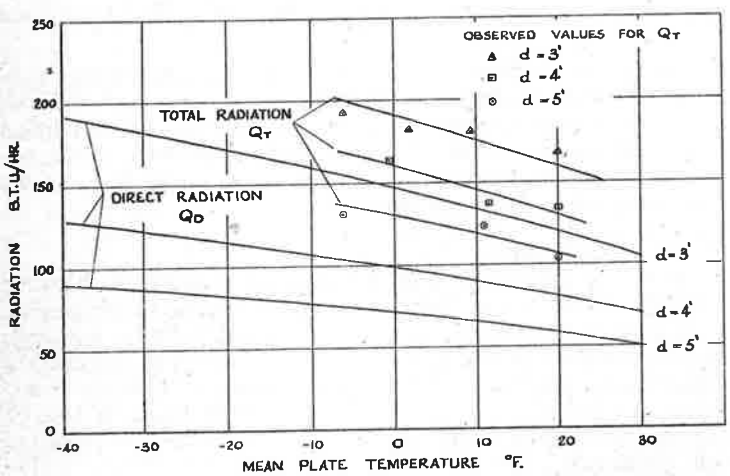

Fig. 6.—Radiation Exchange between Artificial Body at 85°F. and Radiant Cooling Panel for Room Temperature 85°F.

(*a*) Q_D, the direct radiation from the body to the panel, which is the radiation exchange from the face which can see the panel, and the panel itself. This can be calculated.

(*b*) Q_R, the radiation exchange between all faces of the body and any element of the walls, floor, or ceiling which is at a different temperature, together with that radiation from the body which reaches the cooling panel after one or more reflections from any of these surfaces. This in practice is very difficult to calculate and should be measured.

In order to calculate the value of Q_D, the emissivities of the body and the cooling panel and the transmittance of the three polythene sheets must be known. Fig. 6 shows values of Q_D calculated on the assumption that $\varepsilon_1 \varepsilon_2 \tau^3 = 0.54$, where $\varepsilon_1 \varepsilon_2$ are emissivities of the artificial body and the absorbing panel and τ is the transmittance of one sheet of polythene.

Q_D is a function of the temperature of the panel T_P, the temperature of the body T_B, and its distance d from the panel. It is independent of the reflectance of the walls or their temperature.

The value of Q_R is the difference between the total radiation exchange Q_T and Q_D, and is a function of T_P, T_B and the reflectance of all the interior surfaces and their temperatures. It is assumed to be nearly independent of the position of the body inside the room, and for the three positions measured can be considered independent of the distance d.

Accordingly, the experiments were planned to obtain numerical values of these two components of the total radiation Q_T, and to check the hypothesis that Q_R is nearly constant for a particular room surface treatment and panel arrangement but varies with panel temperature.

The curves for Q_T in Fig. 6 have been drawn as the best fit for the experimental values shown, consistent with the assumption that $Q_T - Q_D$, i.e., Q_R is constant for a given panel temperature.

Subsequent experiments described below indicate that the values of Q_T in Fig. 6 are too high for a room with low reflectance walls, and that they should be reduced by about 28 per cent. This is due partly to the plate temperature being uneven and also because small variations in wall temperature could have a big effect on $Q_T - Q_D$.

In order to standardize conditions as much as possible in the test room, for future work, the ceiling and those portions of the walls which could be seen by the body were covered with aluminium foil to give a highly reflective surface.

Using the zero convection technique the radiation loss from the artificial body was measured for one, two and three, radiant panels at a room condition of 92°F.D.B., 84°F.W.B.

Measurements were taken for one and two polythene layers insulating the front of the panels, and the performance for three layers was calculated. The results are shown in Figs. 7 and 8.

It will be seen that when one polythene layer is used, the radiation from the body increases as the panel temperature decreases until the point is reached when the polythene is at the dewpoint of the room air. At this stage, moisture condenses on it and the limit of operation is reached.

With two layers, the plate can be operated at a lower temperature before the limit is reached, and with three layers it would be still lower due to the extra insulation provided by the air spaces.

These operating limits depend on the wet bulb depression for the room and the extent to which the polythene is heated, but for the test conditions they were panel temperatures of 15°F. for one, and −3°F. for two layers.

It can be seen that the single layer gave the best cooling effect since absorption by the additional layers more than offsets the lower operating temperature of the panel.

It is reasonable to enquire whether an open plate with no cover would give even better performance after allowing for the increased loading due to condensation and convection. This, however, must operate above 32°F., but its refrigeration plant would have an improved coefficient of performance at the higher suction temperature. Such a plate was tested and it was found that the power input to the compressor was considerably greater and the cooling effect less than for the polythene covered panels.

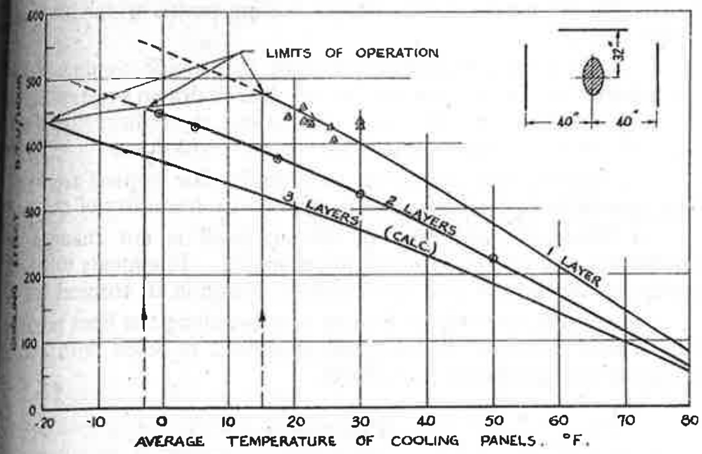

Fig. 7.—*Radiation Exchange between Artificial Body at 92°F. and three Radiant Cooling Panels for Room Temperature 92°F.*

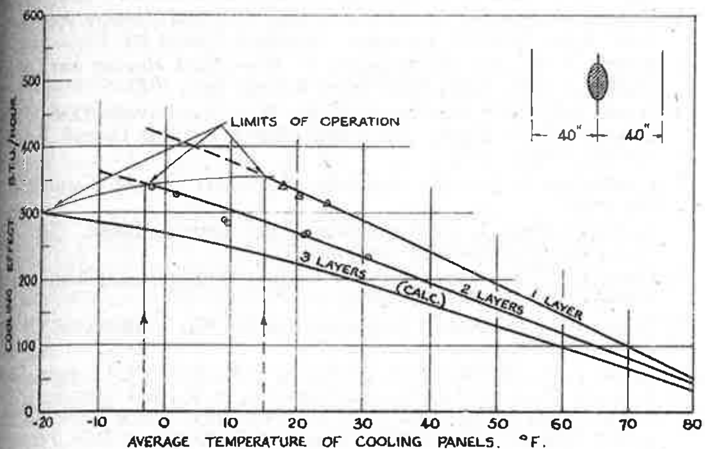

Fig. 8.—*Radiation Exchange between Artificial Body at 92°F. and two Radiant Cooling Panels for Room Temperature 92°F.*

Using three panels each 6 ft. by 4 ft. in the manner indicated in Fig. 7, a cooling effect of 450 B.Th.U. per hour could be obtained with one polythene layer.

For two panels Fig. 8 the maximum was 350 B.Th.U. per hour.

In order to check the effect of humidity on radiation exchange, observations were taken at both 40 per cent and 84 per cent R.H. at 85°F.D.B. temperature. It was found that there was no significant difference.

This is not conclusive evidence that absorption of radiation by water vapour in the room is unimportant over longer distances of perhaps 20 or 30 ft. It is, however, believed to be negligible for distances of the order of 5 ft. This is presumably due to two influences.

Firstly, the peak radiation from the human body which is at about nine microns wavelength, corresponds to a window in the water vapour absorption spectrum and secondly, one of the strong water vapour absorption bands occurs around seven microns which happens to coincide with the strong absorption band in the polythene sheet. Nevertheless, if radiant cooling were to be used over a considerable distance, this would need to be investigated more carefully.

3.3 *Radiant Heat Exchange in a Room*:

Determination of optimum area and arrangement of panels in a room offers an interesting study which has not yet been seriously undertaken. The desirability of treating portion of the walls and ceilings to increase their reflectance for 4 to 35μ radiation should be investigated. This will be influenced by the relative temperatures of the subject's skin, clothes, and the walls.

Since the skin temperature under conditions where cooling is required is likely to be close to that of the surroundings, it will be important to know this more precisely. Not enough is known at present on the relationship of skin temperature to comfort in the presence of a radiant heat sink.

When considering the radiation exchange between human subjects and panels in the walls and ceiling of a room, the form or shape factor of the subject in relation to the panel, as well as its distance away, must be known.

For subjects sitting and lying down, ceiling panels are suitable whilst wall panels result in better shape factors for standing subjects. It will be obvious that the walls of the room and its contents will radiate to the cooling panels as well as the occupants. However, by increasing the reflectance of the walls and ceiling the effectiveness of the panels may be increased, both by reflecting more radiation onto the panels and by reducing the radiation from the walls themselves.

The cooling effect obtained with either two or three panels is adequate for the physiological experiments which represent the next stage of the project. Although a considerable amount of work remains to be done on the radiation exchange between the panels, the room surfaces, and the occupants, it is clear that some measure of the effect on the comfort of human subjects is now necessary.

This is influenced by the amount and type of clothing worn and the form or shape factor of the subject with respect to the panels. Exposed skin has a very low reflectance to 10 μ radiation approximately 0.05 (i.e., nearly a black body) whilst cotton, woollen, and nylon cloth, irrespective of colour, is also quite good, having a reflectance of about 0.1 (Ref. 11). Accordingly, a lightly clothed subject could be expected to have a satisfactory radiation exchange with cooling panels if suitably oriented.

3.4 *Power Consumption*:

For the three 24-sq. ft. panels used in the above experiments under optimum operating conditions, the total power consumption was 600 W. This was obtained from measurements of refrigerant flow through the panels by estimating the power input to a typical commercial compressor operating under these conditions, and adding the power to run the small fan to blow room air over the external polythene sheet.

It is difficult to relate this to the power needed to air condition the space by conventional means. It would appear that radiant cooling would not require any power but might possibly use substantially less.

4.—Applications.

If radiant cooling can be shown to be successful from a physiological point of view it will involve a completely different approach to comfort air conditioning. In fact it should not be confused with air conditioning since the temperature and the humidity of the air are not changed. This has important advantages as well as some disadvantages. The advantages are that there is no need to restrict ventilation in any way, and tropical houses built on the pattern of having louvre walls to encourage cross ventilation would be quite satisfactory for radiant cooling of the occupants. Because the air is not conditioned, the system is likely to be appreciably more economical to operate than conventional air conditioning systems. On the other hand the panels are relatively bulky and will present installation and transport problems.

4.1 *Unit Construction*:

Since a satisfactory panel temperature is about 20°F., this may be obtained either by circulating brine or by direct expansion of refrigerant from self-contained sealed compressors associated with one or more panels constructed as a single unit. The condenser would preferably reject its heat outside the room. It is conceivable, however, that the condenser could be inside the room provided it were well ventilated and screened from radiation exchange with the occupants. The increase in the mean radiant temperature of the surroundings on this account could be made quite small by suitable design and the simplicity of installation is attractive.

4.2 *Bedrooms*:

It is often contended that living conditions in the Tropics would be made much more attractive if people could get a good night's sleep in comfortable surroundings. At one stage during the planning of the present research programme it was suggested that a small air conditioning unit should be developed in the form of a one-man plastic tent for just this purpose.

A radiant cooling panel mounted a few feet above the bed looks to be a more attractive solution, especially as it would have a very good shape factor from the point of view of radiation exchange.

4.3 *Condensation on Polythene Film*:

Two methods of preventing condensation on the outer film have been described. The heater suffers from the disadvantage of considerably increasing the power consumption and is not applicable to a horizontal panel. The fan which circulates room air is satisfactory for any mounting position but becomes less effective as the wet bulb depression decreases. Various alternatives are under consideration.

4.4 *Reflectance of Walls*:

It will be apparent that the cooling panel will absorb radiation from the walls and all interior surfaces as well as from the occupants. If the radiation due to the empty room is Q_P, the ratio $\frac{Q_T}{Q_P}$ may be called the utilization factor.

This will be influenced by the number of occupants, their shape factor in relation to the radiant cooling panels, and the reflectances of the interior surfaces. For most paints the reflectance in the region 4 to 35μ is very much lower (about 0.1) than in the visible region of the spectrum, where it might be about 0.7. It is not impossible, however, to develop appropriate paints which would have a high reflectance, perhaps 0.8, for this long wavelength radiation independent of their colour as seen by the eye. Such a surface treatment could increase the utilization factor. A thorough analysis of the influence of reflectance on the overall radiation exchange is necessary before a clear picture can be obtained.

5.—Summary of Conclusions.

1. It is considered that cooling of human subjects at a rate exceeding 300 B.Th.U. per hour by radiation alone in a room at 92°F. is possible by means of the radiant cooling panels which have been described.

2. Whilst this should be adequate to provide comfort cooling for subjects at rest, no firm conclusions can be drawn since systematic observations have not yet been carried out to confirm that human subjects will be comfortable under these conditions.

3. This method of cooling is attractive for tropical areas since the radiant heat exchange is not affected by humidity of the air.

4. Since the condition of the air itself is not changed, the method is not restricted to enclosed spaces. It appears to be well suited to the louvre wall construction common in tropical houses.

5. Radiant cooling for human comfort along the lines proposed has considerable possibilities but it should be used with caution until more information is available.

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